Recent Results for the PHENIX Experiment

Axel Drees, IS2023, June 2023, Copenhagen, Denmark

- Selected results from p+p
- Small systems p+Au, d+Au, ^{3}He+Au
  - Disentangling centrality biases, initial state and final state effects
- Selected results from Au+Au
- Summary

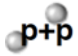
Stony Brook University

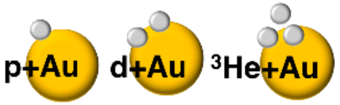
PHENIX Data Sets

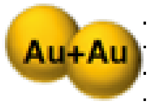
- PHENIX stopped data taking after 2016
- Ongoing analysis of large data sets taken in 2014, 2015, and 2016

√s [GeV]	p+p	p+Al	p+Au	d+Au	³He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	★								
200	✓	★	★	★	★	✓	✓	★	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

- Focus of this talk:
  - Polarized pp
    - p+p, $\sqrt{s_{NN}} = 510$ GeV
  - Small systems
    - p+Al, p+Au, d+Au, ^{3}He+Au
    - $\sqrt{s_{NN}} = 200$ GeV
  - Large systems
    - Au+Au
    - $\sqrt{s_{NN}} = 200$ GeV



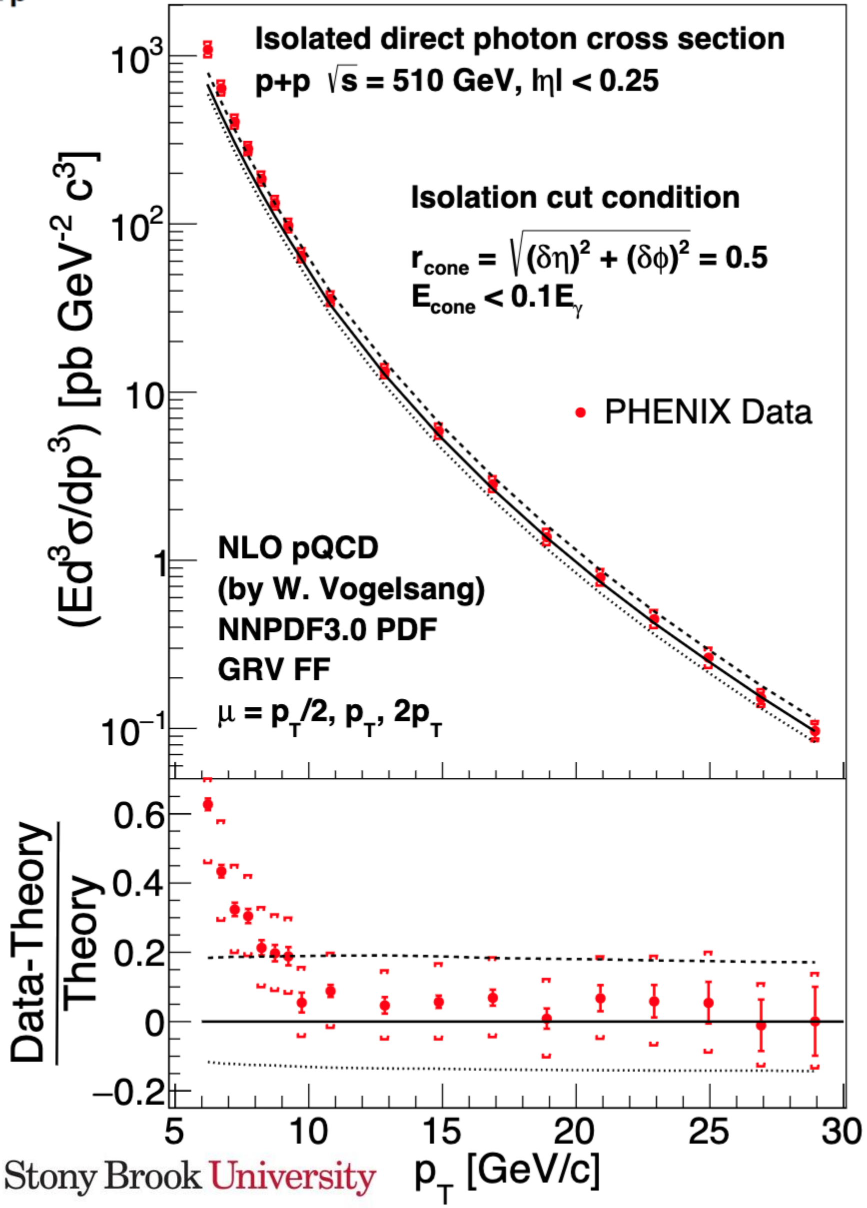




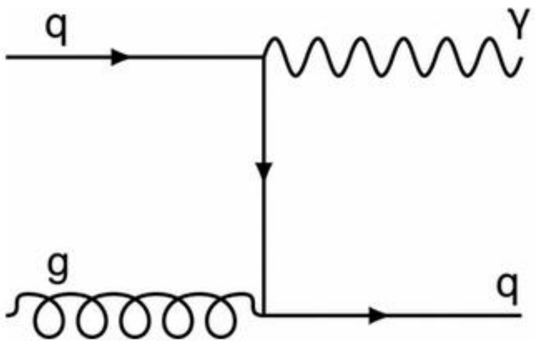
Results in this talk published or shown for the first time in 2022/23

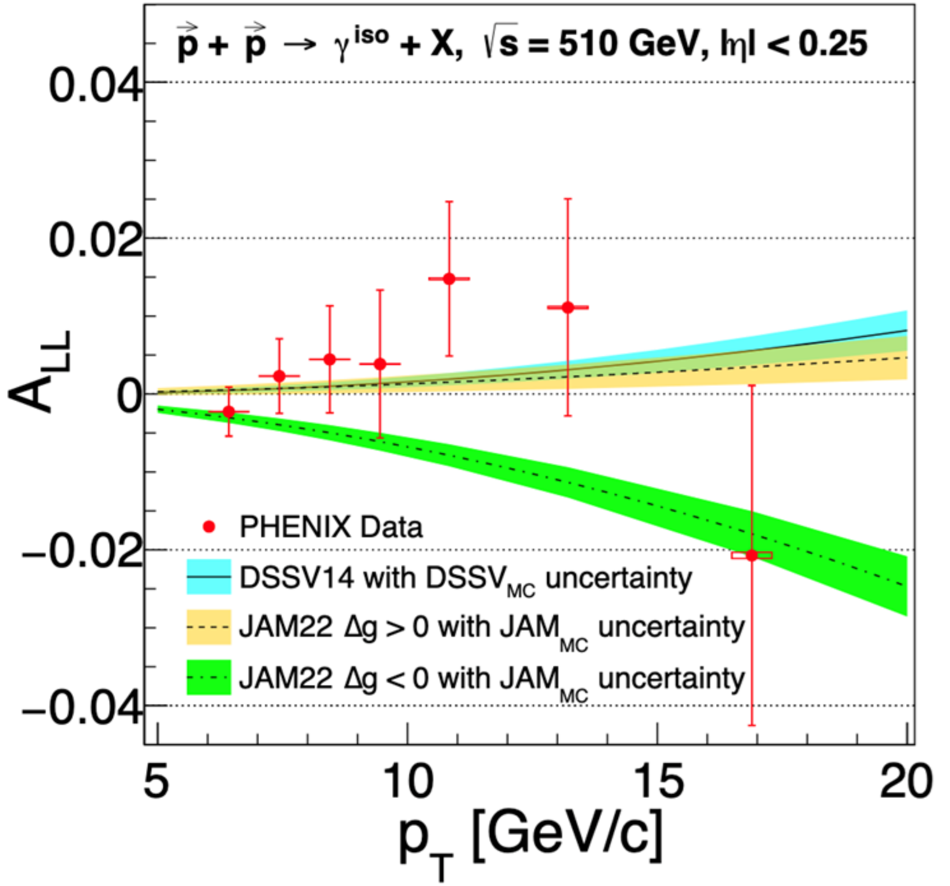
Direct Photon in Polarized p+p at 510 GeV

PHENIX: arXiv:2202.08158 (Accepted for publication in PRL)



- Double helicity asymmetry isolated direct photons

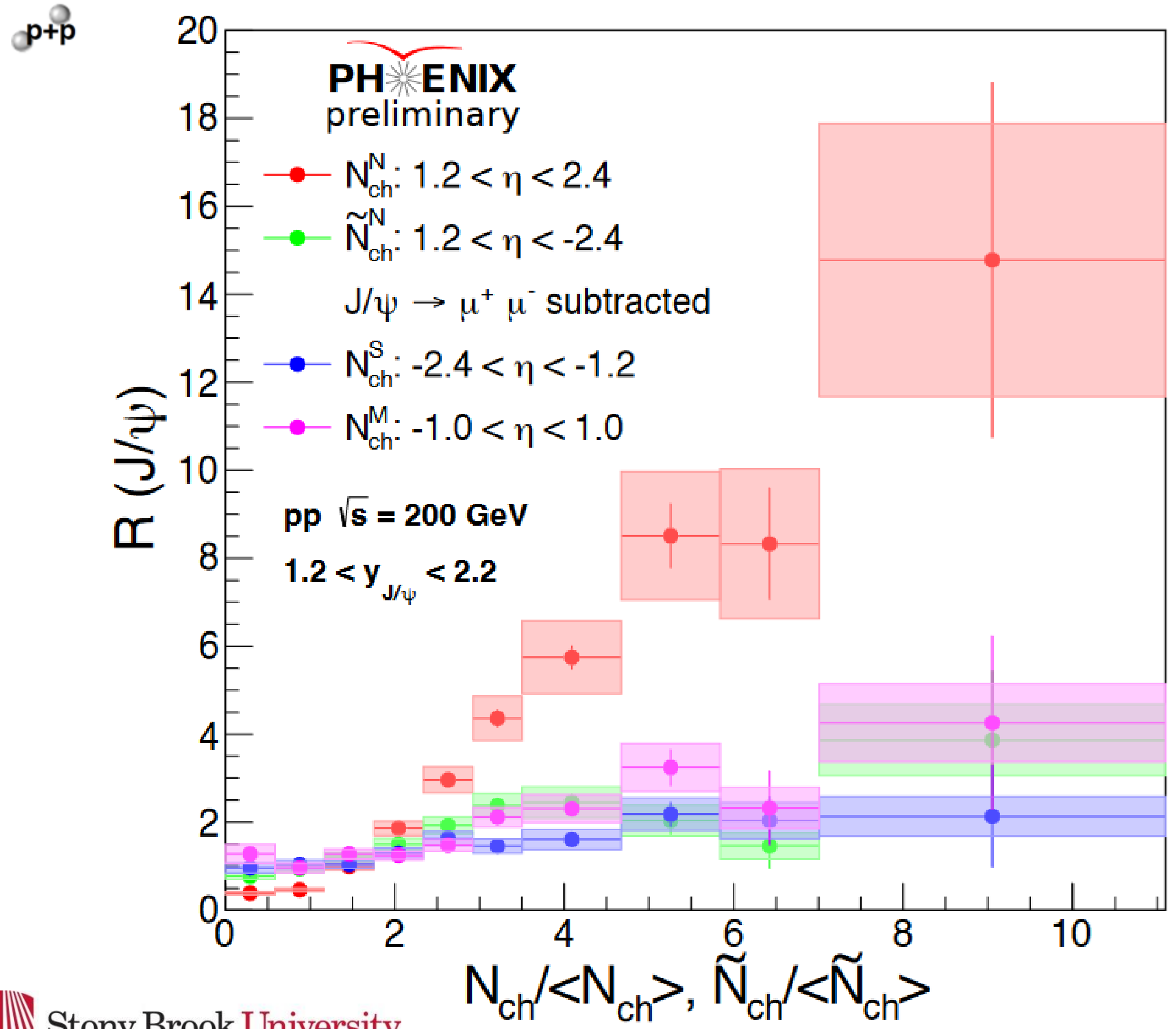




First measurement sensitive to sign of Δg
$\Delta g<0$ excluded at 2.8 σ level

Charmonium Production from p+p at 200 GeV

$$R_{J/\psi} = \frac{N_{J/\psi}}{\langle N_{J/\psi} \rangle}$$



- **J/ψ vs event multiplicity**
  - J/ψ enhanced in high N_{ch} events
  - Observed at RHIC and LHC

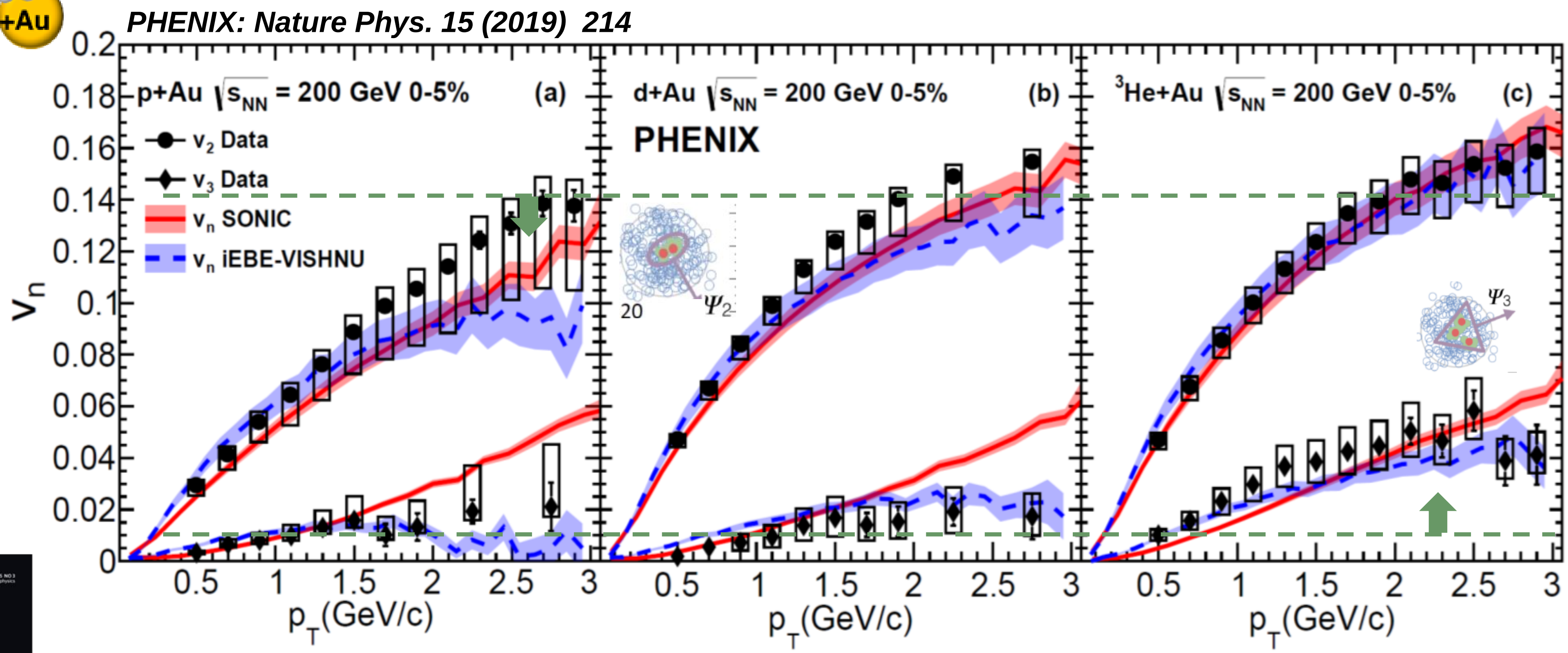
Contribution from Multi Parton Interactions (MPI)?

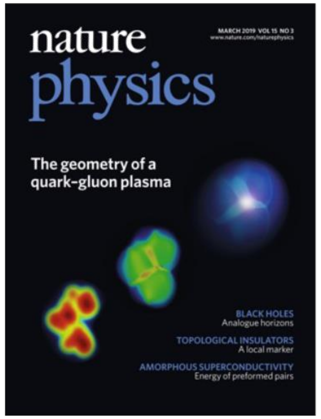
- **Caveats:**
  - Rapidity range of N_{ch} measurement
  - Are J/ψ decay products counted?

PHENIX: Zhaozhong Shi
Parallel Session 7 We 16:30

Evidence for QGP Droplets in Small Systems

PHENIX: Nature Phys. 15 (2019) 214



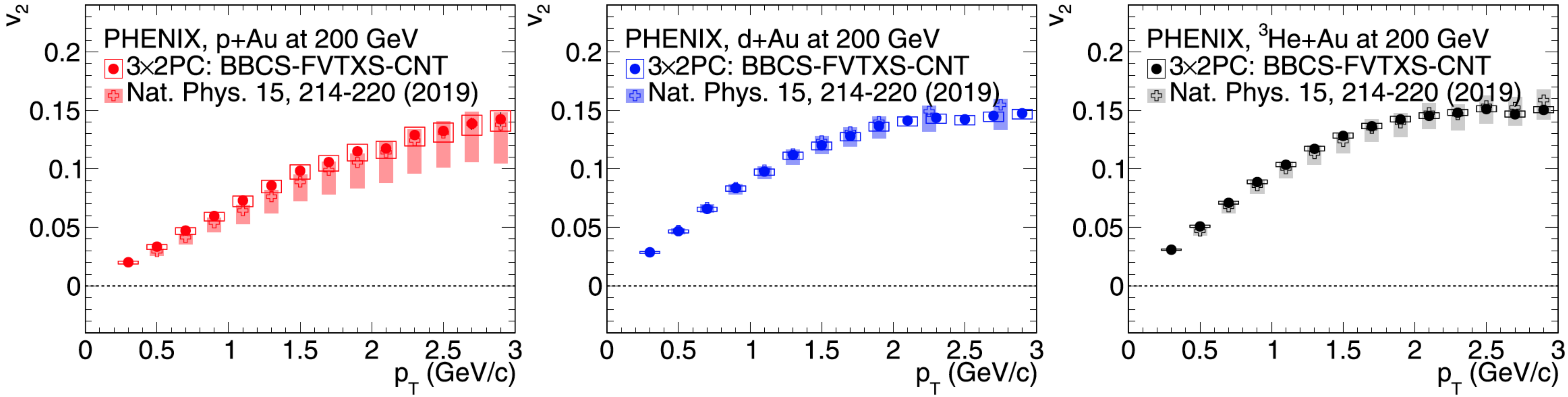


- **Geometrical ordering as expected from hydrodynamical models**
  - v_2 p+Au < d+Au ~ ^{3}He+Au
  - v_3 p+Au ~ d+Au < ^{3}He+Au

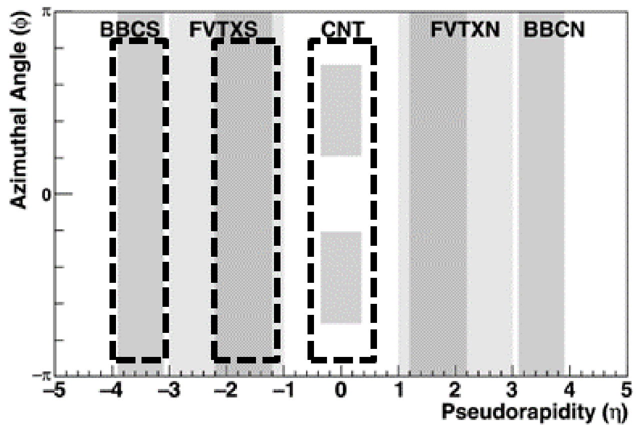
Anisotropy of charged particle production consistent with hydrodynamic expansion

Independent Study of Anisotropy

PHENIX: PRC 107 (2023) 024907

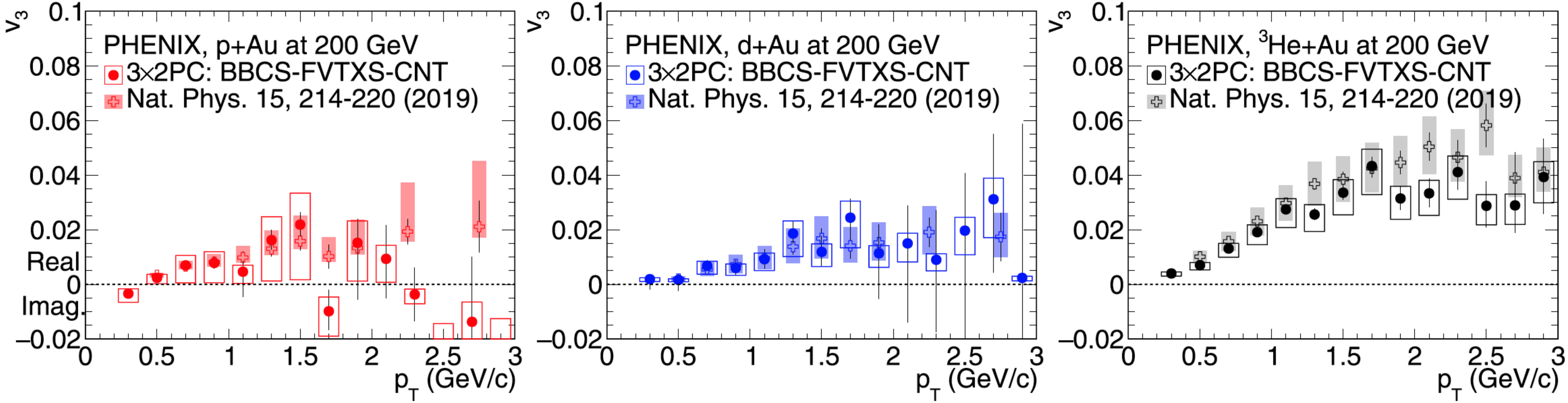


- **Using two particle correlations over large rapidity range**
  - **Different systematics, different sensitivity to non flow effects**
  - **Consistent v_2**



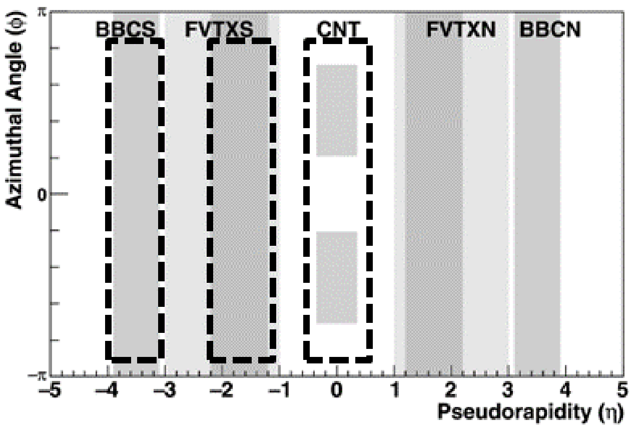
Independent Study of Anisotropy

PHENIX: PRC 107 (2023) 024907



- **Using two particle correlations over large rapidity range**
  - Different systematics, different sensitivity to non flow effects
  - Consistent v_2
  - Consistent v_3

Confirm geometrical ordering of v_2 and v_3



Further studies constrain non flow contribution PHENIX: PRC 105 (2022) 024901

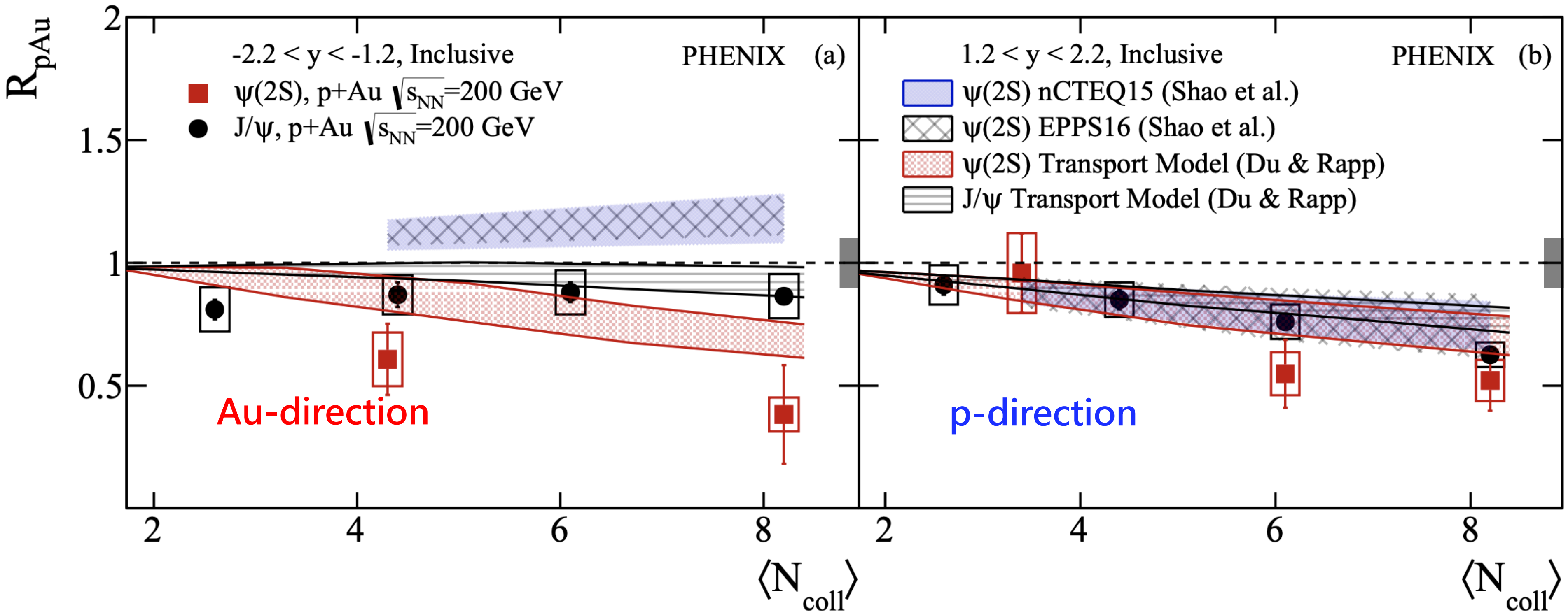
J/ψ and $\psi(2S)$ in p+Au

p+Au

PHENIX: PRC 105 (2022) 064912

$$R_{xA}(p_T) = \frac{Y_{xA}(p_T)}{\langle N_{coll}\rangle\, Y_{pp}(p_T)}$$

PHENIX



- **Similar modification of J/ψ and $\psi(2S)$ in p-direction**
- **Stronger ψ $(2S)$ suppression in Au-direction**
  - **nPDF only can not describe the data**
  - **Qualitatively agree with the transport model with final-state effects**

Qualitatively consistent with QGP formation

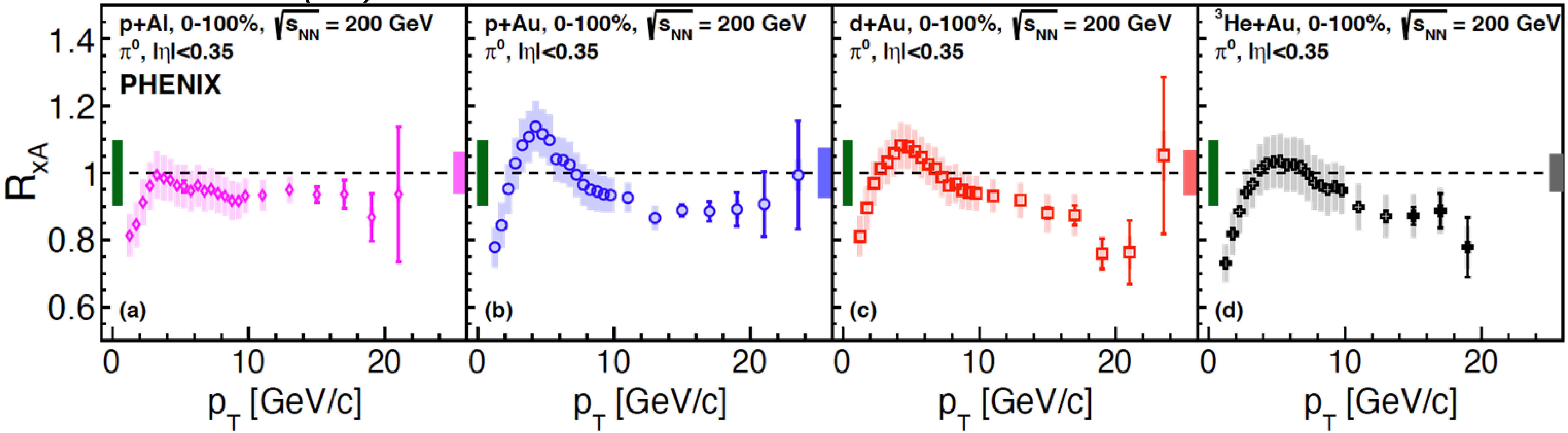
Nuclear Modification of π^0 spectra in Small Systems

p+Al p+Au d+Au ³He+Au Inclusive Cross Section

$$R_{xA}(p_T) = \frac{Y_{xA}(p_T)}{\langle N_{coll}\rangle\, Y_{pp}(p_T)}$$

PHENIX

PHENIX: PRC 105 (2022) 064902

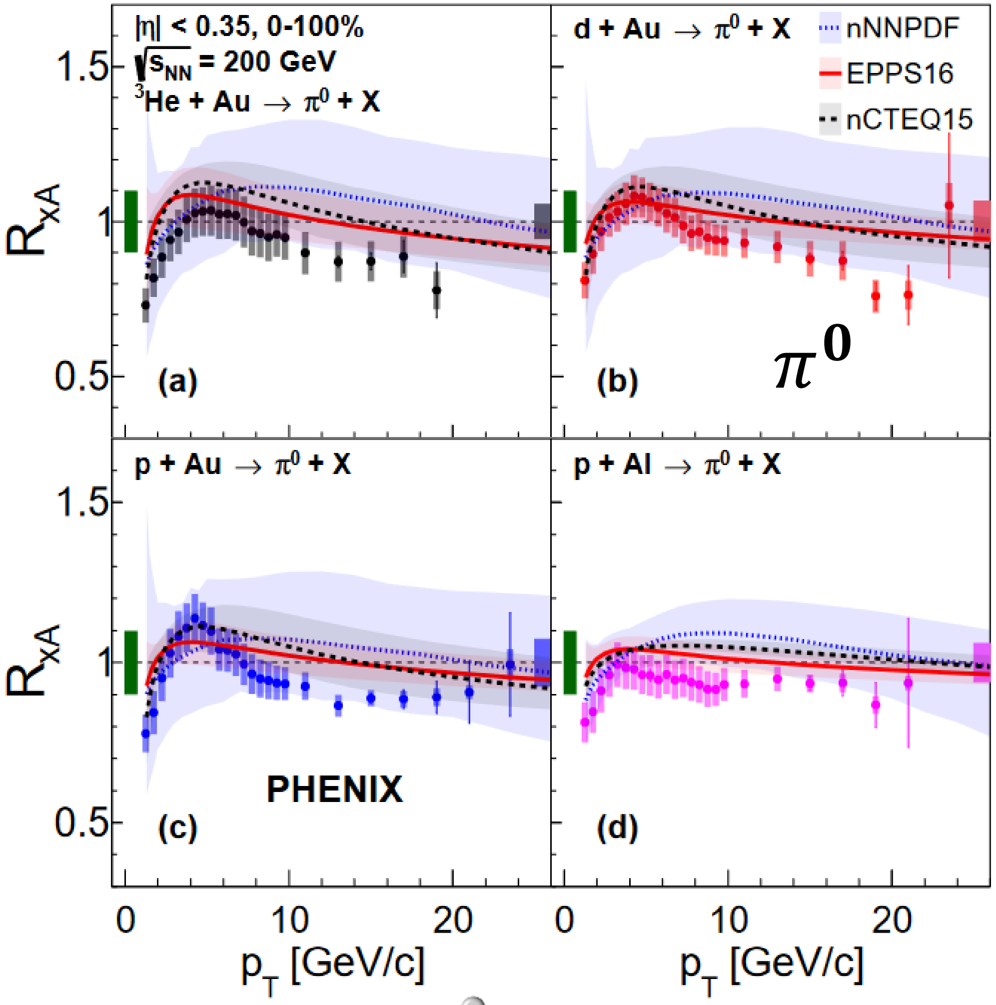


- Cronin peak in intermediate range $2 < p_T < 6$ GeV/c
  - Peak increase with "target" A in p+A
  - Broadening/decrease/shift of peak with increasing "projectile" p+Au → d+Au → ³He+Au
- High $p_T > 6$ GeV/c
  - R_{xA} consistent with unity p+Al ~ p+Au ~ d+Au ~ ³He+A

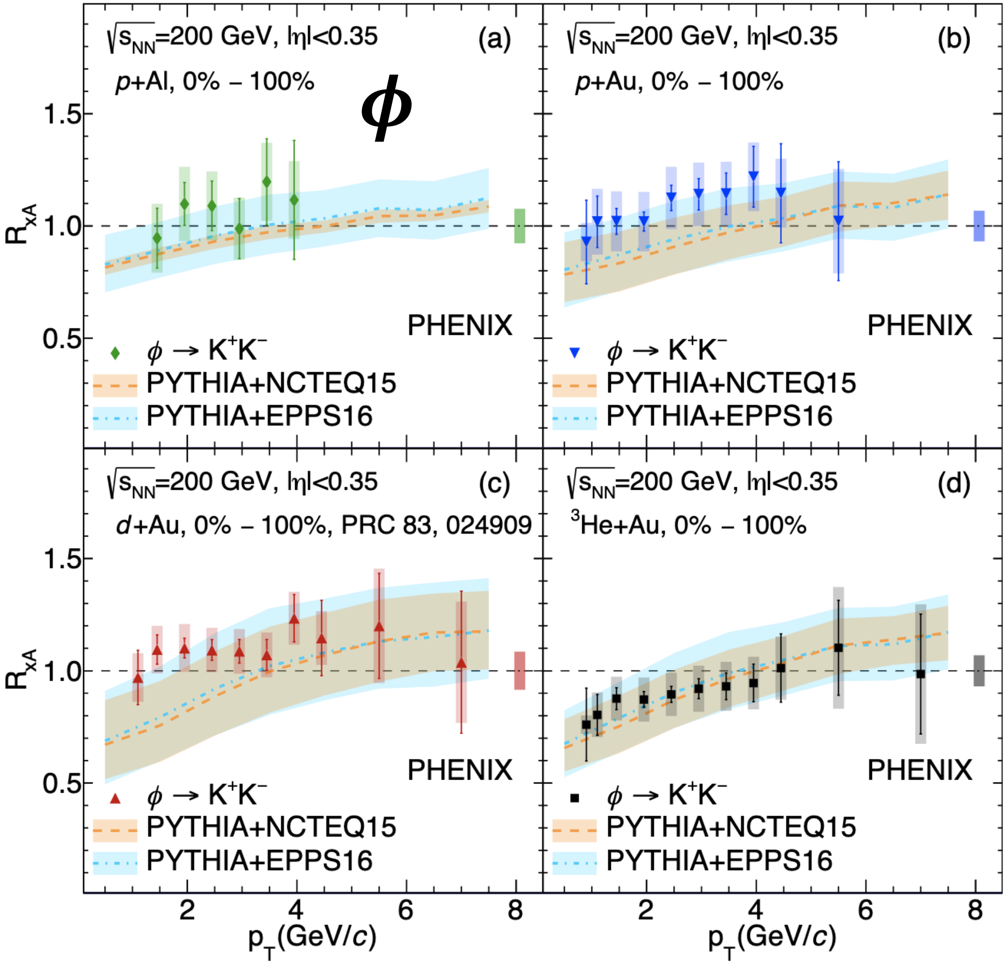
Modification of "Cronin" peak
No/little suppression at high p_t

Comparison to Nuclear PDFs

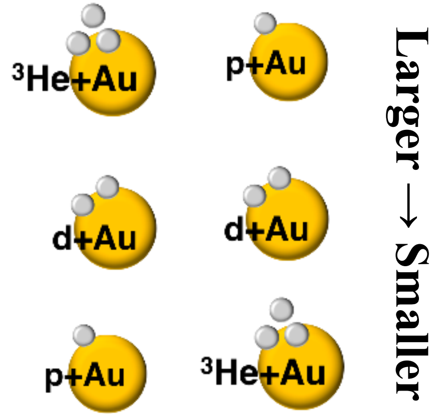
PHENIX: PRC 105 (2022) 064902



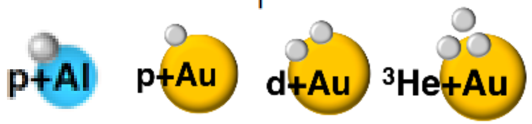
PHENIX: PRC 106 (2023) 014908



Nuclear effects with system size



nPDF   Data

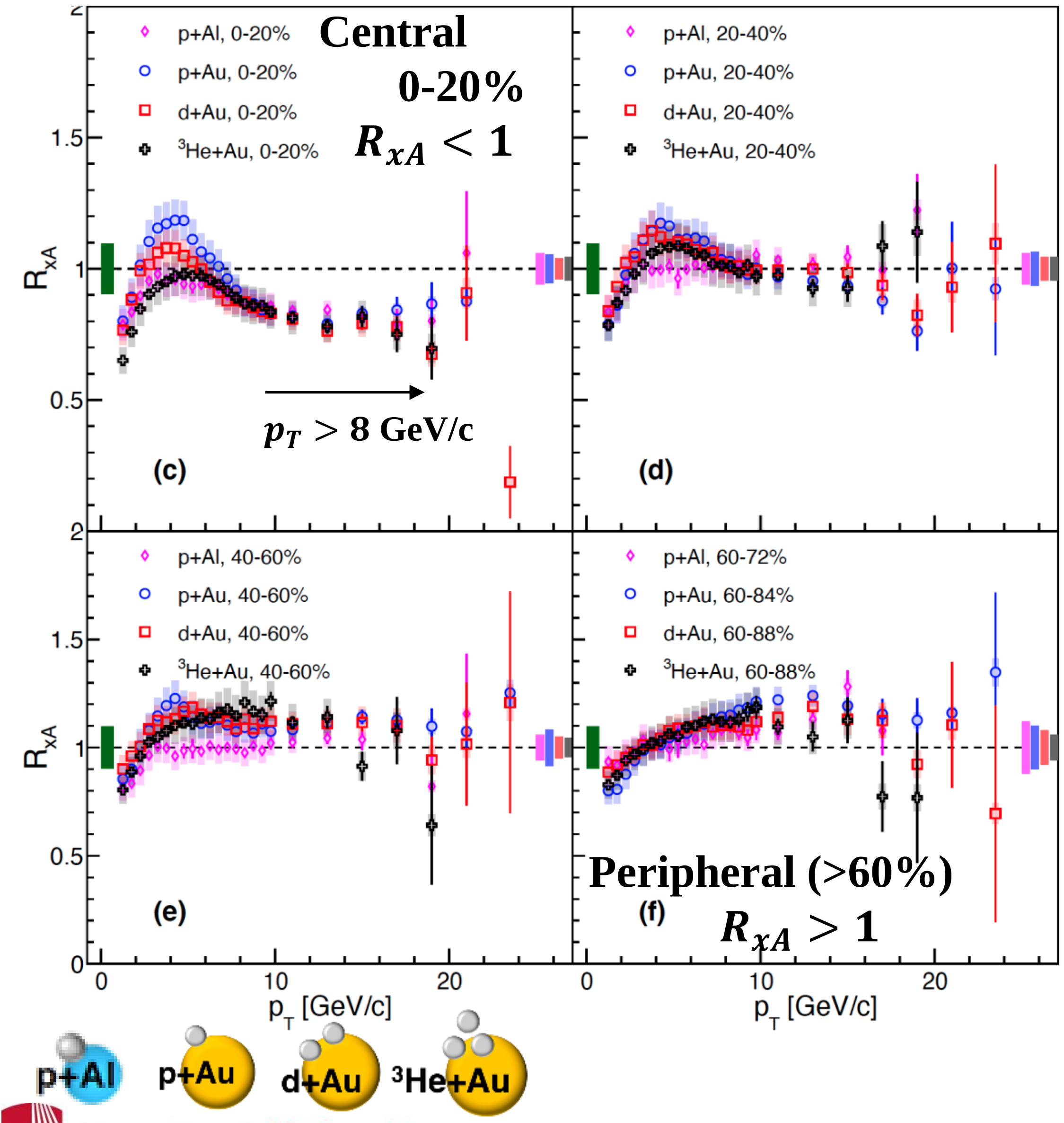


Inclusive Cross Section

Consistent with nuclear PDFs within large uncertainties, but trends qualitatively different from data

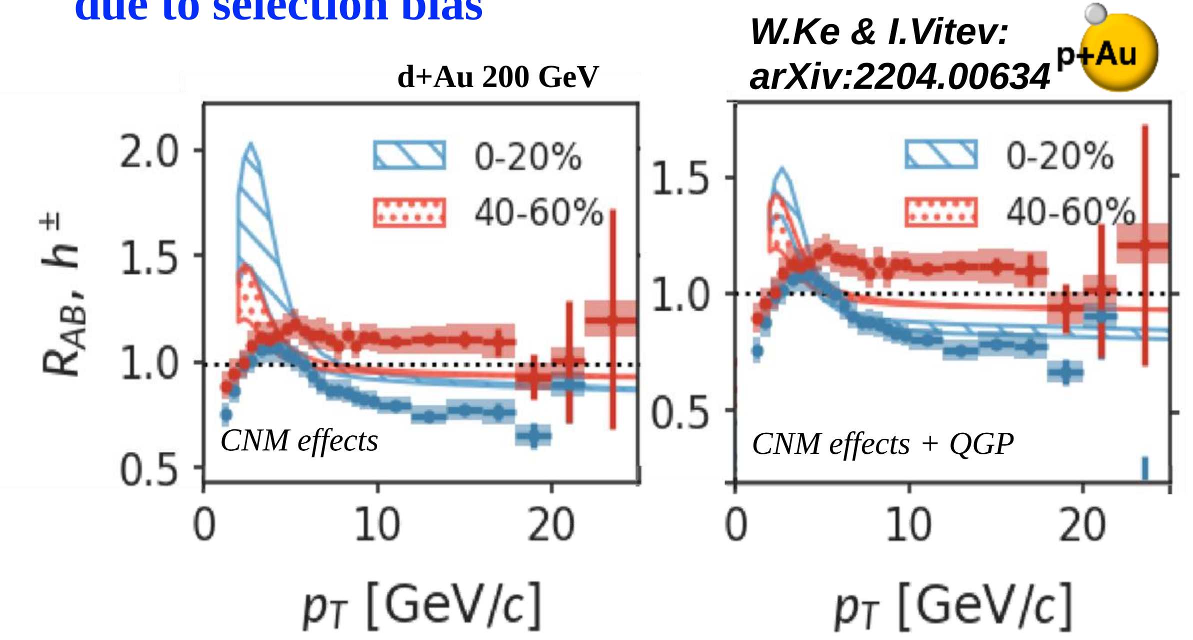
Centrality Selected Small System Collisions

PHENIX: PRC 105 (2022) 064902



- π^0 R_{xA} from p+Au, d+Au, ^{3}He+Au
  - Central: 20% suppression - consistent with energy loss
  - Peripheral: 15 % enhancement - unexplained, likely due to selection bias

W.Ke & I.Vitev: arXiv:2204.00634



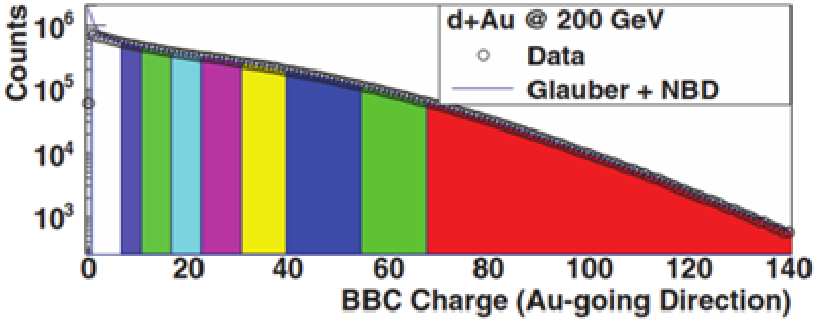
- Similar observations at RHIC & LHC

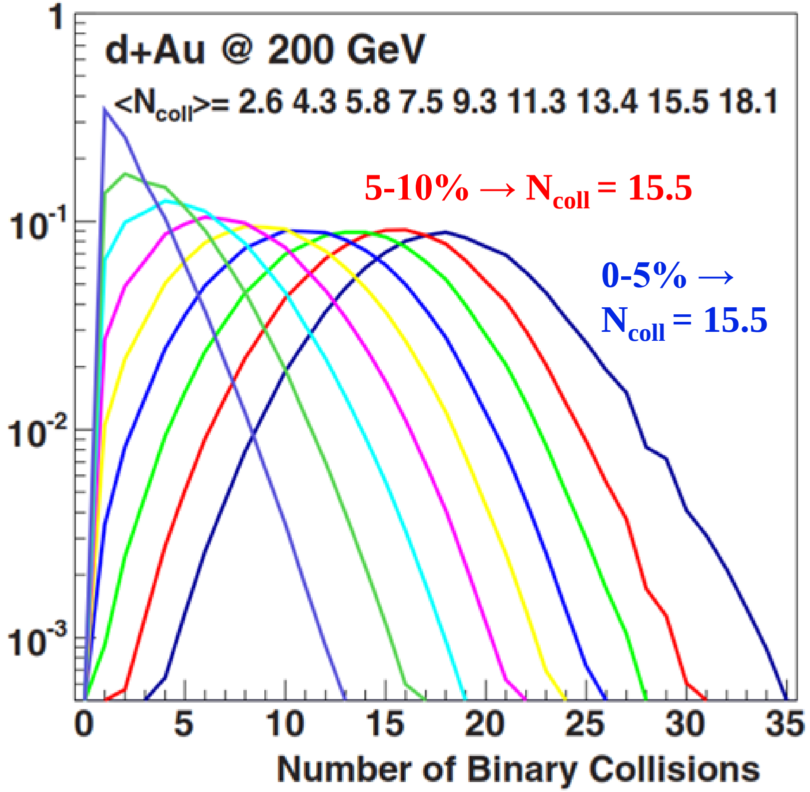
Inconclusive R_{xA} for high p_T in small systems
Bias or final state effects?

Mapping Event Activity to Centrality With Glauber Model

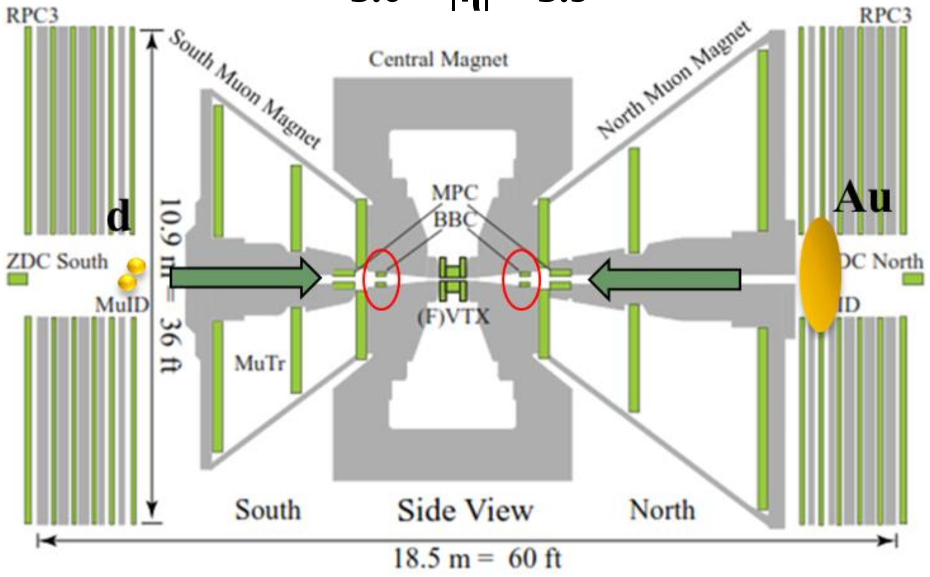
d+Au

PHENIX: PRC90 (2014) 034902





PHENIX Beam-Beam Counters (BBC)
$3.0 < |\eta| < 3.9$

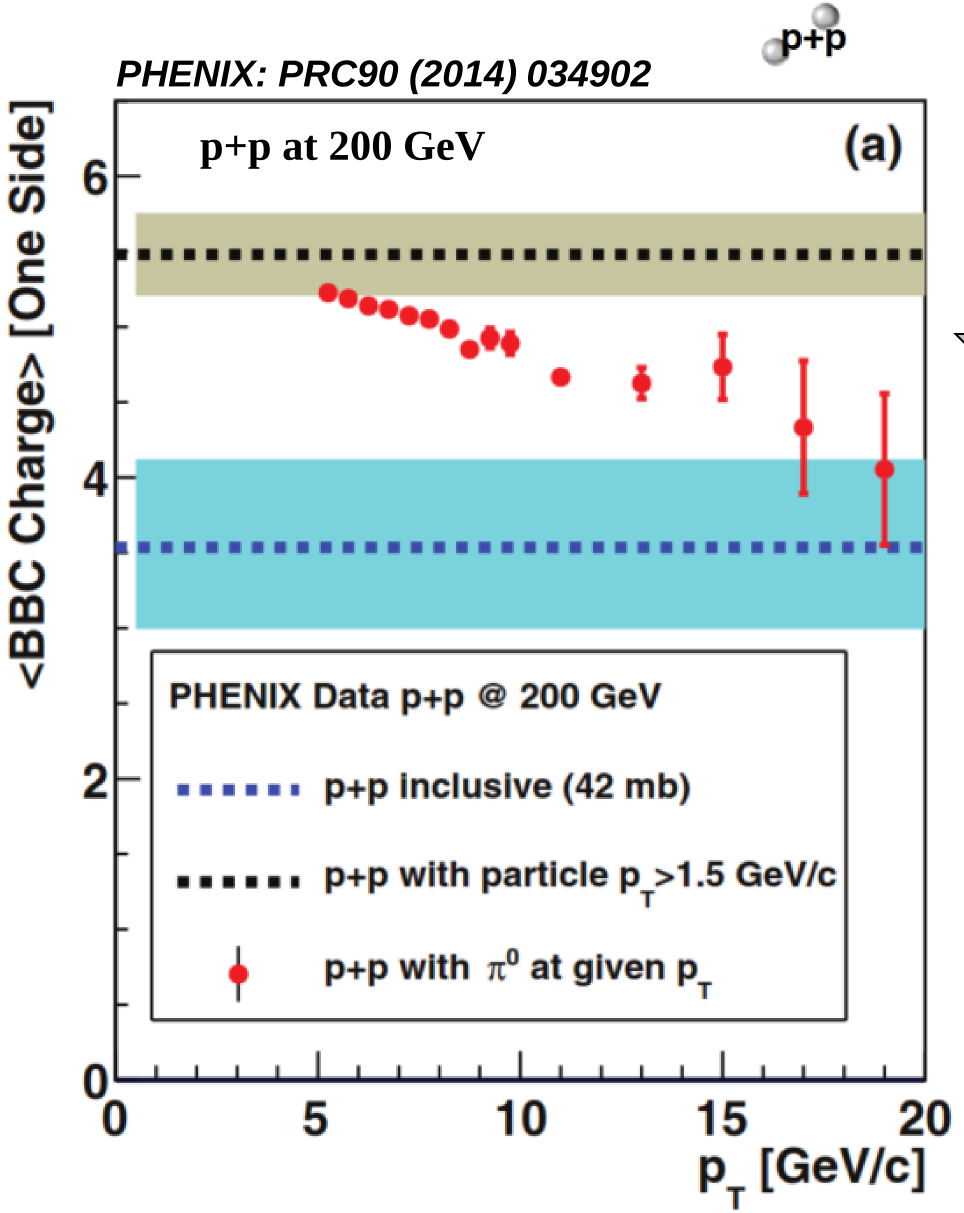


- **Procedure for small systems**
  - **Measure event activity (N_{ch}) in BBC on Au going side**
  - **Fit event activity to superposition of negative binomial distributions for each nucleon-nucleon collision**
  - **Select events in percentiles of event activity (0-5%, 5-10%, etc.) for data & model**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

Bias in Event Activity from Hard Scattering

- **Reduced forward event activity in nucleon-nucleon collision with hard scattering**
  - Averaged out in Au+Au collisions
  - High p_T events shifted to lower EA and lower N_{coll} in small systems
  - Increases R_{AB} in peripheral events, probably p_T dependent

Bias in event selection for hard probes in small systems



BBC N_{ch} reduced when high p_T π^0 event

Use Direct Photons to Minimize Selection Bias

- **No nuclear modification of direct γ**
  - Au+Au direct γ scale with N_{coll}

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

- **Use direct γ to measure factor "N_{coll}" to scale hard scattering processes**

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

- **Redefine Nuclear Modification Factor**

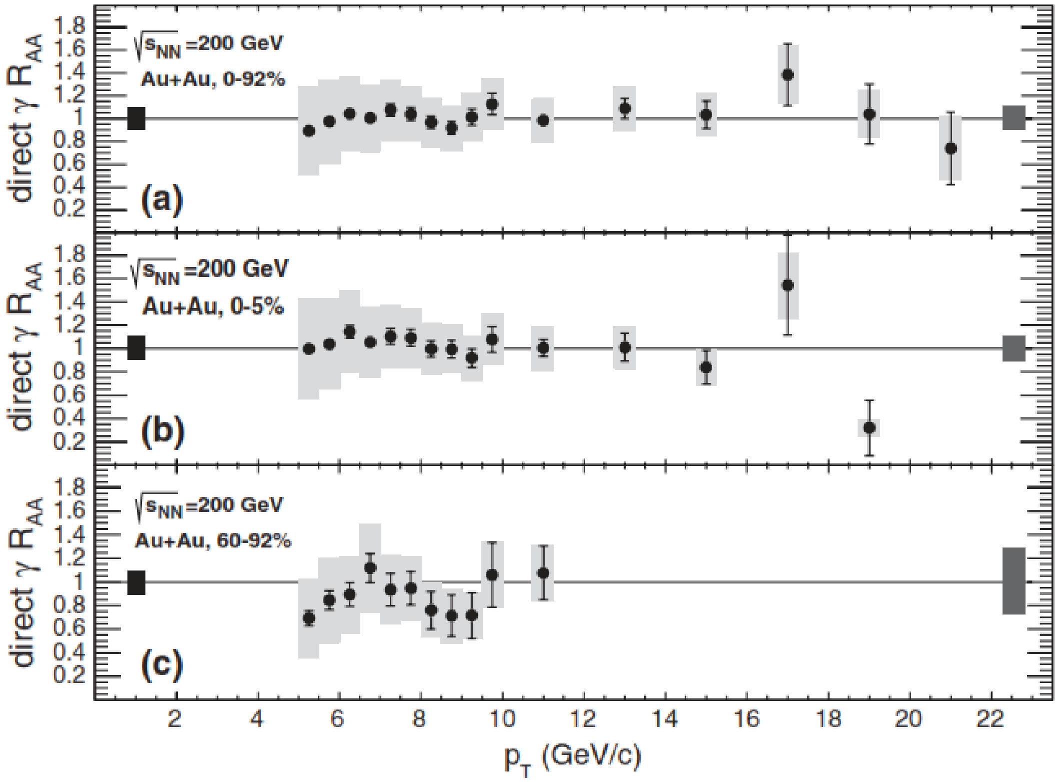
$$R_{AB,EXP}^{\pi^0}(p_T) = \frac{Y_{AB}^{\pi^0}(p_T)}{Y_{pp}^{\pi^0}(p_T)} \times \frac{Y_{pp}^{\gamma^{dir}}(p_T)}{Y_{AB}^{\gamma^{dir}}(p_T)} = \frac{(\gamma^{dir}/\pi^0)^{pp}}{(\gamma^{dir}/\pi^0)^{AB}}$$

  - Insensitive to event selection bias
  - No Glauber model dependence
  - Largely insensitive to CNM effects
  - Partially accounts for p_T dependent bias
  - Many systematic uncertainties cancel

Au+Au

PHENIX

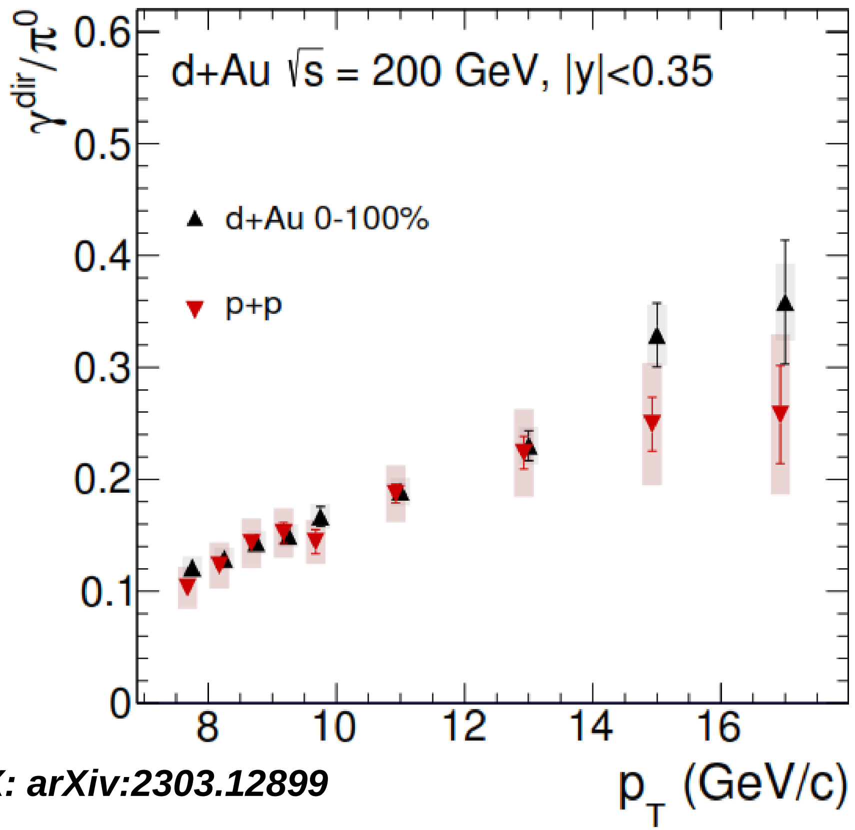
PHENIX: PRL109 (2012) 152302



Search for final state effects simultaneously measure direct γ and π^0

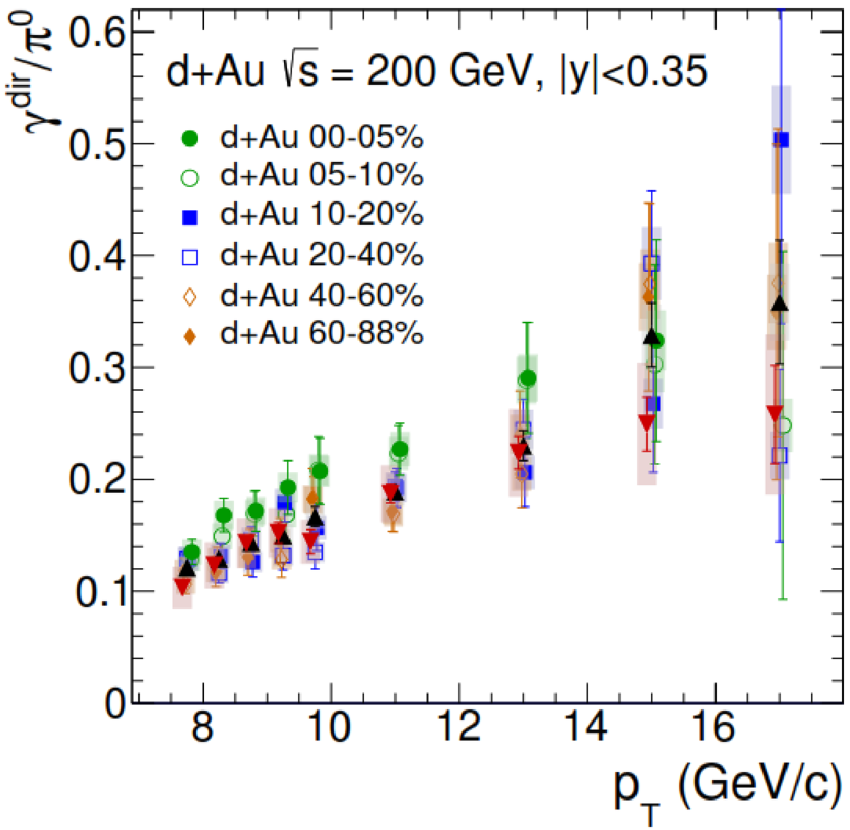
γ^{dir} to π^0 Ratio in d+Au and p+p Collisons

- γ^{dir}/π^0 for inclusive samples (0-100%)
  - Equal for p+p to d+Au
  - p+p systematic dominated by 2003 γ^{dir} data



PHENIX: arXiv:2303.12899

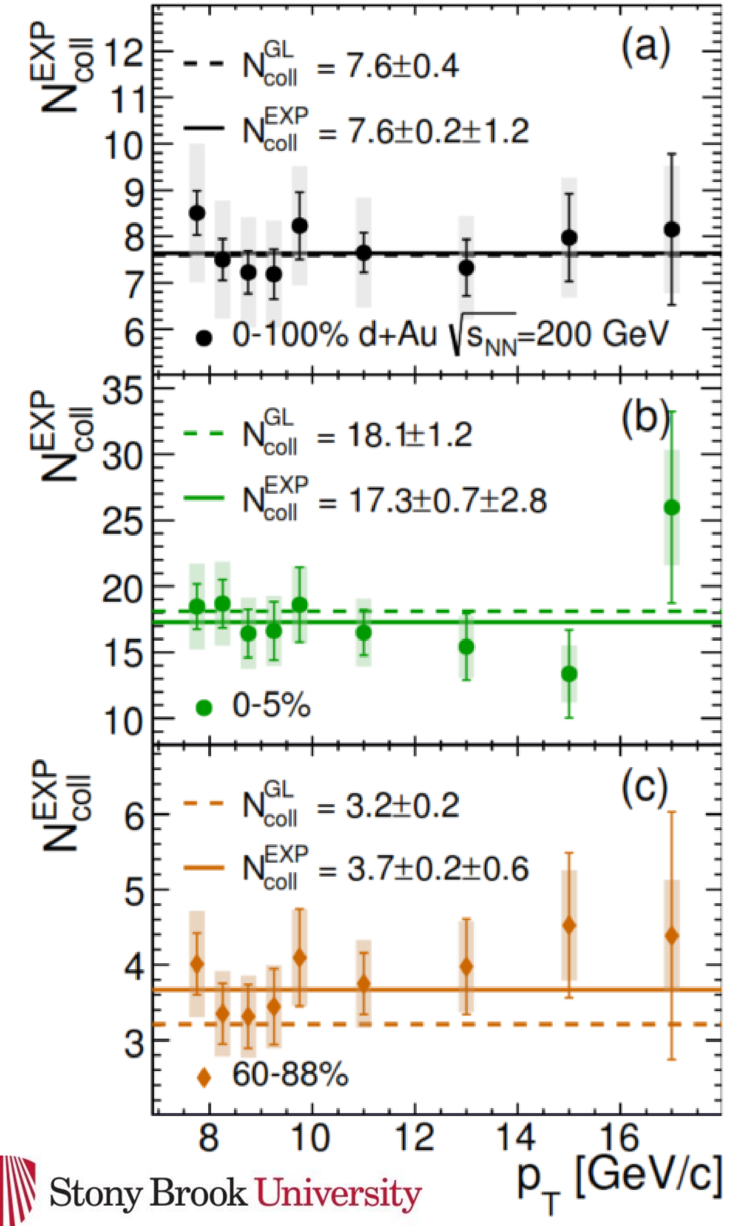
- γ^{dir}/π^0 for different centrality
  - Peripheral events consistent with min. bias
  - 0-5% visibly larger



No or similar modification of γ^{dir}/π^0 for most d+Au selections
Different modification for 0-5% central d+Au

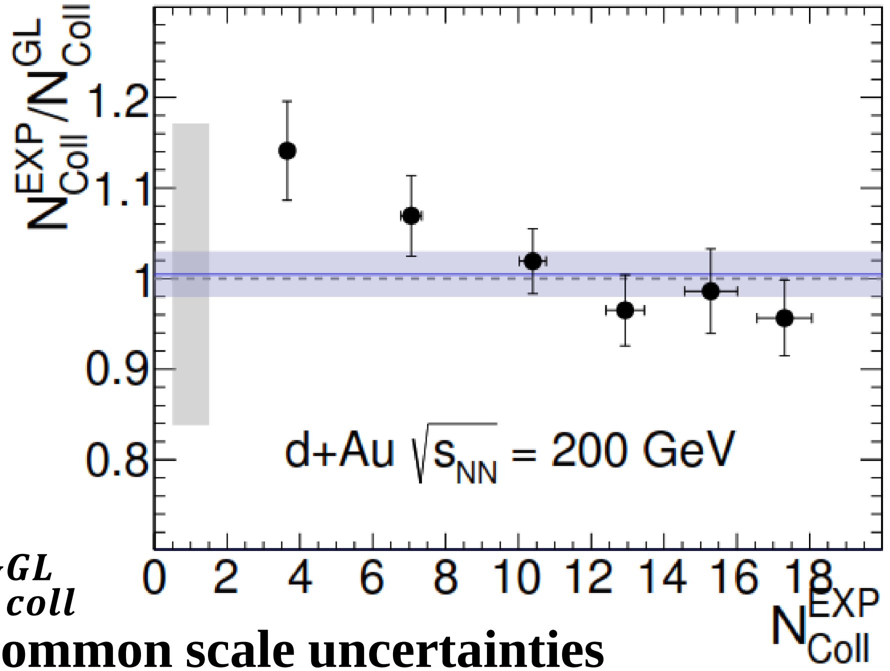
Evaluating Bias in N_{coll}^{GL} from Glauber Model

PHENIX: arXiv:2303.12899



- **Determine scaling factor N_{coll}^{EXP} from γ^{dir}**
  - Independent of p_T for 7.5 to 18 GeV/c
  - N_{coll}^{EXP} and N_{coll}^{GL} consistent within scale uncertainties

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



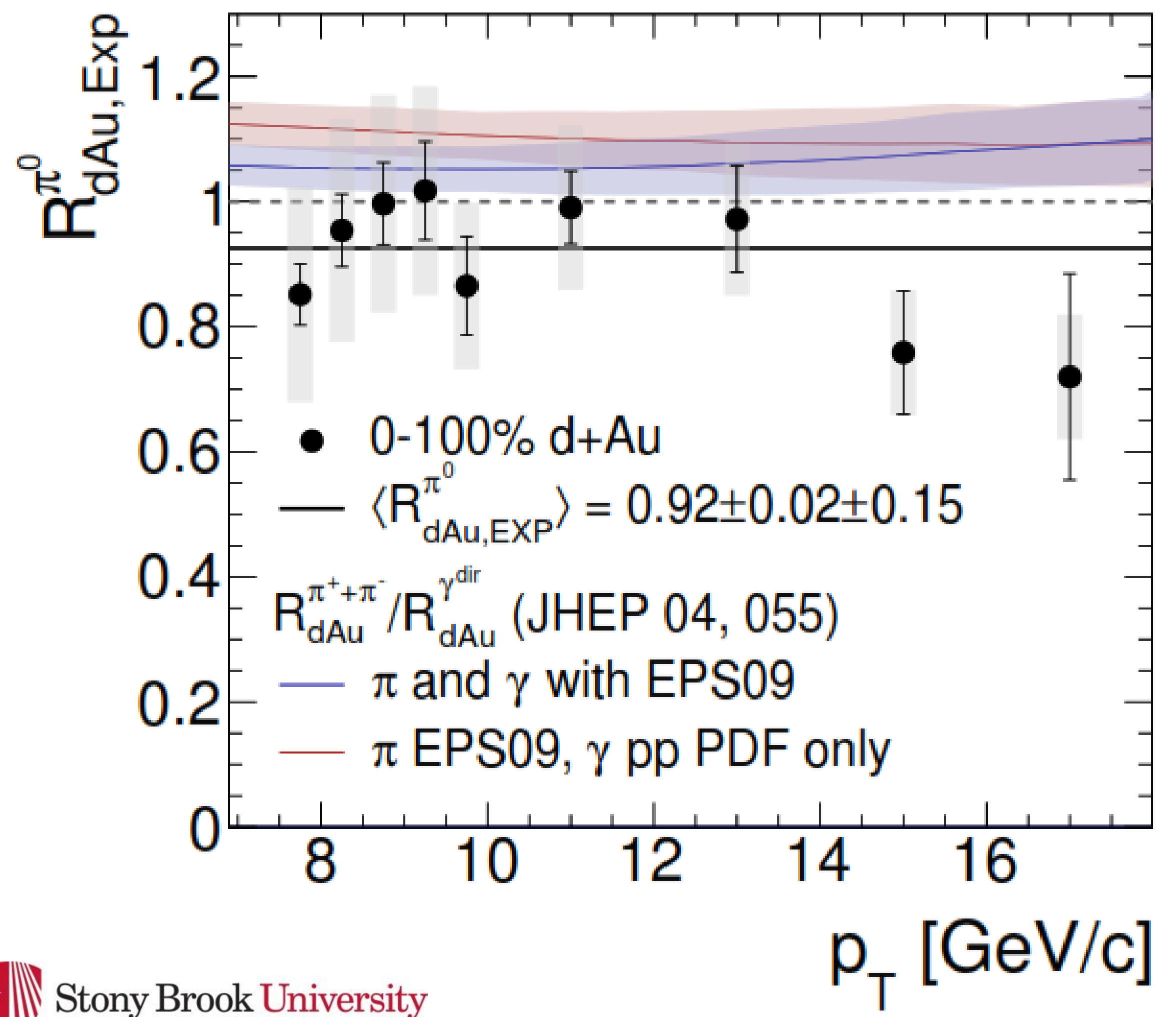
- **Visible trend in N_{coll}^{EXP} and N_{coll}^{GL} with centrality within common scale uncertainties**
  - Good agreement in central collisions within 5%
  - 15% deviation in peripheral collisions

Bias in event selection:
Event activity reduced in presence of hard scattering

Nuclear Modification Factor for π^0 in inclusive d+Au

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

PHENIX: arXiv:2303.12899



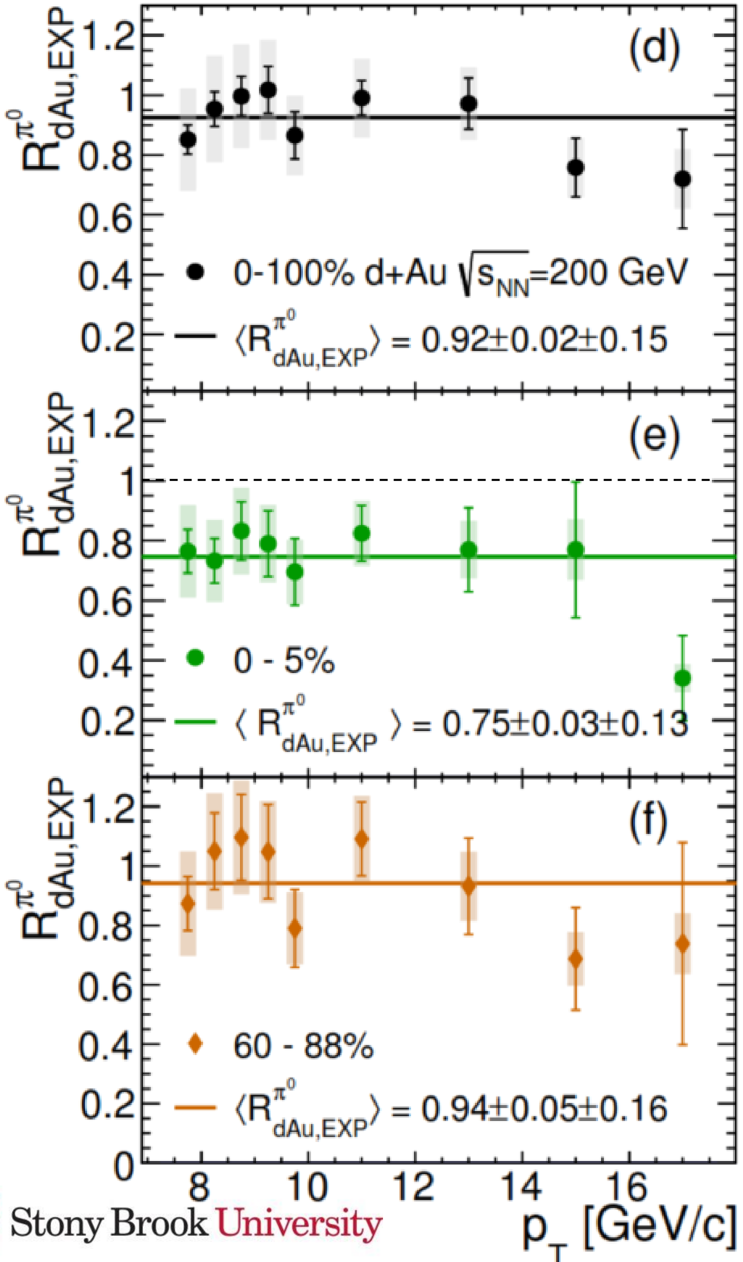
- **Redefined $R^{\pi^0}_{dAu,EXP}(p_T)$**
  - **No significant p_T dependence**
  - **Average value:**
    $R^{\pi^0}_{dAu,EXP}(p_T) = 0.92 \pm 0.02 \pm 0.15$
  - **Consistent with unity within 16% scale uncertainty**
  - **Consistent with 5% enhancement from CNM effects***

Small or no final state modification in inclusive d+Au

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

Centrality Dependence of $R^{\pi^0}_{dAu,EXP}(p_T)$

PHENIX: arXiv:2303.12899



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

- **Peripheral d+Au collisions**

  $$R^{\pi^0}_{dAu,EXP}(p_T) = 0.94 \pm 0.05 \pm 0.16$$

  - Consistent with inclusive d+Au sample

- **Central d+Au collisions**

  $$R^{\pi^0}_{dAu,EXP}(p_T) = 0.75 \pm 0.03 \pm 0.13$$

  - Clear suppression of π^0 yield
  - About 20% relative to inclusive sample

Suppression of π^0 in central 0-5% d+Au

Centrality Dependence of $R^{\pi^0}_{dAu,EXP}$

PHENIX: Niveditha Ramasubramanian
Poster 137 at Reception Mo 19:00

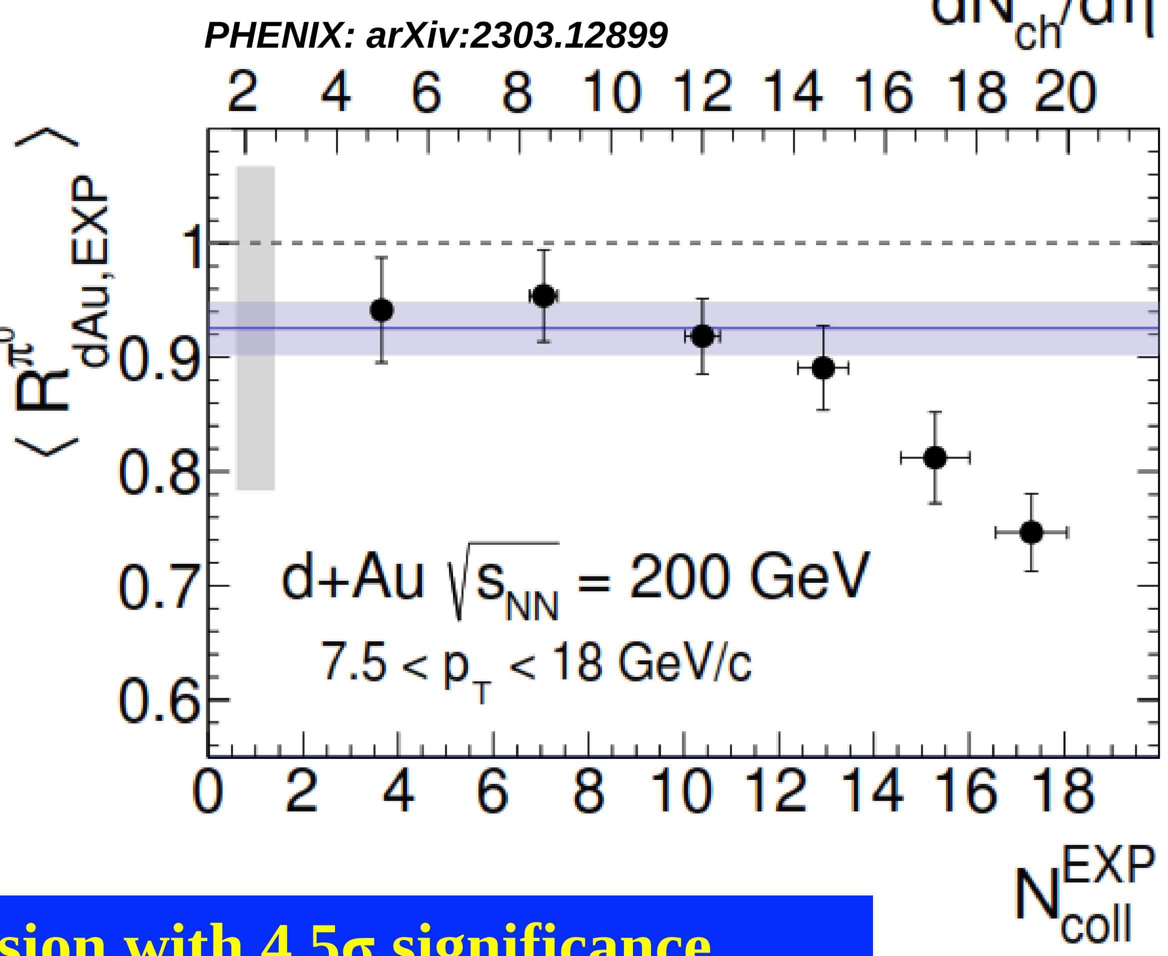
- $R^{\pi^0}_{dAu,EXP}$ verses N^{EXP}_{coll} or $dN_{ch}/d\eta$
  - Assess significance relative to min. bias sys. uncertainty and CNM effects cancel
  - $N^{EXP}_{coll} < 14$ consistent with inclusive d+Au

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

  - Suppression for $N^{EXP}_{coll} > 14$, i.e. top 10% centrality

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

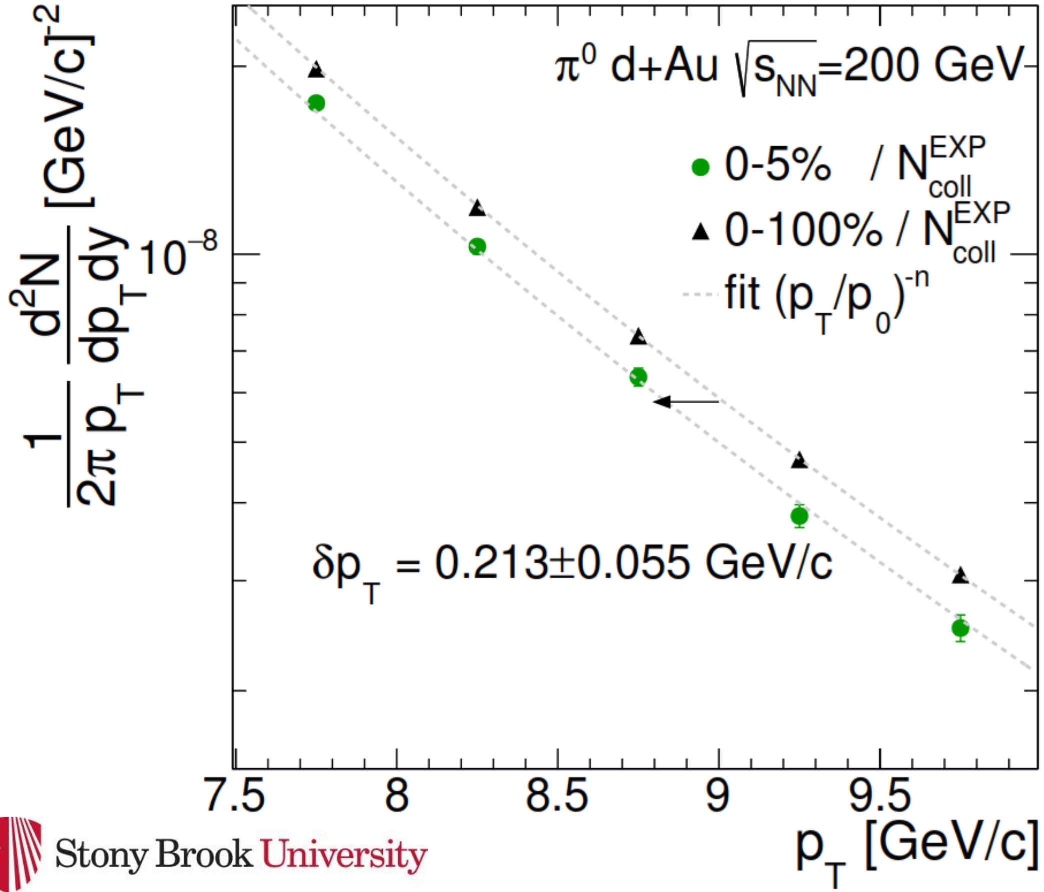
  - Increasing suppression with N^{EXP}_{coll} or $dN_{ch}/d\eta$



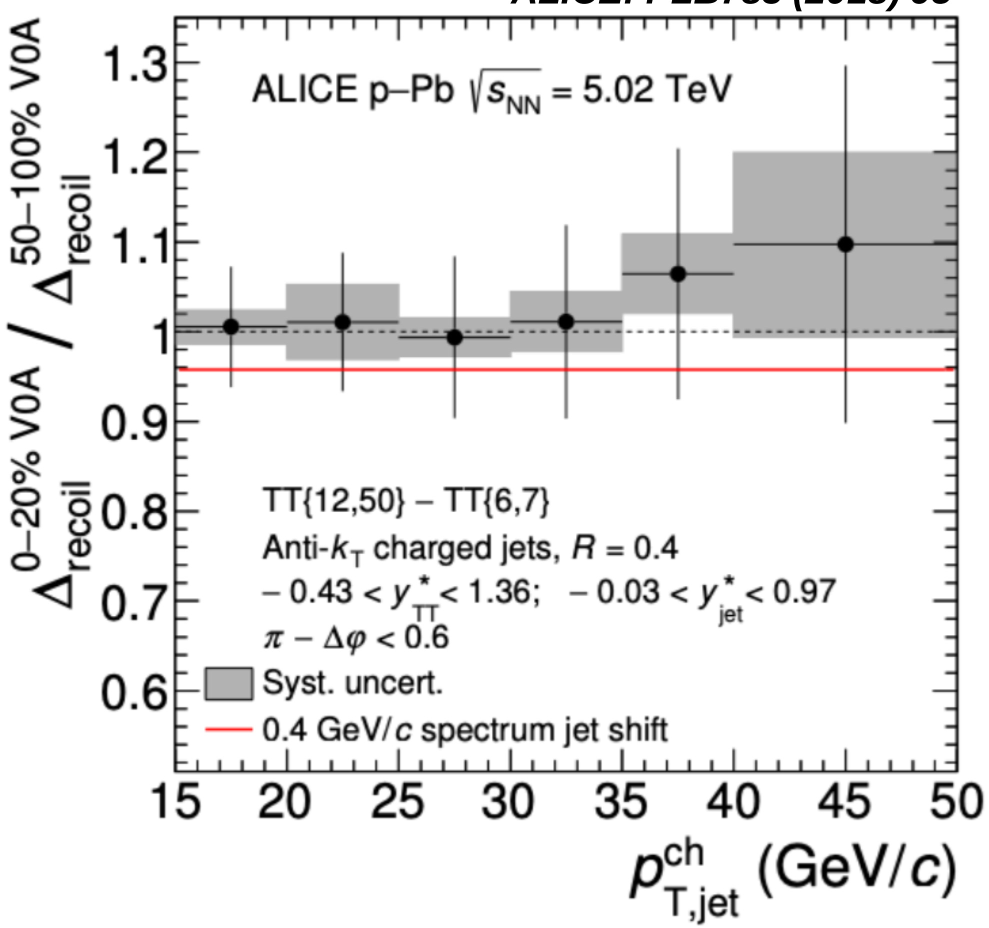
20% high p_T π^0 suppression with 4.5σ significance in final state of 0-5% central d+Au collisions at 200 GeV

Comparison to ALICE limit from Jets

- **PHENIX π^0 suppression in 0-5% d+Au**
  - **Assume π^0 is leading particle**
  - **Use momentum loss δp_T estimate from** *PHENIX:PRC93(2016)24911*
  - **20% suppression relative to 0-100%**
  - **momentum shift $\delta p_T \sim 0.2$ GeV/c**

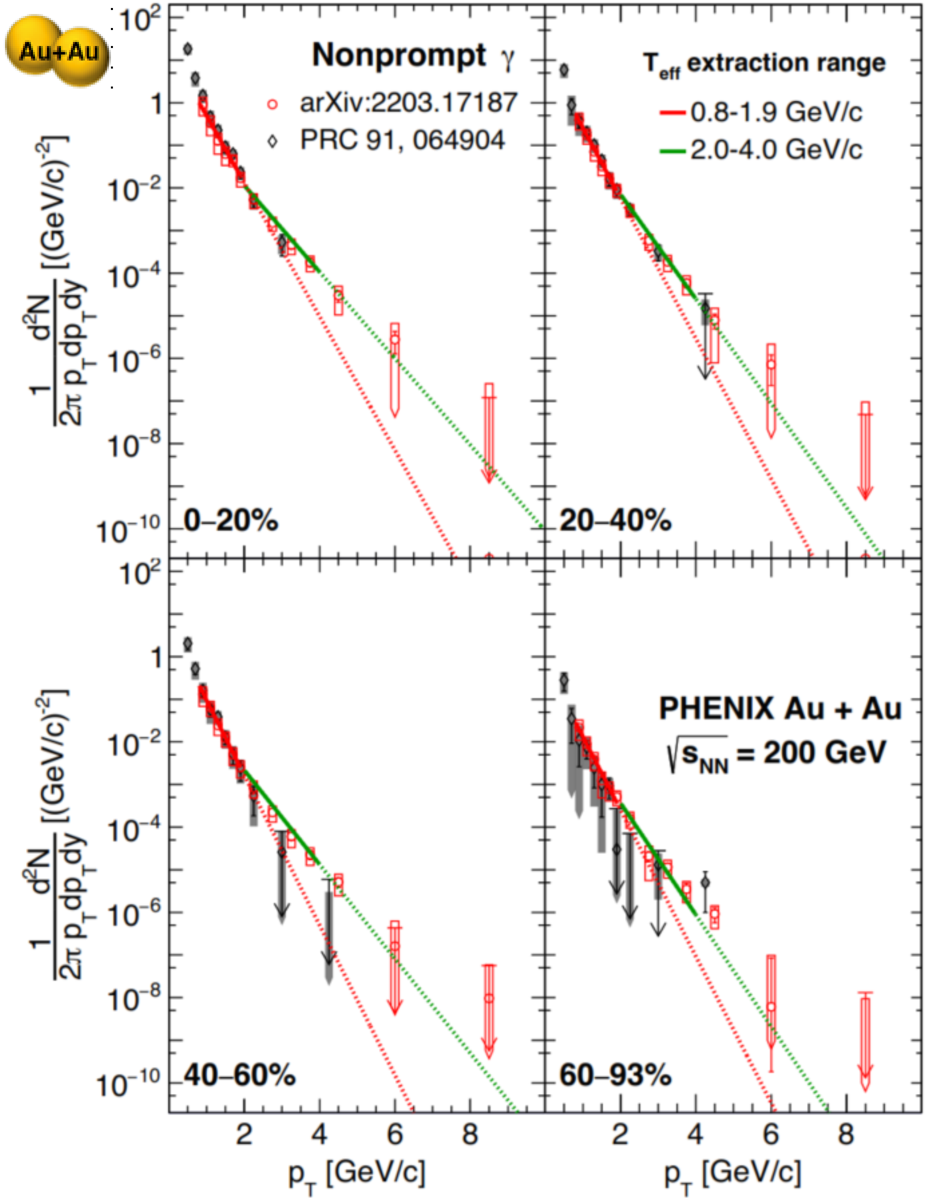


ALICE: PLB783 (2018) 95



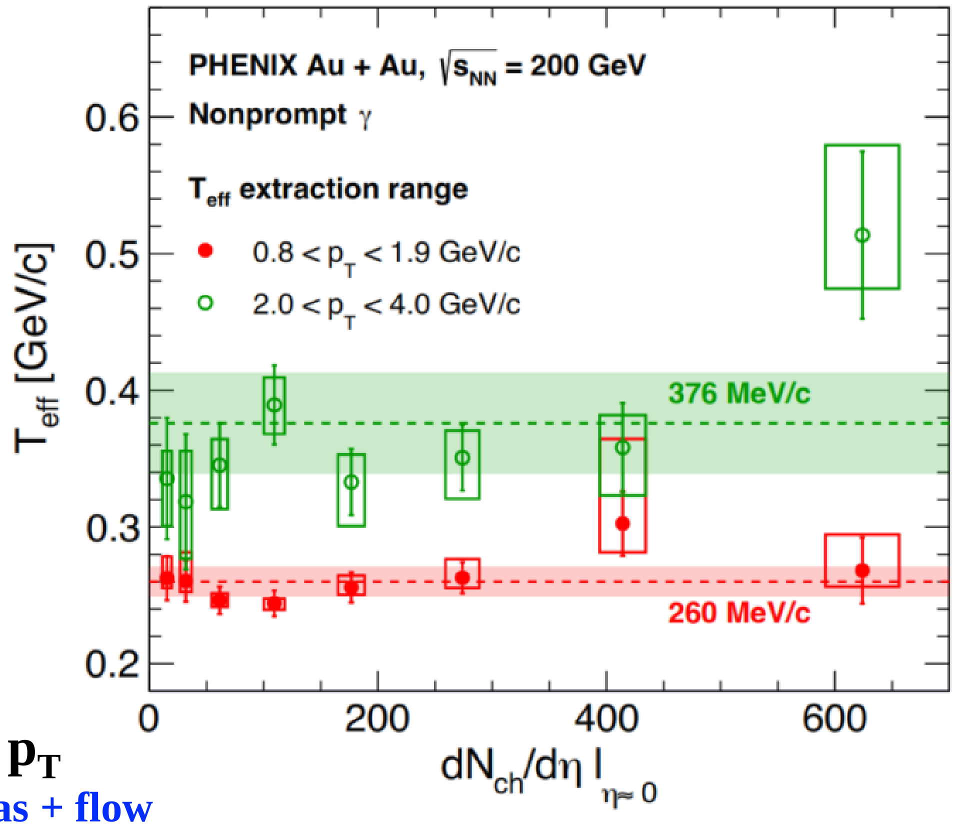
- **ALICE limit 0-20% p+Pb at 5.02 TeV:**
  - **for charged jet $p_T > 15$ GeV/c**
  - **ΔE move outside of R=0.4 cone in recoil jet < 0.4 GeV at 90% CL**

Non-Prompt Direct Photons from Au+Au



High statistics Au+Au
$\sqrt{s_{NN}} = 200$ GeV
data taken 2014

PHENIX: arXiv 2203.17187



- **Increasing T_{eff} with p_T**
  - **Low p_T : Hadron Gas + flow**
  - **Medium p_T: additional contributions from source with $T > T_C$**

Possibly Contribution from QGP or pre-equilibrium phase

Summary

- **Polarized p+p at 510 GeV:**
  - Isolated direct photons consistent with zero or small positive Δg
- **Small systems p+Al, p+Au, d+Au, ^{3}He+Au at 200 GeV:**
  - v_2/v_3 consistent with geometrical ordering expected from hydro expansion
  - ψ’ suppressed more than J/ψ in Au direction, consistent with final state effects
  - High p_T γ^{dir} resolve bias in event selection bias inherent to Glauber model approach
  - First evidence for significant 20% final state suppression of high p_T π^0 (7.5 to 18 GeV/c) in central 0-5% d+Au collisions

Small system data consistent with QGP droplets in central collisions

- **Au+Au collsions at 200 GeV:**
  - Non prompt γ^{dir} sensitive to early emission prior to Hadron gas formation

Other PHENIX Presentations at IS2023

- **Measurements of J/ψ production vs event multiplicity in the forward rapidity in p+p and p+Au collisions in the PHENIX experiment**

  PHENIX: Zhaozhong Shi
  Parallel Session 7 We 16:30

- **Disentangling centrality bias and final state effects in small system collisions**

  PHENIX: Niveditha Ramasubramanian
  Poster 137 at Reception Mo 19:00

- **Lévy HBT analysis of Bose-Einstein correlations**

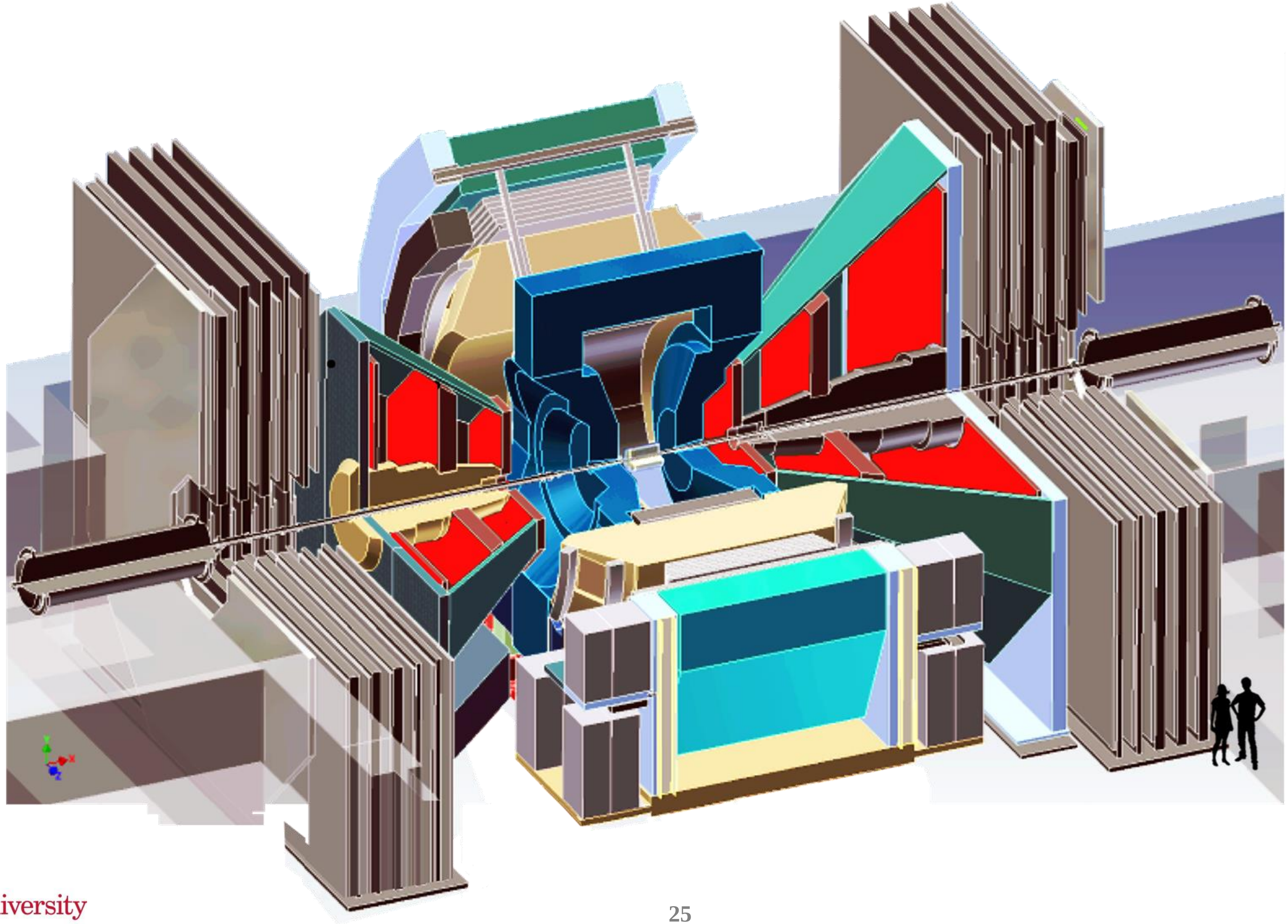
  PHENIX: Sándor Lökös
  Poster 136 at Reception Mo 19:00

- **π^0 and γ^{dir} at high p_T from high statistics 2014 data set**

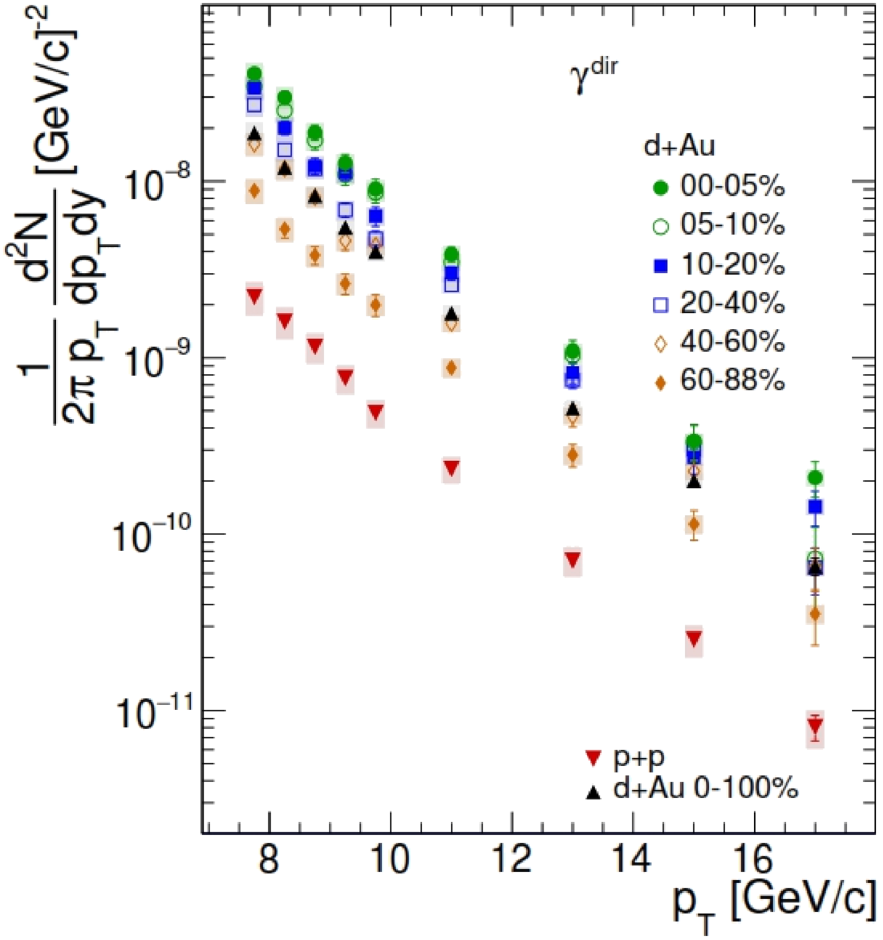
  PHENIX: Nour Jalal Abdulameer
  Poster 156 at Reception Mo 19:00

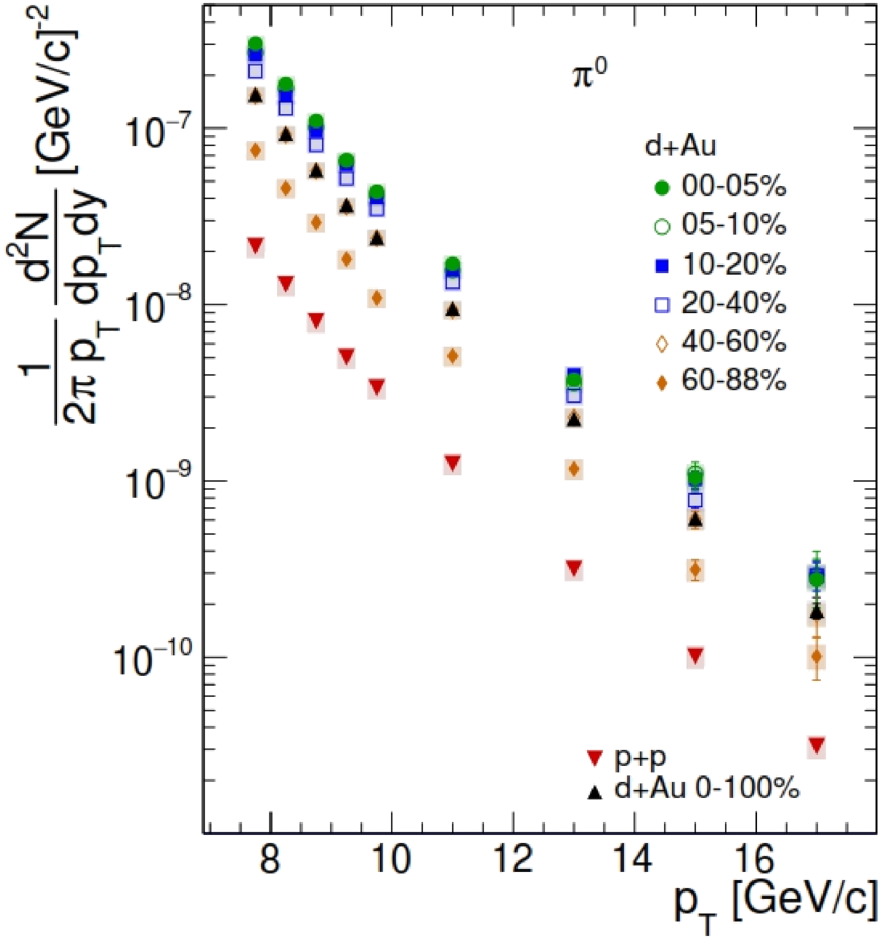
Backup

PHENIX Experiment at RHIC



γ^{dir} and π^0 Yields from d+Au and p+p at 200 GeV





PHENIX

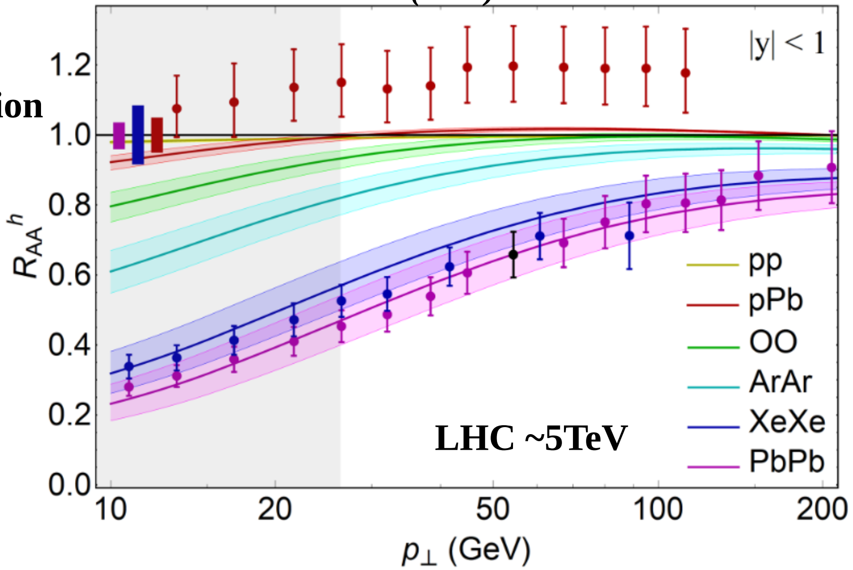
- **High p_T γ^{dir} (7.5 < pt < 18 GeV/c)**
  - **First centrality selected data from d+Au**
  - **min. bias d+Au data consistent with 2003 data:** *PHENIX:PRC87(2013)54907*
  - **p+p reference from:** *PHENIX:PRD86(2012)72008*
- **High p_T π^0 (7.5 < pt < 18 GeV/c)**
  - **d+Au data from 2016 consistent with 2008 data:** *PHENIX:PRC(2022)64902*
  - **p+p reference data from:** *PHENIX:PRC(2022)64902*

Energy Loss in Small Systems?

Nuclear modification factor: $R_{AB}(p_T) = \frac{Y_{AB}(p_T)}{\langle N_{coll} \rangle Y_{pp}(p_T)}$

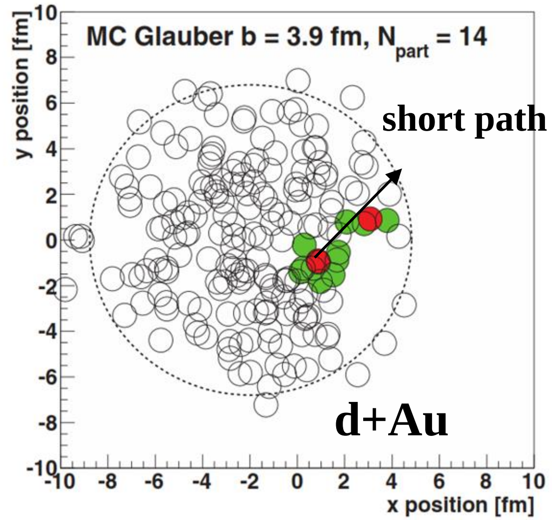
A. Huss et al. PRC103 (2021) 054903

Predict few % suppression

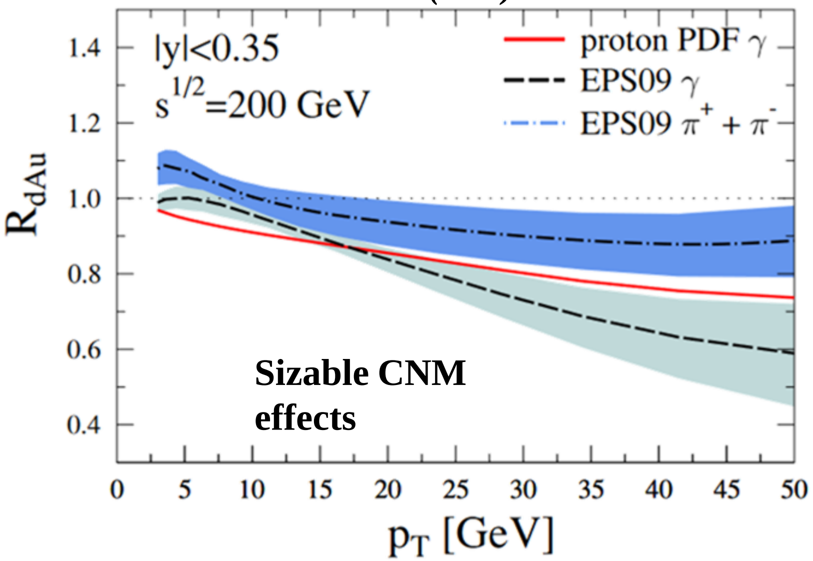


PHENIX: PRC90 (2014) 034902

PHENIX



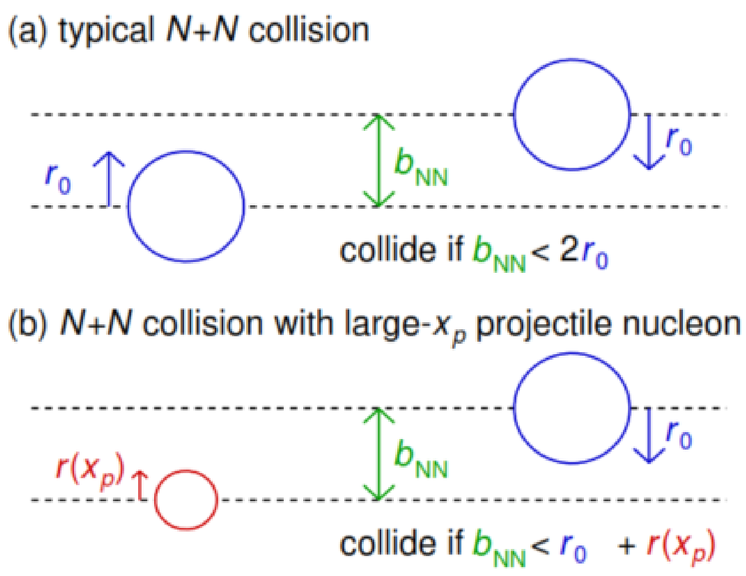
F. Arleo et al. JHEP04 (2011) 055



- **Expectation/Predictions**
  - **Small system size → few fm path length**
  - **Limited energy loss (<10% in min bias p+Pb at LHC)**
  - **Competing CNM effects of possibly similar size**

Small Signature → Challenging Measurement

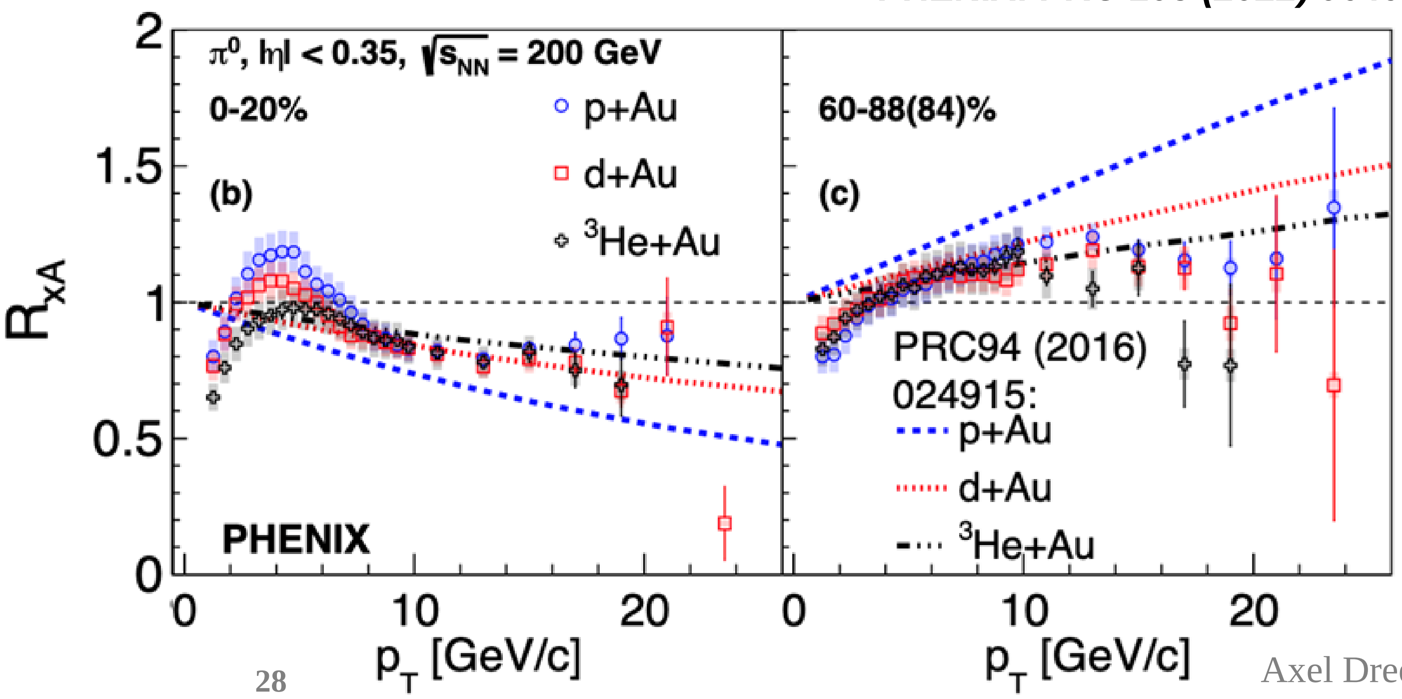
High-x Proton Size Fluctuation



McGlinchy, Nagle, Perepelitsa PRC 94 (2022) 024915

- **Hard scattering of parton with high x in pAu**
  - **nucleons has smaller than average size**
  - **Ncoll and Npart smaller**
  - **Smaller number of produced particles**
- **Characteristic Projectile Dependence**
  - **Projectile nucleons interact independently**
  - **Dilution of effect with increasing Nproj**
  - **Ordering of modification pAu > dAu > ^{3}HeAu**

PHENIX: PRC 105 (2022) 064902



Expected ordering with system size not observed