Disentangling centrality bias and final-state effects in the production of π^0 using direct photons in d+Au collisions at 200 GeV

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: N_{Coll}^{EXP}
- Nuclear modification factor in d+Au (PHENIX: arXiv:2303.12899)

WWND39

The 39th Winter Workshop on Nuclear Dynamics

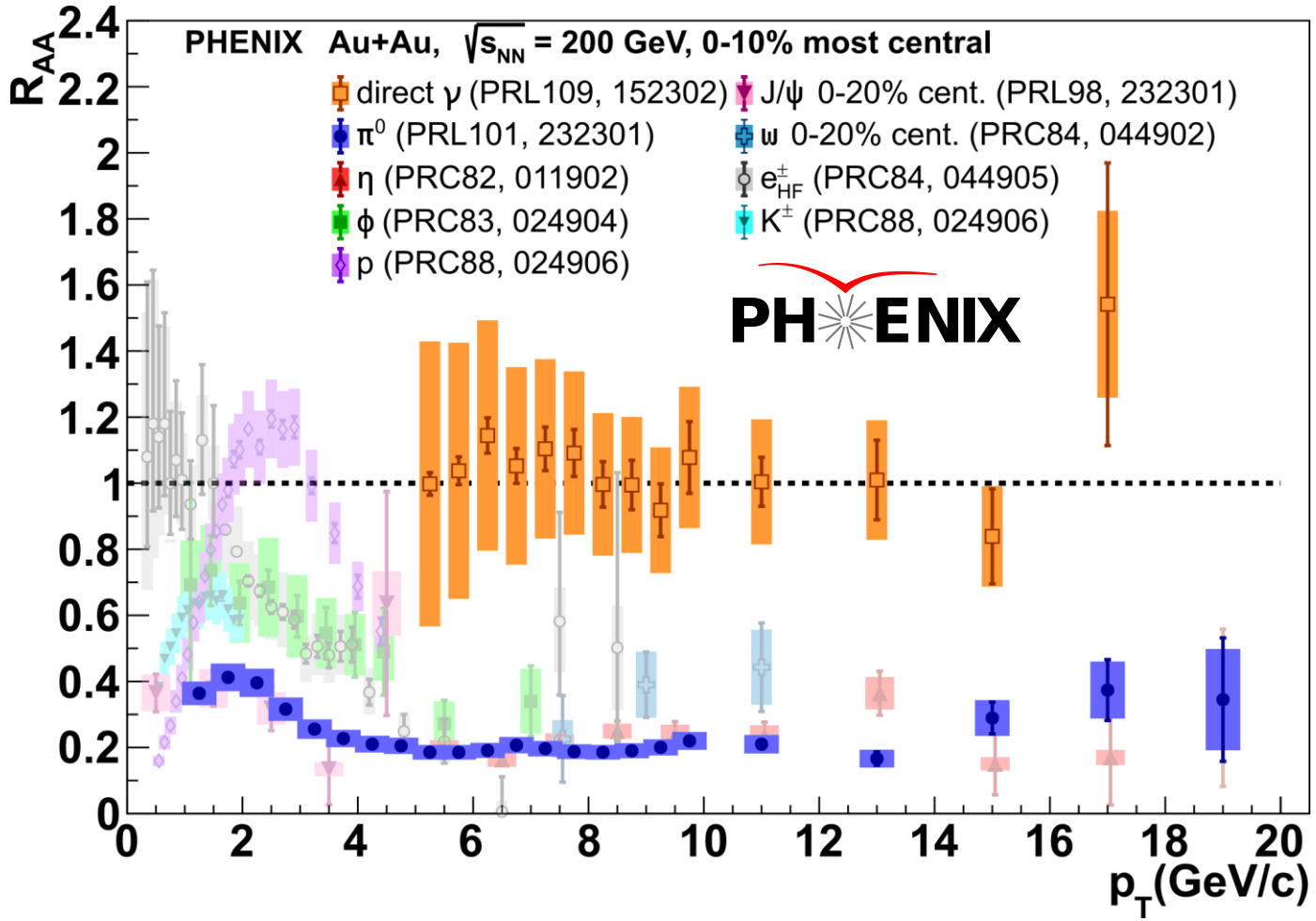
Stony Brook University

PHENIX

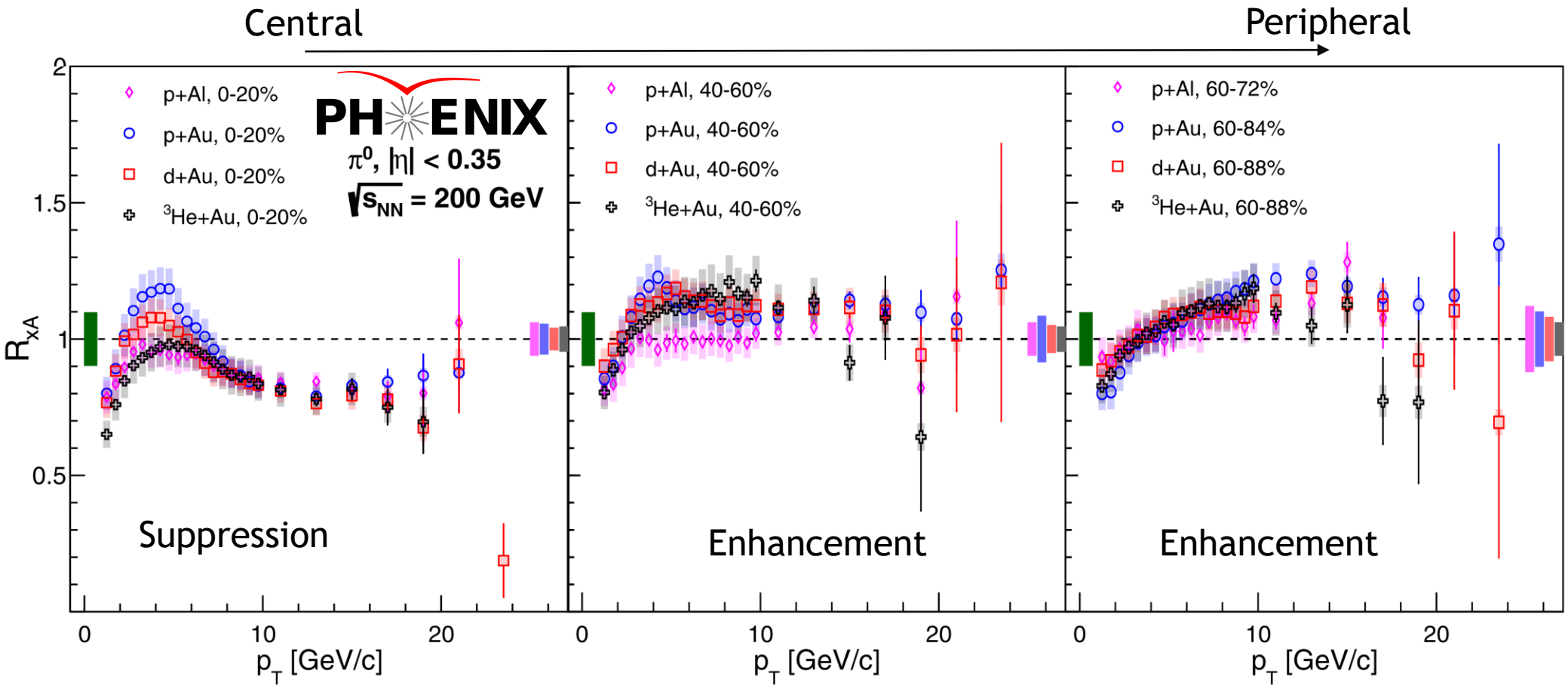
Nuclear modification factor: R_{AB}^{χ}

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

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



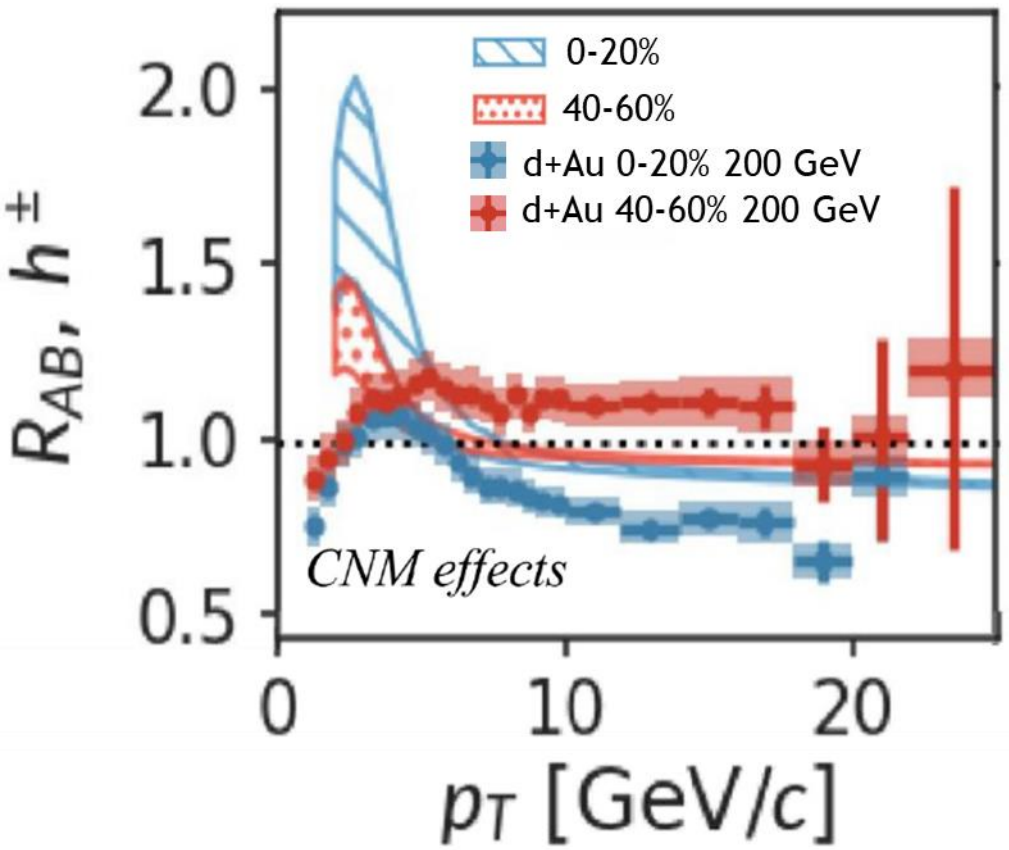
Nuclear modification factor in small systems



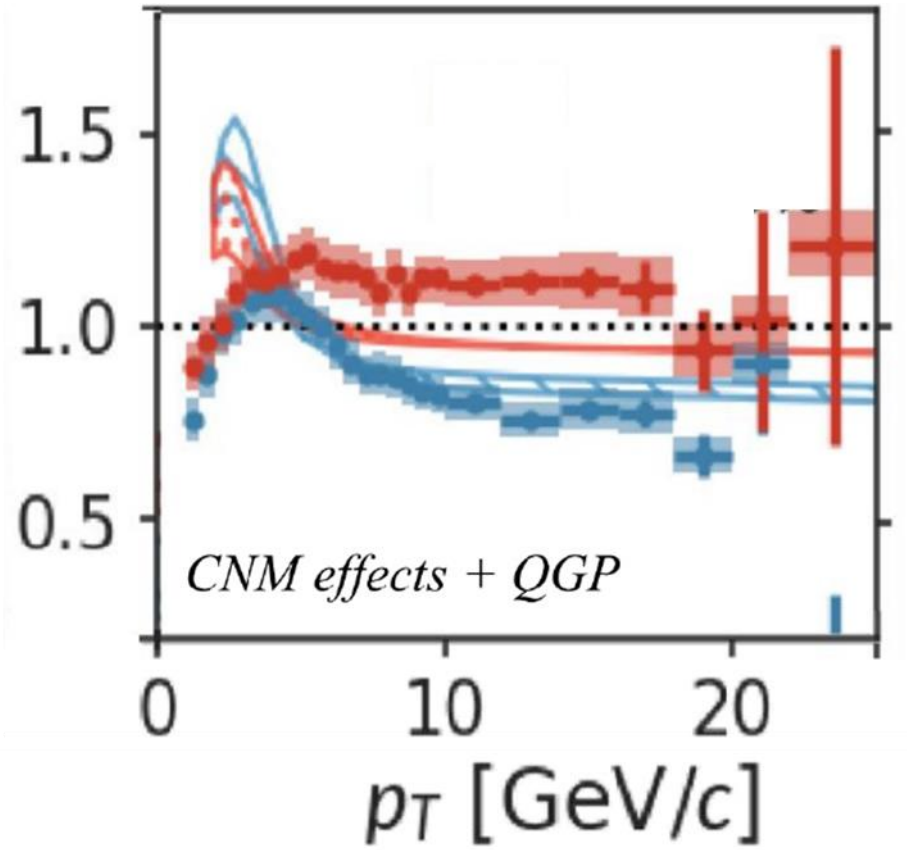
PHENIX: PRC105 (2022) 064902

- Final state effect?
- No physical explanation

Nuclear modification factor in d+Au



CNM alone can't explain the suppression



CNM + QGP can't explain the enhancement

W. Ke, I. Vitev: PRC107 (2023) 064903

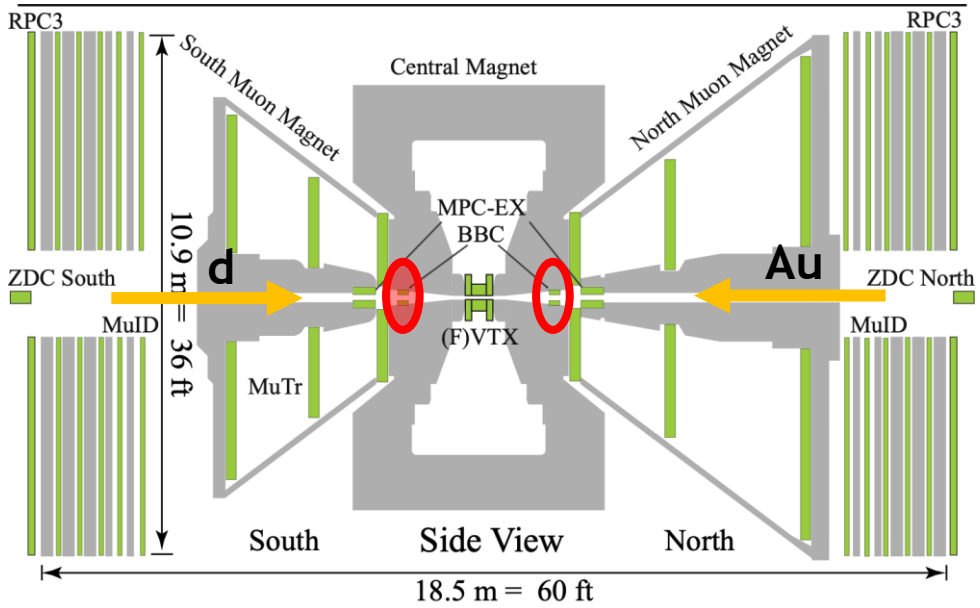
How is centrality determined in PHENIX?

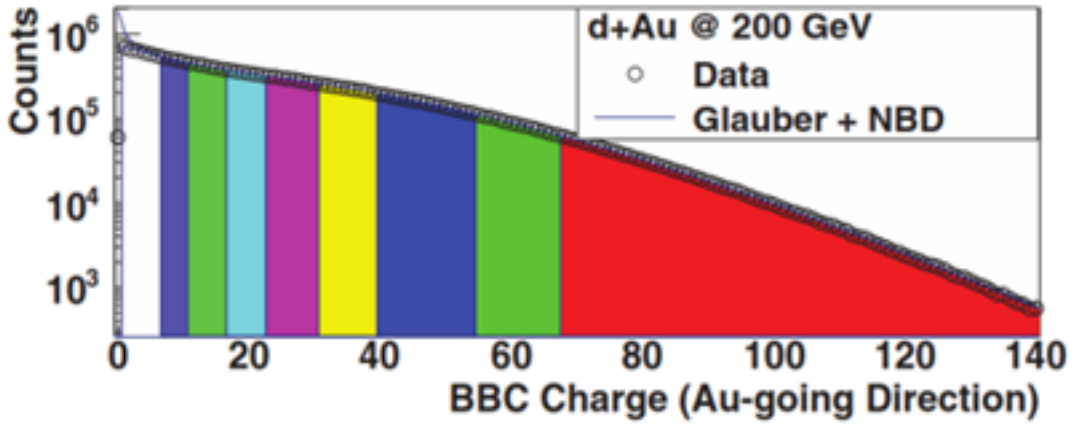
- Centrality is determined by charge deposition in the BBC, on the Au going direction

$$\frac{dN_{ch}}{d\eta} \Rightarrow N_{Coll} \underbrace{\Longleftrightarrow}_{Model/Theory} N_{part} \underbrace{\Longrightarrow}_{Theory} b$$

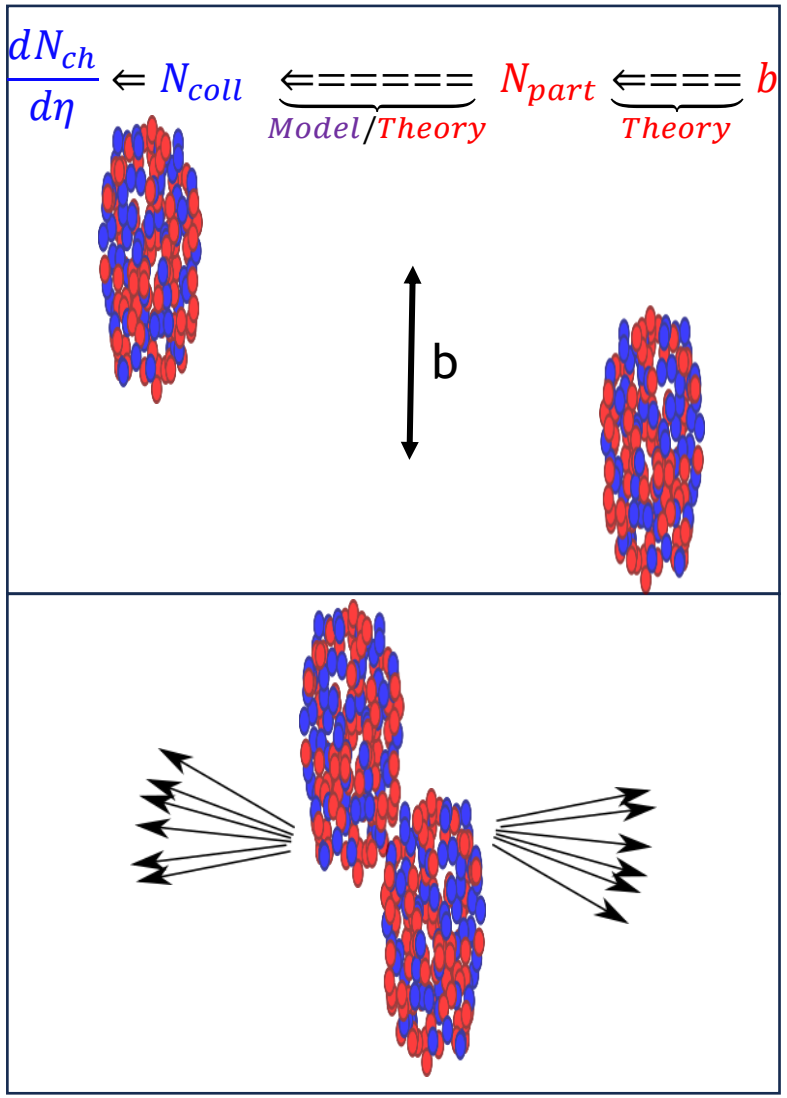
- $N_{Coll}^{GL} \propto \left(\frac{dN_{ch}}{d\eta}\right)^{a}$: Not directly measurable!
  - Obtained through Glauber model

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





Glauber model in A+A



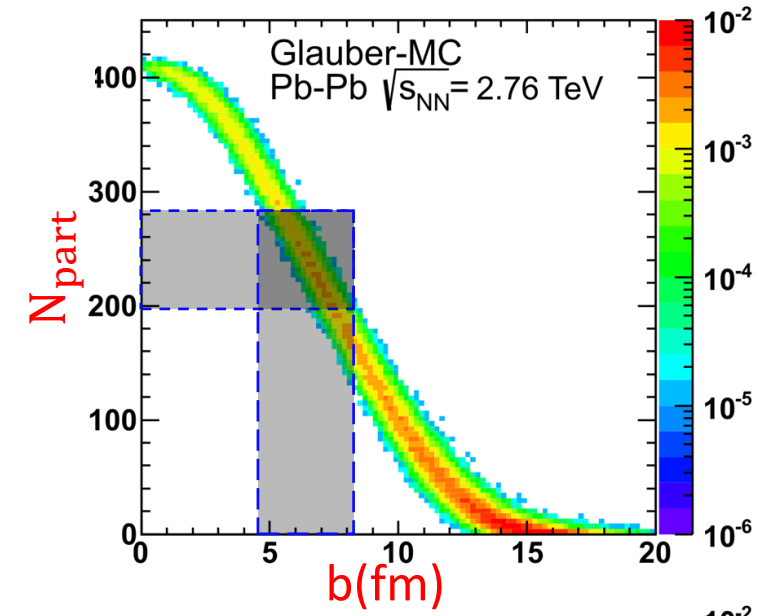
Glauber picture:

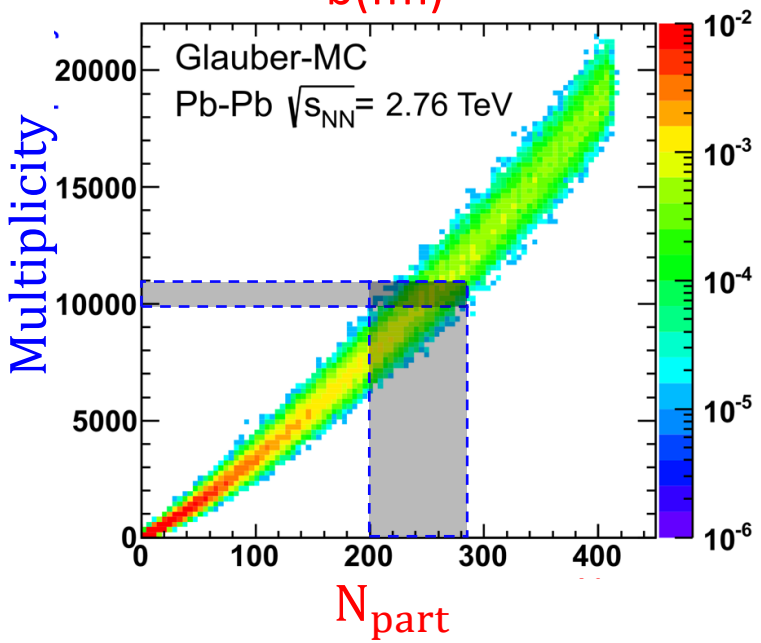
I. Smaller b, larger N_{part}

II. Larger N_{part}, larger $\frac{dN_{ch}}{d\eta}$

III. $N_{part} \Leftrightarrow N_{Coll}^{GL}$

A narrow range of multiplicity (centrality class) in A+A maps to a narrow range of impact parameters

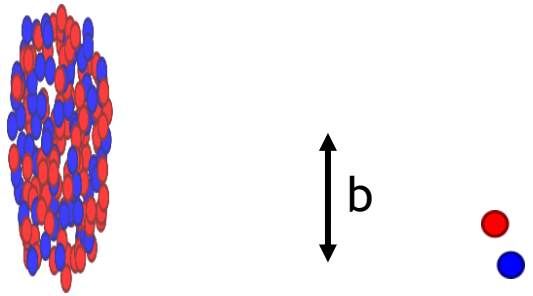


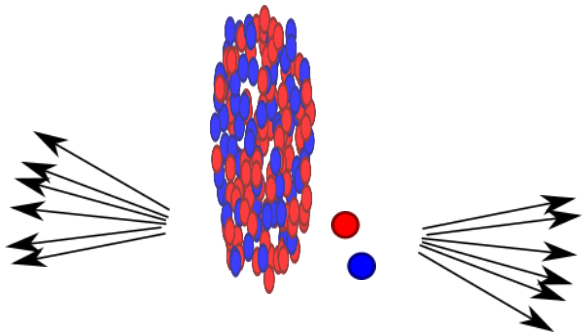


ALICE: PRC91 (2015) 064905

Glauber model in d+A ?

$\frac{dN_{ch}}{d\eta} \Leftarrow N_{coll} \underbrace{\Leftarrow\!\!=\!\!=\!\!=\!\!=\!\!=\!\!=}_{Model/Theory} N_{part} \underbrace{\Leftarrow\!\!=\!\!=\!\!=\!\!=}_{Theory} b$





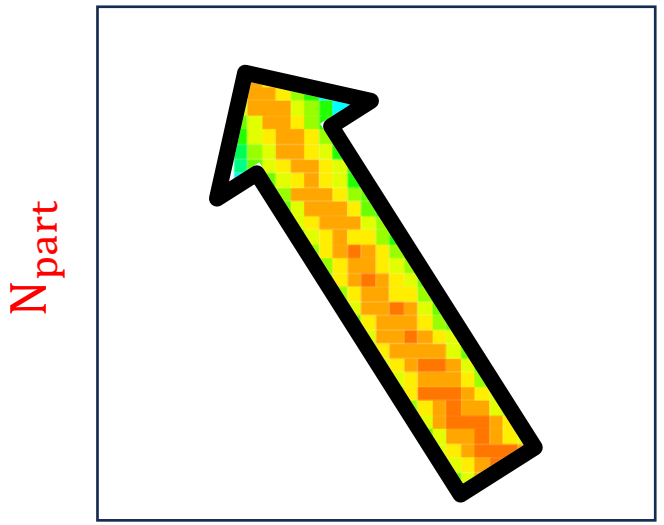
Glauber picture:

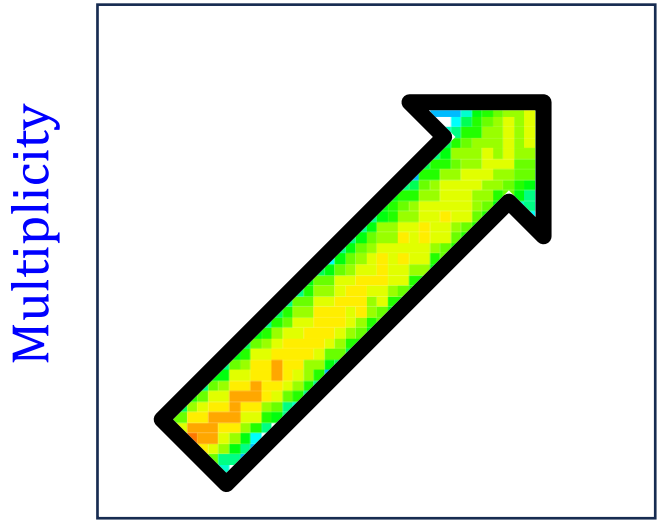
I. Smaller b, larger N_{part}

II. Larger N_{part}, larger $\frac{dN_{ch}}{d\eta}$

III. $N_{part} \overset{?}{\Leftrightarrow} N_{Coll}^{GL}$

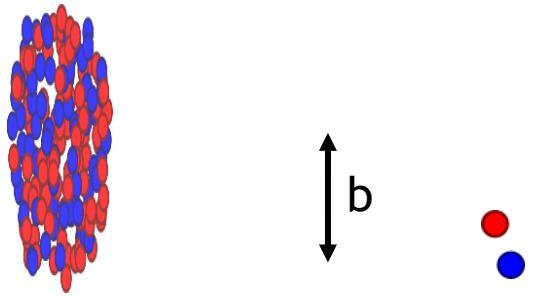
Is this still true?

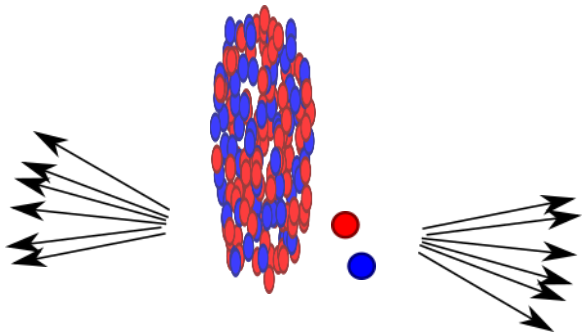




Glauber model in d+A !

$\frac{dN_{ch}}{d\eta} \Leftarrow N_{coll} \underbrace{\Leftarrow\!\!=\!\!=\!\!=\!\!=\!\!=\!\!=}_{Model/Theory} N_{part} \underbrace{\Leftarrow\!\!=\!\!=\!\!=\!\!=}_{Theory} b$





~~Glauber picture:~~

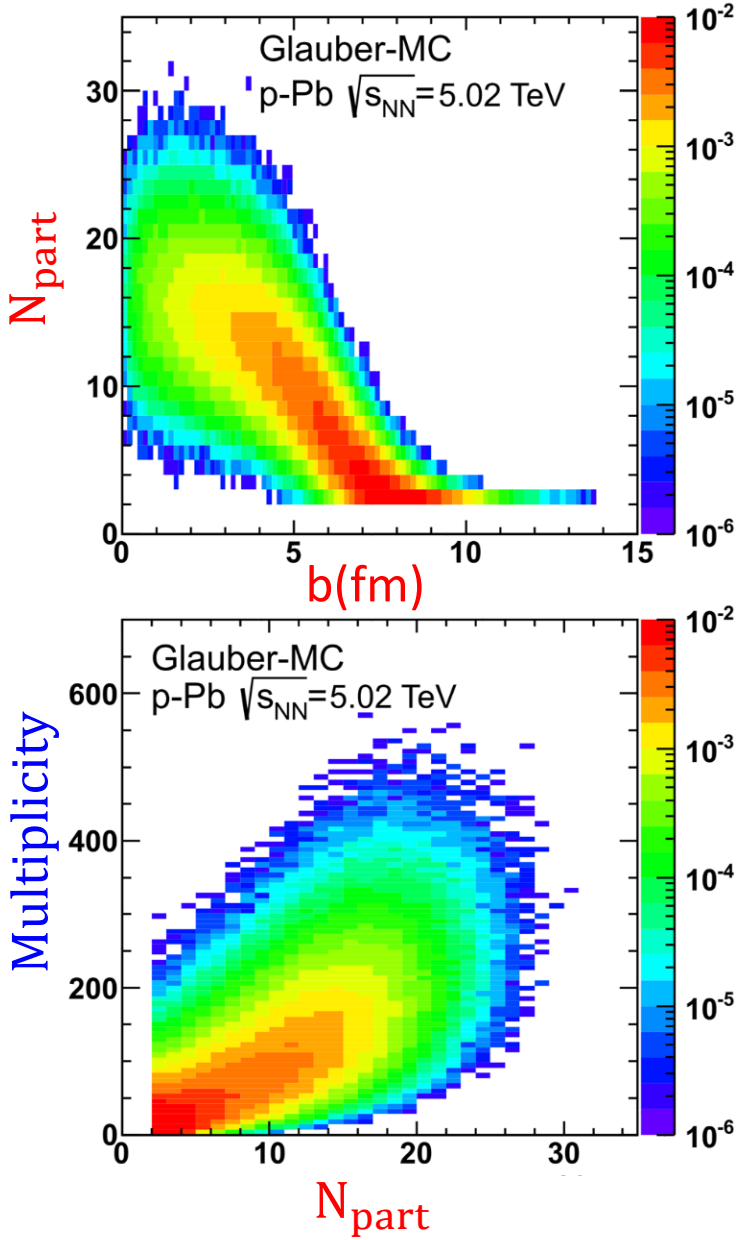
I. Smaller b, larger N_{part}

II. Larger N_{part}, larger $\frac{dN_{ch}}{d\eta}$

III. ~~$N_{part} \Leftrightarrow N_{Coll}^{GL}$~~

Glauber model fails to describe small systems!

N_{Coll}^{GL} is biased!



ALICE: PRC91 (2015) 064905

Glauber model in d+A !

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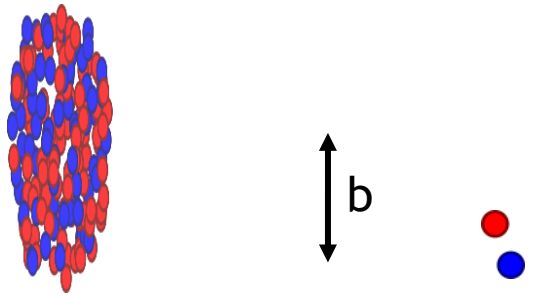

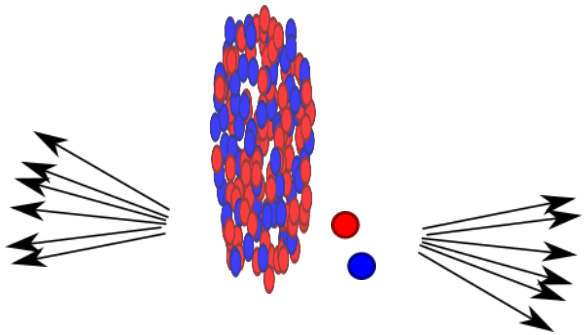

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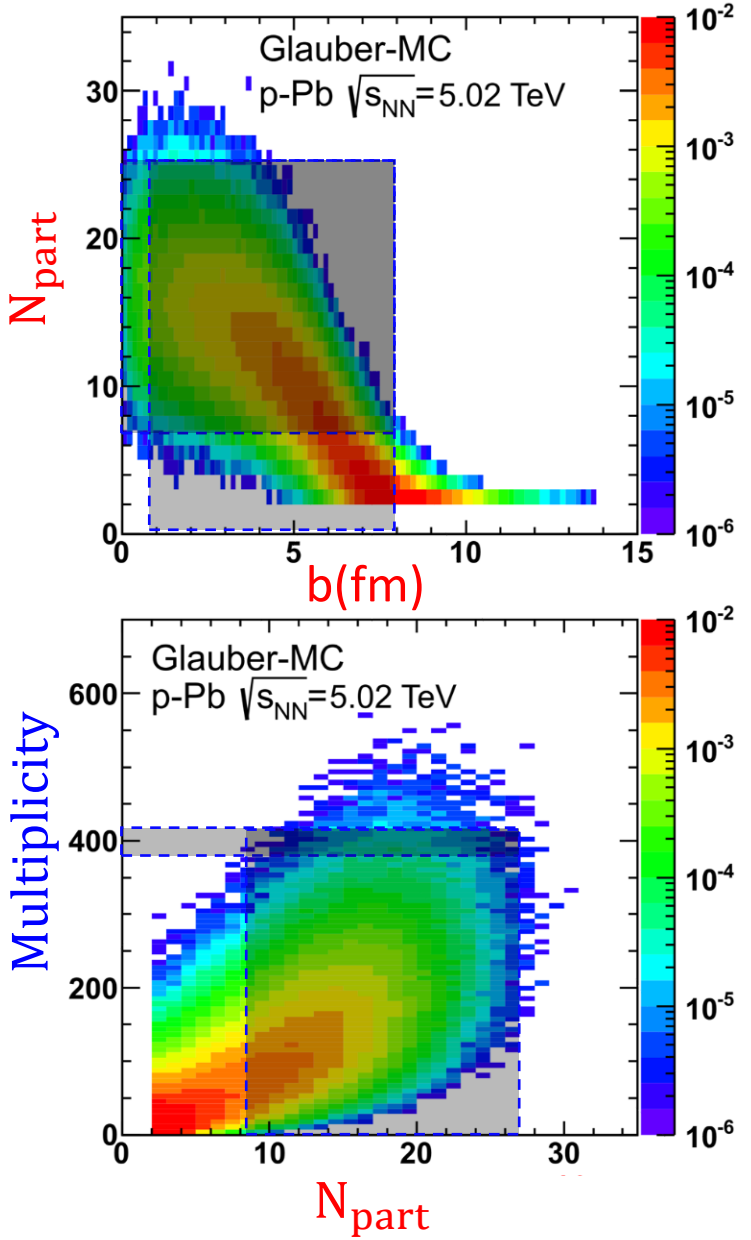
Glauber model fails to describe small systems!

A narrow range of multiplicity (centrality class) in d+A maps to a **wide** range of impact parameters



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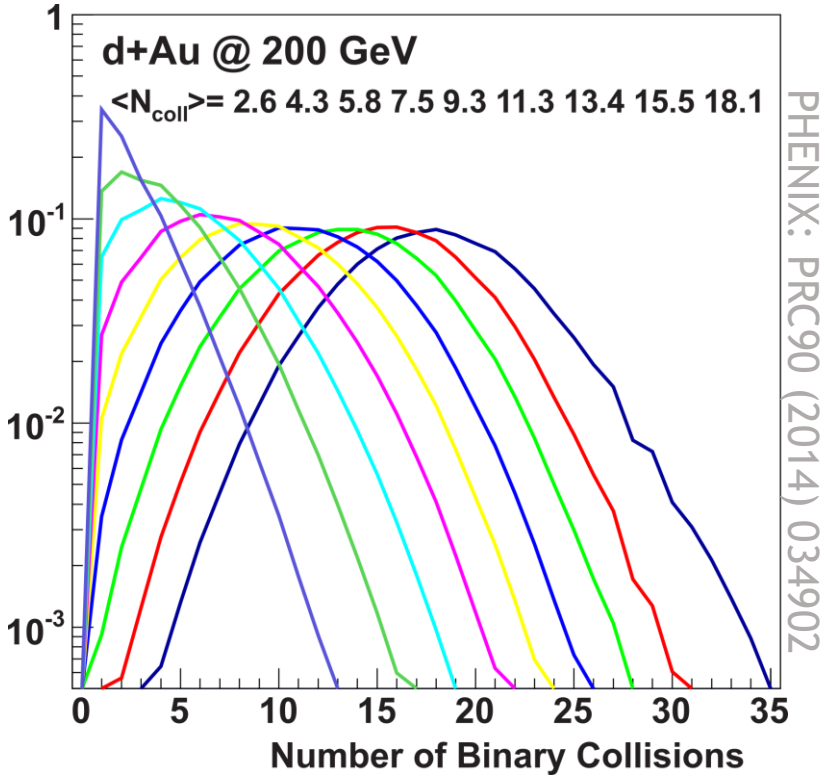
Glauber model in d+A !

$$\frac{dN_{ch}}{d\eta} \Leftarrow N_{coll} \underbrace{\Leftarrow\!\!=\!\!=\!\!=\!\!=\!\!=\!\!=}_{Model/Theory} N_{part} \underbrace{\Leftarrow\!\!=\!\!=\!\!=\!\!=}_{Theory} b$$



PHENIX: PRC90 (2014) 034902

0-5%, 5-10%, 10-20% ,..., 70-88%

~~Glauber picture:~~

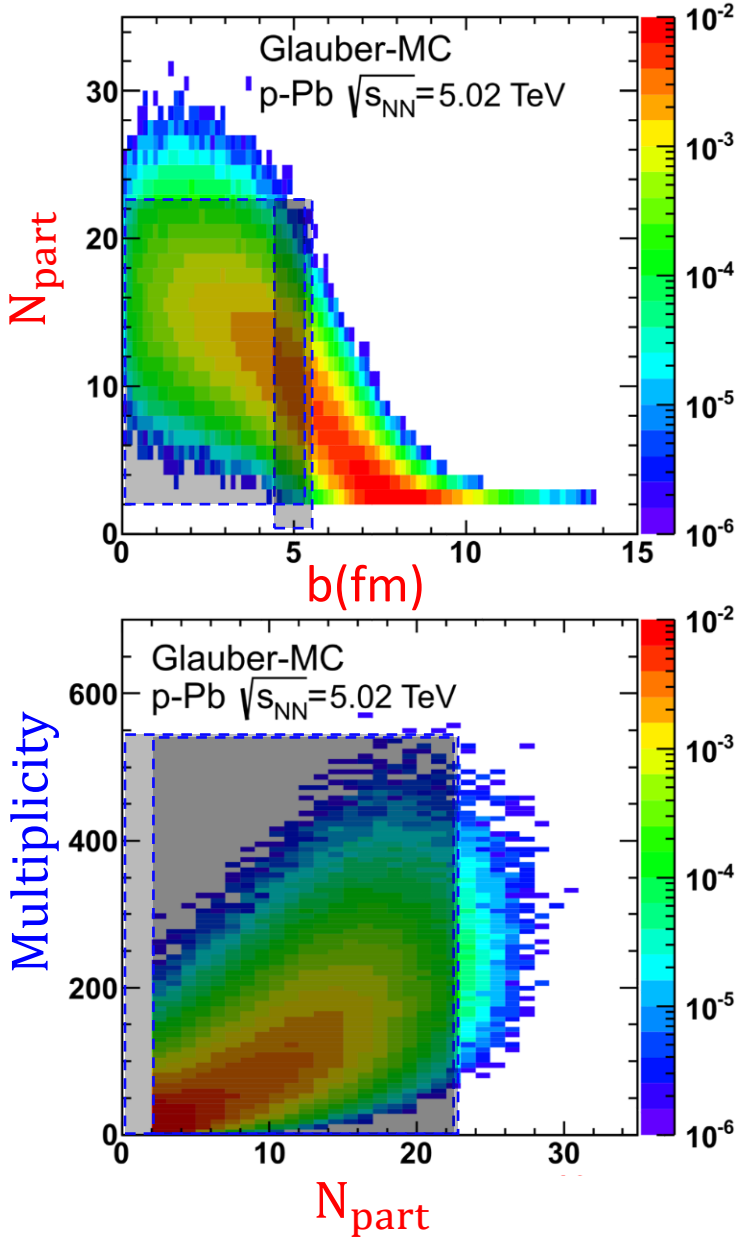
I. Smaller b, larger N_{part}

II. Larger N_{part}, larger $\frac{dN_{ch}}{d\eta}$

III. ~~$N_{part} \Leftrightarrow N_{Coll}^{GL}$~~

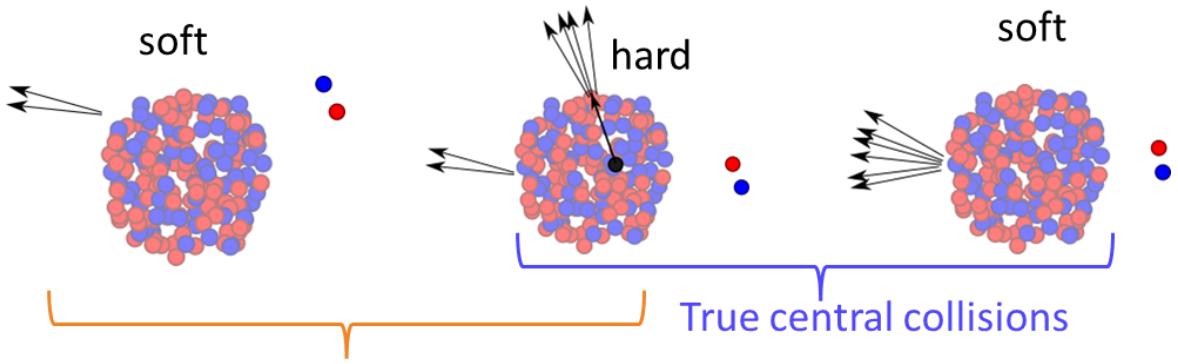
Glauber model fails to describe small systems!

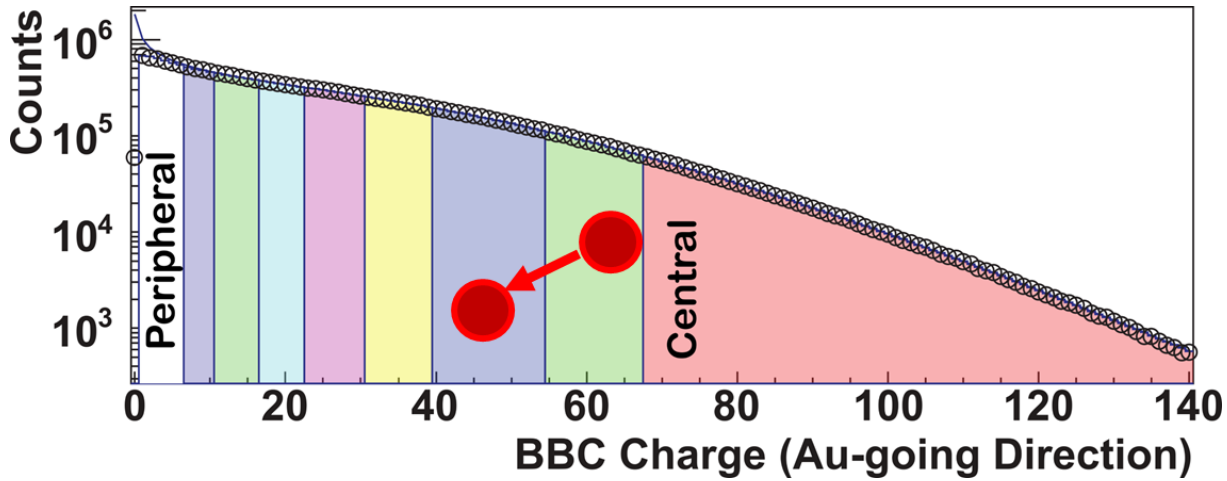
A narrow range of impact parameters in d+A maps to a **wide** range of multiplicity (centrality class)



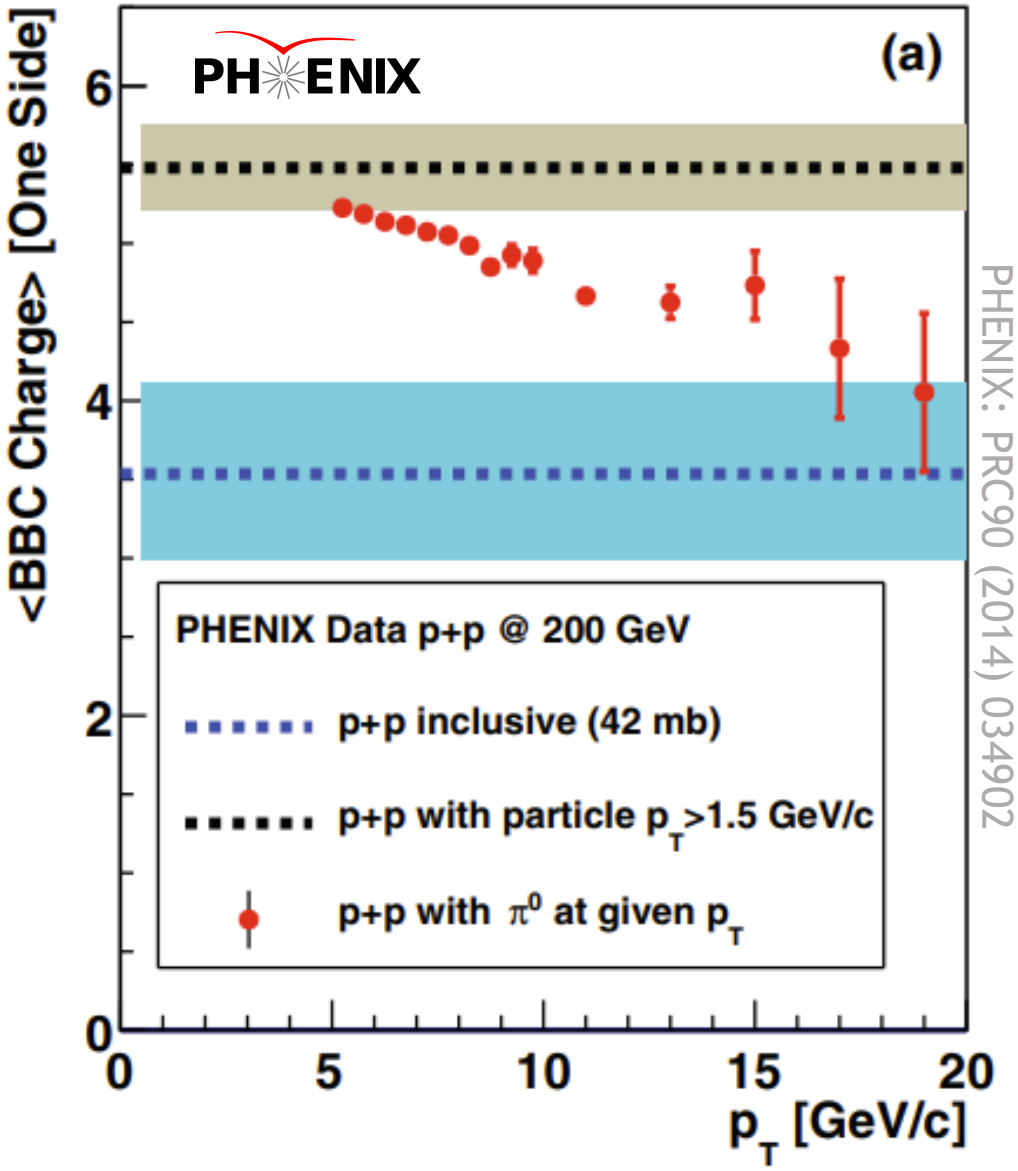
ALICE: PRC91 (2015) 064905

There IS centrality bias in small systems!



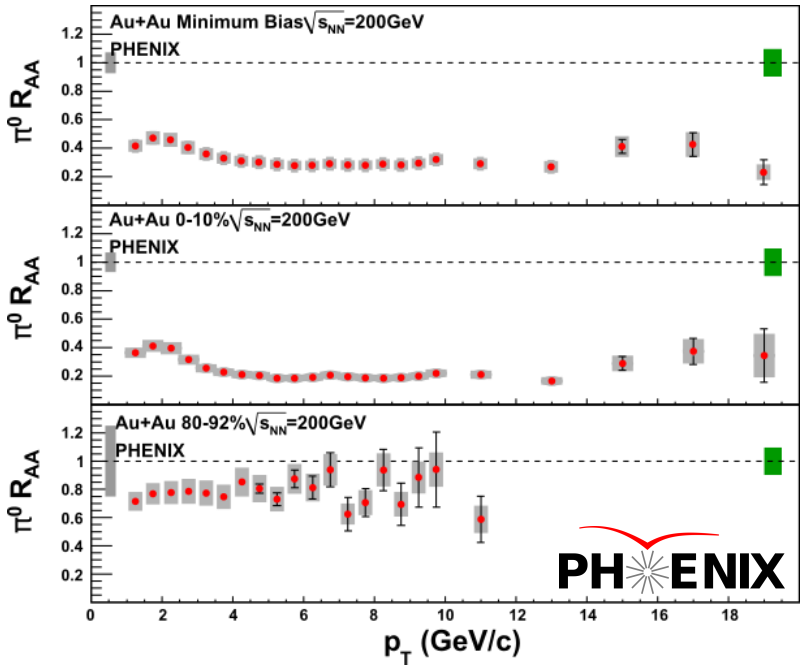


Think conservation of energy: more midrapidity, less forwards/backwards

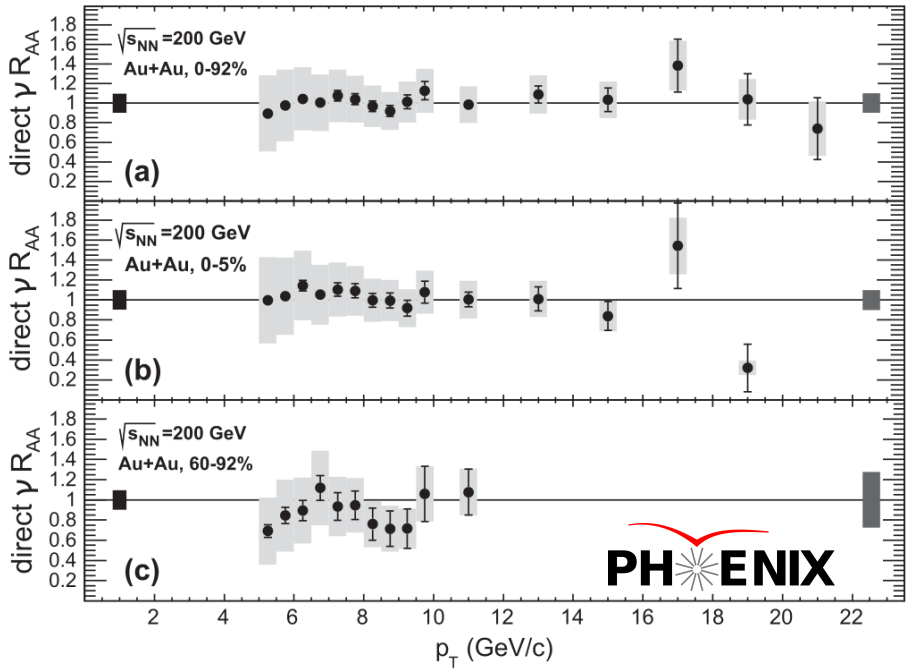


$\frac{\gamma^{dir}}{\pi^0}$: An observable of centrality bias

PHENIX: PRL101 (2008) 232301



PHENIX: PRL109 (2012) 152302



Corrected direct γ spectrum
(centrality independent)

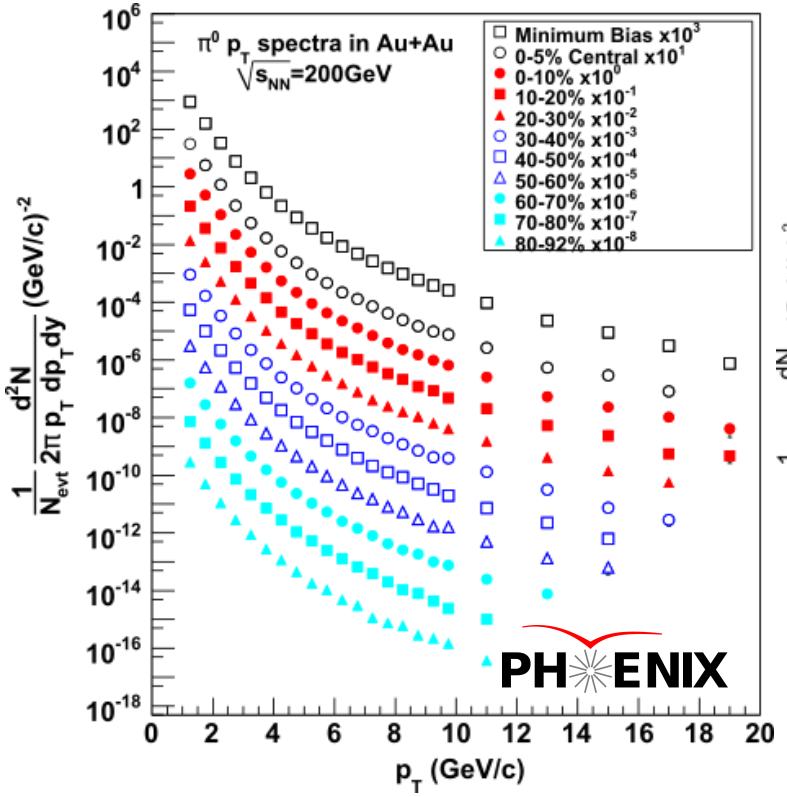
Corrected π^0 spectrum
(centrality dependent)

π^0s are affected by final state effects

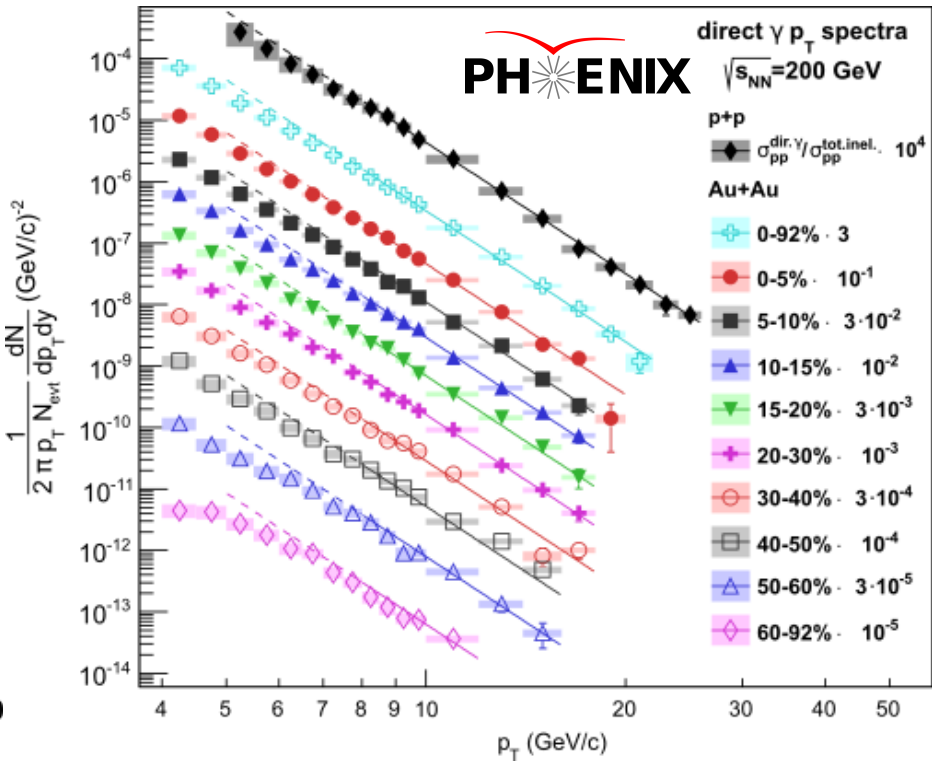
γ^{dir}s are NOT affected by final state effects

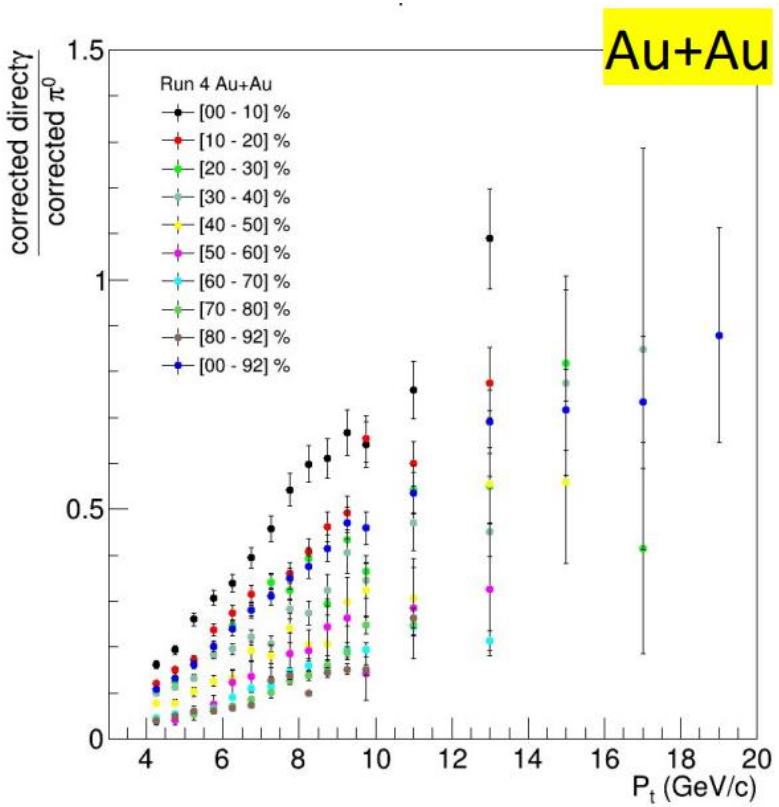
$\frac{\gamma^{dir}}{\pi^0}$: An observable of centrality bias

PHENIX: PRL101 (2008) 232301



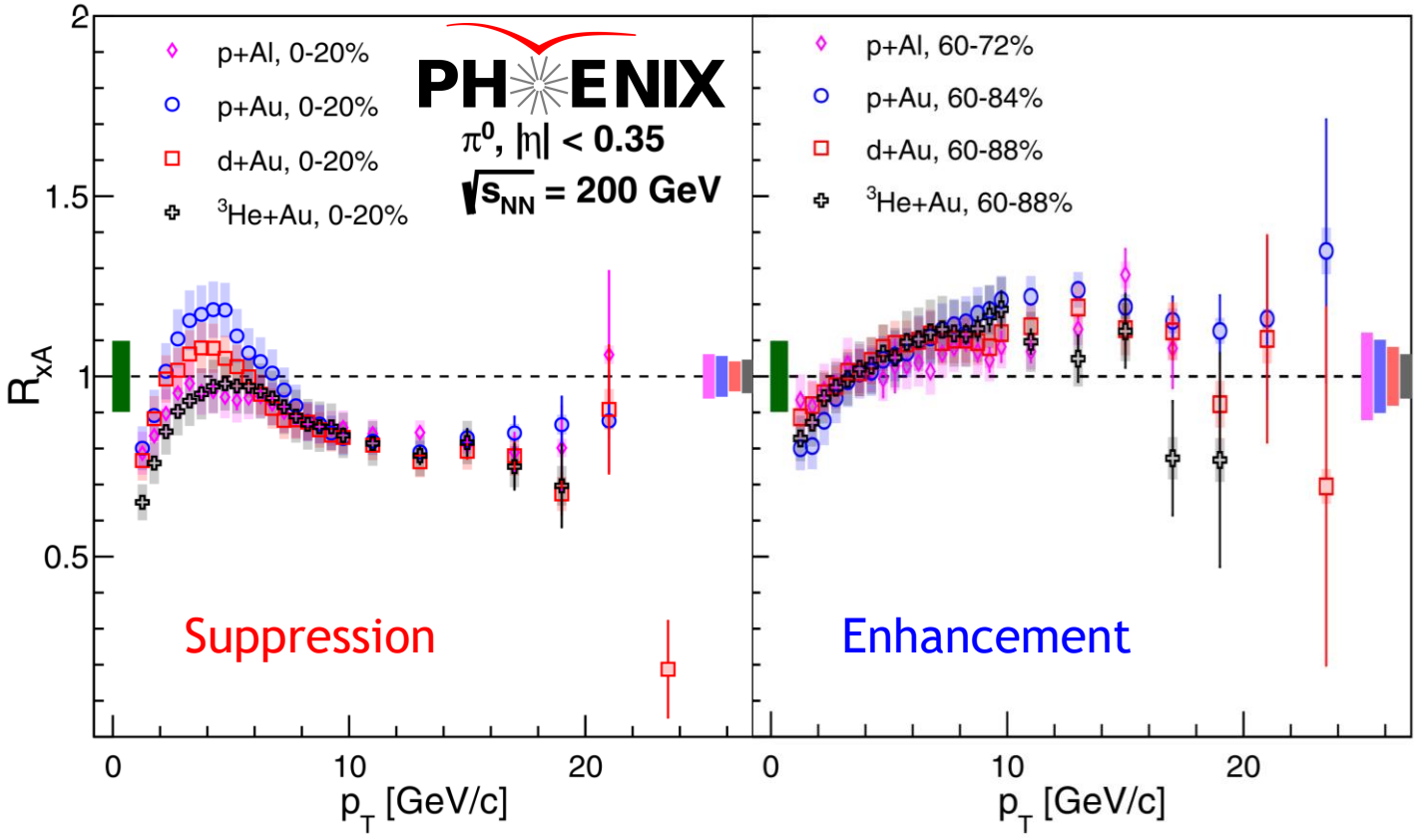
PHENIX: PRL109 (2012) 152302

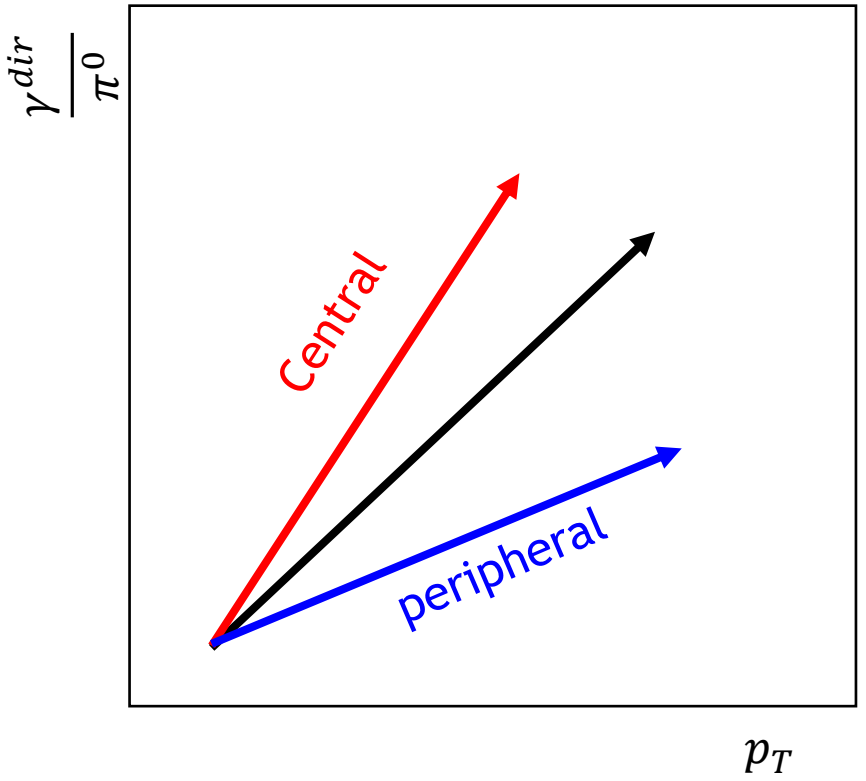




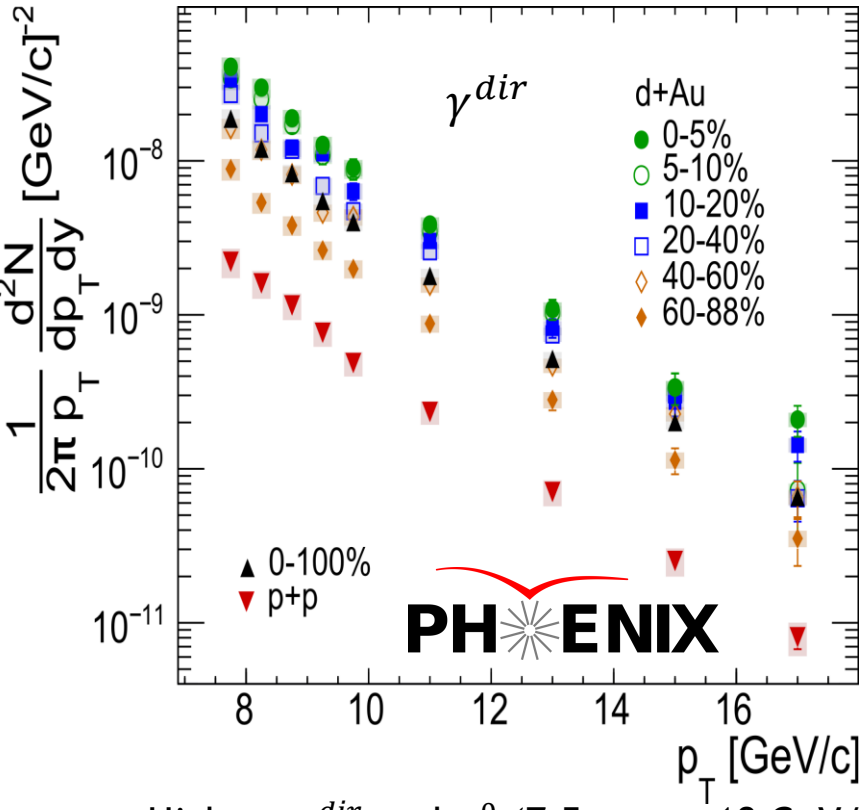
$\frac{\gamma^{dir}}{\pi^0}$: An observable of centrality bias

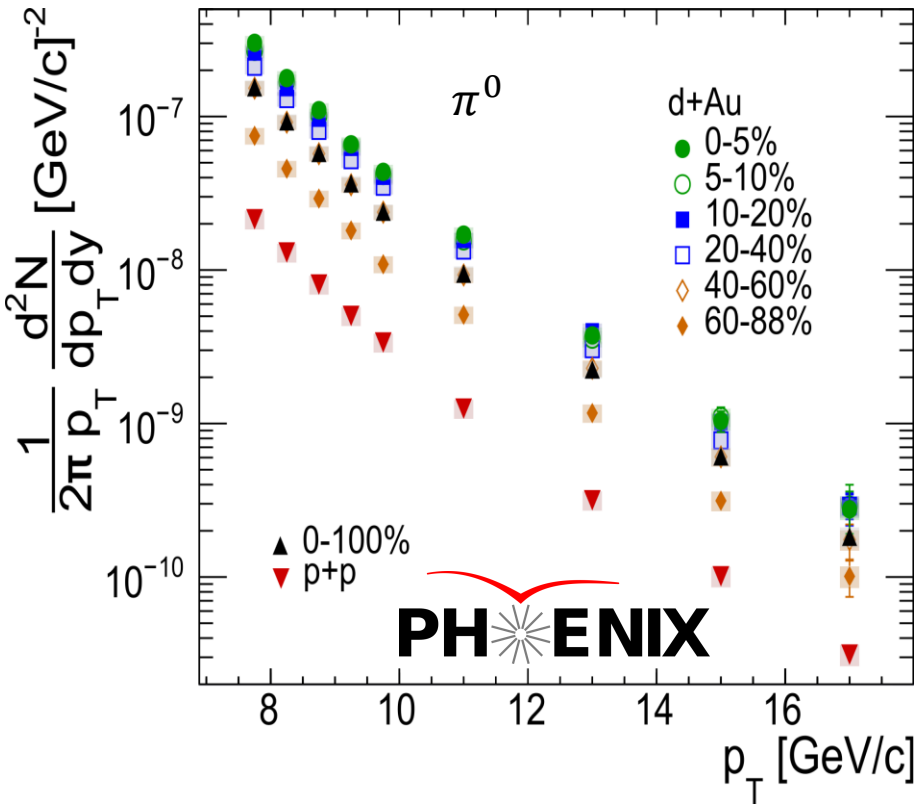
PHENIX: PRC105 (2022) 064902

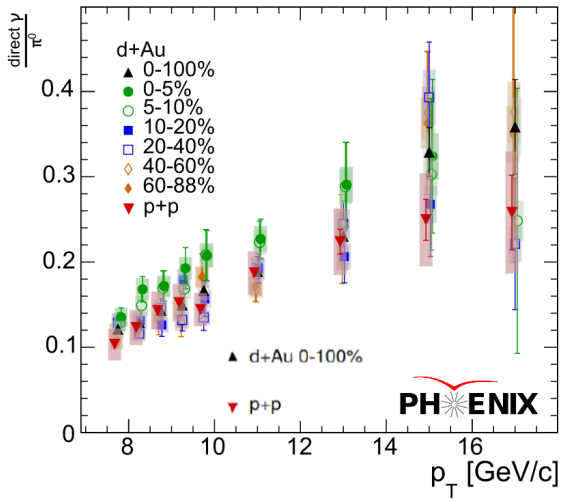




$\frac{\gamma^{dir}}{\pi^0}$: An observable of centrality bias





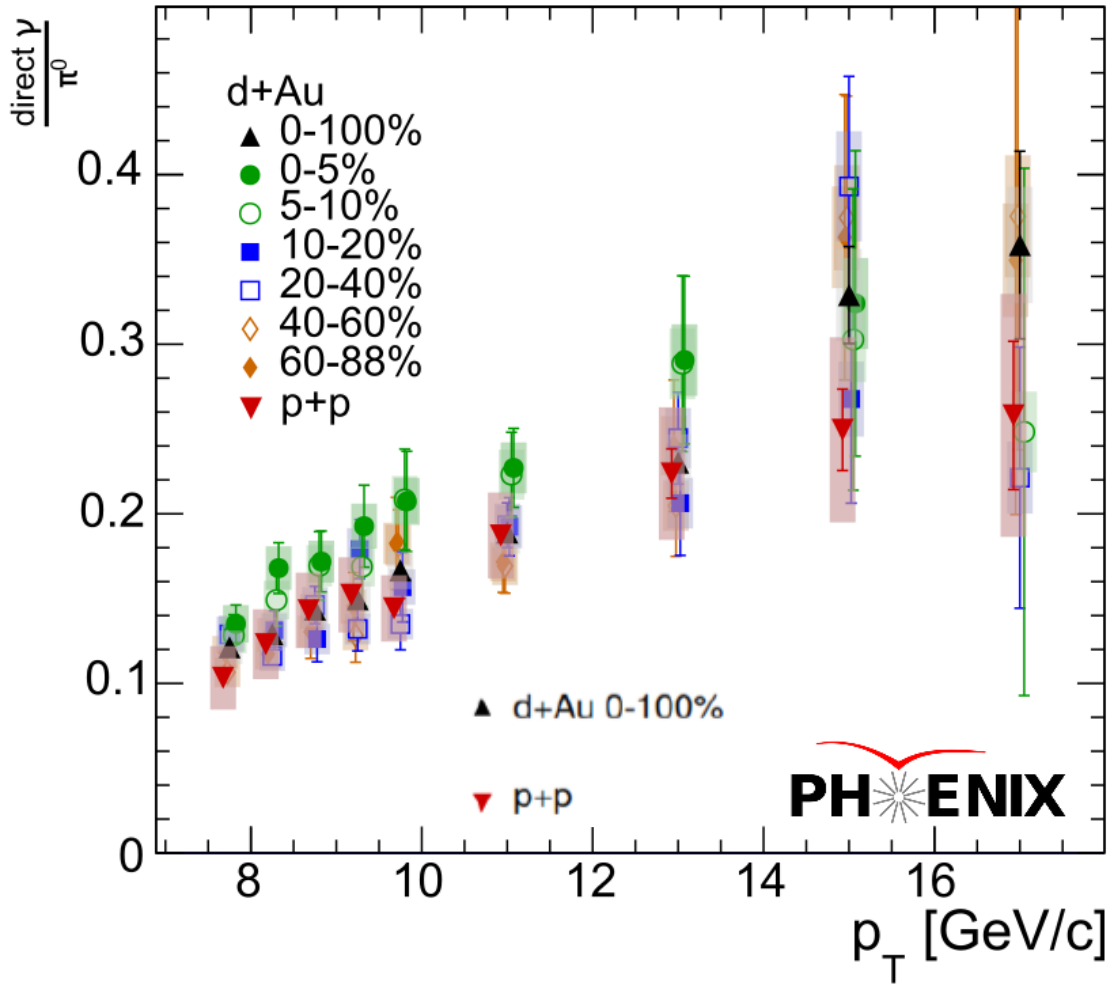


PHENIX: arXiv:2303.12899

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)

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



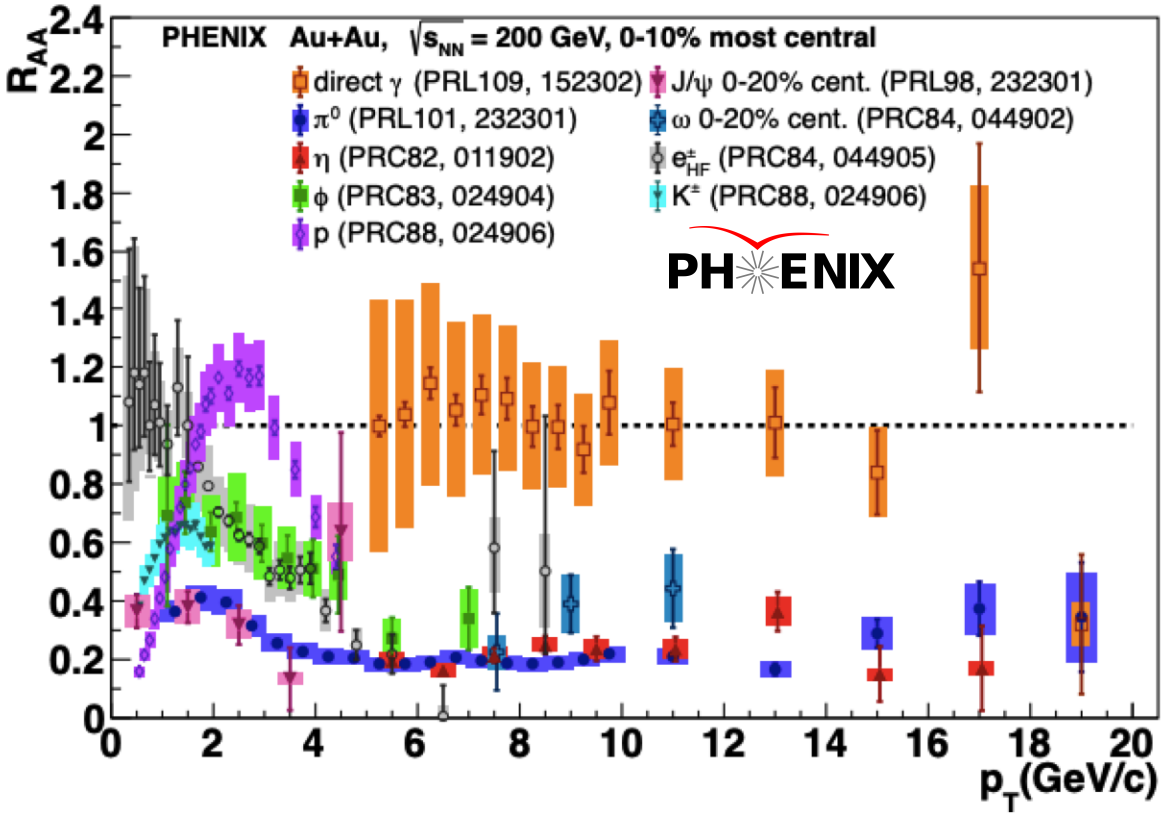
PHENIX: arXiv:2303.12899

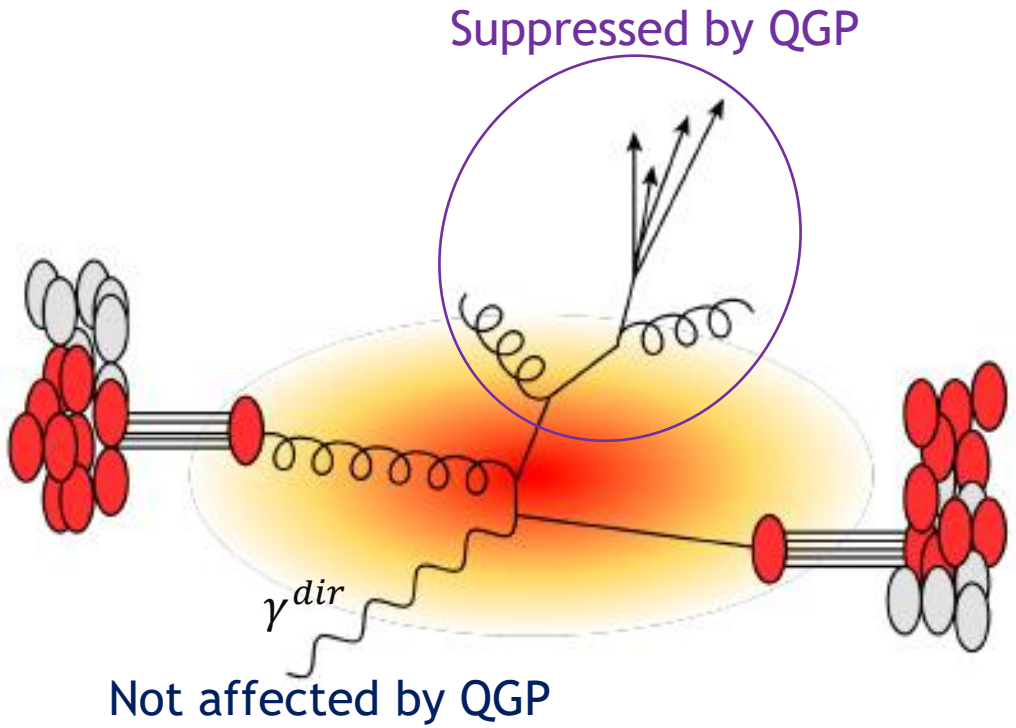
Corrected direct γ spectrum
(centrality independent)

Corrected π^0 spectrum
(centrality dependent)

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

Direct photons to the rescue!





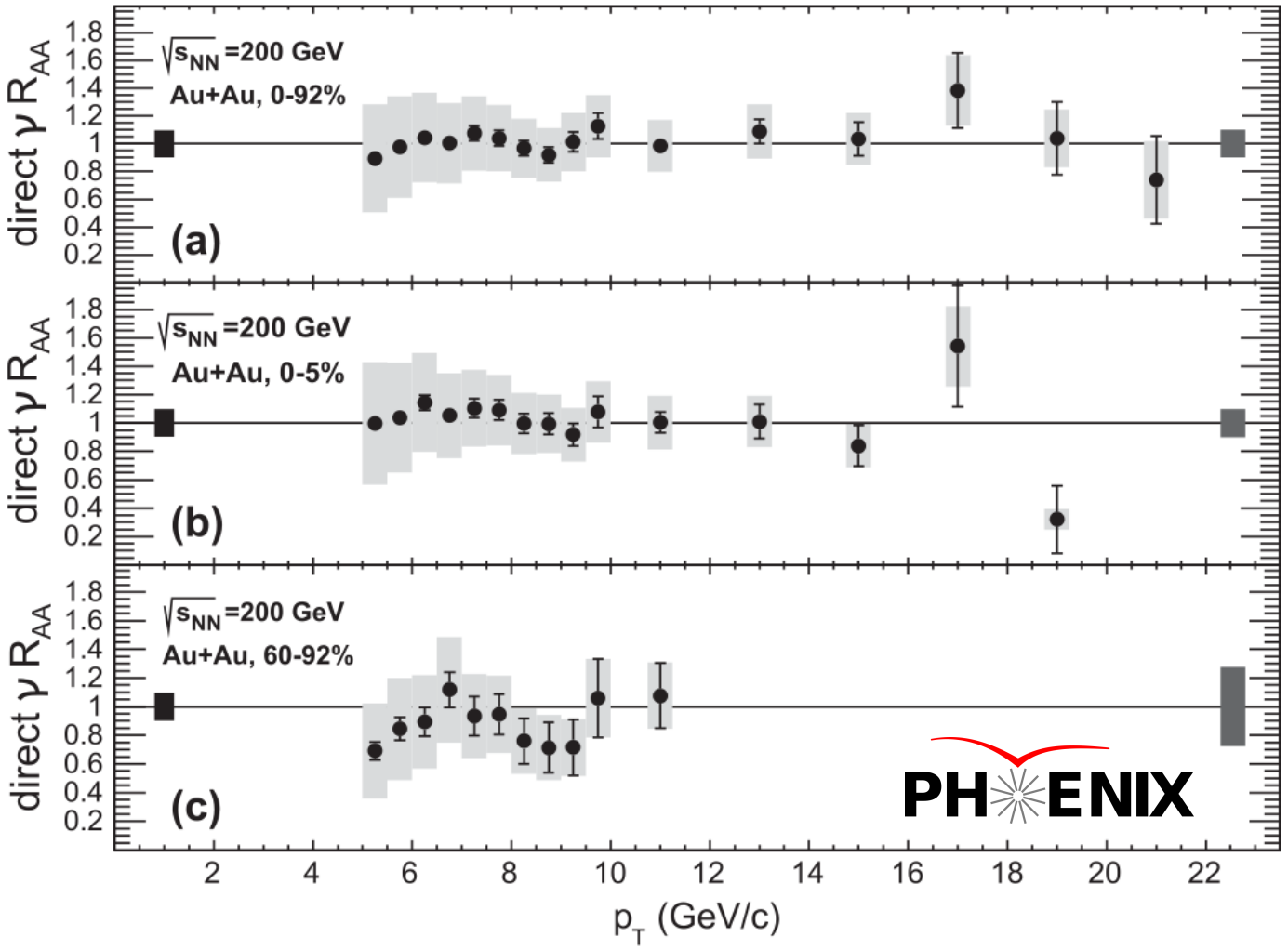
- Unlike color charged matter, direct photons are unaffected by QGP.
- γ^{dir} can be used as an **unbiased direct measure of event activity**

Direct measurement of the N_{coll}

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

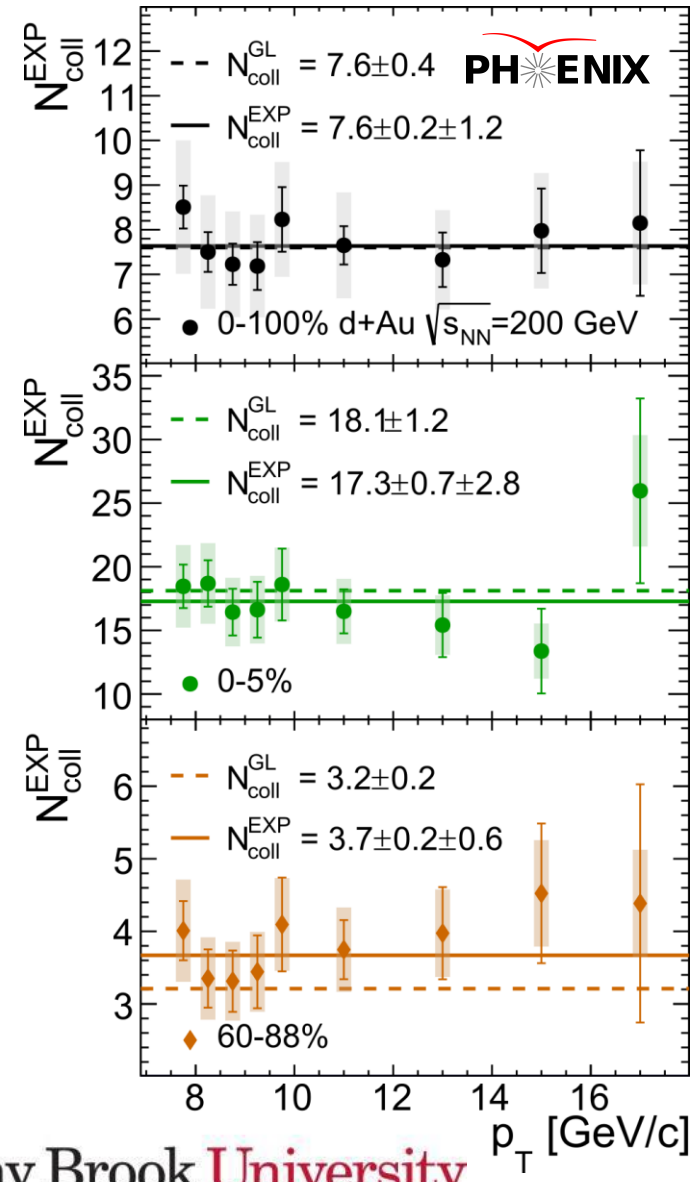
- The ratio of direct photon yields can be used as a measure of N_{coll}:

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



PHENIX: PRL109 (2012) 152302

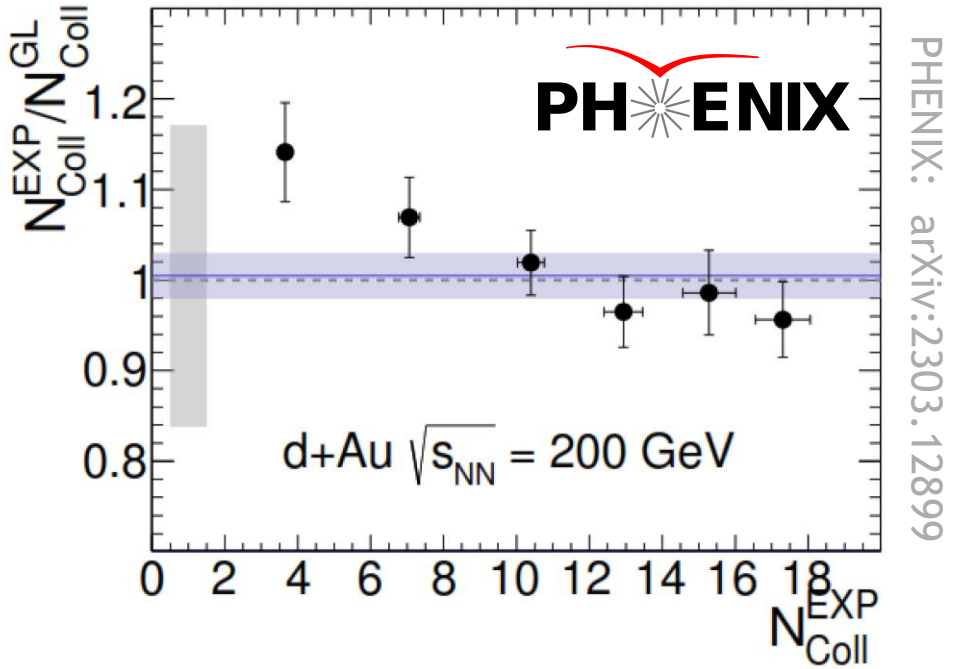
Comparison with Glauber N_{coll}



PHENIX: arXiv:2303.12899

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

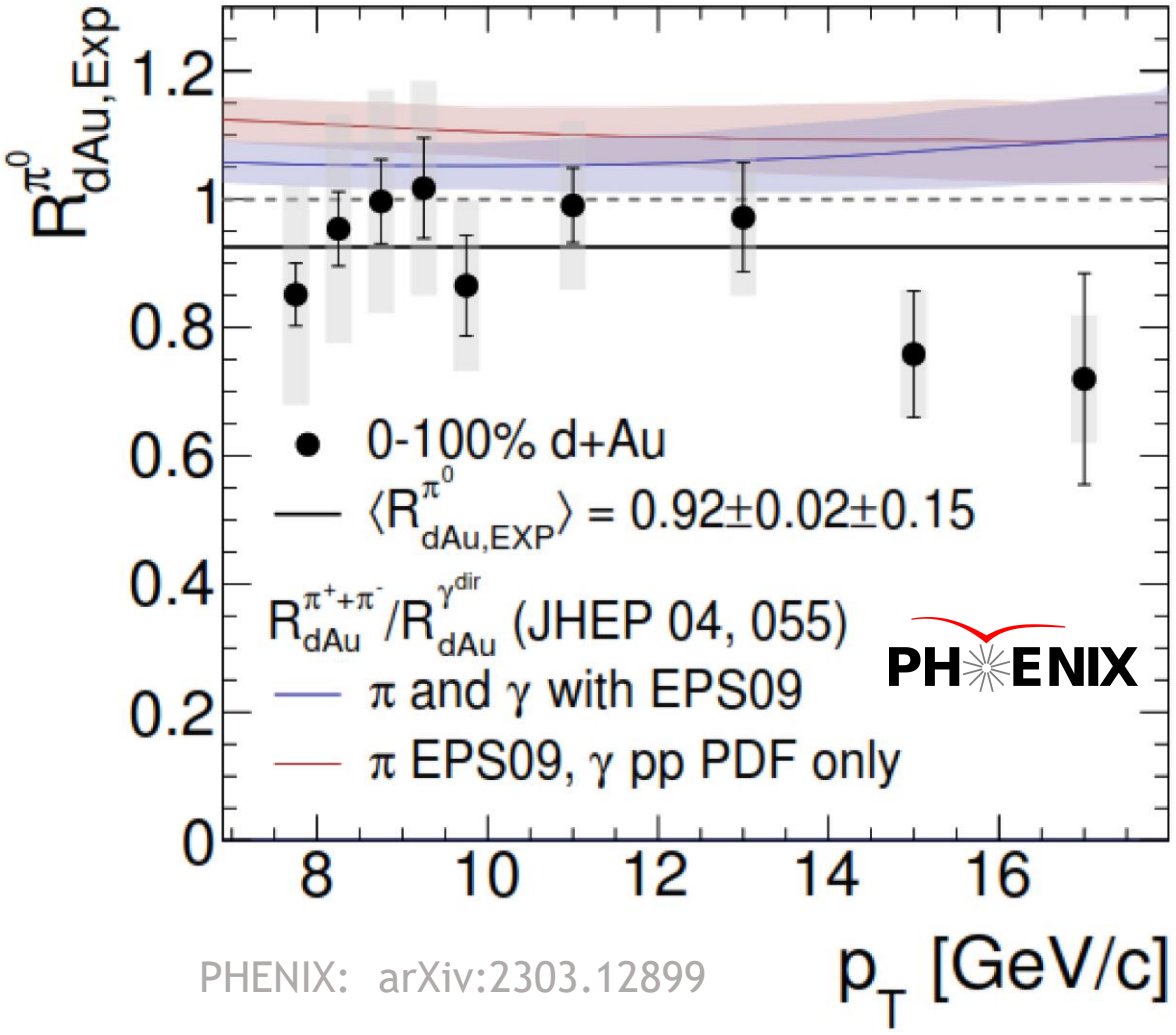
- Good agreement between N_{Coll}^{EXP} and N_{Coll}^{GL} is seen in central collisions
- 15% deviation is seen in peripheral collisions



PHENIX: arXiv:2303.12899

Peripheral → Central

Nuclear modification factor for π^0 in d+Au



PHENIX: arXiv:2303.12899

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

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

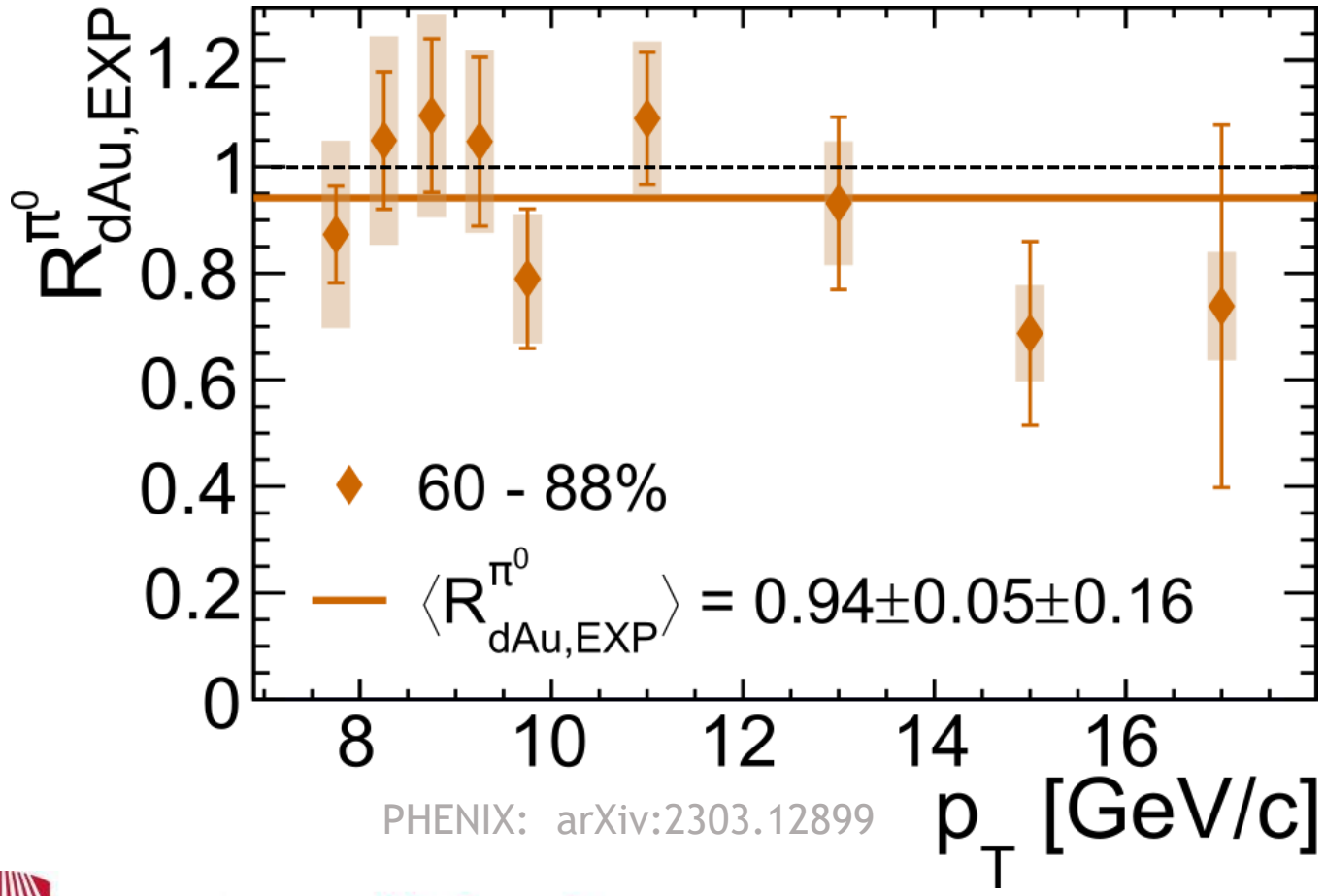
$$\left\langle R^{\pi^0}_{dAu,exp} \right\rangle = 0.92 \pm 0.02 \pm 0.15$$

  - 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

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



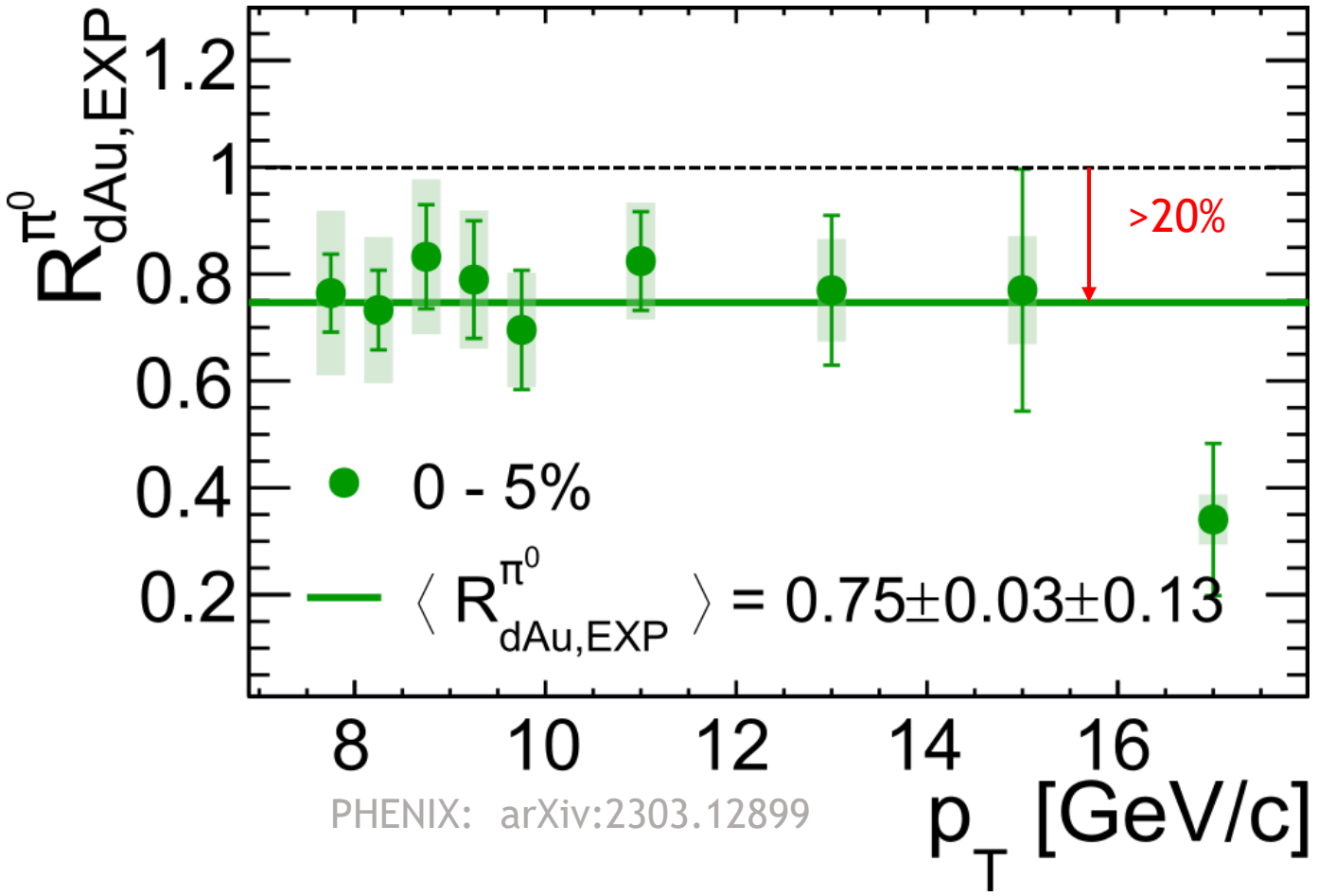
PHENIX: arXiv:2303.12899

- Peripheral collisions are consistent with inclusive
- No peripheral enhancement

Nuclear modification factor for π^0 in d+Au

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

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



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Nuclear modification factor for π^0 in d+Au

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

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

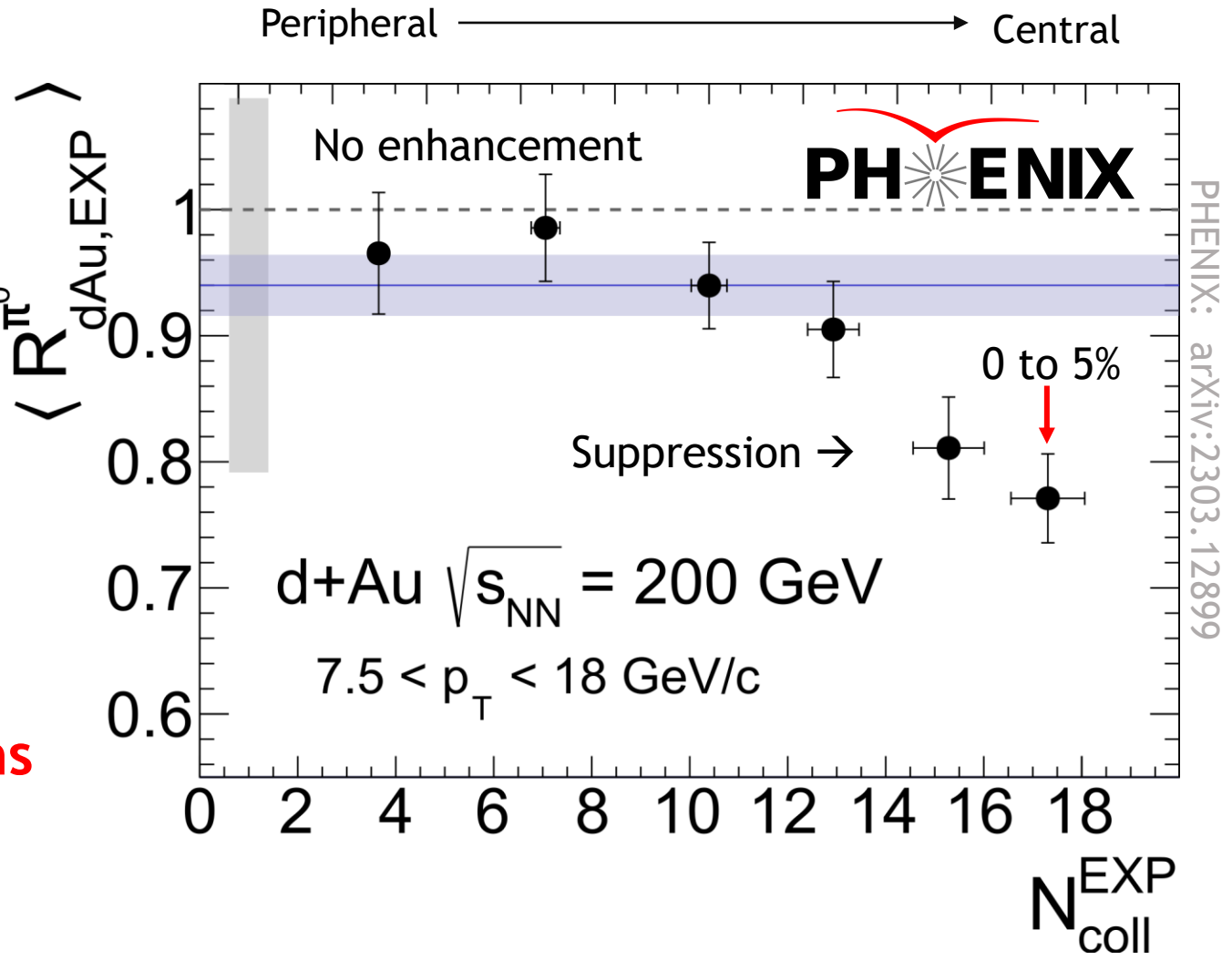
$$\frac{R^{\pi^0}_{dAu,exp}(60-88\%)}{R^{\pi^0}_{dAu,exp}(0-100\%)} = 1.017 \pm 0.56$$

  - 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!

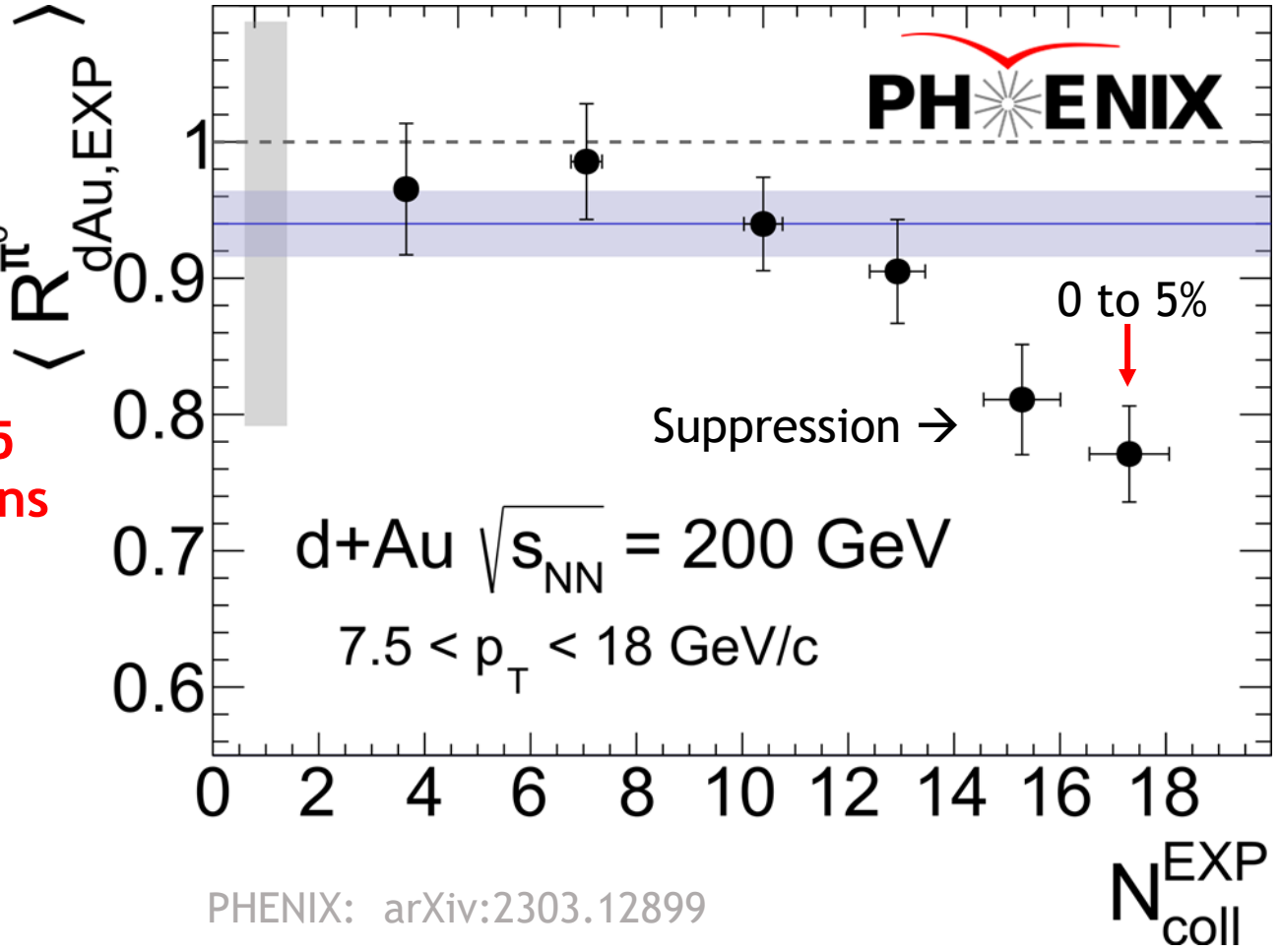


Summary

- 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

Stony Brook University

Backup:

Data analysis

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

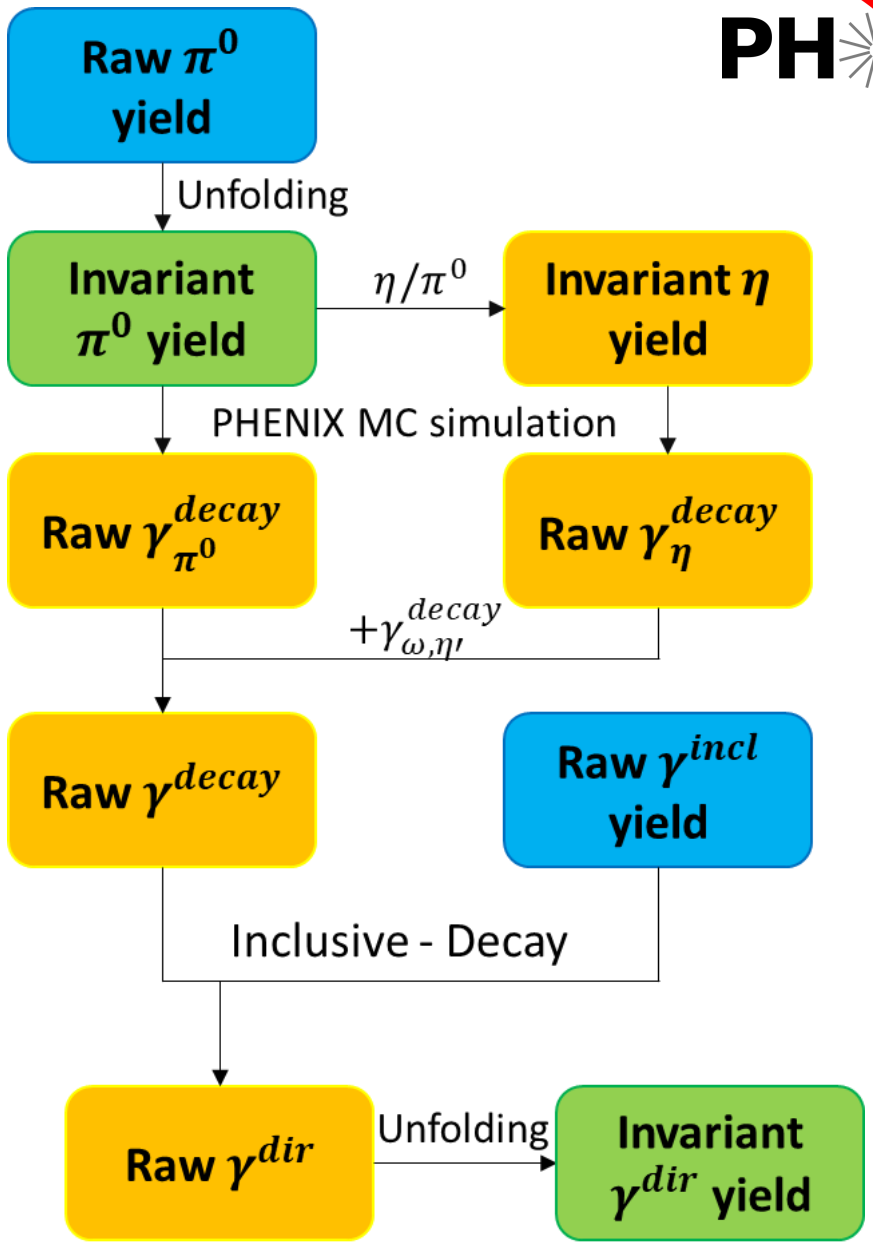
- π^0 reconstructed from γ clusters on the EMCal
- Triggered on high p_T range. Analysis done for γ and π^0 on $p_T > 7.5$ GeV

Analysis chain:

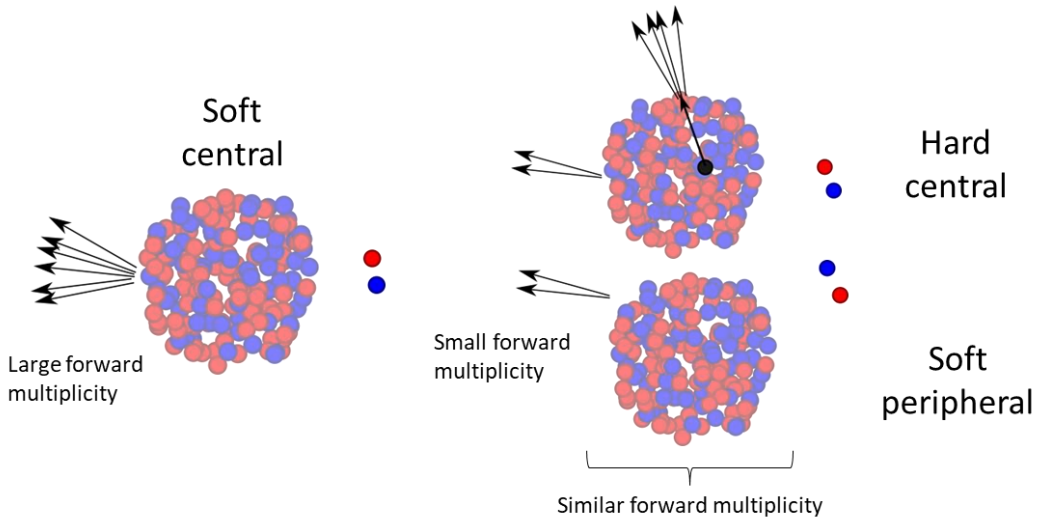
- Reconstructed Raw π^0 from γ showers ($\pi^0 \rightarrow \gamma\gamma$)
- Raw spectra is unfolded to obtain Invariant π^0
  - $\frac{\eta}{\pi^0}$ ratio used to obtain invariant η yield
- Model π^0 and η decay in PHENIX to obtain γ^{decay}
- Subtraction of decay from inclusive raw γ to obtain Raw γ^{dir}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

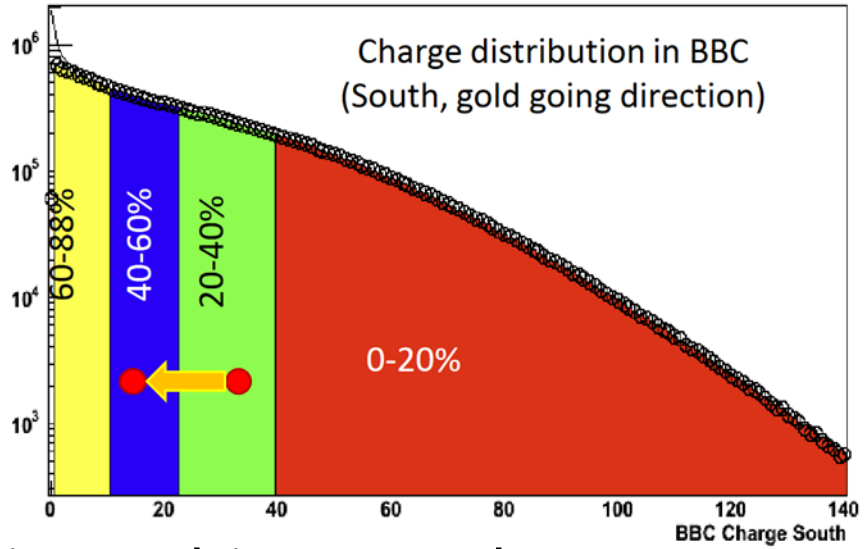
Systematic uncertainties

- $\sim 12\%$ 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

RATIO:

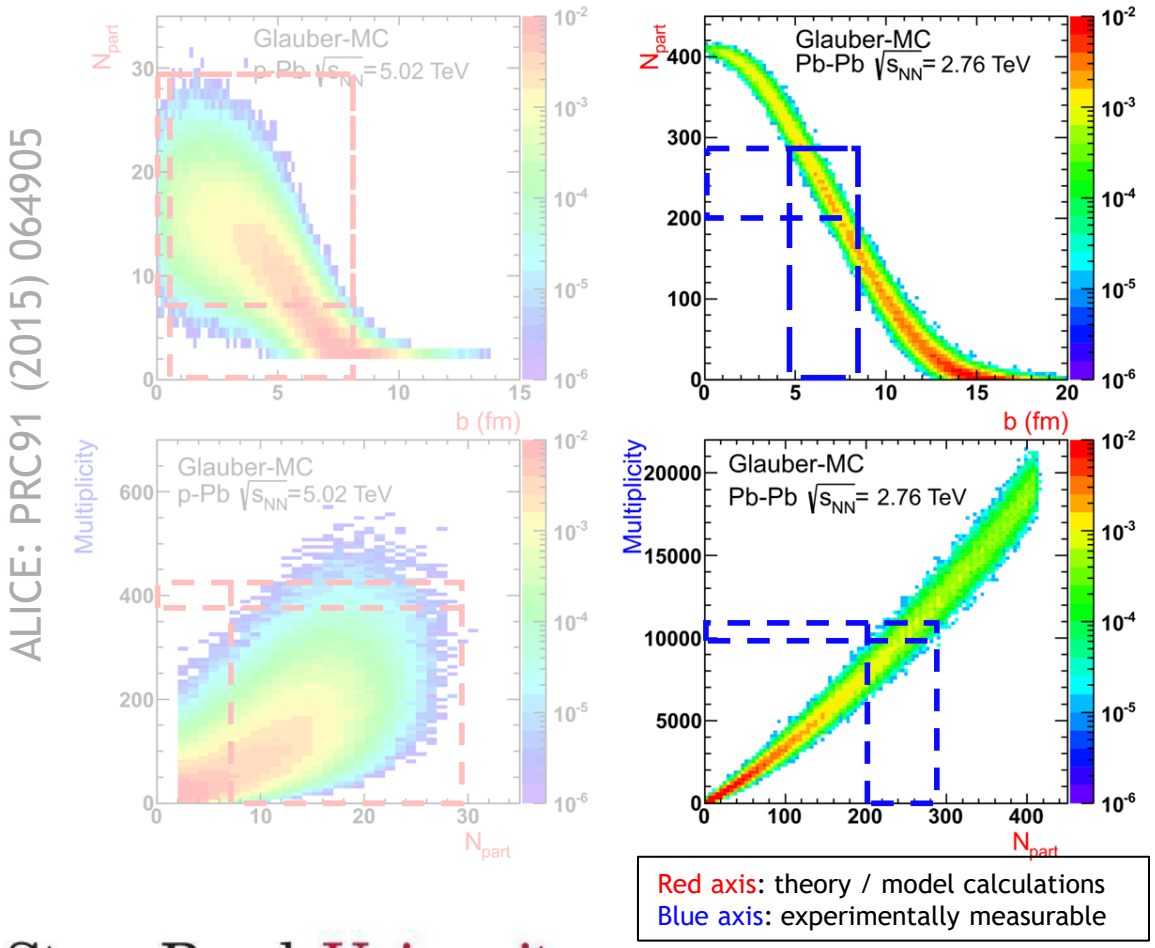
Corrected direct γ spectrum (centrality independent)

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



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

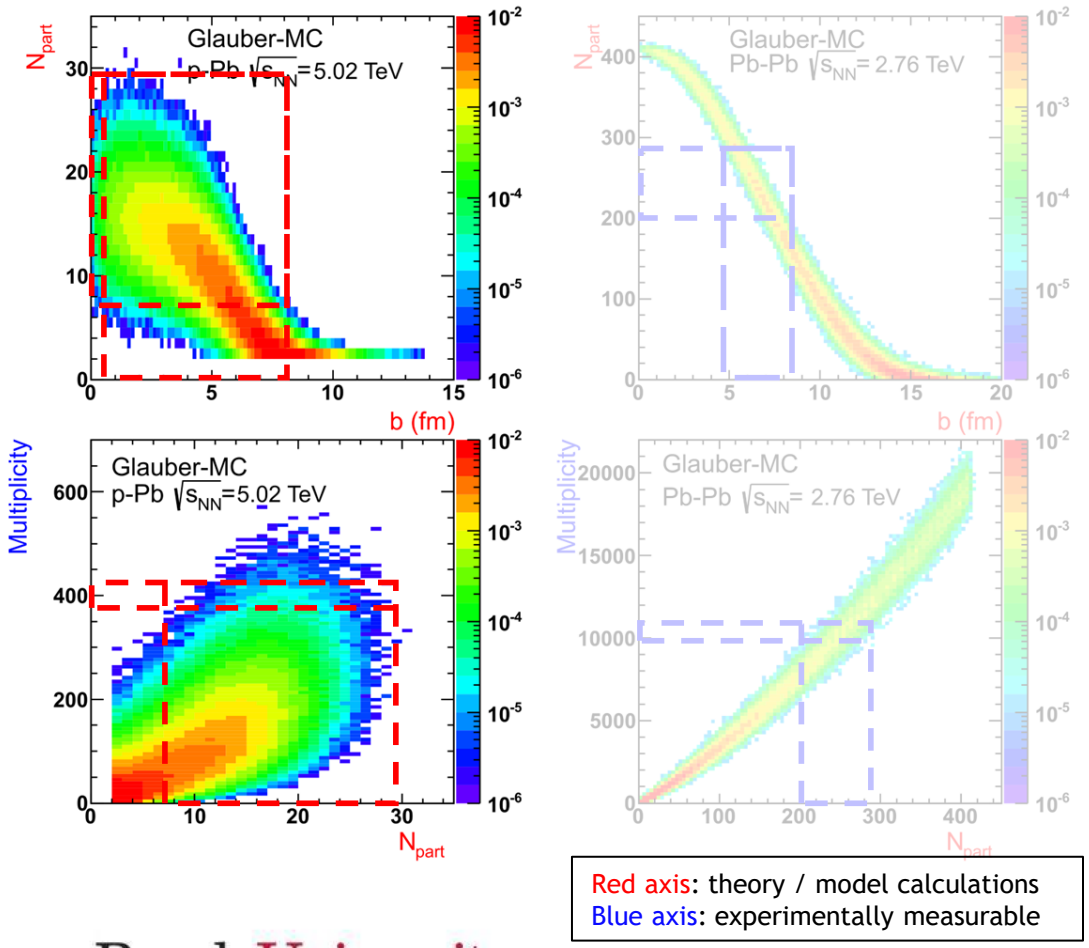
- Centrality is determined by event activity in the BBC, on the Au going direction

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

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

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

Event activity to centrality



ALICE: PRC91 (2015) 064905

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

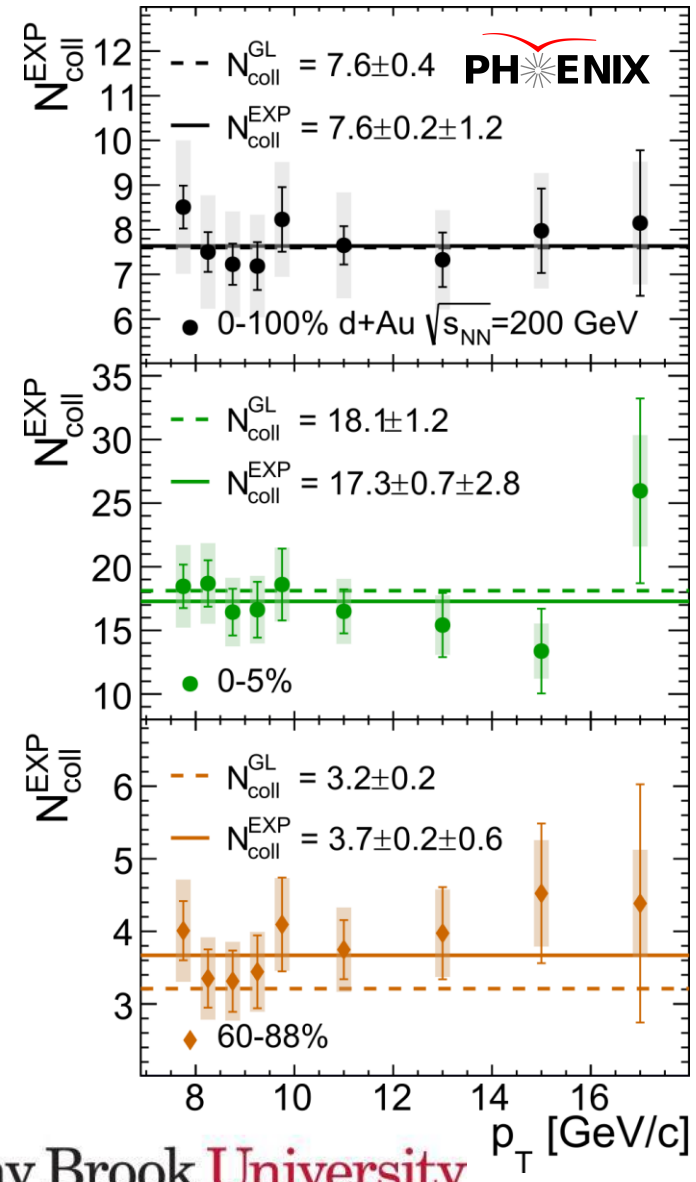
- Centrality is determined by event activity in the BBC, on the Au going direction

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

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

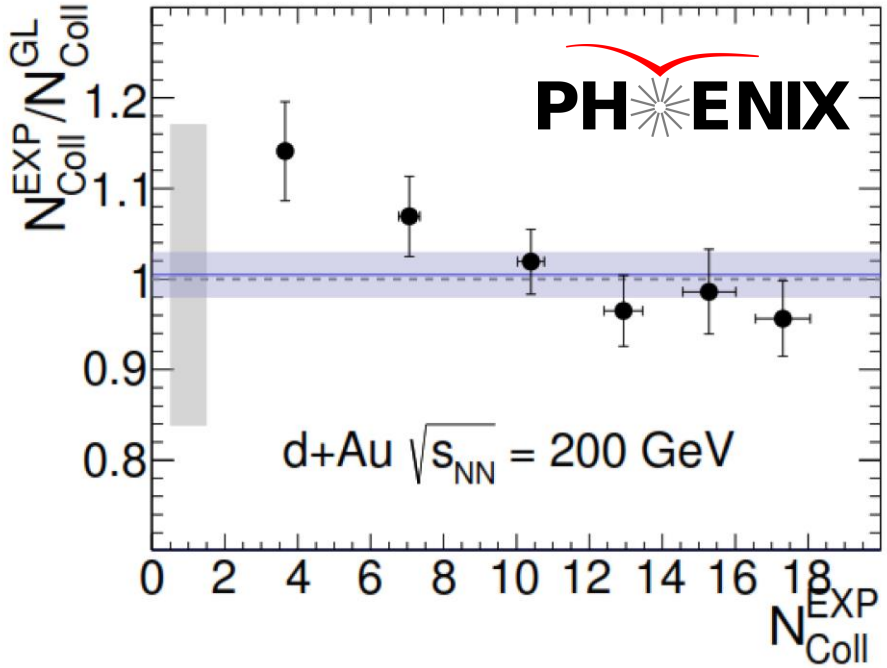
- A 0-20% centrality p+Pb collision is equivalent to an impact parameter of 3 fm, with large variance

Comparison with Glauber N_{coll}



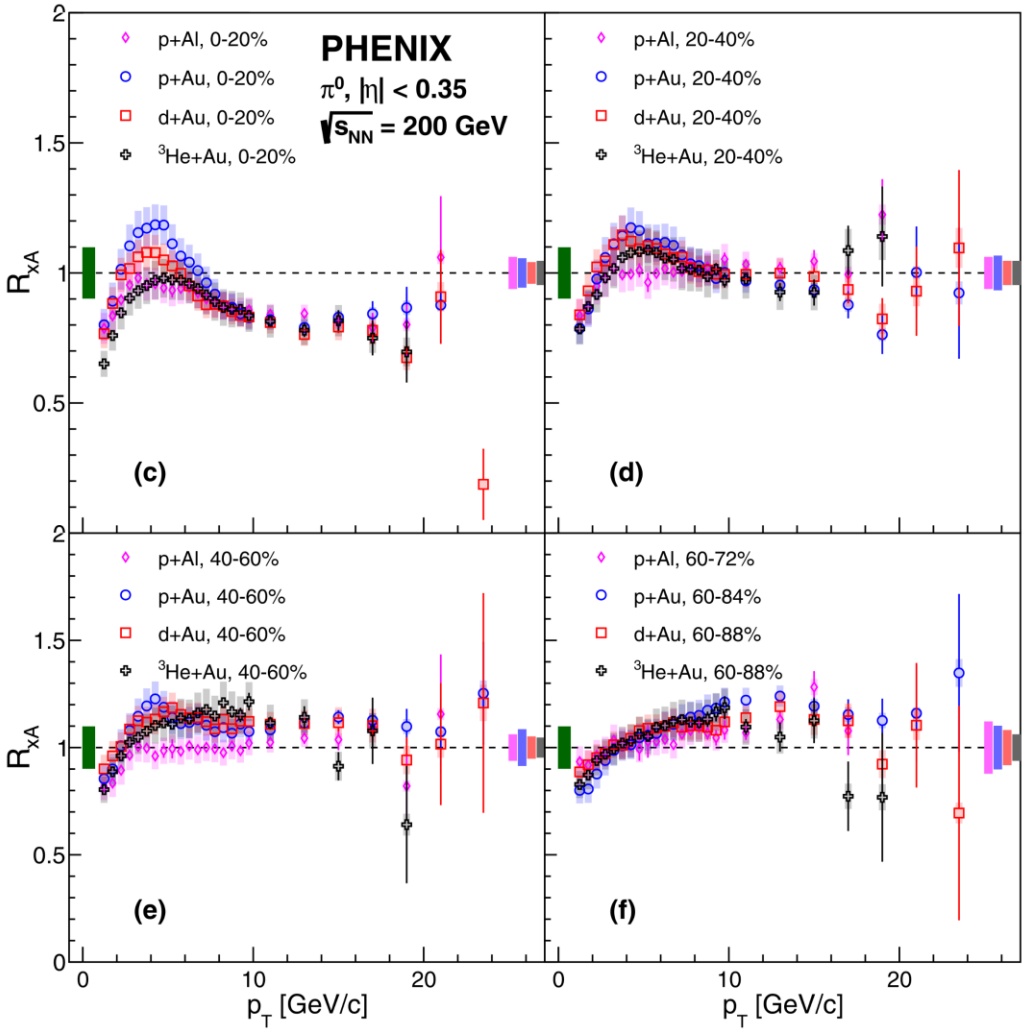
$$N_{Coll}^{EXP} = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$$

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



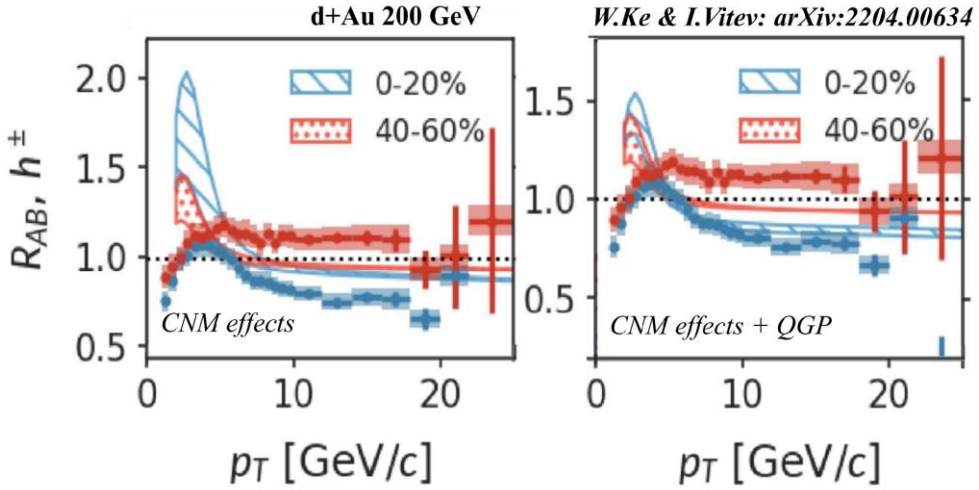
The uncertainties are highly correlated, so even though the points seem consistent with GL within uncertainty (grey band), the consistent decreasing trend is good evidence of deviation

Nuclear modification factor in d+Au



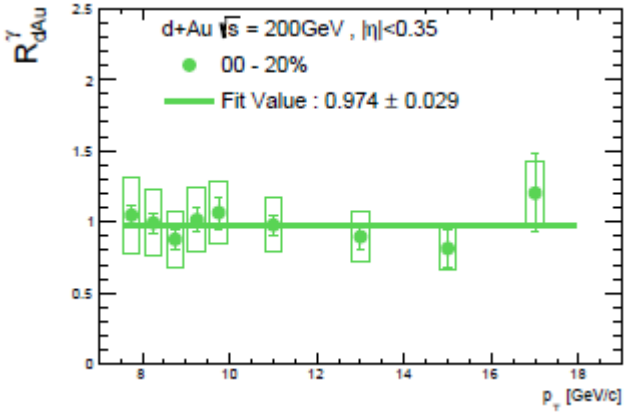
PHENIX: PRC105 (2022) 064902

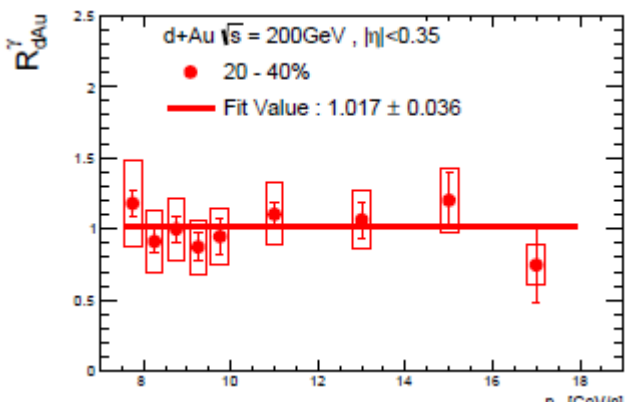
- For high p_T π^0s in small systems, large centrality dependence is observed:
  - Suppression for central events

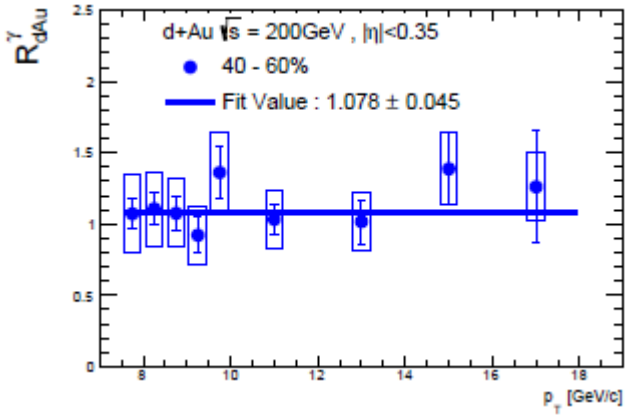


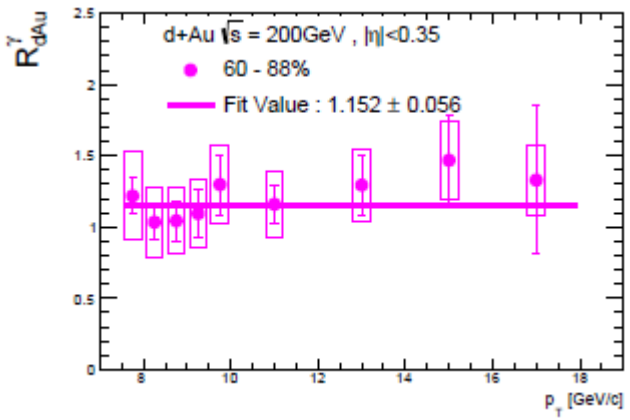
- Suppression for the central events could be explained with QGP formation. Enhancement cannot be trivially explained from physical arguments.

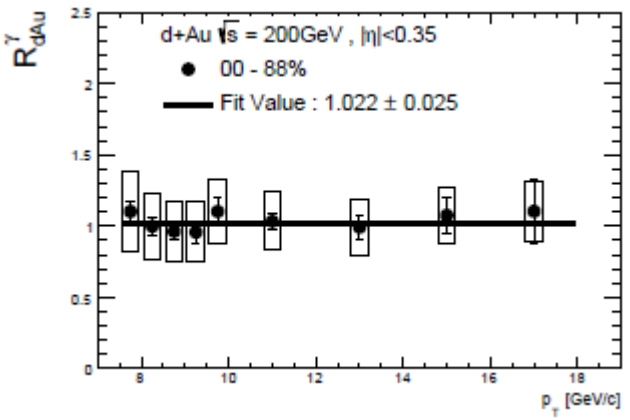
$R_{dAu}^{\gamma^{dir}}$

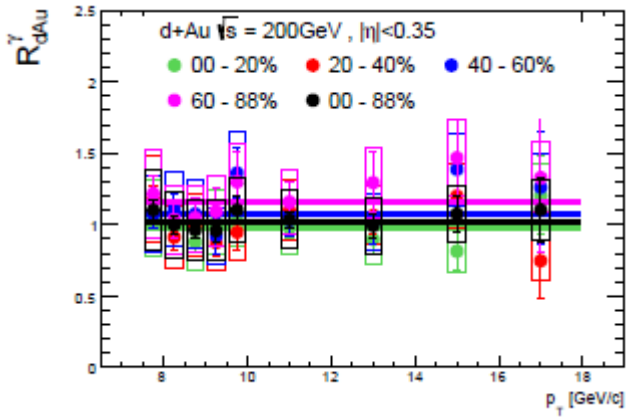




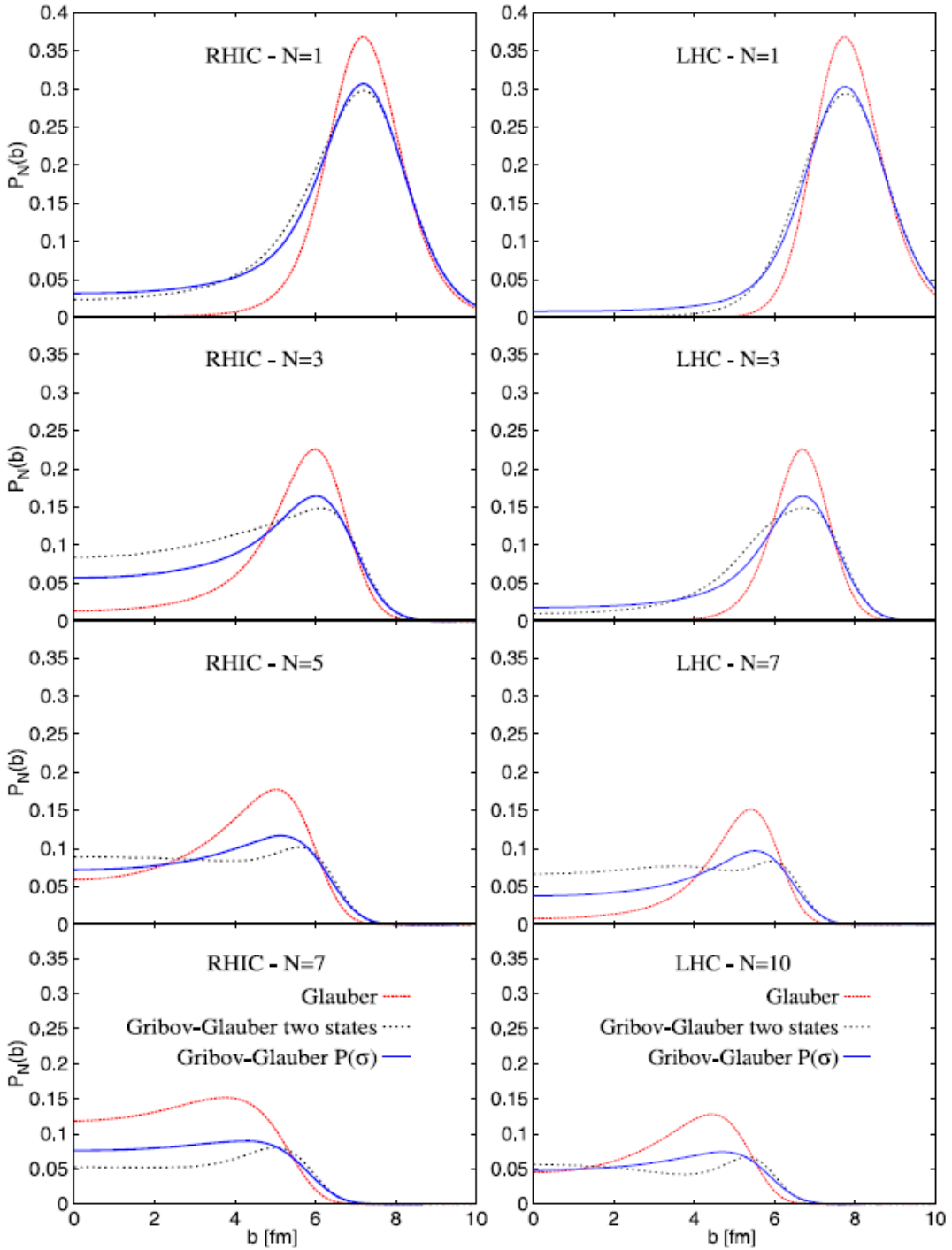








M. Alvioli, M. Strikman
Physics Letters B 722 (2013) 347-354



The probability *PN (b)* of having *N* inelastically interacting (wounded) nucleons in a *pA* collision, vs. impact parameter *b*, when using simple Glauber (red curves), a two states model (black curves) and a distribution *Ph(σtot)* (blue curves);

$$R_{AB,exp}^{\pi^0}(p_T) = \frac{\left(\gamma^{dir}/\pi^0\right)^{pp}}{\left(\gamma^{dir}/\pi^0\right)^{AB}}$$

$\frac{\gamma}{\pi^0}$: same normalization
peak extraction
energy scale

In pp – pp cross section

Double: Hadron contamination

Assumption: $R_{AA}^{\gamma^{dir}} \equiv 1$

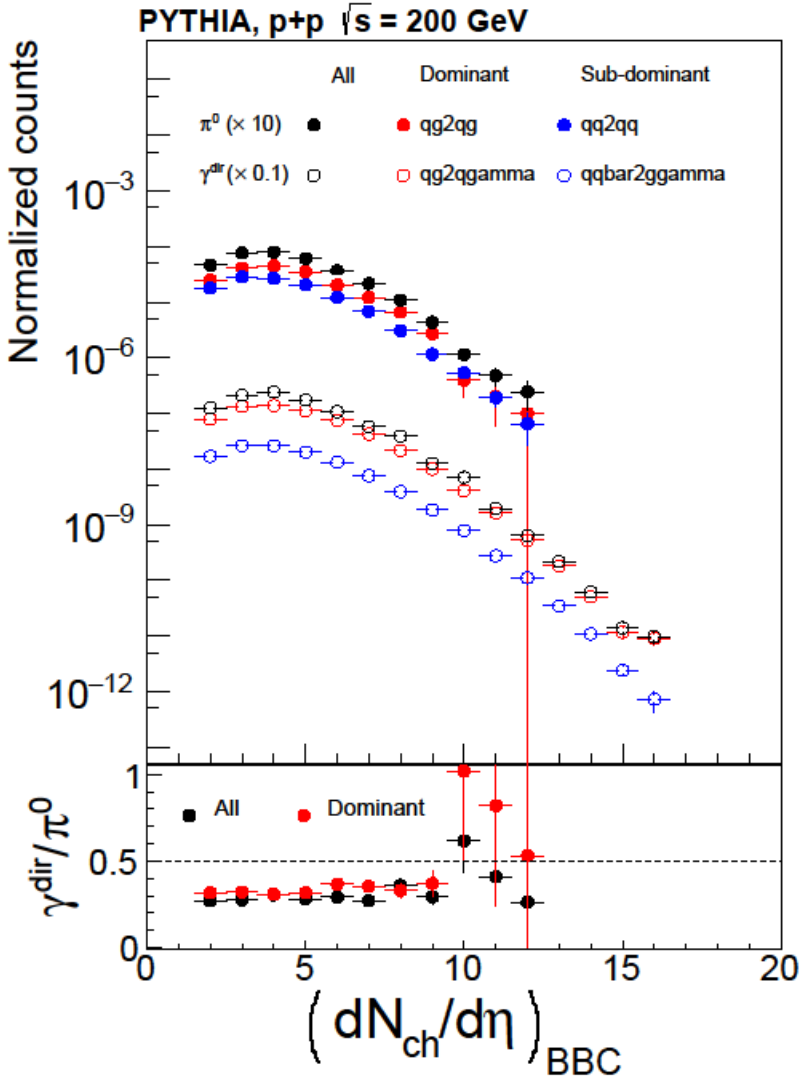
Glauber Bias

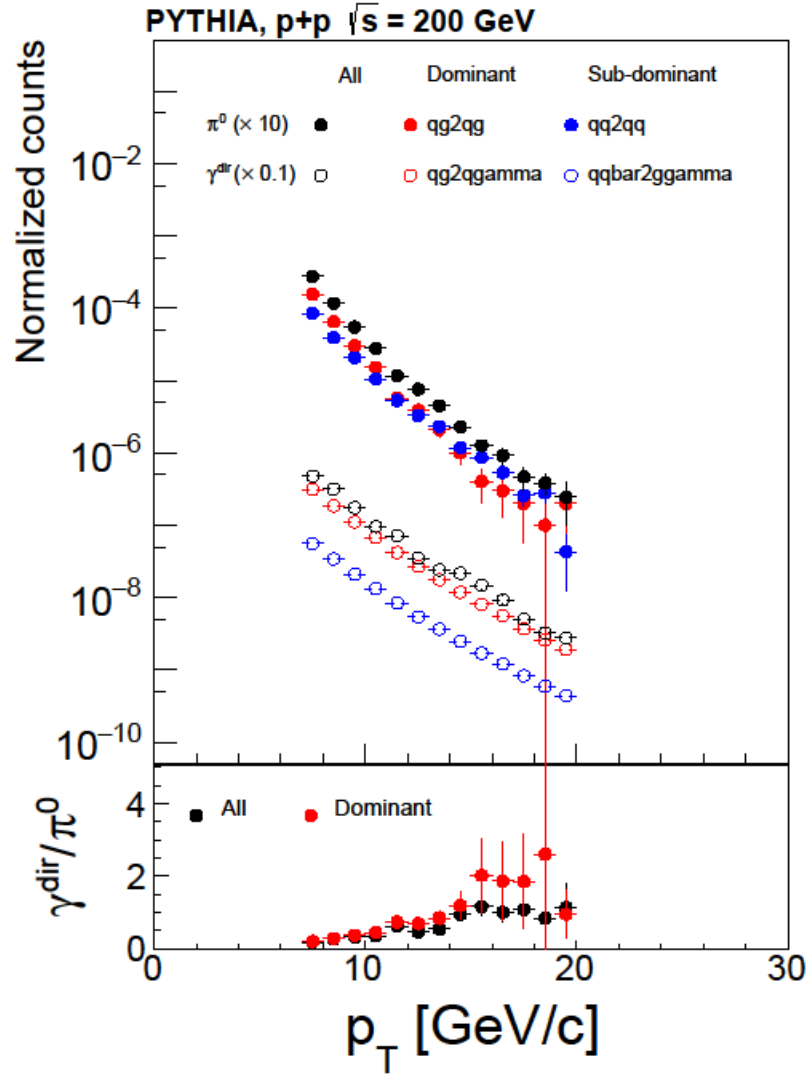
Pp cross section

Centrality bias

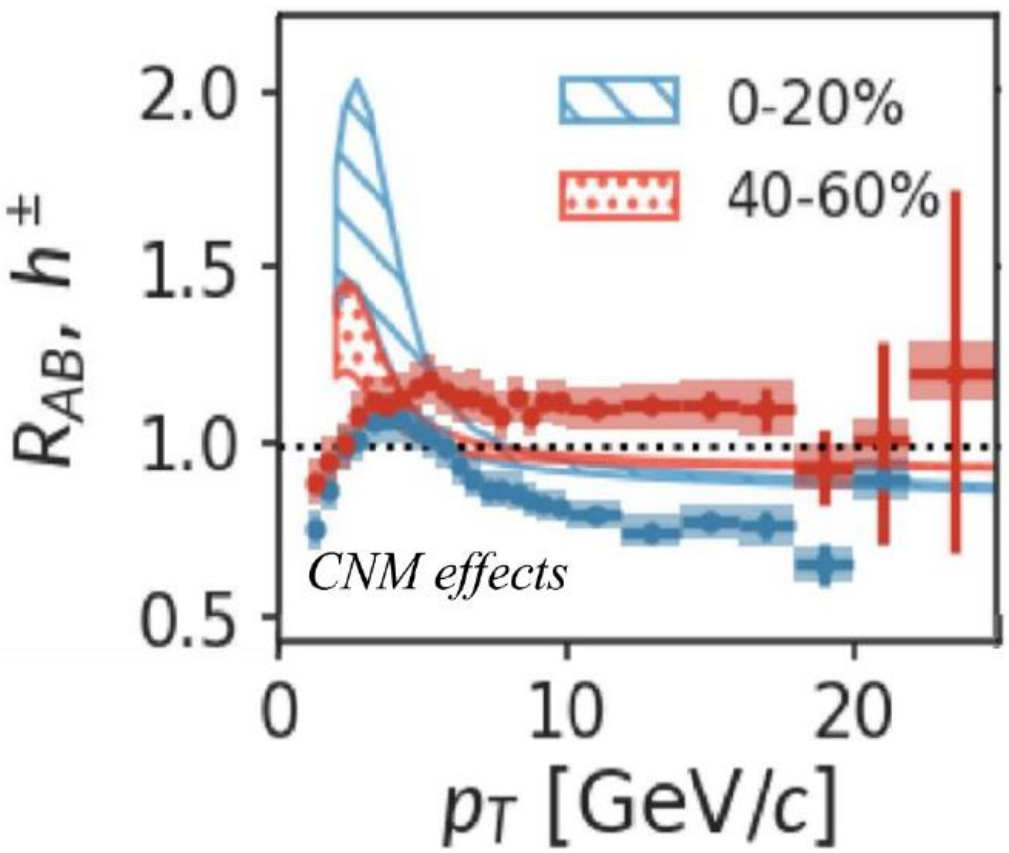
Model dependent

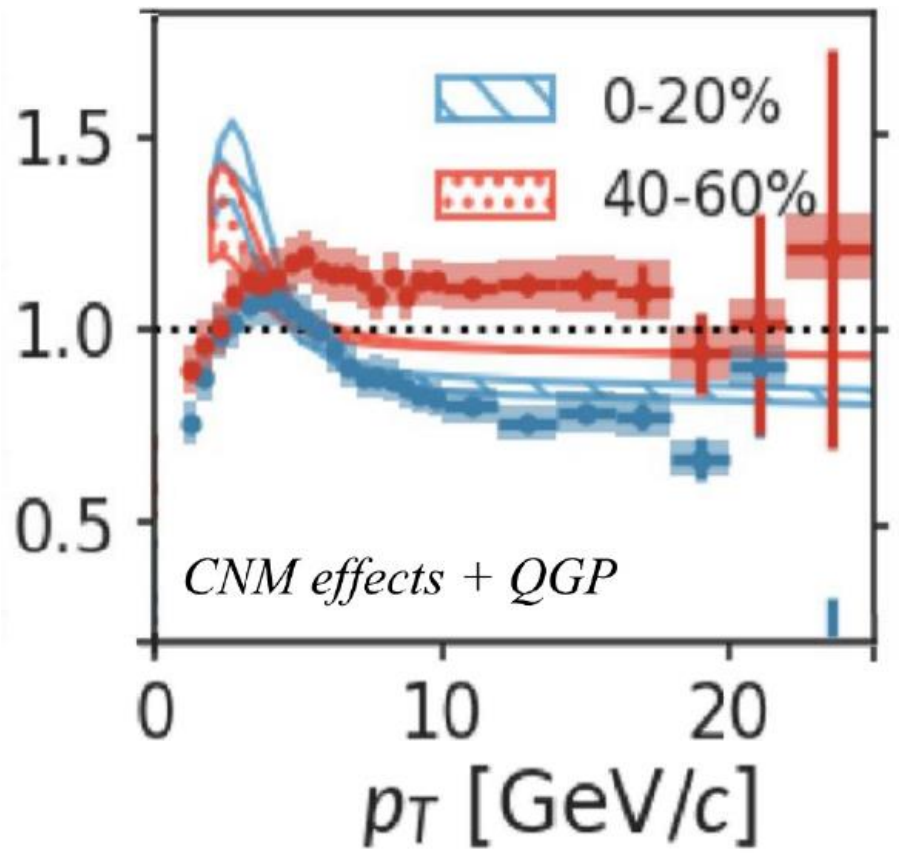
$$R_{AB,GL}^{\pi^0}(p_T) = \frac{Y_{AB}^{\pi^0}}{N_{Coll}^{GL} \cdot Y_{pp}^{\pi^0}}$$


PYTHIA, p+p √s = 200 GeV
All
Dominant
Sub-dominant
π⁰ (× 10)
γ^dir (× 0.1)
qg2qg
qq2qq
qg2qgamma
qqbar2ggamma
Normalized counts
10⁻³
10⁻⁶
10⁻⁹
10⁻¹²
All
Dominant
γ^dir/π⁰
1
0.5
0
0
5
10
15
20
⟨ dN_ch/dη ⟩_BBC

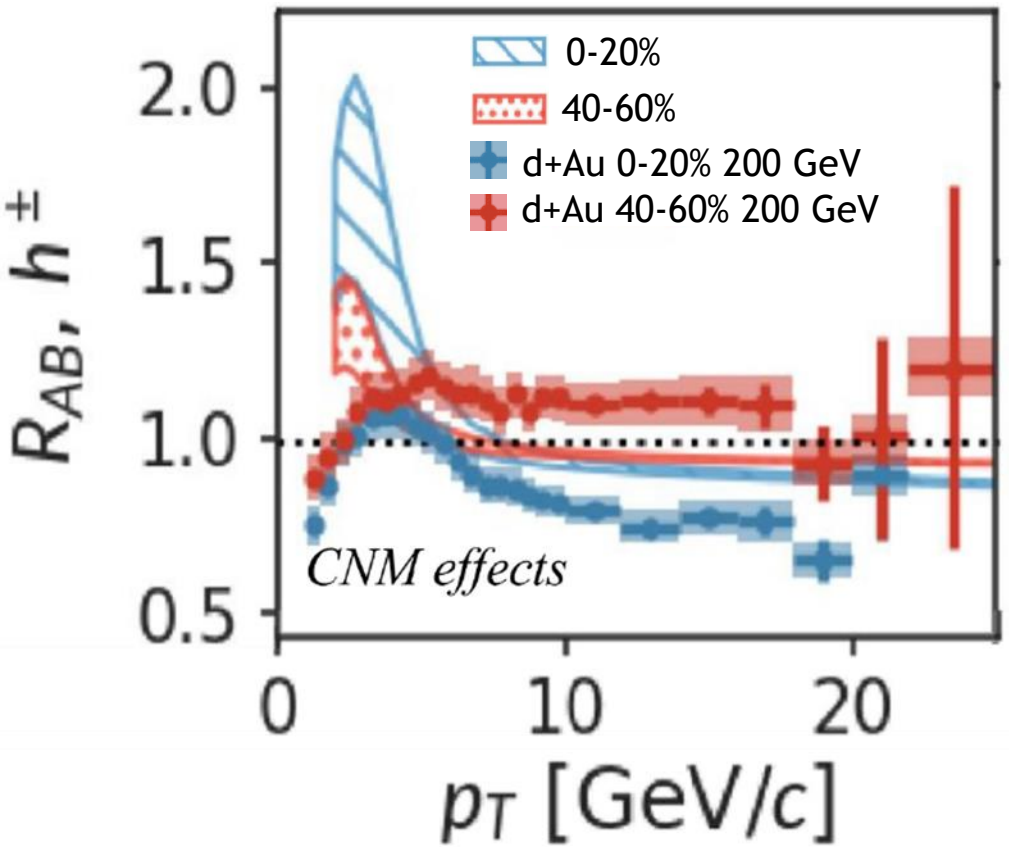

PYTHIA, p+p √s = 200 GeV
All
Dominant
Sub-dominant
π⁰ (× 10)
γ^dir (× 0.1)
qg2qg
qq2qq
qg2qgamma
qqbar2ggamma
Normalized counts
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
All
Dominant
γ^dir/π⁰
4
2
0
0
10
20
30
p_T [GeV/c]

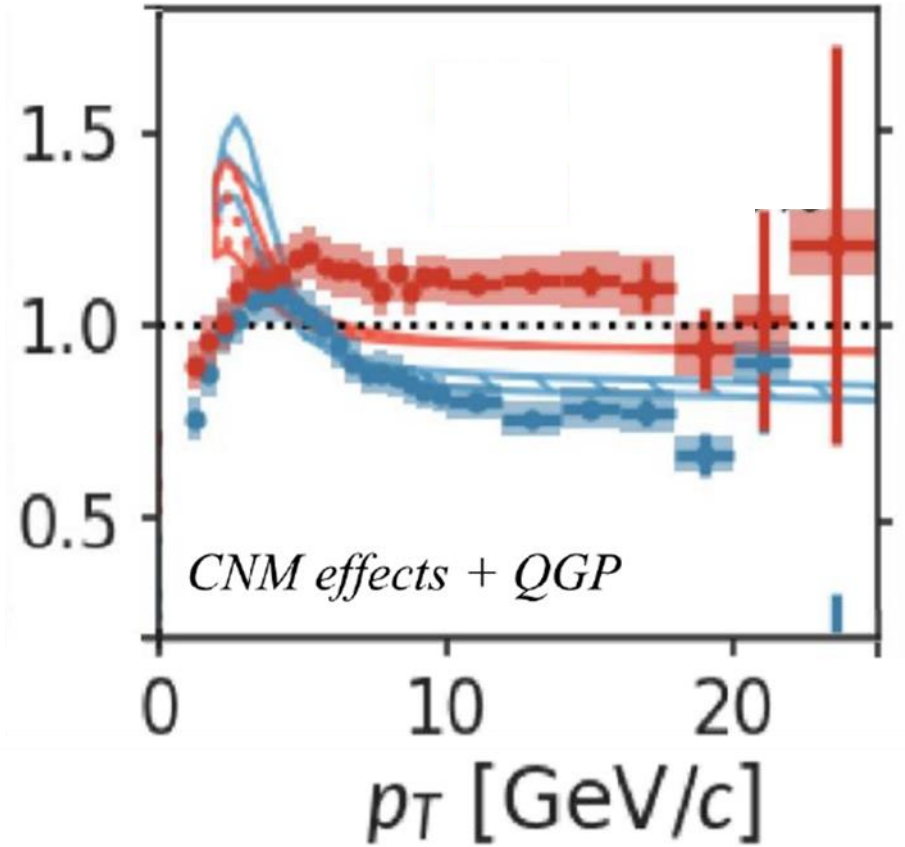

PHENIX





W. Ke, I. Vitev: PRC107 (2023) 064903


0-20%
40-60%
d+Au 0-20% 200 GeV
d+Au 40-60% 200 GeV
R_{AB}, $h^{\pm}$
2.0
1.5
1.0
0.5
CNM effects
0
10
20
p_T [GeV/c]


1.5
1.0
0.5
CNM effects + QGP
0
10
20
p_T [GeV/c]