Differential π^0 and photon modification in *d*+Au collisions

[based on nucl-th/2404.17660]

PHYSICAL REVIEW C **110**, L011901 (2024)

Letter

Contribution to differential π^0 and γ_{dir} modification in small systems from color fluctuation effects

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A major complication in the search for jet quenching in proton- or deuteron-nucleus collision systems is the presence of physical effects which influence the experimental determination of collision centrality in the presence of a hard process. For example, in the proton color fluctuation picture, protons with a large Bjorken-x ($x \gtrsim 0.1$) parton interact more weakly with the nucleons in the nucleus, leading to a smaller (larger) than expected yield in large (small) activity events. A recent measurement by the PHENIX Collaboration compared the yield of neutral pion and direct photon production in d + Au collisions, under the argument that the photon yields correct for such biases, and the difference between the two species is thus attributable to final-state effects (i.e., jet quenching). The main finding suggests a significant degree of jet quenching for hard processes in small systems. In this paper, I argue that the particular photon and pion events selected by PHENIX arise from proton configurations with significantly different Bjorken-x distributions, and thus are subject to different magnitudes of modification in the color fluctuation model. Using the results of a previous global analysis of data from the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC), I show that potentially all of the pion-to-photon difference in PHENIX data can be described by a proton color fluctuation picture at a quantitative level before any additional physics from final-state effects is required. This finding reconciles the interpretation of the PHENIX measurement with others at RHIC and LHC, which have found no observable evidence for jet quenching in small systems.

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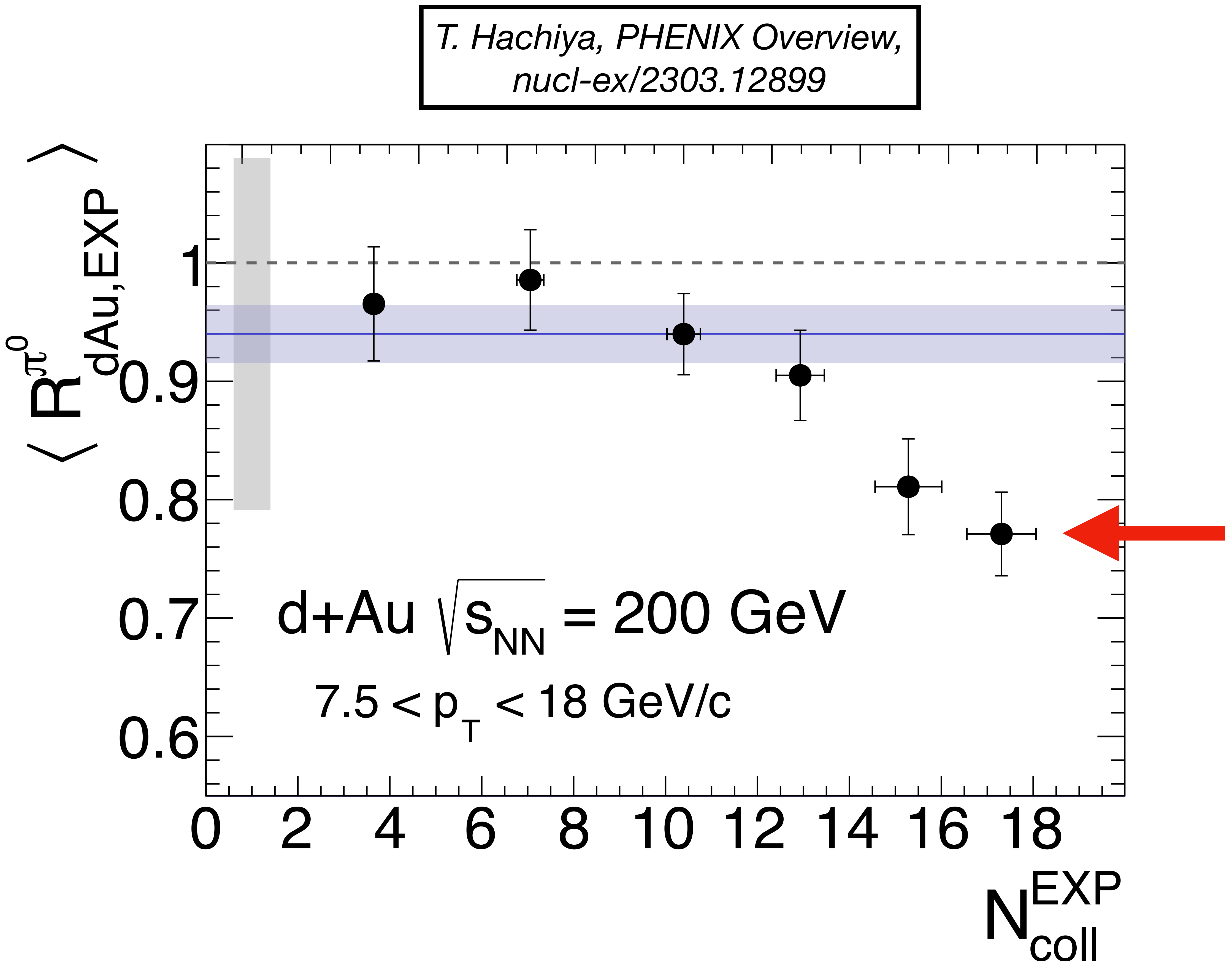
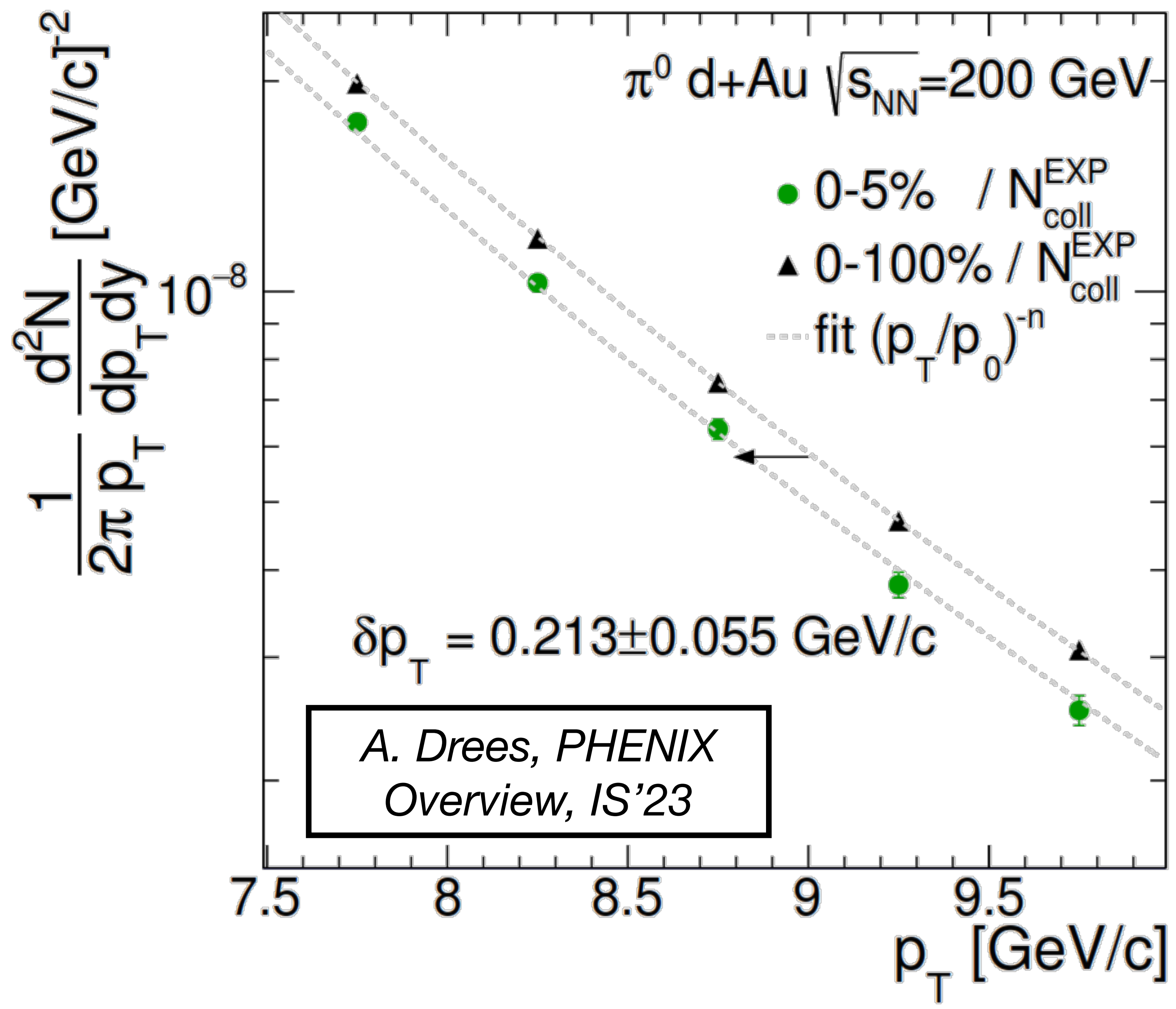
HP2024 NAGASAKI

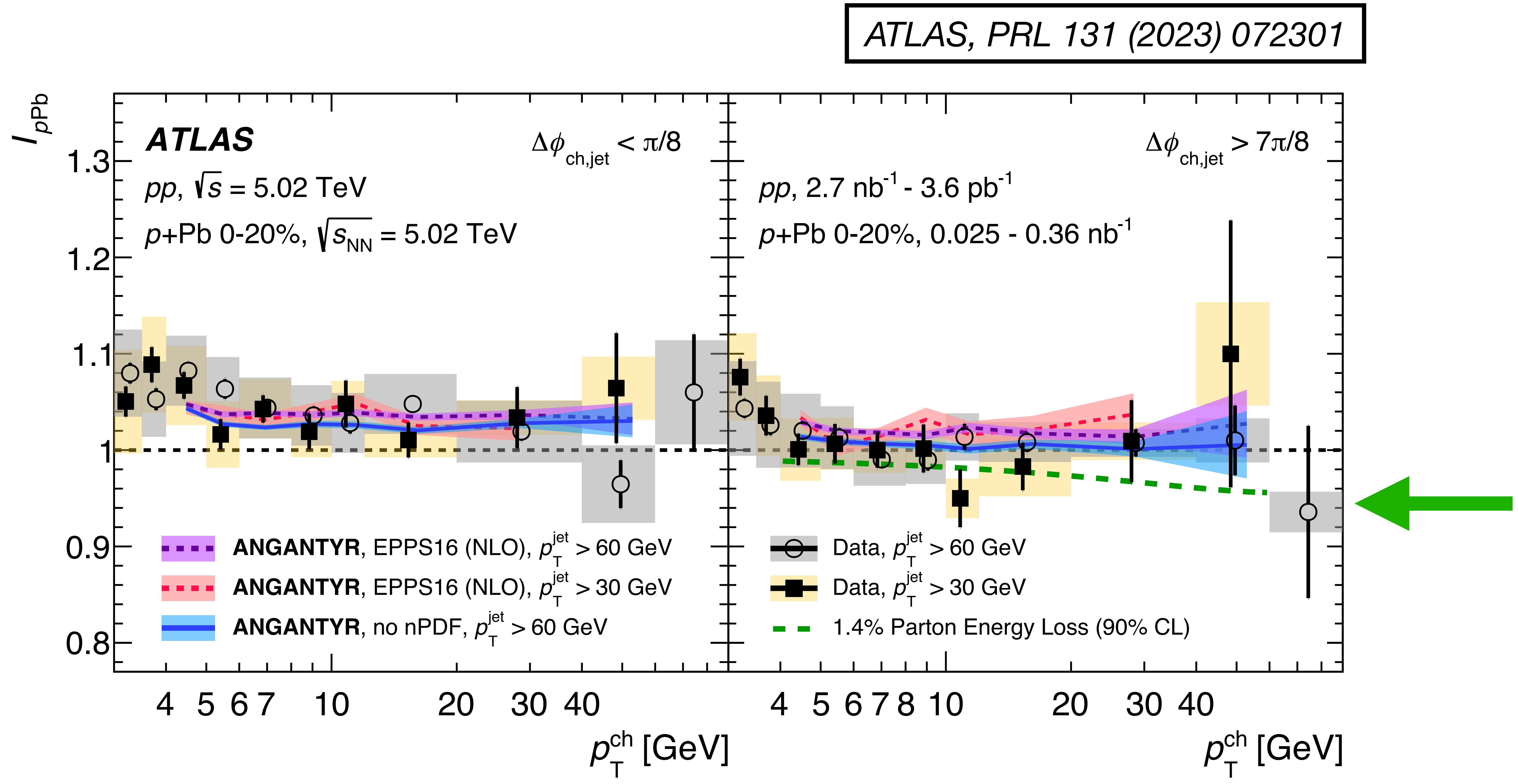
Measurement of π^0/γ modification in *d*+Au



- PHENIX measures the double ratio $R_{\mathrm{dAu}}(\pi^0)/R_{\mathrm{dAu}}(\gamma_{\mathrm{dir}})$ in small systems
  - ➡ Argument: the normalization to the number of photons takes out **all** centrality bias effects, and any modification is a **final-state effect**
- For centrality averaged events,
  $R_{\mathrm{dAu}}(\pi^0)/R_{\mathrm{dAu}}(\gamma_{\mathrm{dir}}) = 0.92 \pm 0.02\ (\mathrm{stat})\ \pm 0.15\ (\mathrm{syst})$
- In the **most central** events,
  $R_{\mathrm{dAu}}(\pi^0)/R_{\mathrm{dAu}}(\gamma_{\mathrm{dir}}) = 0.77 \pm 0.03\ (\mathrm{stat})\ \pm 0.13\ (\mathrm{syst})$

Context with other small systems measurements



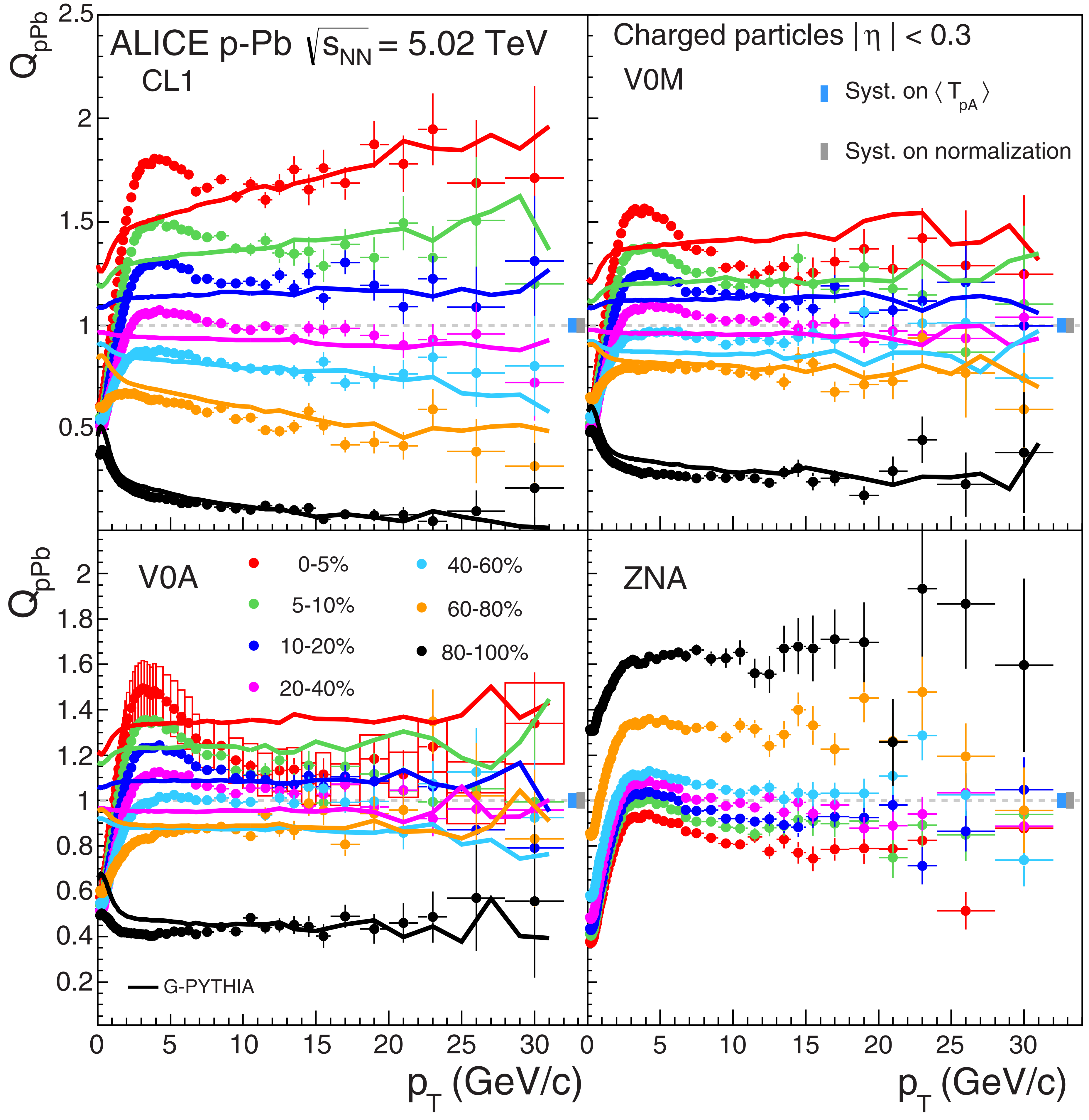


The PHENIX results would require $\delta p_T / p_T \approx$ 1-2% in 0-5% *d*+Au collisions

At LHC energies, limit of $\delta p_T / p_T < 1.4\%$ at 90% CL (in 0-20% ZDC-selected *p*+Pb events)

Well-known “multiplicity” bias

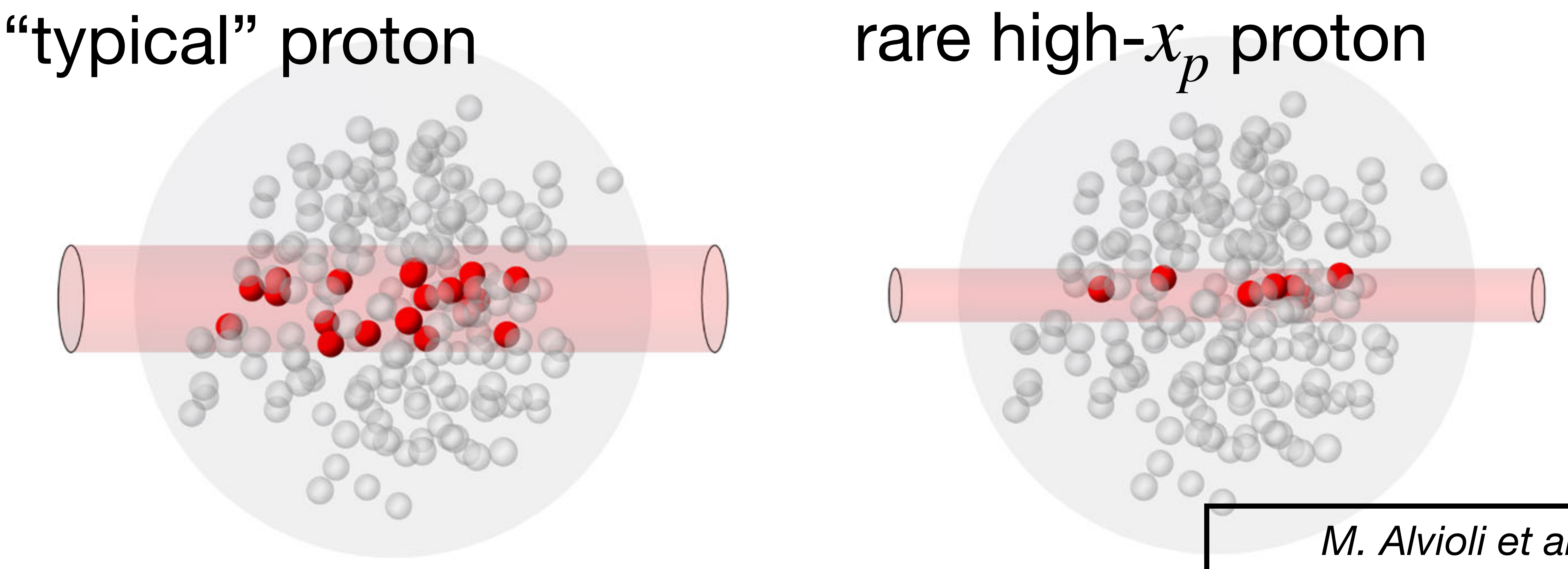
- Increased event activity in the presence of a hard-scattering
  - ➡ overestimate hard scattering yields in high-multiplicity events, underestimate them in low-multiplicity events
- This particular bias does not have a strong process (γ_{dir} vs. π^0) or kinematic dependence
  - ➡ the PHENIX strategy likely eliminates this particular bias ✅



ALICE, PRC 91 (2015) 064905
+ much work by PHENIX, Steinberg, Morsch, Loizides, others

A different bias for extremely high-x_p process

- For hard-scattering processes with Bjorken-*x* in the proton, $x_p \gtrsim 0.1$:
  - ➡ data at RHIC and LHC: there is an **anti**-correlation between increasing x_p and the backward multiplicity (i.e. in the nucleus-direction)
  - ➡ i.e. relative movement of events from “central” to “peripheral” category
  - ➡ observed indirectly as an $R_{\mathrm{CP}} < 1$

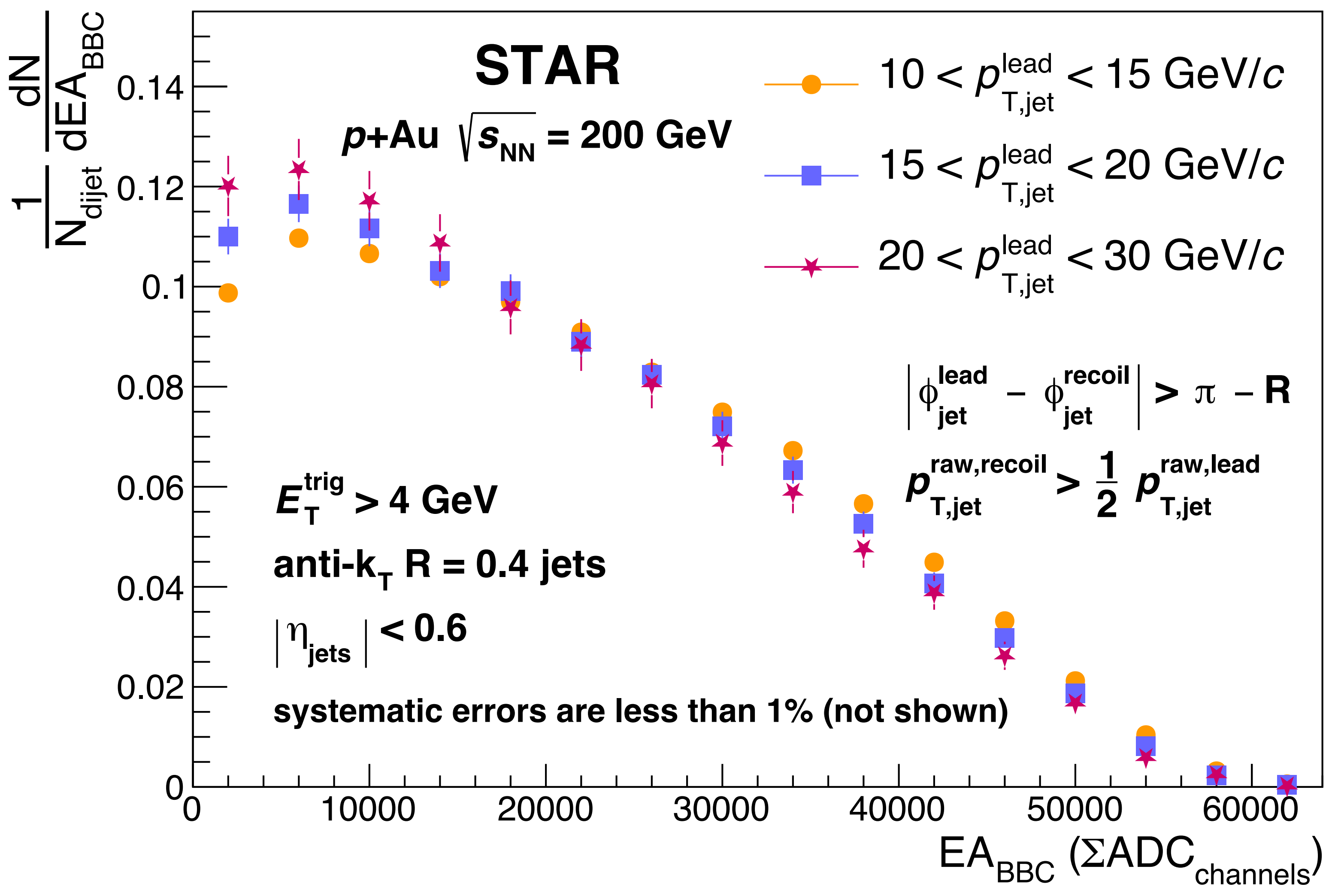


M. Alvioli et al
PRD 98 (2018) 071502(R)

- One compelling explanation: **proton color fluctuations**
  - ➡ protons with a large-x_p parton are quite different than “average” protons, and strike fewer nucleons in the nucleus

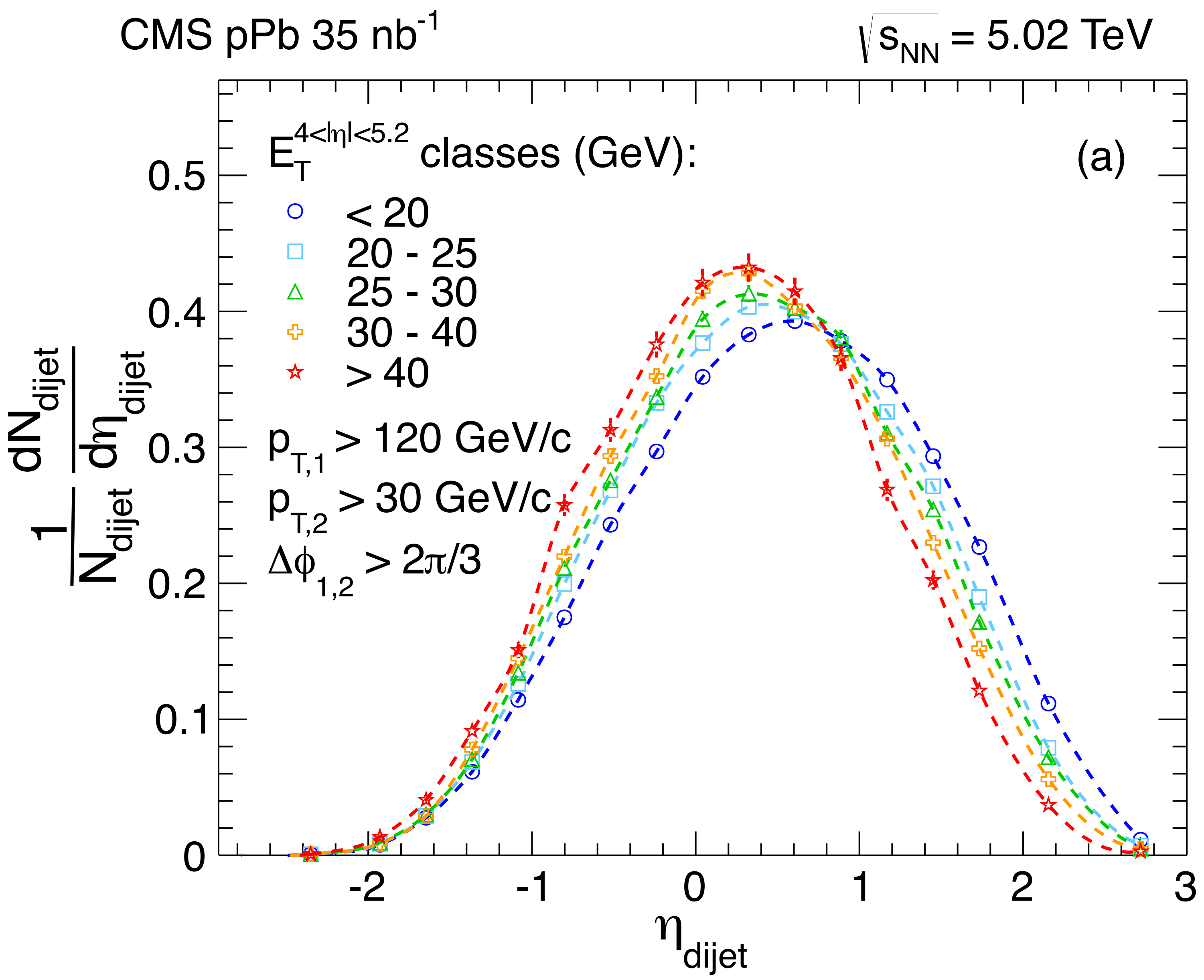
Evidence for x_p-UE^{backward} anti-correlation

I. Mooney, STAR Overview
nucl-ex/2404.08784



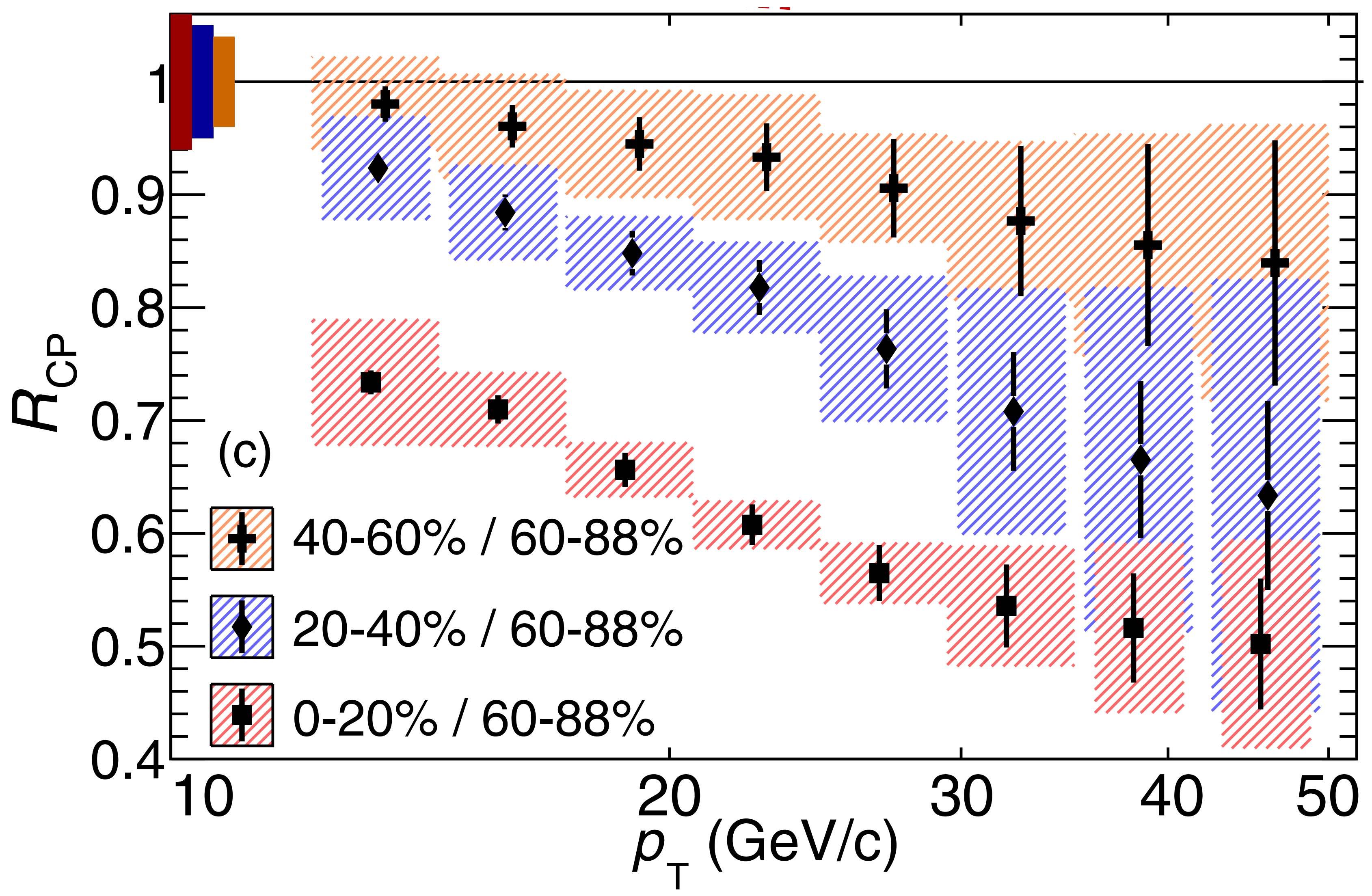
Systematic shift of multiplicity distribution under **increasingly higher p_T^{lead}** selections

CMS, EPJC 74 (2014) 2951



Strong UE-dependence of the yield of jets, **increasing with more forward** (higher-x_p) selections

PHENIX, PRL 116 (2016) 122301



Strongly suppressed R_{CP} for jets, **increasing with p_T**

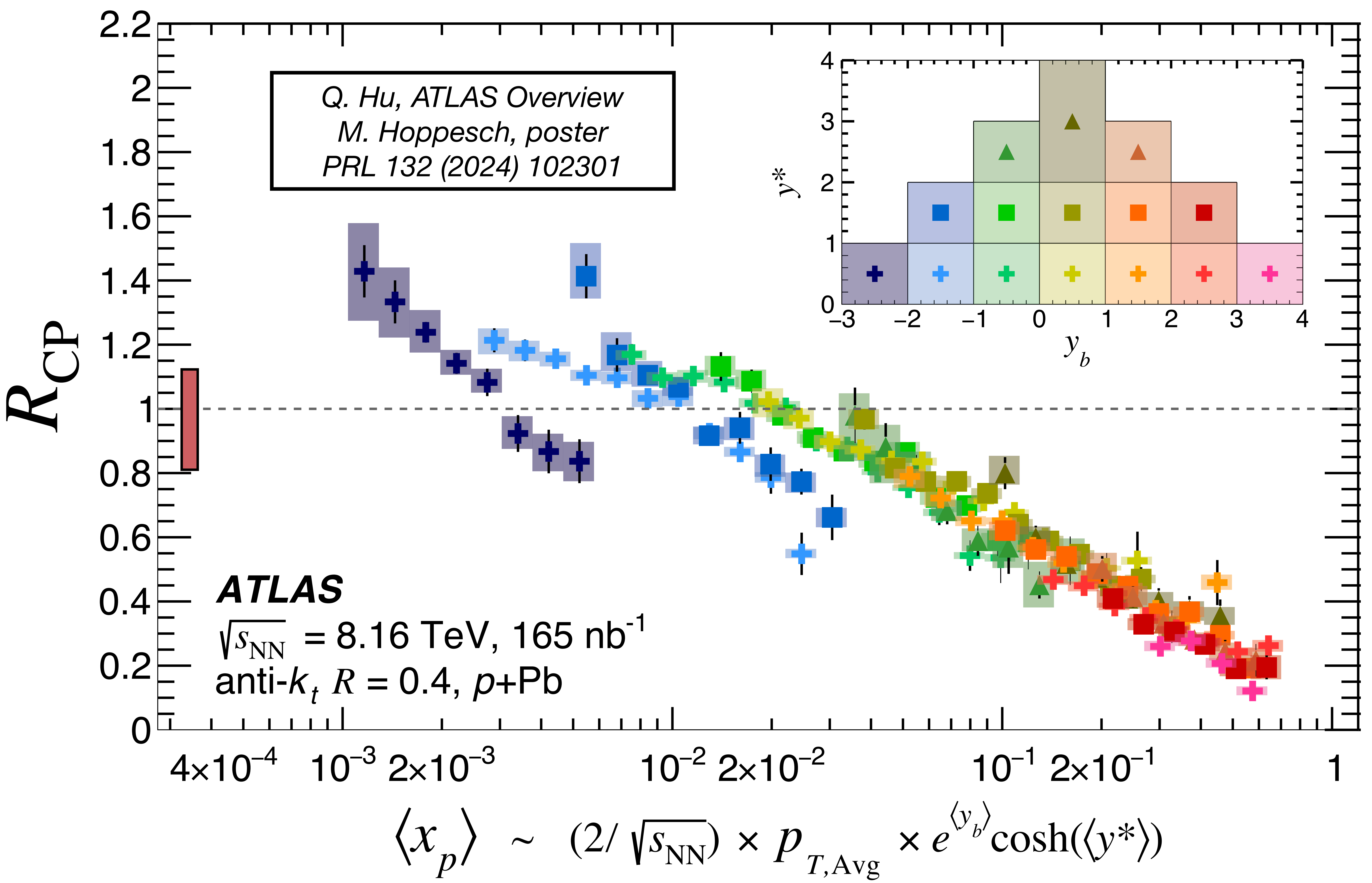
Evidence for x_p-UE$^{\text{backward}}$ anti-correlation

- Recent ATLAS measurement of the R_{CP} for dijet events

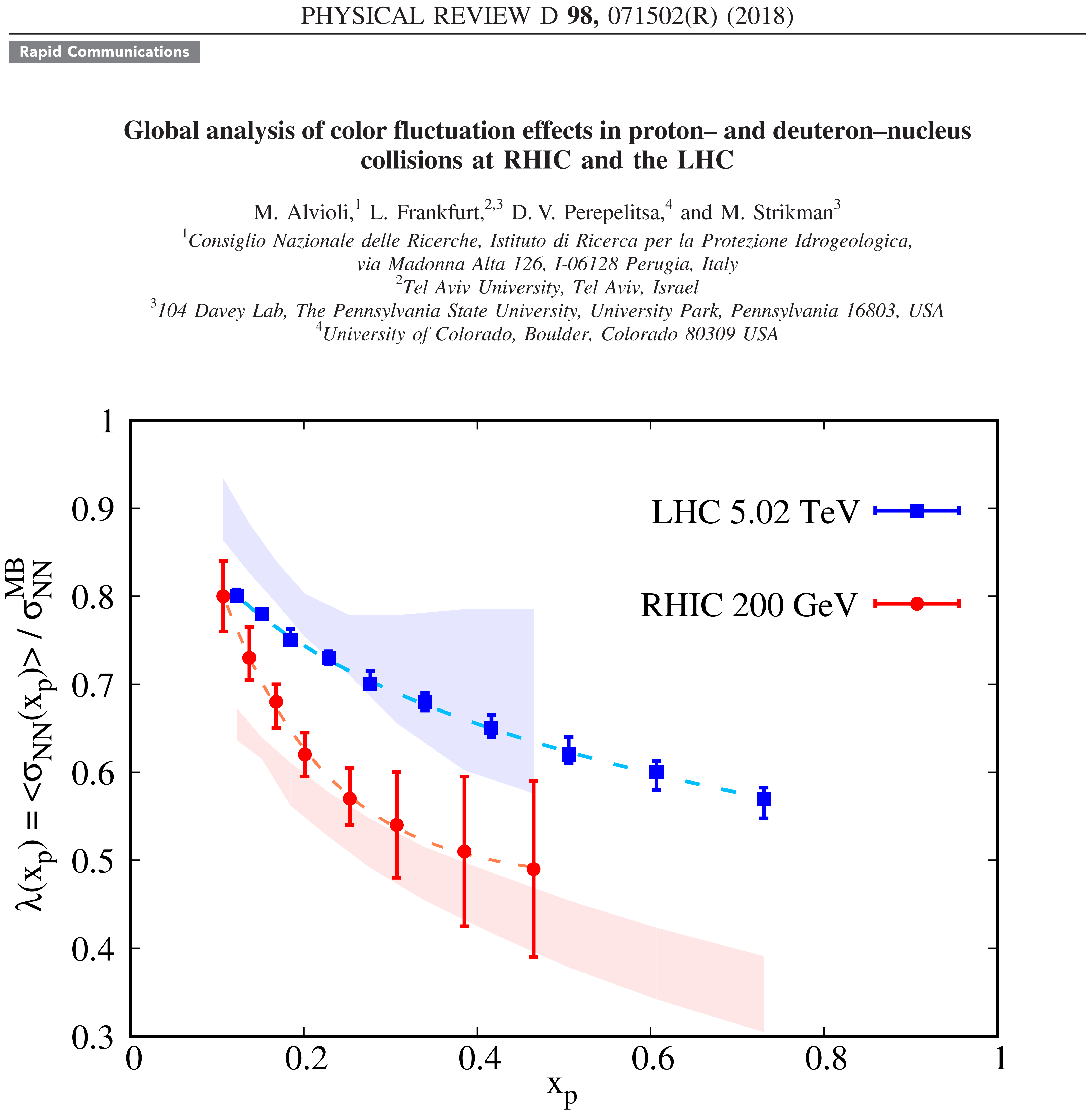
  ➡ event-level parton kinematics (x_p, x_A, Q^2) estimated via the dijet kinematics

- Modification is (mostly) a universal function just of x_{p}

  ➡ strongly supportive of color fluctuation picture

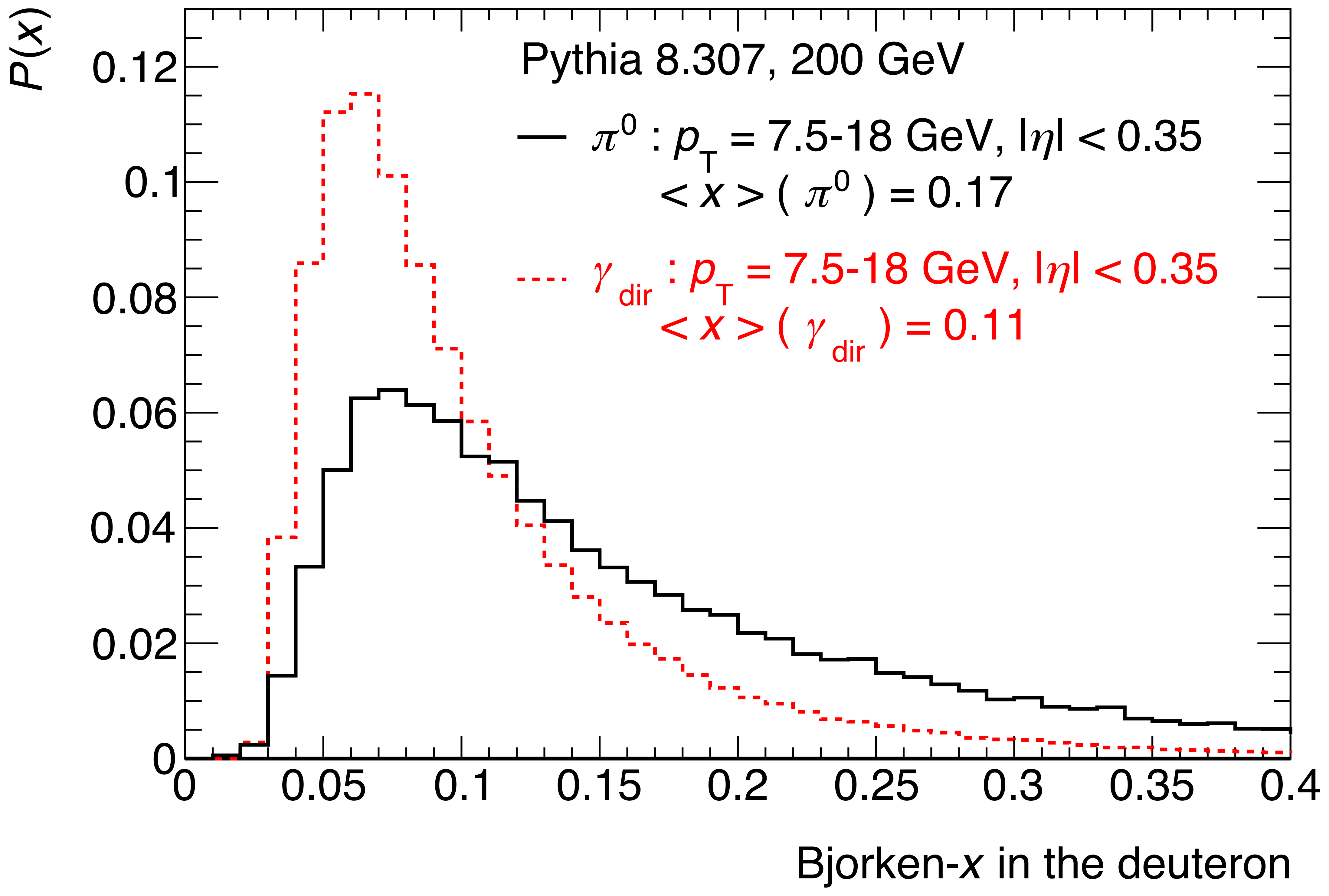


Quantifying color fluctuation effects



- An analysis of earlier ATLAS & PHENIX data quantitatively extracted the magnitude of the proton's "shrinking"
  - ➡ The effective nucleon-nucleon cross-section for a proton depleted by a high-x_p parton is $\lambda(x_p) \times \sigma_{NN}$
  - ➡ $\lambda(x_p) < 1$ and decreases quickly with x_p
  - ➡ I use the results of this Color Fluctuation Model (CFM) with **no changes to the parameters or introduction of additional physics**

x_p ranges probed by PHENIX measurement

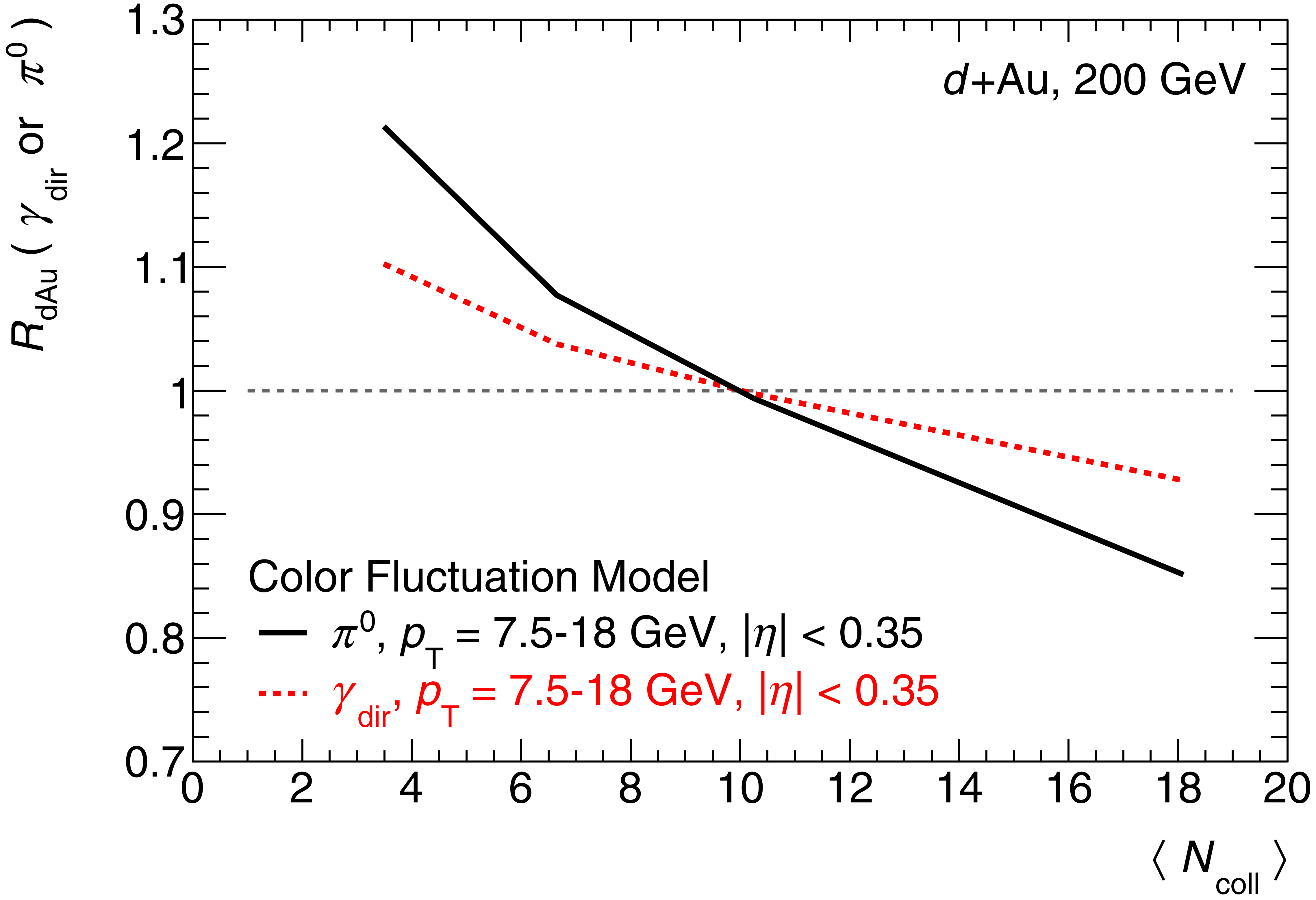


- MC simulation, matching specific PHENIX acceptance & kinematics
- For **direct photons**, typical x_p values probed are $x_p \sim p_T^{\gamma}/E_{\mathrm{beam}} \sim 0.11$
- However, **neutral pions** carry only a fraction of the fragmenting parton's p_{T}

➡ $\langle x_{\mathrm{p}} \rangle \approx 0.17$, with long tail to large-x_p values (28% from $x_p > 0.2$)

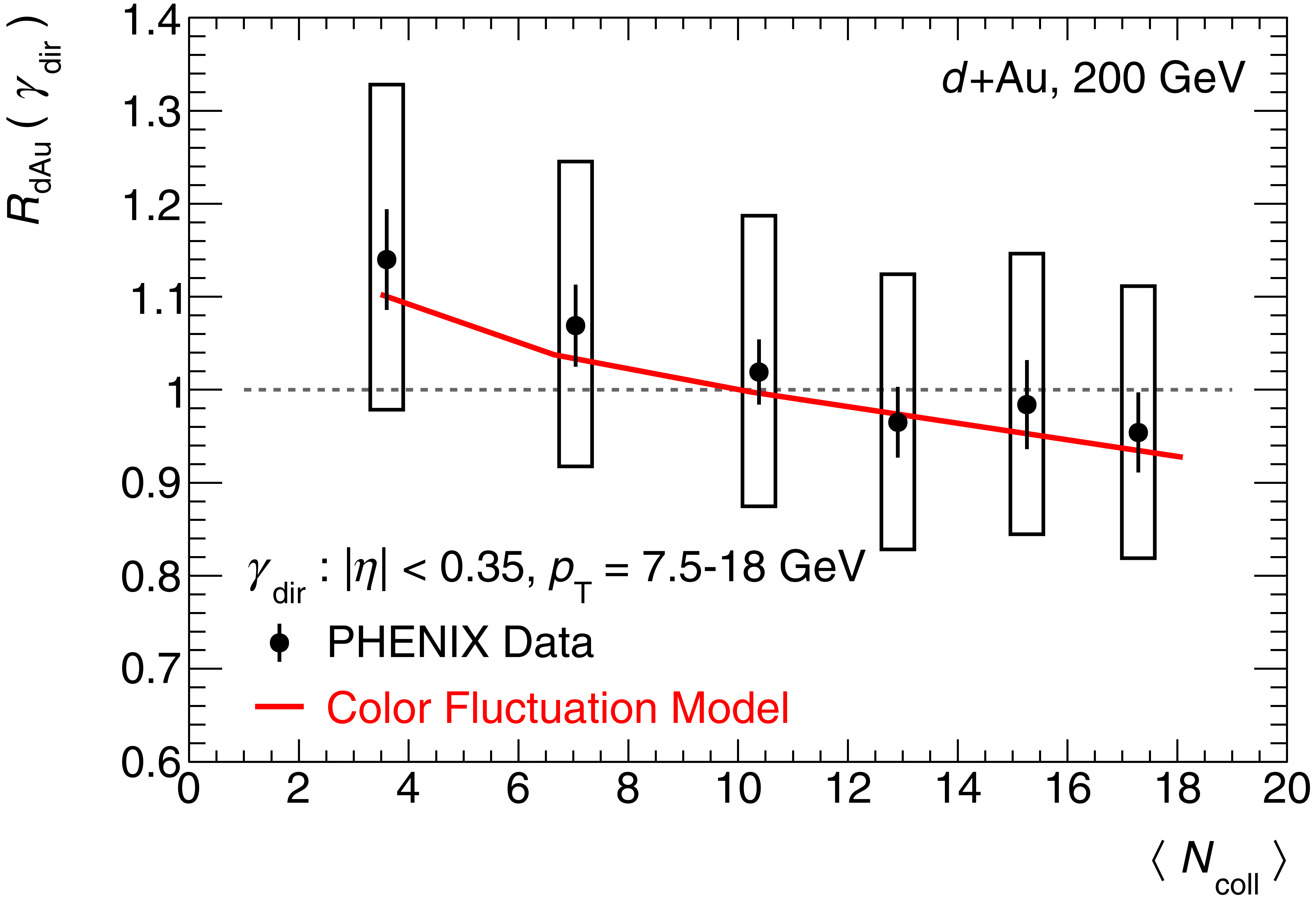
➡ they will incur stronger CFM effects

Color fluctuation effect for γ_{dir} vs. π^0



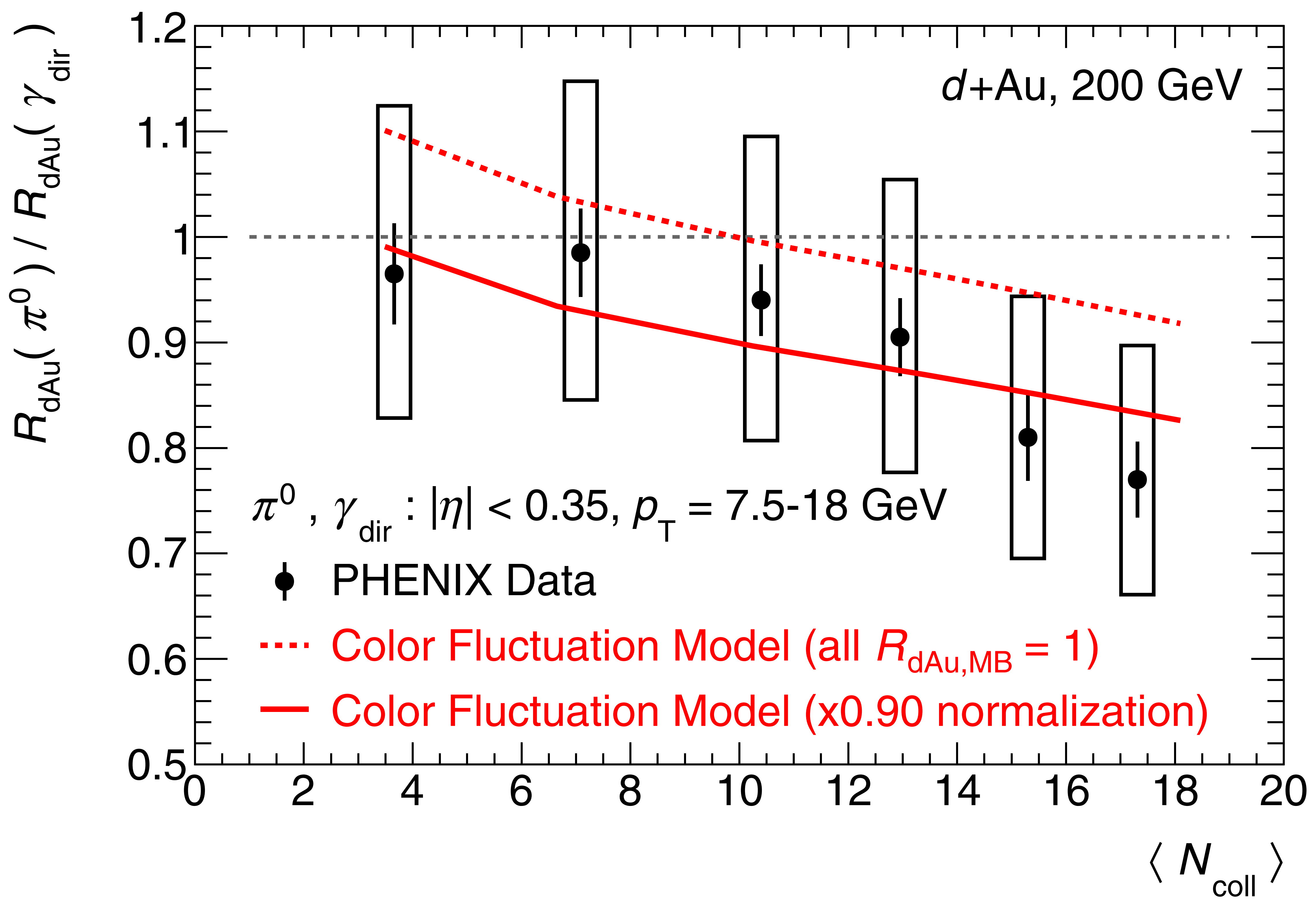
- I apply the CFM to these x_{p} distributions and the PHENIX Glauber+NBD centrality model
  - ➡ The CFM has no physics to change the minimum-bias R_{dAu} — all results are only relative enhancements/suppressions
- Note the stronger effect for **pions** (higher $\langle x_{\mathrm{p}} \rangle$) than **direct photons** (lower $\langle x_{\mathrm{p}} \rangle$)
  - ➡ These **only partially cancel** - the PHENIX $\pi^0/\gamma_{\mathrm{dir}}$ observable is sensitive to this x_p-dependent effect **!**

Benchmarking: direct photon R_{dAu}



- Compare the CFM to PHENIX direct photon R_{dAu} data vs. centrality
  - ➡ The data has a modest enhancement at low N_{coll}, suppression at high N_{coll}, and min-bias $R_{\mathrm{dAu}} \approx 1$
- The **Color Fluctuation Model** predicts a modification pattern exactly like this
  - ➡ The predicted modifications are modest since x_p is not too high

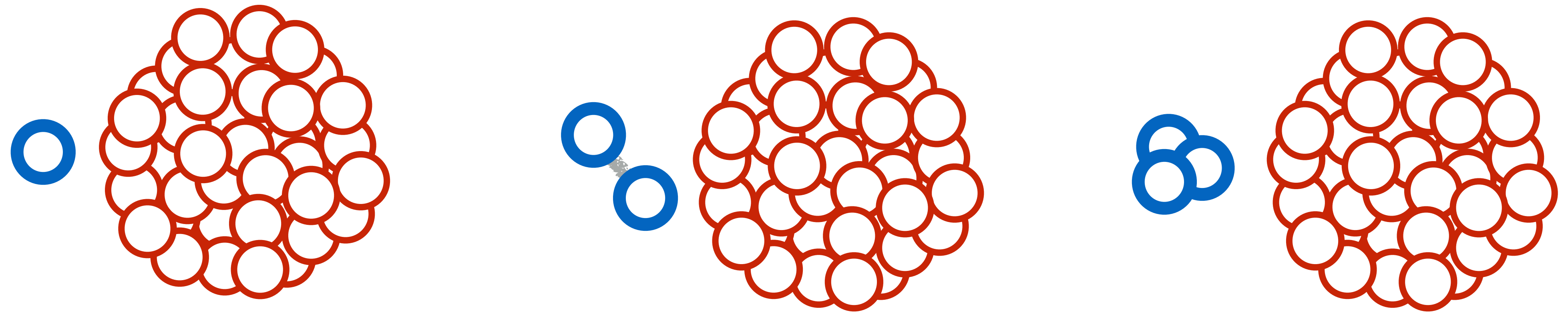
Comparison to $\pi^0/\gamma_{\rm dir}$ data



- Compare the CFM to the PHENIX $R_{\rm dAu}(\pi^0)/R_{\rm dAu}(\gamma_{\rm dir})$ vs. $N_{\rm coll}$ results
  - ➡ The dashed red line is the CFM assuming all min-bias $R_{\rm dAu} = 1$
  - ➡ But the PHENIX measurement in MB has $R_{\rm dAu}(\pi^0)/R_{\rm dAu}(\gamma_{\rm dir}) = 0.92 \pm 0.02\ ({\rm stat})\ \ \pm 0.15\ ({\rm syst})$
- The solid red line is the CFM with x0.90 MB normalization to better match what is observed in data
  - ➡ Great agreement vs. $N_{\rm coll}$ without any need for final-state physics effects!

How to take out the color fluctuation effect?

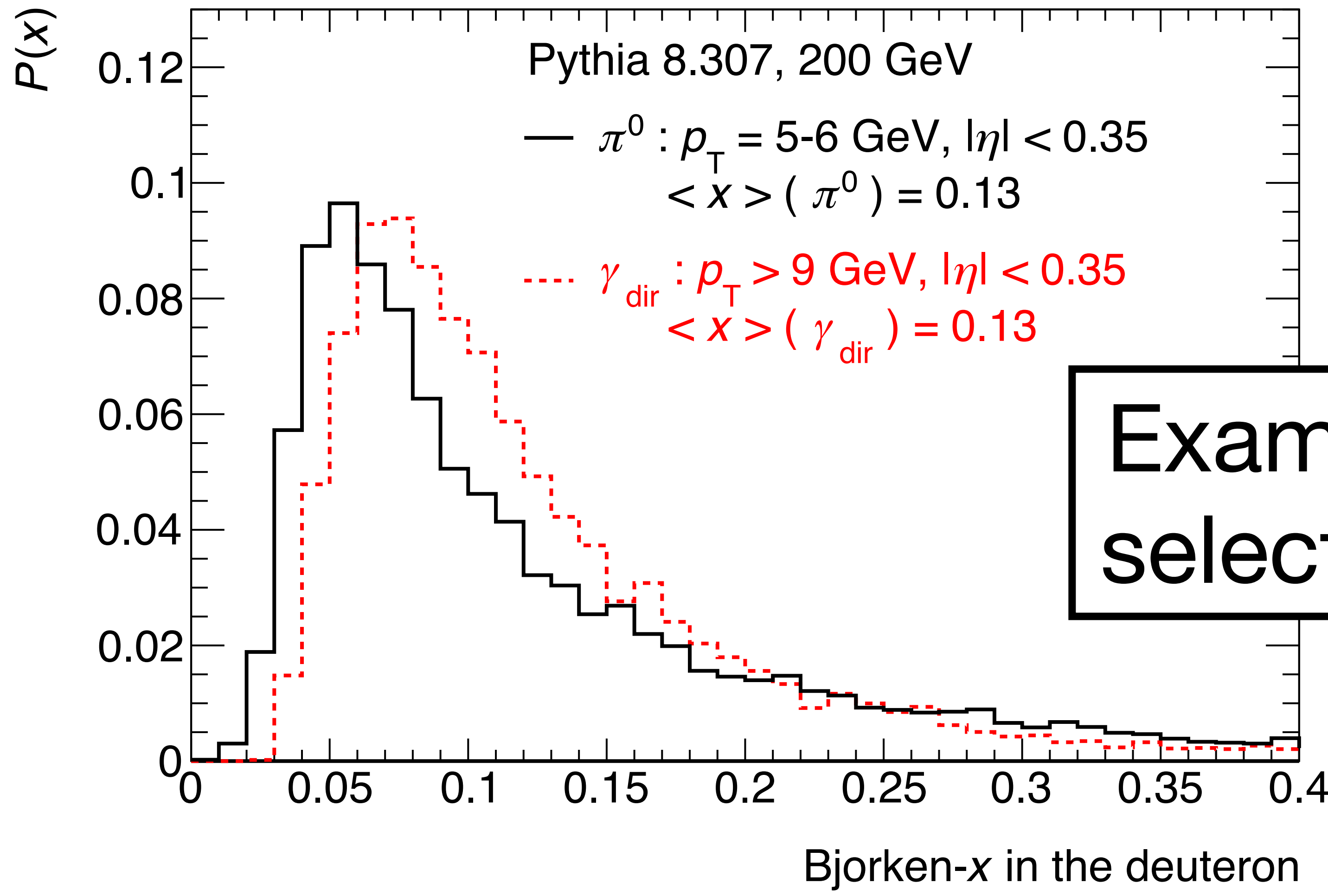
➡ Change projectile size



D. McGlinchey et al
PRC 94 (2016) 024915

- **Final-state energy loss** should **increase** from *p*+Au to *d*+Au to ^{3}He+Au, etc.
- The impact of **color fluctuations** in one nucleon is **diluted** as one increases the projectile size

➡ Choose matching $<x_p>$ selections

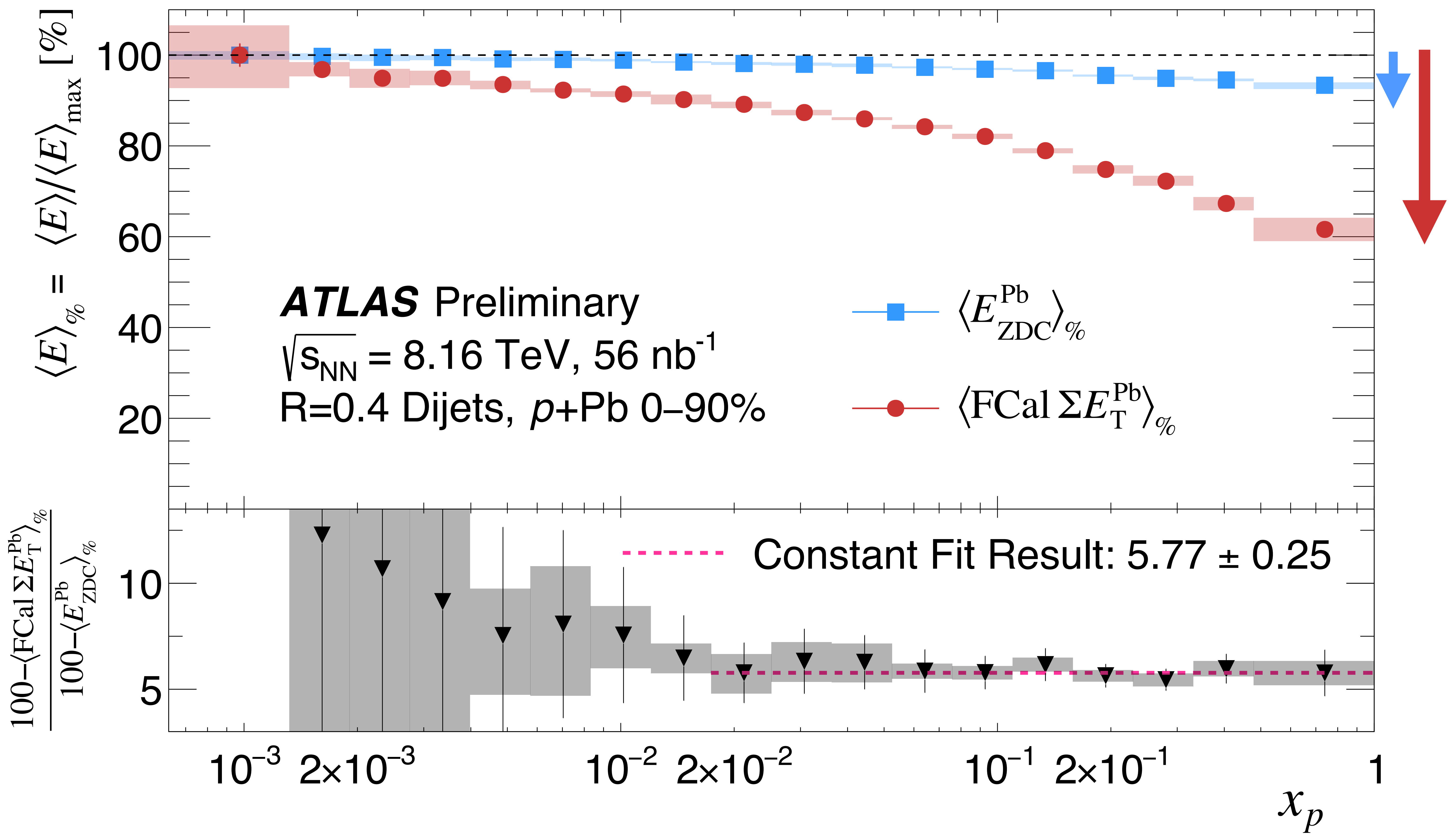


Example selection

- Example ranges of p_T^{γ} and $p_T^{\pi^0}$ with similar sampled x_p distributions
- Use γ's and full jets in, e.g., sPHENIX *p*+Au

sPHENIX

Spectator neutrons are much less biased



Q. Hu, ATLAS Overview
M. Hoppesch, poster

Study by ATLAS presented at HP'24 on sensitivity of FCal vs. ZDC to large-x_p selections

Major bias to the **backward multiplicity** from a high-x_p process

Bias to the **spectator neutrons** from a high-x_p process is smaller by a factor of 6!

Downside: loss of sensitivity to very central events

Conclusion

- Some centrality bias effects are process- or kinematics-dependent

- The PHENIX $\pi^0/\gamma_{\rm dir}$ ratio is moderately sensitive to color fluctuation effects, due to the different x_p distributions

  ➡ the data are quantitatively reproduced by a previous Color Fluctuation Model with no new parameters or retuning

  ➡ **no additional final-state effects needed to explain the PHENIX data**

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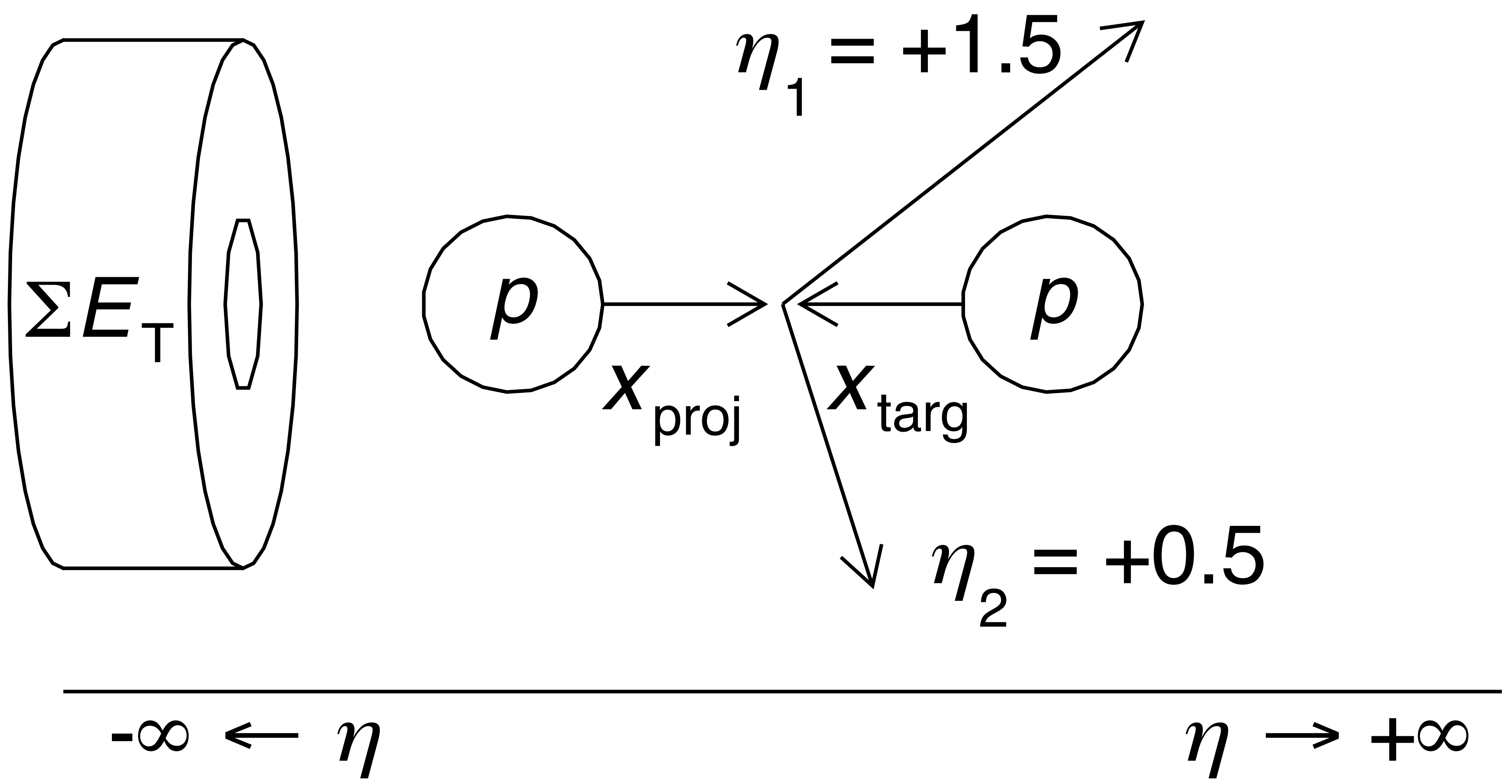
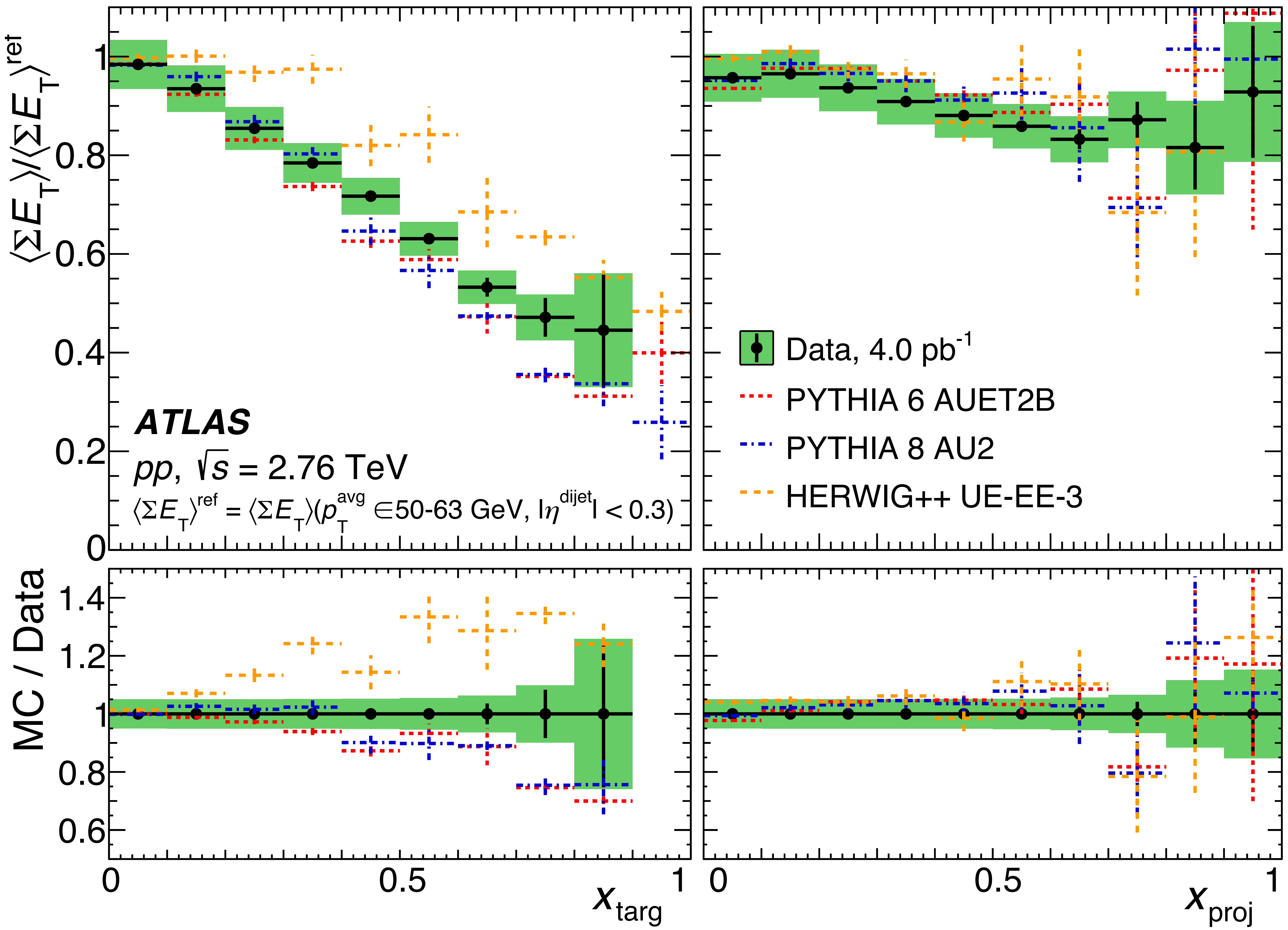
<u>More information</u>:
DVP, PRC 110 (2024) L011901
nucl-th/2404.17660

Is there a x_p-UE$^{\text{backward}}$ anti-correlation just in *p*+*p* collisions?

➡ **Not really.**

ATLAS, PLB 756 (2016) 10





Increasing *x* in the proton heading **towards** the multiplicity detector

Increasing *x* in the proton heading **away** from the multiplicity detector (this is where the signal would be)