11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

Disentangling centrality bias and final state effects on high p_T π^0 using direct γ in d+Au at 200 GeV

Axel Drees, Hard Probes 2023, March 2023, Aschaffenburg, Germany

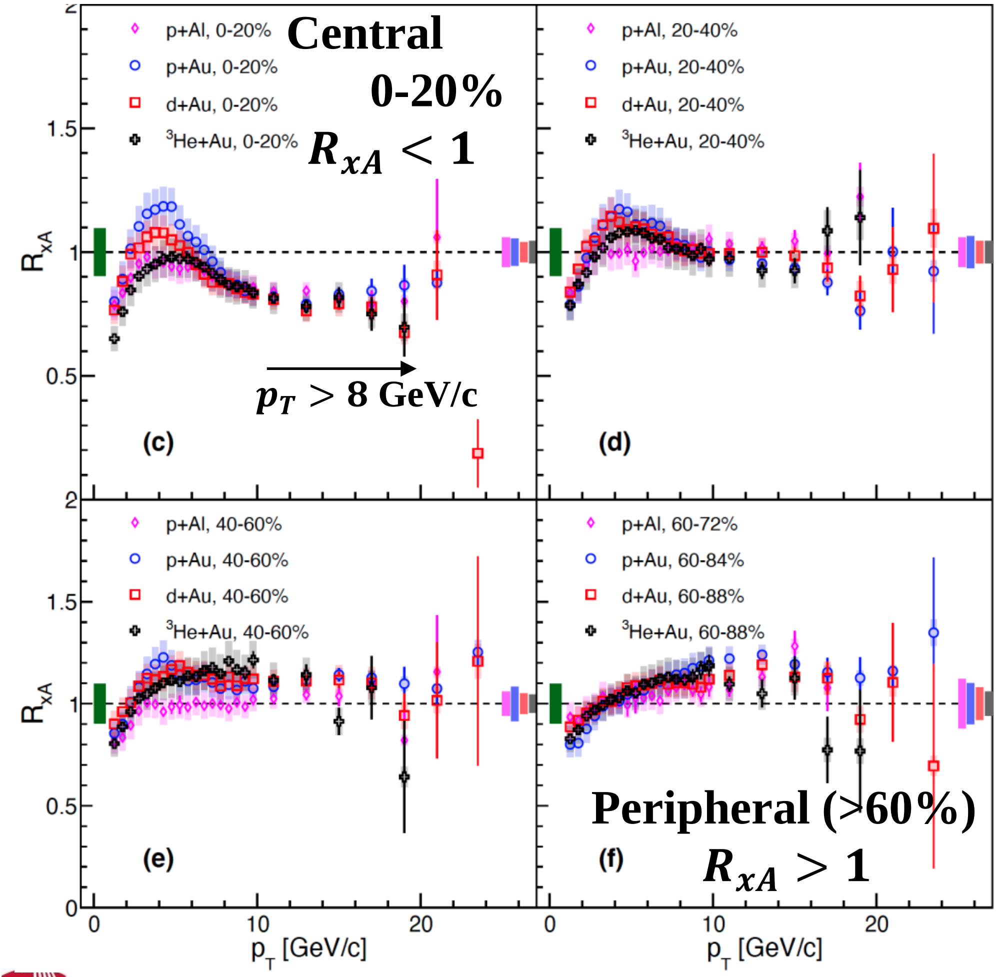
- **Introduction**
  - Challenges measuring final state effects for high p_T π^0 in small systems
  - Resolution using direct photons to scale hard scattering processes
- **New results from final PHENIX run in 2016 - arXiv:2303.12899**
  - Previously observed enhancement in peripheral collisions due to event selection bias
  - Final state suppression of 20% in central 0-5% d+Au collisions
- **Summary/Outlook**

Challenges to Identify Final State Effects in Small Systems

Nuclear modification factor:

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

PHENIX: PRC 105 (2022) 064902



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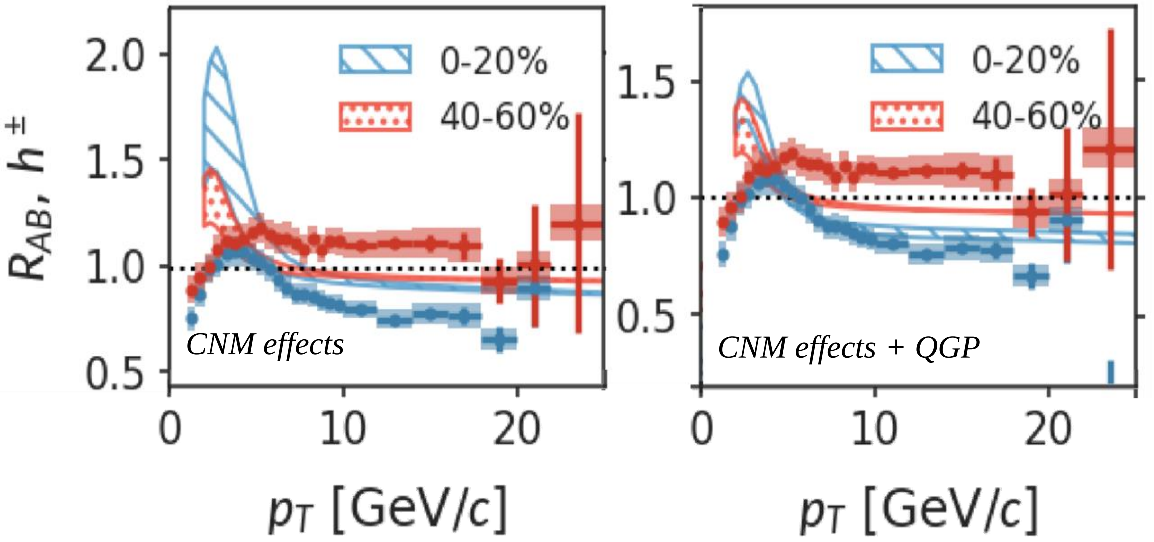
- π^0 R_{xA} from pAu, dAu, ^{3}HeAu
  - Central: 20% suppression - consistent with energy loss
  - Peripheral: 15 % enhancement - unexplained, likely due to selection bias

d+Au 200 GeV *W.Ke & I.Vitev: arXiv:2204.00634*

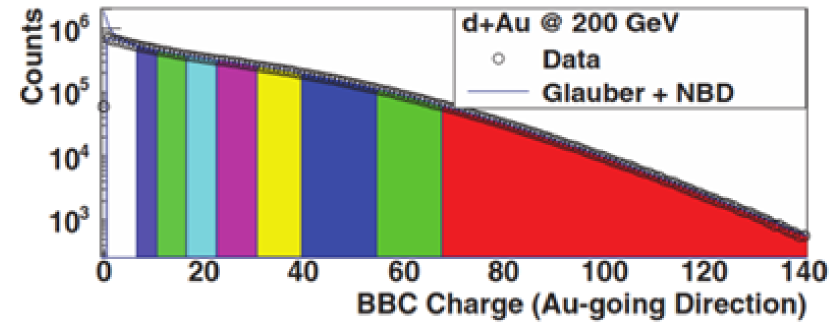


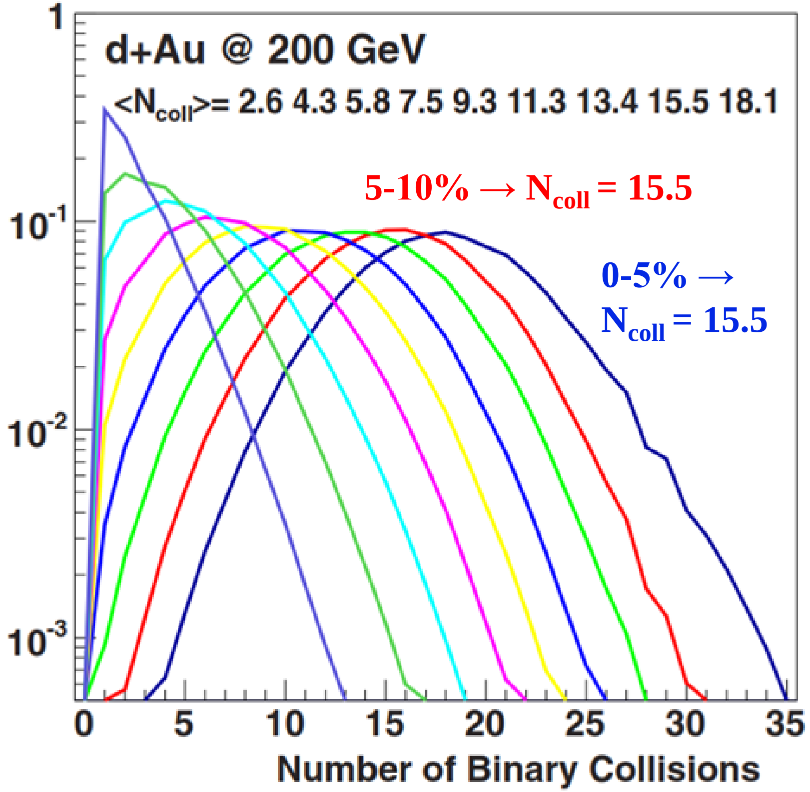
  - Similar observations at RHIC & LHC

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

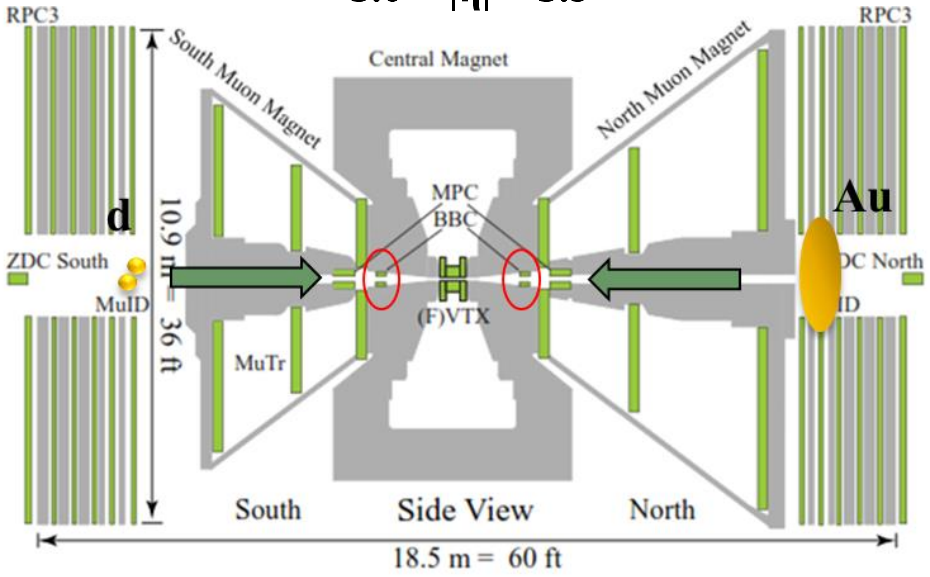
Mapping Event Activity to Centrality With Glauber Model

PHENIX: PRC90 (2014) 034902





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



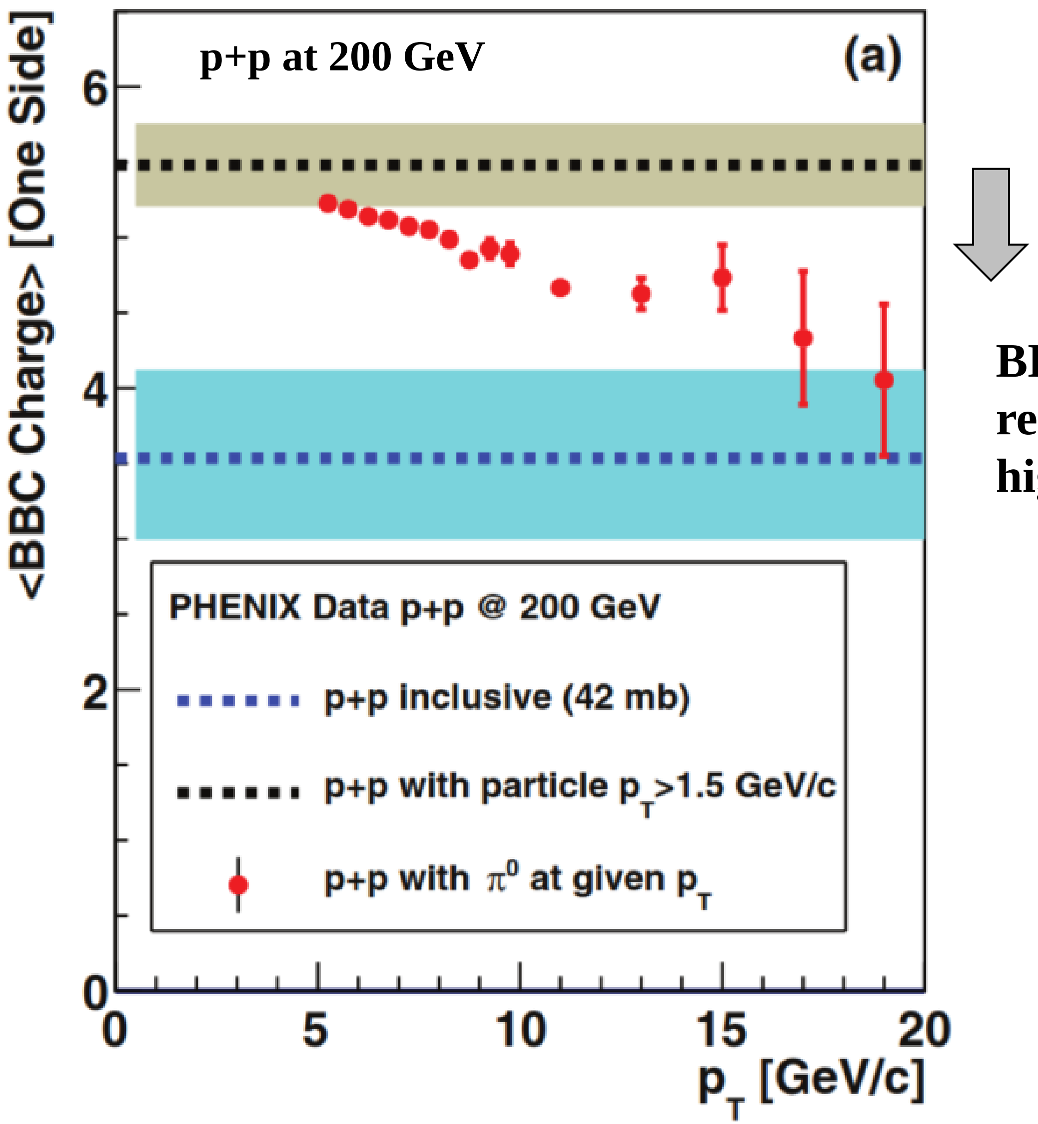
- **Procedure for small systems**
  - **Measure event activity (N_{ch}) in BBC on Au going side**
  - **Fit event activity to superposition of negative binomial distributions for each nucleon-nucleon collision**
  - **Select events in percentiles of event activity (0-5%, 5-10%, etc.) for data & model**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

PHENIX: PRC90 (2014) 034902



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**

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

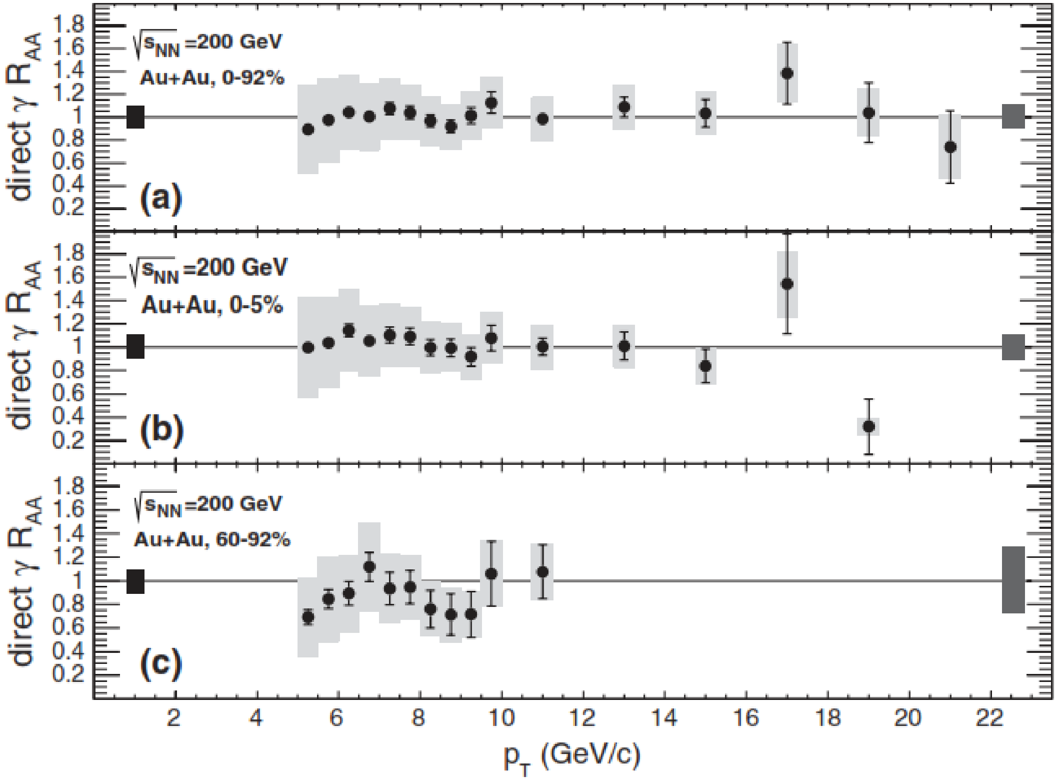
- **Redefine Nuclear Modification Factor**

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

  - 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

PHENIX

PHENIX: PRL109 (2012) 152302



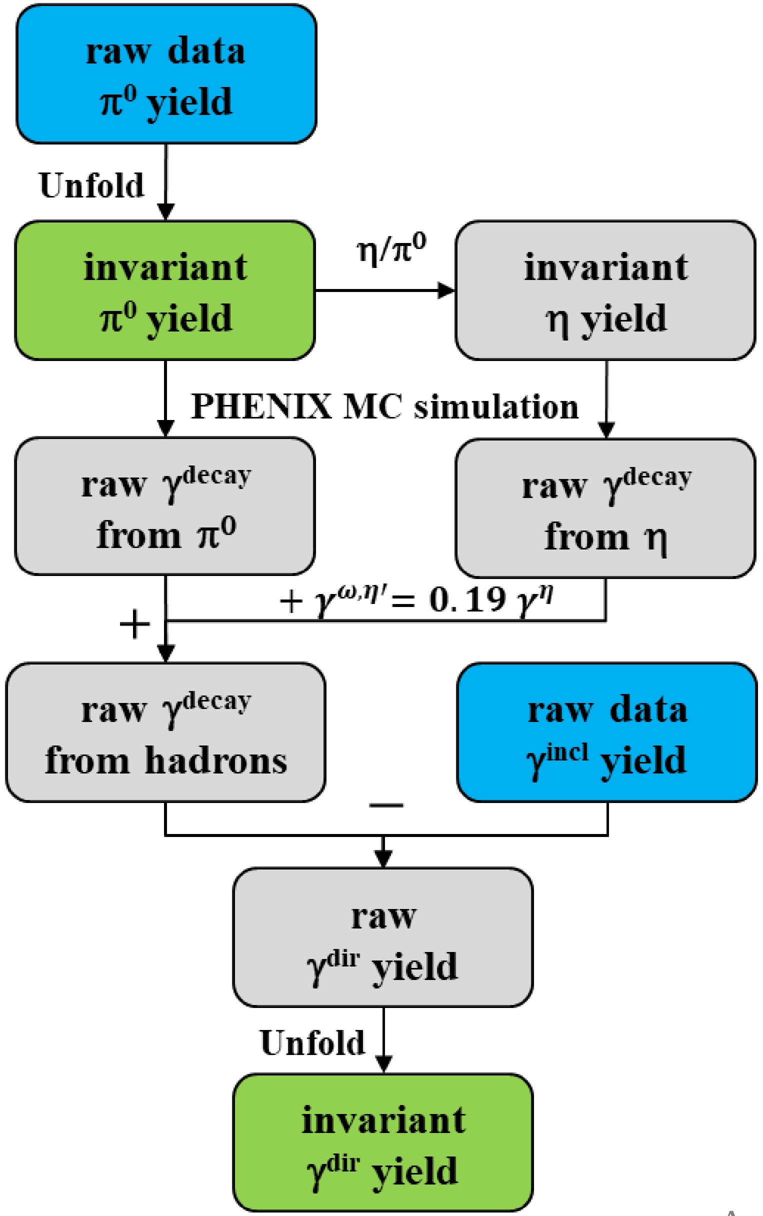
Search for final state effects simultaneous measure direct γ and π^0

High p_T π^0 and γ from d+Au at 200 GeV

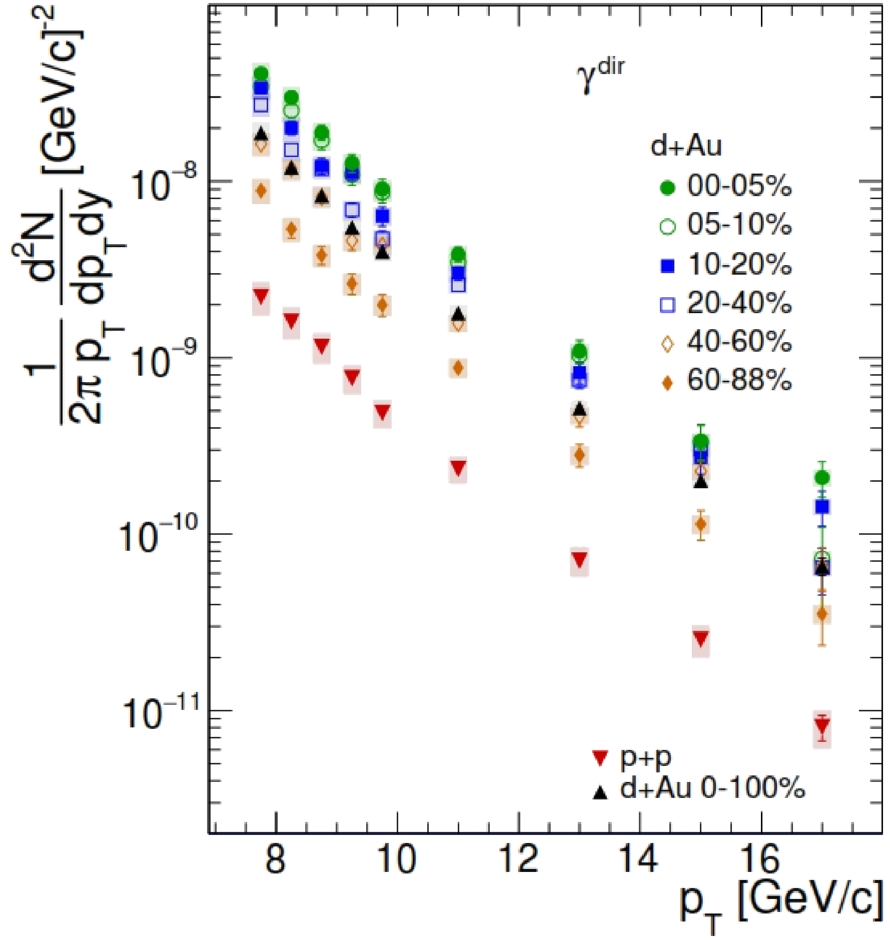
- **Data set 2016 d+Au at 200 GeV**
  - Taken with EMCal trigger
  - Corresponding to 50 nb^{-1}
  - π^0 and γ momentum range $p_T > 7.5$ GeV/c

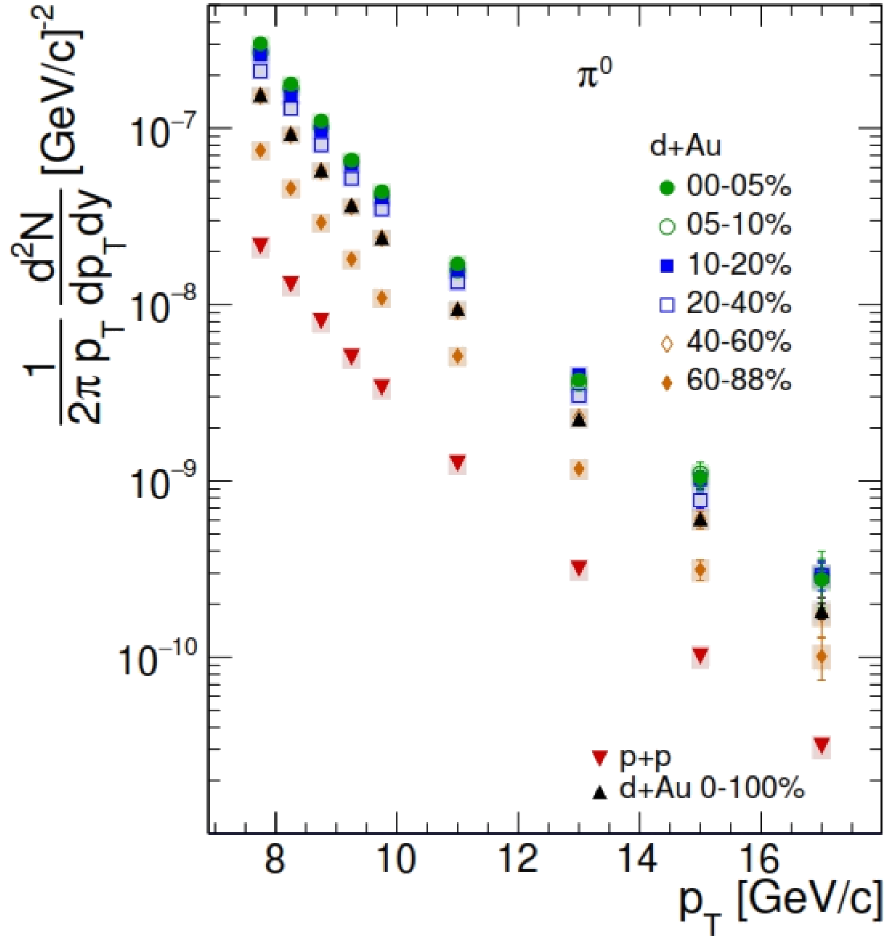
- **Analysis of PHENIX EMCal data**
  - Reconstruct γ showers and $\pi^0 \rightarrow \gamma\gamma$
  - Correct π^0 spectrum
  - Model hadron decay γ showers in PHENIX
  - Subtract from γ showers raw γ^{dir}
  - Correct γ^{dir} spectrum

- **Systematic Uncertainties**
  - ~ 12% for π^0 and γ^{dir} (energy scale 8% and detector material 7%)
  - Reduce to 6% in γ^{dir}/π^0 ratio
  - Uncertainty on γ^{dir}/π^0 common to all centrality selection



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

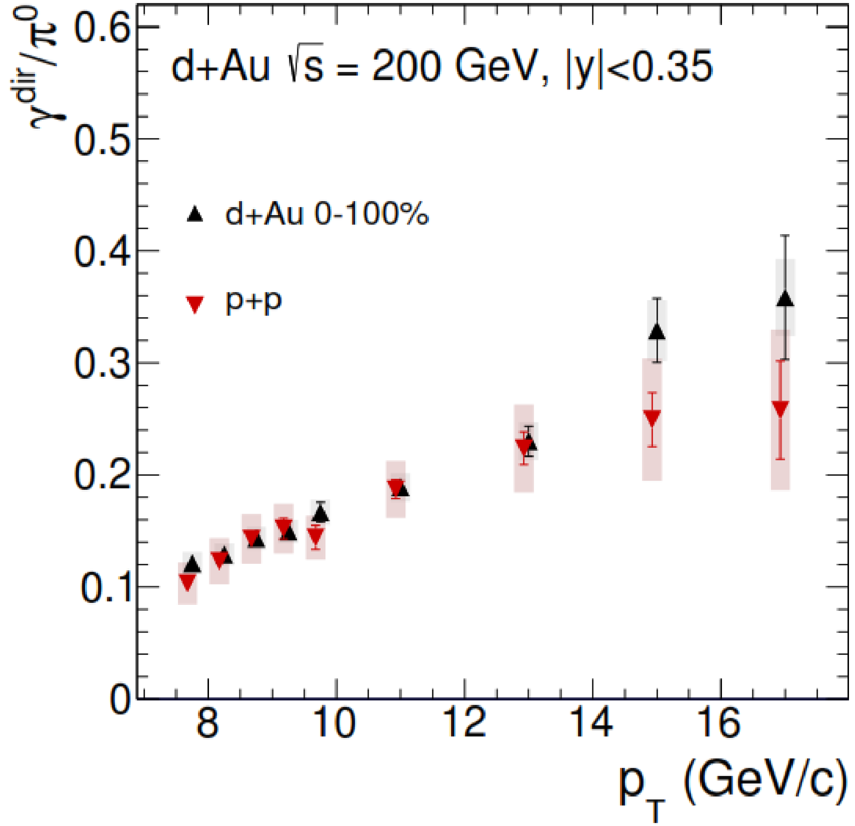




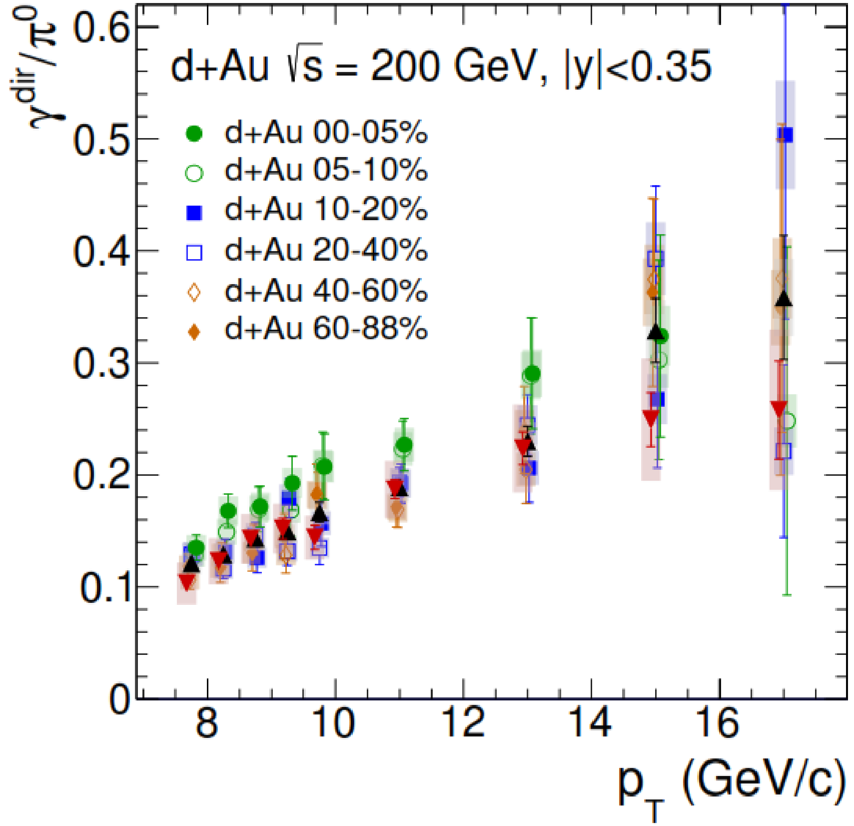
- **High p_T γ^{dir} (7.5 < pt < 18 GeV/c)**
  - **First centrality selected data from d+Au**
  - **min. bias d+Au data consistent with 2003 data:** *PHENIX:PRC87(2013)54907*
  - **p+p reference from:** *PHENIX:PRD86(2012)72008*
- **High p_T π^0 (7.5 < pt < 18 GeV/c)**
  - **d+Au data from 2016 consistent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

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

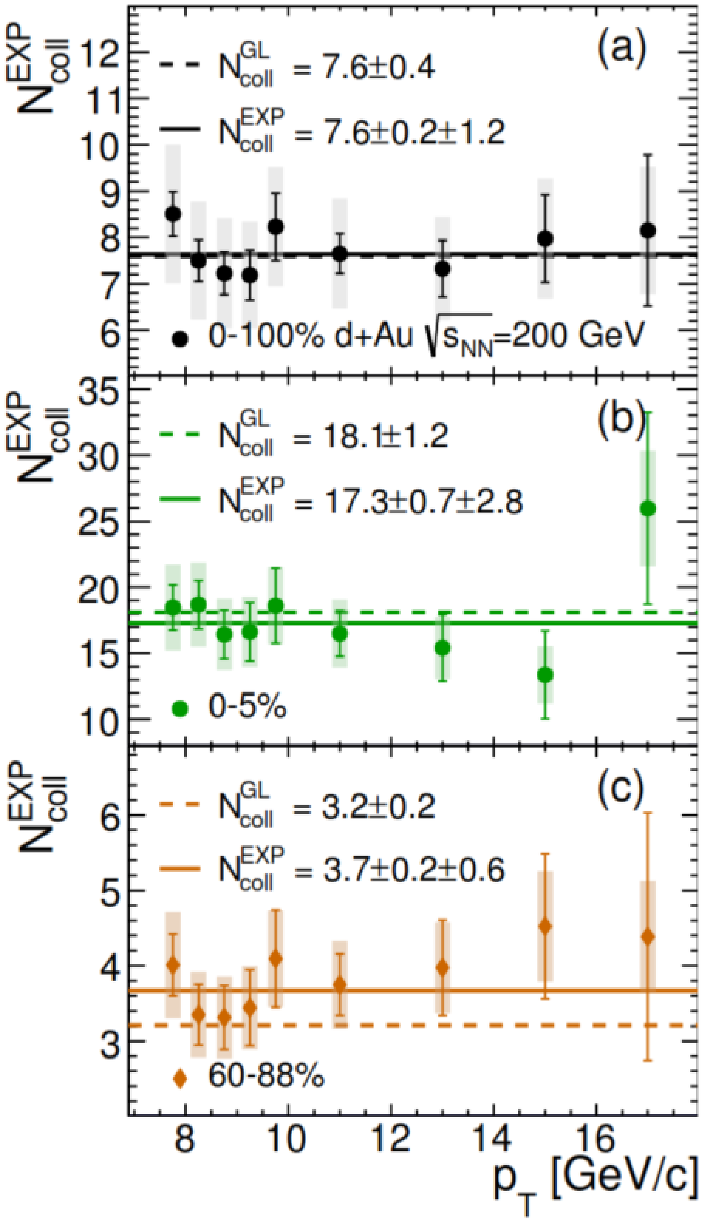


- γ^{dir}/π^0 for different centrality
  - Peripheral events consistent with min. bias
  - 0-5% visibly larger



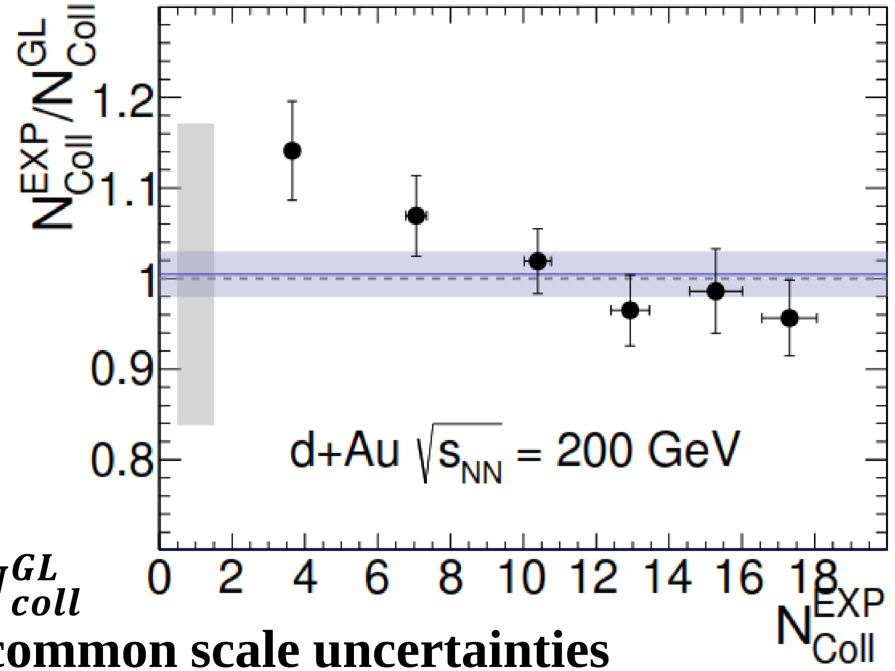
No or similar modification of γ^{dir}/π^0 for most d+Au selections
Different modification for 0-5% central d+Au

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



- **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

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

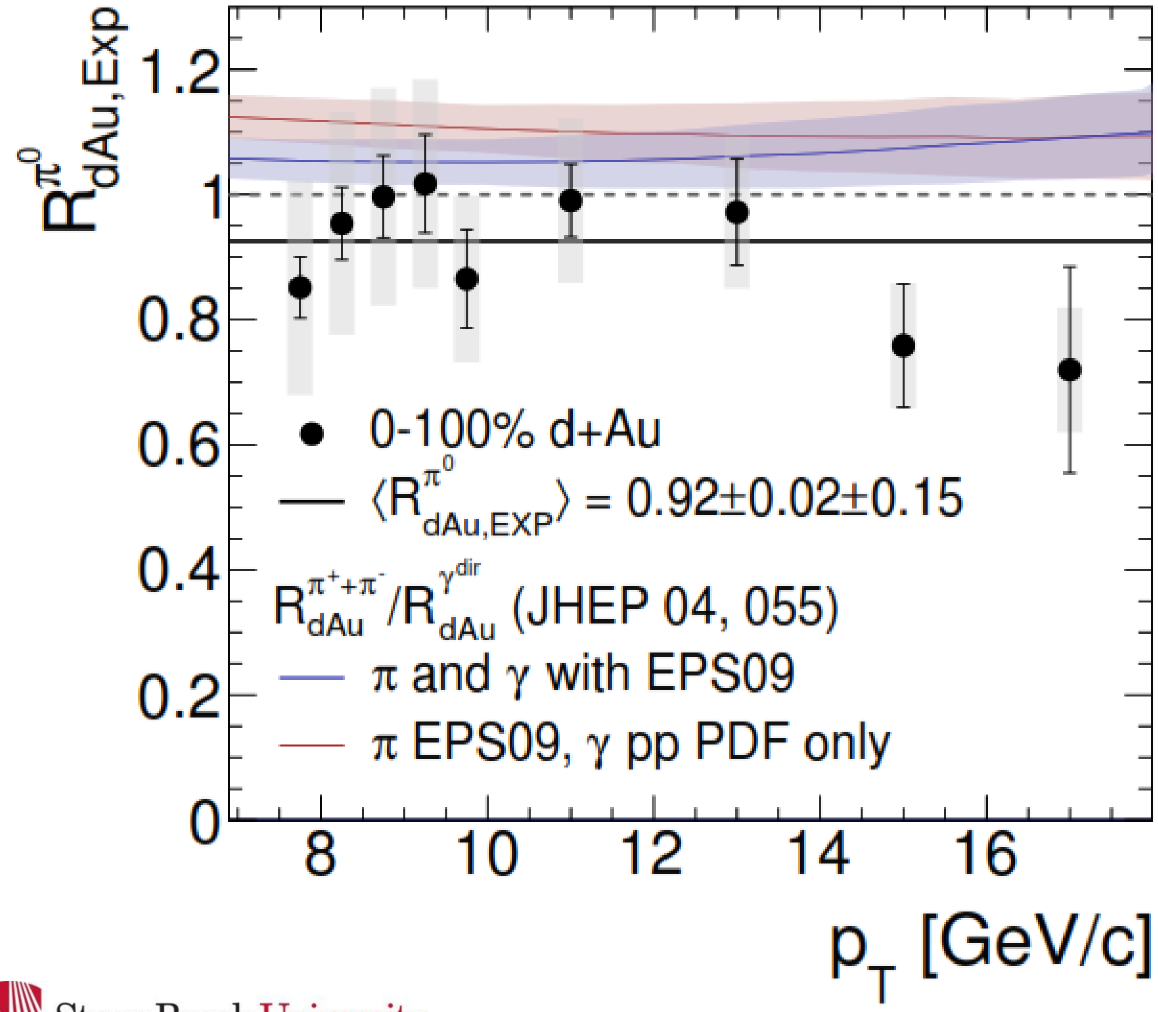


- **Visible trend in N_{coll}^{EXP} and N_{coll}^{GL} with centrality within common scale uncertainties**
  - Good agreement in central collisions within 5%
  - 15% deviation in peripheral collisions

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

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

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



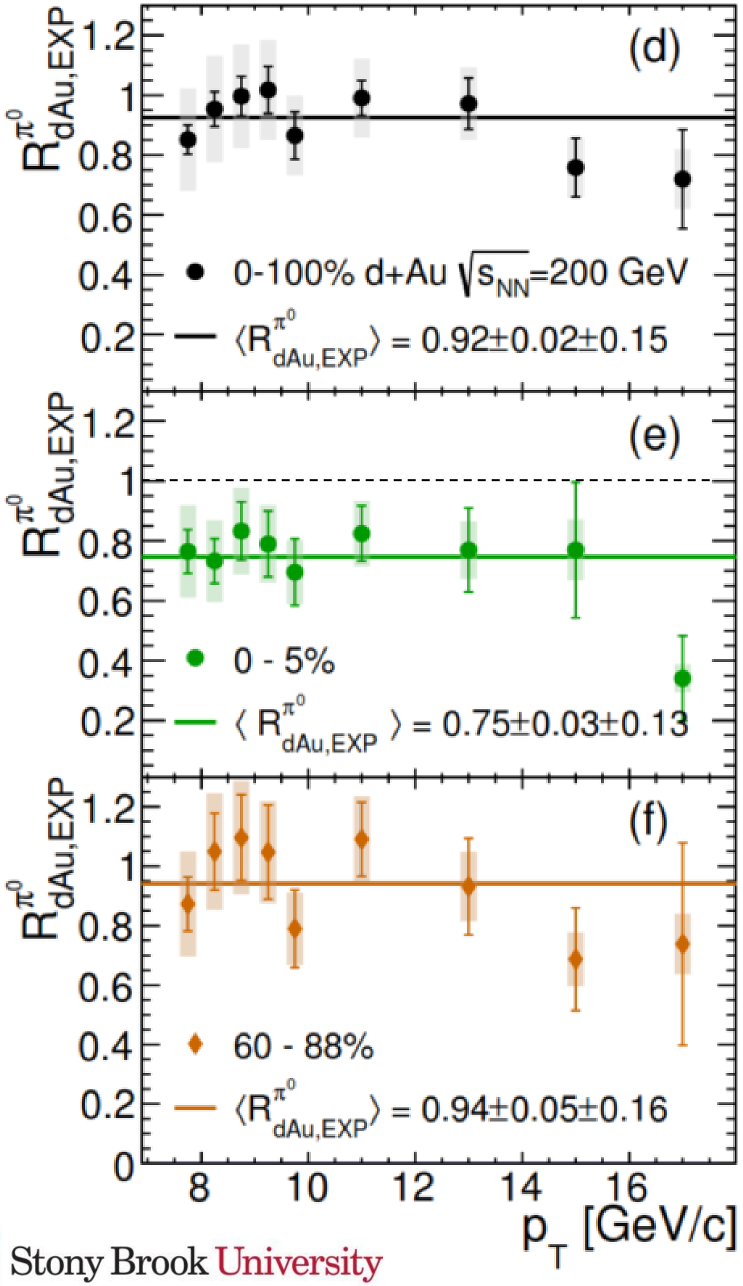
- **Redefined $R^{\pi^0}_{dAu,EXP}(p_T)$**
  - No significant p_T dependence
  - Average value:

    $R^{\pi^0}_{dAu,EXP}(p_T) = 0.92 \pm 0.02 \pm 0.15$
  - 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 $R^{\pi^0}_{dAu,EXP}(p_T)$



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

- **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 $R^{\pi^0}_{dAu,EXP}$

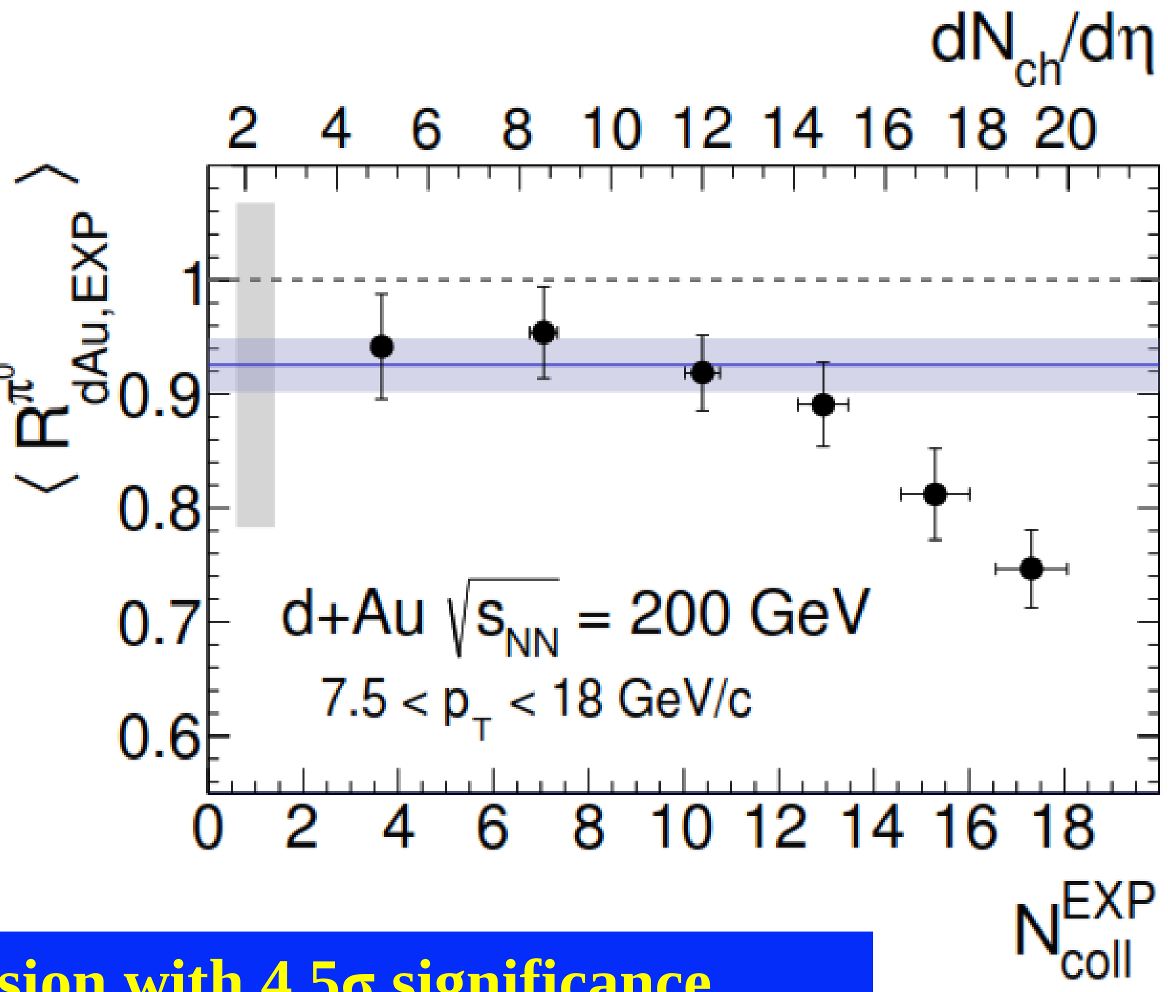
- $R^{\pi^0}_{dAu,EXP}$ verses N^{EXP}_{coll} or $dN_{ch}/d\eta$
  - Assess significance relative to min. bias sys. Uncertainty and CNM effects cancel
  - $N^{EXP}_{coll} < 14$ consistent with inclusive d+Au

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

  - 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

Summary and Outlook

- **Key results:**
  - **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**
  - **Previously observed enhancement of π^0 in peripheral events due to an event selection bias**

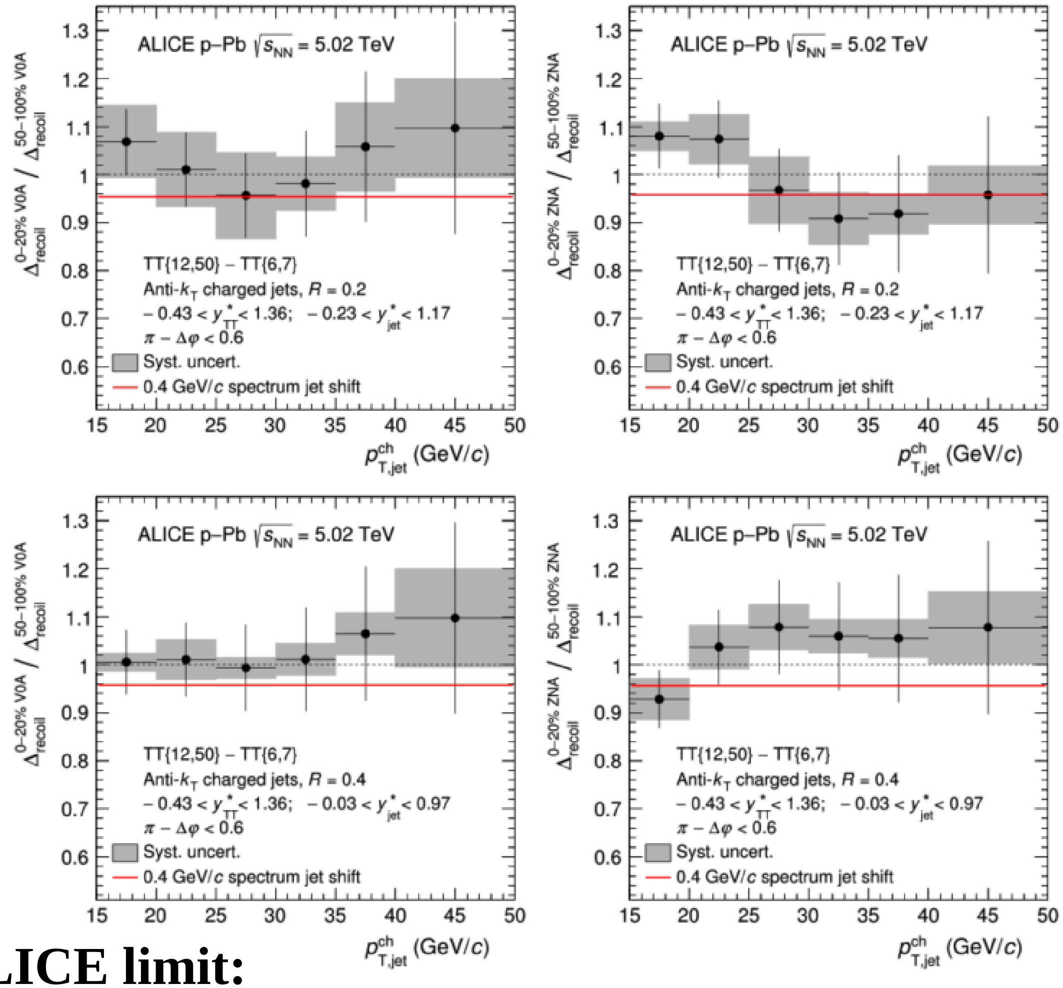
- **New method to measure effective N_{coll}^{Exp}:**
  - **Ratio of γ^{dir} in sample to that in p+p**
  - **Resolves ambiguity between final state effect – CNM effect – event selection bias inherent to Glauber model approach**

- **Further ongoing investigations:**
  - **Size dependence of final state effect: p+Au < d+Au < ^{3}He+Au ???**
  - **Reduce systematic uncertainty on γ^{dir}/π^0 from p+p**

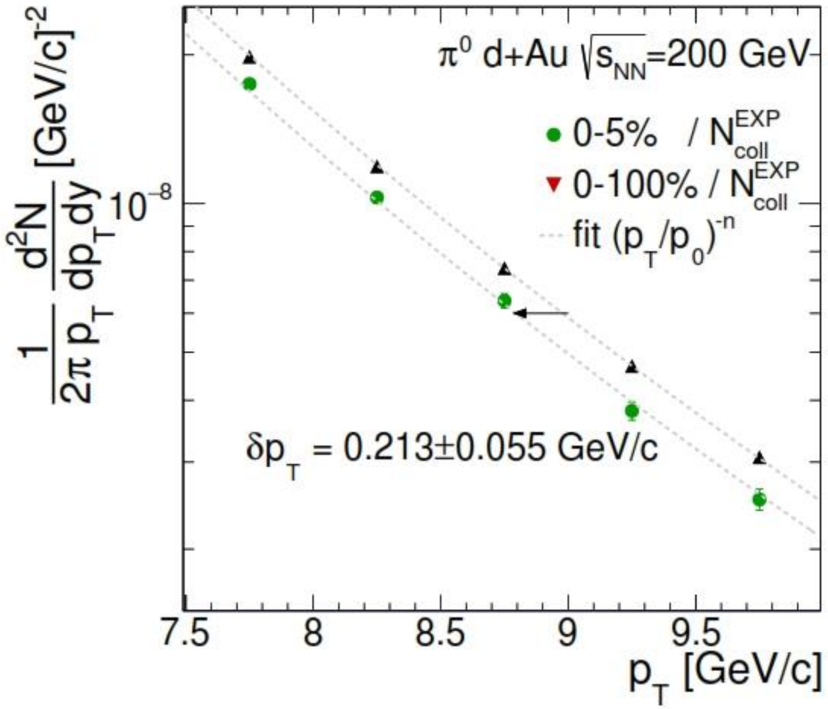
Backup

Comparison to ALICE limit from Jets

ALICE: PRL109 (2012) 152302



- **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**



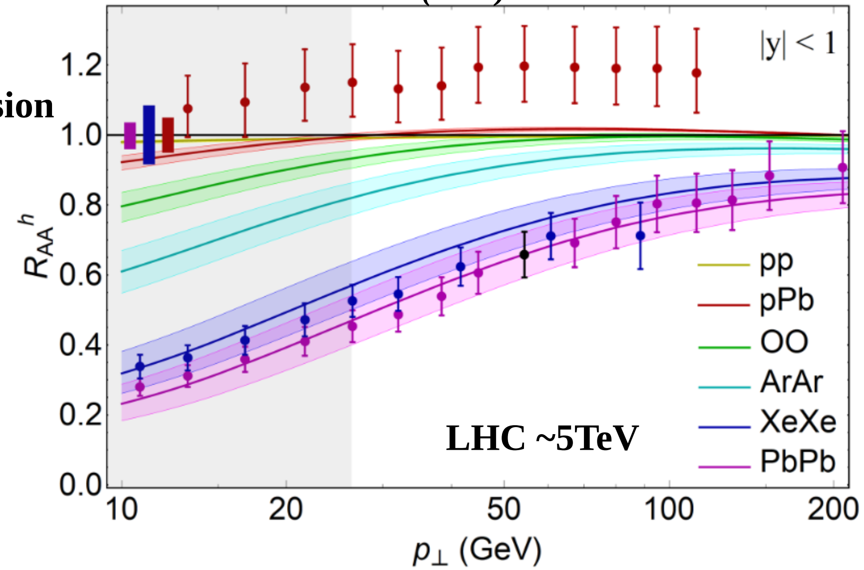
- **ALICE limit:**
  - **p+Pb at 5.02 TeV with 0-20% EA**
  - **for charged jet p_T > 15 GeV/c**
  - **ΔE move outside of R=0.4 cone in recoil jet < 0.4 GeV at 90% CL**

Energy Loss in Small Systems?

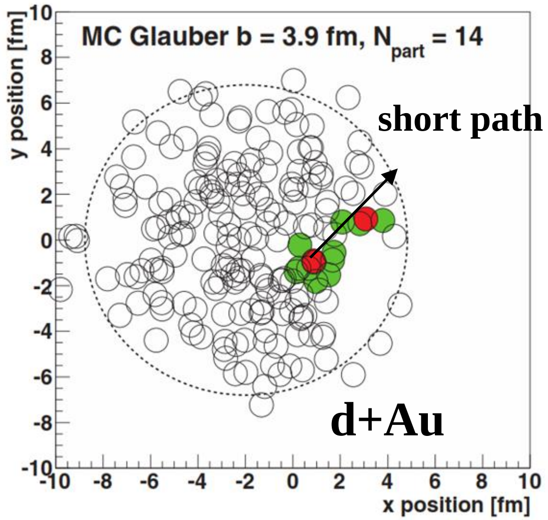
Nuclear modification factor: $R_{AB}(p_T) = \dfrac{Y_{AB}(p_T)}{\langle N_{coll} \rangle Y_{pp}(p_T)}$

A. Huss et al. PRC103 (2021) 054903

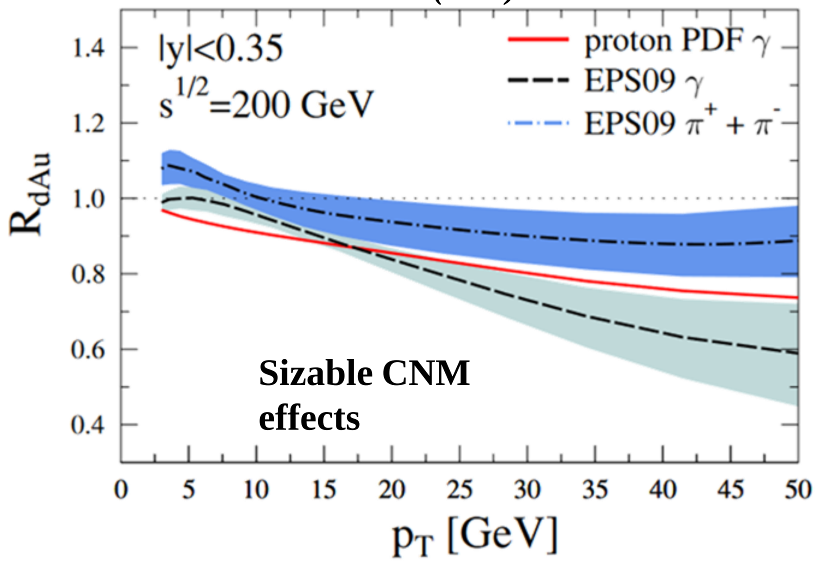
Predict few % suppression



PHENIX: PRC90 (2014) 034902



F. Arleo et al. JHEP04 (2011) 055

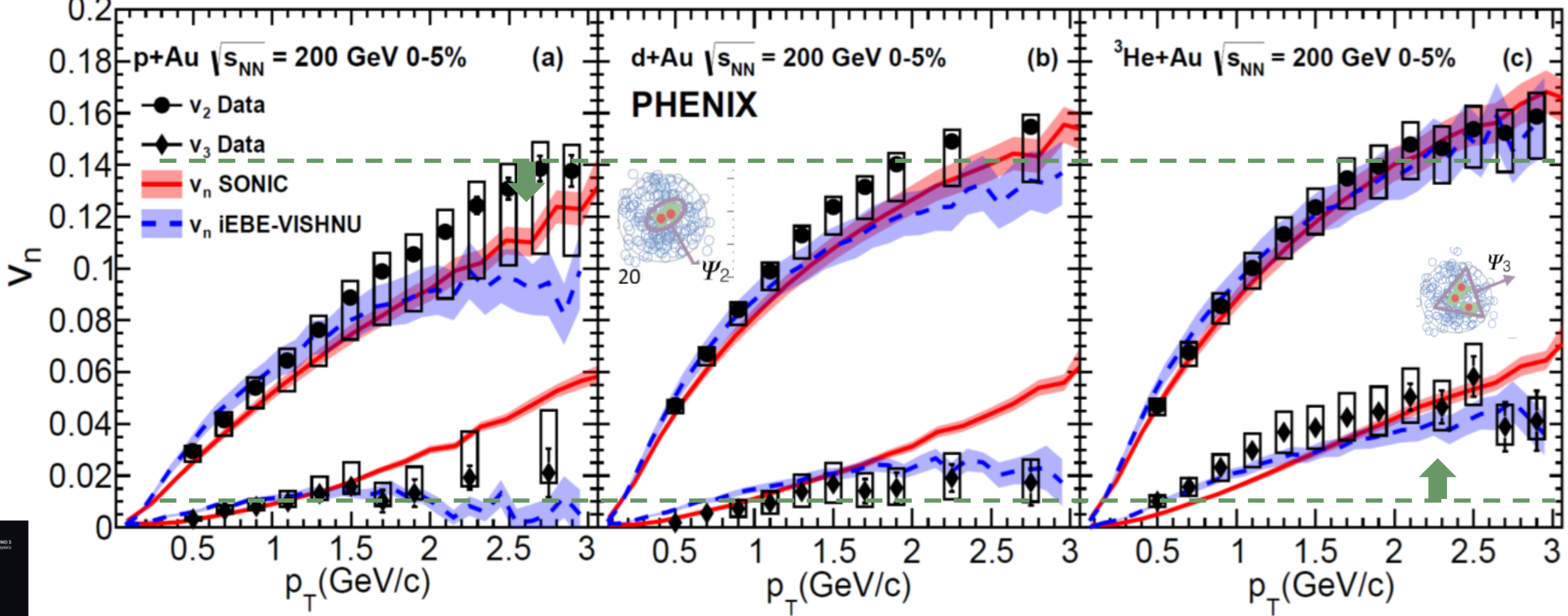


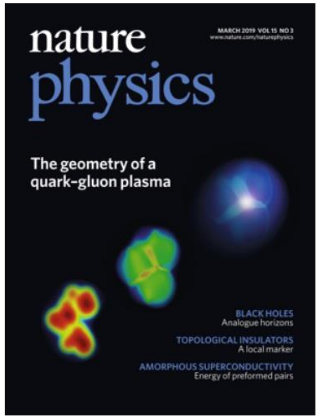
- **Expectation/Predictions**
  - **Small system size → few fm path length**
  - **Limited energy loss (<10% in min bias p+Pb at LHC)**
  - **Competing CNM effects of possibly similar size**

Small Signature → Challenging Measurement

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