Direct Photon Production and Azimuthal Anisotropy at Low Transverse Momentum Measured in PHENIX

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Hard Probes 2016
Outline

- Direct photons and motivation
- Measurement of photons in PHENIX
- Result: direct photon $v_2$ and $v_3$
- New Conversion Photon Reconstruction Technique
- Summary and outlook
Photon Production in Heavy Ion Collision

- Direct photon
  - color blind probes (leave the medium without further interaction)
  - info of the entire evolution of the colliding system (integrated over space and time)

- More differential measurement would disentangle the photon production sources
Measurement at PHENIX — 3 Methods

- **calorimetric measurement**
  - $\gamma$
  - good resolution at high $p_T$
  - low $p_T$ is contaminated by hadrons

- **internal conversions**
  - $\gamma^* \rightarrow e^+ + e^-$
  - bkg from hadron decay photon reduced by a factor of 5 (small bkg)
  - 1/1000 signal reduction

- **external conversions**
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3 independent measurements in good agreement with each other

\[ \sqrt{s_{NN}} = 200\text{GeV} \]
Direct Photon $v_n$ Measurement in Au+Au

- Event plane method
  \[ \frac{dN}{d\phi} = 1 + \sum 2v_n \cos(n(\phi - \Psi_n)) \]
  Measure azimuthal distributions of photons with respect to event plane

- To determine direct photon $v_2$, $v_3$

- Inclusive photon $v_2$, $v_3$
  
  external conversions / calorimetric method

\[ v_n^{\text{dir}} = \frac{R_\gamma v_n^{\text{inc}} - v_n^{\text{dec}}}{R_\gamma - 1} \]

arxiv:1509.07758
Estimate decay photon $v_n$

- Use measured yield and anisotropy of charged and neutral pions
- $v_n$ for heavier mesons estimated by $KE_T$

$$v_n^{\text{meson}}(KE_T) = v_n^\pi(KE_T) \quad \text{with} \quad KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$

- Use the meson yields and $v_n$ in MC, process them through all decay chains including photons to calculate the decay photon $v_n$
Systematic Uncertainty on \(v_n\)

- Using Gaussian error propagation

\[
\sigma_{v_n}^2 = \left(\frac{R_\gamma}{R_\gamma - 1}\right)^2 \times \sigma_{v_n}^{inc} + \left(\frac{1}{R_\gamma - 1}\right)^2 \times \sigma_{v_n}^{dec} + \left(\frac{v_n^{dec} - v_n^{inc}}{R_\gamma - 1}\right)^2 \times \sigma_{R_\gamma}^2 + \sigma_{EP}^2
\]

- Non-linear dependence of uncertainty on \(R_\gamma\)
  - Modeling the probability distribution of possible values of \(v_n^{dir}\)
  - Assuming the individual statistical and systematic uncertainties follow Gaussian probability distributions

### Systematic Uncertainties for \(v_2\)

<table>
<thead>
<tr>
<th>Sources</th>
<th>0~20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_\gamma)</td>
<td>5.5%</td>
</tr>
<tr>
<td>(v_2^{inc})</td>
<td>4%</td>
</tr>
<tr>
<td>(v_2^{dec})</td>
<td>5%</td>
</tr>
<tr>
<td>Event plane</td>
<td>3%</td>
</tr>
</tbody>
</table>
Direct Photon $v_n$

- To determine direct photon $v_2$, $v_3$

\[ v_n^{\text{dir}} = \frac{R_\gamma v_n^{\text{inc}} - v_n^{\text{dec}}}{R_\gamma - 1} \]

- Large $v_2$ observed (comparable to hadron $v_2$ in low $p_T$ region)
- Strong centrality dependence
- Showing trend to 0 toward high $p_T$
- Unclear $v_2 \rightarrow 0$ for $p_T \rightarrow 0$

- Sizable $v_3$ observed ($\sim v_2/2$)
- Independent of centrality
Comparison with Theoretical Models

- Thermal photons (HG+QGP), pQCD with fireball scenario
  - H. van Hees, C. Gale, R. Rapp PRC 84 054906 (2011)
  - Include finite initial flow at thermalization
  - Include resonance decays and hadron-hadron scattering
  - Blue shift of HG spectrum included

- Microscopic transport (PHSD)
  - Parton-Hadron-String dynamics
  - Include large contribution from hadron-hadron interaction in HG using Boltzmann transport
  - Include thermal photons from QGP

- Enhanced non-equilibrium effects (glasma, etc.)
  - C. Gale et al., PRL114, 072301 + priv.comm. with Y Hidaka and J-F. Paquet
  - Semi-QGP is the QGP near \( T_c \)
  - Annihilation and Compton processes around hadronization time are naturally included

- Enhanced early emission from magnetic field
  - Initial strong magnetic field produces anisotropy of photon emission
  - Magnetic field + thermal photons (lattice QCD)
Direct Photon Puzzle

- Large yield & large $v_2$
  - Large yield: emission from the **early stage** when temperature is high
  - Large $v_2$: emission from the **late stage** when the collective flow is sufficiently built up

**Challenge for theoretical model to describe large yield and $v_2$ simultaneously!**
New Conversion Photon Reconstruction Technique

Identify and reconstruct photons via external conversion to $e^+e^-$ pairs

- Previous method used single $e^+/e^-$ tracks (2010)
  - Conversions at fixed radius (Hadron Blind Detector readout plane at 60cm, ~3%)
- New method used $e^+e^-$ pairs (>2011)
  - Conversions at any material (VTX 3rd and 4th layer, ~10%)
Future Measurements

- Run10 AuAu at 39GeV and 62GeV will provide more insight in direct photon production (with the previous published method)
- Larger statistics from Run14 AuAu will provide accurate measurement of $v_n$ ($v_2$, $v_3$, $v_4$) at low $p_T$
- $v_n$ measurement in most central CuAu will provide useful input in understanding of chiral magnetic field effect, if any
- $pA$, He3Au, dAu results will help to understand properties of the medium created in small systems
- New pp results will extend the measurement to lower $p_T$
Conclusions

- PHENIX has detailed measurements of the direct photon $v_2, v_3$ in $\sqrt{s} = 200\text{GeV}$ Au+Au collisions

- A sizable $v_2$ and $v_3$ are observed for direct photons, provide constrains to theoretical model

- Theoretical picture still incomplete to describe large yield and $v_2$ simultaneously

- More future measurements from PHENIX are coming
THANKS!
BACKUPS
Res\( (\Psi_n) \) is measured with 2-subevent method.

(a) RxN Inner+Outer (S+N)
   South: \(-2.8 < \eta < -1\)
   North: \(1 < \eta < 2.8\)

(b) MPC (S+N)
   South: \(-3.7 < \eta < -3.1\)
   North: \(3.1 < \eta < 3.9\)

PHENIX
Au+Au 200GeV
Photon Identification

- **EMCal method**: measure photons that deposit energy in the EMCal
  - Shower shape cut
  - Charged track veto cut

- **External conversion method**: measure photons that convert in detector material
  - Focus on conversions at HBD backplane (~60cm)
  - Identified by the invariant mass of the e+e- pairs
    - Artificial mass due to vertex origin assumption when reconstructing momentum
    - Calculate momentum both assuming vertex origin and true origin
- Ratio of the inclusive photon to decay photon yield
  - Using external conversion method

\[ R_\gamma = \frac{\gamma^\text{incl}}{\gamma^\text{hadron}} = \frac{\langle \epsilon_\gamma f \rangle}{\left( \frac{N_\gamma^\text{incl}}{N_\gamma^\pi^0} \right)_{\text{Data}}} \]

\[ \frac{\gamma^\text{hadron}}{\gamma^\pi^0} \left( \frac{N_\gamma^\text{incl}}{N_\gamma^\pi^0} \right)_{\text{Sim}} \]

(a) 0-20%
(b) 20-40%
(c) Au+Au \( \sqrt{s_{\text{NN}}} = 200\text{GeV} \)
(d) PRL 104, 132301

Present data

\[ p_T \text{ [GeV/c]} \]
Disentangling different photon sources

More differential measurement would disentangle the photon production sources

<table>
<thead>
<tr>
<th>Sources</th>
<th>$p_T$</th>
<th>$v_2$</th>
<th>$v_3$</th>
<th>$v_n$ t-dep.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>All $p_T$</td>
<td>Positive down to $p_T=0$</td>
<td>Zero</td>
<td></td>
</tr>
<tr>
<td>Primordial (jets)</td>
<td>High $p_T$</td>
<td>$\sim$zero</td>
<td>$\sim$zero</td>
<td></td>
</tr>
<tr>
<td>QGP (thermal)</td>
<td>Mid $p_T$</td>
<td>Positive and small</td>
<td>Positive and small</td>
<td></td>
</tr>
<tr>
<td>Jet-Brems.</td>
<td>Mid $p_T$</td>
<td>Positive</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Jet-photon conversion</td>
<td>Mid $p_T$</td>
<td>Negative</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Hadron-gas (thermal)</td>
<td>Low $p_T$</td>
<td>Positive and sizable</td>
<td>Positive and sizable</td>
<td></td>
</tr>
</tbody>
</table>
Fitting function

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

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(8.3 ± 7.5) × 10^3</td>
<td>2.26 ± 0.78</td>
<td>-3.45 ± 0.08</td>
</tr>
</tbody>
</table>

- The actual lowest data point in the fit is 1 GeV
- The fit < 1 GeV is motivated by Drell-Yan measurement

\( \sqrt{s_{NN}} = 200 \text{ GeV} \)