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Observation of medium-induced yield enhancement and acoplanarity broadening of low-p_{T} jets in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with ALICE

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We present the measurements of the semi-inclusive distributions of charged-particle jets recoiling from a trigger hadron in proton–proton (pp) and 0–10% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, searching for medium-induced yield enhancement and acoplanarity broadening effects in low transverse momentum (p_{T}) jets. This technique provides precise data-driven subtraction of the large uncorrelated background yield in jet measurements, enabling the measurement of recoil jet distributions to the large jet radius at low p_{T} in central Pb–Pb collisions. Trigger-normalized recoil jet distributions are reported as a function of $p_{\mathrm{T,jet}}$ and as a function of the azimuthal angle ($\Delta\varphi$) between trigger hadron axis and recoil jet. Comparisons of the jet yield distributions in pp and Pb–Pb collisions show a significant medium-induced yield enhancement at low p_{T} and at large-angle jet deflection for large radius. Comparisons to theoretical calculations incorporating jet quenching will also be discussed.

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1. Introduction

Research on heavy-ion (HI) collisions at ultra-relativistic energies explore the properties of strongly interacting nuclear matter under extreme conditions of high energy density and temperature. The Quark–Gluon Plasma (QGP), which is a hot and dense state of deconfined matter, is expected to be formed in HI collisions [1]. Studying the QGP in the laboratory improves our understanding of quantum chromodynamics (QCD), the theory of the strong interaction. A jet is a collimated spray of particles originating from initial hard scattered partons at the early stage of the collisions. In pp collisions, measurements of jet production provide stringent tests of high-order perturbative QCD calculations. In nucleus–nucleus collisions, the hard-scattered partons propagate through the QGP medium and interact with it. This interaction redistributes energy in the shower, leading to yield suppression of hadrons and high-p_T jets, modification of jet substructure, and medium-induced acoplanarity ("jet quenching") [2]. Comparison of jet quenching measurements with theoretical calculations provides unique insight into the dynamics and transport properties of the QGP.

Measurement of reconstructed inclusive jets at low p_T and large R in Pb–Pb collisions is challenging, due to the large and non-uniform uncorrelated background. However, the semi-inclusive jet measurements provide a precise handle of uncorrelated recoil jet yield relative to a trigger [3]. These measurements employ a statistical approach to mitigate the uncorrelated background, which enables well-controlled systematic measurements of reconstructed jets at very low p_T and large R in central Pb–Pb collisions without selection bias. The semi-inclusive measurements allow us to study not only the p_T distributions of the recoil jets, but also the azimuthal distributions. This measurement is also sensitive to jet azimuthal broadening effects. In vacuum, this broadening effect occurs via Sudakov radiation. In medium, additional jet angular deflection may occur due to multiple soft scatterings and medium response, resulting in modification of the azimuthal correlation between the trigger hadron and the recoiling jet. In addition, the tail of this azimuthal correlation is sensitive to Molière scatterings off quasi-particles in the medium [4, 5].

In these proceedings, we present an analysis of semi-inclusive charged-particle jet production in pp and in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV to search for jet yield enhancement at low p_T and jet azimuthal broadening effects with ALICE data.

2. Analysis

The analyzed data for pp collisions at $\sqrt{s}$ = 5.02 TeV were collected in 2015 and 2017 during ALICE Run 2 using a Minimum Bias (MB) trigger. The data for central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV were collected in 2018 using MB and centrality-enhanced triggers. A detailed description of the ALICE experimental setup can be found in Refs. [6, 7]. The measured jets are reconstructed from charged-particle tracks using the ALICE Inner Tracking System (ITS) and Time Projection Chamber (TPC). Accepted tracks are required to have $p_T > 0.15$ GeV/c and pseudorapidity $|\eta| < 0.9$. Charged-particle jets are then reconstructed using the k_T and anti-k_T algorithms with E-scheme recombination in the FastJet package [8–10] with resolution parameters $R = 0.2$ and 0.4. The jet acceptance is $|\eta_{jet}| < 0.9 - R$ with additional selection on jet area [3]. The analysis is based on the semi-inclusive distribution of charged-particle jets recoiling from a high-p_T

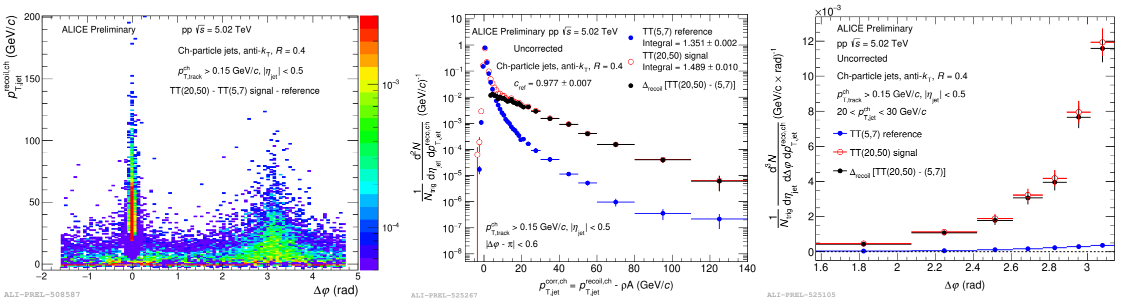

Figure 1: Raw 2-dimensional Δ_{recoil} distributions as a function of $\Delta\varphi$ and recoil jet p_{T} in pp collisions at $\sqrt{s} = 5.02$ TeV for $R = 0.4$ (left). Trigger-normalized recoil jet yield distributions as a function of $p_{\mathrm{T,jet}}$ (middle) and $\Delta\varphi$ for $p^{\mathrm{reco}}_{\mathrm{T,ch\ jet}} \in [20, 30]$ GeV$/c$ (right).

trigger track, measured as $\left.\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^3N_{\mathrm{jet}}}{\mathrm{d}\eta_{\mathrm{jet}}\,\mathrm{d}p_{\mathrm{T,jet}}\,\mathrm{d}\Delta\varphi}\right|_{p_{\mathrm{T}}^{\mathrm{trig}}\in\mathrm{TT}}$, where $\Delta\varphi$ is the azimuthal angle between trigger track and recoil jet, the trigger track is in a given p_{T} interval ($p_{\mathrm{T,trig}}$). The observable Δ_{recoil} is then defined as the difference of the normalized semi-inclusive yields in Signal and Reference trigger track p_{T} intervals ($\mathrm{TT_{Sig}}$, $\mathrm{TT_{Ref}}$):

$$\Delta_{\mathrm{recoil}}\,(p_{\mathrm{T,jet}}, \Delta\varphi) = \left.\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^3N_{\mathrm{jet}}}{\mathrm{d}\eta_{\mathrm{jet}}\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\Delta\varphi}\right|_{p_{\mathrm{T}}^{\mathrm{trig}}\in\mathrm{TT_{Sig}}} - c_{\mathrm{Ref}}\cdot\left.\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^3N_{\mathrm{jet}}}{\mathrm{d}\eta_{\mathrm{jet}}\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\Delta\varphi}\right|_{p_{\mathrm{T}}^{\mathrm{trig}}\in\mathrm{TT_{Ref}}}, \quad (1)$$

where the scaling factor c_{Ref} is extracted from data and its value is within a few percent of unity. In this analysis, the Signal trigger track p_{T} interval is $20 < p_{\mathrm{T,trig}} < 50$ GeV$/c$ and Reference trigger track p_{T} interval is $5 < p_{\mathrm{T,trig}} < 7$ GeV$/c$. Using the Δ_{recoil}, the uncorrelated jet yield is suppressed in a data-driven way and the combinational background of Δ_{recoil} distributions is greatly reduced.

When the 2-dimensional (2D) trigger-normalized recoil jet distributions ($p_{\mathrm{T,jet}}$, $\Delta\varphi$) were first obtained for $\mathrm{TT_{Sig}}$ and $\mathrm{TT_{Ref}}$ respectively, the raw 2D Δ_{recoil} was calculated from the difference between the two TT p_{T} intervals yields, as shown in the left panel of Fig. 1 for $R = 0.4$. The middle and right panels of Fig. 1 show the projections of these 2D distributions on the X ($\Delta\varphi$) and Y ($p_{\mathrm{T,jet}}$) axes, the middle panel shows the recoil jet p_{T} distributions and right panel shows the $\Delta\varphi$ distributions in $20 < p_{\mathrm{T,jet}} < 30$ GeV$/c$.

The raw Δ_{recoil} distributions must be corrected for smearing of recoil jet energy resolution and jet energy scale, as well as the background fluctuations. The correction is carried out using a 2D Bayesian unfolding technique [11] with a 4-dimensional response matrix building detector-level jet p_{T} and $\Delta\varphi$ to the particle level with PYTHIA8 MC simulation. The systematic uncertainties were calculated for each observable and setting separately by considering several variations, such as uncertainty due to the tracking efficiency, scaling factor c_{Ref}, unfolding process (regularization parameter, prior, binning and closure test) and background subtraction. The total systematic uncertainty is a quadratic sum of the individual uncertainties. The dominant systematic uncertainty for pp collisions arises from tracking efficiency, while for Pb–Pb collisions it arises from the unfolding prior.

3. Results

Figure 2 shows the I_{AA} distributions as a function of $p_{\mathrm{T,jet}}$ for $R = 0.2$ and 0.4, which is the ratio of $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}})$ in Pb–Pb over that in pp collisions for a broad range of $p_{\mathrm{T,jet}}$ ($7 < p_{\mathrm{T,jet}} < 140$ GeV/c). In the low $p_{\mathrm{T,jet}}$ range ($p_{\mathrm{T,jet}} < 20$ GeV/c), the $I_{\mathrm{AA}}(p_{\mathrm{T,jet}})$ are consistent with or above unity for both R, indicating the jet energy redistribution and energy recovery due to jet quenching. In the middle range $p_{\mathrm{T,jet}} \in [20, 60]$ GeV/c, $I_{\mathrm{AA}}(p_{\mathrm{T,jet}})$ have a larger suppression in central Pb–Pb collisions with respect to pp collisions. There is a clear upward trend in $I_{\mathrm{AA}}(p_{\mathrm{T,jet}})$ as $p_{\mathrm{T,jet}}$ increases from the interplay of jet quenching on hadron and jet production. Fig. 2 also shows the comparison of I_{AA} with different theoretical calculations. The results are compared with JETSCAPE calculations [12], which includes a medium modified parton shower by MATTER and LBT at parton virtuality, and the Hybrid Model [5, 13], which implements energy loss with an AdS-CFT approach and a response of the medium to the lost energy. The JETSCAPE calculations generally describe the data at $p_{\mathrm{T,jet}} > 20$ GeV/c for both jet radii R. The Hybrid Models with all effects overestimate the suppression, except for the model with wake effect (medium response) at low $p_{\mathrm{T,jet}}$ which catches the yield enhancement.

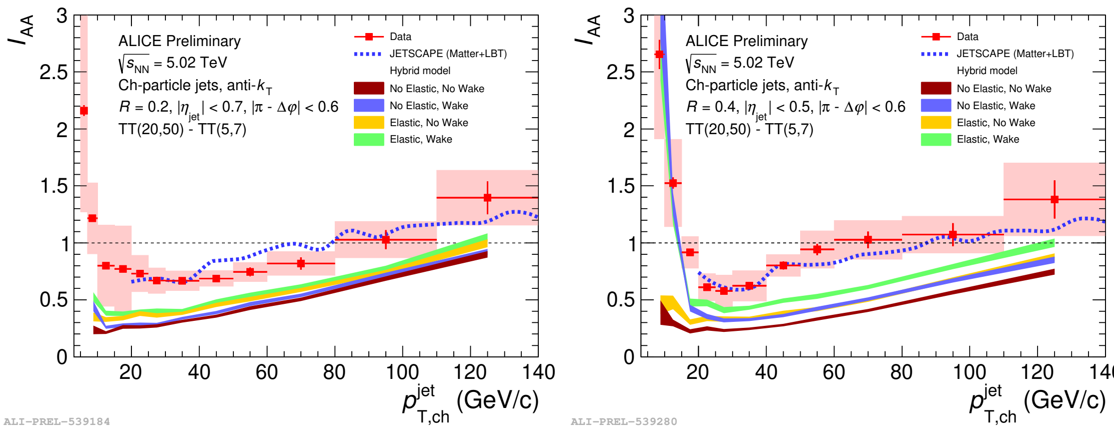

Figure 2: $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ from the $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}})$ distributions measured for $R = 0.2$ and 0.4 in central Pb–Pb and pp collisions. Data are compared with JETSCAPE and the Hybrid Model predictions.

Figure 3 and Figure 4 show the fully-corrected $\Delta_{\mathrm{recoil}}(\Delta\varphi)$ distributions in pp and 0–10% Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, for $R = 0.2, 0.4$ in $p_{\mathrm{T,jet}} \in [10, 20]$ GeV/c and $p_{\mathrm{T,jet}} \in [30, 50]$ GeV/c. The left panel of Fig. 3 shows the $\Delta_{\mathrm{recoil}}(\Delta\varphi)$ distributions in pp collisions at higher $p_{\mathrm{T,jet}} \in [30, 50]$ GeV/c and compare with PYTHIA and pQCD calculations. Both predictions provide a reasonable description of the data within uncertainties. These pp data are used as a reference to compare with the results in Pb–Pb collisions to obtain the distribution on the right panel. The red points in this panel are 0–10% Pb–Pb $\Delta_{\mathrm{recoil}}(\Delta\varphi)$ results and blue curves are pp results. Comparing these two yields obtains the $I_{\mathrm{AA}}(\Delta\varphi)$ distribution shown in the bottom panel, the $I_{\mathrm{AA}}(\Delta\varphi)$ is suppressed below unity for 0.4 in $p_{\mathrm{T,jet}} \in [30, 50]$ GeV/c interval, as expected from jet energy loss. However, in the region $p_{\mathrm{T,jet}} \in [10, 20]$ GeV/c (left panel in Fig. 3), the $I_{\mathrm{AA}}(\Delta\varphi)$ is found to be larger than unity, indicating a marked enhancement in yield and acoplanarity broadening at wide angles in central Pb–Pb collisions relative to vacuum fragmentation for $R = 0.4$. This is the first observation of significant medium-induced acoplanarity broadening of semi-inclusive jet measurements for larger $R = 0.4$ at low $p_{\rm T,jet}$ in Pb–Pb collisions with ALICE. However, this medium-induced acoplanarity broadening vanishes for the small radius $R = 0.2$ in same $p_{\rm T,jet}$ interval, as shown in the right panel of Fig. 4. The $I_{\rm AA}(\Delta\varphi)$ is also compared to different calculations which can exhibit the relative contributions of various energy loss mechanisms in heavy-ion collisions. JETSCAPE and calculations that include medium-induced $p_{\rm T}$ broadening [4] reasonably describe the data at high $p_{\rm T,jet}$ region; these calculations are not available at low $p_{\rm T,jet}$. The Hybrid Model with all variations shows a flat distribution, overestimating the suppression of measured data at high jet $p_{\rm T}$; no broadening effect is observed at low $p_{\rm T,jet}$.

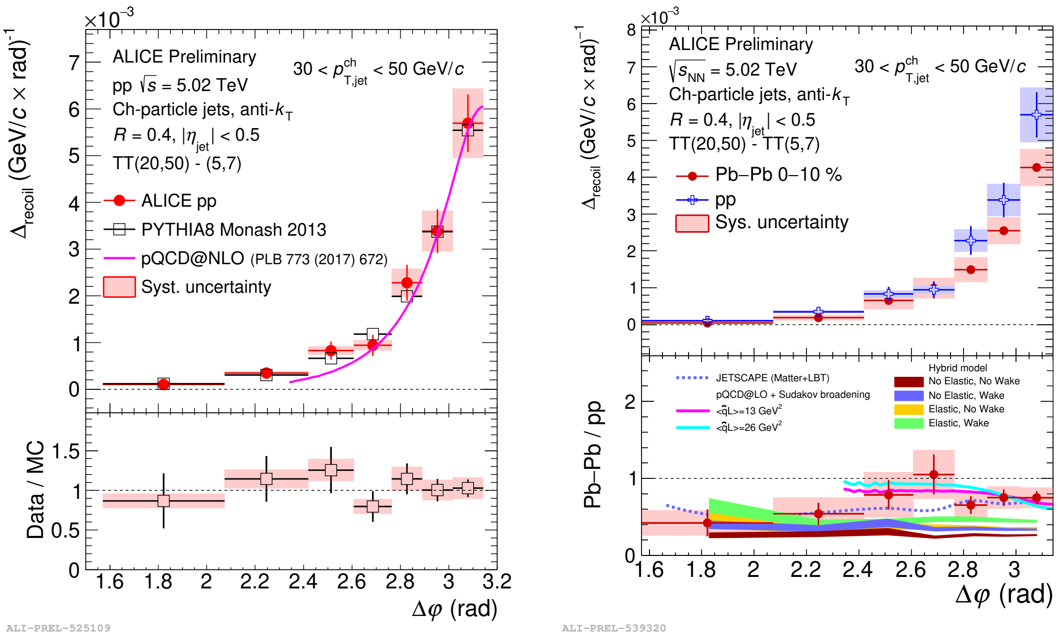

Figure 3: Corrected $\Delta_{\rm recoil}(\Delta\varphi)$ distributions for $R = 0.4$ in pp (left) and Pb–Pb (right) collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, for interval in recoil jet $p_{\rm T,jet} \in [30, 50]$ GeV/c. Data are compared with different predictions from PYTHIA, a pQCD calculation, JETSCAPE and the Hybrid Model.

4. Summary and Outlook

We have measured the R dependence of recoil jet yields and acoplanarity using the semi-inclusive distributions of charged-particle jets recoiling from a high-$p_{\rm T}$ trigger hadron in pp and central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Model calculations based on the PYTHIA8 event generator and next-to-leading order (NLO) pQCD calculation are found to be consistent with the measurements in pp collisions. We observe marked medium-induced recoil yield enhancement and acoplanarity broadening effect for $p_{\rm T} \in (10, 20)$ GeV/c and large $R = 0.4$. This effect may arise from in-medium hard scatterings, medium response, or the reconstruction of soft jet fragments. We look forward to unravelling these possible origins by studying the profiles and substructures of semi-inclusive measurements.

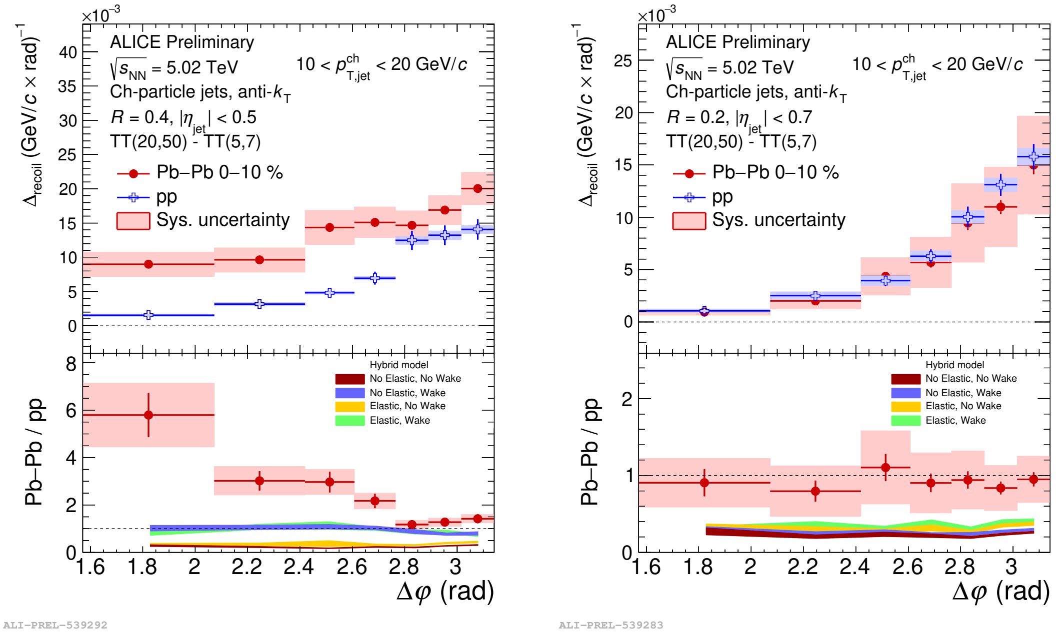

Figure 4: Corrected $\Delta_{\rm recoil}(\Delta\varphi)$ distributions for $R = 0.4$ (left), and 0.2 (right) in pp and Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, for interval in recoil jet $p_{\rm T,jet} \in [10, 20]$ GeV/c. $I_{\rm AA}(\Delta\varphi)$distributions are compared to different predictions from a pQCD calculation, JETSCAPE and the Hybrid Model.

Acknowledgements

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