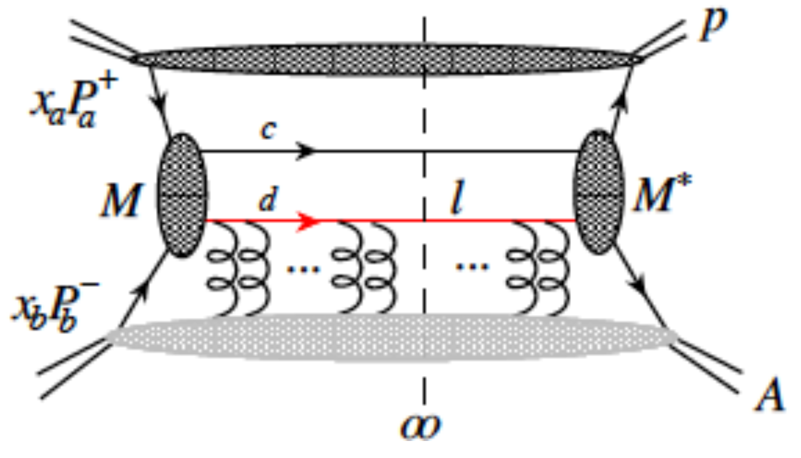
Assessing di-hadron measurements at RHIC and the LHC as signals of saturation

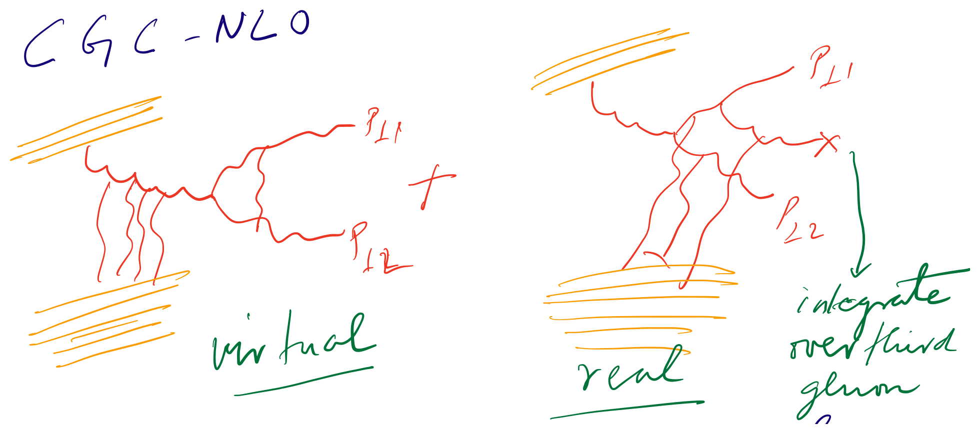
Dennis V. Perepelitsa (University of Colorado Boulder)
22 August 2024
INT Program 24-2b: Heavy Ion Physics in the EIC Era

INSTITUTE for NUCLEAR THEORY

Question for this INT Program

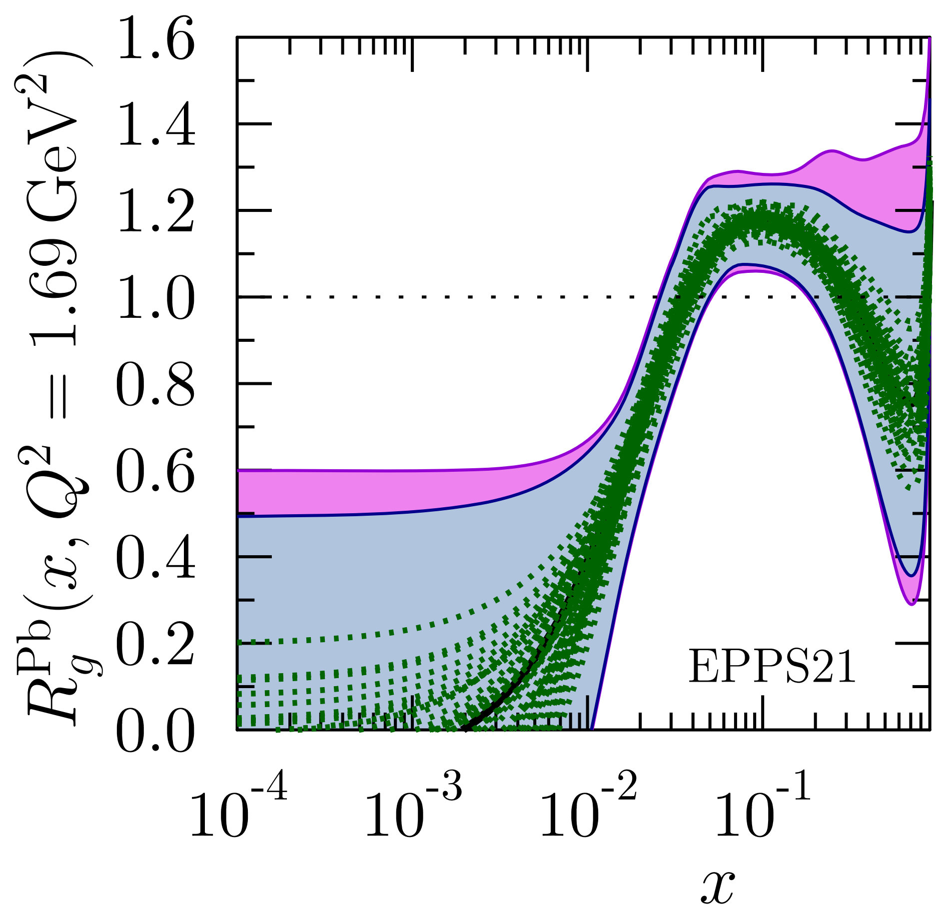


Coherent multiple scattering



Glasma diagram (courtesy Raju Venugopalan)

dynamical description of effects in the initial state of the cold nucleus	⟷ ?	pQCD + collinear factorization + nuclear PDF modification universal in (x, Q^2)

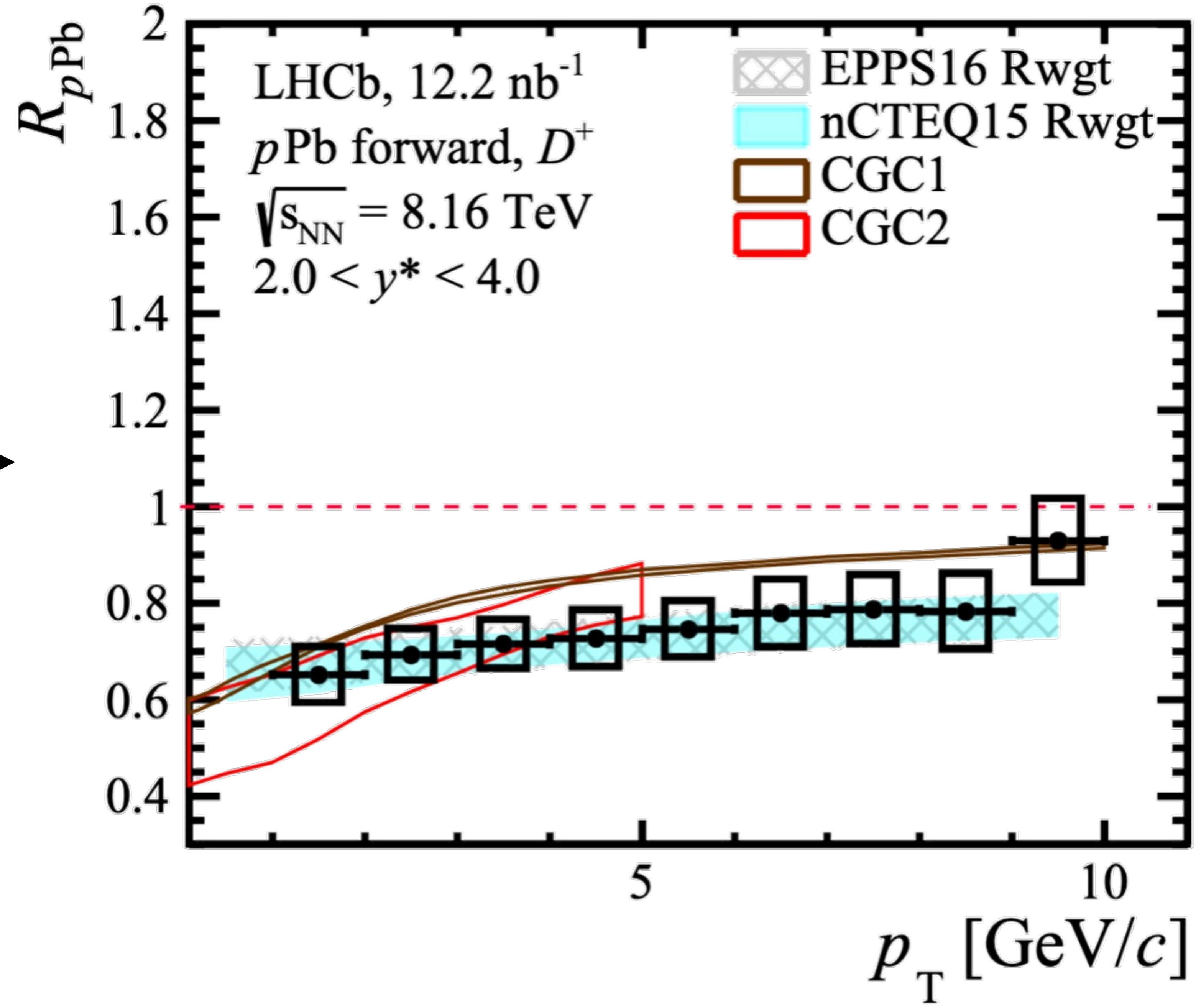


Gluon density modification in nuclei

- Two different approaches to describing effects in (semi-)hard processes in *p*+A collisions.
- Are they describing distinct phenomena? Or different ways of capturing the same physics?
- Specific question: **can an "ordinary" pQCD+nPDF picture describe recent di-hadron/ jet saturation measurements at RHIC and LHC?**
  - ➡ i.e. does the way we extract nPDFs partially encode non-linear QCD phenomena?

Question for this INT Program

Matt Durham (Tues.)



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- Specific question: **can an "ordinary" pQCD+nPDF picture describe recent di-hadron/ jet saturation measurements at RHIC and LHC?**
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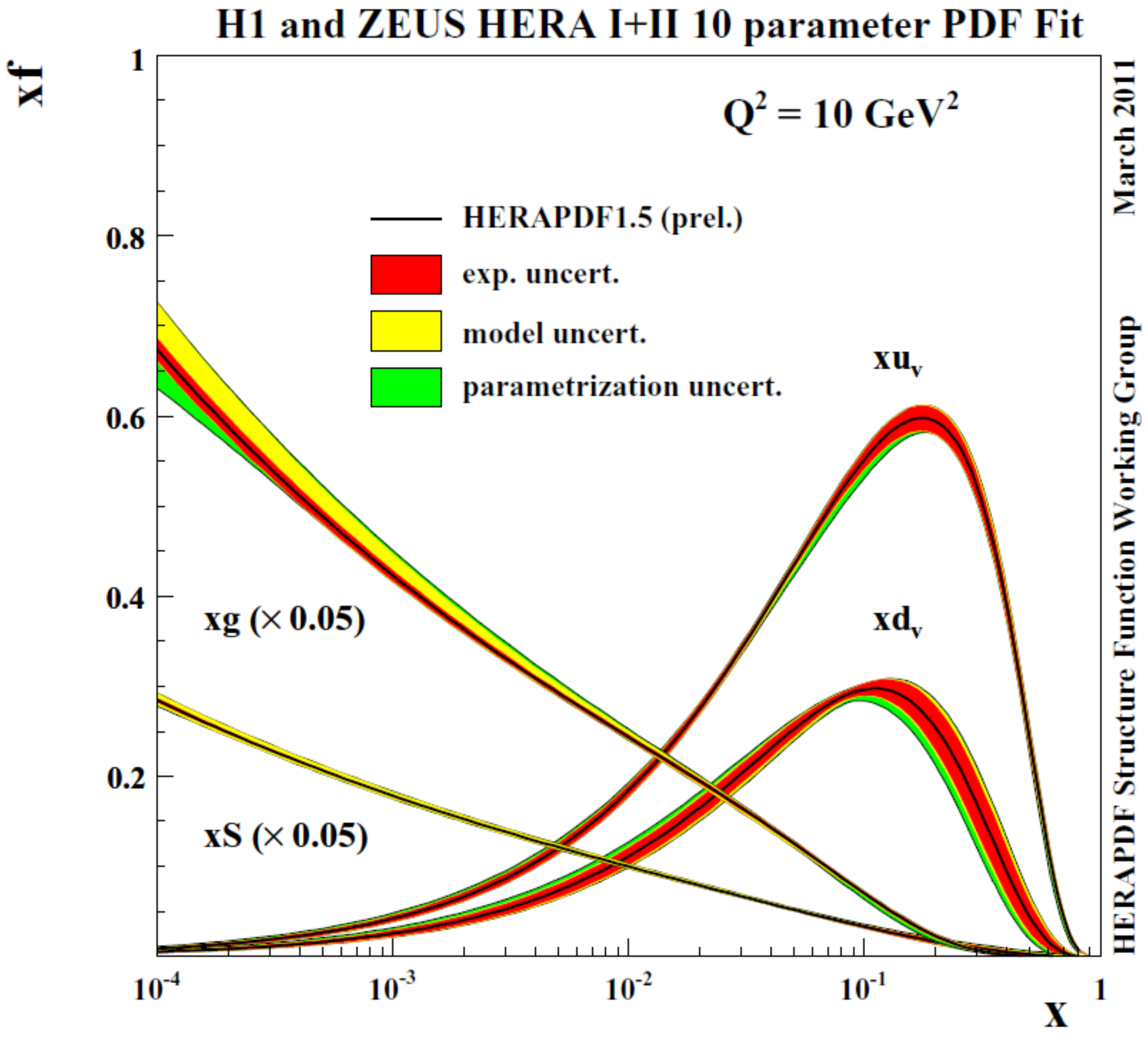
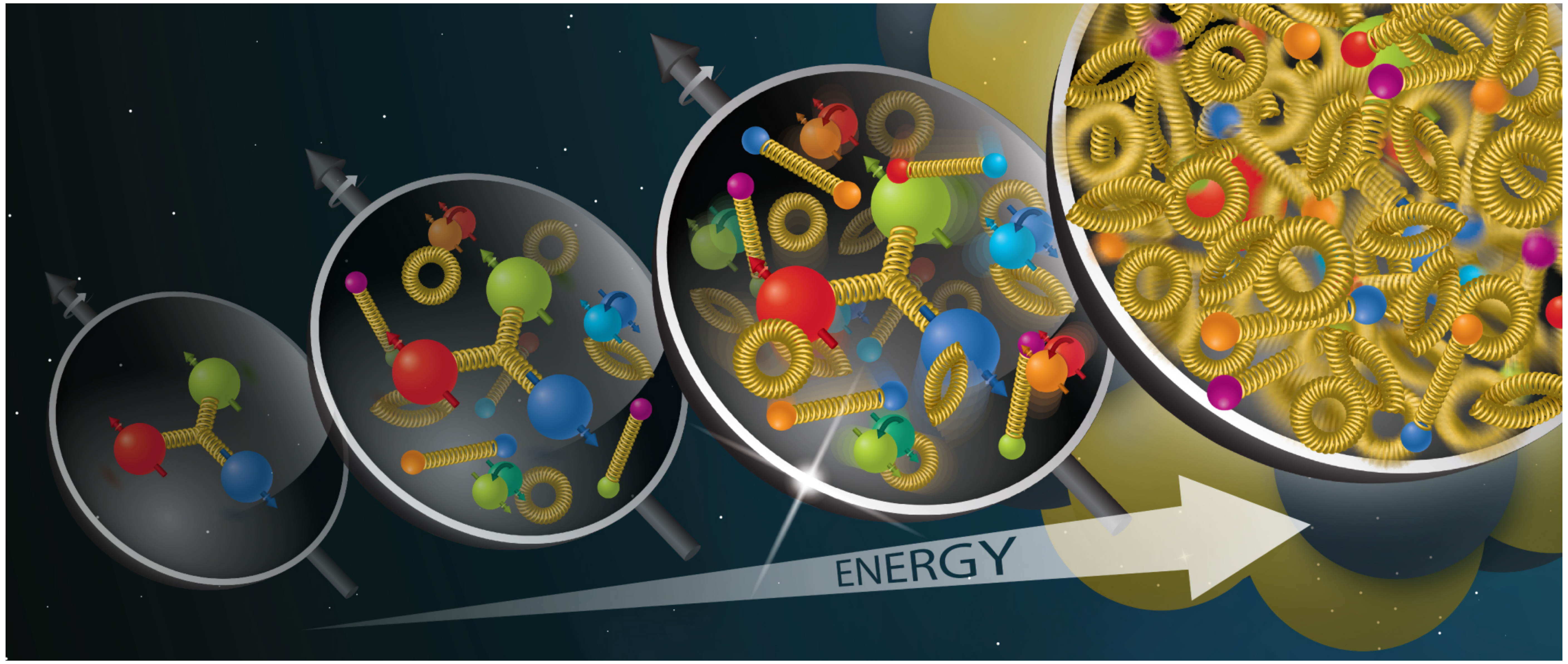
Saturated gluon matter



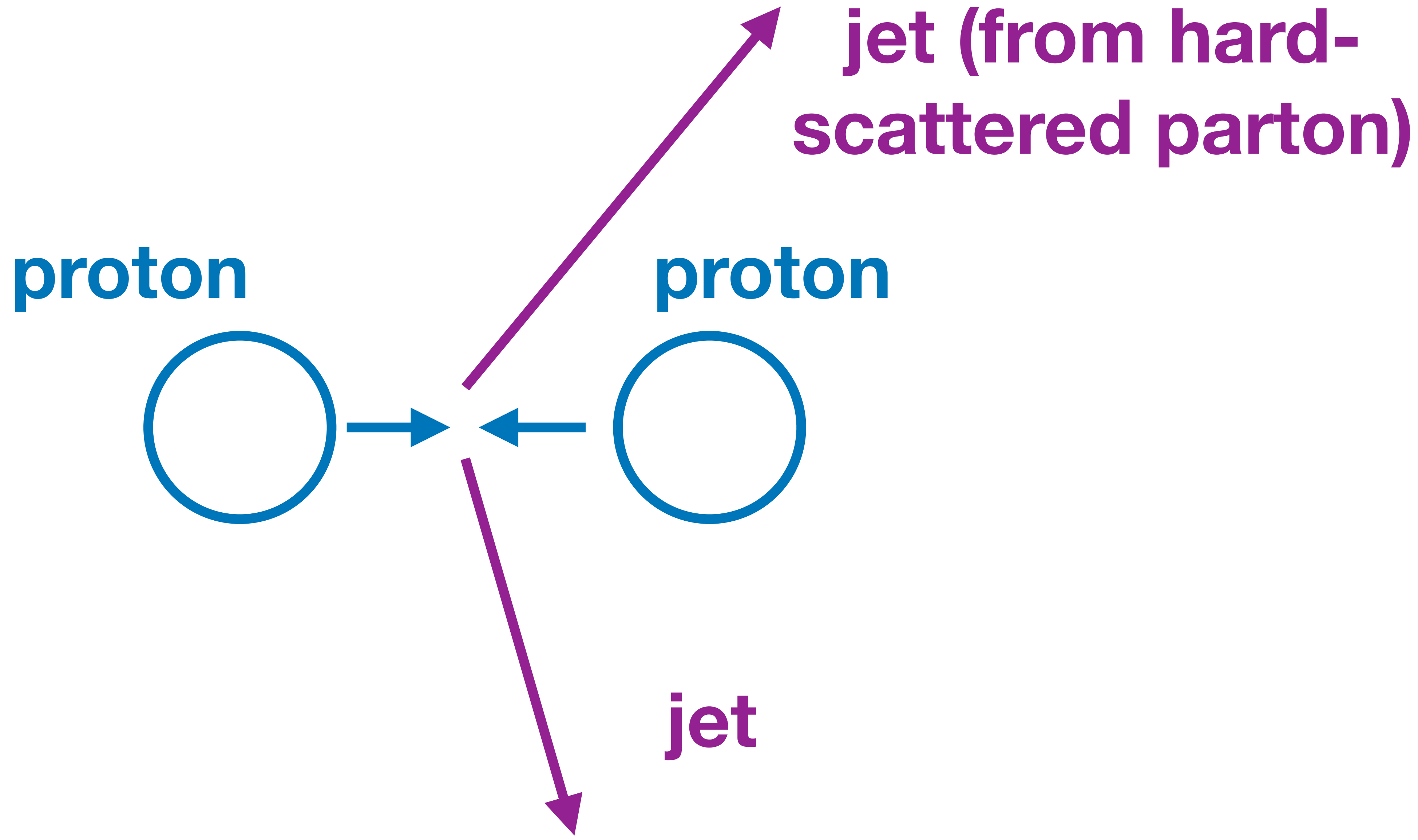


Rising gluon density will eventually violate unitarity — non-linear dynamics **must** take over

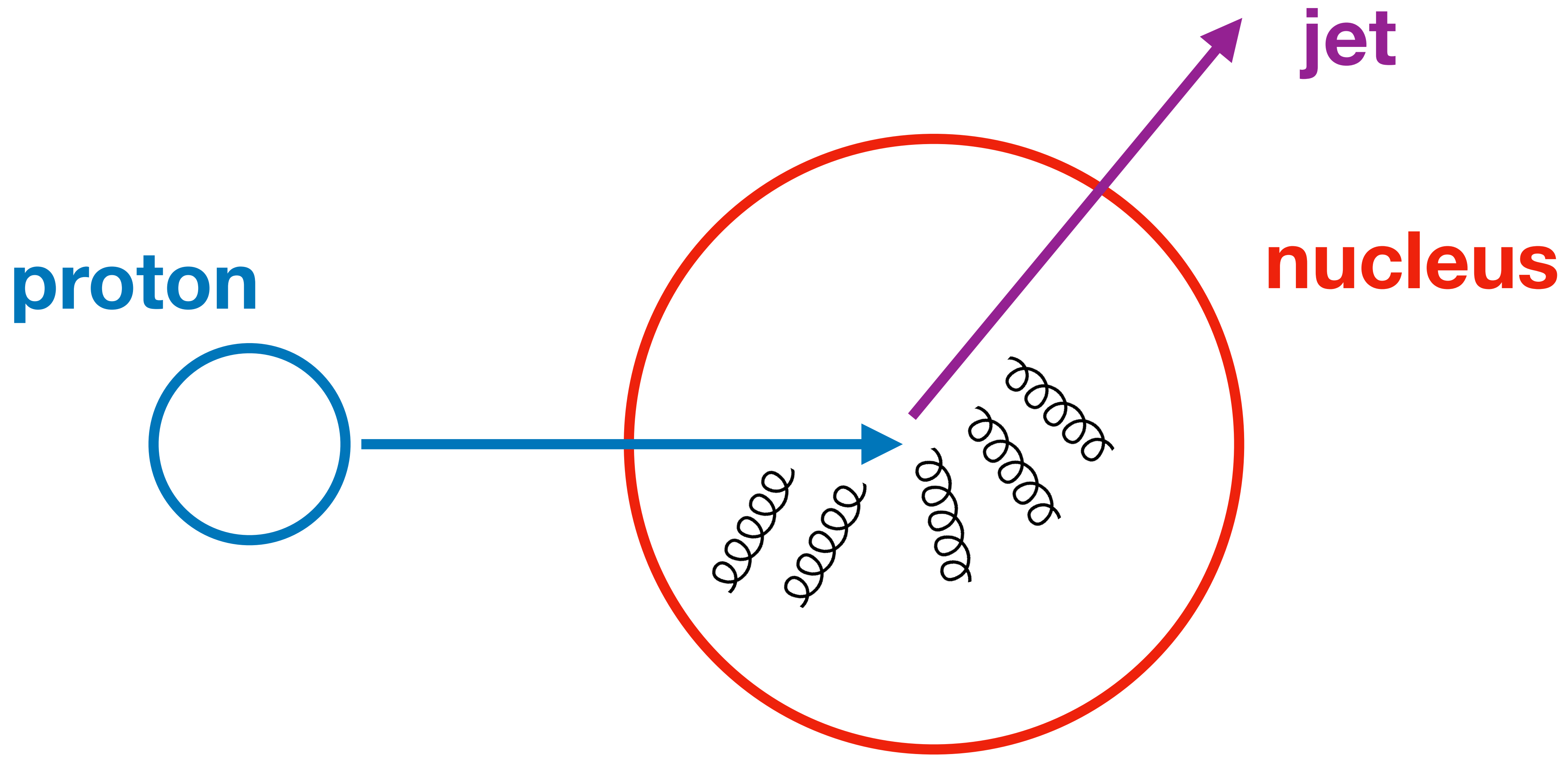
Novel domain of QCD inside all hadrons — but most accessible in heavy nuclei

What are the observable consequences in *p*+A and *e*+A collisions?

Mono-jet production in saturated nuclei



Ordinary pQCD di-jet production in, e.g., proton-proton collisions



Parton in **proton** interacts coherently with **saturated gluons** in nucleus

➡ forward "**mono-jet**"

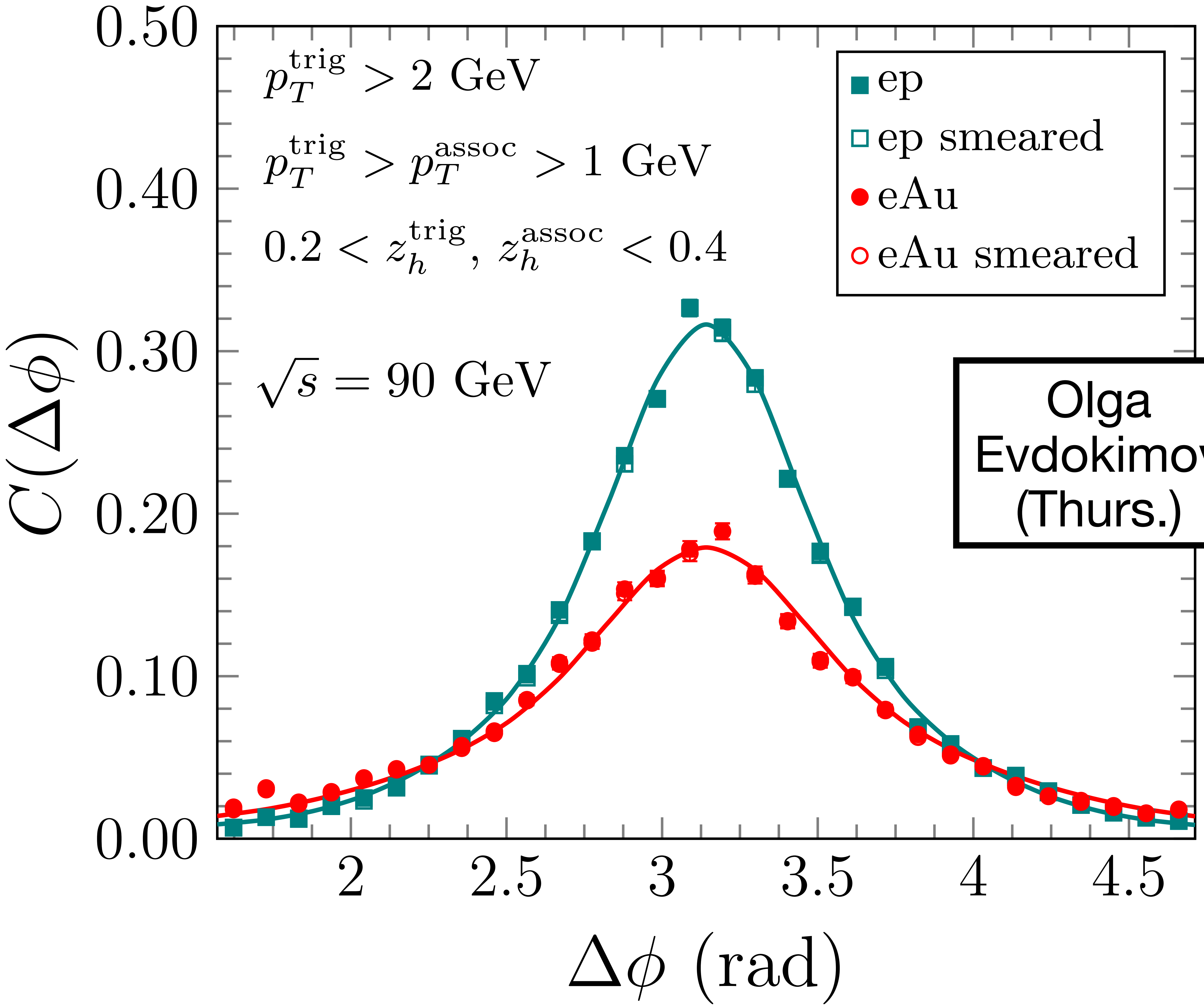
Di-hadron correlations at EIC

Early EIC measurement, seen as one of several potential “smoking guns” for saturation

Fine control on parton-level kinematics, strong expected signal

Note the expected (1) decrease in per-trigger yield, and (2) broadening of the remaining correlation function

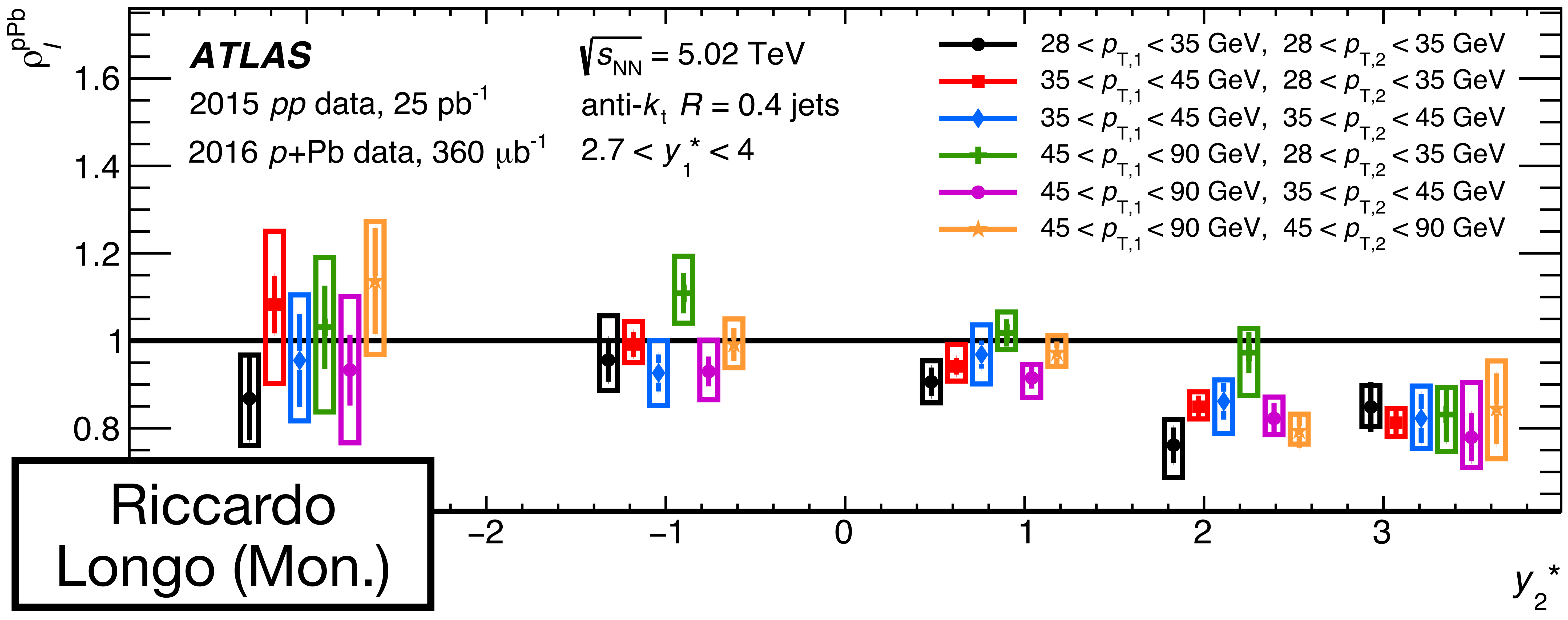
EIC Yellow Report, physics.ins-det/2103.05419



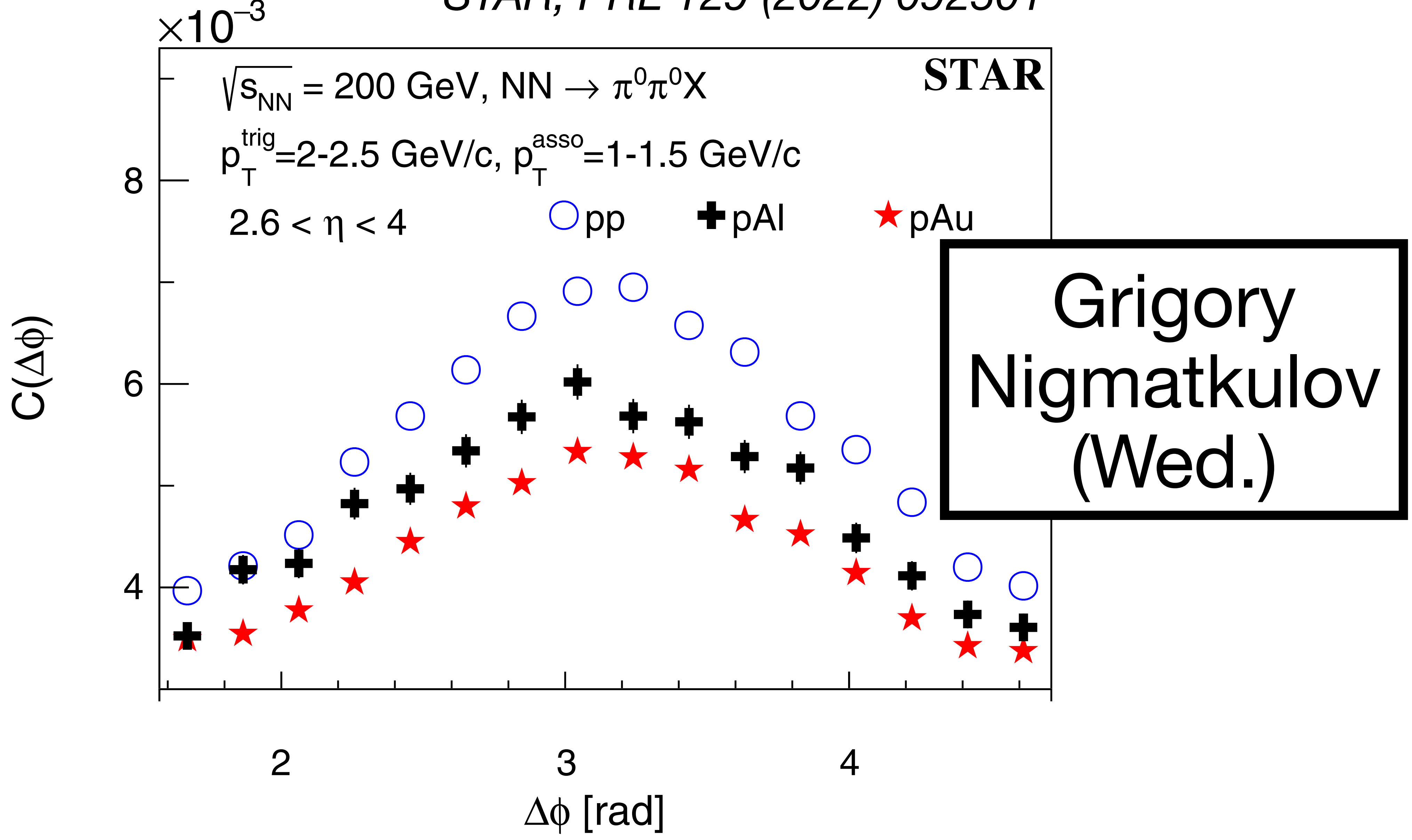
Olga Evdokimov (Thurs.)

Focus on two recent measurements at RHIC and LHC

ATLAS, PRC 100 (2019) 034903



STAR, PRL 129 (2022) 092501



Forward di-jets in *p*+Pb by ATLAS

Forward di-hadrons in *p*+Au by STAR

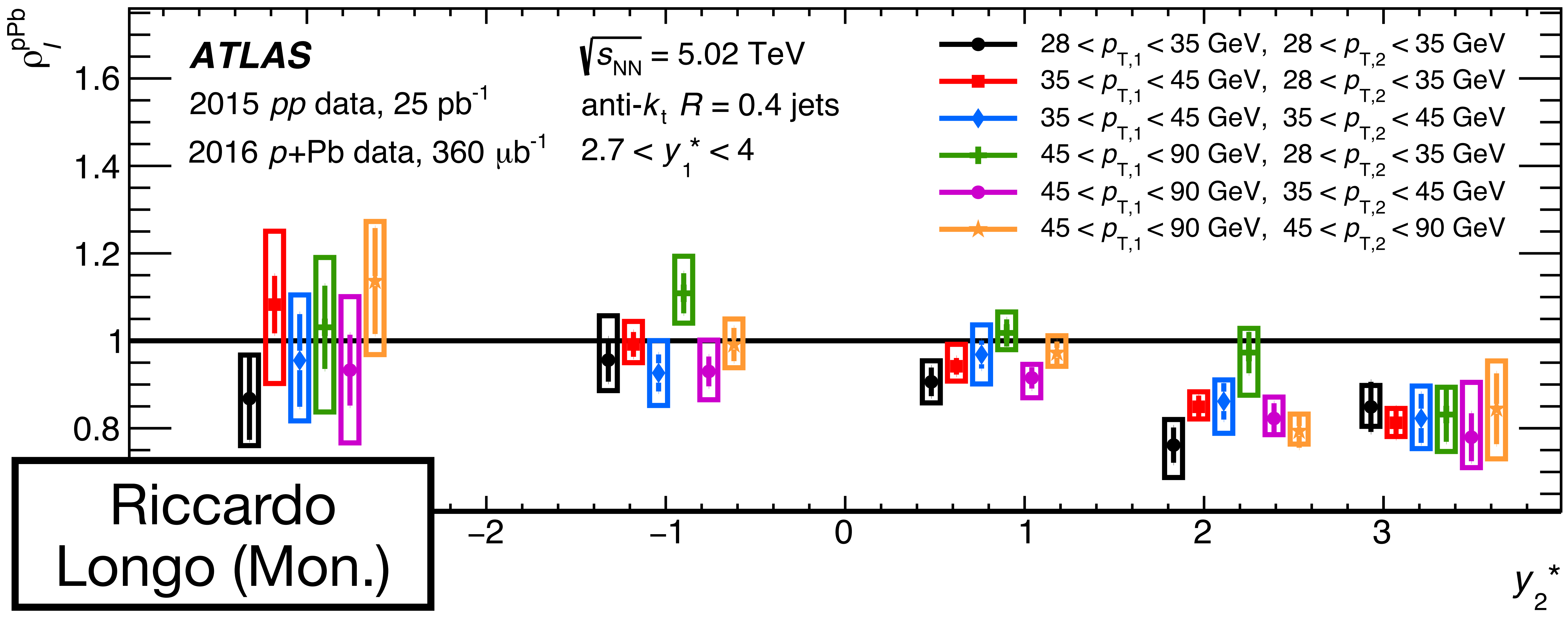
In both RHIC & LHC measurements: a **depleted per-trigger yield**, interpreted as **compatible with saturation**

Both performed just in centrality-integrated *p*+A events

A challenging aspect of both measurements: no change in $\Delta\phi$ correlation shape…

Focus on two recent measurements at RHIC and LHC

ATLAS, PRC 100 (2019) 034903



Riccardo Longo (Mon.)

Forward di-jets in *p*+Pb by ATLAS

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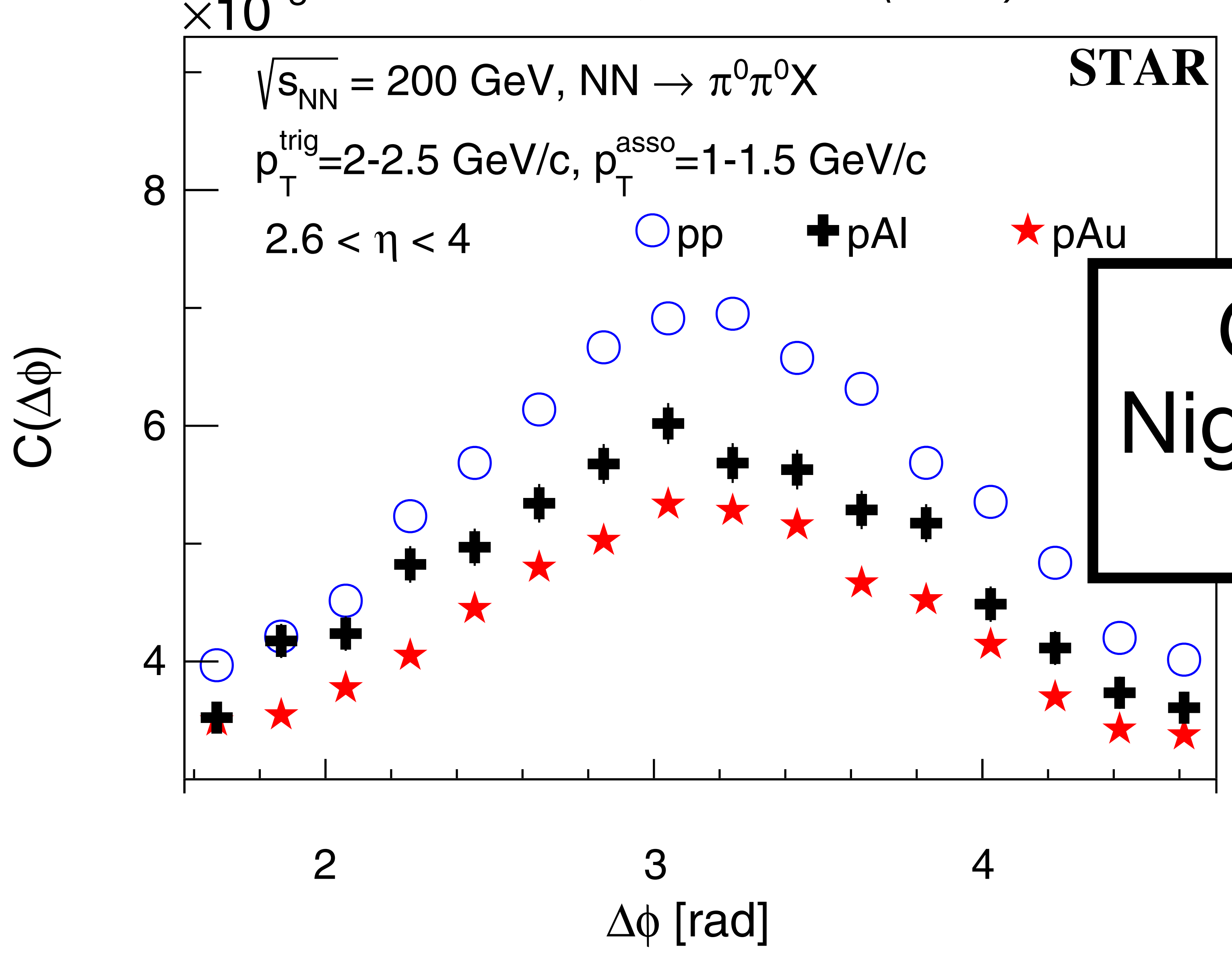

Grigory Nigmatkulov (Wed.)

Forward di-hadrons in *p*+Au by STAR

Question **quantitatively** explored in this talk:

How much of the effect in data is compatible with an “ordinary” universal nuclear PDF (nPDF) modification in a collinear factorization picture?

Does that mean these effects aren’t saturation *per se*? Or do nPDFs partially encode “exotic” non-linear QCD physics?

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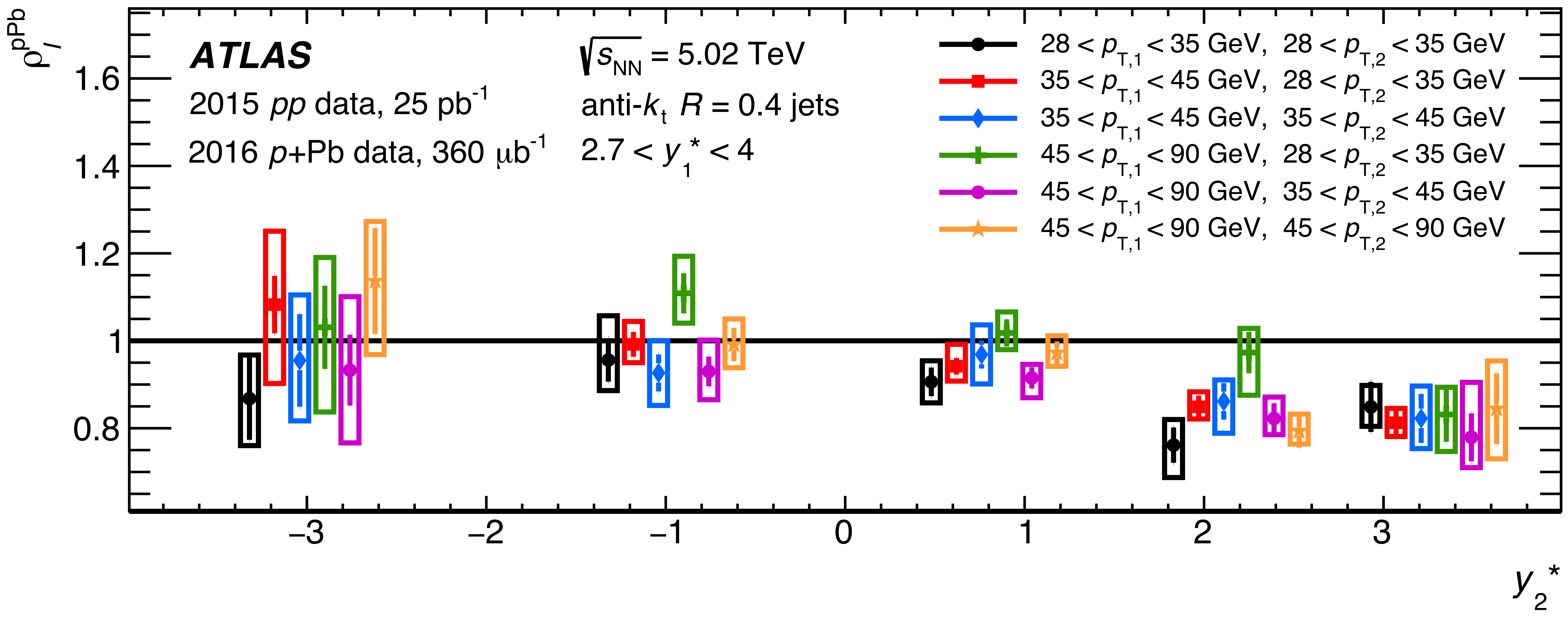

STAR, PRL 129 (2022) 092501

Forward di-jets in *p*+Pb by ATLAS

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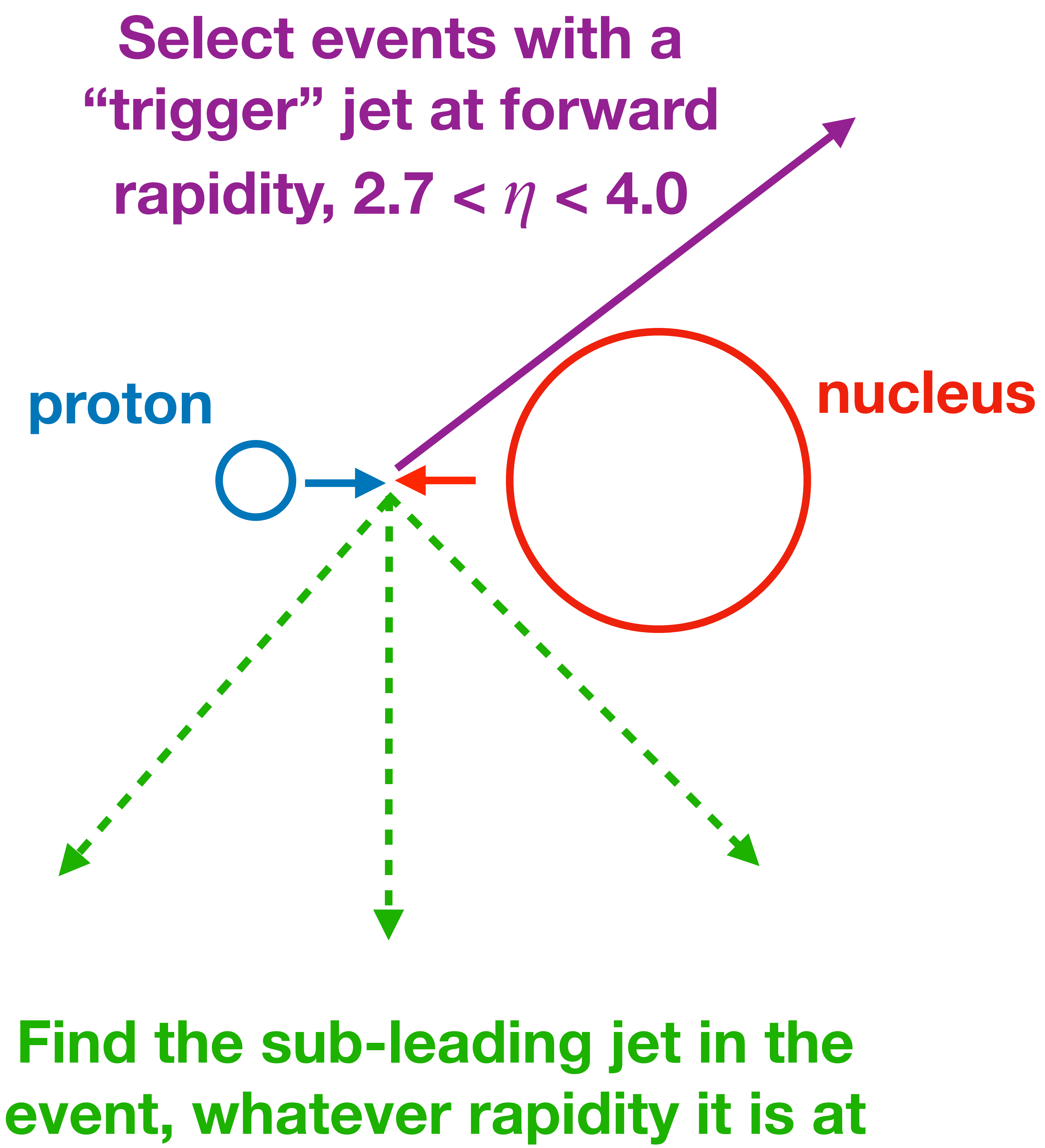
ATLAS measurement selection



Measure the per-trigger yield (also as a function of $\Delta\phi$)

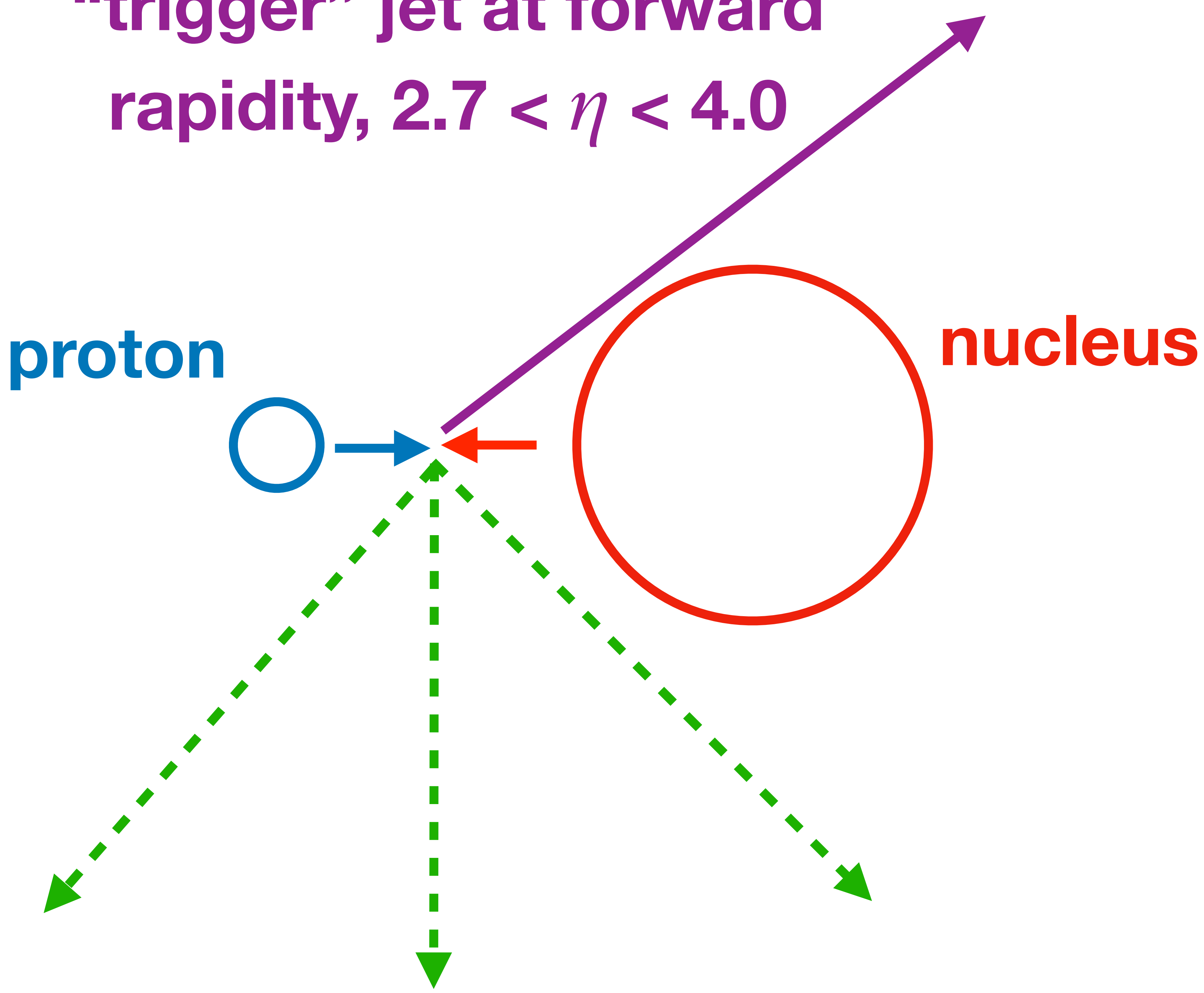
$$I_{12}(p_{\mathrm{T},1}, p_{\mathrm{T},2}, y_1^*, y_2^*) = \frac{1}{N_1} \frac{d^4 N_{12}}{dy_1^* dy_2^* dp_{\mathrm{T},1} dp_{\mathrm{T},2}}$$

$$C_{12}(p_{\mathrm{T},1}, p_{\mathrm{T},2}, y_1^*, y_2^*) = \frac{1}{N_1} \frac{dN_{12}}{d\Delta\phi}$$

Note the normalization by number of trigger jets N_1

The per-trigger normalization is sometimes argued to "cancel out" any overall suppression in the cross-section

ATLAS measurement selection



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Note the normalization by number of trigger jets N_1

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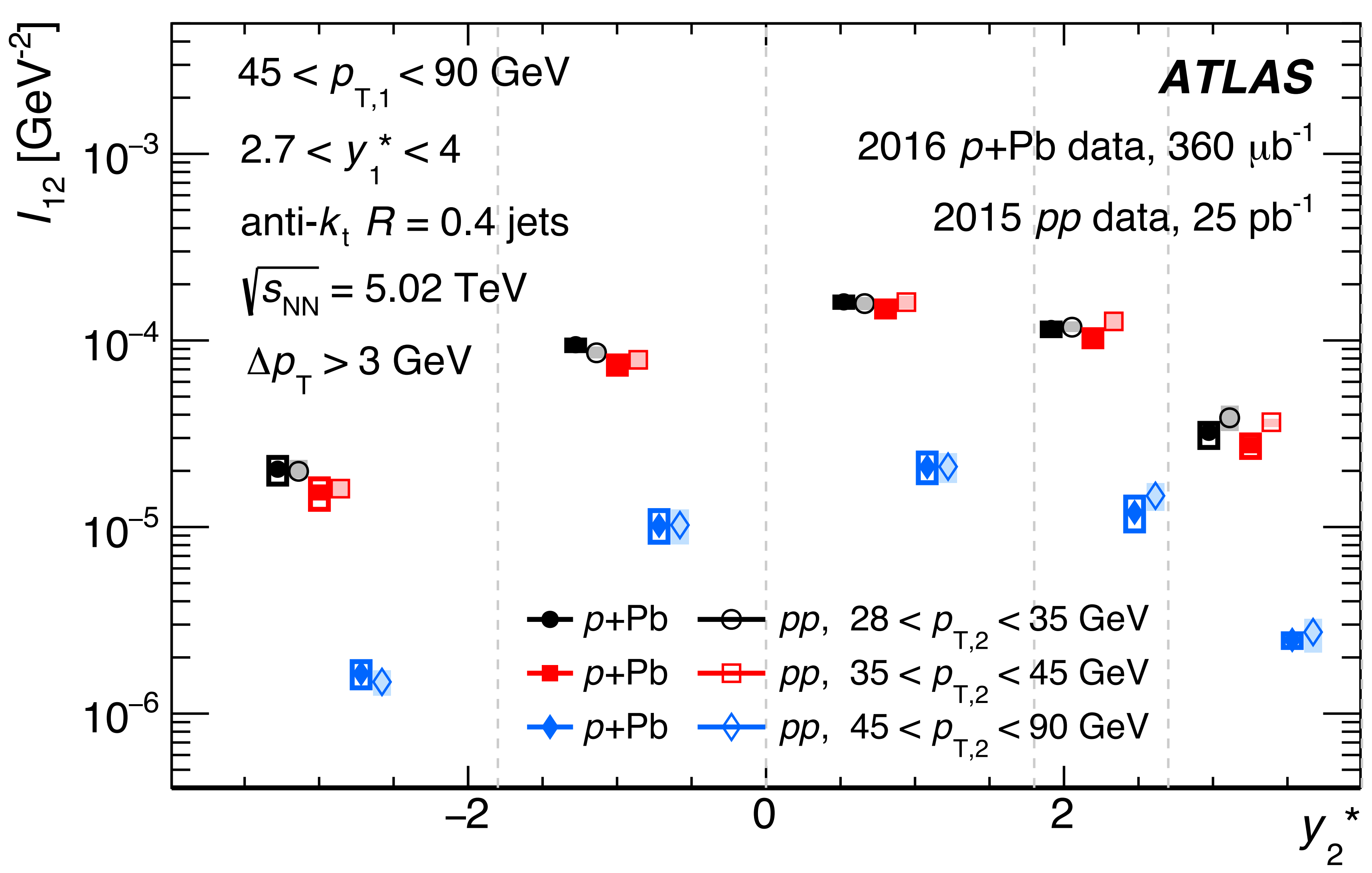
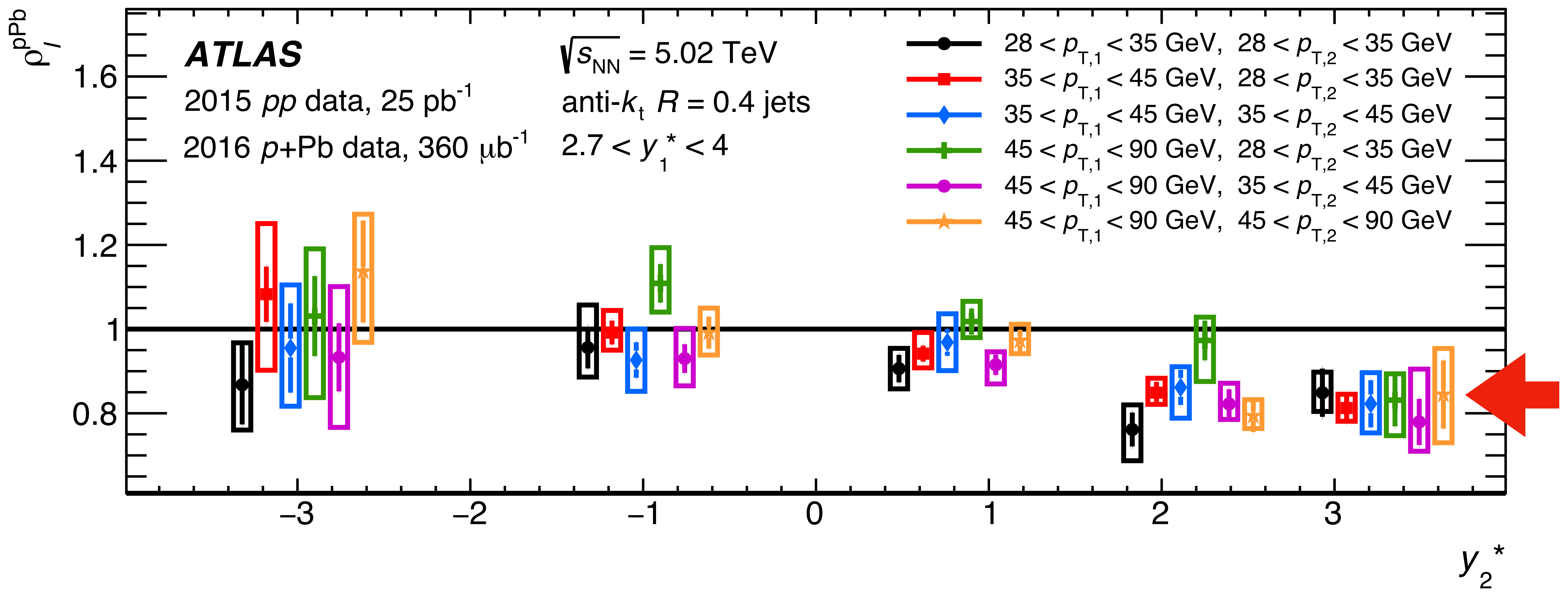
➡ One can show that this is only a partial cancellation and **nPDF effects appear in this observable**

Forward di-jet data at LHC





Select events with a forward jet, measure the yield as a function of the sub-leading jet

Above: comparison of the per-trigger jet yield between *p*+*p* and *p*+Pb

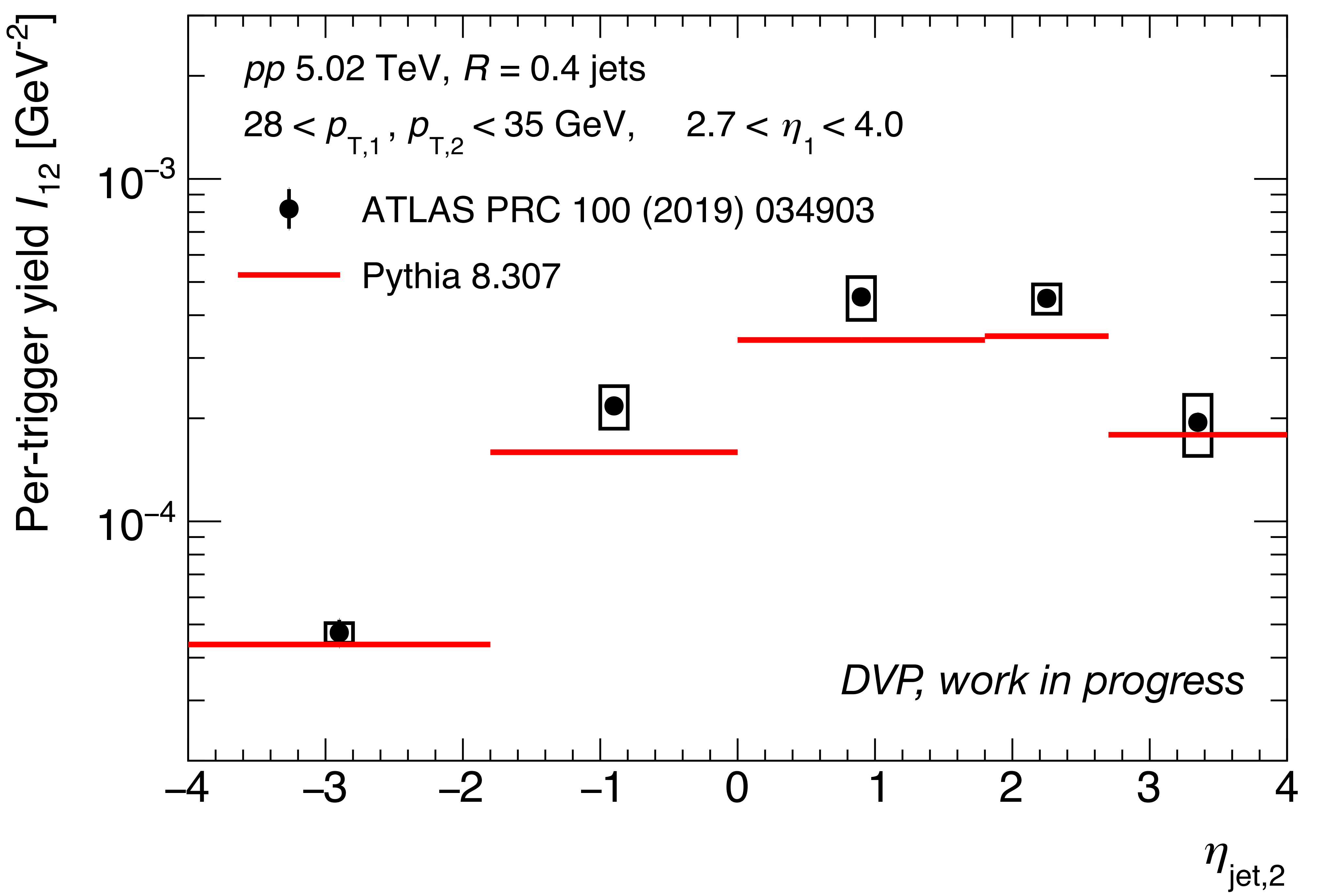
Modest but significant (~15%) suppression for forward-forward pairs, which is not present for forward-central pairs

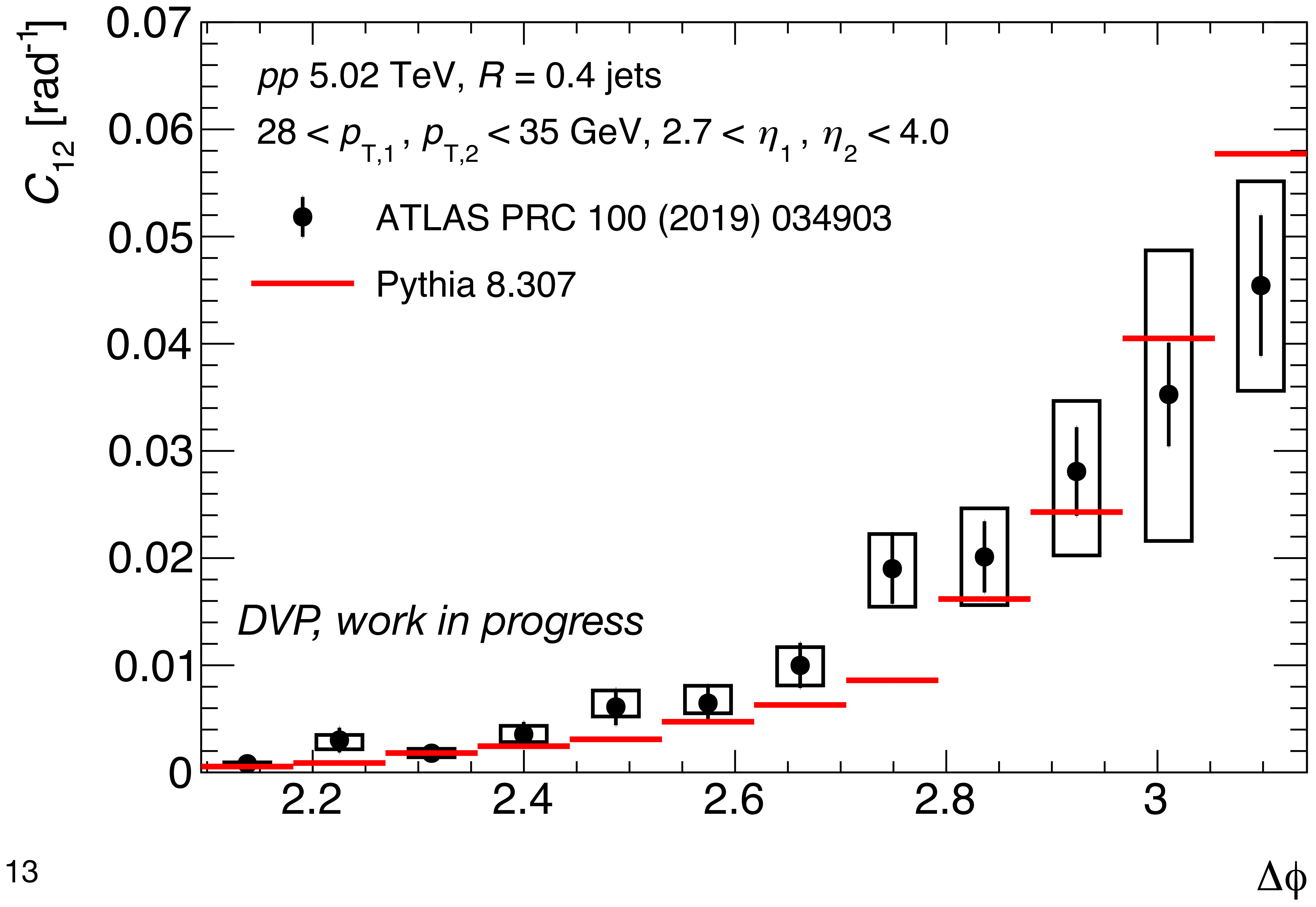
Suppression compatible with saturation physics explanation, but no change in jet-jet azimuthal correlation width (backup slide)

Simulation setup

- Not a “state of the art” calculation, but an MC study to gauge the size of nPDF effects
- Pythia 8.307, HardQCD, $\hat{p}_{\mathrm{T}_{\mathrm{min}}}$ = 14 GeV (safe for $p_{\mathrm{T}}^{\mathrm{jet}} > 28$ GeV)
- Benchmark per-trigger jet yields (left) and azimuthal correlation (right) with ATLAS *p*+*p* data

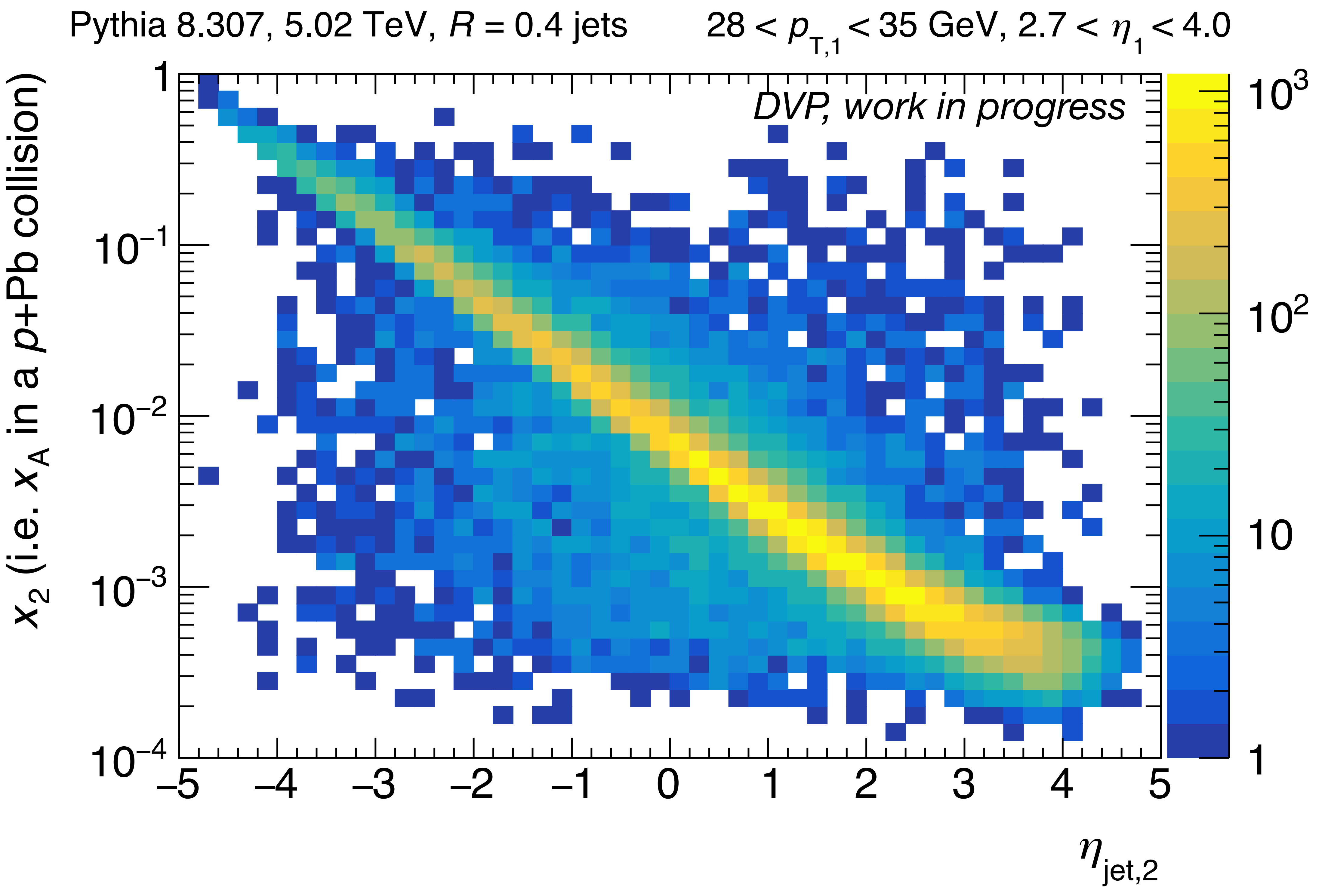
➡ Reasonable agreement on overall physics process, within the limitations of Pythia as LO+ISR/FSR/PS generator

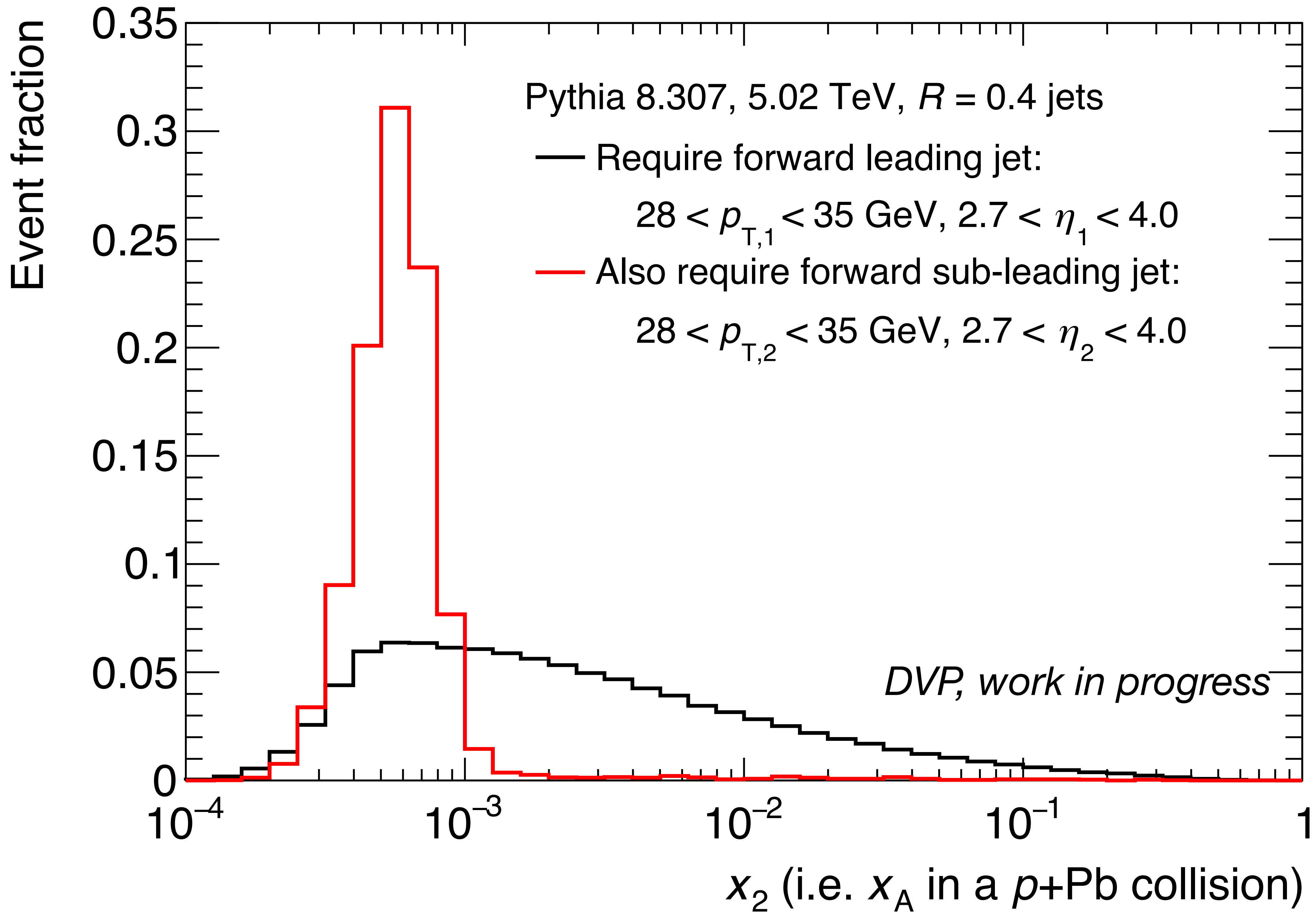




x_A values probed

- Consider all events with a leading jet at forward (proton-going) rapidity, $2.7 < \eta < 4.0$





The typical x_A in the nucleus is then highly sensitive to the rapidity of the sub-leading jet

Compare x_A distribution for **all events w/ a forward jet** vs. **those which have two forward jets**

These will have different average nPDF modification!

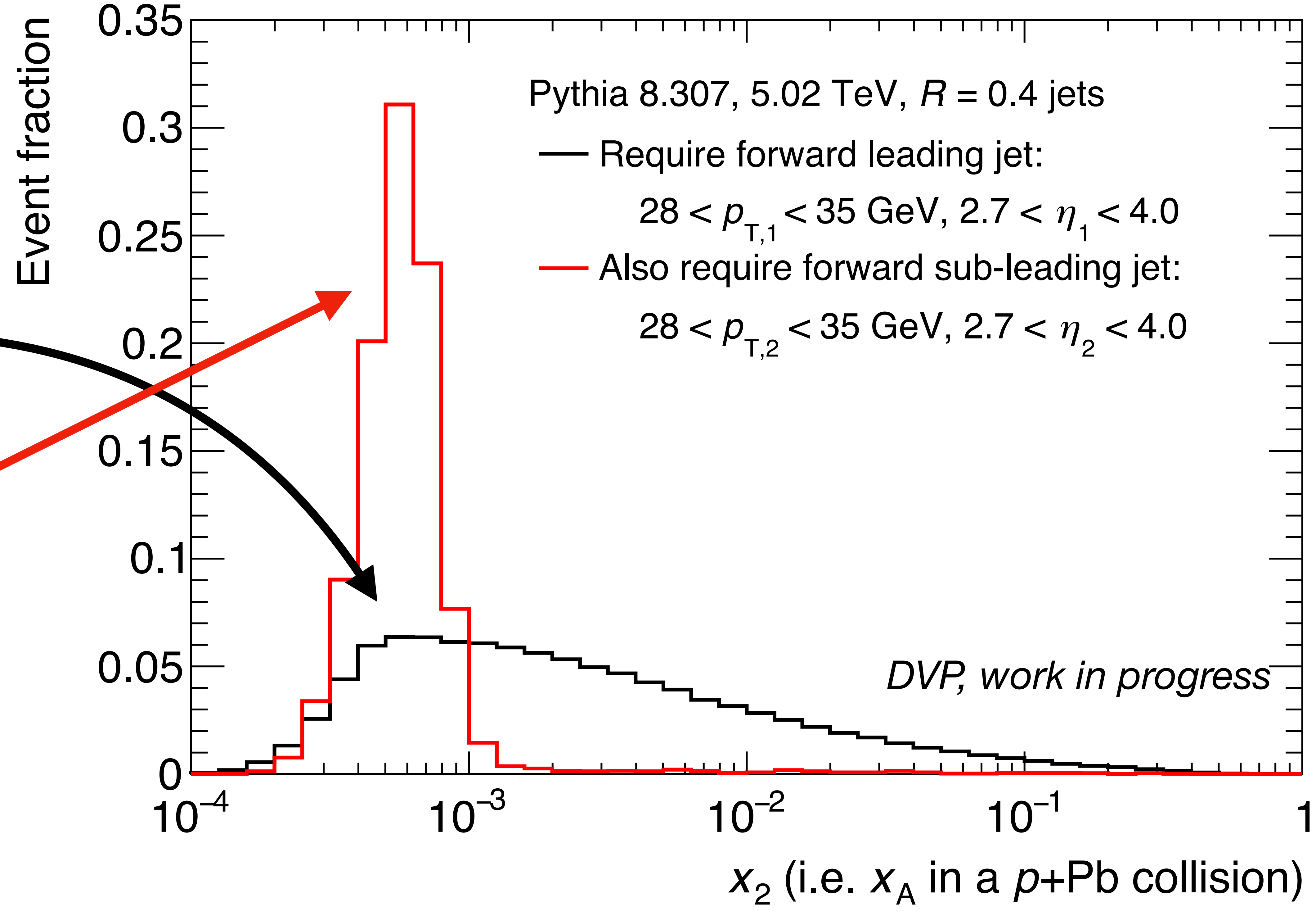
x_A values probed

For example, for these kinematic selections, using EPPS21NLO:

Events with a forward leading jet (and no other specific requirement) have an overall R_{pA} of 0.89

The subset of these which also have a forward sub-leading jet have an R_{pA} of 0.84

These cancel only partially, and thus nPDF effects will give a suppressed per-trigger yield ~ R_{pA}(dijet) / R_{pA}(trigger jet only) ~ 0.94

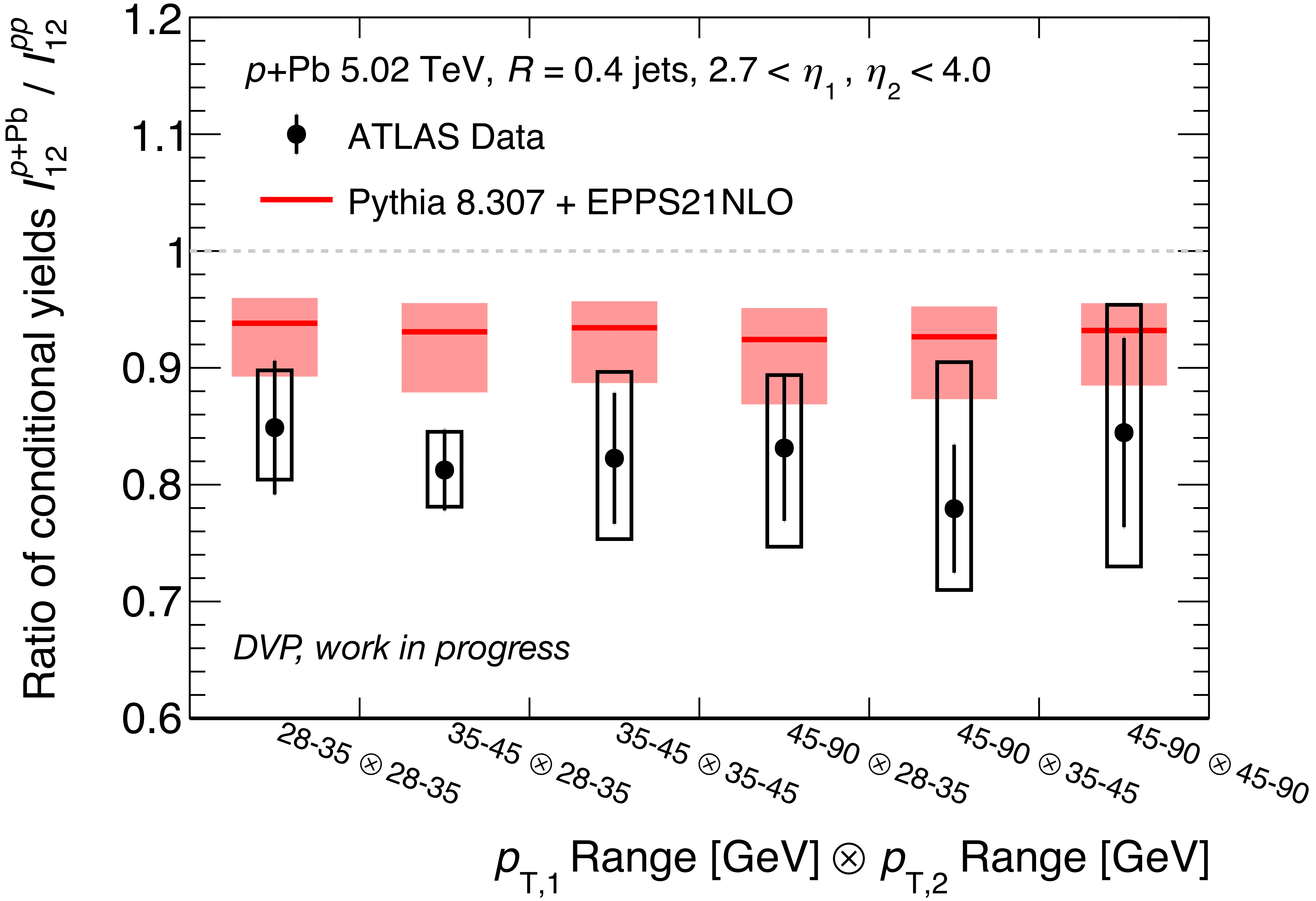


Compare x_A distribution for **all events w/ a forward jet** vs. **those which have two forward jets**

These will have different average nPDF modification!

Per-trigger suppression from EPPS21

- Use EPPS21NLO ^{197}Au and free nucleon sets through LHAPDF6, weighting Pythia events by $f^{\text{Au}}_{\text{flavor}}(x_A, Q^2)/f^{\text{free nucleon}}_{\text{flavor}}(x_A, Q^2)$
- Evaluate 48 nuclear uncertainties, add in quadrature
- Systematically compare to ATLAS data in different $p_{T,1} \otimes p_{T,2}$ selections



- Surprising result: the nominal nPDF estimate is ~half of the observed effect in data!

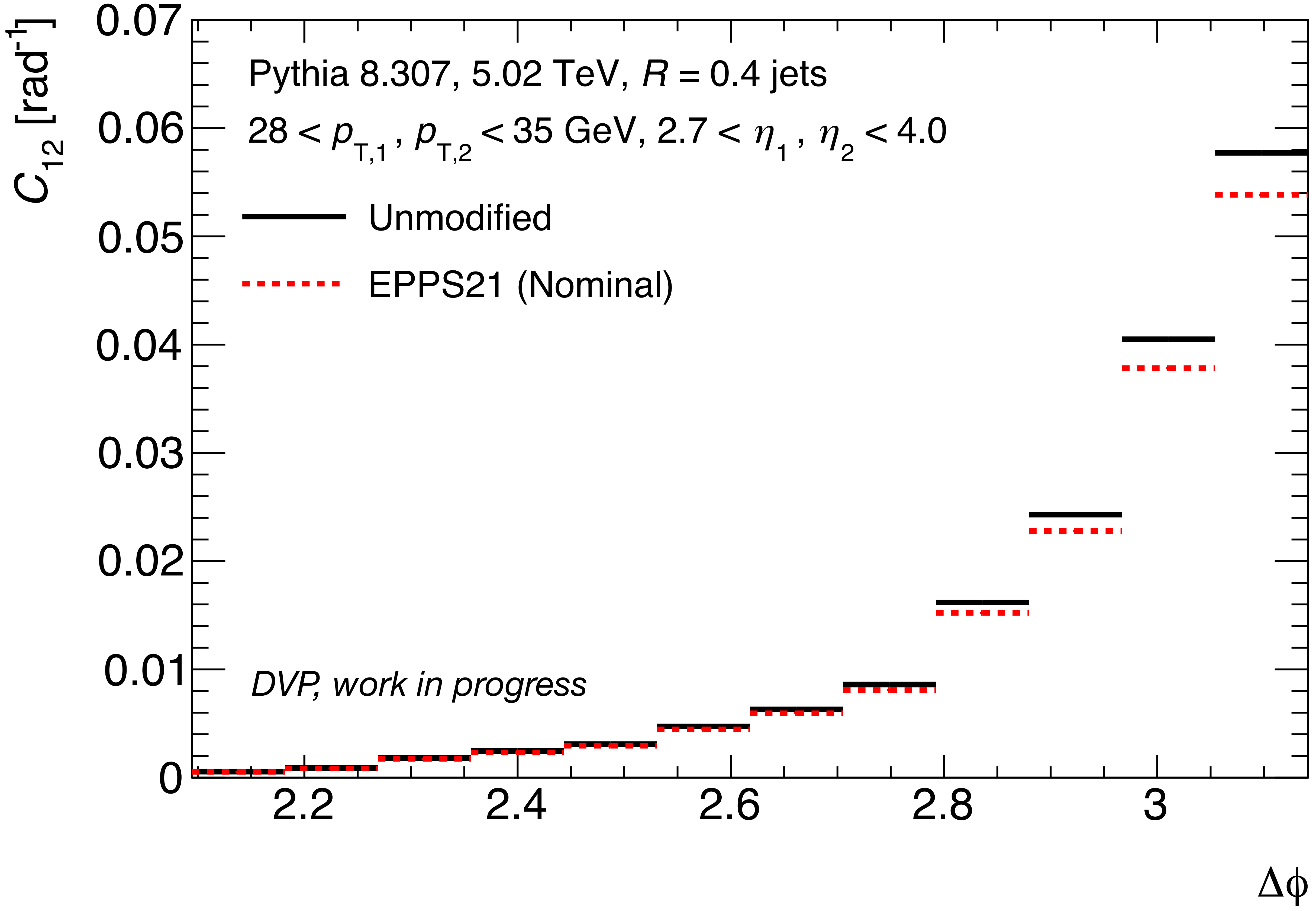
➡ When considering full theory + data uncertainties, the **full suppression effect could be described by an (“ordinary”, linear) nPDF modification picture**

$\Delta\phi$ broadening from EPPS21?

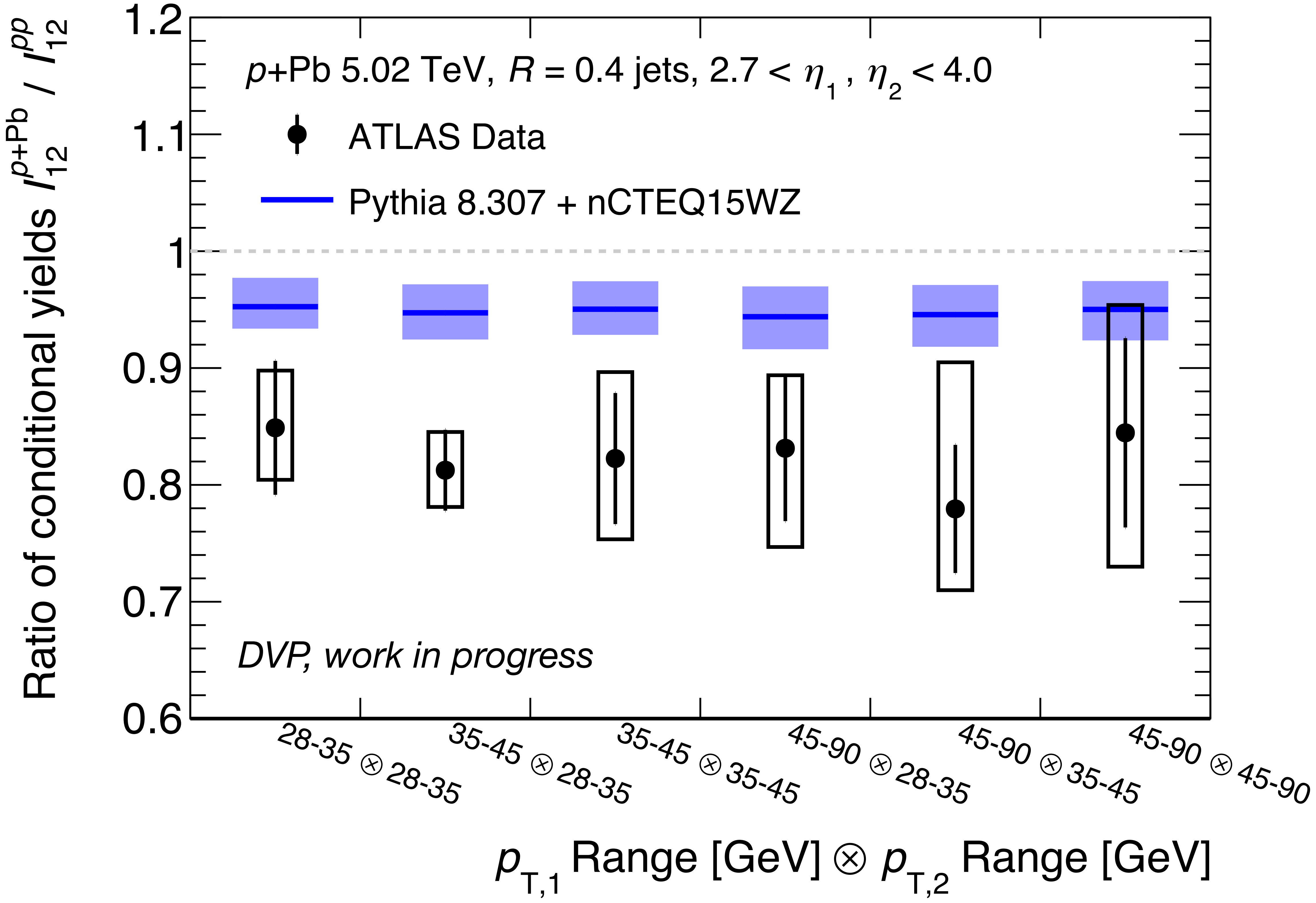
- On the other hand, no significant change in shape of $\Delta\phi$ distribution from nPDF effects

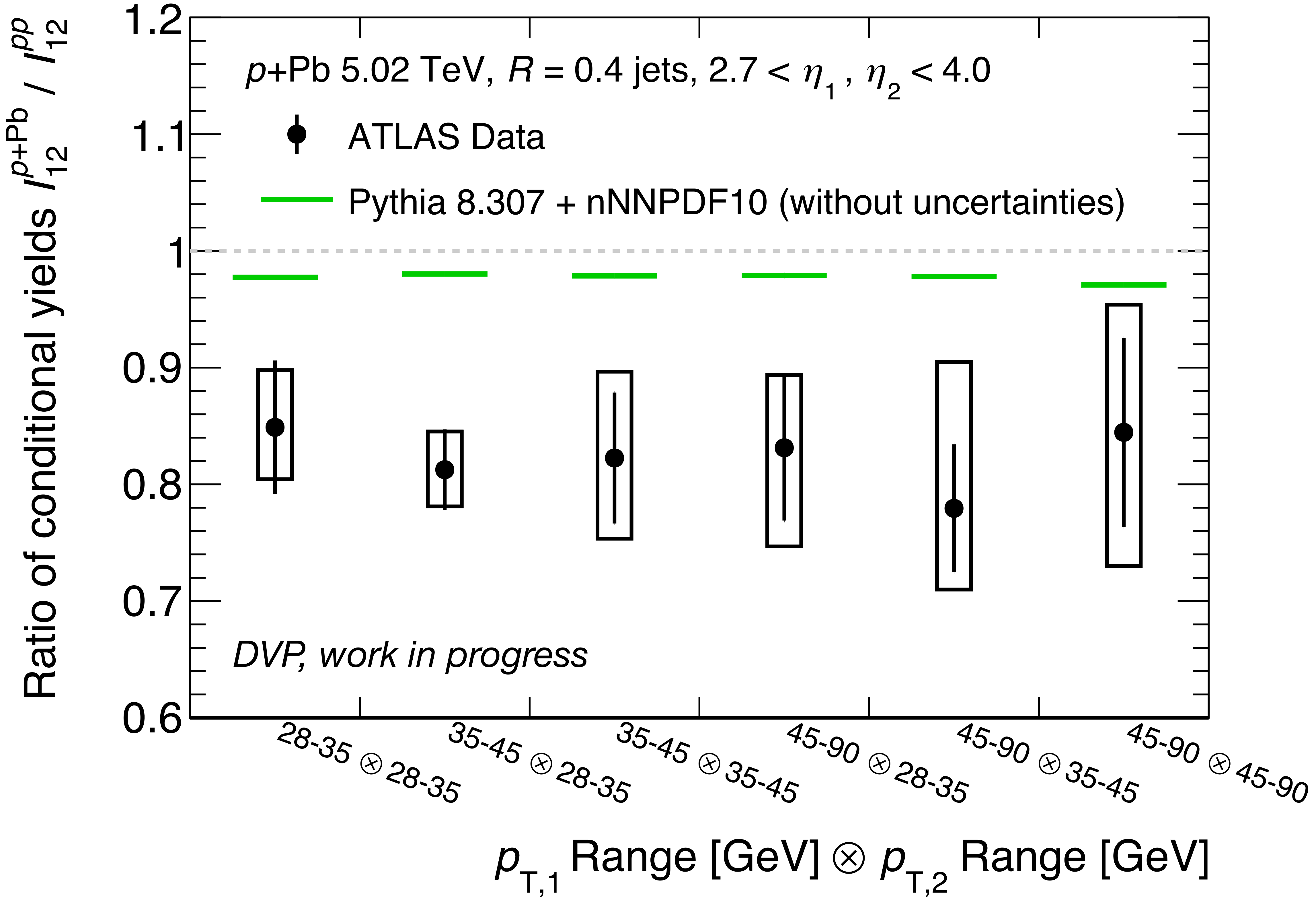
  ➡ Same pattern as in the data

- The nPDF picture "naturally" results in (1) a suppression of the per-trigger yield, but (2) an unmodified width of the correlation function



Sensitivity to other nPDF set choice





nCTEQ15WZ

nNNPDF 1.0 (note: no uncertainties)

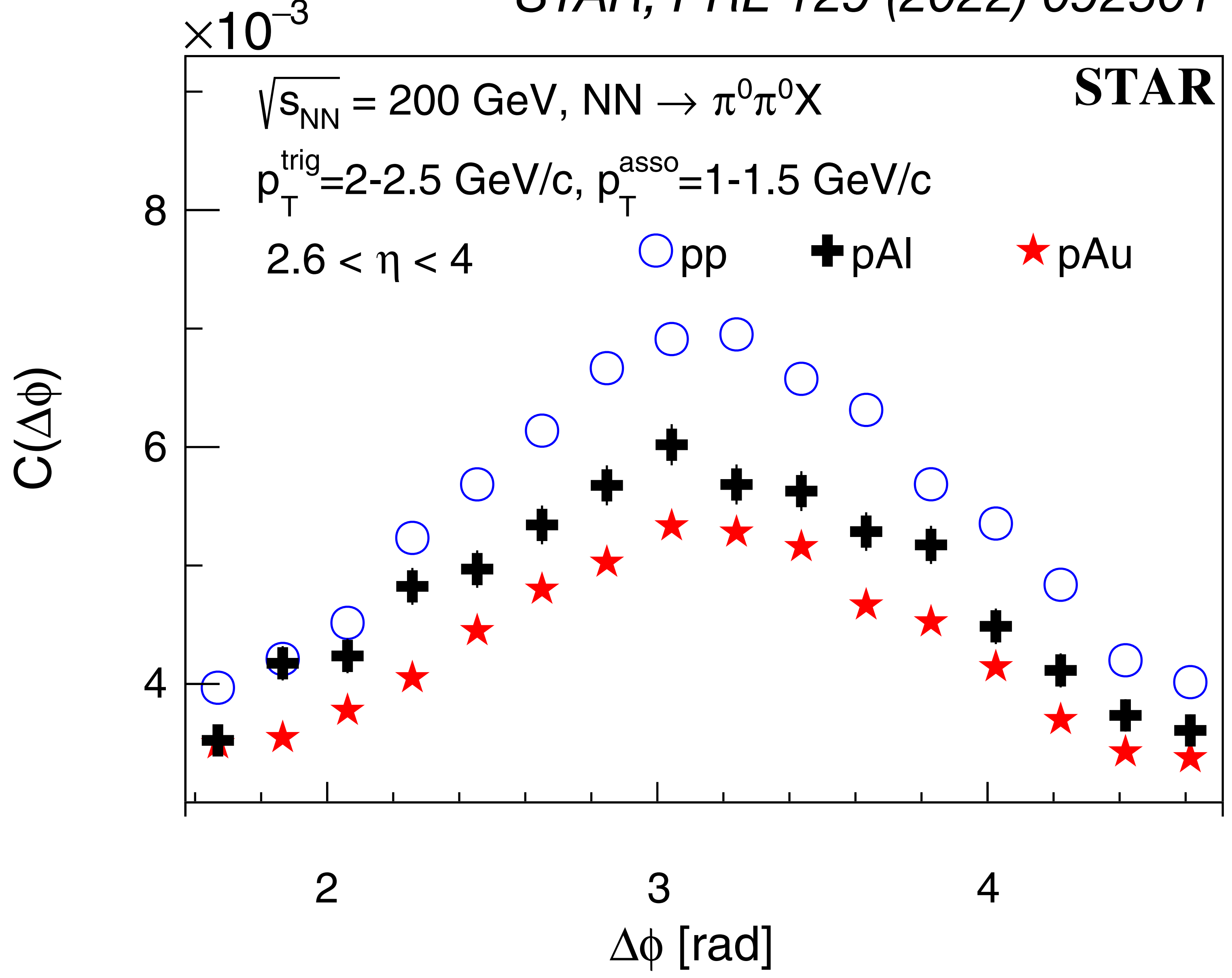
- Other (older) nPDF sets show a smaller impact, compatible with only part of the suppression

➡ **Takeaway question**: are some of the effects arising from non-linear QCD included in nPDF extractions? Are these pictures overlapping or redundant?

Focus on two recent measurements at RHIC and LHC

ATLAS, PRC 100 (2019) 034903

STAR, PRL 129 (2022) 092501



Forward di-jets in p+Pb by ATLAS

Forward di-hadrons in p+Au by STAR

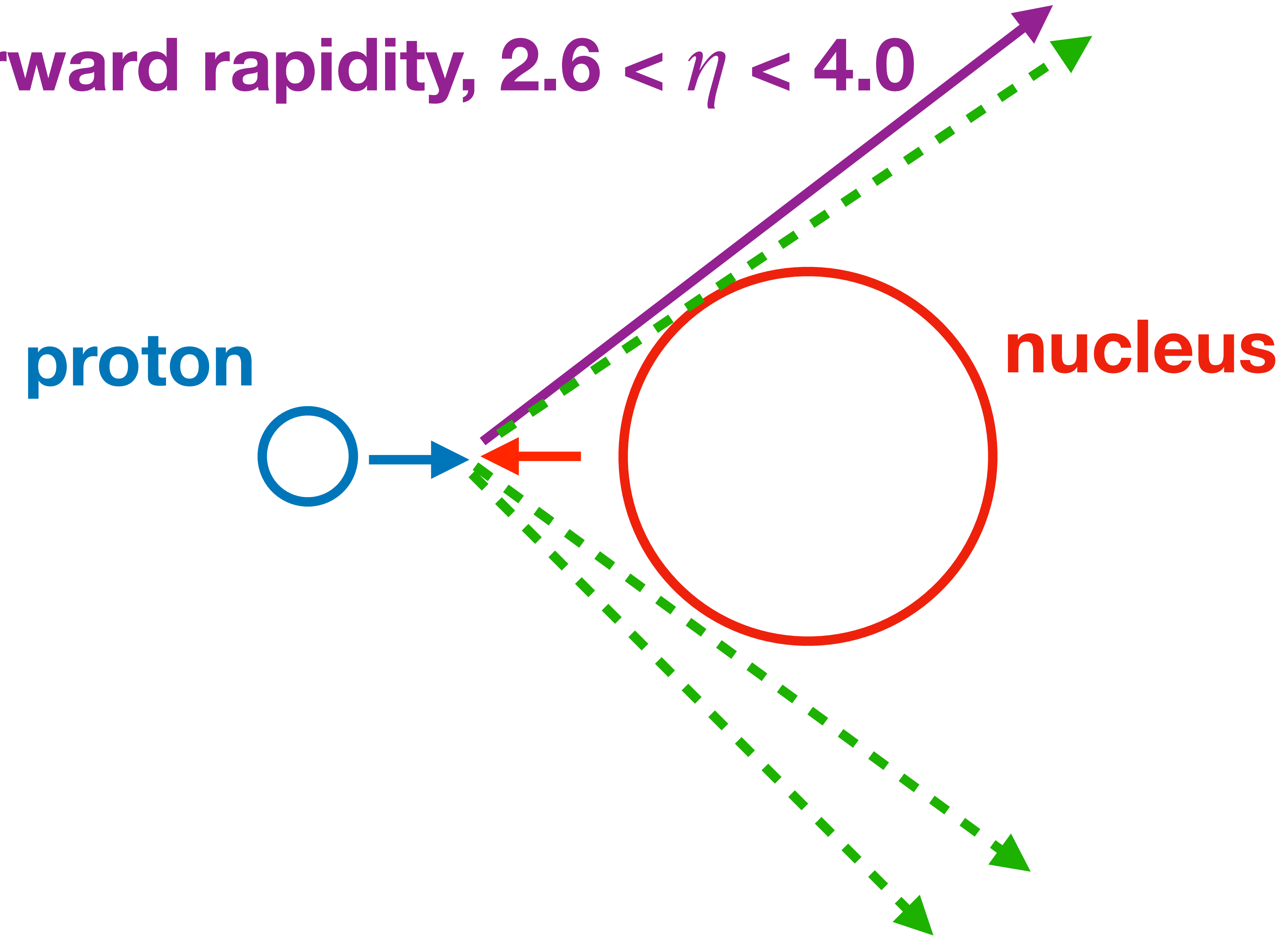
Question **quantitatively** explored in this talk:

How much of the effect in data is compatible with an "ordinary" universal nuclear PDF (nPDF) modification in a collinear factorization picture?

Does that mean these effects aren't saturation *per se*? Or do nPDFs partially encode "exotic" non-linear QCD physics?

STAR measurement selection

Select "trigger" π^0's at forward rapidity, 2.6 < η < 4.0



Consider "associated" π^0's in the same rapidity region, whatever the $\Delta\phi$ between them

Measure the per-trigger yield
(also as a function of $\Delta\phi$)

$$C(\Delta\phi) = [N_{\text{pair}}(\Delta\phi)/(N_{\text{trig}} \times \Delta\phi_{\text{bin}})]$$

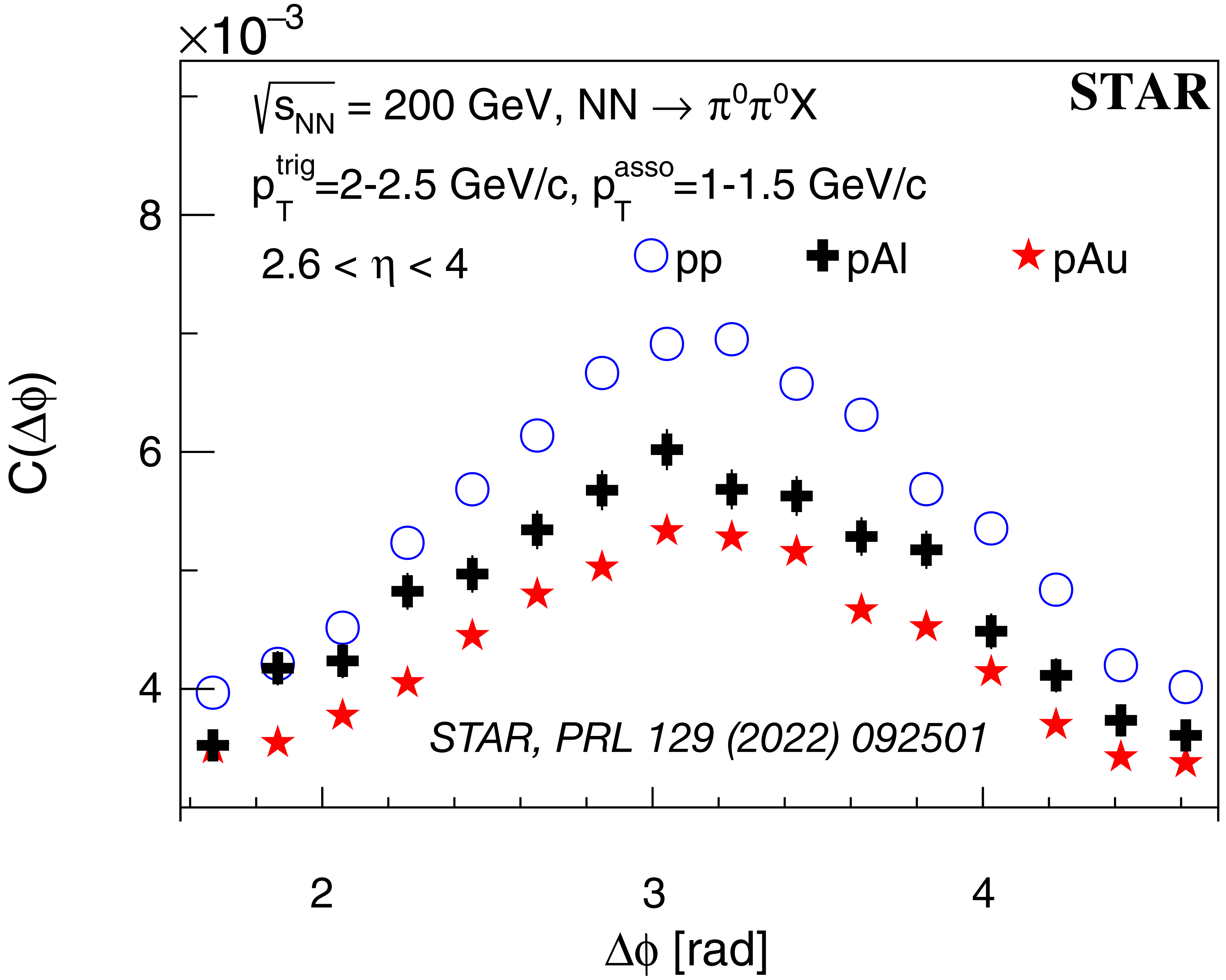
Like the ATLAS case, this observable can evaluated in an nPDF picture, but with caveats:

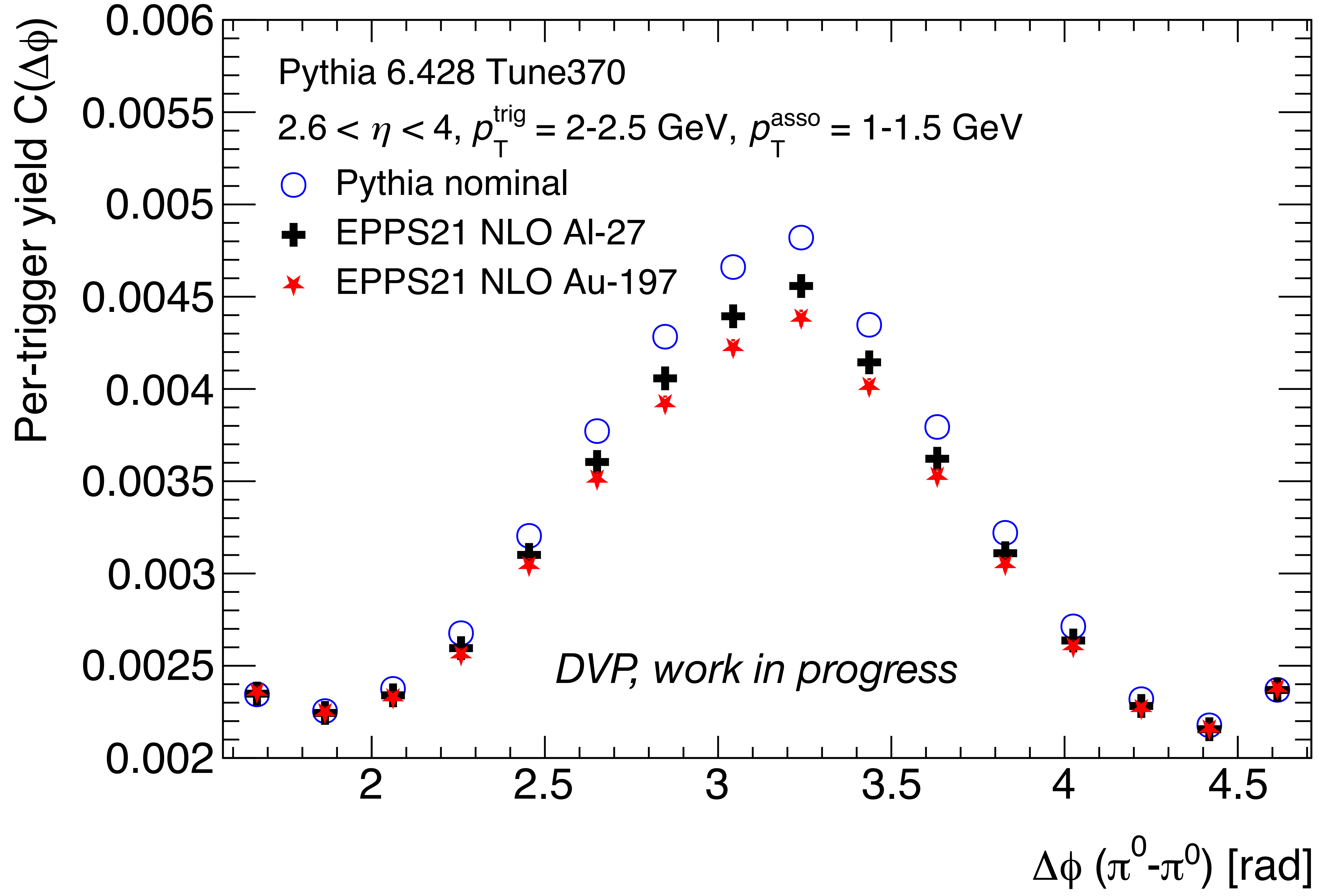
- ➡ looser connection to underlying (x, Q^2) from using hadrons rather than jets
- ➡ challenge to evaluate some nPDF sets in regions Q^2 down to 1 GeV^2
- ➡ STAR results are after subtracting pedestal contribution in data - non-trivial to model

(*) To protect from occasional negative nPDF values, I evaluate at $Q^2 = \max(Q^2, 1.8\ GeV^2)$ as suggested in EPPS paper

Simulation setup

- Pythia 6.428 Tune 370 (CTEQ6L1), ISUB 95 and 96
  - ➡ Chosen to match STAR Supplementary Material - **many thanks to Xiaoxuan Chu (BNL)**
  - ➡ Events weighted using EPPS21 Au-197 and Al-27 sets to evaluate nPDF effects(*)

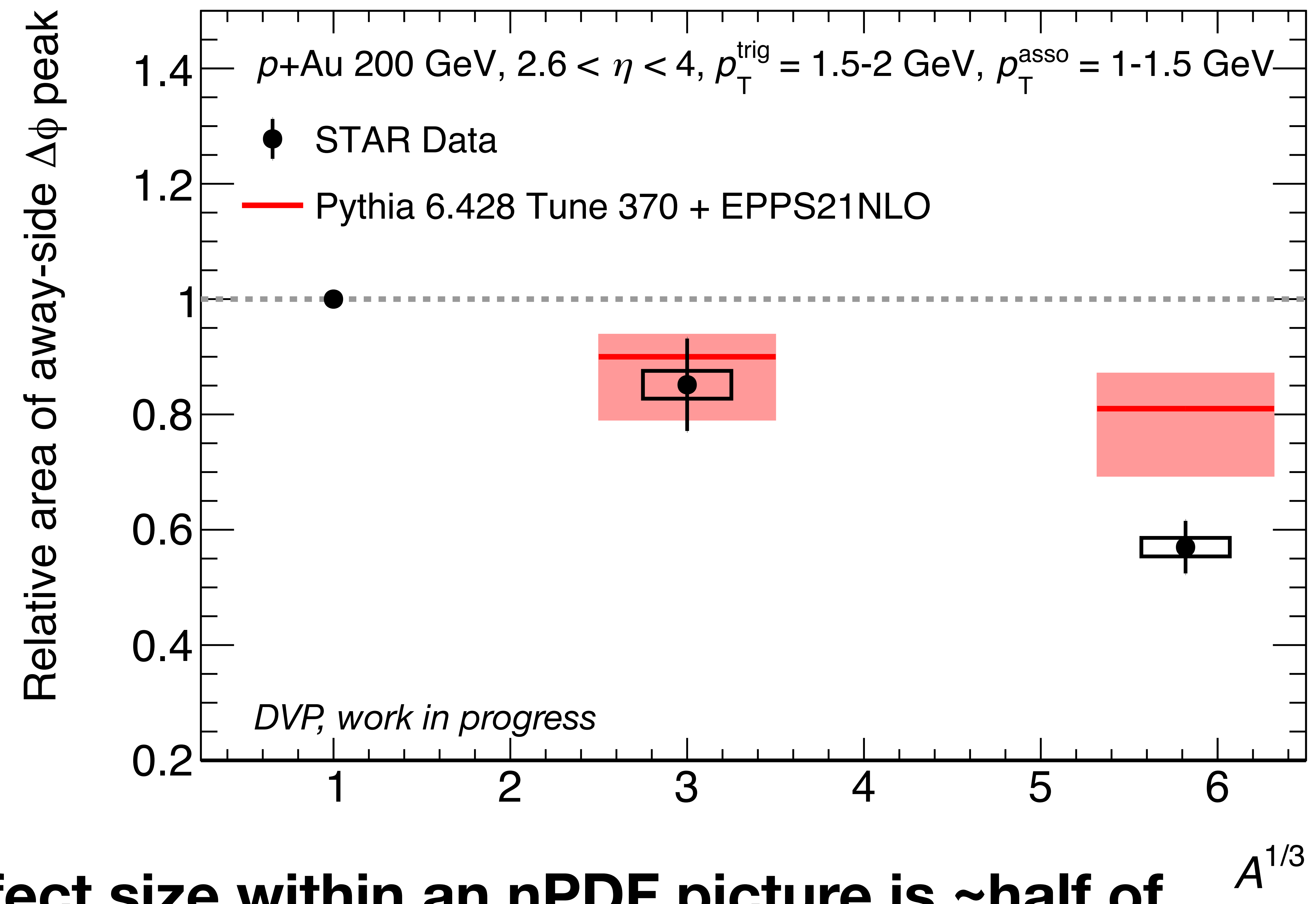




➡ Imperfect description of correlation function shape, but **clear (modest) impact from nPDF effects**

Area suppression from EPPS21

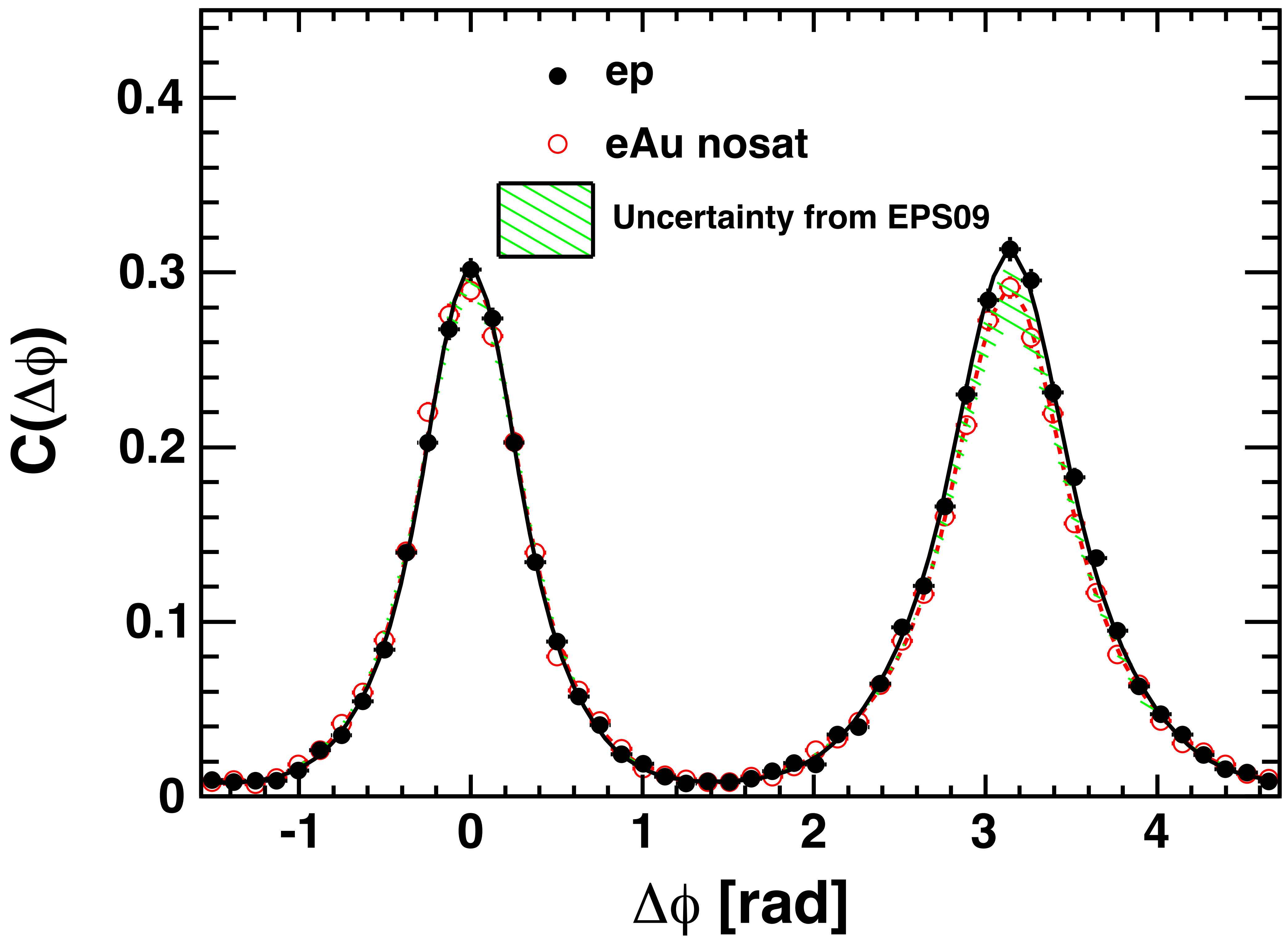
- Evaluate EPPS21 nuclear uncertainties, systematically compare to STAR data
  - ➡ one particular $p_{\mathrm{T},1} \otimes p_{\mathrm{T},2}$ selection shown here, for both *p*+Al and *p*+Au cases
  - ➡ there are may be other (unevaluated) uncertainties related to my pedestal/peak separation



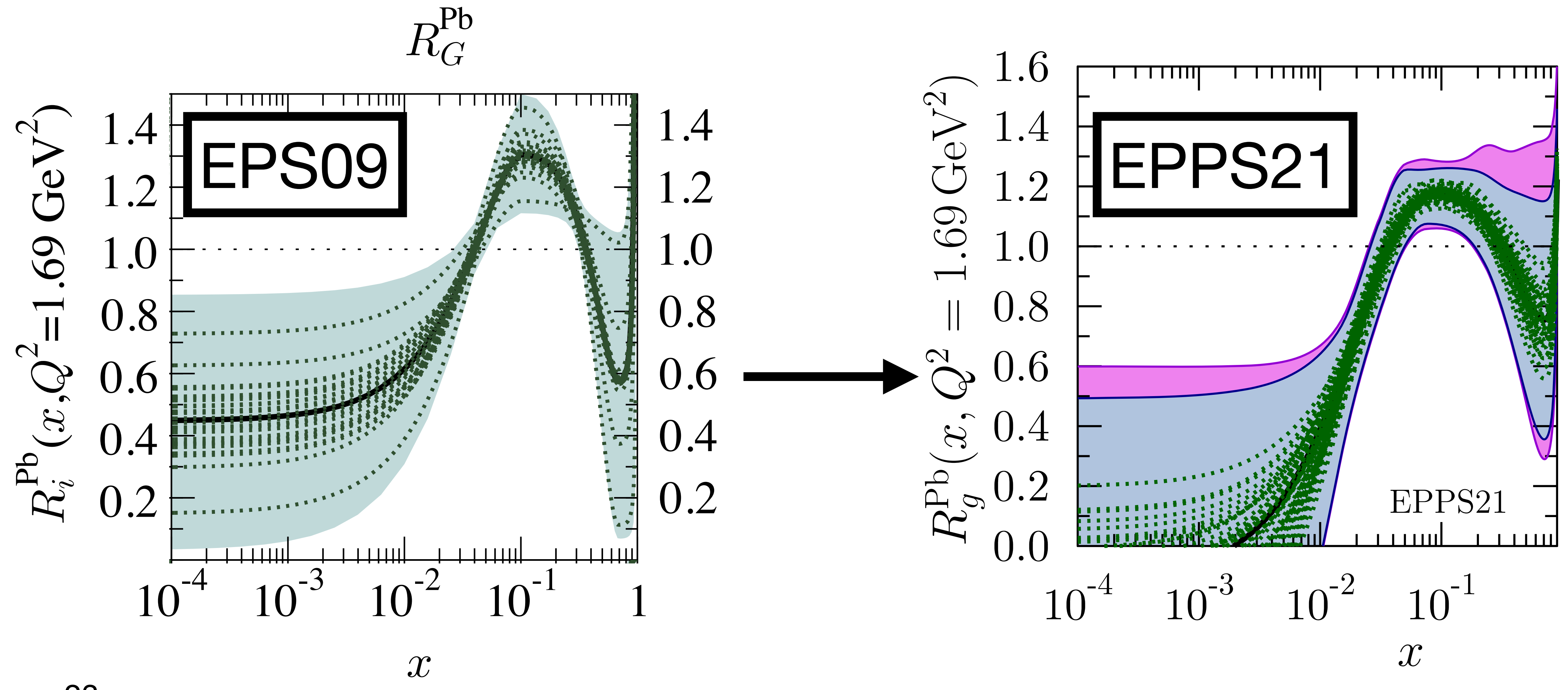
- Again, a surprising result: the **estimated effect size within an nPDF picture is ~half of the observed suppression effect** in *p*+Au data! (And the ~entire effect in *p*+Al)
  - ➡ **Takeaway question**: does this mean there is less saturation than we think? Or — is the universal, nPDF-based approach partially including some of the effects of saturation on hard process dynamics? How do we disentangle this …

Comment #1 …

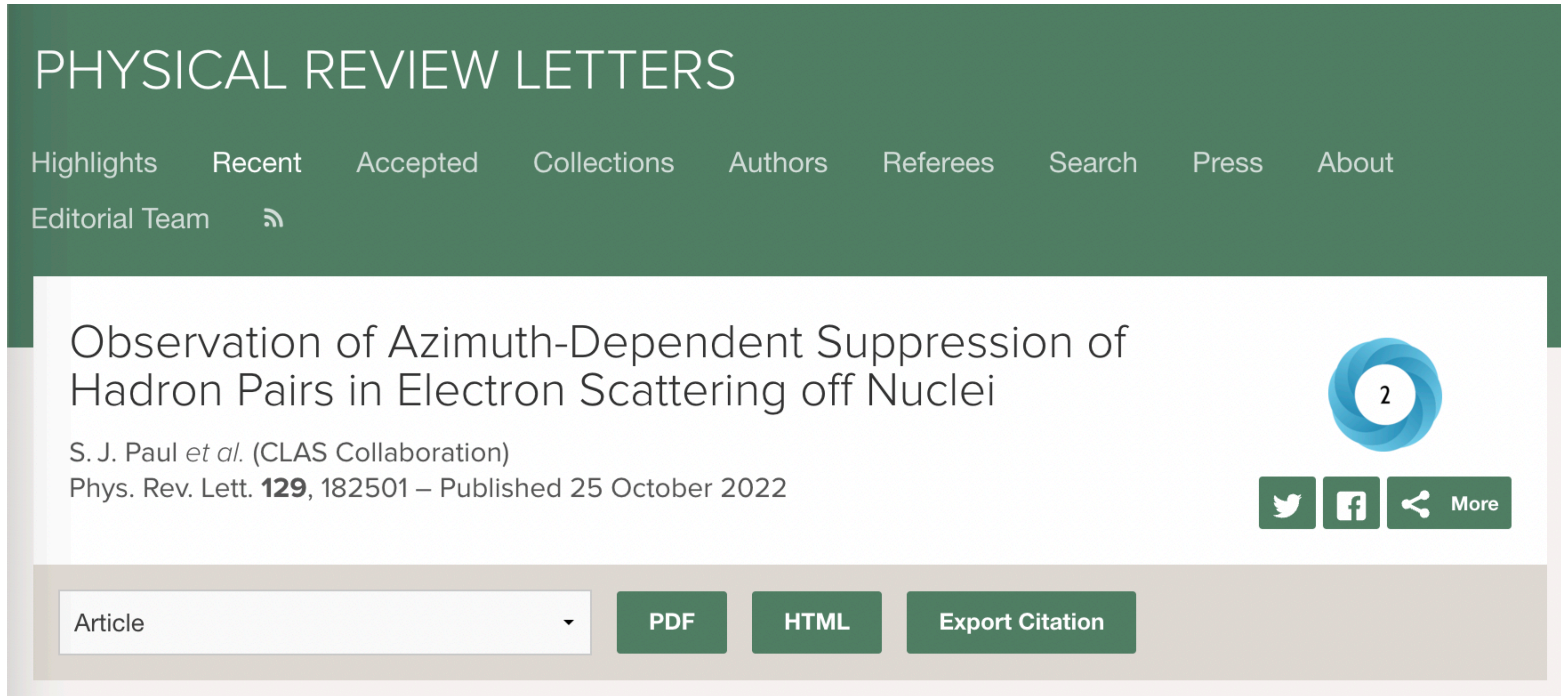
Zheng, et al, PRD 89 (2014) 074037



- An earlier study found that EPS09 (e.g.) predicts very modest effects in di-hadron correlations at EIC
  - ➡ EPPS21 has significantly stronger gluon shadowing, based on LHC data
  - ➡ probably interesting to re-evaluate with updated knowledge of EIC kinematics & global nPDF sets?



Comment #2 …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Observation of Azimuth-Dependent Suppression of Hadron Pairs in Electron Scattering off Nuclei

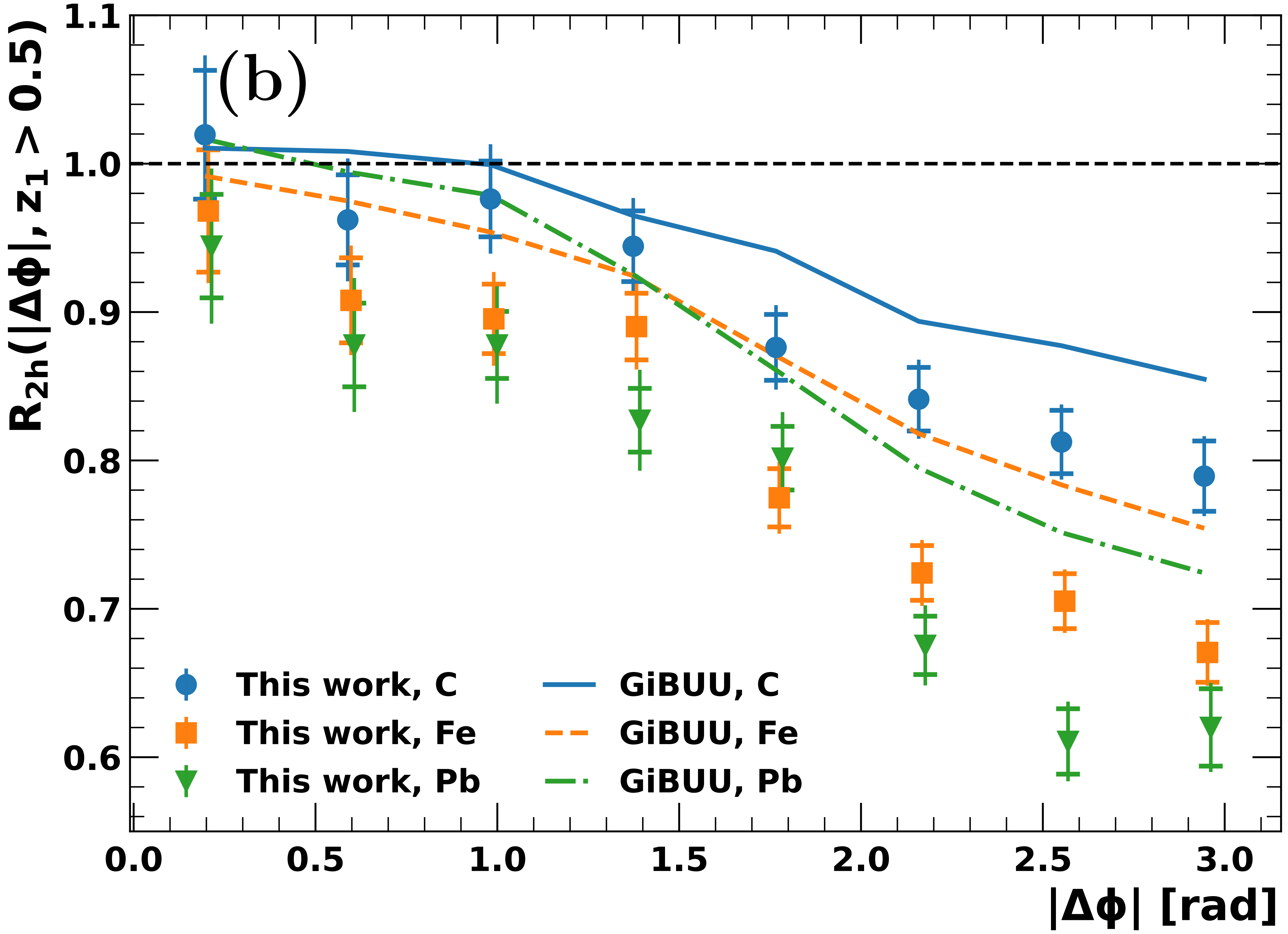
S. J. Paul *et al.* (CLAS Collaboration)

Phys. Rev. Lett. **129**, 182501 – Published 25 October 2022

Article PDF HTML Export Citation

Measurement in fixed target $e + A$ at JLab

CLAS, PRL 129 (2022) 182501



Very different kinematics, different way of presenting the data … but the same physics effects (at much larger x_A).

How could saturation possibly play a role here? How do we understand together with RHIC (and future EIC) data?

Comment #3 …

Multiplicity-based centrality selections for hard processes have turned out to be sensitive to all kinds of (unintended) physics.

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

Letter

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

Dennis V. Perepelitsa*

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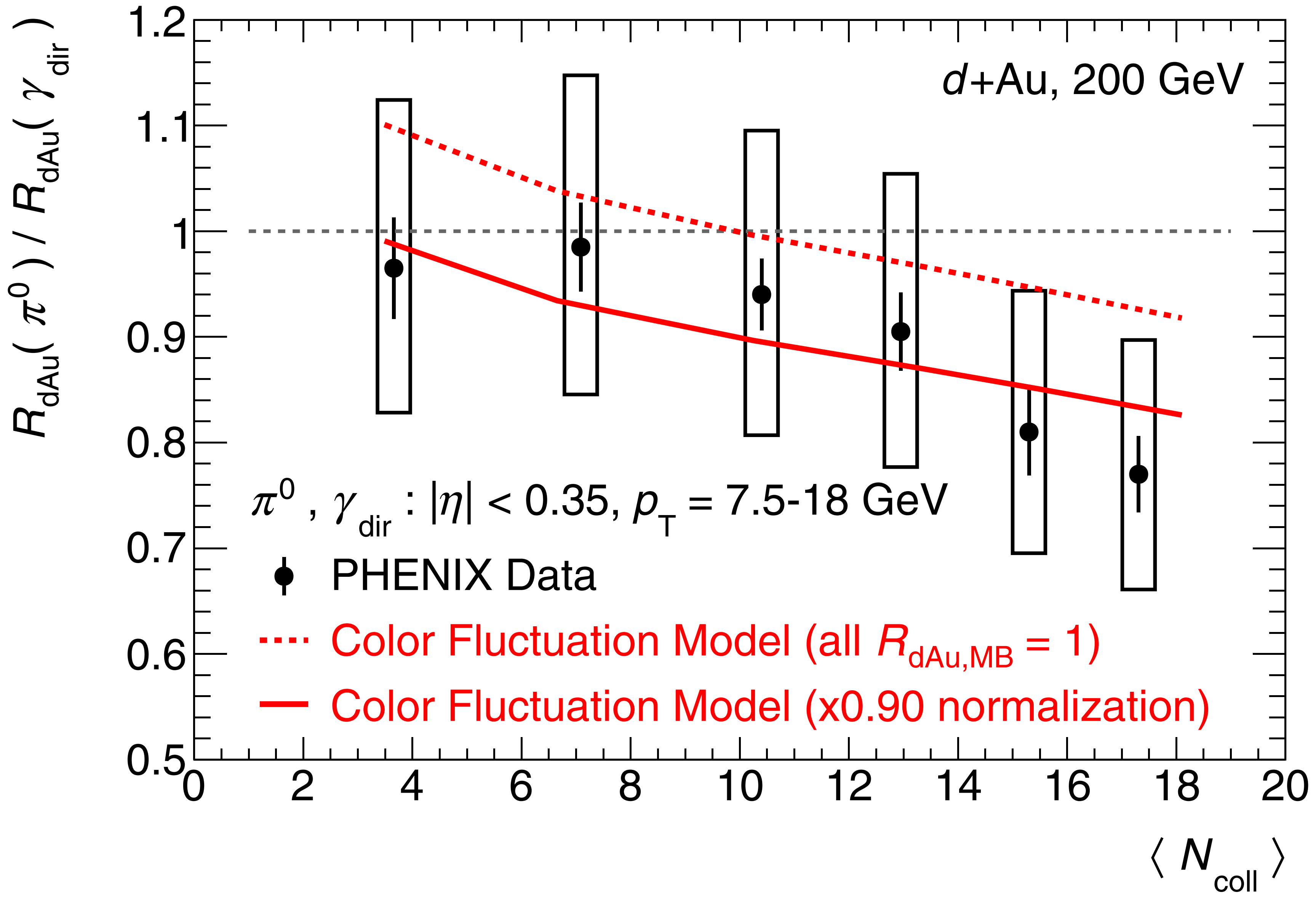
(Received 6 May 2024; accepted 20 June 2024; published 1 July 2024)

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.

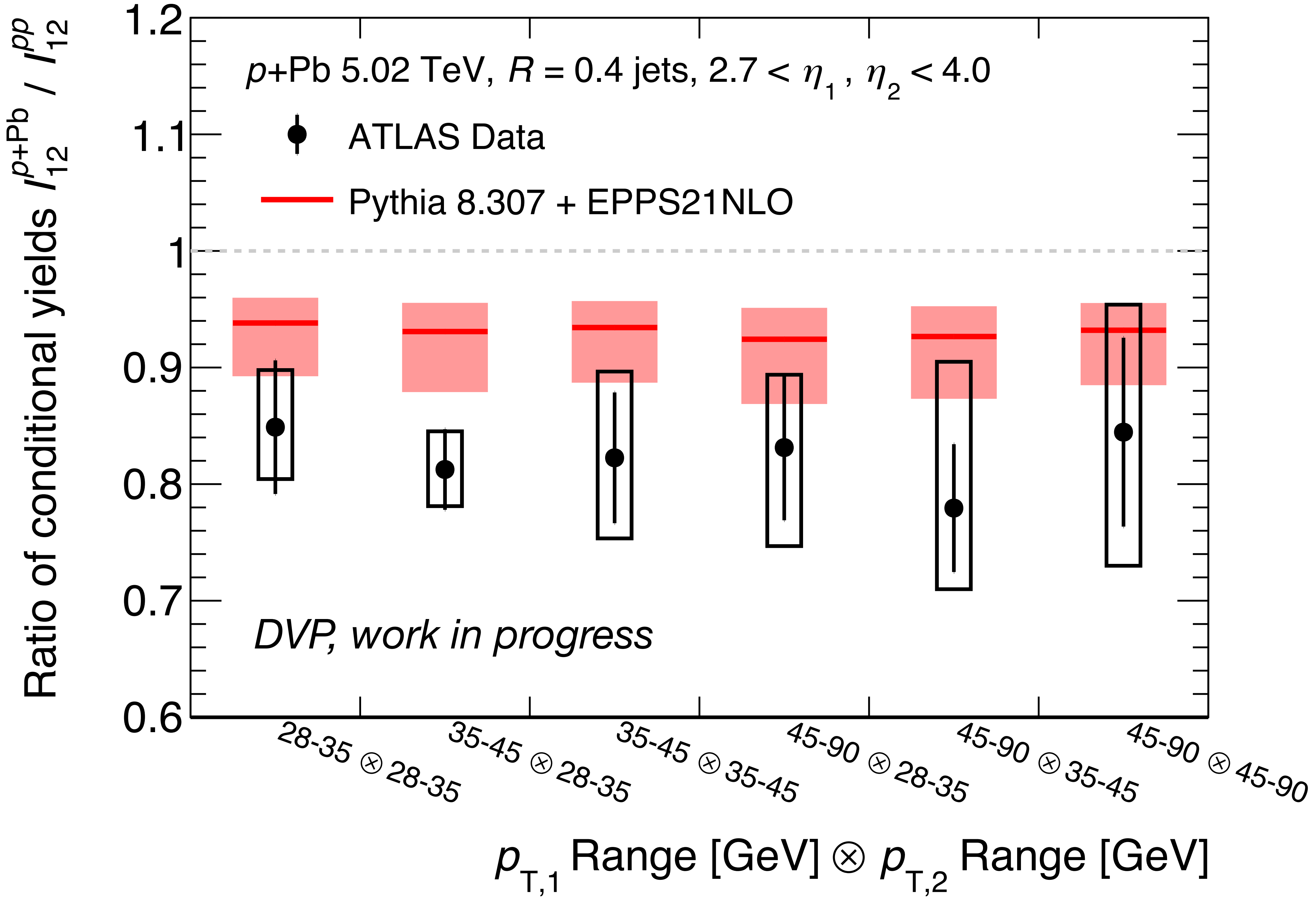
DOI: 10.1103/PhysRevC.110.L011901

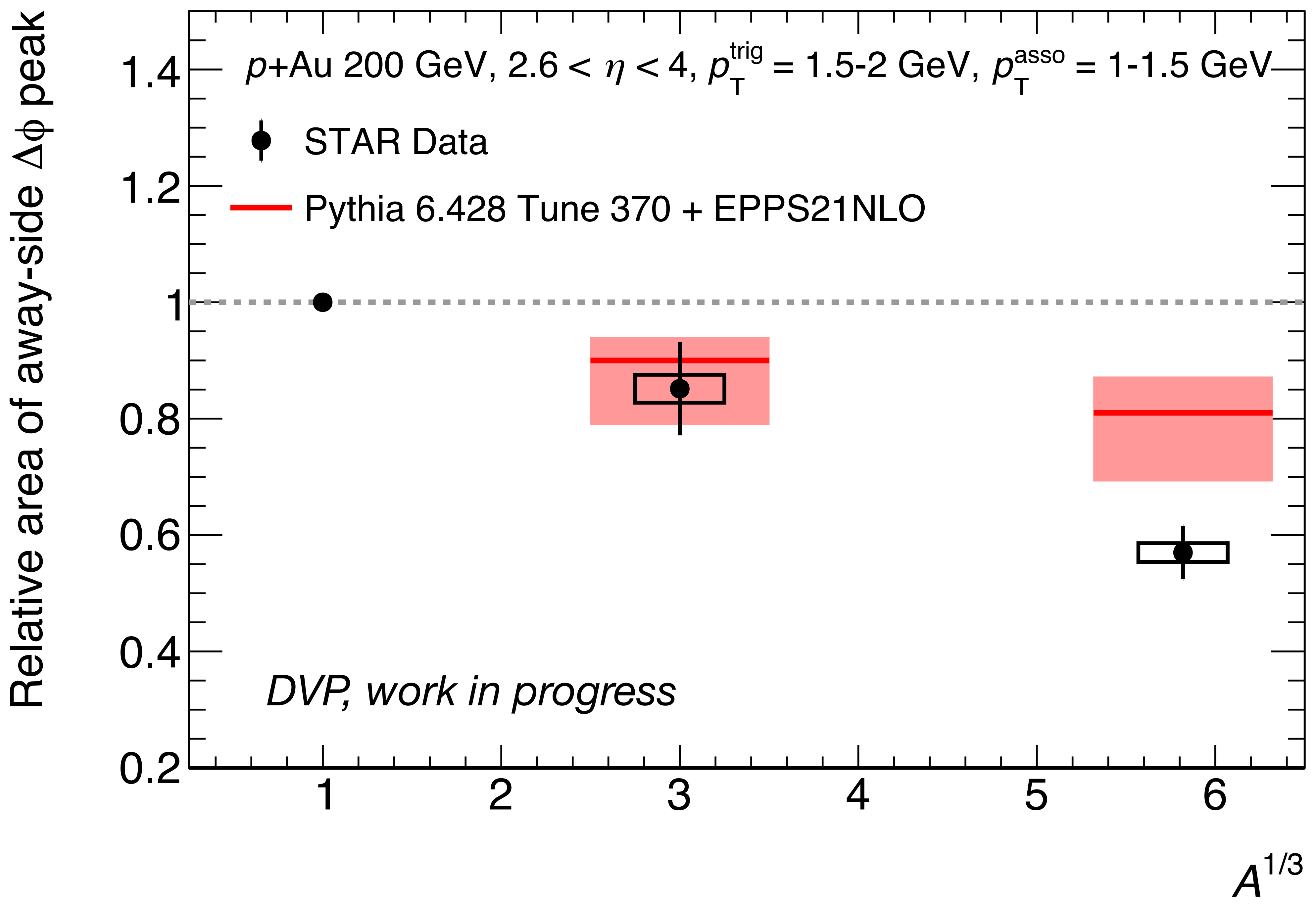


Iurii Mitrankov (Wed.)

Recent example: PHENIX $\pi^0/\gamma_{\mathrm{dir}}$ suppression in d+Au collisions - conjectured to be small system energy loss - also compatible with a large-x_p "color fluctuation" picture

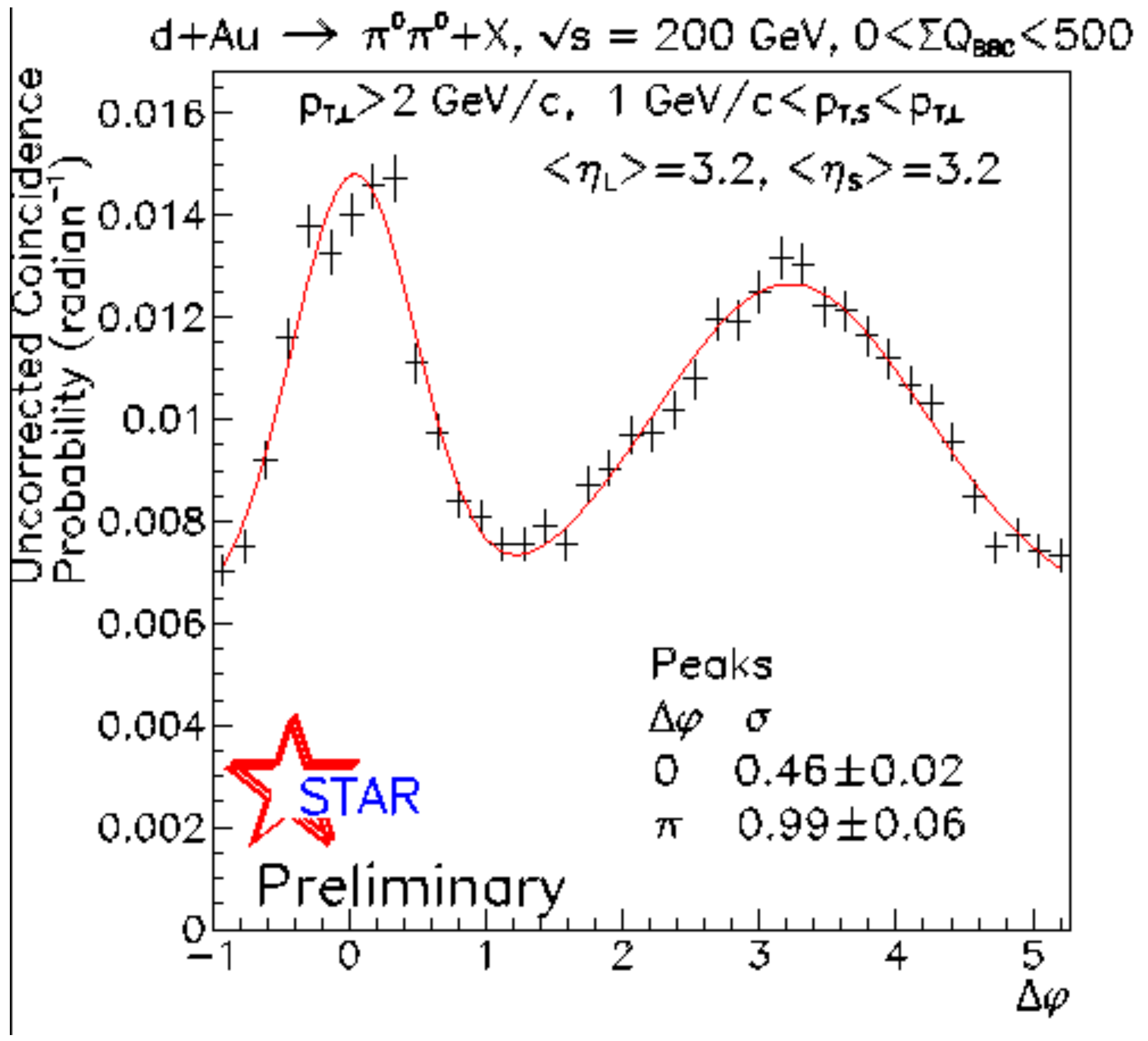
Conclusion

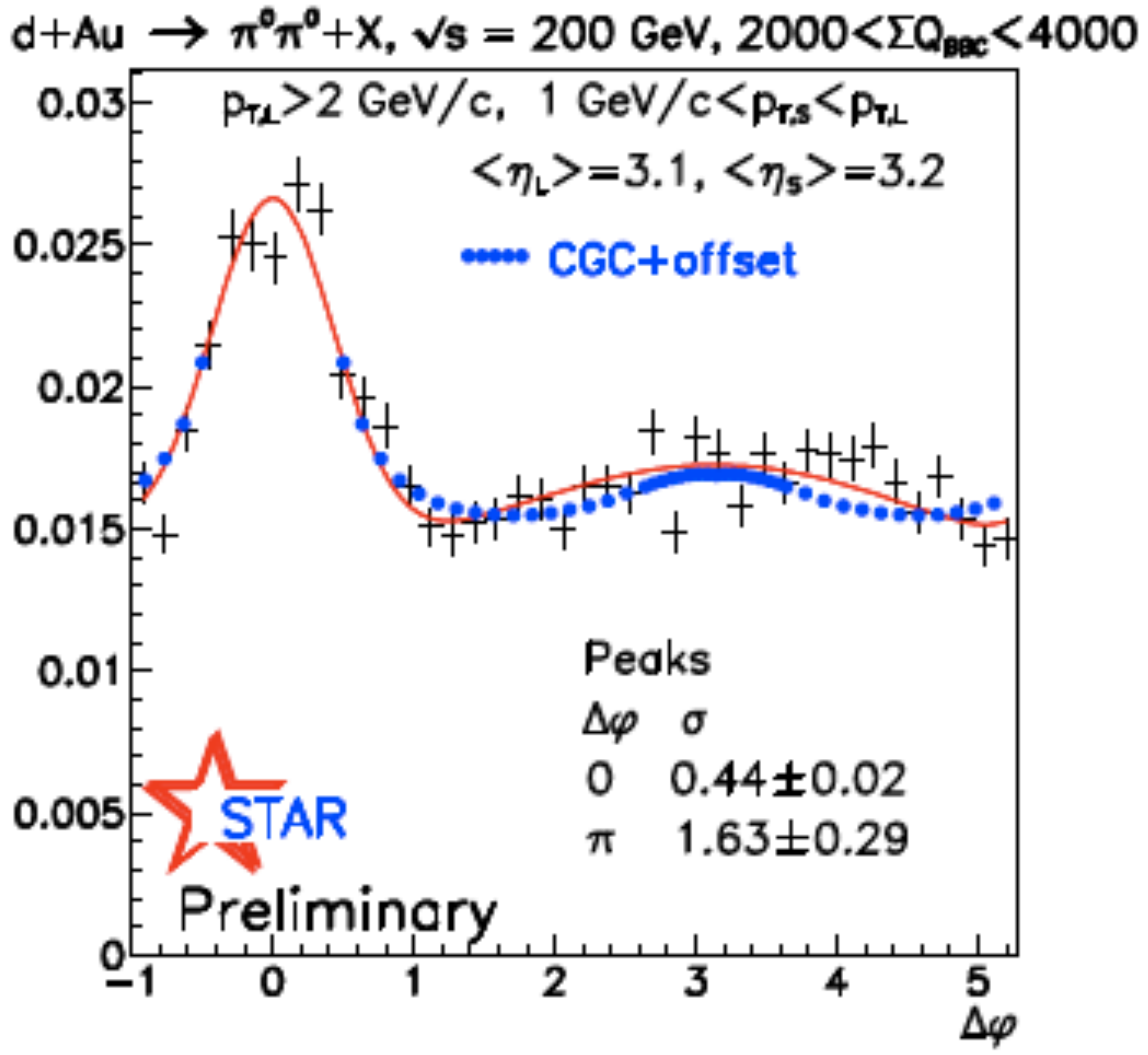




- Fact: A straightforward application of nPDF effects to LHC *p*+Pb di-jet and RHIC *p*+Au di-hadron data is compatible with a significant fraction of reported "saturation" signals
  - ➡ Should a collinear factorization + nPDF picture be expected to describe this? What are the limitations of these approaches?
  - ➡ n.b. EPPS21 authors note that they do not observe any "inconsistency" in the input datasets — nuclear data are compatible with a universal modification in (x, Q^2).

Early measurements in *d*+Au at RHIC





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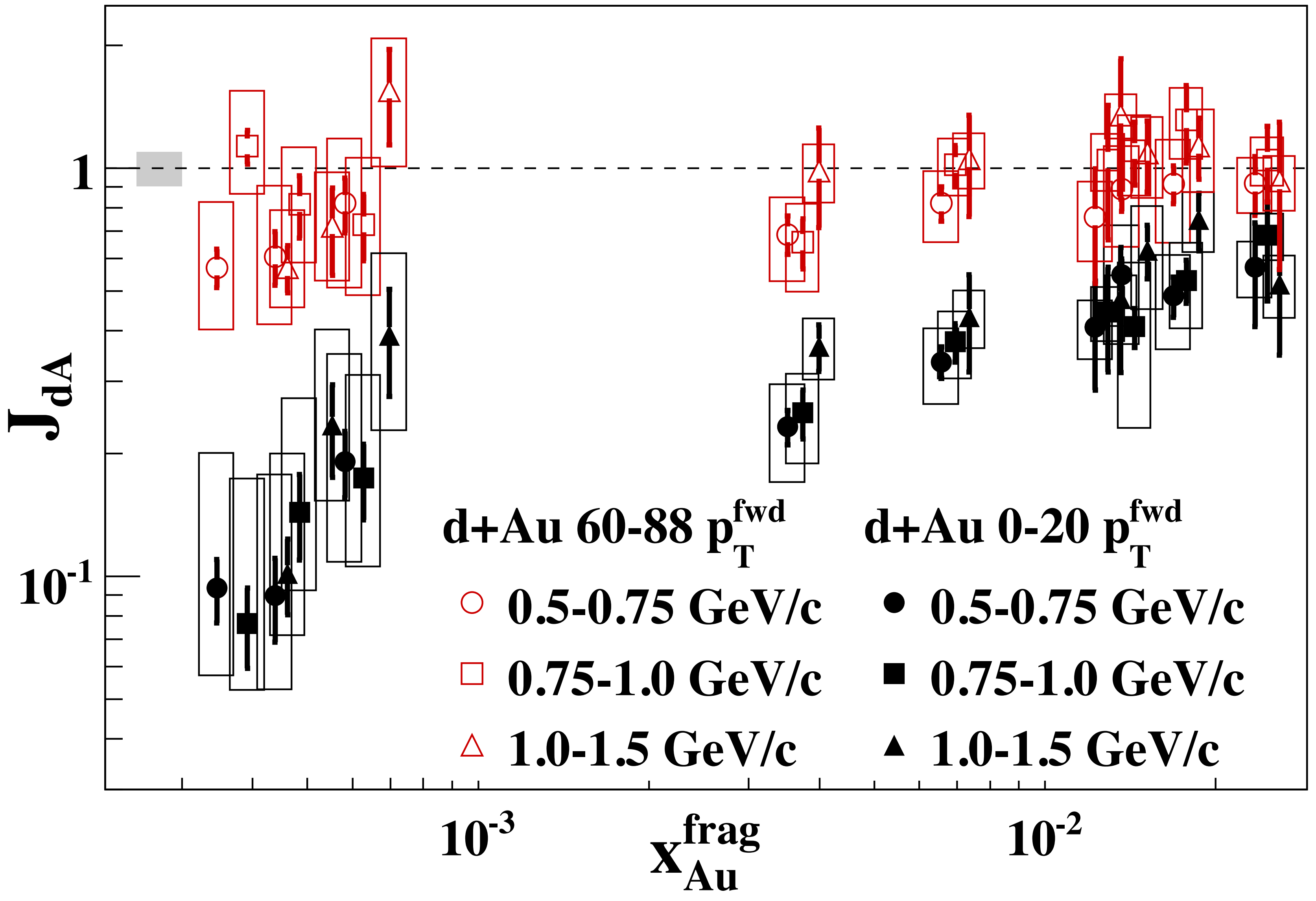
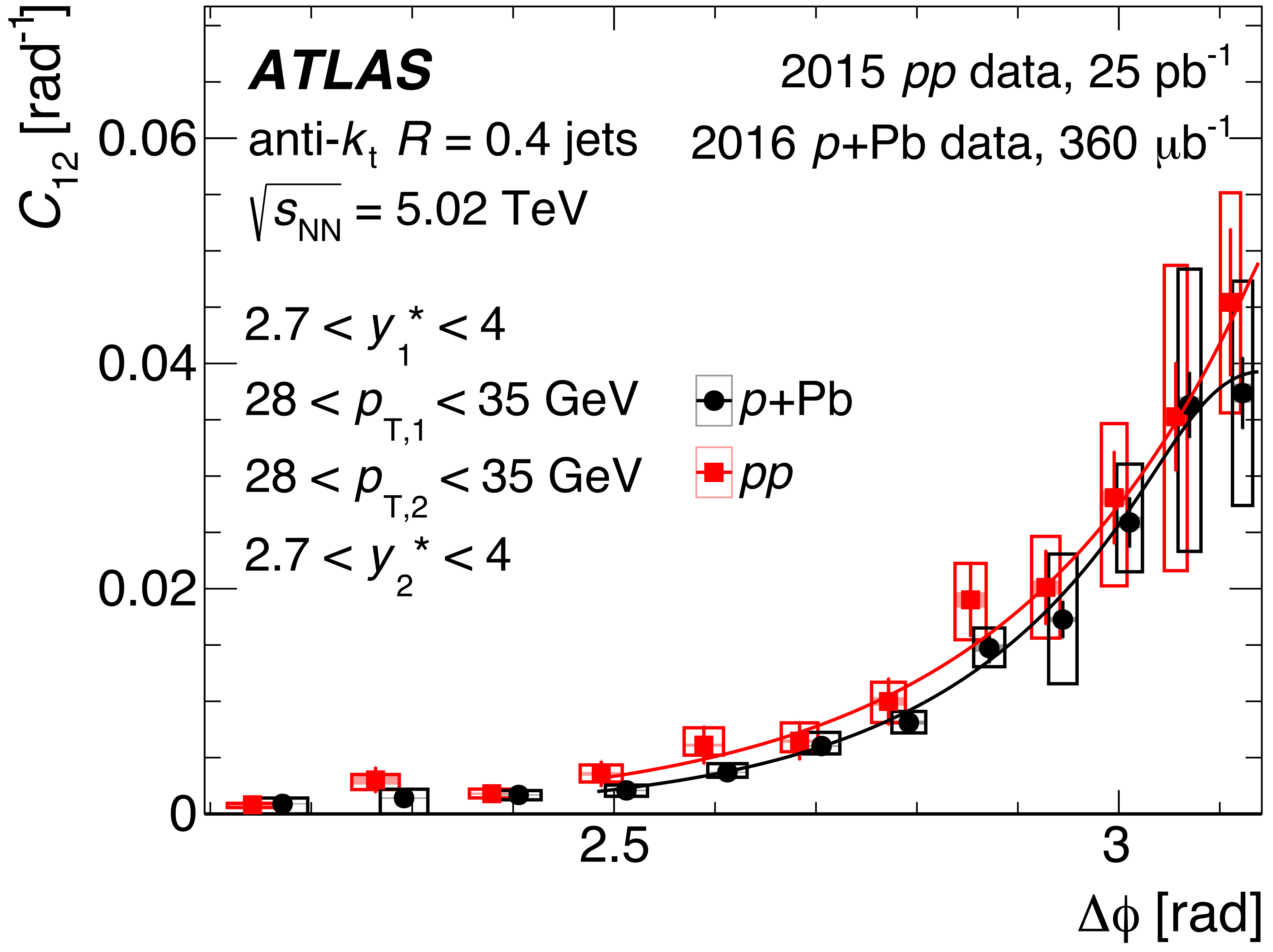


Strongly suppressed/broadened away-side correlation in *d*+Au $\rightarrow \pi^0\pi^0 + X$

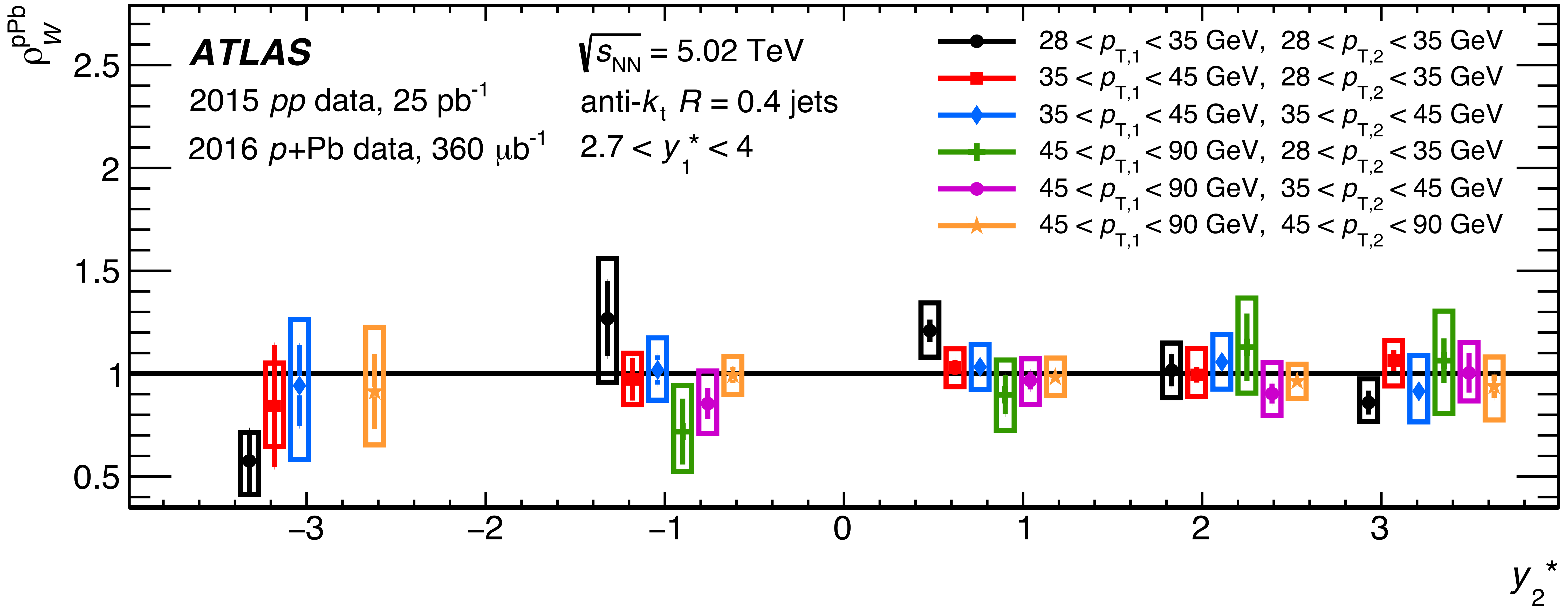
Strong suppression of per-trigger yields for forward di-hadrons

- Dramatic effects seen STAR and PHENIX!
- Note: both of these historical measurements involve centrality selections in *p*/*d*+A collisions, which we would be more cautious about if performed now (discussed later)

Forward di-jet data at LHC - angular broadening



Comparison of the $\Delta\phi$ distribution between forward di-jet pairs in ***p+p*** and ***p*+Pb**



Ratio of $\Delta\phi$ width in *p*+Pb / *p*+*p*

No significant change in width observed for any kinematic selection

- ATLAS sees a change in per-trigger yield, but via an overall suppression that doesn't change the width of the correlation function

➡ Together, these features of the data are **a challenge for saturation-based explanations**