Journal Club presentation
Neutral pion production in Au+Au collisions

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July 4, 2014
Neutral pion production with respect to centrality and reaction plane in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

arXiv:1208.2254 [nucl-ex]
Outline

- **Introduction**
  - Neutral pion $\pi^0$
  - Centrality
  - Reaction plane and event plane
  - $R_{AA}(p_T)$ and $R_{AA}(\Delta\phi, p_T)$

- **Experiment and Signal extraction**
  - Dataset and PHENIX
  - EMCal and Signal extraction
  - Acceptance and efficiency
  - Systematic uncertainties

- **Results from paper**
  - Invariant Yield of $\pi^0$
  - $\pi^0/\eta$ ratio
  - $R_{AA}(p_T)$ and $R_{AA}(\Delta\phi, p_T)$ in different centrality classes
Neutral pion $\pi^0$

- $|\pi^0\rangle = \frac{1}{\sqrt{2}} (|u\bar{u}\rangle - |d\bar{d}\rangle)$
- Meson mass $134.976$ MeV/$c^2$
- Average lifetime $(8.52 \pm 0.18) \cdot 10^{-17}$ s
- Decay:
  - $\pi^0 \rightarrow \gamma\gamma$ with 98.823% probability
  - $\pi^0 \rightarrow e^+ + e^- + \gamma$ with 1.174% probability
- Used as a probe for azimuthal asymmetries in collective flow and nuclear suppression
- Can be identified over a very wide $p_T$ range (crucial for systematic uncertainties)
Centrality in heavy ion collisions

- defined by impact parameter $b$
- central collisions (small $b$):
  - large participating zone (hot/dense, also called fireball)
  - large $N_{\text{part}}$
- peripheral collisions (large $b$):
  - large spectators (cold, flying away undisturbed)
In PHENIX the Beam-Beam Counters (BBC, $3.0 < |\eta| < 3.9$) and the Zero-Degree Calorimeters (ZDC) are used.

From Monte-Carlo calculation based on Glauber model $N_{\text{part}}$, $N_{\text{coll}}$ and $b$ are estimated.
Event plane and reaction plane

- Reaction plane given by the beam direction and the impact parameter vector of the collision (cannot be directly observed)
- Event plane method is used and estimates the angle of the reaction plane
- Event plane is determined for the 2\textsuperscript{nd} harmonic of the Fourier expansion of the azimuthal distribution (assumed to be the dominant coefficient)
- Event flow vector $\vec{Q}$ and azimuth of the event plane $\Psi_2$ for 2\textsuperscript{nd} harmonic can be expressed as

$$
\vec{Q} = \left( \sum_{i=1}^{M} w_i \cos(2\phi_i), \sum_{i=1}^{M} w_i \sin(2\phi_i) \right)
$$

$$
\Psi_2 = \frac{1}{2} \tan^{-1} \left( \frac{Q_y}{Q_x} \right)
$$

- $M$ - number of particles for event plane determination (multiplicity of event)
- $\phi_i$ - azimuthal angle of each particle
- $w_i$ - weight for optimization of resolution
Event plane measurement in PHENIX

In PHENIX two detectors are used:
- Pair of muon-piston calorimeters (MPC) with PbWO$_4$ crystals
- Pair of reaction-plane detectors (RxNP) with plastic szintillators

Event plane resolution is defined as

$$\langle \cos[2(\Psi_N - \Psi_S)] \rangle$$

(N = north detector, S = south detector)
Event plane resolution in PHENIX:
- Higher values indicate better resolution
- Resolution is centrality dependent (maximum at 40-50%)
Suppression of high $p_T$ hadrons ("jet quenching")

- Nuclear modification factor $R_{AA}$ used for medium properties extraction
- Decrease from unity interpreted as loss of parton momentum due to a medium (QGP)

\[
R_{AA}(p_T) = \frac{\langle T_{AB} \rangle \times d^2 \sigma_{pp}^{\pi^0} / dp_T dy}{N_{AA}^{\pi^0} / dp_T dy} \tag{1}
\]

\[
\langle T_{AB} \rangle = \frac{N_{\text{coll}}}{\sigma_{pp}^{\text{inel}}} \tag{2}
\]

- To constrain $\langle L \rangle$ of the parton, $R_{AA}$ is measured as a function of $\Delta \phi$

\[
F(\Delta \phi_i, p_T) = \frac{N(\Delta \phi_i, p_T)}{\frac{1}{6} \sum_{i=1}^{6} N(\Delta \phi_i, p_T)} \tag{3}
\]

\[
R_{AA}(\Delta \phi_i, p_T) = F(\Delta \phi_i, p_T) \times R_{AA}(p_T) \tag{4}
\]
Correction of $R_{AA}(\Delta \phi, p_T)$ with $v_2$

- $v_2$ is second Fourier expansion coefficient of the single inclusive azimuthal distribution with
  $\Delta \phi = \Psi - \phi$

$$\frac{dN}{d\Delta \phi} = \frac{N}{2\pi} (1 + 2v_2 \cos(2\Delta \phi)) \quad (5)$$

- Assumption that $v_2$ is dominant in expansion and used for correction of $F(\Delta \phi_i, p_T)$

$$F(\Delta \phi_i, p_T) = F(\Delta \phi_i, p_T)^{meas} \times \frac{1 + 2v_2^{corr} \cos(2\Delta \phi)}{1 + 2v_2^{raw} \cos(2\Delta \phi)} \quad (6)$$

$$v_2^{corr} = \frac{v_2^{raw}}{\langle \cos[2(\Psi_N - \Psi_S)] \rangle} \quad (7)$$
Dataset and the PHENIX experiment

- 3.8e09 minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the PHENIX experiment at RHIC in 2007
- BBC and ZDC for centrality measurement
- PbSc and PbGl calorimeters for photon measurement
Two processes form the shower: Pair production and bremsstrahlung

Identifies photons by using cuts on the shower shape and comparing it to an ideal shape

In this analysis hadron contamination is small due to $p_T$ region above 5 GeV/c
Signal extraction

- \( m_{\gamma\gamma} \) calculated in bins of photon pair \( p_T \)
  \[
  m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos(\phi))}
  \] (8)

- Pair has to pass asymmetry cut
  \[
  \alpha = \left| E_{\gamma_1} - E_{\gamma_2} \right|/(E_{\gamma_1} + E_{\gamma_2}) < 0.8
  \] (9)

- Distance between impact position of the photons larger than 8cm

- Combinatorial background with event mixing method and then normalized to spectrum and subtracted

- Yields are extracted by integrating over \( \pm 2.5\sigma \) range around peak
Acceptance and efficiency

Acceptance: Limited detector dimensions, dead areas, ...

Efficiency: Ratio of $N_{\text{measured}}/N_{\text{emitted}}$

- Important factor is merging in the EMCal where photons are too close to each other and cannot be resolved
- Two sources of $\pi^0$ not coming from the vertex:
  - $\pi^0$ produced by hadrons interacting with the detector material
  - Feed-down products from weak decays of higher mass hadrons
- Both sources were found to be negligible at 1% for $p_T > 2.0$ GeV/c
- In analysis single $\pi^0$ generated in GEANT3 framework uniform in $\phi$ and $|\eta| < 0.5$, output is tuned to fit real data and to reproduce inactive detector areas
## Systematic uncertainties

<table>
<thead>
<tr>
<th>$p_T [\text{GeV}/c]$</th>
<th>indep</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield extr. (%)</td>
<td>5.0</td>
<td>4.0</td>
<td>3.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>E scale (%)</td>
<td>6.0</td>
<td>6.0</td>
<td>7.0</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>PID (%)</td>
<td>4.0</td>
<td>3.0</td>
<td>4.0</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Merging (%)</td>
<td></td>
<td></td>
<td>4.5</td>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td>Acceptance (%)</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off-vertex (%)</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (%)</td>
<td>1.8</td>
<td>8.8</td>
<td>7.8</td>
<td>9.7</td>
<td>29.4</td>
</tr>
</tbody>
</table>
Invariant Yield of $\pi^0$

- Distributions well described by power law function
  \[ f(p_T) = A \cdot p_T^{-n} \]

<table>
<thead>
<tr>
<th>System</th>
<th>A</th>
<th>n</th>
</tr>
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<tbody>
<tr>
<td>Au+Au 0-5%</td>
<td>23.3</td>
<td>7.58 ± 0.07</td>
</tr>
<tr>
<td>Au+Au 0-10%</td>
<td>26.3</td>
<td>7.66 ± 0.05</td>
</tr>
<tr>
<td>Au+Au 10-20%</td>
<td>32.1</td>
<td>7.81 ± 0.05</td>
</tr>
<tr>
<td>Au+Au 20-30%</td>
<td>25.6</td>
<td>7.81 ± 0.06</td>
</tr>
<tr>
<td>Au+Au 30-40%</td>
<td>24.9</td>
<td>7.96 ± 0.06</td>
</tr>
<tr>
<td>Au+Au 40-50%</td>
<td>20.0</td>
<td>8.02 ± 0.08</td>
</tr>
<tr>
<td>Au+Au 50-60%</td>
<td>15.0</td>
<td>8.09 ± 0.10</td>
</tr>
<tr>
<td>Au+Au 60-70%</td>
<td>5.04</td>
<td>7.92 ± 0.13</td>
</tr>
<tr>
<td>Au+Au 70-80%</td>
<td>6.32</td>
<td>8.33 ± 0.19</td>
</tr>
<tr>
<td>Au+Au 80-93%</td>
<td>5.16</td>
<td>8.79 ± 0.31</td>
</tr>
<tr>
<td>Au+Au 0-93%</td>
<td>16.4</td>
<td>7.86 ± 0.02</td>
</tr>
<tr>
<td>p+p(σ) 2005</td>
<td>16.7</td>
<td>8.14 ± 0.05</td>
</tr>
</tbody>
</table>
\( \eta/\pi^0 \) ratio as function of \( p_T \)

- Compared to data from 2004 the new data shows smaller uncertainties and higher \( p_T \) reach.
- New data is also consistent with 2004 data and with PYTHIA-6.131 \( p+p \) calculation.
- Data is within 1-\( \sigma \) consistent with a constant fit of:
  \( \eta/\pi^0 = 0.45 \pm 0.01 \) for minbias,
  \( \eta/\pi^0 = 0.47 \pm 0.01 \) for 0-20%,
  \( \eta/\pi^0 = 0.51 \pm 0.01 \) for 20-60%,
  \( \eta/\pi^0 = 0.51 \pm 0.02 \) for 60-93%.
$R_{AA}$ in different centrality classes

(a) Au+Au Minimum Bias $\sqrt{s_{NN}}$=200GeV
(b) Au+Au 0-10% $\sqrt{s_{NN}}$=200GeV
(c) Au+Au 20-30% $\sqrt{s_{NN}}$=200GeV
(d) Au+Au 40-50% $\sqrt{s_{NN}}$=200GeV
(e) Au+Au 60-70% $\sqrt{s_{NN}}$=200GeV
(f) Au+Au 80-93% $\sqrt{s_{NN}}$=200GeV

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Slope of $R_{AA}$ in high $p_T$

- In central collisions $R_{AA}$ slowly rises at higher $p_T$ (left plot)
- Slope is significantly different from zero (right plot)
Centrality dependence of $R_{AA}(p_T, \Delta \phi)$

(a) Au+Au 0-10% $\sqrt{s_{NN}}=200$GeV
(b) Au+Au 10-20% $\sqrt{s_{NN}}=200$GeV
(c) Au+Au 20-30% $\sqrt{s_{NN}}=200$GeV
(d) Au+Au 30-40% $\sqrt{s_{NN}}=200$GeV
(e) Au+Au 40-50% $\sqrt{s_{NN}}=200$GeV
(f) Au+Au 50-60% $\sqrt{s_{NN}}=200$GeV
Centrality and $\Delta \phi$ dependence of $R_{AA}(p_T, \Delta \phi)$

- Elliptical overlap region with short axis in reaction plane $\rightarrow$ small $\Delta \phi$ leads to larger $R_{AA}(p_T, \Delta \phi)$

- Difference in in-plane and out-of-plane suppression increases with eccentricity (decreasing $N_{\text{part}}$) $\rightarrow$ values converge with increasing centrality
Take home message

- $R_{AA}(p_T)$ alone fails to describe the different path lengths in the medium (it averages the energy loss over different paths)
- Instead $R_{AA}(p_T, \Delta \phi)$ with respect to the event plane shows the strong path lengths dependence of the parton momentum loss
- Elliptic/Asymmetric shape of the overlap region and the medium was observed
\( S_{\text{loss}} \) calculation and comparison to ALICE

1. \( T_{AA} \) scale
2. Move along fit to scaled p+p data
3. Calculate \( \delta p_T = p_T(p+p) - p_T(Au+Au) \)

\[ S_{\text{loss}} (\delta p_T / p_T) = \begin{cases} \text{(global)} = 0.3\% & \text{for } (p+p) \text{ data} \\ \text{(global)} = 1.0\% & \text{for } Au+Au \text{ data} \end{cases} \]

\[ S_{\text{loss}} (\delta p_T / p_T) = \begin{cases} \text{(global)} = 0.7\% & \text{for } Pb+Pb \text{ data} \\ \text{(global)} = 2.9\% & \text{for } Au+Au \text{ data} \end{cases} \]