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

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Introduction

Jet shower in vacuum

Evolution of highly virtual parton via gluon radiation

- Precise understanding in pQCD
- Reference process for nucleus collisions
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Jet shower in vacuum

Evolution of highly virtual parton via gluon radiation
- Precise understanding in pQCD
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Jet shower in-medium

- Parton energy loss via medium-induced gluon radiation and elastic collisions $\rightarrow$ jet quenching
- Consequences of jet quenching:
  1. Yield suppression of high-$p_T$ hadrons and jets
  2. Modification of jet substructure
  3. Medium-induced acoplanarity $\rightarrow$ semi-inclusive measurements of trigger-jet acoplanarity (trigger: high-$p_T$ hadron, $\gamma$ or $Z$)
Hadron-jet acoplanarity

Regions of interest

1. Small $|\Delta \varphi - \pi|$  
   - Direct estimation of jet transport coefficient $q$
   - Negative radiative correction $\rightarrow$ reduction of broadening (B. G. Zakharov, arxiv:2003.10182)
Hadron-jet acoplanarity

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1. Small $|\Delta \varphi - \pi|$ 
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2. Large $|\Delta \varphi - \pi|$ 
   - Single hard scattering $\rightarrow$ large angle scattering of parton on QGP quasi-particles
   - Probe short distance quasi-particle structure of QGP (F. D’Eramo, Rajagopal, Y. Yin, JHEP 01 (2019) 172)
Hadron-jet acoplanarity via semi-inclusive measurements

Per trigger normalized yield of jets recoiling from high-$p_T$ hadron

\[
\frac{1}{N_{\text{trig}}^{AA}} \frac{d^2N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{ch}d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}}\in TT} = \left( \frac{1}{\sigma^{AA\rightarrow h+X}} \frac{d^2\sigma^{AA\rightarrow h+jet+X}}{dp_{T,\text{jet}}^{ch}d\eta_{\text{jet}}} \right) \bigg|_{p_{T,h}\in TT} \rightarrow \text{Calculable in pQCD}
\]

Cross section for trigger hadron production
Differential cross section for coincidence production of trigger hadron and recoil jet

Semi-inclusive measurements provide:

- Unbiased jet population
- Access to low $p_T$ jets → more sensitive to medium-induced broadening
- Data driven approach for removal of uncorrelated background yield
  → essential for precise acoplanarity measurements
Hadron-jet acoplanarity: $\Delta_{\text{recoil}}$ observable

- Jets recoiling from a high-$p_T$ trigger hadron
- Data-driven approach to remove uncorrelated background yield

$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{AA}} \frac{d^2N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{ch}d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{Ref}} \cdot \frac{1}{N_{\text{trig}}^{AA}} \frac{d^2N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{ch}d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Ref}}$$

**TT**$_{\text{Sig}}$: $20 < p_T < 50 \text{ GeV}/c$

**TT**$_{\text{Ref}}$: $5 < p_T < 7 \text{ GeV}/c$

\[ p_{T,\text{trig}} > 0.15 \text{ GeV}/c \eta_{\text{trig}} < 0.7, \text{ anti-}\kappa_T R = 0.2 \]
Hadron-jet acoplanarity: $\Delta_{\text{recoil}}$ observable

- Jets recoiling from a high-$p_T$ trigger hadron
- Data-driven approach to remove uncorrelated background yield

\[ \Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{AA}} \frac{d^2N_{\text{jet}}^{AA}}{d\varphi_{\text{jet}} d\eta_{\text{jet}}} \bigg|_{P_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{Ref}} \cdot \frac{1}{N_{\text{trig}}^{AA}} \frac{d^2N_{\text{jet}}^{AA}}{d\varphi_{\text{jet}} d\eta_{\text{jet}}} \bigg|_{P_{T,\text{trig}} \in \text{TT}_{\text{Ref}}} \]
Results: Run 1 Pb-Pb $\sqrt{s_{\text{NN}}} = 2.76$ TeV

- Limited statistics
- Uncorrected for $p_T$ and angular smearing
- Anti-$k_T$ charged-particle jets $R = 0.4$ with $p_T \in (40, 60)$ GeV/c
- Fit function:

$$f(\Delta \phi) = p_0 \times e^{(\Delta \phi - \pi)/\sigma} + p_1$$

- Suppression of Pb-Pb data comparing to PYTHIA pp
- No evidence for medium-induced acoplanarity within uncertainties
Results: Run 2 Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV

- x9 larger statistics with respect to Run 1 data
- Anti-$k_T$ charged-particle jets $R = 0.2$ with $p_T \in (30, 40)$ GeV/c
- Fully corrected hadron-jet $\Delta \phi$ distribution
- Recoil jet yield suppressed compared to pp PYTHIA data
- Indication of narrowing of acoplanarity distribution in $30 < p_{T,jet}^{ch} < 40$ GeV/c

Radiative corrections?

B. G. Zakharov, arxiv:2003.10182

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High-particle multiplicity pp collisions
Quark-gluon plasma formation in small collision systems?

Collective flow

CMS, arXiv:1305.0609v3
Quark-gluon plasma formation in small collision systems?

Collective flow

Azimuthal correlation between two particles

pp 7 TeV

Minimum bias events

High-multiplicity events

CMS, JHEP 09 (2010) 091

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

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Jet quenching in high particle multiplicity pp collisions

$R_{AA}$ nuclear modification factor measurements

$$R_{AA} = \frac{\frac{d^2N_{AA}}{dydp_T}}{\left(T_{AA}\right)\frac{d^2\sigma^{INEL}_{pp}}{dydp_T}}$$

undefined Glauber scaling factor for

high particle multiplicity pp

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$R_{AA}$ nuclear modification factor measurements

$$R_{AA} = \frac{d^2 N_{AA}/dyd\rho_T}{\langle T_{AA} \rangle d^2 \sigma_{pp}^{INEL}/dyd\rho_T}$$

Semi-inclusive measurements

$$\frac{1}{\sigma_{AA\rightarrow h+jet+X}} \left. \frac{d^2 \sigma_{AA\rightarrow h+jet+X}}{dp_T^{ch}, jet d\eta_{jet}} \right|_{h \in TT} = \frac{1}{\sigma_{pp\rightarrow h+X}} \left. \frac{d^2 \sigma_{pp\rightarrow h+X}}{dp_T^{ch}, jet d\eta_{jet}} \right|_{h \in TT} \times \langle \frac{T_{AA}}{T_{AA}} \rangle_{h \in TT}$$

Glauber scaling factors $\langle T_{AA} \rangle$ cancel identically

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Minimum bias events

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

- Data from 2016 - 2018
- Online triggers based on V0 arrays:
  - Minimum bias (MB): 0.098 pb^{-1}
  - High-multiplicity (HM): 13 pb^{-1}

- Offline event activity (EA) selection:
  \[ V0M = V0A + V0C \rightarrow \text{sum of signals} \]
- Scaled multiplicity \( V0M/\langle V0M \rangle \)
  \( \langle V0M \rangle \) - mean of MB distribution

\[ pp \ data \ \sqrt{s} = 13 \ TeV \]
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● Anti-$k_T \ R = 0.4$ charged-particle recoil jets

Uncorrected data

● Estimated uncertainty from tracking efficiency

● Significant suppression and broadening of HM data when compared to MB
Acoplanarity versus event activity: uncorrected data and PYTHIA 8

- Anti-\(k_T\) \(R = 0.4\) charged-particle recoil jets

Uncorrected data
- Estimated uncertainty from tracking efficiency
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PYTHIA 8 simulation
- Does not account for jet quenching
- Exhibits qualitatively similar suppression effect as real data
PYTHIA 8 simulation

Recoil jet pseudorapidity distribution vs. event activity

- HM bias imposed by V0M selection enhances probability to find a high-$p_T$ recoil jet in V0
- Lower enhancement in V0A is caused by asymmetric coverage of V0 arrays
- HM selection biases recoil jets
  
  ★ V0M is defined as the number of charged, final state particles within V0A & V0C acceptances

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Recoil jet pseudorapidity distribution vs. event activity

- HM events → suppressed probability to have 1 hard recoil jet in ALICE central barrel w.r.t. MB
- HM bias imposed by V0M selection enhances probability to find a high-\(p_T\) recoil jet in V0
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★ VOM is defined as the number of charged, final state particles within V0A & V0C acceptances

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Enhancement of multi-jet events

ALICE Simulation

Recoil jet pseudorapidity distribution vs. event activity

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ALICE preliminary

pp $\sqrt{s} = 13$ TeV

PYTHIA 8 Monash

Anti-$k_T$ charged jets, $R = 0.4$

Events with $TT(20,30)$

Recoil jets: $|\phi_{\text{jet}} - \phi_{\text{jet}}| > \pi/2$

$p_T^{\text{jet}} > 25$ GeV/c

$0 < \text{V0M/(V0M)} < 3$

$3 < \text{V0M/(V0M)} < 5$

$5 < \text{V0M/(V0M)} < 9$

$\eta_{\text{jet}}$

$\lambda_{\text{jet}}$ (rod) (rad)

- HM events $\rightarrow$ suppressed probability to have 1 hard recoil jet in ALICE central barrel w.r.t. MB

- HM trigger $\rightarrow$ bias towards multi-jet final states

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Enhancement of multi-jet events

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Uncorrected

Anti-$k_T$ charged jets, $R = 0.4$

$20 < p_T^{\text{jet}} < 30$ GeV/c

$A_{\text{ch}} > 0.30$

$|\eta_{\text{jet}}| < 0.5$

Hadron $TT(20,30) \rightarrow TT(8,7)$

MB data

Correlated syst. uncert. MB

HM data $5 < \text{V0M}/\text{V0M} < 9$

Correlated syst. uncert. HM

MB, TT(20,30)

$\times$ HM, TT(20,30)

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Summary

Pb-Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV

- Fully corrected hadron-jet $\Delta \varphi$ distribution for $R = 0.2$ jets in $30 < p_{T,\text{jet}} < 40$ GeV/$c$
- Suppression with respect to PYTHIA pp data
- Observation of narrowing of $\Delta \varphi$ distribution with respect to pp → signs of radiative corrections?
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pp collisions $\sqrt{s} = 13$ TeV

- Significant suppression and broadening of uncorrected high-particle multiplicity $\Delta_{\text{recoil}}(\Delta \varphi)$ distribution with respect to minimum bias one
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pp collisions $\sqrt{s} = 13$ TeV

- Significant suppression and broadening of uncorrected high-particle multiplicity $\Delta_{\text{recoil}}(\Delta\phi)$ distribution with respect to minimum bias one
- Qualitatively similar effects are observed in PYTHIA 8 events:
  - High-multiplicity bias → enhance probability to have high-pT recoil jet in V0 acceptance
  - Bias towards multi-jet final state induced by high-multiplicity trigger: increased acoplanarity due to standard QCD effect → obscures possible jet quenching signal
  - Multi-jet final state → generic bias for all measurements in small collision systems
Backup slides
Pb-Pb data $\sqrt{s_{NN}} = 5.02$ TeV

2018 Pb-Pb data sample
- 133M most central events (0-10 %)

Inner tracking system $|\eta| < 0.9$
- Tracking and vertexing

Time projection chamber $|\eta| < 0.9$
- Tracking

V0 arrays
- Centrality determination
- **V0A**: $2.8 < \eta < 5.1$ & **V0C**: $-3.7 < \eta < -1.7$

Jet reconstruction
- Track $p_T > 150$ MeV/c
- Anti-$k_T$ $R = 0.2$ charged-particle jets
- Fiducial cut $|\eta_{\text{Jet}}| < 0.7$