Jet energy redistribution and broadening using hadron+jet measurements in pp and Pb-Pb collisions with ALICE

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Probing jet quenching via hadron+jet measurement

- Measure trigger-normalised yield of charged-particle jets recoiling from high-\(p_T\) trigger hadrons:
  - opening angle (\(\Delta \phi\)) of jet relative to trigger axis
  - transverse momentum (\(p_{T,jet}\)) of recoil jet

Measure \(p_{T,jet}\) and \(\Delta \phi\): Probe energy loss and acoplanarity simultaneously

First measurement: Run 1 data (Pb-Pb only)

This talk: Run 2 data (Pb-Pb and pp)

Two new papers: arXiv:2308.16131
               arXiv:2308.16128

Jaime Norman (University of Liverpool)
Jet acoplanarity

Acoplanarity distribution:
- in vacuum: Sudakov broadening
- in medium: additional broadening due to scattering

- **Multiple soft scatters** - access jet transport coefficient
  \[ <p_T^2> = \hat{q}L \]

- **Single hard ‘Molière’ scattering** - possibility to resolve weakly interacting scattering centres

Impact of medium response
- Energy of high-\(p_T\) jets transferred to medium
  → **Can impact jet observables,** in particular at low \(p_T\)

Combinatorial background
- Challenge for low-\(p_T\) jet measurements, but broadening effects largest at low \(p_T\)
  → to access this region, treatment of underlying event crucial

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F. D’eramo et al, *JHEP* 05 (2013) 031

See also substructure measurements
H. Bossi, 5th Sept 11:20

See also posters on other observables sensitive to medium response:
C.Pliatskas, energy flow
S. Weyhmiller, PID in jets

See also mixed event technique
N. Gruenwald, 5th Sept 11:40
Measurement technique: statistical approach

- **Subtract combinatorial background**: difference between two exclusive trigger track-classed distributions: ‘signal’ and ‘reference’:

\[
\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^ch d\Delta \varphi d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}} \in T_{\text{Sig}}} - c_{\text{ref}} \cdot \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^ch d\Delta \varphi d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}} \in T_{\text{Ref}}}
\]

- **Statistical approach** - uncorrelated yield corrected solely at level of ensemble-averaged distributions

- **Data-driven subtraction of all combinatorial background**
  low-\(p_T\), large \(R\) measurements possible

- **Perturbatively calculable**
  difference of ratios between high-\(p_T\) hadron and jet production cross sections

\(c_{\text{Ref}}\): normalisation constant
Measurement technique: raw distributions

- **Subtract combinatorial background**: difference between two exclusive trigger track-classed distributions: ‘signal’ and ‘reference’:

\[
\Delta_{\text{recoil}} = \left. \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3N_{\text{jet}}^{\text{AA}}}{dp_{T,\text{jet}}^{\text{ch}} d\Delta \varphi d\eta_{\text{jet}}} \right|_{p_{T,\text{trig}} \in \text{TT}_\text{Sig}} - c_{\text{ref}} \left. \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3N_{\text{jet}}^{\text{AA}}}{dp_{T,\text{jet}}^{\text{ch}} d\Delta \varphi d\eta_{\text{jet}}} \right|_{p_{T,\text{trig}} \in \text{TT}_\text{Ref}}
\]

\[p_{T,\text{jet}}^{\text{reco, ch}} = p_{T,\text{jet}}^{\text{raw, ch}} - \rho A_{\text{jet}} \]

\[\text{TT}_{\text{sig}}: 20 < p_{T,\text{trig}} < 50 \text{ GeV/c} \]

\[\text{TT}_{\text{ref}}: 5 < p_{T,\text{trig}} < 7 \text{ GeV/c} \]
Measurement technique: raw distributions

- **Subtract combinatorial background**: difference between two exclusive trigger track-classed distributions: ‘signal’ and ‘reference’:

\[
\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{\text{AA}}} \int_{\Delta \varphi} d^3N_{\text{jet}}^{\text{AA}} dp_{T,\text{jet}}^{\text{ch}} d\Delta \varphi d\eta_{\text{jet}} \bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{ref}} \cdot \frac{1}{N_{\text{trig}}^{\text{AA}}} \int_{\Delta \varphi} d^3N_{\text{jet}}^{\text{AA}} dp_{T,\text{jet}}^{\text{ch}} d\Delta \varphi d\eta_{\text{jet}} \bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Ref}}}
\]

- \( p_{T,\text{jet}}^{\text{reco, ch}} = p_{T,\text{jet}}^{\text{raw, ch}} - \rho A_{\text{jet}} \)

- \( \text{TT}_{\text{sig}}: 20 < p_{T,\text{trig}} < 50 \text{ GeV/c} \)

- \( \text{TT}_{\text{ref}}: 5 < p_{T,\text{trig}} < 7 \text{ GeV/c} \)
Measurement technique: raw distributions

- Subtract combinatorial background: difference between two exclusive trigger track-classed distributions: ‘signal’ and ‘reference’:

\[
\Delta_{\text{recoil}} = \int \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{ch} d\Delta \phi d\eta_{\text{jet}}} - c_{\text{ref}} \cdot \int \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{ch} d\Delta \phi d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}}^{\text{TT}_{\text{Sig}}}} - \bigg|_{p_{T,\text{trig}}^{\text{TT}_{\text{Ref}}}}
\]

\[
p_{T,\text{jet}}^{\text{reco,ch}} = p_{T,\text{jet}}^{\text{raw,ch}} - \rho A_{\text{jet}}
\]

\(\text{TT}_{\text{sig}}: 20 < p_{T,\text{trig}} < 50 \text{ GeV/c}\)

\(\text{TT}_{\text{ref}}: 5 < p_{T,\text{trig}} < 7 \text{ GeV/c}\)
Measurement technique: corrections to raw distributions

- **Subtract combinatorial background**: difference between two exclusive trigger track-classed distributions: ‘signal’ and ‘reference’:

\[
\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{ch} d\Delta \varphi d\eta_{\text{jet}}} \Bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{ref}} \cdot \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{ch} d\Delta \varphi d\eta_{\text{jet}}} \Bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Ref}}}
\]

- **Calibration of reference distribution** for precise uncorrelated background subtraction:

  1. \( p_{T,\text{jet}}^{\text{reco}} \) scale (‘horizontal’)

  2. Yield scale (‘vertical’) \( c_{\text{Ref}}^{\text{Ref}} \)

    \[
    \rightarrow \text{extracted from data, } \Delta \varphi/R/\text{coll. syst. dependent, takes values between 0.75 and 1}
    \]

- **Raw distributions unfolded** for detector effects and residual background fluctuations

- **All correction steps fully validated** via closure test (PYTHIA embedded into Pb-Pb, compare unfolded to truth)
Fully-corrected $\Delta_{\text{recoil}}(p_{T,\text{ch jet}})$ distributions in pp and Pb-Pb collisions

- $\Delta_{\text{recoil}}$ distributions measured from $7 < p_{T,\text{ch jet}} < 140$ GeV/c in pp and Pb-Pb collisions

Among lowest jet $p_T$ measurement in Pb-Pb collisions at the LHC!
$I_{AA}(p_{T, ch\, jet})$ - recoil jet yield modification in Pb-Pb collisions

\[ I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})} \]

- **Suppression** at $20 < p_{T, ch\, jet} < 80$ GeV/$c$
  \rightarrow jet energy loss

- **Rising trend with** $p_{T, ch\, jet}$
  \rightarrow interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T, jet} > > p_{T, trig}$

Models (Hybrid, JETSCAPE) capture rising trend

\[ p_{T, jet} > > p_{T, trig} \]

\[ p_{T, jet} \sim p_{T, trig} \]

- **JETSCAPE**
  Energy loss based on MATTER (high virtuality) and LBT (low virtuality)

- **JEWEL**
  Medium response effects via treatment of ‘recoils’

- **Hybrid model**
  Elastic (Molière) scatterings and wake (medium response) included

[Image of diagram with plots and data points]
$I_{AA}(p_{T,\text{ch jet}})$ - recoil jet yield modification in Pb-Pb collisions

\[
I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}
\]

- **Suppression** at $20 < p_{T,\text{ch jet}} < 80 \text{ GeV/c}$
  → jet energy loss

- **Rising trend with** $p_{T,\text{ch jet}}$
  → interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T,jet} > > p_{T,\text{trig}}$

- **Rise at low** $p_{T,\text{ch jet}}$
  → Energy recovery? Reproduced by models including medium response
$I_{AA}(p_{T,\text{ch jet}})$ - recoil jet yield modification in Pb-Pb collisions

\[ I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})} \]

- $R=0.5$ consistent with no suppression
- Little suppression captured by JEWEL (recoils on)
- Indication of intra-jet energy recovery within cone radius~0.5 for mid-$p_{T,\text{ch jet}}$?
### $\Delta_{\text{recoil}}(\Delta \phi)$ distributions in pp and Pb-Pb collisions

<table>
<thead>
<tr>
<th>$R_{\text{ch.jet}}$</th>
<th>$p_{T,\text{ch.jet}}$</th>
<th>10 &lt; $p_{T,\text{ch.jet}}$ &lt; 20 GeV/c</th>
<th>20 &lt; $p_{T,\text{ch.jet}}$ &lt; 30 GeV/c</th>
<th>30 &lt; $p_{T,\text{ch.jet}}$ &lt; 50 GeV/c</th>
<th>50 &lt; $p_{T,\text{ch.jet}}$ &lt; 100 GeV/c</th>
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<tbody>
<tr>
<td>$R=0.2$</td>
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<tr>
<td>$R=0.4$</td>
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<td>$R=0.5$</td>
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</tbody>
</table>

**Legend:**
- Pb-Pb 0–10%
- pp
- Sys. uncertainty

**ALICE** $\sqrt{s_{NN}} = 5.02$ TeV
Ch-particle jets, anti-$k_t$
TT(20,50) – TT(5,7)

**References:**
- arXiv:2308.16131
- arXiv:2308.16128

**New paper**
$\Delta_{recoil}(\Delta \phi)$ distributions in pp and Pb-Pb collisions

- Significant azimuthal broadening for $R=0.4$ and $R=0.5$ at low $p_{T, \text{ch jet}}$
$I_{AA}(\Delta \varphi)$ - recoil jet azimuthal modification in Pb-Pb collisions

- **No broadening for [20,100] GeV/c → significant broadening for [10,20] GeV/c**
  - Wake in Hybrid model captures yield enhancement, but no broadening seen when including elastic component
  - pQCD w/ broadening agrees with data - lacking precision to resolve difference between two $\hat{q}$ values
  - JEWEL (recoils on) captures all features of data

New paper

arXiv:2308.16131
arXiv:2308.16128

**pQCD + Sudakov broadening**
Leading order pQCD, azimuthal broadening via jet transport coefficient


$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

(4.7σ deviation of $I_{AA}$ from flat)
Transition to broadening from $R=0.2 \rightarrow R=0.4$ for $[10,20]$ GeV/c: Soft radiation mimicking a jet may scale with $R^2$

- broadening due to medium response or medium-induced soft radiation rather than large-angle scattering?

- All features of distribution reproduced by JEWEL with recoils on
Low jet $p_{T,jet}$: inclusive vs recoil

JEWEL describes other observables less well

- e.g. opposite picture (recoils on/off) for inclusive jets at low $p_{T,jet}$
- → no model incorporating medium response describes all measured observables

(Recoil jet $p_{T,jet}$ spectrum also described less well in vacuum by JEWEL, see backup)
Summary and outlook

• First observation of significant low-$p_{T,\text{jet}}$ yield and large-angle enhancement in Pb-Pb collisions with ALICE!

• Medium response favoured as cause for both effects (Molière scattering disfavoured)

• Full interpretation requires description within a consistent theoretical framework! Future global analyses of multiple observables

See arXiv:2308.16128 for this and more!
Backup
\[ \Delta_{\text{recoil}} \text{ ‘reference’ calibration} \]

Calibration of reference distribution required:

1. \( p_{T,\text{jet}}^{\text{reco}} \) scale (‘horizontal’)

2. Yield scale (‘vertical’)

\[ p_{T,\text{jet}}^{\text{reco}} = p_{T,\text{jet}}^{\text{raw}} - A \cdot \rho \]

- Jet \( p_T \) corrected by underlying event density \( \rho \)
- \( \rho \) depends on trigger-track content of HI event
  - Harder component \( \rightarrow \) larger average \( \rho \)
- Scaling \( \rho \) in reference-classed events by 1.7 GeV/c brings absolute \( \rho \) scale into agreement in both event classes
  \( \rightarrow \) greater precision in subtraction of uncorrelated yield

Established technique

Calibration of reference distribution required:

1. $p_T^{\text{reco}}$ scale ("horizontal")
2. Yield scale ("vertical")

- Integrals of signal and reference distributions consistent
- Conservation of jet density - uncorrelated low-$p_T^{\text{jet}}$ region ‘misaligned’ due to difference in correlated jet yield at high $p_T^{\text{jet}}$
- factor $c_{\text{Ref}}$ applied to reference distribution to align signal and reference distributions in low-$p_T^{\text{jet}}$ region
Δ_{\text{recoil}} ‘reference’ calibration

- Correction Δφ-dependent
- more correlated yield
  → larger $c_{\text{Ref}}$ correction
$\Delta_{\text{recoil}}(p_{T,\text{ch jet}})$ in pp collisions

ALICE
$\sqrt{s} = 5.02$ TeV
Ch-particle jets, anti-$k_T$
$TT(20,50) - TT(5,7)$
$|\Delta\phi - \pi| < 0.6$

$R = 0.2$, $|\eta_{\text{jet}}| < 0.7$

$R = 0.4$, $|\eta_{\text{jet}}| < 0.5$

$R = 0.5$, $|\eta_{\text{jet}}| < 0.4$

ALI-PUB-555799
\[ \Delta_{\text{recoil}}(p_{T,\text{ch jet}}) \text{ in Pb–Pb collisions} \]

ALICE

- $\sqrt{s_{NN}} = 5.02$ TeV
- Ch-particle jets, anti-$k_T$
- $|\Delta\varphi - \pi| < 0.6$

- $R = 0.2$, $|\eta_{\text{jet}}| < 0.7$
- $R = 0.4$, $|\eta_{\text{jet}}| < 0.5$
- $R = 0.5$, $|\eta_{\text{jet}}| < 0.4$

JETSCAPE (Matter+LBT)
JEWEL (recoils off)
JEWEL (recoils on, 4MomSub)

Ratio to fit

\[ \frac{\text{fit}}{\text{data}} \]

$\Delta\text{recoil}$ (GeV/c × rad)$^{-1}$

$|\Delta\varphi - \pi| < 0.6$

$|\eta_{\text{jet}}| < 0.7$

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

$|\eta_{\text{jet}}| < 0.4$

$R = 0.2$

$R = 0.4$

$R = 0.5$

$|\Delta\varphi - \pi| < 0.6$

$|\eta_{\text{jet}}| < 0.7$

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

$|\eta_{\text{jet}}| < 0.4$

New paper

arXiv:2308.16131
arXiv:2308.16128

ALI-PUB-555819
Jet acoplanarity: pp collisions (R=0.4)

- Theoretical predictions yield good description of pp $\Delta \varphi$ distributions for $10 < p_{T,\text{ch jet}} < 100 \text{ GeV}/c$.
Jet acoplanarity: Pb-Pb collisions (R=0.4)

- JEWEL (recoils on) provides best low-$p_T,\text{ch jet}$ description of data, though over predicts high-$p_T,\text{ch jet}$ tails of distribution

- JETSCAPE provides best high-$p_T,\text{ch jet}$ description of data

Maybe simplify text
$I_{AA}(p_{T,ch \ jet})$ - recoil jet yield modification in Pb-Pb collisions

\[
I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}
\]

- Expected that high $p_T$ hadrons leading fragment of jet originating from QGP surface ('surface bias')

- $p_T^{\ jet} \sim p_T^{\ trig}$: suppression - surface bias picture holds

- $p_T^{\ jet} > > p_T^{\ trig}$: trigger hadron may not be leading fragment or from higher order process - interplay between jet and hadron suppression can lead to enhanced $I_{AA}$

- New insight into interplay between hadron and jet suppression
Dealing with background in heavy-ion collisions

- Combinatorial background a major challenge for jet measurements in heavy ion collisions - what is a ‘true’ jet from a hard scattering and what is from uncorrelated sources?

- **Especially important for low** $p_T$ **measurements** where $p_T^{jet} \sim p_T^{bkg}$

- Techniques developed to deal with combinatorial background
Studying intra-jet broadening through R-ratios

- $R=0.2 / R=0.5$ ratio deviates from inclusive jet ratio for $p_{T,\text{ch jet}} < p_{T,\text{trig}}$
- Suppressed LO processes - preference for more, small $R$ jets w.r.t. large $R$ jets to be reconstructed?

- Hints that $R=0.2$ jets suppressed more than $R=0.5$ jets in Pb-Pb w.r.t pp in 30-60 GeV/c
- Energy recovery for wider jets?