\( \gamma + \text{jet} \) and \( \pi^0 + \text{jet} \) in central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) in STAR

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γ+jet in heavy-ion collisions

- γ does not interact strongly in QGP → recoil jet is a “tomographic probe”
  However, NLO effects generates $p_T$-imbalance; calculable
- Comparison of γ+jet at RHIC and the LHC: valuable tool to explore jet quenching


[Dai et al., PRL 110, 142001]
**γ+jet and π0+ jet measurements in STAR**

**STAR: jet-like correlation measurement**

Comparison between γ+jet and π0+jet:
- Vary quark vs. gluon of recoil jets
- Vary recoil mean path length

Two challenges:
- Discrimination of γ/π0 trigger
  [STAR, PLB760 (2016) 689–696]
  Resolved using STAR colorimeter system
- Uncorrelated jets in recoil jets region
  [STAR, PRC 96 no. 2, (2017) 024905]
  Resolved using Mixed Event (ME) method

**In this talk**
- Recoil jet yield suppression for jet R = 0.2 and 0.5
- Modification of jet shape
- Jet energy loss due to quenching: RHIC vs. LHC

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STAR detectors and online trigger

- Online trigger: BEMC High Tower (HT) trigger to select events of large energy depositions

- Au+Au $\sqrt{s_{NN}} = 200$ GeV (Year 2014 data)
- Integrated luminosity: 13 nb$^{-1}$
- 0-15% central collisions
γ_{dir}/π^0 discrimination and offline trigger

- HT trigger to select γ/π^0 events using BEMC
- Shower Maximum Detector (SMD)
  → Provides spatial resolution for electromagnetic shower
  → Discrimination between γ_{dir} and π^0 using TSP method

Transverse Shower Profile (TSP) distribution

\[ \text{TSP} = \frac{E_{\text{cluster}}}{\sum_i r_i e_i^{1.5}} \]

\( E_{\text{cluster}} \): Cluster energy
\( r_i \): distance of the SMD strips from the center of cluster
\( e_i \): individual SMD strip energies

Background (%) in γ_{rich}-sample

\[ \gamma_{\text{rich}} = \gamma_{\text{dir}} + π^0 \text{ decays photons; } \]
\[ \gamma_{\text{dir}} \text{ purity } \rightarrow 65-88\% \text{ between } E_T^{\text{ trig }}: 9-20 \text{ GeV} \]

- π_{rich}^0 :~95% pure
- \( E_T^{\text{ trig }} \) bins in this measurement:
  9-11, 11-15, 15-20 GeV

\[ \gamma_{\text{rich}} = \gamma_{\text{dir}} + π^0 \text{ decays photons; } \]
\[ \gamma_{\text{dir}} \text{ purity } \rightarrow 65-88\% \text{ between } E_T^{\text{ trig }}: 9-20 \text{ GeV} \]
Charged jet reconstruction

- Constituent charged tracks: $p_T^{\text{track}} < 30 \text{ GeV/c}; |\eta| < 1$
- Anti-$k_T$ algorithm [FastJet]; jet R = 0.2 and 0.5
- Recoil jet region: $\phi^{\text{trig}} - \phi^{\text{jet}} \in [3\pi/4, 5\pi/4]$
- $|\eta^{\text{jet}}| < 1$ - R
Corrections and uncertainties

Event-by-event correction:
- Uncorrelated background energy density ($\rho$)
  \[ p_{T,\text{jet}}^{\text{reco,ch}} = p_{T,\text{jet}}^{\text{raw,ch}} - \rho \times A; \]
  \[ \rho = \text{median}\left\{ \frac{p_{T,\text{jet}}^{\text{raw}}}{A_{\text{jet}}} \right\}; \quad A: \text{Area of the jet} \]

Ensemble-level correction:
- Uncorrelated jet yield correction: Mixed Event approach
- Jet Energy Scale (JES) smearing correction: Unfolding
  - Factorize instrumentation and background fluctuation effects
  - Unfolding: SVD; iterative Bayesian

Main contributions to systematic uncertainties
- Unfolding (iteration parameter and prior variation)
- Choice of ME normalization region
- Instrumentation effects [largest effect: tracking efficiency]
- Direct photon purity
Semi-inclusive $\gamma_{\text{rich}} + \text{jet}$ $p_{T,\text{jet}}^{\text{reco, ch}}$ distribution

**R = 0.2**

STAR Preliminary

Au+Au 200 GeV, 0-15%
anti-$k_T$
$R = 0.2$

(i)

$\gamma_{\text{rich}} + \text{jet}$

(ii)

$< 11 \text{ GeV} \ [\text{SE}]$

$11 < E_{\text{trig}} < 15 \text{ GeV} \ [\text{SE}]$

$15 < E_{\text{trig}} < 20 \text{ GeV} \ [\text{SE}]$

$R = 0.5$

(iii)

$< 0$: yield independent of $E_T^{\text{trig}}$

ME reproduces shape of SE

(iv)

$> 0$: yield dependent of $E_T^{\text{trig}}$

SE dominates over ME at high-$p_{T,\text{jet}}^{\text{raw, ch}}$

- Same Event (SE): Uncorrelated jets + correlated jets
- Mixed Event (ME): Uncorrelated (combinatorial) jets

- $p_{T,\text{jet}}^{\text{reco, ch}} < 0$: yield independent of $E_T^{\text{trig}}$
- ME normalization: crosshatching region
- Correction for uncorrelated yield: ME subtraction
- Correction for JES smearing: Unfolding

Recoil charged jet

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\( p+p \) reference for this measurement

\( \gamma_{\text{dir}+\text{jet}} \) and \( \pi^0+\text{jet} \) \( p+p \) reference:
- STAR data: insufficient statistical precision for this analysis at present
- Use PYTHIA validated by STAR measurements

We will show both references to illustrate differences.
For \( \gamma_{\text{dir}+\text{jet}} \):
- \( R=0.2 \): negligible differences
- \( R=0.5 \): 10-40% differences

Two versions of PYTHIA:
- PYTHIA8 Tune 4C: used for QM2019 presentation of this analysis
- PYTHIA6 Perugia 2012 STAR tune: validation by STAR \( p+p \) data [STAR, Phys. Rev. D 100, 052005 (2019)]
Corrected semi-inclusive $\gamma_{\text{dir}}+\text{jet}$ and $\pi^0+\text{jet}$ $p_T$ spectra

- $\gamma_{\text{dir}}$ and $\pi^0$ trigger recoil jet $p_T$ spectra strongly dependent on jet $R$ and trigger $E_T$

Systematic (lighter band) and statistical (darker band) uncertainties
Recoil jet yield suppression for $R=0.2$ and $0.5$

\[ I_{AA}(p_{T,\text{jet}}^{\text{ch}}) = \frac{Y(p_{T,\text{jet}}^{\text{ch}})_{\text{Au+Au}}}{Y(p_{T,\text{jet}}^{\text{ch}})_{p+p}} \]

$Y(p_{T,\text{jet}}^{\text{ch}}) \rightarrow$ Per trigger recoil jet yield as a function $p_{T,\text{jet}}^{\text{ch}}$

$p+p$ reference: PYTHIA-8

Systematic (lighter band) and statistical (darker band) uncertainties

- $\gamma_{\text{dir}}^{+}\text{jet}$ and $\pi^{0+}$ jet show similar level of suppression
- No significant trigger $E_T$ dependence
- Larger recoil jet yield suppression for $R=0.2$ than $R=0.5$

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Recoil jet yield suppression: *PYTHIA-6 STAR vs PYTHIA-8*

\[ \gamma_{\text{dir} + \text{jet}}: 15 < E_T^{\text{trig}} < 20 \text{ GeV} \]

**R=0.2**

**pp reference: PYTHIA-8**

\[ \gamma_{\text{dir} + \text{jet}}, \text{Au+Au 200 GeV, 0-15%, anti-k}_T \]

**R=0.5**

**pp reference: PYTHIA-6 STAR tune**

PYTHIA-6 STAR tune vs PYTHIA-8:
- R=0.2: negligible change
- R=0.5: significant shift in central value but consistent within other systematic uncertainties

Systematic (lighter band) and statistical (darker band) uncertainties

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Recoil jet yield suppression: *Data vs. Model*

\[ \gamma_{\text{dir}+\text{jet}}: 15 < E_T^{\text{trig}} < 20 \text{ GeV} \]

Comparison to Theory

Jet-fluid: jet shower + medium response
LBT: coupled LBT+hydro
All order in opacity

pp reference: PYTHIA-8

R=0.2

R=0.5

pp reference: PYTHIA-6 STAR tune

Systematic (lighter band) and statistical (darker band) uncertainties

\[ p_T\text{-dependence of suppression is different in theory predictions and data.} \]
Measurement of jet radial profile

- Ratio of recoil jet yields $R=0.2/R=0.5$
- Jet radial profile in vacuum requires ratio $< 1$ in pp collisions (PYTHIA)
- In-medium modification of jet shape? Compare p+p and Au+Au

\[
\frac{Y \left( p_{T,\text{jet}}^{\text{ch}} \right)^{R=0.2}}{Y \left( p_{T,\text{jet}}^{\text{ch}} \right)^{R=0.5}}
\]

Systematic (lighter band) and statistical (darker band) uncertainties

- $\gamma_{\text{dir}} + \text{jet}$ consistent with PYTHIA-6 STAR tune $\rightarrow$ would indicate no significant in-medium broadening
- Quantitative difference: PYTHIA-6 STAR tune vs. PYTHIA-8
- $\pi^0 + \text{jet}$ and hadron+jet are consistent
Jet $p_T$-spectrum shift: RHIC vs. LHC

Characterization of average out-of-cone parton energy loss

- $\pi^0$ PHENIX $\delta p_T$: ~2-3 GeV/$c$ within $p_T$:10-18 GeV/$c$
  Similar to STAR jet measurements [PHENIX, PRC 87, 034911 (2013)]

Indication of smaller in-medium energy loss at RHIC than the LHC
γ_{\text{dir}} + \text{jet} \text{ measurement in STAR (outlook)}

(Dai, Vitev and Zhang, PRL 110, 142001)

Ongoing in STAR:

- \( x_J : 9 < E_T^{\text{trig}} < 20 \text{ GeV} \) [poster ID#253 by Annika Ewigleben]
- \( p+p \sqrt{s} = 200 \text{ GeV} \): \( \gamma_{\text{dir}} + \text{jet} \) and \( \pi^0 + \text{jet} \)

\[ x_J = \frac{p_{T,jet}}{E_T^\gamma} \]
Summary

First measurement of $\gamma_{\text{dir} + \text{jet}}$ and $\pi^0 + \text{jet}$ spectra in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

- p+p reference: PYTHIA-6 STAR tune, PYTHIA-8
- Recoil jet yield suppression: similar magnitude for $\gamma_{\text{dir} + \text{jet}}$ and $\pi^0 + \text{jet}$
  - Theoretical calculations do not reproduce $p_T$ dependence
  - Jet-fluid, LBT and All-order opacity
- Jet energy loss at RHIC
  - Consistent between measurement channels (inclusive, $\gamma_{\text{dir} + \text{jet}}$ and $\pi^0 + \text{jet}$)
  - Indication of being smaller than the LHC
- R-dependence of suppression; jet shape modification
  - PYTHIA-6 (STAR) vs PYTHIA-8 give different pictures; to be resolved with measured p+p reference

Thank you!

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