ALICE 3: A next-generation heavy-ion detector for LHC Run 5

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Abstract. The ALICE Collaboration has proposed a completely new apparatus, ALICE 3, for the LHC Run 5. The detector consists of a large pixel-based tracking system covering eight units of pseudorapidity, complemented by multiple systems for particle identification, including silicon time-of-flight layers, a ring-imaging Cherenkov detector, a muon identification system, and an electromagnetic calorimeter. A track pointing resolution better than 10 microns for $p_{\mathrm{T}} > 200$ MeV/c can be achieved by placing the vertex detector on a retractable structure inside the beam pipe. ALICE 3 will, on the one hand, enable novel studies of the quark-gluon plasma and, on the other hand, open up important physics opportunities in other areas of QCD and beyond. The main new studies in the QGP sector focus on low-p_{T} heavy-flavour production, including beauty hadrons, multi-charm baryons and charm-charm correlations, as well as on precise multi-differential measurements of dielectron emission to probe the mechanism of chiral-symmetry restoration and the time-evolution of the QGP temperature. Besides QGP studies, ALICE 3 can uniquely contribute to hadronic physics, with femtoscopic studies of the interaction potentials between charm mesons and searches for nuclei with charm, and to fundamental physics, with tests of Low's theorem for ultra-soft photon emission. This contribution will cover the latest detector concept, the state-of-the-art physics performance, and the status of the detector R&D.

1 Introduction

The ALICE Collaboration is proposing a new apparatus, ALICE 3, for LHC Phase IIb Run 5 to investigate the quark gluon plasma (QGP) properties beyond current limits. Despite the rich planned physics programme enabled by the current Run 3 upgrade (ALICE 2) and the forthcoming Run 4 upgrade (ALICE 2.1), fundamental questions regarding our understanding of the underlying dynamics of the QGP will remain open, calling for a next-generation experiment featuring substantial advances in detector performance, acceptance and rate capability. Following the submission of a Letter of Intent in 2022 [1], the ALICE 3 concept necessary to achieve the target scientific programme was refined in the recently published Scoping Document [2]. This paper is organised as follows. Section 2 summarises the ALICE 3 key physics goals and observables. The baseline detector concept is presented in Section 3, followed by projections on ALICE 3 physics performance in Section 4. Finally, Section 5 outlines the status of the R&D activities on the different ALICE 3 subsystems.

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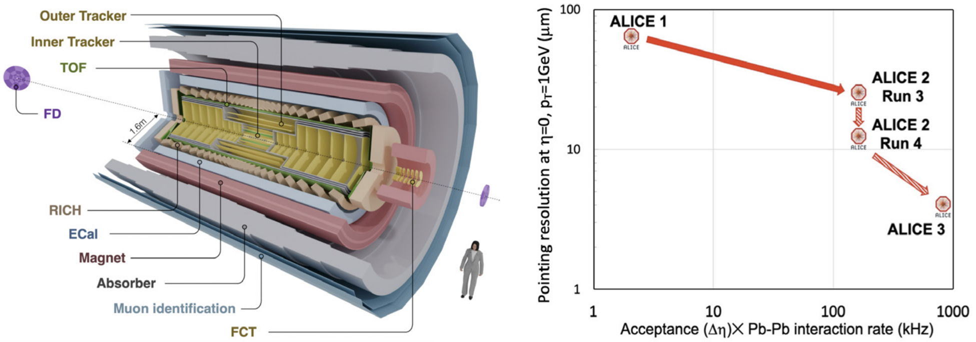

Figure 1. Left: ALICE 3 state-of-the-art detector concept. Right: Improvement of pointing resolution at $p_{\mathrm{T}} = 1$ GeV/c and $\eta = 0$ and expected effective statistics in Pb-Pb from ALICE 1 to ALICE 3.

2 ALICE 3 physics goals

The key ALICE 3 physics goals include understanding the thermalisation of heavy quarks in the QGP, accessing the QGP time evolution with thermal radiation, characterising the cross over to the hadronic phase and probing chiral symmetry restoration in the medium. The ALICE 3 design is thus optimized for measurements of low transverse momentum (p_{T}) heavy-flavour production, including charm-charm correlations, multi-charm baryon and beauty hadron production, as well as multi-differential measurements of dileptons, including invariant-mass spectra, their transverse momentum dependence and azimuthal anisotropy, and net-quantum number fluctuations over a large rapidity range. Besides QGP studies, ALICE 3 also addresses open questions on hadronic physics, with unique contributions to femtoscopic studies of the interaction potentials between charm mesons and searches for nuclei with charm, and fundamental physics, with tests of Low's theorem for ultra-soft photons.

3 ALICE 3 detector concept

The measurements outlined in Section 2 set requirements on vertexing, tracking, particle identification (PID) and rate capabilities, leading to the baseline ALICE 3 detector concept shown in the left panel of Fig. 1. The proposed detector is based on a silicon pixel tracking system with unique pointing resolution over eight units of pseudorapidity ($|\eta| < 4$) embedded in a superconducting solenoidal magnet providing a 2 T field. The tracker is complemented by multiple subsystems for PID, including silicon time-of-flight layers (TOF), a ring-imaging Cherenkov detector (RICH), an electromagnetic calorimeter (ECal), a muon identification system including a hadron absorber and muon detection chambers (MID) and a forward photon conversion tracker (FCT) for ultra-soft photon detection. Forward detectors (FD) for event characterisation are also planned. The leading requirements are a pointing resolution better than 10 μm for $p_{\mathrm{T}} > 200$ MeV/c, achieved by installing the vertex detector (VD) layers on a retractable structure in secondary vacuum inside the beam pipe, and relative p_{T} resolution of 1% at midrapidity, achieved with a tracker outer radius of 80 cm. The outstanding improvement by orders of magnitude in terms of both pointing resolution and effective statistics from ALICE 1 (Runs 1-2) to ALICE 3 is shown in the right panel of Fig.1. For charged PID, the TOF, the RICH and the MID systems are designed to achieve an overall better than 3σ e/π, π/K and K/p separation up to 3, 10 and 17 GeV/c momentum, respectively, and efficient muon detection down to $p_{\mathrm{T}} \approx 1.5$ GeV/c. This drives the leading requirements for a time resolution down to 20 ps for the TOF layers, and radiators with a refractive index of 1.03 in a configuration providing an angular resolution down to 1.5 mrad for the RICH layer.

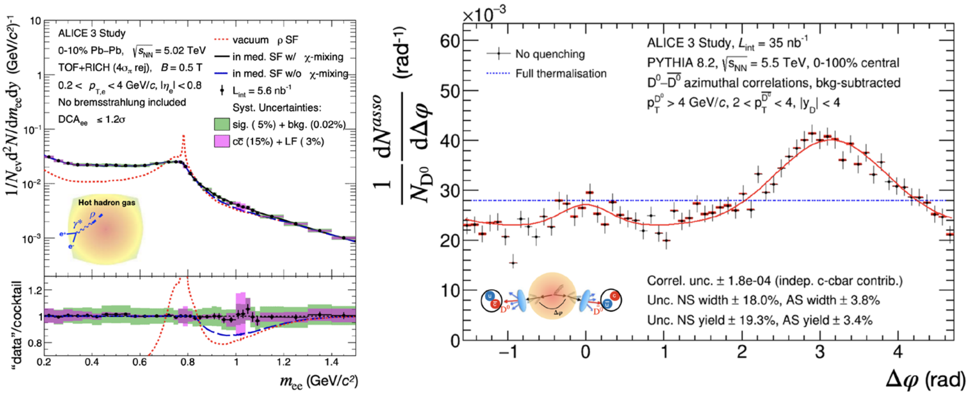

Figure 2. Left: Simulated background-subtracted m_{ee} spectrum in central (0-10%) Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV using the expected ρ SF in medium under the hypothesis of ρ-a_1 mixing compared with expectations for the ρ SF in vacuum and in medium without mixing. Right: Simulated $D^0\bar{D}^0$ azimuthal correlation distribution in minimum-bias Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.52 TeV. A comprehensive discussion of the statistical and systematic uncertainties is provided in [1].

4 ALICE 3 physics performance

In this section, the projections of the baseline detector specifications on a selection of dielectron and heavy-flavour correlation measurements crucial for the ALICE 3 physics programme are reported. The left panel of Fig 2 shows the expected background-subtracted thermal dielectron invariant mass (m_{ee}) spectrum for central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02. The dielectron spectral function (SF) in the ρ^0 mass region is directly sensitive to the manifestation of chiral symmetry restoration via mixing of vector and axial vector mesons (ρ-a_1 mixing [3]). The improvements offered by the ALICE 3 design are expected to provide the unprecedented precision required to observe the predicted effect at 3σ level. The right panel of Fig. 2 shows the ALICE 3 projection for $D^0\bar{D}^0$ azimuthal correlations for minimum-bias Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.52 TeV. The angular correlation of heavy-flavour hadrons pairs is a powerful probe of the degree of thermalization of heavy-quarks in the medium. This measurement in heavy-ion collisions will be out of reach in LHC Runs 3 and 4, since it requires excellent pointing resolution and identification purity, as well as large η acceptance, and it will be only possible with the target specifications of the ALICE 3 upgrade.

5 ALICE 3 R&D status and plans

A primary focus of the R&D programme for the various ALICE 3 subsystems is the selection of the technologies. The baseline technology for the tracker and the FCT layers are CMOS Monolithic Active Pixel Sensors (MAPS) based on the 65 nm CMOS imaging process. For the TOF sensors, Low Gain Avalanche Diodes (LGADs), both monolithic in CMOS technology and hybrid, and Silicon Photomultipliers (SiPMs) are under study, with CMOS LGADs being the baseline. The RICH design is based on aerogel tiles as Cherenkov radiators and SiPM-based photodetector modules. The ECal concept is based on Pb-scintillator sampling technology and includes a high-energy resolution segment based on $PbWO_4$ crystals at midrapidity with SiPM readout. The MID consists of a steel hadron absorber followed by dedicated muon chambers made of scintillator bars readout using SiPMs. Alternative options to scintillators, based on Multi-Wire Proportional Chambers (MWPCs) and Resistive Plate Chambers (RPCs) are also under study. For the superconducting magnet, various options for the superconducting cable are under investigation, with Al-cladded Nb-Ti Rutherford cable

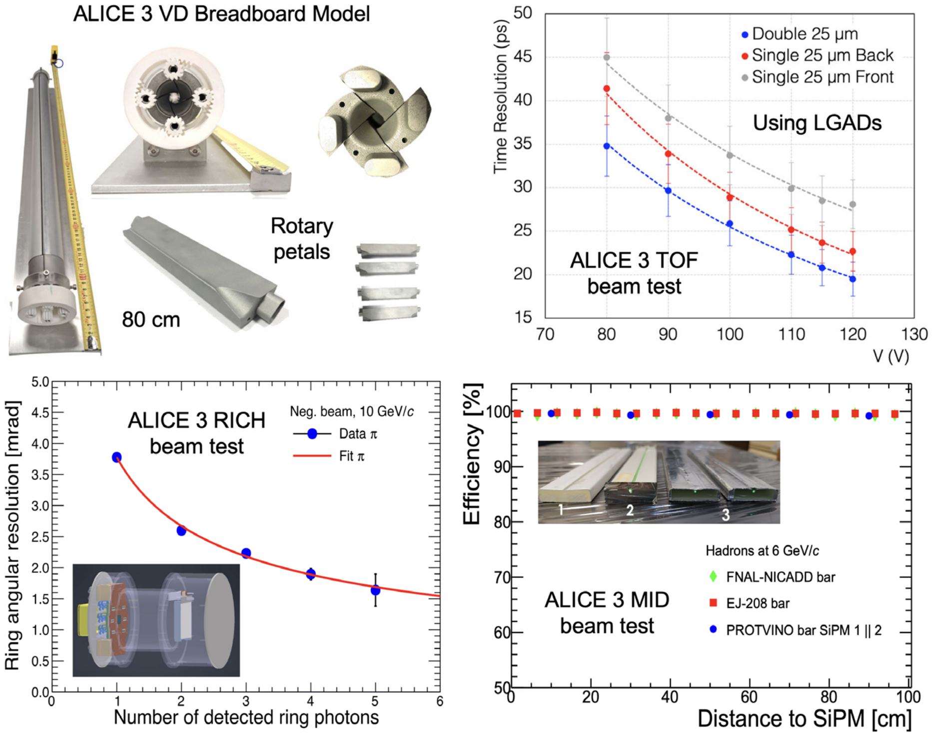

Figure 3. Top left: Breadboard model of the ALICE 3 retractable vertex detector. Top right: TOF beam test results for the intrinsic time resolution measured as a function of the voltage applied achieved using single and double LGADs having a thickness of 25 μm [4]. Bottom left: RICH beam test results for the ring angular resolution measured as a function of the number of detected photons with pions at 10 GeV/*c* for a RICH prototype [5]. Bottom right: MID beam test results for detection efficiency measured as a function of the distance to SiPM using 1 m long scintillator bars from various producers [6].

being the baseline. Alternative ALICE 3 layouts without the ECal and featuring a reduced magnet radius, as well as operation with reduced field strength, are under study as scoping options with a reduced cost. Mechanical aspects are also a key part of the R&D effort, particularly for the integration of the VD in secondary vacuum inside the beam pipe, together with the industrialization of the module concepts, especially for the outer tracker layers. Radiation tolerance studies are being conducted to ensure that the selected technologies can sustain the expected radiation levels throughout ALICE 3 operation. Proof-of-concept prototypes are being designed, constructed, and evaluated in dedicated beam test campaigns. Fig. 3 shows the components of a breadboard model with rotory petals developed for the retractable VD, together with beam test results for the TOF, RICH and MID systems validating the target intrinsic time resolution, ring angular resolution and detection efficiency, respectively, with the present technologies.

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