JET PRODUCTION AND MODIFICATION IN HEAVY-ION COLLISIONS WITH THE ALICE DETECTOR*

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These proceedings summarize two analyses recently reported by the ALICE experiment at CERN. The first analysis investigated the distribution of the relative transverse momentum of the subleading prong, k_{T}, in substructure of jets produced in Pb–Pb and pp collisions at a center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, searching for possible modifications induced by quasiparticles in the quark–gluon plasma (QGP). The same datasets were also used in the second analysis, which measured jets recoiling from a high-p_{T} hadron. The first analysis found no evidence supporting a quasiparticle description of the QGP, whilst the second observed significant medium-induced jet acoplanarity broadening for low-p_{T} jets, potentially attributable to a jet-induced medium response.

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1. Introduction

The quark–gluon plasma (QGP) is a phase of strongly interacting matter resulting from a phase transition of QCD at temperatures of approximately 155 MeV [1]. It is studied in ultrarelativistic heavy-ion collisions, where it exists for only a few fm/c. Probing such a short-lived medium requires observables generated early in the collision. Jets, originating from hard-scattering processes, provide such probes. As they traverse the QGP, jets experience modifications to their yield and internal structure, a phenomenon known as jet quenching. Key open questions addressed using jets as probes include: What length scales does the propagating parton resolve in the medium? Can we be sensitive to the QGP microstructure? How does the medium modify the jet, and conversely, how does the jet perturb the medium? Does it induce a medium response such as a wake?

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2. Search of quasiparticles in QGP with jet substructure measurements

Partons propagating through the medium interact with its constituents and acquire transverse momentum kicks. If the QGP can be described as a weakly coupled plasma of screened quasiparticles, the transverse-momentum kicks experienced by a propagating parton are expected to follow a Gaussian distribution at small k_{T}, arising from multiple soft scatterings below the resolution scale of the probe, while a power-law tail at large k_{T} reflects rare hard (Molière) scatterings off of resolved medium quasiparticles [5]. It was suggested in Ref. [2] that such momentum transfers could enhance large-angle deflections in jet substructure.

This effect was searched for in the substructure of charged-particle anti-k_{T} jets with $R = 0.2$, reconstructed in Pb–Pb collisions. The jet constituents were reclustered using the Cambridge/Aachen algorithm to form an angular-ordered shower, and the sequence of mergings was then unwound to access the splitting tree. Two grooming techniques were applied to identify perturbative splittings. The first method is the Soft Drop groomer [7], which selects the first splitting satisfying $z > 0.2$, where z is the fraction of the splitting momentum carried by the subleading prong. The second method uses the dynamical grooming criterion [8] to select splittings that have large value of the transverse momentum component of the subleading prong relative to the leading prong, k_{T}. The dynamical grooming searched for a splitting which maximized the expression $z(1-z)p_{\mathrm{T,split}}\Delta R/R$, where $p_{\mathrm{T,split}}$ is the transverse momentum of the parent splitting and ΔR is the opening angle of the splitting.

The leading and subleading prongs of the selected splittings were used to calculate

$$k_{\mathrm{T}} = p_{\mathrm{T,subleading}} \sin \Delta R \,,$$

where $p_{\mathrm{T,subleading}}$ is the transverse momentum of the subleading prong. The k_{T} distributions measured in Pb–Pb collisions were corrected for the purity of the leading and subleading prongs, as well as for instrumental effects and the underlying event, which affect the jet energy scale, the opening angle, as well as the p_{T} of the subjets. They were compared with the corresponding distributions obtained from pp collisions in the charged-particle jet transverse-momentum range $60 < p_{\mathrm{T,jet}}^{\mathrm{ch}} < 80$ GeV/c. The ratios of the k_{T} distributions in Pb–Pb and pp collisions are shown in Fig. 1.

For splittings selected by dynamical grooming, the accessible k_{T} range is limited due to a low-k_{T} cutoff imposed to maintain high purity of the subleading prong. The ratio for Soft-Drop-selected splittings exhibits a decreasing trend, consistent with medium-induced jet core narrowing and indicates a suppression of large-k_{T} splittings in Pb–Pb relative to pp collisions.

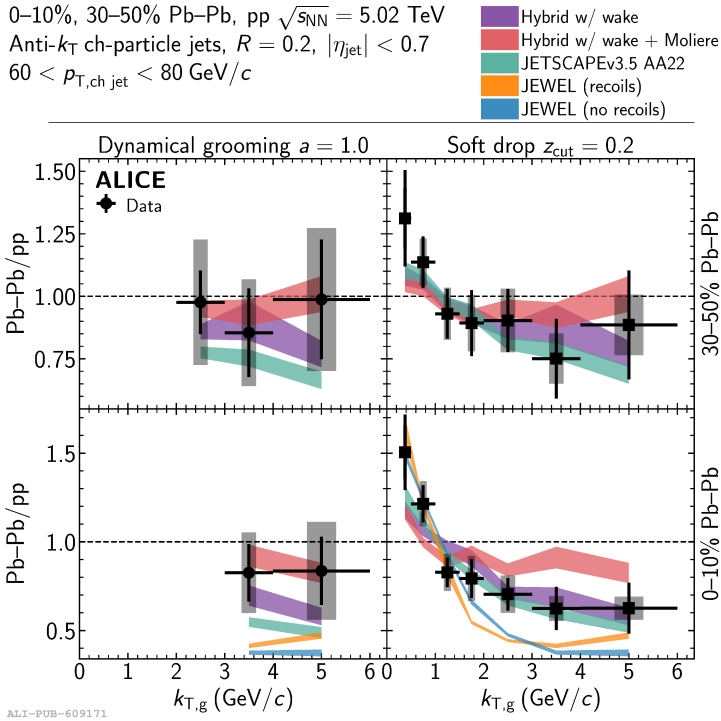


Fig. 1. Ratio of relative transverse momentum of the subleading prong, k_T, distributions in splittings selected by dynamical grooming (left) and Soft Drop grooming (right) measured in Pb–Pb and *pp* collisions. The upper row shows the ratio for semi-central Pb–Pb collisions (30–50% centrality) and the bottom row for central Pb–Pb collisions (0–10% centrality). Data are compared to models. See the text for further details. Taken from Ref. [2].

The data are compared with model calculations describing jet–medium interactions. JEWEL [9] models the medium using Bjorken expansion and simulates hard scattering with PYTHIA 6; parton energy loss in the QGP is implemented via the BDMPS formalism. JEWEL can include or exclude recoiling medium partons in the final state. The Hybrid model [10] describes the QGP using relativistic hydrodynamics, with hard processes generated by PYTHIA 8. Medium-induced energy loss is modeled using an AdS/CFT-inspired approach, and the model incorporates medium response including shock-wave propagation and Molière scattering. Finally, the JETSCAPE framework [11] combines hydrodynamic medium evolution with a virtuality-dependent treatment of parton–medium interactions. The decreasing trend of the k_T ratio obtained with Soft Drop grooming is qualitatively reproduced by all models. For the central Pb–Pb events, the Hybrid model including hard Molière scatterings overpredicts the data at large-k_T, whereas the ver-

sion with only the medium wake provides a better description in this region. The JETSCAPE model, which also incorporates hard Molière scatterings, remains consistent with the measurement. The undershoot of JEWEL may be partially related to its treatment of the *pp* reference [2]. These comparisons indicate that while the Hybrid+Molière implementation overestimates the data, the data do not rule out the presence of hard Molière scatterings in the medium. Further improvements in the modelling are required for a more robust interpretation of the data.

3. Hadron–jet correlation measurement

The recently published ALICE papers [3, 4] investigated how jet quenching affects the p_{T} and acoplanarity of jets that recoil from high-p_{T} hadrons in Pb–Pb collisions. High-p_{T} hadrons unambiguously signal the presence of a hard scattering process in a heavy-ion collision.

The analysis employs a statistical, data-driven approach to extract a semi-inclusive, combinatorial-free yield of jets recoiling from high-p_{T} trigger hadrons (TT). This method does not impose a fragmentation bias on the analyzed jet sample and is suitable also for jets with large cone radius R and low p_{T}. The method can be illustrated using the left panels of Fig. 2, which show per-trigger normalized p_{T} spectra of recoil jets associated with trigger hadrons of $p_{\mathrm{T}} = 20$–50 GeV/c (red) and $p_{\mathrm{T}} = 5$–7 GeV/c (blue). Note that the spectrum extends into the negative range of jet p_{T} because the jet p_{T} was corrected for average underlying-event (UE) contribution estimated on an event-by-event basis in central (0–10%) Pb–Pb collisions. After this correction combinatorial background jets from UE will have their jet p_{T} distribution centered around zero. The negative-p_{T} region is signal free. There we see that the red and blue spectra essentially overlap, as here the TT is typically associated with a jet composed entirely of the UE particles uncorrelated to a hard scatter. This indicates that the number of uncorrelated pairs is largely independent of TT p_{T}. On the positive-p_{T} side, the spectra differ: higher-p_{T} TT corresponds to a larger four-momentum transfer and therefore a harder recoil-jet spectrum. When the red and blue spectra are subtracted, the uncorrelated contribution is removed, and the resulting distribution represents part of the yield correlated with the TT. The subtracted spectrum is denoted Δ_{recoil}

$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\,|\Delta\varphi|}\bigg|_{\mathrm{TT}\{20,50\}} - c_{\mathrm{Ref}} \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\,|\Delta\varphi|}\bigg|_{\mathrm{TT}\{5,7\}}. \tag{1}$$

Here, c_{Ref} is a correction factor close to one that accounts for the saturated phase space in the recoil region, where signal and background jets compete for occupancy [3, 4]. It is estimated from the ratio of per trigger normal-

ized recoil jet yields measured for TT{20,50} and TT{5,7} in the region of negative jet p_{T}. The Δ_{recoil} can be constructed also as a function of the azimuthal opening angle between TT and jet, $\Delta\varphi$, as seen in the left panels in Fig 2.

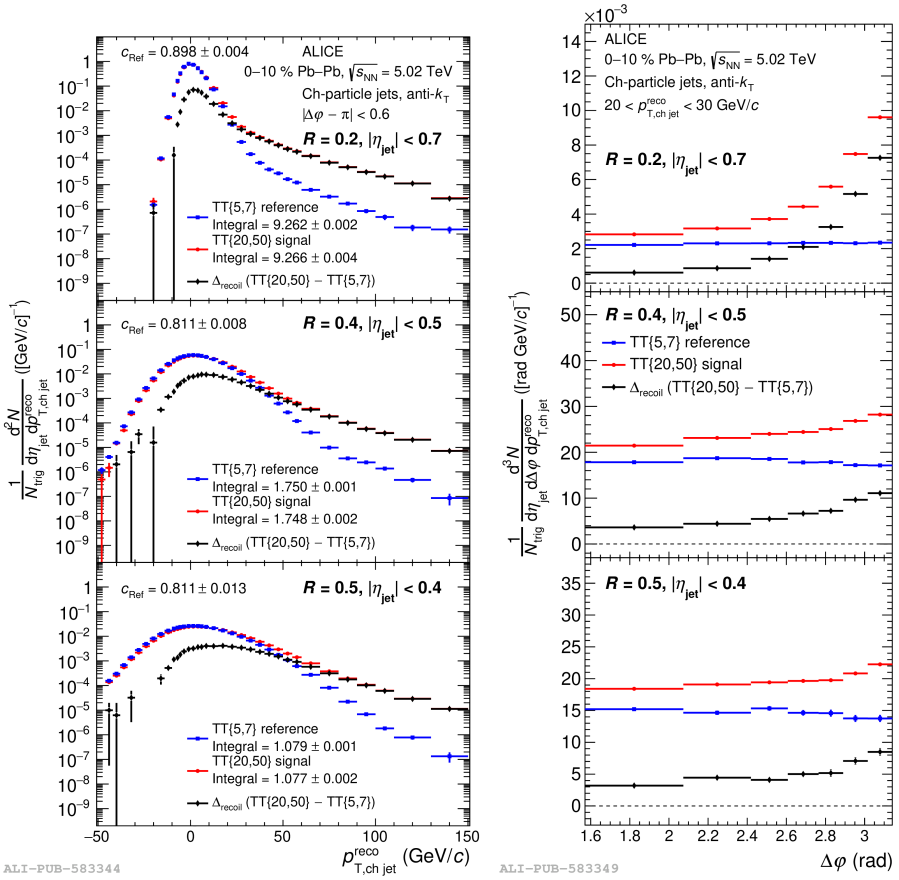


Fig. 2. Per trigger normalized yield of recoil jets associated to trigger hadrons with p_{T} 20–50 GeV/c (red) and 5–7 GeV/c (blue). Left: As a function of underlying event corrected recoil-jet p_{T}. Right: As a function of relative azimuthal angle between TT and recoil jet. Taken from Ref. [4]. Black data points represent the corresponding Δ_{recoil} distributions calculated from Eq. (1).

Δ_{recoil} specta were corrected for instrumental effects and jet-energy-scale smearing due to local UE fluctuations. The ratio of corrected spectra for $R = 0.2$ and $R = 0.4$ jets from Pb–Pb and pp is shown in Fig. 3. Both ratios exhibit a suppression in the intermediate p_{T} region and a rising trend with jet p_{T}. In the case of $R = 0.4$ jets, there is also a large enhancement

in low-p_{T} jet yield. This indicates that the quenched energy might appear in the form of TT-correlated low-p_{T} jets. The data are again compared to the JEWEL, JETSCAPE, and Hybrid models. All modes qualitatively catch the rising trend at high p_{T}. Note that the enhancement at low jet p_{T} is reproduced by the Hybrid model and JEWEL only when the medium response is considered.

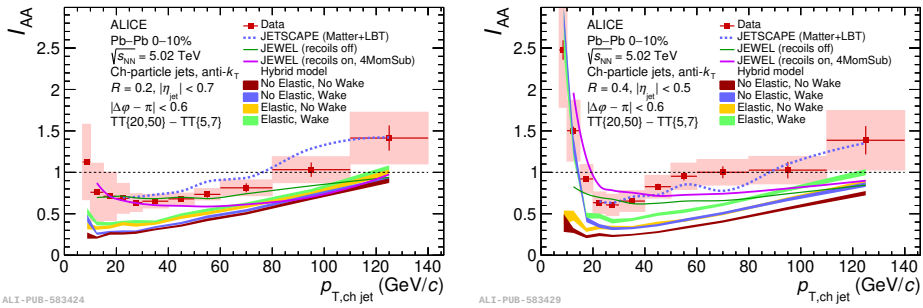


Fig. 3. Ratio of Δ_{recoil} from central (0–10%) Pb–Pb collisions and pp collisions. The ratio is shown for recoil jets with $R = 0.2$ (left panels) and $R = 0.4$ (right panels). Data are compared with model calculations describing jet–medium interactions. The Hybrid model calculaltions are provided with and without accounting for single hard Molière scattering ("Elastic" *versus* "No Elastic") and with and without medium response ("Wake" *versus* "No Wake"). Taken from Ref. [4].

The steepness of the I_{AA} rise as a function of jet p_{T} depends on the chosen trigger-track p_{T} interval (Fig. 4). For TT in the 15–20 GeV/c range, it is noticeably steeper than for TT in the 30–50 GeV/c range. A detailed understanding of this trend will require further model studies. For instance, hints of the TT p_{T} ordering of I_{AA} are seen in JETSCAPE calculations, although the simulation does not fully reproduce the magnitude of the effect.

Finally, Fig. 5 presents I_{AA} as a function of $\Delta\varphi$. The distributions are shown for different recoil-jet radii. Each panel corresponds to a different jet p_{T} interval. The leftmost panel shows recoil jets with $10 < p_{\mathrm{T,jet}}^{\mathrm{ch}} < 20$ GeV/c. In this range, the acoplanarity distribution exhibits a pronounced enhancement at large angles relative to the trigger hadron for $R = 0.4$ and $R = 0.5$ jets, but such enhancement is not present for $R = 0.2$ jets. In the other $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ intervals, the I_{AA} data are compatible with either no suppression or mild suppression. The strong R dependence of I_{AA} observed in the lowest p_{T} bin disfavors an interpretation of the enhancement purely in terms of hard Molière scattering, for which a pronounced jet–radius dependence is not expected. The trends observed in the data are reproduced by the JEWEL calculation that includes medium recoils, whereas the version without recoils is incompatible with the measurement.

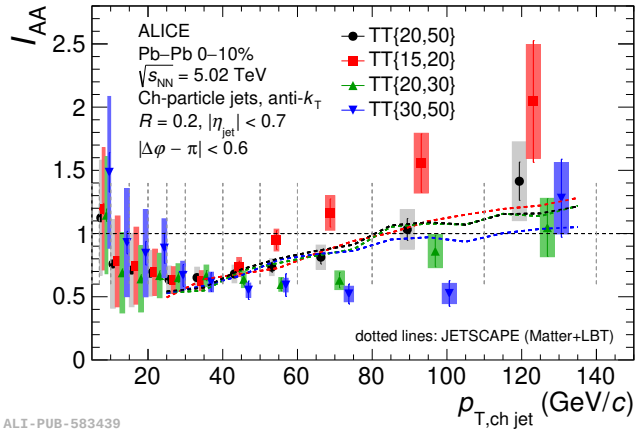


Fig. 4. Ratio of Δ_{recoil} from central (0–10%) Pb–Pb collisions and pp collisions for $R = 0.2$ jets and for different choices of trigger track p_{T} ranges. Taken from Ref. [4].

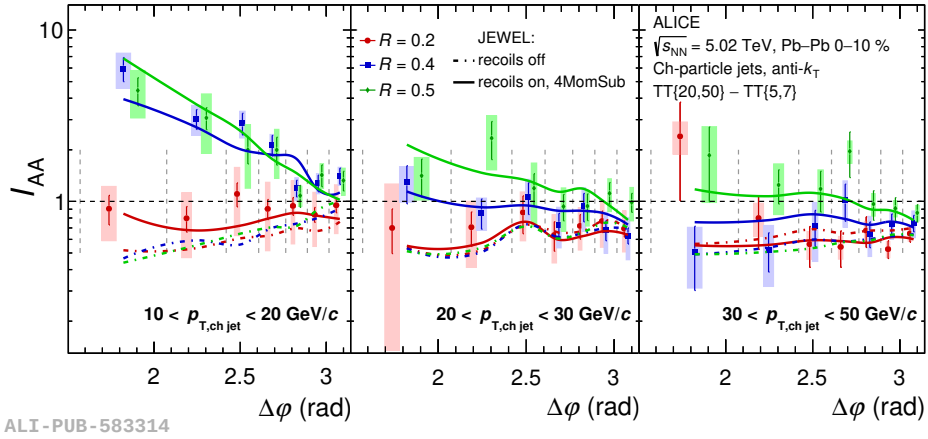


Fig. 5. Recoil-jet I_{AA} in central Pb–Pb collisions a function of the $\Delta\varphi$ angle between TT and recoil jet. The I_{AA} is shown in different jet p_{T} bins for charged-particle anti-k_{T} recoil jets with different R. Taken from Ref. [3].

4. Summary

Jets produced in heavy-ion collisions provide complementary approaches for probing the quark–gluon plasma (QGP). The analysis of jet substructure is sensitive to medium-induced modifications of the parton shower. An enhancement of large-k_{T} splittings in groomed jets could indicate a quasi-

particle structure of the QGP. However, the recent ALICE measurement of large-k_{T} splittings in Pb–Pb collisions does not provide compelling evidence for such a signal when compared to available models.

Additional insight into jet–medium interactions is obtained from hadron–jet coincidence measurements, which enable a statistical subtraction of uncorrelated jets and allow for studies of low-p_{T} jets with large radius. The ALICE measurement of jets recoiling from a high-p_{T} hadron reveals an enhancement of low-p_{T} recoil jets, possibly originating from the redistributed energy of quenched higher-p_{T} jets. These low-p_{T} jets also exhibit significant medium-induced acoplanarity broadening, described by models with medium response included. Overall, these measurements provide complementary constraints on the mechanisms of jet quenching and the nature of jet–medium interactions.

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