The Measuring of Direct Photon Azimuthal Anisotropy In Au+Au 200GeV Collisions at RHIC-PHENIX

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What is direct photon?

Direct photons are all photons except those originating from hadron decay. They penetrate the medium without the interaction. It is challenging to identify photon sources. 

by $p_T$ distribution? emitting angle?

- hard scattering
- Jet fragmentation
- jet-photon conversion
- (thermal) radiation from QGP
- (thermal) radiation from HG

2015/03/13 Direct photon (M. Sanshiro)
Direct photon $p_T$ spectra

The $p_T$ spectra in Au+Au collision is enhanced compared with that in p+p collision scaled by the number of binary collisions less than 4 GeV/c. The excess of $p_T$ spectra is fitted and effective temperature is extracted. (Freeze-out temperature of hadrons are about 100MeV)

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Effective temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% - 20%</td>
<td>239 ± 25 ± 7 (MeV)</td>
</tr>
<tr>
<td>20% - 40%</td>
<td>260 ± 33 ± 8 (MeV)</td>
</tr>
<tr>
<td>40% - 60%</td>
<td>225 ± 28 ± 6 (MeV)</td>
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</table>

Photons in low $p_T$ are mainly radiated from very hot medium at early time of collisions.

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Elliptic flow of direct photon

High $p_T$: very small $v_2$
It could be because photons produced in the initial hard scattering are dominant plus no interaction of photon in QGP ($R_{AA} \approx 1$).

Low $p_T$: Comparable to hadron $v_2$ at around 2 GeV/c
It is suggested that photons are emitted from late stage.
Direct photon puzzle

Thermal radiation photons are dominant in low $p_T$ region.

$p_T$ spectra:
Emitted from very hot medium ($T_{\text{eff}} \approx 240\text{MeV}$).
-\> Photons are dominantly emitted at early stage.

Elliptic flow:
It was expected that photon has small $v_2$, since it includes ones from early stage having small $v_2$.
-\> Photons are dominantly emitted at late stage.

There is a discrepancy, and it is called “direct photon puzzle”. There is no models to explain both observables simultaneously.
Third order azimuthal anisotropy ($v_3$)

$N(\phi - \Psi_n) \propto 1 + 2 \sum v_n \cos \{n(\phi - \Psi_n)\}$

$v_n = \langle \cos \{n(\phi - \Psi_n)\} \rangle$

The higher order flow is originating from the fluctuation of the shape of participant zone. It is expected to constrain the initial geometry calculating model and $\eta/s$ of QGP.

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Analysis flow

1. $\pi^0$, $\gamma^{\text{inc.}}$, $v_n$ measurement

2. $\gamma^{\text{dec.}}$, $v_n$ estimation from $\pi^0$, $v_n$
Meson spectra are assumed by $m_T$ scaling.
Meson $v_n$ are assumed by the number of constituent quark (NCQ) scaling.

3. $\gamma^{\text{dir.}}$, $v_n$ extraction

$$v_n^{\text{dir.}} = \frac{R_\gamma v_n^{\text{inc.}} - v_n^{\text{dec.}}}{R_\gamma - 1}$$

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The comparison of neutral pion and direct photon $v_n$

- In high $p_T$ region
  Direct photon $v_n$ is close to zero.
  It is consistent with the expectation that prompt photons having $v_n \approx 0$ are dominant. ($R_{AA} \approx 0$)

- In low $p_T$ region
  Direct photon has non-zero and positive $v_2$ and $v_3$. 

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Centrality dependence of $\gamma^{\text{dir.}}$ and $\pi^0 v_n$ in low $p_T$

Strong dependence for $v_2$ : weak dependence for $v_3$

It could be suggested that photon $v_n$ is created by the expansion of the medium from the initial geometry.
Blast wave model prediction for photon observables

Based on hydrodynamic model. Hadron observables in low $p_T$ region are well described by the parameters when kinetic freeze-out.

6 parameters
- Kinetic freeze-out temperature : $T_f$
- Average transverse rapidity : $\langle \rho \rangle$
- Rapidity anisotropy : $\rho_2$, $\rho_3$
- Spatial density anisotropy : $s_2$, $s_3$

Fitting range

Out-plane

$\langle \rho \rangle - \rho_n$

1 - $s_n$

Expanding direction

In-plane

$\langle \rho \rangle + \rho_n$

1 + $s_n$

PIDed Hadron $p_T$ spectra

Centrality:0-20%

$T_f=104.48\pm0.57$[MeV]

$\langle \rho \rangle =0.661\pm0.004$

PIDed Hadron $v_2$

$\rho_2=0.021\pm0.002$

$s_2=0.032\pm0.004$

PIDed Hadron $v_3$

$\rho_3=0.016\pm0.001$

$s_3=0.006\pm0.001$
Photon observables predicted by blast wave model

The photon $p_T$ spectra and $v_n$ are predicted as a massless particle.

The $p_T$ spectra predicted with $T_f=104$ MeV & $\langle \rho \rangle=0.66$ and $T_f=240$ MeV & $\langle \rho \rangle=0$ are similar. It could be due to blue shift correction. The $v_n$ with $\langle \rho \rangle=0$ is zero.
Summary

Direct photon azimuthal anisotropy is measured in Au+Au 200 GeV collisions at RHIC-PHENIX experiment.

- **In high \( p_T \) region**
  - Photon \( v_n \) is close to zero while hadron shows non-zero \( v_n \).
  - Prompt photons which are \( v_n \approx 0 \) are dominant.

- **In low \( p_T \) region**
  - It is found non-zero and positive \( v_3 \) in low \( p_T \).
    - Photon \( v_n \) is created by the expansion of medium from the initial geometry.
  - Blast wave model describes photon observables well.
    - It is suggested that the evolution of the medium is needed to be taken into account.
Photon analysis in heavy ion collision

The properties of photon in high energy heavy ion collision

- emitted during all stages of the collisions
- don’t interact with the medium

We can access the evolution of the collision.
Hadronic decay photon

The $p_T$ spectra and $v_n$ are estimated from $\pi$.

- $p_T$ spectra: $m_T$ scaling
- $v_n$: quark number scaling

$\pi$, $\rho$, $\eta$, $\eta'$, $\omega$ all $\gamma^{\text{dec.}}$

Contribution ratio ($R^i$)

Meson $p_T$ spectra

$\gamma^{\text{dec.}}$ $p_T$ spectra

Meson $v_2$

$\gamma^{\text{dec.}}$ $v_2$

$m_T$ scaling

\[ p_T' = \sqrt{p_T^{2,\pi^0} + M_{\text{meson}}^2 - M_{\pi^0}^2} \]

decay photon $v_n$

\[ v_n^{\text{dec.}} = \sum_i R^i v_n^{\text{dec.i}} \]
Data set: Au+Au $\sqrt{s_{NN}}=200\text{GeV}$ collisions
4.4 billion events are analyzed.

$$\nu_n = \left\langle \cos \left\{ n(\phi - \Psi_n) \right\} \right\rangle$$
The excess of direct photon

The excess of direct photon has been measured in the wide $p_T$ range.

The methods of virtual photon and external conversion photon are sensitive to low $p_T$ region.

Less than 4 GeV/c, direct photons are included by 20% in inclusive photon.

$$R_\gamma = \frac{N_{inc.}}{N_{dec.}}$$
Why direct photon $v_3$ is measured?

Radial flow effect (blue shift effect): It makes apparent temperature higher than true temperature. Photons from late state are dominant. $v_2 > 0 : v_3 > 0$

Large magnetic field: Direction of magnetic field is strongly related with $\Psi_2$(R.P.) but not with $\Psi_3$. $v_2 > 0 : v_3 \approx 0$

$v_3$ measurement could provide additional constraint on photon production mechanism.
Azimuthal anisotropy (Elliptic flow)

\[ N(\phi - \Psi_{R.P.}) \propto 1 + 2 \sum v_n \cos \{n(\phi - \Psi_{R.P.})\} \]
\[ v_2 = \langle \cos \{2(\phi - \Psi_{R.P.})\} \rangle \]
charged particle dφ distribution

- anisotropic pressure gradient in participant zone (Initial state)
- QGP expansion (hydrodynamic motion, \(\eta/s\))
  \((\eta \text{ is shear viscosity and } s \text{ is entropy density})\)
- hadron production mechanism (coalescence)

(1) : **Initial geometry** is converted into final azimuthal anisotropy
(2) : (expected to be) sensitive to \(\eta/s\)

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It is expected that the emitted angle of photons depends on their sources.

- Initial hard scattering: $v_2 \approx 0$
- Medium induced: $v_2 \leq 0$
- Jet fragmentation: $v_2 \geq 0$
- Radiation from expanding medium: $v_2 > 0$

The measurement of photon azimuthal anisotropy is a powerful probe to identify the photon sources.
$\Psi_2$ and $\Psi_3$ are uncorrelated.
Photons by external conversion

Published
Real photons in EMCal: 1 - 20 GeV/c
  large errors at low $p_T$ (resolution, contamination)
Virtual photons from $e^+e^-$: 1 - 4 GeV/c

New method
Real photons are measured by $e^+e^-$ pair
from external photon conversion
at the HBD readout plane.
  ✓ less hadron contamination
  ✓ good momentum resolution
$p_T$ range: 0.4 - 5 GeV/c
Extended to lower $p_T$
low statistics

2015/03/13

$M_{HBD}$: Real track
$M_{vtx}$: Measured track
External conversion photon

1) real photon converts to $e^+e^-$ in HBD backplane
2) default assumption: track come from the vertex
3) momentum of the conversion tracks will be mis-measured (see black tracks)
4) apparent pair-mass (about 12MeV) will be measured for photons
5) assume the same tracks originate in the HBD backplane
6) re-calculate momentum and pair mass with this “alternate tracking model”
7) for true converted photons $M_{\text{atm}}$ will be around zero
Identification photon sources from $p_T$ spectra

The photon sources are identified via the $p_T$ spectra.
It is observed that

- all harmonics have mass ordering
- there are meson and baryon splitting

All particles are scaled by modified NCQ scaling.

(a) : $v_2(KE_T)/n_q$
(b) : $v_n^{1/n}$ scaling
(a)+(b) : $v_n(KE_T)/n_q^{n/2}$
Meson $p_T$ spectra estimation

$$p_{T,\text{meson}} = \sqrt{p_{T,\text{pion}}^2 + M_{\text{meson}}^2 - M_{\text{pion}}^2}$$

Since it is difficult to measure mesons except for pion, the other mesons $p_T$ spectra are estimated by $m_T$ scaling from pion experimental data.

$$\frac{d\sigma}{p_T dp_T} = T(p_T) F_0 + (1 - T(p_T)) F_1,$$
$$T(p_T) = \frac{1}{1 + \exp \left\{ \frac{(p_T - t)}{w} \right\}},$$
$$F_0 = \frac{\{ \exp (-a p_T - b p_T^2) + p_T / p_0 \}^n},$$
$$F_1 = \frac{A}{p_T^n}.$$
Meson $v_n$ estimation

It has been known that hadron $v_n$ as a function of $KE_T$ are scaled by the number of constituent quark. Meson $v_n$ is estimated from pion $v_n$.

$$p_{T,\text{meson}} = \sqrt{\left(\sqrt{p_{T,\pi}^2 + M_\pi^2} - M_\pi + M_{\text{meson}}\right)^2 - M_{\text{meson}}^2}$$
Model comparison of photon $v_2$

(Orange) Transport model considering photons from hadron phase
(Blue, red) Fireball model
Hydrodynamic calculations (cyan, pink, and violet) including photons from late state, are much underestimated.
Model comparison of $v_2$ and $v_3$

![Graphs showing model comparison of $v_2$ and $v_3$]

Dark violet is based on magnetic field effect, upper limit is shown. Model calculations of photon $v_3$ are much smaller than experimental data. The data of $v_3$ may help to constrain parameters in model calculations.

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The ratio of $v_2$ to $v_3$ in $p_T$ region

- Photons don’t have strong centrality dependence at around 2-3 GeV/c
- Pions increase from central to peripheral

Photon and pion show different centrality dependence.
Phonon observables predicted by blast wave model

The $p_T$ spectra is well described by

- Low temperature ($T_f=104$) with radial flow $<\rho>=0.66$
- High temperature ($T_f=240$) with radial flow $<\rho>=0$
  $v_n=0$ with radial flow $<\rho>=0$

Blast wave could suggest that photon puzzle is understood by the radial flow effect.
$\pi^0$ and $\gamma^{\text{dir.}}$ $v_2$ measurement by STAR

$\gamma^{\text{dir.}}$ $v_2$ in high $E_T$ region are consistent with 0 within systematic uncertainty, while $\pi^0$ has positive $v_2$. 

Ahmed M. Hamed shown at QM
It is also observed that $\gamma^{\text{dir.}} v_2$ is positive in low $p_T$ at LHC-ALICE. $v_3$ measurement is ongoing.