Photon-Jet studies at RHIC

Recent jet-like correlation measurements
and a way towards photon-triggered jets at RHIC

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RHIC/AGS Annual Users’ Meeting, 2016
Why we should study $\gamma$-jet in heavy ion collisions?

Direct photon+jet coincidence is a good tomographic probe to study the QGP in HIC

- Doesn’t interact with QCD medium
- Transverse energy approximates that of initial parton $p_T$ in $\gamma$-jet events
- Volume emission dominates for $\gamma$-trigger events

Compelling measurements:
- $\gamma$-hadron correlations (advantage in AuAu due to bg.)
- $\gamma$-tagged jet reconstruction
What physics we are looking for?

- Parton energy loss in QCD medium depends on
  - Initial energy of parton, color factor, path length, gluon density, transport coefficient, etc.

An interesting comparison with $\pi^0$-jet

- Recoil parton from direct photon predominantly quarks, whereas that of $\pi^0$ are gluons (D. de Florian et al., PRD 91, 014035 (2015), T. Kaufmann et al., PRD 92, 054015 (2015))
  - $\gamma$-triggered parton (jet) loses less energy than that of $\pi^0$-trigger
    - due to color factor ($C_A/C_F = 9/4$)
- $\gamma$-triggers are mainly volume emission, whereas $\pi^0$-triggers are surfaced biased
  - on ave. $\gamma$-triggered parton (jet) loses less energy than that of $\pi^0$-trigger
    - due to path length

- Energy loss as a function of
  - Trigger $p_T$ of direct photon
  - Associated hadron $p_T$
Experimental techniques and challenges

- Direct photon discrimination from neutral hadrons (like $\pi^0, \eta$)
  - STAR experiment: Transverse shower profile method
  - PHENIX experiment: Statistical subtraction method (from meson decays)
  - Isolation cuts

- Background subtraction
  - Underlying event bg., flow component in azimuthal correlations, etc… both in $\gamma$-hadron correlation and in $\gamma$-tagged jet reconstruction

- Different systematic effects from unknown sources

- Finally, we need large statistics

**Observables at RHIC**

$$I_{AA}(x) = \frac{Y^{Au+Au}(x)}{Y^{p+p}(x)}$$

where

- $x = p_T^\gamma$
- $p_T^{assoc}$
- $z_T = \frac{p_T^{assoc}}{p_T^\gamma}$

Ratio of Au+Au to p+p per trigger yields

Trigger $p_T$

Associated hadron $p_T$

Fraction of momentum carried by the away-side hadron

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Jet-like azimuthal correlation functions

- In $\gamma_{\text{rich}}$ small peak due to some contamination of $\pi^0$
- Background subtracted from flow modulated background level determined using ZYA1 method
- Near-side yield is by definition zero for direct-photon trigger

\[ \xi = \ln(1/z_T) \]

PRL 111, 032301 (2013)

- $\gamma_{\text{dir}}$-hadron correlations in $p+p$ and $Au+Au$
- At low $z_T$, sys. uncertainty due to higher flow ($n>2$) components seems noticeable in $Au+Au$

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Associated yields of $\pi^0$-hadron correlations

From STAR experiment
Some discussion of $\pi^0$–hadron correlations

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

- Away-side yields show suppression
- Near-side shows no suppression

- By integrating $z_T$ times near-side yields, STAR exp. estimated $85(\pm3)\%$ fraction of energy carried by $\pi^0$ over “jet energy” ($\pi^0$ + charged hadrons) in pp $200$ GeV

- In PYTHIA, it is found to be $80(\pm5)\%$ which is consistent with data

arXiv:1604.01117
Yields associated with $Y_{\text{dir}}$ – trigger: Fragmentation function

Using statistical subtraction method:

$$Y_{\text{dir}} = \frac{R_{\gamma} Y_{\text{inc}} - Y_{\text{dec}}}{R_{\gamma} - 1}$$

Where,

$$Y_{\text{inc}} = \frac{1}{N_{\text{inc}}} \frac{dN_{h-\gamma_{\text{inc}}}}{d\Delta\phi}$$

$$R_{\gamma} = \frac{N_{\text{inc}}}{N_{\text{dec}}} \sim 1.4 \text{ to } 2.3 \text{ vs. } p_t$$

- Fragmentation function is modified
- Not const. at all $z_T/\xi$

PRL 111, 032301 (2013)

PRL 109, 152302 (2012).
Yields associated with $Y_{\text{dir}}$ – trigger: Fragmentation function

$Y_{\gamma_{\text{dir}}+h} = \frac{Y^{a}_{\gamma_{\text{rich}}+h} - RY^{a}_{\pi^{0}+h}}{1 - R}$

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

Purity of $\gamma_{\text{rich}}$ sample

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

- Fragmentation function is modified
- Away-side yields show suppression in Au+Au collisions as compared with p+p
Within large uncertainties, $I_{AA}^{\pi^0-h}$ and $I_{AA}^{\Upsilon_{dir}-h}$ show

- similar suppression: No clear path length and color factor effect observed
- strong suppression: particularly for $z_T > 0.2$

Indication of less suppression at low $zT$, but not significant

- More significant effect in $I_{AA} (p_T^{assoc})$

Models are consistent with data
Nuclear modification factor: $I_{AA}$ of $\Upsilon_{dir}$

**STAR experiment**

$12 < p_{T_{trig}} < 20$ GeV/c

**PHENIX experiment**

$5 < p_{T_{trig}} < 9$ GeV/c

- At low $z_T$, $I_{AA}$ is less suppressed at high $p_{T_{trig}}$ than at low $p_{T_{trig}}$
- At high $z_T$, similar level suppression in both $p_{T_{trig}}$ regions

- Redistribution of energy in YaJEM model to differentiate between PHENIX and STAR $I_{AA}$
- Qin, ZOWW models don’t show enhancement at low $z_T$ (for 12-20 GeV/c)

arXiv:1604.01117

PRL 111, 032301 (2013)
Comparison with other theoretical model

Only considering trend of $I_{AA}$ as a function of $z_T$

Unlike Qin, ZOWW models, YaJEM model includes energy loss by gluon radiation that redistributed to soft particles

Hence, large enhancement at low $z_T$ compared with high $z_T$
Energy loss in azimuthal windows

STAR experiment

$12 < p_T^{\text{trig}} < 20 \text{ GeV/c}$  [$\pm 35^0 \text{ vs } \pm 80^0$]

• High trigger $p_T$, no recovery of energy loss even at wider azimuthal angle
  $[12 < p_T^{\text{trig}} < 20 \text{ GeV/c} \rightarrow 0.1 < z_T < 0.4 \rightarrow 1.2 < p_T^{\text{asso}} < 8 \text{ GeV/c}]$

• Low trigger $p_T$, recovery at smaller $z_T$
  $[5 < p_T^{\text{trig}} < 9 \text{ GeV/c} \rightarrow 0.1 < z_T < 0.4 \rightarrow 0.5 < p_T^{\text{asso}} < 3.6 \text{ GeV/c}]$

soft particles coming out at wider azimuthal window !!!!

PHENIX experiment

arXiv:1604.01117

PRL 111, 032301 (2013)
Energy Loss as a function of associated hadron $p_T$

STAR experiment

- Soft associated particles are less suppressed compared with high $p_T$
- Energy loss as a function of $z_T$ and associated hadron $p_T$ respond similarly

arXiv:1604.01117
Energy Loss as a function of triggered direct photon $p_T$

STAR experiment

Energy loss is insensitive to the energy of triggered direct photon at high $p_T$ (8-20 GeV/c)

arXiv:1604.01117
What we have observed so far?

From RHIC measurements

• Within uncertainties, no clear path length and color factor effect observed in $\pi^0$ vs. $\gamma$ triggers !!!!
  - May be these effects are very sensitive!!!!
  - Precision measurement may be required

• “Modified” FF not independent of $p_T^{\text{trig}}$

• Less suppression or even enhancement at low $p_T^{\text{assoc}}$

• Soft particles ($p_T^{\text{assoc}} < 2 \text{ GeV/c}$) coming out at wider azimuthal angles

• Energy loss is insensitive to the energy of triggered $\gamma$ at high $p_T$ (8-20 GeV/c) at RHIC

What next?

$\gamma$ tagged Jet reconstruction-

Full jet reconstruction can give us full energy of away-side recoil parton

(But there are many experimental challenges)
Direct photon tagged jet reconstruction at RHIC

PHENIX proposal

- Including $\pi^0$ suppression in HIC, $\gamma/\pi^0$ ratio exceeds unity above $p_T > 15$ GeV
- In pp, we need to do proper isolation cut
- It is possible to have $\gamma$-jet measurement at top RHIC
- Along with that comparison with $\pi^0$-jet measurement could also be interesting too

Better to have simulation study before data analysis.....

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Pythia simulation study of γ-Jet measurement

Event display from AuAu

- HT trigger can provide neutral triggers ($\pi^0, \gamma$) in STAR experiment
- Preliminary simulation studies using Pythia8 have been done
γ-tagged recoil jet in Pythia8

Uncorrelated jet candidates

π-3π/4

π-π/2

π-π/4

π+π/4

π+3π/4

π0, γ

Recoil Side

8 < p_T^{trig} < 20 GeV/c
Full jet reconstruction

Uncorrelated jet are used to subtract background
Comparison charged vs full jet reconstruction

- For full Jet reconstruction, nice peak at $15 < p_{T}^{\text{trig}} < 20$ GeV/c

Work is ongoing using STAR data for $\text{Au+Au}$ and $\text{p+p}$ collisions.....

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Summary and Outlook

- $I_{AA}$ measurement for $\gamma$-trigger hadron correlations is discussed from low to high $p_T$ range (5-9 and 12-20 GeV/c) at RHIC
- Within uncertainties, no clear path length and color factor effect observed in $\pi^0$ vs. $\gamma$ triggers!!!!
  - May be these effects are very sensitive!!!!
  - Precision measurement may be required
- “Modified” FF not independent of $p_T^{\text{trig}}$
- Less suppression or even enhancement at low $p_T^{\text{assoc}}$
- Soft particles ($p_T^{\text{assoc}} < 2$ GeV/c) coming out at wider azimuthal angles
- Energy loss is insensitive to the energy of triggered $\gamma$ at high $p_T$ (8-20 GeV/c) at RHIC

Work is ongoing in STAR experiment to measure both $\gamma$- and $\pi^0$-tagged charged/Full jet reconstruction to have good understanding on parton energy loss at RHIC energy….

In the Future - sPHENIX …
Interesting Direct photon-Jet physics is ongoing at RHIC

Stay tuned.....

Thank you!
Back Up
$12 < p_T^{\text{trig}} < 20 \text{ GeV/c} \otimes p_T^{\text{assoc}} > 1.2 \text{ GeV/c}$

Away-Side

$D(z_T)$

$p+p$ [$\gamma_{\text{dir}}$ - $h^+$]

$p+p$ [$\pi^0$ - $h^+$]

$z_T$, $z_T^{\text{corr}}$
Transverse shower profile method

STAR BEMC

**Shower Maximum Detector (BSMD)**

**BEMC module**

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

- Wider shower represents small TSP and vise versa
  - TSP cuts tuned to get
    - a nearly pure sample of \( \pi^0 \) (called “\( \pi^0_{\text{rich}} \)”)  
    - a sample of enhanced fraction of \( \gamma_{\text{dir}} \) (\( \gamma_{\text{rich}} \))

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