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Chapter 14

ALICE upgrades for the high-luminosity heavy-ion programme

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1. High-luminosity heavy-ion programme

The successful heavy-ion campaign with different collision systems during LHC Runs 1 and 2 has produced many new results improving our understanding of the quark–gluon plasma, see Ch. 5. Despite the significant progress, many fundamental questions about its nature remain open and require new and/or refined measurements. The areas we lack knowledge in include: the properties of the initial stage (e.g. temperature and chiral symmetry restoration), the nature of the interaction of high-energy partons with the plasma, the mechanisms of equilibration in the plasma, and the transition of partons to hadrons (hadronisation). The unique potential of the LHC to study the hottest and longest-lived quark–gluon plasma available in the laboratory, with large heavy-flavour abundances at vanishing baryo-chemical potential, calls for an extensive heavy-ion programme in future runs. Further experimental progress relies on improved detector performance in combination with the accumulation of larger data samples. This has motivated upgrade programmes for both the accelerator and the experiments.

Until Run 2, the instantaneous Pb–Pb luminosities were limited to $\sim$8 kHz by the acceptable rate of bound-free pair production in the LHC. With the upgrade of the collimation system during LS2, Pb–Pb interaction rates of $\sim$50 kHz become possible, now limited by the bunch intensities available from the injector chain. This will allow the accumulation of an integrated Pb–Pb luminosity of $\sim 13\,\mathrm{nb}^{-1}$ during the course of Runs 3 and

4. To arrive at even larger data samples, possible measures to increase the available bunch intensities are studied for Runs 5 and 6, including the option of lighter ions to mitigate space charge effects in the SPS and LEIR.

Significant upgrades of the experiment are required to benefit from the increased instantaneous luminosities and to meet the requirements on the detector performance, e.g. the pointing resolution needed for secondary vertexing. Many measurements rely on the extraction of a signal on top of combinatorial background. The resulting need to record all collisions without trigger or event selection has driven the major upgrade to ALICE 2, which has been installed during LS2, see Sec. 2. Some further extensions (ITS3, FoCal) are planned for installation during LS3, see Sec. 3. Recently, ALICE 3 has been conceived and proposed as the next-generation heavy-ion experiment for Run 5 and 6, see Sec. 4.

2. ALICE 2 (Run 3)

The needs for the measurements of dielectrons and heavy-flavour hadrons in Runs 3 and 4 have driven the conception of the LS2 upgrades with the recording of all collisions with improved vertex reconstruction as a core requirement.[1] The upgrades were completed within budget and on schedule for the start of Run 3,[2] leading to the experimental setup shown in Fig. 2. The Time Projection Chamber (TPC) constitutes the main tracking detector. At interaction rates of 50 kHz, every drift time interval of ∼100 µs contains an average of 5 collision. As such, the TPC has to be read out continuously. This was made possible by replacing the MWPC-based read-out chambers with new chambers based on GEM foils, which limits the ion backflow to about 1 %, hence no gating is required to suppress the accumulation of space charge in the drift volume.[3,4]

In order to improve the pointing resolution, a thinner and lighter Inner Tracking System (ITS2) was constructed.[5] With an active area of $\sim 10\,\mathrm{m}^2$ equipped with ALPIDE sensors,[6] it is the largest tracker based on CMOS monolithic pixel sensors. The three innermost layers, with radii of 23 mm, 31 mm and 39 mm, each consisting of material corresponding to 0.35 % of a radiation length, form the inner barrel, which improves the pointing resolution by a factor of 3. The outer barrel is composed of two times two layers and covers the radii up to the inner radius of the TPC.

The muon system has seen a complete overhaul of the readout electronics and some consolidation on the detectors. It has been further extended by the Muon Forward Tracker (MFT), an assembly of 5 tracking disks installed on the muon side close to the interaction point. The detector is based on the same ALPIDE sensor developed for the ITS2 and allows the propagation of muon tracks to the primary vertex.

In addition, a new Fast Interaction Trigger (FIT) has been installed, which serves as interaction trigger, online luminometer, indicator of the vertex position, and forward multiplicity counter. It comprises two arrays of quartz Cherenkov radiators (FT0-A/C), a large, segmented scintillator disk (FV0), and two arrays of scintillator pads (FDD).

In addition to consolidation work, all detectors have upgraded their readout to either implement continuous readout or increase the trigger rates. The change of the readout paradigm from triggered to continuous operation has also required a completely new approach to the data processing. An integrated online-offline software framework has been developed to receive and process the incoming data. The detector data arrive at the so-called First-Level Processors (FLP) at a rate of $\sim 3.5\,\mathrm{TB\,s^{-1}}$, where they are pre-processed (e.g. zero-suppressed) and then sent to Event Processing Nodes (EPN) at a rate of about $\sim 600\,\mathrm{GB\,s^{-1}}$. The EPN farm comprises 2000 GPUs in 250 nodes to run the synchronuous reconstruction, whose output is stored on grid storage at a rate of $\sim 100\,\mathrm{GB\,s^{-1}}$. The output of a subsequent aynchronuous reconstruction pass, running on the LHC computing grid with improved calibration input, then forms the basis for the physics analyses.

The upgraded detector will enable new measurements during the course of Runs 3 and 4, which will also add pO and OO to the already established collision systems (pp, p–Pb, Pb–Pb). The prospects and expected physics performance have been discussed extensively in the report on the physics prospects at the HL-LHC.[7]

3. ALICE 2.1 (Run 4)

A further upgrade of the inner barrel of the ITS (ITS3) and the installation of a Forward Calorimeter (FoCal) are under preparation for installation during LS3 and operation in Run 4.

The ITS3 project aims at enhancing the physics capabilities for the measurements of dielectrons and heavy-flavour probes by further improving the pointing resolution. The notion that the active silicon constitutes only about 15 % of the material in the three innermost layers of the ITS2 motivates their replacement with wafer-scale, cylindrical sensors without external services and almost no support structures.[8] As part of the R&D

activities, it has already been shown that thinned silicon wafers ($\leq$50 µm) can be bent and stabilised in the form of half-cylinders with very little support material (carbon foam). Furthermore, it has been demonstrated that the performance of ALPIDE sensors is unaffected by the bending.[9] The ongoing R&D studies aim at establishing the production of wafer-scale sensors through the stitching of repeated sensor units in the Tower 65 nm CIS process. Together with the reduced power density and cooling by a forced air flow, this allows the construction of an ultra-lightweight detector consisting only of the silicon cylinders and carbon foam wedges in the active area resulting in $\sim$0.05 % of a radiation length per layer. In combination with the reduction of the beam pipe radius and thickness as well as the inner radius of the first ITS3 layer, this will further improve the pointing resolution as well as reduce the conversion probability in the first layer, see Fig. 1.

A central objective of the FoCal project is to constrain the gluon PDFs down to very low $x \approx 10^{-5}$. This can be achieved by measuring isolated (non-decay) photons in the pseudo-rapidity region $3.4 < \eta < 5.8$. To this end, a highly granular electromagnetic calorimeter will be combined with a hadronic calorimeter. The former is based on a stack of tungsten absorber plates with silicon pixel and silicon pad layers for read-out. This provides excellent resolution for the shower profile and two-photon separation. The hadronic calorimeter will be based on copper tubes with integrated scintillating fibres. The impact of the detector on the measurement of the gluon PDFs is shown in Fig. 1.

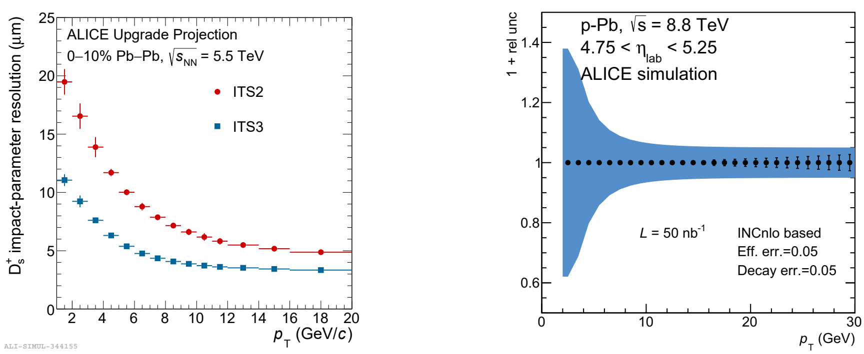

Fig. 1. ALICE 2.1 performance. Left: Improvement of pointing resolution with ITS3. Right: Relative uncertainties for the measurement of the ratio of isolated photons produced in p–Pb and pp collisions.[10]

4. ALICE 3 (Runs 5 and 6)

Two key challenges of the heavy-ion programme of LHC Runs 5 and 6 are the multi-differential measurement of dielectrons and the systematic measurement of (multi-)heavy-flavoured states.[11] The former is crucial for understanding the time dependence of thermal electromagnetic emission from the plasma and the mechanisms responsible for chiral symmetry restoration. This requires the measurement of a very clean electron sample down to low transverse momenta and the effective rejection of electrons from background processes, such as weak decays of heavy-flavoured hadrons and photon conversion before the first detection layer. The goal of the heavy-flavour programme is to understand the transport properties of the quark-gluon plasma, the mechanisms of equilibration in the plasma, and the effects relevant for the formation of hadrons. For the latter, multi-charmed hadrons are of particular interest since they are expected to show enhancements by orders of magnitude if the charm quarks (produced independently in early hard scatterings) can combine. The measurement of heavy-flavoured probes demands the best possible pointing resolution for the reconstruction of the decay vertices in combination with the highest possible statistics, which in turn requires a large acceptance of the detector. The latter is also required for the measurement of correlated charm production and the measurement of the pseudo-rapidity dependence. A further goal is the systematic measurement of hadron-hadron correlations in the charm sector to extract the interaction potentials of the strong interaction and the nature of (exotic) bound states. In addition to these pillars of the physics programme, there is a wide area of additional topics, including the measurements of baryon fluctuations, jet substructure, ultra-soft photons as well as searches for beyond the standard model phenomena.

The physics programme cannot be carried out at any other existing or planned experiment and defines the main experimental requirements. Foremost, the detector must provide good tracking and particle identification over a large acceptance and down to very low transverse momenta ($<100\,\mathrm{MeV}/c$). Excellent pointing resolution is required for background rejection and the reconstruction of the decay chains of heavy-flavoured probes. The detector is further optimised for the required high interaction rates and the resulting hit densities as well as radiation load.

These requirements have led to the detector concept shown in Fig. 2. Charged particle tracking in a magnetic field is realised by an all-silicon tracker arranged in barrel layers and forward disks in a cylindrical volume

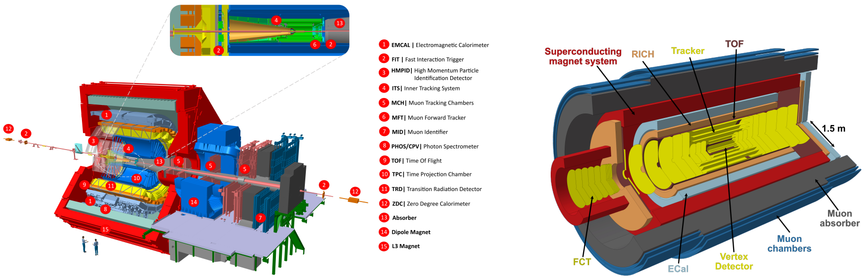

Fig. 2. Left: Overview of the ALICE 2 detector for Run 3, the insert shows the inner tracking system and the muon forward tracker (refer to the text for further details).[2] Right: Overview of the ALICE 3 concept with the planned detector systems.[11]

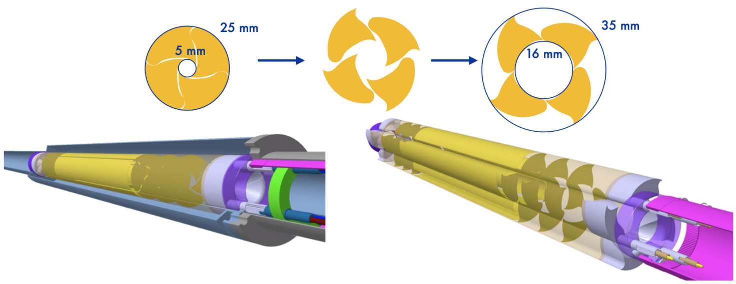

Fig. 3. Conceptual study of an iris-like mechanics for the retractable vertex detector.

of $R \approx 80\,\text{cm}$ and $L = \pm 4\,\text{m}$. This poses the challenge to minimise the material over a large surface in order to achieve the best possible momentum resolution. The magnetic field is provided by a superconducting magnet system, for which the coil configuration can be optimised starting from the baseline of a solenoidal coil providing $B = 2\,\text{T}$. To achieve the required pointing resolution, a vertex detector is proposed for installation inside the beam pipe to measure the first hit as close as possible to the interaction point, i.e. at a radius of $\sim$5 mm. While such a small aperture is possible at the LHC's top energy, a larger aperture of $\sim$16 mm is required at injection energy. This implies the need for a retractable detector, for which the concept of an iris-like mechanism is studied, see Fig. 3. The tracker is complemented by a particle identification system comprising time-of-flight and RICH detectors to cover the low-to-intermediate transverse momentum range. The former consists of an inner and outer barrel layer as well as a forward disk on both sides of the experiment, all of which are equipped with silicon timing sensors providing a TOF resolution of 20 ps. The RICH detectors, based on aerogel radiators and silicon photon sensors, are installed behind the outer TOF layers. The system is further extended by an electromagnetic calorimeter covering the area of the central barrel and one endcap. In addition to the instrumentation with Pb-scintillator technology, a high-resolution segment is equipped with PbWO4 crystals for measurements of photons at very low energies. Outside of the magnet system, a hadron absorber is installed and followed by two layers of muon chambers for the identification of muons. A dedicated forward conversion tracker allows the measurement of photons at very low transverse momenta, making use of the Lorentz boost in the forward direction.

Two flavours of pixel sensors will be optimised for use in the vertex detector and the outer tracker. While the former requires high spatial resolution (∼2.5 µm) on wafer-scale sensors, the latter requires a sensor with moderate spatial resolution (∼10 µm) that is optimised for high yield and power consumption. In both cases a time resolution on the order of 100 ns is required. As baseline the technology node of the ITS3, i.e. the Tower 65 nm CIS process, is pursued but alternatives could be considered. For the silicon timing sensors, the primary goal is to implement a gain layer in monolithic CMOS sensors. Alternatively, LGADs or SPADs could be considered as sensors. For the photon detection in the RICH detector, a monolithic implementation of SPADs is targeted. The proposed detector is based on technologies of general interest for particle detectors and the R&D programme is relevant for the field at large.

The performance of ALICE 3 has been studied for the running scenario of six years of Pb–Pb collisions over the course of Runs 5 and 6.[11] Figure 4

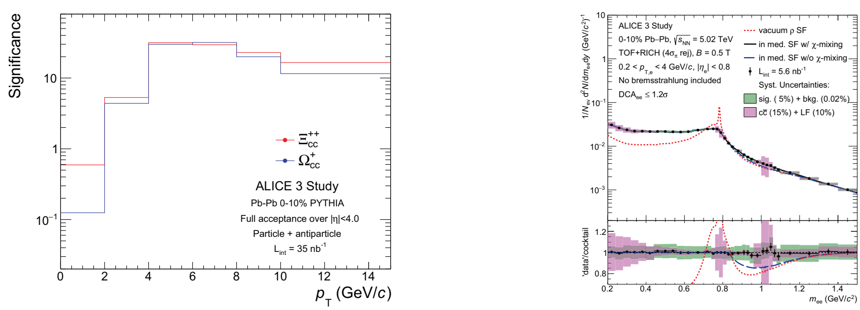

Fig. 4. ALICE 3 physics performance.[11] Left: Significance of multi-charm reconstruction using strangeness tracking. Right: Dielectron invariant mass spectrum.

shows the expected performance for the measurement of multi-charm states and the invariant mass spectrum of dielectrons.

5. Conclusions

The continued heavy-ion programme is an important aspect of the full exploitation of the LHC physics potential. With the upgrades for Runs 3 and 4, there are excellent prospects for new results over this decade. Beyond that, the ALICE 3 programme provides a roadmap for exciting heavy-ion physics in the 2030s with a novel and innovative detector concept.

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