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Results on QGP by ATLAS and CMS

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Summary. — Quantum chromodynamics (QCD) on the lattice predicts that at high temperatures and energy densities, hadronic matter undergoes a phase transition and turns into a state of deconfined quarks and gluons known as quark-gluon plasma (QGP). This state of matter is typically thought to be created in the collisions of two heavy nuclei at ultrarelativistic energies, like the ones reached at the LHC. Despite the multiyear effort, much remains to be learned about parton densities in nuclei, the search for the possible onset of parton saturation, how the properties of QGP emerge at a microscopic level from the interactions among the individual partons and how subsequently vary across its phase diagram. The ATLAS and CMS Collaborations fully exploit the opportunities offered by high-density QCD studies with ion and proton beams that allow the study of cold nuclear matter effects, the onset of nuclear saturation, and long-range correlations. Additionally, experiments put emphasis on the examination of hadrons at high transverse momentum, fully reconstructed jets, heavy quarkonia, open heavy flavor particles, and jet quenching. Altogether, measurements at varying length scales provide quantitative information about the strongly coupled QGP, complementing the bulk and collective observables of the soft sector.

1. – Introduction

The heavy-ion program at the LHC has proven to be a successful and indispensable part of the ATLAS [1] and CMS [2] physics programs. These proceedings review the wealth of studies at the LHC exploiting opportunities offered by ion and proton beams in the realm of high-density QCD. Long-term commitments to the lifetime of the LHC program also requires synergies among experts in the accelerator, experimental, and theory communities.

2. – Early time dynamics and nPDFs

The presence of a nuclear environment has long been observed to modify the parton densities in the nucleus, as compared to those in a free nucleon [3]. Such nonperturbative effects are modeled using nuclear PDFs (nPDFs) determined with data in the same collinear factorization approach as for free protons. Measurements of electroweak

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(EW) bosons in proton-nucleus and nucleus-nucleus collisions [4] probe quark nPDFs [5], whereas dijets and top quarks are sensitive to gluon modifications at different Bjorken-x. Precision measurement of EW bosons in peripheral nucleus-nucleus collisions provide an experimental reference for the expected yields of high-p_{T} probes in the absence of final-state effects, which can lead to an improved understanding of the onset of jet quenching in smaller systems like in proton-proton (pp) collisions (see sect. **4**).

These systems also constitute a starting point for understanding the relative importance of two competing mechanisms that give rise to the azimuthal anisotropies observed, *i.e.*, the hydrodynamic expansion of the system against the momentum correlations in the initial state. Significant, nonzero v_2 and v_3 values are measured in photonuclear events, as shown in fig. 1 (left), whereas in photon-proton interactions no long-range near-side ridge-like structure is found within the multiplicity range reached [6].

Quasi-real photons, exchanged in relativistic heavy-ion interactions, are also powerful probes of the gluonic structure of nuclei. The first measurement of the coherent J/ψ photoproduction cross-section off lead nuclei has been presented as a function of the photon-nuclear center-of-mass energy per nucleon ($W_{\gamma\mathrm{N}}^{\mathrm{Pb}}$), by applying a forward neutron tagging technique. As shown in fig. 1 (right), the cross-section appears to plateau above $W_{\gamma\mathrm{N}}^{\mathrm{Pb}} \approx 40\,\mathrm{GeV}$, up to $400\,\mathrm{GeV}$, where a new regime of gluon momentum fraction (Bjorken-$x \approx 6 \times 10^{-5}$) in a heavy nucleus is probed.

3. – Heavy quarks and quarkonia

The suppression of hadron production in heavy-ion collisions, encompassing both nucleus-nucleus and proton-nucleus collisions, can be quantified using the nuclear modification factor. Heavy flavor quarks, especially charm and bottom, are produced at an early stage in hard scattering processes and hence probe QGP over its full evolution. Measurements at Relativistic Heavy-Ion Collider (RHIC) and LHC energies show

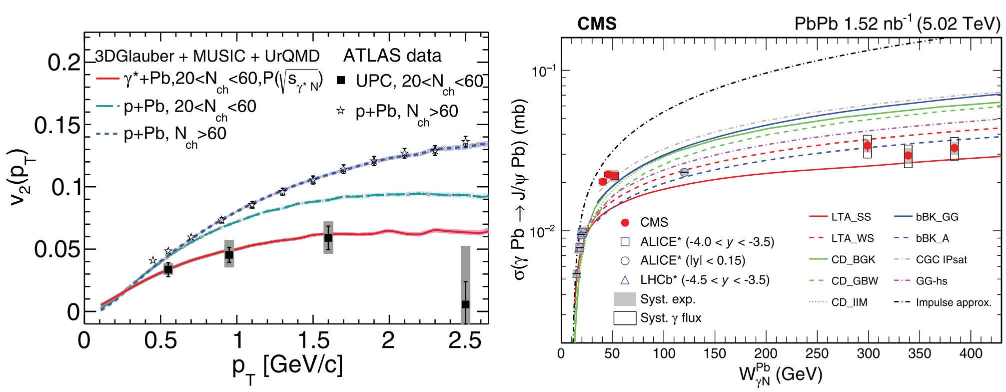

Fig. 1. – Left: the p_{T}-differential elliptic flow coefficient $v_2(p_{\mathrm{T}})$ of charged hadrons in PbPb and γ^*Pb collisions from simulations compared to ATLAS data [7,8]. Right: the total coherent J/ψ photoproduction cross-section as a function of $W_{\gamma\mathrm{N}}^{\mathrm{Pb}}$ from the CMS measurement in pPb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [9]. Approximated results (implied by the asterisk) from the ALICE [10, 11] and LHCb [12] experiments are displayed for specific rapidity regions, where the two-way ambiguity effect is expected to be negligible. Predictions from various theoretical calculations are shown by the curves.

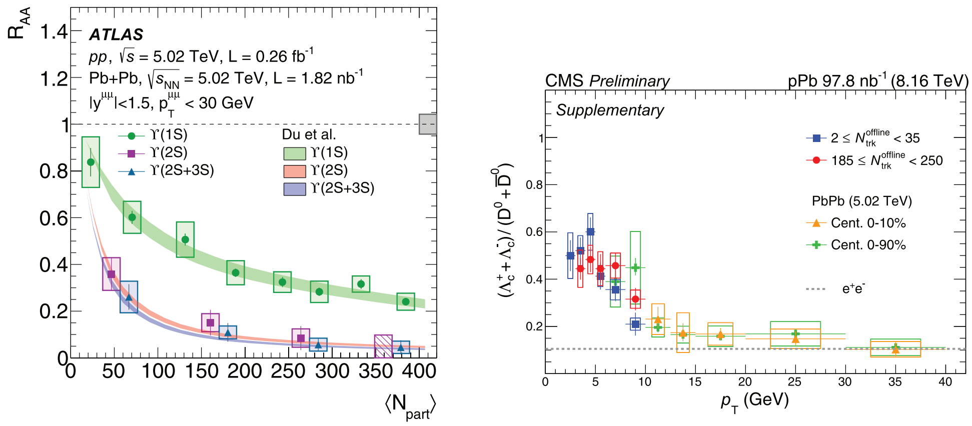

Fig. 2. – Left: the nuclear modification factor of $\Upsilon(2\mathrm{S})$, $\Upsilon(3\mathrm{S})$, and combined $\Upsilon(3\mathrm{S})$ with $\Upsilon(4\mathrm{S})$ as a function of centrality at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [16] compared to calculations (the bands represent 95 % confidence level limits). Right: the Λ_c^+/D^0 yield ratio in PbPb [17] (with multiplicity $2 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 35$ and $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$) and pPb [18] (with centrality 0–10 and 0–90 %) collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ and $5.02\,\mathrm{TeV}$, respectively. The ratio of production yields of charm hadrons in $\mathrm{e}^+\mathrm{e}^-$ collisions is plotted for reference too [19].

strong suppression of charmonia and bottomonia in nucleus-nucleus collisions compared to pp collisions [13]. As shown in fig. 2 (left), the suppression increases for more central events, as well as for the excited states $\Upsilon(3\mathrm{S})$ and $\Upsilon(4\mathrm{S})$ (now observed in pPb collisions [14]) relative to $\Upsilon(2\mathrm{S})$, namely the ground state. Discrimination between the different implementations of effects underlying the dynamics of quarkonium states in the QGP requires additional precision data from upcoming runs at RHIC and the LHC. Same for the B_c^+ measurement [15] which sets forth a promising new probe of the interplay of suppression and enhancement mechanisms in the production of heavy flavor mesons in the QGP.

There have also been paradigm shifts in our understanding of the production of heavy flavor particles through the fragmentation-dependent measurement of the J/ψ interaction with the QGP [20]. Models that describe Υ meson production and its dynamics in high-multiplicity pp collisions are also studied using charged hadrons in events with Υ mesons [21].

Thus, a thorough understanding of both the in-medium interactions and the subsequent hadronization processes is needed to correctly interpret the experimental data. Through a quark-recombination mechanism, a corresponding yield enhancement of hadrons containing strangeness (*e.g.*, B_s^0) is expected relative to corresponding hadrons that do not contain strange quarks (*e.g.*, B^+) [22]. Similarly, the production of Λ_c^+ baryons probes the parton coalescence contribution for baryon production for a variety of collision systems. The parton coalescence effect is expected to be stronger with increasing system size and can enhance the baryon relative to the meson yield at intermediate p_{T}. A large, p_{T}-dependent enhancement in the $PcgLp/\mathrm{D}^0$ yield ratio in heavy ions relative to pp collisions is seen (fig. 2, right), as predicted by models including the coalescence of charm and light-flavor quarks in Λ_c^+ baryon production. The first measurement of Λ_c^+/D^0 yield ratios in proton-lead collisions is also presented as a function of p_{T} and final-state multiplicity [17]. Interestingly, no strong multiplicity dependence is observed for charm hadrons within the experimental uncertainties. The difference between these results for charm quarks and previous ones for light quarks might indicate that coalescence processes of heavy quarks saturate earlier than those of light quarks.

4. – Medium modifications

A precise measurement of inclusive charged-hadron production in all collision systems delivered by the LHC was recently presented in wide ranges of centrality, p_T, and pseudorapidity (η) [23]. These data provide comprehensive constraints on theoretical descriptions of soft and hard processes in the QGP in a variety of collision systems. Theoretical models typically describe the nuclear modification factor better in central collisions and in the p_T range from $\approx$10 to about 100 GeV, while they tend to deviate from the data at higher p_T or in more peripheral collisions. Complementary to these measurements, inclusive jet spectra reconstructed using different distance parameters R, *e.g.*, in the anti-k_T algorithm, are of great interest because they are less sensitive to hadronization effects than observables involving individual final-state hadrons. The measurements of jet spectra are extended to large-area jets, with R up to 1.0 [24]. For the most central pPb collisions, strong suppression is observed for jets with p_T reconstructed independently of R, revealing a significant tension in view of the large area jet data.

The interactions between high-energy partons and the QGP are expected to depend on the QCD color charge and mass. Therefore, inclusive and b-jets are sensitive to different effects in the QGP. Medium-induced gluon radiation is expected to be suppressed for heavy quarks by the dead-cone effect. Measurements of heavy quark jets are also expected to be sensitive to the mixture of radiative and collisional energy loss in the QGP. The larger measured ratio of the nuclear modification factors between b and inclusive jets in central pPb collisions suggests that the observed differences may arise primarily from the different mixture of quark and gluon jets, with the b quark mass effect being subdominant in the measured kinematic range. As shown in fig. 3 (left), the measurements compared to theoretical calculations suggest a role for mass and color-charge effects in partonic energy loss. At the same time, comparisons between photon-tagged and inclusive jet measurements —which have a large gluon-initiated jet fraction— provide a strong confirmation of larger jet quenching for gluon jets compared with quark jets [27].

Although the anisotropic flow for hadrons has been extensively studied, relatively few similar measurements have been performed for jets so far. Jet yields can exhibit correlations with the symmetry planes in an event since the evolving parton showers experience various in-medium path lengths or medium densities as they pass through the QGP. Fourier coefficients v_2–v_4 are determined for jets from events containing jets [28] (also back to back [26]). As shown in fig. 3 (right), these results are qualitatively consistent with expectations from a path-length dependence of in-medium energy loss. Simultaneous constraints imposed by measurements of nuclear modification factors and Fourier coefficients could provide important information to understand heavy-quark transport and QGP properties [29].

Collectivity is unambiguously observed in smaller collision systems, including collisions with pp and PbPb. On the contrary, while jet quenching is observed in pPb collisions, no evidence has been found in these small systems to date, possibly raising fundamental questions about the nature of the system created in these collisions. There have been recent data which serve as a sensitive probe of jet quenching effects and place strong limits on the degree to which the propagation and fragmentation of hard-scattered partons is modified in small hadronic collisions. Examples, as shown in fig. 4,

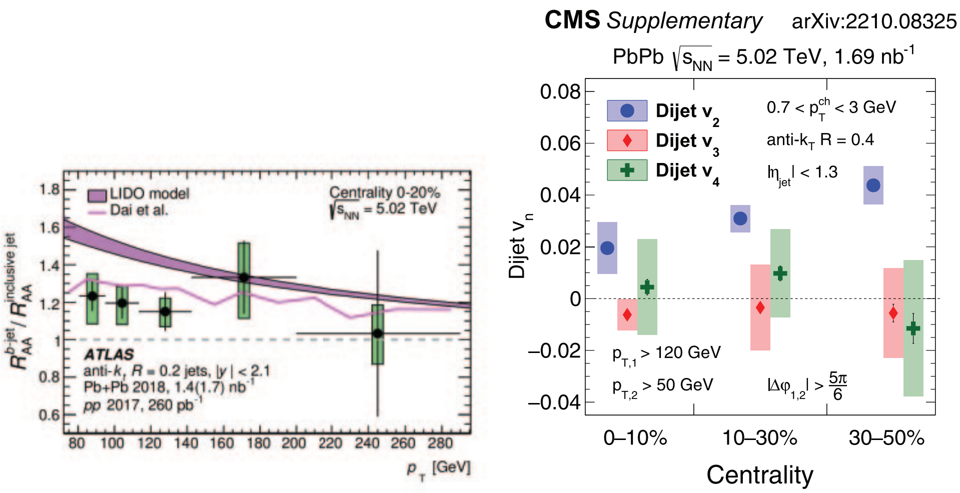

Fig. 3. – Left: the ratio of the nuclear modification factors of b to the inclusive jets for each centrality class. Ratios are compared with theory calculations (the width of the band shows variation of one of the parameters in the modeling) [25]. Right: dijet v_2, v_3, and v_4 results presented as a function of centrality [26].

are the measurements of charged-hadron yields and their ratios I_{PbPb} in the azimuthal directions away from and near to jets in PbPb collisions, compared with those in pp collisions [30], or ”jet hadrochemistry” studies focusing on the relationship between the ridge that spans an extended rapidity range and hard or semi-hard scattering processes in pp collisions [31]. Future measurements applying these techniques in PbPb collisions, or extending the current one to higher p_{T}, can give insight into possible differences (or similarities) between jet and underlying-event correlations in pp and PbPb collisions.

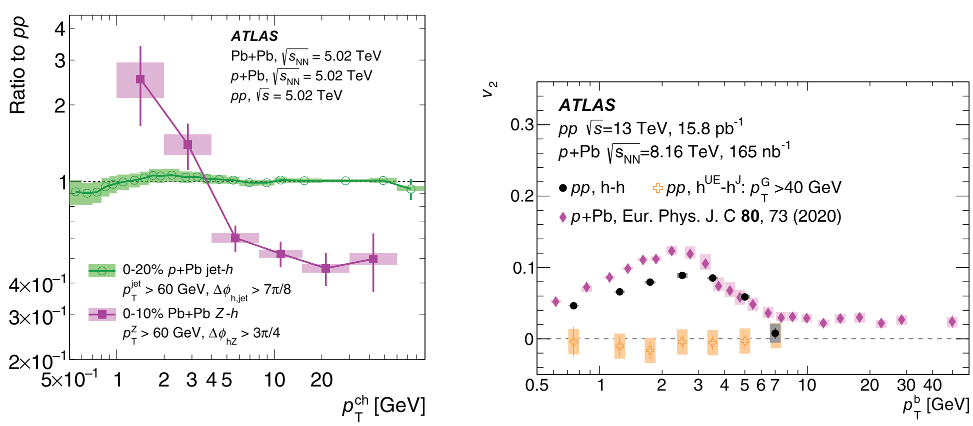

Fig. 4. – Left: comparison of the jet-hadron I_{PbPb} in 0–20 % PbPb collisions (green) with the same quantity I_{AA} but using Z-hadron events in 0–10 % pPb collisions (pink) [30]. Right: comparison of the v_2 measured in the “hh” (*i.e.*, excluding charged particles associated with jets from the correlation analysis) and “hjet” (*i.e.*, considering particles within jets and charged particles from the underlying event) classes to that measured in PbPb events [31].

5. – Outlook

As illustrated by the ATLAS and CMS future plans [32], the continuation of the LHC heavy-ion physics program into Run 3 and beyond is a unique opportunity in the upcoming decade. The predicted factor of ten increase in integrated luminosity compared to the initial LHC program, combined with new and improved ATLAS and CMS detector components, will open the door for refined studies of QGP properties and complement the planned trajectory of the LHC pp program. This program has strong complementarity with other key research efforts in the nuclear physics QCD community (*i.e.*, existing efforts at RHIC and the upcoming Electron-Ion Collider), synergizes with technical developments in the high-energy physics community, and will play a key role in strengthening our understanding of both QCD and QED [33, 34]. Many phenomena in nuclei are nonperturbative and, therefore, not easily handled by a computational framework. However, a coordinated application of the QCD parton model for conventional hadrons, an effort to grasp exotic hadron spectroscopy [35], and advances from lattice QCD calculations [36, 37] could yield a fundamentally improved understanding of the characteristics of nuclei and their interactions.

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