Jet fragmentation in two-particle correlations in pp, p-Pb, and Pb-Pb collisions

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Jet energy loss

- Strong jet quenching is observed in heavy-ion collisions

- Analyses based on fully reconstructed jets:
  - strong di-jet energy asymmetry
    [ATLAS PRL 105(2010) 252303, CMS, PRC 84, 024906 (2011)]
  - centrality dependence of jet fragmentation
    [CMS arXiv:1406.0932]
  - quenched energy reappears at low $p_T$, also outside the jet cone
    [CMS, PRC 84, 024906 (2011)]

Two-particle correlations provide additional information
Energy loss in di-hadron correlations

- $I_{AA}$ measurements by ALICE for $8 < p_{T, trig} < 15 \text{ GeV/c} \ & \ 3 \text{ GeV/c} < p_{T, assoc} < p_{T, trig}$

near side parton is sensitive to medium

- modification of jet fragmentation (softening)?
- modification of quark/gluon jet ratio?
- bias of the parton $p_T$ spectrum after energy loss due to trigger selection?

- Near side $I_{AA}$ at lower $p_{T, assoc}$?

- Near side modification in longitudinal jet shape?
Jet fragmentation

"Wide" component: high virtuality, soft QCD radiation

"Narrow" component: hadronization as in vacuum
Pb-Pb

Medium-induced jet energy loss
Di-hadron correlations

- Studying lower energy jets on statistical basis
- Background is averaged over many events
- Basic quantities

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

Near side (intra jet):
Single jet properties
- jet fragmentation

Away side (inter jet):
Di-jet properties
- accoplanarity + momentum imbalance due to \( k_T \)
- additional medium-induced modification of recoil jet
• Analyze per-trigger yield
  positive and negative
  $\Delta \eta$ symmeterized

\[
Y(|\Delta \eta|) = \frac{1}{N_{\text{trigg.}}} \frac{dN}{d|\Delta \eta|}
\]

• Correlation functions corrected for experimental effects:
  single-particle efficiency and pair acceptance (event mixing)

• Background level estimated by fit:

• Evaluate ratio:

\[
I_{AA}(|\Delta \eta|) = \frac{Y_{\text{Pb-Pb}}(|\Delta \eta|)}{Y_{\text{PP}}(|\Delta \eta|)}
\]
**$I_{AA}$ at low $p_T$**

Near side $I_{AA}$ in 0-10%: moderate enhancement by ~ 20-50%

60-90%: less enhancement, no $p_T$-dependence

Same with identified ($\pi^0$) trigger

Only AMPT describes data qualitatively
Interpreting $I_{AA}$

Cartoon showing possible scenarios of jet shape modification

- **broadening**
- **unmodified/scaled**
- **narrowing**

| Ratio | $dN/d|\Delta\eta|$ |
|-------|-------------------|
| rising | $I_{AA}(|\Delta\eta|)$ | flat | falling |

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Vargyas - 12th International Workshop on High-pT Physics in the RHIC/LHC era
\( I_{AA} \) at intermediate \( p_T \)

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

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

Gray band gives scaling uncertainty
Brown boxes show point-to-point variable systematic uncertainty
Trend of $I_{AA}(|\Delta \eta|)$ shows a possible onset of jet shape modification in $\Delta \eta$ (narrowing). Only at high $p_T$. 

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

Near side $I_{AA}$ in 0-10% central Pb-Pb collisions exhibits enhancement of 20-50% down to $p_{T,assoc} = 0.7 \text{ GeV/c}$

Previous talk by Monika:
Lower $p_T$ broadening (in both $\Delta \eta$ and $\Delta \phi$)

At high-$p_T$ ($8 < p_{T,\text{trig}} < 15 \text{ GeV/c} + 4 \text{ GeV/c} < p_{T,\text{assoc}} < p_{T,\text{trig}}$)
we see a hint for narrowing along $\Delta \eta$

Energy loss of high-$p_T$ partons?
p-Pb, pp

System- and energy-dependence of fragmentation
Jet fragmentation

“Wide” component: high virtuality, soft QCD radiation

“Narrow” component: Hadronization as in vacuum

Separate components with high-$p_T$ trigger
Observables

Two-particle correlation of charged hadrons

Trigger: leading particle (~ jet axis)

\[ j_T = \frac{|\vec{p}_t \times \vec{p}_a|}{|\vec{p}_t|} \quad x_\parallel = \frac{\vec{p}_t \cdot \vec{p}_a}{\vec{p}_t^2} \]

Near-side only

Definition of near-side:

\[ \vec{p}_t \cdot \vec{p}_a > 0 \]
Simulation (two-component model)

No Final State Radiation (FSR) – nearly Gaussian shape

With FSR – long tail
In reality (3 components)

Additional background: randomized pairs

3 component fit

RMS and yield from fit

\[
\frac{1}{N_{\text{trigg}}} \frac{1}{j_T} \frac{dN}{dj_T} = B_0 \times \text{background} + \frac{B_2}{\sqrt{2\pi} B_1} e^{-\frac{j_T^2}{2B_1^2}} + \frac{B_3 B_5^{B_4}}{\Gamma(B_4)} \frac{e^{-\frac{B_5}{j_T}}}{j_T^{B_4+1}}
\]
Resonance decays

Any trigger

Stable trigger
Narrow component (RMS)

\[ 0.2 < x_{||} < 0.4 \]

\[ 0.4 < x_{||} < 0.6 \]

\[ 0.6 < x_{||} < 1.0 \]

Almost no \( p_T \)-dependence

Similar result for pp and p-Pb

No dependence on \( \sqrt{s} \)

Good agreement with PYTHIA8

Universal hadronization?
Narrow component (yield)

0.2 < x_∥ < 0.4

0.4 < x_∥ < 0.6

0.6 < x_∥ < 1.0

PYTHIA8 overestimates the yield
Wide component RMS

\[0.2 < x || < 0.4\]
\[0.4 < x || < 0.6\]
\[0.6 < x || < 1.0\]

Rising trend in \(p_T\)

Similar result for pp and p-Pb

Good agreement with PYTHIA8
Wide component (yield)

0.2 < x_∥ < 0.4

0.4 < x_∥ < 0.6

0.6 < x_∥ < 1.0

Agreement with PYTHIA8 (within uncertainties)
Universality of hadronization

No dependence on $\sqrt{s}$

Thank you for your attention!

- Narrowing in high-$p_T$ along $\Delta \eta$
- Broadening and enhancement in low-$p_T$

Pb-Pb, pp

- Experimental separation between hadronization and showering
- No broadening in p-Pb (cold nuclear effects)
- Narrow: no $p_T$-dependence of hadronization
- Wide: increasing with $p_T$, more radiation with higher virtuality