Particle production in ultra-relativistic proton-proton and heavy ion collisions at the Large Hadron Collider

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Abstract.
Recent results concerning the main features of particle production in proton-proton and heavy ion collisions at the energy regime of the Large Hadron Collider, as recently made available from the ALICE, ATLAS, CMS and LHCb Collaborations, are discussed.

1. Introduction

The production of hadronic particles in nuclear, particle and cosmic-ray physics is of special interest to understand the underlying mechanisms leading to such reaction products and to test the predictions from non-perturbative QCD processes. The yield of identified hadrons, their multiplicity distributions, as well as the rapidity and transverse momentum spectra are the basic observables in proton-proton and heavy ion collisions at any energy regime, from a few GeV per nucleon to the new ultra-relativistic LHC regime, spanning c.m. energies of a few TeV.

The measurement of such global observables when entering a new energy regime has produced over the past years, since the beginning of the RHIC era (c.m. energies up to 200 GeV), new and interesting insights about the involved production mechanisms, allowing in turn to strongly improve the theoretical description of such processes and tune the corresponding event generators. The study of particle production is also an important tool to provide a description of the expected background for the measurements of hard and rare interactions.

In pp collisions at ultra-relativistic energies the bulk of the particles produced at mid-rapidity have transverse momenta below 1 GeV/c. First principles calculations based on perturbative QCD are not able to provide detailed predictions of particle production. The experimental measurements of the basic properties of particle production is thus essential to provide reliable input for hadronic model calculations. Moreover, a detailed investigation of identified hadrons as a function of the transverse momentum is required.

2. The new energy regime at the LHC

The Large Hadron Collider (LHC) at CERN started its physics program on November 2009, providing the first proton beams at $\sqrt{s}$=0.9 TeV. Since then, an increasing amount of physics data has been collected by all running experiments, by the study of pp, PbPb and pPb collision events.

The study of heavy ion collisions at high bombarding energies is now a mature field. After the pioneering experiments in Berkeley and Dubna in the 70's with relativistic heavy ions, the

first experiments at ultra-relativistic energies date to 1986 with light ions at the Brookhaven AGS and the CERN SPS. Heavier projectiles became available in the AGS since the end of 1992 and at the SPS since the end of 1994. Only a few years later, in 2000, with the opening of the Relativistic Heavy Ion Collider (RHIC), the first Au-Au collisions at a centre-of-mass energy of 130 GeV were studied. Since then, a variety of new physics signals and results have been obtained at RHIC. As a result of these experiments, a first understanding of the new high energy density state created in such energetic collisions as an extremely strongly interacting and almost perfect fluid has emerged. According to experimental evidence obtained so far at RHIC, one of the properties of such medium is of being able to absorb much of the energy of fast partons (quarks and gluons) traveling through it, a process referred to as jet quenching. Moreover, it exhibits little internal friction, i.e. very small viscosity.

The first proton-proton collisions at the new Large Hadron Collider were observed in November 2009, and only one year later, in November 2010, the first Lead ion beams collided at a c.m. energy of 2.76 TeV, providing a large data set on nucleus-nucleus collisions in a new energetic regime. In about 25 years, the available energy in the center-of-mass system has thus increased by four orders of magnitudes, giving access to new physics and unexplored regions of the nuclear matter territory.

A variety of new probes and results are coming out from the first ion runs at LHC. Even though the ALICE detector was the setup officially designed to study heavy ion collisions, both ATLAS and CMS are pursuing a rich program devoted to the study of the nuclear matter at extreme energy density, such as reached in heavy ion collisions. After the first two data taking periods with Lead ions, and an exploratory short pilot run with p-Pb collisions in 2012, a series of specific results originating from such studies has emerged and is currently discussed in the heavy ion community.

Understanding the bulk of reaction products in such collision events is mandatory to explore the role of specific processes observed in heavy ion collisions, so that it is generally accepted that, beside their interest in itself, proton-proton collision events are an essential reference for a comparison to data obtained in proton-nucleus or nucleus-nucleus collisions.

While the discussion of the large variety of physics results and experimental probes employed in such studies largely exceeds the scope of the present paper, the production of hadronic particles in proton-proton and heavy-ion collisions, which has now been studied by all large experiments running at CERN LHC, is the topic of interest for this contribution.

3. Experimental setups at the Large Hadron Colliders

Several large detectors have been built and are currently operating at the Large Hadron Collider. Some of them are specialized detectors, which aim at the investigation of specific aspects of the proton-proton and heavy ion collisions. General purpose detectors, which have the required performance to address all the main features of particle production in ultra-relativistic pp and AA collisions are the ALICE (A Large Ion Collision Experiment) [1], ATLAS (A Toroidal LHC Apparatus) [2] and CMS (Compact Muon Solenoid) [3] installations, while LHCb (LHCbeauty) [4] was designed especially for precision measurements of CP violation and rare decays of B hadrons, exploring the forward rapidity region.

Due to the experimental conditions at the LHC, all the detectors required fast, radiation-hard electronics and sensor elements. In addition, a high detector granularity was needed to handle the particle fluxes and to reduce the influence of overlapping events. For the study of the global properties of particle production large acceptance in pseudorapidity with almost full azimuthal angle coverage is required. Good charged-particle momentum resolution and reconstruction efficiency in the inner tracker are also essential.

While a full description of such detectors has been given, prior to the startup of LHC, in Ref. [1, 2, 3, 4], here only a brief recall of their main features is reported.

3.1. The ALICE detector

The choice and design of ALICE was driven by the physics requirements as well as by the experimental conditions expected in nucleus-nucleus collisions at the LHC. The most stringent design constraint is the extreme particle multiplicity. The design of ALICE was originally optimized for a value of about $dN_{ch}/d\eta = 4000$, and tested with simulations up to twice such value.

The overall dimensions of the ALICE detector are 16x16x26 m^3, with a total weight of approximately 10,000 tons. ALICE consists of a central barrel, which measures hadrons, electrons, and photons, and a forward muon spectrometer. The central part covers polar angles from 45° to 135° and is embedded in a large magnet, with a magnetic field of up to 0.5 T. The central barrel contains a set of tracking detectors and a set of particle identification detectors, followed by two different electromagnetic calorimeters for photon and jet measurements. Most of the central detectors cover the full azimuthal range. On one side, at small angles relative to the beam direction is a muon spectrometer which includes a dipole magnet generating a maximum field of 0.7 T. Additional detectors are placed at forward rapidity for event selection, timing reference and to measure global features of the reaction.

3.2. The ATLAS detector

The ATLAS detector has nominally a forward-backward symmetry with respect to the interaction point. The magnet configuration includes a thin superconducting solenoid surrounding the inner-detector, and three large superconducting toroids (one barrel and two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters. The inner detector is immersed in a 2 T solenoidal field, has full coverage in ϕ and covers the pseudorapidity range $|\eta| < 2.5$.

Pattern recognition, momentum and vertex measurements, and electron identification are achieved with a combination of pixel and strip detectors in the inner part of the tracking volume, and straw-tube tracking detectors.

Extensive calorimetry, with different techniques, is also used in the ATLAS installation, to provide precision measurements of electrons and photons around the inner tracker and good reconstruction of jets and missing energy in the overall pseudorapidity range.

3.3. The CMS detector

The CMS detector is a general purpose installation able to cope with all the main signatures and probes of the high-luminosity pp collisions at LHC. The central feature of the CMS apparatus is a superconducting solenoid, 15 m long and 6 m internal diameter, with a 3.8 T field. In the field volume several detectors are located: the silicon pixel and strip tracker, the lead tungstate electromagnetic calorimeter, the brass/scintillator hadron calorimeter and the muon detection system. CMS has also extensive forward calorimetry. The tracker measures charged particles within the pseudorapidity range -2.4 < η < 2.4, providing an impact-parameter resolution of about 100 μm and an absolute p$_T$ resolution of about 0.7 % for charged particles of momentum 1 GeV/c, of relevance for the study of particle production.

3.4. The LHCb detector

The LHCb experiment is dedicated to precision measurements of CP violation and rare decays of B hadrons. The detector is is a single-arm magnetic dipole spectrometer with a polar angular coverage with respect to the beam line of approximately 15 to 300 mrad in the horizontal bending plane, and 15 to 250 mrad in the vertical non-bending plane.

The LHCb spectrometer acceptance, -2.5 < η < -2.0 and 2.0 < η <4.5, allows also the forward pseudorapidity region to be probed. For the reconstruction of charged particles, the LHCb tracking system consists of silicon microstrip modules surrounding the proton-proton
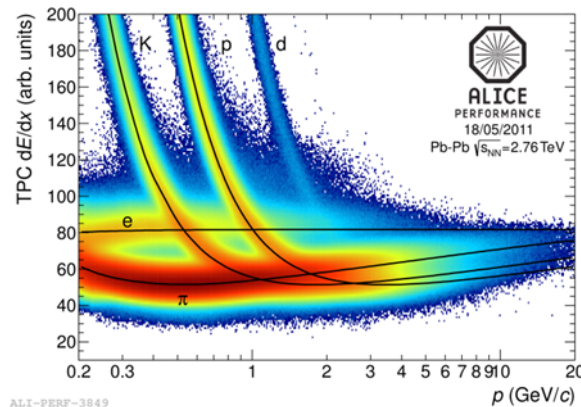
Figure 1. Particle identification performance in the ALICE TPC.

interaction region, a tracking station before the dipole magnet, which also employs microstrip technology, and three tracking stations - with silicon microstrips and straw tubes - after the magnet.

3.5. Particle reconstruction and identification
The study of particle production, especially in a large multiplicity heavy ion collision, requires optimal capabilities of the detector, in terms of primary and secondary vertex reconstruction, impact parameter and momentum resolution, tracking efficiency. As an example, in the ALICE detector, tracking in the central barrel is provided by an Inner Tracking System (ITS), a six-layer, silicon vertex detector, and by a large Time-Projection Chamber (TPC). A Transition Radiation Detector (TRD) is also used for tracking in the central region improving the transverse momentum resolution at high momentum. Because of the high particle density, the innermost four layers need to be truly two-dimensional devices, i.e. silicon pixel and silicon drift detectors, while the outer layers are equipped with double-sided silicon microstrip detectors. The need for efficient and robust tracking has led to the choice of a TPC as the main tracking detector. With its large granularity, this tracking device can guarantee reliable performance even in a large multiplicity environment.

Particle identification (PID) over a large part of the phase space and for many different particles is an important design feature of any detector at LHC.

In case of the ALICE detector, essentially all known PID techniques are employed: specific ionization energy loss dE/dx, time-of-flight, transition and Cherenkov radiation, electromagnetic calorimetry, muon filters, and topological decay reconstruction. As an example, Fig.1 shows the typical particle identification performance plot for the ALICE TPC.

Even though all the LHC detectors have wide capabilities for the reconstruction and identification of primary and secondary particles emitted in the collisions, several differences exist between them, in terms of geometrical acceptance, impact parameter and momentum resolution, PID efficiency, particle detection thresholds, and so on. For a detailed understanding of the capabilities of each LHC detector the reader is addressed to their general description [1, 2, 3, 4].

4. Results from proton-proton collisions
4.1. Multiplicity
The multiplicity of charged particles produced in a high energy collision is a key quantity to characterize the hadronic final state. The pseudorapidity density and the multiplicity distributions for primary charged particles are among the basic observables to be measured
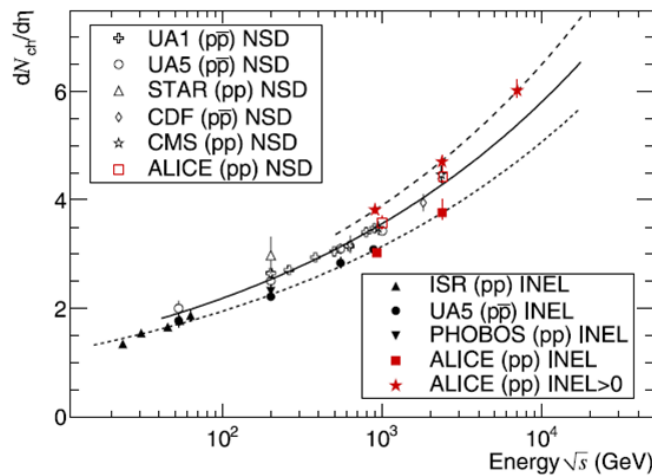
Figure 2. Pseudorapidity density of charged particles measured at LHC by different experiments in the central pseudorapidity density [5].

and understood. Several predictions from theoretical models were refined in recent years, taking into account data from RHIC, so that the first data from LHC were of crucial importance to check the ability of such models to reproduce new data at the higher energy regime. These observables were indeed measured at LHC by the various Collaborations as soon as a new beam energy was available for physics.

ALICE, ATLAS and CMS have measured charged particle multiplicities in the central pseudorapidity region, while LHCb has mainly covered the forward region.

Concerning the evolution of the average charged particle multiplicity with the centre-of-mass energy, the ALICE Collaboration has reported values of the charged particle pseudorapidity densities $dN_{ch}/d\eta$, measured in the central pseudorapidity region $|\eta| < 1$, equal to 3.81±0.01, 4.70 ±0.01 and 6.01±0.01 (errors are statistical only) at 0.9, 2.36 and 7 TeV centre-of-mass energy respectively [5]. It was observed that the experimental values of such pseudorapidity densities are generally higher with respect to model predictions, except in a few cases. The data obtained at 7 TeV demonstrate, in agreement with the result from CMS [6], that the measured multiplicity density increases with the energy much more than provided by the models considered.

The energy dependence of the charged-particle pseudorapidity density in the central pseudorapidity region has been extracted from the various data sets measured at LHC and compared for different event classes, see Fig.2 [5]. The lines indicate a power law fit to the data.

4.2. Multiplicity distributions

Multiplicity distributions were measured for various ranges of the pseudorapidity, both in the central pseudorapidity region and at forward rapidities. Typical results are shown in fig.3, as reported by the CMS Collaboration [7], at 0.9, 2.36 and 7 TeV centre-of-mass energy, compared to earlier measurements performed by UA5 and to the results from the ALICE Collaboration [5]. Similar set of results in the pseudorapidity interval $|\eta| < 2.5$ have been also reported by the ATLAS Collaboration [8].

Figure 4 shows unfolded charged particle multiplicity distribution for different bins in pseudorapidity, as measured by the LHCb Collaboration [9], together with the predictions from different event generators. None of them is fully able to describe these multiplicity distributions over the full LHCb acceptance. In general, the models underestimate charged
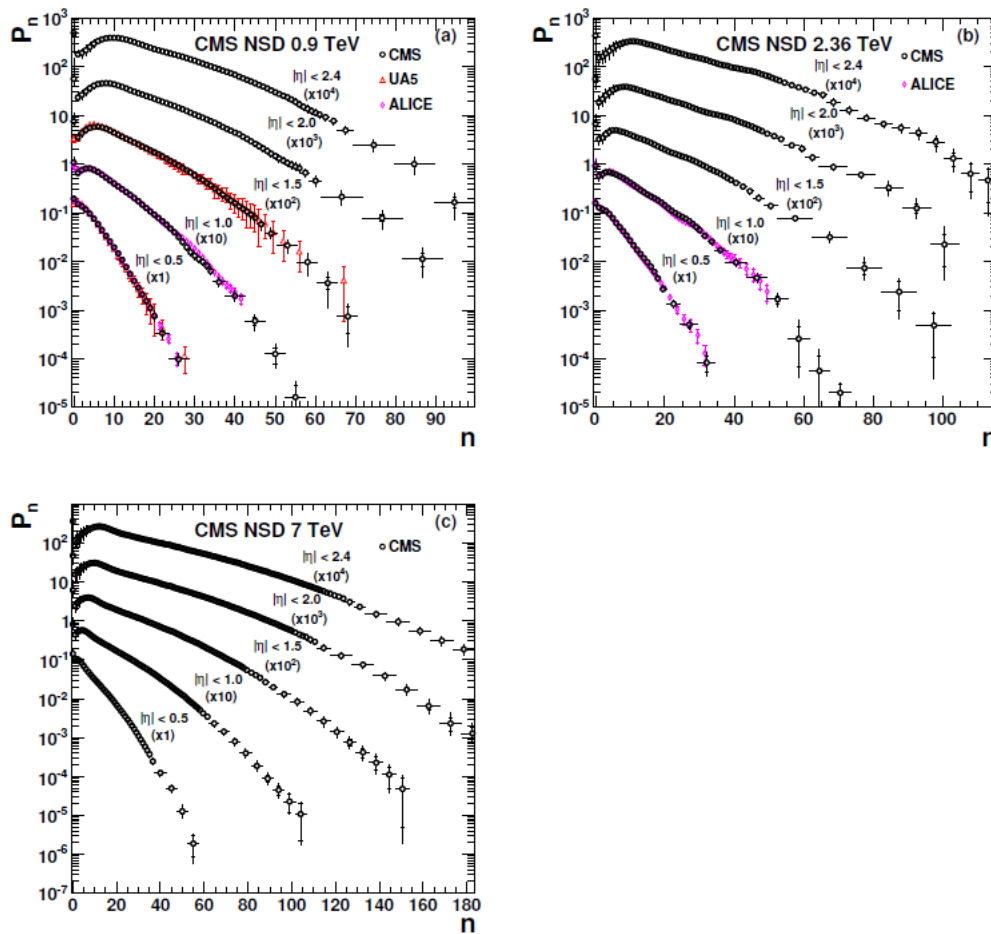
Figure 3. Charged hadron multiplicity spectrum, measured at 0.9, 2.36 and 7 TeV in increasing ranges of the pseudorapidity, from 0.5 to 2.4. Results from the CMS and ALICE Collaborations are shown, togeher with the results of earlier measurements from the UA5 Collaboration [7].

particle production, in agreement with the measurements by the other LHC experiments in the central region.

4.3. Pseudorapidity distributions

The charged particle pseudorapidity density as a function of the pseudorapidity has been measured at various energies, both in the central region, and at forward rapidity by LHCb [9], and compared with the current predictions of event generators.

For instance, high-statistics measurements of the charged primary particle pseudorapidity density in pp collisions at centre-of-mass energies of 0.9 TeV and 2.36 TeV with the ALICE detector have been reported in Ref. [10]. The results at 0.9 TeV are consistent with UA5 earlier measurements of antiproton-proton at the same energy, and consistent at both energies with the CMS measurements. A comparison with various models shows that none of the investigated models and tunes describes the results well. In particular, they underestimate the increase in the average multiplicity seen in the data between 0.9 TeV and 2.36 TeV.

The ATLAS Collaboration has measured charged-particles pseudorapidity distributions at centre-of-mass energies of 0.9, 2.36 and 7 TeV under different trigger conditions. As an example, fig.5 shows the result at 7 TeV in the range $|\eta| < 2.5$, under the condition $n_{ch} > 1$ and $p_T > 500$
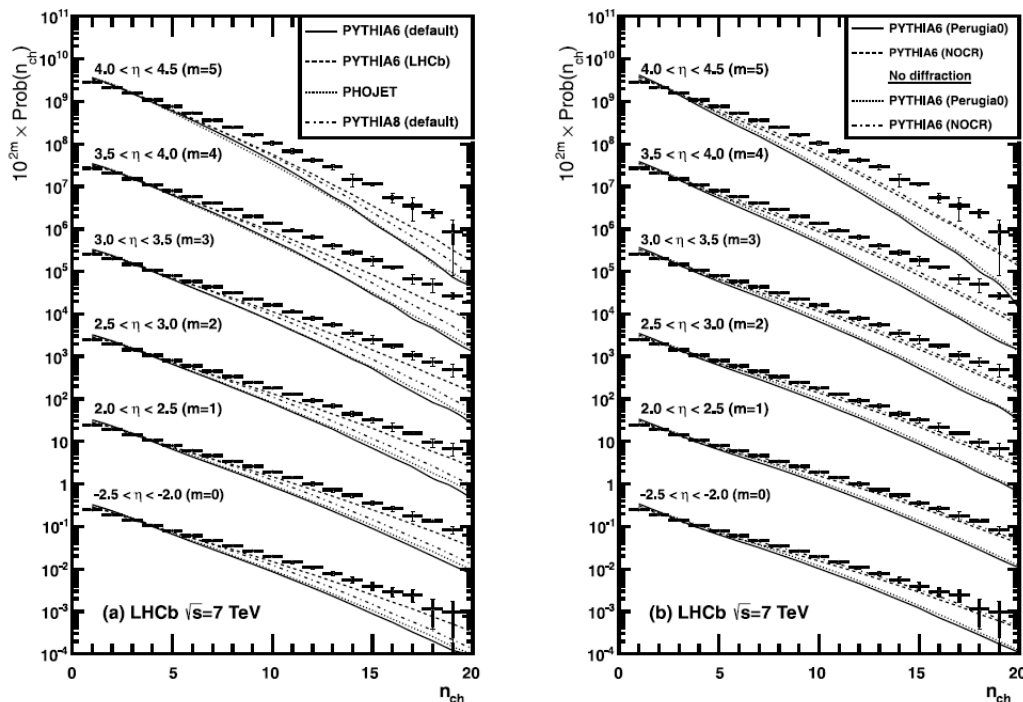
Figure 4. Charged particle multiplicity distributions for different bins in pseudorapidity, as reported by the LHCb Collaboration [9].

MeV, together with the predictions from various models.

In the forward region, $\eta > 2.5$, minimum bias events measured by LHCb were seen to give a distribution not reproduced by any of the models considered. Different event selections were also considered to extract hard QCD events from the data sample, for instance by imposing that at least one track in the forward region has transverse momentum larger than 1 GeV/c. Although the predictions are in such case in better agreement than for minimum bias events, all models still fail to provide a detailed description of the average charged particle multiplicity per unit of pseudorapidity [9].

4.4. Transverse momentum spectra

Transverse momentum spectra and yields of identified hadrons at midrapidity are the next key quantities to be measured in high energy collisions. Such data allow to extract the detailed shape of the transverse momentum spectra, the average transverse momentum, the ratios between the yields of the various species and the antiparticle/particle ratios, thus providing a good set of benchmarks for the currently employed theoretical models.

A first analysis of identified hadrons (π^+, π^-, K^+, K^-, p, $\bar{p}$) at 0.9 TeV has been carried out by ALICE, down to very low p_T, see Fig.6 [11]. A fit of the data with a Levy function was seen to reproduce the data well and was used to extract the average p_T and the total yields of the various species. Transverse momentum spectra of charged positive and negative hadrons were published by CMS at 0.9 and 7 TeV [12] in a very large momentum range, up to 200 GeV/c and in the pseudorapidity interval $|\eta| < 2.4$. Fig.7 shows this result, compared to the predictions of different PYTHIA tunes.

Spectra of identified hadrons produced in pp collisions at 0.9, 2.36 and 7 TeV have also been measured at midrapidity by CMS in the transverse momentum region 0.1-1.7 GeV/c and
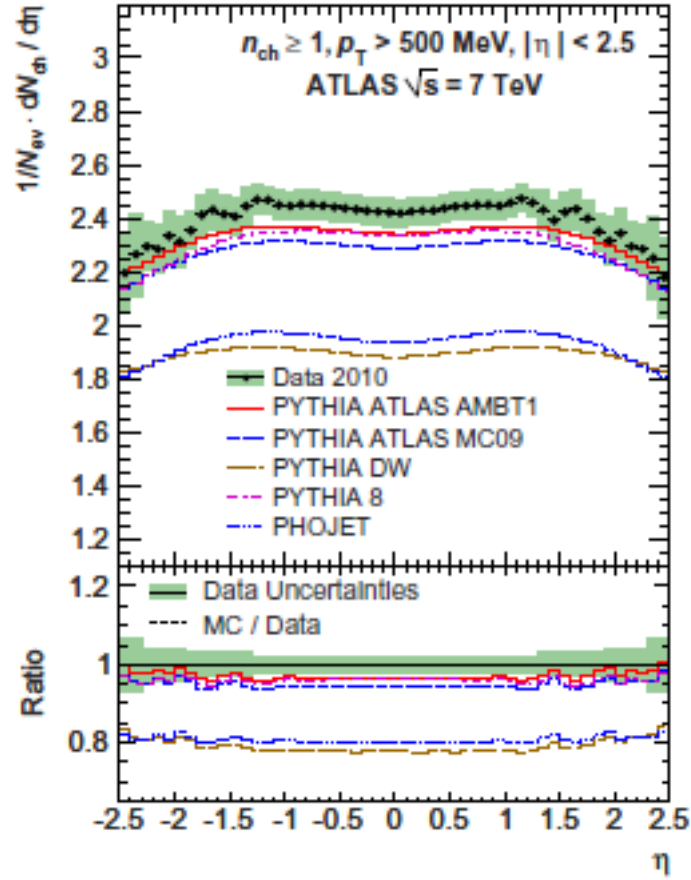
Figure 5. Inclusive charged-particle multiplicity as a function of the pseudorapidity, in the interval $|\eta| < 2.5$ and $p_T >$ 500 MeV, measured by the ATLAS Collaboration [8].
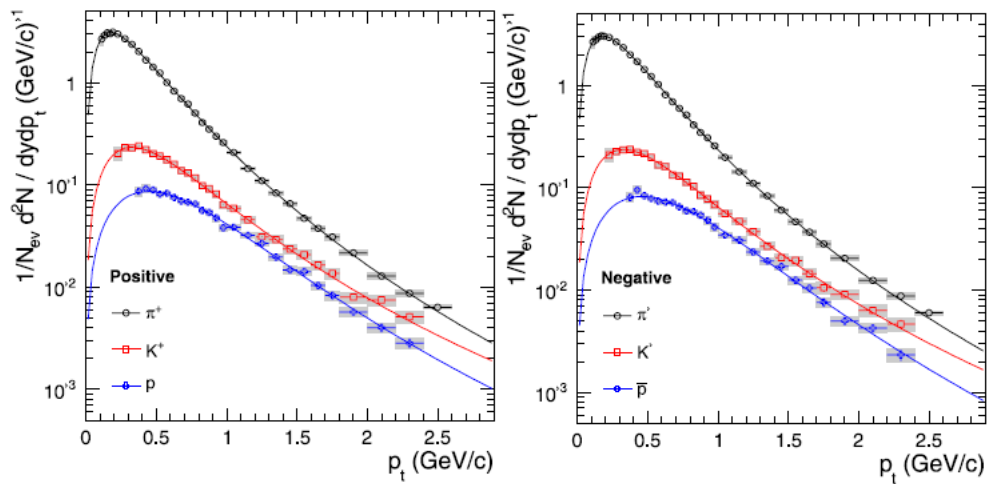

Figure 6. Transverse momentum spectra of identified hadrons measured at 0.9 TeV by the ALICE Collaboration [11].
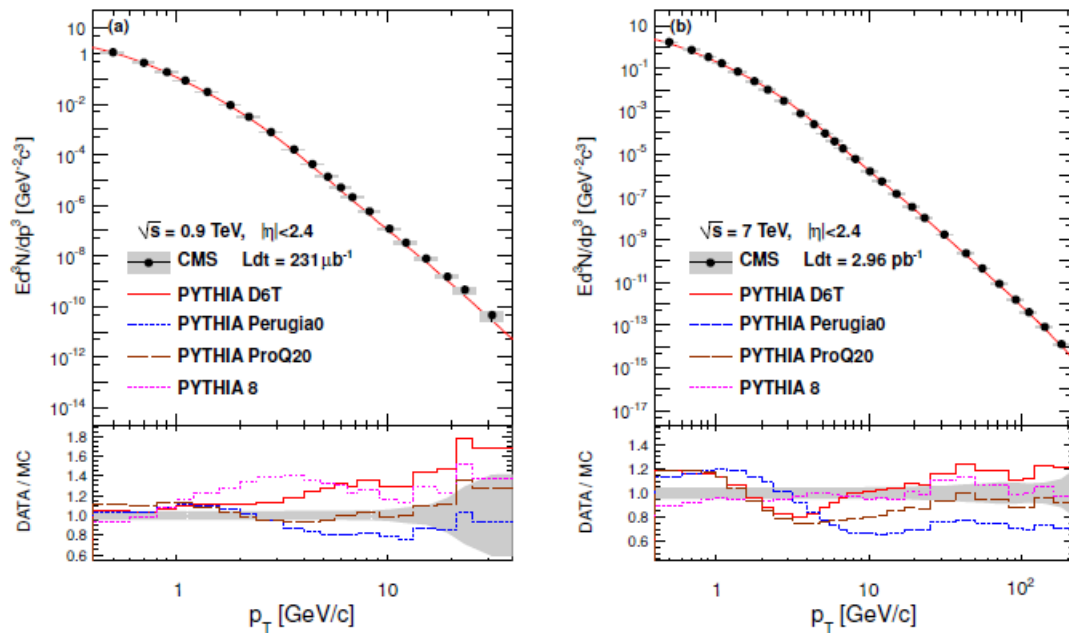
Figure 7. Transverse momentum spectra of charged hadrons measured at 0.9 and 7 TeV by the CMS Collaboration in a large momentum range [12].

$|y| < 1$ [13]. Fig.8 shows the experimental distributions obtained for pions, kaons and protons, together with the corresponding negative hadrons. A selection of events according to their multiplicity has also been made, allowing to study particle production as a function of the event multiplicity. The results show that particle production has a strong correlation with such variable, rather than with the centre-of-mass energy [13].

The average transverse momentum as a function of the particle multiplicity, as reported by the ATLAS Collaboration [8] is shown in fig.9, at the centre-of-mass energies of 0.9 and 7 TeV, together with its ratio to the value provided by different models.

5. Heavy ion collisions

Heavy ion collisions at LHC were believed to generate a system at unprecedented temperatures and energy densities, thus opening a new frontier in the study of QCD matter. The basic step in order to characterize this system is the measurement of the charged particle pseudorapidity density, which is an essential observable to estimate the initial energy density and strongly constrains the various proposed production mechanisms. They predicted values differing by a factor 2 before the new LHC heavy ion data could be obtained.

The first measurement of the charged-particle pseudorapidity density produced in central Pb-Pb collisions at a centre-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV was obtained with the ALICE detection setup [14]. Primary charged particles, including decay products (except those originating from the weak decay of strange particles) were measured in the pseudorapidity interval $|\eta| < 0.5$, thus obtaining the value of the primary charged-particle density $dN_{ch}/d\eta$ in central Pb-Pb collisions. A value of $dN_{ch}/d\eta = 1584 \pm 4$ (stat) ± 76 (syst) was obtained, which corresponds to a normalized value per participant pair of $dN_{ch}/d\eta/(0.5 < N_{part} >) = 8.3 \pm 0.4$ (syst).

The evolution of the charged-particle pseudorapidity density per participant pair with the centre-of-mass energy is shown in Fig.10, for central nucleus-nucleus collisions and for non single
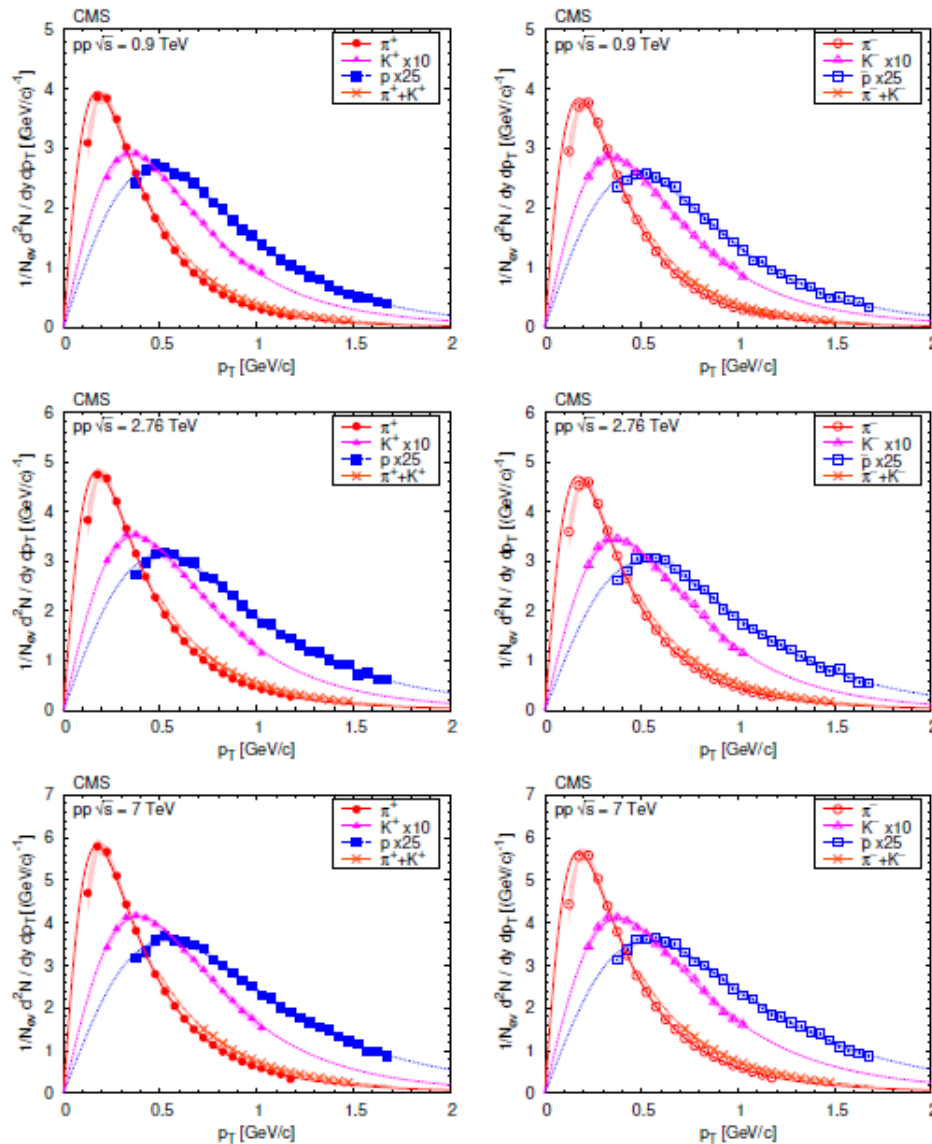
Figure 8. Transverse momentum spectra of identified hadrons measured at 0.9, 2.36 and 7 TeV by the CMS Collaboration [13].

diffractive pp collisions. Solid lines in this plot show the curves $(s_{NN})^n$, where the exponent n is larger (0.15) for nucleus-nucleus and smaller (0.11) for pp collisions, demonstrating a steeper energy dependence for heavy ion collisions. Comparing this value to that obtained for pp and $p\bar{p}$ collisions at similar energies, an increase by a factor 1.9 is observed.

An increase of a factor 2.2 is instead observed when comparing such value to those previously measured at RHIC for Au-Au collisions at a centre-of-mass energy $\sqrt{s}_{NN} = 0.2$ TeV.

The observed value of this quantity was compared to the various predictions which were available prior to obtain the LHC data, following their tuning to RHIC data at 0.2 TeV (fig.11). Some of them, based on the HIJING model tuned to pp data at 7 TeV, on the dual parton model or on the ultra-relativistic quantum molecular dynamics model, are consistent with the measurement. Other models exhibit various levels of agreement, with several of them sensibly underestimating the experimental result, and a hydrodynamical model, with a scaling of the
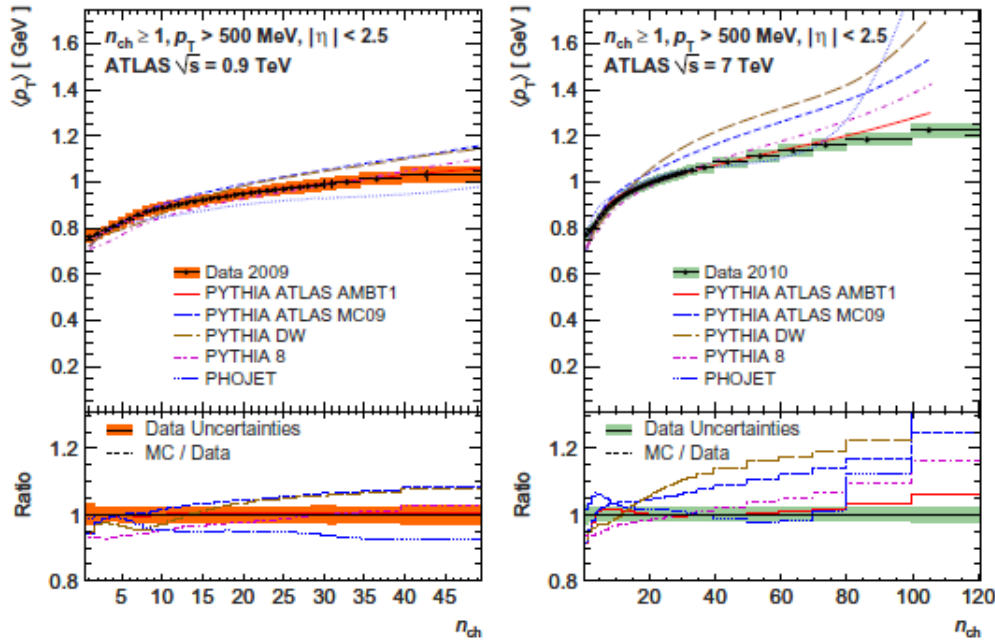
Figure 9. Average transverse momentum as a function of the charged particle multiplicity, as reported by the ATLAS Collaboration [8].
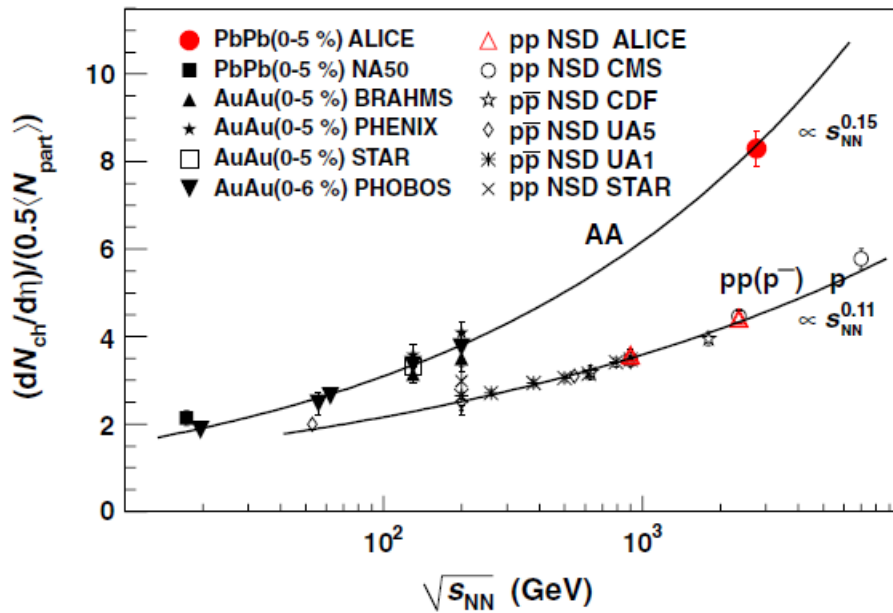

Figure 10. Charged-particle pseudorapidity density per participant pair as a function of $\sqrt{s}_{NN}$, for central nucleus-nucleus collisions and nonsingle diffractive pp and $p\bar{p}$ collisions [14].

multiplicity from pp collisions, strongly overestimating the result.

Heavy ion collisions may be characterized by centrality, thus allowing to extend the understanding of the contribution of hard and soft processes to particle production. It is thus important to measure the dependence of the charged particle multiplicity upon the centrality.
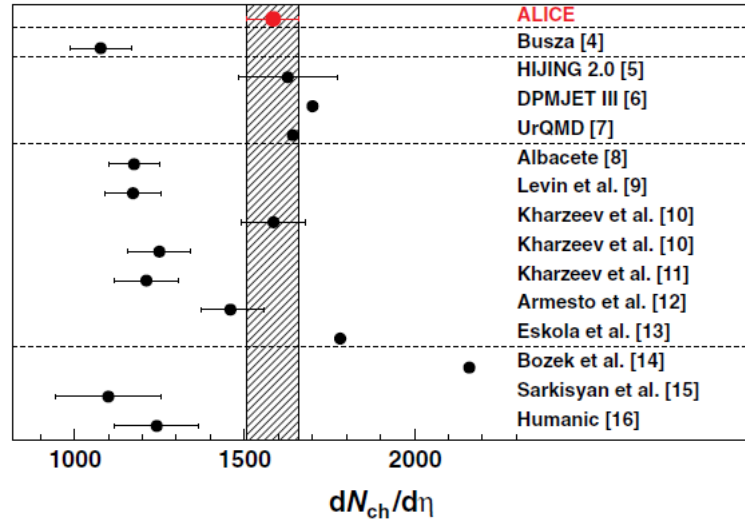
Figure 11. Comparison of the experimental value of the charged-particle pseudorapidity density, as obtained by the ALICE Collaboration [14], to the existing theoretical predictions available at the time.
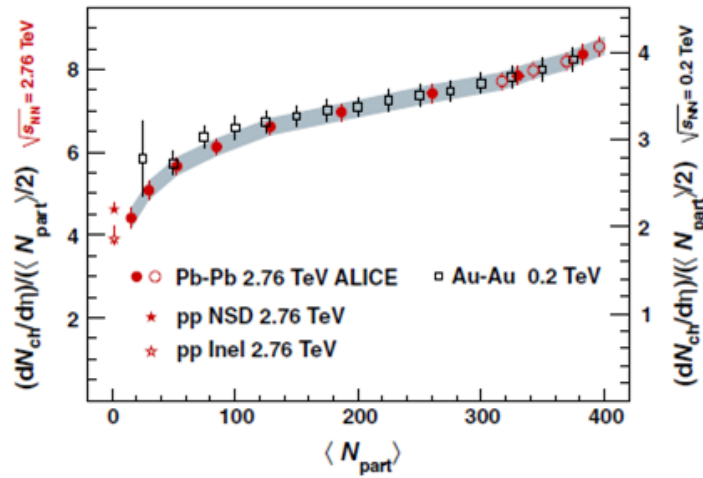

Figure 12. Dependence of $(dN_{ch}/d\eta)/(< N_{part} > /2)$ on the number of participants, for Pb-Pb collisions at $\sqrt{s}_{NN} = 2.76$ TeV (ALICE Collaboration [15]), compared to Au-Au data at $\sqrt{s}_{NN} = 0.2$ TeV from RHIC.

This has been done by the ALICE Collaboration [15] by appropriate selection of the collision events into nine centrality classes, covering the most central 80 % of the hadronic cross section. As it is seen in Fig.12, the charged-particle density per participating nucleon pair increases by a factor 2 when going from peripheral to central collisions, and its trend is similar to that observed at lower centre-of-mass energy. A comparison to different theoretical predictions shows that some models (HIJING 2.0, or different versions of saturation models), which were tuned after the most central $(dN_{ch}/d\eta)$ value was published, reasonably reproduce the trend.

6. Conclusion

Systematic measurements of the main features of particle production in the new energy regime of the Large Hadron Collider have been undertaken by all major LHC Collaborations, for proton-proton and heavy ion collisions. Charged-particle multiplicities have been extracted from the analysis of collision events at different centre-of-mass energies, and in different pseudorapidity regions. Multiplicity distributions have been reported, with a high statistics, such as to observe high-multiplicity events even in pp collisions at midrapidity. Forward rapidity distributions have been measured as well, up to η=4.5. Moreover, the pseudorapidity distributions have been measured in a wide pseudorapidity range and under different trigger conditions. Transverse momentum spectra of charged (positive and negative) hadrons have been measured as well, in a huge momentum range, and the average transverse momentum extracted as a function of the particle multiplicity. Concerning heavy ion collisions, the very first Pb-Pb data have made it possible to measure the charged particle multiplicity, which was one of the expected new results at LHC, allowing to characterize the collision dynamics. Also differential results, as a function of the centrality, have been already obtained.

As a result of these new experimental findings, a lot of efforts has been put to provide a systematic comparison to model predictions, either tuned on the old RHIC results or on the basis of the first LHC pp data, and this has given new inputs for an improvement of the theoretical descriptions.

Work is still in progress however on the experimental aspects of the understanding of the detailed features of particle production at LHC. Additional data analysis is in progress by all the Collaborations to extend the systematics to identified hadrons and to other particle species, such as those particles which are reconstructed through their decay. The pilot run on pPb collisions, which will be extended in 2013, is believed to provide a lot of new data helpful to understand the transition between pp and nucleus-nucleus collisions. A corresponding effort will be put on the improvement of the existing theoretical descriptions of the collision dynamics. This will help to understand the particle production mechanisms at high energy in the overall context of the properties of matter under extreme conditions.

7. References

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