DIRECT PHOTON PRODUCTION AT RHIC

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Direct photon

- Direct $\gamma = \text{Inclusive } \gamma - \text{hadron decay } \gamma$
- Passes through the medium without the strong interaction
  - High $p_T (>5 \text{ GeV}/c)$: hard scattering ($R_{AA} \sim 1: N_{\text{coll}}$ scaling works)
  - Low $p_T (p_T < 3 \text{ GeV}/c)$: Thermal radiation from hadron and QGP phases (Include fruitful information from QGP)
- Difficulty of measurement
  - Most of measured photons are from hadron decay products.
  - Photons from all stages after collisions are detected.

\[ R_{AA} = \frac{dN_{\text{AA}}}{d^4p_{\text{dy}}} \Bigg/ \left( \langle N_{\text{coll}} \rangle \frac{dN_{\text{pp}}}{d^4p_{\text{dy}}} \right) \]

Direct photon spectra
Centrality dependence of direct photon yield

- **p+p**
  - Consistent with NLO pQCD
- **Au+Au**
  - Excess at \( p_T < 3 \text{ GeV/c} \)
  - Exponential shape (consistent with thermal)
  - Centrality dependence of inverse slope is small.

### Inverse slope

\[
A \exp\left(-\frac{p_T}{T}\right) + T_{AA} \times A_{pp} (1 + \frac{p_T^2}{b})^{-n}
\]

<table>
<thead>
<tr>
<th>Centrality</th>
<th>( dN/dy (p_T &gt; 1 \text{ GeV/c}) )</th>
<th>( T ) (MeV)</th>
<th>( \chi^2/\text{DOF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20%</td>
<td>1.50 ± 0.23 ± 0.35</td>
<td>221 ± 19 ± 19</td>
<td>4.7/4</td>
</tr>
<tr>
<td>20–40%</td>
<td>0.65 ± 0.08 ± 0.15</td>
<td>217 ± 18 ± 16</td>
<td>5.0/3</td>
</tr>
<tr>
<td>Min. Bias</td>
<td>0.49 ± 0.05 ± 0.11</td>
<td>233 ± 14 ± 19</td>
<td>3.2/4</td>
</tr>
</tbody>
</table>

Direct photon spectra at $d+$Au and $p+p$

- Excess in $d+$Au?
  - No exponential excess
- High-$p_T$ direct photon results from PHENIX and STAR
  - $d+$Au
    - Agree with $T_{AB}$ scaled pQCD
    - consistent with PHENIX and STAR
  - $p+p$
    - Agree with pQCD and PHENIX
- Low-$p_T$ direct photon
  - No publication data at STAR
System size dependence of $\gamma$ fraction

- $\gamma$ fraction = $\text{Yield}_{\text{direct}} / \text{Yield}_{\text{inclusive}}$
- Largest excess above pQCD is seen at Au+Au.
Initial temperature at Au+Au

- Initial temperature $T_i$
  - $300 \sim 600$ MeV (different assumptions)
  - Depends on thermalization time $\tau_0$

$T_c \sim 170$ MeV from lattice QCD

Theory calculations:
d’Enterria, Peressounko, EPJ46, 451
Huovinen, Ruuskanen, Rasanen, PLB535, 109
Srivastava, Sinha, PRC 64, 034902
Turbide, Rapp, Gale, PRC69, 014903
Liu et al., PRC79, 014905
Alam et al., PRC63, 021901(R)
Direct photon $v_2$
Expectation of direct photon $v_2$

- Thermal photon in quark matter
  - $v_2 > 0$ at low $p_T$
  - $v_2 \sim 0$ at high $p_T$
- Thermalization time $\tau_0$
  - Early (smaller $v_2$)
  - Late (larger $v_2$)
- Constrain $\tau_0$
  - Measure $v_2$ at low $p_T$

Chatterjee, Srivastava, PRC79, 021901 (2009)
Inclusive photon $v_2$

Calculation of direct photon $v_2$

$=\text{inclusive photon } v_2$
- background photon $v_2(\pi^0, \eta, \ldots)$

$\gamma = R \cdot v_2^{inc.} - v_2^{BG}$

$V_2^{dir.} = \frac{R \cdot v_2^{inc.} - v_2^{BG}}{R - 1}$
Check for hadron contamination

- Direct measurement (black)
  - Identify photons with EMCals
  - Contain hadronic source at low \( p_T \)
- External conversions (blue)
  - Identify electron pair \( (\gamma \rightarrow e^+e^-) \) from gamma conversion
- Good agreement at low \( p_T \)
  - No hadronic contamination
Inclusive photon and $\pi^0 \nu_2$

- $\pi^0 \nu_2$
- similar to inclusive photon $\nu_2$
- Two interpretations
  - There are no direct photons
  - Direct photon $\nu_2$ is similar to inclusive photon $\nu_2$
Direct photon $v_2$

- $v_2$ at low $p_T$
  - $\approx 15\%$ at $p_T=2.5\text{GeV/c}$
- $v_2$ goes to 0 at high $p_T$
  - Hard scattered photons dominate
Theory Comparison: Direct photon $v_2$

- Larger $v_2$ than the prediction
  - Data: ~15% at $p_T=2.5\text{GeV}/c$
  - Model: ~5% at $p_T=2.5\text{ GeV}/c$
- Need help from theorists
  - There are not any models to reproduce the data
  - To constrain $\tau_0$ with the improved models

Model: Chatterjee, Srivastava PRC79, 021901 (2009)
Data: PHENIX, arXiv:1105.4126
Centrality dependence of direct photon $v_2$

- **High $p_T$ ($p_T$ > 5 GeV/c)**
  - $v_2 \sim 0$ (independent of centrality)
  - Consistent with STAR results within large error.

- **Low $p_T$ ($p_T$ < 3 GeV/c)**
  - Inconclusive centrality dependence

PHENIX, arXiv:1105.4126

STAR, arXiv:1008.4894
Summary

• Direct photon yield
  • Large excess at $p_T<3$ GeV/c (big result at RHIC)
    • Not initial state effects
  • $T_i = 300-600$ MeV from hydro calculation
    • Above critical temperature (170 MeV) from lattice QCD calculation

• Direct photon $\nu_2$
  • Large positive $\nu_2$ at low $p_T(<3$ GeV/c)
    • Model underestimates the data
    • We expect the improvement of model to constrain $\tau_0$
  • $\nu_2 \sim 0$ at high $p_T(>5-6$ GeV/c)
    • Photons from hard scatterings are dominant source
    • Consistent with the interpretation of direct photon $R_{AA} \sim 1$
Backups


**Systematic error of direct photon \( v_2 \)**

<table>
<thead>
<tr>
<th>Source</th>
<th>1–3( \text{GeV/c} )</th>
<th>10–16( \text{GeV/c} )</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>inclusive ( \gamma ) ( v_2 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remaining hadrons</td>
<td>2.2%</td>
<td>N/A</td>
<td>A</td>
</tr>
<tr>
<td>( v_2 ) extraction method</td>
<td>0.4%</td>
<td>0.6%</td>
<td>B</td>
</tr>
<tr>
<td>( \pi^0 ) ( v_2 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>particle ID</td>
<td>3.7%</td>
<td>6.0%</td>
<td>A</td>
</tr>
<tr>
<td>normalization</td>
<td>0.4%</td>
<td>7.2%</td>
<td>A</td>
</tr>
<tr>
<td>shower merging direct ( \gamma )</td>
<td>N/A</td>
<td>4.0%</td>
<td>B</td>
</tr>
<tr>
<td>( R_{\gamma} )</td>
<td>3.1%</td>
<td>22%</td>
<td>A</td>
</tr>
<tr>
<td>common reaction plane</td>
<td>6.3%</td>
<td>6.3%</td>
<td>C</td>
</tr>
</tbody>
</table>

**TABLE I:** Representative values of systematic uncertainties contributing to the direct photon \( v_2 \) measurement, shown for various \( p_T \) ranges for minimum bias collisions.

PHENIX, arXiv:1105.4126
Comparison with other models

PHENIX Experiment: arXiv:1105.4126

From Vicki’s slide
@ EPIC meeting, Jul.6-8, 2011

Holopainen, Räsänen, Eskola, arXiv:1104.5371v1

Thanks to J. Nagle