PROCEEDINGS OF SCIENCE

Measurements of jet quenching via hadron-jet correlations in Pb–Pb and high-particle multiplicity pp collisions with ALICE

Kotliarov Artem* **for the ALICE Collaboration**

Nuclear Physics Institute of the Czech Academy of Sciences, Rez, Czech Republic

E-mail: kotliarov@ujf.cas.cz

Semi-inclusive measurements of hadron-jet acoplanarity are utilized to search for jet quenching effects in the 0–10% most central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and the high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV. In the Pb–Pb system, where quark–gluon plasma formation is established, a narrowing and suppression of the acoplanarity is observed relative to the PYTHIA-simulated pp reference. In contrast, the acoplanarity distributions that were measured in the high-multiplicity pp events exhibit a marked broadening and suppression with respect to the analogous distributions obtained from the minimum bias events. The observed features are, however, qualitatively reproduced by the PYTHIA 8 Monte Carlo event generator, which does not incorporate jet quenching. The PYTHIA simulations reveal that the observed suppression and broadening are the consequence of a bias induced by the ALICE high-multiplicity trigger, which increases the probability to observe a high-p_{T} recoil jet in the acceptance of the forward trigger detectors and which biases toward multi-jet final states.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker

PoS(EPS-HEP2021)293

1. Introduction

The high energy densities and temperatures which are reached in ultrarelativistic heavy-ion collisions lead to formation of the hot and dense, strongly interacting matter, known as quark–gluon plasma (QGP). High-Q^2 probes, such as jets [1], arise before the medium is formed and equilibrated. Therefore, jets experience the whole evolution of the QGP. Interaction of jets with the QGP results in modification of the jet shower, known as jet quenching [2]. One of the signatures of jet quenching is the medium-induced acoplanarity or jet centroid deflection. The jet deflection can be measured using the hadron-jet correlation technique [3] by studying the broadening of the acoplanarity distribution in azimuth. In proton–proton (pp) collisions, hadron-jet acoplanarity gets broader due to Sudakov radiation [4]. The acoplanarity can further be increased when the jet interacts with the medium. In Ref. [5], it has been however proposed that radiative corrections to the in-medium modification can be negative, which would lead to the reduction of the broadening or even narrowing of the acoplanarity spectrum relative to vacuum.

In these proceedings, measurements of the hadron-jet medium-induced acoplanarity in the most central (0–10%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV and the high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV are presented, utilizing the semi-inclusive $\Delta_{\rm recoil}$ observable [3]

$$\Delta_{\rm recoil}(p_{\rm T,Jet}^{\rm ch,reco}, \Delta\varphi) = \left.\frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jets}}{{\rm d}p_{\rm T,jet}^{\rm ch,reco}{\rm d}\Delta\varphi}\right|_{p_{\rm T,trig} \in {\rm TT}_{\rm Sig}} - c_{\rm Ref} \left.\frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jets}}{{\rm d}p_{\rm T,jet}^{\rm ch,reco}{\rm d}\Delta\varphi}\right|_{p_{\rm T,trig} \in {\rm TT}_{\rm Ref}}, \quad (1)$$

where the right-hand side part represents a difference of two per trigger normalized yields of jets that recoil from high transverse momentum ($p_{\rm T}$) charged trigger-tracks (TT), selected from two exclusive $p_{\rm T}$ intervals denoted $\rm TT_{Sig}$ and $\rm TT_{Ref}$. The yields are expressed as a function of jet transverse momentum $p_{\rm T,jet}^{\rm ch,reco}$, which is corrected for contribution from the underlying events, and the azimuthal angle $\Delta\varphi$ that is subtended by the direction of the TT and recoil jet. The $c_{\rm Ref}$ denotes a correction factor close to 1 extracted from data [3, 6]. The subtraction removes background jet yield uncorrelated with the TT in a purely data-driven way [3]. The $\Delta_{\rm recoil}$ observable allows us to measure jets without imposing fragmentation bias on their population. Therefore, it provides opportunity to extend measurements toward low-$p_{\rm T}$ jets, which are more sensitive to medium induced effects [4].

2. Pb–Pb collisions

The Pb–Pb collision data at $\sqrt{s_{\rm NN}} = 5.02$ TeV were collected by the ALICE in 2018. A description of the ALICE detector can be found in Ref. [7]. This analysis utilized the 0–10% most central events which were selected by the online trigger based on the signal from the forward V0 detectors [8].

Jets were reconstructed from charged tracks using the anti-$k_{\rm T}$ algorithm with $R = 0.2$ and boost-invariant $p_{\rm T}$-scheme. Constituent tracks were constrained to the pseudorapidity range $|\eta| < 0.9$ and were required to have $p_{\rm T} > 0.15$ GeV/c. The accepted jets were required to have centroid within the ALICE fiducial volume $|\eta_{\rm jet}| < 0.9 - R$. Jet $p_{\rm T}$ was corrected for the expected underlying event contribution [9].

The distributions of recoil jets as a function of the jet $p_{\rm T}$ and $\Delta\varphi$ were constructed for $\rm TT_{Sig}$ and $\rm TT_{Ref}$ utilizing statistically independent data sets. The chosen trigger-track $p_{\rm T}$ intervals were

$20 < p_{\mathrm{T,trig}} < 50$ GeV/c for $\mathrm{TT_{Sig}}$ and $5 < p_{\mathrm{T,trig}} < 7$ GeV/c for $\mathrm{TT_{Ref}}$. These TT classes are denoted TT(20,50) and TT(5,7). Figure 1 shows the corresponding projections of the recoil jet distributions on the jet p_{T} and $\Delta\varphi$ axes. The left panel of Fig. 1 shows that per trigger normalized

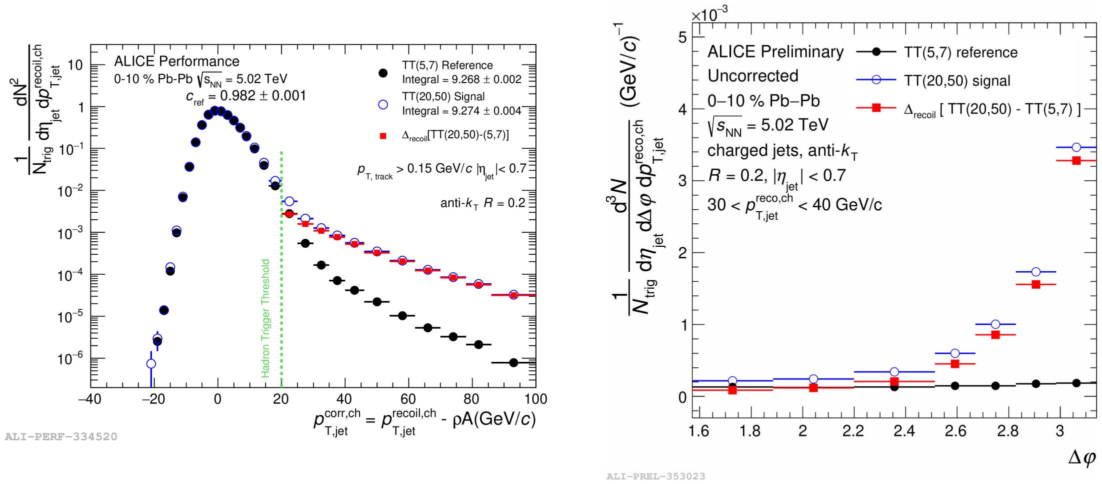

Figure 1: Recoil jet yield normalized per trigger as a function of the jet p_{T} (left) and $\Delta\varphi$ angle (right) for TT(20,50), TT(5,7), and the corresponding Δ_{recoil} spectra (Eq. 1). See text for details.

distributions have similar shape in the region where jet p_{T} is negative or close to zero. In this interval jet population mainly consists of combinatorial background jets, which are uncorrelated with the TT. The right panel of Fig. 1 presents the acoplanarity distributions obtained for jets having p_{T} in the range 30–40 GeV/c, which are nearly back-to-back with respect to the TT.

The two dimensional Δ_{recoil} distribution (Eq. 1) was corrected for the local fluctuations of the underlying events and instrumental effects by means of the Bayesian unfolding procedure [10]. Figure 2 shows a projection of the fully-corrected Δ_{recoil} distribution on the $\Delta\varphi$ axis for jets in the range 30–40 GeV/c. The systematic uncertainties of the $\Delta_{\mathrm{recoil}}(\Delta\varphi)$ spectrum incorporate the uncertainties due to tracking efficiency, unfolding procedure, variation of c_{Ref}, and jet matching criteria. The measured spectrum is compared with the corresponding one obtained from the PYTHIA 8 Monash tune simulations [11] of pp collisions at $\sqrt{s} = 5.02$ TeV. The bottom panel of Fig. 2 shows the ratio of the recoil jet yields in the most central Pb–Pb events and the PYTHIA pp reference. Due to jet quenching, the ratio is less than 1. The rising trend toward $\Delta\varphi \approx \pi$ indicates narrowing of the acoplanarity spectrum measured in the most central Pb–Pb events.

3. Proton–proton collisions

The measurements of hadron-jet acoplanarity in pp collisions at $\sqrt{s} = 13$ TeV were based on the data samples recorded with the minimum bias (MB) and high-multiplicity (HM) triggers. Both triggers employed signals provided by the V0A and V0C forward scintillator arrays [8]. The MB trigger required a time coincidence of the signals, whereas the HM trigger summed the signal amplitudes, and selected the events where the total signal, denoted as V0M, was 5 times larger than an average signal from a MB event, denoted as ⟨V0M⟩. Event activity of the HM sample was classified in terms of scaled multiplicity V0M/⟨V0M⟩.

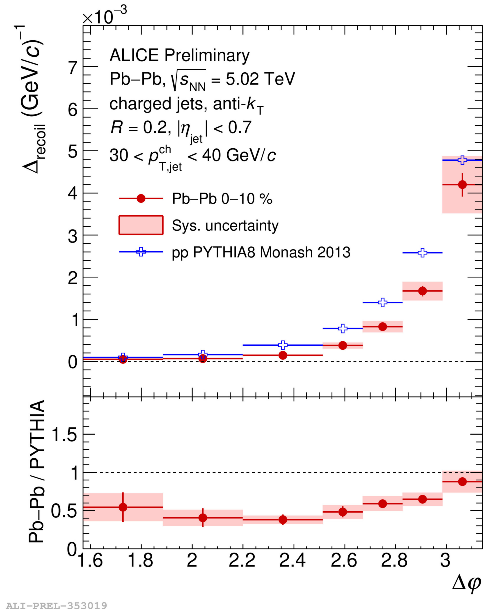

Figure 2: Comparison of the fully-corrected $\Delta_{recoil}(\Delta\varphi)$ distribution measured in Pb–Pb collisions to the corresponding distribution from the PYTHIA pp events. Color boxes represent the systematic uncertainties.

Two exclusive event sets were defined for the MB and HM data samples based on exclusive trigger-track p_T classes: $20 < p_{T,trig} < 30$ GeV$/c$ and $6 < p_{T,trig} < 7$ GeV$/c$ for TT_{Sig} and TT_{Ref}, respectively. Charged-particle jets were reconstructed using the anti-k_T algorithm with $R = 0.4$. Other details of the jets reconstruction can be found in Section 2.

Comparison of uncorrected acoplanarity $\Delta_{recoil}(\Delta\varphi)$ distributions measured in the MB and HM events is shown in the left panels of Fig. 3. Each panel corresponds to different intervals of recoil jet p_T. Significant suppression at $\Delta\varphi \approx \pi$ and broadening is seen for the acoplanarity distributions obtained from the HM sample when compared to the corresponding distributions from the MB data. These modifications resemble expected signatures of jet quenching in the HM pp collisions.

The hadron-jet acoplanarity distributions were further investigated utilizing the PYTHIA 8 Monash simulations [11] of pp collisions at $\sqrt{s}$ = 13 TeV, see the right panels of Fig. 3. The simulations exhibit the same features as the uncorrected measurements, although the PYTHIA 8 does not account for jet quenching. Therefore, these modifications are not due to jet quenching. In order to search for the causes of these striking phenomena, the PYTHIA pp events were further analyzed.

The left panel of Fig. 4 shows pseudorapidity distribution of recoil jets with $p^{ch}_{T,jet} > 25$ GeV$/c$, reconstructed within $|\eta_{jet}| < 5.6$, which covers the acceptance of the V0 detectors, as a function of event multiplicity. The probability to find a high-p_T recoil jet within the acceptance of the V0 detectors starts to grow when the event multiplicity increases. The probability is higher within the coverage of the V0C detector than the V0A owing to its closer location to the interaction point [8].

The right panel of Fig. 4 shows frequency of the MB and HM events with TT(20,30) which have a given number of high-p_T recoil jets reconstructed in the ALICE fiducial volume. Both distributions are steeply falling. The bottom panel presents the ratio of HM and MB spectra. The ratio indicates that the HM data have lower relative frequency of events with a single high-p_T recoil

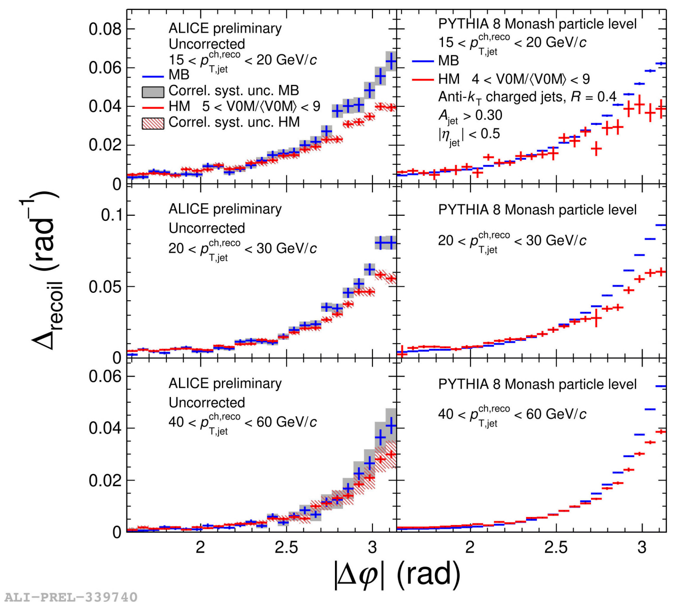

Figure 3: Comparison of acoplanarity distributions for different jet $p_{\mathrm{T,Jet}}^{\mathrm{ch,reco}}$ intervals in the MB and HM events. Left and right panels show corresponding uncorrected data and PYTHIA 8 Monash distributions.

jet when compared to the MB data. The missing high-p_{T} recoil jet may induce the HM trigger and does not balance the TT in the ALICE central barrel. This results in the suppression of the acoplanarity spectra seen in Fig. 3. Besides that, the HM data sample exhibits higher relative abundance of events with multiple high-p_{T} recoil jets in the final state. Such multi-jet topologies have on average greater acoplanarity.

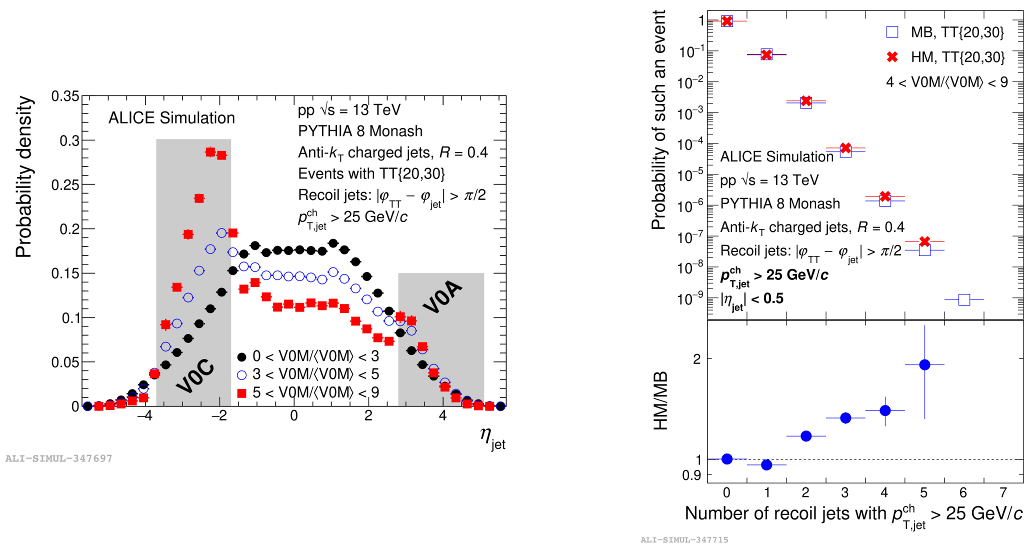

Figure 4: Left: Pseudorapidity distribution of recoil jets with $p_{\mathrm{T,jet}}^{\mathrm{ch}} > 25$ GeV/c in events with TT(20, 30) for different event activity bias V0M/⟨V0M⟩. The gray boxes represent the V0A and V0C acceptances. Right: Probability density distribution of the number of recoil jets with $p_{\mathrm{T,jet}}^{\mathrm{ch}} > 25$ GeV/c in MB and HM events with TT{20, 30}. Bottom panel shows HM/MB ratio of the probability density functions.

4. Conclusion

The measurements of the recoil jet acoplanarity have been performed in the 0–10% Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV and the pp collisions at $\sqrt{s} = 13$ TeV. The fully-corrected acoplanarity distribution measured in Pb–Pb collisions exhibits suppression and narrowing when compared to the PYTHIA pp reference. However, for a definitive interpretation of these results, measurements from pp collisions at $\sqrt{s} = 5.02$ TeV are needed. In case of the pp analysis, the HM acoplanarity spectra are suppressed and broadened relative to the MB ones. However, the generated PYTHIA acoplanarity distributions show similar modifications. The PYTHIA simulations indicate that the HM trigger enhances the probability to find a high-$p_{\rm T}$ recoil jet within the pseudorapidity coverage of the V0 detectors. Furthermore, the HM trigger biases toward events with multiple recoil jets in a final state, which leads to an increase of hadron-jet acoplanarity. These phenomena obscure any possible jet quenching signal.

Acknowledgments: This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic project LTT17018.

References

[1] G. P. Salam, *Towards Jetography*, Eur. Phys. J. C **67** (2010), 637-686.

[2] S. Cao and X. N. Wang, *Jet quenching and medium response in high-energy heavy-ion collisions: a review*, Rept. Prog. Phys. **84** (2021) no.2, 024301.

[3] J. Adam *et al.*, [ALICE], *Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb–Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV*, JHEP **09** (2015), 170.

[4] L. Chen, G. Y. Qin, S. Y. Wei, B. W. Xiao and H. Z. Zhang, *Probing Transverse Momentum Broadening via Dihadron and Hadron-jet Angular Correlations in Relativistic Heavy-ion Collisions*, Phys. Lett. B **773** (2017), 672–676.

[5] B. G. Zakharov, *Radiative* $p_\perp$*-broadening of fast partons in an expanding quark–gluon plasma*, Eur. Phys. J. C **81** (2021) no.1, 57.

[6] S. Acharya *et al.* [ALICE], *Constraints on jet quenching in p–Pb collisions at* $\sqrt{s_{\rm NN}} = 5.02$ *TeV measured by the event-activity dependence of semi-inclusive hadron-jet distributions*, Phys. Lett. B **783** (2018), 95–113.

[7] K. Aamodt *et al.*, [ALICE], *The ALICE experiment at the CERN LHC*, JINST **3** (2008), S08002.

[8] E. Abbas *et al.*, [ALICE], *Performance of the ALICE VZERO system*, JINST **8** (2013), P10016.

[9] B. Abelev *et al.*, [ALICE], *Measurement of Event Background Fluctuations for Charged Particle Jet Reconstruction in Pb–Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV*, JHEP **03** (2012), 053.

[10] T. Adye, *Unfolding algorithms and tests using RooUnfold*, doi:10.5170/CERN-2011-006.313.

[11] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA 8.1: the Monash 2013 Tune*, CERN-PH-TH-2014-069, arXiv:1404.5630 [hep-ph].