Jet acoplanarity via hadron+jet measurements in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE

Jaime Norman on behalf of the ALICE collaboration
University of Liverpool
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Introduction

Jet production in vacuum

- Evolution of hard parton + gluon radiation
  - Precisely calculable in QCD
  - Reference for measurements in heavy-ion collisions

Jet modification in heavy-ion collisions

- Consequences of medium effects include:
  1. **Energy redistribution to larger angles** (jet quenching)
  2. **Modification to jet substructure**
  3. **Jet deflection** (acoplanarity)

- Can be studied through semi-inclusive measurements of a jet recoiling from a trigger (e.g. $\gamma$-jet, Z-jet, or hadron-jet)
Jet acoplanarity

- Opening angle ($\Delta \phi$) of recoil jet relative to trigger axis

Run 1 measurement:

- Statistics-limited
- Mid-$p_T$ jets ($40 < p_T^{\text{jet}} < 60$ GeV/c)
- Uncorrected for angular/$p_T$ smearing
- No medium-induced effects observed within uncertainties
Jet acoplanarity

- Opening angle ($\Delta \varphi$) of recoil jet relative to trigger axis

2 regions of interest:

1. $\Delta \varphi \sim \pi$:
   - Vacuum broadening (Sudakov radiation)
   - Multiple soft scattering in the QGP may further broaden $\Delta \varphi$ distribution
   - Radiative corrections may be negative $\rightarrow$ reduction of broadening

Low-$p_T$ jets are most sensitive to $\Delta \varphi$ broadening effects

M. Gyulassy et al., arxiv:1808.03238
B. G. Zakharov, arxiv:2003.10182

\[ \langle p^2_T \rangle = \hat{q}L \]
Jet acoplanarity

- Opening angle ($\Delta \varphi$) of recoil jet relative to trigger axis

2 regions of interest:

2. $\Delta \varphi \ll \pi$: Large-angle deflection of hard partons off quasiparticles

- Probe short distance partonic structure of the QGP

\[ \Delta \varphi < p_{T}^2 \]

Low-$p_T$ jets are most sensitive to $\Delta \varphi$ broadening effects

F. D’Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172
Detector and data sample

Analysis uses 2018 Pb-Pb data sample
133M recorded 0-10% central-triggered events

Factor $\sim 9x$ increase w.r.t Run 1

ITS $|\eta| < 0.9$
6-layer silicon tracker
Tracking, vertexing,

TPC $|\eta| < 0.9$
Tracking

V0
Triggering
Centrality determination
Method

→ **Measure trigger-normalised yield of jets recoiling from a trigger hadron**

\[
\frac{1}{N_{\text{jet}}^{\text{jet}}} \frac{d^3 N_{\text{jet}}^{\text{jet}}}{dp_T^{\text{jet}} d\Delta \phi d\eta_{\text{jet}}} \bigg|_{p_{T,h} \in TT} = \left( \frac{1}{\sigma_{pp \rightarrow h+X}} \frac{d^3 \sigma_{pp \rightarrow h+jet+X}}{dp_T^{\text{jet}} d\Delta \phi d\eta} \right) \bigg|_{p_{T,h} \in TT}
\]

→ Well defined in pQCD (ratio of high \( p_T \) hadron/jet cross sections)

**Recoil jets:**

→ **Statistical subtraction of combinatorial background:**
  
  - Unbiased fragmentation
  - Access **Low** \( p_T \) jets: reduce vacuum broadening; most sensitive to jet deflection
  - Access **Large** \( R \) jets: access to intra-jet broadening

→ Expected geometrical bias towards longer in-medium path lengths

D. de Florian, Phys. Rev. D 79, 114014
Method - $\Delta_{\text{recoil}}$ observable

- **anti-$k_T$ R=0.2 charged jets** recoiling from a high-$p_T$ hadrons in two exclusive trigger track (TT) classes

- **Subtract combinatorial background**: difference between ‘signal’ and ‘reference’ distributions:

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

Jet $p_T$ corrected for underlying event density $\rho$:

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

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

**TT$_{\text{ref}}$:** $5 < p_{T,\text{trig}} < 7$ GeV/c
**Method - \( \Delta_{\text{recoil}} \) observable**

- \( \Delta_{\text{recoil}} \) is measured as a function of the jet \( p_T \) and \( \Delta \phi \)

\[
\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{\text{ch}} d\Delta \varphi d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{ref}} \cdot \frac{1}{N_{\text{trig}}^{AA}} \frac{d^3N_{\text{jet}}^{AA}}{dp_{T,\text{jet}}^{\text{ch}} d\Delta \varphi d\eta_{\text{jet}}} \bigg|_{p_{T,\text{trig}} \in \text{TT}_{\text{Ref}}}
\]
2D corrections: $p_T$ and $\Delta \varphi$

- Distributions corrected for residual background fluctuations and detector inefficiencies via **2d Bayesian techniques**

  T. Adye, CERN-2011-006 pp.313-318

- Construct **4d response** mapping detector-level jet $p_T$ and jet $\varphi$ to particle level

- Correct $p_T$ and $\Delta \varphi$ simultaneously

  - $p_T$ smearing accounts for main correction

Good $\Delta \varphi$ resolution
($\sim$50 mrad for 25 GeV/c jets)
Results

- First measurement of the fully-corrected hadron+jet $\Delta \phi$ distribution

- Recoil jet yield suppressed with respect to PYTHIA

- Indication of a narrowing of $\Delta \phi$ distribution in $30 < p_T < 40$ GeV/c

B. G. Zakharov, arxiv:2003.10182

Systematic uncertainties: tracking, unfolding (choice of prior, binning, regularisation parameter), $c_{\text{ref}}$ scaling + jet matching
Summary and outlook

• First measurement of the fully-corrected hadron+jet $\Delta\varphi$ distribution for $R = 0.2$ jets in $30 < \pT^{ch}_{T,\text{jet}} < 40$ GeV/c

• Suppression with respect to pp (PYTHIA)

• Indication of narrowing of $\Delta\varphi$ distribution with respect to pp (PYTHIA)
  - radiative corrections at play?

• Next steps:
  
  • pp reference: large-statistics 2017 pp sample at $\sqrt{s} = 5.02$ TeV (~1 billion events)
  
  • Push the measurement to low $\pT$ and large $R$

  Detailed characterisation of jet acoplanarity and yield modification over a broad kinematic region