HP2024
NAGASAKI

Measurement of high p_T direct photon and π^0s in small collision systems at PHENIX

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

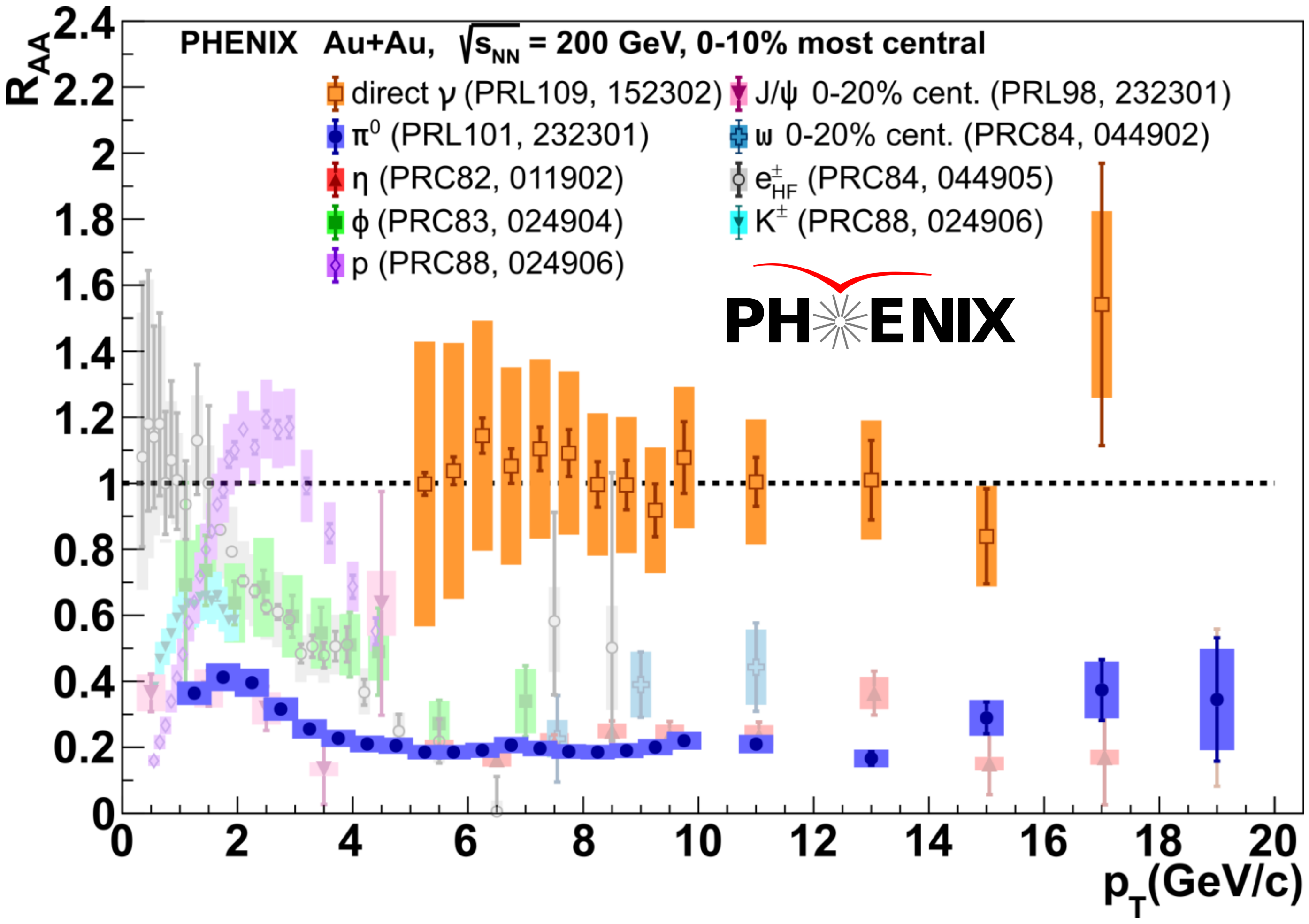
Outline:

- Motivation: $R_{AB}(p_T)$
- Selection bias, Energy conservation in small systems
  - Glauber Model in Small systems
- Direct Photons, Bjorken-x
- Nuclear modification factor in d+Au (PHENIX: arXiv:2303.12899)

Stony Brook University

PHENIX

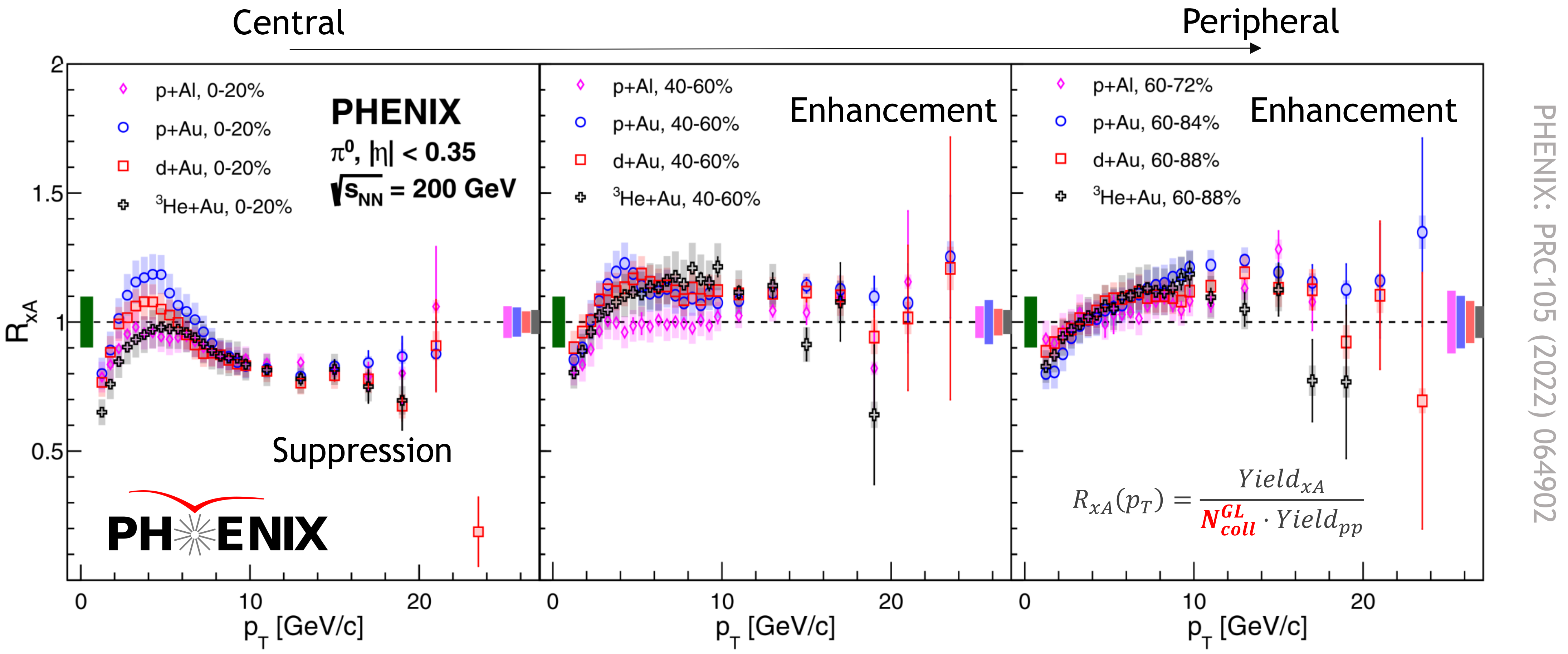
Nuclear modification factor in Au+Au



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

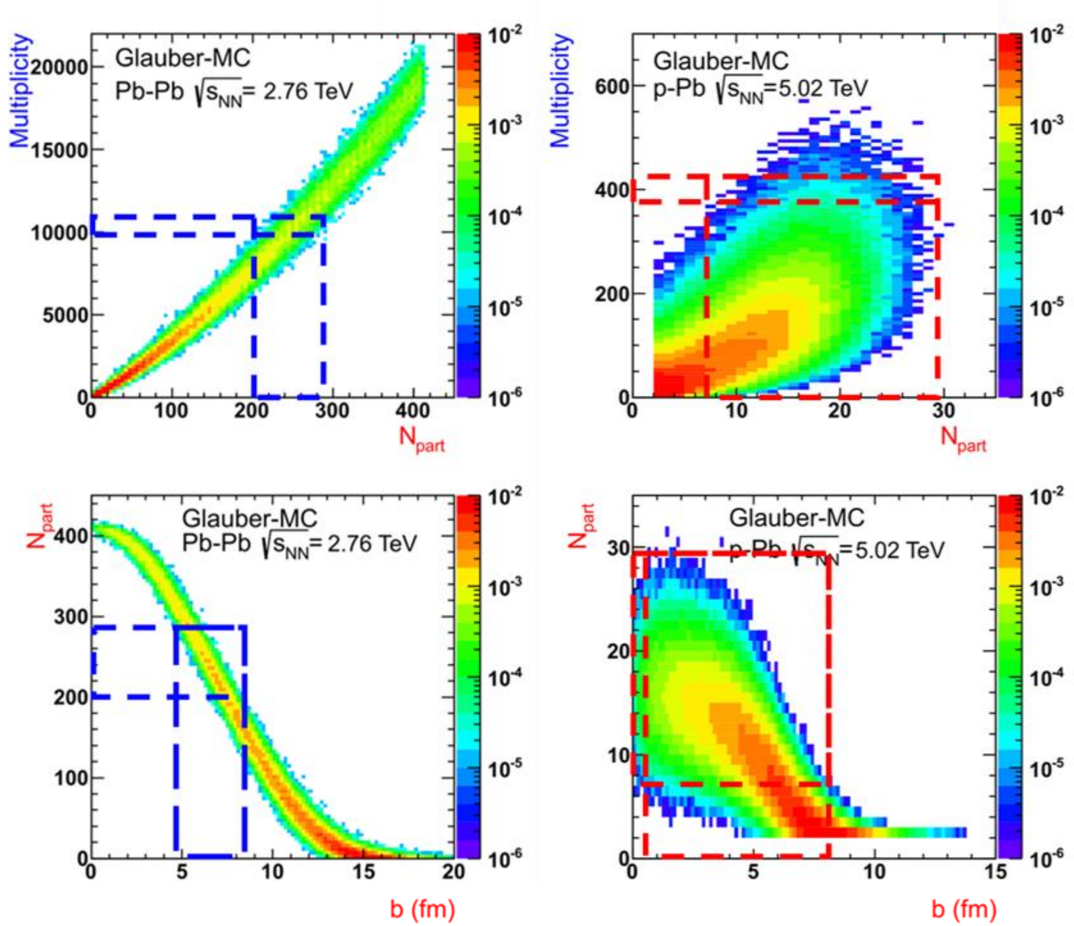
- For neutral pions (hadrons), $R_{AB}^{\pi^0}$ shows suppression in large systems
- For photons, R_{AB}^{γ} is consistent with 1

Nuclear modification factor in small systems



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

Is the Glauber Model good both in small and large systems?



ALICE: PRC91 (2015) 064905

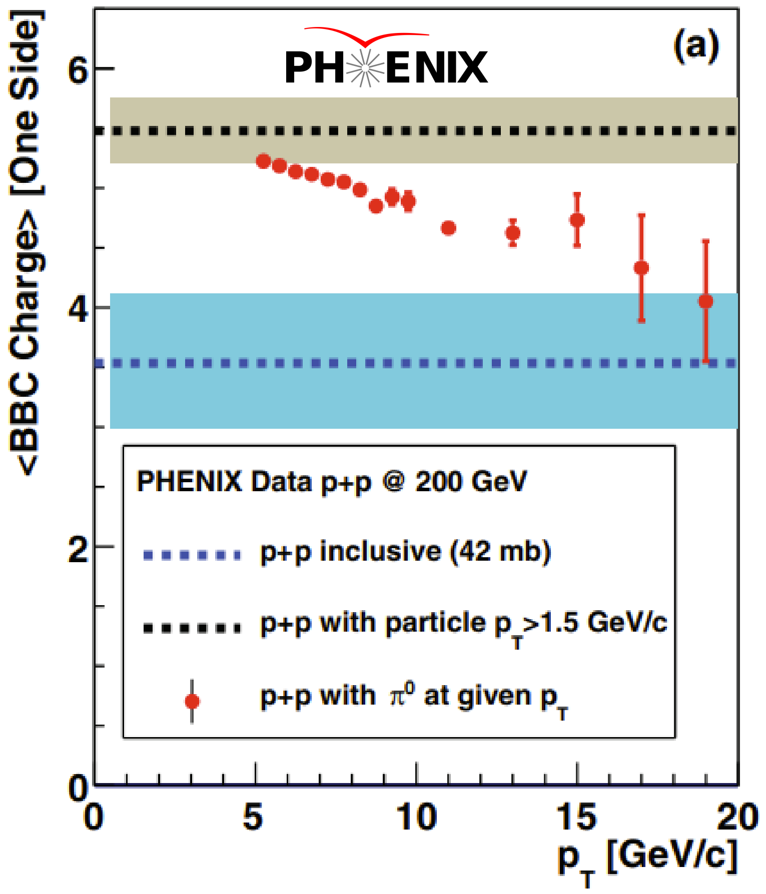
Red axis: theory / model calculations
Blue axis: experimentally measurable

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

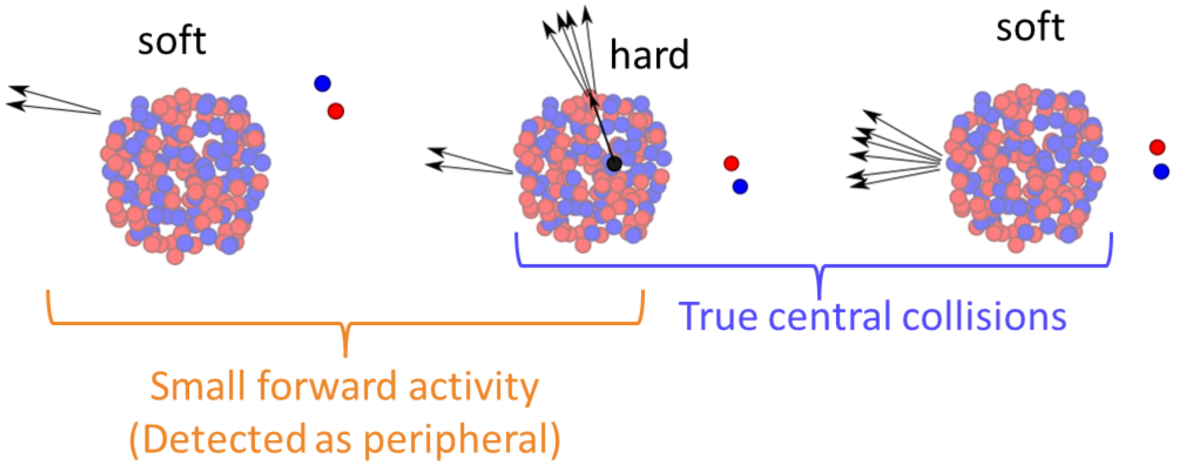
- Multiplicity window = centrality class
  - Measurable
- $N_{coll}^{GL} \propto \left(\frac{dN_{ch}}{d\eta}\right)^{a}$: Not directly measurable!
  - Obtained through Glauber model

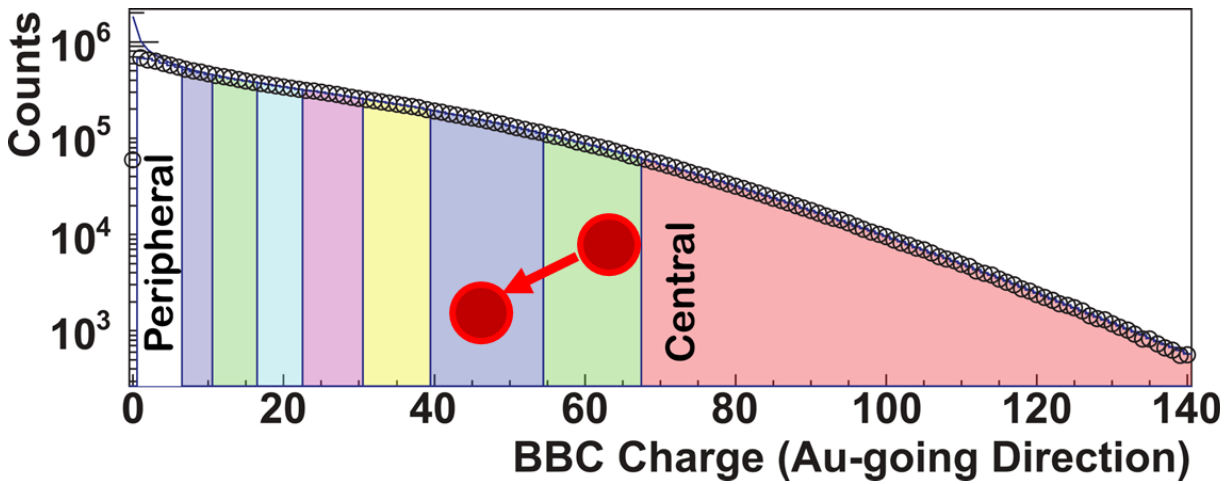
There IS bias in small systems!

Centrality is determined by event activity in the BBC, on the Au going direction (PHENIX)



PHENIX: PRC90 (2014) 034902





more midrapidity, less forwards/backwards

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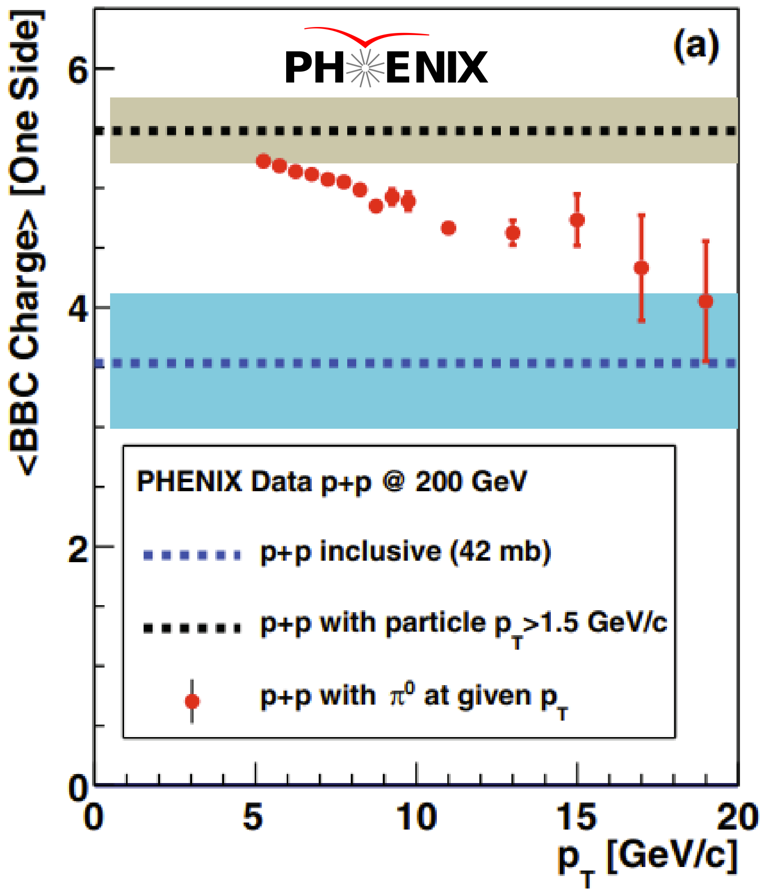
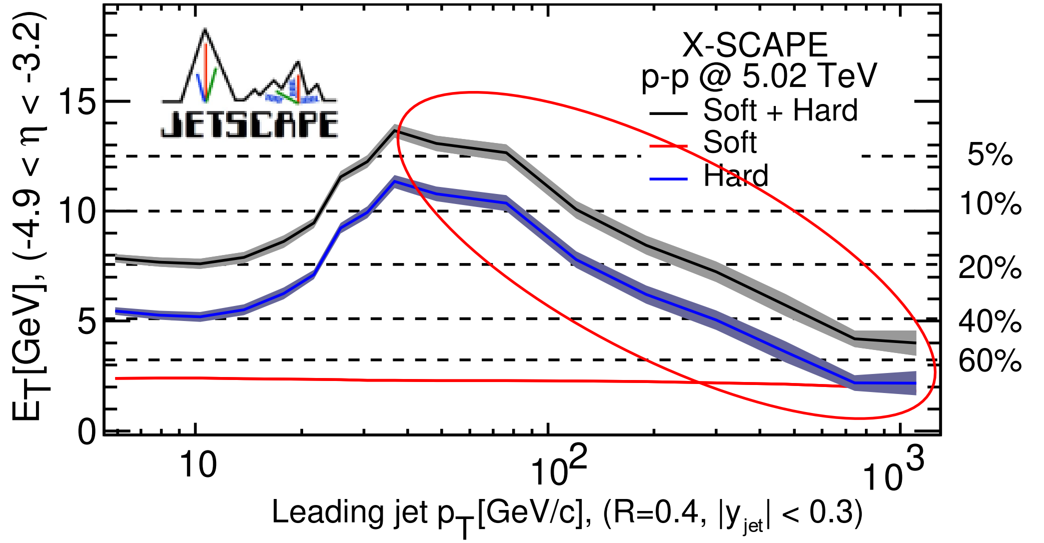
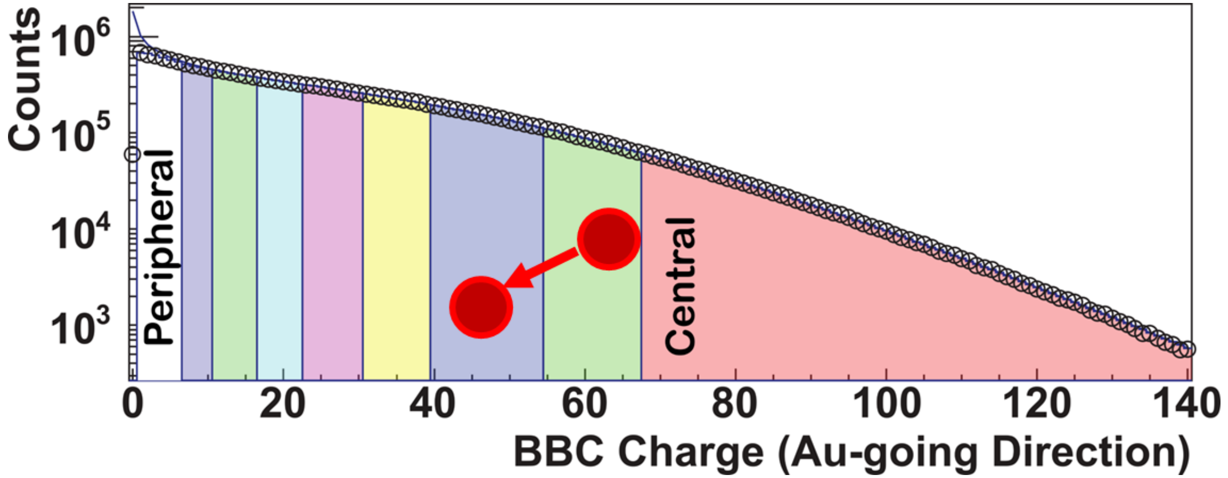


PHENIX: PRC90 (2014) 034902

JETSCAPE: arXiv: 2407.17443

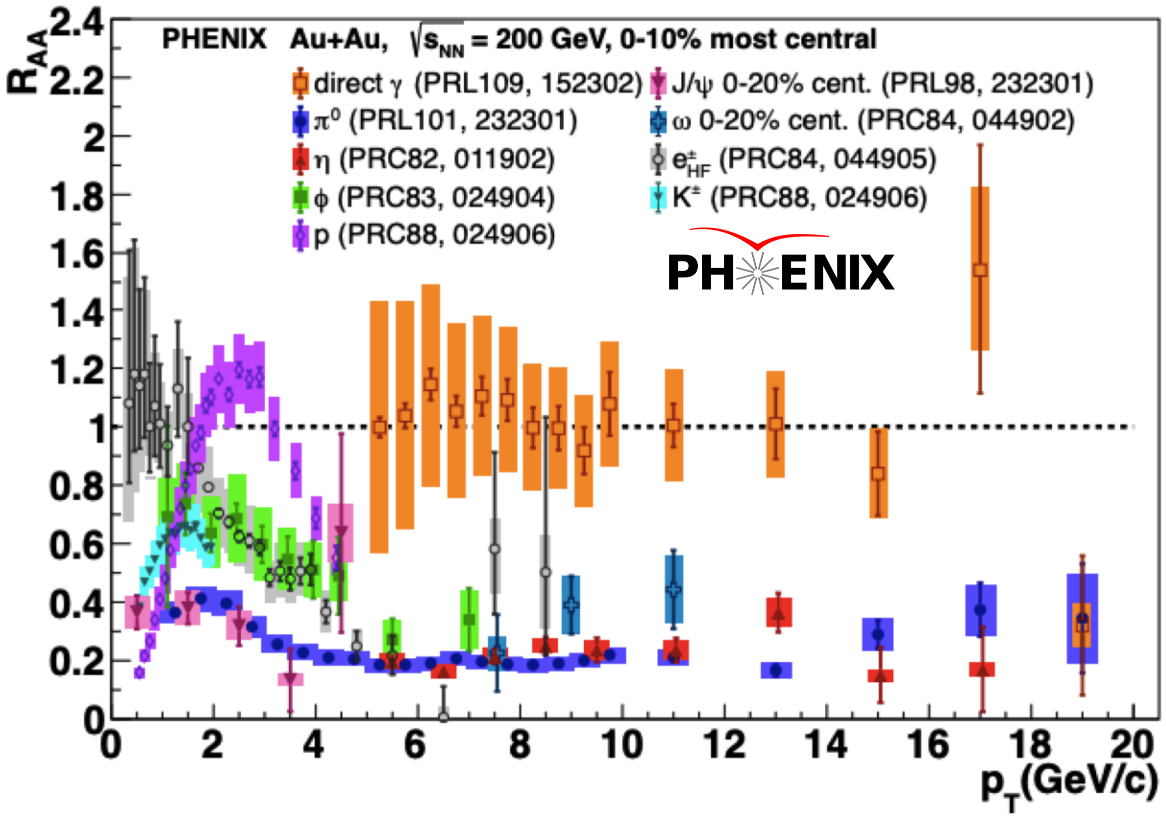


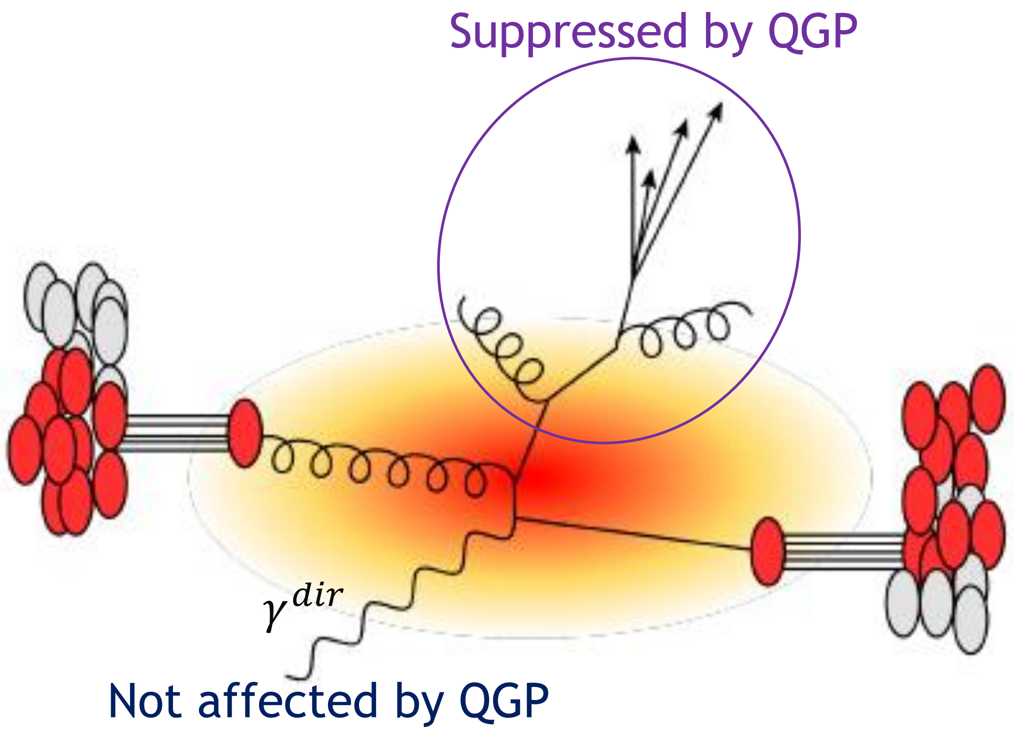


more midrapidity, less forwards/backwards

"Correlations between hard probes and bulk dynamics in small systems"
Sangyong Jeon – in ~30 minutes!

Direct photons to the rescue!





- Unlike color charged matter, direct photons are unaffected by QGP.
- γ^{dir} can be used as a less biased direct measure of N_{Coll}

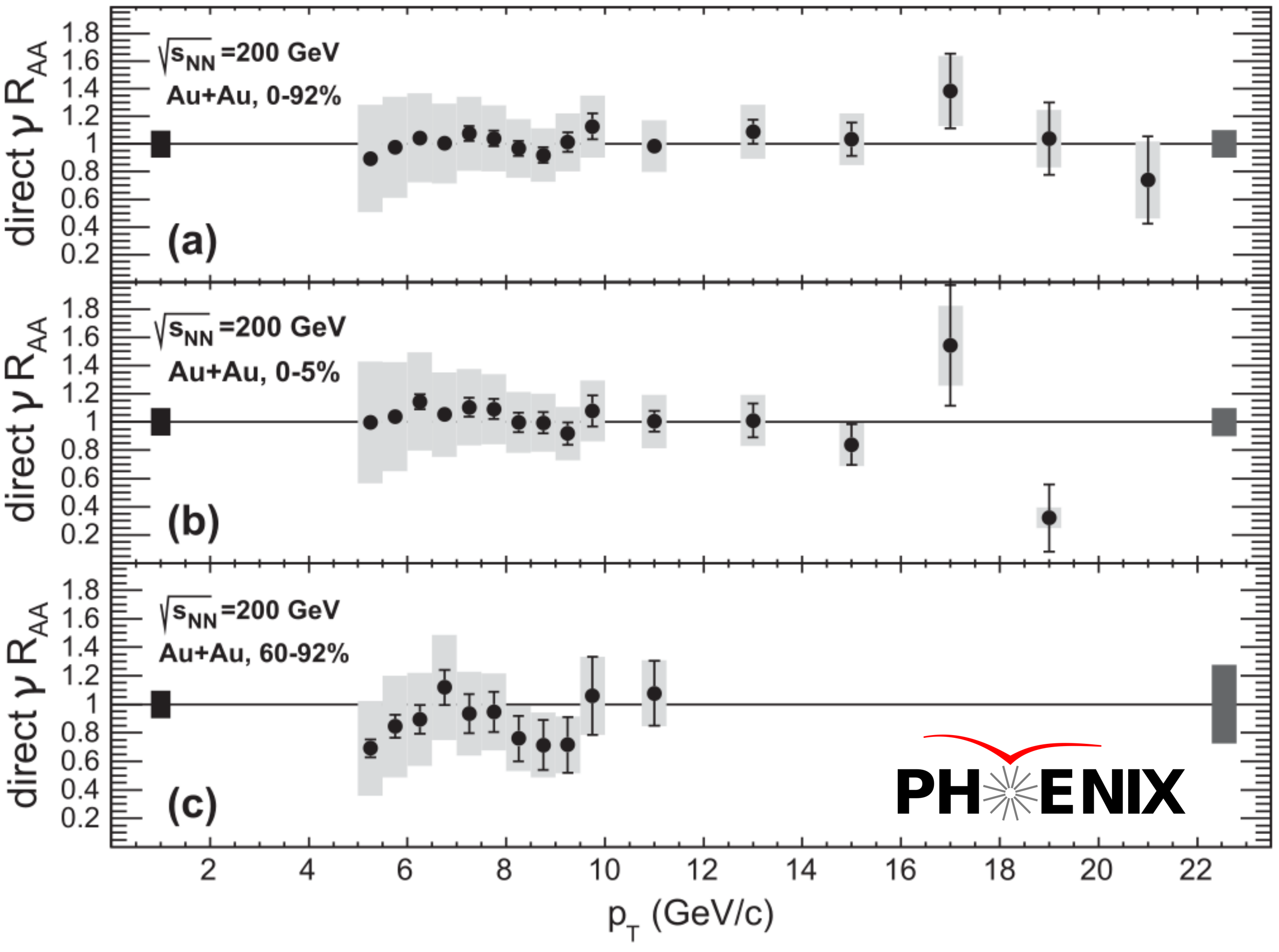
Direct measurement of the N_{coll}

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

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

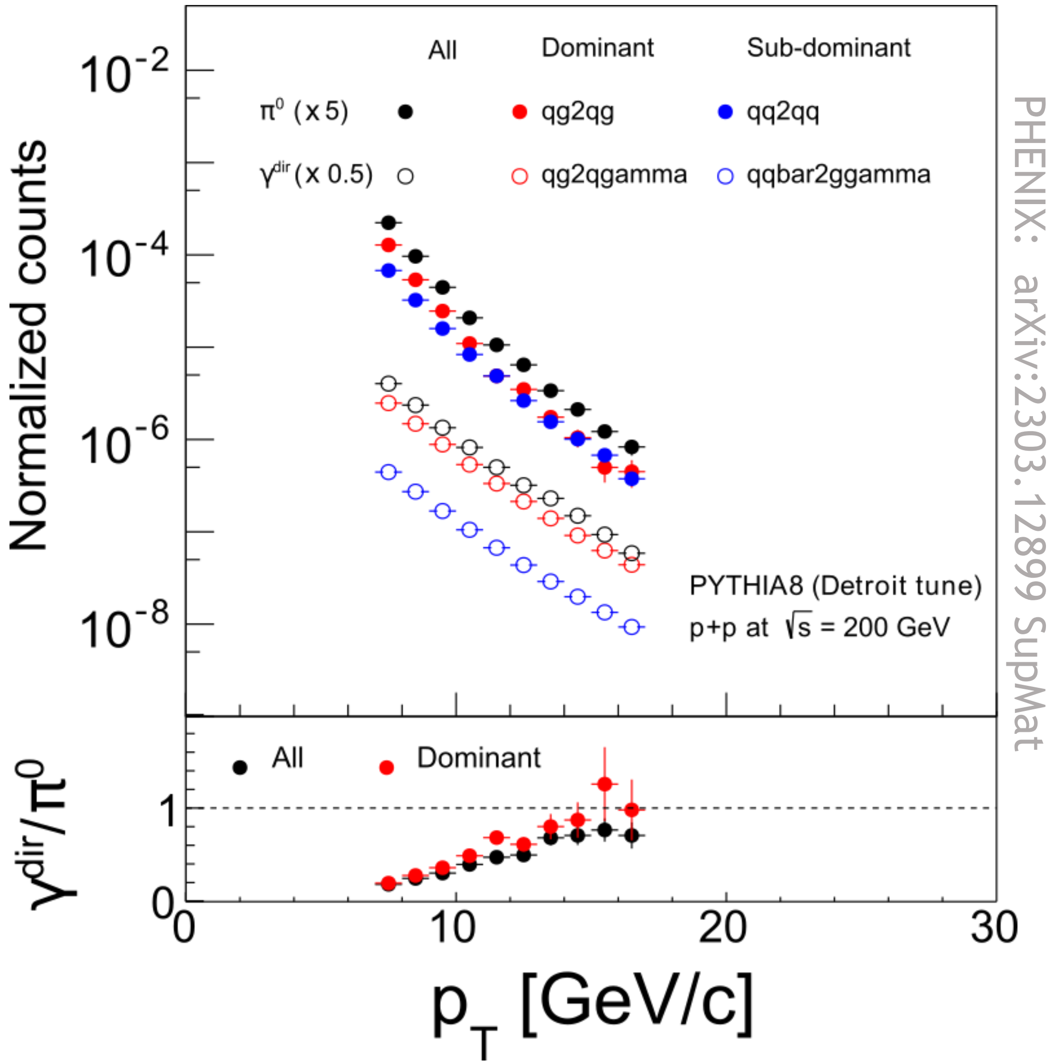
$$N_{Coll}^{EXP} = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$$

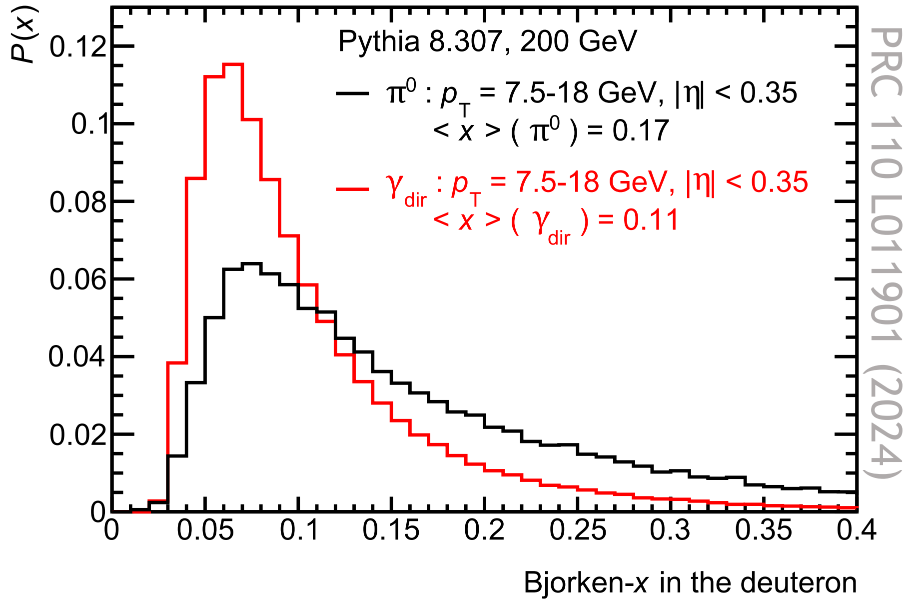
$$R_{AB,exp}^{\pi^0}(p_T) = \frac{Y_{AB}^{\pi^0}(p_T)}{N_{Coll}^{EXP} \cdot Y_{pp}^{\pi^0}(p_T)} \Rightarrow \frac{(\gamma^{dir}/\pi^0)^{pp}}{(\gamma^{dir}/\pi^0)^{AB}}$$



PHENIX: PRL109 (2012) 152302

The Bjorken-x bias





- To first order, the same kinematic bias would affect both $p+p$ and $d+\mathrm{Au}$

$$R^{\pi^0}_{dAu,exp}(p_T) = \frac{(\gamma^{dir}/\pi^0)^{pp}}{(\gamma^{dir}/\pi^0)^{dAu}}$$

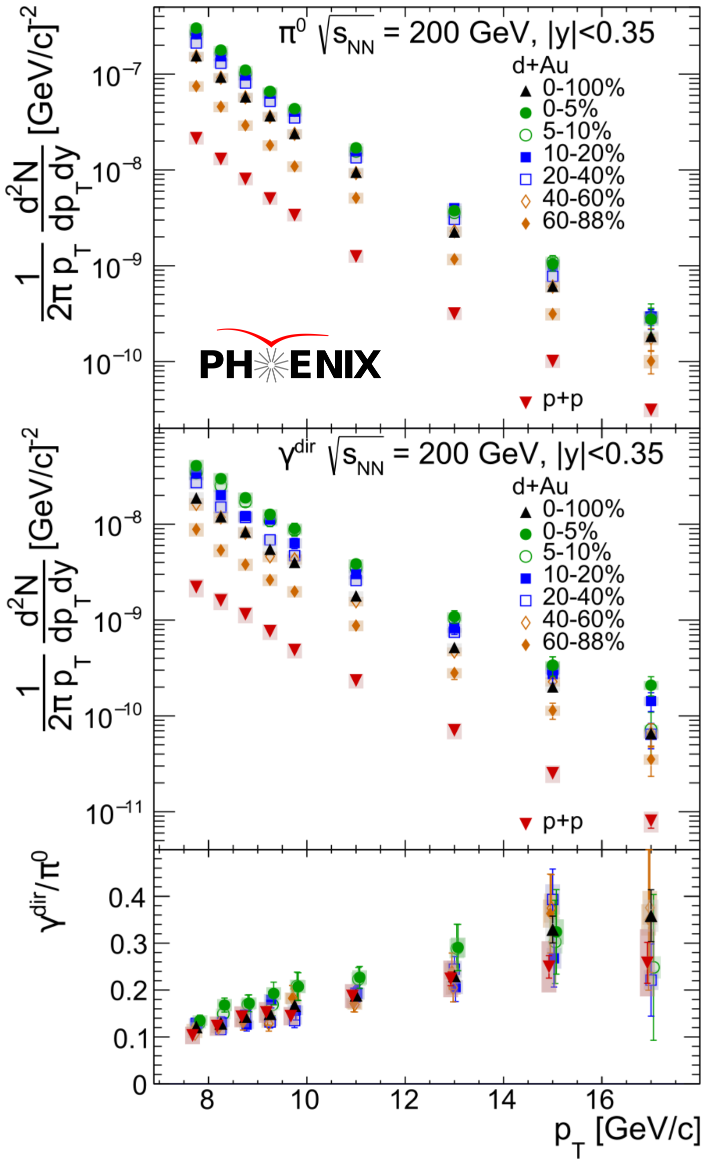
The Bjorken-x bias

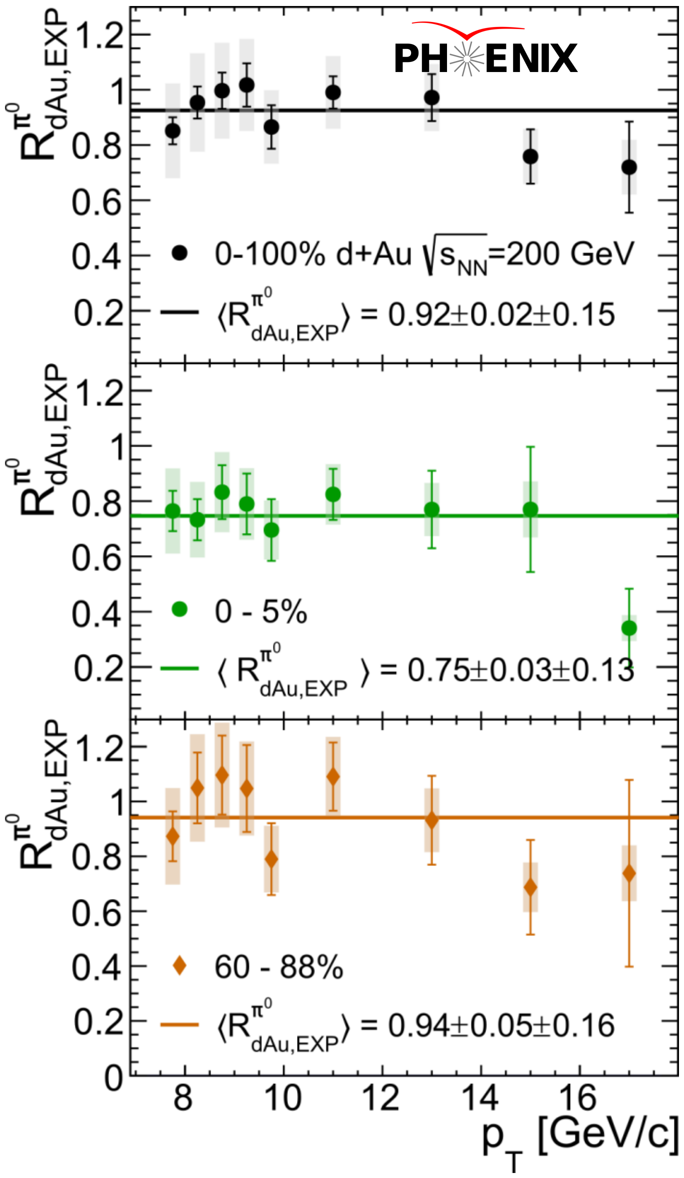
- High p_T γ^{dir} and π^0 (7.5 < p_T < 18 GeV/c)
  - γ^{dir} consistent with 2003 min bias data (PHENIX: PRC87(2013)54907)
  - π^0 consistent with 2008 data (PHENIX:PRC(2022)64902)

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

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

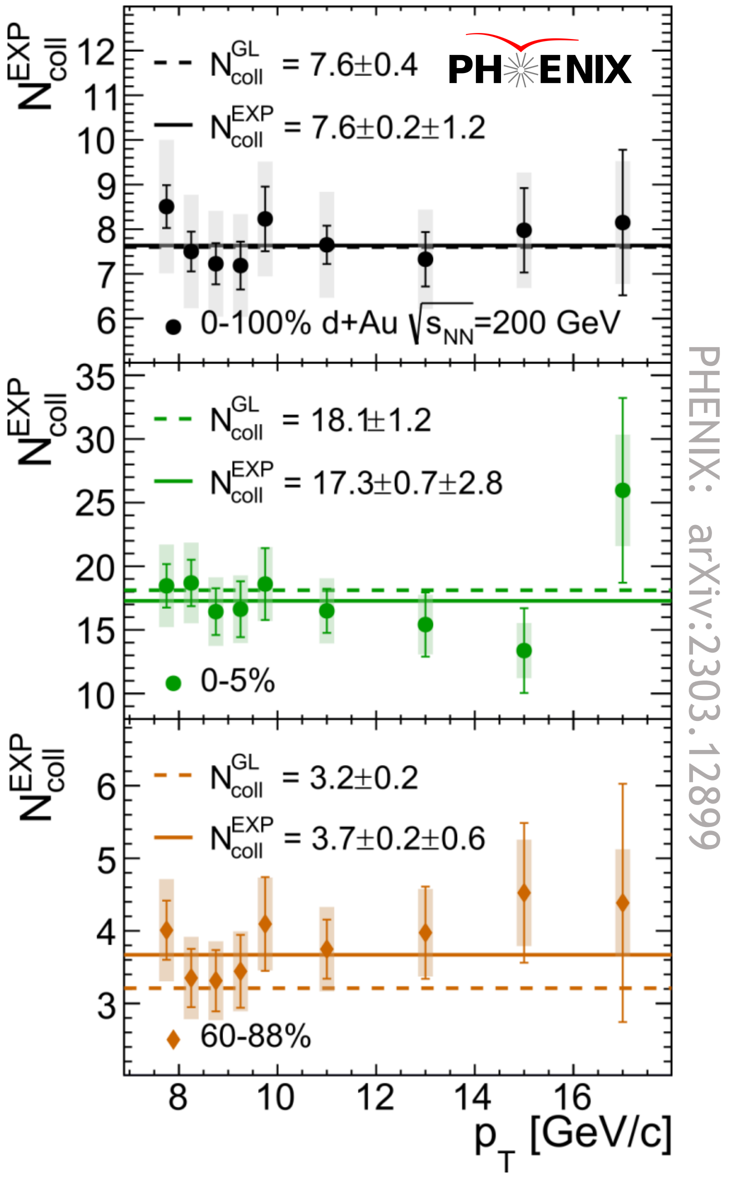
- No obvious p_T dependence.
  - pp and dAu $\left(\gamma^{dir}/\pi^0\right)$ behave similarly





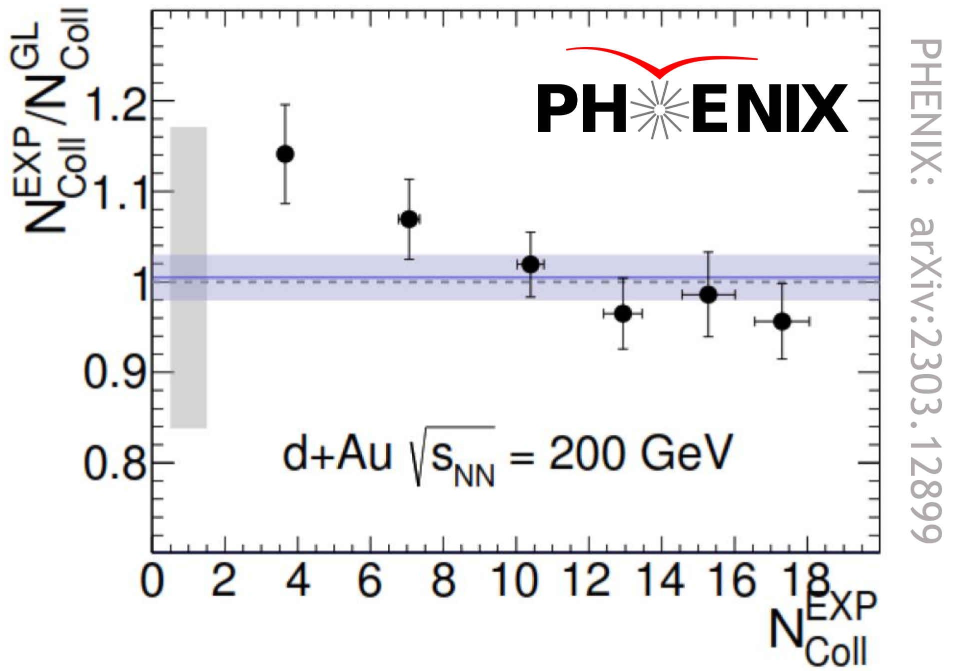
PHENIX: arXiv:2303.12899

Comparison with Glauber N_{coll}



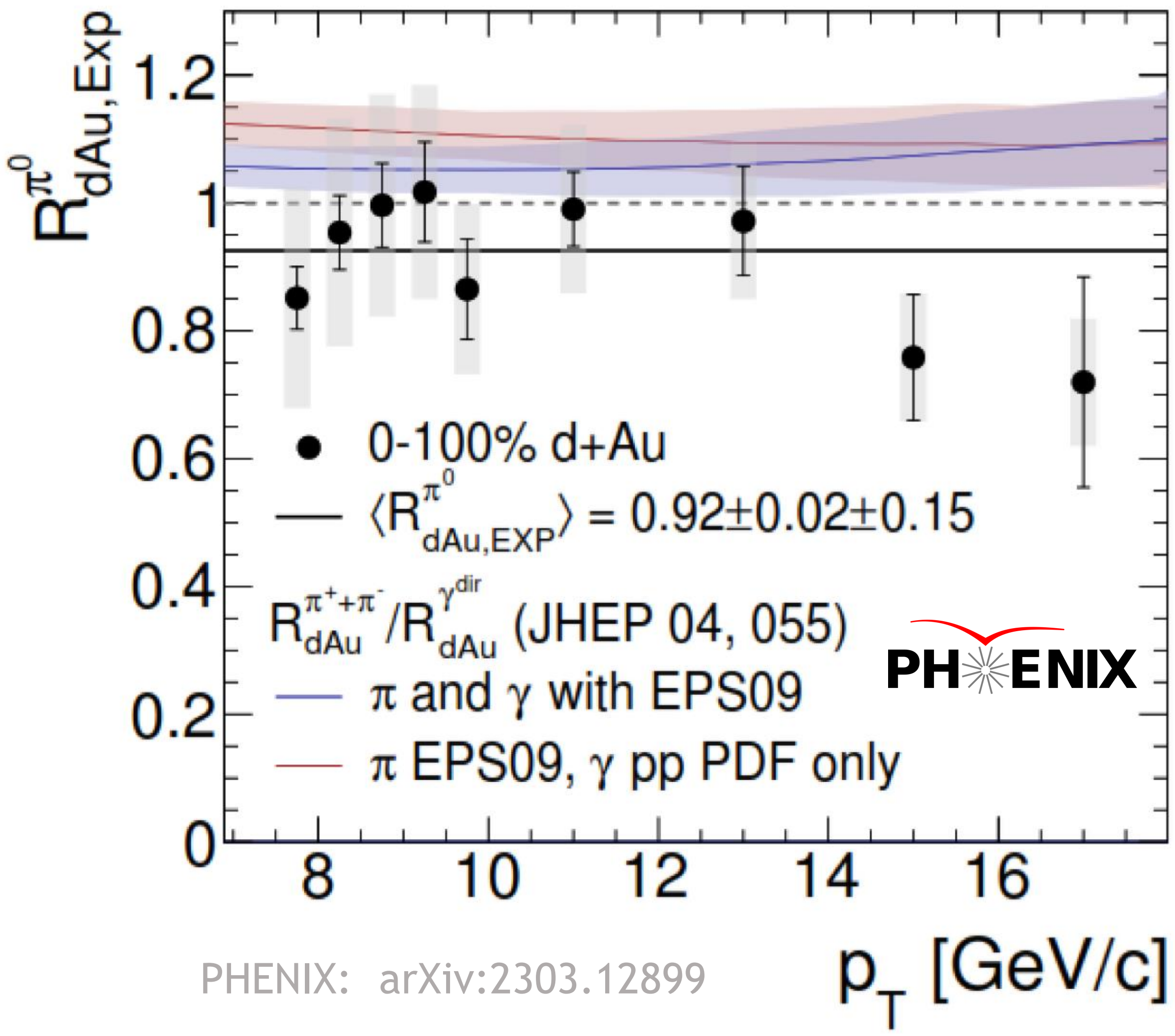
$$N_{Coll}^{EXP} = \frac{Y_{AB}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$$

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



Peripheral → Central

Nuclear modification factor for π^0 in d+Au



PHENIX: arXiv:2303.12899

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

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

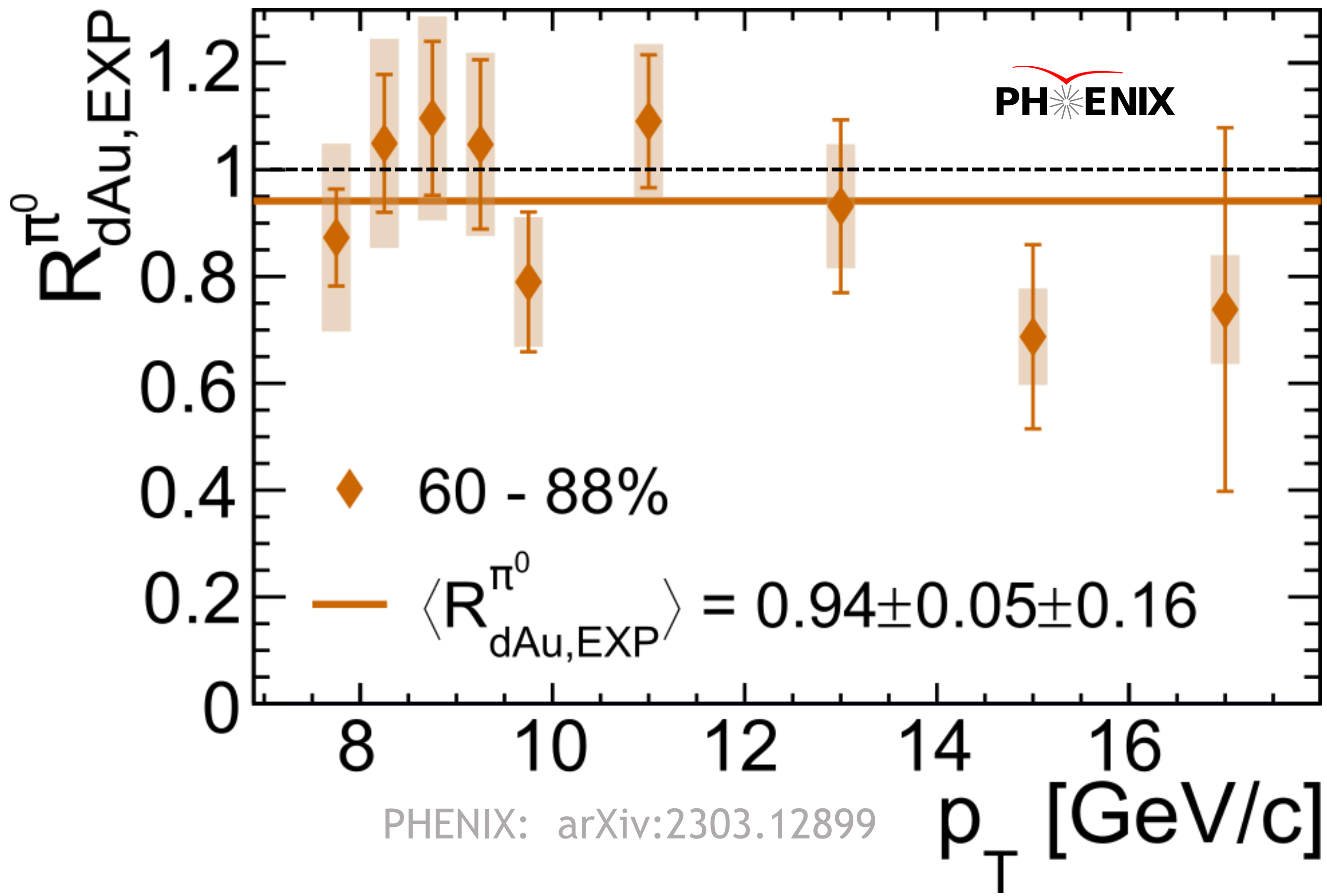
$$\left\langle R^{\pi^0}_{dAu,exp} \right\rangle = 0.92 \pm 0.02 \pm 0.15$$

  - 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

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



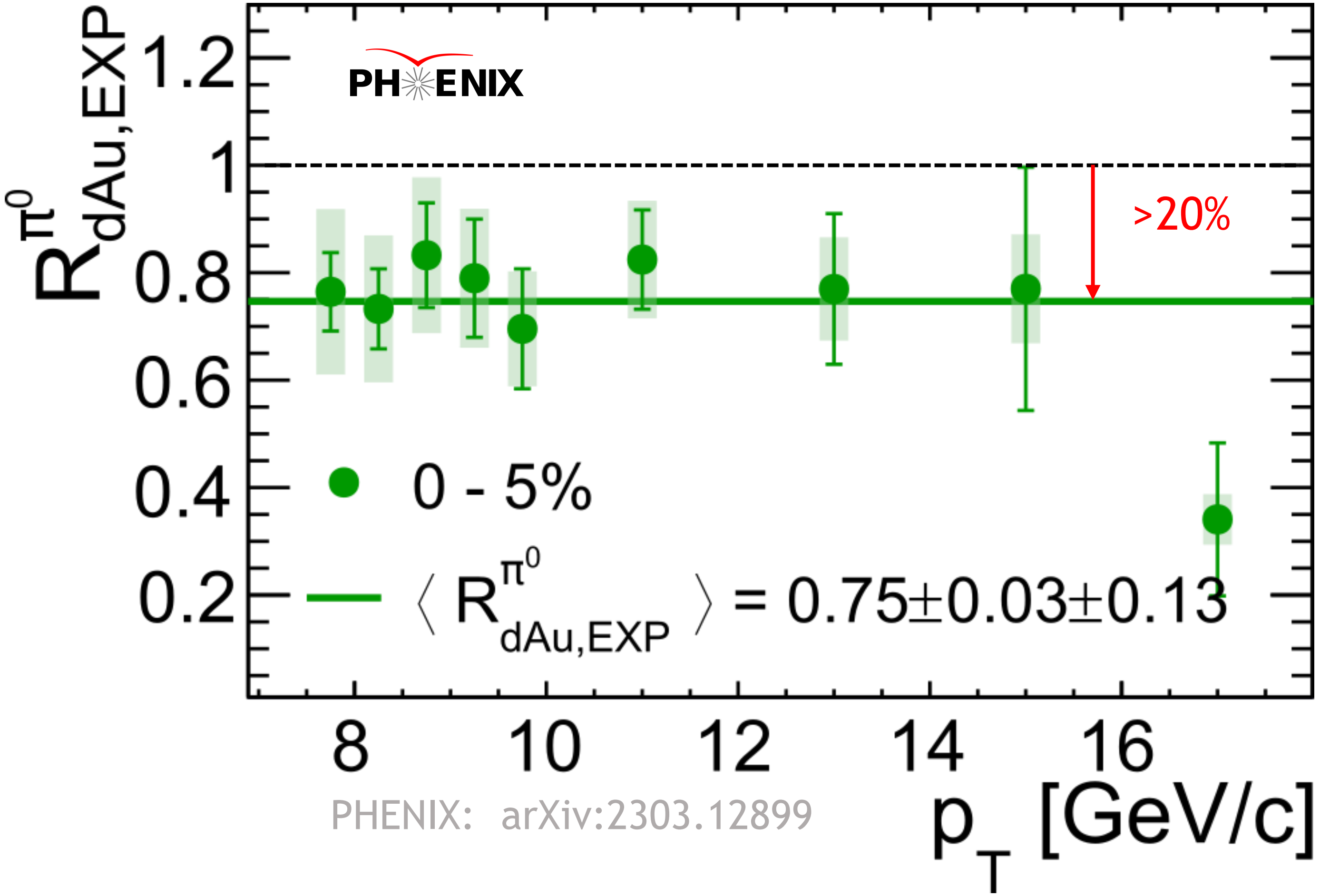
PHENIX: arXiv:2303.12899

- Peripheral collisions are consistent with inclusive (0-100%)
- No peripheral enhancement

Nuclear modification factor for π^0 in d+Au

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

- 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 $R_{dAu,exp}^{\pi^0}$ vs N_{coll}^{exp}

- For $N_{coll}^{exp} < 14$:

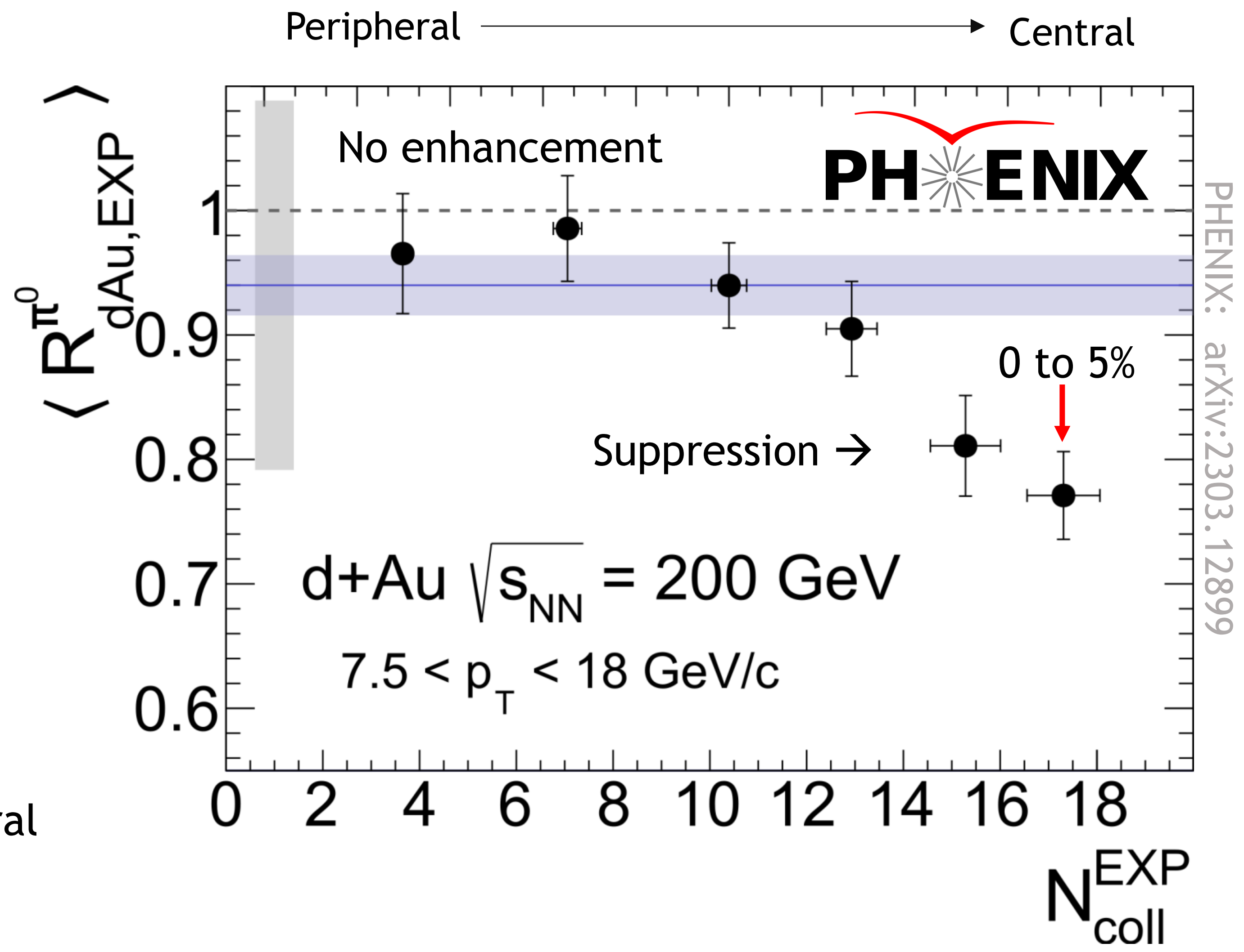
$$\frac{R_{dAu,exp}^{\pi^0}(60-88\%)}{R_{dAu,exp}^{\pi^0}(0-100\%)} = 1.017 \pm 0.56$$

  - Consistent with inclusive d+Au

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

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

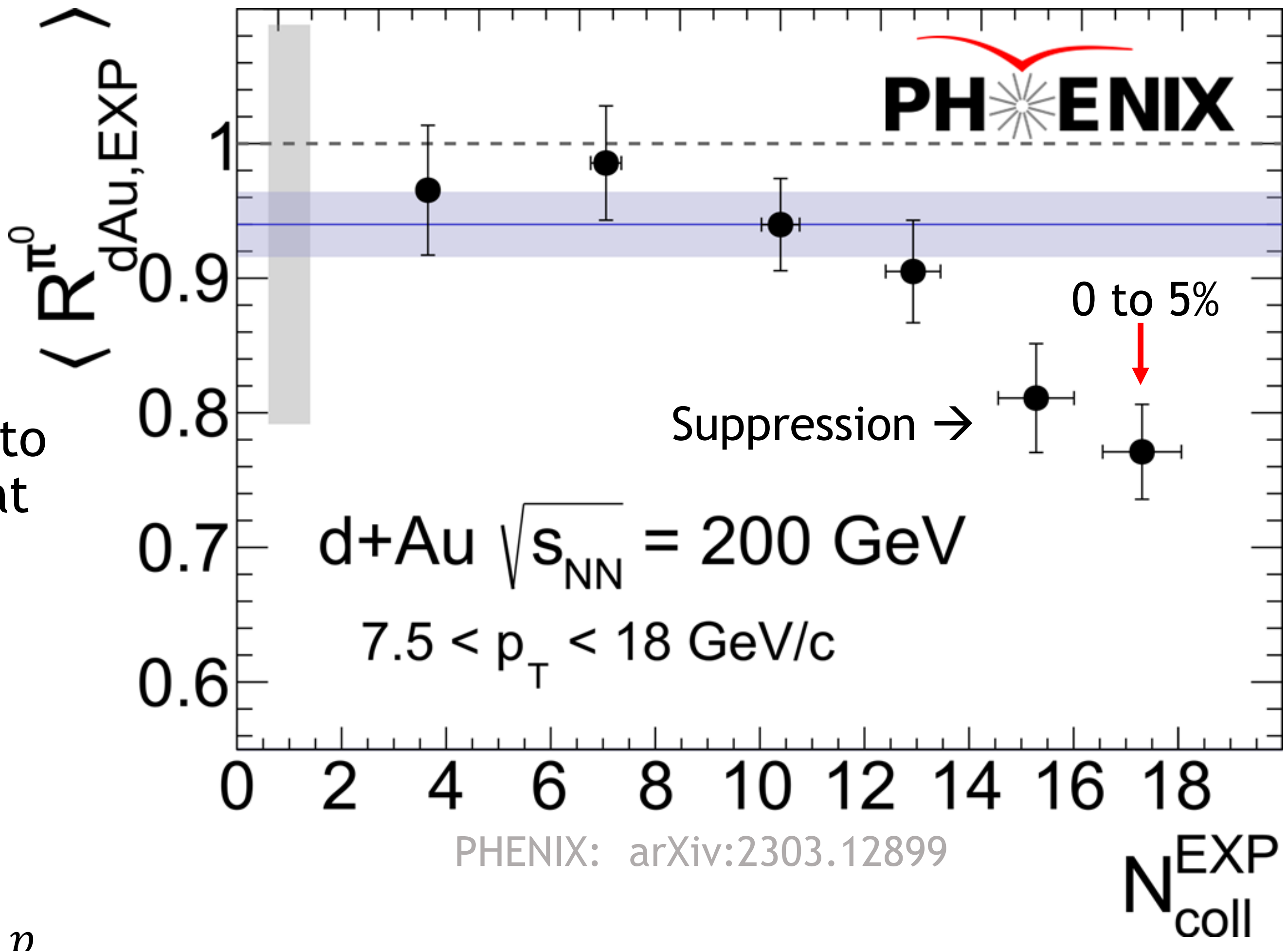
- 20% suppression with 4.5σ significance in central d+Au collisions at 200GeV!



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 in 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 $\lessgtr$? d+Au $\lessgtr$? ³He+Au
  - Reduction of systematic uncertainties from $p+p$ dataset



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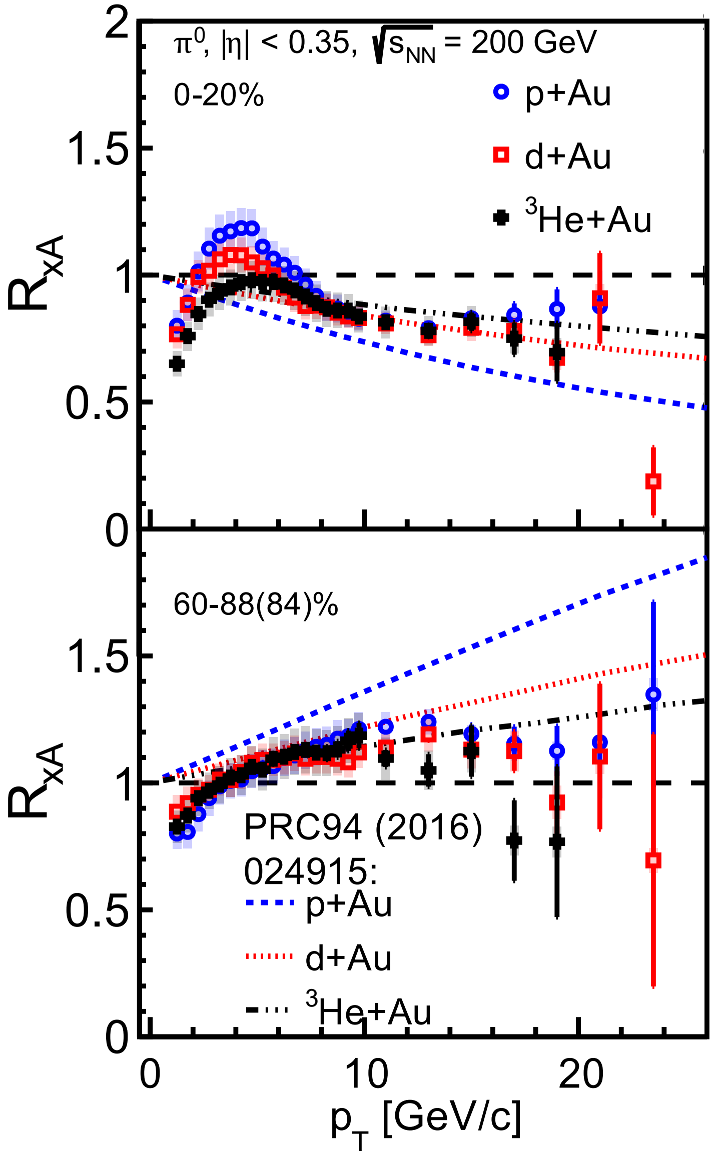
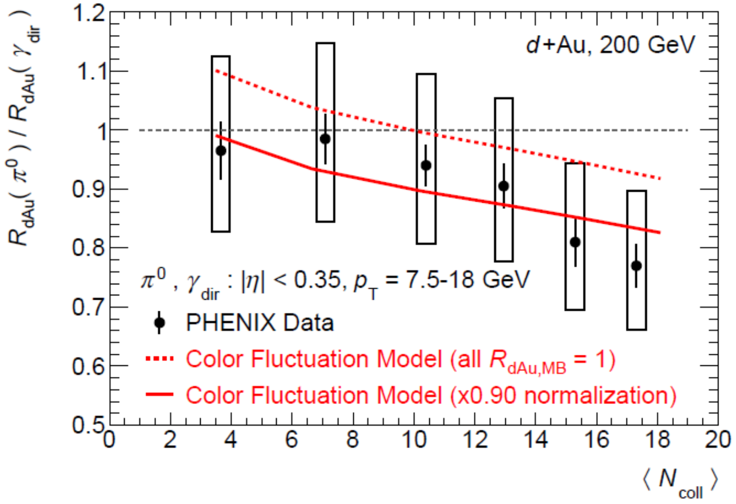
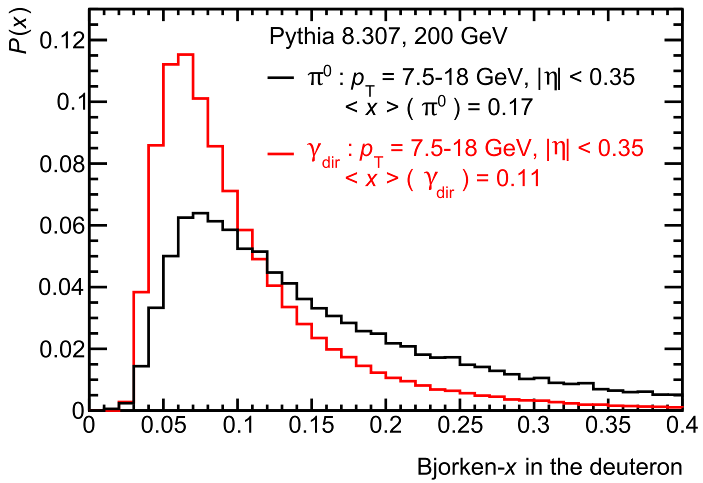
Backup:

The Bjorken-x bias



PHENIX: PRC105 (2022) 064902





PRC 110 L011901 (2024)

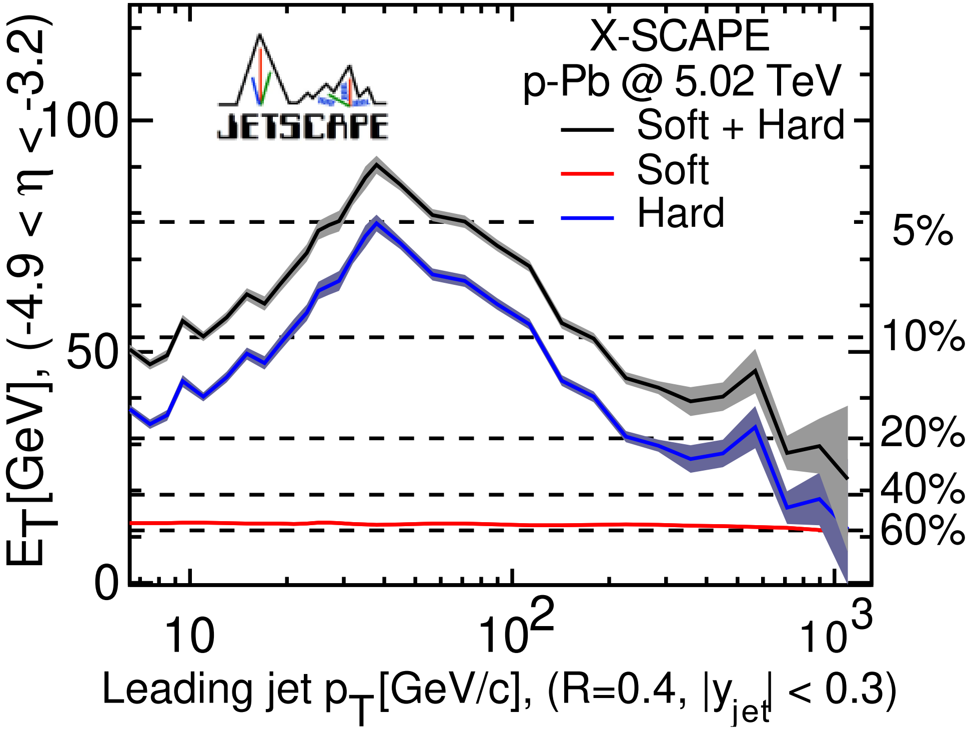
- Even so, the final answer to this puzzle comes from the (upcoming) systematic study of small systems

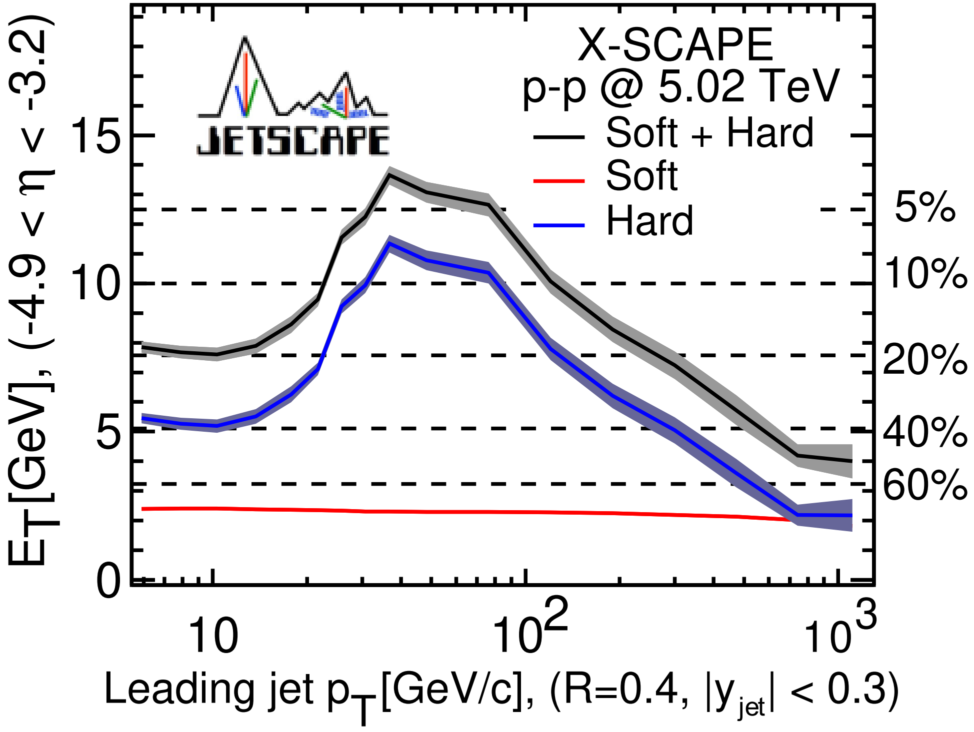
- Final State
  ^{3}He > d > p

- p Size fluctuation
  p > d > ^{3}He

Energy conservation in small systems

- Pb + Pb
  - 208 + 208
- p + Pb
  - 1 + 208
- p + p
  - 1 + 1
- d + Au,
- ^{3}He + Au,...



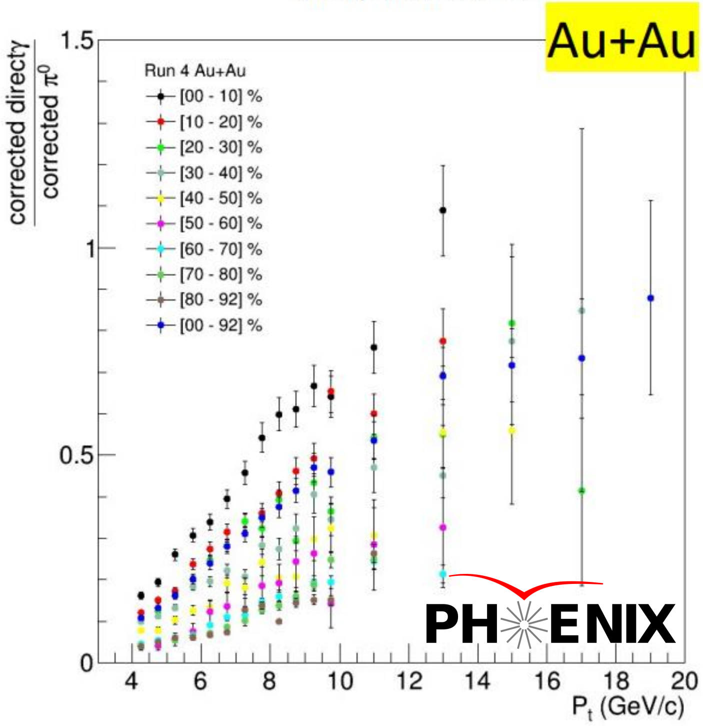


JETSCAPE: arXiv: 2407.17443

"Correlations between hard probes and bulk dynamics in small systems"
Sangyong Jeon – in ~30 minutes!

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

Neutral π^0's : arXiv:0801.4020
direct γ : arXiv:1205.5759



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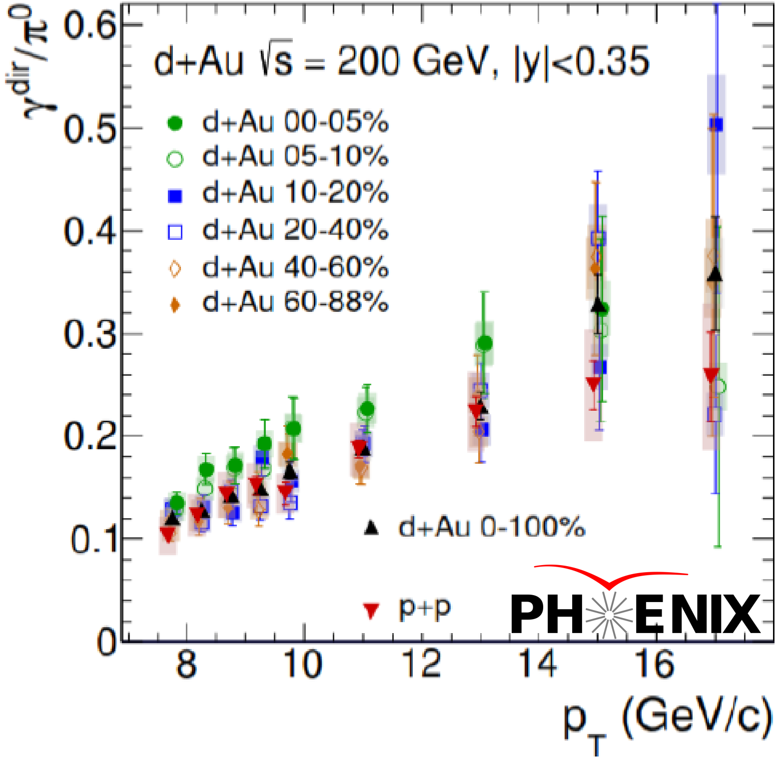


Corrected direct γ spectrum
(centrality independent)

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

Data analysis

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

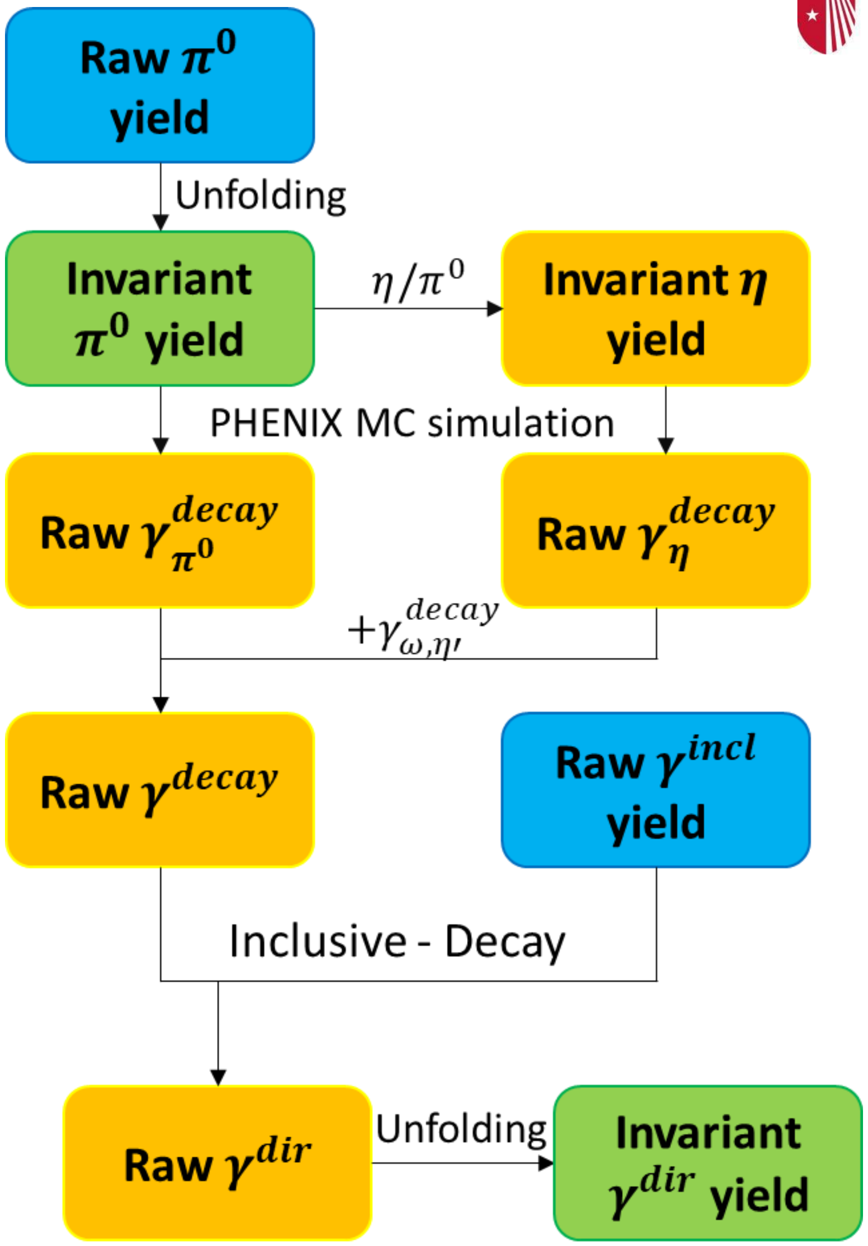
- π^0 reconstructed from γ clusters on the EMCal
- Triggered on high p_T range. Analysis done for γ and π^0 on $p_T > 7.5$ GeV

Analysis chain:

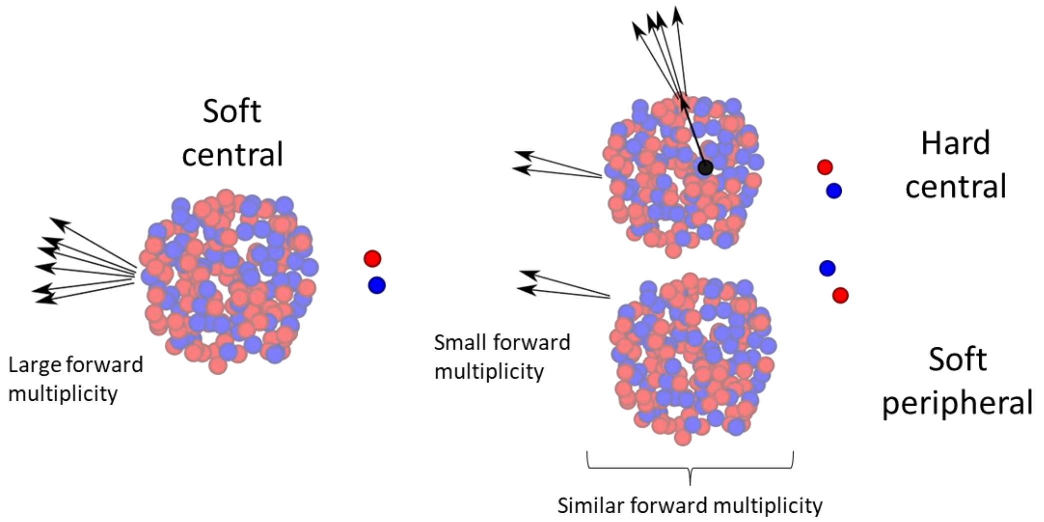
- Reconstructed Raw π^0 from γ showers ($\pi^0 \rightarrow \gamma\gamma$)
- Raw spectra is unfolded to obtain Invariant π^0
  - $\frac{\eta}{\pi^0}$ ratio used to obtain invariant η yield
- Model π^0 and η decay in PHENIX to obtain γ^{decay}
- Subtraction of decay from inclusive raw γ to obtain Raw γ^{dir}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

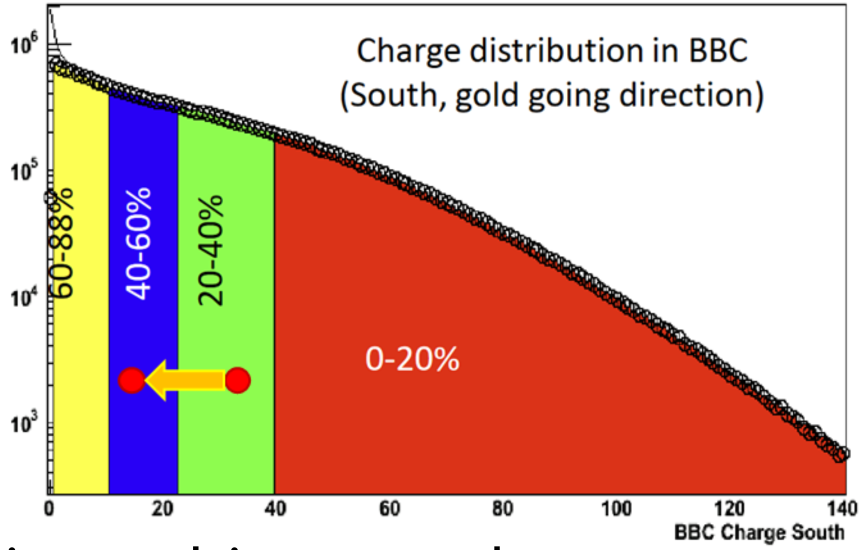
Systematic uncertainties

- $\sim 12\%$ 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)

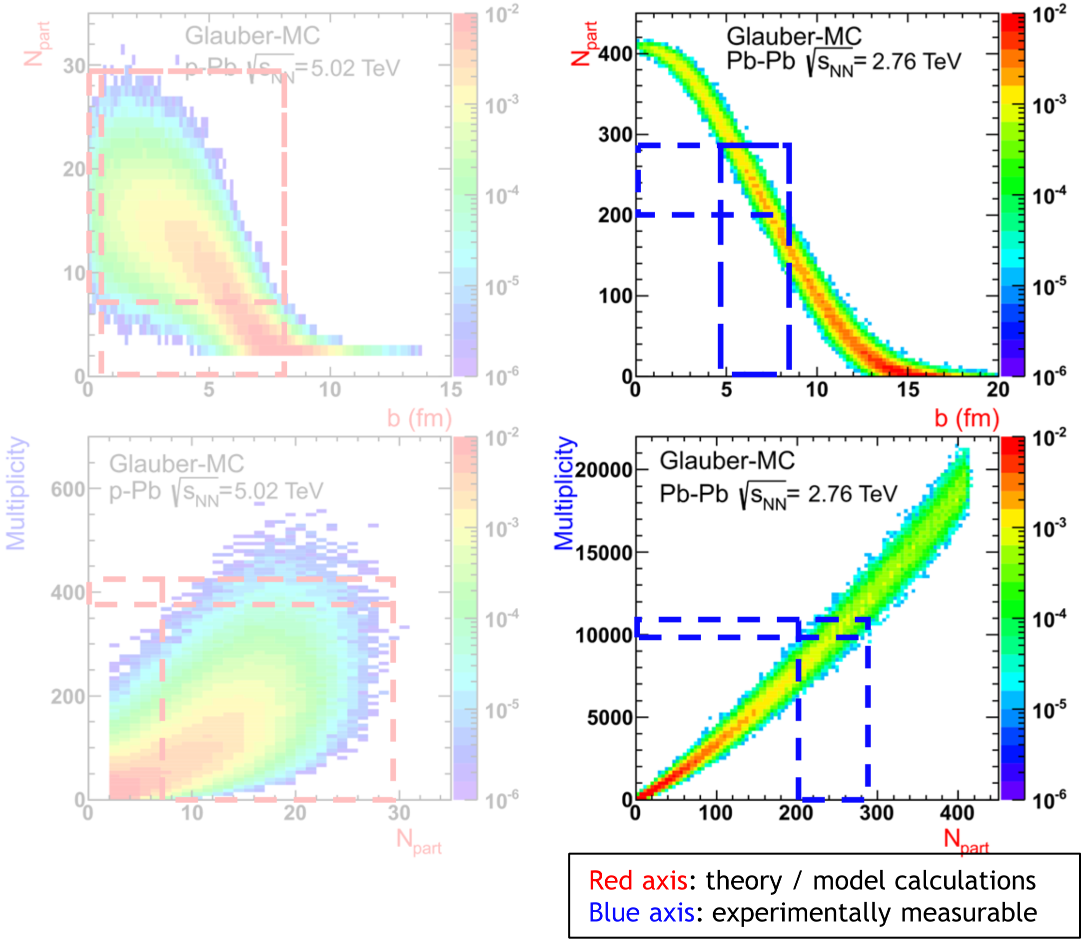
Corrected π^0 spectrum (centrality dependent)

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

ALICE: PRC91 (2015) 064905

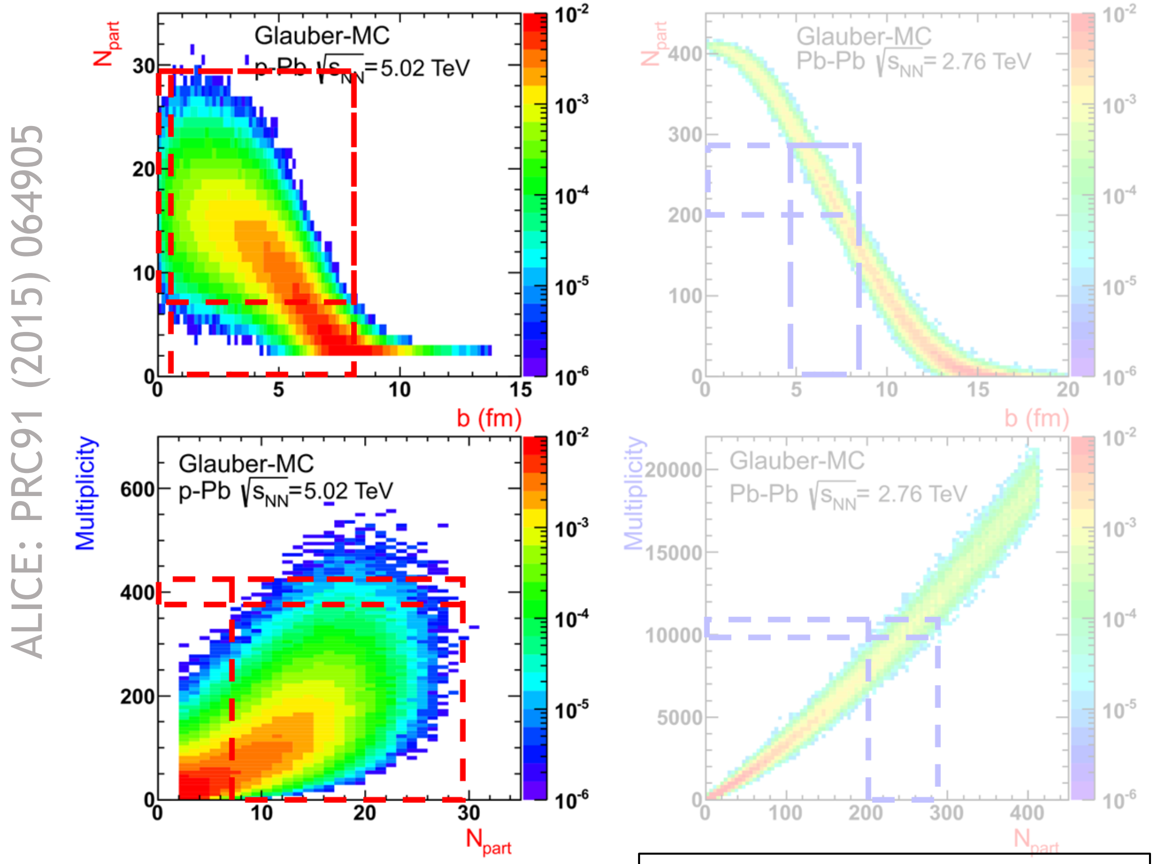


- Centrality is determined by event activity in the BBC, on the Au going direction

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

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

Event activity to centrality



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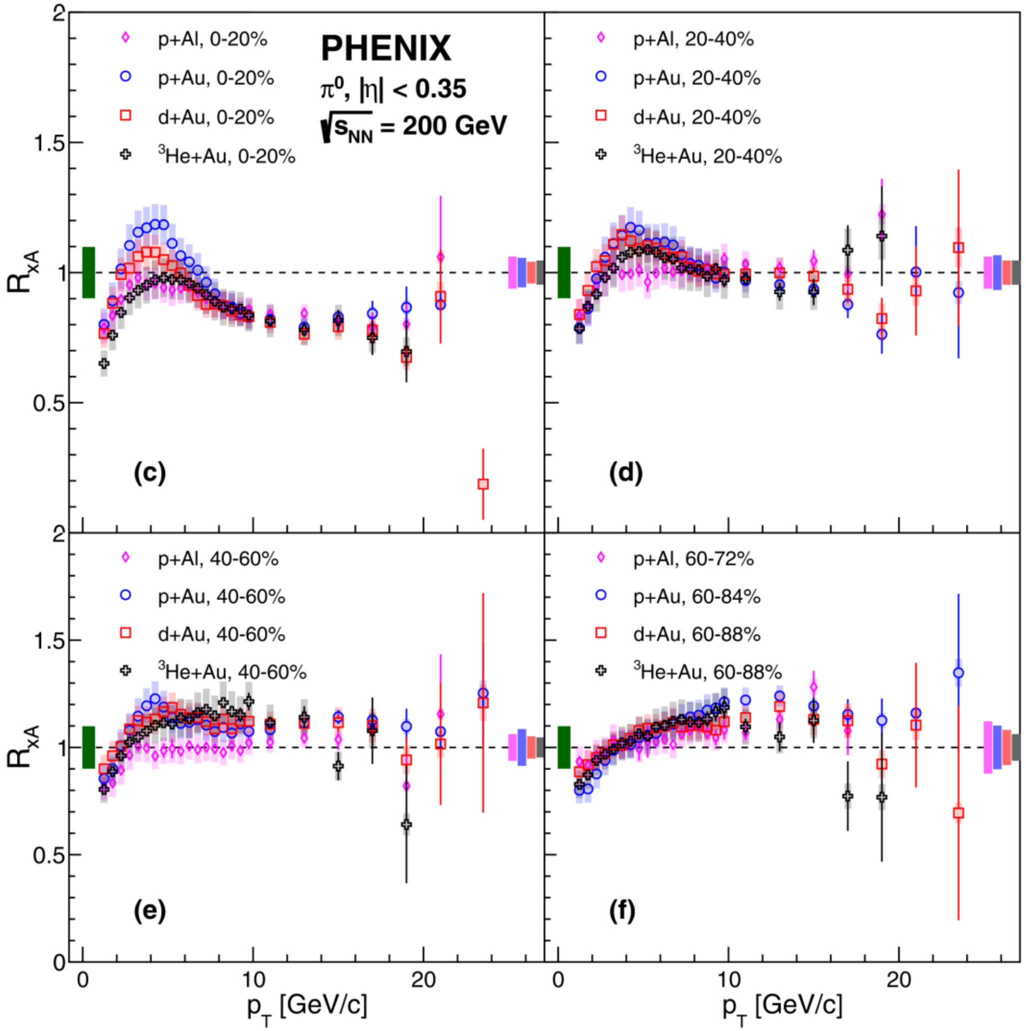
Nuclear modification factor in d+Au



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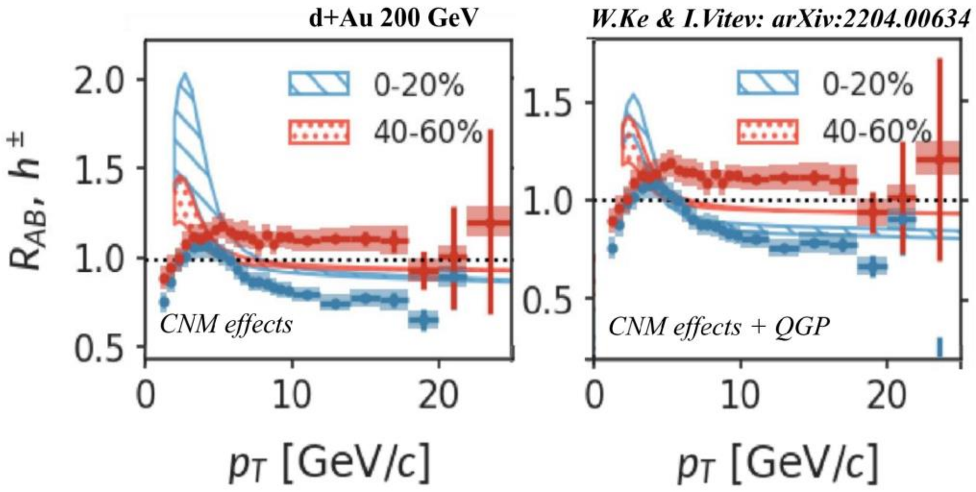
- For high p_T π^0s in small systems, large centrality dependence is observed:
  - Suppression for central events



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

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

$\frac{\gamma}{\pi^0}$: 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

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

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