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

Filip Křížek

ÚJF AV ČR & FJFI ČVUT

20th Conference of Czech and Slovak physicists
Phase diagram of strongly interacting matter

Collisions of ultra-relativistic heavy-ions probe high-energy-density and high-$T$ corner of the phase diagram, where quark-gluon plasma is expected to exist.
Probing quark-gluon plasma

- Collective flow of final state particles indicate perfect fluidity of QGP.

Azimuthal correlation between two particles across wide separation in pseudorapidity → established early in time.

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
CMS EPJ C72 (2012) 2012

- Jet quenching: interaction of hard quarks and gluons with the medium → suppression of high $p_T$ hadrons and jets, jet substructure modification, medium induced jet deflection.

Jet quenching:

Nuclear modification factor:

$$R_{AA} = \frac{Y_{AA}}{\langle N_{coll} \rangle Y_{pp}}$$

ALICE, PRC 95 (2017) 064606

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QGP in small systems?

(b) CMS MinBias, 1.0GeV/c<p_T<3.0GeV/c
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c

pp minimum bias
pp high multiplicity

CMS, JHEP 09 (2010) 091

Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV
CMS EPJ C72 (2012) 2012

HM pp and p-Pb collisions exhibit collectivity but without a visible sign of jet quenching.
Jet quenching in high-multiplicity pp

- Measurement of nuclear modification factor in pp:
  - binary collision scaling undefined $\rightarrow$ measurement impossible
- Medium induced deflection $\rightarrow$ increase of dijet acoplanarity
pp collisions at $\sqrt{s} = 13$ TeV

- Data from 2016-2018
- Online triggers:
  - Minimum bias (MB) $0.098 \text{ pb}^{-1}$ (3.2G events)
  - High multiplicity (HM): 13 pb$^{-1}$
- Offline event activity (EA) selection:
  \[ V0M = V0A + V0C \]
  Scaled multiplicity \( V0M/\langle V0M \rangle \)
  \( \langle V0M \rangle = \text{mean of MB distribution} \)
  Enables comparison of runs with differing V0 gain, and with theory
- $5 < V0M/\langle V0M \rangle < 9 \approx 0.1\%$ of MB cross section

\[ V0A : 2.8 < \eta < 5.1 \quad V0C : -3.7 < \eta < -1.7 \]
Semi-inclusive recoil jet analysis

Spectra are not corrected for instrumental effects and background $p_T$-smearing

$TT\{X,Y\}$ means $X < p_{T,\text{trig}} < Y \text{ GeV/c}$

$A_{\text{jet}} = \text{jet area}$

- Charged-particle jets recoiling from a high-$p_T$ hadron (Trigger Track, TT)
- Jet-wise correction for estimated event density $\rho$: $p_{T,\text{jet}}^{\text{ch, reco}} = p_{T,\text{jet}}^{\text{ch, raw}} - \rho A_{\text{jet}}$
- Ensemble-level: correct for uncorrelated jet yield

$$\Delta_{\text{recoil}} \left( p_{T,\text{jet}}^{\text{ch}} \right) = \frac{1}{N_{\text{trig}}} \left. \frac{dN_{\text{jet}}}{dp_{T,\text{jet}}^{\text{ch}}} \right|_{TT\{20,30\}} - \left. \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{dp_{T,\text{jet}}^{\text{ch}}} \right|_{TT\{6,7\}}$$
A coplanarity measured with $\Delta_{\text{recoil}}$

$\Delta_{\text{recoil}} (\Delta \varphi)$ as a function of TT-jet opening angle $\Delta \varphi$ for a fixed jet $p_T$:

$$
\Delta_{\text{recoil}} (\Delta \varphi) = \frac{1}{N_{\text{trig}}} \left. \frac{dN_{\text{jet}}}{d\Delta \varphi} \right|_{\text{TT\{20,30\} \\ & p_{T,jet}^{\text{ch}}}} - \frac{1}{N_{\text{trig}}} \left. \frac{dN_{\text{jet}}}{d\Delta \varphi} \right|_{\text{TT\{6,7\} \\ & p_{T,jet}^{\text{ch}}}}
$$

$20 < p_{T,jet}^{\text{ch}} < 30$ GeV/c
A coplanarity versus event activity

Significant suppression of HM wrt MB which resembles jet quenching

Data not unfolded; estimated uncertainty from tracking efficiency

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Systematic check: Is the effect from high track density?

\[ \Delta_{\text{recoil}} \text{ for } \text{TT}\{20,30\} - \text{TT}\{6,7\} \]

- Generated PYTHIA detector-level events with TT
- Embedded them into real MB and HM pp events
- Compared \( \Delta_{\text{recoil}} \) distributions from PYTHIA Truth and Embedding (Hybrid)

All distributions agree → suppression is not due to instrumental effects or analysis procedure
$\Delta_{\text{recoil}}$ in raw data and PYTHIA

Qualitative comparison to PYTHIA 8 Monash shows similar suppression pattern →

The effect may not be due to jet quenching

Use PYTHIA to explore the origin of the effect
New PYTHIA high statistics simulations

Charged particles $|\eta_{\text{trk}}| < 6$

Fully covering V0C: $-3.7 < \eta < -1.7$ and V0A: $2.8 < \eta < 5.1$

- Events containing TT\{20,30\} or TT\{6,7\} in $|\eta| < 0.9$

- Anti-$k_T$ track-based jets with $R = 0.4$ in
  1) ALICE central barrel: $|\eta_{\text{jet}}| < 0.5$
  2) broad pseudorapidity range: $|\eta_{\text{jet}}| < 5.6$

V0M defined by the number of charged, final state particles in V0A & V0C
HM in PYTHIA is $4 < \text{V0M/} \langle \text{V0M} \rangle < 9$; HM in real data is $5 < \text{V0M/} \langle \text{V0M} \rangle < 9$
PYTHIA 8 Monash: recoil jet $\eta$ distribution vs $\rho_{T,jet}$

HM events:

- significant bias in distribution of high-$\rho_T$ recoil jets
- strong enhancement in forward trigger acceptance
- collision system is symmetric but V0s have asymmetric coverage
  → sharply different effects on $\eta$-bias

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PYTHIA 8 Monash: recoil jet $\eta$ distribution vs event activity (EA)

Does high-EA selection enhance:
- recoil jet distribution at large $|\eta|$? → Yes
- near-side jet distribution at large $|\eta|$? → No →
  HM selection biases recoil jets

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New observable to characterize the multi-jet distribution vs EA:

- Distribution of the number of recoil jets above $p_T$ threshold per triggered event

→ HM trigger suppresses events with 1 hard recoil jet in the ALICE central barrel

→ HM trigger enhances multi-jet events in small systems

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Summary

ALICE data: Recoil jet yield suppression and broadening in HM events for $p_{T,\text{ch jet}} < 60 \text{ GeV/c}$

- Similar effect observed in PYTHIA

PYTHIA suggests:
- HM induces bias towards multi-jet events in small systems
- This bias must be taken into account in all studies of small collision systems at high multiplicity