Can a universal nPDF picture describe di-hadron saturation signals?

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Description of di-hadron saturation signals within a universal nuclear PDF picture

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Di-hadron and di-jet correlation measurements in proton–nucleus (p+A) and electron–nucleus collisions are widely motivated as sensitive probes of novel, non-linear QCD saturation dynamics in hadrons, which are particularly accessible in the dense nuclear environment at low values of Bjorken-x (x_{A}). Current measurements at RHIC and the LHC observe a significant suppression in the per-trigger yield at forward rapidities compared to that in proton–proton collisions, nominally consistent with the "mono-jet" production expected in a saturation scenario. However, the width of the azimuthal correlation remains unmodified, in contradiction to the qualitative expectations from this physics picture. I investigate whether the construction of these observables leaves them sensitive to effects from simple nuclear shadowing as captured by, for example, universal nuclear parton distribution function (nPDF) analyses. I find that modern nPDF sets, informed by recent precision measurements sensitive to the shadowing of low-x_{A} gluon densities in LHC and other data, can describe all or the majority of the di-hadron/jet suppression effects in p+A data at both RHIC and the LHC, while giving a natural explanation for why the azimuthal correlation width is unmodified. Notably, this is achieved via a (x_{A}, Q^2)-differential suppression of overall cross-sections only, without requiring additional physics dynamics which alter the inter-event correlations.

[based on nucl-th/2501.18347]

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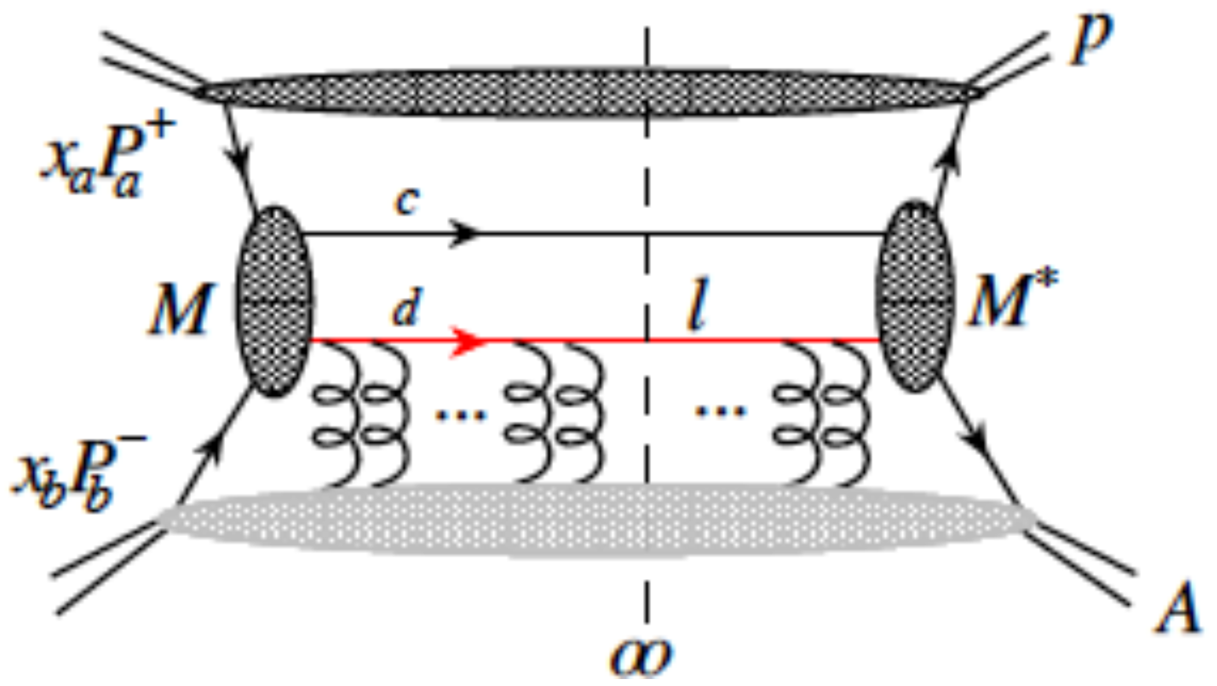
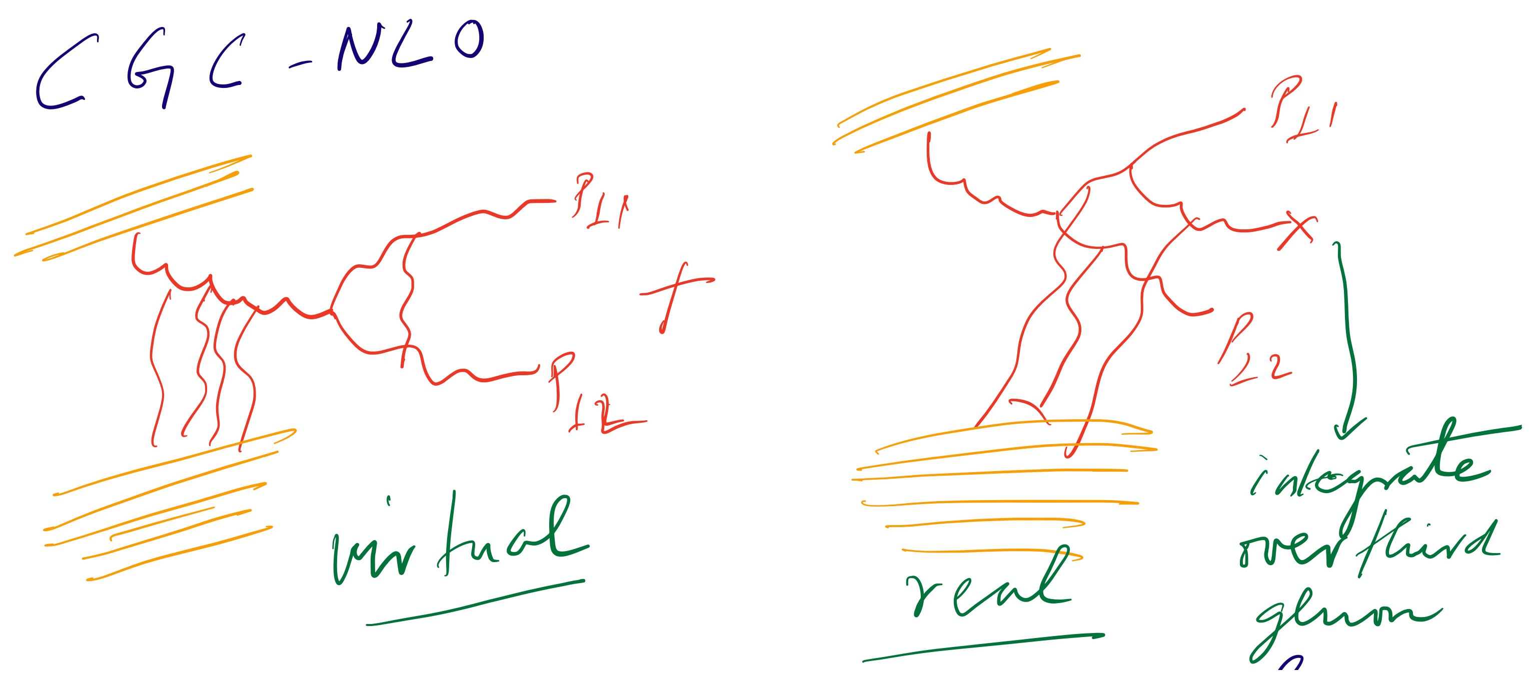
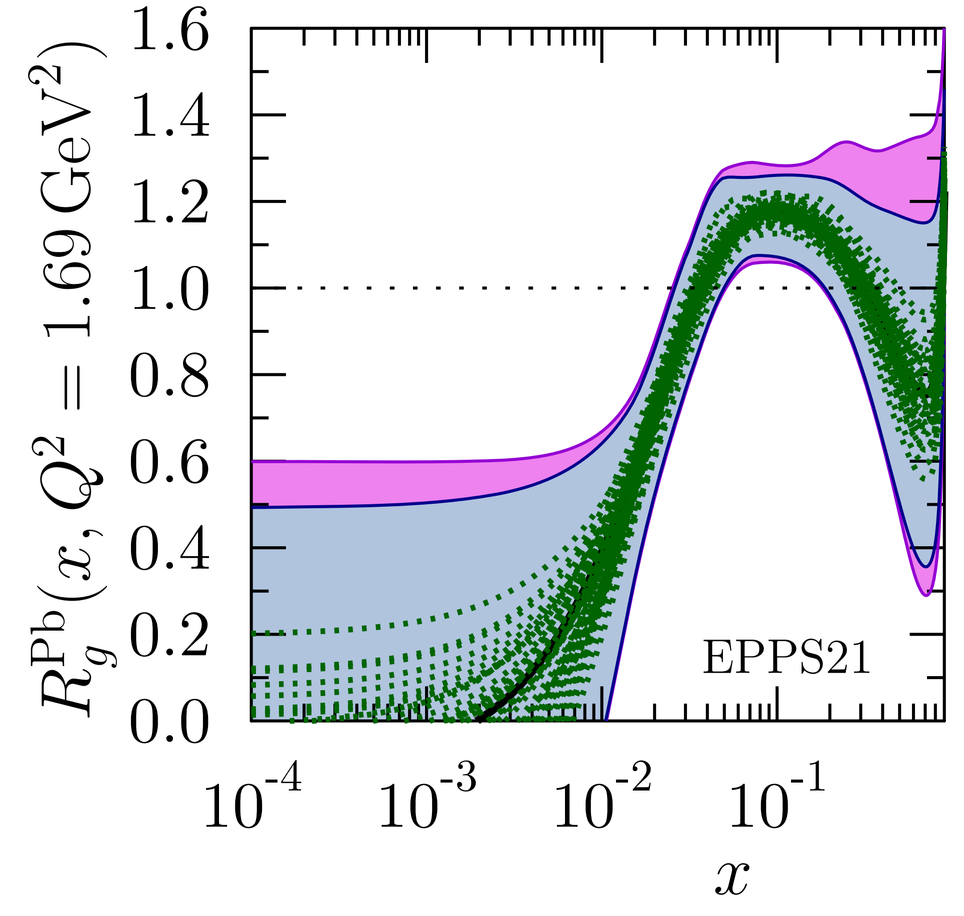
Frameworks for *p*+A collisions



Coherent multiple scattering



Glasma diagram (courtesy Raju Venugopalan)



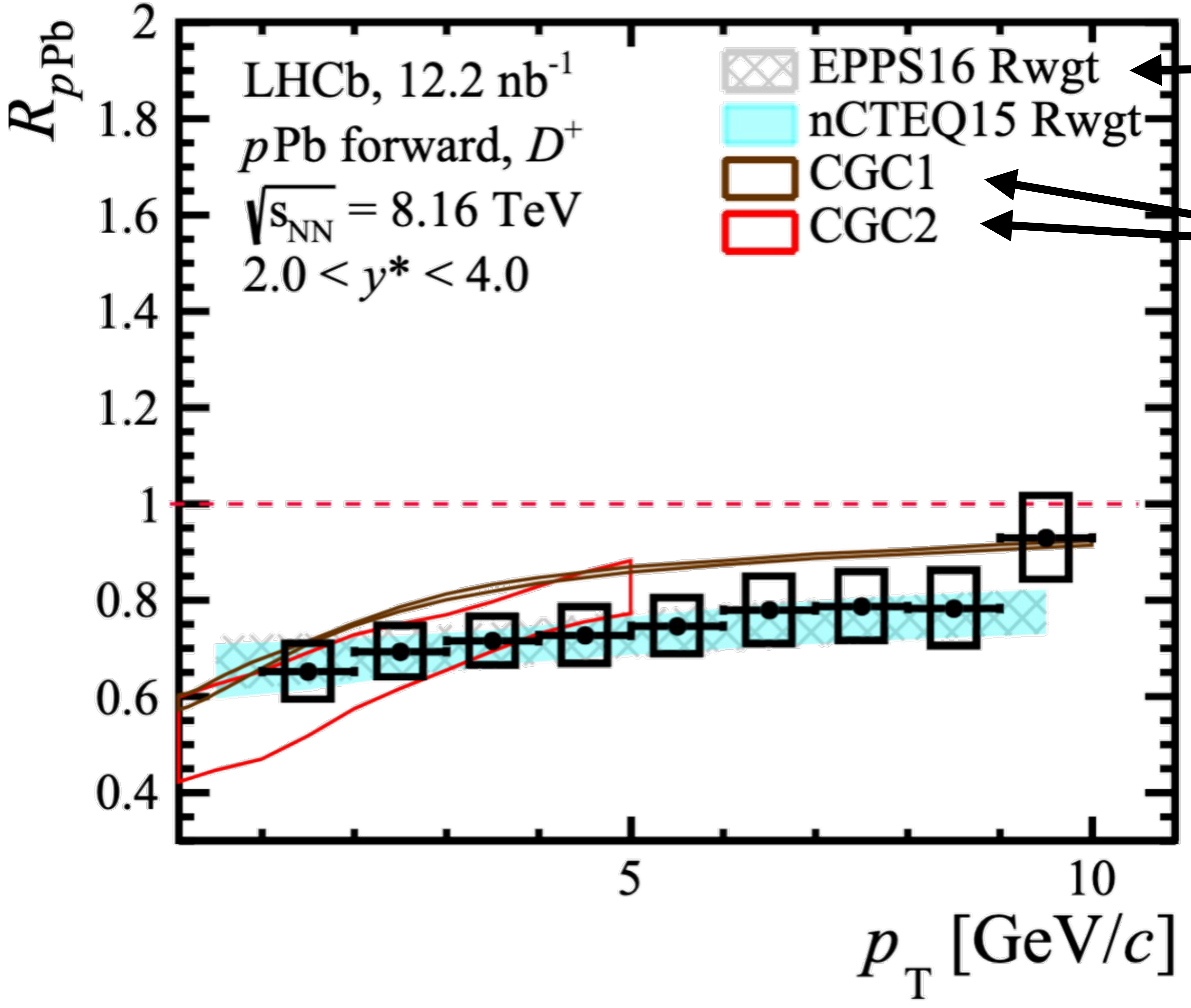
Gluon density modification in nuclei

dynamical description of effects in the initial state of the cold nucleus

pQCD + collinear factorization + nuclear PDF modification universal in (x_A, Q^2)

Two different approaches to describing effects in (semi-)hard processes in *p*+A collisions.

Frameworks for *p*+A collisions

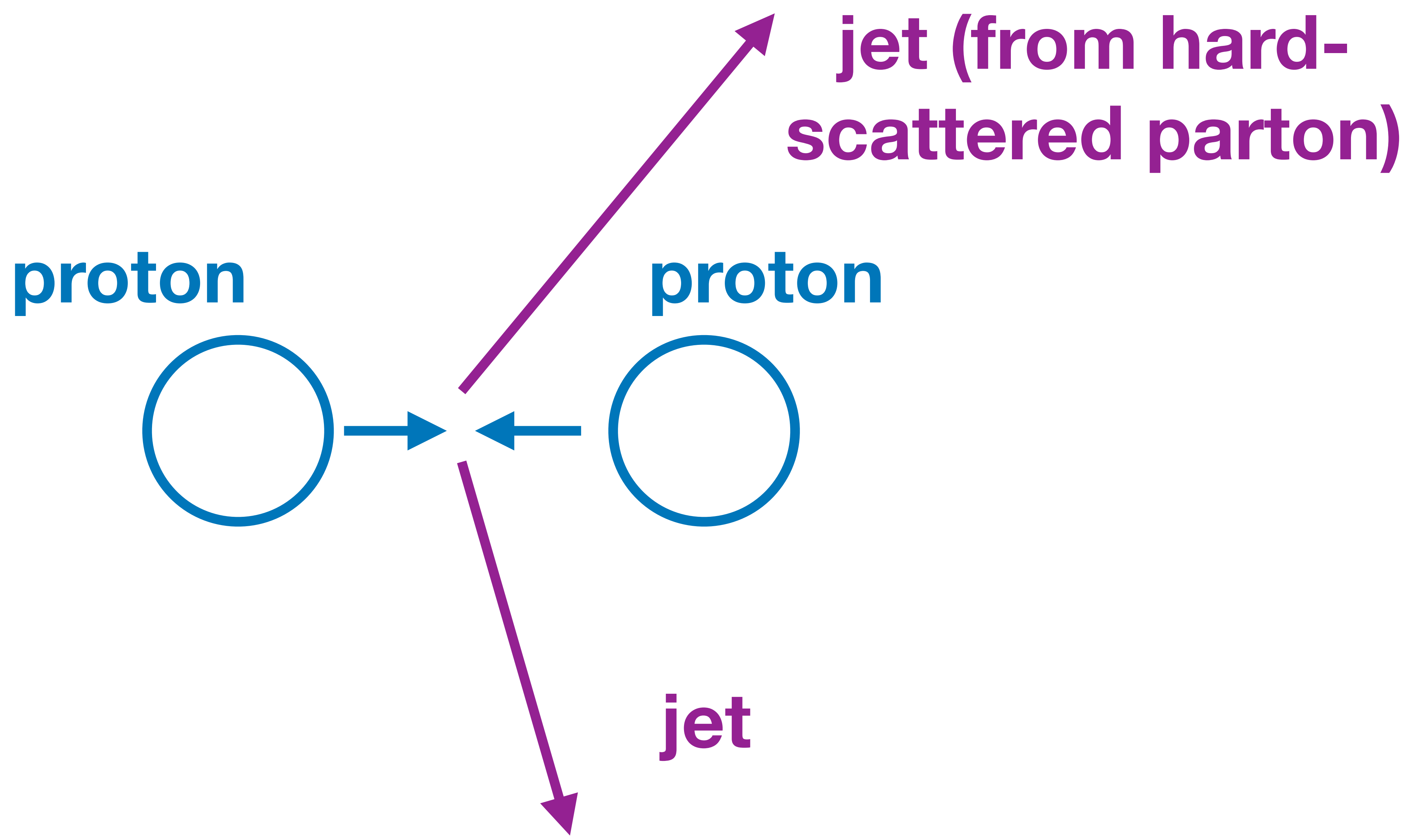


Nuclear PDF modification (nPDF) approach

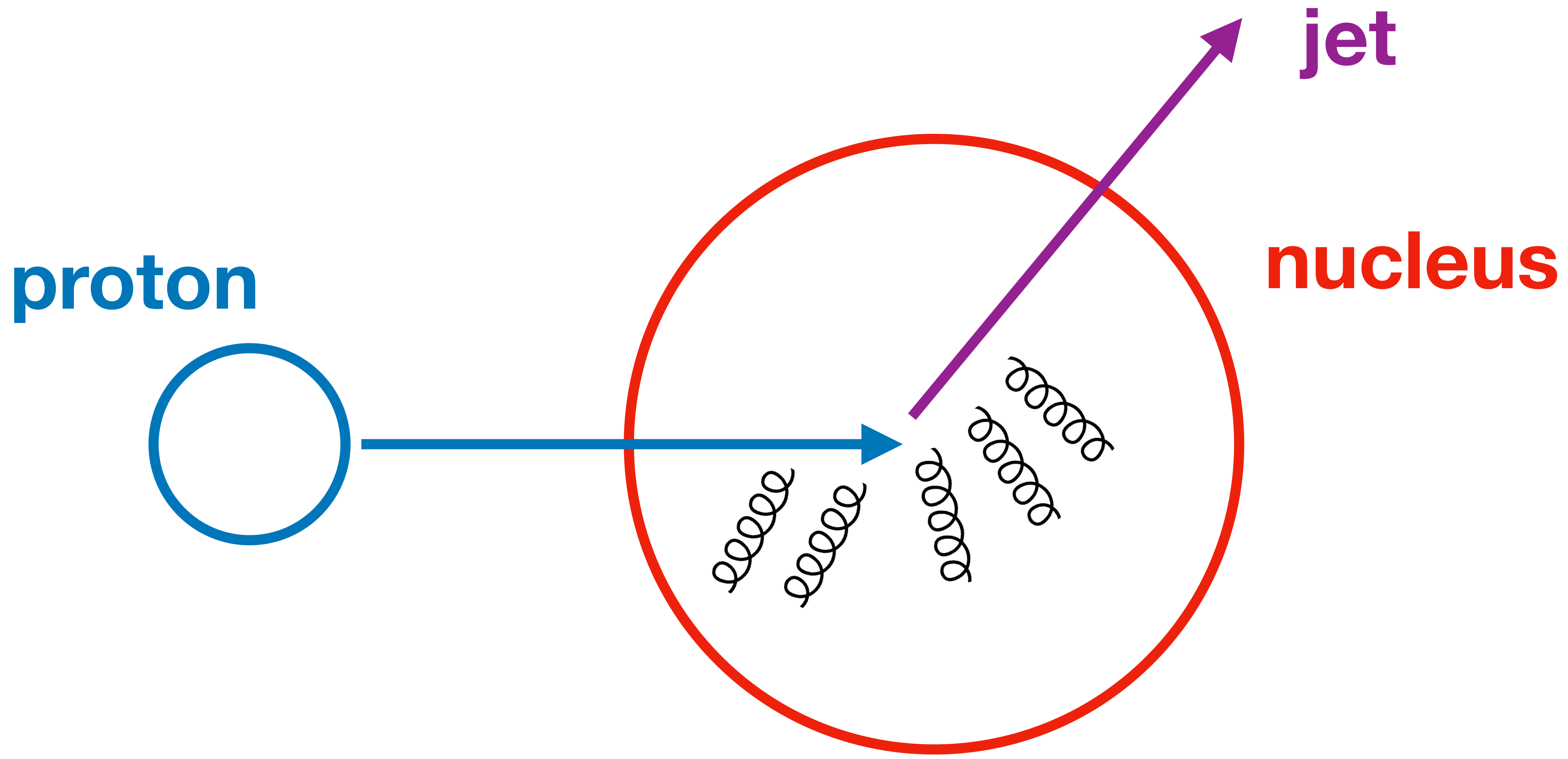
Color Glass Condensate (CGC) effective theory calculation

Are these describing distinct phenomena? Or different ways of capturing the same physics?

Mono-jet production in saturated nuclei



"Ordinary" leading-twist 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

General expectation in saturation picture:

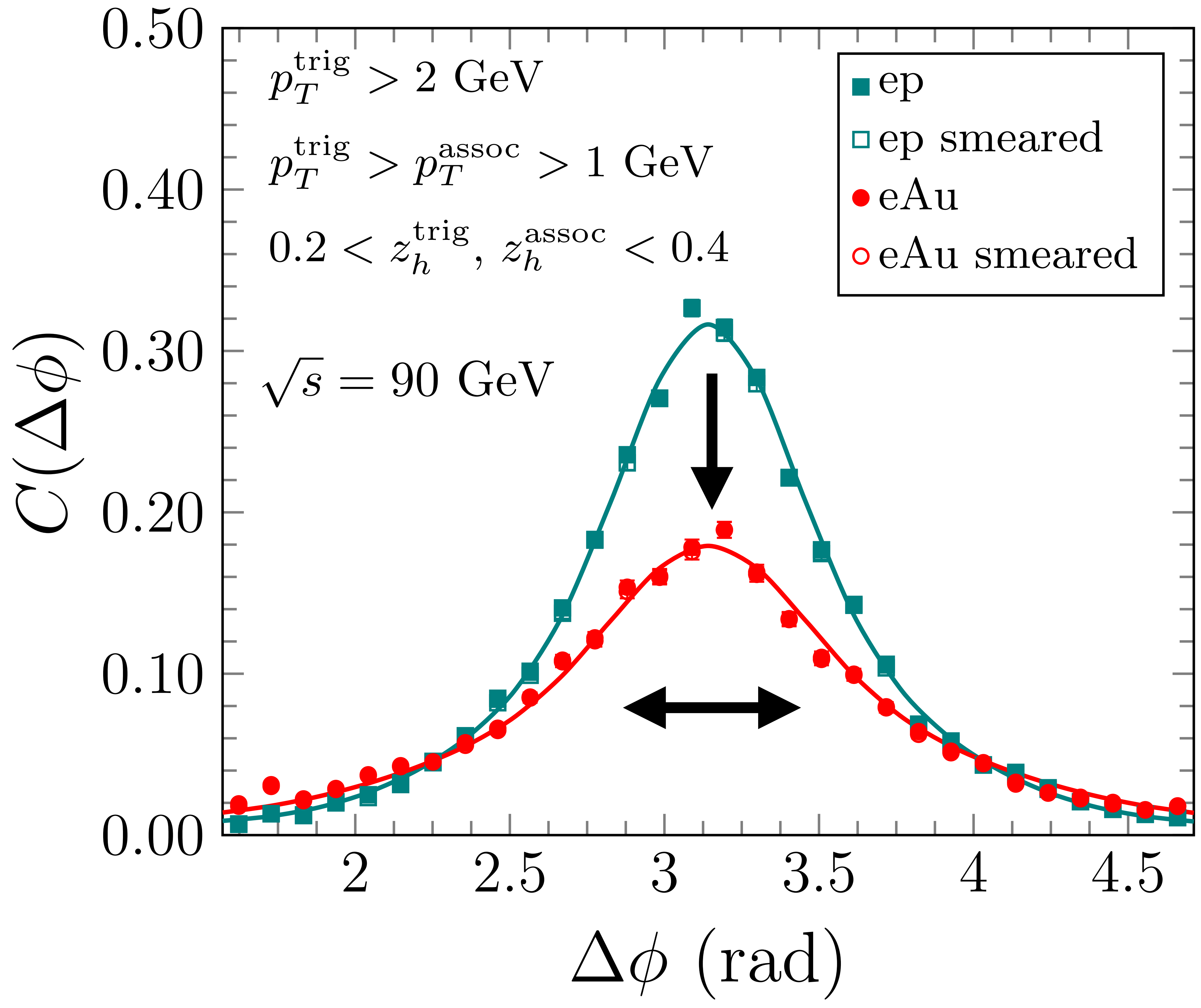
(1) **decrease** in per-trigger yield ↓

(2) **broadening** of the remaining correlation function ↔

Long history within CGC framework:

Jalilian-Marian, Kovchegov (2004)
Kharzeev, Levin, McLerran (2005)
Marquet (2007)
Stasto, Xiao, Yuan (2012)
Kutak, Sapeta (2012)
Albacete, Giacalone, Marquet, Matas (2019)
… many, many others

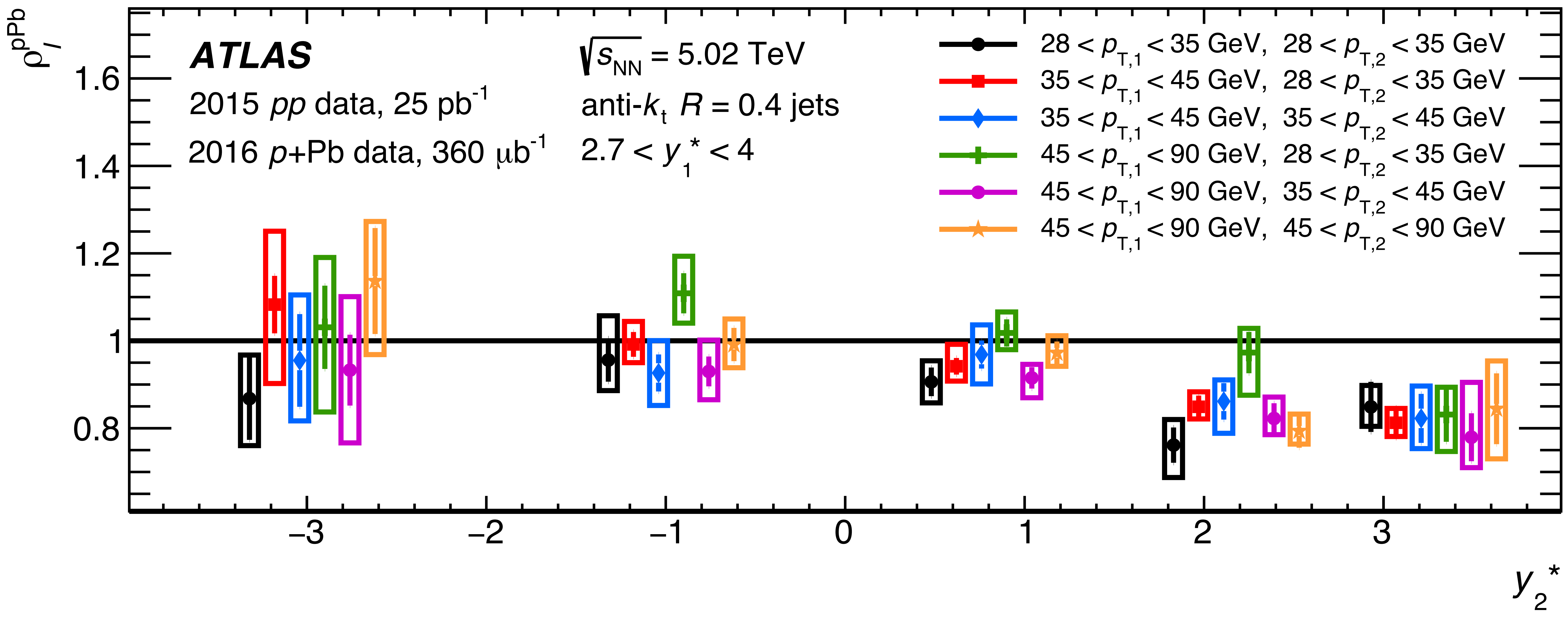
EIC Yellow Report, physics.ins-det/2103.05419



Also expected "smoking gun" signal of saturation at EIC!

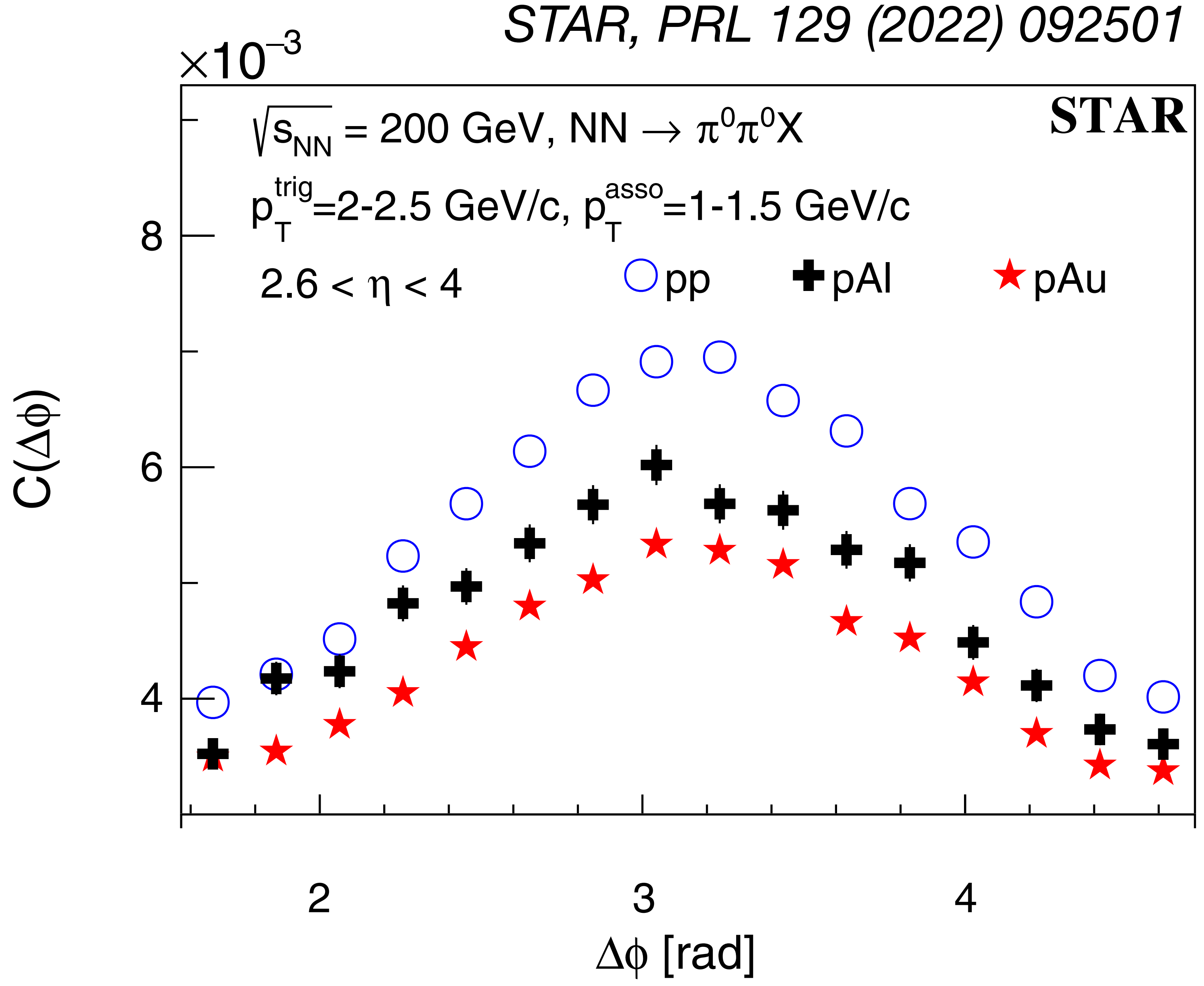
Recent measurements at RHIC and LHC

ATLAS, PRC 100 (2019) 034903



Forward di-jets in p+Pb by ATLAS

STAR, PRL 129 (2022) 092501



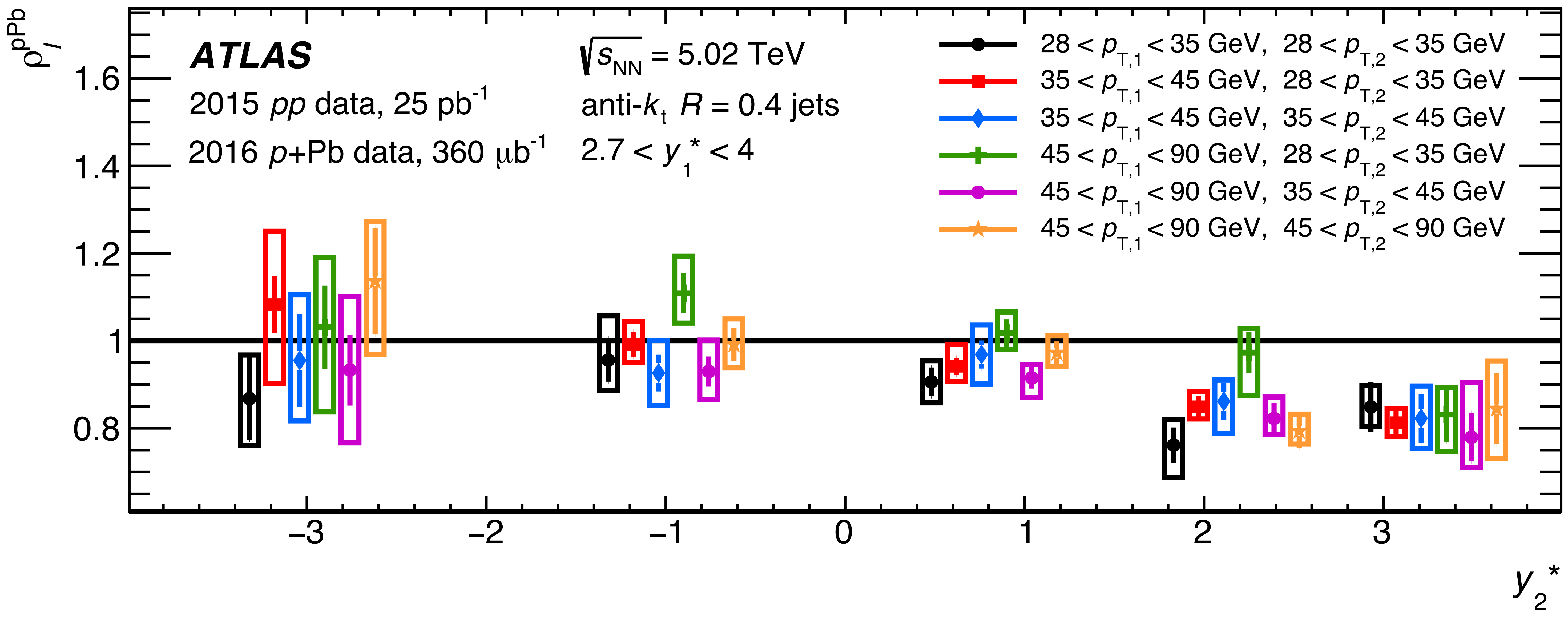
Forward di-hadrons in p+Au by STAR

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

In both measurements, **no change in $\Delta\phi$ correlation shape** — challenging for saturation description …

Recent measurements at RHIC and LHC

ATLAS, PRC 100 (2019) 034903



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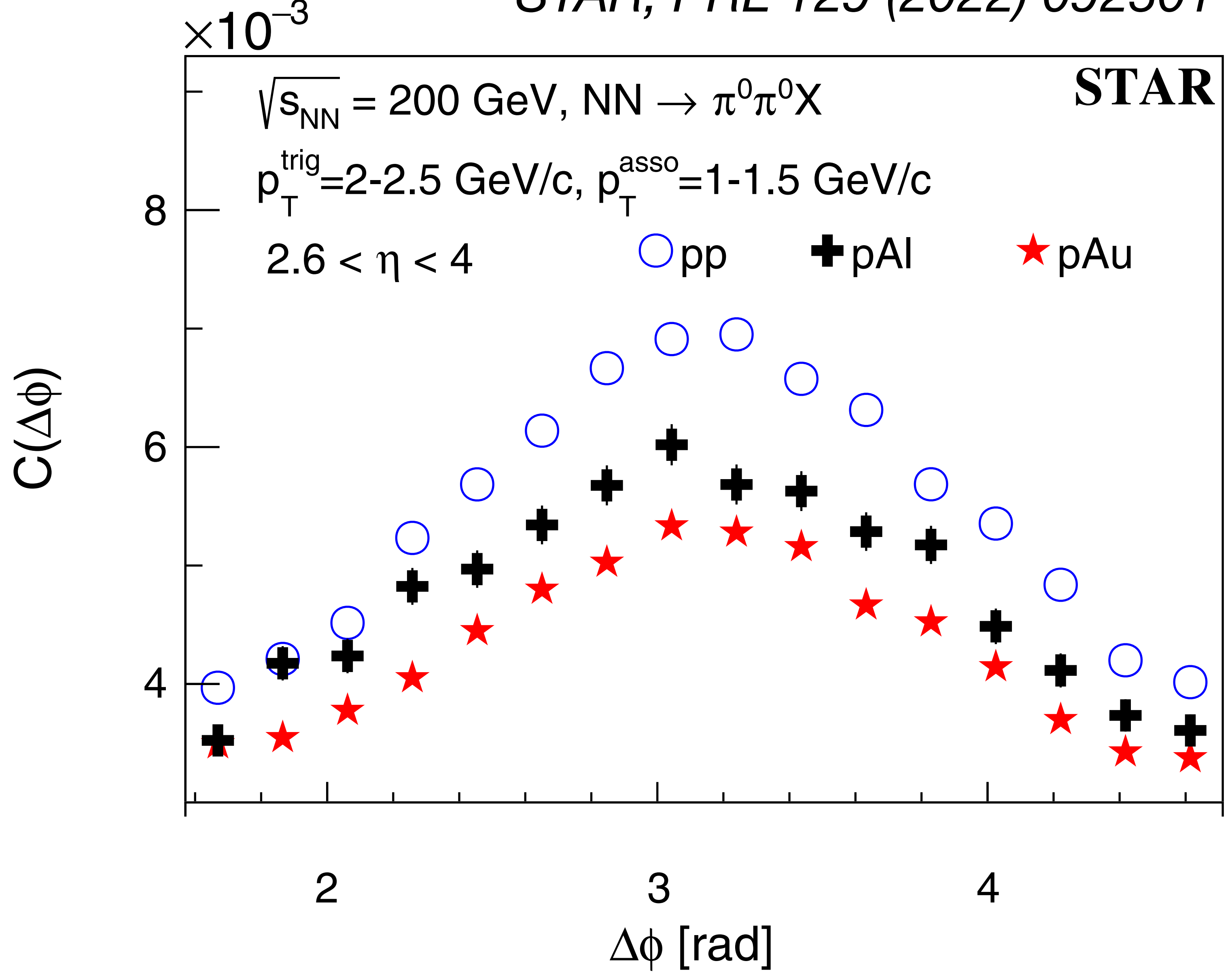


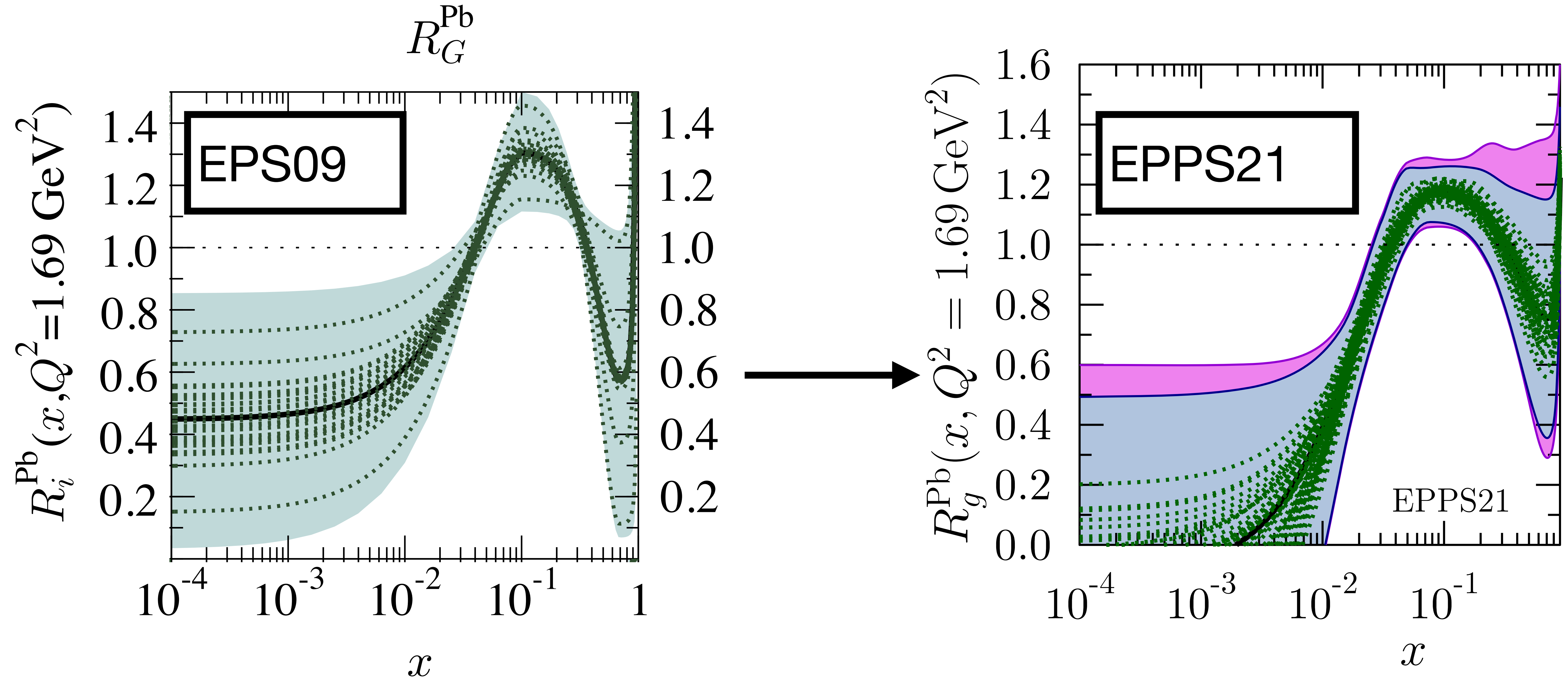
Forward di-hadrons in p+Au by STAR

This talk: what part of the effect in data, if any, could be described with "ordinary" nPDF modification, i.e. in a collinear factorization picture?

An exploratory study using MC event generators to gauge the possible signal from recent nPDF sets …

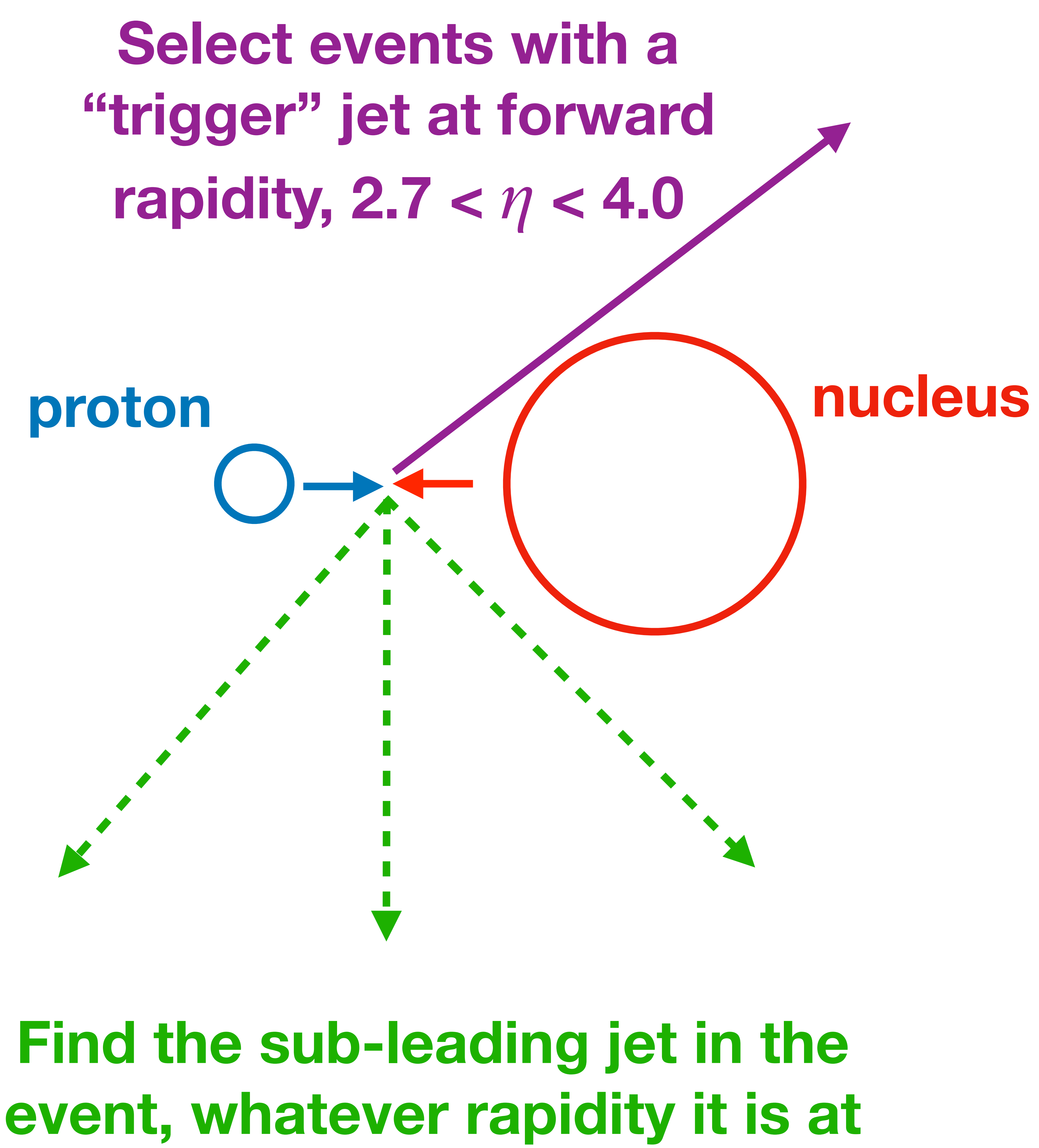
Shadowing in recent nPDF sets

- Many nPDF sets have recent updates incorporating LHC data sensitive to the low-x_A region - very strong shadowing!



- Note: nPDF's can't change inter-event correlations. They can only statistically upweight/downweight sets of events, and based only on their (x_A, Q^2)

ATLAS measurement selection



Measure the per-trigger yield

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

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

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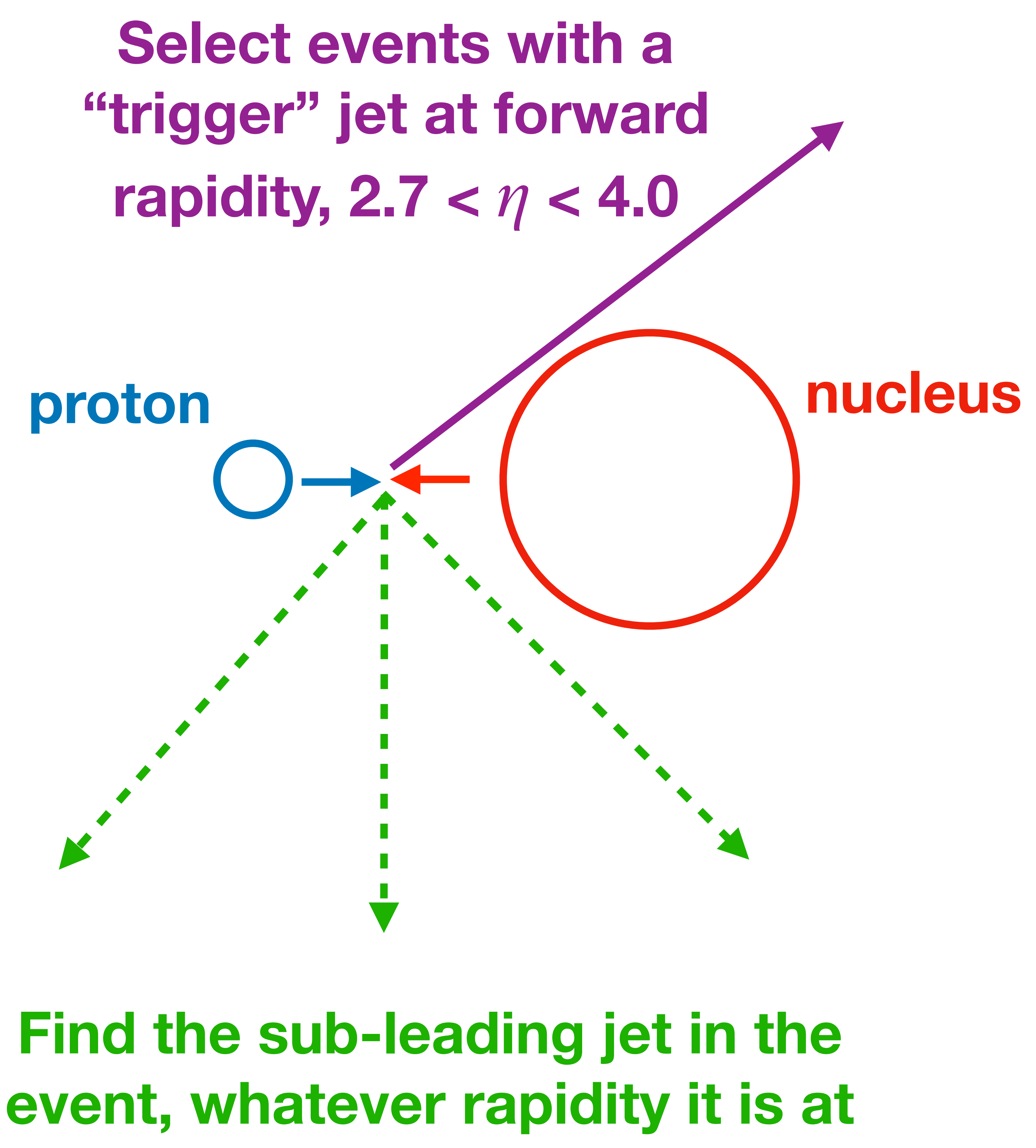

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The per-trigger normalization is sometimes argued to "cancel out" any overall suppression in the cross-section

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

Example of nPDF effect

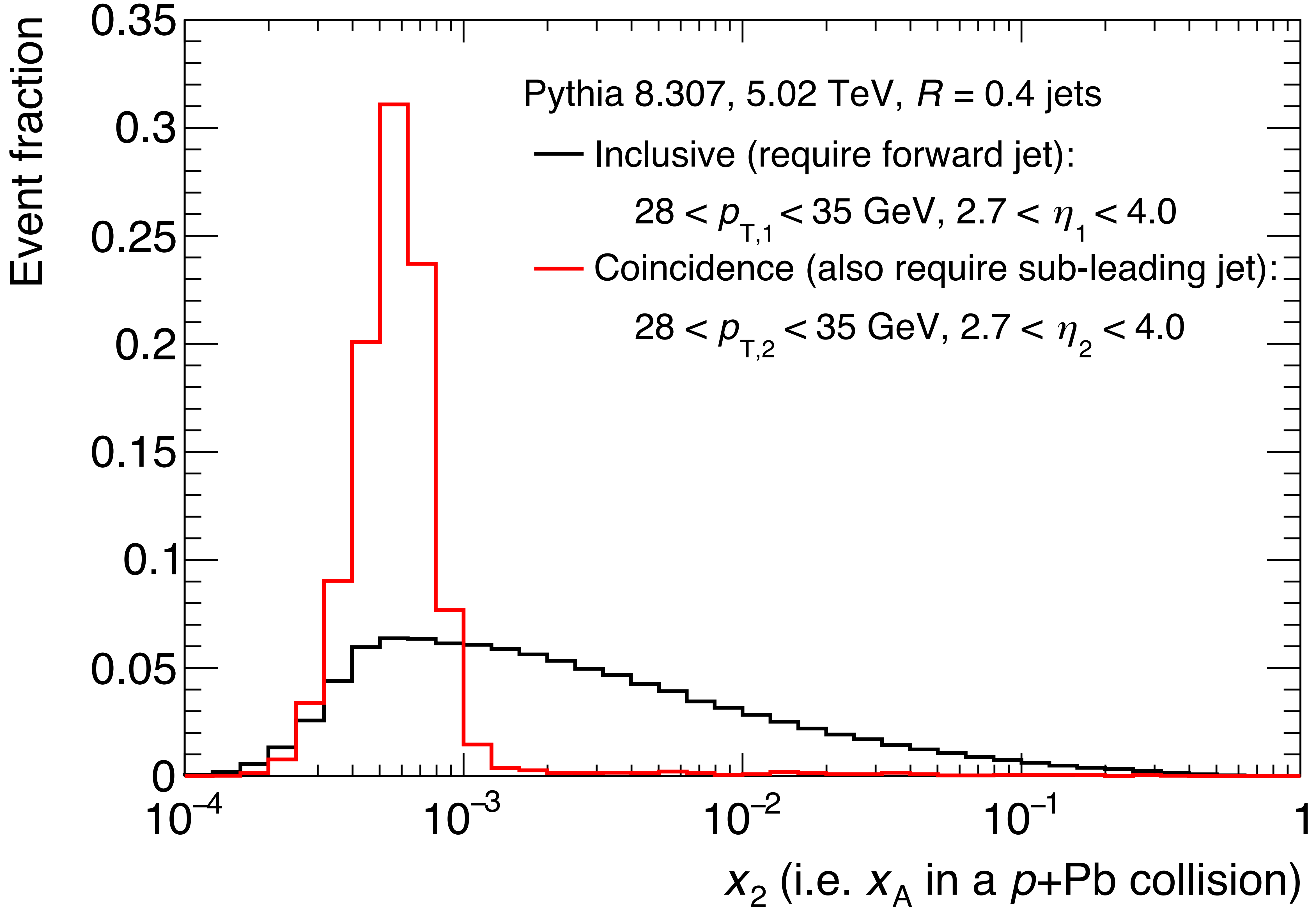
Pythia 8.3, HardQCD, benchmarked against ATLAS di-jet yields & $\Delta\phi$ correlation in *p*+*p* data

Different x_A distributions for:

“Inclusive” (all events w/ a forward jet)

“Coincident” those which have two forward jets

nucl-th/2501.18347



Nominal shadowing in EPPS21NLO:

R_{pA}(inclusive) ~ 0.89, R_{pA}(coincident) ~ 0.84

Per-trigger yield = N_{12} / N_1 suppressed by ~ 0.84/0.89 ~ 0.94 !

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Per-trigger suppression from nPDFs

- Systematically compare to **ATLAS data** in different $p_{T,1} \otimes p_{T,2}$ selections
- Evaluate effects from **EPPS21NLO** for ^{208}Pb + nuclear uncertainties
- Surprising: the nominal nPDF estimate is ~half of the observed effect in data!
  - ➡ Considering full theory + data uncertainties, nPDFs compatible with the *full suppression effect*
  - ➡ Similar central value in **nNNPDF**, but smaller suppression in **nCTEQ15** (no errors shown)

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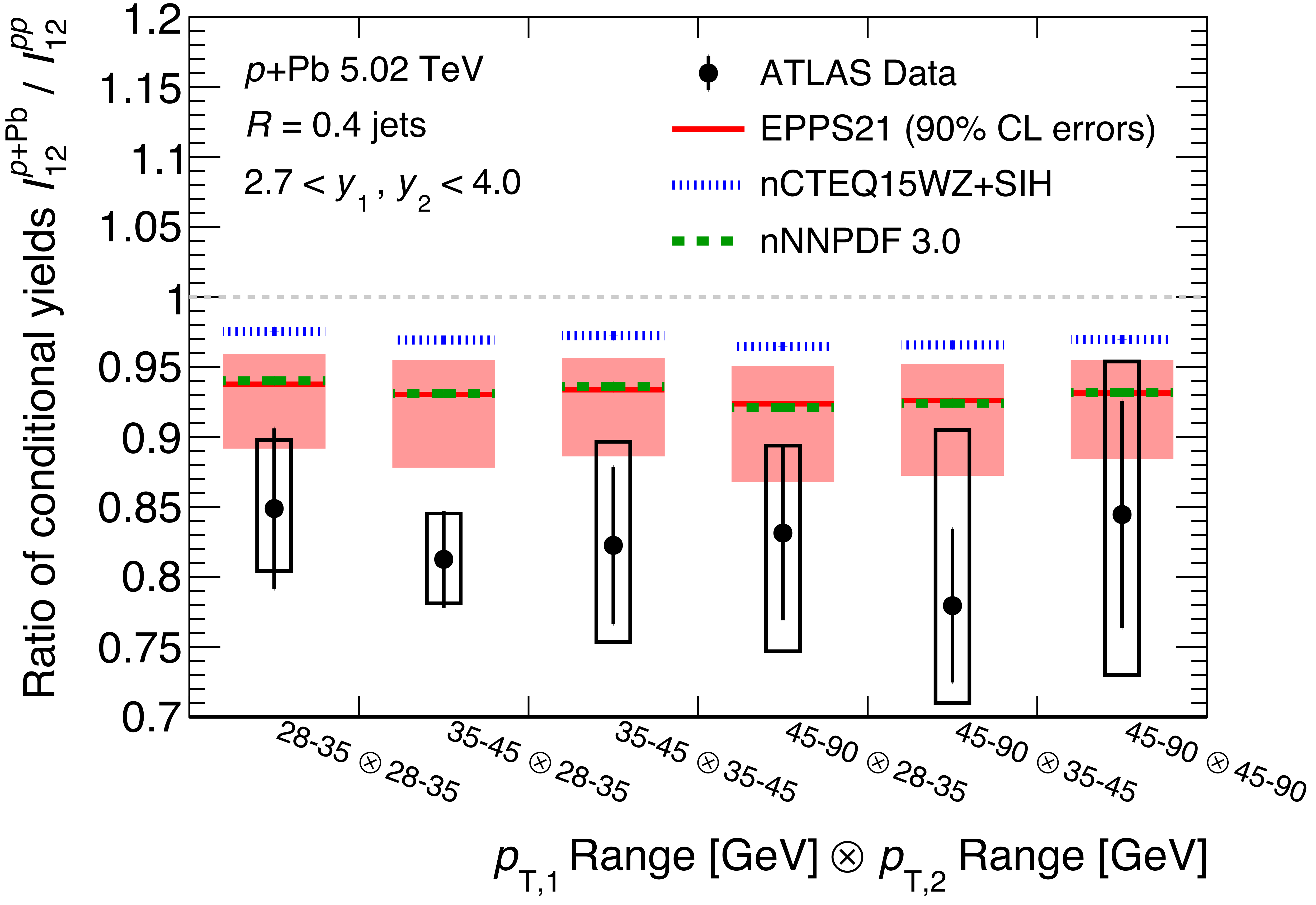

$\Delta\phi$ broadening from nPDF sets?

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

  ➡ Same pattern as in the data

- Thus the nPDF picture "naturally" results in:

  1. a suppression of the per-trigger yield,

     while at the same time,

  2. no broadening (since inter-event correlations aren't changed)

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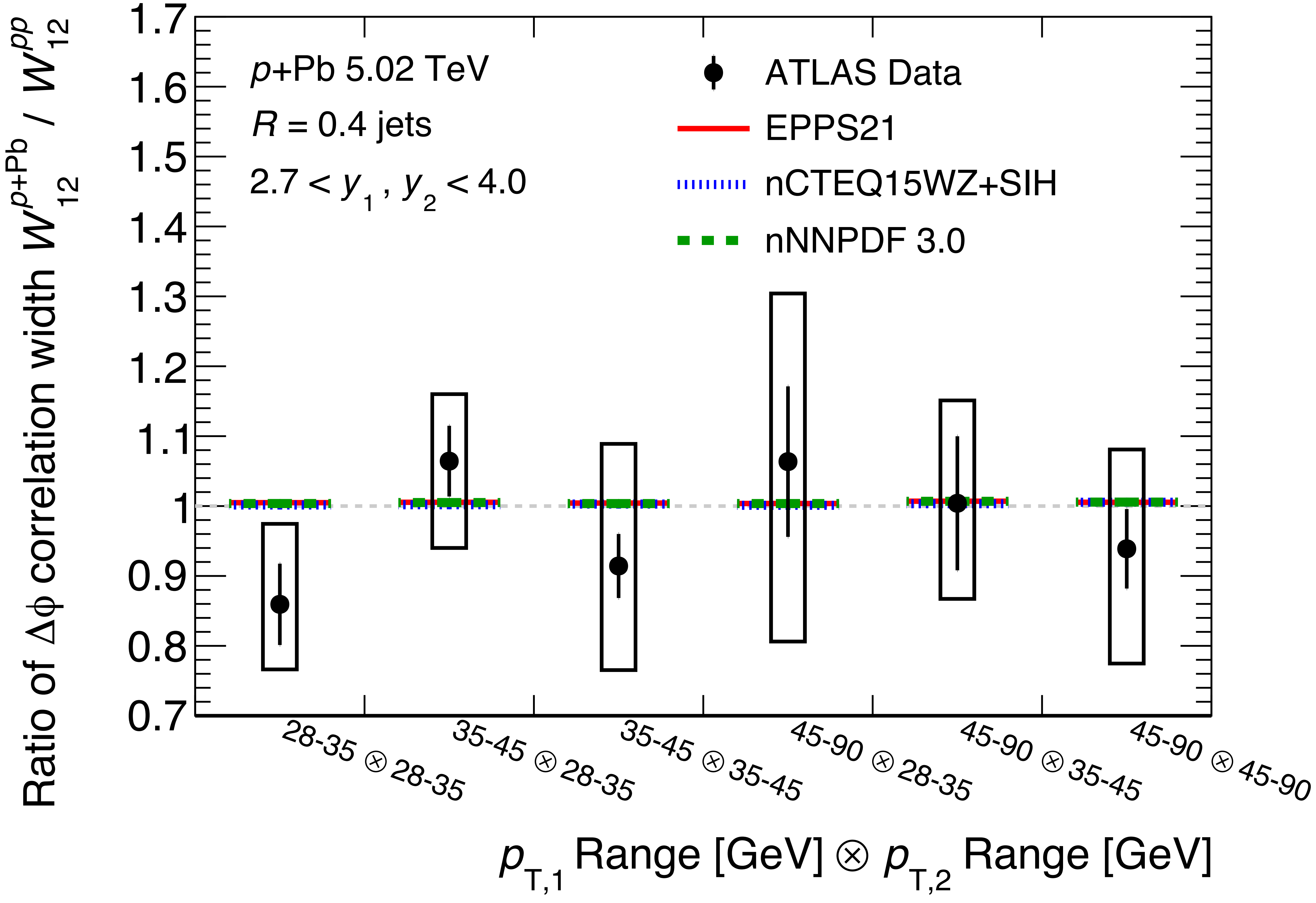
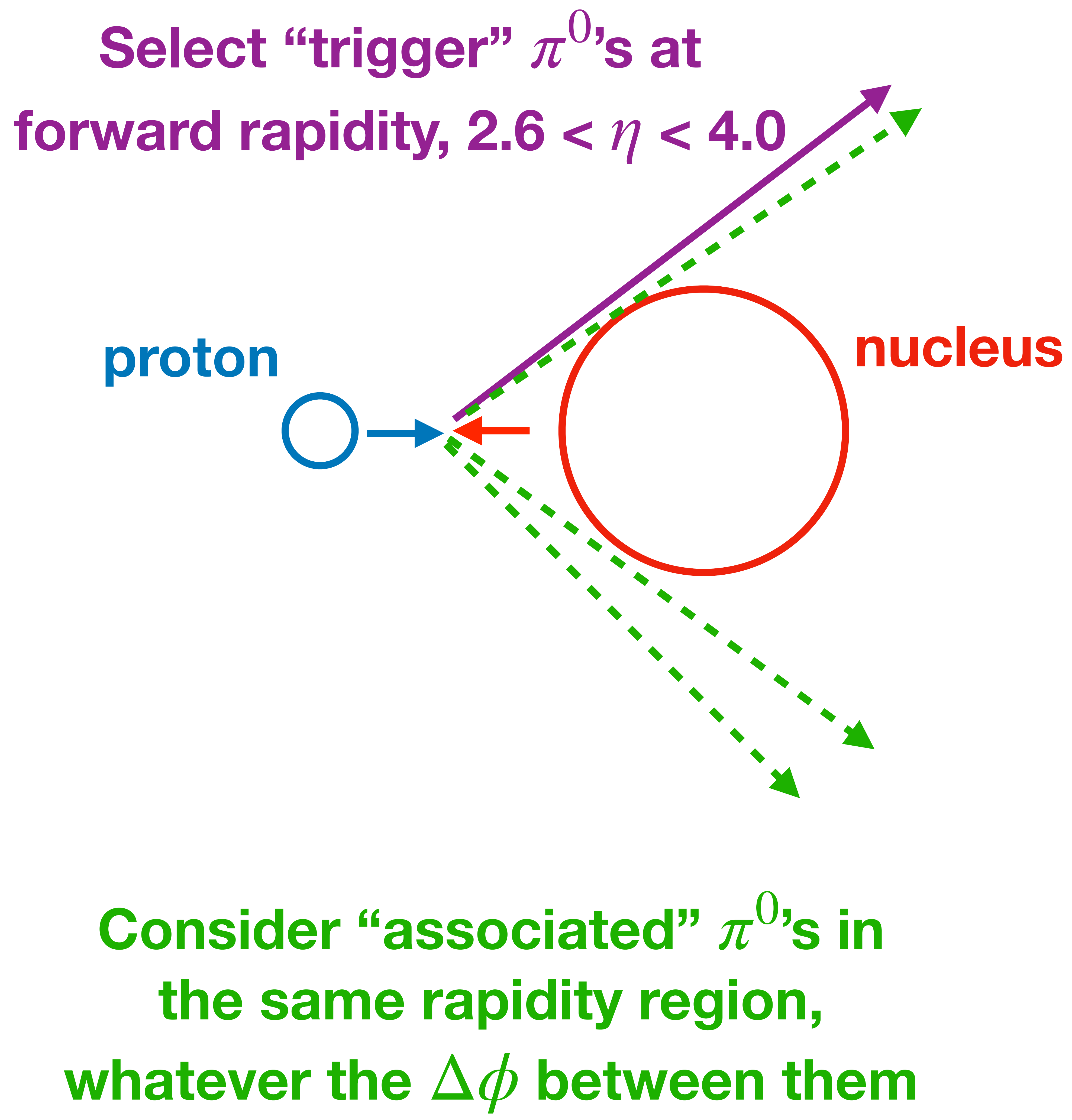


STAR measurement selection



Measure the per-trigger yield

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

nPDF effects survive here too!

Modeling more challenging:

- ➡ looser connection to underlying (x_A, Q^2) from hadrons (not jets)
- ➡ challenge to evaluate some nPDF sets in regions Q^2 down to 1 GeV^2
- ➡ pedestal+peak separation in data - non-trivial to model

Example of nPDF effect

- Use the exact STAR Pythia6 tune
- Per-trigger di-hadron correlation function, in **nominal Pythia6** and **EPPS21-reweighted**
- Clear suppression of the “back-to-back” di-hadron contribution - just from nPDFs
  - ➡ same reason as the ATLAS case — both the “inclusive” and “coincident” cross-sections are suppressed, but the “coincident” one is more strongly so

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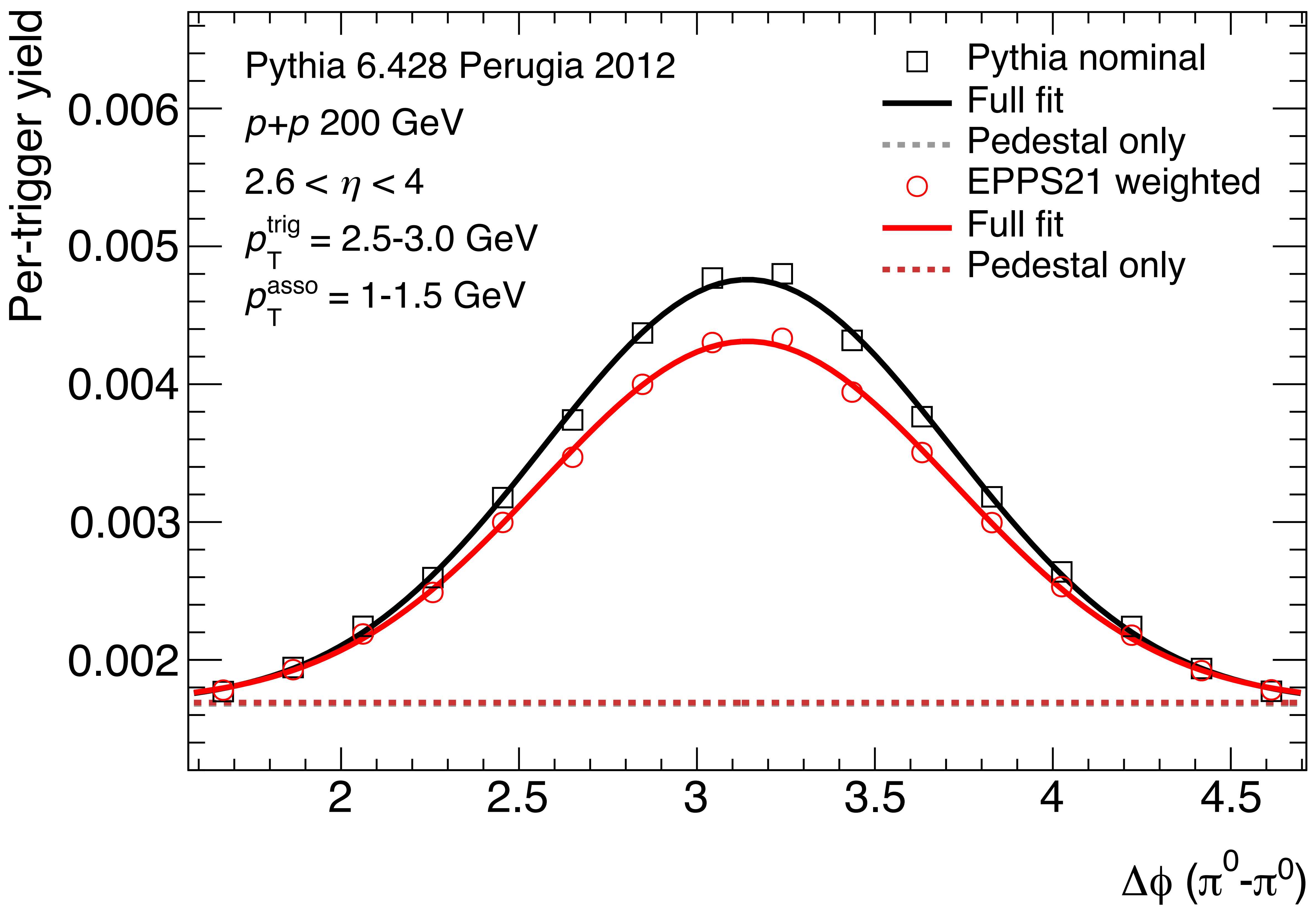

Per-trigger suppression from nPDFs

- Systematically compare to **STAR data** in different p_T^{assoc} selections
- Evaluate **EPPS21**, **nNNPDF**, **nCTEQ15** nPDF sets for ^{197}Au
- In all but the lowest p_T^{assoc} selection, nPDFs can plausibly describe the data within the combined uncertainties

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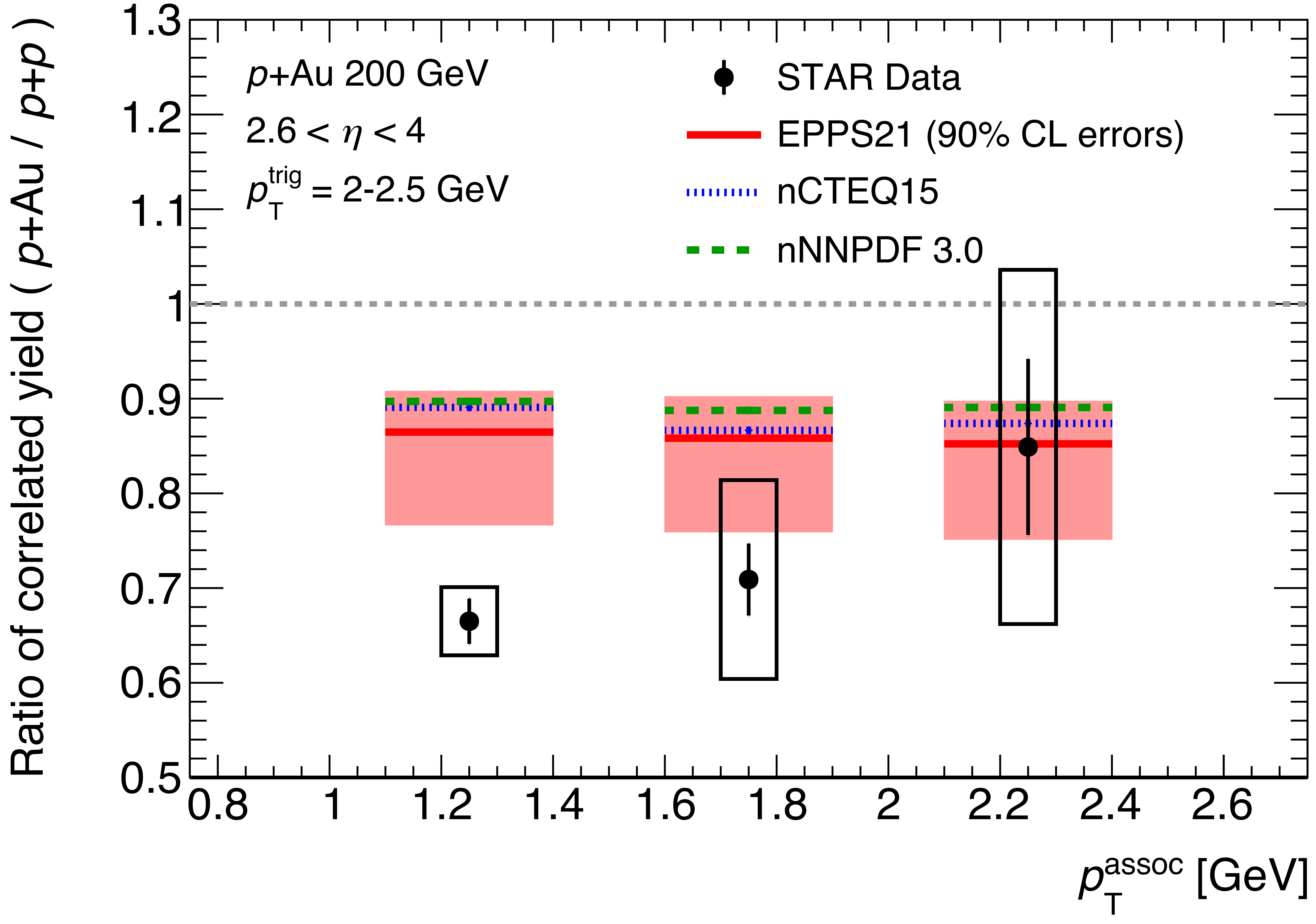

$\Delta\phi$ broadening from nPDF sets?

- Minimal change in shape of $\Delta\phi$ distribution from nPDF effects

  ➡ Same result as in the data

  ➡ Interestingly, a slight (~5%) broadening within **nCTEQ15**, also compatible with data

- Again the nPDF picture gives (1) per-trigger suppression, but (2) no broadening

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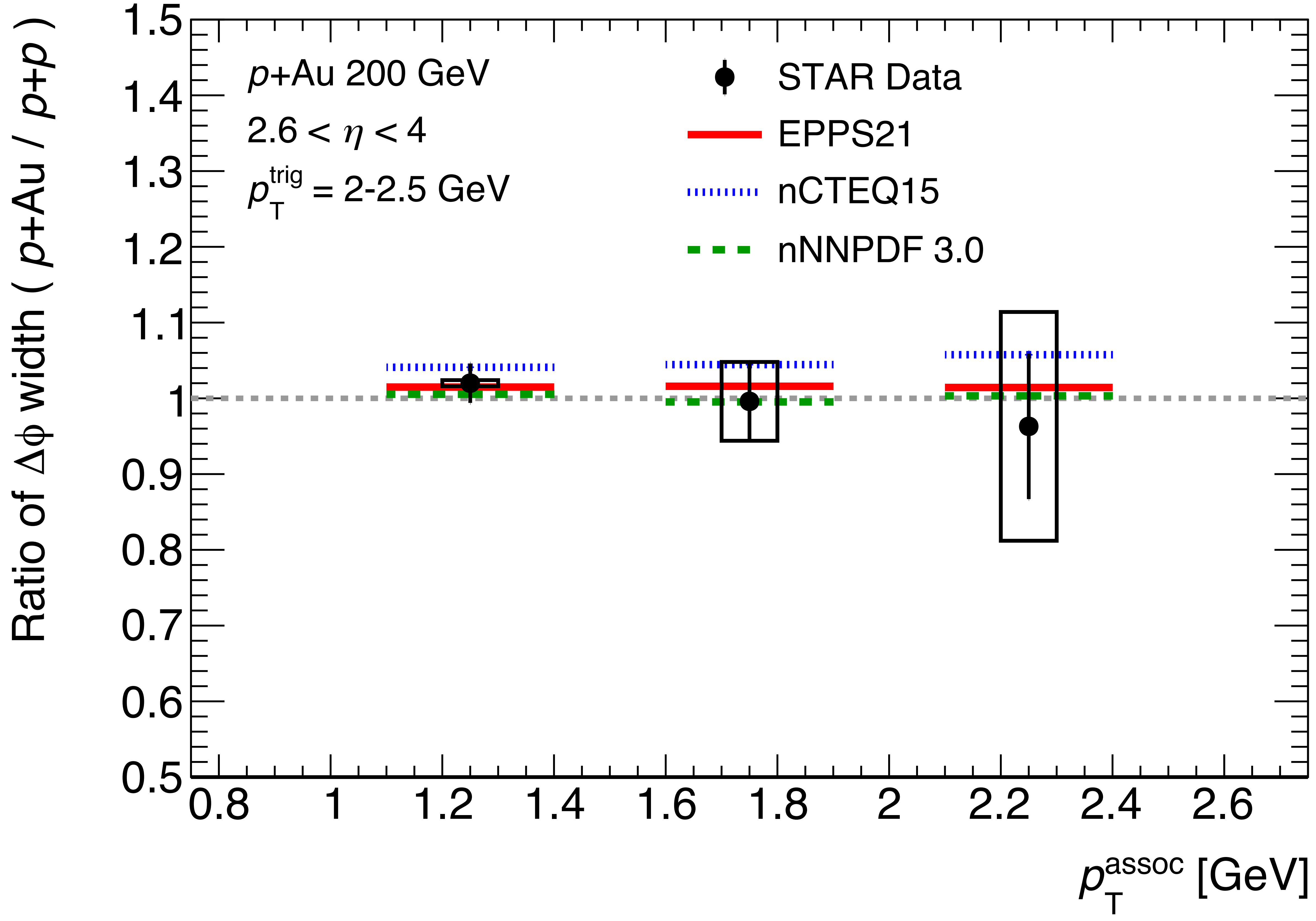

A-dependence of di-hadron suppression

- nPDF picture quite compatible with *p*+Al data as well

  ➡ Implies that even the "A"-dependence of the data can be accommodated within an nPDF picture

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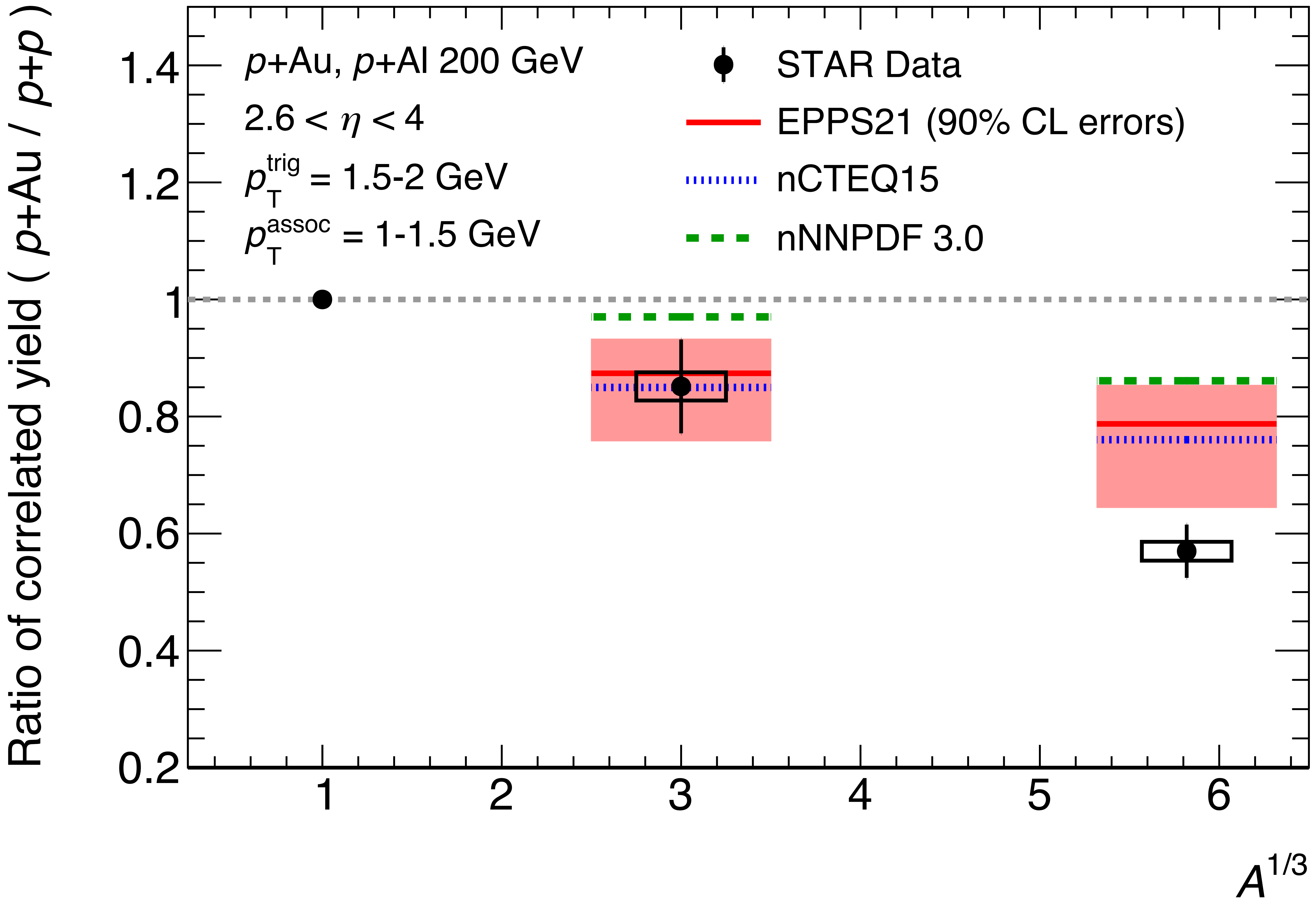

Conclusion

- “Out of the box” nPDF sets can plausibly produce “saturation-like” signals for di-jet/hadron observables, at both RHIC and LHC
  - ➡ At surface level, this is plausible — nPDFs agnostically encode whatever the effects of the underlying physics are (including non-linear QCD effects)
  - ➡ However, nPDFs have limited capabilities — they can only re-weight classes of events, and cannot modify their inter-event properties (kinematic correlation)
  - ➡ Thus, it is surprising to recover “dynamical” signatures just from <u>compositional reweighting of otherwise unmodified events</u>

Outlook

- How does this impact identifying saturation at RHIC/LHC and EIC?
  - ➡ Need multiple corroborating observables — shouldn't rely on single smoking gun
  - ➡ Identify where the nPDF "picture" (collinear factorization + leading-twist pQCD) breaks down or where global data become inconsistent with a (x_A, Q^2)-universal prescription
    - ➡ For example, is there an experimentally-observed emergent scale Q_s
- Finally — this is an exploratory study with many limitations (Pythia is only LO+PS+IS/FS, modeling pedestal+peak in *p*+Au at RHIC, kinematic applicability, etc.) — would benefit from a proper theoretical treatment!

Thank you!

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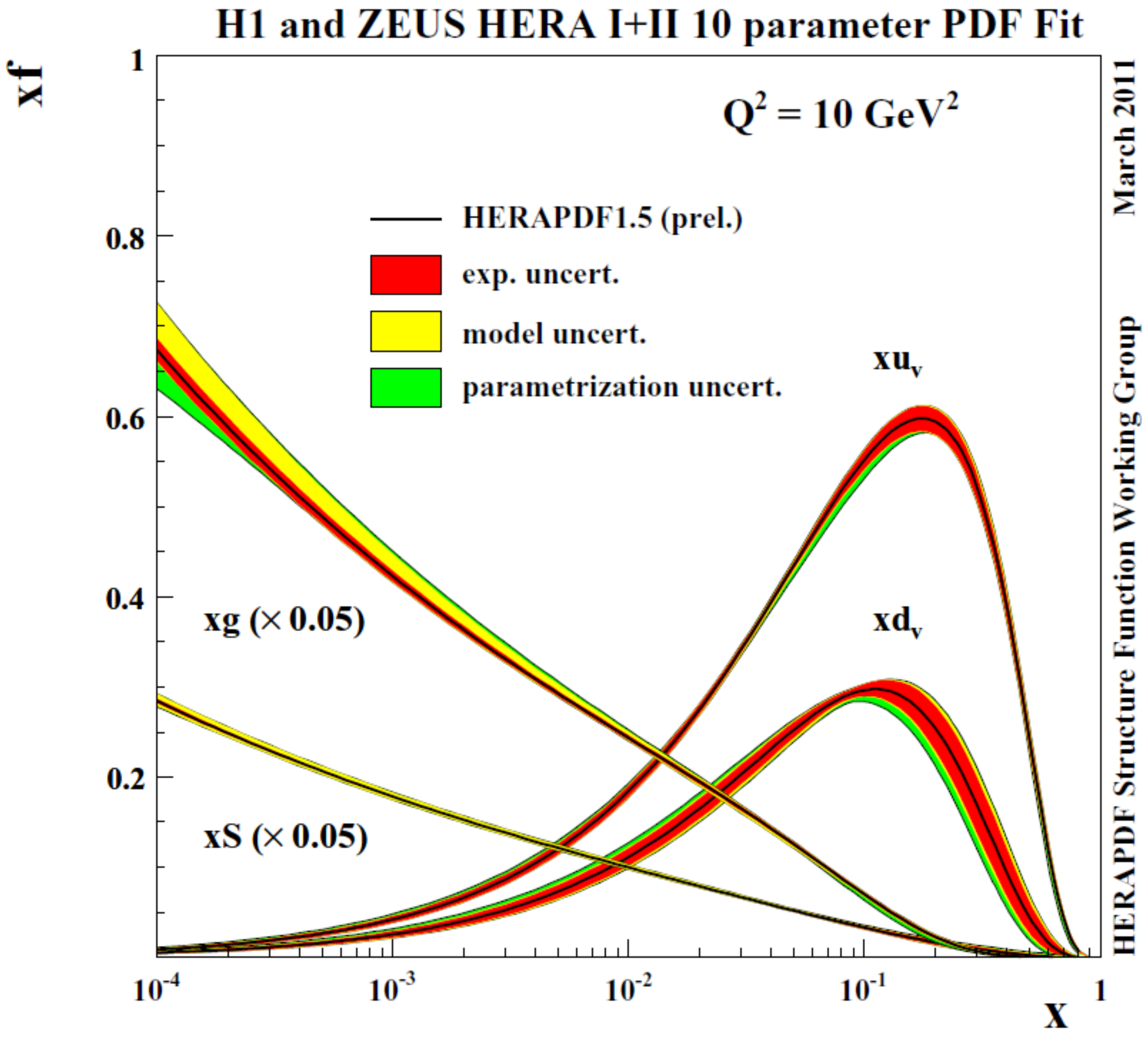
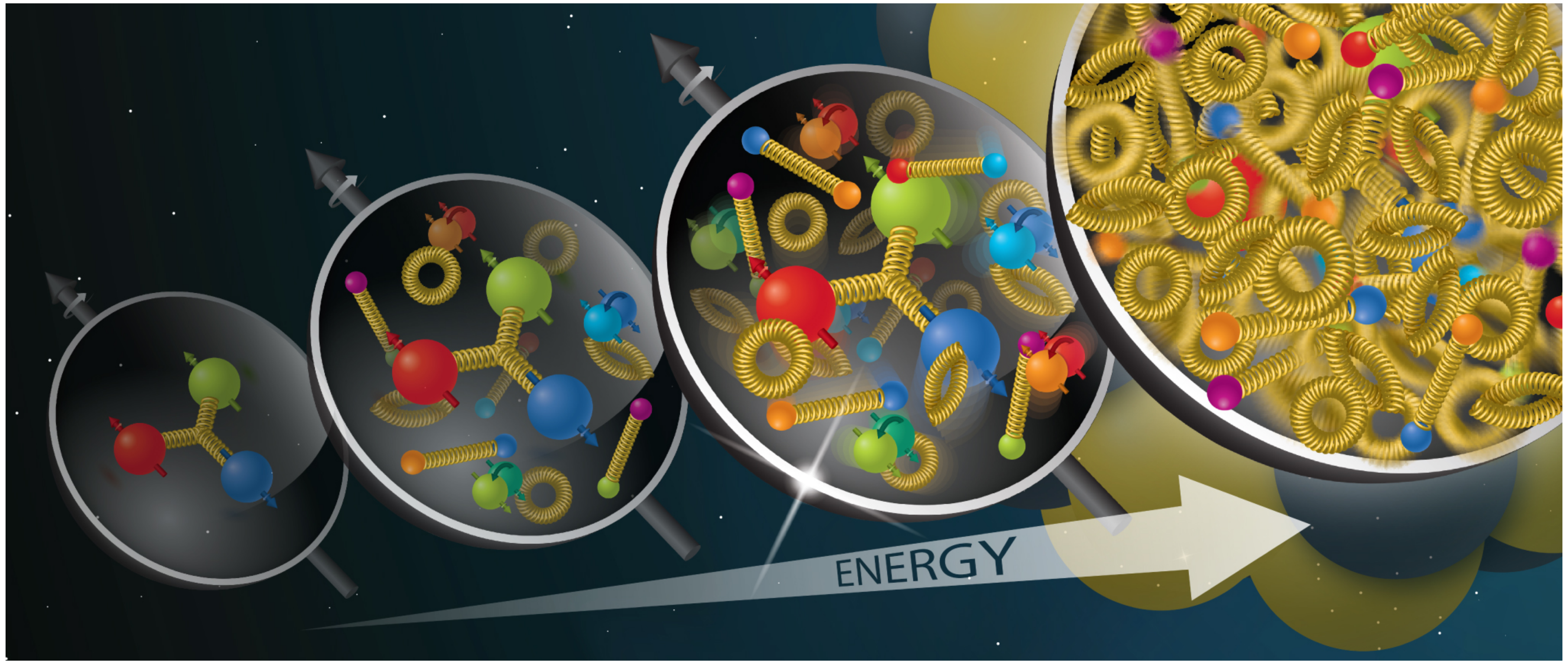
Saturated gluon matter



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

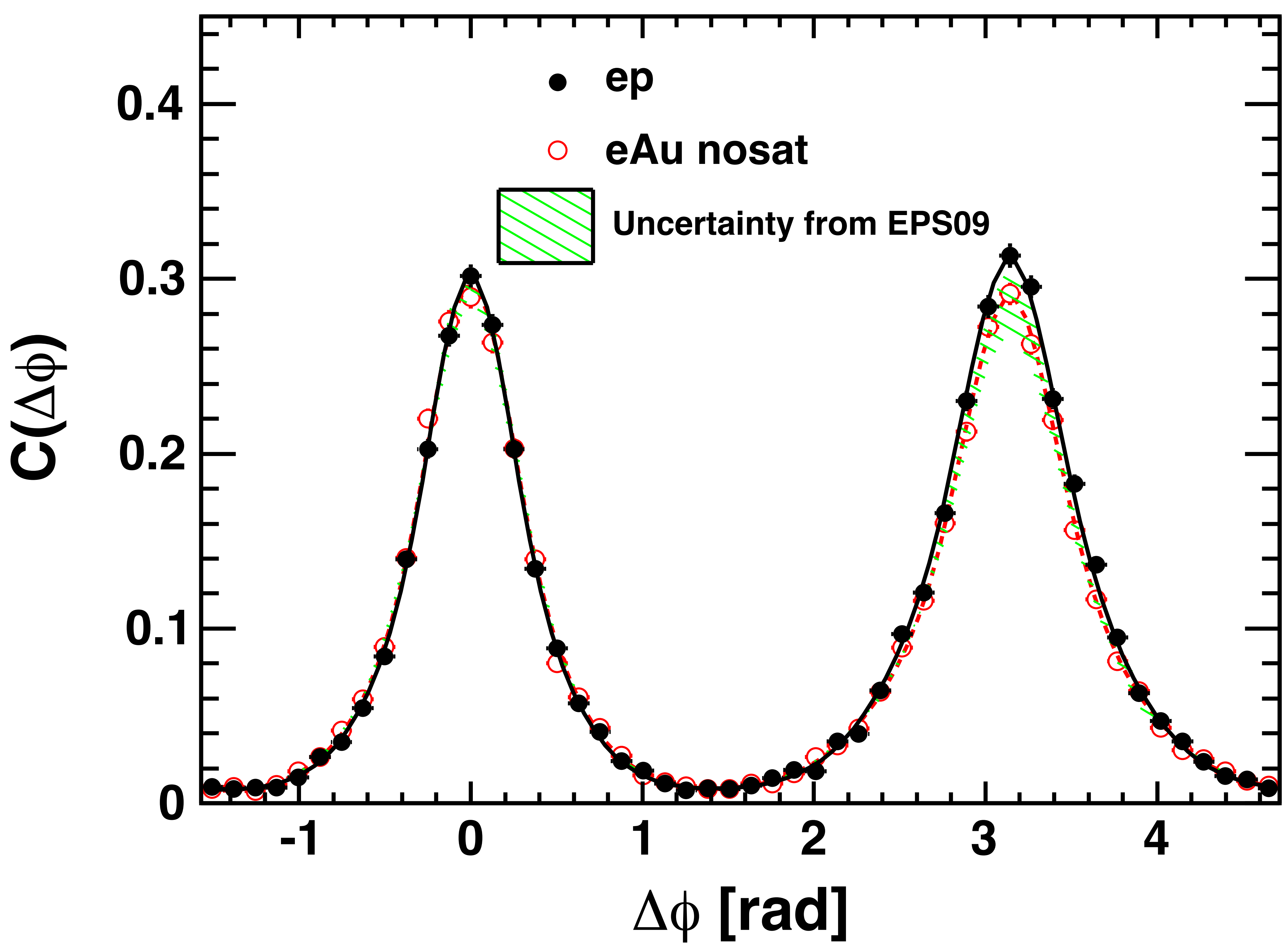


Novel domain of QCD inside all hadrons — but most accessible in heavy nuclei

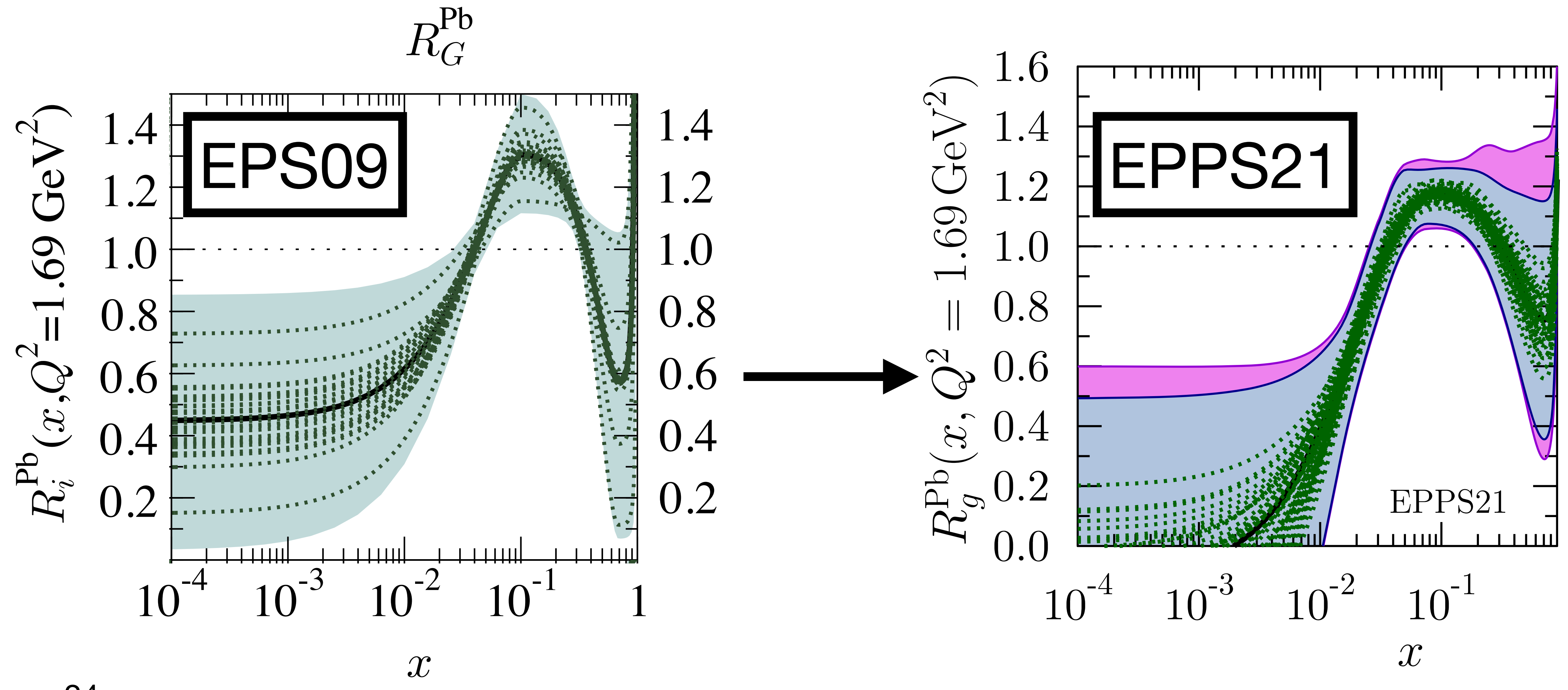
What are the observable consequences in *p*+A and *e*+A collisions?

Connection to EIC

Zheng, et al, PRD 89 (2014) 074037

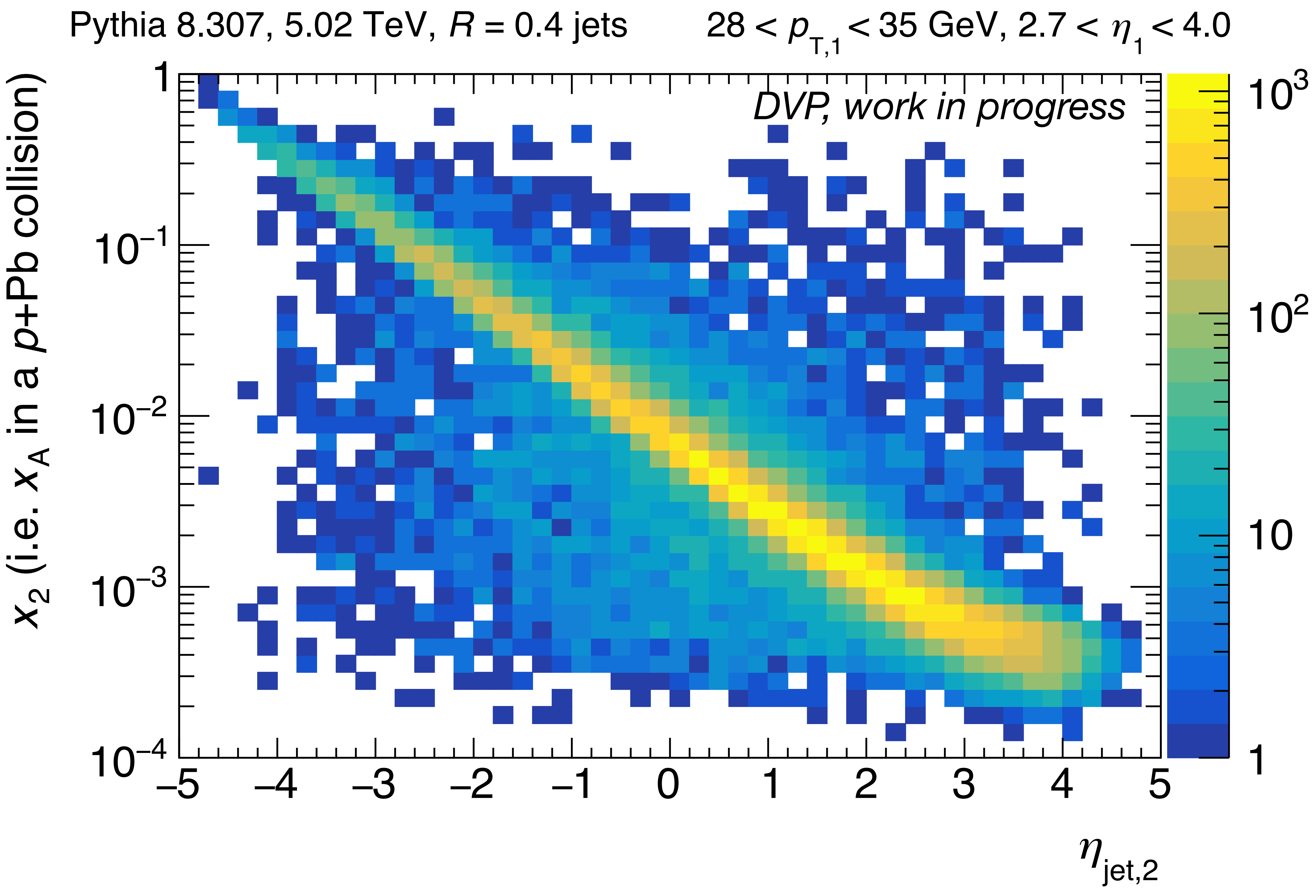


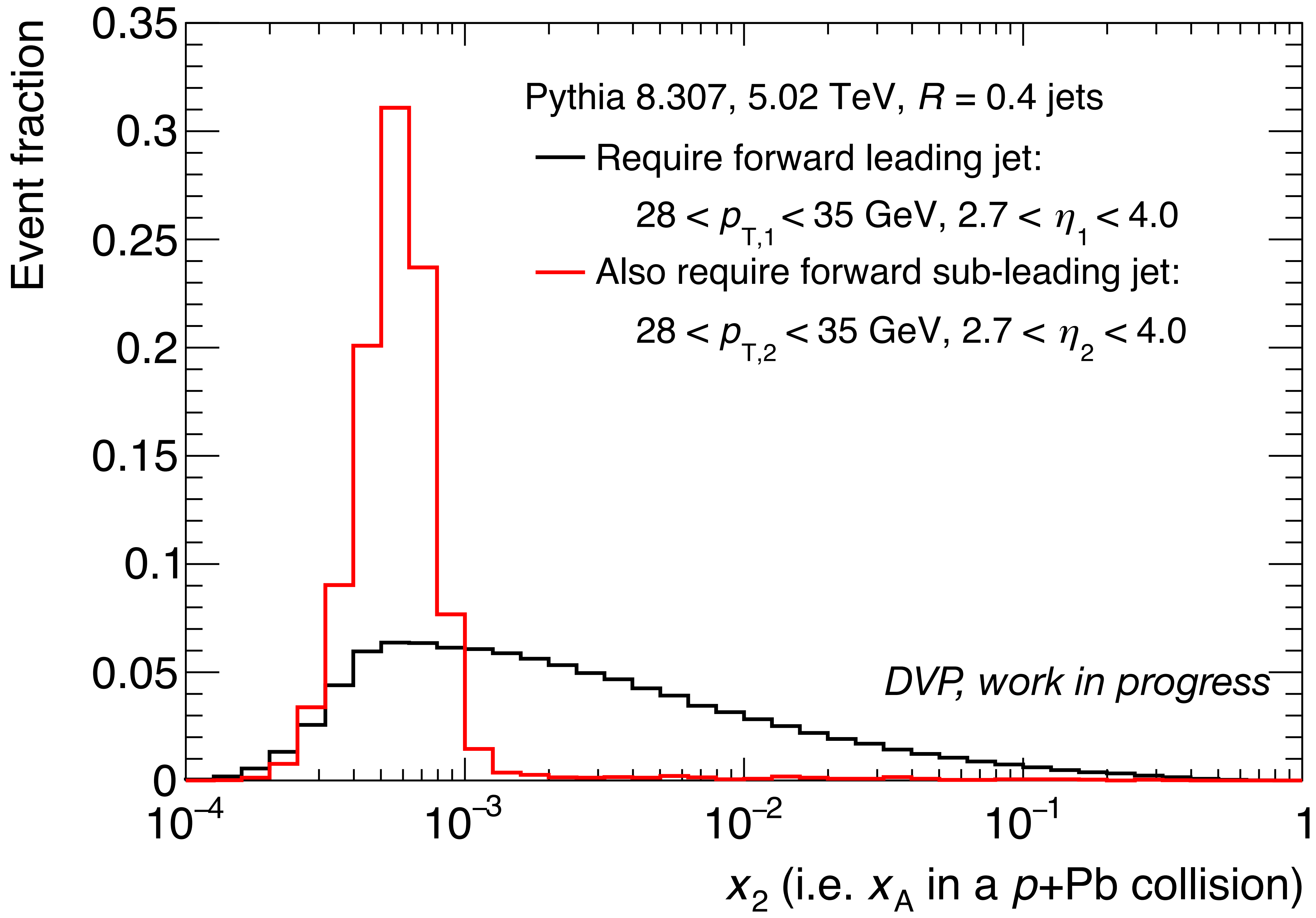
- An earlier study found that EPS09 (e.g.) predicts very modest effects in di-hadron correlations at EIC
  - ➡ EPPS21 has significantly stronger gluon shadowing, based on LHC data
  - ➡ probably interesting to re-evaluate with updated knowledge of EIC kinematics & global nPDF sets?



x_A values probed

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



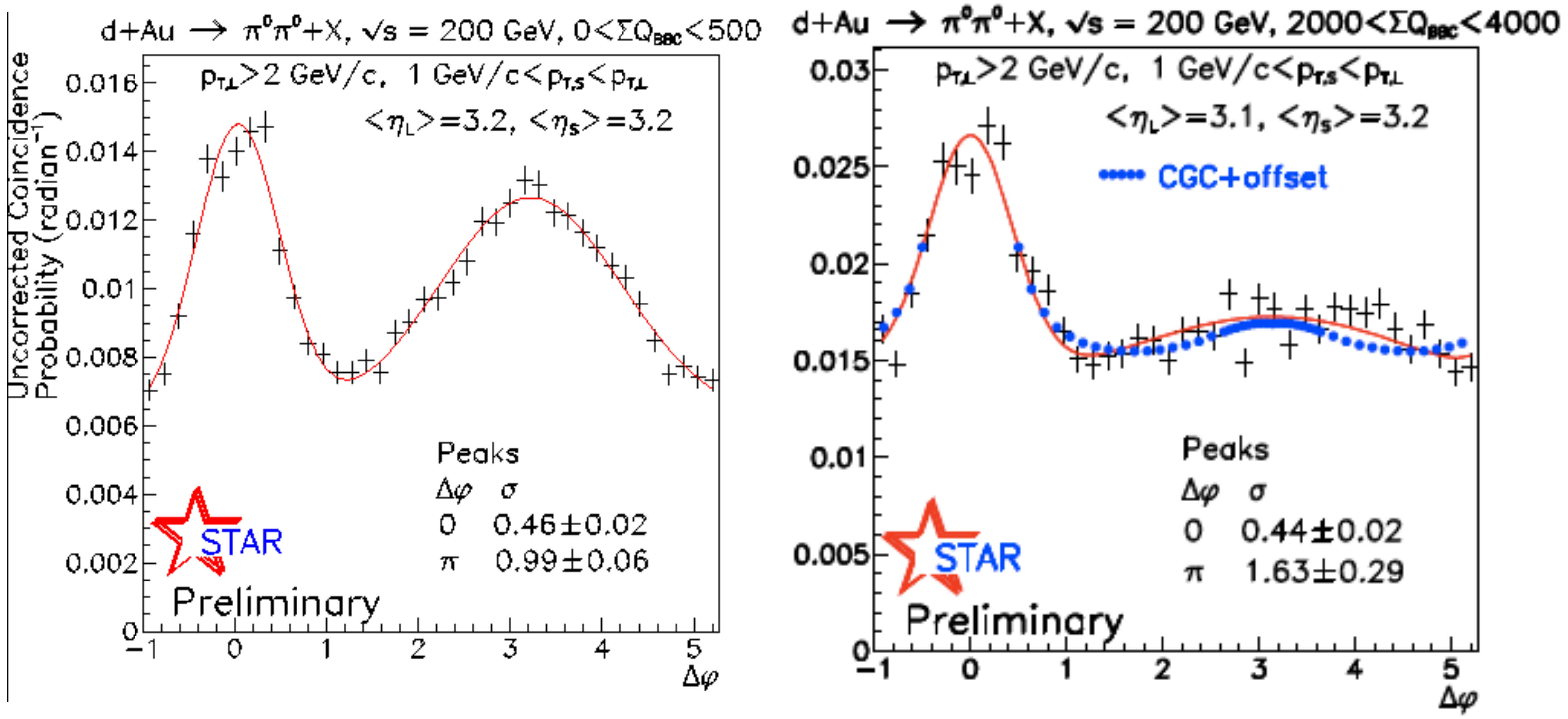


The typical x_A in the nucleus is then highly sensitive to the rapidity of the sub-leading jet

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

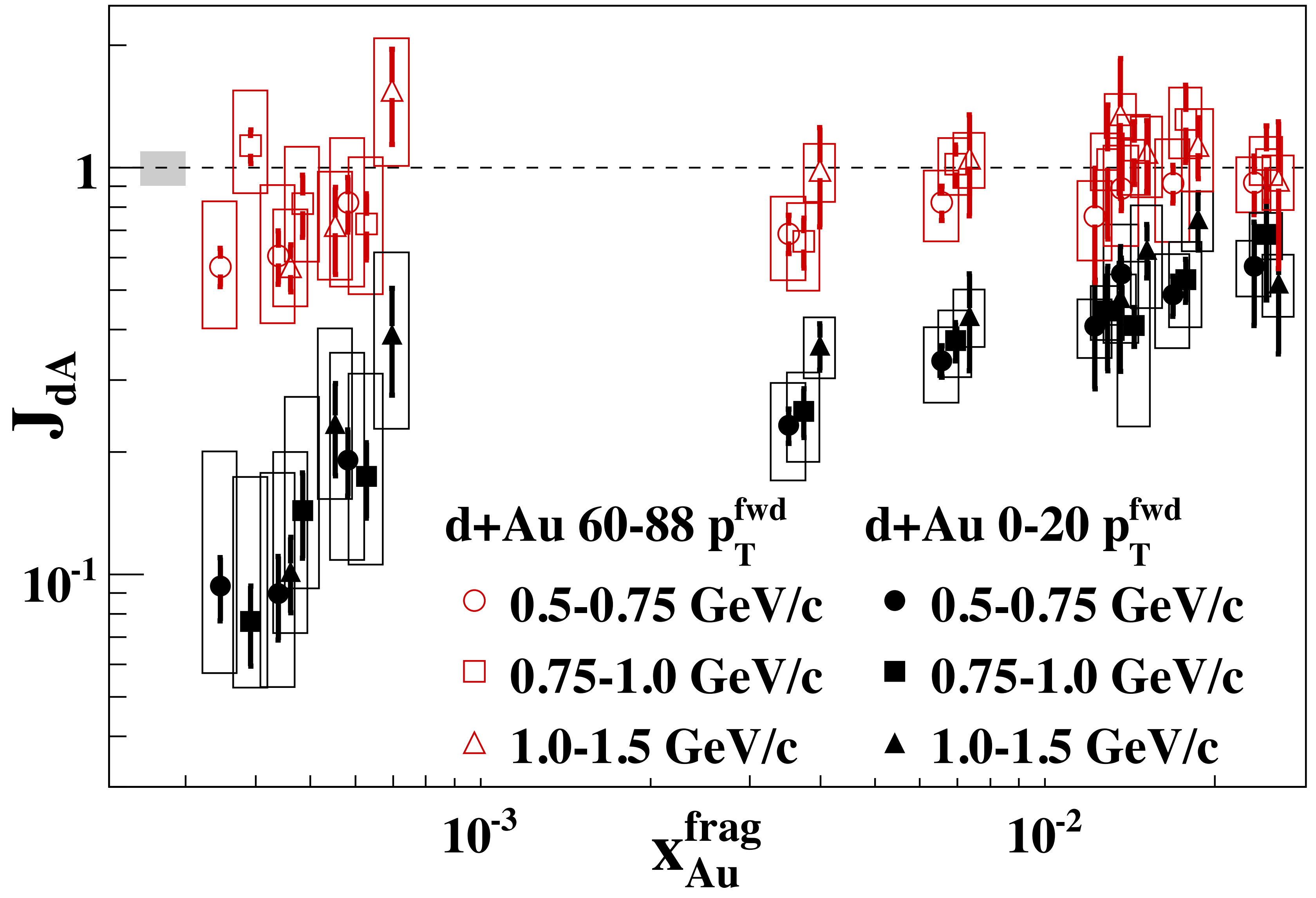
These will have different average nPDF modification!

Early measurements in *d*+Au at RHIC



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

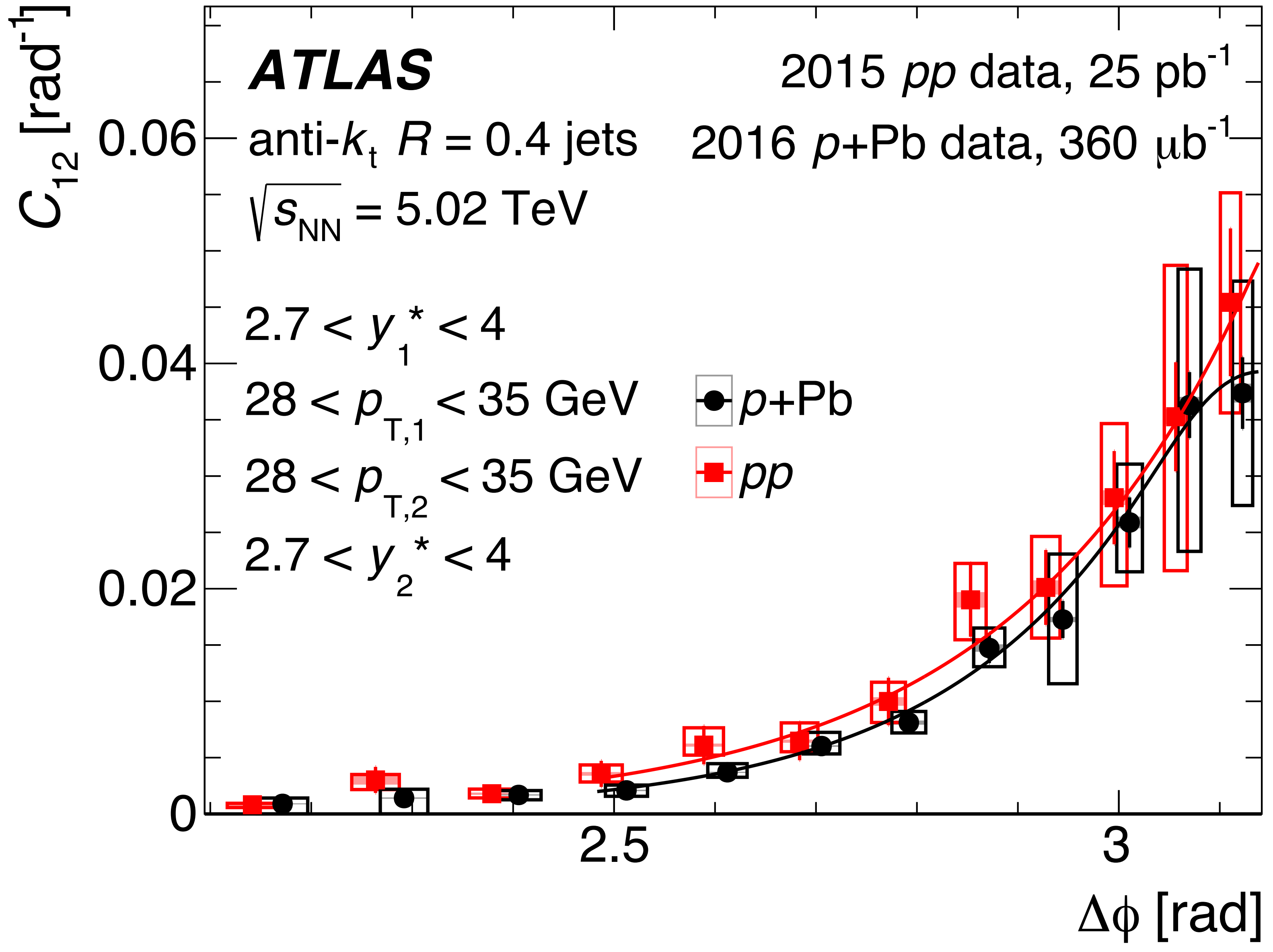
PHENIX PRL 107 (2011) 172301



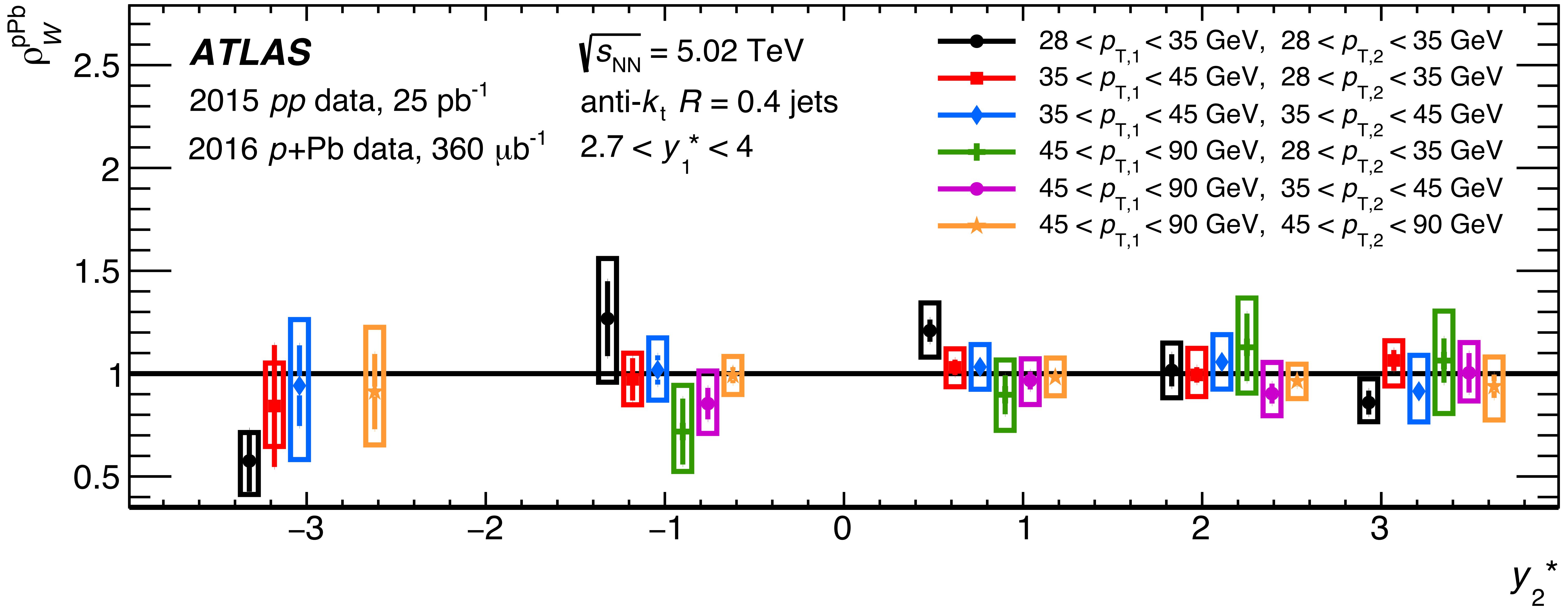
Strong suppression of per-trigger yields for forward di-hadrons

- 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

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**

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