Heavy-ion results from the LHC

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I. INTRODUCTION

In November 2010, the first heavy-ion run began at the LHC. Pb nuclei were collided at the centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV, about 14 times higher than that achieved at RHIC. The integrated luminosity delivered by the LHC during the 5 weeks of running was 10 $\mu$b$^{-1}$. Three experiments collected data with Pb–Pb collisions, namely ALICE, ATLAS and CMS.

Heavy-ion collisions at relativistic energies are aimed at studying nuclear matter at extreme conditions of temperature and energy density, where Lattice QCD predicts the matter to be in a state where quarks and gluons are deconfined over volumes much larger than the size of a hadron (see e.g. [1]). Such a state is called Quark Gluon Plasma (QGP). The goal of heavy-ion collision experiments is to collect evidence for the existence of this new state of matter and to study its properties.

Pb–Pb collisions at the LHC are expected to generate a medium that has a higher initial temperature and energy density than that generated at lower values of $\sqrt{s}$. Experimental measurements in this new energy regime are a key benchmark for models that reproduce the features observed at lower collision energy. Furthermore, the input from the LHC is also crucial to shed light on some issues that are not yet completely understood from the SPS and RHIC results (e.g. the $J/\psi$ suppression). Also, the steep increase with $\sqrt{s}$ of the cross-section for QCD scatterings with high virtuality results in copious production of hard partons at the LHC, thus allowing one to reach higher precision on the experimental observables related to high momentum and heavy flavoured particles. Finally, at LHC energies, new (higher mass) probes, such as W and Z$^0$ bosons, become available and provide new tools to study the properties of the medium.

II. COLLISION GEOMETRY AND SYSTEM EVOLUTION

Nuclear collisions are characterized by the impact parameter between the colliding nuclei, i.e. the distance between the centers of the nuclei in the transverse plane. The impact parameter defines the centrality of the collision: in head-on (“central”) collisions a large number of nucleons participates in the interaction and many binary nucleon-nucleon collisions occur, leading to a large energy deposit in the reaction volume. Conversely, collisions with large impact parameter (“peripheral”) have lower number of participant nucleons and binary collisions and consequently lower energy densities are attained. Experimentally, the definition of the collision centrality is based on the assumption that the impact parameter is monotonically related to the particle multiplicity or the energy produced in the collision. It is typically expressed in terms of fractions (percentiles) of the total hadronic cross section. Starting from the centrality-related experimental observables, the collision geometry can be reconstructed utilizing the Glauber model [2], which describes a nuclear collision in terms of multiple-scattering of nucleons in nuclear targets, together with a model for particle production. This approach allows one to compute the average numbers of participant nucleons ($\langle N_{\text{part}} \rangle$), of elementary nucleon-nucleon collisions ($\langle N_{\text{coll}} \rangle$), and other geometrical quantities for each centrality interval [3].

The main difference between a nucleus-nucleus collision and a p–p collision is the larger collision volume where a dense medium of strongly interacting matter (fireball) is formed. The evolution of the produced medium goes through various stages which are schematically described in the following (see e.g. [4] for more details). The fireball first goes through an early non-equilibrium stage. Re-scatterings among its constituents can establish thermal equilibrium. If the system thermalizes quickly enough and at sufficiently large energy density, it is expected to be in the QGP phase. Experimental results indicate that, for central Au-Au collisions at RHIC, thermal equilibrium is reached at a time $\tau_{eq} = 0.6$ fm/$c$ after the collision.
when the temperature of the fireball is \( \approx 360 \text{ MeV} \), well above the critical values for deconfinement [4]. The thermalized medium undergoes a collective hydrodynamic expansion driven by the pressure gradients generated by the high temperatures and densities that characterize these stages of the collision evolution [5]. As a consequence, the fireball cools down and its energy density decreases. When the energy density reaches the critical threshold for deconfinement \( (\epsilon \approx 1 \text{ GeV/fm}^3) \), the partons convert to hadrons (hadronization). After this phase transition, hadrons keep re-scattering off each other, thus building up further collective flow, until the system becomes so dilute that all hadronic interactions cease and the particles decouple (“freeze-out”). The freeze-out is actually anticipated to occur in two stages [4]. First (at higher temperatures) inelastic processes stop, thus freezing the abundances of the various hadron species (chemical freeze-out). Afterwards (at lower temperatures), also elastic collision among hadrons cease and the particle momenta get frozen (thermal freeze-out). At the thermal freeze-out, the bulk of hadrons which underwent the thermalization and the successive collective expansion have an approximately exponential transverse momentum spectrum reflecting the temperature of the fireball at that point, blue-shifted by the average transverse collective flow [4]. The evolution of the fireball from the moment when local thermal equilibrium is reached until the thermal freeze-out can be described with hydrodynamics [5].

The bulk of particles produced in heavy-ion collisions are low-momentum (soft) hadrons that have undergone the collective expansion and have abundances and momenta that are fixed at the stages of the chemical and thermal freeze-out. Experimental observables for low-momentum particles produced in Au-Au collisions at RHIC are well described by hydrodynamics with a QGP equation of state and very low shear viscosity (see e.g. [5, 6]). The results from the LHC in collisions of the two nuclei and \( \tau \) is the formation time. For the most central collisions at the LHC, the resulting value is \( \tau \approx 16 \text{ GeV}/(\text{fm}^2) \), about a factor 3 larger than the corresponding value at RHIC [12, 13].

The system size is measured from the HBT radii extracted from the study of two-pion correlations. For central collisions, it is found to be larger by a factor two with respect to the one observed in central collisions at RHIC [12, 13].

III. GLOBAL EVENT CHARACTERISTICS

The measurement of the multiplicity of produced particles, quantified by the charged particle density per unit of rapidity \( (dN_{ch}/d\eta) \), is a global observable that provides insight into the density of gluons in the initial stages and on the mechanisms of particle production. All three experiments have measured \( dN_{ch}/d\eta \) at mid-rapidity as a function of the collision centrality [7,10]. The multiplicity in the most central collisions at the LHC is larger by a factor \( \approx 2.1 \) with respect to central collisions at top RHIC energy, in disagreement with the scaling with \( \log s \) observed at lower energies (see top panel of Fig. 1). The centrality dependence of \( dN_{ch}/d\eta/(N_{\text{part}}/2) \) has a similar shape to that observed at RHIC (Fig. 1 bottom panel) and is reasonably reproduced both by models based on gluon saturation in the initial state and by two-component Monte Carlo models [8,10].

The produced transverse energy \( E_t \) was estimated by ALICE by measuring the charged hadronic energy with the tracking system and adding the contribution of neutral particles. The measured \( E_t \) per (pseudo)rapidity unit can be used to estimate the energy density with the Bjorken formula [11]:

\[
\epsilon_{Bj} = \frac{1}{A} \frac{dE_t}{dy} \bigg|_{y=0} \tag{1}
\]

where \( A \) is the transverse overlapping area in the collision of the two nuclei and \( \tau \) is the formation time. For the most central (0–5%) collisions at the LHC, the resulting value is \( \epsilon_{Bj} \approx 16 \text{ GeV}/(\text{fm}^2) \), about a factor 3 larger than the corresponding value at RHIC [12, 13].
sions at the top RHIC energy [11].

A typical feature of the medium produced in heavy-ion collisions is the presence of collective motions arising from the large pressure gradients generated by compressing and heating the nuclear matter. The first type of collective motion is called radial flow and it stems from the isotropic expansion of the fireball. It is accessed experimentally by measuring the transverse momentum \( p_t \) spectra of identified hadrons which at low \( p_t \) show a thermal (Boltzmann) distribution blue-shifted by the collective velocity of the system expansion. The \( p_t \) spectra of identified hadrons (\( \pi, K \) and \( p \)) have been measured by ALICE in a wide momentum range [15]. The spectra are seen to be harder (i.e. characterized by a less steep distribution and a larger \( \langle p_t \rangle \) than those observed at RHIC at \( \sqrt{s_{NN}}=200 \) GeV. This is a first indication for a stronger radial flow at the LHC. Deeper insight is obtained by fitting the \( \pi, K \) and \( p \) spectra with a blast-wave function [16], which allows one to extract an estimate of the parameters of the system at the thermal freeze-out, namely the freeze-out temperature and the radial flow velocity. The radial flow velocity from blast-wave fits results, for the most central collisions at the LHC, about 10\% higher than what observed in central collisions at top RHIC energy [13].

The build-up of a collective motion is also signaled by the presence of anisotropic flow patterns in the transverse plane due to an initial geometrical anisotropy in the spatial distribution of the nucleons participating in the collision [17]. Rescatterings among the produced particles convert this initial geometrical anisotropy into an observable momentum anisotropy. For non-central collisions, the geometrical overlap region of the colliding nuclei present an almond-like shape and the impact parameter defines a preferred direction in the transverse plane. The anisotropy of produced particles is characterized by the Fourier coefficients \( v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle \), where \( n \) is the order of the harmonic, \( \varphi \) is the azimuthal angle of the particle and \( \Psi_n \) is the angle of the initial state spatial plane of symmetry. If the matter distribution in the colliding nuclei varied smoothly, the plane of symmetry would coincide with the reaction plane (i.e. the plane defined by the impact parameter and the beam direction) and odd Fourier coefficients would be zero by symmetry. However, due to fluctuations in the spatial distribution of the participating nucleons in the colliding nuclei, the plane of symmetry \( \Psi_n \) fluctuates event-by-event relative to the reaction plane. This gives rise to the presence of odd harmonics, such as \( v_3 \) and \( v_5 \), in the particle azimuthal distributions. Since the impact parameter vector and the spatial planes of symmetry are not directly measurable, various experimental techniques have been developed to estimate the anisotropic flow coefficients from measured correlations among the observed particles [18].

Elliptic flow has been studied by all three experiments [19–24]. The \( p_t \) integrated elliptic flow of charged particles is found to increase by about 30\% from the highest RHIC energy of \( \sqrt{s} = 200 \) GeV to LHC energy [19].

The \( p_t \)-differential elliptic flow is sensitive to the evolution and freeze-out conditions of the expanding medium. The measured \( v_2(p_t) \) at the LHC is found to be compatible with that observed at RHIC. The 30\% increase in the integrated elliptic flow is therefore coming from an increase in the average transverse momentum, due to the increase of the radial flow with increasing \( \sqrt{s} \). The larger radial flow leads also to a more pronounced mass dependence of the elliptic flow. In Fig. 2 the measured \( v_2(p_t) \) for identified pions, kaons and protons is shown for semi-peripheral (40–50\%) collisions. Hydrodynamic model predictions, based on the assumption that the QGP shear viscosity over entropy ratio does not change from RHIC to LHC [22], are shown in the figure and provide a good description of \( v_2(p_t) \) for the three particle species. This is not the case in more central (10–20\%) reactions where the hydrodynamic prediction does not provide a reasonably good description of anti-protons [24]. This mismatch is also observed for the \( p_t \) spectra of identified protons [15] and it may be due to a larger radial flow in the data. At RHIC energies, a better description of the antiproton flow was obtained by introducing a hadronic cascade after the hydrodynamic evolution. The results obtained for elliptic flow indicate that the hot and dense matter created in heavy-ion collisions at the LHC still behaves like a strongly interacting fluid with exceptionally low viscosity, as that observed at RHIC [6, 22].

Higher Fourier harmonics have been measured by the three experiments [25–26]. In the most central events, dominated by fluctuations in the initial geometrical configuration, the elliptic \( (v_2) \) and triangular \( (v_3) \) flow are found to have similar magnitude.

The presence of higher harmonics provides a natu-
eral explanation of the structures observed in the two-particle azimuthal correlations at low $p_t$, namely the “ridge” at $\Delta \varphi \approx 0$ and large $\Delta \eta$ and the double-bump in the away side ($\Delta \varphi \sim \pi$). These structures were first observed at RHIC in Au-Au collisions [27] and their interpretation is a long standing puzzle: models based on jet-medium interactions were at first developed (e.g. [28]), while more recently an explanation based on triangular flow was proposed [29]. These structures in the two-particle correlations have been studied in detail by performing a Fourier analysis of the $\Delta \eta - \Delta \varphi$ correlations with large $\Delta \eta$ gap [25, 30, 31]. The data are found to be well described by the first five terms of the Fourier series. At low $p_t$ (i.e. $p_t \lesssim 3 - 4$ GeV/c), the Fourier components extracted from two-particle correlations are found to factorize into single-particle harmonic coefficients which are in agreement with the anisotropic flow coefficients. This suggests that the features observed in two-particle correlations at low $p_t$ are consistent with the collective response of the system to the initial state geometrical anisotropy.

IV. CHARACTERIZATION OF THE MEDIUM WITH HARD PROBES

Particles with large transverse momentum and/or mass, which are produced in large-virtuality parton scatterings, are powerful tools to probe the medium created in heavy-ion collisions. The production of such “hard probes” in nuclear collisions is expected to scale with the number of nucleon–nucleon collisions in the nucleus–nucleus collision (binary scaling). The experimental observable used to verify the binary scaling is the nuclear modification factor:

$$R_{AA} = \frac{\text{Yield in AA}}{\langle N_{\text{coll}} \rangle \cdot \text{Yield in pp}}$$

where $\langle N_{\text{coll}} \rangle$ is the average number of binary (nucleon-nucleon) collisions for the considered centrality class. If no nuclear effects are present, $R_{AA}$ should be equal to 1 by construction. It is anticipated that the medium created in the collision affects the abundances and spectra of the originally produced hard probes, resulting in a value of $R_{AA}$ different from 1. In particular:

- **Quarkonia** are expected to melt in the QGP due to color screening of the force which binds the $c\bar{c}$ (or $b\bar{b}$) state [32]. The suppression is predicted to occur both for the charmonium ($J/\psi$, $\Upsilon$, $\chi_c$, ...) and bottomonium families ($\Upsilon(1S, 2S, 3S)$) above (or close to) the critical temperature for the phase transition. Furthermore, the quarkonium suppression is anticipated to occur sequentially according to the binding energy, i.e. strongly bound states (such as $J/\psi$ and $\Upsilon(1S)$) should melt at higher temperatures relative to more loosely bound states. It has also to be considered that with increasing $\sqrt{s}$, due to the more abundant production of charm in the initial state, charmonium regeneration from $c$ and $\bar{c}$ recombination at hadronization time can lead to an enhancement in the number of observed $J/\psi$ [35].

At the LHC, the $J/\psi$ yield has been measured by all the three experiments. ATLAS measured $J/\psi$ at mid-rapidity and high $p_t$ (80% of $J/\psi$’s measured by ATLAS have $p_t > 6.5$ GeV/c) and reported a suppression which increases with increasing centrality [36]. CMS measured the nuclear modification factor of prompt and secondary $J/\psi$’s at mid-rapidity, finding a suppression which increases with centrality [37]. Also in this case, high $p_t (> 6.5$ GeV/c) $J/\psi$ are measured. The $R_{AA}$ measured at the LHC at mid-rapidity shows more suppression than observed by the PHENIX and STAR experiments at RHIC at central rapidity. It should be noticed that PHENIX measured $J/\psi$ mesons down to $p_t = 0$, while the preliminary results from STAR [38] are for high-$p_t$ ($> 5$ GeV/c) $J/\psi$’s and show a systematically higher $R_{AA}$ than observed by PHENIX at low-$p_t$. It has also to be considered that the CMS results are for prompt $J/\psi$ at high $p_t$, while PHENIX and STAR measured inclusive $J/\psi$ (i.e. including those from B feed-down). CMS also reported the $R_{AA}$ for non-prompt $J/\psi$’s from B feed-down which are found to be less suppressed than the prompt ones. In this case, the mechanism that gives rise to the observed suppression is not the quarkonium melting: $B$ mesons decay well outside the medium, but arise from the fragmentation of a $b$ quark which suffers energy loss when traversing the colored medium. Additional information about $J/\psi$ suppression at the LHC is presented by the ALICE measurement [39] which is performed at forward rapidity and down to $p_t = 0$ for inclusive $J/\psi$. The resulting $R_{AA}$ shows
a suppression almost independent of centrality and smaller than that observed by PHENIX at forward rapidity. In summary, the LHC results on $J/\psi$ suppression provide hints that the $J/\psi$ suppression is $p_t$ dependent and that regeneration may play an important role at low $p_t$. A deeper understanding requires studies of initial state effects by measuring $J/\psi$ production in p–A collisions at LHC energy.

CMS also measured Υ states in both p–p and Pb–Pb collisions at $\sqrt{s} = 2.76$ TeV, resolving the 1S, 2S and 3S states. The strongly-bound Υ(1S) state is found to be suppressed: the preliminary measurement of the nuclear modification factor integrated over centrality is $R_{AA} = 0.62 \pm 0.11 \pm 0.10$ [31]. The suppression of the higher-mass states is measured relative to the ground state, by building a double ratio between $\Upsilon(2S+3S)$ and $\Upsilon(1S)$ yields in Pb–Pb and p–p. The result is:

$$\frac{[\Upsilon(2S + 3S)/\Upsilon(1S)]_{pp}}{[\Upsilon(2S + 3S)/\Upsilon(1S)]_{pp}} = 0.31^{+0.19}_{-0.15}(\text{stat}) \pm 0.03(\text{syst})$$

which indicates that the excited states are significantly more suppressed than the ground state. The probability to measure such a value, or a lower one, if the true double ratio is equal to one, is less than 1% [10].

B. Parton energy loss in the QCD medium

As mentioned above, hard partons, produced at the initial stage of the collision, traverse the medium and are expected to be sensitive to its energy density, through the mechanism of in-medium partonic energy loss. The amount of energy lost is sensitive to the medium properties (density) and depends also on the path-length of the parton in the deconfined matter as well as on the properties of the parton probed in the medium. The nuclear modification factor as a function of $p_t$ is therefore considered:

$$R_{AA}(p_t) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}$$

where $\langle T_{AA} \rangle$ is the average nuclear overlap function computed with the Glauber model for the considered centrality class [3]. The parton energy loss manifests itself as an $R_{AA}$ value lower than 1 at large $p_t$. Already at RHIC energies, the production of high $p_t$ (in the range 5-10 GeV/c) hadrons was found to be strongly suppressed (by a factor five) in the most central collisions [41].

The higher centre-of-mass energy attained at the LHC allows extension of the $p_t$ range where the $R_{AA}$ is measured, thus providing important constraints to the particle energy loss models. Moreover, the more abundant production of charm and beauty enables higher precision measurements of the energy loss for heavy quarks, thus providing a further benchmark for theoretical models. Radiative energy loss models predict that quarks lose less energy than gluons (that have a larger colour charge) and that the amount of radiated energy decreases with increasing quark mass. Hence, a hierarchy in the values of the nuclear modification factor is anticipated, namely the $R_{AA}$ of B mesons should be larger than that of D mesons that should in turn be larger than that of light-flavour hadrons (e.g. pions), which mostly originate from gluon fragmentation.

The $R_{AA}$ of unidentified charged particles has been measured by ALICE [42] and CMS [43]. In particular, the CMS $R_{AA}$ (which extends up to $p_t = 100$ GeV/c) is shown in Fig. 3 for the 0–5% centrality class compared to the ALICE measurement and to results from experiments at lower energies. The $R_{AA}$ is smaller at the LHC, suggesting a larger energy loss relative to RHIC energies and indicating that the density of the medium created in the collision increases with the increase of $\sqrt{s}$. It should also be considered that the fraction of hadrons originating from gluon jets increases with increasing centre-of-mass energy and, in radiative energy loss models, this is expected to give rise to a lower $R_{AA}$ because gluons lose more energy than quarks while traversing the QGP. The $R_{AA}$ presents a minimum at $p_t \approx 6 – 7$ GeV/c and then increases slowly up to about 40 GeV/c. For $p_t$ above 40 GeV/c the $R_{AA}$ seems to level off at a value of approximately 0.5. Also at momenta of 100 GeV/c a significant suppression of charged hadron yield is still present.

Medium-blind probes, such as photons and $Z^0$ bosons, can be used to test that the initial production of hard probes follows the expected binary scal-
ing, so as to separate initial and final state effects in the observed $R_{AA}$. High energy (prompt) photons are produced directly from the hard scattering of two partons. In nuclear collisions, they traverse the produced medium without suffering from strong interaction, thus providing a direct test of pQCD production and initial state effects (such as nuclear modification of the parton distribution functions). From the experimental point of view, the measurement of prompt photons is challenging because of the huge background from $\pi^0$ and $\eta$ decays. CMS has performed a measurement of isolated photon production in Pb–Pb collisions as a function of centrality [4]. The measured $E_t$ spectra of isolated photons in Pb–Pb are compared with a theoretical (NLO pQCD) $p$–$p$ reference from JETPHOX 1.2.2 [3] that provides a good description of the photon cross section in $p$–$p$ collisions at $\sqrt{s} = 7$ TeV. The resulting $R_{AA}$ is found to be compatible with unity within uncertainties. This confirms that the initial production of hard probes follows the expected scaling of the production rate from $p$–$p$ to $AA$ by the number of nucleon-nucleon collisions. Z bosons have been measured in Pb–Pb collisions by ATLAS [33] and CMS [46] via their decay into $\mu^+\mu^-$. The measured $Z^0$ yield scaled by the number of nucleon-nucleon collisions is found to be independent of centrality within uncertainties. Furthermore, the $Z^0$ yield in Pb–Pb results to be compatible within uncertainties with the theoretical next-to-leading order pQCD $p$–$p$ cross sections scaled with the number of binary collisions.

As mentioned above, to provide further insight into the energy loss mechanisms, it is interesting to measure the nuclear modification factors for identified particles, in particular for heavy-flavoured hadrons. The suppression of open charm and open beauty has been measured by ALICE with three different techniques: exclusive reconstruction of $D^0$ and $D^+$ hadronic decays at mid-rapidity, single electrons after subtraction of a cocktail of background sources at mid-rapidity, and single muons at forward rapidity [47]. The measurement of prompt $D^0$ and $D^+$ $R_{AA}$ is shown in the left panel in Fig. 4. A strong suppression is observed, reaching a factor 4–5 for $p_t > 5$ GeV/$c$. At high $p_t$ the suppression is similar to the one observed for charged pions, while at low $p_t$ there seems to be an indication for $R_{AA}(D) > R_{AA}(\pi^+)$. As mentioned in section [II.A] CMS has measured the $R_{AA}$ of displaced $J/\psi$, i.e. coming from B meson decays, and reported a value of $R_{AA} = 0.36 \pm 0.08 \pm 0.03$ for the 20% most central collisions. Also in this case, $J/\psi$ mesons are measured for $p_t > 6.5$ GeV/$c$. The physical mechanism behind this suppression is the $b$ quark energy loss. The larger $R_{AA}$ of $J/\psi$ from $b$ with respect to that measured for prompt $D$ mesons is a first indication for the $b$ quark to lose less energy than the $c$ quark, as anticipated by radiative energy loss models.

![FIG. 4: Nuclear modification factor for prompt $D^0$ and $D^+$ mesons in the 20% most central collisions compared with the charged pions. Statistical (bars), systematic (empty boxes), and normalization (full box) uncertainties are shown. Taken from [47].](image)

**C. Jet quenching**

In-medium QCD energy loss is also predicted to affect fully reconstructed jets, due to “jet quenching”. The study of jet modification in heavy ion collisions is predicted to be a powerful tool to probe the properties of the QGP. In particular, in-medium parton energy loss can significantly alter the observed energy balance between the most energetic (“leading”) and the second most energetic (“sub-leading”) jets in the event. It is also interesting to measure the azimuthal angle between the two jets and verify if significant deviations with respect to back-to-back emission ($\Delta\phi_{dijet} \approx \pi$) are observed.

Jet reconstruction in the high-multiplicity environment of high energy heavy-ion collisions is a challenging task that was pioneered in Au-Au reactions at RHIC. In particular, jet measurements have been carried on in STAR: inclusive jet cross-section, di-jet coincidence rate and hadron-jet correlations. They all converge toward a picture of broadening and softening of the jet fragmentation [48].

At the LHC, ATLAS and CMS reported results with fully reconstructed jets, using the energies measured in $\eta, \phi$ cells with the calorimeters and analyzed with different algorithms (anti-kt, iterative cone) for jet reconstruction as well as with different techniques for the subtraction of the background from the underlying event.

ATLAS [49] reported shortly after the Pb–Pb run the observation of a significant imbalance between the measured transverse energies of di-jets in opposite hemispheres. The jet energy imbalance is quantified by the asymmetry $A_J$ defined as:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

(3)
where $E_{T1}$ is the transverse energy of the leading jet and $E_{T2}$ the one of the most energetic jet in the opposite hemisphere. $A_J$ is positive by construction. It is required that $E_{T1} > 100$ GeV and $E_{T2} > 25$ GeV and therefore di-jets in which the sub-leading jet is below the 25 GeV threshold are not included in the $A_J$ calculation.

The measured distributions of $A_J$ in peripheral Pb–Pb collisions is similar to that observed in p–p events as well as to that expected from Monte Carlo simulations without in-medium energy loss. For more central collisions, the $A_J$ distribution broadens, does not show a peak at $A_J = 0$ and its mean is shifted to higher values. In particular, for the most central events a peak is visible at $A_J \approx 0.5$. The different characteristics of the $A_J$ distribution in central Pb–Pb collisions with respect to p–p indicate an increased rate of highly asymmetric di-jet events. This observation is consistent with a degradation of the parton energy while traversing the medium produced in Pb–Pb collisions. The azimuthal separation between the two jets has also been studied and shows that the two jets are essentially back-to-back in all centrality bins with no additional azimuthal broadening relative to that expected from QCD effects in vacuum.

Di-jet imbalance studies have also been performed by the CMS collaboration [50] in a different energy range ($p_t$ thresholds at 120 and 50 GeV/c for the leading and sub-leading jets respectively) and lead to the same conclusion about the presence of a significant excess of imbalanced di-jets in central collisions. This modification of the jet momentum balance implies a corresponding modification in the distribution of the jet fragmentation products which can be addressed by studying track-jet correlations. In particular, the missing jet energy can be either transported out of the cone area used to define the jet, or it can be carried by low-momentum particles which are not measured in the calorimeter jets. The overall momentum balance in the di-jet events was studied using the projection of the missing $p_t$ of reconstructed charged tracks onto the leading jet axis:

$$ p_T^J = \sum_i -p_T^i \cos (\phi_i - \phi_{Leading\ Jet}), \quad (4) $$

The results of this analysis show that, for charged-particle jets, if tracks down to $p_t = 0.5$ GeV/c are considered, the momentum balance is indeed recovered within uncertainties also for the most central collisions. In particular, a large negative contribution to $\langle p_T^J \rangle$ (i.e. in the direction of the leading jet) comes from particles with $p_t > 8$ GeV/c that is balanced by the contribution from lower $p_t$ particles, with a large fraction of the balancing momentum carried by tracks with $p_t < 2$ GeV/c. Further insight is obtained by studying $\langle p_T^J \rangle$ separately for tracks inside and outside cones of size $\Delta R = \sqrt{\Delta \tau^2 + \Delta \eta^2} = 0.8$ around the leading and sub-leading jets. The results show that a large part of the energy needed for balancing the jet momenta is carried by soft particles ($p_t < 2$ GeV/c) radiated at large angles with respect to the jet axes ($\Delta R > 0.8$) [50].

The observed large fraction of highly imbalanced di-jets in central Pb–Pb collisions and the corresponding softening and widening of the fragmentation pattern of the sub-leading jet are consistent with a high degree of jet quenching in the produced medium.

First studies of fragmentation functions in Pb–Pb collisions have been performed by ATLAS [51] and CMS [52]. The results show that the hard component of jet fragmentation functions in heavy-ion collisions resemble those of PYTHIA di-jet events (with partons fragmenting in the vacuum) for both leading and sub-leading jets, in different centrality bins and different di-jet imbalance ($A_J$) bins.

V. SUMMARY AND CONCLUSIONS

The first Pb–Pb run at the LHC enabled the study of heavy ion physics at a center of mass energy about 14 times higher than at the largest $\sqrt{s}$ attained at RHIC. ALICE, ATLAS and CMS experiments collected data during this first heavy ion run demonstrating excellent performance and complementary capabilities, that allowed (together with the impressive performance of the accelerator) a large variety of high quality results for all the experimental observables that have been studied. The overall picture that emerges from the “soft” (low $p_t$) sector is that the medium produced in Pb–Pb collisions at the LHC is strongly interacting, has exceptionally low viscosity and can be well described by hydrodynamics. In general, the results from soft physics observables show a smooth evolution from RHIC to LHC. By comparing the high precision measurements at the LHC with model predictions and with the results obtained at lower energies at the SPS and at RHIC, it will be possible to obtain a deeper insight into the properties of the QGP. Furthermore, with the first heavy ion run, the LHC experiments started to exploit the abundance of high $p_t$ and large mass probes which is a unique and novel aspect of heavy-ion collisions at LHC energies. From the hard physics sector we expect to find answers to some of the issues that have not been addressed completely by the experiments at lower collision energies, such as the $J/\psi$ (and quarkonia) suppression, the prediction of a different energy loss of beauty, charm and light hadrons and the medium modification of jet fragmentation properties.
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[1] F. Karsch, J. Phys. Conf. Ser. 46 (2006) 122.
[2] R. J. Glauber in Lectures in Theoretical Physics, NY, 1959, Vol. 1, 315.
[3] M. Miller et al., Ann.Rev.Nucl.Part.Sci. 57 (2007) 205.
[4] U. W. Heinz, arXiv:hep-ph/0407360v1
[5] P. F. Kolb, U. W. Heinz in Hwa, R.C. (ed.) et al.: Quark gluon plasma, 634-714 [nucl-th/0305084].
[6] M. Luzum and P. Romatschke, Phys. Rev. Lett. 103 (2009) 262302.
[7] K. Aamodt et al., ALICE Collaboration, Phys. Rev. Lett. 105 (2010) 252301.
[8] K. Aamodt et al., ALICE Collaboration, Phys. Rev. Lett. 106 (2011) 032301.
[9] G. Aad et al., ATLAS Collaboration, arXiv:1108.6027v1 [hep-ex], submitted to PLB.
[10] S. Chatrchyan et al., CMS Collaboration, J. High Energy Phys. 08 (2011) 141.
[11] J.D. Bjorken, Phys. Rev. D 27 (1983) 140.
[12] A. Toia for the ALICE Collaboration,QM2011 proceedings, arXiv:1107.1973 [nucl-ex].
[13] CMS Collaboration, CMS-PAS-HIN-11-003, http://cdsweb.cern.ch/record/1354215
[14] K. Aamodt et al., ALICE Collaboration, Phys.Lett. B 696 (2011) 328.
[15] M. Floris for the ALICE Collaboration,QM2011 proceedings, arXiv:1108.3257 [hep-ex].
[16] E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48 (1993) 2462.
[17] J. Y. Ollitrault, Phys. Rev. D 46 (1992) 229.
[18] S. A. Voloshin, A. M. Poskanzer and R. Snellings, arXiv:0809.2949 [nucl-ex].
[19] K. Aamodt et al., ALICE Collaboration, Phys.Rev. Lett. 105 (2010) 252302.
[20] G. Aad et al, ATLAS Collaboration, arXiv:1108.6018v1 [hep-ex], submitted to PLB.
[21] CMS Collaboration, CMS-PAS-HIN-10-002, http://cdsweb.cern.ch/record/1347788
[22] C. Shen, U. W. Heinz, P. Huovinen, H. Song, arXiv:1105.3226 [nucl-th].
[23] R. Snellings for the ALICE Collaboration,QM2011 proceedings, arXiv:1106.6284 [nucl-ex].
[24] K. Aamodt et al., ALICE Collaboration, Phys. Rev. Lett. 107 (2011) 032301.
[25] ATLAS Collaboration, ATLAS-CONF-2011-074, http://cdsweb.cern.ch/record/1352458
[26] CMS Collaboration, CMS-PAS-HIN-11-005, http://cdsweb.cern.ch/record/1361385
[27] J. Adams et al., STAR Collaboration, Phys. Rev. C 73 (2006) 064907, A. Adare et al., PHENIX Collaboration, Phys. Rev. C 78 (2008) 014901, B. Alver et al., PHOBOS Collaboration, J. Phys. G35, 104080 (2008).
[28] J. Casalderrey-Solana, E. V. Shuryak, D. Teaney, J. Phys. Conf. Ser. 27 (2005) 22.
[29] B. Alver and G. Roland, Phys. Rev. C 81 (2010) 054905.
[30] K. Aamodt et al., ALICE Collaboration, arXiv:1109.2501 [nucl-ex].
[31] S. Chatrchyan et al, CMS Collaboration, JHEP 07 (2011) 076.
[32] T. Matsui, H. Satz, Phys. Lett. B178 (1986) 416.
[33] A. Majumder, M. Van Leeuwen, Prog.Part.Nucl.Phys 66 (2011) 41.
[34] D. d’Enterria, Springer Verlag, Landolt-Boernstein Vol. 1-23A, arXiv:0902.0011 [nucl-ex].
[35] P. Braun-Munzinger, J. Stachel, arXiv:0901.2500 [nucl-th].
[36] G. Aad et al., ATLAS Collaboration, Phys. Lett. B 697 (2011) 294.
[37] CMS Collaboration, CMS PAS HIN-10-006, http://cdsweb.cern.ch/record/1353586.
[38] Z. Tang for the STAR Collaboration,QM2011 proceedings, arXiv:1107.0532 [hep-ex].
[39] G. Martinez Garcia for the ALICE Collaboration,QM2011 proceedings, arXiv:1106.5889 [nucl-ex]
[40] S. Chatrchyan et al, CMS Collaboration, Phys. Rev. Lett. 107 (2011) 052302.
[41] Nuclear Physics A, Volume 757 (2005) 1-283.
[42] K. Aamodt et al., ALICE Collaboration, Phys.Lett. B 696 (2011) 30.
[43] CMS Collaboration, CMS-PAS-HIN-10-005, http://cdsweb.cern.ch/record/1352777
[44] CMS Collaboration, CMS-PAS-HIN-11-002, http://cdsweb.cern.ch/record/1352779.
[45] S. Catani et al., JHEP 05 (2002) 028.
[46] S. Chatrchyan et al, CMS Collaboration, Phys. Rev. Lett. 106 (2011) 212301.
[47] A. Dainese for the ALICE Collaboration,QM2011 proceedings, arXiv:1106.0412 [nucl-ex].
[48] M. Ploskon for the STAR collaboration, Nucl.Phys. A830 (2009) 255c, E. Bruna for the STAR collaboration, arXiv:1110.2795 [nucl-ex].
[49] G. Aad et al, ATLAS Collaboration, Phys. Rev. Lett. 105 (2010) 252303.
[50] S. Chatrchyan et al, CMS Collaboration, Phys. Rev. C 84 (2011) 024906.
[51] ATLAS Collaboration, ATLAS-CONF-2011-075, http://cdsweb.cern.ch/record/1353220.
[52] CMS Collaboration, CMS-PAS-HIN-11-004, http://cdsweb.cern.ch/record/1354531.