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HIGH-p_{T} PROCESSES MEASURED WITH ALICE AT THE LHC*

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From studies of single-particle spectra, particle correlations, and jet production in heavy-ion collisions we can obtain information about the density and the dynamic properties of the Quark-Gluon Plasma (QGP). The observed suppression of high-p_{T} particle production (R_{AA}) and away-side jets (I_{AA}) is generally attributed to energy loss of partons as they propagate through the plasma. We present the results obtained from the analysis of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded by ALICE in November 2010. The nuclear modification factors R_{AA} and I_{AA}, and the status of full jet reconstruction in Pb–Pb is presented. Comparison with the RHIC measurements at lower collision energy and with theory models is shown.

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1. Introduction

This paper reports on measurements of single-particle inclusive spectra and two-particle azimuthal correlations for hadrons as a function of transverse momentum (p_{T}) and event centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded by ALICE [1] in November 2010.

The measurement is motivated by the results [2,3,4,5,6] from the Relativistic Heavy Ion Collider (RHIC), which showed that hadron production at large transverse momentum in central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV is suppressed by a factor 4–5 compared to expectations from an independent superposition of nucleon–nucleon collisions. This observation is typically expressed in terms of the nuclear modification factor which is defined as the

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ratio of the charged particle yield in Pb–Pb to that in pp, scaled by the number of binary nucleon–nucleon collisions $\langle N_{\rm coll}\rangle$. In absence of nuclear modifications R_{AA} is equal to unity at high $p_{\rm T}$

$$R_{AA}(p_{\rm T}) = \frac{\left(1/N_{\rm evt}^{AA}\right) d^2N_{\rm ch}^{AA}/d\eta dp_{\rm T}}{\langle N_{\rm coll}\rangle \left(1/N_{\rm evt}^{pp}\right) d^2N_{\rm ch}^{pp}/d\eta dp_{\rm T}}\,. \tag{1}$$

At RHIC it was also measured [7] that the back-to-back dihadron correlations are considerably reduced in the most central Au–Au collisions as compared to pp, indicating a substantial interaction as the hard-scattered partons or their fragmentation products traverse the medium. It is quantified by comparison of hadron yields measured in Pb–Pb (Y_{AA}) and pp (Y_{pp}) collisions

$$I_{AA}(p_{\rm T},\Delta\phi) = \frac{Y_{AA}(p_{\rm T},\Delta\phi)}{Y_{pp}(p_{\rm T},\Delta\phi)}\,. \tag{2}$$

The Y_{AA} and Y_{pp} are extracted from the background subtracted per-trigger particle yield ($D(\Delta\phi) = dN_{\rm assoc}/N_{\rm trig}d(\Delta\phi)$), where azimuthal correlation is built between a high-$p_{\rm T}$ triggered leading hadron ($p_{\rm T,\,trig} > p_{\rm T,\,thresh}$) and all associated particles ($p_{\rm T,\,assoc} < p_{\rm T,\,trig}$) in one event. In absence of nuclear modifications the I_{AA} is equal to unity by construction.

2. Results

2.1. R_{AA} charged particles

The nuclear modification factors out to $p_{\rm T} = 50\,{\rm GeV}/c$ are shown in Fig. 1 (left panel) for different centrality intervals. At all centralities, a pronounced minimum at about $p_{\rm T} = 6$–$7\,{\rm GeV}/c$ is observed. For $p_{\rm T} > 7\,{\rm GeV}/c$ there is a significant rise in the nuclear modification factor until $p_{\rm T} = 30\,{\rm GeV}/c$. This emphasizes the strong relation between the medium density and partonic energy loss.

Fig. 1 (right panel) shows a comparison of R_{AA} in central Pb–Pb collisions (0–5%) at $\sqrt{s_{NN}} = 2.76\,{\rm TeV}$ to calculations from energy loss models [8, 9, 10, 11]. All model calculations have been constrained to match R_{AA} results from RHIC. The qualitative features of our data are described by all models, including the strong rise of R_{AA} below $p_{\rm T} = 30\,{\rm GeV}/c$ and the flattening off at higher $p_{\rm T}$. A more quantitative comparison of model calculations to the present data will help to put tighter constraints on the underlying energy loss mechanisms.

In Fig. 2 (left panel) R_{AA} measured with ALICE is compared to measurements at lower collision energy ($\sqrt{s_{NN}} = 200\,{\rm GeV}$) by the PHENIX and STAR experiments [12,13] at RHIC. At $p_{\rm T} = 1\,{\rm GeV}/c$ the measured value of R_{AA} is similar to those of RHIC. The position and shape of the maximum at

$p_{\mathrm{T}} \approx 2\,\mathrm{GeV}/c$ and the subsequent decrease are similar at RHIC and LHC. At $p_{\mathrm{T}} = 6$–$7\,\mathrm{GeV}/c$ R_{AA} is smaller than at RHIC indicating that a very dense medium is formed in Pb–Pb collisions at the LHC.

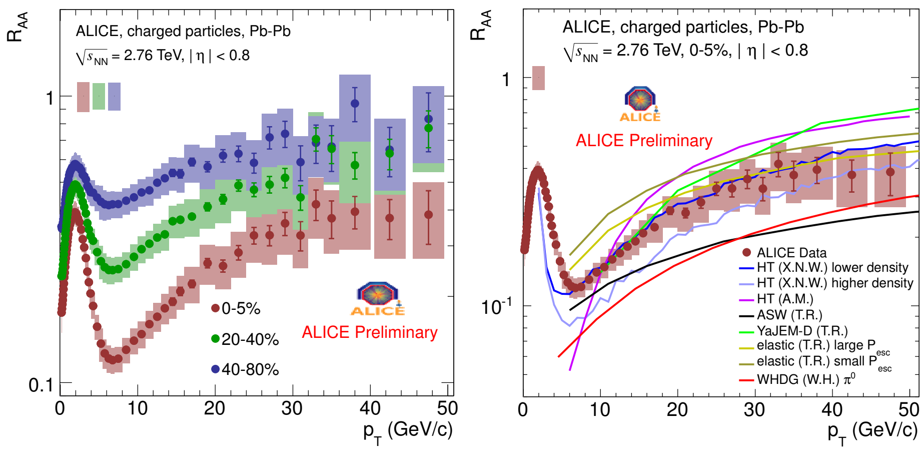

Fig. 1. Left: R_{AA} of charged particles measured with ALICE in central Pb–Pb collisions in three centrality intervals. Right: R_{AA} of charged particles measured with ALICE in central Pb–Pb collisions (0–5%) in comparison to model calculations. The error bars at $R_{AA} = 1$ denote contributions from normalization uncertainties.

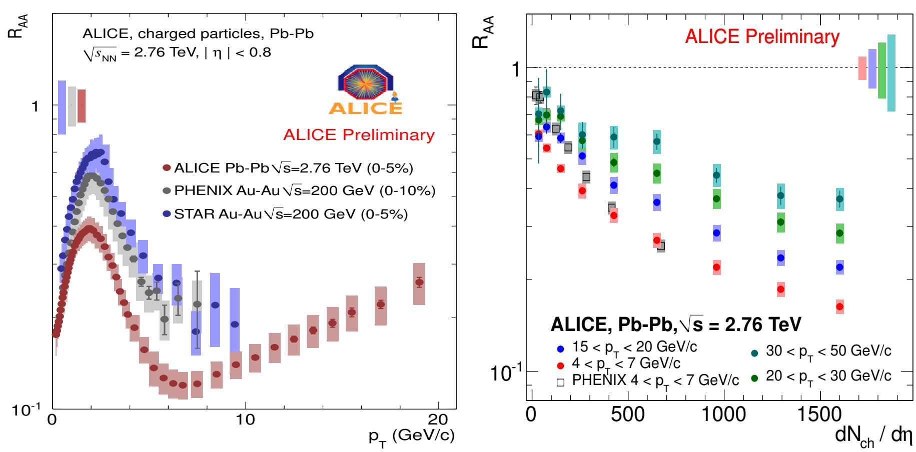

Fig. 2. Left: R_{AA} of primary charged particles measured with ALICE in central Pb–Pb collisions (0–5%) in comparison to RHIC measurements. The error bars at $R_{AA} = 1$ denote the contributions from normalization uncertainties. Right: R_{AA} of charged particles showed as a function of particle density ($dN_{\mathrm{ch}}/d\eta$) in four p_{T} intervals. Comparison to PHENIX measurements is also shown. The error bars at $R_{AA} = 1$ denote p_{T}-dependent systematic uncertainties on pp reference spectrum. The normalization uncertainties on pp spectrum (3.5% independent of p_{T}) are not plotted.

The R_{AA} measured as a function of charged particle density $dN_{\rm ch}/d\eta$ (from [14]) in four $p_{\rm T}$ intervals is shown in Fig. 2 (right panel). The strongest R_{AA} dependence as a function of $dN_{\rm ch}/d\eta$ is observed for low-$p_{\rm T}$ particles ($4 < p_{\rm T} < 7\,{\rm GeV}/c$), and becomes weaker with larger $p_{\rm T}$. There is also shown the PHENIX R_{AA} measurement in the lowest $p_{\rm T}$ interval. It is comparable with R_{AA} measured by ALICE for $dN_{\rm ch}/d\eta > 400$. For smaller $dN_{\rm ch}/d\eta$, PHENIX and ALICE measurements differ what might be related to the collision geometry and have to be further studied.

More analysis details related to R_{AA} can be found in [15, 16].

2.2. R_{AA} of identified hadrons

The analysis of charged pions at high $p_{\rm T}$ is based on statistical particle identification using the specific energy loss dE/dx in the TPC [17]. In the region of the relativistic rise of the energy loss ($p_{\rm T} > 3\,{\rm GeV}/c$), the separation of pions from kaons and protons is nearly independent of $p_{\rm T}$ out to $p_{\rm T} = 50\,{\rm GeV}/c$. The fraction of pions from all charged particles is determined in bins of $p_{\rm T}$ by fitting the dE/dx distribution with four Gaussians for p, K, π and e.

The reconstruction of weak decays $K^0_{\rm s} \rightarrow \pi^+ + \pi^-$ and $\Lambda \rightarrow p + \pi$ [18] allows us to study different suppression patterns for baryons and mesons, which may give a handle on how to separate quark and gluon energy losses. In Fig. 3 (left panel) the R_{AA} for $K^0_{\rm s}$ and Λ are shown in central Pb–Pb collisions in comparison to inclusive charged particles and pions out to $p_{\rm T} = 16\,{\rm GeV}/c$. For $p_{\rm T} > 6\,{\rm GeV}/c$, a significant suppression for $K^0_{\rm s}$ and Λ is seen which is similar to that of inclusive charged particles and pions. At lower $p_{\rm T}$, the R_{AA} of Λ is significantly larger than that of $K^0_{\rm s}$ which is in line with the observation of a strong and centrality-dependent enhancement of $\Lambda/K^0_{\rm s}$ [19].

The measurement of heavy-favor production at high-$p_{\rm T}$ provides unique observables of jet quenching. The suggestion that massive quarks experience reduced energy loss due to the suppression of forward radiation ("dead cone effect") has not been borne out by RHIC measurements. The first results from the LHC indicate (Fig. 3, right panel) that the suppression of D mesons might be smaller than for pions at $p_{\rm T} < 5\,{\rm GeV}/c$ (more analysis details can be found in [20]). Higher statistics of Pb–Pb data and comparison data in p–Pb collisions should allow to study this region with more precision and disentangle the initial-state nuclear effects, which could be different for light and heavy flavor.

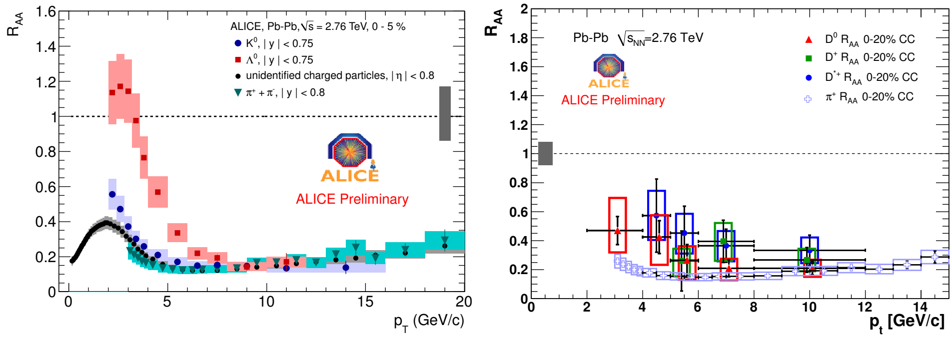

Fig. 3. Left: R_{AA} of charged particles, π, K^0_s and Λ measured with ALICE in the central Pb–Pb collisions (0–5%). Right: R_{AA} of charged pions and D mesons measured with ALICE in the central Pb–Pb collisions (0–20%). The error bars at $R_{AA} = 1$ denote contributions from normalization uncertainties.

2.3. I_{AA} of charged particles

The dihadron back-to-back azimuthal correlations provide more differential information about in-medium parton energy loss as compared to R_{AA}. It is quantified by measuring the ratio of yields in Pb–Pb and *pp* collisions (I_{AA}) which are extracted from the near-side ($\Delta\phi \approx 0$) and away-side ($\Delta\phi \approx \pi$) peaks.

Fig. 4 shows the I_{AA} for central (0–5%) and peripheral (60–90%) collisions after background subtraction which is based on three different schemes: flat pedestal, v_2 and η-gap (more details in [21]). The significant difference between I_{AA} values is visible in the lowest $p_{\mathrm{T,\,assoc}}$ bin what confirms a small bias due to the flow anisotropies in this p_{T} region. In central collisions, a strong yield suppression is observed on the away-side ($I_{AA} \approx 0.6$) which is consistent with in-medium parton energy loss. On the other hand, there is an unexpected yield enhancement ($I_{AA} \approx 1.2$) on the near-side which has not been observed at lower collision energies [7]. In peripheral collisions, the yields are not modified and I_{AA} is consistent with unity on both the near- and away-side.

2.4. Full jet reconstruction in ALICE

The ALICE electromagnetic calorimeter (EMCal) [1] was fully installed in January 2011. Thus jets from the first Pb–Pb collisions in ALICE (2010 run) are reconstructed based on charged particles only. The tracks are reconstructed using the Time Projection Chamber (TPC) and vertexing information from the Inner Tracking System (ITS). This ensures maximum azimuthal angle (ϕ) uniformity of reconstructed tracks with transverse momenta down to $p_{\mathrm{T}} = 150$ MeV/c.

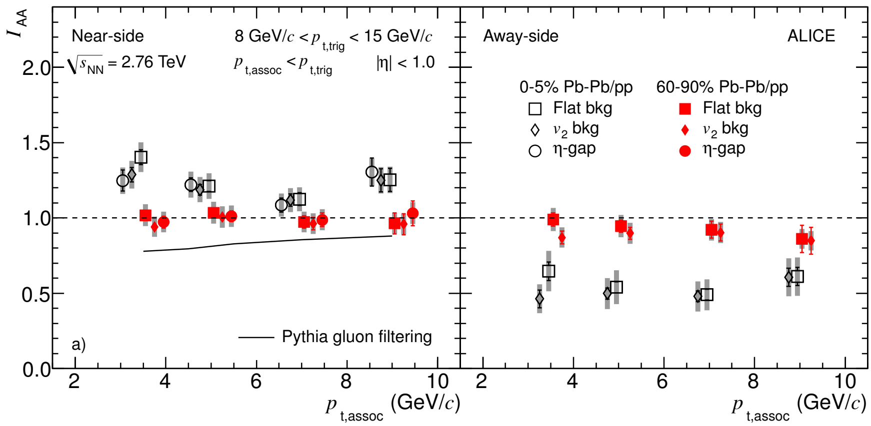

Fig. 4. I_{AA} of charged particles measured with ALICE in Pb–Pb collisions in two centrality intervals (0–5%, 60–90%). For better visibility, the data points are slightly displaced on the $p_{T,\,assoc}$-axis. The shaded bands denote systematic uncertainties. The line (near-side) shows a PYTHIA 8 calculations illustrating the effect of gluon filtering in the medium (more details in [21]).

The full jets are reconstructed using the anti-k_T algorithm [22] and are corrected for the background in each event using the jet area A with $p_{T,\,jet}^{ch} = p_{T,\,jet}^{rec} - \rho A$. Here, the background density ρ is calculated on an event-by-event basis as the median for the p_T/A ratio of reconstructed k_T-clusters in $|\eta| < 0.5$ by using k_T algorithm [23]. The resulting raw jet spectra are shown in Fig. 5 for two different track p_T cut-off values. The dif-

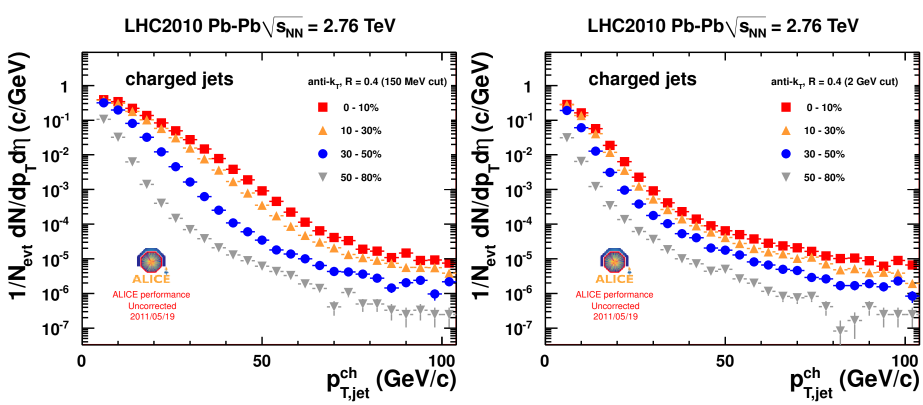

Fig. 5. Reconstructed raw charged jet spectra in four centrality intervals using the anti-k_T algorithm ($R = 0.4$) after background subtraction (details in the text). Shown are spectra for two different track p_T cut-off values: $p_T > 150\,\mathrm{MeV}/c$ (left) and $p_T > 2\,\mathrm{GeV}/c$ (right), respectively.

ference in the shape of the p_{T} distributions in central collisions, clearly visible for the small track p_{T} cut-off, is due to the background fluctuations which dominate over a wide p_{T} range. The analysis of the jet background sources in Pb–Pb collisions is ongoing (more details in [24]).

3. Summary

The results indicate a strong suppression of charged particle production in Pb–Pb collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$ and a characteristic centrality and p_{T} dependence of the nuclear modification factors R_{AA} and I_{AA}. The suppression observed in central Pb–Pb collisions at the LHC is stronger than in central Au–Au collisions at RHIC. The comparison of ALICE data to model calculations indicates a large sensitivity of high-p_{T} particle production to details of energy loss mechanisms.

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