

# Latest results of the ALICE Collaboration and plans for ALICE 3

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The ALICE experiment is devoted to the study of the quark-gluon plasma (QGP) created in heavy-ion collisions at the CERN LHC. The experimental setup allows for the study of many different observables that contributed to the characterization of the properties of the QGP. The ALICE experiment went through a major upgrade during LS2 to profit from the increased LHC luminosity and to improve the tracking resolution. An additional upgrade is planned for LS3. A new experiment, ALICE 3, was proposed as next major upgrade in LS4. In this contribution, a selection of recent physics results was presented together with a glimpse of the next upgrades during LS3 and LS4, with the main focus on ALICE 3 and its physics program.

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## 1. Introduction

Heavy-ion collisions at ultrarelativistic energies allow to explore the phase diagram of QCD matter. Lattice QCD calculations predict that a state of matter where quarks and gluons are deconfined, known as the QGP, is produced above a given energy density. In order to characterize the QGP several probes can be used, each of them being sensitive to different properties. Furthermore, the complete evolution of the heavy-ion collision is studied, from the pre-equilibrium phase, the QGP phase, hydrodynamical expansion and hadron gas phase up to the kinetic and thermal freeze-out.

Figure 1 displays the ALICE experiment at the CERN LHC during Run 2. The description of the apparatus and its performance can be found in Refs. [1, 2]. The LHC schedule with the different data taking runs, shutdown periods and ALICE configurations is shown in Fig. 2.

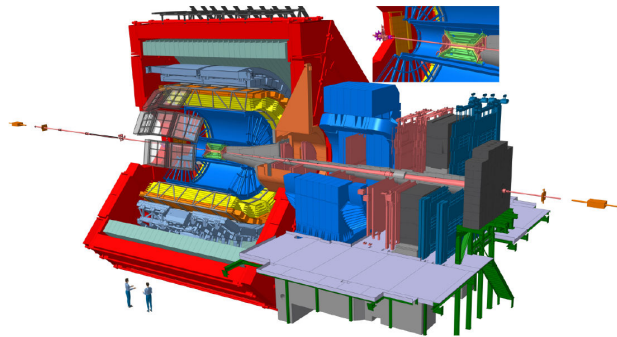


FIGURE 1. Schematic view of the ALICE apparatus during Run 2.



FIGURE 2. LHC schedule with the different data taking runs, shutdown periods and ALICE configurations.

The ALICE collaboration consists of more than 2000 people distributed over more than 175 institutes in about 40 countries. A large number of physics results was published in more than 400 papers. A review of the most important results was made available recently [3]. In the following, few selected recent results will be described. Furthermore, some details on the already started Run 3 are given as well as a glimpse of the future upgrades and the physics program.

## 2. Global properties

The multiplicity of charged particles produced at mid-rapidity in heavy-ion collisions is a key observable to characterize the properties of the matter created in these collisions. The dependence of  $dN_{ch}/d\eta$  on collision system, center-of-mass energy and collision geometry are basic observables for understanding the different particle production mechanisms. ALICE measured a power law dependence on the charged particle multiplicity density as a function of the center of mass energy per nucleon pair in pp and Pb-Pb collisions [4]. A larger exponent for nuclear collisions as compared to pp collisions evidences that more energy is available for particle production in these collisions compared to pp.

One of the strengths of ALICE is its particle identification capabilities as a result of using most of the available techniques and the low transverse momentum ( $p_T$ ) reach. Thus, a broad set of high precision measurements of identified particles differentially as a function of transverse momentum and collision centrality were carried out in pp, ppb and Pb-Pb collisions [5]. The spectra become flatter with increasing charged particle multiplicity, the effect being more pronounced for heavier particles. The low  $p_T$  spectra were parametrized with blast-wave fits across the systems obtaining freeze-out temperature  $T_{kin}$  and radial flow velocities  $\beta_T$  that depend strongly on  $dN_{ch}/d\eta$  [6]. With all these differential measurements, computed integrated yields of different particle species with respect to those of charged pi-

ons were studied as a function of charged particle multiplicity with the main focus on strange and multistrange particles [7] as strangeness enhancement was proposed as a signature of QGP formation in nuclear collisions. A continuous evolution of strangeness production between different collision systems and energies is observed. The magnitude of the strangeness enhancement grows with the strange quark content. The hadron yields are mostly related to the final state charged particle multiplicity density rather than collision system or beam energy. Furthermore, multiplicities of hadron species containing only light quarks measured at midrapidity in central Pb-Pb collisions, spanning over nine orders of magnitude in abundance values, are well described by statistical hadronization models [3].

Studies of the azimuthal anisotropy of particle production have contributed significantly to the characterization of the system created in heavy-ion collisions. Anisotropic flow reflects the conversion of the initial state spatial anisotropy into final state anisotropies in momentum space. Elliptic flow in Pb-Pb, p-Pb and pp collision was measured [8] using two ( $v_2\{2\}$ ) and four-particle ( $v_2\{4\}$ ) cumulants for different particle species. A mass ordering was found at low  $p_T$ , and at intermediate  $p_T$  baryon vs meson grouping that can be interpreted as quark-level flow and recombination. Models including quark coalescence describe the measurements over a large  $p_T$  range, which confirms the relevance of the quark coalescence hadronization mechanism in the particle production in pp, p-Pb and Pb-Pb collisions at the LHC.

Viscous hydrodynamic calculations using various initial state models were able to describe multiplicity distributions, particle momentum spectra and integrated flow measurements. Uncertainties in the initial state translated into large uncertainties on the extracted shear viscosity over entropy ratio,  $\eta/s$ , value. Some progress was achieved in the last years.

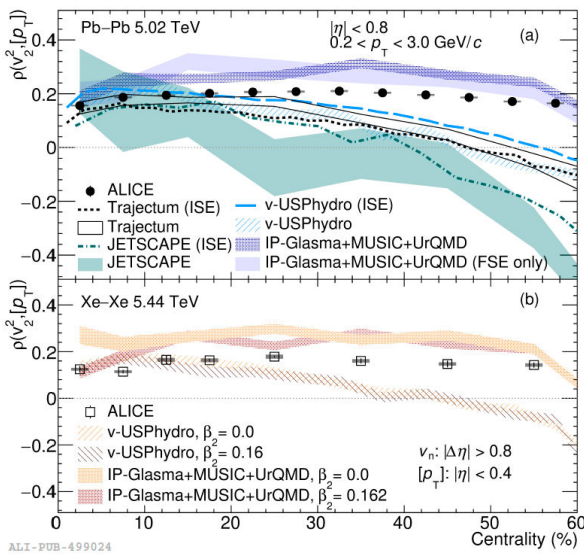


FIGURE 3. Centrality dependence of  $\rho(v_n^2, [p_T])$  in Pb-Pb and Xe-Xe collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and  $\sqrt{s_{NN}} = 5.44$  TeV, respectively, compared to different model calculations.

Novel approaches utilizing Bayesian statistics and a multi-parameter model-to-data comparison of different observables like multiplicity, transverse momentum, and flow are used to quantitatively extract estimates of the temperature-dependent specific shear and bulk viscosity simultaneously with related initial-condition properties [9] or to characterize additional aspects of high-energy nuclear collisions [10].

Correlations of  $v_2$  vs mean  $p_T$ ,  $\rho(v_n^2, [p_T])$ , as a function of centrality (Fig. 3) are mainly driven by the correlations of the size and the shape of the system in the initial state, and as such provide a novel way to characterize the initial state and help pin down the uncertainty of the extracted properties of the quark-gluon plasma. The sensitivity of the correlations of  $v_2$  vs mean  $p_T$  vs centrality,  $\rho(v_n^2, [p_T])$  to the initial conditions can be observed in Fig. 3 [11]. Data for Pb-Pb and Xe-Xe collisions are closer to IP-Glasma initial condition as compared to Trento initial conditions. Therefore, including measurements of  $\rho(v_n^2, [p_T])$  vs centrality in Bayesian global fitting approaches could result in better constraint on the initial state in nuclear collisions.

The two-particle transverse momentum correlator  $G_2$  was proposed [12, 13] because of its sensitivity to the transport characteristics of the QGP. The longitudinal width evolution

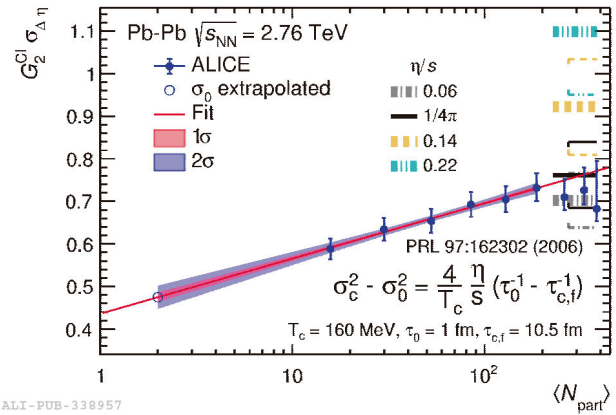


FIGURE 4. Width of  $G_2$  in  $\Delta\eta$  as a function of  $\langle N_{part} \rangle$  for Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV.

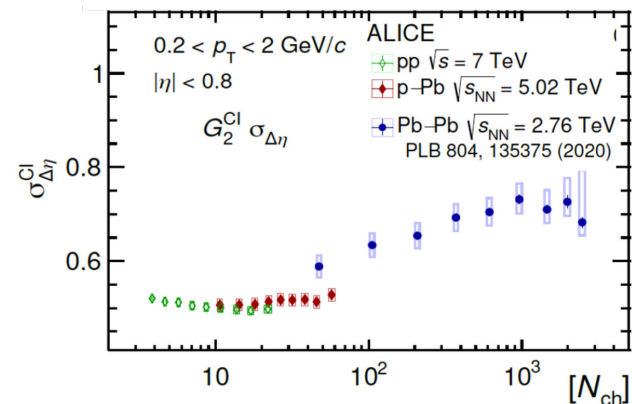


FIGURE 5. Width of  $G_2$  in  $\Delta\eta$  as a function of charge particle multiplicity for pp, p-Pb and Pb-Pb collisions.

with collision centrality carries information about  $\eta/s$  [14], while it does not have any explicit dependence on the initial state fluctuations in the transverse plane of the system. The  $G_2$  width evolution measured as a function of centrality in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV [15] (Fig. 4) favours small values of  $\eta/s$  at LHC energies. Furthermore, no evidence for shear viscous effects was found in pp and p-Pb collisions based on  $G_2$  (Fig. 5), or the system lifetime was too short for viscous forces to play a significant role [16].

ALICE data on the longitudinal width of  $G_2$  were used to compute values of  $\eta/s$  as a function of the charged particle multiplicity, obtaining  $\eta/s$  values in the range from  $0.04 \pm 0.02$  (sys) to  $0.07 \pm 0.03$ (sys) for LHC energies [17].

### 3. Electromagnetic radiation

Photons and dileptons (lepton-antilepton pairs from internal conversion of virtual photons) are produced throughout all stages of the collisions. They are unique probes of the QGP because they leave the medium unaffected by the strong interaction. They provide information about the temperature and the radial expansion velocity of the QGP.

Dileptons carry mass that can be used to distinguish between different sources of the radiation, and which allows for temperature measurements without a blue shift. At low invariant mass ( $m_{ee} < 1.1$  GeV/c<sup>2</sup>), the dielectron production is sensitive to the properties of short-lived vector mesons in the medium related to chiral symmetry restoration ( $\rho$ - $a_1$ , vector-axial vector meson mixing). The intermediate-mass region ( $1.2 < m_{ee} < 2.7$  GeV/c<sup>2</sup>), is where the thermal black-body radiation dominates and the early temperature of

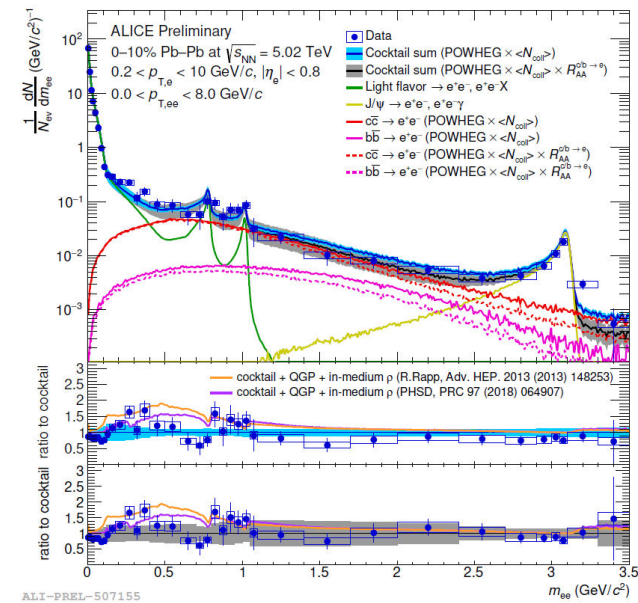


FIGURE 6. Dielectron invariant mass distribution for central 0-10% Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV compared to the hadronic cocktail for two different versions of the correlated background from heavy flavour hadron decays. Middle and bottom plots show the respective ratio to the cocktails excluding the vacuum  $\rho$ .

the system can be extracted after subtraction of the very large background of correlated dielectron pairs from semi-leptonic charm and beauty hadron decays. Figure 6 shows the dielectron invariant mass distribution for central 0-10% Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV compared to the hadronic cocktail for two different versions of the correlated background from heavy flavour hadron decays. Middle and bottom plots show the respective ratio to the cocktails excluding the vacuum  $\rho$ .

Data show an indication for an excess at lower mass compatible with the thermal radiation from the partonic and hadronic gas phase [18, 19] up to  $m_{ee} < 0.5$  GeV/c<sup>2</sup> while the model calculations overestimate the data for  $0.5 < m_{ee} < 0.7$  GeV/c<sup>2</sup>. The intermediate mass region agrees better with the expectations of the models for the cocktail including HF suppression [20].

Direct photons are photons not coming from hadronic decays. Experimentally, they can be measured using a double ratio  $R_\gamma$  defined as

$$R_\gamma = \frac{(N_{\gamma,inc}/N_{\pi^0})_{measured}}{(N_{\gamma,decay}/N_{\pi^0})_{sim}}, \quad (1)$$

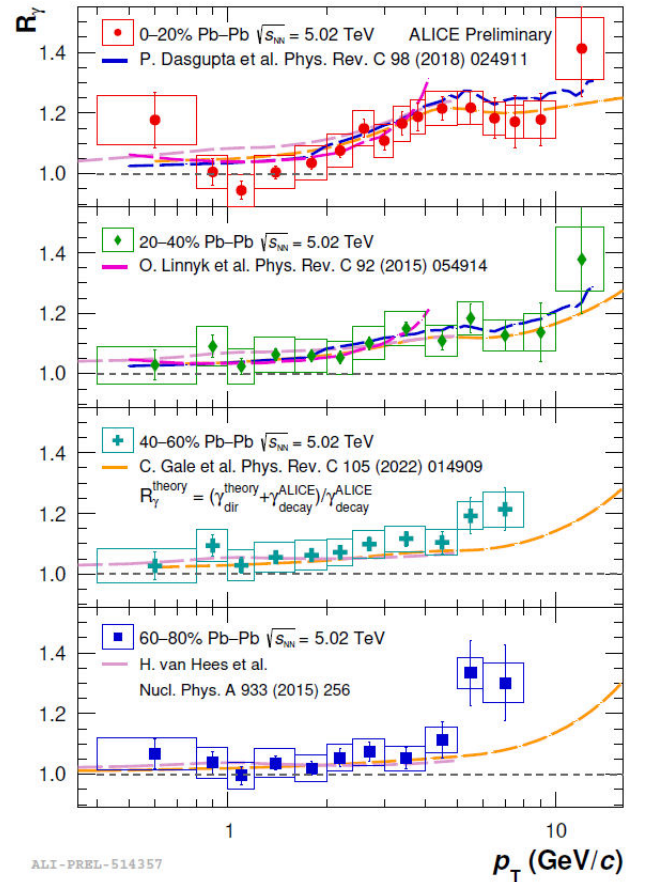


FIGURE 7.  $R_\gamma$  as a function of  $p_T$  from central a) to peripheral b) Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV together with expectations from model calculations that include thermal photons, (and pre-equilibrium photon) and prompt photons.

in order to cancel correlated uncertainties. The decay photon spectra are estimated employing the decay cocktail framework [21] using as input the measured  $\pi^0$  and  $\eta$  meson spectra and  $m_T$  scaling for non measured spectra. The  $R_\gamma$  as a function of  $p_T$  is shown in Fig. 7 from central a) to peripheral b) Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV.

At low  $p_T$  where the thermal radiation dominates the measurement the value of  $R_\gamma$  is close to 1, which entails a small contribution from thermal and pre-equilibrium photons. For  $p_T > 3$  GeV/c, a value of  $R_\gamma > 1$  is measured which is attributed to prompt photons from hard scatterings. At low  $p_T$ , model calculations with thermal and pre-equilibrium photons agree better with the data than if only prompt photons [22] are included. Several model calculations that contain different assumptions (microscopic transport approach or relativistic hydrodynamic with different initial conditions, thermalization times with and without pre-equilibrium photons) are able to describe the data. The current uncertainties do not allow for discrimination among the different theoretical model calculations [22–31]. More precise results are expected with the full Run 2 and Run 3 data.

## 4. Quarkonia

Quarkonia are flavorless mesons whose constituents are a heavy quark and its own antiquark ( $c\bar{c}$  or  $b\bar{b}$  for charmonium or bottomonium, respectively). Most of the states are stable with respect to strong decay into open charm or open bottom because of the mass threshold. In the late 80s, it was realised that colour screening prevents  $c\bar{c}$  binding in a deconfined medium [32]. Consequently, the observation of  $J/\psi$  suppression would provide a signature of QGP formation. Furthermore, the sequential suppression of the different quarkonia states would deliver information about the  $T$  of the QGP [33–35]. Later, it was realised that another mechanism, the (re)generation, will compensate the suppression once the charm quark multiplicity would become sizeable [33–35].

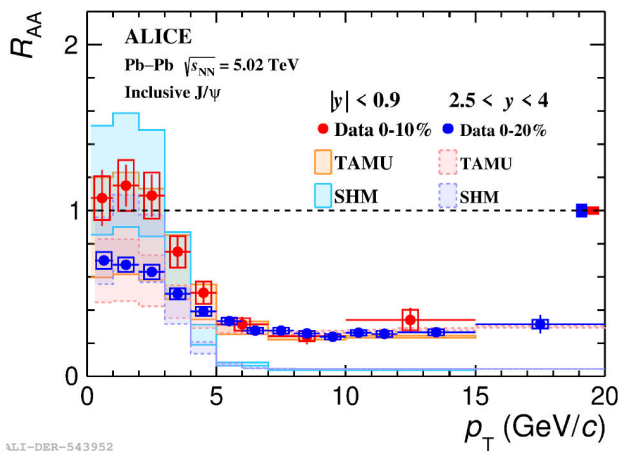


FIGURE 8.  $R_{AA}$  for  $J/\psi$  as a function of  $p_T$  for the central and forward rapidity regions in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV compared to TH-TAMU and SHM model calculations.

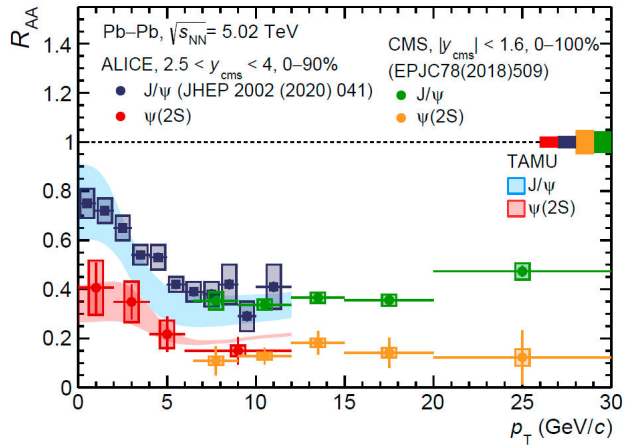


FIGURE 9.  $R_{AA}$  for  $\Psi(2S)$  and  $J/\psi$  as a function of  $p_T$  in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV compared with theoretical model calculations and results from the CMS experiment.

The measured  $J/\psi$   $R_{AA}$  as a function of  $p_T$  for the central and forward rapidity regions in central Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. is displayed in Fig. 8 compared to the TH-TAMU and SHM model calculations [33].  $R_{AA}$  is higher at midrapidity than at forward rapidity for  $p_T < 3$  GeV/c in the most central collisions as can be explained by a large contribution from (re)generation to the  $J/\psi$  yields.

The first accurate measurement of the inclusive  $\Psi(2S)$  down to zero  $p_T$  for  $2.4 < y < 4$  has been achieved by ALICE [39]. Figure 9 displays the  $p_T$ -dependent  $\Psi(2S)$   $R_{AA}$  compared to the  $J/\psi$   $R_{AA}$ . The  $\Psi(2S)$  has ten times lower binding energy and shows two times larger suppression at low  $p_T$  as compared to the  $J/\psi$ . The strong increase of  $R_{AA}$  towards low  $p_T$  for both quarkonia states is an indication of (re)generation. The ALICE results are in good agreement with CMS results and with theoretical model calculations.

## 5. Open heavy flavour

Heavy quarks are interesting probes to characterize the QGP, because due to their large mass the production even at low  $p_T$  is driven by hard scatterings in the early stages of the collision and additional thermal production is negligible.

Thus, heavy quarks experience the full space-time evolution of the hot and dense QCD medium. At low  $p_T$ , heavy quarks undergo Brownian motion in the medium, carrying, hence, information of the equilibration process. High  $p_T$  heavy quarks interact with the QGP and lose energy via inelastic (radiative) processes. Open heavy flavor can be measured in ALICE through various channels. Some hadronic decay channels can be fully reconstructed to zero  $p_T$ .

The average  $R_{AA}$  of prompt  $D^0$ ,  $D^+$ , and  $D^{*+}$  mesons for Pb-Pb collisions in the 0–10% centrality class is shown in Fig. 10 [40]. Compared to the  $R_{AA}$  of charged pions it is larger for  $p_T < 8$  GeV/c. All models shown in Fig. 10 agree with the data, with some tension at low  $p_T$ . The comparison of D-meson  $R_{AA}$  and  $v_2$  (Fig. 11) to models implementing charm - quark transport in a hydrodynamically expanding

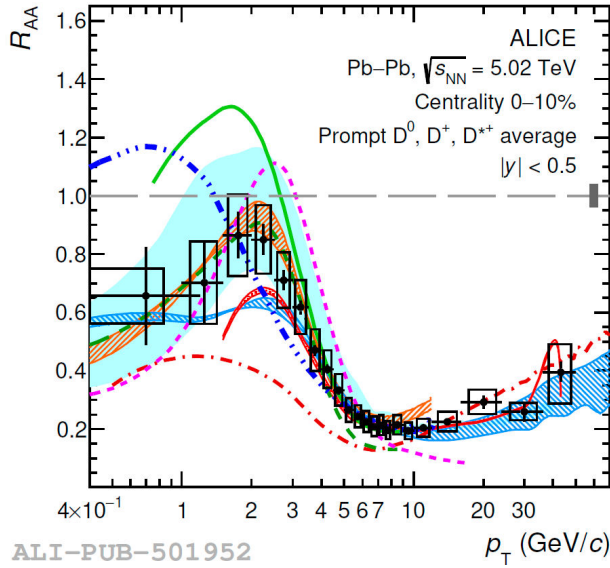


FIGURE 10. Average  $R_{AA}$  of prompt  $D^0, D^+,$  and  $D^{*+}$  mesons in the 0-10% centrality class in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV compared with predictions of models implementing the charm-quark transport in a hydrodynamically expanding medium.

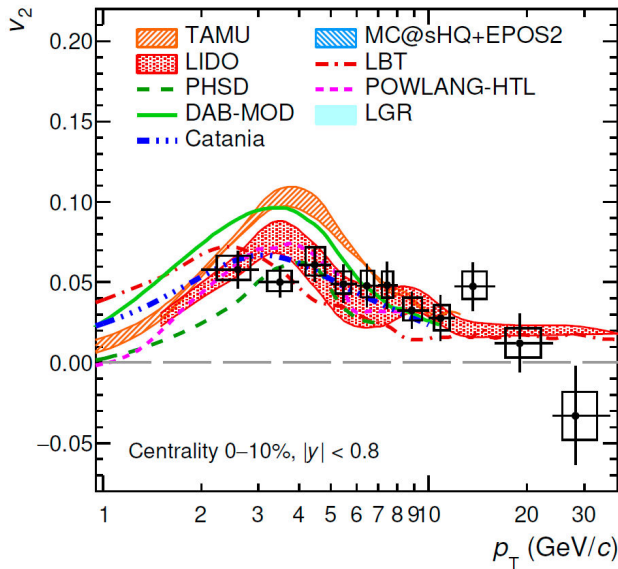


FIGURE 11. Average elliptic flow  $v_2$  of prompt  $D^0, D^+,$  and  $D^{*+}$  mesons in the 0-10% centrality class in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV compared with predictions of models implementing the charm-quark transport in a hydrodynamically expanding medium.

medium gives information of the interaction of heavy quarks with the medium, constraining the spatial diffusion coefficient. The resulting spatial diffusion coefficient  $D_s$  extracted from the ALICE measurement ( $1.5 < 2\pi D_s T_c < 4.5$ ) together with a compilation of the values as obtained from measurements and model calculations is shown in Fig. 12. This value of  $D_s$  translates into a relaxation time of the charm quark  $\tau_{\text{charm}} \sim 3-8$  fm/c.

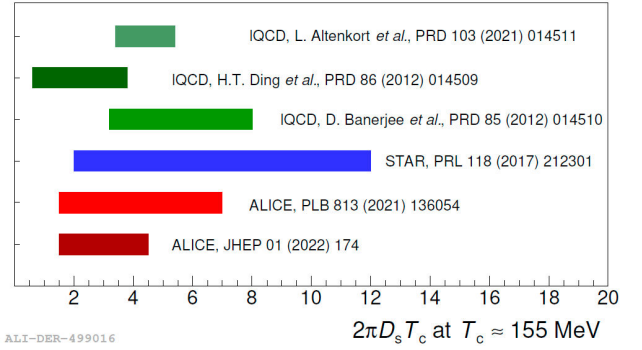


FIGURE 12. Compilation of values for the spatial diffusion coefficient  $D_s$  with their respective uncertainties as obtained by measurements and model calculations.

## 6. Jets

The production of jets, *i.e.* collimated sprays of particles arising from fragmentation of partons produced in high  $Q^2$  interactions, in pp collisions can be well described in pQCD calculations. Thus, by measuring jet suppression in Pb-Pb collisions over a wide set of parameters, properties of the QGP can be extracted.

Jet suppression is quantified using the  $R_{AA}$  with a novel machine learning (ML) based approach to subtract underlying Pb-Pb event fluctuations from jet energy (see Fig. 13) that allows measurements at transverse momenta as low as 40 GeV/c for a large resolution parameter of  $R = 0.6$  in most central Pb-Pb collisions (or  $p_T > 20$  GeV/c for  $R = 0.2$ ) [41]. A large suppression is still present for  $R = 0.6$  implying that the lost energy is still not recovered within the jet "cone". A comparison of  $R_{AA}$  for  $R = 0.6$  and  $R = 0.2$  indicates that the suppression may be even larger for large-cone ( $R = 0.6$ ) low- $p_T$  jets. The larger acceptance achieved both in  $p_T$  and resolution parameter  $R$ , thanks to the ML-based approach, is crucial for discriminating among different models. A comparison of model calculations to the jet  $R_{AA}$  is shown in Fig. 13). The calculations generally describe the data in central collisions for the smaller resolution parameters ( $R = 0.2$  and  $0.4$ ). JEWEL with recoils predicts significantly higher values for  $R_{AA}$  at  $R = 0.6$  than measured.

## 7. ALICE in Run 3 and Run 4 at the LHC

ALICE went through a major upgrade during the LS2 which enables data taking in a continuous readout mode to profit from the increased LHC luminosity and improves the tracking resolution [42]. The upgrades comprise a new inner tracking system (ITS2), new GEM-based readout chambers of the time projection chamber, new muon forward tracker (MFT), new trigger and readout and a new online/offline (O2) software [43].

On July 5, 2022, LHC Run 3 started officially: proton beams collide now at a center of mass energy of 13.6 TeV,

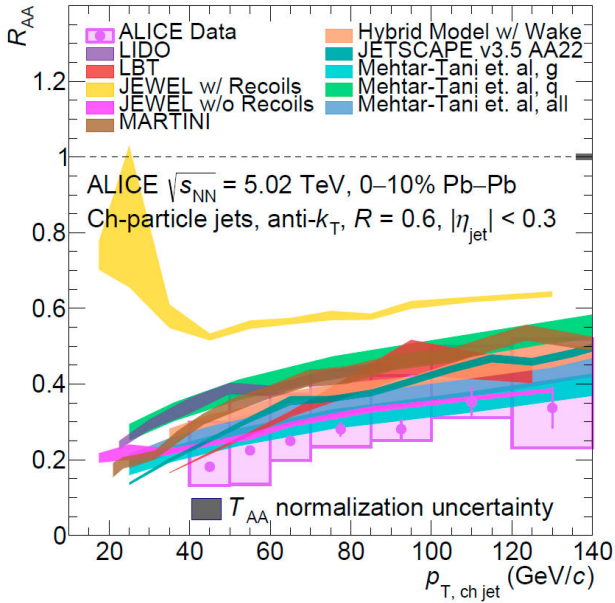


FIGURE 13. Nuclear modification factor ( $R_{AA}$ ) for charged particle jets with  $R = 0.6$  obtained using the ML-based method compared to different model predictions [41].

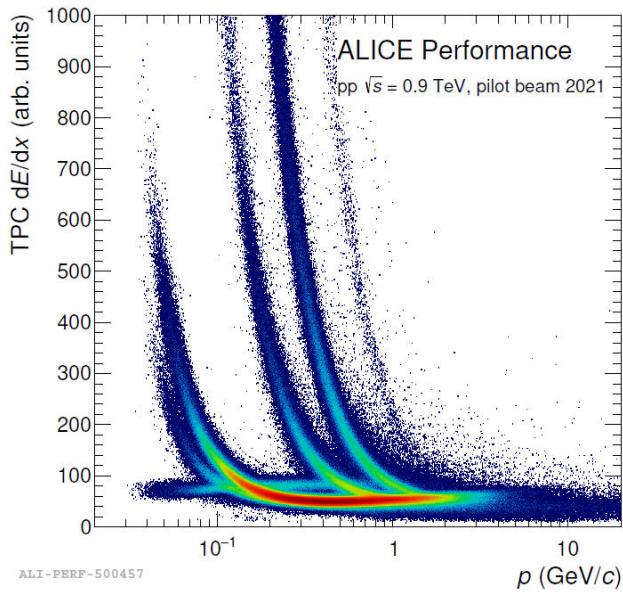


FIGURE 14. Specific energy loss ( $dE/dx$ ) in the TPC versus momentum for pp collisions at  $\sqrt{s} = 0.9$  TeV during the 2021 pilot beam.

the highest energy ever reached. Commissioning with pilot beams during 2021 showed the expected performance of the upgraded experiment in terms of tracking and particle identification (see Fig. 14). A total integrated luminosity of  $15 \text{ pb}^{-1}$  was recorded during 2022 at different interaction rates ranging from 3 kHz up to 1 MHz. Additionally, a test run with Pb beams at  $\sqrt{s_{NN}} = 5.36$  TeV took place prior to the winter break that is crucial to prepare and optimize the data processing and compression. During the upcoming LS3 (see

Fig. 2), the FoCal detector [44] will be installed and the current ITS2 will be replaced by the ITS3 [45].

## 8. ALICE 3 for Run 5 and Run 6

A huge progress on the characterization of the QGP was already achieved thanks to ALICE results in Run 1 and Run 2, and will continue to deepen with the Run 3 and Run 4 scientific program. However, several essential questions like the fundamental properties of the quark-gluon plasma driving its constituents to equilibration, a comprehensive study of the QGP hadronization mechanisms, the partonic equation of state and its temperature dependence and the underlying dynamics of chiral symmetry restoration will still remain unanswered after Run 3 and Run 4. Thus, the ALICE Collaboration proposed to install a next generation multipurpose detector, ALICE 3 [46,47], for Run 5 and Run 6 (see Fig. 2).

ALICE 3 (see Fig. 15) is based on the use of monolithic active pixel sensors (MAPS) in combination with deep sub-micron commercial CMOS technologies. The rate capabilities would be a factor of about 50 higher with respect to ALICE in Run 4, being able to exploit the whole delivered p-A and A-A luminosities. ALICE 3 is a large acceptance detector, covering a pseudorapidity range of  $|\eta| < 4$  and  $p_T > 0.02$  GeV/c. The expected track point resolution is  $\sigma_{DCA} \sim 10 \mu\text{m}$  at a  $p_T = 0.2$  GeV/c. The detector will deliver particle identification for  $\gamma$ ,  $e^\pm$ ,  $\mu^\pm$ ,  $K^\pm$  and  $\pi^\pm$ . Such an experiment will be able to deliver systematic measurements of (multi)heavy-flavoured hadrons down to low  $p_T$ , precision differential measurements of dileptons complemented with direct photon measurements, as well as correlation and fluctuation measurements over a large rapidity range among others.

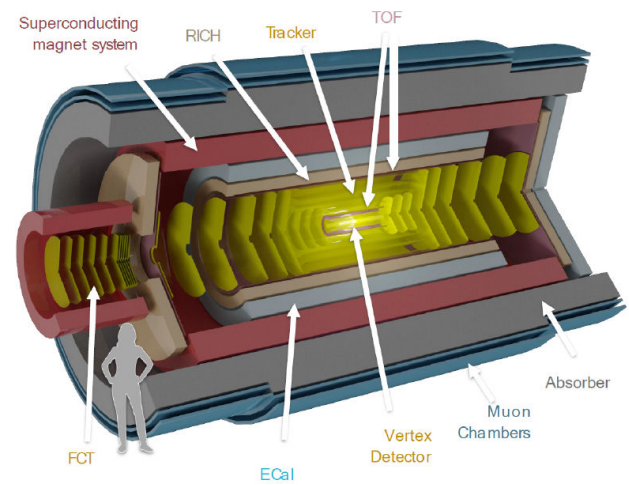


FIGURE 15. Schematic view of the ALICE 3 experiment with the inner and outer trackers, RICH, TOF detectors, ECal and muon detectors in the central and forward/backward barrels, and the forward conversion tracker (FCT) specialized in low momentum photons.

The double-differential analysis of dilepton production in transverse momentum and mass provides access to the time evolution of the temperature. The excellent capabilities of ALICE 3 in terms of good  $e$ -PID down to low  $p_T$ , small detector material budget ( $\gamma$  background) and an excellent pointing resolution (heavy-flavour decay electrons), translate into the expected invariant mass spectrum of thermal  $e^+e^-$  pairs produced in central Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV as depicted in Fig. 16. It would be possible to probe the time dependence of the QGP temperature by fitting the thermal dielectron  $m_{ee}$  spectrum for  $m_{ee} > 1.1$  GeV/c<sup>2</sup> (QGP radiation dominated) in bins on pair  $p_T, ee$  with

$$\frac{dN_{ee}}{dm_{ee}} \propto (m_{ee}T)^{3/2} e^{-m_{ee}T}. \quad (2)$$

The thermal dielectron elliptic flow as a function of  $m_{ee}$  and  $p_T, ee$  would be within reach with ALICE 3. Furthermore, the high precision thermal dielectron spectrum at  $m_{ee} < 1.2$  GeV/c<sup>2</sup> allows to access the chiral symmetry restoration effects like the  $\rho$ - $a_1$  mixing [18, 47, 48].

Real photons will be measured in ALICE 3 with the photon conversion method (PCM) and with the electromagnetic calorimeter (ECAL). The excellent tracking of photon conversion products together with the large acceptance will allow

high precision measurements of  $\pi^0$  and  $\eta$  down to zero  $p_T$  reducing the systematic uncertainties of the dominant photon background sources and, therefore, of the direct photon measurements. ALICE 3 will then improve on the measurements of the temperature and elliptic flow of direct photons. By combining the information of real and virtual photons the temperature and the radial expansion velocity of the QGP can be determined.

## 9. Conclusions

Much progress on the characterization of the QGP was achieved thanks to ALICE results in LHC Run 1 and Run 2. Some of the questions that remained open mainly due to statistics will be addressed during the already ongoing Run 3 and Run 4. Others will have to be postponed to Run 5 and Run 6 with the completely new ALICE 3 experiment.

## Acknowledgements

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