Measurements of semi-inclusive $\gamma$+jet and hadron+jet distributions in heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV with STAR

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Recoil jet study in Au+Au collisions exploring

Part 1. Jet suppression with different triggers

Part 2. Jet acoplanarity with different triggers

Part 3. Outlook on jet study in smaller collision systems
Probing QGP through jet-medium interaction

**Jet:** a collimated spray of hadrons produced by energetic quark or gluon

Jet production calculable in QCD

**Consequences of parton-medium interaction**
- Jet energy loss
- Acoplanarity
- Substructure modification

**Parton energy loss in medium**
- Collisional energy loss
- Radiative energy loss

Jet energy loss (yield suppression) and jet acoplanarity (excess jet yield away from back-to-back) can be studied using semi-inclusive recoil jet.
\( \gamma_{\text{dir}}/\pi^0 + \text{jet} \) to study jet energy loss

- Direct-photon (\( \gamma_{\text{dir}} \)) triggers are of great interest as they constrain the scattering kinematics

- Comparison between \( \gamma_{\text{dir}} + \text{jet} \) and \( \pi^0 + \text{jet} \)

\( q/g \) fraction; path length dependence; spectrum shape

Jet quenching observable

\( I_{AA} \) quantifies jet energy loss

\[
I_{AA} = \frac{\gamma^{AuAu}}{\gamma^{pp}}
\]
STAR detector and dataset

**Time Projection Chamber (TPC)**
- charged particles (|\(\eta\)| < 1, full azimuth)

**Barrel Electromagnetic Calorimeter (BEMC)**
- trigger on energetic \(\gamma_{\text{dir}}/\pi^0\)

**Barrel Shower Maximum Detector (BSMD)**
- discriminates \(\gamma_{\text{dir}}/\pi^0\) based on transverse shower profile

Au+Au (2014) and p+p (2009) at \(\sqrt{s_{\text{NN}}} = 200\) GeV
- BEMC trigger (\(E_T^{\text{tower}} \gtrsim 6\) GeV)
- Charged particles: |\(\eta\)| < 1

Ru+Ru and Zr+Zr (2018) at \(\sqrt{s_{\text{NN}}} = 200\) GeV
- Charged particles: |\(\eta\)| < 1
Analysis procedure of recoil jet yield

Discrimination of $\gamma_{\text{dir}}/\pi^0$

Recoil jet yield

Uncorrelated background subtraction

Correction for detector and heavy-ion background effects (Using unfolding)

Transverse Shower Profile (TSP):

$TSP \equiv \frac{E_{\text{cluster}}}{\sum_i e_i r_i^{1.5}}$

$E_{\text{cluster}}$: cluster energy
$r_i$: distance of the SMD strips from the center of cluster
$e_i$: individual SMD strip energy
Analysis procedure of recoil jet yield

Discrimination of $\gamma_{\text{dir}}/\pi^0$

- anti-$k_T$ algorithm
- $|\eta_{\text{jet}}| < 1 - R_{\text{jet}}$
- $|\phi_{\text{trig}} - \phi_{\text{jet}}| < \pi/4$

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Mixed-Event (ME) approach
### Analysis procedure of recoil jet yield

All ME tracks are fully uncorrelated to estimate combinatorial jet background

\[
\text{jet yield} = \text{Same Event} - f^{ME} \times \text{Mixed Event}
\]

\(f^{ME} \) : normalization factor extracted from data

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**Mixed-Event (ME) approach**

Mixed Event Generation for Jets

- Pick one random track per real event → add to mixed event
- Sample from real event distribution
- Mix only similar centrality (8), \( \Psi_{EE} \) (4), z-vertex position (20)

Courtesy of A. Schmah

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**STAR Preliminary**

Au+Au 200 GeV, 0-15% anti-\(k_T \)

- \( R = 0.2 \)
  - \( 9 < E_T^{\text{jet}} < 11 \) GeV [SE]
  - \( 11 < E_T^{\text{jet}} < 15 \) GeV [SE]
  - \( 15 < E_T^{\text{jet}} < 20 \) GeV [SE]

- \( R = 0.5 \)
  - 2dN/N_{\text{jet}} d^2p_{T,\text{jet}}\)d^0_{\gamma,\text{jet}}

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Analysis procedure of recoil jet yield

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Discrimination of \( \gamma_{\text{dir}}/\pi^0 \)

- anti-\( k_T \) algorithm
- \( |\eta_{\text{jet}}| < 1 - R_{\text{jet}} \)
- \( |\phi_{\text{trig}} - \phi_{\text{jet}}| < \pi/4 \)

Recoil jet yield

Uncorrelated background subtraction

Correction for detector effects and heavy-ion background (Using unfolding)

Mixed-Event (ME) approach

Mapping from “truth” to “measured”

Unfold measured to true jet population
Semi-inclusive recoil jet spectra

Trigger $E_T$:

$\pi^0$: [9, 11], [11, 15] GeV

$\gamma_{\text{dir}}$: [9, 11], [11, 15], [15, 20] GeV

Statistical errors: dark band

Systematic uncertainty (light band) is dominated by:

- Unfolding procedure
- Tracking efficiency
- Direct photon purity

Dashed line: PYTHIA-8 (MONASH tune)
Recoil jet yield is more suppressed for R=0.2 than R=0.5 indicating jet energy redistribution. 
\( \gamma_{\text{dir}} + \text{jet} \) and \( \pi^0 + \text{jet} \) show similar level of suppression.
Recoil jet yield dependence on jet $R$

- $\Re^{0.2/0.5} < 1$ in p+p collisions due to jet radial profile in vacuum
- $\Re^{0.2/0.5}$ is smaller in Au+Au than in p+p indicating in-medium broadening of jet shower
Semi-inclusive $\gamma_{\text{dir}}/\pi^0+$jet azimuthal correlation

Acoplanarity: recoil jet deflected from $\gamma_{\text{dir}}/\pi^0$ axis

$$\Delta \phi = \phi_{\text{trig}} - \phi_{\text{jet}}$$

Contributions to the azimuthal de-correlation

**In vacuum:** Sudakov radiation

**In medium:** multiple soft scattering ($p_T$ broadening) scattering off QGP quasi-particles

Trigger-jet azimuthal correlation distributions

$$\left. \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{d(\Delta \phi)} \right|_{E_T^{\text{trig}}} = \left. \frac{1}{\sigma^{\text{AA-}\text{trig}+\text{jet}}} \frac{d\sigma^{\text{AA-}\text{trig}+\text{jet}}}{d(\Delta \phi)} \right|_{E_T^{\text{trig}}}$$

Dijet Angular Correlation at RHIC

- $qL = 0 \text{GeV}^2$
- $qL = 8 \text{GeV}^2$
- $qL = 20 \text{GeV}^2$
$\pi^0 + \text{jet azimuthal correlation in } p+p \text{ collisions}$

$$E_T^{\text{trig}} = [9,11] \text{ GeV/c}$$

$\Delta \phi$ spectra measurements:

$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{d(\Delta \phi)} \bigg|_{E_T^{\text{trig}}} = \left( \frac{1}{\sigma^{AA\to\text{trig}+\text{jet}}} \frac{d\sigma^{AA\to\text{trig}+\text{jet}}}{d(\Delta \phi)} \right) \bigg|_{E_T^{\text{trig}}}$$

- **R=0.2**
  - $5 < p_T^{\text{jet}} < 10$ GeV/c
  - $10 < p_T^{\text{jet}} < 15$ GeV/c
  - $15 < p_T^{\text{jet}} < 20$ GeV/c
- **R=0.5**
  - $9 < E_T^{\text{trig}} < 11$ GeV

PYTHIA-8 (MONASH tune) is consistent with p+p data
$\gamma_{\text{dir}}/\pi^0+$jet azimuthal correlation in Au+Au collisions

$E_T^{\text{trig}} = [11,15] \text{ GeV/c}$

Evidence for medium-induced acoplanarity in the QGP for $R = 0.5$ jets

Jet deflection in the medium? Medium response? ...

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System size dependence of hadron suppression

\[ R_{AA} = \frac{1}{N_{\text{ev}}^{AA} T_{AA} d^2 \sigma^{NN} / d\eta d p_T} \frac{d^2 N^{AA} / d\eta dp_T}{N_{\text{ev}}^{AA}} \]

Similar \( R_{AA} \) suppression at comparable \( \langle N_{\text{part}} \rangle \) energy density drives the quenching, rather than the collision geometry.

How about jets?

Talk: Tristan Protzman (Mar. 29th, 15:00)
Poster: Isaac Mooney (HMHC-8)
Outlook on system size dependence of jet quenching

Jet quenching comparison for different collision systems:
gain further insights into parton energy loss dependence on
initial energy density vs. collision geometry

<table>
<thead>
<tr>
<th></th>
<th>0-10%</th>
<th>60-80%</th>
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<tbody>
<tr>
<td>Zr+Zr</td>
<td>~454 k</td>
<td>~60 k</td>
</tr>
<tr>
<td>Ru+Ru</td>
<td>~457 k</td>
<td>~62 k</td>
</tr>
</tbody>
</table>

Trigger statistics for 7 < p_{T, trig} < 25 GeV/c

Ongoing measurement...
Summary

• Au+Au
  \( I_{AA} \) are consistent between \( \gamma_{\text{dir}} + \text{jet} \) and \( \pi^0 + \text{jet} \)
  \( \mathcal{R}^{0.2/0.5} \) demonstrate intra-jet broadening

• h+jet study in Zr+Zr and Ru+Ru is ongoing

• \( \Delta \phi \) distributions of \( \gamma_{\text{dir}}/\pi^0 + \text{jet} \) in Au+Au:
  observed excess of jet yield away from back-to-back
  Jet scattering?
  Medium scattering?

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