Centrality Dependence Of Soft Photon Production and Its Collective Flow in Au+Au Collisions At $\sqrt{s_{NN}}=200$GeV

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What are direct photons?

Direct photons: all photons except those coming from hadron decays.

- Good probe since they penetrate the QGP
- Created during all stages of the collision
Previous soft photon results from PHENIX

There is a large excess with respect to scaled p+p, and very large flow in the 1-4 GeV/c region.

2014/05/19 QM2014 @ Darmstadt
Direct photon puzzle

Yield enhancement
Suggests early emission when temperature is high at or above 300MeV

Large elliptic flow ($v_2$)
Suggests late emission, when temperature is low, collective motion is large

It is a challenge for models to explain simultaneously the excess of direct photon yield and the large elliptic flow ($v_2$).
Motivation

To resolve the puzzle and constrain photon production mechanisms, more differential measurements are needed.

- Complete centrality dependence
- Higher order azimuthal anisotropy

In this talk, we’ll extend earlier (published) centrality selections both for yields and $v_2$, and show new results for $v_3$ and $v_2/v_3$. 
Centrality dependence of the $\gamma^{\text{dir.}}$ yield
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: $0.4 \sim 5$ GeV/c
Extended to lower $p_T$
low statistics

2014/05/19
Enhancement of the direct photon yield

The yields from p+p data are fitted by

\[ a \left(1 + \frac{p_T^2}{b}\right)^c \]

extrapolated below 2 GeV/c.

\[ T_{AA} = \frac{<N_{coll}>}{\sigma_{pp}} \]

Compared with a green line which is expected from p+p data, **enhancements** are observed.
Excess photon yield

Excess yield (above expectation from scaled p+p) fitted with an exponential. The slopes are comparable within uncertainties.
Excess of photon yield increases with power-law function, $F = AN_{\text{part}}^\alpha$

$\alpha = 1.48 \pm 0.08 \text{(stat.)} \pm 0.04 \text{(sys.)} \approx 3/2$

The centrality dependence is not an artifact of the very low $p_T$ points:

- same slope as we increase lower limit of integration
- (upper limit is always 2GeV/c).

The shape of direct photon $p_T$ spectra doesn’t depend on centrality.

2014/05/19
Linnyk et al.: PHSD transport model; Linnyk, Cassing, Bratkovskaya, P.R.C 89, 034908(2014)

vHees et al.: Fireball model; van Hees, Gale, Rapp; P.R.C 84, 054906(2011)

Shen et al.: Ohio hydro for two different initial conditions; Shen, Heinz, Paquet, Gale; P.R.C 84, 064903(2014)

The yield itself is still not perfectly described.
$\gamma^{\text{dir.}}$ Azimuthal anisotropy
Flow measurement: the method

The magnitude of the direct photon $v_2$ is comparable to the hadron (and hadron decay photon) $v_2$.

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

Therefore, $R_{\gamma}$ is a crucial component.
$R_\gamma$ measured by real and virtual photons

$R_\gamma = \frac{N_{inc.}}{N_{dec.}}$

Present data external conversion analysis

P.R.L. 104, 132301(2010) virtual photon analysis

$R_\gamma$ measured with real (conversion) photons is consistent with the earlier virtual photon measurement.
Higher order azimuthal anisotropy

\[
\frac{dN}{d(\phi - \Phi_n)} = N_0 [1 + 2 \sum_{n=1}^{\infty} \nu_n \cos\{n(\phi - \Phi_n)\}]
\]

\[\nu_n = \langle \cos\{n(\phi - \Phi_n)\} \rangle >\]

Dominant component is \(v_2\); \(v_3\) comes from participant fluctuations, viscosity dampens higher order terms.
The magnitude of $\gamma^\text{dir.} v_3$ is similar to $\pi^0$, a similar trend as seen in the case of $v_2$.
Photon azimuthal asymmetries may be affected by expansion of QGP.
Centrality dependence of $\gamma_{\text{dir.}} v_3$

$\eta$ range of RxN(I+O) is from 1.0 to 2.8.
Non-zero, positive $v_3$ is observed in all centrality bins.
No strong centrality dependence: similar tendency as for charged hadrons (P.R.L. 107, 252301 (2011)) and $\pi^0$. 

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\( \gamma^{\text{dir.}} \) and \( \pi^0 v_3 \) show similar trend

The centrality (in)dependence of \( \gamma^{\text{dir.}} v_3 \) is also observed for \( \pi^0 v_3 \).
Comparison of $\gamma_{\text{dir.}}$ $v_n$ with the two methods

The calorimeter and conversion photon measurements are consistent within systematic uncertainty. $\gamma_{\text{dir.}}$ $v_n$ are extended to lower $p_T$, by the conversion photon analysis.
Comparison $\gamma^\text{dir.}_2$ with theoretical calculations

van Hees et al: P.R.C 84, 054906 (2011)
Linnyk et al.: PHSD model, private communication
So far all uncertainties are assumed to be uncorrelated. The ratios – both for $\pi^0$ and $\gamma$ – slightly prefer lower $\eta/s$ values.
Summary

Soft photons are expected to do provide important keys to understand photon production mechanisms and medium properties, including viscosity.

Centrality dependence of direct photon yield
The shape of $p_T$ spectra doesn’t have strong centrality dependence. The excess of yield increases with centrality like $N_{part}^\alpha$ with $\alpha \approx 1.48$.

3rd order Azimuthal anisotropy
Direct photon has as large $v_3$ as hadrons, which is similar to the case of $v_2$. Non-zero, positive direct photon $v_3$ is observed in all centrality bins. Direct photon is expected to be a viscometer of QGP.
**Posters for direct photon from PHENIX**

**Systematic studies of the centrality dependence of soft photon production in Au+Au collision with PHENIX**
Photon measurement with external photon conversion method
Benjamin BANNIER (G-01)

**Direct photon collective flow in Au+Au collisions at $\sqrt{s_{_{NN}}}=200$GeV**
Direct photon $v_3$ measurement by real photon with Calorimeter
Sanshiro MIZUNO (H-20)
The detector information

Central Arm: Measure electrons and photons
$|\eta| < 0.35$

Reaction Plane Detector (RxN): Estimate Event Plane
Inner: $1.5 < |\eta| < 2.8$
Outer: $1.0 < |\eta| < 1.5$

MPC: Estimate Event Plane
$3.1 < |\eta| < 3.8$

BBC: Estimate Event Plane
$3.1 < |\eta| < 3.9$
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 $M_{atm}$ will be around zero
Comparable measurement is achieved

Using external photon conversion method achieved good agreement with previous results.

Ncoll-scaled pp fit
external conversion
pp virtual photon
pp in EMCal(Run2003 data)
pp in EMCal(Run2006 data)
AuAu in EMCal(Run2004 data)
AuAu from virtual photon(Run4 data)
The table of excess of direct photon yield

<table>
<thead>
<tr>
<th>$p_T^{\text{min}}$ (GeV/c)</th>
<th>$\alpha$</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>$1.47 \pm 0.19 \pm 0.07$</td>
<td>$(2.77 \pm 2.64 \pm 1.41) \times 10^{-3}$</td>
</tr>
<tr>
<td>0.6</td>
<td>$1.52 \pm 0.23 \pm 0.15$</td>
<td>$(5.78 \pm 6.64 \pm 5.17) \times 10^{-4}$</td>
</tr>
<tr>
<td>0.8</td>
<td>$1.63 \pm 0.22 \pm 0.18$</td>
<td>$(1.68 \pm 1.91 \pm 1.67) \times 10^{-4}$</td>
</tr>
<tr>
<td>1.0</td>
<td>$1.45 \pm 0.19 \pm 0.08$</td>
<td>$(1.99 \pm 1.87 \pm 1.28) \times 10^{-4}$</td>
</tr>
<tr>
<td>1.2</td>
<td>$1.41 \pm 0.18 \pm 0.08$</td>
<td>$(1.49 \pm 1.37 \pm 0.91) \times 10^{-4}$</td>
</tr>
<tr>
<td>1.4</td>
<td>$1.47 \pm 0.20 \pm 0.09$</td>
<td>$(5.00 \pm 5.18 \pm 3.44) \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Centrality ($N_{\text{part}}$) dependence of yield

Theoretical calculation of excess of the photon yield.
The analysis information

\( \gamma_{\text{dir.}} \, v_n \) with external conversion photon analysis
charged \( \pi \, v_n \)

\( \gamma_{\text{inc.}} \, v_n \) with external conversion photon analysis

\( R_\gamma \) with external conversion photon analysis

\( \gamma_{\text{dir.}} \, v_n \) with Calorimeter

\( \pi^0 \, v_n \) with Calorimeter

\( \gamma_{\text{inc.}} \, v_n \) with Calorimeter

\( R_\gamma \) with external conversion photon analysis
Comparison $\gamma^{\text{dir.}} v_3$

$\gamma^{\text{dir.}} v_3$ (RxN(I+O))

$\gamma^{\text{dir.}} v_3$ (RxN(In)+MPC)

RxN(I+O) : $1.0 < |\eta| < 2.8$
RxN(In)+MPC : $1.5 < |\eta| < 3.8$

The magnitude of $v_3$ is comparable.
2nd and 3rd order E.P. correlation

It is known that they have weak correlation.

It is considered that 3rd order of Event Plane is defined as a deformation of initial geometry.
Comparison of inclusive photon $v_n$

Inclusive photon $v_n$ is measured via conversion photon, and $p_T$ range is extended to low $p_T$ region.
The table of systematic uncertainty of $\gamma^{\text{dir.}} \nu_3$

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>$\pi^0$</th>
<th>$\gamma^{\text{inc.}}$</th>
<th>$R_\gamma$</th>
<th>Event Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>15.8</td>
<td>3.2</td>
<td>28.8</td>
<td>5.9</td>
</tr>
<tr>
<td>20-40</td>
<td>3.8</td>
<td>2.1</td>
<td>36.2</td>
<td>9.1</td>
</tr>
<tr>
<td>40-60</td>
<td>8.8</td>
<td>1.4</td>
<td>43.9</td>
<td>23.0</td>
</tr>
<tr>
<td>20-60</td>
<td>4.6</td>
<td>1.5</td>
<td>39.5</td>
<td>13.2</td>
</tr>
<tr>
<td>0-60</td>
<td>8.9</td>
<td>4.0</td>
<td>29.2</td>
<td>6.4</td>
</tr>
</tbody>
</table>

They are the relative value of systematic uncertainty propagated to $\gamma^{\text{dir.}} \nu_3$.

$\pi^0$, $\gamma^{\text{inc.}}$ and $R_\gamma$ is considered to be independent for harmonics.
$v_3$ and $v_4$ have weak centrality dependence while $v_2$ has strong. It indicates $v_3$ and $v_4$ are created by the initial geometry deformation.
Similar trend with RHIC-PHENIX is observed by LHC-ALICE.