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Investigating Hard Splittings via Jet Substructure in pp and Pb–Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with ALICE

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Jets lose energy as they propagate through the Quark-Gluon Plasma, modifying their parton shower. Jet substructure, which provides access to the evolution of jet splittings, is expected to be sensitive to interactions between the medium and the jet, providing the opportunity to further constrain both jet and medium properties. By utilizing grooming techniques, we can focus on the most pertinent hard splittings. Of particular interest is the search for large transverse momentum kicks which may indicate the presence of point-like scatters within the Quark-Gluon Plasma. We explore the jet substructure of inclusive jets in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, utilizing Soft Drop and other grooming methods, as well as the Lund Plane, in order to access the hardest jet splitting, with a particular focus on the hardest k_{T} splitting.

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1. Introduction

As partons from high momentum transfer processes propagate through the medium, they interact with it, losing energy and modifying their parton shower. These interactions between the jet and the hot and dense QCD medium known as the Quark-Gluon Plasma (QGP) are expected to modify the internal jet structure. Jet substructure measurements provide access to jet splittings, and consequently may be sensitive to these modifications.

To perform such measurements, selections are often made on the jet splitting properties via grooming techniques [1–3]. In pp collisions, grooming limits contamination of the jet shower by soft QCD processes, while in Pb–Pb collisions, grooming helps select the hard component of quenched jets. Utilizing these techniques, substructure may provide direct access to medium properties such as color coherence [4], or quasi-particle structure which can be searched for indirectly by looking for large angle Moliere scattering [5].

ALICE [6] is well suited for performing jet substructure measurements due to the precision tracking provided by the Inner Tracking System and Time Projection Chamber in the central barrel. For these measurements, charged-particle $R = 0.4$ anti-k_{T} jets were reconstructed using FastJet 3.2.1 [7] in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV that were collected in 2017 and 2018 respectively. Jets were required to be contained entirely within the ALICE central barrel acceptance. In Pb–Pb collisions, background subtraction is of particular importance. For substructure analysis, ALICE performs background subtraction via Constituent Subtraction [8]. Performance was optimized with the goal of reducing the background contribution while minimizing any possible bias on the substructure variables. These studies determined an optimal value of $\Delta R^{\mathrm{max}} = 0.6$.

2. Groomed Jet Substructure in 30–50% Pb–Pb Collisions

To characterize jet substructure in 30–50% semi-central Pb–Pb collisions, the Soft Drop grooming algorithm [1] was utilized to select the first sufficiently hard splitting. In particular, we measured the shared momentum fraction, z_{g}, the angular separation between the subjets from the selected splitting, R_{g}, and the number of splittings until finding the hard splitting, n_{SD} [1, 3]. In order to avoid background contaminated splittings, splittings were considered sufficiently hard when they passed the requirement of $z_{\mathrm{cut}} = 0.2$ or $z_{\mathrm{cut}} = 0.4$. For each variable, Bayesian iterative 2D unfolding was utilized to correct for background fluctuations and detector effects [9].

The results of this analysis for jets measured within $60 < p_{\mathrm{T ch,jet}} < 80$ GeV/c are shown in Fig. 1 and Fig. 2. In the left panel of Fig. 1, z_{g} measured in Pb–Pb collisions is compared to the same measurement in pp collisions for $z_{\mathrm{cut}} = 0.2$. Within experimental uncertainties, z_{g} is consistent with no modification. n_{SD} is shown in the right panel of Fig. 1, and is also consistent with no modification relative to pp collisions. The left and right panels of Fig. 2 show R_{g} measured in Pb–Pb and pp collisions for z_{cut} values of 0.2 and 0.4, respectively. Both panels show similar behavior, with small angle splittings enhanced in Pb–Pb collisions, while large angle splittings are suppressed. The measurements were tested for consistency with no modification of the ratio from unity by adding the statistical and systematic uncertainties in quadrature. Within the context of this simple metric, both measurements were found to be inconsistent with no modification ($p = 0.03$). The measurements are also compared against model predictions from JETSCAPE [10], and Pablos

PoS(HardProbes2020)146

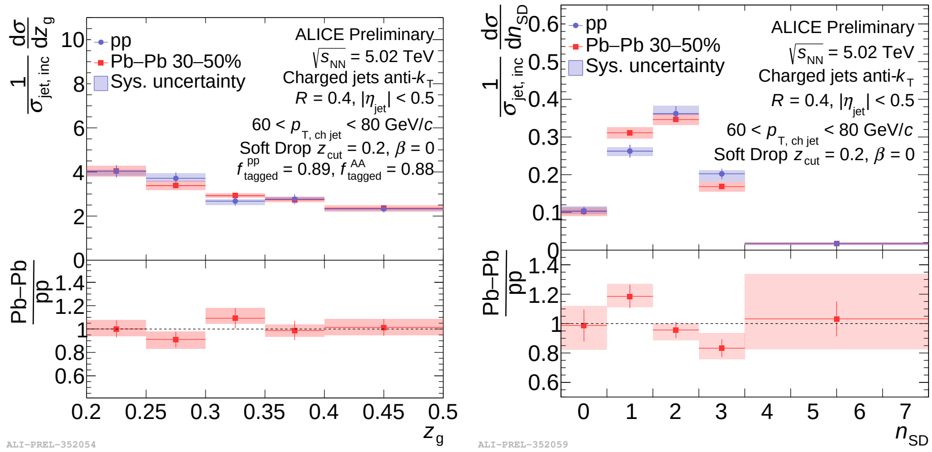

Figure 1: Measurement of z_g (left) and n_{SD} (right) for $R = 0.4$ charged-particle jets in $60 < p_{T ch,jet} < 80$ GeV/c in pp and Pb–Pb collisions. Both measurements are consistent with no modification within experimental uncertainties.

et al [4]. Given the experimental uncertainties, these measurements may have the potential to provide differentiation between model settings and insight into color coherence.

3. Hardest k_T in pp and Pb–Pb Collisions

Beyond measurements of the substructure variables themselves, can jet substructure be used as a tool to isolate the effects of jet-medium interactions? To address this question, we consider the search for the presence of medium scattering centers via the measurement of rare, wide angle scattering relative to the trigger jet axis, known as Moliere Scattering [5]. Searches by ALICE using large-angle hadron-jet decorrelation at $\sqrt{s_{NN}} = 2.76$ are consistent with no medium-induced

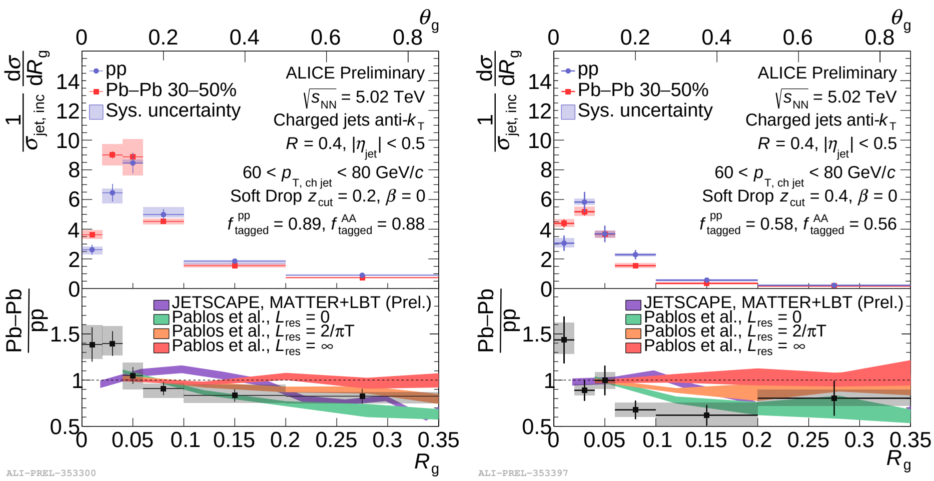

Figure 2: Measurement of R_g for $z_{cut} = 0.2$ (left) and $z_{cut} = 0.4$ (right) for $R = 0.4$ charged-particle jets in $60 < p_{T ch,jet} < 80$ GeV/c in pp and Pb–Pb collisions. Both values of z_{cut} show enhancement for small angle splittings, as well as suppression for large angle splittings. The models are described in the text.

PoS(HardProbes2020)146

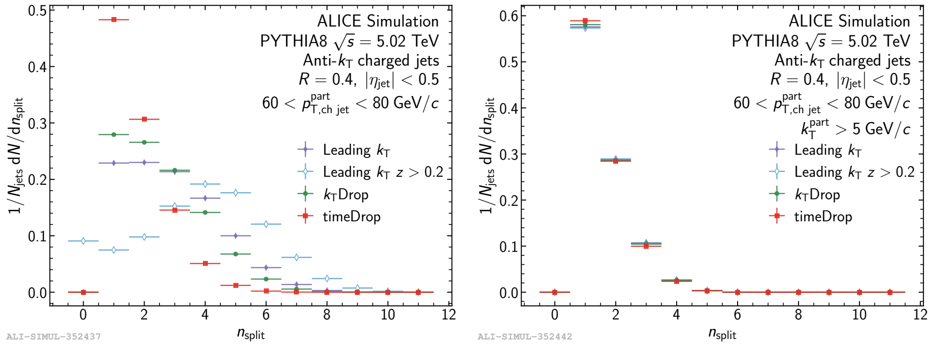

Figure 3: Measurement of the number of splittings until the hardest splitting is identified n_{split} for inclusive k_{T} (left) and $k_{\text{T}} > 5$ GeV/c (right) for $R = 0.4$ charged-particle jets in $60 < p_{\text{T ch,jet}} < 80$ GeV/c in PYTHIA 8 Monash 2013. The splittings selected by the different grooming methods converge at high-k_{T}.

acoplanarity of recoil jets within measurement uncertainties [11]. As an alternative, we investigate the possibility of using jet substructure as a tool to search for these medium scattering centers. As subjets propagate through the medium, they may be deflected by a scattering center, which should lead to an increase in the yield of high-k_{T} splittings in Pb–Pb collisions relative to pp collisions.

In order to identify the hardest k_{T} splitting, we investigated four methods: leading k_{T}, leading k_{T} for all $z > 0.2$ splittings, and Dynamical Grooming [2] with $a = 1$ (known as k_{T}Drop) and $a = 2$ (known as timeDrop). The leading k_{T} selects the maximum k_{T} splitting from all available splittings, while the $z > 0.2$ variation selects the maximum k_{T} out of all splittings with $z > 0.2$. Dynamical Grooming utilizes a hardness measure, $\kappa^{(a)} = z_i(1 - z_i)p_{\text{T,i}}(\frac{\Delta R}{R})^a$, where i identifies a particular splitting, to determine the hardest splitting [2]. All methods consider all iterative splittings, following the leading subjet to the next splitting.

To initially study these grooming methods, they were applied to PYTHIA 8 Monash 2013 [12] at particle level. The performance was characterized through properties such as the number of splittings until the hardest splitting is identified, n_{split}, as shown in Fig. 3. These studies demonstrated that although the grooming methods perform differently at low k_{T}, for sufficiently high k_{T} splittings (here, $k_{\text{T}} > 5$ GeV/c), all grooming methods converge, selecting the same splittings.

With these comparisons in mind, the four grooming methods were applied to measure the hardest k_{T} in pp collisions at $\sqrt{s} = 5.02$ TeV, as shown in Fig. 4. Bayesian iterative 2D unfolding was again employed. For $k_{\text{T}} > 4$ GeV/c splittings, the k_{T} spectra converge for all of the grooming methods. This behavior is consistent with the earlier PYTHIA studies. Each measurement was also directly compared to PYTHIA 8 Monash 2013 by applying the same grooming methods. PYTHIA is broadly consistent with the data within the statistical and systematic uncertainties, although there is a hint of a shape difference that is consistent between all grooming methods.

In order to assess the prospects for measuring the hardest k_{T} in Pb–Pb collisions, we studied the correlation between the hardest k_{T} in the PYTHIA splitting graph vs that which is found via declustering $R = 0.8$ jets. Previous studies showed a clear correlation between the graph and the declustering splittings [13]. To study this correlation in a large background environment, the PYTHIA particles were embedded into a thermal background tuned to 0–10% central data. Using this thermal model, the background contribution is apparent at low to intermediate k_{T}, but a strong

PoS(HardProbes2020)146

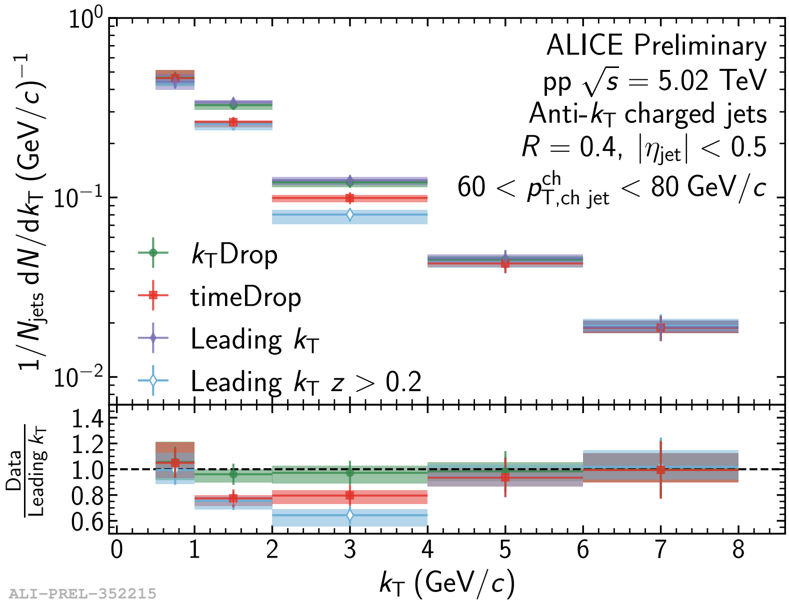

Figure 4: Measurement of the hardest k_T splitting for four grooming methods for $R = 0.4$ charged-particle jets in $60 < p_{T\mathrm{ch,jet}} < 80$ GeV/c in pp collisions and PYTHIA 8 Monash 2013. The splittings selected by the different grooming methods converge at high-k_T. PYTHIA is broadly consistent with the data.

correlation is observed at high-k_T, encouraging the possibility of such a measurement in Pb–Pb.

4. Conclusions and Outlook

We presented fully unfolded z_g, n_{SD}, and R_g measurements in 30–50% semi-central Pb–Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. z_g and n_{SD} are consistent with no modification in Pb–Pb collisions relative to pp collisions, while R_g shows enhancement for small angle splittings and suppression for large angle splittings. These modifications are consistent for both $z_{cut} = 0.2$ and 0.4. The hardest k_T splittings were measured in pp collisions for a variety of grooming methods. The grooming methods selected a consistent set of splittings for $k_T > 4$ GeV/c. The prospects for measuring the hardest k_T splittings in Pb–Pb were also explored as a step towards applying jet substructure as tool to search for point-like scattering centers in the medium via large angle scattering.

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PoS(HardProbes2020)146