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Physics programme of the ALICE 3 experiment for the LHC Runs 5 and 6

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Abstract. Ultrarelativistic heavy-ion collisions are used to study the physics of strongly interacting matter under extreme conditions, similar to those of the early universe. In such collisions a deconfined state of quarks and gluons, the quark-gluon plasma (QGP), is formed. Nuclear collisions at the LHC provide access to the highest-temperature, longest-lived experimentally accessible QGP. After three years of Long Shutdown and intensive installation of detector and accelerator upgrades, ALICE is about to take data at a peak Pb–Pb collision rate of 50 kHz to further characterize the properties of the QGP. Even after the ambitious scientific programme for the upcoming Runs 3 and 4, open questions will remain. Therefore, a next-generation LHC heavy-ion experiment ALICE 3 is proposed for the 2030s. It should give access to next-level measurements of electromagnetic probes and heavy-flavour hadrons, including multi-charm states and exotic hadrons, inaccessible in the LHC Runs 3 and 4.

1 Introduction

ALICE (A Large Ion Collider Experiment) is a general-purpose heavy-ion experiment at the CERN LHC. Its main goal is to study the properties of the quark-gluon plasma (QGP) created in such collisions. After a major upgrade of the detector to ALICE 2, the LHC Run 3, starting in 2022, will give further insight into the properties of the QGP [1]. Despite the rich planned scientific programme, fundamental questions will still remain open beyond Run 4, like the QGP properties driving its constituents to equilibration, the hadronisation mechanisms of the medium, the partonic equation of state and its temperature dependence, and the underlying dynamics of chiral symmetry restoration. To answer such questions, precision differential measurements of dileptons, systematic measurements of (multi-)heavy-flavoured hadrons down to low transverse momentum (p_{T}), and hadron interaction and fluctuation measurements are crucial. They require qualitative improvements in detector performance and statistics, calling for a next-generation heavy-ion experiment ALICE 3 [2].

2 ALICE 3 detector concept

A sketch of ALICE 3 is shown in Fig. 1. It consists of a compact all-silicon tracker with high-resolution vertex detector placed in a superconducting magnet system. Additional detectors are included to identify γ, $e^{\pm}$, $\mu^{\pm}$, $K^{\pm}$ and $\pi^{\pm}$ over a large pseudo-rapidity acceptance ($-4 < \eta < 4$). The full set-up could be installed inside of the current ALICE L3 magnet and

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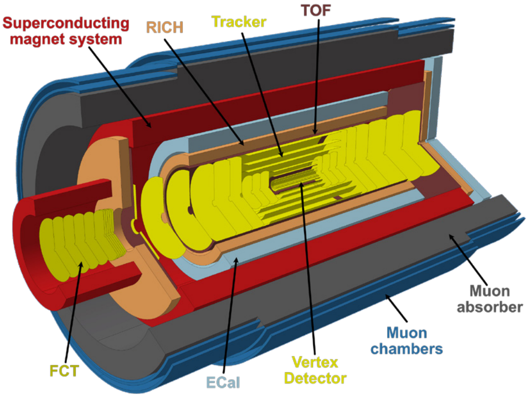

Figure 1. Sketch of the ALICE 3 set-up [2].

collect data during 6 years with one month per year of heavy-ion data taking. The inner tracker is made of three layers of curved wafer-scaled ultra-thin silicon sensors positioned inside the beam pipe [2], featuring an unprecedented low material budget. To provide the required pointing resolution, the first layer is placed at a radius of 5 mm from the beam axis during data taking, thanks to a retractable vertex detector. R&D challenges concern mechanical supports, cooling and radiation tolerance. To illustrate the overall improvement in detector capabilities, the left panel of Fig. 2 shows the expected detector pointing resolution and effective expected statistics of heavy-ion collisions for ALICE 1 (Runs 1 and 2), ALICE 2 (Run 3), ALICE 2.1 (Run 4) and ALICE 3 (Runs 5 and 6). Time-of-flight (TOF) detectors, ring-imaging Cherenkov (RICH) detectors, calorimeters (ECal), muon chambers and a forward conversion tracker (FCT) are foreseen to identify particles. Up to a few GeV/c, $e^{\pm}/pi^{\pm}$ separation will be provided with the TOF detectors, made of silicon sensors with $\approx$ 20 ps timing resolution, whereas for higher momentum the RICH detectors, using aerogel as radiator material, will complete the particle identification capabilities (see right panel of Fig. 2). The overall large total silicon surface requires cost-effective sensor development and automatisation of the detector production. More details on the foreseen technologies, the detector system and the R&D plans can be found in [2].

3 Physics goals and expected performance

3.1 Electromagnetic radiation

The hot medium created in heavy-ion collisions emits black-body radiation in form of real and virtual photons. The latter produce dilepton pairs. In Fig. 3, the expected invariant mass (m_{ee}) spectrum of thermal e^+e^- pairs produced in central Pb–Pb collisions at a center-of-mass energy per nucleon pair, $\sqrt{s_{\mathrm{NN}}}$, of 5.02 TeV and measured with ALICE 3 after one month of data taking is shown [2]. To achieve such statistical and systematic precision, very good electron identification is needed down to low p_{T} ($\geq$ 80 MeV) with a small detector material budget in order to reduce the combinatorial background from γ conversion and π^0 Dalitz decays. Moreover, the excellent pointing resolution of ALICE 3 is decisive to suppress efficiently the very large background from heavy-flavour hadron decays at LHC energies, in particular for $m_{\mathrm{ee}} \geq 1$ GeV/c^2 (see right panel of Fig. 3). In this m_{ee} region, the slope of the m_{ee} spectrum provides direct information about the temperature (T) of the QGP. Whereas

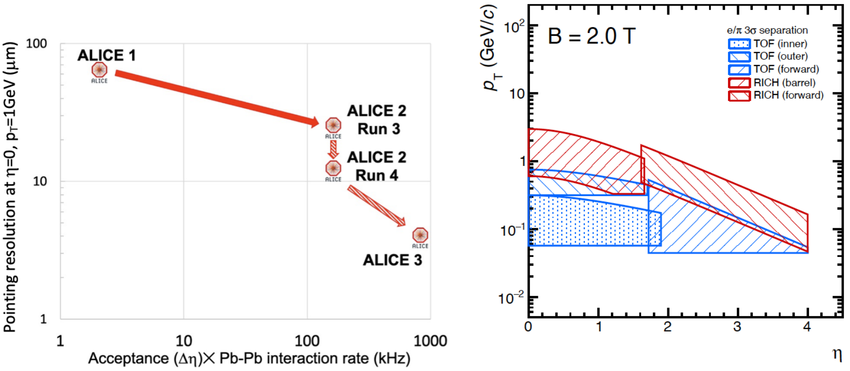

Figure 2. Left: Pointing resolution and effective expected statistics in heavy-ion collisions for ALICE 1, 2, 2.1 and 3 [2]. Right: 3σ separation between $e^{\pm}$ and $\pi^{\pm}$ with the sub-detectors in p_T and η [2].

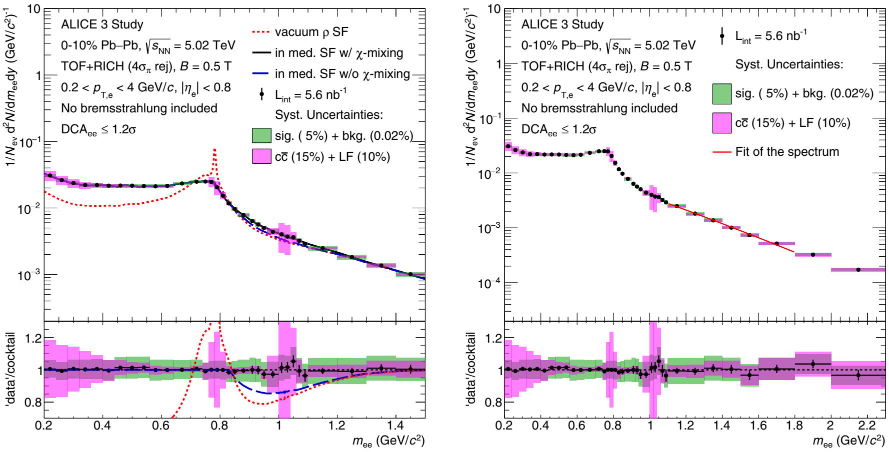

Figure 3. Simulated raw invariant mass spectrum of thermal dielectron from the QGP and hadron gas measured with ALICE 3 in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV after one month of data taking according to theoretical predictions from [3, 4] at low (left) and higher (right) masses [2].

first T measurements are expected with ALICE 2 (Runs 3 and 4), ALICE 3 will open up the possibility to probe the time dependence of T by extracting T as a function of mass or pair transverse momentum $p_{\mathrm{T,ee}}$, as shown on the left panel of Fig. 4. Similarly, the measurement of the thermal dielectron elliptic flow (labelled excess dielectron v_2 in the right panel of Fig. 4) would be for the first time statistically achievable with ALICE 3 as a function of m_{ee} and $p_{\mathrm{T,ee}}$. Such measurements probe the time evolution of the flow field and provide decisive inputs to the so-called photon puzzle, i.e. simultaneous understanding of the yield and v_2 of direct real photons also part of the ALICE 3 programme. Finally, the m_{ee} spectrum of thermal dielectrons at smaller m_{ee} ($m_{\mathrm{ee}} \leq 1.2$ GeV/c^2) is dominated by thermal production of ρ mesons. Their spectral function (SF) is modified in the hot medium where chiral symmetry restoration (CSR) is predicted. The expected high precision measurement of the m_{ee} spectrum

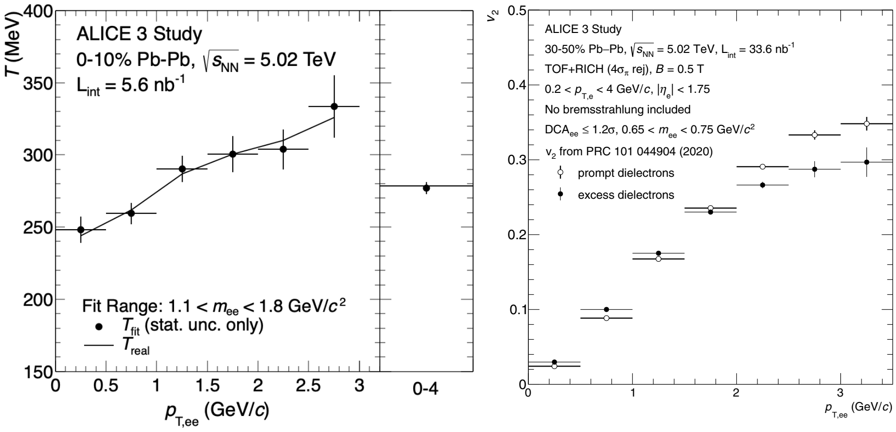

Figure 4. Left: Extracted temperature parameter T_{fit} from the simulated m_{ee} dielectron spectrum for different $p_{\text{T,ee}}$ intervals in central Pb–Pb collisions after one month of data taking with ALICE 3 [2]. Right: Projections for prompt and thermal dielectron v_2 measurements in $0.65 \leq m_{\text{ee}} \leq 0.75\,\text{GeV}/c^2$ with ALICE 3 in semi-central Pb–Pb collisions after six months of data taking [2].

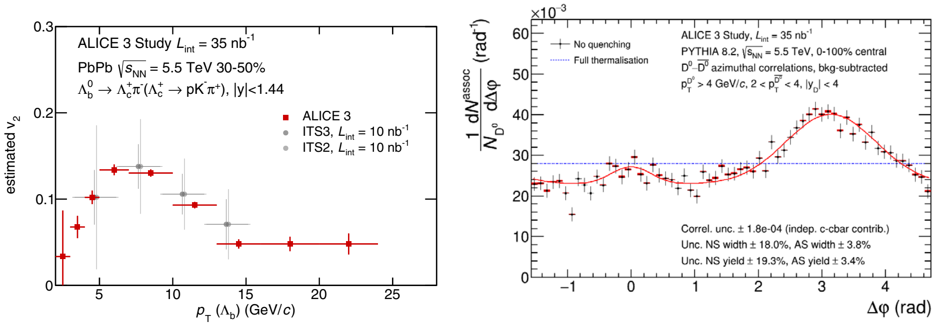

Figure 5. Left: Expected v_2 measurements of the Λ_b baryon with ALICE for Run 3 (ITS2), Run 4 (ITS3) and Runs 5 and 6 (ALICE 3) in semi-central Pb–Pb collisions [2]. Right: Simulated $\text{D}^0\bar{\text{D}}^0$ azimuthal correlation measurements with ALICE 3 in minimum-bias Pb–Pb collisions [2].

in central Pb–Pb collision with ALICE 3 (see left panel of Fig. 3) would allow the study of CSR mechanisms like $\rho - \text{a}_1$ mixing (denoted χ-mixing).

3.2 Heavy-quark transport and correlations

The (heavy-)quark transport properties in the QGP, i.e. the diffusion coefficients, can be extracted from precise nuclear modification factor and v_2 measurements of different charm and beauty hadrons down to low p_T to disentangle effects at the partonic level from those due to the hadronisation process. The left panel of Fig. 5 shows the expected performance for Run 3 (ITS2), Run 4 (ITS3) and Runs 5 and 6 (ALICE 3) for the Λ_b v_2 measurement. The particle identification capabilities, pointing resolution and acceptance of ALICE 3 give an unique access to the low p_T range.

The angular correlation of heavy-flavour hadron pairs is sensitive to the energy loss mechanisms and degree of heavy-quark thermalisation in the QGP, particularly at low p_T. In the

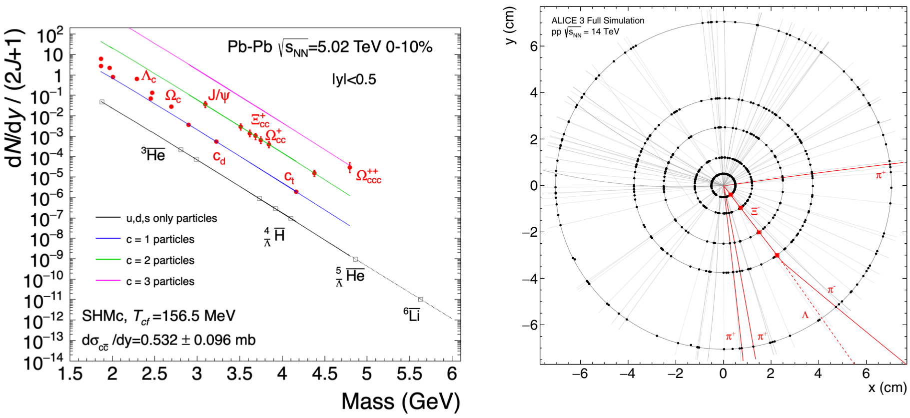

Figure 6. Left: Statistical-thermal model predictions for (anti-)(hyper-)nuclei (black) and (multi-)charm states (red) in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV [5]. Right: ALICE 3 strangeness tracking with the Ξ^{++}_{cc} decay into $\Xi^+_{\mathrm{c}} + \pi^+$ and the successive decay $\Xi^+_{\mathrm{c}} \rightarrow \Xi^- + 2\pi^+$ [2].

right panel of Fig. 5 the projection for $\mathrm{D}^0\bar{\mathrm{D}}^0$ azimuthal correlation measurement in minimum-bias Pb–Pb with ALICE 3 is presented for six years of data taking. Such measurements will not be in reach in heavy-ion collisions after Runs 3 and 4, since they require a high D^0 purity and reconstruction efficiency, as well as a large rapidity coverage.

3.3 Hadron formation

Multi-charm baryons are unique probes of the hadron formation mechanisms since they are expected to be produced essentially by combination of uncorrelated charm quarks in heavy-ion collisions. The yields of multi-charm baryons relative to the number of produced charm quarks are predicted to be significantly enhanced in heavy-ion relative to proton-proton collisions. In the statistical hadronisation model [5], the computed yield of hadron at a given mass scales with g^n_{c}, where g_{c} ($\approx$ 30) is the charm fugacity factor and n the number of constituent charm quarks in the state, as shown for central Pb–Pb collisions at the LHC on the left panel of Fig. 6. With ALICE 2, the measurement of (anti)-hypernuclei up to atomic number $A = 4$ and single-charm states should be in reach. A test of the full physical picture will be only possible with ALICE 3 by measuring additional states, i.e. hypernuclei with $A > 4$ and multi-charm states. With a first tracking layer at only 5 mm of the beam axis at mid-rapidity, strange baryons like Ξ^- can be directly tracked before they decay. This increases significantly the pointing resolution of the reconstructed strange baryon trajectory to the primary vertex, improving the ability to distinguish weak decays from primary or secondary sources. The latters are characteristic of multi-charm baryons, as depicted in the right panel of Fig. 6 with the tracking of the non-prompt Ξ^- strange baryon in the Ξ^{++}_{cc} decay chain. In the left panel of Fig. 7, the expected significances for Ξ^{++}_{cc} and Ω^+_{cc} in central Pb–Pb collisions are shown.

The nature of recently discovered exotic bound states, like T^+_{cc} [6], is still unclear. Molecular states or more compact objects like tetraquarks are both not excluded. Two particle momentum correlation measurement, e.g. between D^0 and D^{*+} for T^+_{cc}, can be used to search for possible DD bound states. The projections for such measurements with ALICE 3 in pp and Pb–Pb collisions for six years of data taking are shown in the right panel of Fig. 7. The very good pointing resolution and large acceptance of the detector would give the unique op-

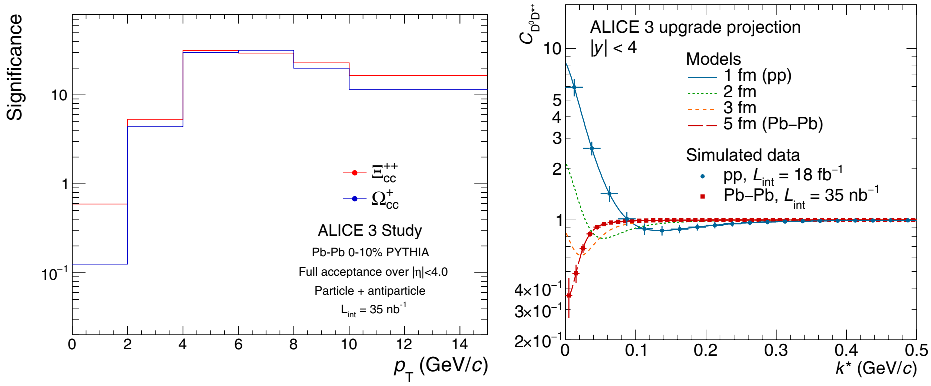

Figure 7. Left: Expected significance of Ξ_{cc}^{++} and Ω_{cc}^{+} measurements in central Pb–Pb collisions for six years of data taking with ALICE 3 [2] as a function of p_T; Right: Expected D^0D^{*+} momentun correlation measurements in Pb–Pb and pp collisions with ALICE 3 after six years of data taking in the presence of a bound state [2].

portunity to perform such studies and determine the properties of the DD interaction potential by looking at the behaviour of the correlation function in the different colliding systems.

3.4 Beyond QGP physics

More physics topics, not related to the QGP, are part of the ALICE 3 programme [2]. The detector and accelerator set-up would open up the possibility to search for axion-like particles (ALP) in ultra-peripheral Pb–Pb collisions with a mass between 0.05 and 5 GeV/c^2 [2]. In hadronic collisions, ultra-soft real and virtual photon productions remain not understood. Although the cross sections are computable using the Low-theorem, large excesses are observed by several experiments at lower $\sqrt{s}$, see [2] for an overview. A systematic study of very-soft γ production is proposed with ALICE 3 using a forward conversion tracker.

4 Conclusions

ALICE 3 is a next-generation multipurpose detector at the LHC, proposed as a follow-up to the present ALICE experiment. Its main goal is to unravel the remaining unknown microscopic dynamics of the strongly-interacting matter produced in heavy-ion collisions. An innovative detector concept is required to allow high precision measurements of electromagnetic probes and heavy-flavour hadrons including multi-charm states and exotic hadrons inaccessible in Runs 3 and 4.

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