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Heavy ions: jets and correlations

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Strongly interacting matter can be studied in the laboratory under extremely high energy density and temperature by creating ultrarelativistic heavy-ion collisions. Jets and correlations are invaluable tools to explore properties of this form of matter. Jets are sensitive to the interactions between energetic partons and the medium and to nuclear parton distribution functions, while correlations reveal details about the collective motion of the constituents of this fluid-like phase and can shed light on the role of the initial state properties. A few recent developments and results from the LHC and RHIC accelerators are discussed in this talk.

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PoS(EPS-HEP 2013)143

1. Introduction

The research of high energy heavy-ion collisions has experienced a remarkable boost since the last edition in this conference series. While the Large Hadron Collider (LHC) has increased the integrated Pb+Pb luminosity twenty-fold in the last two years and expanded the scope of the program by collecting p+Pb data, the Relativistic Heavy Ion Collider (RHIC) has continued its high statistics Au+Au data taking, including steps of the energy scan, and for the first time, U+U and Cu+Au collisions. The analysis of these high statistics data sets is ongoing, with significant advances of both specific areas discussed in this talk: jets and correlation studies. A wide range of theoretical developments were also triggered by these new results, including various interpretations of novel two-particle correlations, and descriptions of jet modifications in the presence of the strongly interacting medium, parton showers, studies of nuclear parton distribution functions.

Only a limited set of recent and most important jet-related results could be included in this brief summary. Namely, jet energy imbalance studies in Pb+Pb and p+Pb collisions; jet suppression at high transverse momenta with respect to proton-proton collisions; nuclear modification of jet shape and fragmentation. Correlations are actively studied between charged particles, between jets and photons; jets and hadrons; two jets; just to name a few. In the following, only a brief discussion on the asymmetries of particle and jet production, on two-particle correlations, and especially on long-range correlations in various collision systems will be presented.

Research in heavy-ion physics is primarily related to understanding Quantum Chromodynamics (QCD) and the strong interaction, which – in spite of a simple-looking Lagrangian and a very profound role in Nature – encompasses a wealth of complicated phenomena. Relativistic heavy-ion collisions are suitable experimental tools to study many of these, due to the attainable large energy density and temperature, and the thereby emerging new phases of matter, characterized by partonic degrees of freedom. The interplay between perturbative and non-perturbative processes makes this subject intriguing and challenging both theoretically and experimentally. Experiments with ultra-relativistic ion collisions may enlighten us about certain aspects of hadron structure at high energy (saturation, nuclear modifications of the parton distribution functions), and the properties of the created hot and dense medium (thermalization, hydrodynamical behavior, the nature of its building blocks and of the interactions between them).

Heavy-ion collisions occur at a randomly distributed impact parameter. In central collisions most of the nucleons interact, while peripheral (grazing) collisions have spectator and participant nucleons. The collision centrality is characterized by one of three quantities: a) the percentile of the total inelastic hadronic cross section, based on a given quantity that has a monotonic relationship with the impact parameter (i.e. 0-10% meaning the 10% most central collisions); b) the number of nucleons participating in the collision (participants, N_{part}); c) the number of binary collisions, N_{coll}, between nucleon pairs. While a) is a measurable quantity, the determination of N_{part} and N_{coll} also relies on a Glauber model and detector simulation. The number of hard/rare processes, such as the production of very energetic jets and hadrons, electroweak bosons and quarkonium states is expected to be proportional to N_{coll} in the absence of nuclear effects, thus N_{coll} is commonly used in comparisons between particle yields measured in p+p and Pb+Pb collisions.

At the RHIC and LHC accelerators, three large experiments are designed for heavy-ion measurements: STAR [1], PHENIX [2] and ALICE [3]. ALICE and STAR feature large volume time

PoS(EPS-HEP 2013)143

projection chambers and are optimized for particle identification, employing virtually all known identification techniques. These experiments have excellent low momentum tracking. ALICE also has a forward muon spectrometer and a low-mass tracker with precise vertexing capabilities, and suited to reconstructing and triggering on jets. PHENIX excels in pion, kaon, proton, electron and photon identification in its central arms, and in muon identification in the muon arms.

ATLAS [4] and CMS [5] are general purpose experiments at the LHC, and they are powerful tools to study ion collisions, especially jets (due to their excellent calorimetry with large angular coverage, $|\eta| < 5$) and correlations (due to their tracking systems, also extended in the $|\eta| < 2.5$ region). Jets can be reconstructed combining the tracks and calorimeter signals, they have excellent muon detection capabilities and track momentum resolution up to hundreds of GeV/c transverse momenta, and equipped with forward calorimeters (ZDC, CASTOR, HF). Their flexible multi-level trigger systems designed for very high luminosities are invaluable for the success of jet and correlation studies. The integrated luminosity of relevant data sets collected by these LHC experiments amounts to about 160 μb^{-1} for Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, 30 nb^{-1} for p+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV and 5 pb^{-1} for p+p collisions at $\sqrt{s} = 2.76$ TeV.

2. Jets in heavy-ion physics

The lifetime of the hot and dense medium created in a heavy-ion collision is too short to apply any external source to irradiate it in order to obtain tomographic information. Instead, internal sources, 'probes' that are created in the collision itself are commonly employed for this purpose. High-p_T jets are a prominent choice, since they have been extensively studied both theoretically and experimentally (in e^+e^- and p+p($\overline{\rm p}$) colliders), and represent color-charged objects (quarks, gluons) that strongly interact with the mentioned medium. Modification of the yields (cross sections), shapes, fragmentation, and correlations of jets with respect to those quantities measured in elementary particle collisions are related to the properties of the strongly interacting matter under these extreme conditions. The first observations of the very sizeable reduction in the jet (hadron) yields at high p_T in heavy-ion collisions when compared to the p+p baseline, was made a decade ago at RHIC by the STAR and PHENIX experiments (confirmed by PHOBOS and BRAHMS), and named 'jet quenching'. At the LHC the jet cross sections are higher, and the separation of jets from the background of the abundant 'soft' processes also pose less experimental complications.

The most frequently used prescription to combine jet components at the LHC is the anti-k_T algorithm [6], with a rather small radius parameter between 0.2 and 0.5, to minimize the fluctuations of the underlying event background. An example to subtract this background is an iterative procedure, where the background is calculated in constant pseudorapidity (η) slices, and subtracted from the energy density measured in the $\eta - \phi$ plane, where ϕ is the azimuthal angle around the beam-line. In the second step, jets are reconstructed, and the background is recalculated with the exclusion of the jets, and the subtraction is repeated. In the following, the jets are reconstructed again, taking into account the refined background subtraction [7].

The first and most spectacular manifestation of the parton energy loss in the strongly interacting medium was a pronounced dijet energy imbalance in central Pb+Pb collisions [8, 9]. At the same time, the jet partners are observed to remain back-to-back in ϕ, suffering no more angular decorrelation than dijets in p+p collisions [9]. These initial results have not been sufficient to clearly

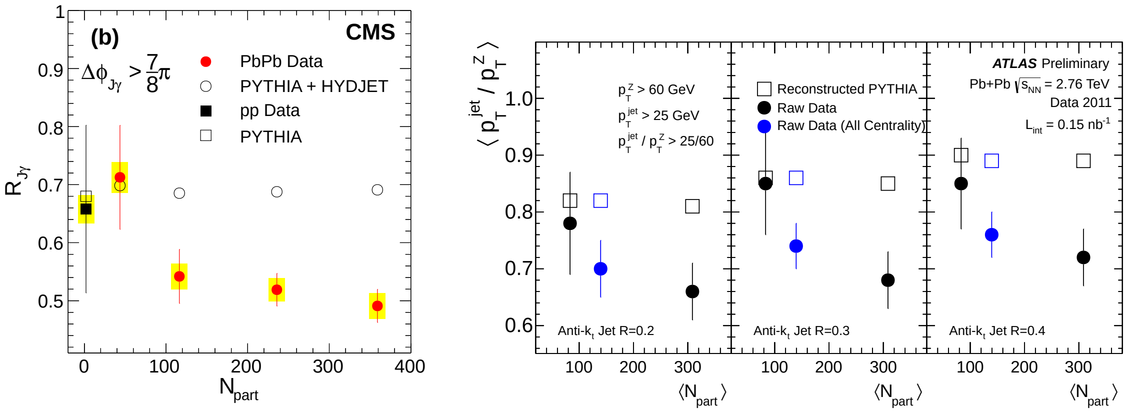

Figure 1: Left panel: Average fraction of isolated photons with an associated jet above 30 GeV/c, $R_{J\gamma}$, as a function of N_{part}. The yellow boxes indicate point-to-point systematic uncertainties and the error bars denote the statistical uncertainty [13]. Right panel: The mean $p_{\text{T}}^{\text{jet}}/p_{\text{T}}^{Z}$ values for different jet cone sizes, compared with PYTHIA Z boson + jet simulated events, as a function of $\langle N_{\text{part}} \rangle$. Bars represent statistical uncertainties. The blue points refer to 0–80% centrality [14].

distinguish between various possible scenarios for parton energy loss, such as soft collinear radiation (GLV and others [10]), hard radiation (PYTHIA-inspired models, modified splitting functions [11]) and large-angle soft radiation (QGP heating, AdS/CFT [12]), and more detailed experimental investigations have continued.

In order to ‘calibrate’ the jet (parton) energy loss, it is instructive to correlate colorless particles, such as high energy photons or Z bosons, with jets. The photon or Z tag provides the direction and p_T of the initial quark to first order. Besides the γ-jet energy imbalance, the fraction of high-p_T photons that had a jet in the azimuthally opposite direction ($\Delta\phi > 7\pi/8$) above a certain p_T threshold was found to be significantly – by about 20% – smaller in the most central Pb+Pb collisions than in p+p collisions [13], as shown on the left panel of Fig. 1. Both γ-jet and Z-jet events exhibit a decreasing trend of the $p_T^{\text{jet}}/p_T^{\gamma(Z)}$ ratio as a function of N_{part}, indicating that jets lose about 15-20% of their p_T in central heavy-ion collisions compared to the same ratio for the p+p reference [13, 14] (right panel of Fig. 1).

The centrality-dependence of the suppression of the inclusive single jet yield can be expressed either by the quantity R_{CP}, which is the ratio between the jet p_T distributions in central and peripheral collisions (each normalized by $\langle N_{\text{coll}} \rangle$ in the respective centrality bin), or by R_{AA}, which has a similar definition except that peripheral ion collisions are replaced by p+p collisions. A continuous evolution of the ratio R_{CP} is found as a function of N_{part} for charged particle jets by ALICE [17] and for full jets by ATLAS [18]. The ratio R_{AA} for full jets was measured by CMS [15], and a suppression of the jet yield by a factor of two was obtained in the $p_T > 100$ GeV/c range for central collisions, as can be seen on the left panel of Fig. 2. The ALICE experiment has also measured the R_{AA} for jets in Pb+Pb collisions [16], which is found to be in qualitative agreement with the nuclear modification factors of charged hadrons (right panel of Fig. 2).

The parton propagation in the medium can give rise to modifications of the jet shape and

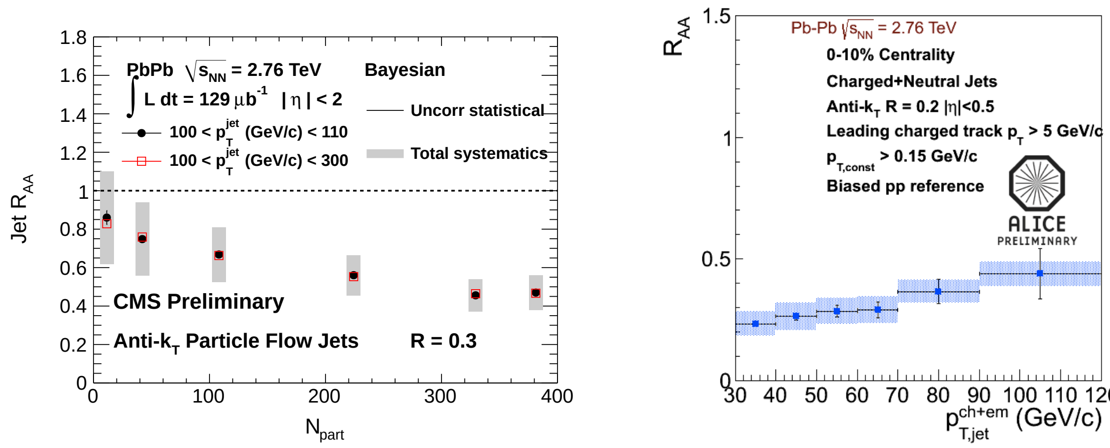

Figure 2: Left panel: Bayesian unfolded jet R_{AA} for anti-k_T jets of R=0.3 as a function of N_{part}. Closed circles represent the jet R_{AA} for $100 < p_T < 110$ GeV/c, and open boxes the jet R_{AA} for $100 < p_T < 300$ GeV/c. Vertical lines represent the uncorrelated statistical uncertainty and the wide grey bands represent the systematic uncertainty combined with the uncertainty from T_{AA} [15]. Right panel: The R_{AA} in the 10% most central events [16]. The statistical and systematic uncertainties from the pp and Pb+Pb analyses are added in quadrature. The combined systematic uncertainties are shown as dotted boxes.

fragmentation pattern, which may serve to clarify the role of various mechanisms in the parton energy loss. The simplest approach to measure jet shapes is to form the ratio of jet cross sections with different radius parameters. Such ratio was found to be comparable between p+p, central and peripheral Pb+Pb collisions by the ALICE experiment for charged particle jets within systematic uncertainties in the $40 < p_T < 110$ GeV/c range [19]. A more sensitive observable to small deviations of the jet structure is the distribution of transverse momentum carried by charged particles as a function of the distance $r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ from the jet axis. A modest but significant excess of this quantity was observed in central Pb+Pb collisions, compared to peripheral and p+p collisions [20]. The number distribution of particles is also increased by about one particle per jet on average, at low p_T in central Pb+Pb collisions, as shown by the fragmentation pattern results of ATLAS and CMS [21, 22]. A low-p_T excess at large angles with respect to the jet axis was also found by PHENIX in γ-hadron correlations [23]. Studies of low-p_T jets and associated hadrons are an essential ingredient to study jet modification, which are however complicated by the underlying event background. The analysis of high-statistics Au+Au datasets at RHIC suggests a jet broadening at low p_T, compared to p+p collisions, deduced from correlations between near-side jets and away-side charged hadrons (as a means to mitigate the bias on the away side).

In summary, the experimental evidence shows that partons (jets) lose a significant amount of energy in the strongly interacting medium, while jet pairs remain in tight azimuthal correlation. Jet fragmentation patterns for leading hadrons are not modified (relative to the jet p_T) as opposed to low p_T, where an excess energy and number of fragments is observed, preferentially at large angles with respect to the jet axis. In the meantime, the theoretical treatment of the the subject advances from treatments of parton energy loss and leading hadrons towards studies of modification of parton showers and jets. Since jet production is a weakly coupled phenomenon, and the medium

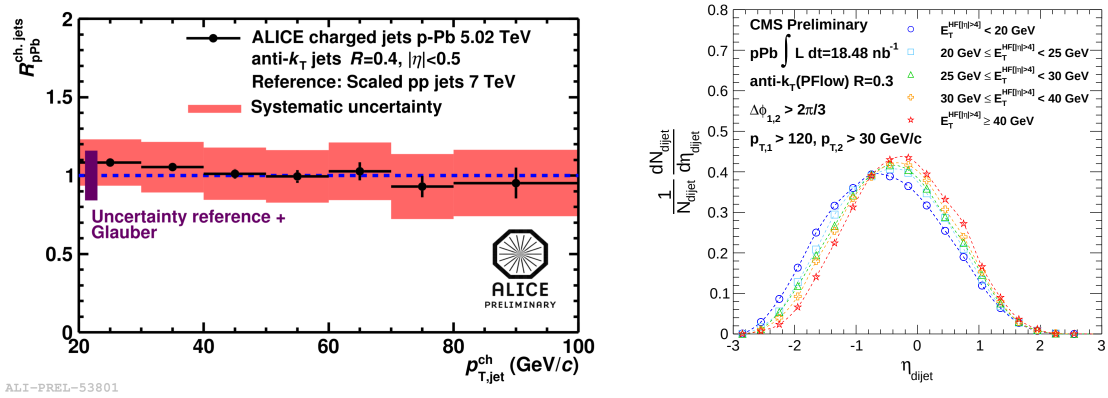

Figure 3: Left panel: Nuclear modification factors, R_{pPb}, for charged particle jets in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV reconstructed with the anti-k_T algorithm [25]. Right panel: Dijet pseudorapidity distributions in five HF activity classes. The distributions are normalized by the number of selected dijet events [26].

shows signs of a strongly coupled fluid, the appropriate theoretical approach should probably be a hybrid and sufficiently complex one. First-principle lattice QCD calculations are also underway to study the jet quenching parameter [24]. Correlation measurements already play an important role here, since various correlations between photons and hadrons, between jets and hadrons, etc., may differentiate between possible theoretical approaches.

The p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV delivered by the LHC in early 2013 serve as an important point of comparison with heavy-ion and elementary collisions. Charged particle jets in minimum bias p+Pb collisions have been shown by the ALICE experiment to have the cross section as expected from p+p collisions and N_{coll} scaling in the $20 < p_T < 100$ GeV/c range, within about 20% systematic and 15% additional scale (reference) uncertainty [25], depicted on the left panel of Fig. 3. This is an experimental indication that the jet suppression observed in Pb+Pb collisions cannot be explained by initial state effects. Although this result does not directly point to any jet suppression, modification of nuclear PDF in p+Pb collisions, other observables may be more sensitive to such effects. The CMS experiment has studied the η distribution of dijets, and a systematic and significant shift of the distribution was observed as a function of the forward transverse energy (activity) in the collision. Dijets in central events are shifted more to the direction of the Pb ion [26], as shown on the right panel of Fig. 3. The shift of the η_{dijet} distribution in minimum bias p+Pb collisions is only reproduced by pQCD calculations if the nuclear modifications of the PDFs are taken into account. The distribution of dijet momentum imbalance, $p_{T,2}/p_{T,1}$, is not modified even in central p+Pb collisions compared to the p+p reference with the present experimental precision [26], although very peripheral Pb+Pb events – comparable in forward energy flow – are not expected to show a significant effect either.

3. Correlation studies with heavy ions

Generally, correlation measurements are widely employed in heavy-ion physics, starting from the collective motion of the strongly coupled medium to the already mentioned hard processes

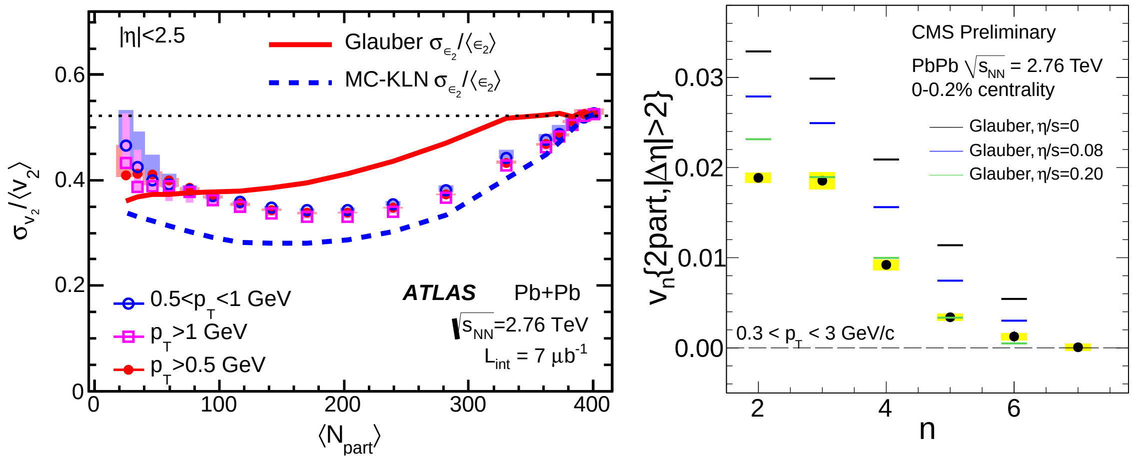

Figure 4: Left panel: $\sigma_{v_2}/\langle v_2 \rangle$ for three p_T ranges together with the total systematic uncertainties [28]. The values of $\sigma_{v_2}/\langle v_2 \rangle$ are compared with the $\sigma_{\varepsilon_2}/\langle \varepsilon_2 \rangle$ given by the Glauber model [29] and MC-KLN model [30]. Right panel: Fourier-components, v_n, measured in ultra-central Pb+Pb collisions, compared to models calculations with different η/s values [31].

involving jets, electroweak bosons and hadrons. A limited selection of recent developments on correlations will be discussed in this section, concentrating on non-perturbative phenomena.

As it was shown by the pioneering measurements at the SPS and RHIC accelerators, the form of matter created in highly energetic heavy-ion collisions is capable of collective motion, which manifests itself as a correlation between the direction of the motion of produced particles and the impact parameter vector, and consequently, also between pairs of final state particles. The azimuthal asymmetry of the almond-shaped initial collision zone translates into an azimuthal asymmetry of the final state particle distribution through hydrodynamical flow. The distribution of final state particles takes the form of $dN/d\phi \propto 1 + \Sigma_{n=1}^{\infty} 2v_n(p_T, y)\cos[n(\phi - \Psi)]$, and the Fourier coefficients, v_n, are related to the properties of the strongly interacting fluid, such as shear viscosity over entropy, η/s. Results on identified particles reveal a quark number scaling of these coefficients, highlighting the role of partonic degrees of freedom. Since asymmetries of single particle distributions are inherited by two-particle distributions, two-particle correlations constitute important and simple experimental means to study these phenomena.

Notably, jets – similarly to charged particles at low p_T – are not emitted uniformly either, but for a very different reason: the parton energy loss in the QCD medium depends on the path length traveled, thus the asymmetric overlap zone implies that the v_2 coefficient of jets will be non-zero, as confirmed by the recent results from ATLAS [27]. Whenever the focus of interest is the collective phenomena of the bulk particles (mostly at low p_T), correlations from jets ('non-flow effects') should be suppressed. A common way to achieve that is to require a large $\Delta\eta$ separation between correlated particles, the small $\Delta\eta$ region being dominated by jets and resonance decays.

The v_2 coefficient, termed 'elliptic flow' has been measured by ALICE, ATLAS and CMS in great detail, as a function of centrality, η [32], particle mass [33] (including open charm [34]), and even its fluctuations event-by-event [28], shown on the left panel of Fig. 4. Higher order

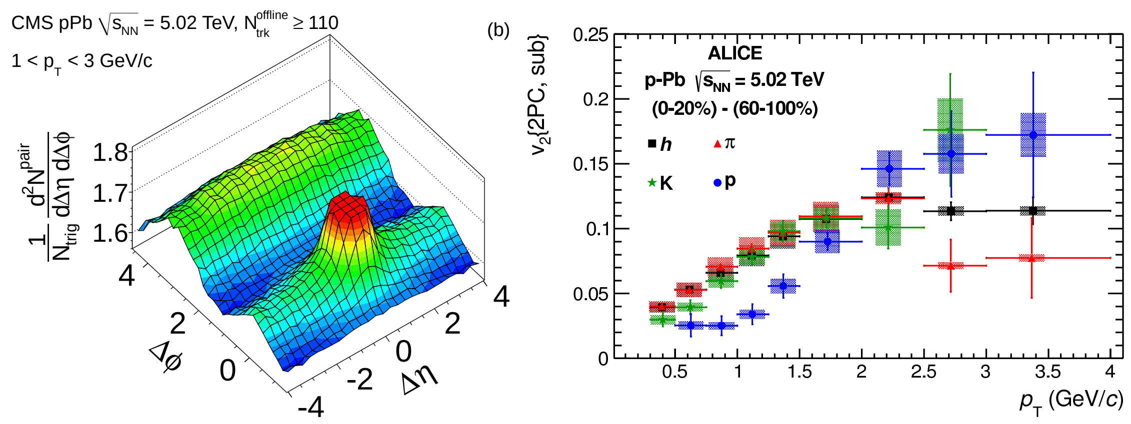

Figure 5: Left panel: 2D two-particle correlation function for p+Pb collisions for charged particle pairs with $1 < p_T < 3$ GeV/c and for $N_{\rm trk}^{\rm offline} \geq 110$ [38]. Right panel: the second Fourier coefficient for hadrons (black squares), pions (red triangles), kaons (green stars) and protons (blue circles) as a function of p_T in central p+Pb collisions after subtraction of the correlation from the peripheral multiplicity class. The data is plotted at the average p_T for each considered p_T interval and particle species under study. Error bars show statistical uncertainties while shaded areas denote systematic uncertainties [44].

coefficients, most importantly v_3, are related to initial state fluctuations and hydrodynamic properties, and the exploration of the full Fourier-spectrum (two-particle correlation functions) has been also carried out [35]. A unique perspective on hydrodynamic flow is offered by the v_n values in ultra-central Pb+Pb collisions and their comparison to hydrodynamic calculations, because of their sensitivity to the η/s quantity [31], as illustrated on the right panel of Fig. 4.

Perhaps the most striking recent correlation measurement emerged from the analysis of very high multiplicity p+p collisions at 7 TeV, where a long-range ($|\Delta\eta| > 2$), near-side ($\Delta\phi < 1$) structure (called the 'ridge') was observed by CMS [36], qualitatively similar to that already seen in Pb+Pb collisions both at RHIC and at the LHC [37]. A similar correlation structure was discovered in central p+Pb collisions as well by CMS [38], as shown on the left panel of Fig. 5. While the interpretation of the ridge in heavy-ion collisions is widely accepted to be a consequence of the fluctuations of the initial geometry and the hydrodynamical evolution, in case of more elementary collisions there are various competing theoretical explanations. Such an expression of hydrodynamical behavior was hardly expected there, and efforts are ongoing to account for the ridge by initial state effects alone, invoking the high-density Color Glass Condensate of the initial state [39]. A similar ridge on the away-side was discovered by ALICE, by subtracting the two-particle correlation function obtained in peripheral p+Pb collisions from that measured in central collisions [40]. The Fourier-coefficients v_2 and v_3 can also be evaluated from the data, using two-particle correlations or other methods, as a function of multiplicity [41] or event activity, as published by ATLAS [42]. Remarkably, the v_3 coefficients appear to be of the same magnitude in p+Pb and Pb+Pb collisions, provided that events with the same charged particle multiplicity are compared [41]. The v_2 and v_3 coefficients have also been measured using the high luminosity d+Au datasets at RHIC [43], yielding qualitatively similar results.

Identified particles may shed more light on the underlying mechanism of the ridge in p+Pb collisions, since a characteristic mass-ordering ($v_2(p) < v_2(K) < v_2(\pi)$ for $p_T < 2$ GeV/c) was observed in heavy-ion collisions both at RHIC [45] and at the LHC [33]. The p_T-dependence of the v_2 coefficient for pions and protons is well described by a hydrodynamical model [46]. Remarkably, a similar mass ordering ($v_2(p) < v_2(\pi) \approx v_2(K)$) was observed by the ALICE collaboration also in high-multiplicity p+Pb collisions, after subtracting the jet-like correlations using low-multiplicity collisions [44] (right panel of Fig. 5). This result suggests that hydrodynamics may also play an important role already in p+Pb collisions at high multiplicity.

4. Summary

Today, the Large Hadron Collider has completed two and a half years of successful heavy-ion research and opened a new era, while the productive RHIC program is still at its best. Jets and other hard probes (photons, W and Z bosons, quarkonium states) serve as excellent tools to study the QCD medium under extreme conditions due to their large production cross sections at LHC energies. On the other hand, it has also become possible to study p+p and p+Pb collisions at very high multiplicities, where several experimental observables and phenomena bears similarities to those in heavy-ion collisions. Various properties of the created medium are studied at a quantitative level with a growing variety of tools, such as parton energy loss via single jets, dijets, γ-jet and Z-jet pairs. Detailed jet shape and fragmentation studies are also emerging. Correlation measurements provide insight into the effects of initial geometry, the hydrodynamical evolution of the system and its physical properties. The continuing LHC program together with the RHIC energy scan, the already collected high statistics datasets and future runs are expected to complement each other towards a more thorough understanding of the rich phenomenology of strongly interacting matter.
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