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RECENT HEAVY-ION RESULTS FROM THE LHC AND FUTURE PERSPECTIVES*

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Strongly interacting matter at high densities and temperatures can be created in high-energy collisions of heavy atomic nuclei. Since 2010, the Large Hadron Collider at CERN provides proton–proton, proton–lead and lead–lead collisions at an unprecedented energy to study the so-called quark–gluon plasma (QGP) state. Several experimental probes have been proposed to determine the properties of the QGP. In this contribution, a selection of recent results from the heavy-ion programme at RHIC and the LHC are reviewed and discussed.

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1. Soft probes

High-energy nucleus–nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and the Large Hadron Collider (LHC) at CERN allow exploring strongly interacting matter at very high temperatures and energy densities. The QCD matter at these conditions is expected to form a system of deconfined quarks and gluons, the so-called quark–gluon plasma, if the critical energy density exceeds about 0.7 GeV/fm^3. Results from RHIC and the LHC provided evidence that the matter created in such collisions exhibits properties consistent with the QGP formation [1–4]. The goal of ultra-relativistic heavy-ion physics is to study the properties of the QGP and determine its properties.

Figure 1 (left panel) depicts the world data of the charge particle multiplicity in proton–proton and nucleus–nucleus collisions [5, 6], which are well-described by a power law fit with $s^{0.155}$ and $s^{0.103}$, respectively. Recent

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measurement from the ALICE experiment ($\mathrm{d}n_{\mathrm{ch}}/\mathrm{d}\eta = 1943 \pm 54$) in 5.02 TeV Pb–Pb collisions fits very well into the observed trend. The multiplicity at this c.m.s. energy is about 2.5 times bigger than at top RHIC energies and the energy density about 3 times larger. The charged particle multiplicity shows a very similar centrality dependence at the LHC and RHIC, and the shape is almost independent of the collision energy [6, 7] (*cf.* Fig. 1, right panel). In particular, measurements of the momentum distribution of emitted particles and comparison with hydrodynamic model calculations have shown that the outwards steaming particles move collectively, with the patterns arising from variations of pressure gradients early after the collision. This phenomenon, called "azimuthal anisotropy", is analogous to the properties of fluid motion. The results from such analyses suggest that colour degrees of freedom carried by quarks and gluons are present in the produced medium, which "flow" with negligible shear viscosity. Thus, the produced QCD matter behaves like a perfect liquid [1–4].

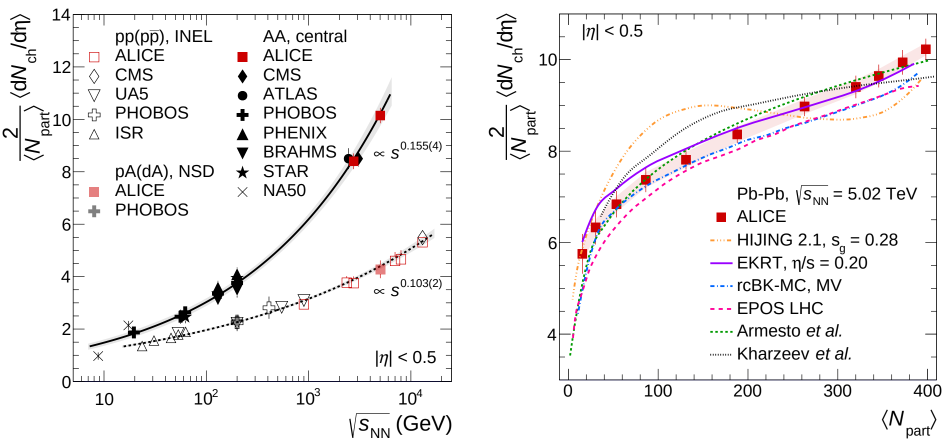

Fig. 1. Charge particle multiplicity in *pp* and *AA* collisions as a function of c.m.s. energy [5] (left panel) and the number of participants [6, 7] (right panel).

2. Hard probes

It has been found that the matter in the collision zone is extremely opaque to the passage of partons from hard scattering processes in the initial state of the collisions. These traversing partons loose energy via gluon Bremsstrahlung in the medium before their fragmention into hadrons. Nuclear effects are typically quantified using the nuclear modification factor R_{AA}, where the particle yield in nucleus–nucleus collisions is divided by the yield in *pp* reactions scaled by the number of binary collisions. $R_{AA} = 1$ would indicate that no nuclear effects, such as Cronin effect, shadowing or gluon saturation, are present and that nucleus–nucleus collisions can be considered as an incoherent superposition of nucleon–nucleon interactions. Figure 2 illustrates the R_{AA} of inclusive charged hadrons measured in a broad kinematical range by the ALICE, ATLAS and CMS experiments [8]. A strong suppression is observed in the most central collisions at mid-rapidity. Further studies are needed to see whether a plateau is present at high-$p_{\rm T}$.

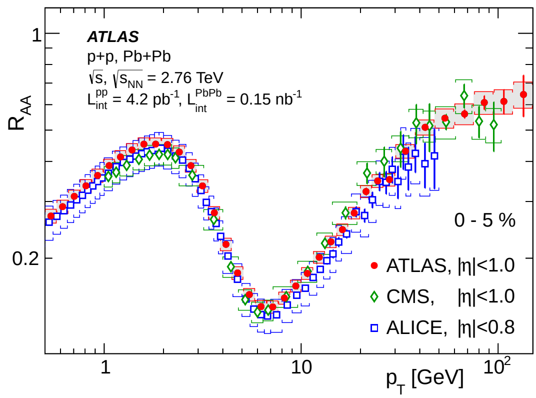

Fig. 2. Nuclear modification factor R_{AA} of inclusive charged hadrons measured in a broad kinematical range by the ALICE, ATLAS and CMS experiments [8].

A profound understanding of the parton energy loss in the medium is one of the current intriguing issues in the field. The study of heavy-flavour (charm and bottom) production in heavy-ion collisions provides key tests of the parton energy loss mechanisms for understanding the properties of the produced medium. Due to their large mass ($m > 1$ GeV$/c^2$), heavy quarks are primarily produced in initial hard partonic scattering processes in the early stages of the collision and, therefore, probe the complete space-time evolution of the medium. Thermal processes later in the collision might have a small contribution to heavy-quark production at low transverse momentum [9]. Theoretical models predicted that heavy quarks should experience smaller energy loss than light quarks while propagating through the QCD medium due to the suppression of small angle gluon radiation, the so-called *dead-cone effect* [10, 11]. Of particular interest is the dependence of the parton energy loss on colour charge and quark mass [12], which gives access to the dynamical properties of the QGP.

Figure 3 (left panel) shows the R_{AA} of prompt D mesons at mid-rapidity in the 10% most central lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV [13, 14], which is strongly suppressed (by factor of 4–5 above 5 GeV$/c$). A detailed model-data comparison is discussed in [15]. There is an indication that prompt D mesons are less suppressed than light quark hadrons at low transverse momentum (*cf.* Fig. 3, right panel) but more precision data is needed before the final interpretation of the data. Measurements in proton–lead collisions provide access to cold nuclear matter effects in the initial state of the collision, such as Cronin enhancement, nuclear shadowing and gluon saturation [16–18]. Figure 4 shows the R_{AA} of prompt D mesons in p–Pb collisions [19] compared with calculations from CGC [20] and NLO pQCD [21]. Also here, more precision data are needed to test and rule out the model calculations.

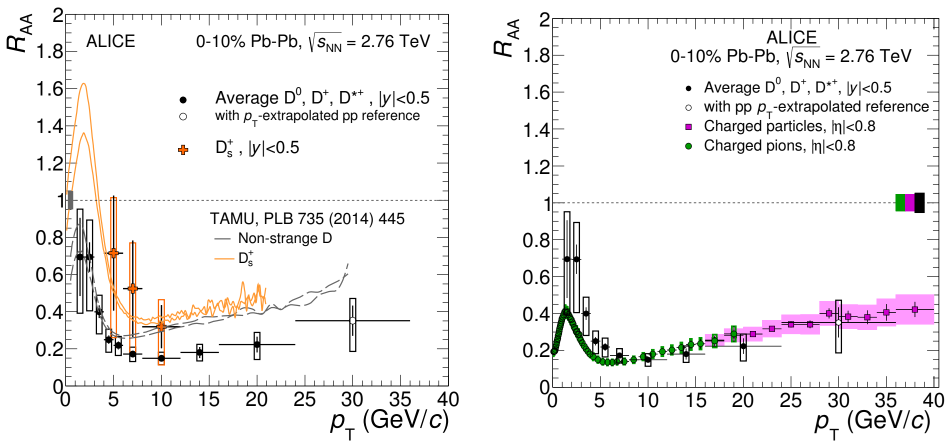

Fig. 3. Nuclear modification factor R_{AA} of prompt D mesons at mid-rapidity in the 10% most central lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to the D_s^+ R_{AA} [13] (left panel) and the charged hadron R_{AA} [14] (right panel).

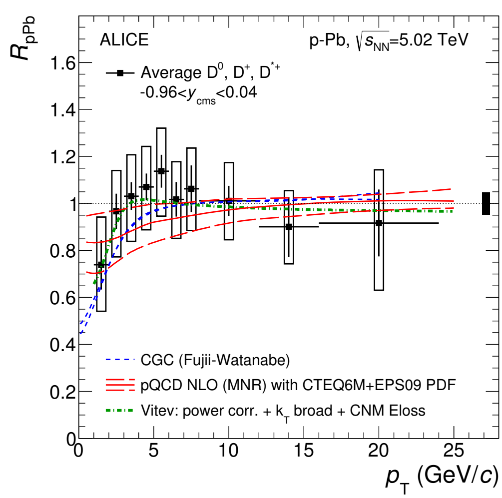

Fig. 4. R_{AA} of prompt D mesons in p–Pb collisions [19] compared with calculations from CGC [20] and NLO pQCD [21].

The centrality dependence of prompt D meson R_{AA} is depicted in Fig. 5 (left panel) together with the R_{AA} of J/Ψ from beauty decays [22]. There is a first indication that beauty is less suppressed than charm in heavy-ion collisions. However, there remains an uncertainty from the comparison in a proper kinematical range. This urge the need for the measurement of directly reconstructed B mesons. The CMS experiment showed first data on the R_{pA} of B mesons in p–Pb collisions [23], which is unity and shows no p_{T} dependence. The detector upgrade of the LHC experiment and the foreseen increase of the LHC interaction rate in Run 3 will make it possible to measure fully reconstructed B mesons in nuclei–nucleus collisions over a broad kinematical range.

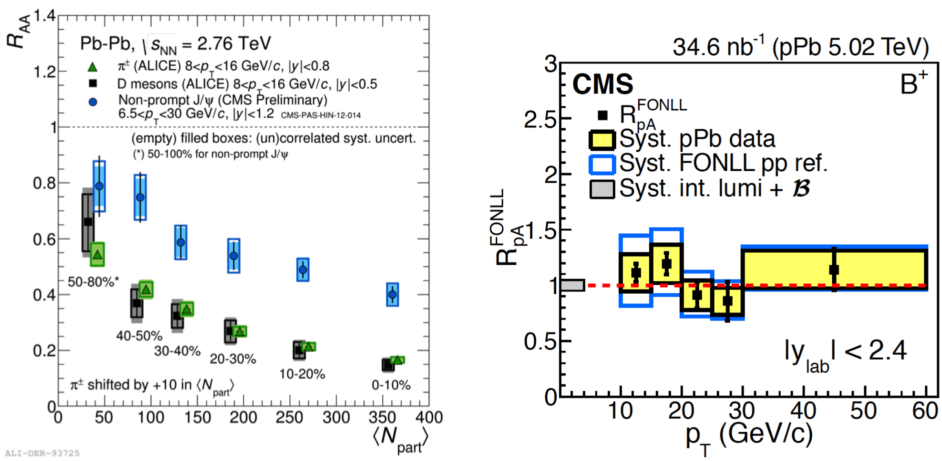

Fig. 5. R_{AA} of prompt D mesons and J/Ψ from beauty decays [22] *versus* collision centrality (left panel) and the R_{pA} of B mesons in p–Pb collisions [23].

3. Summary and outlook

The heavy-ion programme at RHIC and the LHC allowed to further study and characterise the properties of the quark–gluon plasma. Heavy quarks are sensitive penetrating probes to study the dynamical properties of the plasma, especially the quark-mass dependence of the parton energy loss. Measurements in pA systems (d–Au at RHIC and p–Pb at the LHC) provided clear evidence that the suppression of the particle yield in heavy-ion collisions is a final state effect, namely due to the interaction of the hard scattered partons with the QCD matter. Furthermore, a new phenomenon, called the "long-range correlation in pseudorapidity", was observed. Its origin is not fully understood yet and will further be studied with the 2017 p–Pb data of the LHC. The observed medium effects are expected to be even stronger in central lead–lead collisions at the highest LHC collision energy

($\sqrt{s_{NN}} = 5.5$ TeV) that will be available in Run 2 (2015–2018). The increase of the interaction rate for the LHC Run 3 after the second long shutdown in 2019/20 will require a significant upgrade of the experiments to substantially improve the current performances, especially for the measurements of heavy-flavour particles.

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