SEARCH FOR JET QUENCHING IN HIGH-MULTIPLICITY pp COLLISIONS USING INCLUSIVE AND SEMI-INCLUSIVE JET PRODUCTION IN ALICE*

Filip Krizek

for the ALICE Collaboration

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

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These proceedings report on recent experimental searches for jet-quenching effects in pp collisions at $\sqrt{s} = 13$ TeV. The measurements are based on two jet observables: inclusive jet production and the semi-inclusive yield of jets recoiling from a high-transverse-momentum (p_{T}) hadron. Both measurements are carried out differentially in event multiplicity, which is assumed to bias the size of the collision system. To search for jet quenching effects, the shape of the inclusive jet yield in different multiplicity intervals is compared to the one obtained in minimum bias (MB) events. The increase in selected charged-particle multiplicity causes a rise in the jet yield but only minor changes in the slope of the jet spectrum above 20 GeV/c. In the semi-inclusive analysis, recoil jet acoplanarity is measured for events selected on high multiplicity (HM) and compared to the MB population. A striking modification of the acoplanarity distribution, which is nominally characteristic of jet quenching, is observed in the measured HM population. Its origin is elucidated by comparisons with PYTHIA calculations.

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1. Introduction

Several experimental signatures that are attributed to production of the quark–gluon plasma (QGP) in heavy-ion collisions emerge also in much smaller collision systems such as pp or p–Pb, provided that the selected events have a high multiplicity (HM) of charged particles. These HM events exhibit enhanced production of strange hadrons [1] and collectivity [2]. Recently, ATLAS reported that production of high-p_{T} hadrons in HM p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV also exhibits an azimuthal asymmetry that

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can be described by a non-zero v_2 coefficient [3]. Such asymmetry looks like a signature of path-length-dependent energy loss of partons in a medium caused by jet quenching. However, up to now, there is a lack of experimental evidence that this energy loss is reflected as suppression of inclusive high-p_{T} hadron and jet yields in minimum bias p–Pb collisions and the corresponding nuclear modification factors are compatible with unity [4]. It is therefore unclear whether the observed effects are due to QGP formation or whether they emerge due to other phenomena.

The measurement of the nuclear modification factor in pA and AA collisions relies on a geometry picture provided by the Glauber model [5]. However, this model is not applicable for HM pp collisions because the Glauber scaling is undefined. In HM pp collisions, one needs to look for other signatures that could signal the interaction of high-p_{T} partons with the medium. Such signatures can be searched for in changes in jet spectrum shape, modification of jet substructure or increase in dijet acoplanarity [6]. These proceedings present recent ALICE results on the production of inclusive charged-particle jets [7] and semi-inclusive measurement of hadron–jet acoplanarity in pp collisions at $\sqrt{s} = 13$ TeV collected in 2016, 2017, and 2018.

2. Event selection and data analysis

The ALICE detector and data reconstruction procedure are described in detail in Ref. [8]. Event selection was carried out using two online triggers, an MB trigger and an HM trigger, which were defined based on multiplicity signals provided by the ALICE V0 detector. The V0 detector consists of two scintillator arrays called V0A and V0C covering pseudorapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. While the MB trigger was defined by a time coincidence of V0A and V0C signals, the HM trigger required that the sum of both signal amplitudes (denoted as V0M) is at least five times greater than the mean V0M signal in MB events (denoted as $\langle \mathrm{V0M} \rangle$). The share of MB events selected by the HM trigger is 0.1%. Events with multiple reconstructed primary vertex candidates were rejected as a pile-up [7]. The contribution of pile-up events in the selected HM events was further reduced by constraining the V0 multiplicity signal amplitude to the range $5 < \mathrm{V0M}/\langle \mathrm{V0M} \rangle < 9$.

The ALICE detector measures charged-particle tracks in full azimuth and pseudorapidity $|\eta| < 0.9$. Jets were reconstructed from charged-particle tracks with transverse momentum greater than 0.15 GeV$/c$ using the anti-k_{T} algorithm [9]. Particles were assumed to be massless and their four-momenta were combined using the boost-invariant p_{T} recombination scheme. The measurement of inclusive jets was done for several values of jet resolution parameter $R = 0.2$–0.7. The semi-inclusive analysis was carried out with $R = 0.4$ jets. The pseudorapidity of jets was constrained to the range of

$|\eta_{\rm jet}| < 0.9 - R$. The transverse momentum of selected jets was corrected for the expected contribution of the underlying event. The jet energy scale was further corrected for momentum smearing due to instrumental effects and local underlying event fluctuations with unfolding techniques. Further details about these correction steps can be found in Ref. [7].

3. Results

The shape of the inclusive charged-particle jet $p_{\rm T}$ spectrum is sensitive to the interplay of jet quenching and surface bias effects. Relative changes in the spectrum shape can be represented by a ratio of the spectrum measured in MB events and a corresponding spectrum measured in events biased with V0M multiplicity selection, see Fig. 1. The data suggests that in the region above ≈ 20 GeV$/c$, where jet production is governed by perturbative QCD processes, the spectrum slopes are to a large extent insensitive to the imposed multiplicity bias. On the other hand, the imposed bias affects the yield. Abundance of jets with $p_{\rm T}$ above ≈ 20 GeV$/c$ is about 100-times less probable in low multiplicity events (60–100%) when compared to the events with the highest V0 multiplicity bias (0–1%). This effect might arise from an increase in the average number of hard scatterings per collision.

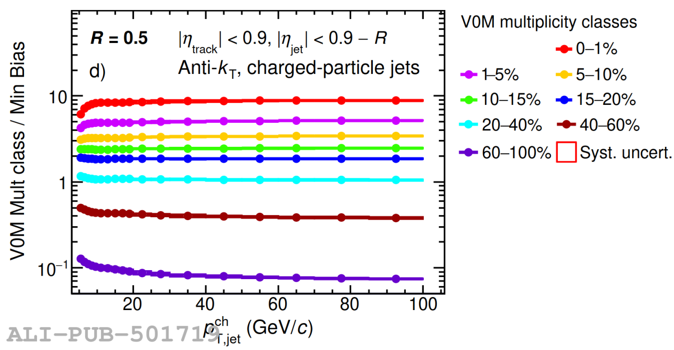

Fig. 1. Ratios of inclusive $p_{\rm T}$ spectra of charged-particle jets measured in *pp* collisions at $\sqrt{s} = 13$ TeV with different charged-particle V0 multiplicity selection to the minimum bias spectrum. Taken from Ref. [7].

Jet quenching might also modify the radial distribution of jet-constituent-$p_{\rm T}$ around the jet axis and induce changes in ratios of jet spectra measured for different jet cone radii. Figure 2 shows such ratios for different choices of the V0 multiplicity bias. It can be seen that while the ratio of jets with small radii $R = 0.2/R = 0.3$ is not affected by the multiplicity bias, the ratio for $R = 0.2/R = 0.7$ jets exhibits a hint of ordering. This trend is however captured also by PYTHIA 8 Monash simulation [7, 10], thus likewise here, there is no sign of jet quenching.

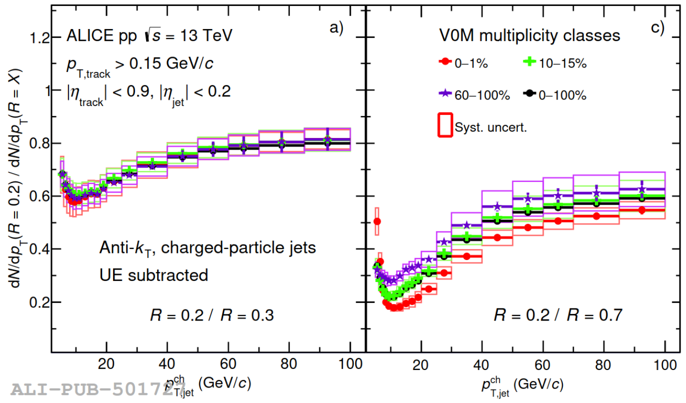

Fig. 2. Ratio of inclusive charged-particle jet spectra for different jet R measured in pp collisions at $\sqrt{s} = 13$ TeV with a bias on charged-particle V0 multiplicity. Taken from Ref. [7].

Hadron–jet acoplanarity was quantified by measuring an azimuthal angle subtended between transverse momentum vectors of a chosen high-$p_{\rm T}$ hadron (so-called trigger track or TT) and a jet, $\Delta\varphi = \varphi_{\rm jet} - \varphi_{\rm TT}$. The size of the angle was recalculated to the range of $(-\pi, \pi)$ rad and it was constrained to the interval $\pi/2 < |\Delta\varphi| < \pi$ rad. Trigger tracks were required to have their transverse momentum in some selected interval and in the case of an event with multiple TT candidates, one of the candidates was chosen randomly. The jet yield that is associated with the TT can be split into a part where the jet was correlated with the hard scattering process which produced the TT, and the remaining part where the jet and the TT were uncorrelated. This uncorrelated yield is then removed on a statistical basis in a data-driven way [11]. The correction procedure normalizes the measured jet yield per one trigger. In the first order of approximation, the per trigger yield of jets, which are uncorrelated with TT, is independent of TT $p_{\rm T}$. Hence, by subtracting two per trigger normalized yields of jets, which are associated with two exclusive trigger track $p_{\rm T}$ bins, this contribution is removed

$$\varDelta_{\rm recoil} = \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p_{\rm T,jet}^{\rm ch} {\rm d}\,|\Delta\varphi|}\bigg|_{\rm TT\{20,30\}} - c_{\rm Ref}\,\frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p_{\rm T,jet}^{\rm ch} {\rm d}\,|\Delta\varphi|}\bigg|_{\rm TT\{6,7\}} . \tag{1}$$

In the equation above, TT$\{X,Y\}$ denotes trigger track transverse momentum range $X < p_{\rm T,trig} < Y$ GeV$/c$. Trigger tracks for both TT intervals were searched for in statistically-independent subsets. The scaling factor $c_{\rm Ref}$ is introduced to account for the invariance of the jet density with TT interval [11].

Figure 3 presents the fully corrected Δ_{recoil} distributions measured in MB and HM *pp* collisions at $\sqrt{s} = 13$ TeV. It can be seen that the abundance of jets, which are back-to-back to TT in azimuth, is lower in HM events when compared with MB events. The suppression is nevertheless quantitatively reproduced by PYTHIA 8 Monash calculation [10], which does not account for jet quenching. The PYTHIA event generator was therefore used to search for the origin of this effect.

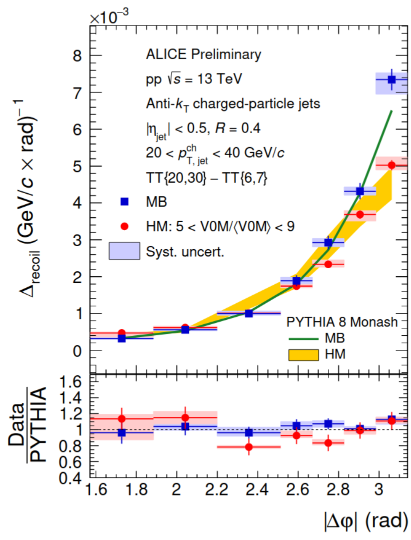

Fig. 3. (Color online) Fully corrected distribution of hadron–jet acoplanarity measured in MB and HM *pp* collisions at $\sqrt{s} = 13$ TeV. Data are compared with a particle-level PYTHIA calculation represented by color bands. Systematic uncertainties on the data are shown as boxes. Their major sources stem from uncertainties in track reconstruction efficiency ($\lesssim 5\%$) and unfolding closure ($\lesssim 5\%$).

Figure 4 shows pseudorapidity distributions of high-p_{T} recoil jets associated with a 20–30 GeV/c trigger track as simulated by PYTHIA 8 Monash. The generated PYTHIA events were assigned to MB or HM event classes using charged particles which were emitted in the acceptance of V0A and V0C detectors. Similarly to the experiment, the MB selection required simultaneous occurrence of charged particles in the acceptance of the V0A and V0C detectors, while the HM selection set a lower threshold on the number of particles in both arrays. The left-hand side panel shows that recoil jets in MB events have pseudorapidity distributions which are symmetric around midrapidity. The analogous distributions for HM events are asymmetric. The imposed HM bias increases the probability to have a high-p_{T} recoil jet in the V0C array. The observed asymmetry results from the asymmetric coverage of the V0 arrays. The recoil jet which induces the HM trigger will be missed in the midrapidity range where one performs the measurement of hadron–jet acoplanarity. This leads to the observed suppression.

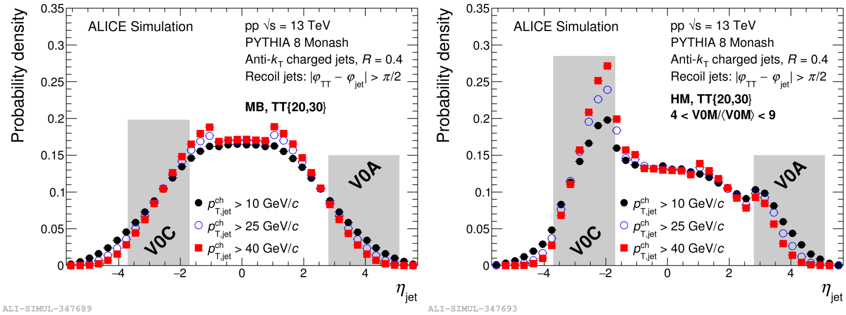

Fig. 4. Pseudorapidity distribution of recoil jets associated with 20–30 GeV/c trigger track in MB and HM pp collisions at $\sqrt{s} = 13$ TeV simulated by PYTHIA 8 Monash. The V0A and V0C detector acceptances are highlighted in gray color.

In summary, the presented inclusive and semi-inclusive jet measurements did not reveal any signs of jet quenching. Jet quenching, if present, is below precision of the current measurements. It was shown that the HM selection imposed by the ALICE V0 affects the measurement, namely the HM trigger can be induced by a high-p_T jet. The selection on HM in general biases towards multi-jet final states. These effects can mask potential jet-quenching signatures and can be a significant issue for HM analyses in small collision systems.

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