Direct-photon+hadron correlations to study parton energy loss with the STAR experiment

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Motivation: Direct photon and its advantage

- Compton scattering ($qg\rightarrow q\gamma$) dominates for the direct photon production
- It doesn’t interact strongly in medium
  - Transverse energy approximates that of initial parton $p_T$ in photon-jet events
- A good tomographic probe of the quark-gluon plasma in high-energy heavy-ion collisions
  - Volume emission dominates for dir. photon trigger hadron correlation unlike di-hadron correlation
  
Zhang et al., PRL 103, 032302 (2009)

Parton energy loss in medium depends on

- Initial energy ($E$), Path length ($L$), Color factor ($C_R$), coupling strength ($\alpha_s$), transport coefficient ($\hat{\gamma}$) etc.
  - Initial energy: $\gamma_{\text{dir}}$-h± correlation at different $p_T^{\text{trig}}$
  - Path length or Color factor: comparison between $\gamma_{\text{dir}}$-h± and π0-h± correlation (Away-side hadrons of $\gamma_{\text{dir}}$ triggered should suppress less compared with that of $\pi^0$)
Medium Effect: Direct photon-hadron and Di-hadron correlation

- The medium effect for $\gamma_{\text{dir}}$-hadron and $\pi^0$-hadron by,

  \[ I_{AA} = \frac{D(z_T)}{D(z_T)_{pp}} \]

  **Nuclear modification factor:**

  $D(z_T)_{AA}$: per trigger away-side yield for A+A collisions
  $D(z_T)_{pp}$: per trigger away-side yield for p+p collisions

  \[ 8 < p_T^{\text{trig}} < 16 \text{ GeV/c}, \ 0.3 < z_T < 0.9 \]

**Key questions on**
- What about lost energy?
- Redistribution in medium or recovery at low $z_T$?

**Beside, small $z_T$ dominated by volume emission**

**Zhang et al., PRL 103, 032302 (2009)**

**To understand medium effect at low $z_T$**
- Triggered by high $p_T$ $\gamma_{\text{dir}}$ and $\pi^0$: $12 < p_T^{\text{trig}} < 20$ GeV/c
- Low $p_T$ associated hadron: $p_T^{\text{assoc}} > 1.2$ GeV/c

(STAR Collab., PRC 82, 034909)

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STAR detector system: Advantage and data sets

- Barrel ElectroMagnetic Calorimeter (BEMC) to identify EM clusters
- Time Projection Chamber (TPC) for identifying charged hadron tracks
- STAR detector system gives unique opportunity full $2\pi$-azimuth and wide $|\eta| < 1.0$, both for BEMC and TPC
- Triggered on high energy tower in the BEMC

- Au+Au 200 GeV  
  (year-11: Int. Luminosity of 2.8 nb$^{-1}$)
- p+p 200 GeV  
  (year-9: Int. Luminosity of 23 pb$^{-1}$)

- Discrimination between $\pi^0 \rightarrow \gamma\gamma$ and $\gamma_{dir}$ is key part of this analysis

  - By Transverse Shower Profile (TSP) method
  - Using Barrel shower Maximum detector (BSMD)
Transverse shower profile: $\pi^0/\gamma_{\text{dir}}$ discrimination

- BSMD $\eta$-strips and $\phi$-strips along with BEMC tower give information about Transverse Shower Profile (TSP)

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

- $E_{\text{cluster}}$: Cluster energy, $e_i$: BSMD strip energy, $r_i$: distance of the strip from the center of the cluster

- Wider shower represents small TSP and vise versa

- TSP cuts are tuned to get
  - a nearly pure sample of $\pi^0$ (called "$\pi^0_{\text{rich}}$"")
  - a sample with enhanced fraction of $\gamma_{\text{dir}}$ (called "$\gamma_{\text{rich}}$"")

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**Correlation functions**

- Raw correlation functions for $\pi^0_{\text{rich}}$ and $\gamma_{\text{rich}}$ triggered associated hadrons in $|\eta| < 1.0$
- Uncorrelated background is then subtracted and $\Delta \phi$ acceptance is corrected using the mixed events (modulated with elliptic flow for Au+Au collisions)
Yields associated with $\pi^0$ - trigger

- Near-side and away-side yields are extracted within $|\Delta\phi| \leq 1.4$ and $|\Delta\phi - \pi| \leq 1.4$

- AuAu central (0-12%) collisions compare with pp collisions at 200 GeV colliding energy

- Away-side yields show suppression in AuAu collisions as compared with pp collisions

- Near-side shows no significant suppression

- By integrating near-side yields, we estimated 85(±3)% fraction of energy carried by $\pi^0$ over “jet energy” ($\pi^0 +$ charged hadrons) in pp 200 GeV
Yields associated with $\gamma_{dir} - \text{trigger}$: Fragmentation function

Away-side yields are extracted within $|\Delta \phi - \pi| \leq 1.4$

$$Y_{\gamma_{dir} + h} = \frac{Y_{a\gamma_{rich} + h} - RY_{a\pi^0 + h}}{1 - R}$$

$Y_{a(n)}$ and $Y_{\pi^0 + h}$: away-side (near-side) yields of associated particles per $\gamma_{rich}$ and $\pi^0$ trigger, respectively.

Purity of dir. Photon over photon rich sample

$$1 - R = \frac{N_{\gamma_{dir}}}{N_{\gamma_{rich}}}$$

(1 - $R$) are ~40% and ~70% for p+p and Au+Au central (0-12%) collisions, respectively

- Away-side yields show suppression in Au+Au collisions as compared with p+p
Nuclear modification factor: \( I_{AA} \) of \( \Upsilon_{dir} \) and \( \pi^0 \)

\[ I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}} \]

- \( I_{AA}^{\pi^0-h} \) and \( I_{AA}^{\Upsilon_{dir}-h} \) show similar and strong suppression
- At very low \( z_T \) (0.1 < \( z_T < 0.2 \)), both \( I_{AA}^{\pi^0-h} \) and \( I_{AA}^{\Upsilon_{dir}-h} \) show less suppression than at high \( z_T \)
- Models don’t include absorption and redistribution of lost energy in the medium
The nuclear modification factor, $I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}}$, is defined as the ratio of the yield in Au+Au collisions to that in pp collisions. In the STAR preliminary report, data is shown for Au+Au 200 GeV (0-12%) collisions with $p_T^{\text{Trig}}$ ranging from 12 to 20 GeV/c and $p_T^{\text{assoc}}$ from 1.2 GeV/c.

- These error bars are largely correlated, but within these uncertainties, no significant dependence of suppression on integration window is observed both for $\Upsilon_{\text{dir}}-h^\pm$ and $\pi^0-h^\pm$.

$I_{AA}$ results at high $p_T^{\text{Trig}}$ (12 < $p_T^{\text{Trig}}$ < 20 GeV/c) show no significant dependence on the integration window.
Nuclear modification factor: $p_{T}^{\text{assoc}}$ and $p_{T}^{\text{Trig}}$ dependence

- Clear away-side $p_{T}^{\text{assoc}}$ dependence of suppression
- No direct photon trigger energy dependence of suppression at high-$p_{T}$
- Both the models explain the data well

G.-Y Qin et al., PRC 80, 054909 (2009)

$$I_{AA} = \frac{D(z_T)_{AA}}{D(z_T)_{pp}}$$
Summary

- \( \gamma_{\text{dir}} \) + hadron and \( \pi^0 \) + hadron correlation study help to understand the effect of medium formation in AuAu comparison with pp collisions.

- Transverse shower profile technique is used to discriminate between direct photon and neutral pion sample.

- Away-side hadron of triggered dir. photon and \( \pi^0 \) show similar suppression, whereas at very low \( z_T \) suppression is less compared to high \( z_T \).
  - No direct photon trigger energy dependence of suppression is observed at high-\( p_T \).
  - \( I_{AA}^{\pi^0-h} < I_{AA}^{\gamma_{\text{dir}}-h} \) isn’t observed in \( 0.1 < z_T < 0.9 \) range, within uncertainties.

- Clear away-side \( p_T^{\text{assoc}} \) dependence of suppression is observed for \( I_{AA}^{\gamma_{\text{dir}}-h} \).

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Back Up
Extraction of associated Yields: Of $\Upsilon_{\text{dir}}$ and $\pi^0$ trigger

- Near-side and away-side yields are extracted within $|\Delta \phi| \leq 1.3$ and $|\Delta \phi - \pi| \leq 1.3$
- Extracted raw yields are corrected for charge particle reconstruction efficiency

- Extraction of $\Upsilon_{\text{dir}}$ associated yields:
  Assuming near side $\Upsilon_{\text{dir}}$ associated hadron yield is zero,

\[
Y_{\Upsilon_{\text{dir}}+h} = \frac{Y^a_{\Upsilon_{\text{rich}}+h} - \frac{RY^a_{\pi^0+h}}{1-R}}{1-R}
\]

\[
R = \frac{Y^n_{\Upsilon_{\text{rich}}+h}}{Y^n_{\pi^0+h}}
\]

and

\[
1 - R = \frac{N_{\Upsilon_{\text{dir}}}}{N_{\Upsilon_{\text{rich}}}}
\]

- The values of $(1 - R)$ are found to be $\sim 40\%$ and $\sim 70\%$ for pp and AuAu central $(0-10\%)$ collisions, respectively

$Y^a(n)$ : away-side (near-side) yields of associated particles per $\Upsilon_{\text{rich}}$ trigger

$Y^a(n)$ : away-side (near-side) yields of associated particles per $\pi^0$ trigger

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Contribution of $\pi^0$ energy over total jet energy

83%-88% fraction of energy carried by $\pi^0$ over total jet energy