Journal Club presentation
Neutral pion production in Au+Au collisions

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July 4, 2014

Paper for this presentation

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

arXiv:1208.2254 [nucl-ex]

Outline

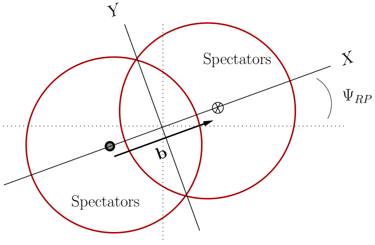
- **Introduction**
  - Neutral pion π^0
  - Centrality
  - Reaction plane and event plane
  - $R_{\mathrm{AA}}(p_{\mathrm{T}})$ and $R_{\mathrm{AA}}(\Delta\phi, p_{\mathrm{T}})$
- **Experiment and Signal extraction**
  - Dataset and PHENIX
  - EMCal and Signal extraction
  - Acceptance and efficiency
  - Systematic uncertainties
- **Results from paper**
  - Invariant Yield of π^0
  - π^0/η ratio
  - $R_{\mathrm{AA}}(p_{\mathrm{T}})$ and $R_{\mathrm{AA}}(\Delta\phi, p_{\mathrm{T}})$ in different centrality classes

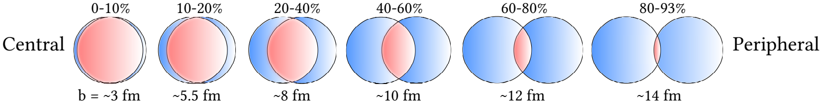
Neutral pion π^0

- $|\pi^0\rangle = \frac{1}{\sqrt{2}}\left(|u\overline{u}\rangle - |d\overline{d}\rangle\right)$
- 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)

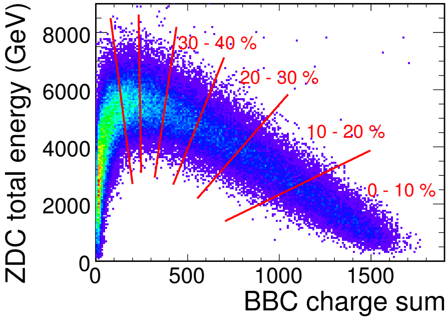
Centrality in heavy ion collisions

- defined by impact parameter b
- central collisions (small b):
  - large participating zone (hot/dense, also called fireball)
  - large N_{part}
- peripheral collisions (large b):
  - large spectators (cold, flying away undisturbed)





Centrality measurement



- 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_{part}, N_{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^{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 Ψ_2 for 2^{nd} harmonic can be expressed as

$$\vec{Q} = \begin{pmatrix} \sum_i^M w_i \cos(2\phi_i) \\ \sum_i^M w_i \sin(2\phi_i) \end{pmatrix}$$

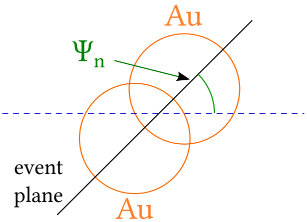
$$\Psi_2 = \frac{1}{2} \tan^{-1} \left(\frac{Q_y}{Q_x} \right)$$

M - number of particles for event plane determination (multiplicity of event)

ϕ_i - azimuthal angle of each particle

w_i - weight for optimization of resolution

Event plane measurement in PHENIX

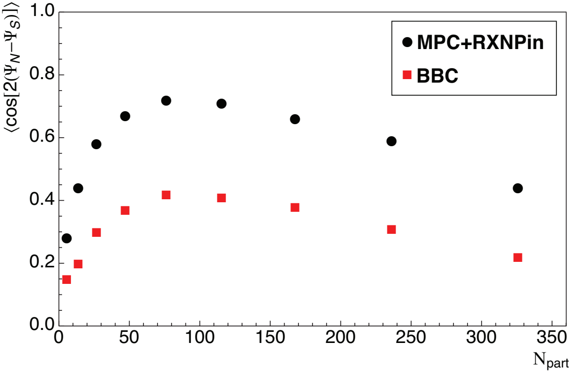


- In PHENIX two detectors are used:
  - Pair of muon-piston calorimeters (MPC) with $PbWO_4$ crystals
  - Pair of reaction-plane detectors (RxNP) with plastic szintillators
- Event plane resolution is defined as

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

(N = north detector, S = south detector)

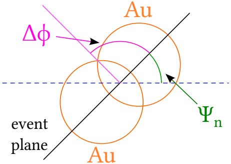
Event plane resolution



- 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)



$$R_{AA}(p_T) = \frac{(1/N_{AA}^{evt})d^2N_{AA}^{\pi^0}/dp_Tdy}{\langle T_{AB}\rangle \times d^2\sigma_{pp}^{\pi^0}/dp_Tdy} \qquad (1)$$

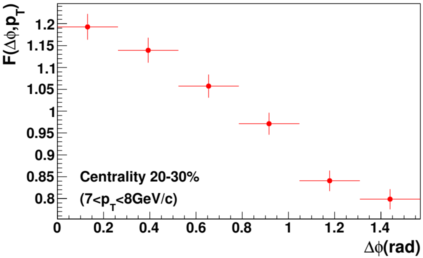
$$\langle T_{AB}\rangle = \langle N_{coll}\rangle/\sigma_{pp}^{inel} \qquad (2)$$

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

$$F(\Delta\phi_i, p_T) = \frac{N(\Delta\phi_i, p_T)}{\frac{1}{6}\sum_{i=1}^{6} N(\Delta\phi_i, p_T)} \qquad (3)$$

$$R_{AA}(\Delta\phi_i, p_T) = F(\Delta\phi_i, p_T) \times R_{AA}(p_T) \qquad (4)$$

Correction of $R_{\mathrm{AA}}(\Delta\phi, p_{\mathrm{T}})$ with v_2



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

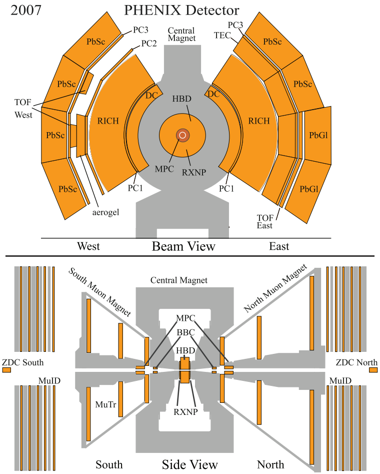
$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi} = \frac{N}{2\pi}(1 + 2v_2\cos(2\Delta\phi)) \qquad (5)$$

- Assumption that v_2 is dominant in expansion and used for correction of $F(\Delta\phi_i, p_{\mathrm{T}})$

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

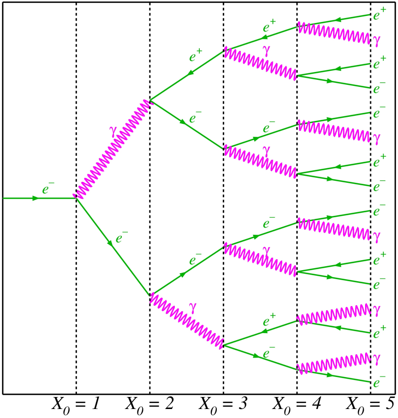
$$v_2^{\mathrm{corr}} = \frac{v_2^{\mathrm{raw}}}{\langle\cos[2(\Psi_N - \Psi_S)]\rangle} \qquad (7)$$

Dataset and the PHENIX experiment



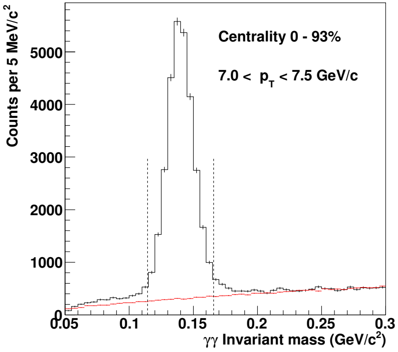
- 3.8e09 minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the PHENIX experiment at RHIC in 2007
- BBC and ZDC for centrality measurement
- PbSc and PbGl calorimeters for photon measurement

EMCal



- 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

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos(\phi))} \qquad (8)$$

- Pair has to pass asymmetry cut

$$\alpha = |E_{\gamma_1} - E_{\gamma_2}|/(E_{\gamma_1} + E_{\gamma_2}) < 0.8 \quad (9)$$

- Distance between impact position of the photons larger than 8cm
- Combinatorial background with event mixing method and then normalized to spectrum and substracted
- Yields are extracted by integrating over $\pm 2.5\sigma$ range around peak

Acceptance and efficiency

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

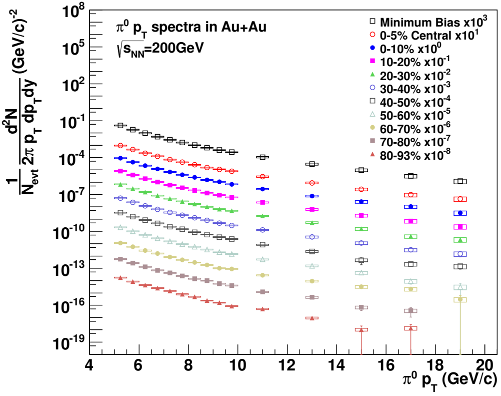
Efficiency: Ratio of $N_{\mathrm{measured}}/N_{\mathrm{emitted}}$

- Important factor is merging in the EMCal where photons are too close to each other and cannot be resolved
- Two sources of π^0 not coming from the vertex:
  - π^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 π^0 generated in GEANT3 framework uniform in ϕ and $|\eta| < 0.5$, output is tuned to fit real data and to reproduce inactive detector areas

Systematic uncertainties

p_T[GeV/c]	indep	6	8	10	16
Yield extr. (%)		5.0	4.0	3.0	2.0
E scale (%)		6.0	6.0	7.0	7.0
PID (%)		4.0	3.0	4.0	5.0
Merging (%)				4.5	28.0
Acceptance (%)	1.0				
Off-vertex (%)	1.5				
Total (%)	1.8	8.8	7.8	9.7	29.4

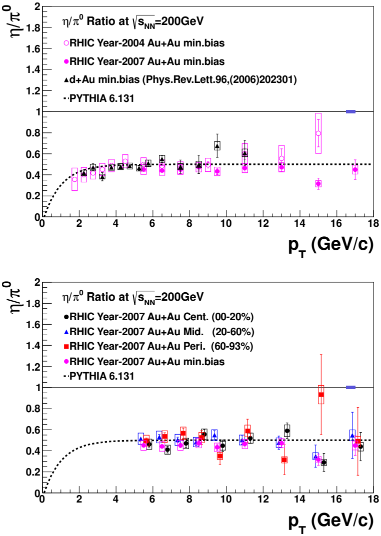
Invariant Yield of π^0



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

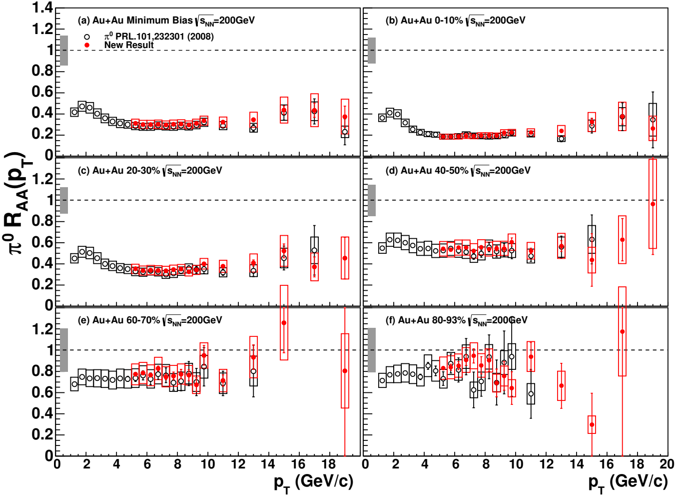
System	A	n
Au+Au 0-5%	$23.3^{+3.67}_{-3.11}$	7.58 ± 0.07
Au+Au 0-10%	$26.3^{+2.9}_{-2.6}$	7.66 ± 0.05
Au+Au 10-20%	$32.1^{+3.9}_{-3.4}$	7.81 ± 0.05
Au+Au 20-30%	$25.6^{+3.3}_{-2.9}$	$7.81^{+0.06}_{-0.05}$
Au+Au 30-40%	$24.9^{+3.9}_{-3.3}$	7.96 ± 0.06
Au+Au 40-50%	$20.0^{+3.9}_{-3.2}$	8.02 ± 0.08
Au+Au 50-60%	$15.0^{+3.6}_{-2.8}$	8.09 ± 0.10
Au+Au 60-70%	$5.04^{+1.73}_{-1.24}$	7.92 ± 0.13
Au+Au 70-80%	$6.32^{+3.12}_{-2.02}$	$8.33^{+0.19}_{-0.18}$
Au+Au 80-93%	$5.16^{+4.85}_{-2.38}$	$8.79^{+0.31}_{-0.29}$
Au+Au 0-93%	$16.4^{+0.93}_{-0.87}$	7.86 ± 0.02
p+p(σ) 2005	$16.7^{+1.73}_{-1.55}$	8.14 ± 0.05

η/π^0 ratio as function of p_T

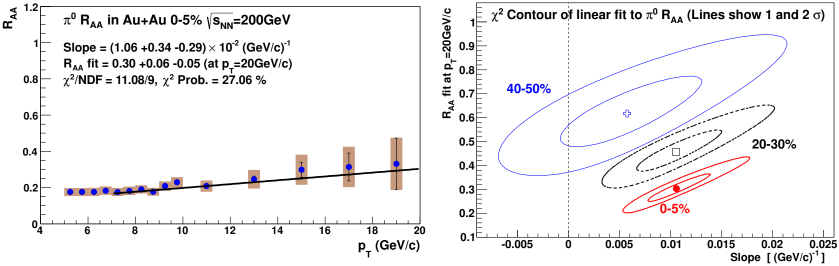


- Compared to data from 2004 the new data shows smaller uncertainties and higher p_T reach
- New data is also consistent with 2004 data and with PYTHIA-6.131 p+p calculation
- Data is within 1-σ consistent with a constant fit of
  $\eta/\pi^0 = 0.45 \pm 0.01$ for minbias,
  $\eta/\pi^0 = 0.47 \pm 0.01$ 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

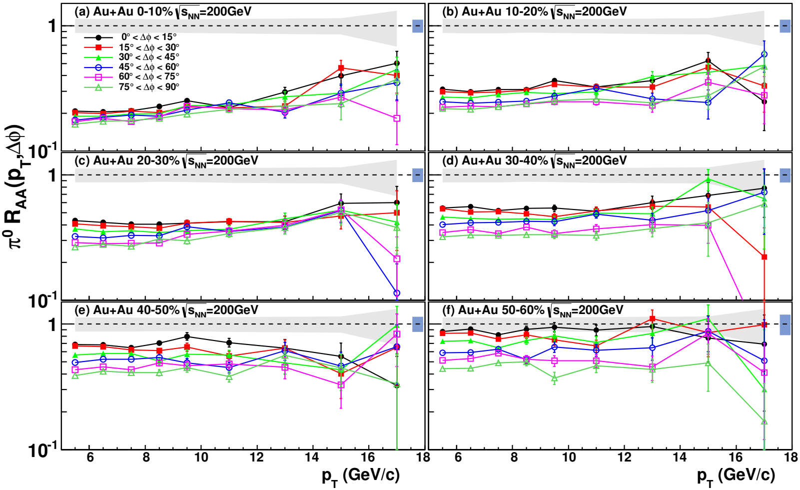


Slope of R_{AA} in high p_T

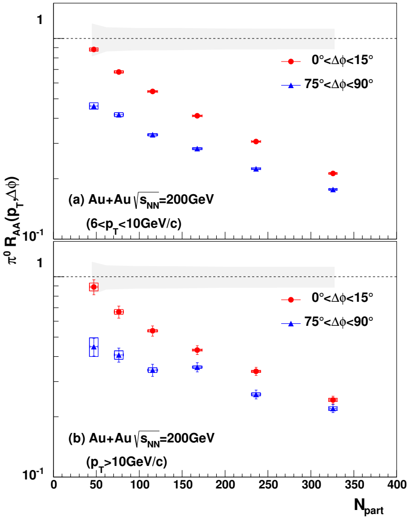


- In central collisions R_{AA} slowly rises at higher p_T (left plot)
- Slope is significantly different from zero (right plot)

Centrality dependence of $R_{AA}(p_T, \Delta\phi)$



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_{part}) $\rightarrow$ values converge with increasing centrality

Take home message

- $R_{\mathrm{AA}}(p_{\mathrm{T}})$ alone fails to describe the different path lengths in the medium (it averages the energy loss over different paths)
- Instead $R_{\mathrm{AA}}(p_{\mathrm{T}}, \Delta\phi)$ 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

Backup

$S_{\rm loss}$ calculation and comparison to ALICE