Heavy Ions at the LHC

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1 The first LHC heavy ion run

On November 7, 2010, LHC provided the first Pb–Pb collisions at a centre of mass energy per nucleon pair of $\sqrt{s_{\rm NN}} = 2.76\,{\rm TeV}$. In the following 30 days the machine delivered an integrated luminosity of about $10\,\mu{\rm b}^{-1}$ per experiment corresponding to $\approx 80\,{\rm M}$ hadronic minimum-bias interactions. By the end of the period, the luminosity reached $3 \cdot 10^{25}\,{\rm cm}^{-2}{\rm s}^{-1}$. Notably, the intensity of $1.2 \cdot 10^{8}$ ions/bunch was 70% above the design value. ALICE [1], ATLAS [2] and CMS [3] participated in the heavy ion data taking and operated flawlessly. They presented first results a few weeks after the start of data taking. From RHIC to LHC the centre of mass energy has increased by a factor of 14. Therefore, the most pressing questions were: what are the conditions to study the Quark Gluon Plasma at the LHC? How much denser, hotter and more extended is the medium produced in central Pb–Pb collisions?

2 Measurement of basic medium properties

A first answer to these questions came from the measurement of the charged-particle density at mid-rapidity $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta|_{\eta=0}$. At RHIC, the low particle density was a surprise and ruled out most of the theoretical models. Hence, it was not unexpected, that many predictions for the LHC were lower than the value of about 1600 measured for the 5% most central Pb–Pb collisions [4]. Normalized by the number of participant nucleon pairs this value is about a factor of 2.1 higher than at the RHIC energy and the corresponding normalized transverse energy density increases by a factor of 2.5 [5, 6, 7]. Quite strikingly, the shape of the centrality dependence of both quantities is approximately the same at LHC and RHIC. Moreover, when plotted as a function of $\sqrt{s_{\rm NN}}$, the phenomenological power-law rise is significantly stronger in nucleus–nucleus collisions ($s^{0.15}$) as compared to pp ($s^{0.11}$), in agreement with a larger mini-jet contribution at higher energies. From the measured transverse energy density at mid-rapidity a rough estimate of the energy density of the produced medium can be derived. Assuming the same formation time, it is at least a factor of 3 above RHIC corresponding to a larger than 30% increase in temperature.

The extension of the medium can be assessed by interferometry of identical bosons, a method developed in analogy to the Hanbury-Brown Twiss optical intensity interferometry used to determine the space-time structure of extended sources in astronomy. In particle interferometry, the 3-dimensional momentum correlation function is constructed. It measures the size of the so called homogeneity region from which the volume of the QGP can be inferred. ALICE has measured the HBT radii in three orthogonal directions for central Pb–Pb collisions [8]. Results obtained at different energies are conveniently compared by plotting the radii against the cubic root of the charged particle density. A linear increase consistent with model predictions is observed. The homogeneity volume is the product of the three radii. Compared to RHIC, it has increased by a factor of 2.

One of the most important results from RHIC is, that the medium produced in central Au–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ behaves like an almost perfect liquid, i.e. it is strongly coupled having a very low shear viscosity. These properties are related to the ability of the medium to transform the initial spatial anisotropy of the reaction zone into a momentum space anisotropy. The latter is measured by the Fourier decomposition of the azimuthal angle distribution of the produced particles with respect to the reaction plane. The second term, v_2, is related to the pressure gradient created in the almond-shaped collision region and is called elliptic flow. As compared to RHIC, v_2 increases by 30% in mid-central collisions (40-50%) [9] showing that the system created at LHC still behaves like an almost perfect liquid. Interestingly, the p_{t} depedence of v_2 does not change between RHIC and LHC. It increases up to about $3\,\mathrm{GeV}/c$ above which it steadily falls [9, 10]. This behavior points to the change in another collective behavior, namely a stronger radial expansion at LHC. Indeed, this is confirmed by the analysis of the spectral shapes of pions, kaons and protons (about a 10% increase of the mean radial velocity $\langle \beta_r \rangle$ according to blast wave fits) [11].

Higher harmonics in the Fourier expansion can arise from fluctuations in the initial nucleon distribution. At LHC, they have been measured up to $n = 6$ showing a weaker centrality dependence than v_2 and their relative importance grows for very central collisions [12]. The shapes of di-hadron azimuthal angle correlations are directly affected by all flow components. In particular, the higher-order components represent a natural explanation of structures previously discussed under the name of *ridge* and *Mach cone*.

3 Medium modification of hard probes

Hard processes produce partons or particles at the very early stage of the heavy-ion collisions. These traverse the hot and dense medium and their yield and kinematics are influenced by its presence. Their measurement in pp (no medium) and pA collisions (cold nuclear matter) provide a reference for A–A collisions. Any differences can be attributed to the presence of the medium allowing the study of its properties. The suppression of particle yields in central heavy-ion collisions is usually quantified as the ratio between the yields in A–A to the yield in pp scaled by the number of binary collisions in A–A (R_{AA}). Alternatively one can compare central collisions to peripheral collisions (R_{CP}).

For direct γ production, no yield modification is expected, since photons do not interact strongly with the medium. Hence, they represent an excellent test for initial state effects (nuclear modified parton distribution functions). High p_{t} particles and hadron jets, are the manifestation of high $\hat{p}_{\mathrm{t}}$ partons that are produced in initial hard scatterings of partons from the incoming nuclei. Prior to hadronization, partons lose energy in the high color-density medium due to gluon radiation and multiple collisions. This phenomenon is known as jet quenching. Measurements of the modification of hadron spectra and jet structures are sensitive to the relevant degrees of freedom of the medium and the nature of the interaction with the medium. Finally, the suppression of quarkonia production ('melting') is sensitive to the temperature of the medium.

Direct γs. CMS identifies direct γs through isolation and shower shape cuts. They have measured the direct gamma R_{AA} between 20 and 80 GeV [13]. No nuclear modification is observed within the experimental uncertainties.

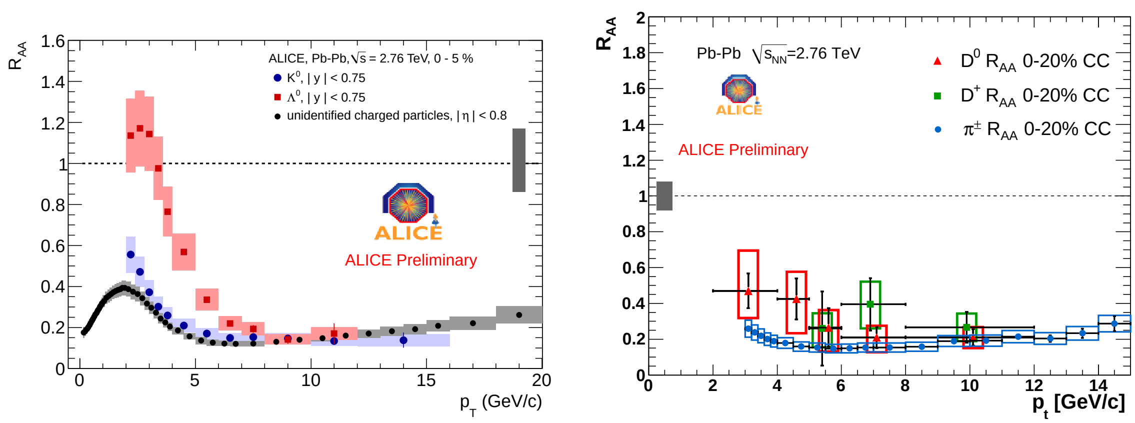

Figure 1: Nuclear modification factor R_{AA} for unidentified charged particles, Λ, K^0_s [14] (left panel) and D^0 and $\mathrm{D}^{\pm}$ compared to charged pions [16] (right panel).

High p_{t} Particle Suppression. Fig. 1 (left panel) shows $R_{\mathrm{AA}}(p_{\mathrm{t}})$ measured in central Pb–Pb collisions for inclusive charged particles, Λs and K^0_s [14]. The measurements indicate a strong suppression of high-p_{t} particles, consistent with a large energy loss of hard scattered partons. As at RHIC, baryons behave very differently at intermediate energies. However, for $p_{\mathrm{t}} > 8$ GeV, the suppression of all hadron species becomes universal. The suppression observed at LHC is stronger than in central Au–Au collisions at $\sqrt{s_{\rm NN}} = 0.2\,{\rm TeV}$ and the suppression is still about 50% at $100\,{\rm GeV}/c$ [15].

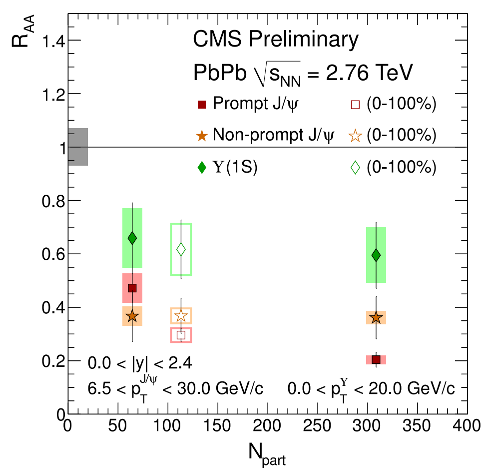

Figure 2: Number of participant dependence of $R_{\rm AA}$ for prompt and non-prompt J/ψ as well as for Υ(1S) [18].

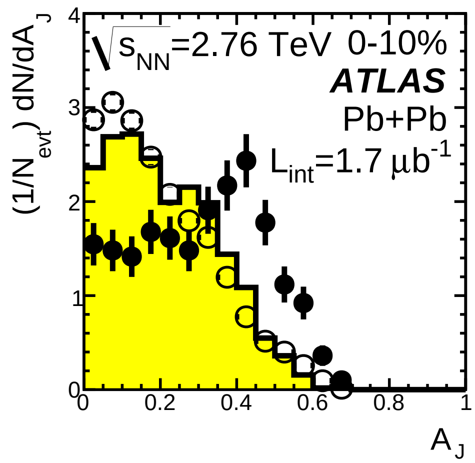

Figure 3: Distribution of the di-jet energy imbalance $A_{\rm J}$ for central Pb–Pb collisions (closed symbols), pp (open symbols) and jets embedded into HIJING (histogram) [20].

Heavy Flavor Production. ALICE has performed a direct measurement of charm suppression in central Pb–Pb collisions identifying D mesons in the decay channels $\rm D^+ \to K^-\pi^+\pi^+$ and $\rm D^0 \to K^-\pi^+$ [16]. In Fig. 1 (right panel), the D meson $R_{\rm AA}$ is compared to the charged pion $R_{\rm AA}$. Surprisingly above 5-6 GeV/c the suppression is almost the same. Due to the stronger coupling of gluons to the QCD medium (Casimir factor) one would expect that gluon dominated inclusive particle production is more suppressed than charm production. In addition, heavy quarks are expected to be less suppressed because of the so called dead cone effect.

Inclusive lepton spectra are dominated by semi-leptonic heavy flavor decays. At very high $p_{\rm t}$ semileptonic b-hadron decays are expected to dominate. ALICE observes that in central Pb–Pb collisions the inclusive lepton yield is suppressed by a factor of 3 [17].

A direct observation of b-quark suppression has been possible through the identification of non-prompt J/ψs. CMS separate prompt production and non-prompt J/ψ from B-decays using the distance between $\mu^+\mu^-$ vertex and primary vertex [18]. High-$p_{\rm t}$ prompt and non-prompt productions are strongly suppressed in central Pb–Pb collisions (Fig. 2). The measurement is consistent with the suppression of high-$p_{\rm t}$

muons observed by ALICE.

Di-Hadron Jet-like Correlations Di-Hadron correlations are studied by plotting the azimuthal angle difference ($\Delta\varphi$) between a trigger particle and associated particles satisfying certain p_{t} cuts. At high p_{t}, these correlations are dominated by jet fragmentation and exhibit the typical features of di-jet events, i.e. peaks at $\Delta\varphi = 0$ (near-side) and $\Delta\varphi = \pi$ (away-side). I_{AA} probes the interplay between the parton production spectrum, the relative importance of quark–quark, gluon–gluon and quark–gluon final states, and energy loss in the medium. On the near-side I_{AA} provides information about the fragmenting jet leaving the medium, while on the away-side it additionally reflects the probability that the recoiling parton survives the passage through the medium. The sensitivity of I_{AA} and R_{AA} to different properties of the medium makes the combination particularly effective in constraining models. In the 5% most central collisions, ALICE observes that the yield of charged particles with transverse momenta $p_{\mathrm{t}} > 3\,\mathrm{GeV}/c$ associated to trigger particles in the range $8 < p_{\mathrm{t}} < 15\,\mathrm{GeV}/c$ on the away-side drops to about 60% of that observed in pp collisions, while on the near-side a moderate enhancement of 20-30% is found [19].

Jets At LHC jet rates are high at transverse energies where jets can be reconstructed above the fluctuations of the background produced by the underlying event. The measurement of modifications of the longitudinal and transverse fragmentation function in heavy-ion collisions is sensitive to the details of the medium-induced energy loss. In particular, if the radiated energy stays inside the jet cone the longitudinal fragmentation function can be measured with a jet energy close to the original parton energy. In the absence of out-of-cone radiation, one expects an increase of particles carrying a low momentum fraction from the radiated energy and a suppression of particles with a high momentum fraction. This can be tested by studying di-jets events for which one expects in this case, that the transverse energy of the jets is approximately equal.

Quite interestingly, in central Pb–Pb collisions di-jet events with a large energy imbalance have been observed for leading jet transverse energies above 100 GeV. The imbalance is quantified using the transverse energy asymmetry $A_{\mathrm{J}} = (E_{\mathrm{T1}} - E_{\mathrm{T2}})/(E_{\mathrm{T1}} + E_{\mathrm{T2}})$. The ATLAS measurement of A_{J} for the highest centrality bin is shown in Fig. 3 [20]. It is compared to the corresponding distribution for pp events and Pythia jets embedded in HIJING. A significant excess of di-jets with a large energy imbalance is observed in the most central collisions when compared to pp collisions and Pythia jets embedded into HIJING. The di-jet energy imbalance has been confirmed by CMS [21]. The effect of energy loss is also visible in the measurement of the R_{CP} of the inclusive jet yield. Quite independently of the jet energy and cone radius, R_{CP} reaches about 0.5 in central collisions and approaches unity in peripheral collisions [20].

Furthermore, the azimuthal angle correlations between leading and sub-leading jets in different centrality bins has been measured. Surprisingly, despite the large energy imbalance no angular de-correlation is observed. CMS studied also the longitudinal fragmentation function and does not observe any modification within experimental errors for central Pb–Pb collisions. The energy imbalance and invariance of the fragmentation functions are in qualitative agreement with a strong out of cone energy loss and the fragmentation of the remnant parton in vacuum. A detailed analysis of the differential angular momentum flow shows that the deficit of high p_t particles in the jet cone is balanced by low-p_t particles outside the jet cone.

Quarkonia At LHC, high-precision measurements of the J/ψ, Ψ' and the Upsilon family, $\Upsilon(1, 2, 3S)$, can be performed. The sequential suppression of heavy quarkonia of increasing binding energy has been proposed as a thermometer of the QGP. However, since about 50 $c\bar{c}$ pairs are produced per central Pb–Pb collision, regeneration effects can potentially increase charmonium production. Indeed, the ALICE measurement of the J/ψ R_{AA} as a function of number of participants in the kinematic range $2.5 < y < 4$ and $p_t > 0$ [22] shows that the J/ψ is less suppressed as compared to the RHIC energy ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ and $1.2 < y < 2.2$) [23]. CMS has measured the J/ψ R_{AA} for $p_t > 6.5\,\mathrm{GeV}/c$ [18]. For the 10% most central collisions, they report a suppression by a factor of ≈ 5. This observation at high p_t is also seen by ATLAS ($R_{CP}(0 - 10\%)/(40 - 80\%) \approx 0.5$) [24]. For the same centrality bin, the low-p_t dominated ALICE result is ≈ 0.8. This trend is opposite to what has been found at RHIC, i.e. less suppression at high p_t as compared to low p_t. This further substantiates the possible influence of recombination effecs at low p_t.

The first measurement of the suppression of Upsilon states comes from CMS [25]. For the $\Upsilon(1S)$ they report $R_{AA} = 0.6 \pm 0.15$. The suppression of excited Υ states is presented as the double ratio $(\Upsilon(2S + 3S)/\Upsilon(1S))|_{Pb-Pb}/(\Upsilon(2S + 3S)/\Upsilon(1S))|_{pp}$ reducing the systematic error due to efficiency and acceptance corrections. The measured value of $0.31^{+0.19}_{-0.14}$ shows that the excited states that have a lower binding energy are suppressed with respect to the ground state.

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