Azimuthal Correlation of direct $\gamma$ and $\pi^0$ with charged hadrons at STAR

Ahmed Hamed
For the STAR Collaboration

2010 RHIC & AGS Annual Users’ Meeting
BNL, 7-11th June, 2010

Ahmed Hamed
(Texas A&M University)
How many bodies are required before we have a problem?

G. E. Brown: History carries the answer
In eighteenth-century Newtonian mechanics, the three-body problem was insoluble.

With the birth of relativity and QED, the two- and one-body problems became insoluble.

And within modern QFT, the problem of zero bodies (vacuum) is insoluble.

So, if we are out after exact solutions, no bodies at all is already too many!

R. D. Mattuck
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- Current Picture
- New Probes
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Evolution of jet suppression picture at RHIC

Hadrons suppression in central Au+Au is:

- final-state effect
- surface-biased
- tangential-biased and/or punch-through
- Non interacting jets

Medium needs more penetrating probes

- Direct $\gamma$
- Full jet reconstruction

this talk
Andrew Adare`s talk
Elena Bruna`s talk

- 2+1 correlations

Hua Pei`s talk
Azimuthal correlation of direct γ/π⁰-charged hadrons

1. Direct γ-charged hadrons

- High-p_T γ^{dir} balances the p_T of the other outgoing parton k_T effect (several hundred MeV “theoretically” and ~3GeV reported by PHENIX).

   Energy loss dependence on parton initial energy

2. Direct γ-charged hadrons vs. π⁰-charged-hadrons

- λ_{γ^{dir}} is large enough that its momentum is preserved, and also samples uniform spatial distribution of the hard scattering vertex inside the medium → “no surface and no tangential biases”

   Energy loss dependence on path length

- If Compton scattering is the dominant process for γ^{dir} productions

   Energy loss dependence on color factor

- At same trigger (γ/π⁰) energy, the outgoing parton of π⁰-h coincidence is more energetic than that of γ^{dir}–h coincidence.
**Expectation on the away-side of $\gamma^{\text{dir}}$ and $\pi^0$**

Conjecture of energy loss functional form for particular medium

$$P(\Delta E) \propto F( E, L, C_R, f )$$

“independent variables”

1. $F(L)$: The recoiling jet from $\pi^0$ travel on average longer distance within the medium than that of $\gamma^{\text{dir}}$

2. $F(C_R)$: If the Compton scattering is the dominance channel for $\gamma^{\text{dir}}$ productions, then recoiling jet of $\pi^0$ is a mix of $q/g$ while for $\gamma^{\text{dir}}$ the dominance is $q$.

*These two factors cause the recoil jet from $\pi^0$ to lose more energy than that of $\gamma^{\text{dir}}*$

3. $F(E)$: The energy of the recoiling jet from $\pi^0$ is greater than that of $\gamma^{\text{dir}}$.

✓ This factor needs to be measured

According to theoretical models:

Relative phase:  \[ \frac{dE_{\text{rad}}}{dz} \propto C_R \alpha_s E <q_{\perp}^2> \]
\[ \frac{dE_{\text{rad}}}{dz} \propto C_R \alpha_s \ln(E) <q_{\perp}^2> \]

Static Medium: \[ \frac{dE_{\text{rad}}}{dz} \propto L^2 \]
Dynamic Medium: \[ \frac{dE_{\text{rad}}}{dz} \propto L \]

Notice: We don’t measure energy loss but $l_{AA}$, how $l_{AA}$ is related to $\Delta E$?
LO production of direct $\gamma$ and backgrounds

Very challenging measurements due to the S/B ratio, $\pi^0$ is the major source of bg.

The Compton-scattering process

$$\rightarrow \gamma/\pi^0 > \alpha_{\text{em}}$$

$\rightarrow$ High-pt direct photons are produced at a rate comparable to that of single particles.

<table>
<thead>
<tr>
<th>S/bg at $\sqrt{s}$=200 GeV at mid-rapidity at $p_T$ &gt; 8 GeV/c</th>
<th>p+p</th>
<th>Au+Au (central)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma^{\text{dir}}/\pi^0$</td>
<td>~1:5</td>
<td>~1:1</td>
</tr>
<tr>
<td>$\gamma^{\text{dir}}/\eta$</td>
<td>~1:1.25</td>
<td>~1:0.25</td>
</tr>
<tr>
<td>$\gamma^{\text{dir}}/\gamma^{\text{frag}}$</td>
<td>~1:0.4</td>
<td>?</td>
</tr>
</tbody>
</table>
Fragmentation photons

Fragmentation photons $\gamma_{\text{frag}}$

$\gamma_{\text{frag}}$ seems to be accompanied by additional hadrons.

$$zD_{\gamma/q}(z,Q^2) = e_q^2 \frac{\alpha}{\gamma_\pi} \left[ 1 + (1-z)^2 \right] \ln(Q^2/\Lambda^2) \sim \alpha_{\text{em}}/\alpha_s$$

$$zD_{\gamma/g}(z,Q^2) = 0$$

Example of Bremsstrahlung diagrams

- The sub-process of $\gamma_{\text{frag}}$ is of order of $O(\alpha_s^2)$ but its yield is comparable to $\gamma_{\text{dir}}$ LO process $O(\alpha_s \alpha_{\text{em}})$.

- The relative contributions of $\gamma_{\text{dir}}$ and $\gamma_{\text{frag}}$ are strongly depend on the region explored in the PDF → collider energy and kinematics.

  “more problematic at LHC than at RHIC”

- The $\gamma_{\text{frag}}$ contribution is expected to fall off more rapidly in $x_T$ than the other lowest order of $\gamma_{\text{dir}}$. (G. Sterman et al. Rev. Mod. Phys. 67, 157 (1995))

- $\gamma_{\text{frag}} / \gamma_{\text{dir}} \sim 30-40\%$ at $p_{\gamma_T} > 8$ GeV/c at mid-rapidity at RHIC energy. D. De Florian and W. Vogelsang, Phys. Rev. D72, 014014 (2005)
STAR detector and on-line γ-rich event selections

- STAR is well-suited detector for correlation measurements

TPC: $|\eta| < 1, 0 < \phi < 2\pi$

L2gamma trigger in AuAu (2007)

Bht2-mb: ZDC coincidence, and $E_{T(tower)} > 5.76$ GeV
Tagger for express stream: Based on bht2-mb, with additional higher $E_{T(cluster)} > 7.44$ GeV. “Cluster_size ≤ 2 towers”

1 γ-triggered event each 5k minbias event $\rightarrow 500 \, \mu b^{-1}$ of AuAu 2007 @ 200GeV

$\sim 11 \, pb^{-1}$ of pp 2006 @ 200GeV
STAR detector and off-line $\gamma$-rich event selections

✓ Correlate neutral clusters “triggers” (BEMC-BSMD) with tracks (TPC)

Offline: event selection and analysis

- vertex within ±55 cm of the center of TPC.
- at least one cluster with $E_T > 8$ GeV, $E_{\text{smd}1} > 0.5$ GeV, $E_{\text{smd}2} > 0.5$ GeV, and no track with $p > 3$ GeV/c pointing to that cluster.

In Au+Au: 28% of the integrated luminosity has $E_T > 8$ GeV of which 96.5% left at least 0.5 GeV on each planes of SMD of which 93% has no track with $p > 3$ GeV/c pointing to it.
Azimuthal correlation functions of neutral clusters

Both near and away-side yields increase with trigger energy.

The increase on the away side is larger due to the trigger bias.

Final-state medium effects cause the away-side to be increasingly suppressed with centrality, without significant broadening.

The suppression of the near-side yield in central relative to peripheral is consistent with the expected increase of the $\gamma/\pi^0$ ratio with centrality at high energy.
How to separate $\gamma_{\text{dir}}$ from neutral bg.

Either to reconstruct $\pi^0$ or to use the transverse shower shape analysis to distinguish between $\pi^0$ and $\gamma_{\text{dir}}$
**Methods of $\gamma^{\text{dir}}$ extraction**

- **Standard Method**
  1. Measure inclusive photons.
  2. Reconstruct other sources of photons “hadrons”!
  3. Subtract photons from decay of $\pi^0$, $\eta$ etc.

PHENIX is well-adapted for this method due to the calorimeter granularity and the distance between the calorimeter to the interaction point $\rightarrow \pi^0$ reconstruction in central Au+Au up to $p_T \sim 20$ GeV/c

- Limited at very high $p_T$, effective method for both symmetric and asymmetric hadron decays

- **Transverse Shower Profile Method**

  STAR is well-suited for the transverse shower shape analysis due to the Shower Maximum Detector $\rightarrow \gamma/\pi^0$ discrimination up to $p_T \sim 26$ GeV/c. M. Beddo et al., Nucl. Instrum. Meth. A499, 725 (2003)

  - Effective at very high $p_T$, but limited only for the symmetric hadron decays

B. I. Abelev et al., hep-ex: 0912.3838
**Novel Method**

Statistical measurement of $\gamma$-jet yields

- Use the transverse shower shape to select $\gamma^\text{dir}$ free ($\pi^0$-rich) sample and $\gamma^\text{rich}$ sample from the neutral clusters.

- Impose the condition of zero-near side yield associated with $\gamma^\text{dir}$

$$Y_{\gamma^\text{dir}+h} = \frac{Y_{\gamma^\text{rich}+h} - \mathcal{R}Y_{\gamma^\text{bg}+h}}{1 - \mathcal{R}}$$

$$\mathcal{R} = \frac{N_{\gamma^\text{bg}}}{N_{\gamma^\text{rich}}} \quad \text{(a measure of bg in the $\gamma^\text{rich}$ sample)}$$

- Shower shape analysis doesn’t measure all bg, it measures only the $\pi^0$ in its symmetric decay mode.

  All sources of bg are approximated to the measured $\pi^0$

$$Y_{\gamma^\text{dir}+h} = \frac{Y_{\gamma^\text{rich}+h} - \mathcal{R}Y_{\pi^0+h}}{1 - \mathcal{R}}$$

$$\mathcal{R} \approx \frac{N_{\pi^0}}{N_{\gamma^\text{rich}}} = \frac{Y_{\gamma^\text{rich}+h}}{Y_{\pi^0+h}}$$

Are $\mathcal{R}$ values reasonable?

Do the other sources of bg have similar correlations with charged hadrons as that of the measured $\pi^0$?

**Note**: $\sim 10\%$ of all $\pi^0$ (8-16GeV/c) decay asymmetrically with one gamma has $p_T > 8$ GeV/c within STAR-BEMC acceptance. $\eta$ causes similar level of background as asymmetric $\pi^0$. 

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The two photons originated from $\pi^0$ hit the same tower at $p_T > 8\text{GeV/c}$.

The shower shape is quantified with the cluster energy, measured by the BEMC, normalized by the position-dependent energy moment, measured by the BSMD strips.
Transverse Shower Profile Results
Shower Profile of single $\gamma$ vs. two close $\gamma$s

The probability distribution is peaked at smaller value in AuAu than in pp due to the larger relative fraction of $\gamma^{\text{dir}}$.

The rejection power of direct photons is $\sim 90\%$.
The level of bg in the $\gamma_{\text{rich}}$ sample: ~55-30% from pp to central Au+Au, and doesn’t show strong dependence neither on $p_T$ trig nor on $p_T$ assoc.
2. Correlation functions of neutral clusters, $\pi^0(\gamma^{\text{dir}}$ free), and $\gamma^{\text{rich}}$ samples

$\gamma^{\text{rich}}$ sample has lower near-side yields compared to those of the $\pi^0$ rich, but not zero!

Shower-shape analysis is only effective for rejecting two close $\gamma$ showers, leaving background $\gamma$. From asymmetric decays of $\pi^0$, $\eta$, $\gamma^{\text{frag}}$.

The level of uncorrelated bg is dramatically suppressed relative to the signal over the measured range of $p_T^{\text{assoc}}$ \rightarrow\text{“negligible v2 contribution”}.
3. $z_T$ dependence of $\pi^0-h^\pm$ and $h^\pm-h^\pm$ near and away-side yields.

For $\pi^0-h^\pm$:
Correlated systematic $\sim 7\text{-}13\%$
and point-to-point uncertainties are less than 5%.

A general agreement of $\sim 20\text{-}30\%$
b/w the results from $\pi^0-h^\pm$ and $h^\pm-h^\pm$ is clearly seen in both near and away-side yields → the $\pi^0$-rich sample is free of $\gamma^{\text{dir}}$. 

arXiv:0912.1871
Assumption Justifications
1. Do other sources of bg. have similar correlations with $h^\pm$ as the measured $\pi^0$? 

PYTHIA simulation indicates, within ~10% at the same $p_T$ trig, that the correlations of $\gamma$ triggers from asymmetric hadron decays are

- Similar to those of symmetrically decaying $\pi^0$ triggers.
- Similar to the measured correlations of $\pi^0$-rich triggers.
Do other sources of bg. have similar correlations with $h^\pm$ as the measured $\pi^0$?

- $\gamma^{\text{frag}}$ has different correlation with the charged particle compared to that of $\pi^0$ with insensitivity to the charged rejection cut.

2 classes of consideration for $\gamma^{\text{frag}}$:

1. The $\gamma^{\text{frag}}$ which has near side yield are estimated using the $\chi^2$ analysis, by comparing the shape of the near-side correlation of $\gamma^{\text{rich}}$ to $\pi^0$ rich triggers, and is taken into account in the systematic errors.

2. The $\gamma^{\text{frag}}$ which has no near side yield within the integrated region “$|\Delta\phi| \leq 0.63$ rad” remains in the $\gamma^{\text{dir}}$ measurements, but was studied by varying the PID cuts and included in final syst. Errors.
Extraction of the associated yields with $\gamma^{\text{dir}}$

$$Y^{\gamma_{\text{dir}} + h} = \frac{\left(Y^{\gamma_{\text{rich}} + h} - R Y^{\pi^0 + h}\right)}{1 - R}$$
z_T dependence of away-side associated-particle yields for \( \pi^0 \) triggers and \( \gamma^{\text{dir}} \) triggers.

**Data:** \( \gamma^{\text{dir}} \) vs. \( \pi^0 \)

\( \star \) At given \( z_T \), the away-side yield per \( \pi^0 \) trigger is significantly larger than that per \( \gamma^{\text{dir}} \) trigger.

- **p+p**
  - \( \gamma^{\text{dir}} \) carries the total scattered constituent momentum while \( \pi^0 \) carries only a fraction of it.
  - different proportions of q and g recoiling from \( \gamma^{\text{dir}} \) and \( \pi^0 \) triggers.

- **Au+Au**
  - different path length for the recoiling jet from \( \pi^0 \) trigger and \( \gamma^{\text{dir}} \) trigger.
  - color factor effect on energy loss.

**Data vs. theory**

\( \star \) The yields in p+p and Au+Au are well described by theoretical models:
1. Zhang et al., no \( \gamma^{\text{frag}} \) contributions.
2. Qin et al., significant contribution of \( \gamma^{\text{frag}} \).
Medium effect as a function of $z_T$

$$I_{AA} = \frac{D(z_T)_{pp}}{D(z_T)_{AuAu(0-10\%)}}$$

for the recoiling jet of $\pi^0$ and $\gamma^{\text{dir}}$ triggers:

- $I_{AA}$ of $\pi^0$ vs. theory
  - agrees with Zhang et al. within the current uncertainties.

- $I_{AA}$ of $\gamma^{\text{dir}}$ vs. theory
  - disfavors Renk-YaJEM → lost energy is distributed to very low pt and large angle.
  - agrees with Renk-ASW, Qin et al., and Zhang et al. within current uncertainties.
  - shows no strong rise at low $z_T$.

Data: $I_{AA}$ of $\pi^0$ vs. $I_{AA}$ of $\gamma^{\text{dir}}$

- similar level and pattern of suppression for $I_{AA}$ of $\pi^0$ and $\gamma^{\text{dir}}$ triggers and both are $z_T$-independent → effect of fluctuations in energy loss dominates over the effect of geometry !!! (Phys. Rev. C80, 014901 (2009)).
Energy loss dependence of parton initial energy

Why $I_{AA}^{\gamma_{\text{dir}}} = I_{AA}^{\pi^0}$?

Recall, we expect the recoil parton of $\pi^0$ to lose more energy than that of $\gamma_{\text{dir}}$ due to the longer path length and color factor.

$$P(\Delta E) \propto F(E, L, C_R, f)$$

Is it compensated with $P(\Delta E) \propto F(E)$?

$I_{AA}^{\gamma_{\text{dir}}}$ shows no strong dependence on $E$.

Then

The energy loss dependence on:

1. Path length
2. Color factor

is not observed within the covered kinematics region.
Summary

1. STAR, due to its acceptance, is capable of multi-analysis for more penetrating probes.

2. Direct photon-charged hadron coincidence measurement is clean probe for the energy loss dependence of parton initial energy.

3. Comparison of direct photon-charged hadron coincidence measurement with the neutral pion-charged hadron coincidence measurement provides tool for the energy loss dependence of path length and color factor.

4. STAR reported a novel method utilizing the transverse Shower Shape analysis for direct photon-charged hadrons coincidence measurements.

5. Within the covered kinematic range, the energy loss shows no dependence on parton initial energy, path length through the medium, and color factor.

6. Although different theoretical models assume energy loss dependence on path length, and parton initial energy; the theoretical predictions do not show significant difference between direct photons and neutral pions away-side suppression within the covered kinematic ranges!!!

BOTH THEORY AND EXPERIMENT DON’T SUPPORT THE EXPECTATION “within the covered kinematics range”, IS THE EXPECTATION WRONG? OR IS THE CURRENT PICTURE WRONG?
Outlook

- Probe the low $z_T$ region.
- Comparison between the direct $\gamma$-triggered and $\pi^0$-triggered azimuthal correlations with charged hadrons and fully reconstructed jets in different collision systems.
- Performance of the same azimuthal correlation measurements with respect to the reaction plane.
- Measurement of $v_2$ of direct $\gamma$ and $\pi^0$ at high $p_T$.
- Measurement of direct $\gamma$ ridge.
- Study of LPV using direct $\gamma$ and $\pi^0$. 

![Graph showing data for RHIC-II run numbers and luminosity](image)
If a model fit data, it is really great!

“No amount of experimentation can ever prove me right; a single experiment can prove me wrong”

Albert Einstein

RHIC enjoys a plenty of beautiful data for very difficult problem in which vacuum means too many bodies, so careful and very critical interpretations are required.