Study of path-length dependent energy loss of jets in p-Pb and Pb-Pb collisions with ALICE

Caitie Beattie
On Behalf of the ALICE Collaboration

Quark Matter
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Jet energy loss

- Jets lose energy due to interactions with the QGP!
- Microscopic mechanism is well-studied theoretically.
- Theoretical relationship between mechanism and path-length dependence.

Assuming a static medium in the weakly coupled limit...

\[ \sim L \]

\[ \sim L^2 \]

Jet energy loss

- Jets lose energy due to interactions with the QGP!
- Microscopic mechanism is well-studied theoretically.
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But how can we access this experimentally?

Assuming a static medium in the weakly coupled limit...

Event-plane angles

Semicentral collisions generate an anisotropic overlap region.

It is expected that the in-plane axis will be shorter than the out-of-plane axis.

Parton energy loss is expected to be greater along the out-of-plane axis if path-length dependence is a leading effect.
The ALICE detector

1. Time Projection Chamber
   Excellent tracking of charged particles.

2. EMCal
   Used for measurement of neutral constituents.

3. V0
   Forward detector used to measure event-plane angles.

ALICE is well-suited to measure soft-hard correlations of interest.

\[ \text{Pb-Pb, } \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
Approaches to constraining path-length dependence

1. Event-Shape Engineering

2. $v_2$ Measurements

3. Correlation Studies
   - $\pi^0$ - hadrons
   - jet - hadrons
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Event-shape engineering

Event-Shape Engineering (ESE) classifies events according to their anisotropy **within a centrality class.**

\[ q_2 = \frac{|Q_2|}{\sqrt{M}} \]

\[ Q_2 = \frac{1}{M} \left( \sum_{i=1}^{M} \cos(2\varphi_i), \sum_{i=1}^{M} \sin(2\varphi_i) \right) \]

\( \varphi_i = \) azimuthal angle of \( i^{th} \) particle

\( M = \) multiplicity
Event-shape engineering

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How can we exploit this to study path-length dependent energy loss?
Event-shape engineering

Greater **in- vs. out-of-plane differences** are predicted for large $q_2$ events than for small $q_2$ events.

$$\bar{L} = \int \frac{1}{\gamma} u_\mu \, dL^\mu$$

$\gamma$ = Lorentz factor  
$u_\mu$ = local fluid velocity

$q_2$ class  
$\Delta\phi$ limit

- 0 - 100%  
- 0 - 10%  
- 90 - 100%

Beattie, et. al., arxiv:2203.13265
Event-shape engineering

Greater **in- vs. out-of-plane differences** are predicted for large $q_2$ events than for small $q_2$ events.

To study this in data, we can consider the jet **spectra** separated by ESE class.
Event-shape engineering

Comparison of jet spectra from large and small $q_2$ events is consistent with unity.

ALICE Preliminary
30–50% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
Charged-particle jets, anti-$k_T$, $R = 0.2$
$p_T^{\text{lead track}} > 5$ GeV/c, $|\eta_{\text{jet}}| < 0.7$

Additional $q_2^{\text{V0A}}$ cut imposed for autocorrelations.
Event-shape engineering

Large $q_2$ events show significant out vs. in plane difference at mid $p_T$
Event-shape engineering

Small $q_2$ events show less out vs. in plane difference at mid $p_T$

ALICE Preliminary
30–50% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
Charged-particle jets, anti-$k_T$, $R = 0.2$
$p_T^{lead \text{ track}} > 5$ GeV/c, $|\eta_{jet}| < 0.7$
**Event-shape engineering**

Suppression of out-of-plane yields relative to in-plane, more significant for large $q_2$!

**Diagram Description:**
- **ALICE Preliminary**
  - 30–50% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
  - Charged-particle jets, anti-$k_T$, $R = 0.2$
  - $p_T^{\text{lead track}} > 5$ GeV/c, $|\eta_{\text{jet}}| < 0.7$

**Graph Details:**
- Ratios corrected for reaction-plane resolution
- 30% large $q_2^{\text{VOC}}$
- 30% small $q_2$

**Note:**
- Additional $q_2^{\text{V0A}}$ cut imposed for autocorrelations.
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   \[ \pi^0 \text{- hadrons} \]
   \[ \text{jet - hadrons} \]
Jet-particle $v_2$

We can explore lower in $p_T$ by considering the jet particle $v_2$. 

![Graph showing the correlation between $v_2$ and $p_T$]
Jet-particle $v_2$

We can explore lower in $p_T$ by considering the jet particle $v_2$.

Non-zero $v_2$ is indicative of suppressed out-of-plane jet activity, consistent with path-length dependence.
But when we look in p-Pb, we also see non-zero $v_2$!

Is the jet particle $v_2$ indicative of jet quenching, or something else?

See talks by Filip Krizek and Marianna Mazzilli!
Jet-particle $v_2$

When comparing p-Pb and Pb-Pb, we see the $v_2$ magnitude is different but comparable.

Are different mechanisms at play for the $v_2$ in p-Pb and Pb-Pb?
Jet-particle $v_2$

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$\pi^0$ - hadrons
jet - hadrons
Correlation studies

We can look for high-$p_T \pi^0$s (or jets), and study the modification of associated hadrons.

Look first at near-side and away-side yields.

Then consider how these comparisons vary with event-plane.
\[ \pi^0 \text{ - hadron correlations} \]

No evidence of modification...

...for wide range of \( p_T^{\text{assoc}} \) to high precision.
\( \pi^0 \) - hadron correlations

...but none predicted by JEWEL (w/o recoils).

**NEW for QM!**

Jet Energy Loss
Event Shape Engineering
Jet Particle \( v_2 \)
Correlations
Conclusions
Backup

Path-length not the leading contributor for this observable.
Jet-hadron correlations

Away-side modification at low $p_T^{assoc}$ ...

...with work being done to push to lower $p_T^{assoc}$. Stay tuned!
Jet-hadron correlations

Away-side modification at low $p_T^{assoc}$...

NEW for QM!

Jet Energy Loss
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Jet Particle $v_2$
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Suppression not seen in JEWEL (w/o recoils).

Caitie Beattie
Yale University

Quark Matter 2022
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2. \( v_2 \) Measurements

3. Correlation Studies
   \( \pi^0 \)-hadrons
   jet - hadrons
Summary

• **Event-Shape Engineering** studies show significant event-plane dependence in more anisotropic events.
• Non-zero jet-particle $v_2$ shows event-plane dependence in p-Pb and Pb-Pb.
• **Correlation** studies show mixed event-plane dependence, depending on observable.

Not all event-plane observables are sensitive to path-length differences.

**Observables that are most sensitive show results consistent with path-length dependent energy loss.**
<table>
<thead>
<tr>
<th>Summary</th>
<th>ALICE Jet Results at QM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal:</strong> energy loss, path length dependence</td>
<td>Transverse: wide vs. narrow, quark/gluon, intrajet broadening</td>
</tr>
<tr>
<td>Isolated photon-jet correlations: Alwina Liu</td>
<td>ALICE</td>
</tr>
<tr>
<td>Tues. 16:30</td>
<td>Path length dependence in Pb–Pb and p–Pb collisions: Caitie Beattie</td>
</tr>
<tr>
<td>Wed. 8:40</td>
<td>Jet angularity and fragmentation in Pb-Pb: James Mulligan Wed. 10:00</td>
</tr>
<tr>
<td>Search for jet quenching in high-multiplicity pp collisions: Filip Krizek</td>
<td>ALICE</td>
</tr>
<tr>
<td>Wed. 12:50</td>
<td>Heavy-flavor jets from small to large systems: Marianna Mazzilli Wed. 14:40</td>
</tr>
<tr>
<td></td>
<td>R-dependence of jet suppression and groomed jet splittings in Pb–Pb: Hannah Bossi Thurs. 18:10</td>
</tr>
<tr>
<td></td>
<td>Jet acoplanarity and energy flow within jets in Pb–Pb and pp: Rey Cruz-Torres Thurs. 18:30</td>
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Yale University  
Quark Matter 2022
Backup: The $R_{pPb}$

The $R_{pPb}$ is consistent with unity.

Backup: Jet-Particle $v_2$

Signal – extracted using double Gaussian

Background – obtained from sum of flow harmonics

**Data**

ALICE Preliminary

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

TPC-TPC Correlation Fit

V0A: 0-10%

**Signal**

ALICE Preliminary

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

TPC-TPC Correlation Fit

V0A: 0-10%

**Background**

ALICE Preliminary

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

TPC-TPC Correlation Fit

V0A: 0-10%
**Backup: Jet-Hadron Analysis - Reaction Plane Fit**

\[
d^2 N^{bgd}(\Delta \phi, \Delta \eta) = \pi \beta R \left( 1 + \sum_{n=1}^{\infty} 2 \nu_n^R, t \nu_n^a \cos n \Delta \phi \right)
\]

\[
\beta R = B \left( 1 + \sum_{k=2,4,6,\ldots} 2 \nu_k^t \cos k \phi_s \sin k c \frac{R_n}{k c} \right)
\]

**ALICE Performance**

- **Inclusive orient.**
  - $2.0 < \langle p_T^{assoc} \rangle < 3.0$ GeV/c
  - $p_T^{lead} > 3$ GeV
  - $p_T^{beam} > 5$ GeV/c

**Mid-plane orient.**

\[ \chi^2/\text{NDF} = 44.8/48 = 0.934 \]

**Out-of-plane orient.**

- Background dominated
- Signal dominated

**Background:** $0.8 < |\Delta \eta| < 1.2$

- **ALICE** $\sqrt{s}_{NN} = 5.02$ TeV, 30–50%
- **Anti-k_T** $R = 0.2$
- **Signal + Background:** $|\Delta \eta| < 0.6$
- Scale uncertainty: 4%