Study of high pT $\pi^0$ and direct photon in small system collisions at 200 GeV

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Outline

- Background and Motivation
- Centrality determination in Glauber Model
- Bias in centrality determination
- Yield of High $p_T$ $\pi^0$ and $\gamma$
- Determination of $N_{coll}$ experimentally
- Summary
Nuclear Modification Factor

\[ R_{AB}(p_T) = \frac{d^2N_{AB}}{dp_Td\eta} \frac{\langle N_{coll} \rangle \star d^2N_{pp}}{\langle N_{coll} \rangle \star Y_{pp}} \]

\( N_{coll} \) : Average number of binary collisions in a type of event according to Glauber Model.

This ratio teaches us how different a heavy ion collision is from just considering it as a scaled p+p collision.

\[ b = 6 \text{fm} \text{ corresponds to } N_{coll} \approx 600 \text{ in } \text{Au+Au} \]
Nuclear modification factor for $\pi^0$ in small systems

$$R_{AB}(p_T) = \frac{dN_{AB}}{dp_T} \frac{\langle N_{coll} \rangle dN_{pp}}{dp_T}$$

Both d+Au and p+Au show large centrality dependence.
- At high $p_T$ we observe suppression in central events and enhancement in peripheral events.
- While formation of QGP could explain suppression in central, there's no obvious explanation for the enhancement in peripheral collisions.

Is the centrality dependence a physics effect or an artifact of the way we determine centrality itself? Are events mis-binned in centrality?
Theoretical prediction of two extreme limits of small colliding systems

- Calculations with cold nuclear matter effect only.

- Calculations with cold and hot medium effects that assume the QGP is described by the hydrodynamic-based model.
Is Glauber model valid for small systems?

**Impact parameter $b$ (Theoretical)**

- Analyzing the 0-20% centrality bin in Pb+Pb is equivalent to studying the class of events with average impact parameter of 3fm with a very small variance.

- Analyzing the 0-20% centrality bin in p+Pb is also equivalent to studying the class of events with average impact parameter of 3fm but with a large variance.

- This difference implies that we cannot draw equivalent physics conclusions about central p+Pb and Pb+Pb events.
BIAS IN EVENT SELECTION

BBC $N_{ch}$ mapped to $N_{coll}$ with Glauber Model

- Measure event activity ($N_{ch}$) in BBC on Au going side
- Fit event activity to superposition of negative binomial distributions for each nucleon-nucleon collision
- Select events in percentiles of event activity (0-5%, 5-10%, etc.) for data & model
- Assign $N_{coll}$ from model to data
BIAS IN EVENT SELECTION

Using direct photons to minimize event selection bias

PYTHIA8 simulation using the Detroit tune

- For both $\gamma^\text{dir}$ and $\pi^0$, the dominant source is quark-gluon scattering

- The fraction of the dominant source to all is about the same for $\gamma^\text{dir}$ and $\pi^0$, independent of $p_T$ and $dN_{ch}/d\eta$ by BBC

Direct photon production is proportional to the production of high $p_T$ $\pi^0$ and is independent of the underlying event multiplicity.
BIAS IN EVENT SELECTION

Using direct photons to minimize event selection bias

- Because of the color-neutral property, $N_{\text{coll}}$ redefined by $\gamma^{\text{dir}}$ yield experimentally

$$N_{\text{coll}}^{\text{EXP}}(p_T) = \frac{Y_{\gamma^{\text{dir}}}(p_T)}{Y_{\gamma^{\text{dir}}_{pp}}(p_T)}$$

- Using the new $N_{\text{coll}}$, $R_{d\text{Au}}$ for $\pi^0$ is written as following

$$R_{d\text{Au}}^{\pi^0, \text{EXP}} = \frac{R_{d\text{Au}, \text{GL}}^{\pi^0}}{R_{d\text{Au}, \text{GL}}^{\gamma^{\text{dir}}}} = \frac{Y_{d\text{Au}}^{\pi^0}/Y_{pp}^{\pi^0}}{Y_{d\text{Au}}^{\gamma^{\text{dir}}}/Y_{pp}^{\gamma^{\text{dir}}}} = \frac{Y_{d\text{Au}}^{\pi^0}}{N_{\text{coll}}^{\text{EXP}} Y_{pp}^{\pi^0}}$$


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RESULTS AND DISCUSSIONS

$\gamma^\text{dir}$ and $\pi^0$ yields from d+Au and p+p at 200 GeV

- $\gamma^\text{dir}$ from d+Au in different centralities
  - d+Au min. bias data 2003: PHENIX:PRC87(2013)54907

- $\pi^0$ from d+Au in different centralities
  - Consistent with 2008 d+Au data
  - d+Au min. bias data: PHENIX:PRC(2022)64902
  - p+p data: PHENIX:PRC(2022)64902
Ratio of $\nu^{\text{dir}}/\pi^0$

- p+p and d+Au are on top of each other
- Peripheral events consistent with min. bias
- Most central stands out
Evaluating bias in $N_{\text{coll}}$ from Glauber Model

\[ N_{\text{coll}}^{\text{exp}}(p_T) = \frac{Y_{dAu}^{\text{dir}}(p_T)}{Y_{pp}^{\text{dir}}(p_T)} \]

Visible trend can be seen
- Good agreement in central collisions
- 15% deviation in peripheral collisions

Bias in event selections based on event activity measured at forward rapidity!
Redefine $R_{dAu}$ for $\pi^0$

$$R_{dAu, \text{EXP}}^{\pi^0} = \frac{Y_{dAu}^{\pi^0}}{N_{\text{coll}}^{\exp} Y_{pp}^{\pi^0}} = \frac{Y_{dAu}^{\pi^0}}{Y_{dAu}^{\gamma_{\text{dir}}}} / \frac{Y_{pp}^{\gamma_{\text{dir}}}}{Y_{pp}^{\gamma_{\text{dir}}}}$$

- In central collisions (0-5%), about 20% suppression of the $\pi^0$ yield
- In peripheral collisions, consistent with d+Au min. bias
Redefined $R_{dAu}$ for $\pi^0$ vs. $N_{coll}^{\text{EXP}}$

- $N_{coll}^{\text{EXP}} < 4$ (60%-88% centrality)

$$\frac{R_{dAu,EXP}^{\pi^0}(60 - 88\%)}{R_{dAu,EXP}^{\pi^0}(0 - 100\%)} = 1.017 \pm 0.056$$

- $N_{coll}^{\text{EXP}} > 14$ (top 10% centrality)

$$\frac{R_{dAu,EXP}^{\pi^0}(0 - 5\%)}{R_{dAu,EXP}^{\pi^0}(0 - 100\%)} = 0.806 \pm 0.042$$

$d+Au \sqrt{s_{NN}} = 200$ GeV

$7.5 < p_T < 18$ GeV/c

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SUMMARY

- First evidence for significant up to 20% final state suppression of high pT π^0 (7.5 to 18 GeV/c) in central 0-5% d+Au collisions
- Previously observed enhancement of π^0 in peripheral events due to an event selection bias
- Using \( N_{coll}^{EXP} \) to resolve ambiguity between final state and CNM effects – event selection bias inherent to Glauber model approach

- Future analysis in p+Au and He+Au system will provide more clarification. Comparing the three systems, with gradually increasing the size, should differentiate between additional bias in centrality determination (predicting decreasing suppression for larger systems) and some unexpected medium effect (causing increasing suppression for larger systems)
THANK YOU FOR YOUR ATTENTION!

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• The data of minimum bias (BBC) and triggered (ERT) p+Au collisions in PHENIX from the 2015 data taking period (Run 15) are used in the parallel study. The expected significance of the measurement based solely on statistical uncertainties is shown below.

• The ratio of the raw inclusive photon and raw π^0 spectra is shown for p+Au collisions. NO corrections are applied yet.

• The fact that the raw γ/π^0 ratios for various centralities are similar is also a hint of the centrality bias in p+Au collisions.
How is centrality determined in A-A (large-on-large) collision?

- The basic assumption underlying centrality classes is that the impact parameter $b$ is monotonically related to particle multiplicity.
- For large $b$ events ("peripheral"), we expect low multiplicity, where as for small $b$ events ("central") we expect large multiplicity.

Impact parameter $b$ (Theoretical) $
\quad N_{\text{part}}$ (Theoretical) $
\quad N_{\text{ch}}$ (Observable)

$N_{\text{part}}$ - number of participating nucleon

$|\eta|<1$

Measurement of number of binary collisions

\[ R_{AA}(p_T) = \frac{dN_{AA}}{dp_T} \frac{dN_{pp}}{\langle N_{coll} \rangle dp_T} \]

\( N_{part} \) - number of participating nucleon

Number of charged particle from experiment

Glauber model gives mapping of charged particle in forward region to number of binary collisions of the event. Tune this to your specific detector.

Au+Au
Suppression of $\pi^0$ and non-suppression of direct $\gamma$

- It is unity at all centralities.
- As expected, the QGP is transparent to direct photons