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ALICE results in p–Pb collisions at the LHC

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ALICE studies the properties of the strongly interacting matter at the extreme energy densities reached in heavy-ion collisions at the LHC. In this context, the measurements in proton-proton and proton-nucleon collisions are mandatory: the former sets the reference, while the latter provides further insight into the effects due to cold nuclear matter, which is crucial in the understanding of heavy-ion collisions.

In this paper, a selection of the recent results in p–Pb collisions at the LHC will be presented.

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1. Introduction

The Quantum Chromodynamics (QCD), the theory describing the strong interactions, predicts that a phase transition occurs at high temperatures and/or baryonic densities, from the hadronic matter to a state where quark and gluons are no more confined into nucleons. This new state of matter is called Quark-Gluon Plasma (QGP). The conditions for its formation could be found in the early universe, few microseconds after the big bang, or inside the core of the neutron stars, where the baryonic density is extremely high. It is however possible to reproduce such conditions also in laboratory, through the collision of heavy ions at ultra-relativistic energies. The hot and dense medium formed during the collision rapidly expands, thus lowering the temperature until the matter returns to the hadronic phase. The produced particles, however, are affected by the QGP formation, and their study can hence provide insight into the medium properties.

The global properties of the QCD matter can be investigated by studying the collective behaviour of the bulk particles produced in the collision. In particular, the measurement of the flow of particles provides information on the degree of thermalisation of the system and on its size. On the other hand, the microscopic properties of the QGP can be accessed through the study of the so called hard probes, *i.e.* particles produced in the initial hard scattering and exposed to the full evolution of the medium, such as heavy quarks (charm and beauty) and high momentum partons fragmenting into jets.

A quantitative understanding of the medium effects requires a comparison with nucleon-nucleon collisions. However, the deviation of the heavy-ion measurements from the ones expected from an incoherent superposition of nucleon-nucleon collisions is not due only to the formation of a strongly interacting medium. The effects arising from the hadronic matter constituting the nuclei must be taken into account. Among these, the most relevant at the Large Hadron Collider energies is the saturation of low momentum gluons, which modifies the particle production, especially at low transverse momenta (p_{T}). The effect can be described either by means of a phenomenological modification of Parton Distribution Functions inside nuclei [1], or with the Colour Glass Condensate effective theory [2], which depicts the nucleus as a coherent gluonic system which saturates at very large densities. These effects can be isolated in nucleon-nucleus collisions, where the energy density is expected to be too small for the plasma formation. However, surprisingly, recent results in p–Pb collisions present features similar to the ones arising from final state effects in Pb–Pb collisions, as presented in the following.

2. The ALICE detector

ALICE is the only experiment at the LHC dedicated to the study of heavy-ion collisions. The investigation of the global properties of the medium requires the measurement of particles down to low p_{T}, where the bulk of the cross section lies. ALICE is hence equipped with a Time Projection Chamber (TPC) and an Inner Tracking System (ITS), made of six layers of silicon, placed inside a solenoidal magnet with 0.5 T magnetic field, which makes it possible to track charged particles down to $p_{\mathrm{T}} \sim 100$ MeV/c. The particle identification (PID) is assured by the use of different detectors and techniques [3]. The VZERO detector, an array of scintillating tiles placed at both sides of the interaction point, provides triggering and an estimation of the centrality

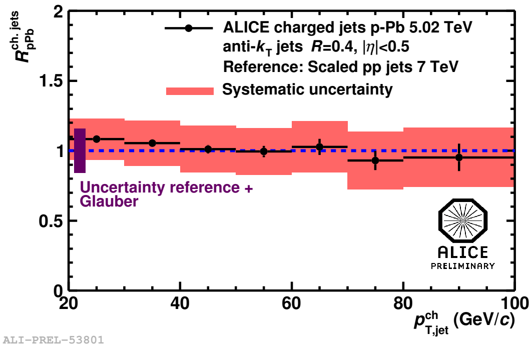

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Figure 1: Nuclear modification factor of charged jets in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV.

of the collision [4]. The latter is a common concept in heavy-ion physics. The centrality is directly related to the impact parameter, and can be inferred by comparison of data with simulations of the collisions [5]. In this case the centrality is determined using the amplitude of the signal in the VZERO detector which is proportional to the particle multiplicity: the higher the signal, the smaller the impact parameter. The Zero Degree Calorimeter (ZDC), symmetrically placed at 116 m from the interaction point, provides a complementary estimation of the collision centrality, by measuring the non-interacting nucleons that continue travelling along the beam line. The detector is completed by a series of forward detectors, in particular the muon spectrometer which measures muons in the pseudo-rapidity range $-4 < \eta < -2.5$. Further details can be found in [3].

3. Hard probes

The hard probes are particles produced in the hard processes occurring among the partons of the colliding nucleons. The outgoing partons travel through the medium, eventually fragmenting into hadrons. The interaction of the parton with the medium leads to modifications in the kinematic distributions of the resulting jet. The effect is quantified by means of the nuclear modification factor ($\rm R_{AA}$), which is defined as the ratio between the yields measured in heavy-ion collisions and the ones measured in proton-proton collisions, scaled by the number of binary nucleon-nucleon collisions. Since the hard probes are produced in the initial hard scattering, they are expected to scale with the number of binary nucleon-nucleon collisions (binary scaling), hence the $\rm R_{AA}$ is expected to be unity if no medium or nuclear effect occur. The $\rm R_{AA}$ of jets measured in heavy-ion collisions is smaller than 1 at high $p_{\rm T}$ [6], which implies a softening of the jet $p_{\rm T}$ spectrum with respect to the one in pp collisions. The result, known as jet-quenching, is interpreted as a consequence of the energy loss of the parent parton in the interaction with the medium. In principle, cold nuclear effects could play a role in the observation. However, the equivalent results in p–Pb collisions (Figure 1) are consistent with 1, thus confirming that the strong reduction of yields observed in Pb–Pb collisions is an hot medium effect.

Among the hard probes, the charm and beauty quarks have unique features. They have large masses and are produced in pairs predominantly at the initial stages of the collisions, with a formation time which si shorter than the one of the medium. Heavy quarks transverse the medium and

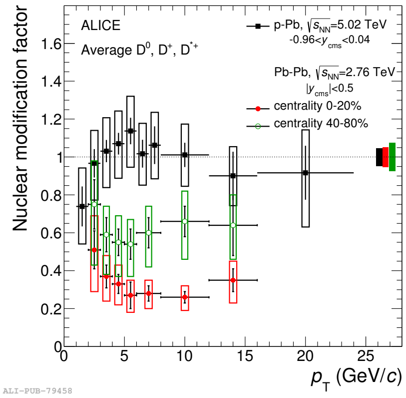

Figure 2: Nuclear modification factor as a function of p_T of D mesons (average of the measurement with D^0, D^+ and D^{*+}) in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (black) and in the 0-20% (red) and 40-80% (green) centrality classes of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [11]. The bar (boxes) are the statistical (systematic) uncertainties. The filled boxes at $R_{AA} = 1$ are the global uncertainties.

interact with its constituents via both inelastic (medium-induced gluon radiation or radiative energy loss) [7, 8] and elastic (collisional) [9] processes. The energy loss depends on the color charge and mass of the involved partons, and increases from beauty to charm and eventually to gluons. This hierarchy can be studied by comparing the nuclear modification factors of B and D mesons and light hadrons [10]. Figure 2 shows the nuclear modification factor of D mesons measured with ALICE in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [11]: a strong suppression is observed at high p_T, which, at variance with expectations, is similar to the one observed for light hadrons. On the other hand, the R_{pPb} is compatible with 1 at high p_T, indicating that the large suppression in Pb–Pb collisions is a genuine hot medium effect.

4. Global features

In semi-central heavy-ion collisions, the overlap region between the nuclei is almond-shaped, with the minor axis lying in the plane defined by the impact parameter and the beam axis (reaction plane). If a thermal equilibrium is reached, the pressure gradient is directed mainly along the impact parameter, and a collective flow is developed in this direction. This is reflected in the transverse momenta, which are preferentially oriented along the same line [12]. The effect can be quantified by the elliptic flow, *i.e.* the second order coefficient (v_2) of the Fourier expansion of the particle azimuthal distribution relative to the reaction plane. A value of v_2 compatible with zero suggests that the system has no memory of the initial spatial asymmetry, while a non-null v_2 indicates a non-isotropic particle emission. ALICE measured the elliptic flow of pions, kaons and protons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [13] (Figure 3, right panel): the v_2 of all species increases as a function of the transverse momentum up to $p_T \sim 3-4$ GeV/c. The mass ordering, which is clearly visible below $p_T \sim 2.5$ GeV/c, is qualitatively described by hydrodynamics. At high p_T, the v_2 seems to scale with the number of constituent quarks. This behaviour can be explained by models invoking quark coalescence as the main hadronization mechanism in this p_T range, and it is interpreted as evidence that quark degrees of freedom dominate in the early stage of the

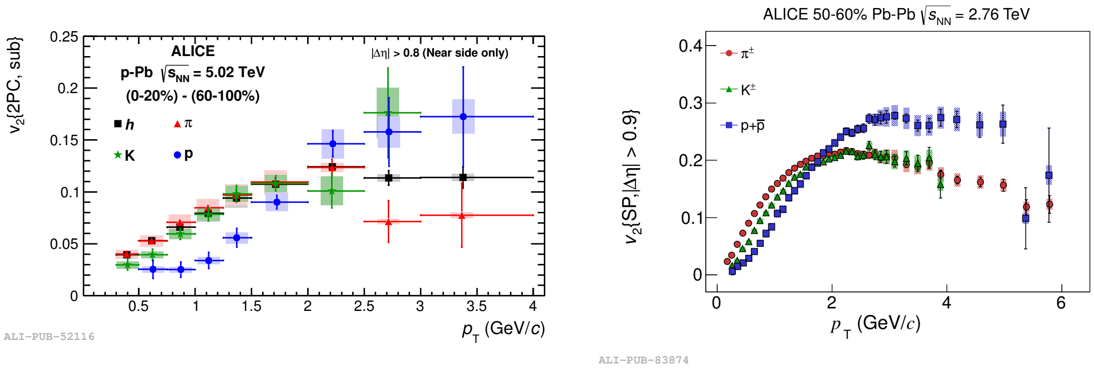

Figure 3: Elliptic flow as a function of p_T for different particle species measured in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (left panel) and in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [13] (right panel).

collision. However, ALICE data show that such scaling is violated by about 20% in the most central collisions [13]. The equivalent measurements in p–Pb collisions are shown in the left panel of Figure 3: the pattern of the v_2 distribution is surprisingly similar to the one measured in Pb–Pb collisions. The unexpected result would suggest that collective effects might be at play already in p–Pb collisions.

Another powerful tool to investigate the particle production mechanism is the two-particle correlations. The study is based on the distribution of the relative pseudo-rapidity ($\Delta\eta$) and the relative azimuthal angle ($\Delta\phi$) between a “trigger” particle and an “associated” particle, selected according to their transverse momenta. In minimum-bias pp collisions, the correlation is dominated by the jet peak in the near side ($\Delta\phi \sim 0$) and by an away side ($\Delta\phi \sim \pi$) structure due to particles originating from the fragmentation of the recoiling jet. In heavy-ion collisions, the presence of a hydrodynamic medium gives rise to additional long-range correlations among particles, resulting in a ridge along $\Delta\eta$ [14]. The measurement was performed in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as well [15]. The typical structure with a narrow peak in the near side and a broader one in the away side is observed in different centralities (Figure 4 left and middle panels). However, a near-side ridge becomes visible with increasing multiplicity. In order to better quantify the effect, the per-trigger yield for the low multiplicity class 60-100% was subtracted from the high multiplicity 0-20% one. The procedure is expected to remove most of the multiplicity-independent correlations, such as the ones due to (back-to-back) jets. The result is shown in the right panel of Figure 4: a near and away-side ridge are observed, very similar in magnitude, which remind of the structures observed in Pb–Pb collisions. It is worth noting that the emergence of similar long-range near-side correlations was also reported in high-multiplicity pp collisions at $\sqrt{s} = 7$ TeV [16]. The interpretation of the p–Pb result is still controversial, with explanations ranging from collective phenomena in final state effects to initial state effects that could be described in the Color Glass Condensate approach [2].

5. Summary

The ALICE experiment studied p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, with the aim of assessing the cold nuclear matter effects affecting the heavy-ion measurements. The nuclear modification

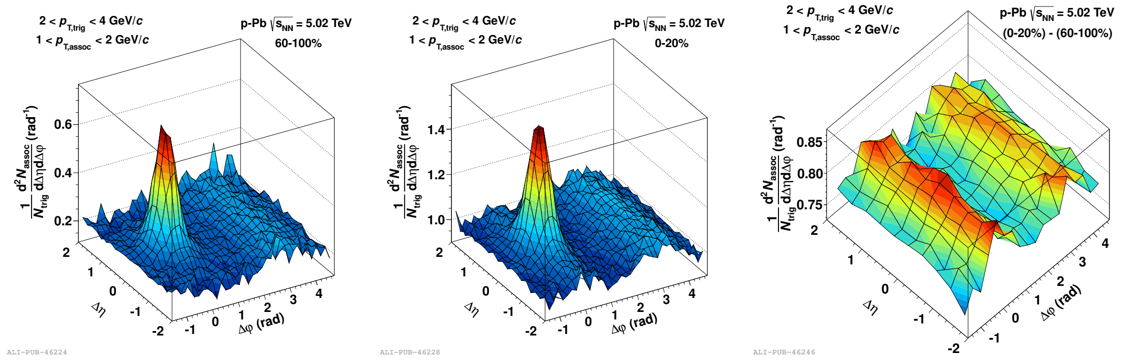

Figure 4: Associated yields per trigger particles for pairs of charged particles in the 60-100% (left panel) and 0-20% (middle panel) multiplicity classes in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [15]. The right panel is obtained subtracting the spectrum in the left panel from one in the middle.

factors of charged hadrons and heavy flavours are found to be consistent with 1 at high transverse momenta, thus indicating that the effects of the nuclear modification of the Parton Distribution Function are small. On the other hand, the measurement of elliptic flow and charged particle pair correlations show an unexpected behaviour, with a pattern close to the one observed in heavy-ion collisions and usually attributed to collective effects arising from pressure gradients in a strongly interacting medium. The nature of the observation is still highly debated, with possible explanation ranging from initial to final state effects. These unexpected results cast a new light on p–Pb collisions, which promise to be an exciting filed in the future.

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