Isolating final state effects in high p_T π^0 production using direct photons in small system collisions with PHENIX

Daniel Firak (for the PHENIX collaboration) - Stony Brook University

Outline:

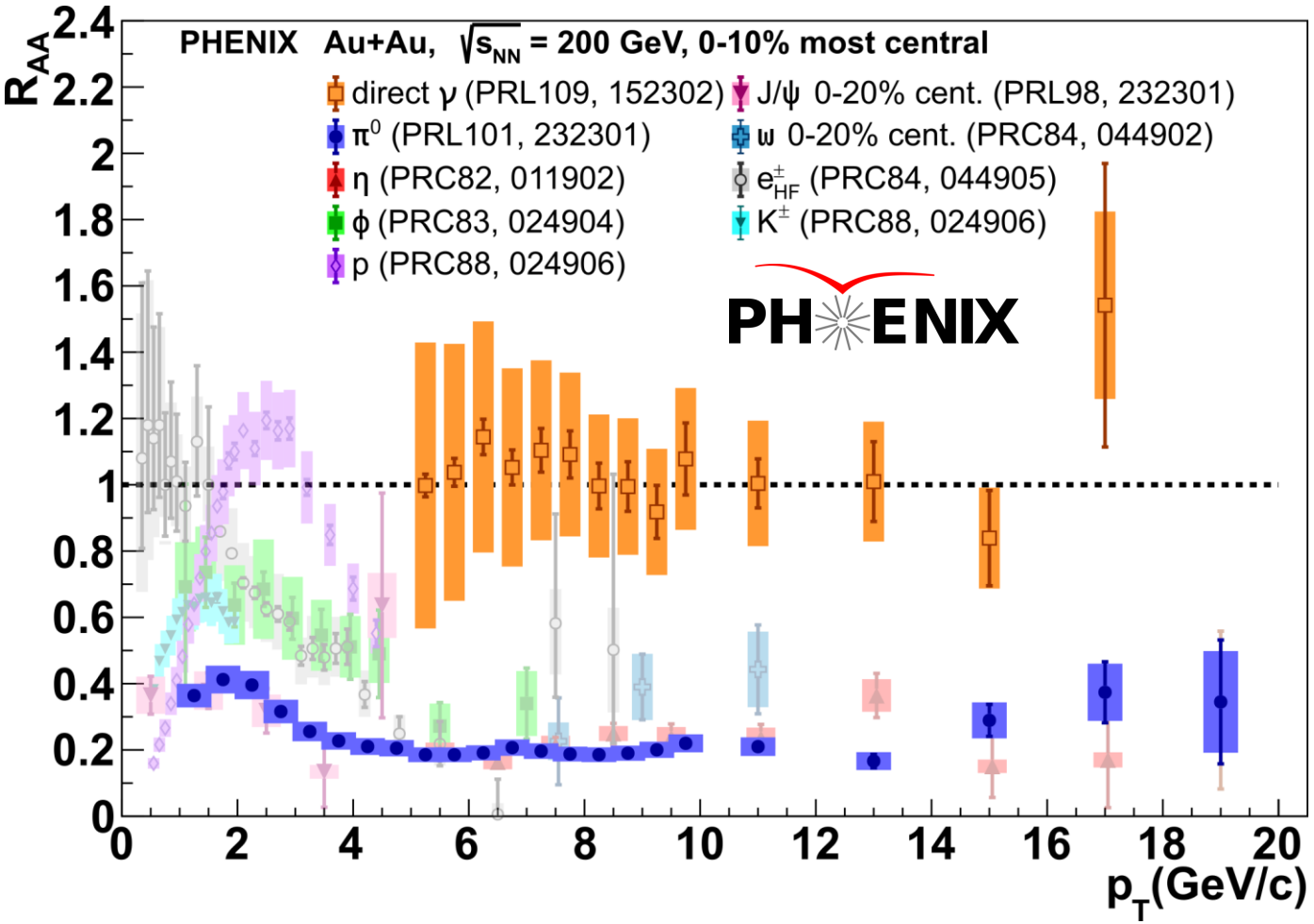
- Nuclear modification factor
- Event activity and bias in event selection
- Results from PHENIX run 2016 d+Au
- Nuclear modification factor in d+Au (PHENIX: arXiv:2303.12899)

Stony Brook University

2023

PHENIX

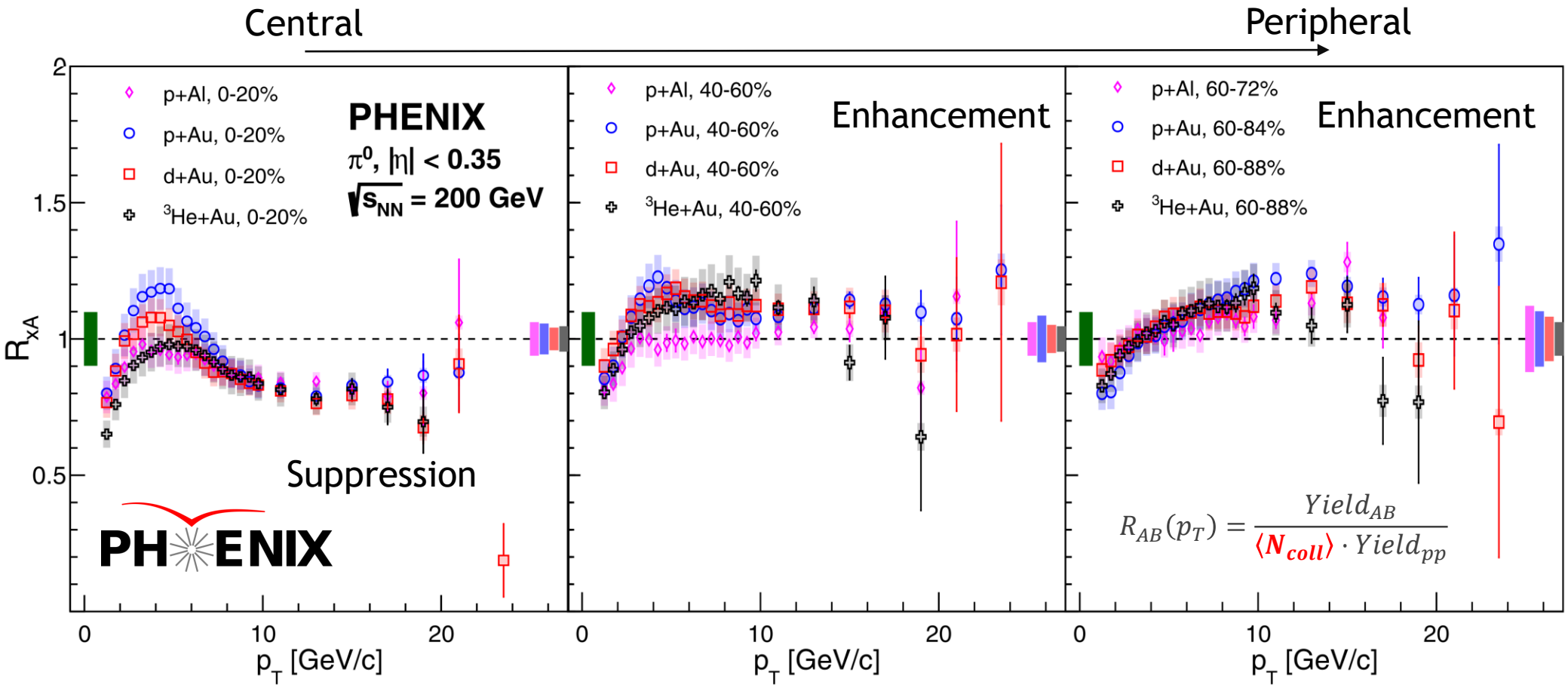
Nuclear modification factor in Au+Au



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

- For photons, R^{γ}_{AB} is consistent with 1
- For neutral pions (hadrons), $R^{\pi^0}_{AB}$ shows suppression in large systems

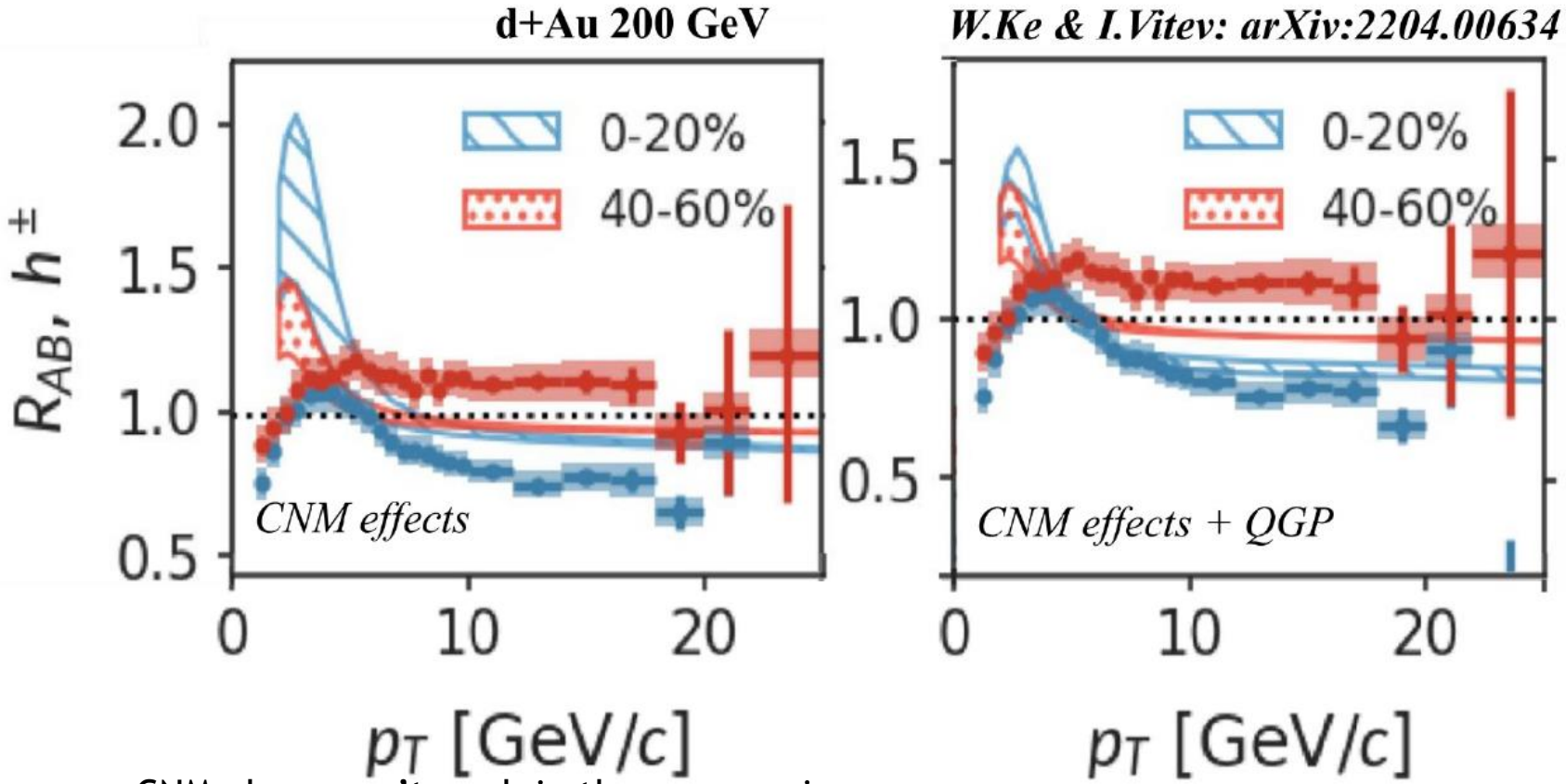
Nuclear modification factor in small systems



PHENIX: PRC105 (2022) 064902

- Suppression for the central events could be explained with QGP formation. Enhancement cannot be trivially explained from physical arguments.

Nuclear modification factor in d+Au

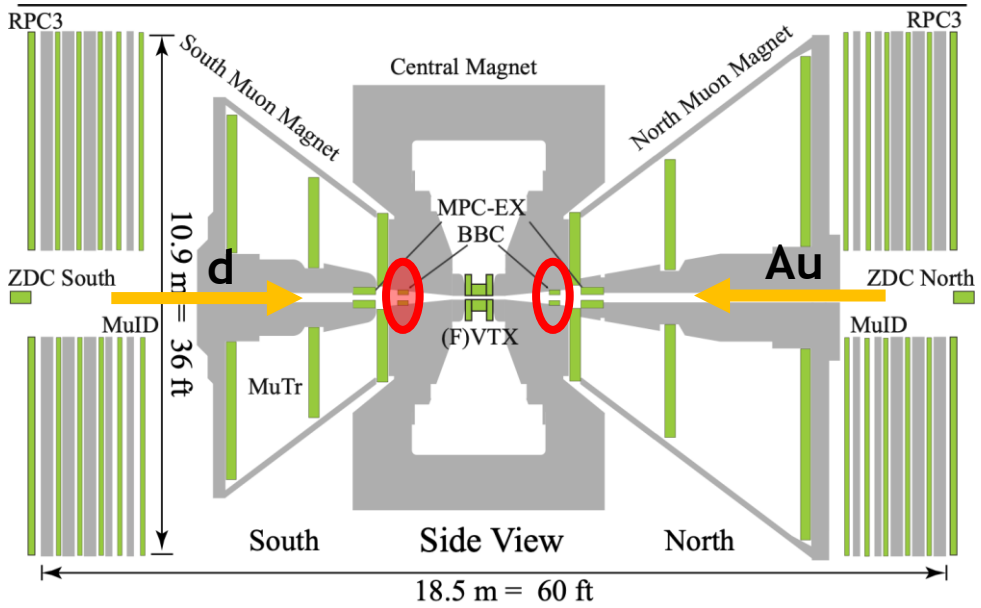


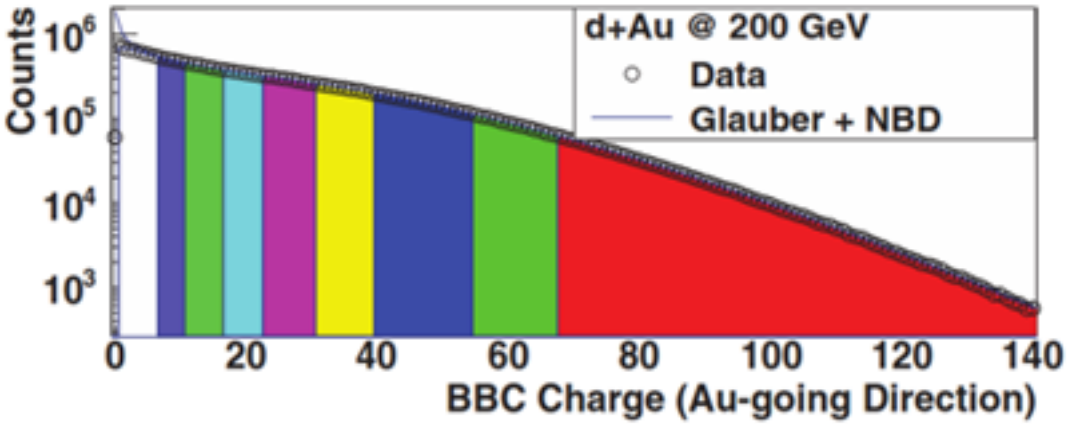
CNM alone can't explain the suppression

CNM + QGP can't explain the enhancement

- Suppression for the central events could be explained with QGP formation. Enhancement cannot be trivially explained from physical arguments.

How is centrality determined in PHENIX?





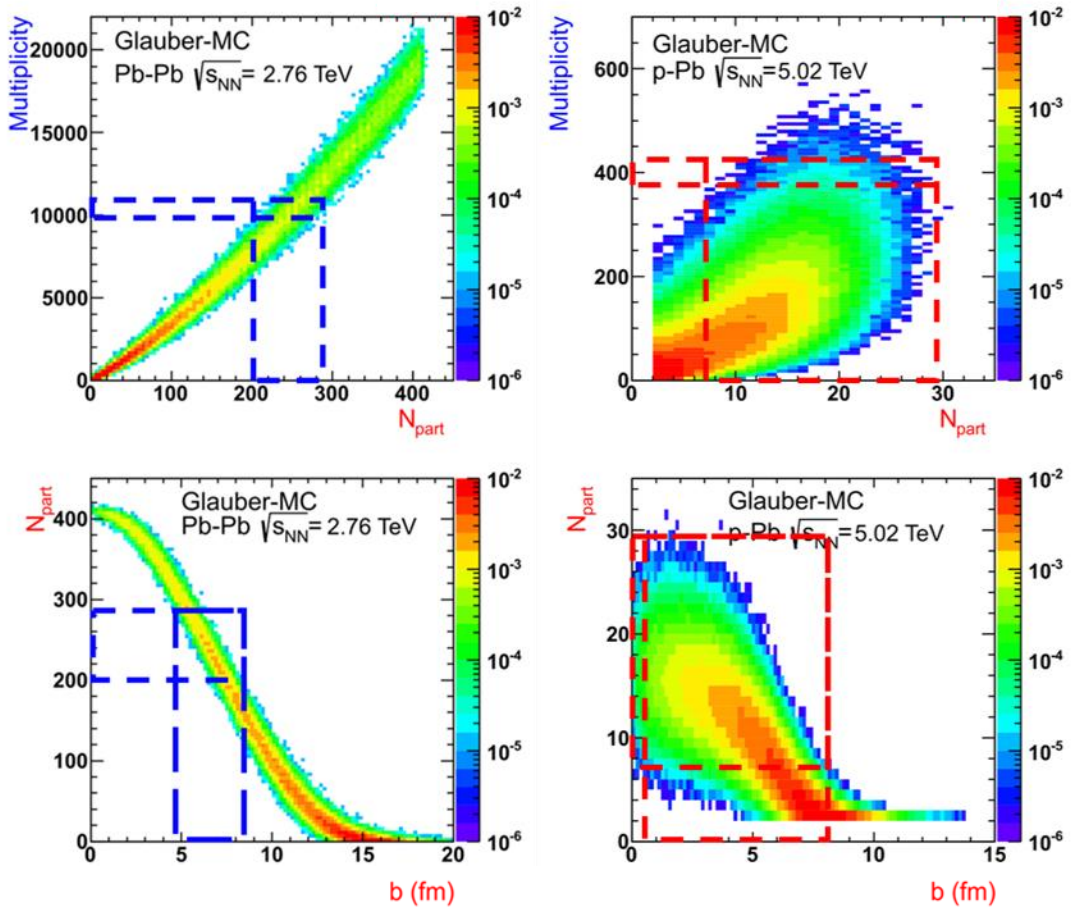
- Centrality is determined by event activity in the BBC, on the Au going direction

$$\frac{dN_{ch}}{d\eta} \Rightarrow N_{coll} \underbrace{\Longrightarrow\Longrightarrow\Longrightarrow}_{Model/Theory} N_{par} \underbrace{\Longrightarrow\Longrightarrow}_{Theory} b$$

- $N_{coll}^{GL} \propto \left(\frac{dN_{ch}}{d\eta}\right)^{a}$: Not directly measurable!
  - Obtained through Glauber model

$$R_{AB}^{\pi^0}(p_T) = \frac{Y_{AB}^{\pi^0}}{N_{coll} \cdot Y_{pp}^{\pi^0}}$$

Is the N_{coll}^{GL} good both in small and large systems?



ALICE: PRC91 (2015) 064905

Red axis: theory / model calculations
Blue axis: experimentally measurable

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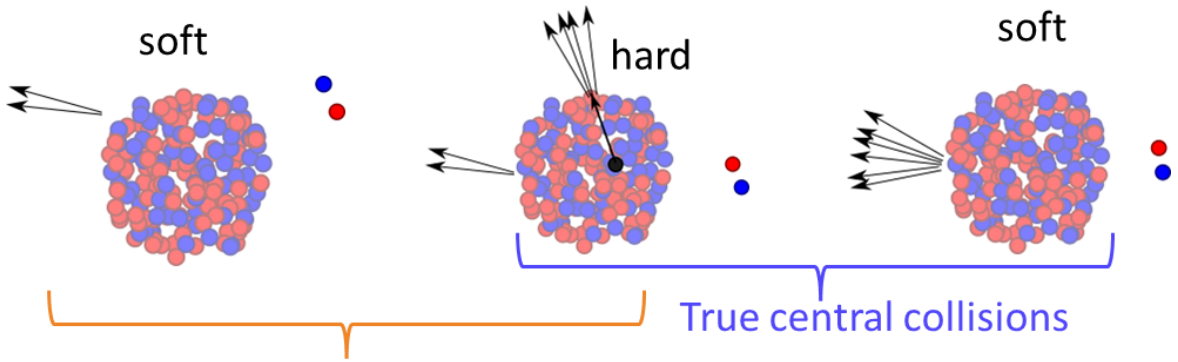
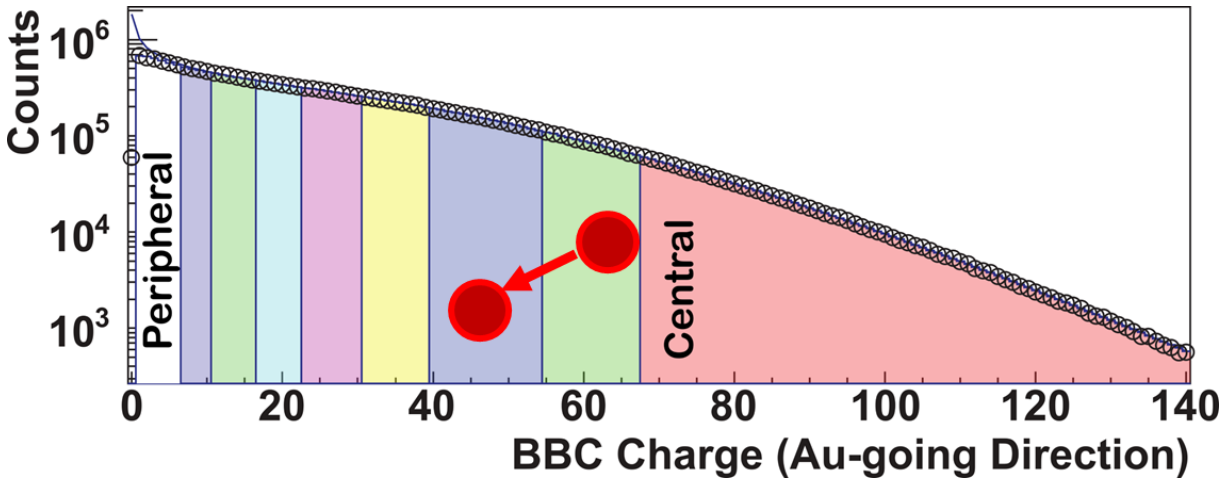
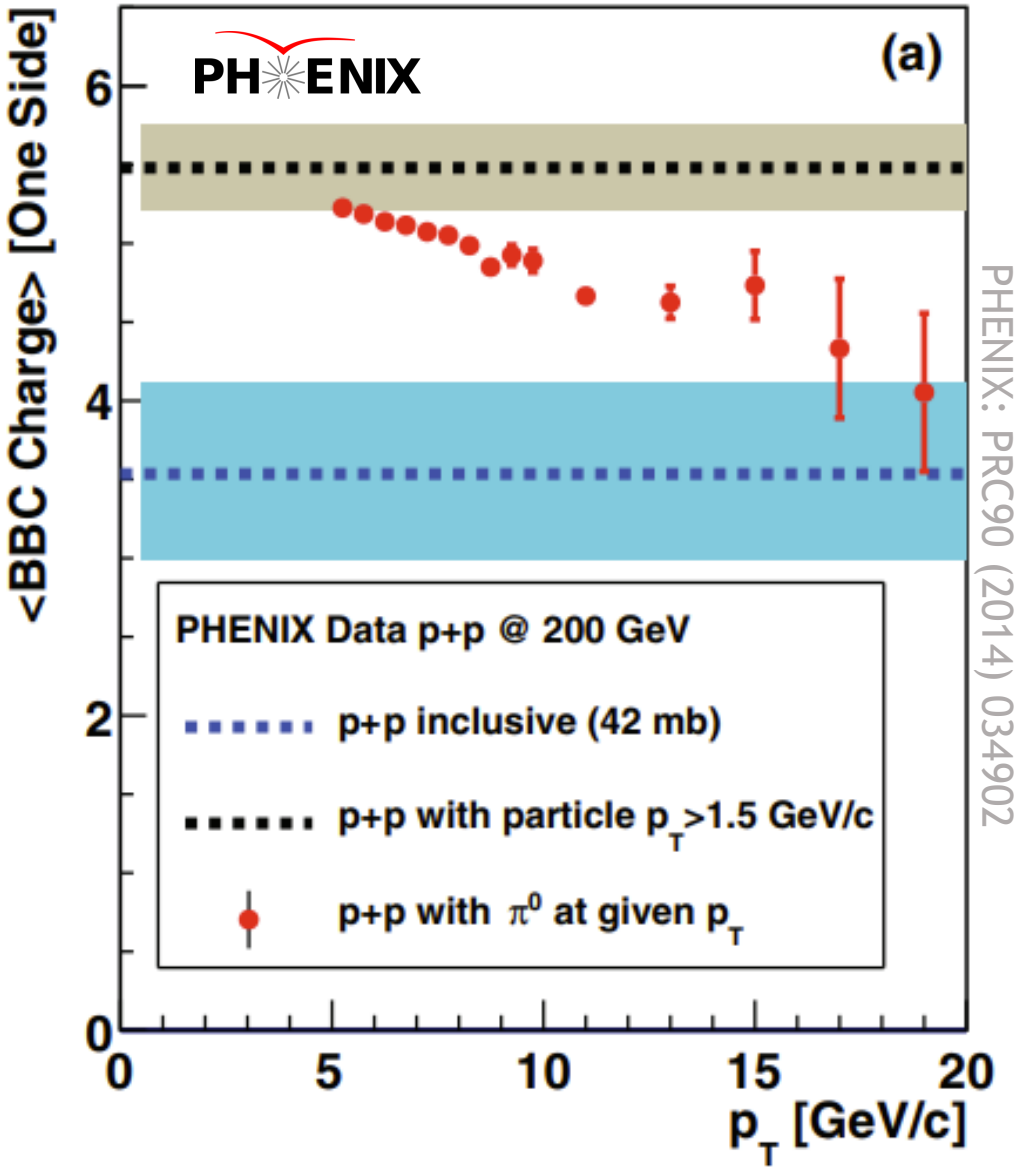
- $N_{coll}^{GL} \propto \left(\frac{dN_{ch}}{d\eta}\right)^{a}$: Not directly measurable!
  - Obtained through Glauber model
- A 0-20% centrality Pb+Pb collision is equivalent to an impact parameter of 3 fm, with **small** variance
- A 0-20% centrality p+Pb collision is equivalent to an impact parameter of 3 fm, with **large** variance

There IS bias in small systems!

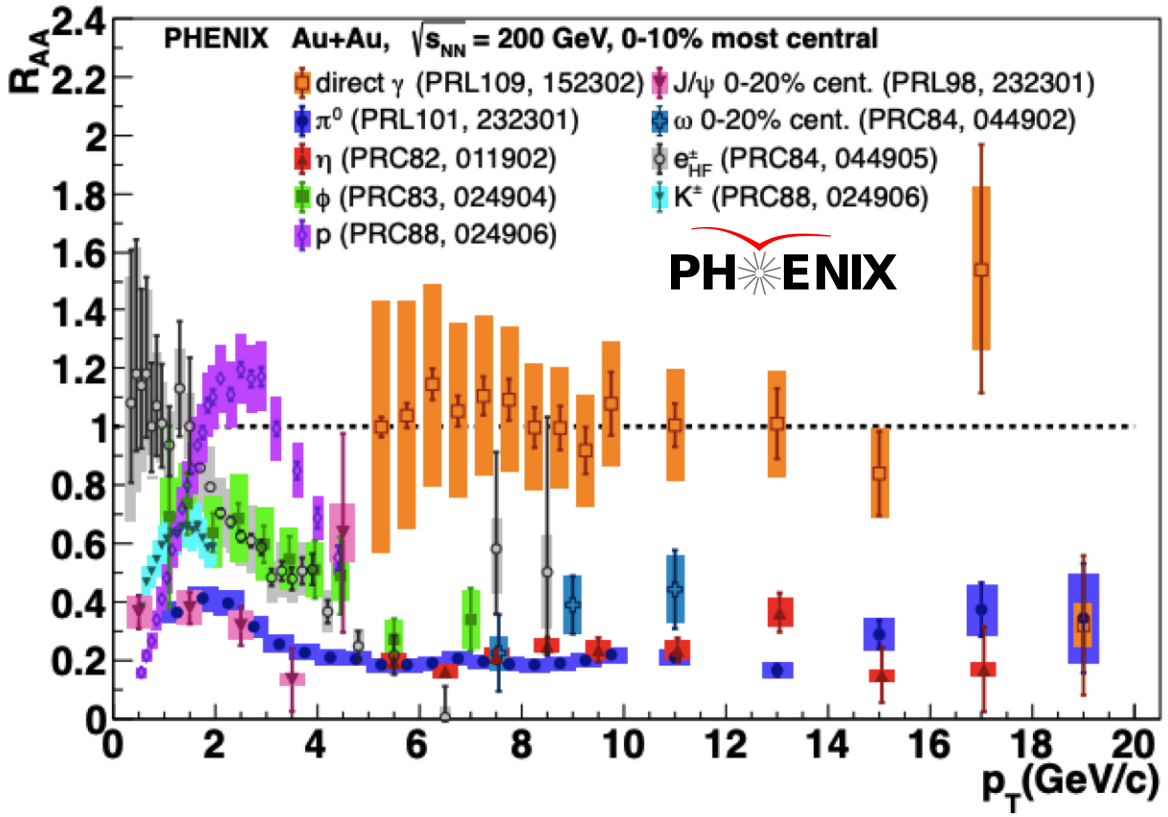


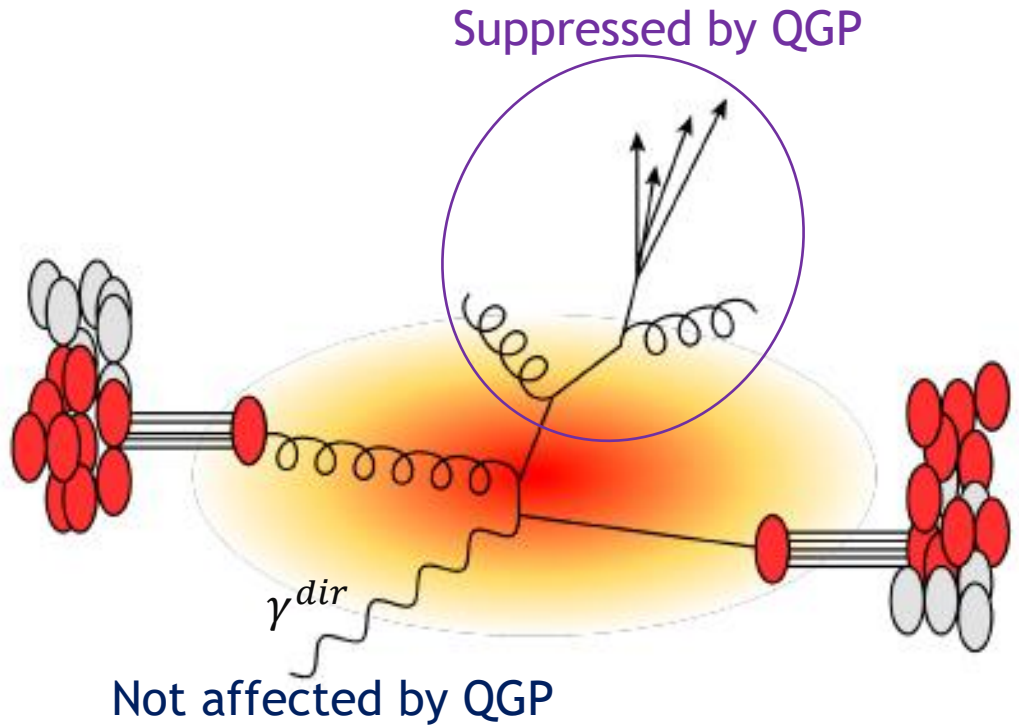




Think conservation of energy: more midrapidity, less forwards/backwards

Direct photons to the rescue!





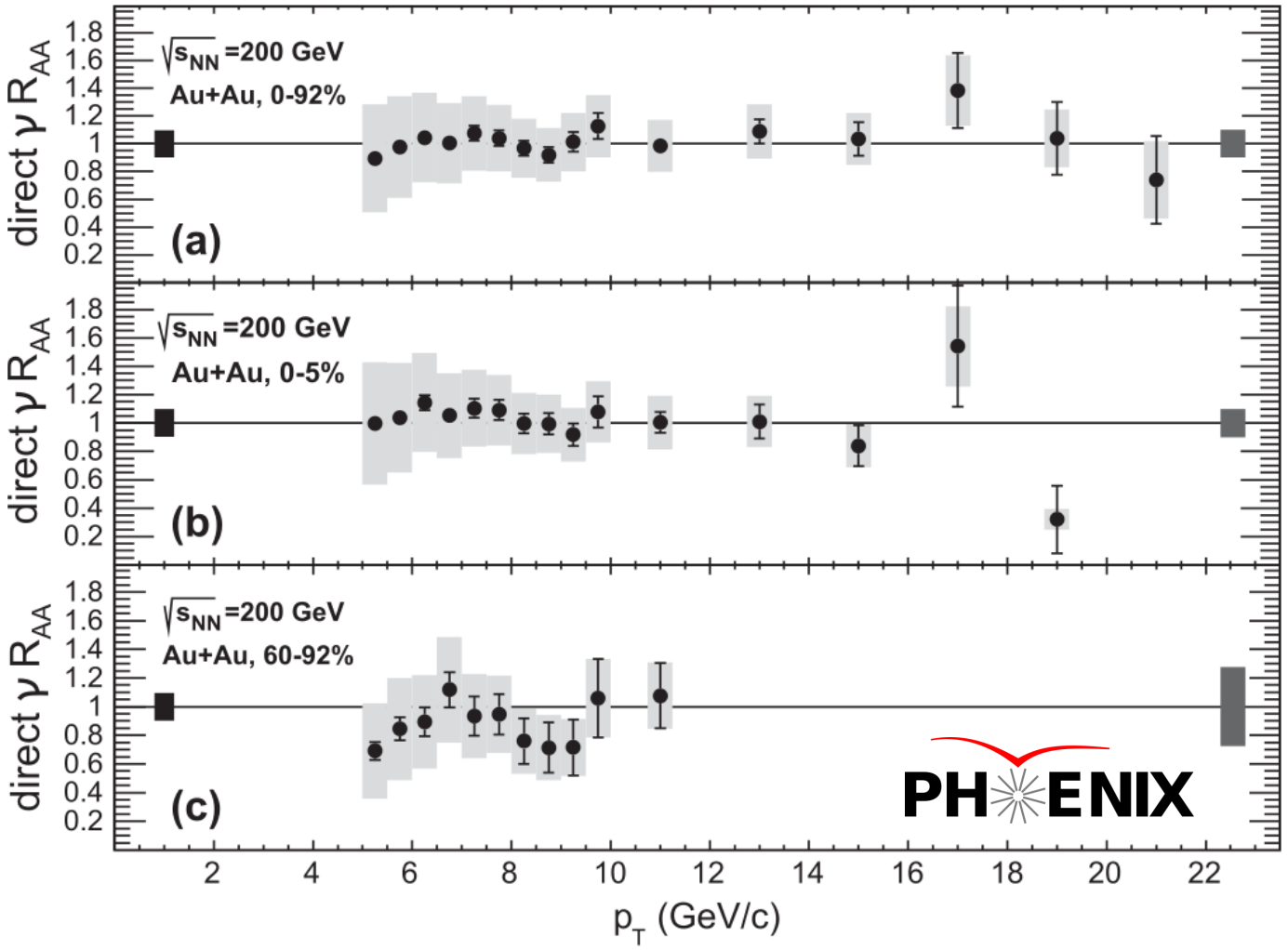
- Unlike color charged matter, direct photons are unaffected by QGP.
- γ^{dir} can be used as an **unbiased direct measure of event activity**

Direct measurement of the N_{coll}

$$R_{AB}^{\gamma^{dir}}(p_T) = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{N_{coll} \cdot Y_{pp}^{\gamma^{dir}}(p_T)} \approx 1$$

- The ratio of direct photon yields can be used as a measure of N_{coll}:

$$N_{Coll}^{EXP} = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$$

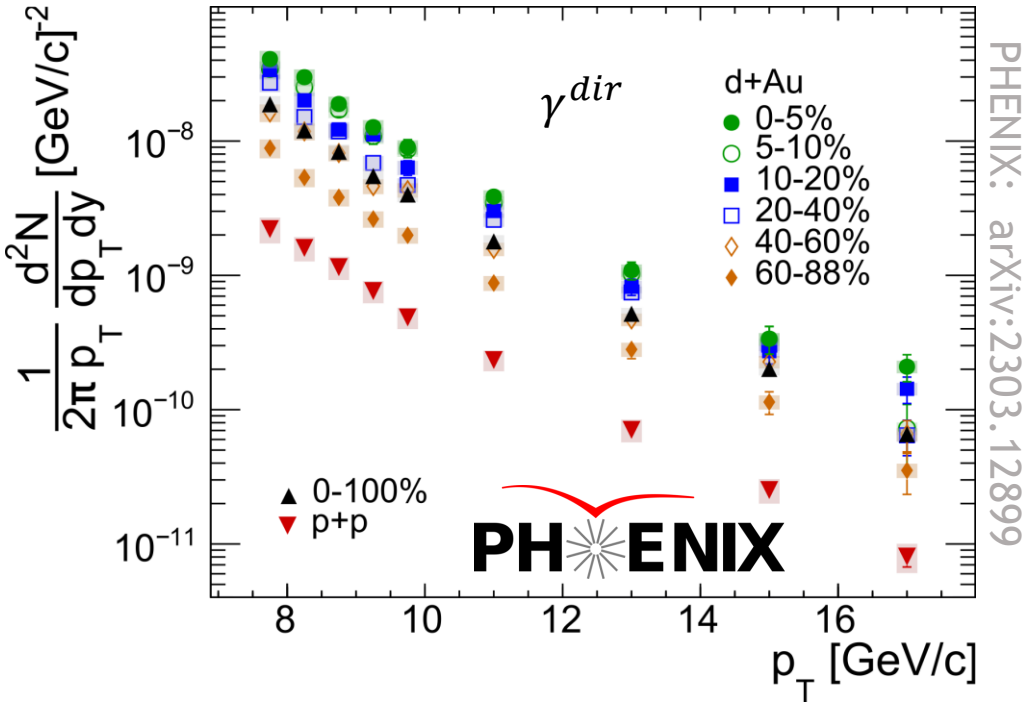


PHENIX: PRL109 (2012) 152302

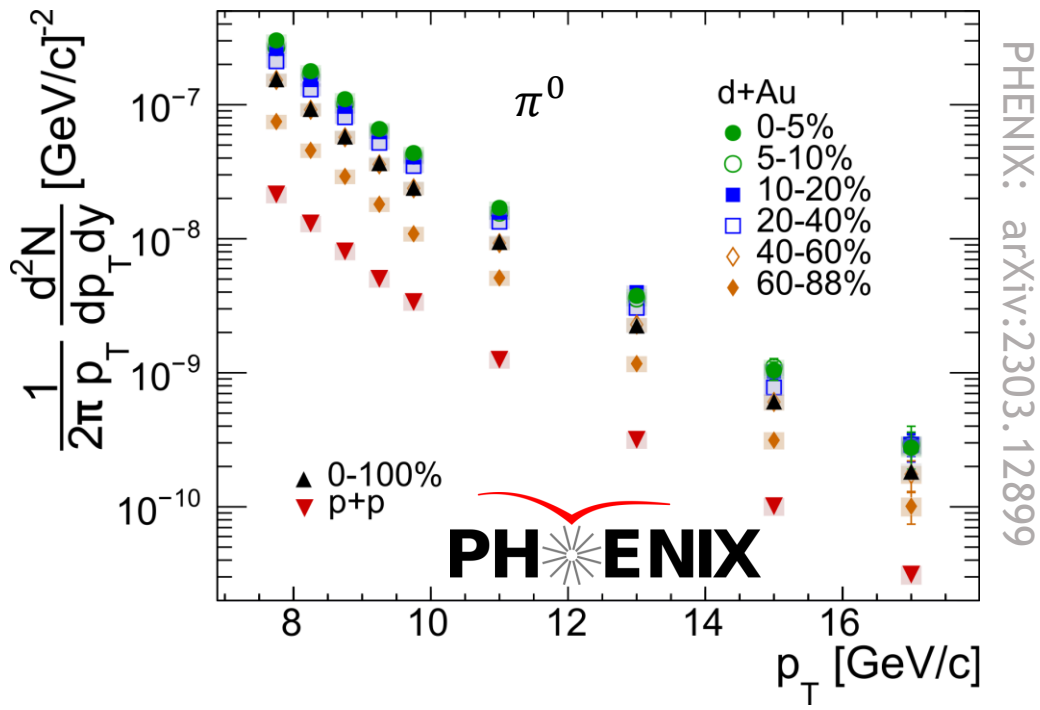
γ^{dir} and π^0 invariant yields:

High p_T γ^{dir} and π^0 (7.5 < p_T < 18 GeV/c)

- γ^{dir} consistent with 2003 min bias data (PHENIX: PRC87(2013)54907)
- π^0 consistent with 2008 data (PHENIX:PRC(2022)64902)

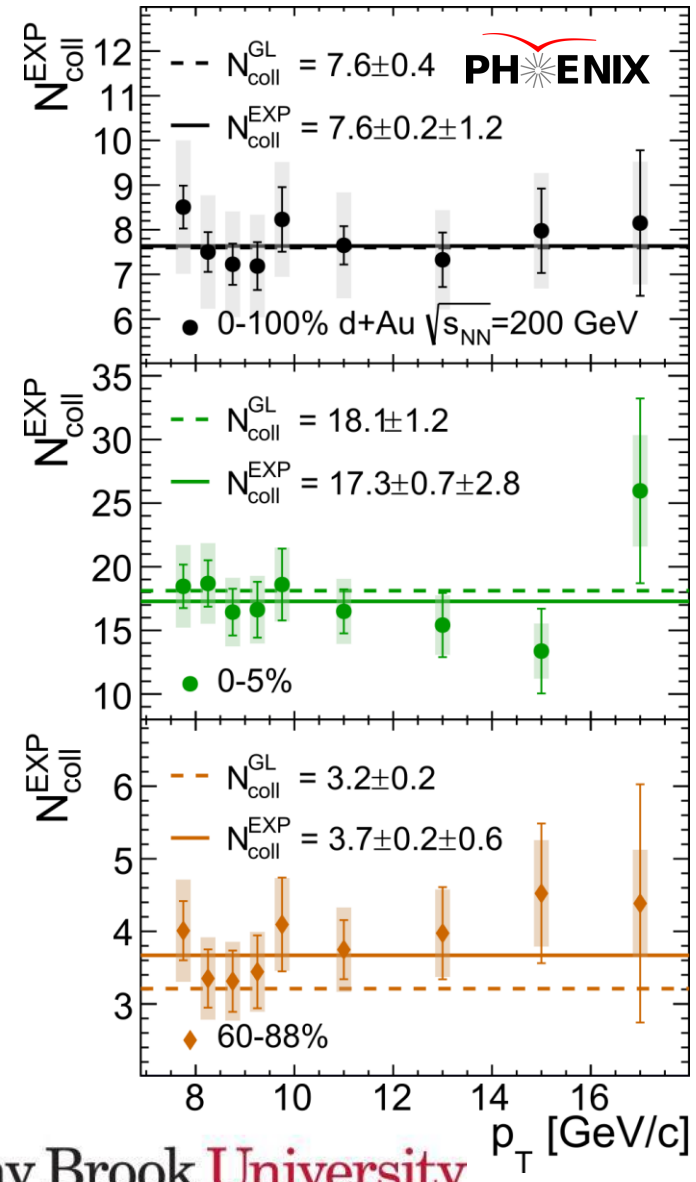


p+p reference: PHENIX: PRD86(2012)72008



p+p reference: PHENIX: PRC(2022)64902

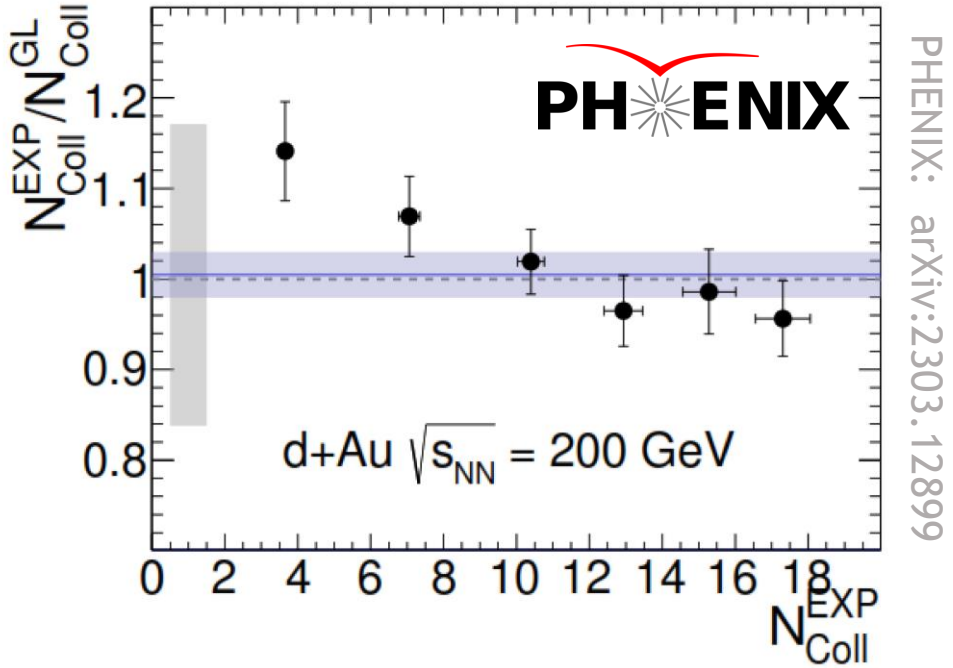
Comparison with Glauber N_{coll}



PHENIX: arXiv:2303.12899

$$N_{Coll}^{EXP} = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$$

- Good agreement between N_{Coll}^{EXP} and N_{Coll}^{GL} is seen in central collisions
- 15% deviation is seen in peripheral collisions



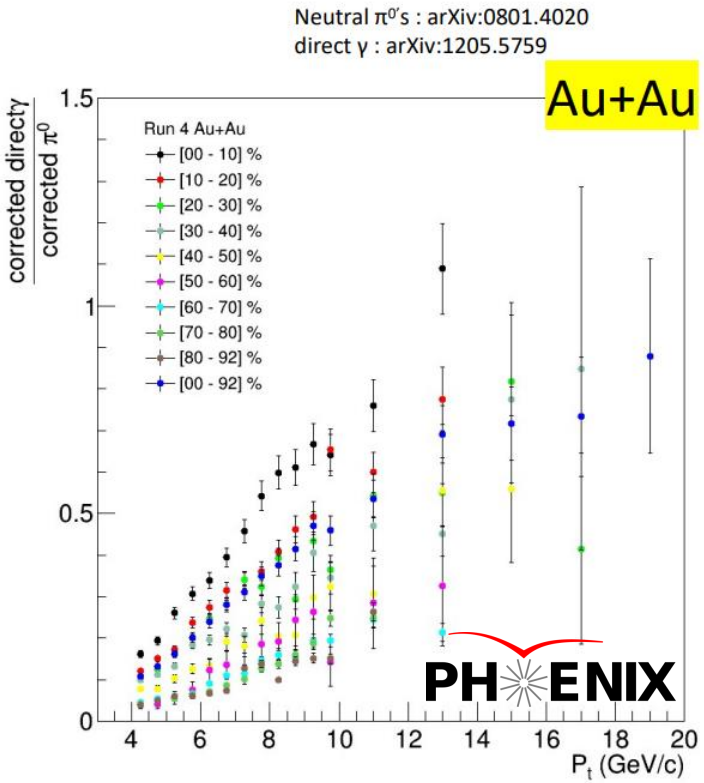
PHENIX: arXiv:2303.12899

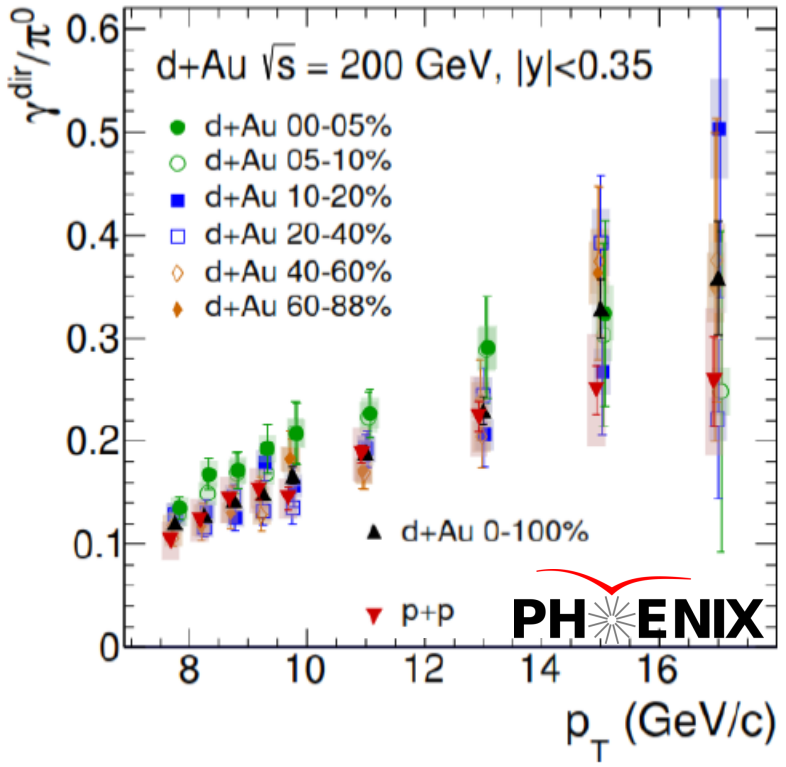
Peripheral → Central

$\frac{\gamma^{dir}}{\pi^0}$: An observable of centrality bias

Corrected direct γ spectrum
(centrality independent)

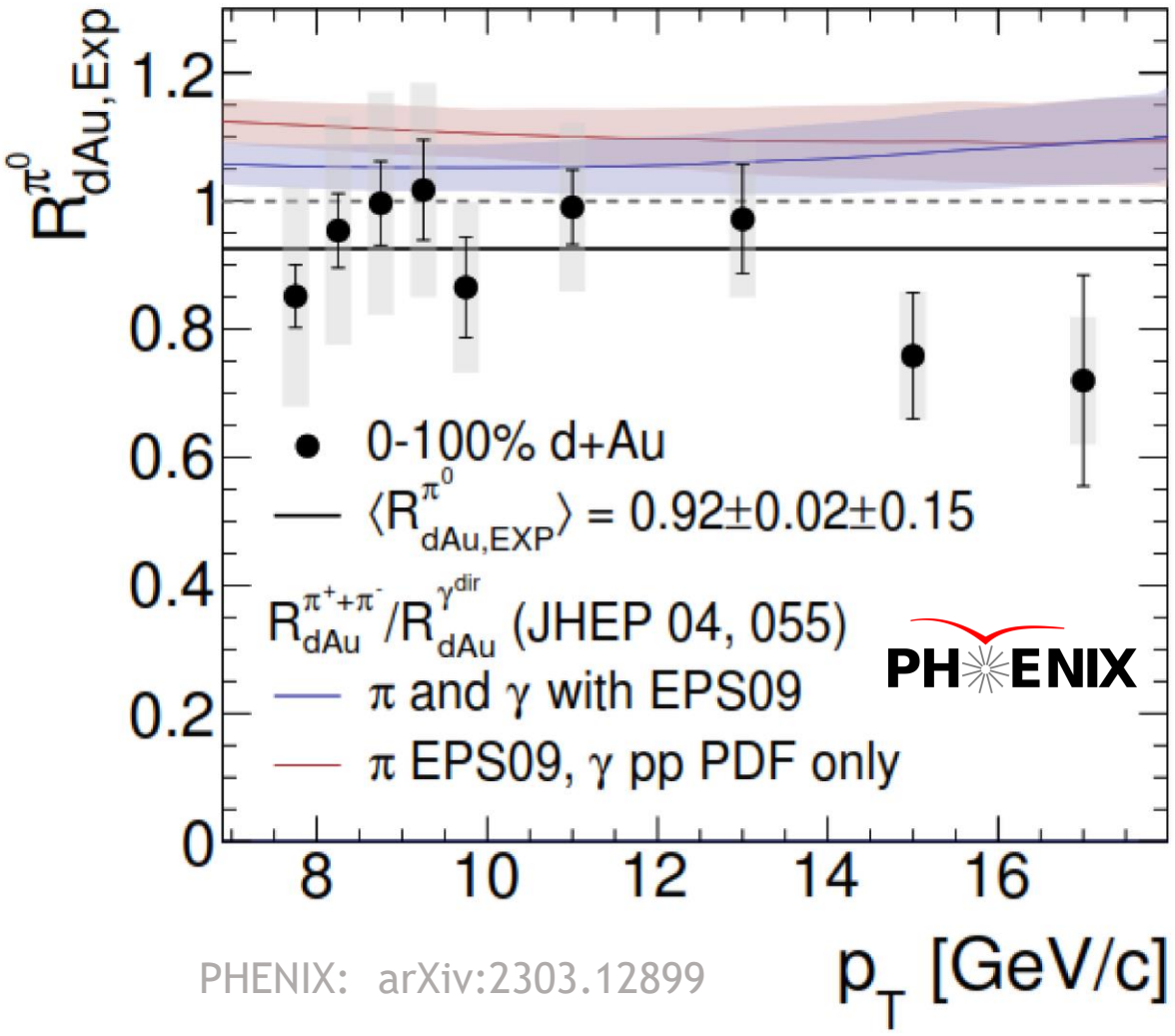
Corrected π^0 spectrum
(centrality dependent)





- Au+Au shows a clear centrality separation
- d+Au shows consistency between peripheral events and min. bias
- Central (0-5%) separates

Nuclear modification factor for π^0 in d+Au



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$$R^{\pi^0}_{AB,exp}(p_T) = \frac{Y^{\pi^0}_{AB}(p_T)}{N^{EXP}_{Coll} \cdot Y^{\pi^0}_{pp}(p_T)} \Rightarrow \frac{\left(\gamma^{dir}/\pi^0\right)^{pp}}{\left(\gamma^{dir}/\pi^0\right)^{AB}}$$

- Minimum bias (0-100%):
  - No significant p_T dependence
  - Average:

$$\left\langle R^{\pi^0}_{dAu,exp} \right\rangle = 0.92 \pm 0.02 \pm 0.15$$

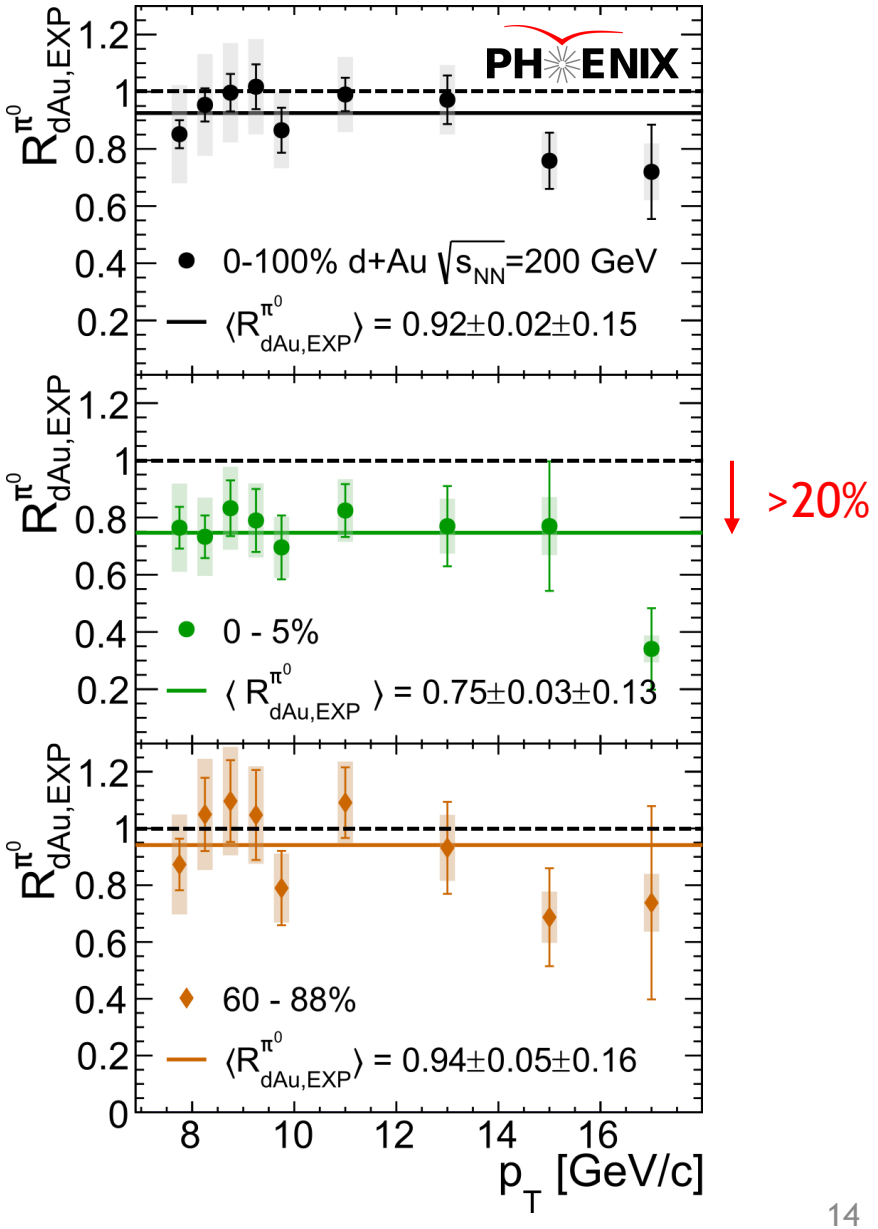
  - Consistent with unity
  - Consistent with 5% enhancement from CNM effects*

*Arleo et al.: CNM effects largely cancel in the γ^{dir}/π^0 in this p_T range

Nuclear modification factor for π^0 in d+Au

$$R^{\pi^0}_{AB,exp}(p_T) = \frac{Y^{\pi^0}_{AB}(p_T)}{N^{EXP}_{Coll} \cdot Y^{\pi^0}_{pp}(p_T)} \Rightarrow \frac{(\gamma^{dir}/\pi^0)^{pp}}{(\gamma^{dir}/\pi^0)^{AB}}$$

- Peripheral collisions are consistent with inclusive
- Central collisions (0-5%) are consistent with **>20% suppression**
  - No enhancement
  - Clear suppression!



PHENIX: arXiv:2303.12899

Nuclear modification factor for π^0 in d+Au

Average $R^{\pi^0}_{dAu,exp}$ vs N^{exp}_{coll}

- For $N^{exp}_{coll} < 14$:

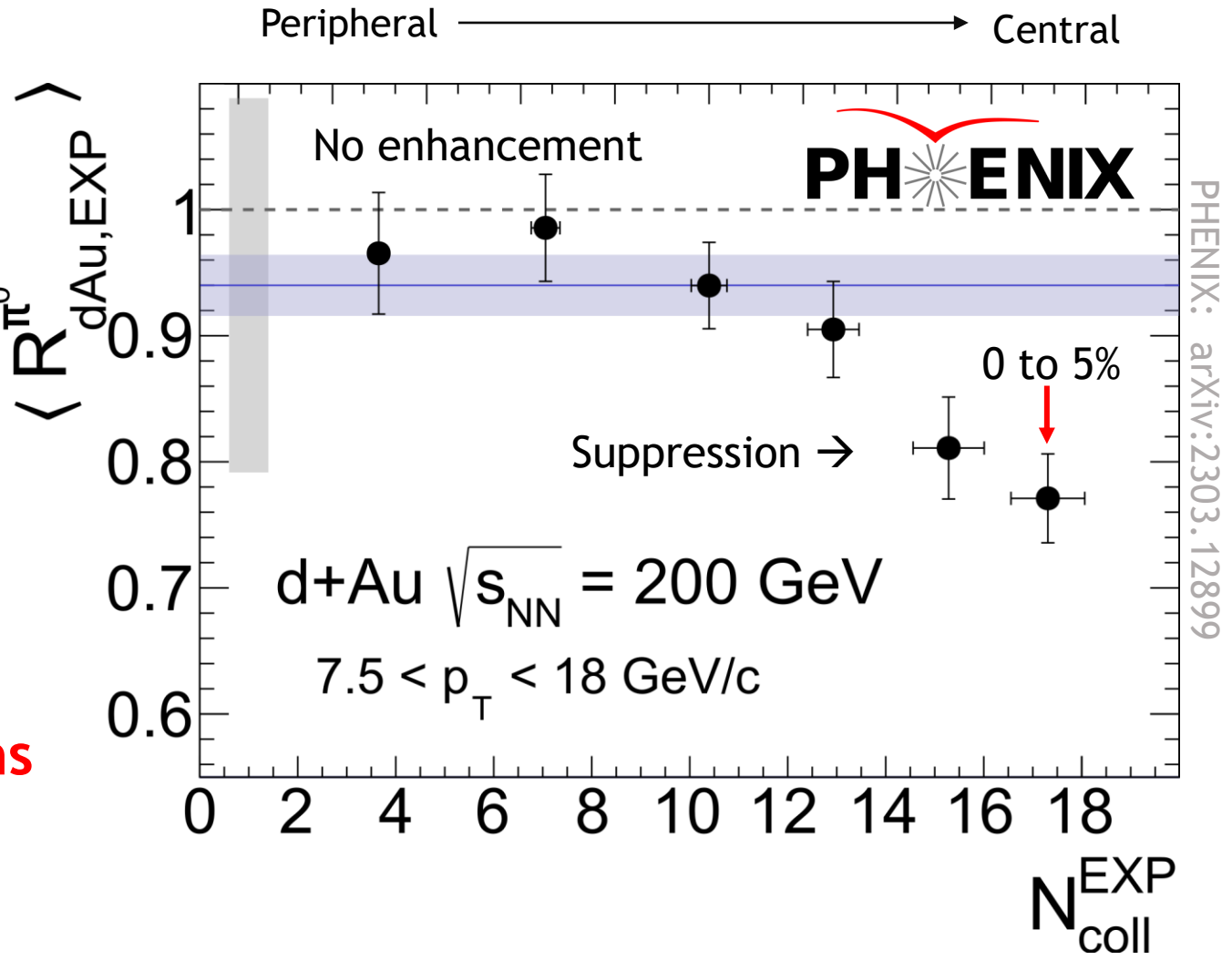
$$\frac{R^{\pi^0}_{dAu,exp}(60-88\%)}{R^{\pi^0}_{dAu,exp}(0-100\%)} = 1.017 \pm 0.56$$

  - Consistent with inclusive d+Au

- Suppression for $N^{exp}_{coll} > 14$.

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

20% suppression with 4.5σ significance in central d+Au collisions at 200GeV!

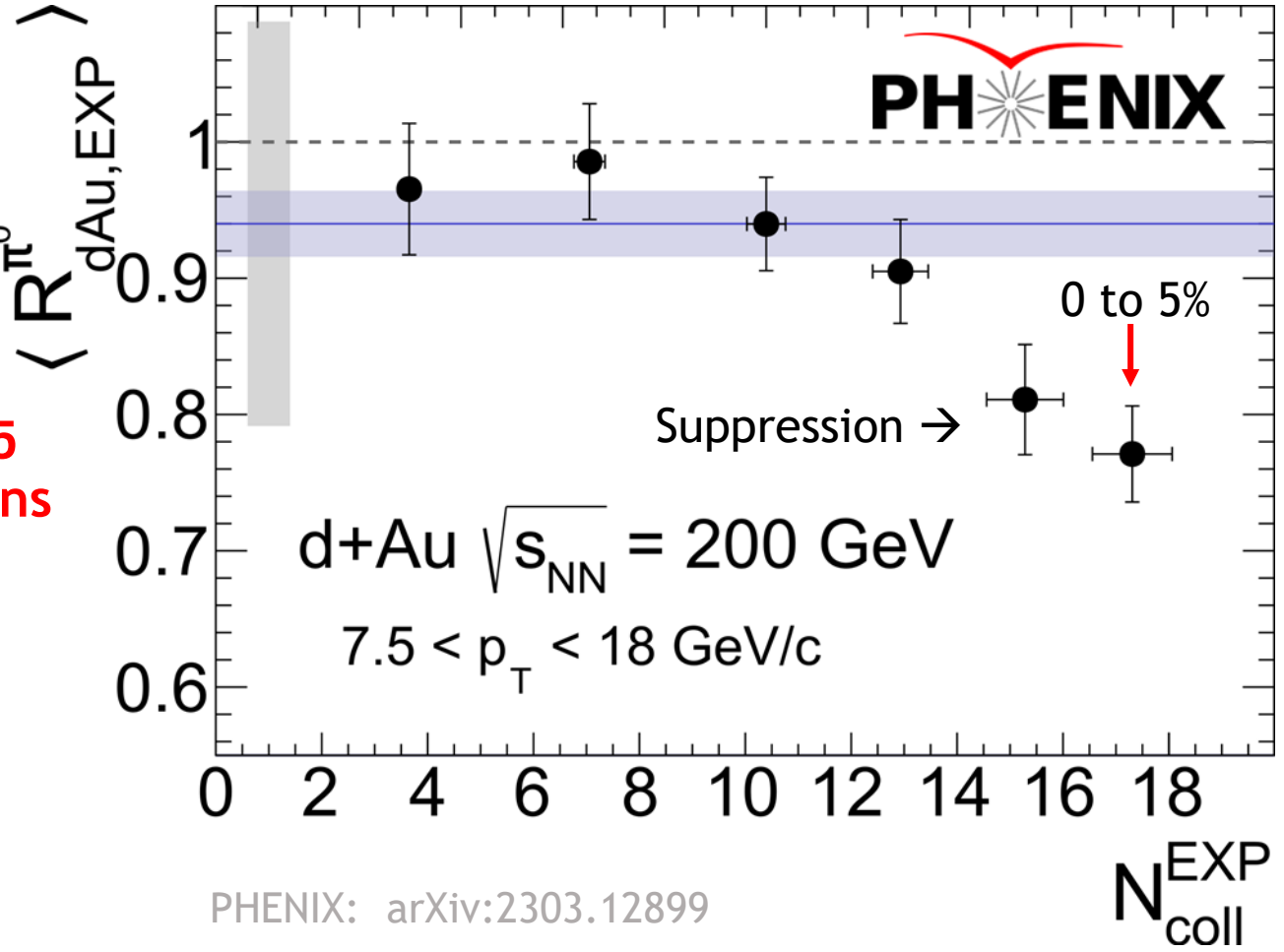


Summary

- New method of obtaining N_{coll}^{exp}
  - Ratio of γ^{dir} in d+Au to p+p
  - No dependence in Glauber model
  - No longer enhancement of peripheral events: selection bias

- **Evidence of suppression (20%!) of high p_T (7.5 to 18 GeV/c) π^0s in central 0-5% d+Au collisions at 200 GeV**

- Further investigations:
  - Ordering of other small systems:
    p+Au $<^?$ d+Au $<^?$ ^{3}He+Au (?)
  - Reduction of systematic uncertainties from p+p dataset



PHENIX: arXiv:2303.12899

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Backup:

Data analysis

The 2016 dataset for d+Au at 200 GeV is used

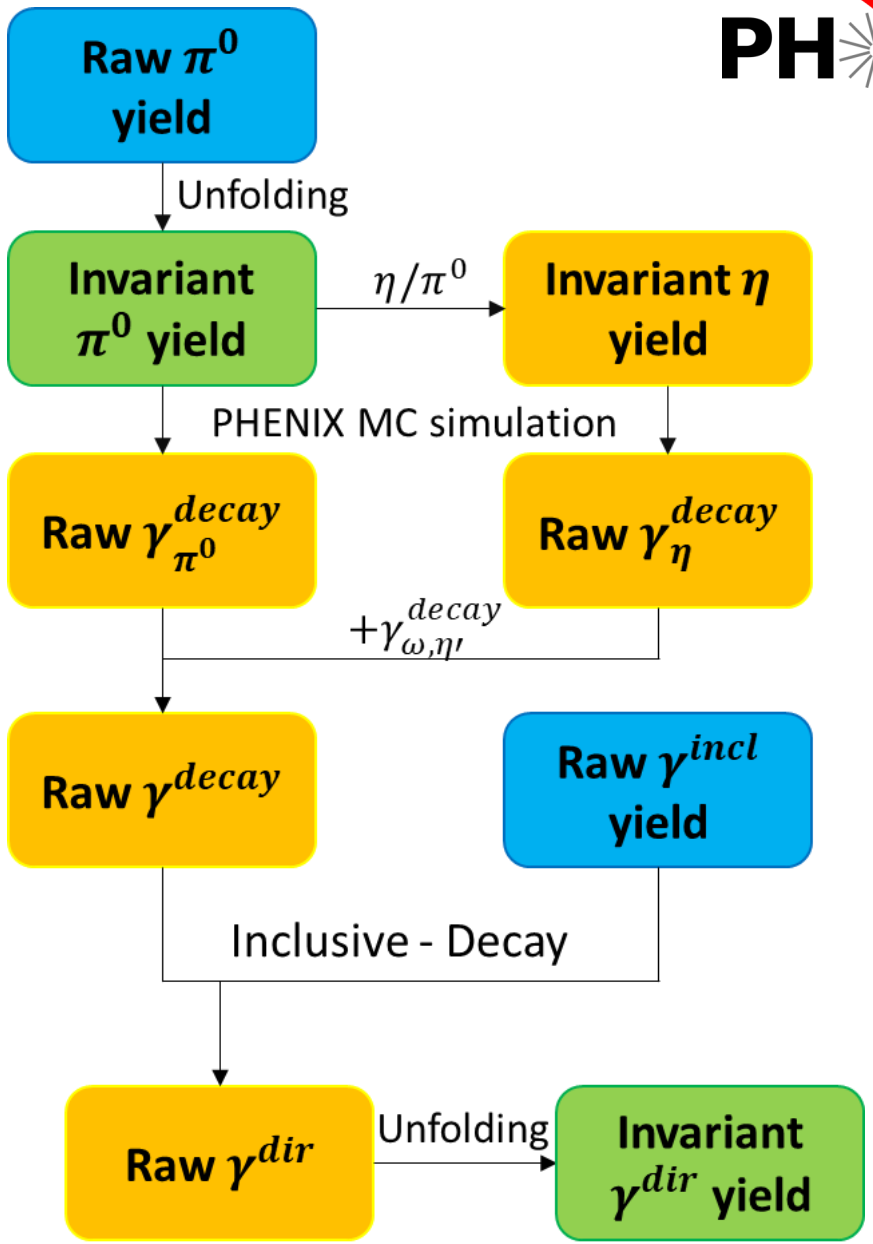
- π^0 reconstructed from γ clusters on the EMCal
- Triggered on high p_T range. Analysis done for γ and π^0 on $p_T > 7.5$ GeV

Analysis chain:

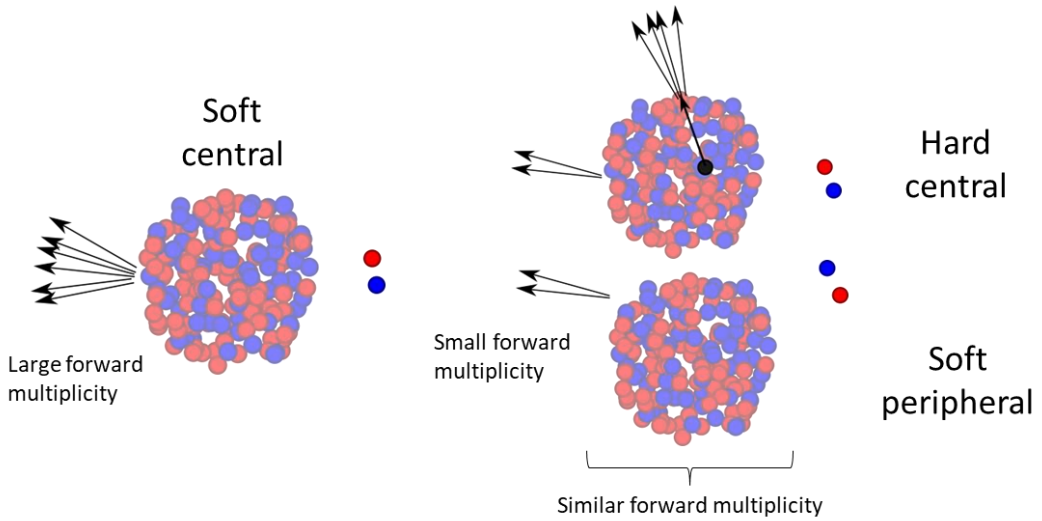
- Reconstructed Raw π^0 from γ showers ($\pi^0 \rightarrow \gamma\gamma$)
- Raw spectra is unfolded to obtain Invariant π^0
  - $\frac{\eta}{\pi^0}$ ratio used to obtain invariant η yield
- Model π^0 and η decay in PHENIX to obtain γ^{decay}
- Subtraction of decay from inclusive raw γ to obtain Raw γ^{dir}
- Unfolding Raw γ^{dir} to obtain Invariant γ^{dir}

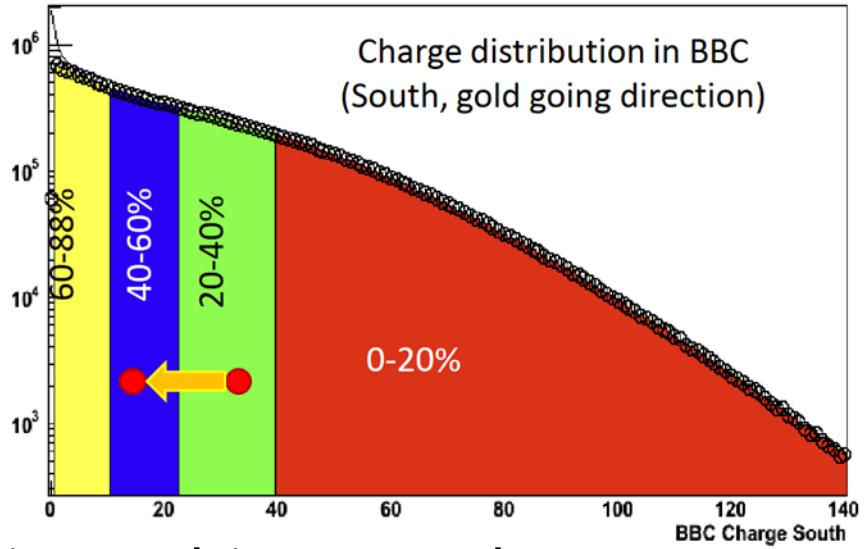
Systematic uncertainties

- $\sim 12\%$ on π^0 and γ^{dir}
- 6% on γ^{dir}/π^0
- Uncertainties on γ^{dir}/π^0 are common to all centralities



Bias in Centrality determination





- Since the event activity is measured in the forward region of the detector, a hard event (think jets) can deplete the forward activity, and would have a high pT event on the central detectors
- This can drive central events to appear as peripheral, explaining a source of “peripheral enhancement” at high pT

$\frac{\gamma^{dir}}{\pi^0}$: An observable of centrality bias

PHENIX

RATIO:

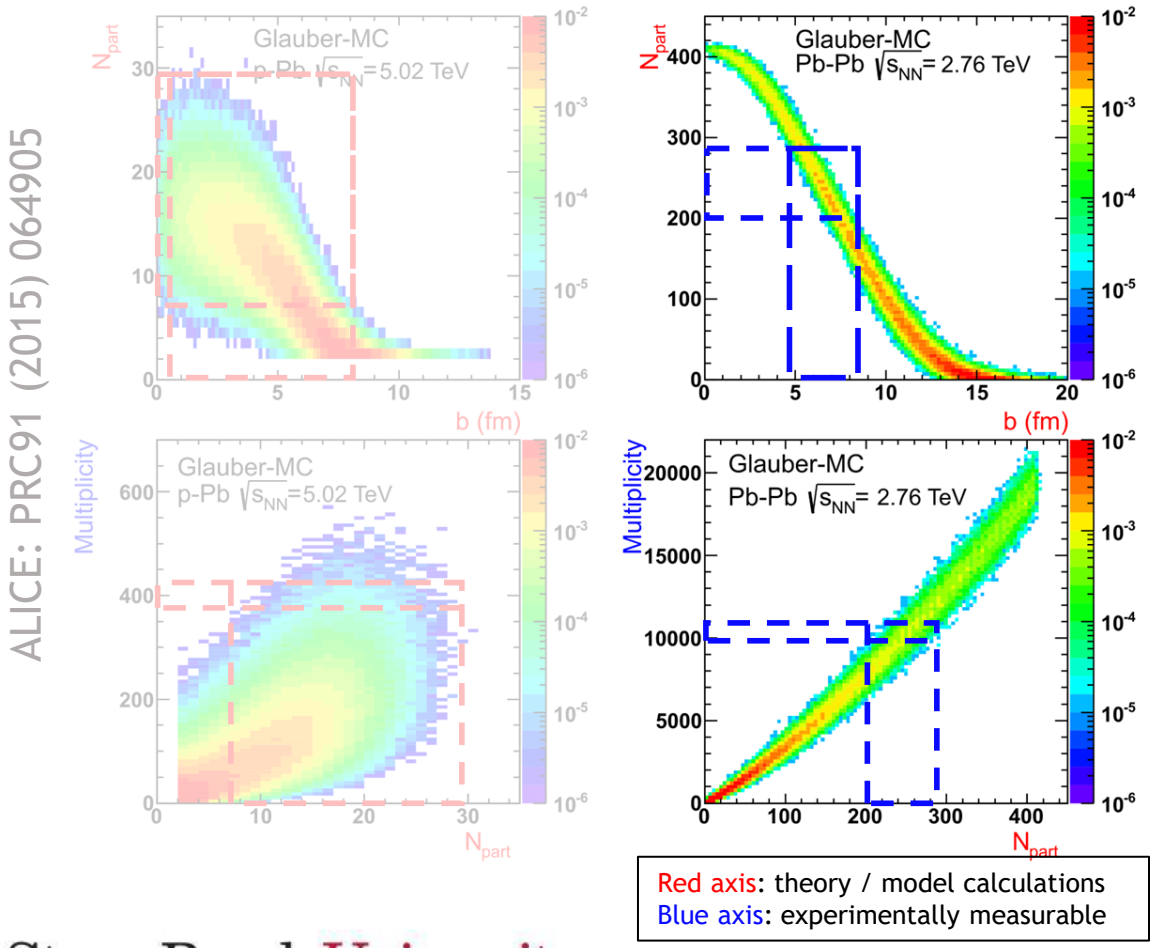
Corrected direct γ spectrum (centrality independent)

Corrected π^0 spectrum (centrality dependent)

Centrality dependent: direct photons are not affected – centrality dependence in π^0 is genuine physics

Centrality Independent: affects direct photons - bias on centrality determination affecting π^0s

Event activity to centrality



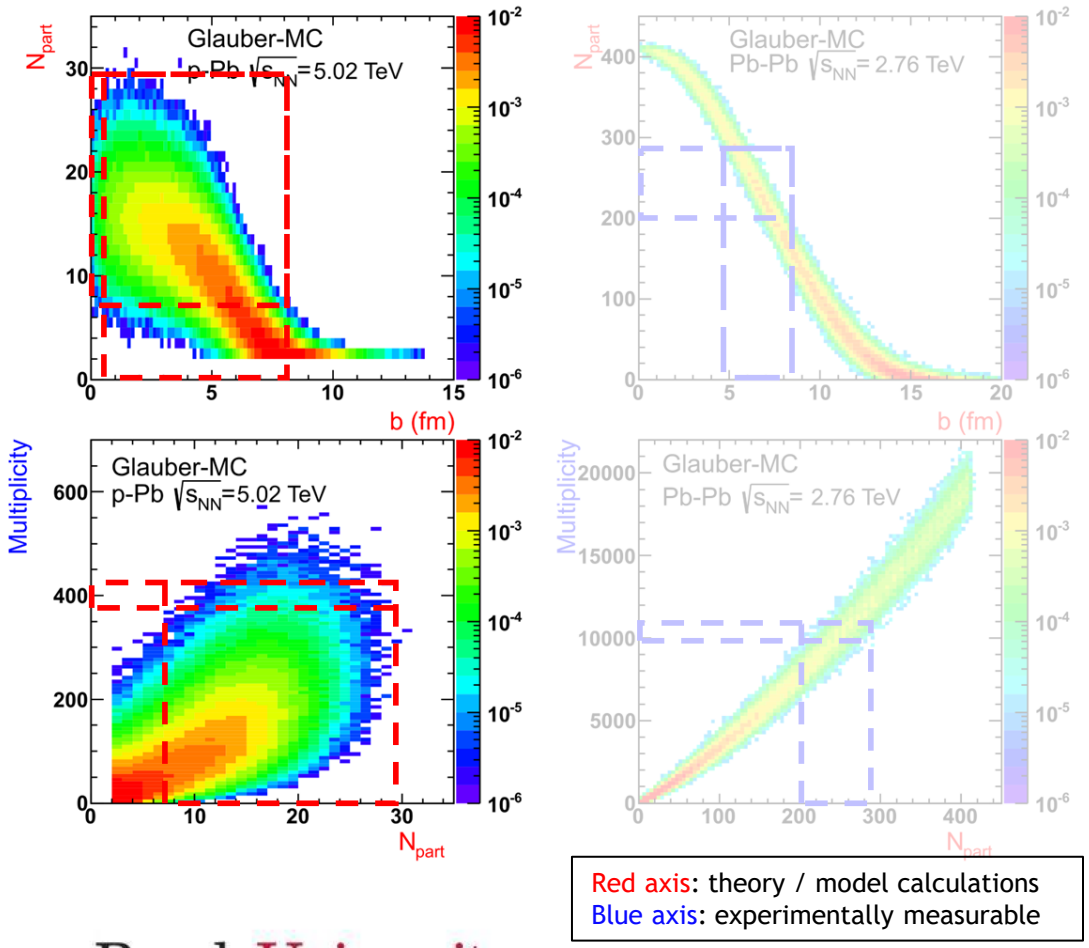
- Centrality is determined by event activity in the BBC, on the Au going direction

$$\frac{dN_{ch}}{d\eta} \Rightarrow N_{coll} \underbrace{\Longrightarrow\Longrightarrow\Longrightarrow}_{Model/Theory} N_{par} \underbrace{\Longrightarrow\Longrightarrow}_{Theory} b$$

$$N_{coll} \propto \left(\frac{dN_{ch}}{d\eta}\right)^{a}$$

- A 0-20% centrality Pb+Pb collision is equivalent to an impact parameter of 3 fm, with **small** variance

Event activity to centrality



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Red axis: theory / model calculations
Blue axis: experimentally measurable

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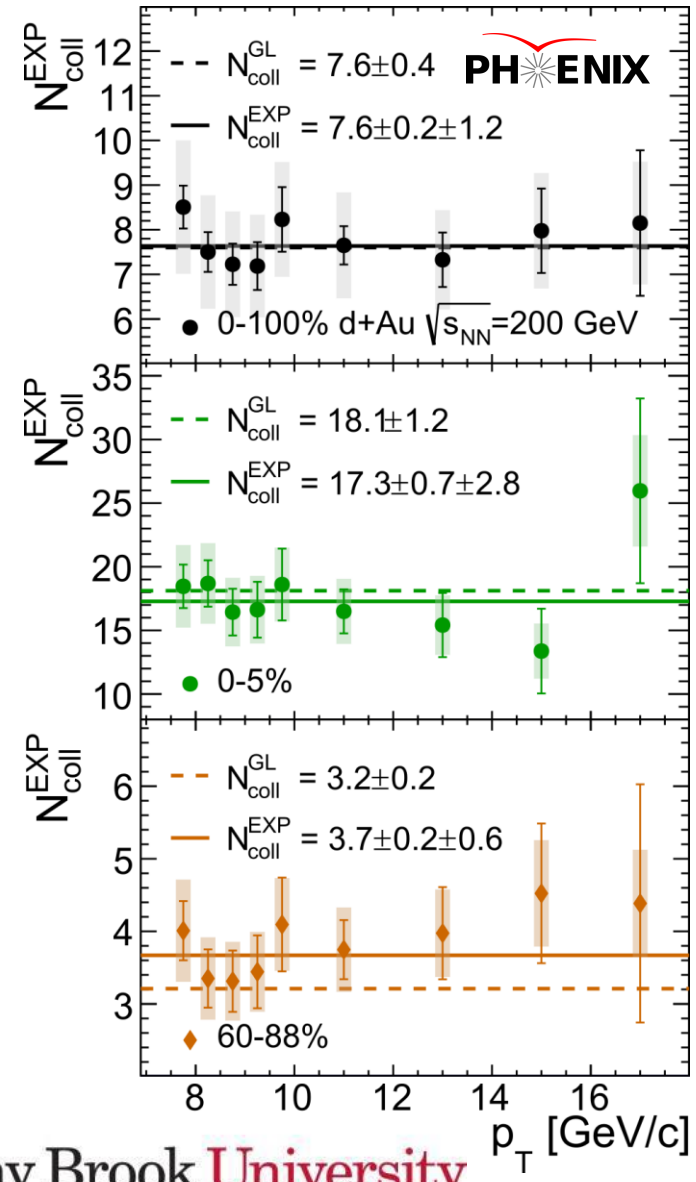
Comparison with Glauber N_{coll}



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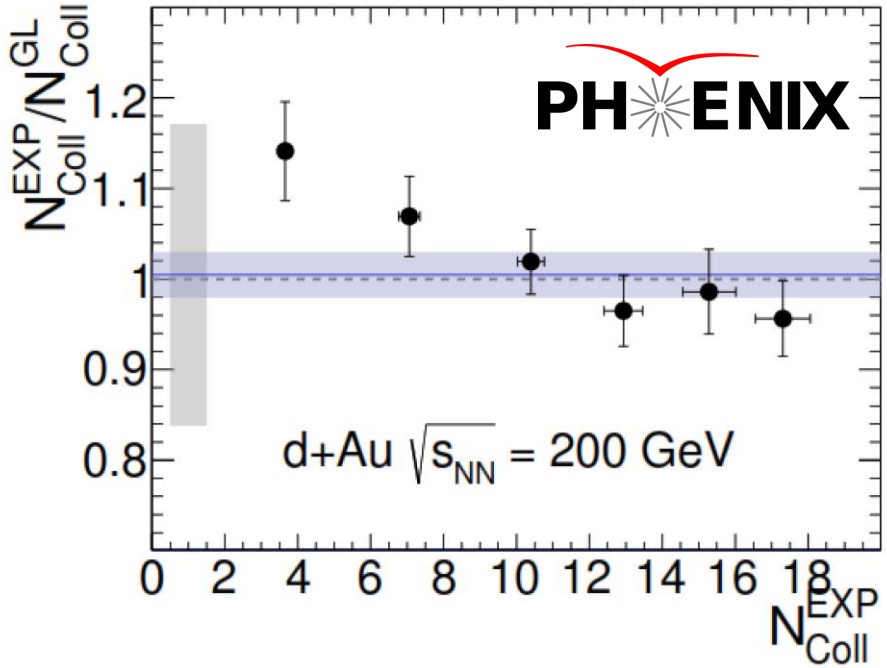
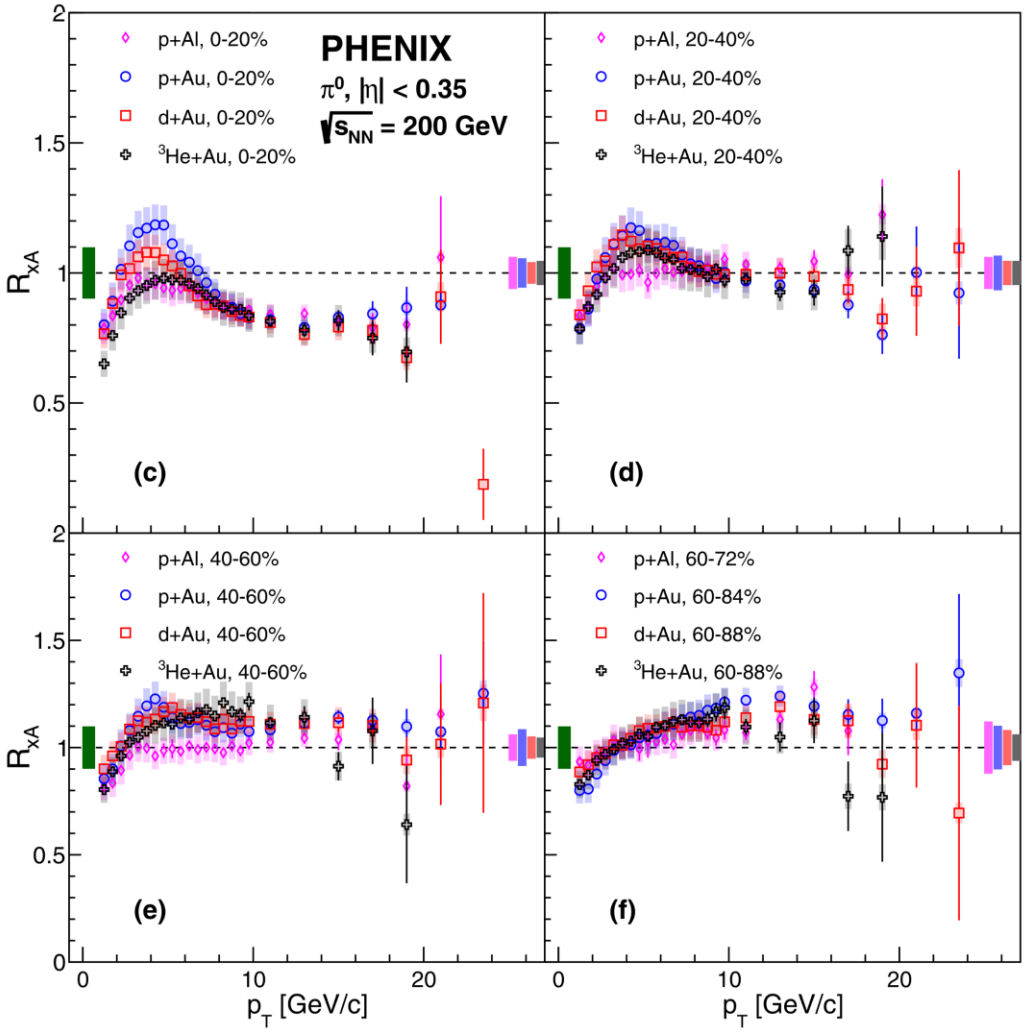


The uncertainties are highly correlated, so even though the points seem consistent with GL within uncertainty (grey band), the consistent decreasing trend is good evidence of deviation

Nuclear modification factor in d+Au



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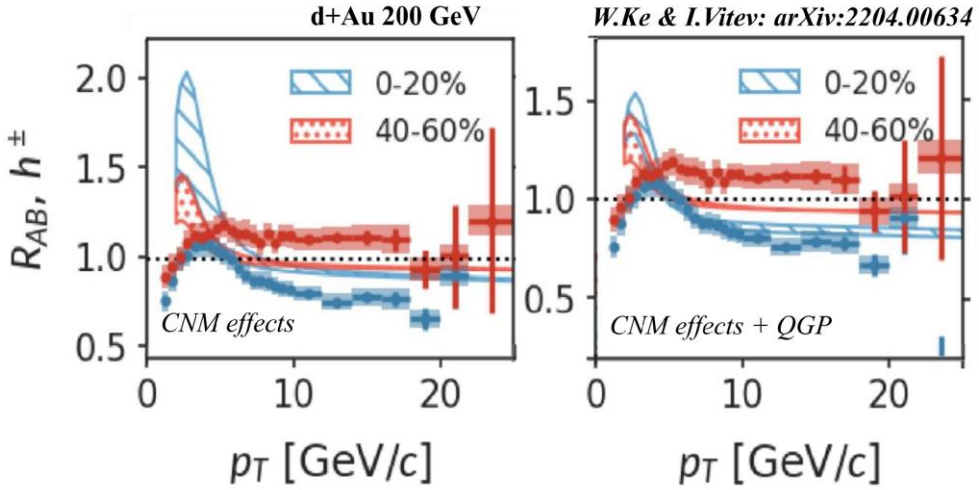
- For high p_T π^0s in small systems, large centrality dependence is observed:
  - Suppression for central events



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