Study of jet fragmentation with two particle correlations in Pb-Pb collisions at 2.76 ATeV by ALICE

Filip Krizek
for the ALICE collaboration
Study of the $E_{\text{loss}}$ mechanism (jets)

- Strong jet quenching is observed in HI collisions at RHIC and LHC.
- Analyses based on full jet reconstruction show
  - strong di-jet energy asymmetry [ATLAS PRL 105(2010) 252303, CMS, PRC 84, 024906 (2011)]
  - jet fragmentation (of the quenched parton) seems to look as unmodified

\[ \text{[P. Steinberg ATLAS talk at QM2011, CMS arXiv:1205.5872]} \]

- quenched energy reappears at low $p_T$, also outside the jet cone

[CMS, PRC 84, 024906 (2011)]

\[ \text{ATLAS, PRL 105 (2010) 252303} \]
Di-hadron correlations

• Indirect method (only 2 hadrons from jet)
• Jet properties studied statistically

Basic quantities

\[ \Delta \varphi = \varphi_{\text{assoc}} - \varphi_{\text{trig}} \]

\[ \Delta \eta = \eta_{\text{assoc}} - \eta_{\text{trig}} \]

\[ R = \sqrt{\Delta \varphi^2 + \Delta \eta^2} \]

\[ I_{AA} = \frac{1/N_{\text{trig}}^{Pb-Pb} \times Y_{Pb-Pb}^{Pb-Pb}}{1/N_{\text{trig}}^{pp} \times Y_{pp}^{pp}} \bigg|_{p_{T,\text{trig}}; p_{T,\text{assoc}}} \]

Near side (intra jet) : Single jet properties such as jet transverse fragmentation momentum

Away side (inter jet) : Di-jet properties such as accoplanarity + mom. imbalance due to \( k_T \)
Study of $E_{loss}$ mechanism (di-hadron correl.)

- $I_{AA}$ measurements by ALICE for $8 < p_{T,\text{trig}} < 15$ GeV/$c$ & $3$ GeV/$c < p_{T,\text{assoc}}$
  - away side $I_{AA} \sim 0.5$
  - near side $I_{AA} \sim 1.2 – 1.3$
  - near side parton is sensitive to medium
    a) modification of jet fragmentation (softening)?
    b) modification of quark/gluon jet ratio (g filtering)?
    c) bias of the parton $p_T$ spectrum after energy loss due to trigger selection?

- How does near side $I_{AA}$ continue at lower $p_{T,\text{assoc}}$?
- Can we see some modification in transverse jet shape at near side?
- Method: Two-particle correlations
Near side $I_{AA}$ (in $R<0.2$) at low $p_{T,\text{assoc}}$

- Signal yield $Y_S$ from a cone (radius $R = 0.2$)
- Background yield $Y_B$ estimated using two $R=0.2$ cones placed at large $\Delta\eta_{\text{Gap}} > 1.1$

$$I_{AA} = \frac{(Y_S - 0.5 \times Y_B) / N_{\text{trig}}|_{\text{Pb-Pb}}}{(Y_S - 0.5 \times Y_B) / N_{\text{trig}}|_{\text{pp}}}$$
Near side $I_{AA}$ (in R<0.2) at low $p_{T,\text{assoc}}$

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$$ I_{AA} = \frac{(Y_S - 0.5 \times Y_B) / N_{\text{trig}}}_{\text{Pb-Pb}} \left| \frac{(Y_S - 0.5 \times Y_B) / N_{\text{trig}}}_{\text{pp}} \right. $$

- Near side $I_{AA}$ in 0-10% central collisions shows moderate enhancement by ~ 20-50%
Analysis of near side peak shape

- Near-side jet peak is centered around $\Delta \eta = 0$
- Estimate $\Delta \eta$-independent effects (e.g. flow) by studying the long-range correlation region ($|\Delta \eta| > 1$)
- Subtract from short-range region ($|\Delta \eta| < 1$)

Pb-Pb 2.76 ATeV Cent 0-10%

\[
4 < p_{T,\text{trig}} < 8 \text{ GeV/c} \quad 1 < p_{T,\text{assoc}} < 2 \text{ GeV/c}
\]

\[
2 < p_{T,\text{trig}} < 3 \text{ GeV/c} \quad 1 < p_{T,\text{assoc}} < 2 \text{ GeV/c}
\]
Evolution of near side peak shape

\[ 2 < p_{T,trig} < 3 \quad \& \quad 1 < p_{T,assoc} < 2 \text{ GeV/c} \]

\[ 4 < p_{T,trig} < 8 \quad \& \quad 2 < p_{T,assoc} < 3 \text{ GeV/c} \]

Pb-Pb 2.76 ATeV
Cent. 0-10%
\[ 2 < p_{T,trig} < 3 \text{ GeV/c} \]
\[ 1 < p_{T,assoc} < 2 \text{ GeV/c} \]

\[ \sigma_{\Delta\phi} \text{ (fit)} \]
\[ \sigma_{\Delta\eta} \text{ (lines)} \]
\[ \sigma_{\Delta\phi} (\text{points}) \]

Scale uncertainty: 20%
\[ \Delta\phi \text{ projection in } |\Delta\eta| < 0.80 \]
\[ \Delta\eta \text{ projection in } |\Delta\phi| < 0.87 \]
**Evolution of near side peak shape**

3 < $p_{T,\text{trig}}$ < 6 GeV/c
1.5 GeV/c < $p_{T,\text{assoc}}$ < $p_{T,\text{trig}}$

Paper reports a clear increase of $\Delta \eta$ width with increasing $<N_{\text{part}}>$ in Au+Au at 200 AGeV
Possible scenario for peak deformation

• Armesto, Salgado, Wiedemann suggested that longitudinal flow can deform the conical jet shape (PRL 93,242301 (2004))

• Interplay between jet and flow

![Diagram showing Vacuum (reference), Static medium: Broadening, Flowing medium: Anisotropic shape]
**AMPT comparison**

- AMPT (A MultiPhase Transport Code, *Phys.Rev.* C72 (2005) 064901) describes collective effects (e.g. $v_2$, $v_3$, $v_4$) in HI collisions at LHC
  - Here version with string melting (2.25) is shown
- It also does rather well for the rms of the near side peak
  - Interplay of jet and flow in AMPT via parton and hadron scattering

**AMPT calculation is shown as lines**
\( I_{AA}(\Delta \eta) \) and jet shape modification

- Analyze \( dN/d|\Delta \eta| \)
  (positive and corresp. negative bins combined)

- Background level estimated by a fit
  Kaplan plus constant (parameters \( A, b, n, k \))
  \[ f(\Delta \eta) = A(1 + b\Delta \eta^2)^{-n} + k \]

- Evaluate the ratio
  \[ I_{AA}(|\Delta \eta|) = \frac{1/N_{\text{trig}}^{\text{Pb-Pb}} \times dN_{\text{Pb-Pb}}^{\text{Pb-Pb}} / d|\Delta \eta|}{1/N_{\text{trig}}^{\text{pp}} \times dN_{\text{pp}}^{\text{pp}} / d|\Delta \eta|} \]

Cartoon showing possible scenarios of jet shape modification
\( I_{AA}(|\Delta \eta|) \) at intermediate \( p_T \) \( (6<p_{T,\text{trig}}<8 \text{ GeV/c}) \)

Pb-Pb events at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

Trend of \( I_{AA}(|\Delta \eta|) \) is consistent with flat.

Gray band gives scaling uncert. Brown boxes show point-to-point variable syst. uncert.
$I_{AA}(|\Delta \eta|)$ at high $p_T$ ($8<p_{T,\text{trig}}<15$ GeV/c)

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

Trend of $I_{AA}$ shows a possible onset of jet shape modification in $\Delta \eta$ (narrowing).
$I_{AA}(|\Delta \eta|)$ at high $p_T$ ($8 < p_{T,\text{trig}} < 15$ GeV/c)

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

- Observed effect on $I_{AA}(\Delta \eta)$ does not need significant modification of near side peak rms
- Cartoon below shows two gaussians having some typical rms of near side peak at high $p_T$
  - rms differ only by 5%
  - $I_{AA}(|\Delta \eta|)$ ratio on the right plot shows similar magnitude of decrease

Trend of $I_{AA}$ shows a possible onset of jet shape modification in $\Delta \eta$ (narrowing).
Summary

- Near side \( I_{\text{AA}} \) measured in 0-10\% centrality bin of Pb-Pb collisions in cone with \( R=0.2 \) exhibits enhancement of 20-50\% down to \( p_{T,\text{assoc}} = 0.7 \text{ GeV/c} \)

- Study of the near side peak shape evolution
  a) Asymmetric near side peak in central Pb-Pb collisions at low \( p_T \)
     - \( \Delta \eta \) rms shows a strong centrality dependence (broadening), contrary to \( \Delta \varphi \)
     - rms well reproduced by AMPT
     - interplay of the jet with flow?

  b) At high \( p_T \) ( \( 8 < p_{T,\text{trig}} < 15 \text{ GeV/c} + p_{T,\text{assoc}} > 4 \text{ GeV/c} \) ) we see a hint for onset of the near side peak modification (narrowing along \( \Delta \eta \))
Backup slides
ALICE, experiment dedicated to HI at LHC

- Studies properties of hot and dense strongly interacting matter under extreme conditions
- $B = 0.5 \, \text{T}, \quad 0.15 < p_T < 100 \, \text{GeV/c}$
- Main tracking devices ITS + TPC
- PID detectors TOF, TRD, HMPID, EMCAL, PHOS
- Forward detectors V0, T0, ZDC, PMD, FMD, MCH
Analysis details

- **Event sample**
  - 15M Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
  - 55M p-p events at $\sqrt{s} = 2.76$ TeV

- **Track selection benefits from uniform $\phi$ acceptance of TPC**
  - $|\eta| < 0.9$
  - Two-track efficiency cut on distance of closest approach of a track pair in the TPC volume

- **Event mixing corrects for two-track acceptance** [in bins of centrality and vertex position]

- **Per-trigger yields corrected for tracking efficiency and contamination** (no influence on shapes)
Near side peak shape evolution

Pb-Pb 0-10%  Pb-Pb 60-70%  p-p

2 < $p_{T,\text{trig}}$ < 3  1 < $p_{T,\text{assoc}}$ < 2

2 < $p_{T,\text{trig}}$ < 8  2 < $p_{T,\text{assoc}}$ < 3

Peak rms in $\Delta \phi$ and $\Delta \eta$ extracted from a fit (sum of two 2D Gaussians)
Low $p_T^{Ta}$ $I_{AA}$ ($R<0.2$) compared with published $I_{AA}$ data (central collisions)