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Search for jet quenching effects in high-multiplicity proton-proton collisions at $\sqrt{s} = 13$ TeV

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The ALICE Collaboration reports results of a novel approach to jet-quenching measurements in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV, searching for broadening of the acoplanarity distribution measured by the semi-inclusive distribution of jets recoiling from a high-p_{T} hadron. Charged-particle jet reconstruction is carried out using the anti-k_{T} algorithm with $R = 0.4$. A data-driven statistical method is used to correct the recoil jet yield for uncorrelated background, including multi-partonic interactions. High-multiplicity (HM) pp events are selected based on charged-particle multiplicity registered in forward scintillator detectors, and their acoplanarity distributions are compared to those for Minimum Bias (MB) events. Significant broadening is observed in the acoplanarity distribution of HM events, consistent with jet quenching. However, qualitatively similar features are also seen in a simulated population of pp collisions generated by PYTHIA 8 Monash, which does not incorporate jet quenching. We utilize these PYTHIA simulations to explore the origin of the observed effect. The PYTHIA simulations suggest that the enhanced acoplanarity results from the bias induced by the HM selection towards multi-jet final states.

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Small collision systems exhibit signatures of collective flow [1, 2]. While this suggests formation of the quark-gluon plasma (QGP), there is at present no significant evidence of jet quenching in such systems [3]. These signatures of collectivity may likewise have different origin, such as string showing [4] or QCD interference [5]. To achieve deeper understanding of QGP formation in small collision systems, improved precision of jet quenching measurements is needed so that various mechanisms can be discriminated.

Jet quenching arises from interaction of the parton shower with the QGP medium [6]. This interaction redistributes energy in the shower, leading to yield suppression of high-p_{T} jets and hadrons, jet substructure modification, and dijet acoplanarity distribution broadening. Di-jet acoplanarity is defined as separation of two jets in azimuth.

ALICE is carrying out jet quenching searches in small systems. The smallest collision systems which exhibit collectivity are pp collisions with a large number of particles in the final state (high multiplicity, or HM). Jet quenching searches in these HM pp collisions cannot be based on the measurement of yield suppression, since binary collision scaling of the reference yield using the Glauber model [7] is not defined for pp collisions. Therefore, we explore jet quenching in HM pp collisions by looking for the broadening of dijet acoplanarity.

The data for pp collisions at $\sqrt{s} = 13$ TeV used in this analysis were taken by the ALICE experiment [8] at the LHC using two on-line triggers: minimum bias (MB) and high multiplicity. Both triggers utilize the V0A and V0C scintillator arrays situated at forward ($2.8 < \eta < 5.1$) and backward ($-3.7 < \eta < -1.7$) pseudorapidity, respectively. The sum of measured V0A and V0C signals (denoted V0M) is proportional to the total number of charged particles that hit V0A and V0C. The mean MB V0M signal is denoted $\langle\mathrm{V0M}\rangle$. The MB trigger required a time coincidence of V0A and V0C signals, while the HM trigger fired when V0M exceeded 5 times the $\langle\mathrm{V0M}\rangle$, corresponding to about 0.1% of the MB cross section.

In the off-line analysis, Event Activity (EA) is expressed in terms of scaled V0M multiplicity, $\mathrm{V0M}/\langle\mathrm{V0M}\rangle$. The scaling compensates V0 scintillator aging, and enables more accurate comparison of measured data and MC models, when selecting for EA. HM events are selected off-line by requiring $5 < \mathrm{V0M}/\langle\mathrm{V0M}\rangle < 9$, where the upper limit reduces residual pileup. Jets are reconstructed from charged-particle tracks having transverse momentum in $0.15 < p_{\mathrm{T,track}} < 100$ GeV/c and pseudorapidity in $|\eta_{\mathrm{track}}| < 0.9$. Charged-particle jets were reconstructed using the anti-k_{T} algorithm with $R = 0.4$ with boost-invariant p_{T}-recombination scheme [11] as implemented by FastJet [12]. Jets are accepted in the pseudorapidity interval $|\eta_{\mathrm{jet}}| < 0.5$. The analysis is based on the semi-inclusive distribution of charged-particle jets recoiling from a high-p_{T} trigger hadron [9, 10]. The acoplanarity distribution is measured using the difference between semi-inclusive distributions with exclusive trigger ranges,

$$\Delta_{\mathrm{recoil}}(\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{20,30\}\&p_{\mathrm{T,jet}}^{\mathrm{ch}}} - \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{6,7\}\&p_{\mathrm{T,jet}}^{\mathrm{ch}}}, \quad (1)$$

where $\mathrm{TT}\{p_{\mathrm{T,low}}, p_{\mathrm{T,high}}\}$ denotes the trigger hadron p_{T} interval in GeV/c; N_{trig} denotes the number of selected trigger tracks; $\Delta\varphi$ is the azimuthal opening angle between the trigger hadron and recoil jet; and $p_{\mathrm{T,jet}}^{\mathrm{ch}}$ is the recoil jet transverse momentum range. In this method, correction for the jet yield uncorrelated with the trigger track is carried out with a data driven approach which does not impose fragmentation bias on reconstructed jets. The uncorrelated yield includes the contribution

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of multi-parton interactions. The semi-inclusive hadron-jet analysis follows the correction scheme described in [3].

The left panel of Fig. 1 shows a comparison of the raw Δ_{recoil} ($\Delta\varphi$) distributions measured in MB and HM pp collisions [9]. The data exhibit suppression and azimuthal broadening of the back-to-back correlation in HM events, which are features to be expected from jet quenching. The effect is not due to the different background environment in MB and HM, or to specific algorithmic choices, but it is a robust physical effect [9]. Figure 1, right panel, shows similar distributions from a simulation using PYTHIA8 Monash [13] at the particle-level. The simulated distribution also exhibits suppression and azimuthal broadening for HM events, similar to the data. However, PYTHIA does not incorporate jet quenching effects.

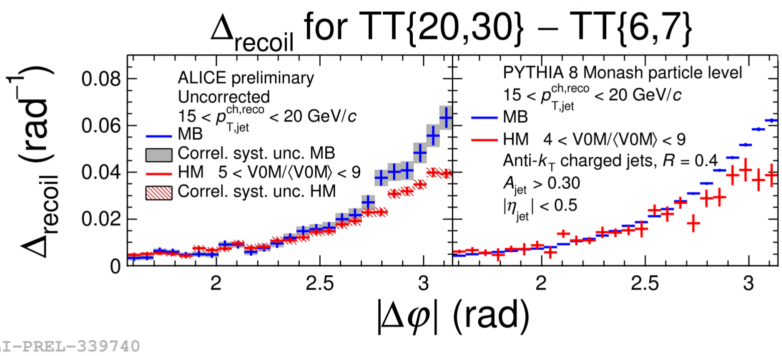

Figure 1: Left: Raw Δ_{recoil} distributions for charged-particle anti-k_{T} R = 0.4 jets measured in HM and MB pp collisions at $\sqrt{s}$ = 13 TeV. Right: The corresponding particle-level Δ_{recoil} distributions simulated by PYTHIA 8 Monash. Taken from [9].

In order to explore the origin of this effect, a new high-statistics PYTHIA 8 Monash simulation was generated. Final-state charged-particle distributions are studied in a wide pseudorapidity range $|\eta| < 6$, covering both V0 arrays. The V0M signal in the simulation corresponds to the charged-particle multiplicity in the η acceptance of the V0 arrays at the particle-level, without accounting for effects of the B-field or interactions in detector material. Accepted events contain a TT within $|\eta| < 0.9$. In the rare case of multiple TT candidates in the same event, one is chosen randomly. Charged-particle jets (anti-k_{T}, R = 0.4) are studied in both the ALICE central barrel (CB) acceptance $|\eta_{\mathrm{jet}}| < 0.5$ and in $|\eta_{\mathrm{jet}}| < 5.6$.

Figure 2 shows η distributions of high-p_{T} recoil jets in MB and HM events with TT{20,30}. The HM trigger is seen to enhance the probability of a high-p_{T} recoil jet in the V0 acceptance, with the asymmetry of the V0A and V0C acceptances generating a larger bias in V0C. Figure 3, left panel, shows η distributions of charged-particle jets for different event EA, and the right panel compares η distributions of near-side and recoil jets for HM events. It is seen that the probability to find a high-p_{T} jet in V0C depends on the EA selection and increases with larger EA. The per-trigger jet yield in V0C is seen to be larger in HM collisions for recoil jets than for near-side jets. Near-side high-p_{T} jets are found predominantly in the CB region, and include the TT as a constituent.

Figure 4 shows the probability distribution of the number of $p_{\mathrm{T,jet}}^{\mathrm{ch}} > 25$ GeV/c recoil jets within the ALICE CB acceptance in MB and HM events. Their ratio shows that HM events have reduced probability for a single recoil jet in the ALICE CB acceptance. This corresponds to the enhanced

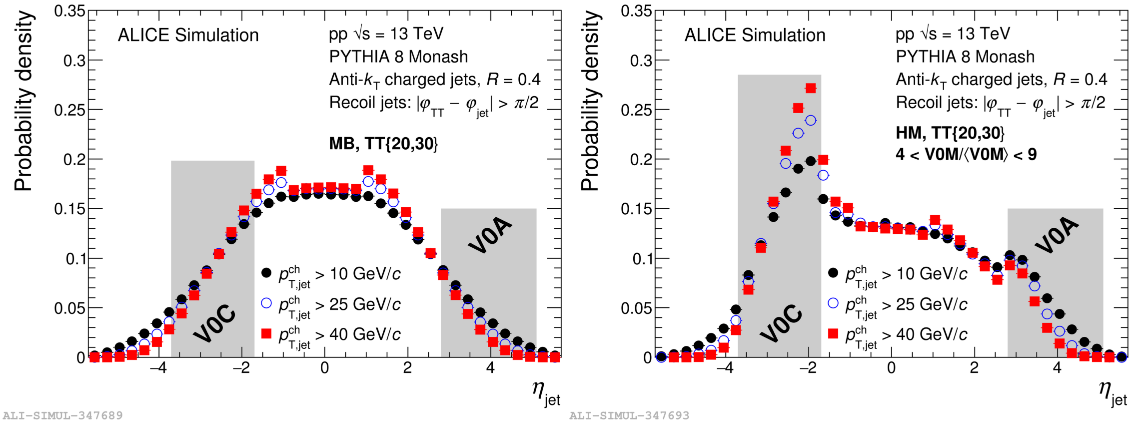

Figure 2: Simulated pseudorapidity distributions of charged-particle recoil jets in pp collisions at $\sqrt{s}$ = 13 TeV (PYTHIA 8 Monash particle level) for events with TT{20,30}. Left: MB. Right: HM. Gray boxes show V0 acceptance.

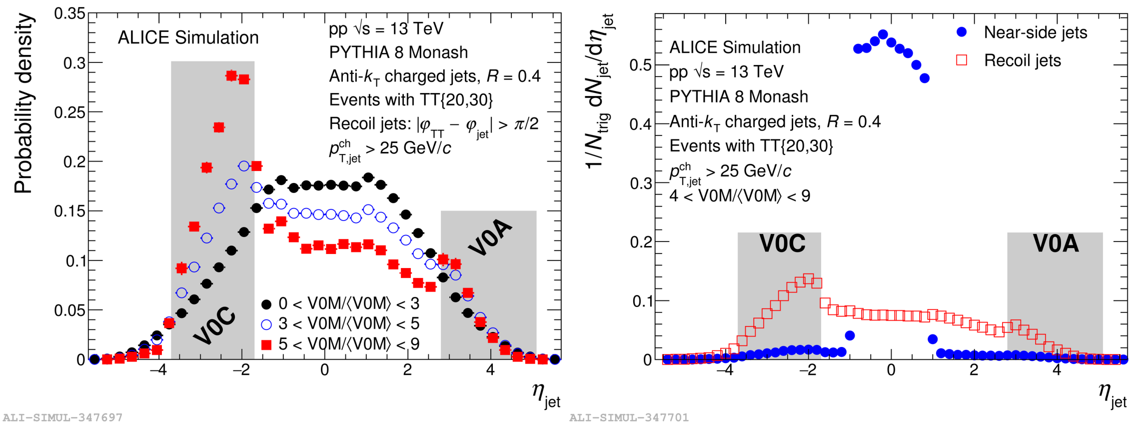

Figure 3: η distribution of charged-particle jets with $p_{T,jet}^{ch}$ > 25 GeV/c in events with TT{20,30}, simulated by PYTHIA 8 Monash.

probability of a recoil jet in the V0 acceptance shown in Fig. 3, thereby suppresses the recoil rate in the ALICE CB. In addition, the HM selection enhances the probability for multiple recoil jets in an event, which broadens the acoplanarity distribution.

In summary, recoil jet yield suppression and broadening that is observed in ALICE high-multiplicity pp $\sqrt{s}$ = 13 TeV events was explored using a PYTHIA simulation. The simulation suggests that in small collision systems, the high-multiplicity trigger biases towards multi-jet final states, which causes suppression and broadening of the acoplanarity distribution. Quenching effects, if present, may be masked by such effects. The simulation suggest that this bias may be measurable in the ALICE central barrel. This bias must be taken into account in all studies of small collision systems at high multiplicity.

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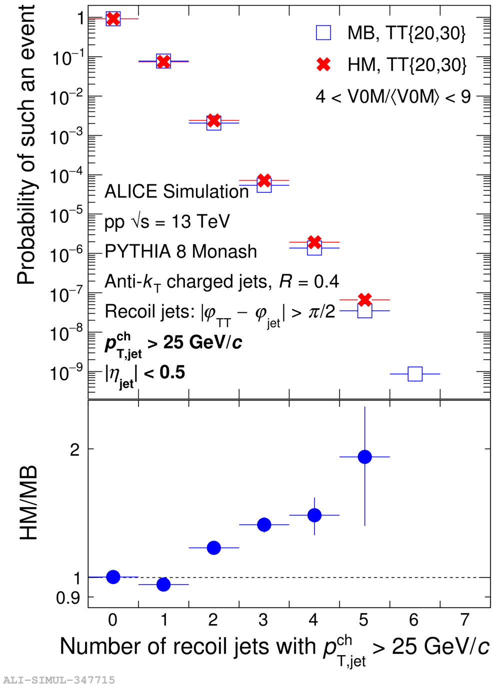

Figure 4: Top panel: Probability distribution of the number of $p^{ch}_{T,jet}$ > 25 GeV/c jets in MB and HM pp $\sqrt{s}$ = 13 TeV events with TT{20,30} simulated by PYTHIA 8 Monash. Bottom panel: Ratio.

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