Probing jet energy redistribution and broadening in pp and Pb-Pb collisions with ALICE

Jaime Norman (University of Liverpool)
EP-LHC seminar
10th October 2023
The quark-gluon plasma

- Phase transition at high temperature or density to deconfined state of quarks and gluons
  - quark-gluon plasma (QGP)
- Calculations on the lattice predicts smooth crossover at ~155 MeV at low baryon density
- Created using ultra-relativistic heavy-ion collisions

fig. H. Caines
QGP (in a nutshell)

Long-distance structure:
QGP is a strongly-coupled liquid (with very low viscosity)

\[ \eta/s \sim 280 \quad \eta/s \sim 0.12 \]

- Lower bound from strongly-coupled gauge theory
  \[ \sim 1/4\pi \sim 0.08 \]

The ‘perfect liquid’!

Short distance structure:
Free quarks and gluons? Complex bound states? degrees of freedom not yet established

What is the structure of the QGP as a function of resolution scale?
Probing the QGP

• To probe the QGP, we have many tools in our toolbox

\[ t = 0 \quad \rightarrow \quad t > 15 \text{ fm/c (} \approx 5 \times 10^{-23} \text{ s)} \]

Examples:

• Hydrodynamic flow
• Hadron chemistry and kinematics
• Electromagnetic radiation from QGP
• Quarkonium disassociation/regeneration
• Partonic interactions with QGP $\rightarrow$ heavy quarks and jets
Jets (in vacuum)

Jet production in pp collisions (vacuum)
- Evolution of hard parton (quark or gluon) → gluon radiation
- Experimentally measured as **collimated spray of hadrons**

Reconstruct jets
→ measure initiating parton

Jet algorithms - precise connection between QCD theory and experiment
- Cluster hadrons measured by our detector, with specified resolution parameter $R$ ~ cone radius
- Should be insensitive to soft/collinear radiation

M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 063

e.g. anti-$k_T$
Jets (in vacuum)

Jet production in pp collisions (vacuum)

- Evolution of hard parton (quark or gluon) → gluon radiation
- Experimentally measured as collimated spray of hadrons

Reconstruct jets → measure initiating parton

Production and evolution well understood over many orders of magnitude → huge achievement of QCD
Jets (in medium)

‘Jet quenching’ - partonic interactions in the QGP

- inelastic (medium-induced gluon emission) and elastic (collisional) processes over full parton shower

Jets provide unique probes of the QGP at multiple scales

\[ R_{AA} = \frac{\text{Yield(PbPb)}}{<N_{\text{coll}}>} \times \text{Yield(pp)} \]

\[ R_{AA} < 1 \text{ - suppression w.r.t. pp} \]

J. Harris, B. Müller, arxiv:2308.05743
Modelling of jet quenching: limiting cases

**pQCD approach**

- Jet-medium interaction described by scattering matrix elements
- Include additional medium-induced radiation

**Non-perturbative description**

- Soft jet-medium interactions through gauge-gravity duality (AdS/CFT) to describe strongly-coupled plasma

Implementation in Monte Carlo generators: simulation of initial state, medium fluid dynamics, multi-stage jet evolution, hadronisation…
Experimentally observable consequences of jet quenching

- Today - multi-pronged measurements of jet and medium modification

Substructure modification    Energy redistribution    Deflection
Experimentally observable consequences of jet quenching

- Today - multi-pronged measurements of jet and medium modification

Substructure modification  Energy redistribution  Deflection
Jet acoplanarity

Broadening of jet transverse to its initial direction

In vacuum:
- Transverse broadening due to gluon emission (Sudakov broadening)

In medium:
- Transverse broadening due to multiple soft scattering

\[ \eta \]


see also:
Jet acoplanarity

Broadening of jet transverse to its initial direction

In vacuum:

- Transverse broadening due to gluon emission (Sudakov broadening)

In medium:

- Transverse broadening due to multiple soft scattering

  - Quantified by jet transport coefficient \( \hat{q} = \frac{< k_{T}^2 >}{L} \)

  (average transverse momentum squared gained per unit path length travelled)

→ Jet acoplanarity provides direct probe of QGP transport coefficient \( \hat{q} \)
Probing short-distance QGP structure

- Lots of recent interest in whether **point-like, single hard (Molière) scatters** can be detected

- Can a Rutherford scattering experiment be performed in the QGP?
  → determine quasi-particle structure of QGP and study how strongly-coupled liquid emerges from constituent degrees of freedom

Fig. modified from F. D’eramo, K. Rajagopal, Y. Yin JHEP 01 (2019)
Probing short-distance QGP structure

- **Strong-coupling limit** - probability of parton to obtain momentum $k_T$ is Gaussian (exponential) distributed

- If medium probed at **short enough distance scales** - scatter off weakly-interacting quasiparticle with probability distribution ‘Rutherford-Like’ power-law distributed
  \[ \sim \frac{1}{(k_T)^4} \] (ignoring radiative corrections)

- Radiative corrections lead to harder power law
  \[ \frac{1}{(k_T)^{4-2\beta}} \] - hard scatters more likely

- Experimentally - can hard scattering be discovered in tails of jet acoplanarity distribution?

F. D’eramo, K. Rajagopal, Y. Yin JHEP 01 (2019)
Jet acoplanarity measurements

- No evidence for QGP-induced acoplanarity so far
  - Theory indicates low $p_T$ jets most sensitive to broadening effects
Medium response to propagating parton

- Jets lose energy due to interaction with medium
  → Medium modified by jets!

Insert out-of-equilibrium probe - see how medium responds
→ transport coefficients, equation of state

Expectation: ‘wake’ effects:
Enhancement around jet
Deletion opposite jet
Sonic boom - $v_{\text{jet}} > c_s \sim 0.5c$

Measured consequences of medium response

See also ATLAS: Phys. Rev. Lett. 126, 072301 (2021)

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \text{PbPb} 1.7 \text{ nb}^{-1}, \text{pp} 304 \text{ pb} \]

Hybrid
- SCET\text{G}
- CoLBT

w/o wake
w/ wake

Cent. 0-30%
\[ p_T^z > 30 \text{ GeV/c} \quad \Delta\phi_{trk, z} > \frac{\pi}{8} \]

Hard particle suppression, soft particle excess
when recoiling from electroweak boson

CMS Supplementary JHEP 05 (2021) 116
PbPb 1.7 nb\(^{-1}\) (5.02 TeV) pp 320 pb\(^{-1}\) (5.02 TeV)

Cent: 0-10%

Anti-\(k_T\) jets, \(R=0.4\)
\[ p_T^{lead} > 120 \text{ GeV}, p_T^{sub} > 50 \text{ GeV} \quad \Delta\psi > \frac{5\pi}{6} \]

\[ \ln x_\perp l < 1.6 \]

\[ \Delta r \]

Soft particle excess surrounding a jet

\[ p_T \]

→ Track-level effects explained by wake effects: how about jets?
Dealing with background in heavy-ion collisions

- Uncorrelated 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 $p_T^{\text{jet}} \sim p_T^{\text{bkg}}$

- Larger-$R$ jets include larger background fraction
Dealing with background in heavy-ion collisions: Statistical correction

- Uncorrelated 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 $p_T^{jet} \sim p_T^{bkg}$

- Larger-$R$ jets include larger background fraction

This talk: correct for background at the level of ensemble-averaged distributions

- Data-driven
- No fragmentation bias

- See also jet-wise approaches:
  - Leading track bias
  - ML-based background estimation


Mixed event bkg

‘Reference’ distribution bkg

Jaime Norman (University of Liverpool)
Probing energy redistribution and jet broadening with ALICE using hadron+jet measurement

Measurements of jet quenching using semi-inclusive hadron+jet distributions in pp and central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:2308.16128
Submitted to PRC

Observation of medium-induced yield enhancement and acoplanarity broadening of low-$p_T$ jets from measurements in pp and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:2308.16131
Submitted to PRL
Analysis: datasets and jet reconstruction

Data samples (from Run 2):

**pp collisions:** min. bias trigger using V0, ITS inner layers
- $\sqrt{s} = 5.02$ TeV: $1040 \times 10^6$ min. bias events, $L_{\text{int}} = 20 \text{ nb}^{-1}$

**Pb-Pb collisions:** centrality-enhanced trigger using V0
- $\sqrt{s_{NN}} = 5.02$ TeV: $89 \times 10^6$ 0-10% most central events, $L_{\text{int}} = 0.12 \text{ nb}^{-1}$

- Charged tracks reconstructed using ITS+TPC
- Charged-particle jets reconstructed using charged tracks as jet constituents
  - Anti-$k_T$ algorithm, $p_{T,\text{track}} > 0.15 \text{ GeV}/c$, $p_T$-recombination scheme
  - Three separate jet radii: $R=0.2$, 0.4 and 0.5
Analysis procedure

1. **Select events** based on the **presence of a high-$$p_T$$ ‘trigger’ hadron**
Analysis procedure

1. Select events based on the presence of a high-$p_T$ ‘trigger’ hadron

   - Hadron distribution follows that of inclusive yield
     → event selection bias solely due to choice of trigger
   - Hadron forms ‘clean’ trigger (e.g. no bkg correction necessary)
   - Observed high-$p_T$ hadrons have surface bias
     → interplay of jet spectrum, FF, energy loss…

   and bias events towards having jets in final state

Adapted from T. Renk, Phys. Rev. C 88, 054902 (2013)
Analysis procedure

1. **Select events** based on the presence of a high-$p_T$ ‘trigger’ hadron

2. **Do jet reconstruction** on these events

3. **Count jets recoiling from the trigger hadron** as function of:
   - opening angle ($\Delta \varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{T,jet}$) of recoil jet

Jet biased to longer in-medium path length
Analysis procedure

1. Select events based on the presence of a high-$p_T$ ‘trigger’ hadron

2. Do jet reconstruction on these events

3. Count jets recoiling from the trigger hadron as function of:
   - opening angle ($\Delta \varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{T,jet}$) of recoil jet

4. Define observable:

\[
\frac{1}{N_{AA}^{trig}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch}d\Delta \varphi d\eta_{jet}} \bigg|_{p_{T,h} \in TT}
\]

\[\text{Trigger-normalised yield of charged-particle jets recoiling from high-$p_T$ trigger hadrons}\]
Analysis procedure

1. **Select events** based on the presence of a high-$p_T$ ‘trigger’ hadron

2. **Do jet reconstruction** on these events

3. **Count jets recoiling from the trigger hadron** as function of:
   - opening angle ($\Delta \varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{T,jet}$) of recoil jet

4. **Define observable**:

   \[
   \frac{1}{N_{trig}^{AA}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch} d\Delta \varphi d\eta_{jet}} \bigg|_{p_{T,h}^{TT}} = \left( \frac{1}{\sigma_{AA \rightarrow h+jet+X}} \cdot \frac{d^3\sigma_{AA \rightarrow h+jet+X}}{dp_{T,jet}^{ch} d\Delta \varphi d\eta} \right) \bigg|_{p_{T,h}^{TT}}
   \]

   - **Perturbatively calculable**
     Ratio between high-$p_T$ hadron and jet production cross sections

   - **Semi-inclusive**
     events selected based on presence of trigger → count all recoil jets in defined acceptance
Analysis procedure

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

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

\( c_{\text{Ref}} \): normalisation constant extracted from data

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

• **data-driven subtraction of all uncorrelated background**
  → Includes multi-parton interaction removal - improves sensitivity to large-angle scattering
  → low-\( p_T \), large \( R \) measurements possible
Analysis procedure: raw distributions

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

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

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

- **TT**\(_{\text{sig}}\): \(20 < p_{T,\text{trig}} < 50\) GeV/c
- **TT**\(_{\text{ref}}\): \(5 < p_{T,\text{trig}} < 7\) GeV/c

---

**h+jet energy redistribution and broadening with ALICE**
Analysis procedure: raw distributions

- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: 'signal' and 'reference':

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

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

- \( \text{TT}_{\text{sig}}: 20 < p_{T,\text{trig}} < 50 \text{ GeV/c} \)
- \( \text{TT}_{\text{ref}}: 5 < p_{T,\text{trig}} < 7 \text{ GeV/c} \)

- **ALICE**

  - \( pp, \sqrt{s} = 5.02 \text{ TeV} \)
  - Ch-particle jets, anti-\( k_T \)
  - \( R = 0.4, |\eta_{\text{jet}}| < 0.5 \)
  - signal \( \text{TT}(20,50) \)

  - **0-10% Pb-Pb, \sqrt{s}_{NN} = 5.02 \text{ TeV}**

![Graph showing distributions and transformations](Image)
Analysis procedure: raw distributions

- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: 'signal' and 'reference':

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

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

**TT_{\text{Sig}}**: \( 20 < p_{T,\text{trig}} < 50 \text{ GeV/c} \)

**TT_{\text{Ref}}**: \( 5 < p_{T,\text{trig}} < 7 \text{ GeV/c} \)
Analysis procedure: raw distributions

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

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

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

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

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

Signal jets dominate

Uncorrelated background dominates
Δ_{recoil} ‘reference’ calibration

Calibration of reference distribution required for precise background subtraction:

- Yield scale (‘vertical’)
- $p_{T,jet}^{reco}$ scale (‘horizontal’)

- Conservation of jet density - uncorrelated low-$p_{T,jet}$ region ‘misaligned’ due to difference in correlated jet yield at high $p_{T,jet}$
- factor ‘$c_{Ref}$’ applied to reference distribution to align signal and reference distributions in low-$p_{T,jet}$ region

Established technique

ALICE: JHEP 09 (2015) 170
Jet $p_T$ corrected by underlying event density $\rho$

Align underlying event density $\rho$ in signal and reference-classed events

Established technique

Unfolding

- **Raw distributions unfolded** for detector effects and residual background fluctuations in both pp and Pb-Pb collisions
  - \( \Delta_{\text{recoil}}(p_{T,\text{jet}}) \): Unfolded in 1 dimension (\(p_{T,\text{jet}}\)) - minimal \(\Delta \phi\) smearing
  - \( \Delta_{\text{recoil}}(\Delta \phi) \): Unfolded in 2 dimensions (\(p_{T,\text{jet}}, \Delta \phi\))
- **All correction steps fully validated** via closure test (PYTHIA embedded into Pb-Pb, compare unfolded to truth)

Systematic uncertainties

- Tracking efficiency
- \(c_{\text{Ref}}\)
- Unfolding (prior, regularisation, binning, algorithm)
- Jet matching
- \(\rho\) correction
- Closure

- **Dominant:**
  - pp: Tracking
  - Pb-Pb: Prior
Models

- **JETSCAPE - Multi-stage event generator**
  - Jet energy loss based on MATTER (high virtuality) and LBT (low virtuality)

- **JEWEL - perturbative treatment to jet quenching**
  - Medium response studied by switching ‘recoils’ on and off (recoil momenta within jet subtracted using prescribed methods)

- **Hybrid model - strong (DGLAP) / weak (AdS/CFT) coupling model**
  - Effect of elastic (Molière) scatterings and wake (medium response) studied by switching effects on and off

  ‘Vacuum’ reference crucial for each model - based on PYTHIA

- **pQCD + Sudakov broadening analytical model**
  - Leading order pQCD, with azimuthal broadening governed by jet transport coefficient
Results

- $\Delta_{\text{recoil}}(p_{T,\text{jet}})$: projection of 2d distribution onto $p_{T,\text{jet}}$ axis within $|\Delta \phi - \pi| < 0.6$
- $\Delta_{\text{recoil}}(\Delta \phi)$: projection of 2d distribution onto $\Delta \phi$ axis for various $p_{T,\text{jet}}$ intervals
Fully-corrected $\Delta_{\text{recoil}}(p_{T,\text{ch jet}})$ distribution in pp collisions

- $\Delta_{\text{recoil}}(p_T)$ described well by PYTHIA8, ‘vacuum’ reference models, and POWHEG

- Modest discrepancy for JEWEL (vacuum) at high $p_{T,\text{jet}}$
Fully-corrected $\Delta_{\text{recoil}}(p_{T,\text{ch jet}})$ distributions in pp and Pb-Pb collisions

- $\Delta_{\text{recoil}}$ distributions measured down to $p_{T,\text{jet}} \sim 7$ GeV/c in pp and Pb-Pb collisions

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

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

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

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

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

- Models (Hybrid, JETSCAPE) capture rising trend

- JEWEL describes low-$p_{T,\text{jet}}$ $I_{AA}$

**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

---

Jaime Norman (University of Liverpool)

K. Zapp, EPJ C, Volume 74, Issue 2, 2014

R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

F. d’Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172

Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)
$I_{AA}(p_{T,ch\text{ jet}})$ - recoil jet yield modification in Pb-Pb collisions

$\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})$

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

\[ |\Delta \varphi - \pi| < 0.6 \]

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

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

- **Rise at low** $p_{T,ch\text{ jet}}$
  → Energy recovery? Reproduced by models including medium response
$I_{AA}(p_{T,ch\text{\ jet}})$ - 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-$p_{T,ch\text{\ jet}}$?
- Redistribution of energy for $R=0.5$ jets more challenging for models
Results

- $\Delta_{\text{recoil}}(p_{T,\text{jet}})$: projection of 2d distribution onto $p_{T,\text{jet}}$ axis within $|\Delta\phi - \pi| < 0.6$
- $\Delta_{\text{recoil}}(\Delta\phi)$: projection of 2d distribution onto $\Delta\phi$ axis for various $p_{T,\text{jet}}$ intervals
\( \Delta_{\text{recoil}}(\Delta \varphi) \) in pp collisions (R=0.4)

- \( \Delta_{\text{recoil}}(\Delta \varphi) \) described well by PYTHIA8, ‘vacuum’ reference models, and POWHEG

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

\( p_{T,\text{ch jet}} \) values:
- 10 < \( p_{T,\text{ch jet}} < 20 \) GeV/c
- 20 < \( p_{T,\text{ch jet}} < 30 \) GeV/c
- 30 < \( p_{T,\text{ch jet}} < 50 \) GeV/c
- ALICE: 50 < \( p_{T,\text{ch jet}} < 100 \) GeV/c
$\Delta_{\text{recoil}}(\Delta \phi)$ distributions in pp and Pb-Pb collisions

$R=0.2$

$R=0.4$

$R=0.5$

$\Delta \phi$
\( \Delta_{\text{recoil}}(\Delta \phi) \) 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 \phi) - $ recoil jet azimuthal modification in Pb-Pb collisions


(4.7\sigma deviation of $I_{AA}$ from flat)
$I_{AA}(\Delta \varphi)$ vs $R$

**Transition to broadening from $R=0.2 \rightarrow R=0.4$ for [10,20] GeV/c:**

- Soft radiation mimicking a jet may scale with $R^2$
- Molière scattering off QGP quasiparticles - $R$-dependence not expected
$I_{AA}(\Delta \phi)$ vs $R$

- **Transition to broadening from** $R=0.2 \rightarrow R=0.4$ for [10,20] GeV/c:
  - Soft radiation mimicking a jet may scale with $R^2$
  - Molière scattering off QGP quasiparticles - $R$-dependence not expected

→ Data favours medium response to jet or medium-induced soft radiation as explanation for observed broadening
$I_{AA}(\Delta \phi)$ compared to models

\[ p_{T,ch\ jet}^{\text{[10,20] GeV/c}} \quad [20,30] \text{ GeV/c} \quad [30,50] \text{ GeV/c} \quad [50,100] \text{ GeV/c} \]

- Hybrid model w/ wake: captures yield enhancement. w/ elastic: negligible broadening
- pQCD w/ broadening via $\hat{q}$ : lacking precision to resolve difference between two $\hat{q}$ values
- JEWEL (recoils on): captures all features of data

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


ALI-PUB-55589
$I_{AA}(\Delta \phi)$ compared to models

$P_{T,\text{ch jet}}$: [10,20] GeV/c

$P_{T,\text{ch jet}}$: [20,30] GeV/c

$P_{T,\text{ch jet}}$: [30,50] GeV/c

$P_{T,\text{ch jet}}$: [50,100] GeV/c

- Hybrid model w/ wake: captures broadening for higher $R$
- JEWEL (recoils on): captures all features of data

$\rightarrow$ Models further confirm picture that measured broadening predominantly due to medium response
$I_{AA}(\Delta \phi)$ vs $R$ compared to JEWEL

- All features of distribution reproduced by JEWEL with recoils on
$I_{AA}(\Delta \phi)$ vs $R$ compared to JEWEL

- All features of distribution reproduced by JEWEL with recoils on …
- … but no model incorporating medium response describes all measured observables
Next steps - precise characterisation of quenching effects

Characterise broadening

Thermalised jets?  Hard component?
Study substructure/fragmentation pattern

hard jet splittings - no clear evidence for Molière scattering

\[ \gamma \rightarrow \text{tagged jet substructure} \]
Requires Molière scattering to describe data

Jaime Norman (University of Liverpool)

ALI-PUBL-555709
Summary and outlook

- First observation of significant low-$p_{T,\text{jet}}$ jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!
- Medium response or medium-induced soft radiation favoured as cause for both measured effects
- Looking forward to further studies with Run 3 data with ALICE after significant upgrade programme

arXiv:2308.16128
arXiv:2308.16131
LHC reached ‘maximum’ number of Pb-Pb bunches 1240b Friday 6th October!

ALICE taking lots of good data with increasing interaction rate!
Run 1 hadron+jet measurement

- Background-subtracted yield of jets recoiling from a high-$p_T$ trigger hadron:
  - Suppression with respect to a pp (PYTHIA) reference
  - No medium-induced broadening within experimental uncertainties
$I_{AA}(p_{T,\text{ch jet}}) - \text{recoil jet yield modification in Pb-Pb collisions}$

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

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

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

- $p_T^{\text{jet}} > p_T^{\text{trig}}$: 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
Studying intra-jet broadening through $R$-ratios

- $R=0.2 / R=0.5$ ratio deviates from inclusive jet ratio for $p_{T,\text{ch, jet}} < p_T^{\text{trig}}$

$\tilde{z} = \frac{p_T^{\text{trig}}}{p_T^{\text{jet}}}$

- $\tilde{z} > 1 \rightarrow$ LO processes suppressed
- preference for more, small $R$ jets w.r.t. large $R$ jets to be reconstructed?
Studying intra-jet broadening through $R$-ratios

- 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?
ALICE in Run 3

Replace TPC wire chambers with gas electron multiplier (GEM) readout

New Inner Tracking System

New forward interaction trigger (FIT)

+ New beam pipe
+ New readout architecture
+ Major computing system upgrade (O2 project)

New Muon Forward Tracker (MFT)
Raw distributions

Pb-Pb

h+jet energy redistribution and broadening with ALICE

Jaime Norman (University of Liverpool)

pp
\[ \Delta_{\text{recoil}}(p_{T,\text{ch~jet}}) \text{ in Pb–Pb collisions} \]

\[ \Delta_{\text{recoil}}(p_{T,\text{ch~jet}}) = \text{rad} \]

\[ \begin{align*}
\text{ALICE} & \quad S_{\text{NN}} = 5.02 \text{ TeV} \\
\text{Ch-particle jets, anti-}k_T & \quad \text{T}(20,50) - \text{T}(5,7) \\
|\Delta \varphi - \pi| & < 0.6
\end{align*} \]

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

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

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

\[ \begin{align*}
\text{JETSCAPE (Matter+LBT)} & \quad \text{fit to data} \\
\text{JEWEL (recoils off)} & \\
\text{JEWEL (recoils on, 4MomSub)} &
\end{align*} \]

\[ \begin{align*}
P_{\text{T,}\text{ch~jet}} & \quad (\text{GeV/c}) \\
\text{Ratio to fit} & \\
0 & \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4
\end{align*} \]

\[ \begin{align*}
P_{\text{T,}\text{ch~jet}} & \quad (\text{GeV/c}) \\
0 & \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \quad 120 \quad 140
\end{align*} \]
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

ALI-PUB-555829
Δ_{recoil} "reference" calibration

Δ_{recoil} (p_{T,ch,jet}^{rec}) analysis

Δ_{recoil} (Δφ) analysis

1.57 < Δφ < 2.07
2.61 < Δφ < 2.76
3.02 < Δφ < 3.14

ALICE
0-18% Pb-Pb
L_{int} = 5.02 TeV
Ch-particle jets, anti-Jpsi

Jaime Norman (University of Liverpool)
h+jet energy redistribution and broadening with ALICE
Calibration of reference distribution required for precise background subtraction:

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

2. Yield scale ('vertical')

- Correction $\Delta \varphi/R$-dependent
- more correlated yield $\rightarrow$ larger $c_{\text{Ref}}$ correction
Dealing with background in heavy-ion collisions: Jet-wise correction

- 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 $p_T^{\text{jet}} \sim p_T^{\text{bkg}}$

- **ML-based approach** - improve background resolution using NN trained on PYTHIA jets

- **Leading track bias approach** - guarantee selection jets with hard component

-- ![Graph showing probability density](attachment:image.png)

---

Jaime Norman (University of Liverpool)