Direct Photons and Photon-Hadron Correlations at PHENIX

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For the PHENIX Collaboration
Direct Photons

- Direct photons: all photons not from hadron decays
- Direct photons are produced in every stage of collisions
  - hard scattering, jet fragmentation
  - Jet-QGP interactions
  - Thermal photons
- Photons do not interact strongly
- Modifications of initial state also affect direct photon production
- Photon-hadron correlations: photon balances jet energy
Direct Photons in Au+Au (Theory)

- Measured spectrum sum of several contributions, hard to disentangle them
- Initial state also changes the production rate of photons compared to p+p
- The measured yield and $R_{AA}$ (nuclear modification factor) are thus difficult to interpret

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_Tdy}{\langle T_{AA} \rangle \cdot d^2\sigma_{pp}/dp_Tdy}$$
Direct Photon Measurement

- PHENIX has different methods to measure direct photons
- Statistical method: measure photons directly with calorimeter, subtract decay photons → high $p_T$
- Internal conversion: measure virtual direct photons ($\gamma^*$), i.e. low mass electron pairs → low $p_T$
- External conversion: measure electron pairs from conversion in the material (HBD backplane)
Direct Photons at high $p_T$: p+p

- From the calorimeter measurement: lower multiplicity than in Au+Au, hence decay photons can be rejected directly
- Good agreement of NLO pQCD with measurement
- Important to understand measurement in Au+Au and d+Au

**Diagram:**

- PHENIX Preliminary
- NLO pQCD
- (by W. Vogelsang)
- CTEQ 6M PDF
- $\mu = 1/2p_T, 2p_T$

**Graph:**

- $E d^2\sigma/dp_T^2$ [pb GeV$^{-2}$c$^{-1}$]
- $(Data\ Theory)/Theory$ vs $p_T$ [GeV/c]
Direct Photons in Au+Au (high $p_T$)

- Spectra measured over broad range
- $R_{AA}$ mostly unity – “isospin” effect at high $p_T$? But: experimentally challenging due to decay photon merging
Other Collision Systems: Investigate possible Isospin effect

- d+Au: initial state, run 3 lacks statistics, run 8 on the way
- Cu+Cu: smaller system, consistent with Au+Au
- Lower energy (62.4 GeV): Isospin effect would be at lower $p_T$, but lack of statistics
Direct Photons at low $p_T$

- Direct photon ratio measured in 4 systems now: $p+p$, $d+Au$, $Cu+Cu$, $Au+Au$
- Heavy ions: enhancement over pQCD: thermal?
- $d+Au$: no significant enhancement
Direct Photon Spectra

- p+p
  - Consistent with NLO pQCD above 2 GeV/c

- Au+Au
  - Significant excess over binary-scaled p+p for $p_T < 3$ GeV/c
  - Inverse slope of exponential fit related to temperature of matter

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

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$dN/dy (p_T&gt;1$ GeV/c)</th>
<th>$T$ (MeV)</th>
<th>$\chi^2$/DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20%</td>
<td>1.10 ± 0.20 ± 0.30</td>
<td>221 ± 23 ± 18</td>
<td>3.6/4</td>
</tr>
<tr>
<td>20-40%</td>
<td>0.52 ± 0.08 ± 0.14</td>
<td>215 ± 20 ± 15</td>
<td>5.2/3</td>
</tr>
<tr>
<td>MB</td>
<td>0.33 ± 0.04 ± 0.09</td>
<td>224 ± 16 ± 19</td>
<td>0.9/4</td>
</tr>
</tbody>
</table>
Do Direct Photons Flow?

- In theory, they do, different effects (jet fragments, medium induced) lead to positive or negative $v_2$

- Calorimeter measurement has large uncertainties so far, so no statement possible for now

[Graphs and images related to the topic of direct photons in heavy-ion collisions]
A New Method on the Way

- Using external conversions to avoid large uncertainties
- Promising first results on inclusive photon $v_2$: good agreement with calorimeter result from Phys. Rev. Lett. 96, 032302 (2006)

Circles: direct measurement
Closed points: conversion method
Now: Photon-Hadron Correlations

- Here, photons are used as trigger to tag the jet, photon energy balances jet energy.
- Direct photon-hadron correlations calculated from inclusive photon-hadron and decay photon-hadron correlations.
- Measure the away side yield per trigger.

$$Y_{\text{direct}} = \frac{R_\gamma Y_{\text{incl}} - Y_{\text{decay}}}{R_\gamma - 1}$$

$$R_\gamma = \frac{N_{\text{incl}}}{N_{\text{decay}}}$$
$I_{AA}$: Jet Suppression, Fragmentation Modification

$I_{AA} = \frac{Y_{AA}}{Y_{pp}} \approx \frac{D_{AA}(z)}{D_{pp}(z)}$

- $I_{AA} < 1$, suppression of away side
- $I_{AA}$ connected to FF modification

Centrality dependence of $I_{AA}$ consistent with $\pi^0 R_{AA}$
Modified Fragmentation

- Use another variable from MLLA (Modified Leading Logarithmic Approximation, hep-ph/0506218): \( \xi = -\ln x_E \)
- \( x_E = -p_T^h/p_T^\gamma \cos(\Delta \phi) \sim z_T \)
- High \( \xi \) means low \( z_T \)
- Using the full away side: PHENIX p+p agrees well with TASSO (Z.Phys. C47, 187) in \( e^+e^- \)
- MLLA and PHENIX Au+Au agree as well
- Take a look at the shape difference
\( l_{AA} \)

- With combined trigger bins 5-15GeV/c and full away side: increase of \( l_{AA} \) at high \( \xi \)
- Fit to a flat line: “average” \( l_{AA} = 0.598 \pm 0.095 \)
$I_{AA}$

- With combined trigger bins 5-15GeV/c and full away side: increase of $I_{AA}$ at high $\xi$
- Fit to a flat line: “average” $I_{AA} = 0.598 \pm 0.095$
- Using TASSO as reference: low $\xi$ consistent with $I_{AA}$, high $\xi$ enhanced
- Shape modified, energy loss!
Summary

- Direct Photons are a powerful tool in HI collisions
  - At high $p_T$: binary scaling works. Possible effects of hot and cold nuclear matter. Need better understanding of initial state (d+Au)
  - At low $p_T$: excess over p+p, interpreted as thermal photons, access to temperature of medium
  - Flow: disentangle different production mechanisms

- Direct Photon-Hadron Correlations probe the matter
  - Away side yield is suppressed at low $\xi$
  - Shape of FF unmodified at low $\xi$, but changes at high $\xi$
  - $I_{AA}$ consistent with $\pi^0 R_{AA}$
Thank you!
Measuring the Fragmentation Function

- Measurement of modified fragmentation function in Au+Au and p+p
- Fit one curve for all jet energies
- Slope in p+p: $6.89 \pm 0.64$, steeper in Au+Au: $9.49 \pm 1.37$

$$D_q(z_T) = \frac{1}{N_{evt}} \frac{dN(T)}{dz_T}$$

$$z_T = \frac{p_T^h}{p_T^\gamma}$$

$$p_T^\gamma \approx p_T^{jet}$$
Measuring External Photon Conversions: Identification

- PHENIX tracks outside magnetic field
  - Need to assume the origin
  - Assume particles come from event vertex
- We are interested in conversions in the HBD backplane (radius ≈ 60cm)
  - Now our assumption is incorrect
  - Gives pairs an artificial opening angle
  - Leads to an apparent mass