Exploring potential jet modification in small collision systems with two particle correlations at PHENIX

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Baseline Measurement
QCD in vacuum

\[ p - p \]

Cold nuclear matter effect

\[ p/d/He^3 - A \]

Small System

Hot nuclear matter effect (QGP effect)

Large System
QGP


- Non-zero charged hadron \( v_n \) measured in small systems
- \( v_n \) depends on initial geometry

More small system measurements are needed to understand QGP effect in large system

Cold nuclear matter and QGP droplet
Probing Jet Modification via Two-particles Correlations

Reconstructed jets in PHENIX
- Parallel C1, Milap Patel
  June 2\textsuperscript{nd} 11:40am CT
- Phys. Rev. Lett. 116, 122301

Compare Au+Au (with QGP) to p+p (no QGP)
- angular width ($\sigma$) $\rightarrow$ jet broadening
- yield ($Y$) $\rightarrow$ energy loss

\[
I_{AA}(p_T^{assoc}) = \frac{Y_{AA}}{Y_{pp}} = \frac{D_{AA}}{D_{pp}}
\]

Modification of fragmentation function

Schematics of jet function from p+p collision
Away-side Yield Modifications in Au+Au Collisions

- Clear modification shown:
  \[ I_{AA} > 1 \] at low \( p_T^{assoc} \) and \( I_{AA} > 1 \) at high \( p_T^{assoc} \)

- Suggesting hard partons lose energy when traversing the QGP leads to jet quenching: suppression of hard jet particle, but enhancement of soft particles

- No significant centrality dependence within uncertainty

\[ I_{AA}(p_T^{assoc}) = \frac{Y_{AA}}{Y_{pp}} \]
Away-side Yield Modifications in d+Au Collisions

Away \( I_{dA} = \frac{Y^A_{dAu}}{Y^A_{pp}} \)

dAu, 0-20%, \( \pi^0-h \)

- \( I_{dA}<1 \) at high \( z_T \), \( I_{dA}>1 \) at low \( z_T \) → Hints to yield modification
- However, the \( I_{dA} \) is consistent with 1 because of the sizable systematic uncertainties
Away-side $I_{AA}$ Comparison

- $I_{AA} > I_{dA}$ in low $p_T$, $I_{AA} < I_{dA}$ in high $p_T$
- Larger away-side yield modification in Au+Au collisions than in d+Au collisions
**Away-side $I_{AA}$ Comparison**

- **Trigger $p_T$ 5-7 GeV/c**
  - $\pi^0$-hadron, $[\pi - \frac{\pi}{2}, \pi + \frac{\pi}{2}]$
  - 200 GeV, 0-20%
  - • Au+Au (2010 & 2011)
  - • d+Au (2008)

- **• $I_{AA} > I_{dA}$ in low $p_T$, $I_{AA} < I_{dA}$ in high $p_T$**
- **• Larger away-side yield modification in Au+Au collisions than in d+Au collisions**

- $\xi = \ln \left( \frac{1}{z_T} \right) = \ln(p_T^\gamma/p_T^h)$
- **Same observation found in the comparison of away-side yield modification from $\gamma$-hadron correlations**
Away-Side Yield Modification in d+Au Collisions

Away-side

\[ I_{dA}^{A} = \frac{\gamma_{dAu}^{A}}{\gamma_{pp}^{A}} \]

dAu, 0-20%, π^0-h

- Hints of suppression at high \( p_T^{assoc} \), and enhancement at low \( p_T^{assoc} \)
- Near-side is consistent with unity
Away-Side Yield Modification in d+Au Collisions

- Hints of suppression at high $p_T^{assoc}$, and enhancement at low $p_T^{assoc}$
- Near-side is consistent with unity
- Double Ratio $R_I = \frac{I_{dA}}{I_{pp}}$ is introduced: some systematic uncertainties are canceled out
Away-Side Yield Modification in d+Au Collisions

Away-side

\[ I_{dA}^{\text{Away}} = \frac{Y_{dAu}^A}{Y_{pp}^A} \]

\( \text{dAu, 0}-20\%, \pi^0-h \)

\[ R_I = \frac{Y_{dAu}^A / Y_{dAu}^N}{Y_{pp}^A / Y_{pp}^N} \]

\( \text{dAu, 0}-20\%, \pi^0-h \)

- \( R_I \) shows away-side suppression at high \( z_T \)
- Clear enhancement of low \( p_T \) jet particles is shown in \( R_I \) results as systematic uncertainty reduced compared to \( I_{dA} \)
Away-Side Yield Modification in d+Au Collisions


Variety of collision systems:
- Initial geometry dependence study in flow harmonic coefficients
- System size dependence study in Jet modification
Away-Side Yield Modification in Small Systems

- $^3\text{He}+\text{Au}$ and $d+\text{Au}$ results are within uncertainty
- $R_I$ of $^3\text{He}+\text{Au}$ results are systematically lower than $d+\text{Au}$
  - more suppressed at high $p_T$ compared to $d+\text{Au}$
  - hints to system size dependence
• Locate the enhancement and suppression of jet particles inside a jet
• Study yield modification at jet substructure level using a new observable, $I_{AA}(\Delta \phi)$
$I_{AA}(\Delta \phi)$ in Au+Au Collisions

Yield modification in position space

- Show modification of jet substructure level
- High associate $p_T$: suppressed overall in $\Delta \phi$. The modification is relatively even

Poster 297, Megan Connors
$I_{AA}(\Delta \phi)$ in Au+Au Collisions

Yield modification in position space

- Show modification of jet substructure level
- High associate $p_T$: suppressed overall in $\Delta \phi$. The modification is relatively even
- Mid associate $p_T$: suppression at the core of the jet, but enhancement shows at the skirt of the jet
$I_{AA}(\Delta \phi)$ in Au+Au Collisions

Yield modification in position space

- Show modification of jet substructure level
- High associate $p_T$: suppressed overall in $\Delta \phi$. The modification is relatively even
- Mid associate $p_T$: suppression at the core of the jet, but enhancement shows at the skirt of the jet
- Low associate $p_T$: enhancement within the away-side jet especially at the skirt of the jet

Poster 297, Megan Connors
Transverse Momentum $\vec{p}_{out}$

Study the associate particle transverse momentum ($\vec{p}_{out}$) w.r.t. the trigger particle:

\[
\vec{p}_{out} = \vec{p}_{asso} \cdot \sin(\Delta \phi)
\]

Associate particle transverse momentum w.r.t. the trigger particle

\[
\vec{p}_{asso} = \vec{p}_{trig} \cdot x_E + \vec{p}_{out}
\]

Longitudinal fraction w.r.t. the trigger particle

\[
x_E = -\frac{\vec{p}_{asso}}{|\vec{p}_{trig}|} \cdot \cos(\Delta \phi)
\]
$\vec{p}_{out}$  Broadening in p+A

Centrality/$N_{coll}$ dependent: broader $\vec{p}_{out}^{p+A}$ as $N_{coll}$ increases
Broadening in p+A

Centrality/$N_{coll}$ dependent: broader $\vec{p}_{out}$ as $N_{coll}$ increases

- Underlying flow? $v_2$ and $v_3$ are ruled out
- Higher $k_T$ for parton in nucleus?
- Energy loss?
Summary from Au+Au Collisions

• Thorough study of yield modification in Au+Au collisions: momentum dependence and angular dependence
• Clear modification is shown in Au+Au than in d+Au collisions
• The new observable, $I_{AA}(\Delta \phi)$, shows yield modification at jet substructure level
Summary from Small Collision Systems

d/³He+Au collisions: yield modification
• Away-side \( I_{dA} \) shows suppression of hard jet particles. However, the yield suppression is smaller than in Au+Au results
• \( R_I \) measurements
  – Reduction of systematic uncertainty
  – Show enhancement of soft jet particles in the away-side, but suppression of hard jet particles

p+A collisions: momentum modification
• Away side broadening in \( p_{out} \) measurement
• Away side \( p_{out} \) broadening shows \( N_{Coll} \) dependence
Both two-particle correlations results show system size dependence.

Back Up
Jet Measurements in d+Au Collisions

- $R_{dA}$ shows centrality dependence
  - $R_{dA} < 1$ in the most central events indicating suppression of jets
  - $R_{dA} > 1$ in the less central events indicating enhancement of jets
- $R_{dA} < R_{AA}$ indicating larger suppression of jets in Cu+Au collisions

**PHENIX** $d+Au$, $\sqrt{s_{NN}} = 200$ GeV, anti-$k_T$, $R=0.3$ jet

- 60-88%
- 40-60%
- 20-40%
- 0-20%

**PHENIX** preliminary

**Cu+Au**, $\sqrt{s_{NN}} = 200$ GeV, anti-$k_T$, $R=0.2$ jet

- 0-20%
- 40-60%
- 20-40%
- 0-20%

E-loss 0-20% (Kang et al)

Ph. Rev. Lett. 116, 122301
Away-side Yield Modifications in d+Au Collisions

- $I_{dA} < 1$ at high $z_T$ and $I_{dA} > 1$ at low $z_T$
Transverse Momentum $\hat{p}_{out}$

\[ |k_T^1 + k_T^2| \]

Hard scattering

\( \hat{p}_T \)

\( \hat{p}_{\text{trig}} \)

\( \hat{p}_{\text{assoc}} \)
Transverse Momentum $\vec{p}_{out}$

$|k_T^1 + k_T^2|$

Hard scattering $\rightarrow$ fragmentation
Study the associate particle transverse momentum ($\hat{p}_{out}$) w.r.t. the trigger particle:

$$\hat{p}^{assoc} = \hat{p}^{trig} \cdot x_E + \hat{p}_{out}$$

Longitudinal fraction w.r.t. the trigger particle:

$$x_E = -\frac{|\hat{p}_{T}^{assoc}|}{|\hat{p}_{T}^{trig}|} \cdot \cos(\Delta\phi)$$

Associate particle transverse momentum w.r.t. the trigger particle:

$$\hat{p}_{out} = \hat{p}_{T}^{assoc} \cdot \sin(\Delta\phi)$$
\( \hat{p}_{out} \) Distribution in p+A

Near side

- \( p_{out} \) from near side is narrower than the away side.
- \( p_{out} \) distribution depends on \( j_T \) only.
- \( p_{out} \) for the near side does not change with \( k_T \).

Away side

- \( p_{out} \) distribution depends on both \( k_T \) and \( j_T \).

\[
x_E = -\frac{\hat{p}_{assoc}^T}{|\hat{p}_{trig}^T|} \cdot \cos(\Delta\phi) \quad \hat{p}_{out} = \hat{p}_{assoc}^T \cdot \sin(\Delta\phi)
\]
\[ p_{out} \text{ Distribution in } p+A \]

**Near side**

\[
1/\varepsilon_{p_{out}} |dN_{p_{out}}/dp_{out}| \ln^{(1)} \left( \frac{p_{out}}{p_{trig}} \right) \]

\[ \frac{1}{N_{p_{out}}} |dN_{p_{out}}/dp_{out}| \ln^{(1)} \left( \frac{p_{out}}{p_{trig}} \right) \]

\[ p + p, p + Au \]

- Narrower near side \( p_{out} \) distribution than the away side as \( p_{out}^{near} \) depends on \( j_T \) only
- \( p_{out}^{away} \) depends on both \( k_T \) and \( j_T \)

\[ x_E = - \frac{|\vec{p}_{assoc}^{\text{assoc}}|}{|\vec{p}_{trig}^{\text{trig}}|} \cdot \cos(\Delta \phi) \]

\[ \vec{p}_{out} = \vec{p}_{assoc}^{\text{assoc}} \cdot \sin(\Delta \phi) \]

Near side \( p_{out} \) does not change with \( k_T \)
$\hat{p}_{out}$ Broadening in p+A

arXiv:1809.09045v1

Near

Away

- No near side $\tilde{p}_{out}$ broadening
- No significant away side broadening in $p + Al$ data
- Away side $\tilde{p}_{out}$ broadening in the $p + Au$ data $\leftrightarrow k_T$ effect?

$x_E = -\frac{|p_T^{assoc}|}{|p_T^{trig}|} \cdot \cos(\Delta\phi)$

$\tilde{p}_{out} = p_T^{assoc} \cdot \sin(\Delta\phi)$
Broadening in p+A

- No near side $\vec{p}_{out}$ broadening
- No significant away side broadening in $p + Al$ data
- Away side $\vec{p}_{out}$ broadening in the $p + Al$ and $p + Au$ data $\leftrightarrow k_T$ effect?
$I_{AA}(\Delta\phi)$ in Au+Au Collisions

Yield modification in position space

Au+Au

$\pi^0$-hadron (0-20%)

200 GeV Au+Au

(2010 & 2011)