PHENIX measurements of low momentum direct photons from large ion collisions as a function of beam energy and system size

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Direct Photon Sources in Heavy Ion Collisions

Direct photons are a unique probe
- Color blind
- Probe the full time evolution

Production of photons:

Hadron gas
- $\pi^+ + \rho^0 \rightarrow \pi^+ + \gamma$
- $\pi^+ + \pi^- \rightarrow \rho^0 + \gamma$
- $\rho^0 \rightarrow \pi^+ + \pi^- + \gamma$
- $\omega \rightarrow \pi^0 + \gamma$

QGP
- $q + \bar{q} \rightarrow g + \gamma$
- $q + g \rightarrow q + \gamma$

Need to subtract decay photons

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\gamma, \gamma^* \text{ from A+A}
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```
Direct
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```
Non-thermal
```

```
Thermal
```

```
Pre-equilibrium
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```
“Prompt” hard scattering
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```
Quark-Gluon Plasma
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```
Hadron Gas
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```
Hadron Decays
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```
\log t (fm/c)
```

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Direct Photon Puzzle
large yield and large $v_2$ in Au+Au

- Large yield $\rightarrow$ early emission
- Large $v_2$ $\rightarrow$ late emission
Direct Photon Puzzle
large yield and large $v_2$ in $Au+Au$

Experimentalist can provide

- measurement of different observables:
  - Yields
  - $v_2$, $v_3$, ....

- Collision energy dependence:
  - 200 GeV, 62 GeV, 39 GeV

- Large systems (hot medium):
  - $Au+Au$, $Cu+Cu$, $Cu+Au$

- Small systems (cold ??):
  - $p+p$, $p+Au$, $d+Au$, $^3He+Au$

New results shown in this talk

Challenging to describe large yield and large anisotropy simultaneously
Photon Measurement Techniques in PHENIX

Three independent methods at PHENIX

- **Measuring energy deposited by photons in Calorimeter**
  - Good resolution at high $p_T$
  - Low $p_T$ contaminated by hadrons

- **Internal photon conversions**
  - Measure virtual photons
  - Reduction in background from $\pi^0$ Dalitz decays by a factor of 5
  - Low $p_T$ reach is limited ($\sim 1$ GeV) as well as high $p_T$

- **External photon conversions**
  - Measure real photons
  - Extends to $p_T << 1$ GeV, little hadron contamination
  - High $p_T$ reach is limited
Photon Measurement Techniques in PHENIX

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PRC91 064904 (2015)

$\frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy}$ vs. $p_T$ [GeV/c]

$\sqrt{s_{NN}} = 200$ GeV

3 independent measurements in good agreement with each other
Direct Photon in $\text{Au}+\text{Au}$ at $\sqrt{s_{NN}} = 62.4$ GeV

External Conversion Technique

- Conversions reconstructed at detector material (HBD back plane)
- $R_\gamma = N_\gamma^{incl}/N_\gamma^{hadron}$

Clear direct photon signal in $\text{Au}+\text{Au}$ at 62.4 GeV

0-20% 0-86%, $\sqrt{s_{NN}} = 62.4$ GeV

20-40% 20-40%, $\sqrt{s_{NN}} = 62.4$ GeV
Direct Photon in \( \text{Au}+\text{Au} \) at \( \sqrt{s_{NN}} = 62.4 \text{ GeV} \)

**Direct photon yield:**

\[
\gamma_{\text{direct}} = (R_\gamma - 1) \times \gamma_{\text{hadron}}
\]

Minimum bias unsubtracted \( \gamma_{\text{prompt}} \)

\[T_{\text{eff}} = 0.211 \pm 0.024 \pm 0.044 \text{ GeV}\]

pQCD calculations by W. Vogelsang
Direct Photon in $\text{Au+Au}$ at $\sqrt{s_{NN}} = 39$ GeV

- Direct photon signal also seen in $\text{Au+Au}$ at $\sqrt{s_{NN}} = 39$ GeV
- Minimum bias unsubtracted $\gamma^{\text{prompt}}$ $T_{\text{eff}} = 0.177 \pm 0.031 \pm 0.068$ GeV

See poster by V. Khachatryan (EM Probes: Board L18)
Centrality Dependence of Thermal Photon Yield in Au+Au at $\sqrt{s_{NN}} = 200$ GeV

$\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \propto N_{\text{part}}^\alpha$, where $\alpha = 1.38 \pm 0.03(\text{stat}) \pm 0.07(\text{syst})$

- Yield grows faster than $N_{\text{part}}$
- $T_{\text{eff}} = 0.244 \pm 0.028 \pm 0.007$ GeV

PRC91 064904 (2015)
Direct Photon $v_n$ in Au+Au at $\sqrt{s_{NN}} = 200$ GeV

PRC94 064901 (2016)

- Sizeable $v_2$ and $v_3(\sim v_2/2)$ observed at low $p_T$, comparable to hadron $v_2$
- Strong centrality dependence for $v_2$, not so clear for $v_3$
- Unclear if $v_2 \rightarrow 0$ for $p_T \rightarrow 0$
Direct Photon in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV

- Analysis done using internal conversion method
- Clear direct photon signal in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV
- $T_{\text{eff}}$ consistent within the large uncertainty with Au+Au

See poster by T. Hoshino (EM Probes: Board J08)
Direct Photon Yield vs $N_{\text{part}}$

- Au+Au $\rightarrow \gamma + X$, $|y| < 0.35$
  - $\gamma_{\text{dir}} - \gamma_{\text{prompt}}$ at $\sqrt{s_{NN}} = 200$ GeV
  - $\gamma_{\text{dir}}$ at $\sqrt{s_{NN}} = 62.4$ GeV
  - $\gamma_{\text{dir}}$ at $\sqrt{s_{NN}} = 39$ GeV

- Cu+Cu $\rightarrow \gamma + X$, $|y| < 0.35$
  - $\gamma_{\text{dir}} - \gamma_{\text{prompt}}$ at $\sqrt{s_{NN}} = 200$ GeV

- $p_T > 1.0$ GeV

Fit = $A \times N_{\text{part}}^\alpha$

$\alpha = 1.35 \pm 0.09$

- Similar increase with $N_{\text{part}}$ for different systems
- Yield increases faster than $N_{\text{part}}$

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Hint of increase of $T_{\text{eff}}$ with $\sqrt{s_{\text{NN}}}$, but also consistent with a constant fit
Good agreement with published $v_2$ results

- 22% of total 2014 data
- Horizontal errors are uncertainty in the $p_T$ reconstruction of $e^+e^-$ resulting from bremsstrahlung due to increased material budget
- Will provide high $p_T$ coverage for both EMCal and Conversion photon methods

See poster by W.Fan (EM probes: Board F03)
Future Measurements: Different Systems

Clear signal visible in all systems
These different systems will provide interesting information

- Direct photon spectrum shape at low $p_T$ in $p+p$
- Are there thermal photons in $p+Au$, $d+Au$, $^3He+Au$ systems?
- $Cu+Au$ collisions to shed light on magnetic field effects if any
Summary and Outlook

Summary

- Well established measurements of low $p_T$ direct photons in Au+Au at 200 GeV
  - Large yield above expected contribution from pQCD
  - Centrality dependence of yield $\sim N_{\text{part}}^{1.4}$
  - Large $v_2$ with respect to reaction plane
- Direct photon spectra measured in Cu+Cu collisions at $\sqrt{s_{\text{NN}}}=200$ GeV and Au+Au collisions at 62.4 and 39 GeV
  - Consistent with the observed $\sim N_{\text{part}}^{1.4}$ dependence
  - Slight increase of $T_{\text{eff}}$ with collision energy

Outlook

- Significantly improved $v_n$ results expected from 2014 Au+Au data
- Data from different collision geometry Cu+Au (2012)
- Low momentum data from p+p (2015)
Back-Ups
Inclusive and Decay Photon $\nu_n$ in $Au+Au$ at $\sqrt{s_{NN}} = 200$ GeV

- Measure azimuthal distribution of photons relative to the reaction plane
- Results using two photon identification techniques EMCal and External conversions
- Model decay photon $\nu_n$ based on the measured $\pi^0\nu_n$
  - Other hadrons ($\eta$, $\eta'$, $\omega$) $\nu_n$ estimated from $KE_T$ scaling
New Conversion Photon Reconstruction Technique (2014 Au+Au data)

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%)

**inclusive photon ($e^+e^-$) mass**

Run14 AuAu @ 200 GeV, Min Bias, $p_T^{\text{min}}$ 1.2–1.4GeV

**$\pi^0$ ($e^+e^-\gamma$) mass**

Run14 AuAu @ 200 GeV, Min Bias, $p_T^{\text{min}}$ 1.2–1.4GeV

bkg/sig = 1.75%