Space-time evolution of nuclear collisions
to be seen by ALICE experiment
using particle correlations

Ewolucja czasowo-przestrzenna zderzeń jądrowych
obserwowana w eksperymencie ALICE
poprzez analizę korelacji cząstek

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2005
Acknowledgments

I would like to thank to Guy Paič, who was my tutor through almost all my PhD studies, for patience and stimulation, for guidance and inspiration, for discussions and explanations. He is the example to follow. I want to thank to Federico Carminati for the tremendous hospitality and immense support during my 3 years stay in his group at CERN as a doctoral student. I wish I always have such a boss. I would like to acknowledge all the PH-AIP group, especially Karel Šafařík for explanations and guidances, Youra Belikov and Marian Ivanov for helping me to deal with the reconstruction software, Andi Peters for his support with the Grid. Without them I would not be able to get all the results presented in this thesis. I would like to thank to Boris Tomášik, Mike Lisa and Urs Wiedemann for cooperation, explanations and fruitful discussions. I thank to my adviser, prof. Jan Pluta. Without him this thesis would not be possible.

I acknowledge all my extraordinary friends at CERN and in Heavy Ion Reaction Group at my university. I thank my parents and brothers for support and love. I am grateful to my wife Luiza for her love and patience through all the long three years when I was absent by her side being at CERN preparing this thesis. Thank you!
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Preface

Physics is a science that deals with the structure of matter and the interactions between the fundamental constituents of the observable universe [1]. When quarks were found to be constituents of nucleons, questions concerning the properties of quark matter immediately were raised. What is especially intriguing is the nature of the strong force, that is responsible for interactions of quarks, which prohibits them to be observed free. They are confined inside hadrons.

We would like to find all the properties of quark matter: phase diagram and equation of state in each of phases. The chromo-dynamical calculations predict that if nuclear matter is at sufficiently high temperatures and/or densities, the distances between hadrons become comparable to distance between quarks inside a hadron. Quarks are deconfined and can freely move inside the system. This phase is called Quark Gluon Plasma (QGP). Physicists attempt to create QGP in laboratory by colliding heavy nuclei with relativistic velocities. In 2007 the construction of the Large Hadron Collider (LHC) at CERN will be completed. This machine will be able to collide lead nuclei with energies of 5.5 TeV per nucleon.

The ALICE experiment, one of the four large experiments at LHC, is dedicated to the study the systems created in heavy ion collisions. The complicated nature of the formed system necessitates a thorough study of a great variety of parameters [3].

In the present thesis we concentrate on a small part of the provisioned analyses, namely on close velocity particle correlations. The work consists of the preparation of analysis tools and their tests using simulated data. It includes implementation of the analysis software, simulation tools, detailed study of the detector effects that artificially modify correlation functions and development of algorithms that allows to remove its influence.

On the physics side we studied the effects on the correlation functions due to the high cross sections for parton (quark or gluon) interactions with large momentum transfer leading to a large number of jets. These jets will represent a source of hadrons with very specific characteristics that are very different from that of particles created in the thermalized medium.

ALICE will also study proton-proton and proton-ion reactions. For this kind of elementary collisions a consistent interpretation of the measured two particle momentum correlations in terms of the collision dynamics is largely missing. We developed a model in order to explain the existing results as the reflection of space-time evolution of the hadronization process on correlations.

The work is organized as follows. The introductory chapter presents the physics motivation of the field of relativistic heavy ion collisions. Current understanding of QGP and predicted observables are presented. We introduce the particle correlations, the theoretical description of the method as well as current experimental status. The importance of the hard processes is underlined. Further, we describe ALICE experimental setup and we explain the motivations supporting the chosen solutions.

The second chapter describes the software tools we have implemented. This includes the analysis foundation library, package for particle correlations analysis, programs for simulating the signal under study. Additionally, the contribution to the core facilities of ALICE Off-Line framework is outlined.

In the third and fourth chapters we present models that allow us to understand the influence of hard processes on particle correlations in ion-ion and proton-proton collisions, respectively.

In the fifth chapter the performance of ALICE in particle momentum correlation measurements is evaluated. We extract the resolutions and particle identification efficiencies as functions of the relative momenta of both particles. We show the obtained correlation functions before applying any correction. We discuss the influence of the splitting and merging of tracks in the reconstruction procedure on the correlation functions. The solutions that allowed removing their impact on the measured parameters are presented, as well as corrections for momentum resolution and particle identification imperfection. We evaluate the systematic errors. At the end we point out to possible deficiencies of the reconstruction software, and draw perspectives for additional improvements and further analyses.
1 Introduction

1.1 Physics of Heavy Ion Collisions

Modern nuclear physics, *inter alia*, explores the Standard Model applied to complex and dynamically evolving systems of finite size. It employs compressed and heated nuclear matter created in a collision of two heavy nuclei moving with ultra relativistic velocities.

The most interesting phenomenon predicted by the Standard Model is occurrence of a phase transition of nuclear matter into new state of Quark-Gluon Plasma (QGP). A comprehensive review of the current understanding of QGP was recently published in the first volume of Alice Physics Performance Report [3]. It describes all theoretical aspects, the signatures and the predicted observables. Another recent review [4] describes the current status of the measurements and lists all the current experimental and theoretical challenges. Hence, in this introduction we will only recall the main points and we are addressing an interested reader to these documents and references herein.

1.1.1 Quark Gluon Plasma - Theoretical predictions

The lattice gauge calculations of Quantum Chromo-Dynamics (QCD) predict that at sufficiently high energy densities and/or temperatures hadronic matter should undergo a phase transition to QGP. In this state quarks and gluons become deconfined. Universe must have been in this state at \( \sim 10^{-5} \) s after Big Bang, before it hadronized. It probably also exists in cores of dense stars. The phase diagram of the hadronic matter is shown in figure 1.1. The simulations show that energy density greater than 1 GeV/fm\(^3\) is needed to reach the QGP phase. LHC will provide many times the threshold energy density. The number of elementary degrees of freedom of the system increases drastically during the phase transition from hadronic matter to QGP. The color force between quarks and gluons decreases dramatically (asymptotic freedom) and so do quark masses. Namely, \( u \) and \( d \) masses are calculated to be equal to \( 1 - 5 \) MeV and \( 3 - 9 \) MeV, respectively. These values are very small relatively to the strong force. Hence, in QGP chiral symmetry restoration is predicted, which is spontaneously broken in the normal hadronic matter phase.

The order of the phase transition is not clear yet. No order parameter has been found to distinguish these two states. Simulations show that the phase transition is of the first order, accompanied by a rapid increase of the entropy density, corresponding to deconfinement. But it depends on the number of light quarks. If \( s \) quark can be considered as a "light" (mass \( 75 - 170 \) MeV) together with \( u \) and \( d \), and there are 3 quarks with negligible masses, the phase transition is of the first order. In this case the transition seems to be dominated by the chiral symmetry restoration effects. On the contrary when we are dealing only with 2 massless quarks the result is a second-order phase transition. However, the assumption about zero quark masses seems to be unrealistic, and the most recent calculations predict that for non-vanishing masses for all quarks, there is no phase transition and it is a simple crossover [5].

Theoretical calculations of the critical temperature \( T_c \) based on the pure gauge \( SU(3) \) theory gives \( T_c \sim 264 \) MeV with an accuracy of a few percent [5,6]. Calculations which take into account dynamical quarks gave the result with higher uncertainty \( T_c \sim 150 - 200 \) MeV. The newest calculations indicate that it is a rapid crossover in narrow temperature interval around \( T_c \sim 170 \) MeV [8].

The theoretical physics of QGP is very imperfect due to the complication level of QCD and lack of experimental data, which would allow to tune models and simulations. Other complications come from inability of use of perturbative theory in QGP physics, due to the big coupling constant of strong interactions and its dependence on momenta of interacting particles. This dependence is called "running" coupling constant and it vanishes for small distances or high momenta of interacting particles and
1 Introduction

Color Superconductor

Chemical potential at a few times nuclear matter density

Temperature

Cooling of a plasma created at LHC ?

Quark-Gluon Plasma
- deconfined
- chiral symmetric

Hadron Gas
- confined
- chiral symmetry broken

Color Superconductor

Figure 1.1: (a) The phase diagram of QCD: The solid lines indicate likely first-order transitions. The dashed line indicates a possible region of a continuous but rapid crossover transition. The open circle gives the second-order critical endpoint of a line of first-order transitions, which may be located closer to the $\mu_B = 0$ axis. (b) Lattice Monte Carlo results on the QCD-phase boundary [9, 10] shown together with the chemical freeze-out conditions obtained from a statistical analysis of experimental data (open symbols) [11, 12]. The dashed line represents the Lattice Gauge Theory (LGT) results obtained in Ref. [10] with the gray band indicating the uncertainty. The filled point represents the endpoint of the crossover transition taken from Ref. [9]. The solid line shows the unified freeze-out conditions of fixed energy per particle $\approx 1$ GeV [11, 12].

reversely, is large for high distances and small momenta. The most reliable simulations concerning QGP are done on non-perturbative lattice, because it is the only rigorous method to compute the equation of the state (EoS) of strongly interacting elementary particle matter.

Another very important topic is Debye screening, which is at the basis of many phenomena associated with QGP. In QCD it has opposite effect to that in QED, where Debye screening causes increase of interaction with decrease of distance. This aspect is strongly connected with the "running" coupling constant in QCD. Virtual gluons carry away color from the quark to the cloud, so as the incident probe penetrates the cloud it sees less and less color, and probed color charge decreases. In QGP all quarks moves in a "common" cloud, and they do not interact with each other, because none of them see any color. Quarks and gluons can move within QGP space without any resistance and that is why QGP is sometimes called a color superconductor. This behavior is expected at large $\mu_B$ and relatively small temperatures (see Fig. 1.1a). A first order transition to this phase is expected with large certainty. If the transition at small $\mu_B$ is not of the first-order then a second-order critical point must exist somewhere in the interior of the QCD diagram.

1.1.2 QGP in laboratory

Nuclei at sufficiently high energy traverse each other and leave behind them a baryonless blob of QGP. This blob evolves in time and cools, passing through different stages, such as mixed phase and a hadron gas, depending on initial energy density. Hadron gas freezes-out in two steps. First chemically, when hadrons decouple from each other and particles are ultimately produced. At this moment the particle composition is fixed and is almost unaffected by the consecutive rescatterings. The system further ex-
pands in space. The moment rescattering ceases is the so called kinetic freeze-out. However, this scenario might be much too simple to predict the behavior of such complex system at such high energy. We really don’t know how long the system will be in each stage, and whether all assumptions made are proper.

Energy density in ultra-relativistic collision can be estimated from Bjorken’s phenomenological formula [22]

$$\varepsilon = \frac{1}{\tau_0 \pi R^2} \frac{dE_t}{dy}$$  \hspace{1cm} (1.1)

where $\tau_0$ is the equilibration time, $R$ - the radius of the nucleus and $dE_t/dy$ is the average transverse energy per unit of rapidity. According to the first Bjorken estimates, collisions with energy of 15 GeV per nucleon pair in the center of mass system ($\sqrt{s}$) is sufficient to reach transition energy density. And indeed, experiments at SPS ($\sqrt{s} = 17$ A GeV) has found a few signatures of the new state [13], although they were not compelling to all the physics community. Even at RHIC, that provides collisions at $\sqrt{s} = 200$ A GeV, the signatures do not confirm unambiguously the creation of QGP [4].

1.2 Hard processes

Hard processes are the interactions between two partons with large momentum transfer $Q$. They lead to jets, i.e. collimated set of final state particles. All the parton virtuality gained in the interaction, ($Q^2 = E^2 - (p^2 + m^2)$, i.e. energy excess over $(p^2 + m^2)$ that is allowed on time scales smaller than $\frac{\hbar}{Q}$) is converted into mass. Hence, virtuality can be approximated by invariant mass of the final state di-jet system $M$. Fig. 1.2 illustrates that as $\sqrt{s}$ increases as partons with smaller Bjorken $x$ are probed. Bjorken $x$ is a dimensionless variable that is determined by the fraction of momentum carried by a constituent of a projectile in the infinite momentum frame. The structure functions that describe the composition of the colliding hadron are defined as its function. The momentum distributions within hadrons are assumed to be universal. Hence, they are of the particular interest because their detailed knowledge reveal the most basic principles of QCD.

![Figure 1.2](image-url)

**Figure 1.2:** The range of Bjorken $x$ and $M^2$ relevant for particle production in nucleus–nucleus collisions at the top SPS, RHIC, and LHC energies. Lines of constant rapidity are shown for LHC, RHIC and SPS [3].

It is predicted that due to limited available phase space the gluon density saturates at some small value of $x$ and ALICE will be able to reach this scale, where the classical thermodynamics drives the time evolution of the system.
With increasing beam energies the cross section of hard processes raises. At the LHC energies they will significantly contribute to the total cross section and, in consequence, to the overall particle production [3]. It is estimated that in Pb-Pb collisions at LHC on average more than 100 jets with total transverse momentum greater than 5 GeV, will be observed per event at ALICE central barrel acceptance ($|\eta| < 0.9$) [14].

Bjorken predicted at early eighties the existence of the jet quenching phenomenon due to the parton energy loss in the dense, strongly interacting medium [15]. It was already observed at RHIC [18–21]. The details of his predictions needed to be revised, because he argued that the dominant effect is elastic multiple scattering and afterwards it was discovered that dominant effect is a kind of bremsstrahlung [16]. Additionally, the gluons emitted in the rescattering undergoes the process described earlier by Bjorken. This way the hard parton energy is very effectively transferred to the medium that is initially made of soft gluons created in the very first stage of the collision [17].

This phenomenon enables the very powerful tool called the jet tomography. Namely, a fast parton is a probe of the medium a the time it travels through. The modifications of the jet spectra (compared to the proton-proton and proton-nucleus collisions) reveal the properties of the matter at early stages of the system evolution. They are sensitive to the geometry of the collision, i.e. they dependent on the impact parameter as well as on the reaction plane orientation (see Fig. 1.4 for impact parameter and reaction plane definitions). Additionally, gluons are stopped faster then quarks and quenching depends on a mass of a quark. Jets also can be analyzed on the opposite direction with respect to high momentum, not strongly interacting photon or $Z^0$ (created in reactions $q + g \rightarrow q + Z^0 \rightarrow q + \mu^+ \mu^-$, $q + q \rightarrow g + Z^0 \rightarrow g + \mu^+ \mu^-$, $g + g \rightarrow q + \gamma$, $g + \bar{q} \rightarrow g + \gamma$).

The large fraction of particles originating from jets may change interpretation of some bulk observables, for example particle correlations. If we assume that the source is a superposition of jet sources and a thermal fireball then the resulting correlations should reflect contributions from:

- pairs of particles from a single jet, which will reflect dimension of the region where the jet fragmented;
- pairs of particles from different jets, which will be given by the size of the initial collision volume;
- pairs where both particles stemming from the decoupling of thermal fireball (larger than the initial collision volume);
- pairs where one particle comes from the thermal fireball and the other one is produced from jet fragmentation.

### 1.3 Particle Correlations

#### 1.3.1 The most basic principles

Two hadrons interact strongly, and eventually electromagnetically if both counter-partners have non zero electric charge. These Final State Interactions (FSI) are as more pronounced as the emitted particles have closer velocities and are closer in space. If they are distinguishable (i.e. not identical) the FSI induced correlations allow to measure the space-time asymmetries of the emission from source created in a collision. If they are identical, amplitude interference plays a role. The span of the induced correlation in momentum is inversely proportional to average size of the particle emission region due to the uncertainty relation.

In both cases the correlation function gives the information about the average dispersion of the effective source around the point of the highest emissivity. For expanding systems, for which momentum-space correlations occur, this dispersion is referred as homogeneity length. It is impossible to find unambiguously all the four dispersions (three spatial and one temporal) and an additional model assumption is always required. In the non-identical particle correlation analysis we can not distinguish if both particle
types are emitted at the same time and the points of the highest emissivity do not coincide or if particles are emitted from the same region but at different times.

This method of source size measurement is commonly called HBT, because it is very similar to the one invented by Hanbury-Brown and Twiss [23] that is used in astronomy to determine star angular dimensions. The correlations of bosons are also frequently referred as BEC (Bose-Einstein Correlations), and of fermions as FDC (Fermi-Dirac Correlations).

Very extensive literature on this subject exists by now, including several reviews, e.g. [24–26]. In this section I will follow the description of Heinz and Wiedemann for identical particle correlations [25] and Lednicky et al for non-identical ones [27, 28].

1.3.2 Theoretical overview

1.3.2.1 Correlations due to Quantum Statistics

As a convention we use bold symbols for four-vectors and symbols with an arrow over them for three-vectors.

The source is fully described by Wigner density \( S(x, p) \) that defines the Lorentz invariant probability \( \mathcal{P}_1 \) of observing a particle with four-momentum \( p \) emitted from space-time coordinate \( x \)

\[
\mathcal{P}_1(p) = E \frac{dN}{d^3p} = E \langle \hat{a}_p^+ \hat{a}_p \rangle = \int d^4x S(x, p) \tag{1.2}
\]

where \( E \) is energy, \( \hat{a}_p^+ \) and \( \hat{a}_p \) are creation and annihilation operators, respectively. Hence, the two particle probability is

\[
\mathcal{P}_2(p_1, p_2) = E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} = E_1 E_2 \langle \hat{a}_{p_1}^+ \hat{a}_{p_2}^+ \hat{a}_{p_2} \hat{a}_{p_1} \rangle \tag{1.3}
\]

\[
= \int d^4x_1 d^4x_2 S(x_1, p_1) S(x_2, p_2) |\Psi|^2. \tag{1.4}
\]

\[
\Psi = \frac{1}{\sqrt{2}} [e^{i(r_1 - x_1)p_1} e^{i(r_2 - x_2)p_2} \pm e^{i(r_1 - x_2)p_1} e^{i(r_2 - x_1)p_2}] \tag{1.5}
\]

where \( \Psi \) is the amplitude of the detection of two particles with momenta \( p_1 \) and \( p_2 \) at \( r_1 \) and \( r_2 \). The upper sign in Eq. 1.5 holds for bosons and the lower one for fermions. This equation assumes completely coherent then interference does not occur and the two particle probability can be expressed as the product of the single particle probabilities.

The two particle correlation function is defined as

\[
C(p_1, p_2) = N \frac{\mathcal{P}_2(p_1, p_2)}{\mathcal{P}_1(p_1) \mathcal{P}_1(p_2)} = N \int d^4x_1 d^4x_2 S(x_1, p_1) S(x_2, p_2) |\Psi|^2 \int d^4x_1 S(x_1, p_1) \int d^4x_2 S(x_2, p_2). \tag{1.6}
\]

where \( N \) is the normalization factor. One can substitute particles momenta \( p_1 \) and \( p_2 \) with their relative momentum \( Q = p_1 - p_2 \) (\( \vec{Q} = \vec{p}_1 - \vec{p}_2 \), \( Q^0 = E_1 - E_2 \)) and pair average momentum \( K = \frac{1}{2}(p_1 + p_2) \) (\( \vec{K} = \frac{1}{2}(\vec{p}_1 + \vec{p}_2) \), \( K^0 = \frac{1}{2}(E_1 + E_2) \)).

Further we use the following relations and approximations:

1. **mass-shell constraint**

\[
K \cdot Q = \frac{1}{2}(p_1^2 - p_2^2) = \frac{1}{2}(m_1^2 - m_2^2) = 0 \tag{1.7}
\]

This relation results from the fact that the detected particles must be on the mass-shell, i.e. \( p_2^2 = E^2 - |\vec{p}|^2 = m \). Since we are investigating here correlations due to the quantum statistics particles must be identical. This indicates that

\[
Q^0 = \vec{K} \cdot \vec{q} / K^0 \tag{1.8}
\]
2. **smoothness assumption**

\[
S(x_1, K - \frac{1}{2}Q) S(x_2, K + \frac{1}{2}Q) \approx S(x_1, K) S(x_2, K).
\]

(1.9)

Emission function does not change in momentum scale of the order of \(Q\). It is justified because the correlation signal is situated at small relative momenta and the approximation is proved to be almost exact for typical hadronic emission functions.

3. **on-shell approximation**

\[
S(x, K) = S(x, K^0, \vec{K}) \approx S(x, E_K, \vec{K}) = S(x, K), \quad E_K = \sqrt{m^2 + \vec{K}^2}.
\]

(1.10)

The emission function \(S(x, p)\) depends in principle on the off-shell momentum \(K\). However, it is convenient and justified to drop this dependence and use on-shell momenta instead.

4. **Gaussian form of the emission function.**

The correlator can be expressed as

\[
C(\vec{Q}, \vec{K}) \approx 1 + \frac{\int d^4x S(x, \vec{K}) e^{i\vec{Q} \cdot \vec{x}}}{\int d^4x S(x, \vec{K})^2}
\]

(1.11)

\[
\approx 1 + \lambda(K) \exp \left( \frac{-1}{\hbar^2 c^2} \sum_{ij} R_{ij}^2(K) Q_i Q_j \right).
\]

(1.12)

where \(R\) are the dispersions around the point of the highest emissivity \(\tilde{x}\)

\[
R_{ij}^2(K) = \langle (\tilde{x}_i - \beta_i \bar{n})(\tilde{x}_j - \beta_j \bar{n}) \rangle,
\]

(1.13)

and \(i, j = 1, 2, 3\) represent the spatial coordinates. \(\lambda\) is the intercept parameter that describes the chaosity of the source.

The correlator (1.11) is a Fourier transform of the emission function \(S(x, \vec{K})\). However, due to the mass shell constraint (see Eq. 1.8) it is not possible to reconstruct \(S(x, \vec{K})\) uniquely from a measured correlator (1.12), because only three of the four independent \(x\) components can be tested. An additional model-dependent relation must be always introduced.

The two basic approaches of deriving equation 1.12 are worked out (see [25] and references herein)

- superposition of non-relativistic wave packets
- classical current parametrization

### 1.3.2.2 Correlations due to the Final State Interactions

#### 1.3.2.2.1 Strong Interactions

The Final State Interactions due to the strong forces can be incorporated into the description presented above by substituting the plane wave amplitude Eq. (1.5) by the non-symmetrized Bethe-Salpeter amplitudes \(\Psi_5(p_1, p_2, x_1, x_2)\). FSI is calculated in pair center of mass system (PRF, Pair Rest Frame) as the elastic scattering of two particles involved. The amplitude can be represented in two particle relative coordinates

\[
\Psi_5(p_1, p_2, x_1, x_2) = e^{iK \cdot x} \Psi_s(K^*, r^*)
\]

(1.14)
where $\mathbf{X} = \frac{1}{2}\mathbf{p}_1 \cdot \mathbf{K} \mathbf{x}_1 + \frac{1}{2}\mathbf{p}_2 \cdot \mathbf{K} \mathbf{x}_2 / 2\mathbf{K}^2$ is the pair four-coordinate, $2\mathbf{k}^*$ is particle momentum difference and $\mathbf{r}^*$ is distance between emission points. The star super-script indicates that a variable is evaluated in PRF. For non-identical particles the generalized momentum difference is defined as

$$\mathbf{Q} = \mathbf{Q} - \frac{\mathbf{K} (\mathbf{Q} \cdot \mathbf{K})}{\mathbf{K}^2}$$

(1.15)

and in PRF $\tilde{\mathbf{K}} = 0$ and $\tilde{\mathbf{Q}} = (0, 2\mathbf{k}^*)$.

At equal emission times ($r^* = t_1^* - t_1^* = 0$) $\Psi_5$ depends only on three-vectors and $\Psi_5(\tilde{\mathbf{k}}^*, \tilde{\mathbf{r}}^*)$ coincides with a stationary solution of the scattering problem. At large $r^*$ it has the asymptotic form of a superposition of the plane and outgoing spherical waves. It is proved that the equal time approximation is valid for thy typical sources created in heavy ion collisions.

Additionally, we assume

- for small relative momenta only the s-waves need to be considered
- absence of Coulomb interaction
- range of interaction is smaller then the initial separation in PRF

then the scattering amplitude can be factorized

$$\Psi_5(\tilde{\mathbf{k}}^*, \tilde{\mathbf{r}}^*) = e^{-i\tilde{\mathbf{k}}^* r^*} + f(\tilde{\mathbf{k}}^*) \Phi_{\tilde{p}_1, \tilde{p}_2}(\tilde{\mathbf{r}}^*)$$

(1.16)

where $f(\tilde{\mathbf{k}}^*)$ is the unsymmetrized s-wave scattering amplitude, and $\Phi_{\tilde{p}_1, \tilde{p}_2}(\tilde{\mathbf{r}}^*)$ is the remaining part that can be integrated over $\tilde{\mathbf{r}}^*$. Hence, the correlation function for the case of strong interaction that we assume does not depend on spin configuration reads

$$C(\tilde{\mathbf{k}}^*, \tilde{\mathbf{K}}) \approx 1 + \int d^4\mathbf{x}_1 d^4\mathbf{x}_2 S(\mathbf{x}_1, \tilde{\mathbf{p}}_1) S(\mathbf{x}_2, \tilde{\mathbf{p}}_2) W(\tilde{\mathbf{x}}_1, \tilde{\mathbf{p}}_1, \tilde{\mathbf{x}}_2, \tilde{\mathbf{p}}_2)$$

(1.17)

$$W(\tilde{\mathbf{x}}_1, \tilde{\mathbf{p}}_1, \tilde{\mathbf{x}}_2, \tilde{\mathbf{p}}_2) = |\Psi_5|^2 = \left( 1 + \frac{(-1)^{2j}}{2j+1} \right) \left\{ |f(\tilde{\mathbf{k}}^*) \Phi_{\tilde{p}_1, \tilde{p}_2}(\tilde{\mathbf{r}}^*)|^2 + 2 Re[f(\tilde{\mathbf{k}}^*) \Phi_{\tilde{p}_1, \tilde{p}_2}(\tilde{\mathbf{r}}^*)] \cos(\tilde{\mathbf{k}}^* \tilde{\mathbf{r}}^*) - 2 Im[f(\tilde{\mathbf{k}}^*) \Phi_{\tilde{p}_1, \tilde{p}_2}(\tilde{\mathbf{r}}^*)] \sin(\tilde{\mathbf{k}}^* \tilde{\mathbf{r}}^*) \right\}$$

(1.18)

The correlation function is sensitive to the sign of the time difference due to the odd term

$$\sin(\tilde{\mathbf{k}}^* \tilde{\mathbf{r}}^*)$$

(1.19)

To determine the mean emission time difference two correlation functions, $C_+$ and $C_-$, are constructed. Note that in the analysis the order in a pair must be always the same i.e. a particle of a given type is always “first”. $C_+$ is constructed for pairs having first particle faster then second, and $C_-$ is build for the reverse case. Detected particles have relativistic velocities ($|\mathbf{v}| \gg r$) and since coordinate along pair velocity reads $r^* = \gamma(r_1 - vt)$ and coordinate transverse to it $r^*_t = r_t$ so $\tilde{\mathbf{r}}^*$ is almost parallel or anti-parallel to the pair velocity. Hence, for pairs having fixed sign of $k^* v$ the sign of the (1.19) term is determined by the time difference $t$. As the consequence the two correlation functions $C_+$ and $C_-$ have different shapes if the emission time of the considered particles is different.

### 1.3.2.2 Coulomb Interactions

The amplitude for the Coulomb interaction of two particles is

$$\Psi_C(\tilde{\mathbf{k}}^*, \tilde{\mathbf{r}}^*) = e^{\delta_k} \sqrt{A_C(\tilde{\mathbf{k}}^*)} e^{-ik^* \mathbf{r}} F\left( \mathbf{r}, 1; \frac{1}{k^* a}, 1 \right)$$

(1.20)

where $e^{\delta_k} = \arg \Gamma(1 + i/k^* a)$ is the Coulomb s-wave phase shift, and

$$A_C(\tilde{\mathbf{k}}^*) = \frac{2\pi}{k^* a} \left[ \exp \left( \frac{2\pi}{k^* a} \right) - 1 \right]^{-1}$$

(1.21)
1.3.2.2.3 Fitting correlations due to FSI  The shape of the correlator for FSI can not be well parameterized by a simple analytical formula, even if the (over) simplified Gaussian approximation of the emission function is applied. For the Coulomb interactions sometimes the approximation of a point like source is applied. Then the amplitude is reduced to $A_C$ defined in Eq. (1.21). However, this approximation is not valid for typical source sizes measured in heavy ion collisions.

Hence, more sophisticated approach is necessary to find the source parameters. CorrFit program [30] is the single tool known to us that enables such a functionality. It simulates a correlation function on the basis of non-correlated two particle spectrum created from mixed pairs (i.e. particles originating from different events) using the weighting algorithm (see section 2.6.1). It assumes some model of the source, i.e. for each pair randomizes the 4-vector distance between particles. For a given set of model parameters it gives the $\chi^2$ value that describes how similar are the obtained and measured correlation functions.

1.3.3 Definitions of the variables used in the close velocity correlations

Several parameterizations of the correlation function exists [25]. Nowadays, the most popular is the three dimensional Bertsch-Pratt one (also called Cartesian) as it allows for the most clear interpretation of the radii. Relative momentum vector is decomposed to the following components, see Fig.1.3:

- **long** parallel to beam
- **side** perpendicular to beam and pair momentum $K$
- **out** perpendicular to long and side

Components in out direction are written with subscript $o$, in side with $s$ and in long with $l$. Also in non-identical particle analysis the Bertsch-Pratt decomposition is of the greatest use. The sign of the out component of $k^*$ vector determines which particle is faster.
1.3 Particle Correlations

The most adequate frame is the so called Longitudinally Co-Moving System (LCMS) where velocity components in beam (longitudinal) direction are equal, because for longitudinally boost-invariant sources all cross-term vanishes. In this frame the correlator (1.12) is reduced to the following form due to the spatial symmetries

\[
C(Q_o, Q_s, Q_l) = 1 + \lambda \exp\left(-\frac{1}{\hbar^2 c^2}(Q_o^2 R_o^2 + Q_s^2 R_s^2 + Q_l^2 R_l^2 + 2Q_o Q_s R_{os})\right)
\]  

(1.22)

The exact relation of the radii (see Eq. 1.13) with the spatial dispersions reads

\[
R_o^2(\phi) = \frac{1}{2}((\langle y^2 \rangle + \langle x^2 \rangle) - \frac{1}{2}((\langle y^2 \rangle - \langle x^2 \rangle) \cos(2\phi) + \beta^2_\perp \langle r^2 \rangle), 
\]

(1.23)

\[
R_s^2(\phi) = \frac{1}{2}((\langle y^2 \rangle + \langle x^2 \rangle) + \frac{1}{2}((\langle y^2 \rangle - \langle x^2 \rangle) \cos(2\phi), 
\]

(1.24)

\[
R_l^2(\phi) = \langle z^2 \rangle, 
\]

(1.25)

\[
R_{os}^2(\phi) = \frac{1}{2}((\langle y^2 \rangle - \langle x^2 \rangle) \sin(2\phi) 
\]

(1.26)

where \(\phi\) is azimuthal angle with respect to the reaction plane (see Fig. 1.4).

\[\text{Figure 1.4: Sketch of a peripheral collision. Reaction (event) plane is defined by impact parameter vector (connects centers of the colliding nuclei) and the beam axis. Principle of the azimuthally sensitive particle correlations analysis.}\]

For central collisions which are azimuthally symmetric, os cross term vanishes

\[
C(Q_o, Q_s, Q_l) = 1 + \lambda \exp\left(-\frac{1}{\hbar^2 c^2}(Q_o^2 R_o^2 + Q_s^2 R_s^2 + Q_l^2 R_l^2)\right)
\]

(1.27)

The exact relation of the radii with the spatial dispersions is the following

\[
R_o^2 = \langle (\vec{x} - \beta_\perp \vec{r})^2 \rangle, 
\]

(1.28)

\[
R_s^2 = \langle \vec{z}^2 \rangle, 
\]

(1.29)

\[
R_l^2 = \langle \vec{z}^2 \rangle. 
\]

(1.30)

Note also that for small opening angles the components long and side are approximately proportional to the relative polar (\(\Delta \theta\)) and azimuthal (\(\Delta \phi\)) angles, respectively. The out component is determined by the difference of the absolute values of transverse velocity and depends on the tracks curvature.

Frequently, only two dimensional correlation functions \(C(Q_T, Q_l)\), where \(Q_T = \sqrt{Q_o^2 + Q_s^2}\), are constructed if limited statistics is available. In the past experiments for identical particle analysis one dimensional \(C(Q_{inv})\) correlation function was the most popular. \(C(Q_{inv})\) is invariant momentum difference

\[
Q_{inv} = \sqrt{M_{inv}^2 - 4m^2}
\]

(1.31)
where $M_{\text{inv}}$ is invariant mass of two particle system and $m$ particle mass at rest. Note that if particle masses are equal then $2k^{\ast} = Q_{\text{inv}}$.

Another parametrization used in the past experiments is

$$C(Q_{t}, Q_{0}) = 1 + \lambda \exp\left(\frac{-1}{\hbar c^2}(Q_{t}^2 R_r^2 + Q_{0}^2 \tau^2)\right)$$  \hspace{1cm} (1.32)

where $Q_{t}$ is the projection of the three momentum difference onto the plane perpendicular to the sum of momenta, $Q_{0}$ is the energy difference and $\tau$ is dispersion (radius) in the time domain.

$e^{+}e^{-}$ experiments frequently define longitudinal direction as parallel to jet or thrust axis.

### 1.3.4 Experimental correlation function

An experimental correlation function is constructed as a ratio of the appropriate two particle spectra

$$C(Q_{i}) = \frac{N(Q_{i})}{D(Q_{i})}$$  \hspace{1cm} (1.33)

where $N$ stands from numerator histogram, $D$ from denominator, $i$ is bin index. Numerator is $Q$ distribution constructed with actual pairs, i.e. particles that originate from the same event. The denominator is reference sample that represents the product of single particle distributions. It does not contain the correlation signal, but ideally it also should expose all the dynamic effects as the numerator.

Several algorithms of constructing the reference sample exist. In the analysis of the relativistic heavy ion collisions the event mixing technique is used. The reference distribution is calculated with the pairs of particles which originate from the different events. However, the application of this technique in some cases, e.g. very low multiplicity events which have a clear jet-like structure ($e^{+}e^{-}$) can be questionable. In such cases other techniques, are applied

- the different sign particles – for example in $\pi^{+}\pi^{+}$ analysis the distribution for $\pi^{+}\pi^{-}$ is used. It is applicable only in the identical particle analysis.
- the Stavinsky algorithm [76] – the distribution for pairs for which one of the particles momentum vector is reversed
- simulated data with correlation effect not included

However, none of them is perfect. The reference distribution obtained with the first method usually bears the signatures of the resonance decays and also needs to be corrected appropriately for the Coulomb final state interactions, what always brings large systematic uncertainties. The Stavinsky algorithm solves the problem only in the case of events having clear di-jet structure. Otherwise, similarly to the mixing, the reference distribution lacks the dynamic effects due to the jet fragmentation topology in the high momentum regime (above 1 GeV). The last method clearly brings huge uncertainty because we never can be sure that the obtained distribution corresponds to the real one in case interference and final state interactions were absent.

### 1.3.5 Current experimental status in particle correlations

Particle correlations were measured for wide range of energies and for a variety of systems. Unfortunately, a direct comparison of the results presented by collaborations is very difficult, since different experiments use slightly different sets of parameterizations and corrections. Thus, one should keep this in mind when drawing any quantitative conclusions from the results presented below. Below we summarize very shortly the existing experimental results for the systems studied in this work.
1.3.5.1 pp collisions

As it can be seen in Table 1.1 that presents HBT radii measured in pp or p\bar{p} experiments, radii do not change in function of the collision energy. Several experiments, e.g. UA1 [35] and E735 [36], observed a clear dependence of radii on event multiplicity (Fig. 1.1).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>R [fm]</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA23 [31]</td>
<td>26</td>
<td>1.02 ± 0.20</td>
<td>0.32 ± 0.08</td>
</tr>
<tr>
<td>NA27 [32]</td>
<td>27.4</td>
<td>1.20 ± 0.03</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>AFS [33]</td>
<td>63</td>
<td>0.82 ± 0.05</td>
<td>0.40 ± 0.03</td>
</tr>
<tr>
<td>CPLEAR [34]</td>
<td>1.88</td>
<td>1.04 ± 0.01</td>
<td>1.96 ± 0.03</td>
</tr>
<tr>
<td>UA1 [35]</td>
<td>200 - 900</td>
<td>0.73 ± 0.03</td>
<td>0.25 ± 0.02</td>
</tr>
<tr>
<td>E735 [36]</td>
<td>1800</td>
<td>(R_t) 1.06 ± 0.07</td>
<td>?? ± ??</td>
</tr>
</tbody>
</table>

Table 1.1: BEC studies of pp collisions. The results compilation is based on [94]

Figure 1.5: The dependence of measured radii on $N_{ch}$.

1.3.5.2 AA collisions

In Fig. 1.6 is shown the dependence of the measured radii on $\sqrt{s}$ and $K_t$ for the collisions of the heaviest ions (Pb-Pb, Au-Au). The radii vary around 5-6 fm at the lowest pair transverse momentum $K_t$ in the range of available energies. They decrease with $K_t$ what is related to collective dynamical expansion.

It was predicted by the models that treat hot nuclear matter as a fluid and apply laws of hydrodynamics in the calculations (so called hydro models) that creation of the QGP phase in a collision will lead to a very long emission time [71]. This would manifest itself in measured ratio of $Q_{out}$ and $Q_{side}$ significantly bigger then unity. Strikingly, at RHIC a large elliptic flow was measured, that suggests that indeed hot partonic matter behaves as a fluid. However, $Q_{out}/Q_{side}$ measured at RHIC is equal to unity within error. This experimental fact is not yet understood and is frequently called as the RHIC HBT puzzle (f.g. [72]).

In Fig. 1.7 an example results of azimuthally sensitive HBT measurements are presented. Clearly the source asymmetry increases together with impact parameter, i.e. as the collision is more peripheral.
The fireball at kinetic freeze-out has the ellipsoidal shape and at RHIC it is more extended in direction perpendicular to the line connecting centers of the colliding nuclei.
1.3 Particle Correlations

Figure 1.7: Azimuthally sensitive HBT radii measured with STAR at $\sqrt{s} = 200$ GeV/A

a) Squared HBT radii relative to the reaction plane angle. The solid lines show allowed fits to the individual oscillations using $R_{\mu}^2(\phi) = R_{\mu,0}^2 + 2R_{\mu,2}^2 \cos(2\phi)$, for $\mu = o, s, l$ and $R_{os}^2(\phi) = 2R_{os,2}^2 \sin(2\phi)$

b) Fourier coefficients of azimuthal oscillations of HBT radii vs. number of participating nucleons, for $\pi^+$ and $\pi^-$ pairs separately ($0.25 < K_t < 0.35$ GeV/c). Larger participant numbers correspond to more central collisions. The plots are taken from [37].
1.4 A Large Ion Collider Experiment (ALICE)

1.4.1 Purpose of the experiment

ALICE aims to provide facilities for studying physics of dense and hot hadronic matter in ultra relativistic heavy ion collisions. The main goal is to study the quark gluon plasma. Furthermore, the detailed characteristics of the phase transitions and QCD bulk matter involving elementary quantum fields will be extracted. It is extremely interesting to establish the equation of state and understand the phase diagram of strongly interacting matter. Moreover ALICE will allow to explore and test QCD in its natural scale ($\Lambda_{\text{QCD}}$) including problems of confinement and chiral symmetry breaking. Many new phenomena that should appear at these energies are hoped to be observed as well.

ALICE is the only experiment at LHC devoted to heavy ion physics. It is designed to be a general purpose experiment sensitive to the majority of all known observables. It includes:

- particle interferometry (expansion dynamics)
- transverse momenta spectra (jet quenching, collective flow)
- hadron ratios which allow to measure strangeness enhancement and quarkonia suppression
- multiplicity fluctuations and event structures
- direct photons
- lepton pairs
- particles decays

ALICE is designed so it can register charged particle multiplicities per unit of rapidity as large as 8000, that were anticipated before RHIC data were available.

The most interesting physics is expected to be extracted from Pb-Pb collisions at the highest energy that LHC can provide. Proton-proton and proton-lead reactions will not only serve the reference data but also give opportunity to study non-perturbative strong coupling phenomena related to confinement and hadronic structure. Collisions involving lower mass ions give possibility to find qualitative and quantitative changes of final state composition and structure as a function of energy density.

1.4.2 Expected observables and QGP signals

There is no direct way to check the existence of quark-gluon plasma. The dynamics of nuclear collision is so complicated, that we need to draw conclusions from indirect signals. Moreover, a unique signal that would confirm QGP formation doesn’t exist, and we have to rely on accumulated observations of the collision.

1.4.2.1 Particle multiplicities

The most trivial, but very important day-one observable is particle multiplicity and its rapidity density. Since it is associated with the energy density it is also connected with most of the other observables. The latter one defines also the detector performance and this way the measurements accuracy. It is very difficult to predict the particle multiplicity at LHC. Before RHIC has started it was on average 6000 charged particle per rapidity unit [38]. Nowadays this number is anticipated to be in the range between 1400 and 3200 (6000 at most) [3], see Fig.1.8.
1.4.2.2 Particle spectra

Detected particles retain memory about the thermal state that they were born in thermal momentum distribution. Most of particles observed in heavy ion collisions are hadrons, mainly light mesons (pions, kaons etc.). The rest of the particles are leptons and photons. Hadrons are emitted predominantly from the chemical freeze-out surface. During expansion they interact strongly with each other, thus they bear much less information about earlier stages of the collision then leptons and photons which do not interact strongly. From hadron spectra we can learn about the kinetic freeze-out temperature, chemical potential, radial flow velocity, directed and elliptic flows and lengths of homogeneities. These parameters let us constrain the dynamical evolution of the fireball [40–46]. Certain event by event fluctuations in the particle composition may give information even about earlier stages [47,48]. The elliptic flow coefficient that describes the anisotropy of the transverse momentum spectra relative to the reaction plane in non-central collisions, provides information about equation of state [49–60].

1.4.2.3 Direct photons

Photon emission is one of the most actively used observables because gammas, unlike hadronic probes, have extremely long mean free path length in hot matter and escape from it without rescattering [61]. First, photons are generated as the result of scattering of constituent ions in hard processes at very early stage of the collision. We call them prompt photons to distinguish from thermal photons which are generated at a later stage when local thermodynamic equilibrium is almost reached. Thermal photons have an approximately exponential spectrum ($p_t$ around 1-3 GeV/c) and are emitted from QGP due to reactions: $gq \rightarrow \gamma q$ (Compton scattering), $qq \rightarrow \gamma q$ (annihilation), $qq \rightarrow \gamma qq$ (bremsstrahlung) and other processes with higher order in $\alpha = 1/137$ and $\alpha_s = 0.4$ (the strong coupling constant) [62]. Thermal emission gives us information about equilibrium state parameters, mainly about the temperature. Prompt photons production rate and momentum distribution depends on momentum distribution of the quarks and gluons at the time of photonic production. This makes them a unique probe of the inner part of the created hot matter on the initial stage of collision. That’s why direct photons are considered as one of the most promising signatures of quark-gluon plasma. However this signal has huge background from hadron decays, mainly $\pi^0$ and $\eta$ mesons, but it is expected that in ultra-relativistic Pb-Pb collision ratio of direct to decay photons will be 5-10% or even more.
1.4.2.4 Strangeness enhancement

Production of strangeness in pp reactions is very regular over wide range of collision energies with an almost constant ratio between newly produced s and u quarks. Similarly, in the scenario in which QGP is not created strangeness production is suppressed comparing to production of up and down quarks, because s quarks are heavier. The suppression increases for particles which have more (anti)strange quarks.

If QGP is formed the strange quark content is rapidly saturated with $s\bar{s}$ pair creation due to $gg$ or $q\bar{q}$ interactions. Thus, strange, antistrange and multistrange hadrons appear in the final state, which are not observed in a purely hadronic scenario and cannot be explained in any other way than by the existence of QGP. Furthermore enhanced strangeness cannot be destroyed by interactions during freeze-out and expansion [63, 64].

The main measurement in strangeness enhancement determination is the $K/\pi$ ratio, which can be obtained with small uncertainty due to the high multiplicities of these particles. It also provides information about time-scale of strangeness equilibration. ALICE will be able to detect other particles containing strange quarks like $F$, $L$, $X$, $W$. Their yields and ratios places more stringent constraints on the origin of the flavor composition observed in $K/\pi$ ratio.

1.4.2.5 $J/\psi$ and $\Upsilon$ suppression. Open charm and beauty enhancement

Heavy quarks are produced in hard partonic scattering processes (gluon fusion) during primary nucleon-nucleon interactions at the very beginning of a collision. The idea of the suppressed $J/\psi(c\bar{c})$ and $\Upsilon(b\bar{b})$ production in the presence of a QGP is based on the color screening [65, 66]. The screening radius in the medium is inversely proportional to the density of color charges and therefore to the energy density. When it becomes smaller than the size of a resonance, the range of the strong force is so much reduced that a bound state can no longer exist. The resonance 'dissolves' and the quarks separate in space to appear later, after hadronization, as two hadrons with open charm or beauty. Thus, in the final state we should not see hidden charm or beauty states and instead open heavy flavor enhancement. The ratio can be normalized to Drell-Yan lepton pair production which is not affected by QGP existence [67].

However suppression can be caused as well via absorption by dense hadronic matter, so it is not a sufficient signal of QGP itself. Fortunately we can distinguish the source of the suppression, QGP and other models (i.e. destruction by comovers) by the dependence of the quarkonia survival probability on the energy density: deconfinement scenario predicts threshold behavior whereas crossover should appear as gradual increase of the suppression with the energy density.

1.4.2.6 Dileptons

Leptons, since they do not interact strongly, are the second most promising signatures of QGP after direct photons. We can observe lepton pairs stemming from mesonic decays and also from process of lepton-antilepton creation from (virtual) photons. Also, bremsstrahlung of quarks (scattering off gluons) can produce lepton pairs. Hence, they carry information about the thermodynamical state at the moment of the production in the same manner that photons [68].

Other very important signal carried by di-leptons pairs is the semi-leptonic decay modes of vector mesons. Due to chiral symmetry restoration in QGP, changed properties (mass, width, branching ratios) of resonances are expected to be seen (comparing to normal hadronic collisions). For example the broadening of $\omega$’s width up to 50-60 MeV is expected i.e. five times more than normal value. Widths and masses can be measured via lepton decays.

The fraction of $J/\psi$’s and $\Upsilon$’s produced during expansion phase and in decays of other particles (f.g. $B \rightarrow J/\psi + \phi$) can be determined in the same way. This allows to measure the factor of suppression in QGP.
1.4 A Large Ion Collider Experiment (ALICE)

Di-leptons unfortunately suffer very vast background. Different sources contributing to the di-lepton yield is shown in Fig. 1.9. The main background stem from pion annihilation, resonance decay (two pions can annihilate, forming either a virtual photon or $\rho$ meson - both may then decay into a di-lepton). They can also be created in Dalitz decays and Drell-Yan processes at high masses.

1.4.2.7 Correlations and multiplicity fluctuations

Large volumes at decoupling would indicate the existence of a phase transition. Also appearance of asymmetries is a sign of QGP. The correlations increase if the QGP is formed. It results in a reduction/enhancement of net/total charge up to an order of magnitude (depending on the model).

Fluctuations measure the so-called susceptibilities of the system

- transverse momentum fluctuations should be sensitive to temperature-energy fluctuations [69] and these measure heat capacity of the system
- charge fluctuations are sensitive to the fractional quark charges [47, 48]

It is important to measure fluctuations and correlations for various acceptances as well as versus centrality and beam energy.

1.4.2.8 Jet quenching

Another important and promising observable is already discussed in section 1.2 the jet quenching phenomenon.

1.4.3 The Large Hadron Collider (LHC)

LHC is constructed in the same 27 km long circular tunnel as Large Electron Positron (LEP) collider at CERN was placed in. This machine will be able to collide lead ions with energy of about 5.52 TeV per nucleon at a center of mass system and protons with 14 TeV. This makes LHC the most powerful accelerator of any existing or planned. The beam will be accelerated up to the speed of 99.9 % of light velocity. In order to keep such a highly energetic beam focused, particles are bend by super-conductive coils generating fast alternating field of 8 T. The LHC machine parameters are presented in Table 1.2.

**Figure 1.9:** Schematic diagram showing different contribution to the di-lepton yield.

![Figure 1.9](image.png)


Table 1.2: Maximum nucleon–nucleon center-of-mass energies, rapidity shifts, geometric cross sections, and lower and upper limits on luminosities for several different symmetric and asymmetric systems.

1.4.4 ALICE setup

The overall view of ALICE is shown in Fig. 1.10. This setup consists of two main parts: the central one that covers ±45° around mid-rapidity over the full azimuth is embedded inside L3 magnet (see below), and the forward part consisting of the muon spectrometer (MUON), multiplicity detectors and zero degree calorimeter.

1.4.4.1 L3 Magnet

ALICE collaboration decided to reuse magnet of L3 experiment that was installed in the same place in the LEP era. It has inner radius of 5.6 m and length of 12 m. It provides uniform magnetic field up to 0.5 T. Predominantly, the maximum value is planned to be used. It allows for full tracking particle identification and tracking down to $p_t = 250$ MeV/c. Particles with lower transverse momenta are reconstructed within the Inner Tracking System (ITS). However, runs with weaker magnetic field are envisaged. They will allow to measure precisely particles with smaller transverse momenta, extending this way the range of the measured observables (spectra, flow profiles, lengths of homogeneity, etc).

1.4.4.2 Inner Tracking System (ITS)

This is the most central sub-detector laying very near from the interaction point (primary vertex). The main goal of the Inner Tracking System (ITS) is the most precise detection of short lived hyperons and charm particles. It can be achieved with precise determination of the primary vertex and of secondary vertices created by decaying resonances. The ITS also plays an important role in measurements of

- multiplicity distributions
- inclusive particle spectra
- jets characteristics

<table>
<thead>
<tr>
<th>System</th>
<th>$\sqrt{s_{NN_{\text{max}}}}$ (TeV)</th>
<th>$\Delta y$</th>
<th>$\sigma_{\text{geom}}$ (barn)</th>
<th>$\mathcal{L}_{\text{low}}$ (cm$^{-2}$s$^{-1}$)</th>
<th>$\mathcal{L}_{\text{high}}$ (cm$^{-2}$s$^{-1}$)</th>
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<td>7.7</td>
<td>$1.0 \times 10^{27}$</td>
<td>$1.0 \times 10^{29}$</td>
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<td>Ar–Ar</td>
<td>6.3</td>
<td>0</td>
<td>2.7</td>
<td>$2.8 \times 10^{27}$</td>
<td>$2.0 \times 10^{29}$</td>
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<tr>
<td>O–O</td>
<td>7.0</td>
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<tr>
<td>N–N</td>
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<td>1.3</td>
<td>$5.9 \times 10^{27}$</td>
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<tr>
<td>$\alpha\alpha$</td>
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<td>0</td>
<td>0.34</td>
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</tr>
<tr>
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<td>0</td>
<td>0.19</td>
<td>$1.1 \times 10^{30}$</td>
<td>$1.0 \times 10^{29}$</td>
</tr>
<tr>
<td>pp</td>
<td>14.0</td>
<td>0</td>
<td>0.07</td>
<td></td>
<td>$5.0 \times 10^{30}$</td>
</tr>
<tr>
<td>pPb</td>
<td>8.8</td>
<td>0.47</td>
<td>1.9</td>
<td>$1.1 \times 10^{29}$</td>
<td></td>
</tr>
<tr>
<td>pAr</td>
<td>9.4</td>
<td>0.40</td>
<td>0.72</td>
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</tr>
<tr>
<td>pO</td>
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<td>0.35</td>
<td>0.39</td>
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</tr>
<tr>
<td>dPb</td>
<td>6.2</td>
<td>0.12</td>
<td>2.6</td>
<td>$8.1 \times 10^{28}$</td>
<td></td>
</tr>
<tr>
<td>dAr</td>
<td>6.6</td>
<td>0.05</td>
<td>1.1</td>
<td>$1.9 \times 10^{29}$</td>
<td></td>
</tr>
<tr>
<td>dO</td>
<td>7.0</td>
<td>0.00</td>
<td>0.66</td>
<td>$3.2 \times 10^{29}$</td>
<td></td>
</tr>
<tr>
<td>$\alpha\text{Pb}$</td>
<td>6.2</td>
<td>0.12</td>
<td>2.75</td>
<td>$7.7 \times 10^{28}$</td>
<td></td>
</tr>
<tr>
<td>$\alpha\text{Ar}$</td>
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<td>0.05</td>
<td>1.22</td>
<td>$1.7 \times 10^{29}$</td>
<td></td>
</tr>
<tr>
<td>$\alpha\text{O}$</td>
<td>7.0</td>
<td>0.00</td>
<td>0.76</td>
<td>$2.8 \times 10^{29}$</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1.10: Layout of the ALICE detector.
• open charm and strangeness production
• heavy quarkonia suppression
• masses and widths of resonances

Another, but not less important facility, is track finding of low $p_t$ particles (down to $\sim 20$ MeV for electrons) in stand alone mode. It gives possibility of studying collective flows and also precise measurement of soft $\gamma$ conversions and Dalitz pairs spectrum in order to suppress this source of di-lepton background. ITS also guarantees high resolution of reconstruction of high $p_t$ particles which is beneficial for all physics topics addressed in ALICE.

Inner Tracking System consists of six cylindrical layers of silicon detectors, see Fig. 1.11. Parameters of given layers are summarized in table 1.3. The architecture of the ITS is dictated by the great track density at small distances to the interaction point. Additionally, it must have a large rapidity acceptance ($|\eta| > 0.9$) to provide data for particle correlations, particle spectra ratios and $p_t$ spectra analysis. What is very important for the ITS, it must be constructed with as minimal amount of material as possible, to minimize multiple scattering effects.

Devices that fulfill all these considerations are semiconductor (silicon) detectors. The optimization of detecting characteristics, number of channels and finally the cost, dictates the usage of three different types of silicon detectors.

![Figure 1.11: Inner Tracking System.](image)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Type</th>
<th>$r$ [cm]</th>
<th>$z$ [cm]</th>
<th>Area [m$^2$]</th>
<th>Channels</th>
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<td>1</td>
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<td>3.9</td>
<td>14.1</td>
<td>0.07</td>
<td>3 276 800</td>
</tr>
<tr>
<td>2</td>
<td>pixel</td>
<td>7.6</td>
<td>14.1</td>
<td>0.14</td>
<td>6 553 600</td>
</tr>
<tr>
<td>3</td>
<td>drift</td>
<td>15.0</td>
<td>22.2</td>
<td>0.42</td>
<td>43 008</td>
</tr>
<tr>
<td>4</td>
<td>drift</td>
<td>23.9</td>
<td>29.7</td>
<td>0.89</td>
<td>90 112</td>
</tr>
<tr>
<td>5</td>
<td>strip</td>
<td>38.5</td>
<td>43.2</td>
<td>2.09</td>
<td>1 148 928</td>
</tr>
<tr>
<td>6</td>
<td>strip</td>
<td>43.6</td>
<td>48.9</td>
<td>2.68</td>
<td>1 459 200</td>
</tr>
</tbody>
</table>

**Table 1.3:** Dimensions of the ITS detectors (active areas).
1.4.4.3 Layers 1 and 2: Silicon Pixel Detectors (SPD)

It was decided to use silicon pixel detectors at the two layers closest to the beam. This device provides the best granularity and track separation of all known particle detectors, but at the expense of large amount of channels and high price. Active area of the detector is rectangular plate (82 mm long, 13.8 mm wide and 0.2 mm thick) made of n-type silicon. On the bottom surface n+ type silicon layer is implanted. The top side consists of matrix of 256 x 160 (in $r\phi$ and $z$ directions, respectively) implanted p+ silicon cells ($50 \times 425 \mu m^2$). A positive voltage ($\sim 50$ V) is applied to the n-side so each cell is a reversed-biased diode. This generates a strong electric field inside the detector that separates electrons and holes created by passing charged particles. Charge is attracted to the pixels and sampled by read-out electronics.

1.4.4.4 Layers 3 and 4: Silicon Drift Detectors (SDD)

SDD has been chosen due to its good track separation and $dE/dX$ measurement ability. Active area of the detector is made of the rectangular (7.25 x 75.3 mm$^2$) plate of n-type silicon. Parallel strips of p+ silicon are implanted on both sides of the plate. Each strip is connected to the voltage divider integrated within the detector. The central strip has the lowest potential and at the ones at the edges the highest. Strips on opposite sides of the plate has the same potential. Holes generated by passing particle are collected by the nearest strip. Electrons are concentrated in the middle plane and created potential drives them to the nearest edge where they are collected by an array of small n+ pads. Charge reaches anodes with approximately Gaussian distribution, thus the coordinate in the direction perpendicular to the drift is derived from the centroid of this distribution. The second coordinate is determined as the mean of the distribution in the time domain (anodes are sampled with 40 MHz rate). Overall space precision of both coordinates is higher then 40 $\mu$m.

1.4.4.5 Layers 5 and 6: Silicon Strip Detectors (SSD)

The outermost layers of the ITS are crucial for the track matching between the TPC and more central parts of the ITS. It was decided to use double sided SSDs because they provide very good resolution of $\sim 17 \mu m$ in one direction and $dE/dX$ measurement ability connected with very small number of channels and relatively small price. High precision only in one direction is sufficient at outermost layers because we are interested in precise position determination mainly in the $r\phi$ direction as it is necessary for the accurate $p_t$ determination. At 40 cm from the interaction point small particle density (0.5 part/cm$^2$) allows to use SSDs.

Active part of the detector is made of n type silicon plate. It is 73 mm long, 42 mm wide and 300 $\mu$m thick. Parallel strips of p+ silicon are implanted on one side n+ silicon strips are implanted on the other side. On each side there is 768 strips, with distance between them of 95 $\mu$m (projection onto longer edge). On one side strips make with shorter edge an angle of 7.5 mrad, and on the other one 27.5 mrad thus relative angle between strips on two sides is $35 \text{ mrad}$ (in wafer plane). The wafers on the 5th layer are flipped with respect to their orientation in the 6th layer. This solution helps to remove ambiguities when considering two signals on both layers together.

All strips are connected to a bias voltage $\sim 60$ V (on one side all strips have the same potential) to create a strong electric field inside the wafer. Thus holes and electrons created by passing charged particle are separated before recombination. Electrons are attracted to the N-side strips and holes to the strips in the P-side. Read-out electronics measure the charge collected on each side. Since it is proportional to the ionization it enables $dE/dX$ measurement.

1.4.4.6 Time Projection Chamber

Time Projection Chamber (TPC) is the main detector in ALICE. It provides excellent continuous tracking ability which was proved in many HEP experiments also in those with very high multiplicities (f.g. NA49
Introduction

Beyond tracking and momentum determination TPC in conjunction with ITS will provide particle identification by $dE/dX$ measurement.

**Figure 1.12:** Time Projection Chamber detector.

The most proper for collider experiments is a cylindrical shape (see Fig. 1.12). TPC is a gaseous drift detector that employs mixture of neon (90%) and carbon dioxide. It guarantees long radiation length and it ensures small multiple scattering rate, space charge and secondary particle production. Constant electric drift field (~ 400 V/cm) points from end-caps where read-out pads are located (ground potential) towards the central plane high voltage electrode (~ 120 kV potential).

The inner radius is 85 cm, outer 250 cm and it is 500 cm long. The inner radius has been chosen on the basis of multiplicity considerations which is of order of $0.1 - 0.2$ part/cm$^2$ on the inner surface of the cylinder. The outer radius has been chosen to achieve track length allowing for $dE/dX$ measurement with 6-7% resolution.

Passing charged particle frees electrons in ionization process that are drifted in electric field towards end-caps where they are captured by the anode wires. Readout system is built of conventional multi-wire proportional chambers.

### 1.4.4.7 Transition Radiation Detector

To study di-electron physics, especially open charm and beauty through their electron decays channels, $J/\Psi$ continuum, spectroscopy of vector meson resonances, efficient electron reconstruction are needed. Transition radiation detector (TRD) aims to provide such data.

As most of all central detectors of ALICE it covers pseudorapidity region of $|\eta| < 0.9$. It lays on the 6 cylindrical surfaces outside TPC and consists of 540 modules, arranged 18 planes in azimuth, each subdivided to 5 along beam direction.

The operational principle of TRD (Fig. 1.13) is based on the radiation emitted during passage of charged particle through the boundary of materials with different refraction indices. Each module is a conjunction of the radiator, made of 100 thin polypropylene foils in CO$_2$ atmosphere, and time expansion chamber converting photons into electrons (electric signal). The large number of foils is dictated by the low probability of the transition radiation photon emission ~1% per boundary.
1.4.4.8 Particle Identification by Time Of Flight

Time Of Flight (TOF) is a detector dedicated to Particle Identification (PID) within ALICE. It covers the same phase space as TRD, TPC, ITS ($|\eta| < 0.9$) and together with them enables event by event analysis. It is to detect particles in momentum range from $0.2 \text{ GeV/c}$ to $2.5 \text{ GeV/c}$. TOF is located at $2.7 \text{ m}$ from the vertex and covers $176 \text{ m}^2$ with $160\,000$ cells of $3 \times 3 \text{ cm}^2$ modules.

Figure 1.13: Operational principle of TRD module.

Figure 1.14: Design of MRPC.
ALICE has decided to use Multi-gap Resistive-Plate Chambers (MRPC), for their excellent time resolution. The scheme of a module is shown in Fig. 1.14. The detector consists two chambers filled with a gas (C$_2$H$_2$F$_4$(90%), i-C$_4$F$_{10}$(5%), SF$_6$(5%)). Each of them contains stack of highly resistive plates. Inside chamber there is high electric field $\sim 110$ kV/cm. This solution has the advantage that the fast signal induced by avalanches generated by a passing particle can be precisely detected because the measured signal is an analog sum of signals from many gaps. On the other hand the avalanches are quickly quenched (they do not propagate over resistive plate) so the charge spectrum is well centered and has no tail.

### 1.4.4.9 High Momentum Particle Identification by Ring Imaging Cherenkov detector

High Momentum Particle Identification (HMPID) is responsible for detection of particles (mainly pions, kaons and protons) in momentum range from 1 to 5 GeV which is crucial for studying jet quenching phenomenon. ALICE collaboration decided to use for this purpose proximity focusing Ring Imaging Cherenkov (RICH) detector with CsI photocathode. HMPID consists of 7 identical modules (1.36 x 1.36 m$^2$) of RICH detectors placed over the TPC in the farthest possible distance of 4.7 m from the interaction point in order to obtain low track density (see Fig. 1.10). Area occupied by HMPID is determined by low production cross-section of high momentum particles (too small to allow event by event analysis).

![Charged particle detector diagram](image)

**Figure 1.15:** Operational principle of a RICH detector.

Working principle of the RICH detector is shown in Fig 1.15. Radiator that is made of C$_6$F$_{14}$ emits Cherenkov radiation after passage of fast particle. Cherenkov photons are converted into electric signal by the system made of Multi-Wire Photo-Cathode (MWPC). Photo-cathode is covered by CsI film which has very good quantum efficiency. MWPC is segmented into pads in order to provide two dimensional read-out.

RICH provides position resolution of 2.1 mm in direction parallel to the beam pipe and 3.3 mm in the second direction. Momentum resolution is 2% in range 0.5 – 5 GeV/c.

### 1.4.4.10 PHOS

PHOtton Spectrometer (PHOS) is designed to detect gammas in momentum range 0.5-10 GeV/c, $\pi^0$'s in range of 1 – 10 GeV/c and $\eta$ mesons in range of 2 – 10 GeV. It is positioned on the bottom of the ALICE


setup and will cover approximately $-0.12 < \eta < 0.12$ in pseudorapidity domain and 100° in azimuthal angle. Total area is 8 m².

PHOS is a high granularity electromagnetic calorimeter consisting 17280 fast scintillating lead-tungstate ($PbWO_4$) crystals of $2.2 \times 2.2 \times 18$ cm² dimensions coupled to large area PIN-diodes with low-noise preamplifier’s. Crystals are faced to the interaction point by plane of the smallest area. Eight crystals are arranged in strip which is the smallest assembly unit. PHOS is made of 4 modules each consisting $90 \times 6$ strips. Each module faces to the interaction point.

### 1.4.4.11 Muon Arm

Forward Muon Spectrometer aims to detect muons produced in decays of $J/\Psi$, $\Psi'$, $\Upsilon$, $\Upsilon'$ emitted in forward direction in angular range from 2° to 9°, what corresponds to $2.5 < \eta < 4$. These particles carry information about very early stages of the collision (hard penetrating probes). The shield, that protects the active modules from radiation damage is needed due to the great number of emitted particles in this pseudorapidity range. Front absorber reduces the particle flux into the muon spectrometer by at least 100 times. It starts 90 cm from the vertex. The front section is made of dense low-Z materials (carbon and concrete) in order to limit multiple scattering. The rear part is designed to shield against neutrons.

Muon arm is supplied with additional dipole magnet which lays outside of the L3 magnet. It provides magnetic field of 0.7 T and the field integral is higher than 3 Tm that is needed for high resolution mass determination of the detected muons. The overall dimensions of the magnet are 5 m in length, 6.6 m wide and 8.6 m high.

The active area of the muon spectrometer consists 10 high granularity cathode strip chambers organized in 5 stations. Each chamber is read by two orthogonal cathode planes so that two-dimensional hit information is provided. The spatial resolution is of the order of 70 μm in the bending plane.

The last part of the muon arm is the trigger system. It consists of two planes of single gap resistive plate chambers (RPC) located about 16 m from the interaction point 1 m apart each other. Stations are located behind 1.2 m thick iron muon filter which shields against low energy background particles. It has to select events containing di-muons (f.e. from $J/\Psi$ decay).

### 1.4.4.12 Zero Degree Calorimeter

Zero Degree Calorimeter (ZDC) measures centrality of the collision (impact parameter) by finding the energy carried away by non-interacting particles (spectators). Two identical sets of devices are placed symmetrically on both sides of the interaction point, each consisting three independent parts.

#### 1.4.4.12.1 Neutron ZDC

Neutron ZDC (NZDC) detector measure energy carried away by neutrons. It is placed 116.13 m from the interaction point almost on the Z axis (1 cm off the horizontal plane) in the point where traveling in opposite directions beams pass by each other during acceleration. At this place beam pipe divides on two and NZDC is located between them. Quartz-fiber calorimeter technique was chosen because it allows to build small, compact and radiation-hard device (distance between pipes is smaller than 10 cm). NZDC is a $7 \times 7 \times 100$ cm³ rectangular parallelepiped made of tantalum with matrix of quartz fibers embedded inside. Fibers are parallel to the beam axis as well as to the longer edge of the device. Spectator neutrons traveling across the absorber/quartz matrix produce shower. Particles that are faster than velocity of light in medium produce Cherenkov photons which are transmitted through fibers to photo multiplier tubes. Energy resolution obtained for 2.7 TeV neutrons is 10.5%.

#### 1.4.4.12.2 Proton ZDC

Proton ZDC is a separate device because separator magnet D1, which deflect protons is placed between the detector placement and collision point. Detection technique is the same as in the NZDC, but instead of tantalum brass is used (longer free path). PZDC is not limited so strongly by available space so it can be build of lighter material which is much cheaper. It consists two devices
Figure 1.16: A schematic diagram of the cross section of a unit cell. The hexagonal section depicts a region of the PCB which provides cathode extension.

20.8 × 12 × 150 cm$^3$ placed 115.63 m from the interaction point and centered 19 cm from the beam axis. Embedded fibers are parallel to the beam and make matrix with 4 mm pitch.

1.4.4.12.3 Electro-Magnetic ZDC Electro-Magnetic ZDC (EMZDC) measures energy carried by photons in forward direction. It uses the same detection technique as other modules, but here lead is used as absorber and the fibers are tilted at 7.5° with respect to the LHC axis. It is placed 115.2 m from the interaction point and its dimensions are 7 × 7 × 21.7 cm$^3$.

1.4.4.13 Photon Multiplicity Detector

This detector measures photon $\eta - \phi$ distributions in pseudo-rapidity region between 2.3 and 3.5 and in full azimuthal angle. It enables observations of fluctuations, flow and formation of disoriented chiral condensates on event by event basis.

ALICE decided to use a preshower detector. It is mounted on the L3 magnet doors, 361.5 cm from the vertex on the opposite side with respect to muon arm. PMD is of rectangular shape (189 × 163 cm$^2$). It is made of the modules, that each consists two identical honeycomb panels, separated with lead plate that serves as a photon converter (thickness of 3X$_0$). The honeycomb is made of copper sheet and its cells are hexagonal chambers (see Fig. 1.16) filled with a mixture of argon (70%) and carbon dioxide. The cell surface has 0.22 cm$^2$. The anode wire that is connected to the readout electronics, and all honeycomb are at an electric potential of -1.4 kV. The panel facing towards the interaction point serves as charged particle veto detector. The thickness of the lead converter was chosen so a few cells are red by a single photon and all gammas produce a shower.

1.4.4.14 Forward Multiplicity Detector

Forward Multiplicity Detector (FMD) provides information about particle multiplicity in rapidity ranges from -3.4 to -1.7 and from 1.7 to 5.1. It is consists of sets of silicon strip detectors that compose rings around the beam pipe, Fig 1.17b. The operational principle of these detectors is identical as Silicon Strip Detectors described in section 1.4.4.4.

The strips make circles with centers at nominal position of the beam, Fig 1.17a. The detailed parameters and coverage of the individual rings is summarized in Tables 1.4 and 1.5.

The flux of particles in the most central Pb-Pb events is so high, that the majority of strips is fired by more than one particle. Hence, multiplicity information will be obtained by measuring the energy deposition in each channel and relating this to the number of charged particles.
Figure 1.17: a) Assembly of an inner ring from 10 modules (left) and an outer ring from 20 modules (right). b) Conceptual layout of the FMD detector system showing the five rings placed around the beam pipe. The three sub-detector systems are called FMD1 (left), FMD2 (middle) and FMD3 (right). The muon arm is to the right.
Table 1.4: The distance \( z \), from the detector to the interaction point, the inner and outer radii, and the resulting pseudo-rapidity coverage of each FMD ring.

<table>
<thead>
<tr>
<th>Ring</th>
<th>( z ) [cm]</th>
<th>( R_{\text{in}} ) [cm]</th>
<th>( R_{\text{out}} ) [cm]</th>
<th>( \eta ) coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMD1 outer</td>
<td>-75.2</td>
<td>15.4</td>
<td>28.4</td>
<td>(-2.29 &lt; \eta &lt; -1.70)</td>
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<tr>
<td>FMD1 inner</td>
<td>-62.8</td>
<td>4.2</td>
<td>17.2</td>
<td>(-3.40 &lt; \eta &lt; -2.01)</td>
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<tr>
<td>FMD2 outer</td>
<td>75.2</td>
<td>15.4</td>
<td>28.4</td>
<td>(1.70 &lt; \eta &lt; 2.29)</td>
</tr>
<tr>
<td>FMD2 inner</td>
<td>83.4</td>
<td>4.2</td>
<td>17.2</td>
<td>(2.28 &lt; \eta &lt; 3.68)</td>
</tr>
<tr>
<td>FMD3</td>
<td>340.0</td>
<td>4.2</td>
<td>17.2</td>
<td>(3.68 &lt; \eta &lt; 5.09)</td>
</tr>
</tbody>
</table>

Table 1.5: Physical dimensions of FMD segments and strips, together with the average number of charged particles hitting each strip in central Pb–Pb collisions.
2 Software and Analysis Methodology

2.1 Introduction

In the field of experimental particle and nuclear physics, software is an integral part of an apparatus. Its performance is directly reflected in the quality of measurement. This is due to the specific aspects of this field where all observables are based solely on properties of particles emitted from a collision. Moreover, in most cases to measure a quantity with a satisfactory precision extremely large number of events (of the order of millions) is required. Hence, highly specialized digital devices are mandatory. They give the possibility to meet those requirements: very precise particle detection on the track by track basis with very high event rate of the order of kHz and higher.

Specialized programs are required to reconstruct track properties from digital detector response and then to perform analysis to obtain a physical result. Each experiment has to prepare reconstruction and analysis software well before data taking process starts. Their functionality is verified on the simulated data. Simulations give opportunity to study the details of the apparatus functionality. Hence, they are an irreplaceable tool in the development of reconstruction and analysis procedures. They also allow to assess resolutions. The detector design also relies on the detailed simulations.

The following set of simulation programs is necessary:

• particle generators

• simulation of particle passage through a material

• calculation of digital detector response on basis of a signal deposited by a particle passing through detector active material

The output of the simulation chain may take the same format as the data provided by the detector Data Acquisition System (DAQ) during data taking. Therefore, the reconstruction software can be used exactly the same way as in the case of the data coming from the real interactions.

This chapter is devoted to a brief presentation of the ALICE Offline framework and our contribution to it. Next, the tools developed and used for particle correlation analyses are presented.
2.2 AliRoot - The ALICE Offline Framework

The ultimate goal of an offline framework is to reconstruct and analyze the physics data. The ALICE framework, AliROOT, is entirely based on ROOT package [73]. It is written in C++ although it contains several external packages (particle generators, transport Monte Carlo simulators) written in Fortran, however, they are all hidden behind the C++ interfaces.

The current schema of the framework is shown in Fig.2.1. There may be itemized the few most important parts:

- **STEER** – foundation classes and main steering applications
- **EVGEN** – wide set of particle generators which have common virtual interface
- **VIRTUAL MONTE CARLO** – common interface for transport programs
- **SUB-DETECTORS** – codes specific to a module (detector) like: geometry, digital response simulations, local signal reconstruction
- **RECONSTRUCTION** – incremental particle trajectory reconstruction and particle identification
- **ANALYSES**

The detailed description of the framework can be found in [74]. What follows is the description of this part of the framework to which we mostly contributed.

![Figure 2.1: Schematic view of the AliRoot framework.](image)

2.3 Data input, output and exchange subsystem of AliRoot

A few tens of different data types is present within AliRoot because hits, summable digits, digits and clusters are characteristic for each sub-detector. Writing all of the event data to a single file, as it used to
be implemented, was causing number of limitations. Moreover, the reconstruction chain introduces rather complicated dependences between different components of the framework, what is highly undesirable from the point of view of software design. In order to solve both problems, we have designed a set of classes that manage data manipulation i.e. storage, retrieval and exchange within the framework.

It was decided to use the “white board” concept, which is a single exchange object where were all data are stored and publicly accessible. For that purpose I have employed TFolder facility of ROOT. This solution solves the problem of inter-module dependencies.

There are two most frequently occurring use-cases concerning the way a user deals with the data within the framework:

1. data production – produce - **write** - **unload** (clean)
2. data processing – **load** (retrieve) - process - **unload**

**Loader**s are the utility classes that encapsulate and automatize the tasks written in bold font. They limit the user’s interaction with the I/O routines to the necessary minimum, providing friendly and very easy interface, which for the use-cases considered above, consists of only 3 methods:

- **Load** – retrieves the requested data to the appropriate place in the white board (folder)
- **Unload** – cleans the data
- **Write** – writes the data

Such an insulation layer has number of advantages. It

- makes the data access easier for the user.
- allows to avoid the code duplication throughout the framework.
- minimize the risk of a bug occurrence resulting from the improper I/O management. The ROOT object oriented data storage extremely simplifies the user interface, however, there are a few pitfalls that are frequently unknown to an inexperienced user.

To make the description more clear we need to introduce briefly basic concepts and the way the AliRoot program operates. The basic entity is an event, i.e. all the data recorded by the detector in a certain time interval plus all the reconstructed information from these data. Ideally the data are produced by the single collision selected by a trigger for recording. However, it may happen that the data from the previous or proceeding events are present because the bunch crossing rate is higher then the maximum detector frequency (pile-up), or simply more than one collision occurred within one bunch crossing.

Information describing the event and the detector state is also stored, like bunch crossing number, magnetic field, configuration, alignment, etc.., In the case of a Monte-Carlo simulated data, information concerning the generator, simulation parameters is also kept. Altogether this data is called the **header**.

For the collisions that produce only a few tracks (best example are the pp collisions) it may happen that total overhead (the size of the header and the ROOT structures supporting object oriented data storage) is non-negligible in comparison with the data itself. To avoid such situations, the possibility of storing an arbitrary number of events together within a **run** is required. Hence, the common data can be written only ones per run and several events can be written to a single file.

It was decided that the data related to different detectors and different processing phases should be stored in different files. In such a case only the required data need to be downloaded for an analysis. It also allows to alter the files easily if required, for example when a new version of the reconstruction or simulation is needed to be run for a given detector. Hence, only new files are updated and all the rest may stay untouched. It is especially important because mass storage systems practically do not allow to erase files. This also gives the possibility for an easy comparison of the data produced with competing algorithms.

All the header data, configuration and management objects are stored in a separate file, which is usually named galice.root (for simplicity we will further refer to it as galice).
2.3.1 The “White Board”

The folder structure is presented in Fig.2.2. It is subdivided into two parts:

- **event data** that have the scope of single event
- **static data** that do not change from event to event, i.e. geometry and alignment, calibration, etc.

During startup of AliRoot the skeleton structure of the ALICE white board is created. The `AliConfig` class (singleton) provides all the functionality that is needed to construct the folder structures.

An event data are stored under a single sub-folder (event folder) named as specified by the user when opening a session (run). Many sessions can be opened at the same time, providing that each of them has an unique event folder name, so they can be distinguished by this name. This functionality is crucial for superimposing events on the level of the summable digits, i.e. analog detector response without the noise contribution (the event merging). It is also useful when two events or the same event simulated or reconstructed with a competing algorithm, need to be compared.

2.3.2 Loaders

I have implemented a set of classes that simplify the data access and storage. The loaders can be represented as a four layer, tree like structure (see Fig.2.3). It represents the logical structure of the detector and the data association.

1. **AliBaseLoader** – One base loader is responsible for posting (finding in a file and putting in a folder) and writing (finding in a folder and putting in a file) of a single object. `AliBaseLoader` is a pure virtual class because writing and posting depend on the type of an object. The following concrete classes are currently implemented:
   - **AliObjectLoader** – It handles `TObject`, i.e. basically any object within ROOT and AliRoot since an object must inherit from this class to be posted to the white board (added to `TFolder`).
   - **AliTreeLoader** – It is the base loader for `TTree`, which requires special handling, because they must be always properly associated with a file.
   - **AliTaskLoader** – It handles `TTask`, which need to be posted to the appropriate parental `TTask` instead of `TFolder`.

`AliBaseLoader` has always the same name as the object it manages (to be able to find it in a file or folder). The user normally does not need to use these classes directly and they are rather utility classes employed by `AliDataLoader`.

2. **AliDataLoader** – It manages a single data type, for example digits for a detector or kinematics tree. Since a few objects are normally associated with a given data type (data itself, quality assurance data (QA), a task that produces the data, QA task, etc.) `AliDataLoader` has an array of `AliBaseLoaders`, so each of them is responsible for each object. Hence, `AliDataLoader` can be configured individually to meet specific requirements of a certain data type.

A single file contains the data corresponding to a single processing phase and solely of one detector. By default the file is named according to the schema `Detector Name + Data Name + .root` but it can be changed in run-time if needed so the data can be stored in or retrieved from an alternative source. When needed, the user can limit the number of events stored in a single file. If the maximum number is exceeded, a file is closed and a new one is opened with the consecutive number added to its name before `.root` suffix. Of course, during the reading process, files are also automatically interchanged behind the scenes and it is invisible to the user.
Figure 2.2: The folders structure. An example event is mounted under “Event” folder.
Figure 2.3: Loaders diagram. Dashed lines separate layers serviced by the different types of the loaders (from top): AliRunLoader, AliLoader, AliDataLoader, AliBaseLoader.

The AliDataLoader class performs all the tasks related to file management e.g. opening, closing, ROOT directories management, etc. Hence, for each data type the average file size can be tuned.

It is important because it is undesirable to store small files on the mass storage systems and on the other hand, all file systems have a maximum file size allowed (e.g. currently 2 GB on the Linux ext2).

3. AliLoader – It manages all the data associated with a single detector (hits, digits, summable digits, reconstructed points, etc.). It has an array of AliDataLoaders and each of them manages a single data type.

The AliLoader object is created by an class representing a detector (inheriting from AliDetector). Its functionality can be extended and customized to the needs of a particular detector by creating a specialized class that derives from AliLoader, as it was done, for instance, for ITS or PHOS. The default configuration can be easily modified either in AliDetector::MakeLoader or by overriding the method AliLoader::InitDefaults.

4. AliRunLoader – It is a main handle for data access and manipulation in AliRoot. There is only one such an object in each run. It is always named RunLoader and stored on the top (ROOT) directory of a galice file.

It keeps an array of AliLoader’s, one for each detector. It also manages the event data that are not associated with any detector i.e. Kinematics and Header and it utilizes AliDataLoader’s for this purpose.

The user opens a session using a static method AliRunLoader::Open. This method has three parameters: the file name, event folder name and mode. The mode can be "new" and in this case a file and a run loader are created from scratch. Otherwise, a file is opened and a run loader is searched in. If successful, the event folder with a provided name (if such does not exist yet) is created and the structure presented in Fig.2.2 is created within the folder. The run loader is put in the event folder, so the user can always find it there and use it for data management.

AliRunLoader provides a simple method GetEvent(n) to loop over events within a run. Calling
it causes that all currently loaded data are cleaned and the data for the newly requested event are automatically posted.

In order to facilitate the way the user interacts with the loaders, AliRunLoader provides the wide set of shortcut methods. For example, if digits are required to be loaded, the user can call AliRunLoader::LoadDigits("ITS TPC"), instead of finding the appropriate AliDataLoader's responsible for digits for ITS and TPC, and then request to load the data for each of them.

2.4 Analysis Foundation Library

The result of the reconstruction chain is the Event Summary Data (ESD) object. It contains all the information that may be useful in any analysis. In most cases only a small subset of this information is needed for a given analysis. Hence, it is essential to provide a framework for analyses, where user can extract only the information required and store it in the Analysis Object Data (AOD) format. This is to be used in all his further analyses. The proper data preselecting allows to speed up the computation time significantly. Moreover, the interface of the ESD classes is designed to fulfill the requirements of the reconstruction code. It is inconvenient for most of analysis algorithms, in contrary to the AOD one. Additionally, the latter one can be customized to the needs of particular analysis, if it is only required.

We have developed the analysis foundation library that provides a skeleton framework for analyses, defines AOD data format and implements a wide set of basic utility classes which facilitate the creation of individual analyses. It contains classes that define the following entities:

- AOD event format
- Event buffer
- Particle(s)
- Pair
- Analysis manager class
- Base class for analyses
- Readers
- AOD writer
- Particle cuts
- Pair cuts
- Event cuts
- Other utility classes

It is designed to fulfill two main requirements:

1. **Allows for flexibility in designing individual analyses** Each analysis has its most performing solutions. The most trivial example is the internal representation of a particle momentum: in some cases the Cartesian coordinate system is preferable and in other cases - the cylindrical one.

2. **All analyses use the same AOD particle interface to access the data** This guarantees that analyses can be chained. It is important when one analysis depends on the result of the other one, so the latter one can process exactly the same data without the necessity of any conversion. It also lets to carry out many analyses in the same job and consequently, the computation time connected with the data reading, job submission, etc. can be significantly reduced.

The design of the framework is described in detail below.
2.4.1 AOD

The AliAOD class contains only the information required for an analysis. It is not only the data format as they are stored in files, but it is also used internally throughout the package as a particle container. Currently it contains a TClonesArray of particles and data members describing the global event properties. This class is expected to evolve further as new analyses continue to be developed and their requirements are implemented.

2.4.2 Particle

AliVAODParticle is a pure virtual class that defines a particle interface. Each analysis is allowed to create its own particle class if none of the already existing ones meet its requirements. Of course, it must derive from AliVAODParticle. However, all analyses are obliged to use the interface defined in AliVAODParticle exclusively. If additional functionality is required, an appropriate method is also added to the virtual interface (as a pure virtual or an empty one). Hence, all other analyses can be run on any AOD, although the processing time might be longer in some cases (if the internal representation is not the optimal one).

We have implemented the standard concrete particle class called AliAODParticle. The momentum is stored in the Cartesian coordinates and it also has the data members describing the production vertex. All the PID information is stored in two dynamic arrays. The first array contains probabilities sorted in descending order, and the second one - corresponding PDG codes (Particle Data Group). The PID of a particle is defined by the data member which is the index in the arrays. This solution allows for faster information access during analysis and minimizes memory and disk space consumption.

2.4.3 Pair

The pair object points to two particles and implements a set of methods for the calculation of the pair properties. It buffers calculated values and intermediate results for performance reasons. This solution applies to quantities whose computation is time consuming and also to quantities with a high reuse probability. A Boolean flag is used to mark the variables already calculated. To ensure that this mechanism works properly, the pair always uses its own methods internally, instead of accessing its variables directly.

The pair object has pointer to another pair with the swapped particles. The existence of this feature is connected to the implementation of the mixing algorithm in the correlation analysis package: if particle A is combined with B, the pair with the swapped particles is not mixed. In non-identical particle analysis their order is important, and a pair cut may reject a pair while a reversed one would be accepted. Hence, in the analysis the swapped pair is also tried if a regular one is rejected. In this way the buffering feature is automatically used also for the swapped pair.

2.4.4 Analysis manager class and base class

The analysis manager class (AliRunAnalysis) drives all the process. A particular analysis, which must inherit from AliAnalysis class, is added to it. The user triggers analysis by calling the Process method. The manager performs a loop over events, which are delivered by a reader (derivative of the AliReader class, see section 2.4.5). This design allows to chain the analyses in the proper order if any depends on the results of the other one.

The user can set an event cut in the manager class. If an event is not rejected, the ProcessEvent method is executed for each analysis object. This method requires two parameters, namely pointers to a reconstructed and a simulated event.

The events have a parallel structure, i.e. the corresponding reconstructed particles and simulated particles have always the same index. This allows for easy implementation of an analysis where both are required, e.g. when constructing residual distributions. It is also very important in correlation simulations.
that use the weight algorithm (see section 2.6.1). By default, the pointer to the simulated event is null, i.e. like it is in the experimental data processing.

An event cut and a pair cut can be set in *AliAnalysis*. The latter one points two particle cuts, so an additional particle cut data member is redundant because the user can set it in this pair cut.

*AliAnalysis* class has the feature that allows to choose which data the cuts check:

1. the reconstructed (default)
2. the simulated
3. both.

It has four pointers to the method (data members):

1. `fkPass1` – checks a particle, the cut is defined by the cut on the first particle in the pair cut data member
2. `fkPass2` – as above, but the cut on the second particle is used
3. `fkPass` – checks a pair
4. `fkPassPairProp` – checks a pair, but only two particle properties are considered

Each of them has two parameters, namely pointers to reconstructed and simulated particles or pairs. The user switches the behavior with the method that sets the above pointers to the appropriate methods. We have decided to implement this solution because it performs faster than the simpler one that uses boolean flags and "if" statements. These cuts are used mostly inside multiply nested loops, and even a small performance gain transforms into a noticeable reduction of the overall computation time. In the case of an event cut, the simpler solution was applied. The `Rejected` method is always used to check events. A developer of the analysis code must always use this method and the pointers to methods itemized above to benefit from this feature.

### 2.4.5 Readers

A Reader is the object that provides data for an analysis. *AliReader* is the base class that defines a pure virtual interface.

A reader may stream the reconstructed and/or the simulated data. Each of them is stored in a separate AOD. If it reads both, a corresponding reconstructed and simulated particle have always the same index.

Most important methods for the user are the following:

- **Next** – It triggers reading of a next event. It returns 0 in case of success and 1 if no more events are available.
- **Rewind** – Rewinds reading to the beginning
- **GetEventRec** and **GetEventSim** – They return pointers to the reconstructed and the simulated events respectively.

The base reader class implements functionality for particle filtering at a reading level. A user can set any number of particle cuts in a reader and the particle is read if it fulfills the criteria defined by any of them. Particularly, a particle type is never certain and the readers are constructed in the way that all the PID hypotheses (with non-zero probability) are verified. In principle, a track can be read with more than one mass assumption. For example, consider a track which in 55% is a pion and in 40% a kaon, and a user wants to read all the pions and kaons with the PID probabilities higher than 50% and 30%, respectively. In such cases two particles with different PIDs are added to AOD. However, both particle
have the same Unique Identification number (UID) so it can be easily checked that in fact they are the same track.

**AliReader** implements the feature that allows to specify and manipulate multiple data sources, which are read sequentially. The user can provide a list of directory names where the data are searched. The `ReadEventsFromTo` method allows to limit the range of events that are read (e.g. when only one event of hundreds stored in an AOD is of interest). **AliReader** has the switch that enables event buffering, so an event is not deleted and can be quickly accessed if requested again.

Particles within an event are frequently sorted in some way, e.g. the particle trajectory reconstruction provides tracks sorted according to their transverse momentum. This leads to asymmetric distributions where they are not expected. The user can request the reader to randomize the particle order with `SetRandom` method.

The AOD objects can be written to disk with the `AliReaderAOD` using the static method `WriteAOD`. As the first parameter user must pass the pointer to another reader that provides AOD objects. Typically it is `AliReaderESD`, but it also can be other one, f.g. another `AliReaderAOD` (to filter out the desired particles from the already existing AODs).

Inside the file, the AODs are stored in a `TTree`. Since the AOD stores particles in the clones array, and many particles formats are allowed, the reading and writing is not straight forward. The user must specify what is the particle format to be stored on disk, because in a general case the input reader can stream AODs with not consistent particle formats. Hence, the careful check must be done, because storing an object of the different type then it was specified in the tree leads to the inevitable crash. If the input AOD has the different particle type then expected it is automatically converted. Hence, this method can be also used for the AOD type conversion.

### 2.4.6 AODs buffer

Normally the readers do not buffer the events. Frequently an event is needed to be kept for further analysis, f.g. if uncorrelated combinatorial background is computed. We have implemented the FIFO (First In First Out) type buffer called `AliEventBuffer` that caches the defined number of events.

### 2.4.7 Cuts

The cuts are designed to guarantee the highest flexibility and performance. We have implemented the same two level architecture for all the cuts (particle, pair and event). Cut object defines the ranges of many properties that a particle, a pair or an event may posses and it also defines a method, which performs the necessary check. However, usually a user wants to limit ranges of only a few properties. For speed and robustness reasons, the design presented in Fig.2.4 was developed.

The cut object has an array of pointers to base cuts. The number of entries in the array depends on the number of the properties the user wants to limit. The base cut implements checks on a single property. It implements maximum and minimum values and a virtual method `Rejected` that performs a range check of the value returned by pure virtual method `GetValue`. Implementation of a concrete base cut is very easy in most cases: it is enough to implement `GetValue` method. The ANALYSIS package already implements a wide range of base cuts, and the cut classes have a comfortable interface for setting all of them. For example it is enough to invoke the `SetPtRange(min, max)` method and behind the scenes a proper base cut is created and configured.

The base cuts performing a logical operation (and, or) on the result of two other base cuts are also implemented. This way the user can configure basically any cut in a macro. Supplementary user defined base cuts can be added in the user provided libraries. In case the user prefers to implement a complicated cut in a single method (class) he can create his base cut performing all the operations.

The pair cut in addition to an array of pointers to the base pair cuts it has two pointers to particle cut, one for each particle in the pair.
2.4.8 Other classes

We have developed a few classes that are used in correlation analyses, but they can be also useful in the others. The first is the TPC cluster map, which is the bitmap vector describing at which pad-rows a track has a cluster. It is used by the anti-splitting algorithm in the particle correlation analysis (see section 5.8).

Another example is the AliTrackPoints class, that stores track space coordinates at requested distances from the center of the detector. It is used in the particle correlation analysis by the anti-merging cut (see section 5.9). The coordinates are calculated assuming the helix shape of a track. Different options that define the way they are computed are available.

2.5 Particle Correlations Analysis Software

We have developed a package for particle correlation analysis called HBT ANalyzer (HBTAN). It uses extensively the foundation library described in the previous section.

All three techniques of the reference distribution construction described in section 1.3.4 are implemented in the package.

The extensive hierarchy of base classes representing functions is implemented, what allows for very easy implementation of new functions. The wide set of correlation, distribution and monitoring functions is available in the module.

The package contains two implementations of the weighting algorithm used for correlation simulations (the one due to Lednicky [79] and CRAB [80]) hidden behind the uniform interface. This feature is described in the next section.

During the design process the following use-cases were taken into account:

- calculation of many correlation functions in a single analysis pass
- calculation of the same kind of function but with different cuts in a single analysis pass
- in Monte-Carlo data analysis comparison between original events and events after detector simulation and reconstruction
- monitoring of a single particle spectra
- resolution plots

Performance was a very important objective during the process of software design and its implementation. This is especially important in particle correlations analysis since it is remarkably time consuming. It consists a quadruply nested loops because during mixing each particle has to be combined with all particles from other events. Hence, each unnecessary calculation or call inside the inner loop may result in hours or even days of computing time.
It is designed the way that enables a user to steer the analysis process by applying cuts at almost any point of the analysis:

- data reading
- the mixing procedure when a particle pair is formed
- in each calculated function

The central object of the package is an analysis (class AliHBTAnalysis). A user can plug into the analysis an arbitrary number of correlation and monitoring functions.

### 2.5.1 Functions

A function is an object that calculates (returns) one histogram. In the correlation analyses of the experimental data the most important function is the one that fills the numerator and denominator histograms for pairs of reconstructed particles. However, more types of functions are needed, including:

- resolution functions (especially required in Monte Carlo data analysis)
- monitoring functions that enable observing distributions of particles properties used in the analysis (influence of cuts)

All these functions have different input parameters and need to be handled separately in the analysis. Functions in the HBT-Analyzer can be systematized according to two criteria: the functionality that they serve and the dimensionality. Using the functionality criterion, correlation and monitoring functions are distinguished. Accordingly, the dimensionality functions are categorized into 1D, 2D and 3D.

#### 2.5.1.1 Correlation functions

Currently two kinds of correlation functions are implemented. They can be one- or two-pair, depending on the input they require to fill one entry. One-pair function is the most important in the real data analysis and it is a base class for any experimental correlation function. Two-pair function is designed for a resolution analysis, where the comparison of the value calculated for a pair of simulated particles with the value evaluated for reconstructed tracks is needed. These functions are also used in so-called weight algorithms, see Section 2.6.1. Implementation of one- and two-triplet functions is foreseen in the future, and it will enable handling three particle correlations. The fact that all of functions mentioned above can be one-, two- or three-dimensional, imposes class hierarchy as shown in Fig.2.5. AliHBTAnalysis class depends only on interfaces defined by AliHBTOnePairFctn and AliHBTTwoPairFctn classes. They define the following pure virtual methods

- ProcessSameEventParticles
- ProcessDiffEventParticles
- Init
- WriteFunction

The first two methods differ in number of input parameters. AliHBTOnePairFctn requires one-pair whereas AliHBTTwoPairFctn needs two pairs. The functionality that is dependent on function dimension is implemented in AliHBTFunction1D, AliHBTFunction2D and AliHBTFunction3D classes, which in turn inherit from AliHBTFunction class. The last one implements methods common for all functions and fixes a user’s interface for (re)naming, writing, resetting, scaling, etc., routines.

The classes that constitute the bottom layer of the diagram are base ones for concretized user classes. In most cases, to create a new correlation function implementation of only two methods is required:
2.5 Particle Correlations Analysis Software

### 2.5.1 Correlation functions

- **Function**
  - `OnePairFctn`
  - `Function1D`
  - `Function2D`
  - `Function3D`
  - `TwoPairFctn`

**Figure 2.5:** Correlation functions inheritance schema. In all cases AliHBT prefix is skipped.

- **OnePairFctn1D**
- **OnePairFctn2D**
- **OnePairFctn3D**
- **TwoPairFctn1D**
- **TwoPairFctn2D**
- **TwoPairFctn3D**

- **MonitorFunction**
  - `MonOneParticleFctn`
  - `MonTwoParticleFctn`
  - `MonOneParticleFctn1D`
  - `MonOneParticleFctn2D`
  - `MonOneParticleFctn3D`
  - `MonTwoParticleFctn1D`
  - `MonTwoParticleFctn2D`
  - `MonTwoParticleFctn3D`

**Figure 2.6:** Monitoring functions class hierarchy.

- double `GetValue(AliHBTPair*)`
- TH1* `GetResult()`

The first one calculates the correlated value for a pair and the second one returns a result histogram. HBT - Analyzer already implements a wide set of most common correlation functions like \(Q_{inv}\), \(Q_{Out}\), \(Q_{Side}\) or \(Q_{Long}\).

#### 2.5.1.2 Monitoring functions

Monitoring functions are designed to create distributions of particle and pair properties that are used in the analysis. This functionality is especially desired when the user requires knowledge concerning the influence of applied cuts on a given distribution. Currently there are one- and two-particle monitoring functions implemented in the HBT - Analyzer.

The inheritance tree of monitoring functions (Fig.2.6) is simpler than the hierarchy of correlation functions. There are no separate base classes for each dimension since they would be irrelevant in this case. They would be completely empty with the definition of just one histogram each.

All classes in Fig.2.6 are abstract and user functions must be derived from the leaf classes.

### 2.5.2 Analysis object

The default way to create reference distributions is the mixing algorithm which is implemented in the AliHBTAnalysis class. The user can set six types of functions, i.e. three types for correlation and monitoring, namely for:

- reconstructed particles,
• simulated particles,
• reconstructed tracks and simulated particles.

The last item corresponds mainly to resolution analysis but it is also used in weight algorithms. Therefore, a more general term is used. In the real data analysis only reconstructed track functions are calculated. Two other types are used only in Monte-Carlo data analysis. The user can specify which data are to be used in the analysis: simulated, reconstructed or both.

In general, all particles are used in the analysis and every particle is mixed with all the others. In order to speed up computation time, the user can set a pair-cut object in the analysis that filters out pairs before passing them to functions. For optimization reasons, this cut is checked progressively. The first check is performed immediately after the first particle is picked up. If the particle does not pass the check then it does not make sense to loop over all the other particles. The next check is performed when the second particle is picked from an event, and at last the pair properties are verified. The pair cut is designed in a way that allows checking the pair properties solely, without examining each particle in a pair to avoid repeating of the tests.

In the case of non-identical particle analysis, or in more general terms, in the case of mutually exclusive cuts on individual particles (a particle cannot be accepted by both cuts) a faster algorithm is used. In such a case, pre-selection of particles is performed. In the outermost event loop all particles are checked if they pass any of individual cuts in a pair. Pointers to particles that passed the first or second particle cut are stored in two separate AODs. Such pre-selected particles are mixed and numerators are filled. AOD with particles that passed a cut on second particle are stored in AliEventBuffer. Before this AOD is pushed to the buffer, the particles that passed a cut on first particle are mixed with the buffered ones and denominators are filled. The choice of a mixing algorithm is made automatically by an analysis object on the basis of the particle-cut properties. One could think that the pre-selection technique is also faster in a general case and that it is enough to make sure that a particle is not mixed with itself. However, in this case the optimal way is particle selection on the level of reading.

The Stavinsky algorithm [76] is implemented in the AliHETAnalysisStavinsky class, that derives from AliHETAnalysis.

2.6 Software for simulating the Correlations

None of the existing event generators is able to simulate relativistic heavy ion collision with correlations arising from quantum statistics and final state interaction effects. These effects are of the quantum origin and require appropriate propagation of the wave functions while generators normally work with the probabilities. Moreover, proper quantum calculation requires solving n! equations, where n is a number of particles in an event, what nowadays is impossible to perform within a finite time. Currently exist two ways which allow to circumvent the problem.

2.6.1 “Weight” method

This algorithm enables calculating the correlation function on the basis of the simulated particle freeze-out momenta and relative distances. Each particle pair \((i,j)\) is weighted with \(\rho_{ij}\), \(x_i\) being 4-vectors \(x_i = (t_i, x_i)\) of the hadronization points,

\[
C(Q, K) = \frac{1}{N(Q,K)} \sum_{i,j} \rho_{ij},
\]

\[
\rho_{ij} = 1 + \cos((p_i - p_j) \cdot (x_i - x_j)).
\]

\(N(Q,K)\) is the number of pairs in a given bin. \(\rho_{ij} - 1\) coincides with the formal Born probability density \(\Psi^*\Psi\) of the Bose-Einstein symmetrized 2-particle plane wave (Eq. (1.5)) [77, 78].
The corrections for strong and Coulomb Final State Interactions are incorporated into the above formula using the amplitudes Eq. (1.18) and Eq. (1.20), respectively. Depending on the particle system, different approximations are used. For identical pion and kaon pairs the s-wave approximation of the interaction is satisfactory. In the case of nucleons, for which the Bohr radius is small (the strong interaction is of the different intensity), more sophisticated approximations are necessary.

The “weight” method allows to calculate correlation effects at the level of the analysis. The correlation functions are obtained the same way as in the regular analysis but numerator histograms are filled with the weight. The space time coordinates at freeze-out must be assigned for each particle. If a generator does not provide them, it is necessary to randomize them according to some model dependent distribution.

To obtain the correlation functions influenced by the detector effects, the simulated momenta need to be provided for each reconstructed pair. The weight is calculated with the simulated parameters but the histograms are filled with the values calculated with the reconstructed momenta. If a particle type is incorrectly reconstructed the weight is 1 so the contamination is taken into account. In such a case, in fact a particle has different mass than reconstructed, what indicates that particles do not have close velocities. Hence, they basically do not interact and the weight is close to 1. Actually, it would be more correct to calculate the weight with the real particle types. However, it is technically difficult and in most cases the approximation is good enough because only particles with close velocities are considered in the analysis. It is not valid if both particles are in fact of the same type as the number of such pairs is normally very small.

We have implemented the pure virtual interface for the codes performing the weight calculations. It is implemented in class AliHBTWeights. We are aware of two programs that implement the algorithm, namely the one due to Lednicky [79] and the second due to Partt called CRAB [81], [80]. There are minimal differences between them resulting from different approximations used in the FSI calculations.

We have interfaced both codes in AliRoot, however, only the quantum statistics calculations are available for CRAB within the ALICE offline framework. Technical difficulties prevented us from implementing the full interface, especially due to the fact that the estimated time-scale needed to overcome all the problems was large, and the Lednicky code provides the same functionality.

Only a single instance of a class performing the weight calculations can be present at the same time. The object can be accessed with the Instance method so it can be properly configured. The weight is obtained by calling the method AliHBT::GetWeight(), which in turn uses the (static) AliHBT::GetWeight(AliHBTPair*). It is highly recommended to use the first solution because it buffers the result and when called again it automatically returns the buffered value.

Since the weight depends only on the relative distance between the particles, alternatively it is sufficient to provide this 4-vector for each pair. We employ this feature when a correlation function of the Gaussian shape needs to be simulated. To obtain Gaussian $Q_{inv}$ (or $Q_{out}Q_{side}Q_{long}$) correlation function the distributions of the relative distance components must be also Gaussian in the pair rest frame (or in LCMS). In these cases it is easier to provide momenta in already appropriately boosted and rotated pair frame and afterwards randomize the distance components, rather than performing the randomization from a non trivial distribution and then transforming particle coordinates taking into account the appropriate Jacobians. If the user wants to simulate a Gaussian correlation function using this approach, it is necessary to pass appropriate argument with SetRandomPosition method. Currently the following options are accepted:

1. kGaussianQInv: Gaussian $Q_{inv}$

2. kGaussianDSL: Gaussian $Q_{out}Q_{side}Q_{long}$

3. kNone: the feature is switched off
2.6.2 HBT Processor

Correlation functions constructed with data produced by any event generator are normally flat in the region of small relative momenta. The HBT-processor “after-burner” [82] randomly reshuffles particle momenta about small values up to the moment when the correlation obtained is sufficiently close to the required shape. The reference distribution needs to be known beforehand in order to calculate the correlation function. Hence, HBT Processor requires several events on input to be able to derive it using the mixing technique.

The HBT processor is a efficient tool to verify the influence of different experimental factors on the shape of the correlation function. However, the correlation signal obtained with this algorithm does not contain many important features. Namely, it is by no means applicable to generate any dynamic effects. The signal has a required shape only within a requested acceptance and even if a subrange is analyzed the correlation function has undetermined shape. Additionally, simulation of a three dimensional correlation function of a required shape is very time consuming.

2.6.3 AliGenCocktailAfterBurner Generator

This class enables usage of afterburners in AliRoot i.e. programs that add a signal by modifying events produced by other generators. We needed to implement such a tool because I decided to use HBT Processor in our studies on the ALICE performance.

AliGenCocktailAfterBurner extends AliGenCocktail generator that allows to combine output of several regular generators. It is especially helpful when one or more rare signal has to be added to a background event. One or more generators and afterburners can be plugged in. First, generators produce all the requested events and afterwards, afterburners are run so all the events are available at the moment an afterburner is executed. This is important in the case of HBT Processor that needs to calculate the combinatorial background before it starts event processing.
3 Effect of hard processes on momentum correlations in Heavy Ion Collisions

3.1 Introduction

In this chapter we describe a simple model to simulate the effect of hard processes on particle correlations. We take to the account all the sources listed in section 1.2. We provide analytical calculations of the correlation function in a special limiting case. We investigate how particle production from jet fragmentation shows itself in the correlation data. We study the visibility of the effect at different proportions of jet production to the total multiplicity and at different transverse momenta.

This work has been done in cooperation with Guy Paić and Boris Tomášik and it was published in [92].

3.2 Simulation tools

3.2.1 Jets

With Pythia [88] we simulate p+p collisions at $\sqrt{s} = 5.5$ TeV. We extract jets in pseudorapidity coverage of the ALICE detector $-1 < \eta < 1$, by making use of a simple clustering algorithm. We identify the highest $p_t$ particle among direct fragmentation products of a single string as the leading one and then search for particles with an opening angle $\Delta \phi$ and relative rapidity $\Delta \eta$ to the leading one that fulfills criterion: $\sqrt{\Delta \phi^2 + \Delta \eta^2} < 2$. Note that we use here direct daughters of a single string, which are not necessarily final. Jets with the sum of $p_t$'s from all particles between 5 and 10 GeV are selected for further study.

Within the jet, the original position of the particles is distributed according to a Gaussian of the width $J$ and all particles are assumed to be produced instantaneously

$$s(x, x_j) = \frac{1}{(2\pi J^2)^{3/2}} \exp \left( -\frac{(\bar{x} - x_j)^2}{2J^2} \right) \delta(t - t_j). \quad (3.1)$$

The jet itself is placed into a random position $(\bar{x}_j, t_j)$.

3.2.1.1 Jet quenching model.

We model the strong jet suppression by a very dense medium by assuming that the jets originate from surface of a cylinder with radius $R$ and length $L$. Eventually, we allow for some finite thickness $\delta R$ for the cylinder surface. It is assumed that the total transverse momentum of the jet is always perpendicular to the cylinder surface and that jets are produced instantaneously.

3.2.1.2 Non-quenching model.

If the early medium does not suppress jets, we should be able to observe jets from hard collisions in all reaction volume. We model such a case by choosing a Gaussian distribution of the jets in the transverse plane, but we keep the uniform distribution in longitudinal direction from $-L/2$ to $L/2$. Instantaneous production is assumed.
3.2.2 Background.

Apart from jet fragmentation, particles can be produced by thermal fireball. If we are interested in jets, these particles represent background for us. Its momentum distribution is such that the total resulting spectrum at low $p_t$ is given by

$$F(p_t) = \frac{d^2N}{p_t dp_t dy} \propto \exp \left(-\frac{m_T}{T}\right), \quad (3.2a)$$

where $T$ is an effective slope parameter. The background spectrum is defined as $F_b(p_t) = F(p_t) - F_j(p_t)$, where $F_j(p_t)$ the spectrum produced by jets.

![Figure 3.1](image)

**Figure 3.1:** Pion $p_t$ spectrum for events containing 100 jets with total multiplicity 3000 charged particles per unit of rapidity. The red squares correspond to particles originating from jets, the green circles - thermal, and black triangles is the sum.

At high $p_t$ the spectrum is dominantly shaped by jet fragmentation. Technically, it eventually shows up when $F_j(p_t)$ supersedes parametrization (3.2a). In order to obtain a smooth total spectrum with exponential low-$p_t$ part and high-$p_t$ tail as given by jets, we choose the normalization of the background spectrum $F_b(p_t) = F(p_t)/2$ when the jet contribution becomes $F_j(p_t) > F(p_t)/2$. In Fig. 3.1 is presented an example spectrum.

The background particles are assumed to be produced instantaneously at the same time as the jets and are distributed in space according to a Gaussian

$$S_b(x, p) = \frac{1}{(2\pi B^2(p_t))^{3/2}} \exp \left(-\frac{x^2}{2B^2(p_t)}\right) \delta(t-t_0). \quad (3.2b)$$

The size of the background source first decreases linearly with $p_t$ up to $p_t = p_t^{\text{max}}$ and than stays constant:

$$B = \begin{cases} B_0 \frac{p_t}{p_t^{\text{max}}} + B_\text{max} \frac{p_t^{\text{max}}}{p_t} & \text{for } p_t < p_t^{\text{max}} \\ B_\text{max} & \text{for } p_t \geq p_t^{\text{max}} \end{cases} \quad (3.2c)$$

where we can specify $B_0$, $B_\text{max}$, and $p_t^{\text{max}}$.

3.3 Theoretical understanding

3.3.1 Calculation of the correlation function

We will calculate the correlation function $C(q, K)$ from its (approximate) relation to the emission function $S(x, K)$ defined by eq.(1.11). Thus if we specify the emission function, calculation of the correlation
function is straightforward. For particle production from jets we will take

$$S(x,p) \propto \sum_{i=1}^{N} \frac{1}{(2\pi J^2)^{3/2}} \exp \left(-\frac{(\vec{x} - \vec{x}_i)^2}{2J^2}\right) \delta(t - t_i), \quad (3.3)$$

where \(N\) is the number of jets and \(J\) the “intrinsic” size of the jet. Here we have assumed that the momentum distribution is not coupled to the position distribution and can be factorized out. Under this assumption the momentum distribution would cancel in the calculation of the correlation function, and we do not write it down when specifying \(S(x,p)\), but indicate its absence by using the \(\propto\) relation.

The correlation function will be calculated in the limit \(N \rightarrow \infty\), where we can replace the summation in eq. (3.3) with integration over the space-time distribution of jets \(D(x')\). In principle, this distribution can depend on the total jet momentum, but we do not assume such a dependence for a moment. Then the emission function becomes

$$S(x,p) = \int d^4x' D(x') \frac{1}{(2\pi J^2)^{3/2}} \exp \left(-\frac{(\vec{x} - \vec{x}')^2}{2J^2}\right) \delta(t - t'). \quad (3.4)$$

We can specify various distributions \(D(x')\) and calculate the resulting correlation functions.

### 3.3.2 Cylindrical source

If the jets are totally suppressed by the medium, only those produced at the surface of the interacting region will actually fragment into hard particles and be detected. For central collisions, they will come from the surface of a cylinder. Then we can write

$$D(x') = \delta(r' - R) \Theta(z' - L/2) \Theta(L/2 - z') \delta(t' - t_0), \quad (3.5)$$

where \(r' = \sqrt{x'^2 + y'^2}\), \(R\) is the radius of the cylinder, \(L\) its length, and an instantaneous production from all jets is assumed. If we are interested in production of particles with a given \(p_T > 0\), only one half of the cylinder should be assumed, the one which produces the given momentum “outwards”, i.e. \(x > 0\). The correlation function can be calculated by using eqs. (1.11) and (3.4). We use the Bertsch-Pratt parametrization (see section 1.3.3) and we take take the three spatial components of the momentum difference \(q\) as independent. Because the production is assumed to be instantaneous, time integrations are trivial. The correlation function reads

$$C(q, K) - 1 =$$

$$C(q_o, q_s, q_l) = \exp \left(-\frac{(q_o^2 + q_s^2 + q_l^2)J^2}{L^2q_l^2}\right) \times \left| \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} d\varphi \exp[iR(q_o \cos \varphi + q_s \sin \varphi)] \right|^2. \quad (3.6)$$

This integral cannot be performed analytically, in general. However, we can derive analytical formulas for the cuts of the correlation function if two of the \(q\)-components vanish. This way we obtain

$$C(q_o, q_s = 0, q_l = 0) - 1 = \exp(-J^2q_o^2) \left\{ J_0^2(q_o R) + H_0^2(|q_o R|) \right\}, \quad (3.7)$$

$$C(q_o = 0, q_s, q_l = 0) - 1 = \exp(-J^2q_s^2) J_0^2(q_s R), \quad (3.8)$$

$$C(q_o = 0, q_s = 0, q_l) - 1 = \exp(-J^2q_l^2) \frac{4}{q_l^2L^2} \sin^2 \left(\frac{q_l L}{2}\right), \quad (3.9)$$

where \(J_0\) is a Bessel function and \(H_0\) a Struve function.

**Observation 1: secondary peaks.** The Bessel function \(J_0\) oscillates and this may show up in the correlation function. For example, \(C(q_o = 0, q_s, q_l = 0)\) may have a peak apart from the main \(q = 0\).
one, given by the second local maximum of the Bessel function. There might be other peaks, but they become less and less pronounced. The second peak of $J_0(x)$ is at $x = 3.83$, so the secondary peak in the correlation function can be expected around $q_s \approx 3.83 \frac{hc}{R}$.

**Observation 2: longitudinal cylinder size.** One may wonder how $J$ and $L$ influence the width of the correlation function in the longitudinal component $q_l$. To study this, the simplest (although not the most precise) approach is to take the second derivative of the correlation function and relate it to $-R_l^2$—the effective size of the source in longitudinal direction. This leads to

$$R_l^2 = 2J^2 + \frac{1}{6}L^2. \quad (3.10)$$

This illustrates that, unless $L \gg J$, the effective longitudinal size is mainly given by the intrinsic jet size $J$ and not the longitudinal extent of jet distribution $L$.

### 3.3.3 Jets produced perpendicularly

In the actual simulation jets were assumed to be produced in such a way, that the jet momentum was always perpendicular to the cylinder surface. Particles within the jets are spread around the mean jet momentum. We will assume that the angles between particle momentum and jet momentum are distributed as

$$P(\vartheta) \propto \exp \left( \frac{\cos \vartheta}{\Phi} \right). \quad (3.11)$$

Since the jet angle is given by the position where it was produced, and the $x$- or outward direction is given by particle momentum, we realize that $\vartheta = \varphi = \angle \vec{p} \vec{r}$, where the vectors are taken in the transverse plane. Thus in this case we modify the distribution $D(x')$:

$$D(x') = D(t', r', \varphi', z') = \exp \left( \frac{\cos \varphi'}{\Phi} \right) \delta(r' - R) \Theta(z' - L/2) \Theta(L/2 - z') \delta(t' - t_0). \quad (3.12)$$

It may happen that a jet final state particle is emitted in the opposite direction to the jet orientation, f.g. as a result of low momentum resonance decay. In accord with the simulation we assume that we can observe jets produced from all around the fireball surface. However, in the jet quenching scenario the restriction to one half of the surface would probably be more realistic, because flowing medium would stop particle moving in the opposite direction. The number of such particles is however relatively small and for clarity we have not applied any additional restriction.

Using again eqs. (1.11) and (3.4) we obtain

$$C(q_o, q_s, q_l) - 1 = \exp \left( - \frac{1}{(q_o^2 + q_s^2 + q_l^2)} \right) \frac{4}{q_l^2 L^2} \sin^2 \left( \frac{q_l L}{2} \right) \frac{1}{(2\pi)^3 I_0(1/\Phi)} \times \left| \int_{-\pi}^{\pi} d\varphi \exp[iR(q_o \cos \varphi + q_s \sin \varphi)] \exp \left( \frac{\cos \varphi}{\Phi} \right) \right|^2. \quad (3.13)$$

Here $I_0$ is the Bessel function. The cut in $q_l$ is again given by eq. (3.9). The cuts along $q_o$ and $q_s$ cannot be calculated analytically.

In the limiting case $\Phi \to \infty$ one recovers the case of no restrictions on jets productions. In that case results of the previous subsection almost apply: the slight difference comes from integrating over the whole range of the azimuthal angle. This leads to a disappearance of the Struve function $H_0$ in eq. (3.7) and the cuts in both $q_o$ and $q_s$ are given by eq. (3.8).

If $\Phi$ is decreased, the second bump due to the Bessel function disappears and is eventually transformed into a “shoulder” such that the correlation function looks like a “double Gaussian”. This behavior is illustrated in Figure 3.2.
3.3 Theoretical understanding

3.3.4 Jets with background

Now we add pions that are produced from a “background” source and not from jets. Thus our emission
function will have two components

\[ S(x, p) = S_j(x, p) + S_b(x, p) \]  

(3.14)

where \( S_j(x, p) \) stands for the pion production from jets, as given by eqs. (3.4) and (3.12), and \( S_b(x, p) \)
describes the background. We will assume that the background is given by an instantaneously emitting
Gaussian source sitting at the center of the cylinder

\[ S_b(x, p) = \mathcal{F} \frac{1}{(2\pi B^2)^{3/2}} \exp \left( -\frac{r^2}{2B^2} \right) \delta(t-t_0), \]  

(3.15)

where the normalization constant \( \mathcal{F} \) is chosen in such a way that a required ratio of pions from jets
to the total number of pions (denoted by \( \mathcal{R}_j \)) is obtained. The total number of particles is obtained by
integrating \( S(x, p) \) over \( x \), the numbers of those coming from jets and background by integrating \( S_j(x, p) \)
and \( S_b(x, p) \), respectively. Thus we can write

\[ \mathcal{R}_j = \frac{\int d^4x S_j(x, p)}{\int d^4x S(x, p)}. \]  

(3.16)

From this we obtain

\[ \mathcal{F} = 2\pi RL_0 \left( \frac{1}{\Phi} \right) \frac{1-\mathcal{R}_j}{\mathcal{R}_j}. \]  

(3.17)
The correlation function can be calculated along the same lines as in previous cases. The general result is

\[
C(q_o, q_s, q_l) - 1 = \frac{\mathcal{R}_j^2}{I_0^2(1/\Phi)} \left[ \exp \left( -\left(\frac{q_o^2 + q_s^2 + q_l^2}{2} \right) \right) \frac{4}{q_l L^2} \sin^2 \left( \frac{q_l L}{2} \right) |\mathcal{J}|^2 \right. \\
+ \left( 1 - \frac{\mathcal{R}_j}{\mathcal{R}_j^2} \right) I_0^2(1/\Phi) \exp \left( -\left(\frac{q_o^2 + q_s^2 + q_l^2}{2} \right) \right) \frac{2}{q_l L} \sin \left( \frac{q_l L}{2} \right) \Re \mathcal{J}, \right. \\
+ 2 \left( 1 - \frac{\mathcal{R}_j}{\mathcal{R}_j^2} \right) I_0(1/\Phi) \exp \left( -\left(\frac{q_o^2 + q_s^2 + q_l^2}{2} \right) \right) \frac{2}{q_l L} \sin \left( \frac{q_l L}{2} \right) \Re \mathcal{J}, \tag{3.18}
\]

where we introduced

\[
\mathcal{J} = \frac{1}{2\pi} \int_{-\pi}^{\pi} d\varphi \exp (i R (q_o \cos \varphi + q_s \sin \varphi)) \exp \left( \frac{\cos \varphi}{\Phi} \right). \tag{3.19}
\]

For later calculations it is useful to note that in a special case we have

\[
\mathcal{J} = I_0 \left( \frac{1}{\Phi} \right) \quad \text{(for } q_o = q_s = 0), \tag{3.20}
\]

Relation (3.18) can be slightly simplified for the cases \( q_o = q_s = 0 \) or \( q_l = 0 \). In the former case we obtain

\[
C(q_o, q_s, q_l = 0) - 1 = \frac{\mathcal{R}_j^2}{I_0^2(1/\Phi)} \left[ \exp \left( -\left(\frac{q_o^2 + q_s^2}{2} \right) \right) \frac{2}{q_l L} \sin \left( \frac{q_l L}{2} \right) \Re \mathcal{J}, \right. \\
+ \left( 1 - \frac{\mathcal{R}_j}{\mathcal{R}_j^2} \right) I_0(1/\Phi) \exp \left( -\left(\frac{q_o^2 + q_s^2}{2} \right) \right) \frac{2}{q_l L} \sin \left( \frac{q_l L}{2} \right) \Re \mathcal{J}, \tag{3.21}
\]

and in the latter

\[
C(q_o = 0, q_s = 0, q_l) - 1 = \\
\mathcal{R}_j^2 \exp(\frac{-q_l^2 L^2}{2}) \frac{4}{q_l^2 L^2} \sin^2 \left( \frac{q_l L}{2} \right) \left[ (1 - \frac{\mathcal{R}_j}{\mathcal{R}_j^2}) \exp(-q_l^2 B^2) \right. \\
+ 2 \mathcal{R}_j (1 - \frac{\mathcal{R}_j}{\mathcal{R}_j^2}) \exp \left( -\left(\frac{q_l^2 J^2 + B^2}{2} \right) \right) \frac{2}{q_l L} \sin \left( \frac{q_l L}{2} \right), \tag{3.22}
\]

Examples of the cuts of the correlation function along the coordinate lines in different \( q \)-components are plotted in Figures 3.3 and 3.4.

The structure in \( q_o \) and \( q_s \) remains qualitatively preserved from the case of no background if the ratio of pions from jets is big enough. Thus there is a “Bessel shoulder” in case of the cut along \( q_o \) and even a secondary “Bessel bump” may show up in \( q_s \).

From eq. (3.22) one can see a more clear structure: indeed the background source brings into the game a Gaussian contribution with a corresponding width, but the interpretation is more complicated because there is an interference term in which sizes of the jets and background mix. One can try to fit the result with a “double-Gaussian”, but this doesn’t completely reproduce the shape (Figure 3.4).
3.3 Theoretical understanding

3.3.5 Gaussian distributed jets

This situation is a simple exercise and might correspond to a no-quenching scenario. In that case jets can be observed from the whole volume of the fireball and we model their distribution by a Gaussian. We still keep the assumption of instantaneous emission and box-like distribution in the longitudinal coordinate

\[ D(x') = D(t', r', \varphi', z') = \exp \left( -\frac{r'^2}{2R^2} \right) \Theta(z' - L/2) \Theta(L/2 - z') \delta(t' - t_0). \]  

Again, using eqs. (1.11) and (3.4) we calculate the correlation function. Since the longitudinal distribution is the same as it was in subsection 3.3.2, the cut of the correlation function along \( q_l \) is given by relation (3.9). In the other two directions we recover a very simple structure

\[ C(q_o, q_s) - 1 = \exp \left( -q_o^2(J^2 + R^2) - q_s^2(J^2 + R^2) \right). \]  

Not surprisingly, a Gaussian source produces a Gaussian correlation function.

**Figure 3.3:** The correlation function in case of Gaussian-distributed background. Parameters used in the calculation: \( J = 1 \text{ fm}, R = 6 \text{ fm}, B = 4 \text{ fm}, \Phi = 0.8, \) and \( \mathcal{R}_j = 0.66. \) (a) as a function of \( q_o, \) (b) as a function of \( q_s. \)

**Figure 3.4:** The correlation function as in Figure 3.3 but as a function of \( q_l. \) \( (L = 2 \text{ fm}) \) Solid line shows the correlation function, dashed line shows a “double-Gaussian” curve: \( (1 - \mathcal{R}_j) \exp(-q_o^2 * B^2) + \mathcal{R}_j \exp(-q_l^2 * (1.3 \text{ fm})^2) \) (note relation (3.10) and that \( \sqrt{2J^2 + 1/6L^2} = 1.63).
3 Effect of hard processes on momentum correlations in Heavy Ion Collisions

![Graphs showing correlation functions](image)

**Figure 3.5:** Projections of the correlation function resulting from simulation of 10 jets produced at the surface of a cylinder with the radius 6 fm and length 1 fm.

![Graphs showing correlation functions](image)

**Figure 3.6:** Correlation function resulting from simulation of 100 jets from a surface of a cylinder with the radius 6 fm and length 2 fm. Curves correspond to a fit with the theoretical curve given by eq. (3.13) multiplied by interception parameter $\lambda = 0.77$. Parameters of the curves are: $R = 5.92\, \text{fm}$, $J = 1.06\, \text{fm}$, $L = 1.82\, \text{fm}$, and $\Phi = 0.86$.

### 3.4 Results

#### 3.4.1 Only jets.

First, we analyze events that contain jets only (and no background). We assume cylindrical geometry with radius of $R = 6\, \text{fm}$, $\delta R = 1\, \text{fm}$, and length $L = 1\, \text{fm}$ (Fig. 3.5) or $L = 2\, \text{fm}$ (Fig. 3.6). Jet radius $J$ is 1 fm.

In Figures 3.5 and 3.6 we show the projections of the correlation functions from simulations with 10 and 100 jets, respectively. In the latter case the simulated correlation function is rather well reproduced by theoretical curves which were calculated from eq. (3.13). A parameter $\lambda < 1$ which multiplies the theoretical expression was added in order to account for the intercept of $C(q = 0)$ which is smaller than 2 because in obtaining the projections we always integrated over finite regions in the remaining two $q$-coordinates.

The structure of the projection in $q_s$ in Fig. 3.6 can be understood from the $\Phi \to \infty$ limit formula, eq. (3.8): the sub-leading peaks stem from the Bessel function. A similar structure in $q_o$ is “dissolved” faster when the jet collimation is finite and leads to the “shoulder” in Fig. 3.6 (left). Projection in $q_l$ can be reproduced by eq. (3.9).

In the simulation, the angular width of the jet depends on transverse momentum of particles. Thus $\Phi$ is not constant. It appears that averaging over $\Phi(p_t)$ is more important in case of a smaller number of jets. Projections in $q_o$ and $q_s$ in Fig. 3.5 result from such averaging and we cannot describe them with the prescription (3.6). Beyond the leading peak we do not see any clear subleading maxima, but the correlation function assumes a shoulder-like shape at larger $q$’s.
3.4 Results

Figure 3.7: Correlation function resulting from simulation of 100 jets from a surface of a cylinder with the radius 6 fm and a “thermal” background source; 2/3 of all pions come from jets. Plotted are cuts along \( q \)-axes.

3.4.2 Jets with background.

If in addition to jets there is also other source of particles, the characteristic features of the correlation function due to jets get diluted. We study this by adding a background source, as described by eqs. (3.2). We choose \( T = 210 \text{MeV}, B_0 = 10 \text{fm}, B_{\text{max}} = 1 \text{fm}, \) and \( p_t^{\text{max}} = 1.2 \text{GeV} \).

In Figure 3.7 we plot the correlation function resulting from a simulation with 100 jets where only 1/3 of the pions are produced by the background. The dimensions of the background source (averaged over \( p_t \)) are comparable with the transverse size of the source of jets, while they are clearly larger than it in the longitudinal direction. Therefore, for the two transverse \( q \)-components the background just weakens the characteristic shape from jets. On the other hand, in \( q_l \) a narrow peak at \( q_l = 0 \) results from the large size of the background.

We checked that if the percentage of jet pions drops as low as 1/6, the \( p_t \)-integrated correlation function is completely determined by the background source and no signal of jets is seen. Note that the proportion of jet particles can be even lower at ALICE: at midrapidity we assume 3000 for \( dN/dy \) of charged particles, out of which about 90% are pions, so we obtain roughly 1350 single-charge pions. Since a jet produces on average 2.4 positive pions in our acceptance region, 100 observable jets with pseudorapidity \(-1 < \eta < 1\) will leave us with 120 single-charge pions per pseudorapidity unit. That makes the ratio of pions from jets to the total pion number about \(120/1350 \sim 1/11\). (We explore this situation in the next subsection.)

3.4.3 High \( p_t \).

We can focus on particles with high transverse momenta where we expect the portion of jet-produced pions to be increased. Hence, it may reduce the effect of the background. In upper part of Figure 3.8 we plot correlation function calculated for jets with a background source as previously, but we use only particle pairs with \( K_t \) above 1.2 GeV in our analysis. A non-Gaussian shape, particularly in \( q_o \) and slightly in \( q_s \), is observed, which is due to contribution from jets.

In bottom part of Fig. 3.8 are presented correlation functions in case jets are distributed according to Gaussian distribution along diameter of the cylinder. Again, \( Q_{\text{out}} \) and \( Q_{\text{side}} \) correlation functions fits well with double Gaussian formula. Clearly, the correlation function bears the information about the volume that jets were produced and remaining thermal part. Although, its interpretation is not straight forward because it is additionally modified by the correlations between particles stemming from jets the fireball.

In the both scenarios the signal due to jets is exposed and modify the shape of the correlation function, if sufficiently large fraction of pions is emitted from jets. However, in the both cases the influence is rather similar, and together with large number of unknown parameters, like

- the strength of the \( p_t \) scaling,
- the influence of collective dynamical expansion (flows),
3 Effect of hard processes on momentum correlations in Heavy Ion Collisions

Figure 3.8: Projections along $q$-axes of the correlation functions resulting from simulation of 100 jets (top) from a surface of a cylinder with the radius 6 fm, (bottom) from a 2D Gaussian distribution in transverse plane also with the radius 6 fm; and a “thermal” background source (with $p_t$ scaling switched on). 1/12 of all particles come from jets and a cut is imposed: $p_t > 1.2 \text{GeV}/c.$ are plotted.

- actual ratio of the pion number from the thermal fireball and hard scatterings,

the direct experimental recognition between the two scenarios might be difficult. However, with help of additional information from others measurements the detailed analysis might help to resolve which scenario takes place.

Due to the limited time a more detailed study of the shape of the correlation function that is necessary in order to understand differences between the two models for jet distribution, was not possible.

3.4.4 How many particles must be produced from jets to see their influence?

We can estimate the contribution to each bin of correlation function as $N_{tot}^2$ ($N_{tot}$ is total number of particles). We write $N_{tot} = N_j + N_b$, where $N_j$ is the number of particles produced by jets and $N_b$ the number of particles coming from the thermal source. Then the number of pairs is written as $(N_j + N_b)^2 = N_j^2 + 2N_jN_b + N_b^2$. In our study, $N_j^2$ corresponds to signal, $N_b^2$ to background, and $N_jN_b$ is the correlation between particles of signal and background. If $N_j \ll N_b$, the signal becomes invisible. Our analysis indicate that at least 25% of particles must be produced from fragmentation of jets to make the signal visible.
4 Effect of hard processes on momentum correlations in $pp$ and $p\bar{p}$ collisions

4.1 Introduction

In the previous chapter we have used a very simple assumption about the shape and dimensions of the jet hadronization volume. We have attempted to understand the existing experimental results from the two particle correlations, especially that a consistent interpretation in terms of the collision dynamics is largely missing.

The size of the source created in $pp$ and $p\bar{p}$ collisions, as measured with momentum correlations, increases with the particle multiplicity (see section 1.3.5.1 and references herein). The correlation of the extracted size with the rapidity density of the collisions, from the HBT analysis, was sometimes described as evidence for the existence of a "source" with a given size. Some alternative explanations have been given invoking long lived resonances and multiple parton interactions [83].

In the present work we are investigating whether the observed behavior may be understood in terms of more trivial explanations related to the details of the hadronization of the partons leading to jets. We know namely, that the point of hadronization of a jet and the point of the initial parton–parton hard scattering do not coincide. The distance between them is the so called hadronization length ($L_{hadr}$).

![Figure 4.1](a) Distribution of the transverse jet momentum, for different $dN_{ch}/d\eta$ ranges. The cut at 3 GeV/c applied in the calculations is visible in the figure. b) Distribution of the mean transverse jet momentum ($p_t$) versus $dN_{ch}/d\eta$. The results were obtained with Pythia at $\sqrt{s} = 1.8$ TeV.

Numerical estimates for the time scale of hadronization vary significantly [84–86], but owing to the Lorentz boost to the laboratory frame, they are proportional to the energy, $L_{hadr} \sim O(1)E_t$ ([87]). Hence, there is a dependence of $L_{hadr}$ on the energy due to the Lorentz boost. On the other hand the energy spectrum of the emitted jets depends on the charged particle multiplicity of the events as shown in Fig.4.1. Hence if we assume that the hadronization occurs at different distances from the initial hard scatterings, depending on the energy of the jet, we can expect that this effect may simulate an extended hadronic source without invoking the presence of a thermalized source of hadrons. We have followed this line of thought in the present work. The work presented in this chapter was published as [93].
4.2 Simulation

The simulation comprises three steps:

1. The simulation of the particle momenta using a standard Pythia event generator. Identification of jets and "underlying event".

2. Creation of a spatial distribution of particle origins according to our perception of the hadronization process.

3. Implementation of the Bose-Einstein effect and creation of the correlation functions.

4.2.1 Event generation and jets identification

With Pythia 6.24 [88] we simulate pp collisions with $\sqrt{s} = 1.8$ TeV. The PYCELL subroutine, that is part of the generator, is used to identify jets. We applied the following parameters:

- pseudo-rapidity range ($\eta$): from -2 to 2
- number of pseudo-rapidity bins: 1200
- number of bins in azimuthal angle: 1200
- threshold transverse energy of particles considered: 0
- minimum transverse energy of particles that are used as jet seeds: 0.7 GeV
- minimum jet transverse energy: 3 GeV
- maximum jet radius $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$: 1

All particles that do not belong to any jet are treated as an "underlying event". Jet axis $\vec{p}_j$ - the direction along which the jet develops - is defined as

$$p_{tj} = \sum_i p_{ti}$$  \hspace{1cm} (4.1)  \\
$$\phi_j = \frac{\sum_i \phi_i p_{ti}}{p_{tj}}$$  \hspace{1cm} (4.2)  \\
$$\eta_j = \frac{\sum_i \eta_i p_{ti}}{p_{tj}}$$  \hspace{1cm} (4.3)  \\
$$\vec{p}_j = (p_{xj}, p_{yj}, p_{zj}) = p_{tj} (\cos \phi_j, \sin \phi_j, \sinh \eta_j)$$  \hspace{1cm} (4.4)

The sums run over all particles that make up a jet. $p_{ti}$, $\phi_i$ and $\eta_i$ are transverse momentum, azimuthal angle and pseudorapidity of the ith particle, respectively.

4.2.2 The Source Models

The events simulated with Pythia are then treated according to our model. Namely, the particles identified above as "underlying events" are given a spatial origin centered around the initial hard scattering point, while particles within a jet are given spatial coordinates of origin according to one of the models described below.

**Tube** It is assumed that the hadronization length ($l_j$, the distance from the hard scattering) depends linearly on the initial parton energy that we approximate by $p_{tj}$ (jet total transverse momentum). Thus,
\( l_j = f_t p_{tj} \), where \( f_t \) is a multiplicative factor that represents our lack of theoretical insight into the process of hadronization. For every parton the loci of hadronization along the jet axis \( (x_i) \) is randomized from Gaussian distributions with a mean equal to \( l_j \) and a \( \sigma_i = l_j/3 \), preventing negative values. In the transverse direction (with respect to the jet axis) the hadronization points are randomized so that the distance to the jet axis follows a Gaussian distribution with a variance equal to \( \sigma_t \) and mean value of zero.

**Dynamic width** The distribution along the jet axis is the same as above while the transverse width \( \sigma_t \) depends linearly on the jet transverse energy and moreover, it is a function of the position along the jet axis (see Fig.4.2) so the distribution of hadronization points is:

\[
\sigma_t(x_i, p_{tj}) = \begin{cases} 
\sigma_t^{\text{max}} \exp\left(-\frac{(l_i-x_i)^2}{w}\right) & \text{if } \sigma_t^{\text{max}} > \sigma_t^{\text{min}} \\
\sigma_t^{\text{min}} & \text{if } \sigma_t^{\text{max}} \leq \sigma_t^{\text{min}},
\end{cases}
\]

\( (4.5) \)

where \( \sigma_t^{\text{max}} = f_t p_{tj} \), \( \sigma_t^{\text{min}} = 0.5 \text{ fm} \) and \( w = \frac{l_j^2}{\ln(\sigma_t^{\text{max}})} \) (\( w \) is chosen so \( \sigma_t(x_i = 0) \) and \( \sigma_t(x_i = 2l_j) \) are equal to \( \sigma_t^{\text{min}} \)).

For both kinds of geometries the hadronization time is equal to \( x_i \).

The positions of the "underlying event" particles are randomized from a single Gaussian distribution with variance \( \sigma_b \). Their emission time is always equal to 0.

### 4.2.3 Simulation of BE correlations and Correlation Functions

Since the generator does not provide for Bose-Einstein correlations they have to be introduced. In our simulation we introduce them using the weighting algorithm due to Lednický, see section 2.6.1.

The correlation functions are calculated for particles with \( |\eta| < 1 \) and \( p_T > 0.1 \text{ GeV} \), while no such a constraint is imposed in the jet finding procedure. We extract the correlation functions with two types of parameterizations, \( C(Q_t, Q_0) \) (eq. (1.32)) and \( C(Q_s, Q_s, Q_t) \) (eq. (1.27)).

When speaking of the correlation function \( C(Q_t) \) we mean the projection of \( C(Q_t, Q_0) \) on the \( Q_t \) axis for \( |Q_0| < 200 \text{ MeV} \). By a double Gaussian fit we mean a 1D fit with the following form of a correlator

\[
C(Q) = 1 + \lambda_1 e^{-(QR_1/(hc))^2} + \lambda_2 e^{-(QR_2/(hc))^2}
\]

\( (4.6) \)

### 4.3 Results

The application of the model described above, in agreement with the intuition, shows that the correlation function indeed changes its shape with increasing multiplicity. Using the experimental data we have attempted to adjust the parameters of the model. We have fixed \( \sigma_t = 0.5 \text{ fm} \) what corresponds to the typical hadronic size. We found that \( \sigma_b = 0.4 \text{ fm} \) reproduces the experimental results at the lowest multiplicities (E735 has measured \( R_t = 0.62 \text{ fm} \) at \( <dN_{ch}/d\eta> = 6.75 \)). In the frame of our model it implies a non-negligible contribution of hard processes in total particle production even at low multiplicities. This observation is in an agreement with other observations at Tevatron [90].

However, we were not able to reach compatibility with the experimental values of \( R_t \) at high multiplicities. The increase of the \( f_t \) parameter causes a decrease of the intercept parameter, while the shape of the correlation function stays approximately unchanged. In fact, the width of the peak, thus \( R_t \) as given by a Gaussian fit even decreases with increasing \( f_t \).

Using the out-side-long (OSL) parametrization we have observed that for this model \( R_{out} \) grows with \( f_t \), while \( R_{side} \) stays approximately unchanged. This finding matches the intuitive representation. Therefore the applied geometry with a constant \( \sigma_t \) limits the growth of \( R_t \). We deduce that \( R_{side} \) must also increase with the jet energy. This led us to the "dynamic width" jet geometry.

Using that model, we have found that we are able to reproduce the experimental results with \( f_t = 1.0 \) and \( f_t = 0.6 \), see Fig.4.6a and 4.4. This is not a unique pair of parameters that gives a good agreement.
Effect of hard processes on momentum correlations in pp and p\bar{p} collisions

\[ l_j = f_l p_j \]

\[ l_t = f_t p_t \]

Figure 4.2: Schema of the "dynamic width" jet geometry model. The spread in transverse direction with respect to the jet axis depends on the position along jet and its magnitude depends on the jet energy.

With E735 result. Within some range we can decrease \( f_l \) and find such a value of \( f_l \) such that we still reproduce the experimental result (Fig.4.6b).

We believe that the precision on the determination of \( f \) values could be improved if results of a 3D HBT analysis were available. Namely, the dependence of \( R_{out} \) and \( R_{side} \) on event multiplicity is required. We have found that \( R_{side} \) increases together with \( f_t \), and \( R_{out} \) together with \( f_l \) (see Table.4.1). It means that we can estimate the size of the jet fragmentation volume using the three dimensional correlation analysis.

In our model the "underlying event" (UE) is somewhat overestimated since we have imposed the cut on the jets of less than 3 GeV and this part has been added to the UE. We have examined how our results change if we reduce UE by removing randomly 50% of particles not assigned to jets. We have found that the obtained radii stay unchanged within 10%.

From Fig.4.7 we see that the correlation functions extend up to large \( Q \)’s (0.4 – 1.0 GeV), similarly to the ones obtained by E735. The slope of the “tail” depends on the multiplicity. The simulated correlation function cannot be well represented by a single Gaussian as expected from the distribution of particle hadronization points shown in Fig.4.3. As it can be seen e.g. in Fig.4.5c, a better fit of the correlation function is obtained using a double Gaussian, albeit it is not yet probably the exact form of a correlator for this kind of source. The two radii may be understood in term of the smaller one representing the correlations among the particles from the "underlying event" and the larger one representing the correlations of jet particles with the ones of the "underlying event", although the interplay of the different factors make such a representation only partially true.

It is important to mention that the extracted radii are much smaller than the extent of the source due to the fact that the particles from the "underlying event" are traveling while the jet did not yet hadronize! Similarly, particles hadronizing first within a jet also moves together with not yet hadronized partons. The same argumentation also explains the weak dependence of \( R_t \) on \( f_l \) in the “tube geometry”.

Fitting such a correlation function with a single Gaussian - as was done in E735 - brings large
Figure 4.3: Cross-section through the 2D distribution of the hadronization points in the plane perpendicular to the beam. The difference in height between contributions from the "underlying event" (the peak for values around 0) and jets (shoulders) is a phase space effect. In fact, the majority of particles originate from jets. The dynamic width jet geometry with $f_l = 1.0$, $f_t = 0.6$ and $<dN_{ch}/d\eta> = 12.4$.

Figure 4.4: a) The $Q_t$ correlation function from our model compared with the correlation function extracted from [36] ($<dN_{ch}/d\eta> = 12.5$) and b) double Gaussian fit to it. The dynamic width jet geometry with $f_l = 1.0$, $f_t = 0.6$ and $<dN_{ch}/d\eta> = 12.4$. 

Double Gaussian Fit

$R_1$: 1.53 $\lambda_1$: 0.220

$R_2$: 0.45 $\lambda_2$: 0.105
Figure 4.5: $Q_t$ correlation functions for the case of the dynamic width geometry with $f_t = 1.0$ and $f_\ell = 0.6$ a) $dN_{ch}/d\eta = 3.2$, b) $dN_{ch}/d\eta = 7.3$, c) $dN_{ch}/d\eta = 17.2$, d) $dN_{ch}/d\eta = 23.0$.

Table 4.1: Dependence of OSL radii on $f_\ell$ and $f_t$ for the $< dN_{ch}/d\eta > = 23.0$. The fits were made imposing a double Gaussian (Eq. 4.6) on 1D projections, taking two other components $> 50$ MeV. In the rows where $R_2$ is not specified fits did not converge and a single Gaussian is used instead.
4.3 Results

Figure 4.6: Results of our model compared to E735 result. The left hand plot shows the best fit to the data obtained with $f_t = 1$ and $f_f = 0.6$ while the right hand plot demonstrates the variation of the results with varying the $f$ values.

Figure 4.7: The same as in Fig.4.4, normalized at $Q_t \sim 500$ MeV and fitted with the single Gaussian form of the correlator.
Table 4.2: $R_t$ radii dependence on $dN_{ch}/d\eta$ at $\sqrt{s} = 14$ TeV, $f_i = 1.0$ and $f_t = 0.6$. The correlation functions were fitted with double Gaussian form of correlator (see Eq. 4.6).

<table>
<thead>
<tr>
<th>$dN_{ch}/d\eta$</th>
<th>$R_{t1}$ [fm]</th>
<th>$\lambda_1$</th>
<th>$R_{t2}$ [fm]</th>
<th>$\lambda_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>1.15</td>
<td>0.15</td>
<td>0.50</td>
<td>0.41</td>
</tr>
<tr>
<td>7.6</td>
<td>1.38</td>
<td>0.20</td>
<td>0.52</td>
<td>0.21</td>
</tr>
<tr>
<td>12.5</td>
<td>1.70</td>
<td>0.18</td>
<td>0.58</td>
<td>0.09</td>
</tr>
<tr>
<td>17.4</td>
<td>1.95</td>
<td>0.15</td>
<td>0.65</td>
<td>0.05</td>
</tr>
<tr>
<td>22.4</td>
<td>2.24</td>
<td>0.12</td>
<td>0.73</td>
<td>0.03</td>
</tr>
<tr>
<td>27.4</td>
<td>2.91</td>
<td>0.10</td>
<td>0.95</td>
<td>0.04</td>
</tr>
<tr>
<td>37.0</td>
<td>3.33</td>
<td>0.07</td>
<td>1.15</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Finally we have calculated, using the parameters extracted for the Tevatron data, the expected correlation of radii with charged particle multiplicities for the maximum LHC energy of 14 TeV. In Table 4.2 we present the results.

### 4.4 Perspectives

The ALICE experiment will measure three dimensional particle correlations in $pp$ collisions within several bins of particle multiplicity. It offers interesting possibilities to test our model and it will allow to draw more precise quantitative conclusions.

On the other hand the wide set of the existing results from $e^+e^-$ experiments at LEP [99–108] offer an interesting case for this research. The system created in these reactions is less complicated then in $pp$ because all the collision energy is transformed into a few jets. Unfortunately, a more complicated nature of particle correlations analysis in $e^+e^-$, that is connected with the presence of the additional correlations due to the jet like event topology, and the limited time did not allow us to study this case. However, we have not found any experimental results that are in contradiction with our model.
5 ALICE performance in correlation analysis

5.1 Introduction

We present the analysis procedures for the extraction of correlation parameters in the experiment. They are verified on the data produced with detailed simulation meaning that the generated tracks were transported through the whole detector using the GEANT3 code. To show the level of complexity it is enough to mention that the simulation of the detector response of one central Pb-Pb collision yielding $dN_{ch}/d\eta \sim 6000$ particles takes on average one day on a modern PC. The simulated data also give information about the performance of the detector. They allow gaining insight in the functioning of the detector and to fine tune the reconstruction and analysis procedures.

The real detector performance may be different from the one obtained with simulations. Clearly, not all effects can be included even in the most sophisticated computer program. However, the experience gathered with such data will greatly facilitate the analysis of the first data.

Technically the correlation analyses are very difficult because a large number of factors can distort the signal

- finite resolution,
- two-track reconstruction inefficiency,
- fake or splitted tracks,
- particle type identification inefficiency,
- correlations due to the detector segmentation

Hence, it is important to understand their influence in order to find algorithms that let correct for them.

In this chapter we present the performance of ALICE setup in the measurements of the hadrons correlations. We focus on the data reconstructed by the central barrel detectors (i.e. ITS, TPC, TRD and TOF). We show the obtained efficiencies and their influence on correlation functions. We present procedures that eliminate their influence on resulting correlation function. Finally, we give estimate of the systematic errors.

5.2 The data and the analysis

The results presented in this chapter were obtained with the data produced during phase 1 of the Physics Data Challenge 2004 (PDC04). We concentrate here on the most central events (impact parameter range from 0 to 2 fm) yielding an average multiplicity of the order of 6000 charged particles per unit of rapidity. To simulate the correlation effects we make use of the weighting algorithm. We verify the obtained results with 500 events simulated by HBT processor.

A particle is considered being of a given mass if its PID probability is bigger than 50%, unless stated explicitly otherwise. In case of the identical particle analysis we always assume the lack of the Final State Interactions. This is justified because in the simulation we know the shape of the correlation induced by FSI and the correction for these effects does not bring any uncertainties. Of course, in the experimental data analysis the exact contribution is unknown, and proper handling is the major problem which brings the most significant contribution to the systematic error.

The details of the analysis procedures like corrections and cuts are described for the case of pion systems, since they are the most copious particle species. If not stated otherwise, the methodology for
Figure 5.1: Correlation functions for a) $\pi^+\pi^+$ and b) $\pi^+\pi^-$ systems and for sizes indicated in the figure. The intercept parameter $\lambda = 1$ was assumed.

the other two particle systems is the same, and for them we only discuss the eventual differences and the results.

5.3 Expected correlation effects

Before starting simulations for any selected values of the space-time parameters let us realize the limits of correlation effects expected for ALICE.

Fig. 5.1 presents the form of the correlation function for the pairs of positively charged pions emitted from a Gaussian source of indicated sizes: 3, 5, 10, 20 fm. The complete calculation have been performed including QS, strong and Coulomb FSI. For the sake of comparison the shapes of correlation functions containing only the QS effect are presented for the smallest (3 fm), and largest (20 fm) sizes.

For the expected size of the order of 6 – 8 fm the $Q_{\text{inv}}$ region where the correlation functions differ from unity is less than 50 MeV/c and the height is on the level of 1.2 despite the assumption of totally chaotic source (the chaosity parameter $\lambda$ equal to one). For the size of 20 fm (the full points) the effect of the Coulomb repulsion almost completely equilibrate the QS positive correlations giving very small effect in the region about 10 MeV/c. It is clear that the traditional approach in which the Coulomb effect is treated as a correction could not be applied in this case. Note also that the long range Coulomb effect can reflect different sizes than QS ones.

Fig. 5.1b shows the correlation function for pairs of unlike sign pions. In this case the Coulomb effect determines the shape of the correlation function. The behavior of the Gamow factor is indicated as a reference. Due to the lack of QS effect and because of the large value of the Bohr radius for two-pion system the sensitivity to the sizes are weaker than for like-sign pions. However, for larger sizes this difference becomes smaller and for the radius of 20 fm the correlation effect for unlike-sign pions exceeds that for identical ones.

The next example, Fig. 5.2a, shows the correlation function for the system of particles with different masses, $\pi^+ p$. As the Bohr radius is substantially smaller in this case, the sensitivity to the sizes are larger than for the system of two pions. Although the sign of particle charge is the same here, the curvature in
5.4 Resolutions

For each considered variable \( X \) we construct histograms of the difference between simulated and reconstructed values, further called \( \Delta X \) or residuum. The order within the difference is always kept so that if any systematical shift is present one can distinguish whether the reconstructed value is statistically under- or over-estimated. In all cases the simulated value is plotted in horizontal axes.

We define resolution (also referred as RMS of \( \Delta X \)) as the standard deviation (sigma) of the Gaussian fit to a \( \Delta X \) distribution. Whenever the mean of \( \Delta X \) is mentioned it is also the fitted value. All the two particle distributions are made for pairs emitted (generated) with small momentum difference in the pair rest frame, namely \( Q_{inv} \) \( < \) 50 MeV/c. We have analyzed all two particle variables that are interesting for interferometry in function of \( K_t \), \( Q_{inv} \), and sometimes a variable itself (f.g. \( \Delta Q_{out} \) vs. \( Q_{out} \)).

5.4.1 Single particle resolutions

The first information we need is the resolution of the reconstructed \( p_t \) (transverse momentum), \( \theta \) (polar angle) and \( \phi \) (azimuthal angle) of each track, since these variables are independent parameters reconstructed by the tracking procedure.

We have studied the distributions of the residuals for pions, kaons and protons. All the results have been published in the ALICE internal note [114]. The summary plots are shown in Fig. 5.3. We observed non-negligible systematic shifts of transverse momentum residuals (Fig. 5.4). The effect was explained as the feature of the reconstruction software that assumes the mass of electron while calculating the corrections for \( dE/dX \). The mass assumption is done after the very first reconstruction pass in TPC.
this point particle type can be determined only on the basis of $dE/dX$ in TPC. And indeed, the systematic shift occurs mostly for the transverse momentum ranges at which $dE/dX$ overlaps with electrons for a given particle type. The actual problem was the lack of the final refit in the reconstruction chain using the most probable mass, when all the information is available. As a consequence a particle is reconstructed with the correct PID and tracked like an electron. The observation was communicated to the tracking developers and appropriate corrections were applied.

The systematic skew is relatively small for pions, and as it can be learned from the following section, it has a negligible influence on the two particle properties. However, the effect exhibits itself for the two particle systems that involve kaons or protons.

The pion transverse momentum resolution (Fig.5.3a) is of the order of 0.7% while the value estimated in ALICE Technical Proposal (TP) [2] is around 1.3%. Taking into account the fact that the results presented in TP were calculated with the magnetic field 0.2 T, while here 0.5 T is used, the results are compatible. The $p_t$ resolutions for kaons and protons are also close to the prediction. Similarly all angular resolutions for all the considered particle types are in good agreement with those in TP [2].

![Figure 5.3](image1.png)

**Figure 5.3:** a) $p_t$, b) $\phi$ and c) $\theta$ resolutions in function of $p_t$.

![Figure 5.4](image2.png)

**Figure 5.4:** a) Mean of $p_t$ residuals versus $p_t$ and b) $dE/dX$ versus momentum in TPC.
5.4.2 Two-particle resolutions

Sample plots of residuals are shown in Fig. 5.5. Almost all variables bear some systematic skews. However, in most of the cases they are much smaller than 1 MeV and they can be neglected.

![Graphs showing two-particle resolutions](image)

**Figure 5.5:** a) $Q_{out}$ and b) $Q_{side}$ resolutions as function of $K_t$ for $\pi^+ \pi^+$

The dependencies of $Q_{inv}$, $Q_{side}$, $Q_{long}$ and $Q_{out}$ resolutions on $K_t$ and $Q_{inv}$ are presented in Figures 5.6, 5.7 and 5.8 for pions, kaons and protons, respectively. Since resolutions of $Q_{out}$ increase strongly with $K_t$ we decided not to put them in the same plots with resolutions of the other components to preserve the histogram clarity. They are shown in Fig. 5.9.

The values of the resolutions for pions are summarized in Table 5.1. The obtained results are very close to the TP predictions. The remaining discrepancies result mainly from the different magnetic field used in the simulations (better transverse momentum resolutions).

![Table 5.1](image)

**Table 5.1:** a) Resolutions of the HBT variables for $\pi^+ \pi^+$ system. b) $2k^*$ resolutions for different particle systems.

The resolutions do not depend on $Q_{inv}$, i.e. the proximity of another track does not deplete statistically the precision of the measurement. The exception is $Q_{out}$ resolution that slightly improves for very small values of $Q_{inv}$. 


Figure 5.6: π⁺π⁺ resolutions of $Q_{\text{inv}}$, $Q_{\text{side}}$, $Q_{\text{long}}$ and $Q_{\text{out}}$ versus a) $K_t$ and b) $Q_{\text{inv}}$. $Q_{\text{out}}$ resolution as function of $K_t$ is presented in Fig.5.9a.

Figure 5.7: $K^+K^+$ resolutions of $Q_{\text{inv}}$, $Q_{\text{side}}$, $Q_{\text{long}}$ and $Q_{\text{out}}$ versus a) $K_t$ and b) $Q_{\text{inv}}$. $Q_{\text{out}}$ resolution as function of $K_t$ is presented in Fig.5.9b.

Figure 5.8: proton – proton resolutions of $Q_{\text{inv}}$, $Q_{\text{side}}$, $Q_{\text{long}}$ versus a) $K_t$ and b) $Q_{\text{inv}}$. $Q_{\text{out}}$ resolution as function of $K_t$ is presented in Fig.5.9c.
5.5 Particle identification efficiency as function of two particle variables

5.5.1 Pions

In figure Fig. 5.10a we present the pion contaminations as function of transverse momentum for different threshold values of the particle identification probabilities. The contamination is below 5% in the $p_t$...
range up to 700 MeV, even for probability threshold as low as 50%. For higher transverse momenta it is necessary to set it as high as 90% in order to obtain the same contamination level. However, in this case almost 50% of correctly identified pions are rejected, what can be seen in Fig. 5.10b. This figure presents the rejection factor i.e. the ratio of correctly identified pions to this number in the case the threshold value is set to 0, from which the reader can see how much the pion statistics is reduced at a given $p_t$.

![Figure 5.10: a) PID contamination versus $p_t$ for different probability threshold, and b) rejection factor for different probability thresholds in function of $p_t$ for $\pi^+$](image)

5.5.2 Kaons

The efficiency is very good at the lowest reconstructible transverse momenta. It worsens with $p_t$ as the $dE/dX$ of kaons and pions become comparable. Around 0.8 GeV the contamination reaches its maximum value of 25% and decreases for higher values since pions and kaons are identified by the time-of-flight.

One can see that the points for the threshold value of 0% and 50% are identical. As it can be learned from the Fig. 5.11 the distribution sharply ends at 50% due to an implicit cut in the reconstruction code. This is also true in case of protons.

From the comparison of the left and right plot in Fig. 5.11 the reader can find out what is the penalty in statistics of the purity enhancement. At some $p_t$ ranges it is more than 50% with the a reduction of contamination only about 3%.

5.5.3 Protons

The PID contamination for protons (Fig. 5.12) is very small at the lowest reconstructible transverse momenta, because $dE/dX$ is much larger than for any other particle type what makes them easy to distinguish, see Fig. 5.4b. With increasing $p_t$ the efficiency decreases and reaches the smallest value (90-92%) at the range where proton $dE/dX$ is very similar to the pion one, i.e. 1.4–1.6 GeV. Afterwards the efficiency increases as pions and protons can be identified with the time-of-flight.

5.5.4 PID probability as the efficiency estimator

In the real data analysis the PID efficiency is unknown. Although in many cases it is desirable to have at least statistical control of the purity of a sample. The distribution of PID probability usually serves as such a tool. In Fig. 5.13b the distributions of the average PID probability and efficiency as function
5.5 Particle identification efficiency as function of two particle variables

**Figure 5.11:** a) PID contamination versus $p_t$ for different probability threshold and b) rejection factor for different probability thresholds in function of $p_t$ for kaons.

**Figure 5.12:** a) PID contamination versus $p_t$ for different probability thresholds and b) rejection factor for different probability thresholds in function of $p_t$ for protons.
of transverse momentum for kaons are compared. We show here the example for which the discrepancy between the two is the largest. The tuning of the PID reconstruction code is necessary in order to use PID probability as the estimator of the efficiency.

5.6 PID contamination as function two particle variables.

The quality of Particle Identification might depend on the proximity of other tracks. For pairs having close trajectories clusters can be shared between two tracks decreasing this way the quality of $dE/dX$ measurement, thus making PID recognition more difficult and less efficient. For such pairs it is easier to swap signals corresponding to the neighboring track when matching signal between sub-detectors.

In the experimental data analysis the pair purity (ratio of the number of pairs with both particles correctly identified to the number of all pairs) can be estimated from the product of the particle PID probabilities, which is further referred as the pair probability. Already from the study of the single particle PID efficiency it is clear that the reconstruction code is not yet tuned and the average particle PID probability in a sample does not coincide with particle purity. However, for completeness of the analysis we compare pair purities with probabilities for like sign two particle systems.

Pair purities and probabilities for $\pi^+\pi^+$, $K^+K^+$ and $pp$ systems as function of $Q_{out}$, $Q_{side}$ and $Q_{long}$ are shown in Fig. 5.14. In all the cases the PID efficiency does not change with any of the Q variables. The very slight dependence on $Q_{out}$ for pions results from the uneven contribution of particles having different transverse momenta to each $Q_{out}$ bin. The efficiency decreases as the contribution of pions with larger $p_t$ increases, see Fig. 5.10a.

The PID efficiency generally depends on the selected kinematic region of a sample. The anti-merging cut also modifies the contamination at small relative momenta. These effects are illustrated in Fig. 5.15, where the PID efficiency and pair probability are shown for two ranges of $p_t$. All these effects influence the purity of the numerator and denominator exactly the same way.

The way we simulate the correlation effects is based on the weight algorithm that lets construct correlation functions for the events having no correlations embedded. However, it raises the question if the presence of the correlations modify the performance of the reconstruction. Namely, there might be an additional dependence of the two particle PID efficiency on relative momentum components if some regions of the phase-space are more (or less) occupied by pion pairs. To verify that we have generated

![Figure 5.13](image_url)

**Figure 5.13:** a) Distribution of PID probability for protons. b) Average kaon PID probability (black squares) and efficiency (red circles) as function of $p_t$
5.6 PID contamination as function two particle variables.

Figure 5.14: Pair probability (black squares) and efficiency (red circles) versus $Q_{\text{out}}$, $Q_{\text{side}}$ and $Q_{\text{long}}$ for a) $\pi^+\pi^+$ b) $K^+K^+$ and c) $pp$. The plots are constructed by projecting 3D histograms for the absolute values of the other coordinates < 20 MeV.

Figure 5.15: Pair probability (black squares) and efficiency (red circles) versus $Q_{\text{out}}$, $Q_{\text{side}}$ and $Q_{\text{long}}$ for $\pi^+\pi^+$ with $p_t$'s a) below and b) over 500 MeV. The plots are constructed by projecting 3D histograms for the absolute values of the other coordinates < 20 MeV. Anti-merging cuts were applied.
500 events using HBT processor after burner. The measured efficiencies were compatible with the ones presented in Fig.5.15.

### 5.7 Event selection for background determination

It is important to mix events which have similar properties (multiplicity, topology) to construct the denominator of the correlation function. Otherwise, correlations due to global event characteristics might occur. In this analysis we use only central events which have similar particle multiplicities and have no flow. Hence there was no necessity of grouping events according to the number of particles or the event plane, which is necessary when analyzing the real data.

We have observed that the obtained correlation functions exhibit influence of the detector topology. It is caused by the mixing events with primary vertices at different positions. Some relative momenta are less efficiently reconstructed due to the detector segmentation, e.g. gaps between ITS modules or TPC sectors, see example in Fig.5.16. The influence of these inefficiencies on the relative momentum distribution is changed if the events have different primary vertex position, namely the induced gaps are smeared out. Of course, all these inefficiencies are always present in numerators. In consequence they are visible in the correlation functions.

For example, we have observed the effect related to the pixel length in SPD’s. The position of the point where the track passes the detector is always assumed to be at the center of a cluster. Since most of clusters are composed of only one pixel, the reconstructed coordinates correspond to the centers of pixels. In consequence some values of $Q_{\text{long}}$ are preferred to others. Hence, it is necessary to mix events having $z$ position of the primary vertex smaller that half width of the pixel, i.e. $225 \mu m$. In our analyses we have grouped all events according to the $z$ vertex position, and only events falling into a single bin were used in event mixing. We have chosen the width of the bin $100 \mu m$ that allowed to remove the effect.

![Figure 5.16:](image)

**Figure 5.16:** a) The correlation due to the Silicon Drift Detector topology: correlation function of polar open angle between two $\pi^+$ for pairs with small azimuthal open angle (<0.06 rad). b) Schema of the effect leading to it. Squares are the pixels, solid lines are tracks from the event having primary vertex at $V_1$, dashed line from from $V_2$. Pairs like 1-2 are relatively less efficiently reconstructed what reflects itself in the shape of numerators. It is not the case for denominators if pairs like 1-2’ are used.
5.8 Track splitting

We have implemented the anti-splitting cut developed from the STAR experiment. It utilizes the binary hit-map which is a bit-vector that has 1 on the n’th field if a given track has a cluster on a n’th padrow of TPC. For each pair of tracks a quality factor $F_{Quality}$ is calculated using the following formula

$$F_{Quality} = \frac{\sum_{n=1}^{N_{padrows}} A(n)}{\sum N_{Clust}}$$

(5.1)

where:

$$A(n) = \begin{cases} 
-1, & \text{if both tracks have cluster on padrow } n \\
0, & \text{if neither track has cluster on padrow } n \\
1, & \text{if only one track has cluster on padrow } n 
\end{cases}$$

(5.2)

where $N_{padrows}$ is number of TPC padrows and $\sum N_{Clust}$ is total number of clusters for both tracks. It can take values in the range $[-0.5, 1]$. A value close to 1 describes a pair of tracks that has high likelihood of being a splitted track e.g. case 2) and 3) in Fig.5.17.

Figure 5.17: a) Four examples of clusters attributed to two tracks: Full circles are clusters assigned to first track and open circles are clusters assigned to the second one. 1) $F_{Quality} = -0.5$, 2) and 3) $F_{Quality} = 1$ and 4) $F_{Quality} = 0.25$. b) Obtained normalized distribution of $F_{Quality}$.

However, it turned out to be void for ALICE because the track reconstruction software already performs all the possible checks and removes all splitted tracks at the level of TPC. In Fig. 5.17b the normalized distribution of $F_{Quality}$ is presented. The STAR experiments rejects all pairs with the factor above 0.6. In our case the fraction of pairs over this value is smaller then $10^{-5}$. This is also supported by the fact that we do not observe any artificial rise of the correlation function for very small momentum differences if no cuts are applied.

However, that is not true if one includes tracks reconstructed by the stand alone ITS tracking. We have found a strong positive correlation for very small $Q$ values when these tracks were included in the analysis. It indicates that the large fraction of the tracks reconstructed by this tracking are already found by the standard tracking. Tracks reconstructed only by the ITS stand-alone tracking, as it was used in PDC04, should not be used for HBT analyses.
5.9 Track merging

5.9.1 Like sign pions

Track merging introduces artificial negative correlation at small relative momentum affecting the shape of the correlation functions. In order to reconstruct correctly the space-time parameters from correlation analysis it is necessary to remove this effect. The HBT radii measured for lower energies at RHIC are of the order of 6 fm [117]. We have assumed the Gaussian source with all radii equal to 8 fm and intercept parameter $\lambda = 1$.

The correlation functions for $\pi^+\pi^+$ pairs are shown in Fig. 5.18a. Merging effect is clearly visible as a minimum at small relative momenta. Note that the effect in side and long is much narrower (15 MeV/c) than in out (150 MeV/c).

![Figure 5.18](image_url)

**Figure 5.18:** a) Projections of the 3-dimensional (3D) $\pi^+\pi^+$ correlation function for one component of relative momentum vector and for the other components smaller than 20 MeV. Red up-pointing triangles show the correlation functions for the reconstructed pion momenta and the QS effects for the parameters listed in the text, green down-pointing triangles are without simulated correlation effect.

b) Possible trajectory topologies of pairs with the same sign of the electric charge and their relation to the sign of $Q_{\text{out}} \cdot Q_{\text{side}}$.

In the real data analysis the presence of merging effect is detected by a non-zero value $R_{\text{outside}}$, when fitting 3-dimensional correlation function for the central events with Eq. (1.22). This condition results from the symmetry constraints [116, 117]. Moreover, the track merging affects differently configurations of positively charged pairs than negatively charged ones, see Fig. 5.18 and 5.19a. Namely, pairs with the negative sign of $Q_{\text{out}} \cdot Q_{\text{side}}$ are more vulnerable in the first case (the merging effect is more pronounced in the 2nd and 4th quadrant of Fig. 5.19a). For the second case pairs with the positive $Q_{\text{out}} \cdot Q_{\text{side}}$ are
5.9 Track merging

more influenced, so the merging is larger in 1st and 3rd quadrant of $Q_{out}Q_{side}$ correlation function. In consequence the correlation function is tilted if the merging is present and the tilt is opposite for positively charged pairs then for negatively ones. It results in opposite sign of the fitted $R_{outside}$ if the track merging is present. Of course, the situation would be reversed if the direction of the magnetic field would be altered.

In order to remove the effect we have introduced the anti-merging cut rejecting pairs of tracks that have smaller average distance while they fly though the TPC volume than the given threshold ($d_{min}$). The average distance is calculated at 10 equidistant radii (every 15 cm) starting from the inner surface of TPC, i.e. 84.1 cm. Track coordinates are computed assuming the helix shape of a track with the parameters as they are reconstructed at inner surface of TPC. The assumption about helix shape of a track is justified since multiple scattering is negligible inside TPC.

To find the appropriate threshold value of the cut the correlation function of $Q_{inv}$ versus average separation is constructed. In Fig. 5.19 the track merging is clearly visible at small $Q_{inv}$. However, one should keep in mind that these two properties are strongly correlated, since identical particles emitted with small relative momenta must have a close trajectories.

![Figure 5.19: a) $Q_{out}Q_{side}$ correlation function ($Q_{long} < 20$ MeV). b) Average separation in TPC versus $Q_{inv}$ correlation function. $\pi^+\pi^+$, $p_t < 500$ MeV. No correlation effect simulated.](image)

We have analyzed the data with several threshold values, see Fig. 5.21. As it can be seen in Fig. 5.20 and 5.21 it reduces the merging effect, but does not remove it completely. As it can be learned from the comparison of plots a) and b) in Fig. 5.20, the remaining effect is situated at different region of $Q_{out}Q_{side}$ space than the cut affects.

This implies that the originally observed track merging is caused by the track reconstruction inefficiency in ITS, because the tracks potentially merged in TPC renders $Q_{out}$ and $Q_{side}$ situated along the valley visible in Fig. 5.20b and the remaining merging is located at smaller values of $Q_{side}$ ($Q_{side}$ is related to the azimuthal angle between two tracks). Hence, the merging occurs for pairs of tracks that cross before TPC.

We have constructed a 3D correlation function: $Q_{inv}$ versus spatial track separation in $z$ and $r\phi$ at a given ITS layer. This lets us determine what are distances between trajectories below which two tracks are reconstructed less efficiently. Positions of a track are calculated assuming helix trajectory. For the 3 most inner layers parameters reconstructed at vertex are used, while for the outer ones, parameters at the inner surface of TPC are taken. Two dimensional projection for the innermost layer is presented in
Figure 5.20: a) $\pi^+ \pi^+ Q_{\text{out}} Q_{\text{side}}$ correlation function and b) and its denominator for $p_t < 500$ MeV. No correlation effect simulated. All tracks having average separation in TPC below 6 cm were rejected.

Figure 5.21: Extracted source parameters in function of the minimum allowed average separation in TPC for $\pi^+ \pi^+$ and $p_t < 500$ MeV.
5.9 Track merging

Fig. 5.22. These correlation functions indicate that the cuts summarized in Table 5.6 should be applied additionally to the TPC average separation cut (we chose $d_{\text{min}}=6$ cm).

**Figure 5.22:** Correlation function of the spatial separation at the first layer of ITS in the case no cut is applied. Lines represent the isolines. No correlation effect simulated.

**Figure 5.23:** Extracted source parameters as a function of the SPD1 anti-merging cut strength for $\pi^+\pi^-$ and $p_\parallel$'s up to 500 MeV. Unity corresponds to 1.5 mm in $r\phi$ and 2 mm in $z$ and both are multiplied by the factor.

Since the reconstruction is done in the incremental way, i.e. tracks are always prolonged from one detector to the another one, we are not able to disentangle different sources of the close track reconstruction inefficiency. It means that if we observe an inefficiency at one of the detectors (f.g. below given average separation in TPC) we can not disentangle if this detector is inefficient this way or it is caused by some other detector (f.g. in ITS) and it is only such reflected in this observable.

Hence, first we have verified if the effect could be removed using the separation cut on the first layer of ITS solely. Obtained results are shown in Fig. 5.23. From this plot, and also from the detailed analysis of other correlation functions it is clear that a combined cut is needed. It has to reject particles passing too close to each other at any layer of ITS (threshold values in Table 5.3) and also in TPC (average separation smaller then 6 cm).

After applying the cuts correlation function is almost free from the merging effects comparing to the one obtained without any cuts. The fit gave the following parameters: $R_o = 7.89 \pm 0.03$, $R_z = 7.87 \pm 0.02$ fm, $R_l = 7.89 \pm 0.02$ fm, $R_{os}^2 = -0.50 \pm 0.23$fm$^2$, $\lambda = 0.923 \pm 0.005$ and $\chi^2/NDF = 1.01$.

Further we have examined how the parameters change with the anti-merging cut strength. We define the threshold values listed in Table 5.3 as the base, and we change them by the multiplicative factor (0
means no cuts). Results are presented in Fig. 5.24. This figure indicates that these values are optimal because making them 50% looser increase considerably $Q_{\text{outside}}$ (although the other parameters almost do not change), and increasing them about 50% significantly removes the signal, what expresses itself in increasing error of $Q_{\text{out}}$. This figure also suggests that the discrepancies from the simulated values are caused by the resolution and not perfect PID effects, that will be discussed in the following section.

![Figure 5.24](image)

**Figure 5.24:** Extracted source parameters in function of the anti-merging cut strength for $\pi^+\pi^+$. Unity corresponds to the set listed in Table 5.3 and the average separation in TPC equal to 6 cm. All threshold values are multiplied by the factor.

In order to estimate the systematic errors we have studied how the extracted parameters change if the cut threshold values are varied. We have increased and decreased about 50%:

1. all threshold values
2. only at the innermost layer of ITS (SPD1)
3. the average separation in TPC
4. all the threshold values in ITS in $z$ direction
5. all the threshold values in ITS in $r\phi$ direction

The results are presented in Table 5.4. None of them has any dramatic influence on the obtained parameters. Their spread defines the systemic errors and the resulting values are listed in Table 5.7.

Further, analysis was repeated for the remaining transverse momentum range, i.e. over 500 MeV. Fig. 5.25a presents the relative efficiency of the pair reconstruction in function of the spatial separation at the first layer of pixel detectors. The region where the inefficiencies occur has different shape comparing to the range of $p_t$ below 500 MeV. In order to remove the merging effect with the same type of cut (i.e. rejecting all points inside a rectangular area) it is necessary to apply such a large threshold values, so the correlation signal is completely removed. Hence, more sophisticated cut setting is needed. We have decided to apply the set of three cuts that are defined in the three first rows of Table 5.6.

We have analyzed data only with the anti-merging cut set at first layer of ITS. As expected, the merging effect was not entirely removed. In Fig. 5.25b is presented the average separation in TPC versus $Q_{\text{inv}}$ correlation function which demonstrates the necessity of applying the cut on the average separation.
Table 5.3: Chosen values of the anti-merging cut in ITS for the low momentum range $\pi^+\pi^+$. 

<table>
<thead>
<tr>
<th>Layer</th>
<th>$r\phi$ [mm]</th>
<th>$z$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (SPD1)</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>2 (SPD2)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>3 (SDD1)</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>4 (SDD2)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>5 (SSD1)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>6 (SSD2)</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.4: Stability of the fitted HBT parameters on variation of the cuts for $\pi^+\pi^+$ and $p_t$ below 500 MeV. Standard corresponds to the set listed in Table 5.3 and TPC anti-merging cut equal 6 cm. See text for details.

<table>
<thead>
<tr>
<th>Type of cut</th>
<th>$R_\phi$ [fm]</th>
<th>$R_z$ [fm]</th>
<th>$R_t$ [fm]</th>
<th>$R^{2\phi}_{zz}$ [fm$^2$]</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>7.90 ± 0.03</td>
<td>7.87 ± 0.02</td>
<td>7.89 ± 0.02</td>
<td>-0.51 ± 0.23</td>
<td>0.923 ± 0.005</td>
</tr>
<tr>
<td>0.5 standard</td>
<td>7.94 ± 0.02</td>
<td>7.85 ± 0.02</td>
<td>7.89 ± 0.02</td>
<td>-0.77 ± 0.20</td>
<td>0.924 ± 0.003</td>
</tr>
<tr>
<td>1.5 standard</td>
<td>7.92 ± 0.04</td>
<td>7.87 ± 0.03</td>
<td>7.88 ± 0.03</td>
<td>-0.32 ± 0.31</td>
<td>0.903 ± 0.009</td>
</tr>
<tr>
<td>0.5 SPD1</td>
<td>7.87 ± 0.03</td>
<td>7.86 ± 0.02</td>
<td>7.91 ± 0.02</td>
<td>-0.41 ± 0.23</td>
<td>0.920 ± 0.005</td>
</tr>
<tr>
<td>1.5 SPD1</td>
<td>7.88 ± 0.03</td>
<td>7.85 ± 0.02</td>
<td>7.87 ± 0.02</td>
<td>-0.27 ± 0.25</td>
<td>0.907 ± 0.006</td>
</tr>
<tr>
<td>0.5 TPC</td>
<td>7.92 ± 0.03</td>
<td>7.88 ± 0.02</td>
<td>7.89 ± 0.02</td>
<td>-0.61 ± 0.22</td>
<td>0.924 ± 0.005</td>
</tr>
<tr>
<td>1.5 TPC</td>
<td>7.89 ± 0.03</td>
<td>7.88 ± 0.02</td>
<td>7.88 ± 0.02</td>
<td>-0.41 ± 0.25</td>
<td>0.919 ± 0.005</td>
</tr>
<tr>
<td>0.5 in $r\phi$</td>
<td>7.87 ± 0.02</td>
<td>7.88 ± 0.02</td>
<td>7.90 ± 0.02</td>
<td>-0.30 ± 0.21</td>
<td>0.927 ± 0.004</td>
</tr>
<tr>
<td>1.5 in $r\phi$</td>
<td>7.89 ± 0.03</td>
<td>7.90 ± 0.02</td>
<td>7.86 ± 0.02</td>
<td>-0.40 ± 0.27</td>
<td>0.912 ± 0.006</td>
</tr>
<tr>
<td>0.5 in $z$</td>
<td>7.90 ± 0.02</td>
<td>7.85 ± 0.02</td>
<td>7.88 ± 0.02</td>
<td>-0.45 ± 0.22</td>
<td>0.921 ± 0.004</td>
</tr>
<tr>
<td>1.5 in $z$</td>
<td>7.88 ± 0.03</td>
<td>7.84 ± 0.02</td>
<td>7.91 ± 0.02</td>
<td>-0.42 ± 0.24</td>
<td>0.912 ± 0.006</td>
</tr>
</tbody>
</table>
We chose the threshold value equal to 3 cm. Additionally, we have decided to use cuts on the remaining layers of ITS that are listed in Table 5.6.

Figure 5.25: a) Correlation function of the spatial separation at the first layer of ITS in case no cuts are applied. b) Average separation in TPC versus $Q_{inv}$ correlation function with SPD1 cuts applied. $p_t$’s over 500 MeV.

The fitted parameters to the obtained correlation functions are presented in Fig. 5.26. Their stability on the cuts threshold values can be learnt from Table 5.6. The resulting systematical errors are listed in Table 5.7.

Figure 5.26: Extracted source parameters in function of the anti-merging cut strength. Unity corresponds to the set listed in Table 5.6 and the average separation in TPC equal to 3 cm. All cut values are multiplied by the cut factor. $\pi^+, \pi^+$ $p_t$’s over 500 MeV.

5.9.2 Non-identical pions

On the first sight the track merging effect should not be present for different charge particle systems, because such a particles are bended in the opposite directions by the magnetic field. However, it may happen that their trajectories cross inside detector (see Fig. 5.27), what may lead to the lower reconstruc-
### Table 5.5: Chosen values of the anti-merging cut in ITS for the high momentum range.

<table>
<thead>
<tr>
<th>Layer</th>
<th>$r \phi$ [mm]</th>
<th>$z$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (SPD1 cut 1)</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>1 (SPD1 cut 2)</td>
<td>0.45</td>
<td>3</td>
</tr>
<tr>
<td>1 (SPD1 cut 3)</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>2 (SPD2)</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>3 (SDD1 cut 1)</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>3 (SDD1 cut 2)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4 (SDD2)</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>5 (SSD1)</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>6 (SSD2)</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

### Table 5.6: Stability of the fitted HBT parameters on variation of the cuts for $\pi^+\pi^+$ and $p_t$ over 500 MeV. Standard corresponds to the set listed in Table 5.5 and TPC anti-merging cut equal 3 cm. See text for details.

<table>
<thead>
<tr>
<th>Type of cut</th>
<th>$R_o$ [fm]</th>
<th>$R_t$ [fm]</th>
<th>$R_f$ [fm]</th>
<th>$R_{o'i}^2$ [fm$^2$]</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>7.63 ± 0.13</td>
<td>7.78 ± 0.10</td>
<td>7.85 ± 0.10</td>
<td>−0.42 ± 0.85</td>
<td>0.891 ± 0.024</td>
</tr>
<tr>
<td>0.5 standard</td>
<td>7.81 ± 0.08</td>
<td>7.67 ± 0.06</td>
<td>8.01 ± 0.06</td>
<td>−1.41 ± 0.62</td>
<td>0.873 ± 0.012</td>
</tr>
<tr>
<td>0.75 standard</td>
<td>7.58 ± 0.10</td>
<td>7.77 ± 0.08</td>
<td>8.02 ± 0.08</td>
<td>−0.96 ± 0.77</td>
<td>0.898 ± 0.017</td>
</tr>
<tr>
<td>1.5 standard</td>
<td>7.32 ± 0.22</td>
<td>7.76 ± 0.15</td>
<td>7.90 ± 0.16</td>
<td>−0.62 ± 1.16</td>
<td>0.854 ± 0.050</td>
</tr>
<tr>
<td>0.5 SPD1</td>
<td>7.49 ± 0.11</td>
<td>7.75 ± 0.09</td>
<td>7.98 ± 0.09</td>
<td>−0.51 ± 0.81</td>
<td>0.893 ± 0.019</td>
</tr>
<tr>
<td>1.5 SPD1</td>
<td>7.46 ± 0.20</td>
<td>7.62 ± 0.13</td>
<td>7.62 ± 0.15</td>
<td>−1.50 ± 1.07</td>
<td>0.825 ± 0.042</td>
</tr>
<tr>
<td>0.5 TPC</td>
<td>7.59 ± 0.13</td>
<td>7.79 ± 0.10</td>
<td>7.87 ± 0.10</td>
<td>−0.75 ± 0.84</td>
<td>0.896 ± 0.024</td>
</tr>
<tr>
<td>1.5 TPC</td>
<td>7.30 ± 0.13</td>
<td>7.86 ± 0.10</td>
<td>7.81 ± 0.10</td>
<td>−0.39 ± 0.87</td>
<td>0.889 ± 0.026</td>
</tr>
<tr>
<td>0.5 in $r \phi$</td>
<td>7.61 ± 0.10</td>
<td>7.84 ± 0.08</td>
<td>7.99 ± 0.08</td>
<td>−0.99 ± 0.77</td>
<td>0.913 ± 0.017</td>
</tr>
<tr>
<td>1.5 in $r \phi$</td>
<td>7.29 ± 0.17</td>
<td>7.77 ± 0.12</td>
<td>7.81 ± 0.13</td>
<td>−1.44 ± 0.99</td>
<td>0.859 ± 0.033</td>
</tr>
<tr>
<td>0.5 in $z$</td>
<td>7.60 ± 0.10</td>
<td>7.79 ± 0.09</td>
<td>8.11 ± 0.09</td>
<td>−0.84 ± 0.81</td>
<td>0.915 ± 0.019</td>
</tr>
<tr>
<td>1.5 in $z$</td>
<td>7.48 ± 0.15</td>
<td>7.81 ± 0.11</td>
<td>7.70 ± 0.11</td>
<td>−0.38 ± 0.88</td>
<td>0.874 ± 0.028</td>
</tr>
</tbody>
</table>

### Table 5.7: Systematic errors for $\pi^+\pi^+$, defined as the spread of the parameters when varying the cut thresholds.

<table>
<thead>
<tr>
<th>$p_t$ range [MeV]</th>
<th>$R_o$ [fm]</th>
<th>$R_t$ [fm]</th>
<th>$R_f$ [fm]</th>
<th>$R_{o'i}^2$ [fm$^2$]</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 500</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.25</td>
<td>0.025</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

5.9 Track merging
tion efficiency for such tracks and in consequence to the artificial correlations. And indeed, we have observed such an effect.

![Figure 5.27: Two possible topologies of track with opposite sign of a charge.](image)

**Figure 5.27:** Two possible topologies of track with opposite sign of a charge.

![Figure 5.28: a) $2k^*$ and b) $2k_{side}^*$, $2k_{long}^*$ correlation functions. $\pi^+ \pi^-$ $p_t$ below 500 MeV.](image)

**Figure 5.28:** a) $2k^*$ and b) $2k_{side}^*$, $2k_{long}^*$ correlation functions. $\pi^+ \pi^-$ $p_t$ below 500 MeV.

Pair of tracks having opposite sign of a charge can form two topologies and one can distinguish them by the sign of $2k_{side}^*$. The measured $2k^*$ correlation function for both, negative and positive $2k_{side}^*$, should be identical due to the symmetry constraint. Hence, a different shape of these functions indicates the presence of the merging.

We have observed the merging effect only for pairs that have positive $2k_{side}^*$, see Fig. 5.28a. It was found that the inefficiencies are related to the cases when two tracks crosses an ITS layer too close to each other. Each of the “deeps” in Fig. 5.28b is associated with the merging at a given layer. The one for $2k^*$ below 20 MeV is related to the pixel detectors, next two - to the drifts, and the last one - to the strips.

Similarly to the $\pi^+ \pi^+$ we have decided to apply a cut based on the calculated track separation. In order to assess the threshold values we have constructed 3D correlation function, $2k_{side}^*$ versus spatial track separation in $z$ and $r\phi$ at a given ITS layer. We have found that the cut with the threshold values listed in Table 5.8 removes the merging effect. In this case there is no necessity of varying threshold values with transverse momentum because the cut does not have critical impact on statistics in the signal region even for high momentum sample.
5.10 Resolution corrections

The measured correlation function is distorted by the finite detector resolution. These distortions lead to a systematic change of the reconstructed HBT parameters. That is why it is necessary to introduce a correction procedure.

We have decided to use the procedure proposed by M.A. Lisa which is also applied in the STAR experiment \[117\]. The idea is based on the fact, that if in Eq. (5.3) \( C(q)_{\text{meas}} \) and \( C(q)_{\text{smear}} \) are identical, one gets the not distorted correlation function \( (C(q)_{\text{ideal}}) \).

\[
C(q) = C(q)_{\text{meas}} \frac{C(q)_{\text{ideal}}}{C(q)_{\text{smear}}} = \frac{N(q)_{\text{meas}}}{D(q)_{\text{meas}}} \frac{N(q)_{\text{ideal}}}{D(q)_{\text{ideal}}} \frac{D(q)_{\text{meas}}}{D(q)_{\text{smear}}} \quad (5.3)
\]

\( C(q)_{\text{meas}} \) and \( C(q)_{\text{smear}} \) stand from measured and smeared correlation functions, respectively. The ideal correlation function is obtained using a model form of a correlator (the Gaussian one in the our case). Its numerator and denominator histograms are both constructed from the mixed pairs (i.e. originating from different events) but numerator is filled with the weight calculated from the model. Similarly, the smeared correlation function is constructed from mixed pairs but distorted particle momenta are used. Numerator is filled with the same weight as the one of the ideal correlation function (calculated with not smeared momenta).

The tracking program reconstructs curvature (i.e. inversed transverse momentum), polar and azimuthal angles. Their distortions in function of \( p_t \) are presented in Fig. 5.29. We use the following parametrization of the errors

\[
X = a_X + b_X p_t + c_X p_t^2, \quad X = \delta p_t / p_t, \delta \theta, \delta \phi \quad (5.4)
\]

<table>
<thead>
<tr>
<th>Layer</th>
<th>( r \phi ) [mm]</th>
<th>( z ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (SPD1)</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>2 (SPD2)</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>3 (SDD1)</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>4 (SDD2)</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>5 (SSD1)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>6 (SSD2)</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 5.8: Chosen values of the anti-merging cut in ITS for the low momentum range \( \pi^+ \pi^- \).
Table 5.9: The fitted parameters of the error parametrization functions.

<table>
<thead>
<tr>
<th>Iteration No.</th>
<th>$R_o$ [fm]</th>
<th>$R_s$ [fm]</th>
<th>$R_l$ [fm]</th>
<th>$R_{2s}$ [fm$^2$]</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.90 ± 0.03</td>
<td>7.87 ± 0.02</td>
<td>7.89 ± 0.02</td>
<td>-0.51 ± 0.23</td>
<td>0.923 ± 0.005</td>
</tr>
<tr>
<td>1</td>
<td>8.03 ± 0.06</td>
<td>7.88 ± 0.05</td>
<td>7.90 ± 0.05</td>
<td>-0.62 ± 0.51</td>
<td>0.941 ± 0.012</td>
</tr>
<tr>
<td>2</td>
<td>8.03 ± 0.03</td>
<td>7.89 ± 0.03</td>
<td>7.91 ± 0.03</td>
<td>-0.63 ± 0.27</td>
<td>0.942 ± 0.006</td>
</tr>
</tbody>
</table>

Table 5.10: Parameters obtained after resolution correction. $p_t$ below 500 MeV.

The fitted parameters are presented in Table 5.9.

The Cartesian momentum components are calculated from the following equations

\[
p_x = p_t \cos \phi \\
p_y = p_t \sin \phi \\
p_z = \frac{p_t}{\tan \theta}
\]

so their distortions are

\[
\delta p_x = \left| p_x \frac{\delta p_t}{p_t} \right| \left| p_y \delta \phi \right| \\
\delta p_y = \left| p_y \frac{\delta p_t}{p_t} \right| \left| p_x \delta \phi \right| \\
\delta p_z = \left| p_z \frac{\delta p_t}{p_t} \right| + \left| p_t \frac{\delta \theta}{\sin^2 \theta} \right|
\]

The correction procedure is used in an iterative way and is proven to converge quickly. The starting values of the parameters are obtained from the fit without correction. The change of the fitted parameters in the consecutive iterations is shown in Tables 5.10 and 5.11.

The most affected parameter is $R_{out}$, especially for the sample with $p_t > 500$ MeV. This is understandable since this component depends linearly on transverse momentum so its resolution also worsens linearly with $p_t$.

Table 5.11: Parameters obtained after resolution correction. $p_t$ over 500 MeV.
of the relative momenta. Of course these points are not taken to the projection, however, the calculated average without these points is smaller than if they were available.

The influence of finite resolution can be seen by comparing theoretical correlation functions with the reconstructed one. For higher values of the simulated radii the fits have not converged.

The reconstructed parameters are very close to the simulated ones. For \( p_t \) range below 0.5 GeV three dimensional fit has given \( Q_{out} = 8.03 \pm 0.03 \text{ fm} \), \( Q_{side} = 7.89 \pm 0.03 \text{ fm} \), \( Q_{long} = 8.91 \pm 0.03 \text{ fm} \) and \( \lambda = 0.947 \pm 0.006 \). The shapes of the reconstructed functions are very close to the simulated ones. In Fig. 5.30 reconstructed correlation functions are compared with the ones obtained using information from the generator. We can see that there is almost no influence of the PID impurity on the shape of the correlation function. The influence of finite resolution can be seen by comparing theoretical correlation function (calculated using simulated momenta and PID) with the reconstructed one.

The non-Gaussian shape of the projections is an artifact related to the anti-merging cut, which removes data points at very small values of the relative momenta. Of course these points are not taken to the projection, however, the calculated average without these points is smaller than if they were available.

For the \( p_t \) range over 500 MeV, with all the corrections applied, we have obtained \( Q_{out} = 8.14 \pm 0.23 \text{ fm} \), \( Q_{side} = 7.90 \pm 0.17 \text{ fm} \), \( Q_{long} = 8.14 \pm 0.17 \text{ fm} \) and \( \lambda = 0.942 \pm 0.043 \).

Using the corrections and the cuts described, ALICE is able to reconstruct as large radii as 15 fm (see Figures 5.31 and 5.32). The radii presented on these plots are the maximum that we managed to reconstruct. For higher values of the simulated radii the fits have not converged.

The remaining discrepancies of the reconstructed parameters are related to

---

<table>
<thead>
<tr>
<th>( p_t ) range</th>
<th>corrected</th>
<th>( R_{o} ) [fm]</th>
<th>( R_{s} ) [fm]</th>
<th>( R_{l} ) [fm]</th>
<th>( R_{os}^2 ) [fm²]</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 500 MeV</td>
<td>no</td>
<td>8.03 ± 0.03</td>
<td>7.89 ± 0.03</td>
<td>7.91 ± 0.03</td>
<td>−0.63 ± 0.27</td>
<td>0.942 ± 0.006</td>
</tr>
<tr>
<td>&lt; 500 MeV</td>
<td>yes</td>
<td>8.03 ± 0.03</td>
<td>7.89 ± 0.03</td>
<td>7.91 ± 0.03</td>
<td>−0.62 ± 0.28</td>
<td>0.947 ± 0.006</td>
</tr>
<tr>
<td>&gt; 500 MeV</td>
<td>no</td>
<td>8.03 ± 0.16</td>
<td>7.75 ± 0.12</td>
<td>7.85 ± 0.12</td>
<td>−0.52 ± 1.04</td>
<td>0.928 ± 0.030</td>
</tr>
<tr>
<td>&gt; 500 MeV</td>
<td>yes</td>
<td>8.04 ± 0.16</td>
<td>7.73 ± 0.12</td>
<td>7.85 ± 0.12</td>
<td>−0.54 ± 1.08</td>
<td>0.958 ± 0.032</td>
</tr>
</tbody>
</table>

**Table 5.12:** Parameters obtained before and after PID correction.

5.11 Correction for imperfect Particle Identification

The shape of the correlation function is also influenced by the contamination due to the inclusion of particle with a different mass than the considered ones. The correlation functions are corrected then in the following way

\[
C(Q)_{\text{pidcorr}} = 1 + (C(Q) - 1) / PID(Q)
\] (5.11)

where \( PID(Q) \) is the PID efficiency function. \( PID(Q) \) is obtained dividing the histogram created the same way as the numerator of a correlation function, but weighted with the pair probability, by the numerator itself. This gives the average PID probability in each bin of a correlation function.

We have found (see Table 5.12) that the correction has almost no influence on the reconstructed radii and the intercept parameter increases about 2%. Correction made with the real efficiency gives very similar result. It was also verified that the correlation function constructed solely with particles which mass is correctly identified gives the coherent result.

5.12 Correlation functions

In this section we present the final results obtained with all the corrections described in the previous sections.

5.12.1 \( \pi^+\pi^+ \)

The reconstructed parameters are very close to the simulated ones. For \( p_t \) range below 0.5 GeV three dimensional fit has given \( Q_{out} = 8.03 \pm 0.03 \text{ fm} \), \( Q_{side} = 7.88 \pm 0.03 \text{ fm} \), \( Q_{long} = 8.90 \pm 0.03 \text{ fm} \) and \( \lambda = 0.947 \pm 0.006 \). The shapes of the reconstructed functions are very close to the simulated ones. In Fig. 5.30 reconstructed correlation functions are compared with the ones obtained using information from the generator. We can see that there is almost no influence of the PID impurity on the shape of the correlation function. The influence of finite resolution can be seen by comparing theoretical correlation function (calculated using simulated momenta and PID) with the reconstructed one.

The non-Gaussian shape of the projections is an artifact related to the anti-merging cut, which removes data points at very small values of the relative momenta. Of course these points are not taken to the projection, however, the calculated average without these points is smaller than if they were available.

For the \( p_t \) range over 500 MeV, with all the corrections applied, we have obtained \( Q_{out} = 8.14 \pm 0.23 \text{ fm} \), \( Q_{side} = 7.90 \pm 0.17 \text{ fm} \), \( Q_{long} = 8.14 \pm 0.17 \text{ fm} \) and \( \lambda = 0.942 \pm 0.043 \).

Using the corrections and the cuts described, ALICE is able to reconstruct as large radii as 15 fm (see Figures 5.31 and 5.32). The radii presented on these plots are the maximum that we managed to reconstruct. For higher values of the simulated radii the fits have not converged.

The remaining discrepancies of the reconstructed parameters are related to

1. resolution effects, namely observed systematic skews that can not be easily corrected.
Figure 5.30: $\pi^+\pi^+$ $Q_{\text{out}}$ (top) $Q_{\text{side}}$ (center) $Q_{\text{long}}$ (down) correlation functions for $p_t$ range below 500 MeV, after anti merging correction. Red up-pointing triangles are the reconstructed functions, black squares are constructed only with having correctly identified PID, blue dots are created using generated momenta and perfect PID, green down-pointing triangles are without simulated Bose-Einstein effect.

Figure 5.31: Extracted source parameters in function of the simulated radii for $\pi^+\pi^+$, $p_t$ below 500 MeV. Only anti-merging cut applied.
2. merging effect which practically can not be removed completely, especially at low transverse momenta where it has the range comparable to the signal due to large multiple scattering. Hence, setting the cuts such that the effect is removed annihilates the correlation signal altogether!

5.12.2 $\pi^+\pi^-$

To fit correlation functions of the non-identical particle systems we make use of CorrFit program, see section 1.3.2.2.3. Of course, we do not expect to observe any time shift in the experimental data. However, since the insufficient statistics has not allowed for the detailed study of pion-kaon nor pion-proton system, we have decided to study this unphysical example. For both, $\pi^+$ and $\pi^-$ we have simulated the same Gaussian source with all the radii equal to 8 fm. However, the emission time for the latter one was set 5 fm/c later then for the former.

The fitted function is presented in Fig. 5.33a. The fit has given $R = 7.99$ fm and $\Delta t = 4.3$ fm. The statistical errors can be read from the $\chi^2$ map in Fig. 5.33b as difference between the fitted value and the one for which $\chi^2$ increases by one. They are equal to 0.25 fm and 0.7 fm/c for radius and time shift, respectively. The systematical uncertainties are derived from the change of the reconstructed parameters on the variation of the threshold values of the cuts. We have found that they are small compared to the statistical ones and are $\sim 0.1$ fm and $\sim 0.2$ fm/c for radius and time, respectively.

5.12.3 Other systems

The limited number of events simulated during Physics Data Challenge 2004 has not allowed for a detailed analysis of the $K^+K^+$ and proton-proton correlations. We have been merely able to study 1D cases, even when adding together $K^+K^+$ and $K^-K^-$, see Fig. 5.34. Also for the non-identical systems that involve pions the statistics was insufficient to perform all the required analyses, for example the merging effect study.

From our analysis it is clear that the merging effect for kaons is significantly larger then for pions, what is connected with the bigger multiple scattering. Consequently, for protons it is even larger then for kaons. The maximum radius that we could reconstruct correctly with proton-proton correlations,

![Figure 5.32: Extracted source parameters in function of the simulated radii for $\pi^+\pi^+$, $p_t$ over 500 MeV. Only anti-merging cut applied.](image)
Figure 5.33: (a) Fitted $\pi^+\pi^-$ correlation function and (b) $\chi^2$ per number of degrees of freedom map of the fit.

Figure 5.34: Fitted $K^+K^+$ (and $K^-K^-$) $Q_{inv}$ correlation function.
using the anti-merging cut described in this document is 6 fm. For kaons it is of the order of 10 fm. Of course, the situation should slightly improve if the higher statistics is available. Also, one can apply the correction based on the merging pattern obtained with Monte-Carlo analysis instead of the cut. However, this procedure brings substantially larger systematic error.

We believe that the results improve with the upgraded versions of the reconstruction code. Currently we try to find if the merging can be reduced at the level of tracking with the cost of the higher fake track fraction.

## 5.13 proton-proton collisions

The sizes expected in pp collisions are of the order of 1-2 fm. Hence, the width of the correlation effect is much wider comparing to the Pb-Pb reactions. This, together with the relatively small track density, makes the correlation analyses easier than in heavy ion collisions. In our simulations we have assumed all radii equal to 1 fm, intercept parameter 1, and lack of final state interactions.

We have used the $10^5$ minimum bias events produced during Alice Data Challenge 2004. We have repeated the procedure described for Pb-Pb events.

![Figure 5.35: Projections of the $\pi^+\pi^+$ correlation function for other components smaller than 100 MeV. No cuts applied.](image)

In pp collisions other correlations than the ones due to QS and FSI are pronounced, which additionally obscure the signal, (see also section 1.3.4). However, these correlations are mostly pronounced in the low multiplicity events and high momentum regime. Anyway we have decided to use the event mixing technique and in order to circumvent the problem we have decided to consider only events having at least 5 charged tracks reconstructed.

The events produced with Pythia bears additional artificial correlations, which are visible for example in Fig. 5.35a ($Q_{out}$ correlation function without Bose-Einstein effect simulated is not flat and has maximum at $Q_{out} \sim 0.5$ GeV/c). They are clearly of non physical origin, since the ones due to the jet topology should have exactly the opposite shape, i.e. maxima at very small and large ($\sim 2$ GeV) $Q$ values. Most probably they originate from an imperfection of the generator. The effect is mostly pronounced in $Q_{out}$ and in the consequence it modifies $R_{out}$ by increasing it by about 10%. In order to remove the effect we have applied the simplest correction: we have divided the obtained correlation function by the one calculated for the events as they are generated by Pythia (without QS). This is justified since in this analysis we would like solely to verify the performance of the reconstruction and the analysis procedures.

We have applied the same anti-merging cut as for the range of transverse momenta below 0.5 GeV in the case of Pb-Pb collisions, (thresholds defined in Table 5.6 and minimum TPC average separation 6 cm). The resulting correlation functions are shown in Fig. 5.36 and the fitted radii are listed in Table 5.13. The resolution correction was applied, however, it has had no influence on the reconstructed parameters.

The reconstructed radii are basically not sensitive to any changes in the applied cuts. Hence, we can conclude that Alice is able to reconstruct HBT radii with very high precision and the most crucial
Table 5.13: The reconstructed $\pi^+\pi^+$ radii. (*) anti-merging, PID and resolution corrected. Corrected means with the artificial correlations present in Pythia events removed, see text for the details.

<table>
<thead>
<tr>
<th></th>
<th>$R_{ij}$ [fm]</th>
<th>$R_{ij}$ [fm]</th>
<th>$R_{ij}$ [fm]</th>
<th>$R_{ij}$[fm$^2$]</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cuts</td>
<td>0.86 ± 0.03</td>
<td>1.00 ± 0.02</td>
<td>1.03 ± 0.02</td>
<td>0.10 ± 0.05</td>
<td>0.937 ± 0.017</td>
</tr>
<tr>
<td>anti-merging</td>
<td>0.90 ± 0.03</td>
<td>0.98 ± 0.02</td>
<td>1.00 ± 0.02</td>
<td>0.07 ± 0.05</td>
<td>0.943 ± 0.019</td>
</tr>
<tr>
<td>(*)</td>
<td>0.89 ± 0.07</td>
<td>0.96 ± 0.05</td>
<td>0.99 ± 0.04</td>
<td>0.08 ± 0.12</td>
<td>0.949 ± 0.050</td>
</tr>
<tr>
<td>Corrected</td>
<td>0.96 ± 0.04</td>
<td>0.97 ± 0.03</td>
<td>0.97 ± 0.02</td>
<td>0.00 ± 0.07</td>
<td>0.908 ± 0.025</td>
</tr>
</tbody>
</table>

contribution to the systematic error, and basically the only one, is the one due to the proper handling of the Coulomb and strong interactions.

Figure 5.36: Projections of the $\pi^+\pi^+$ correlation function for other components smaller then 100 MeV. Anti-merging cuts applied.

5.14 Single event interferometry

The multiplicities expected in central Pb-Pb collisions allows for the analysis on event by event (EbE) basis. Such measurements are interesting because they allow to study fluctuation phenomena. This is a new possibility which opens up at the LHC due to the large expected multiplicities.

We have studied the performance assuming a Gaussian source with $R_{inv} = 8$ fm, $\lambda = 1$. The tracks reconstructed solely in TPC were used in this analysis since that gives the highest number of tracks. No anti-merging cut is applied because it reduces the statistics. Of course, the distributions for the negative and positive pions were added.

The distribution of the fitted radii is presented in the bottom right picture in Fig.5.37. The Gaussian fit has given the mean value 7.59 fm and $\sigma = 0.63$ fm. The systematic shift of the mean value is due to the merging effect. This result shows that it is possible to study event-by-event fluctuation in ALICE.

5.15 Summary and perspective for future work

We have developed all the necessary tools and procedures necessary to measure unbiased parameters from the correlation functions. We have shown that ALICE is able to obtain source parameters with pions with very good precision.

However, the situation is not so good in the case of the kaon and proton correlations. Although, the reconstruction of these particles is more difficult than pions for obvious reasons, our simple estimates shows that it should be possible to improve significantly the situation. Therefore, a closer look at the reconstruction of the kaons and protons is required.
Figure 5.37: Examples of single event \((\pi^+, \pi^+)\) correlation functions for different number of reconstructed pions. Bottom-right: the distribution of the reconstructed radii. Analysis was performed by Hanna Gos.
As an outcome of the presented analyses and the consecutive discussions we find the following points that need to be considered in the future. The appropriate actions need to be undertaken to solve these problems before attempting to analyze the real data.

1. It is essential to be able to preselect events according to their global properties so each job analyzes only similar events. The solution of the STAR experiment, that is based on multiple event buffers, can not be adopted in the ALICE case because of the very large number of bins in z position of the primary vertex. The Offline framework is currently developing the Tag-Database that aims to comply with the requirement. In general, this philosophy of the two particle correlations analysis is the most efficient and error proof. We hope this functionality will be available for the analysis of the next PDC data.

2. Several items could not be done because they require higher statistics then available till now. We estimate that \(10^5\) events with an average \(dN_{ch}/d\eta\) of 6000 is sufficient to perform the following analyses:

- Study track merging within more bins of \(p_t\) \((K_t)\). The best would be to find functional parametrization of the cuts threshold values in function of \(p_t\) or \(K_t\). Having that for pions we can assume the same dependence for the other systems and find the appropriate parameters on the basis of smaller number of bins.
- Azimuthally sensitive HBT for pions. Please note that the information about the simulated event plane vector would be of the great help in this analysis, which is currently not available in Hijing. Hence, it would be useful to add this functionality to the generator or use another one.
- 3D dimensional analysis for kaons and protons, including resolution and PID corrections study
- Detailed analysis and systematic error assessment for non identical systems like pion – kaon and pion – proton.

3. The tuning of the tracking is necessary in order to maximize its performance in close track reconstruction efficiency. Especially it is needed for kaons and protons.

4. The tuning of the PID reconstruction is required. We hope to be able to use the PID probability as an estimator of the PID efficiency. As it was shown in section 5.6 it is certainly not the case at the moment.

The presented work was published as ALICE Internal Notes [114, 115].
6 Conclusions

In this work we aimed to prepare all the necessary procedures required to enable close velocity particle correlations analyses in the ALICE experiment. A number of tools was developed:

• Foundation library for analyses that serves all the basic functionality needed to construct any analyses. It provides very easy interface that facilitate data processing, including iterators, cuts, buffers and many others. Several novel solutions were applied that makes it robust and efficient. It implements Analysis Object Data format, that is designed to fit best to any analysis algorithms. It enables possibility to perform many analysis types together, so production data can be processed even more efficiently.

• Package for particle correlation analysis at ALICE. It is suitable for experimental as well as for Monte-Carlo simulated data processing. It allows for simple configuration of the analysis via macros. It is easily extensible if the user needs special functions or cuts.

• A generic intelligent system for data management for ALICE Offline Framework, which allows for user-friendly data handling, separating simulation, reconstruction and analysis from I/O. The system was designed with robustness and scalability as main requirements. It was introduced in 2003 and since that time it is one of the core components of the framework.

• Tools for particle correlation simulations. Two programs were adapted, HBT-Processor and weight calculator.

All the described software is an integral part of the ALICE Offline framework.

We have shown that the ALICE experiment is able to precisely measure space-time parameters of the system created in a collision.

• We have found resolutions and efficiencies of particle identification for charged pions, charged kaons and protons in function of transverse momentum.

• The resolutions of the variables that are important for the correlation analyzes were determined for various two particle systems involving charged pions, charged kaons, protons and antiprotons in function of relative momenta and pair transverse momentum. We have discussed their impact on the correlation functions and prepared the tool that corrects for this effect.

• The pair identification efficiency was found in function of relative momenta. We have discussed how the obtained contaminations modify correlation functions and we have implemented a procedure that allow to correct them for this effect.

• Influence of the splitting and merging effects on correlation functions is shown. We have developed and implemented methods that allow to eliminate the influence of these effects.

• The maximum reconstructible radii were determined and are around 15 fm for like sign pions. This is factor 2 larger then currently expected at LHC energies and it is a very safe margin.

• Systematic errors were estimated.

• Imperfections of the current reconstruction procedures were pointed out.

In the view of expected large contribution of hard processes we have analyzed their influence on correlation functions. In heavy ion collisions the correlation functions
• are affected by pions produced from fragmentation of jets.

• assume characteristic shape if there is strong suppression of jets due to energy loss of the leading parton in a deconfined medium.

In the latter case, jets are effectively emitted only from the surface of the fireball. Presumably, these characteristic shapes are dissolved in real data because there are much more particles stemming from thermal fireball. Correlation signal of individual jets is not visible if the total number of particles in a function bin is much larger than the number of particles produced by a jet.

• The signal can be studied best by using only pairs with high transverse pair momentum $K_t$ in the analysis.

Although we couldn’t describe the correlation function obtained after such a cut-off by our analytical expressions, we could observe a clear deviation from Gaussian shape. Note that Gaussian shape would result from our background source in the absence of jets. A non-Gaussian shape can influence results of fitting real data by Gaussian parametrization and may cause problems when interpreting such a fit. The same argumentation applies in any case if contribution of hard processes to the total particle production becomes significant (greater than 25%), what can not be ruled out a priori at LHC energies. We have shown that jets lead to structures in the correlation functions at large momentum differences: beyond the main peak at $q = 0$. Thus it is also important to look at the large-q region in order to learn about the characteristics of the source. Especially, that if the influence of jets is not realized and regular fit performed then the obtained radii are smaller than in fact.

We have also attempted to understand the influence of the jet hadronization process on particle correlation in proton-proton collisions. Using an approach which introduces a dependence of the distance of the mean hadronization points of a parton on its energy we have been able to reproduce very satisfactorily both the dependence of the radii, and the trend of the correlation strength lambda with the rapidity density in pp collisions at Tevatron energies. The present results indicate that there is a possibility of an alternative interpretation of the results to those presented in [36] and [91] where the obtained radii are interpreted as evidence for the observation of deconfined matter in pp collisions.

On the other hand the model a posteriori justifies the hadronization scenario envisaged because the free parameter that relates hadronization length to parton energy has been found close to unity for the range of multiplicities analyzed. We have pointed out that a detailed analysis of three dimensional correlation functions gives insight into the hadronization geometry. We believe that ALICE with its wider range of multiplicities in pp collisions offers interesting possibilities to test our model. We have therefore presented here the expected variation of the radii in function of charged particle multiplicities at the LHC.
7 Streszczenie w języku polskim

Wprowadzenie

Tematem niniejszej pracy jest “Ewolucja czasowo-przestrzenna zderzeń jądrowych obserwowana w eksperyencie ALICE poprzez analizę korelacji cząstek”. Eksperyment ALICE jest jednym z czterech, które będą wykorzystywać wiązkę akceleratora LHC (Large Hadron Collider) w Europejskim Laboratorium Fizyki Cząstek (CERN) w Genewie, i jedynym poświęconym całkowicie badaniom materii jądrowej. W LHC będą zderzały się jądra atomowe z nieosiągalnymi dotychczas w laboratorium energiami: 14 TeV dla protonów i 5.5 TeV na nukleon dla jąder ołowiu. Bardzo skomplikowana natura uformowanego w ten sposób układu wymaga gruntownej analizy wielu czynników.

Cele Pracy

W tej pracy skoncentrowano się na wąskiej części przewidywanych badań, a mianowicie na korelacjach cząstek o zблиżonych prędkościach, które pozwalają określić ewolucję czasowo-przestrzenną procesu zderzenia.

1. Praca polegała na przygotowaniu narzędzi do analiz oraz ich przetestowaniu na danych przygotowanych metodą modelowania komputerowego. Składa się na to:
   • implementacja oprogramowania do analiz,
   • przygotowanie narzędzi do symulacji,
   • szczegółowego studium efektów detektorowych, które zniekształcają wyniki pomiarów,
   • przygotowanie i implementacja algorytmów pozwalających, usunąć wpływ tych niepożądanym efektów,
   • oszacowanie niepewności systematycznych,
   • ocena możliwości pomiarów korelacyjnych w eksperyencie ALICE.

2. Po stronie badań fenomenologicznych przestudiowano wpływ tzw. procesów twardych na korelacje cząstek, zarówno w reakcjach jądro-jądro jak i proton-proton. Procesy te są związane z oddziaływaniami partonów (gluonów lub kwarków), w wyniku których przekazywana jest duża wartość pędu. Prowadzą one do emisji skolimowanego zbioru cząstek, które zwyczajowo nazywają się dżetami (ang. jet).
   • Przy energiach LHC oczekiwany przekrój czynny dla procesów twardych w zderzeniach jądro-jądro jest względnie duży. Dżety reprezentują źródła hadronów o specyficznej charakterystyce, które są zupełnie inne od tego stworzonego przez sternalizowany system, który ma kształt “kuli” o przekroju w kształcie funkcji Gausa. Dyspersja tego rozkładu jest zwyczajowo nazywana promieniem. Wysokoenergetyczne partony są bardzo szybko zatrzymywane w plazmie kwarkowo-gluonowej. Jeżeli ten proces występuje to wszystkie obserwowane dżety muszą hadronizować na zewnątrz sternalizowanego medium. Celem analizy jest próba zrozumienia wpływu tego efektu na funkcje korelacyjne. Ujmując bardziej szczegółowo, motywami badań było sprawdzenie poniższych niewiadomych
– czy dżety mają wpływ na efekty korelacji i jaka musi być ich krotność, aby efekt był mierzalny,
– w jaki sposób zniekształcają one mierzone parametry źródła, jeżeli ich wpływ nie zostaje uwzględniony w analizie,
– czy za pomocą analiz korelacji cząstek o małych prędkościach względnych można potwierdzić lub wykluczyć pochłanianie dżetów przez powstałe medium,
– czy taka analiza pozwala wyciągnąć szczególne wnioski ilościowe na temat poszczególnych parametrów źródła, tzn. rozmiarów obszaru, na którym hadronizują dżety oraz sterylizowanego medium.

W eksperymencie ALICE będą także badane reakcje proton-proton oraz proton-jon. Dla tego typu elementarnych zderzeń nie istnieje spójna interpretacja kształtu mierzonych funkcji korelacyjnych w ujęciu dynamiki reakcji. W pracy zaproponowano model, który wyjaśnia istniejące dane eksperymentalne jako odzwierciedlenie ewolucji czasowo przestrzennej procesu hadronizacji w korelacjach cząstek.

Struktura dysertacji

We wstępnym rozdziale przedstawiona jest motywacja badań nad materią jądrową w stanach ekstremalnych. Mianowicie, obliczenia chromodynamiki kwantowej przewidują, że przy odpowiednio wysokich temperaturach i/lub gęstościach zmieniają się jej właściwości. Odległości pomiędzy nukleonami stają się porównywalne z zasięgiem oddziaływań silnych, w konsekwencji czego kwarki i gluony, które normalnie są uwięzione wewnątrz hadronów, mogą poruszać się swobodnie. Materia jądrowa przechodzi w stan plazmy kwarkowo-gluonowej (QGP). W tym stanie przywrócona jest symetria chiralna, która jest spontanicznie łamana w normalnych warunkach.

aktualny stan wiedzy jest zbyt mały, aby stwierdzić czy następuje przejście fazowe czy też nie. Ten stan materii musiał istnieć zaraz po wielkim wybuchu i najprawdopodobniej występuje też we wnętrzach gwiazd neutronowych. Fizyki próbują otrzymać plazmę kwarkowo-gluonową w laboratorium zderzając ze sobą jądra ciężkich pierwiastków. Wyzwaniem stojącym przed współczesną fizyką jądrową jest potwierdzenie istnienia plazmy kwarkowo-gluonowej oraz określenie jej właściwości.

W dalszej części pierwszego rozdziału opisany jest mechanizm zderzenia, ze specjalnym zwróceniem uwagi na procesy twardze i ich znaczenie. Następnie, przedstawiona jest teoria wyjaśniająca mechanizm powstawania korelacji cząstek o małych prędkościach względnych. Wyjaśnione jest szczegółowo, w jaki sposób analiza kształtu funkcji korelacyjnych pozwala określić ewolucję czasowo przestrzenną zderzenia. Opisana jest metodologia analiz korelacji. Dalej, syntetycznie przedstawione są wyniki otrzymane do tej pory w różnego typu eksperymentach.

następnie opisany jest eksperyment ALICE oraz szczegółowo wyjaśniona jest motywacja fizyczna tego eksperymentu. Wymienione są podzielane sygnaury plazmy kwarkowo-gluonowej. Szczególnie przedstawiony jest układ eksperymentalny oraz jego składowe. Opisana jest zasada działania każdego z podsystemów detekcyjnych oraz motywacja wyboru poszczególnych rozwiązań.

Rozdział drugi poświęcony jest oprogramowaniu. Podkreślone jest, że w dziedzinie fizyki jądrowej i cząstek elementarnych oprogramowanie jest integralną częścią aparatury pomiarowej. Współczesne detektory są urządzeniami elektronicznymi, a bezpośrednim efektem pomiaru jest zbiór liczb zapisany w postaci pliku w komputerze. Liczby te opisują wielkości zmierzone przez każdy z czujników. Specjalny program komputerowy przeprowadza proces rekonstrukcji torów, którego celem jest odszyfrowanie jakie cząstki i o jakich parametrach wytworzyły zaobserwowany wzór w detektorze. Dlatego od efektywności zastosowanych algorytmów i ich implementacji zależy jakość pomiarów.

Opisany jest w skrócie schemat oprogramowania do analiz i symulacji. Przedstawione są następujące pakiety opracowane przez autora:

• system zarządzania przepływem, zapismem oraz odczytem danych,
• biblioteka, która jest podstawą do tworzenia wszelkiego typu analiz w ALICE,
• pakiet do analiz korelacyjnych,
• dwa programy, które pozwalają symulować efekty korelacyjne
  – HBT-Processor, którego działanie polega na zmianach pędów cząstek o małe wartości do momentu otrzymania żądanej funkcji korelacyjnej.
  – kalkulator wag, który przypisuje parom cząstek wartości liczbowe (wagi) charakteryzujące efekty statystyki kwantowej oraz oddziaływania w stanie końcowym odpowiadające parametrom ich źródeł oraz ich różnicy pędów.

W rozdziale trzecim przedstawiony jest model teoretyczny, który pozwala zrozumieć wpływ procesów twardych na obserwowane korelacje cząstek w zderzeniach jądro-jądro. Został opracowany algorytm i program komputerowy, który przypisuje cząstkom pozycje i czasy ich emisji według różnych schematów w zależności od tego, czy pochodzą ze sternalizowanego źródła lub też fragmentacji dzetów. W pierwszym przypadku jest to trójwymiarowy rozkład Gausa o średniej wartości pokrywającej się z punktem centralnym kolizji i o dyspersji rzędu promienia jądra ołowiu. W drugim przypadku jest to także trójwymiarowy rozkład Gausa, ale o $\sigma = 1$ fm. Punkt wartości oczekiwanej jest w zależności od wariantu modelu:

• obliczany tak, aby znajdował się na powierzchni walca, a kierunek dzetu był normalny do tej powierzchni, co odpowiada sytuacji w której dzęty hadronizują na zewnątrz medium;

• losowany z rozkładu płaskiego w kierunku wąskiej, oraz losowany z rozkładu Gausa w płaszczyźnie prostopadłej, co modeluje brak efektu zatrzymywania wysokoenergetycznych partonów przez medium.

Dla tak przygotowanych zdarzeń obliczono funkcje korelacyjne przy pomocy kalkulatora wag.

Rozdział czwarty poświęcony jest zderzeniom proton-proton. Niewyjaśnionym faktem eksperymentalnym jest liniowa zależność promieni uzyskanych w analizach korelacyjnych od krotności wyprodukowanych cząstek w rozpatrywanych zdarzeniach. Zostało zauważone, że rozpiętość przestrzenna procesu hadronizacji jest proporcjonalna do energii pierwotnego partonu. W celu sprawdzenia czy ten fakt tłumaczy obserwowaną eksperymentalnie zależność skonstruowano program, który przypisuje cząstkam położenia ich narodzin według zadanego rozkładu. Zdarzenia symulowano przy pomocy programu "Pythia", który aktualnie najlepiej potra symulować zderzenia proton-proton przy wysokich energiach. Dla cząstek powstałych wskutek hadronizacji wysokoenergetycznych partonów, tzn. wchodzących w skład dzetu, położenia były losowane:

• w kierunku osi dzetu z rozkładu Gausa o średniej wartości proporcjonalnej do energii partonu i dyspersji równej jednej trzeciej średniej. Współczynnik proporcjonalności $f_1$ jest wolnym parametrem modelu. Wybór takiego rodzaju rozkładu jest intuicyjny i jest poparty statystycznym charakterem procesu oraz faktem, że hadronizacja nie może rozpocząć się natychmiast po wyboru partonu. Wartość dyspersji jest tak dobrana, aby prawie wszystkie (99.7%) cząstki były emitowane pomiędzy punktem, z którego parton został wybrany (punkt centralny kolizji) a odległością odpowiadającą podwójnej średniej rozkładu. W analizie zostało sprawdzone, że wyniki nie są bardzo czule na zmianę szerokości tego rozkładu.

• w płaszczyźnie prostopadłej z rozkładu Gausa o średniej 0 i stałej dyspersji równej 0.5 fm. Taka wartość została wydana, ponieważ odpowiada ona szerokości struny równej 1 fm, co jest uważane aktualnie za charakterystyczny zasięg oddziaływań silnych.
Przedstawiony powyżej model jest najbliższy aktualnemu rozumieniu procesu hadronizacji.

Punkty emisji cząstek niewchodzących w skład żadnego z dżetów były losowane z trójwymiarowego rozkładu Gausa, którego średnia wartość pokrywa się z punktem centralnym kolizji, a dyspersja jest jednakowa we wszystkich kierunkach i równa $\sigma_0$. Wartość tego parametru jest zdeterynowana przez kształt funkcji korelacyjnej otrzymanej dla zdarzeń o najmniejszej krotności cząstek i jest równa 0.4 fm.

Funkcje korelacyjne były obliczane przy pomocy kalkulatora wag. Procedura ta pozwala znaleźć rozkład, według którego cząstki są emitowane oraz jego parametry, które najpiękniej odtwarzają zmierzone eksperymentalnie funkcje korelacyjne. W analizie posłużono się wynikami eksperymentu E735, w którym analizowano zderzenia proton-antiproton przy energii 1.8 TeV w akceleratorze Tevatron w laboratorium FNAL (Fermi National Laboratory).

Jednakże, nie udało się znaleźć takich parametrów modelu, które pozwoliłyby odwzorować wyniki otrzymane przez eksperyment E735. Po wnikliwej analizie spostrzeżono, że rozmiar obszaru emisji w kierunku prostopadłym do osi dżetu także musi zależeć od energii hadronizującego partonu. W ulepszonym modelu dyspersja rozkładu Gausa, z którego losowane jest położenie w tym kierunku, jest zależna liniowo od energii partonu, a współczynnik proporcjonalności $f_t$ jest następnym wolnym parametrem modelu. Znaleziono takie $f_t$ i $f_l$, że promienie otrzymane dla wszystkich rozpatrywanych krotności cząstek są zgodne z wynikami eksperymentu E735.


Ostatni rozdział zawiera podsumowanie i wnioski, które są wymienione krótko ponizej.

**Wnioski**

Na podstawie przeprowadzonych badań wyciągnięto następujące wnioski:

1. Jeżeli w zderzeniach jon-jon co najmniej 25% cząstek produkowanych jest poprzez mechanizm fragmentacji dżetów to funkcje korelacyjne przyjmują charakterystyczne kształty. Mianowicie, projekcje w kierunku $out$ i $side$ stają się podobne do sumy dwóch funkcji Gausa, zamiast pojedynczej funkcji Gausa, która byłaby obserwowana przy nieobecności procesów twardych. Jednakże, nie można interpretować bezpośrednio szerokości obu funkcji Gausa jako rozmiarów poszczególnych źródeł tzn. obszaru hadronizacji wysokoenergetycznych partonów i stermalizowanej “kuli”. Wynika to z faktu, że funkcje są dodatkowo modyfikowane przez korelacje pomiędzy cząstekami emitowanymi z tych dwóch rodzajów źródeł. Prowadzą one, między innymi, do poszerzenia się węższej z funkcji. W konsekwencji, jeżeli nie zostanie uwzględniony wpływ procesów twardych i zostanie zastosowane standardowe dopasowanie pojedynczej funkcji Gausa, to zrekonstruowany promień będzie mniejszy niż jest w rzeczywistości.

Wyżej wymienione wnioski są prawdą w obu scenariuszach, gdy występuje efekt zatrzymywania przez medium wysokoenergetycznych partonów i przy jego braku. Funkcje korelacyjne otrzymane dla tych dwóch przypadków nie są identyczne, aczkolwiek są zbyt mało charakterystyczne aby wyłącznie na ich podstawie móc jednoznacznie wykluczyć lub potwierdzić obserwację tego efektu. Jeżeli jednak z innych przesłanek będzie można wywnioskować, który ze scenariuszy ma faktycznie miejsce, to wnikliwa analiza funkcji korelacyjnych pozwala wyciągnąć wnioski na

Jednakże, przy spodziewanym przekroju czynnym dla procesów twardych przy energiach LHC, wpływ dżetów będzie niewidoczny. Jedynie w przypadku analizy cząstek o dużym pędzie poprzecznym (>1 GeV/c) jest szansa na zaobserwowanie efektu, ponieważ udział procesów twardych w produkcji cząstek rośnie wraz z ich pędem.

2. Funkcje korelacyjne otrzymane przy pomocy zaproponowanego modelu dla zderzeń proton - (anty)proton są bardzo podobne do tych mierzonych eksperymentalnie. Model ten pozwala zrozumieć niewyjaśnioną do tej pory zależność mierzonych promieni od krotności cząstek w analizowanych przypadkach. Zostało stwierdzone, że rozpiętość przestrzenna procesu hadronizacji rośnie liniowo wraz z energią partonu i nie tylko w kierunku jego emisji (co było już wcześniej wiadome), ale także w kierunku poprzecznym, co jest całkowicie nowym stwierdzeniem. Zależność mierzonych promieni od krotności wyprodukowanych cząstek wynika z faktu, że wraz ze wzrostem tej drugiej rośnie średnia energia dżetów.

Badania istotny jest wniosek, że analizy korelacji cząstek o bliskich prędkościach względnych stwarzają możliwość oszacowania rozmiarów przestrzennych procesu hadronizacji. Brak wyników trójwymiarowych analiz korelacyjnych nie pozwolił już teraz na jednoznaczne określenie parametrów modelu i wyciągnięcie precyzyjnych wniosków ilościowych na ten temat. W eksperymentie ALICE przeprowadzone będą takie pomiary z bardzo dużą precyzją. Dopasowanie parametrów zaproponowanego modelu do tych wyników pozwoli na szczegółowe zrozumienie przestrzennej ewolucji procesu hadronizacji, co nie było dotąd możliwe.

3. Pokazano, że w eksperymentie ALICE można mierzyć precyzyjnie parametry czasowo-przestrzenne systemu powstałego w skutek kolizji jądrowej.

- Znaleziono wartości rozdzielczości i efektywności identyfikacji typu cząstek dla naładowanych elektrycznie pionów, kaonów i protonów w funkcji pędu poprzecznego.
- Określono wartości rozdzielczości zmiennych najważniejszych dla analiz korelacyjnych dla systemów zawierających piony, kaony oraz protony w funkcji pędów względnych oraz pędu poprzecznego pary.
- Przestudiowano efektywność identyfikacji typu pary cząstek w funkcji pędów względnych.
- Omówiono wpływ efektu "rozdzialania" torów przez procedurę ich rekonstrukcji.
- Przedyskutowano dwucząstkową zdolność rozdzielczą detektora oraz jej wpływ na kształt mierzonych funkcji korelacyjnych.
- Opracowano metody, które pozwolą wyeliminować wyżej wymienione efekty, a także procedurę korekcji efektów wywołanych niedoskonałymi rozdzielczością oraz identyfikacją cząstek.
- Wyznaczono zakres mierzalnych w eksperymentie ALICE promieni.
- Oszacowano błędy systematyczne pomiarów.
- Wykazano niedoskonałości aktualnych procedur rekonstrukcji oraz zaproponowano rozwiązania dla dodatkowych ulepszeń i następnych analiz.
- Opracowano specjalistyczne oprogramowanie (HBT-Anlyzer) umożliwiające analizę efektów korelacyjnych w eksperymentie ALICE. Stało się ono integralną częścią oprogramowania eksperymentu i zostało przygotowane do przyszłych pomiarów.
8 References


[75] P.K. Skowronski for ALICE Collaboration, physics/0306111


