

Overview of recent measurements on the physics of small-x at the ATLAS experiment

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July 7, 2026

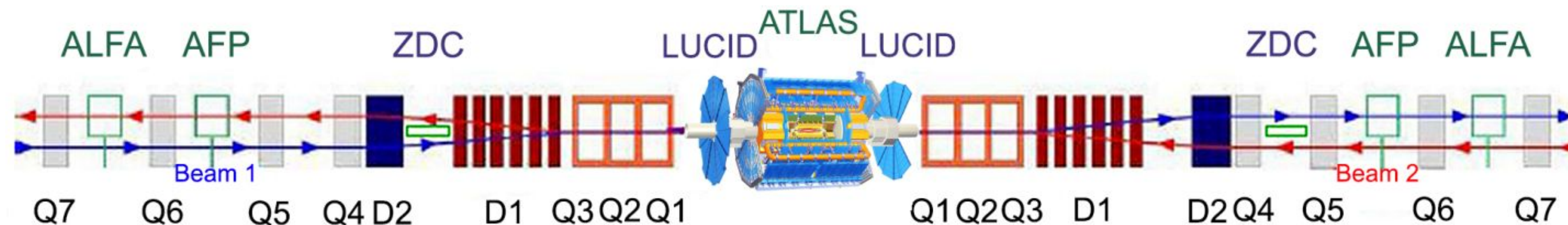
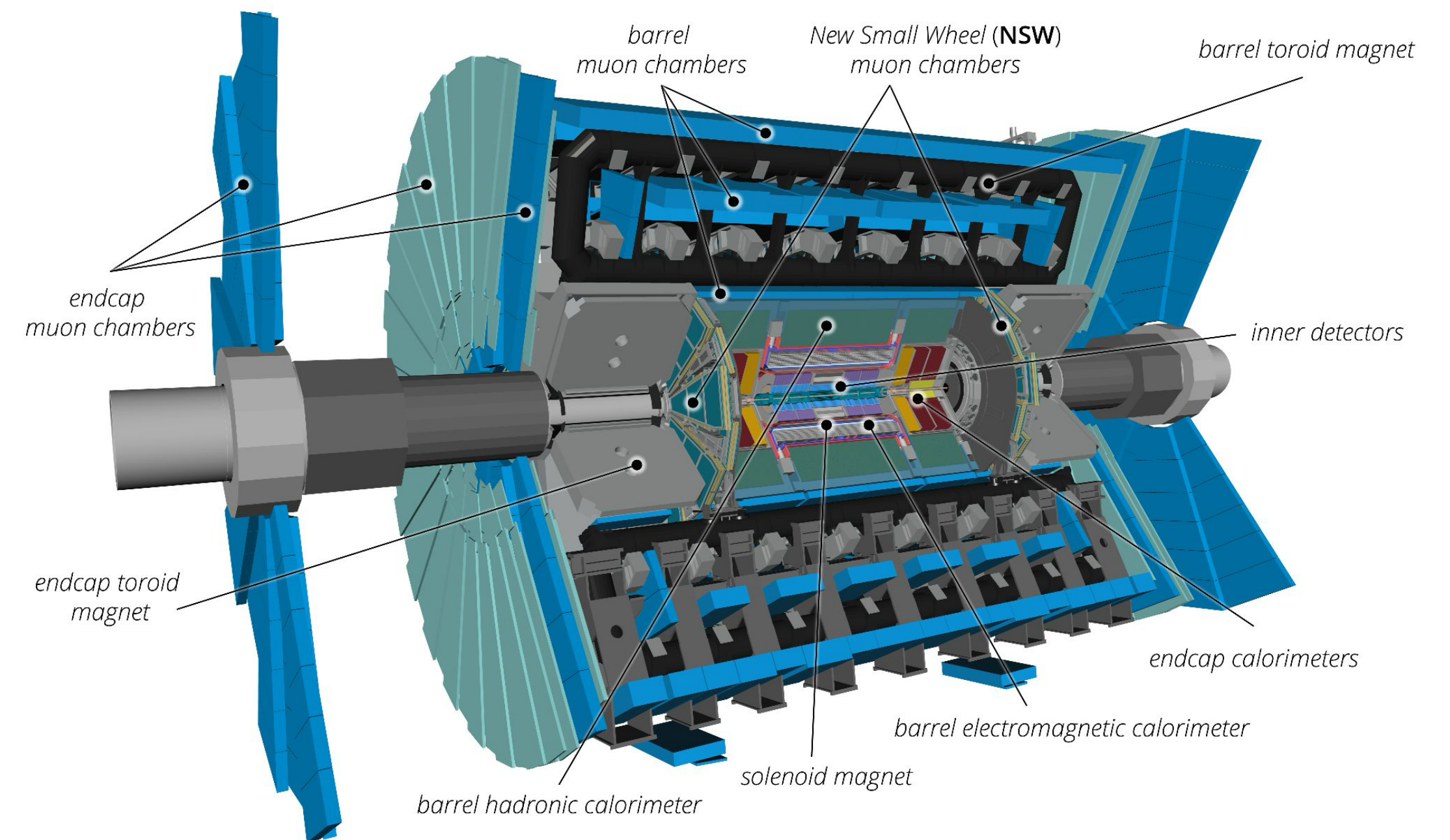
The first workshop on the physics of small-x at the LHC, Wuhan



The ATLAS detector

ATLAS is a large general-purpose detector with almost 4π coverage:

- Inner detector: $|\eta| < 2.5$
- Muon system: $|\eta| < 2.7$ (trigger < 2.4)
- Calorimetry: $|\eta| < 4.9$, including FCal: $3.2 < |\eta| < 4.9$
- ZDCs capture neutral particles at $|\eta| > 8.3$



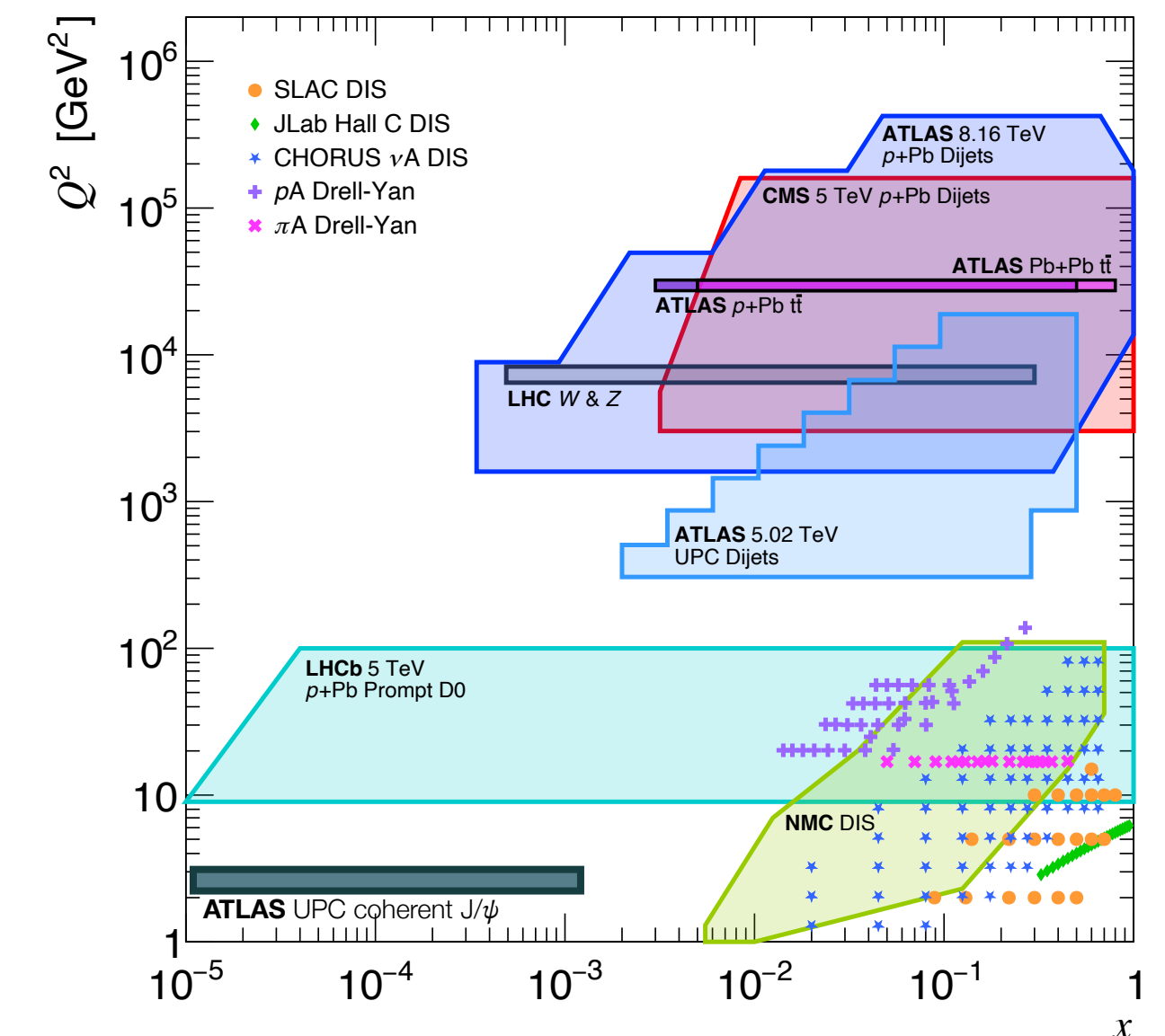
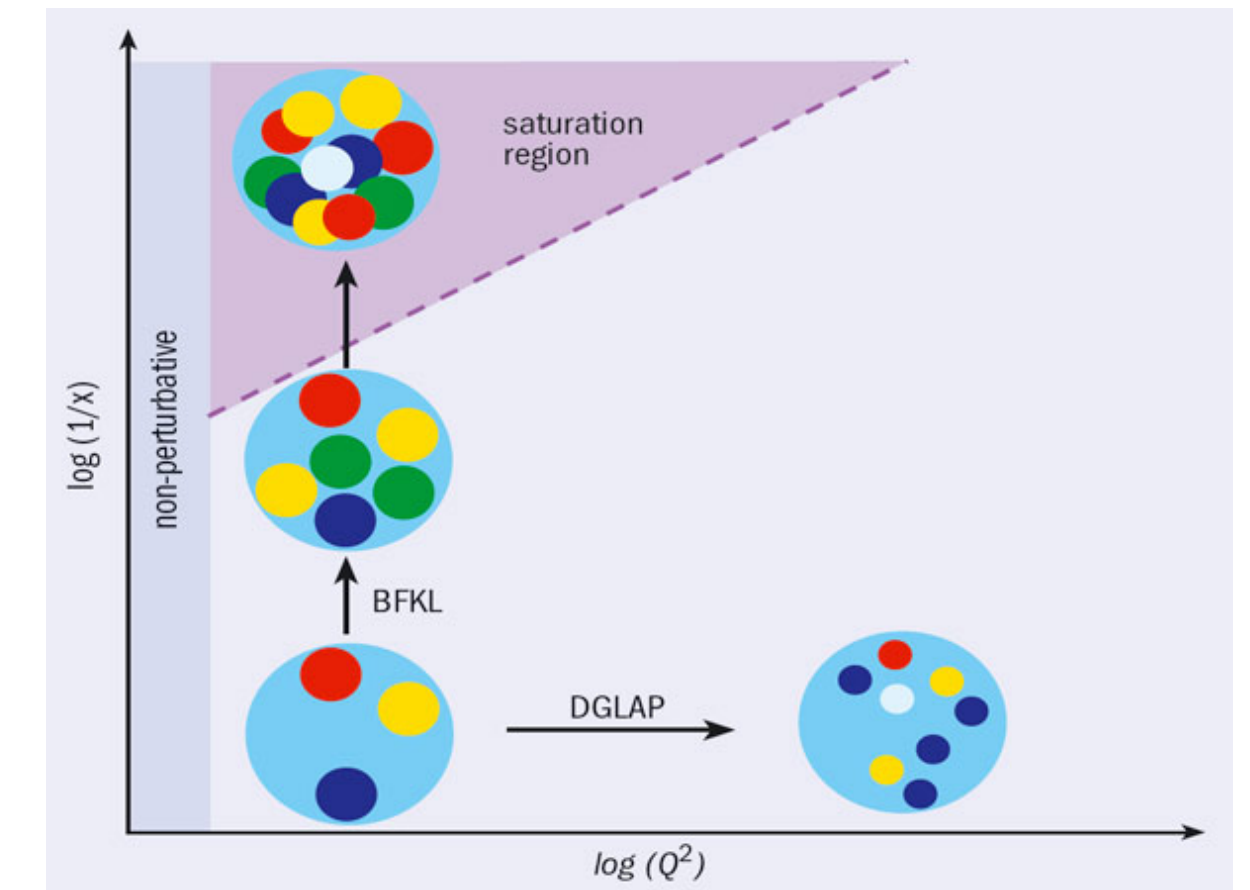
Small-x physics with ATLAS heavy ion data

At LHC energies, nuclei amplify small-x QCD in two ways:

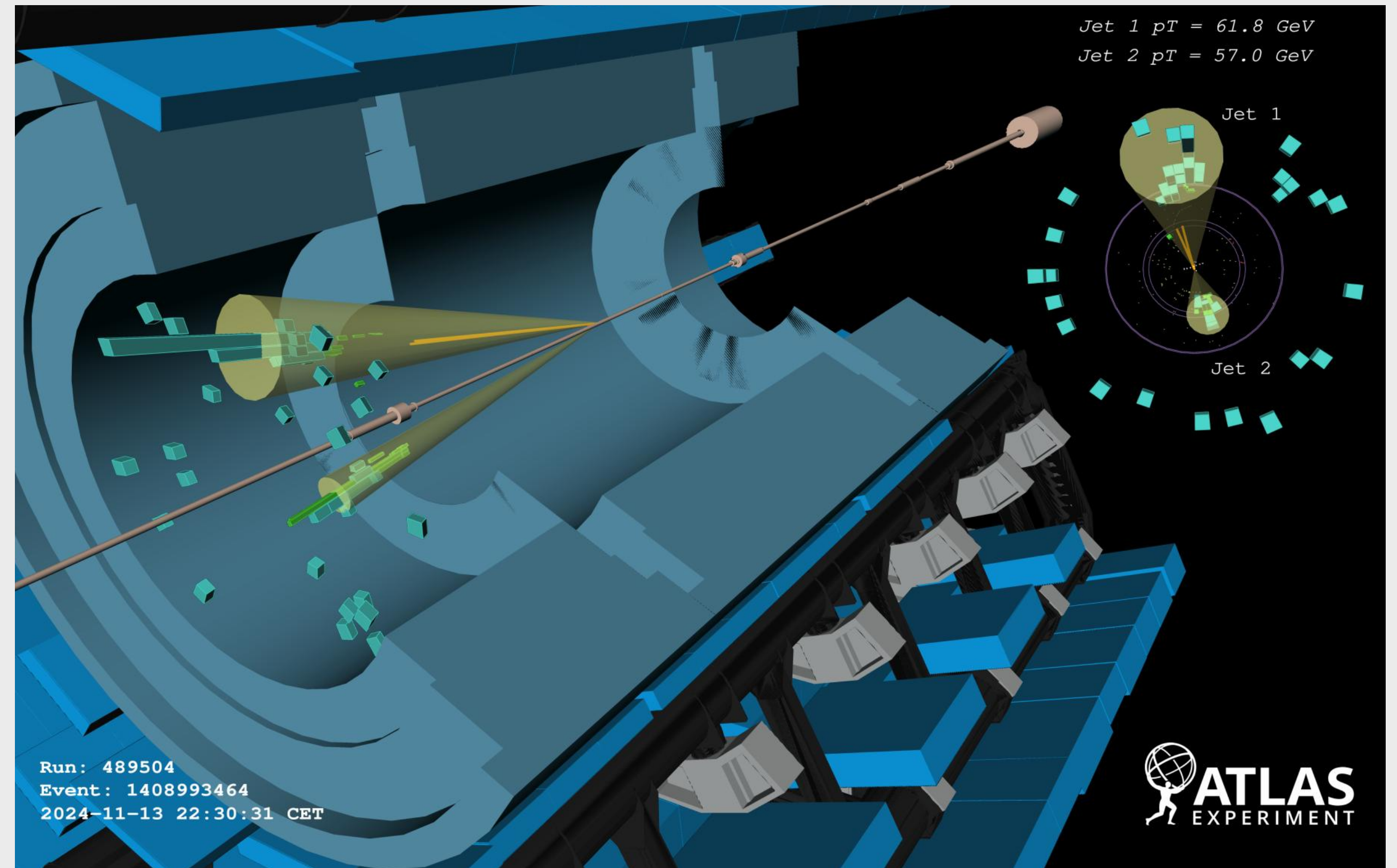
- Large gluon densities in nuclear targets
- Intense Z^2 -enhanced quasi-real photon fluxes in UPCs

ATLAS heavy ion handles:

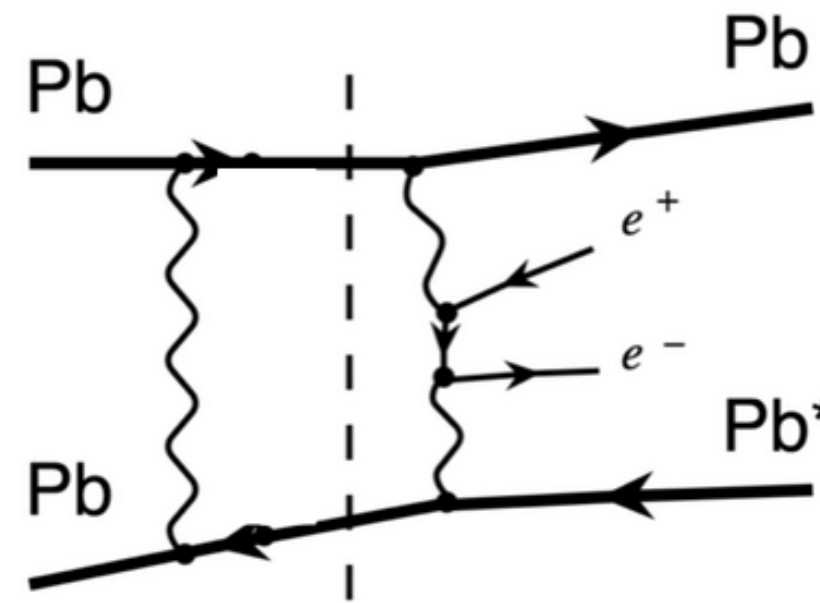
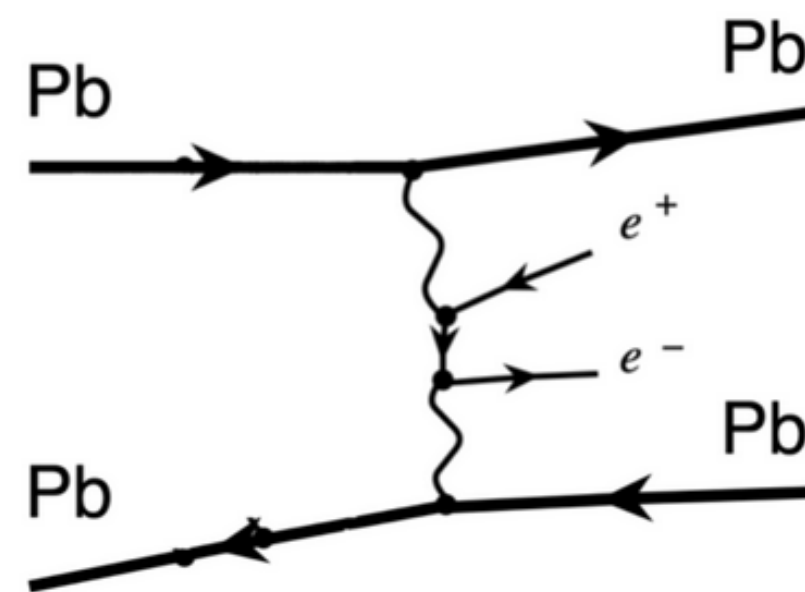
- **UPC jets:** high- Q^2 probes, impact-parameter dependent nuclear modifications
- **Coherent J/ψ :** low- Q^2 , small-x nuclear gluons
- **p +Pb dijets:** centrality bias and color fluctuations
- **γ +A collectivity:** bridging small-x initial states and final-state response



UPC jets

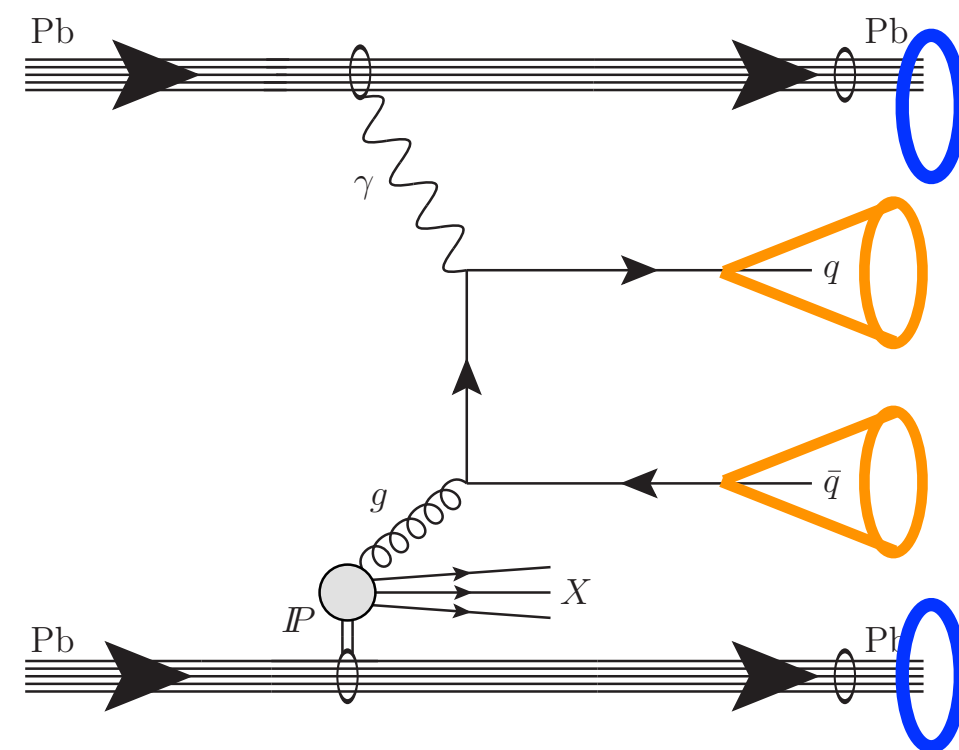


ZDC tagging of nuclear break-up

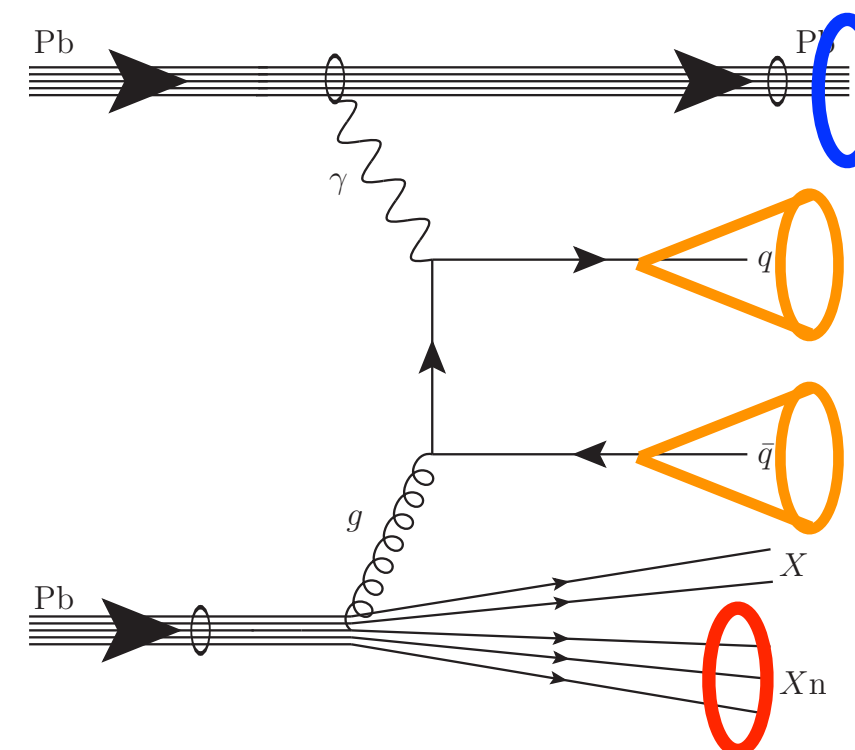


UPC events can be characterized by forward neutrons from nuclear break-up measured in the ZDCs

0n0n topology



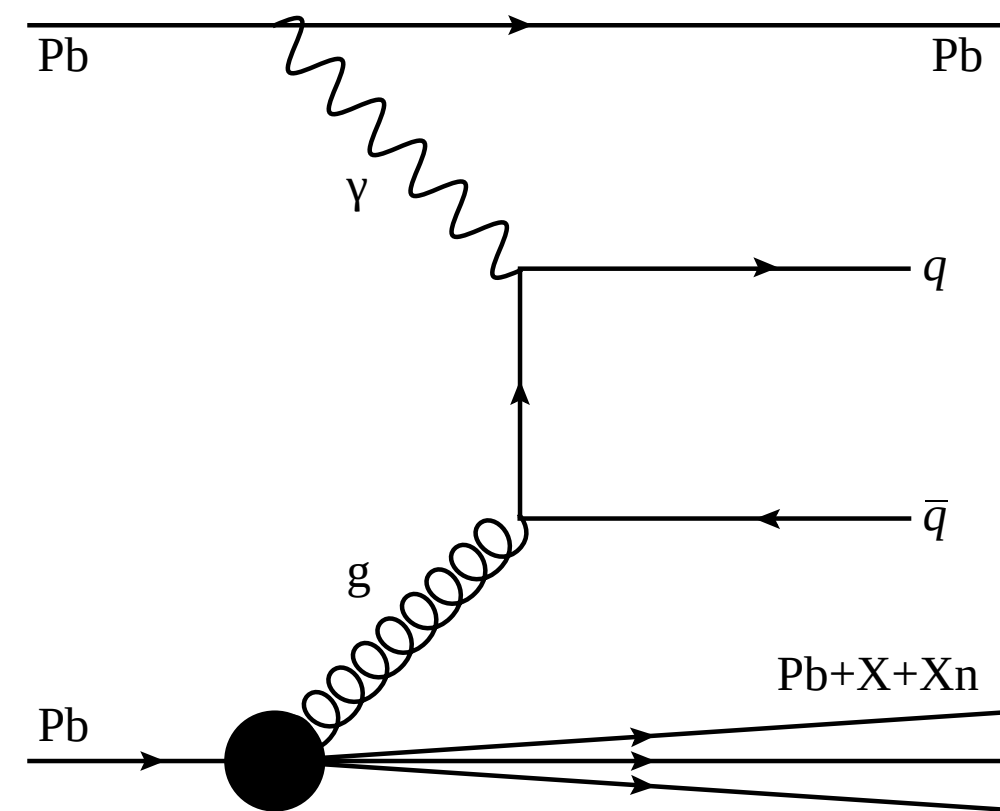
0nXn or **Xn0n** topology



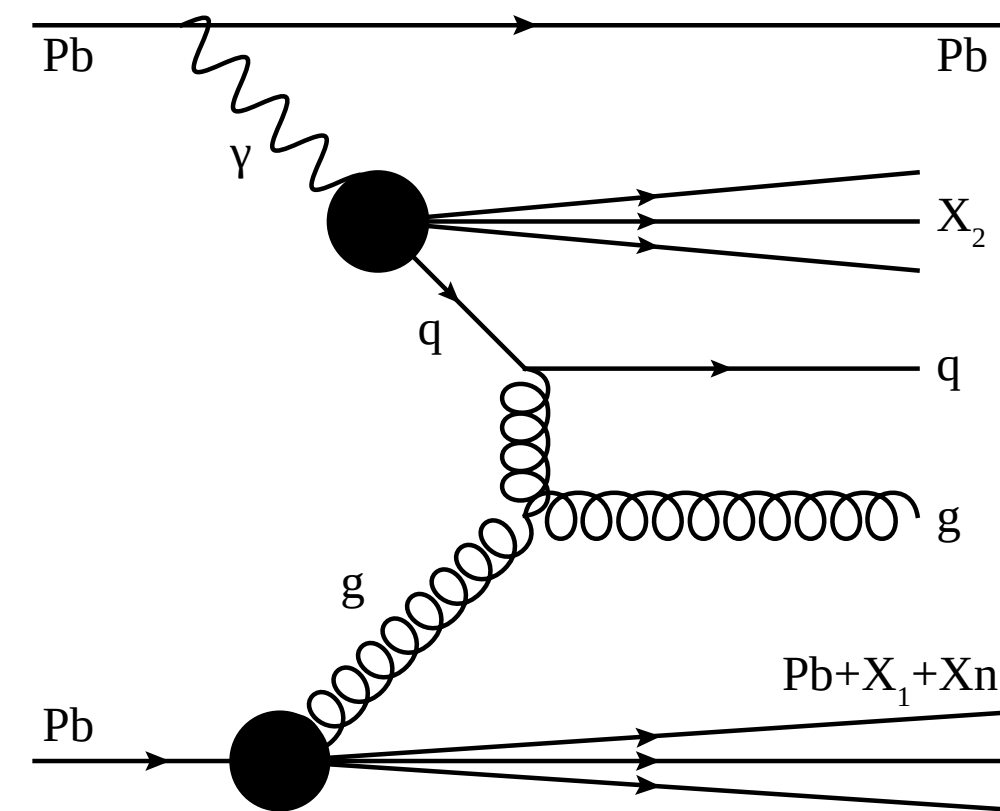
Typical jet production in UPCs

0nXn UPC jet production

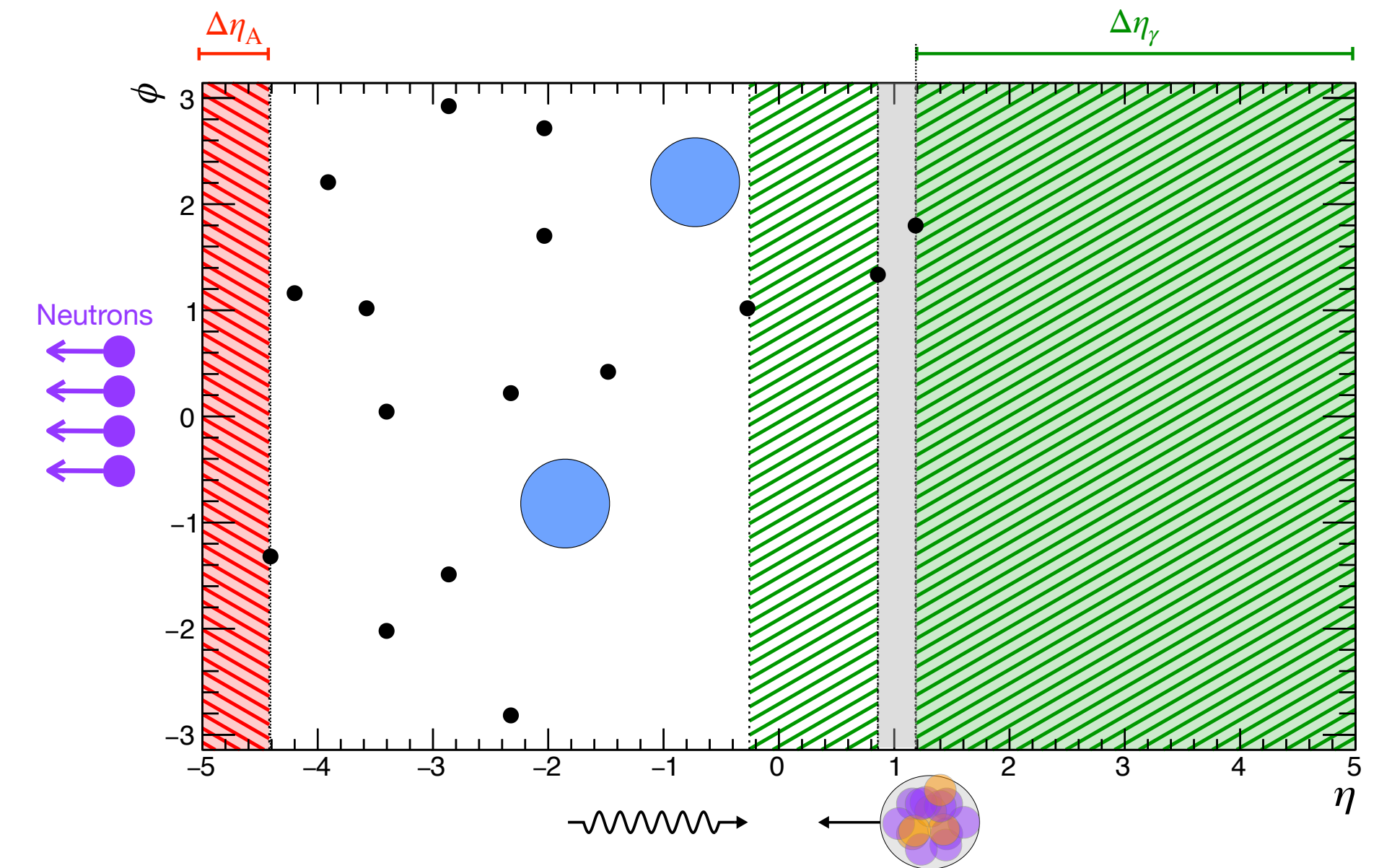
Non-diffractive $\gamma+A$ interaction induces neutron emission in the direction of the struck nucleus



Direct photon process



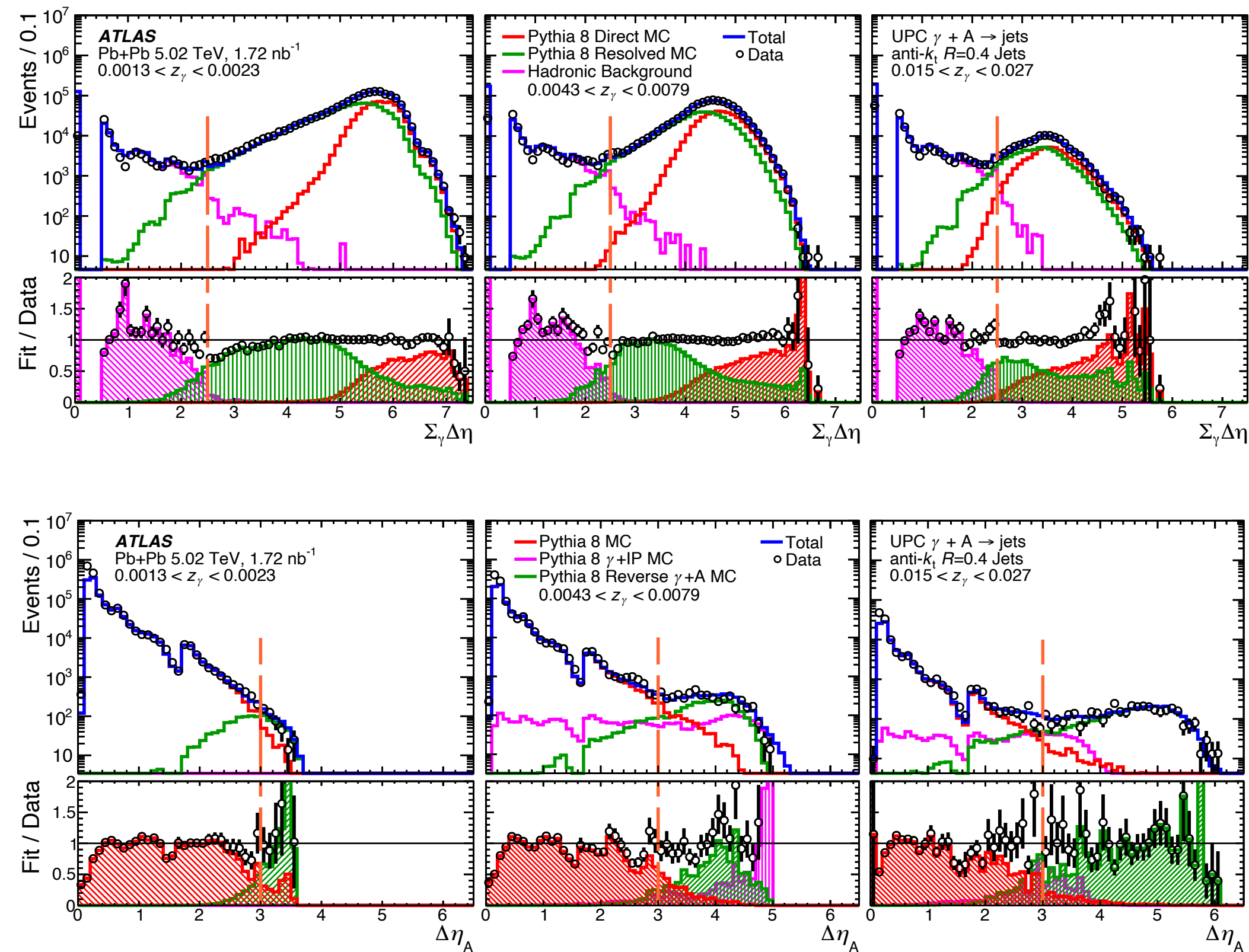
Resolved photon process



0nXn UPC characteristics:

- Forward neutrons
- Large rapidity gaps

Background rejection — 0nXn



Background sources:

- Hadronic background
- Diffractive $\gamma + P$
- Reverse $\gamma + A$

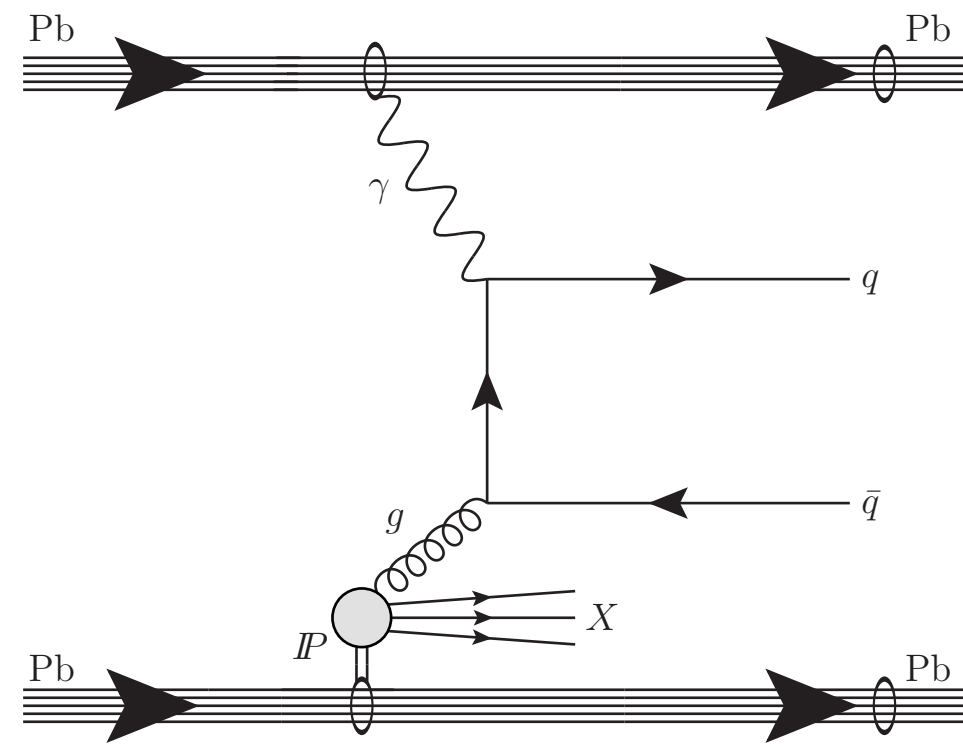
Nuclear break-up mechanisms:

- Hard-scattering nuclear break-up: 0nXn correlated with jets (~96%)
- Electromagnetic dissociation (EMD): 0nXn or Xn0n uncorrelated with jets (10-40% in hard scattering events)

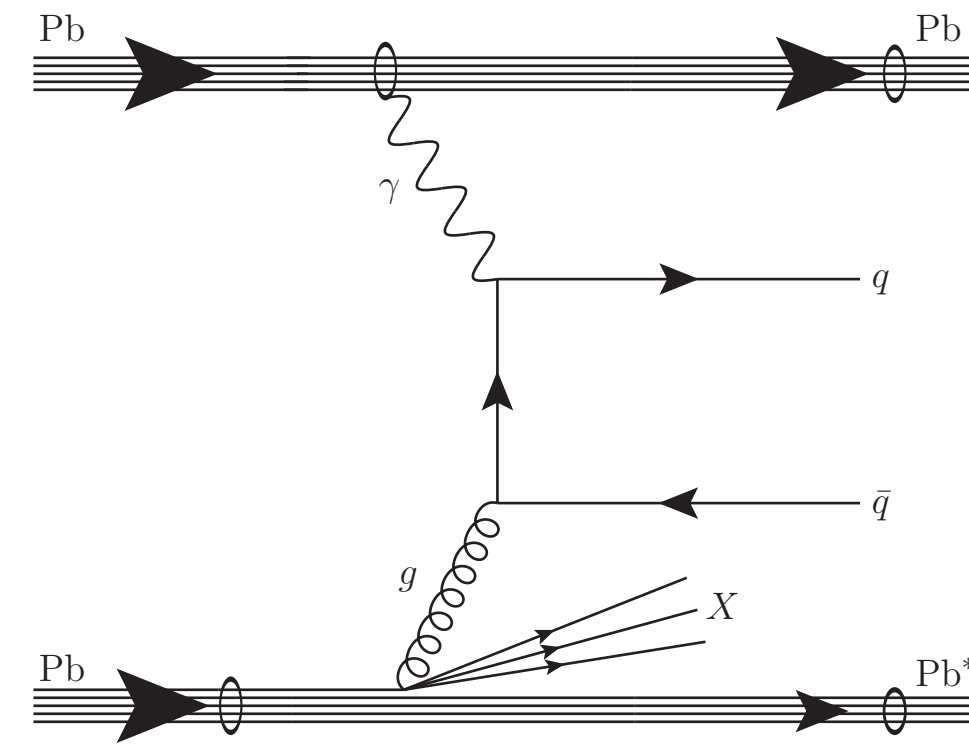
Can be used to separate direct and resolved photon processes

Residual background below 3% after gap selections

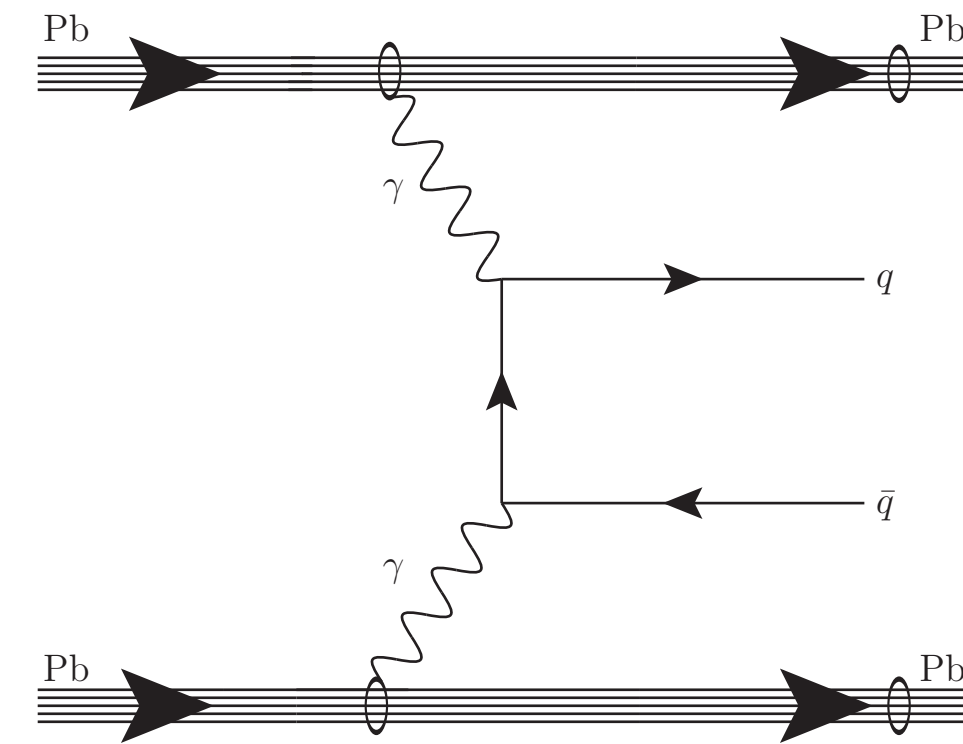
0n0n UPC jet production



Coherent diffractive



Peripheral non-diffractive
photonuclear hard scattering

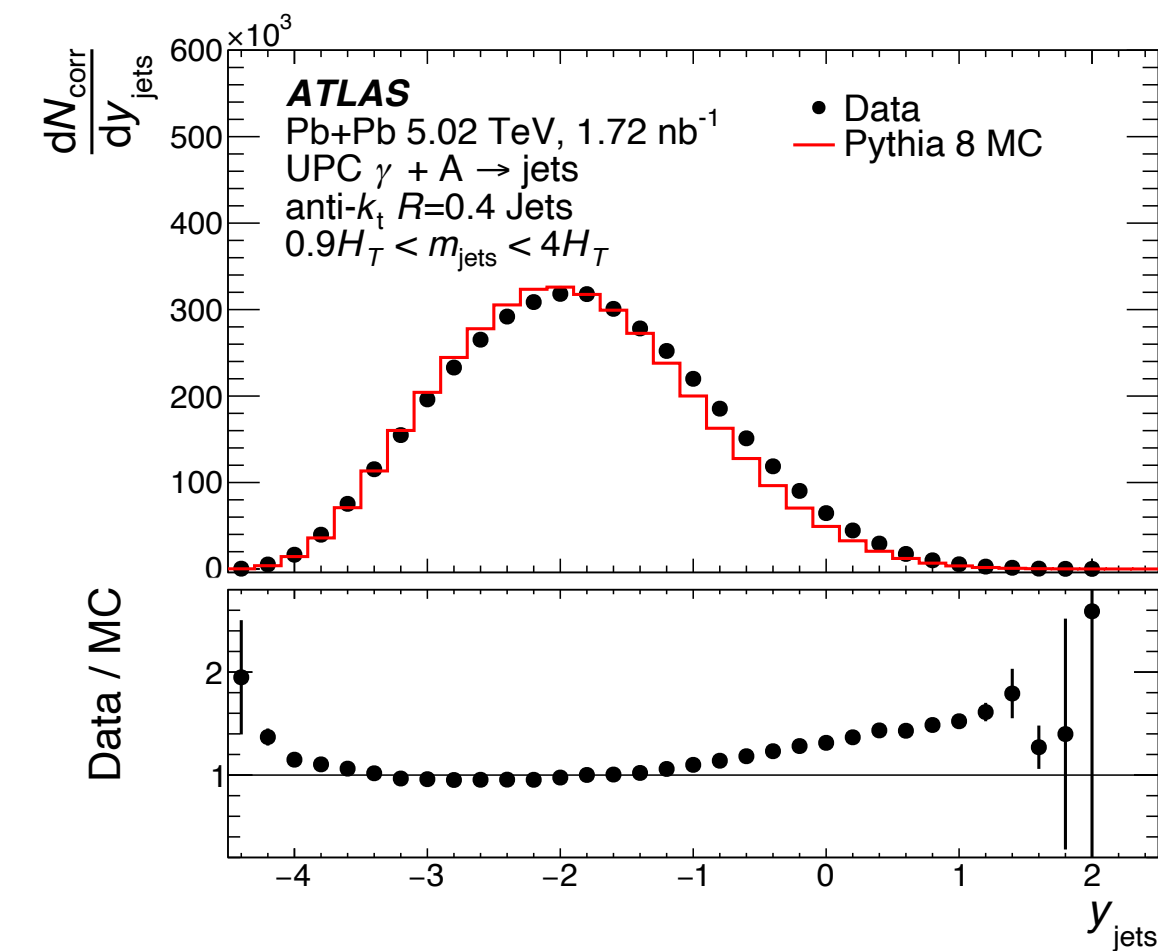
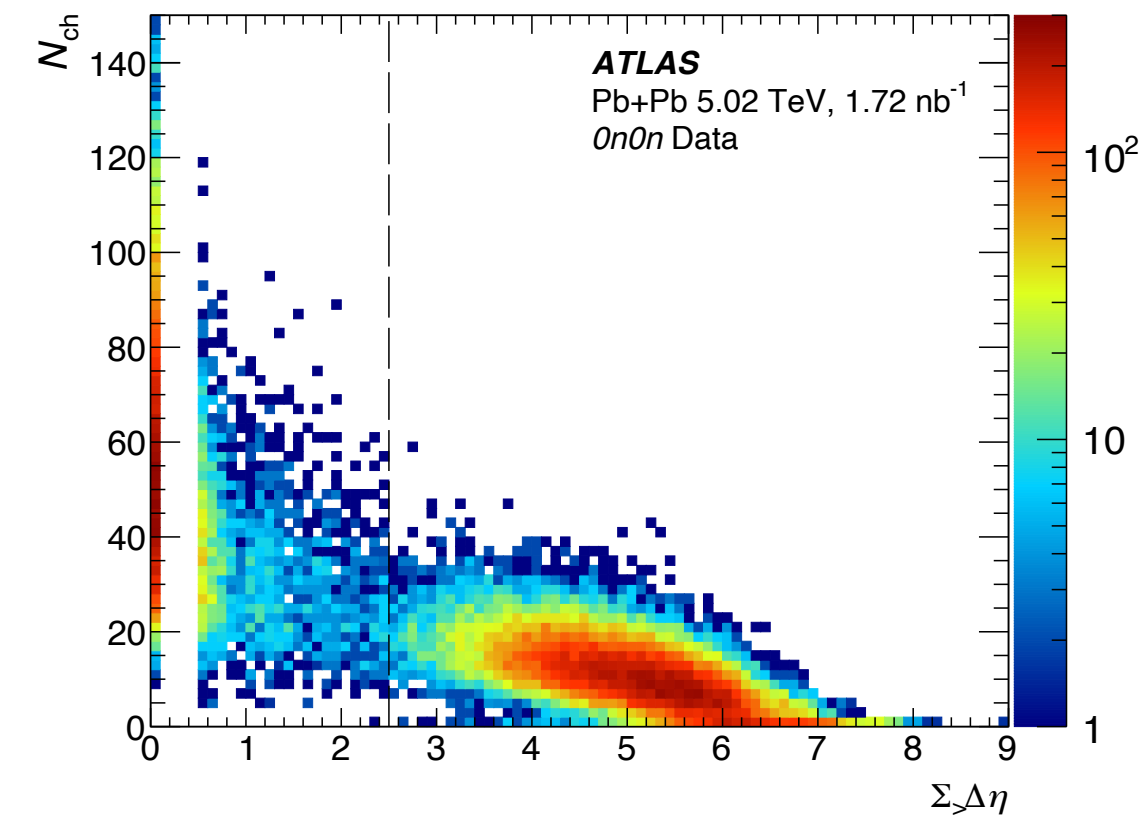
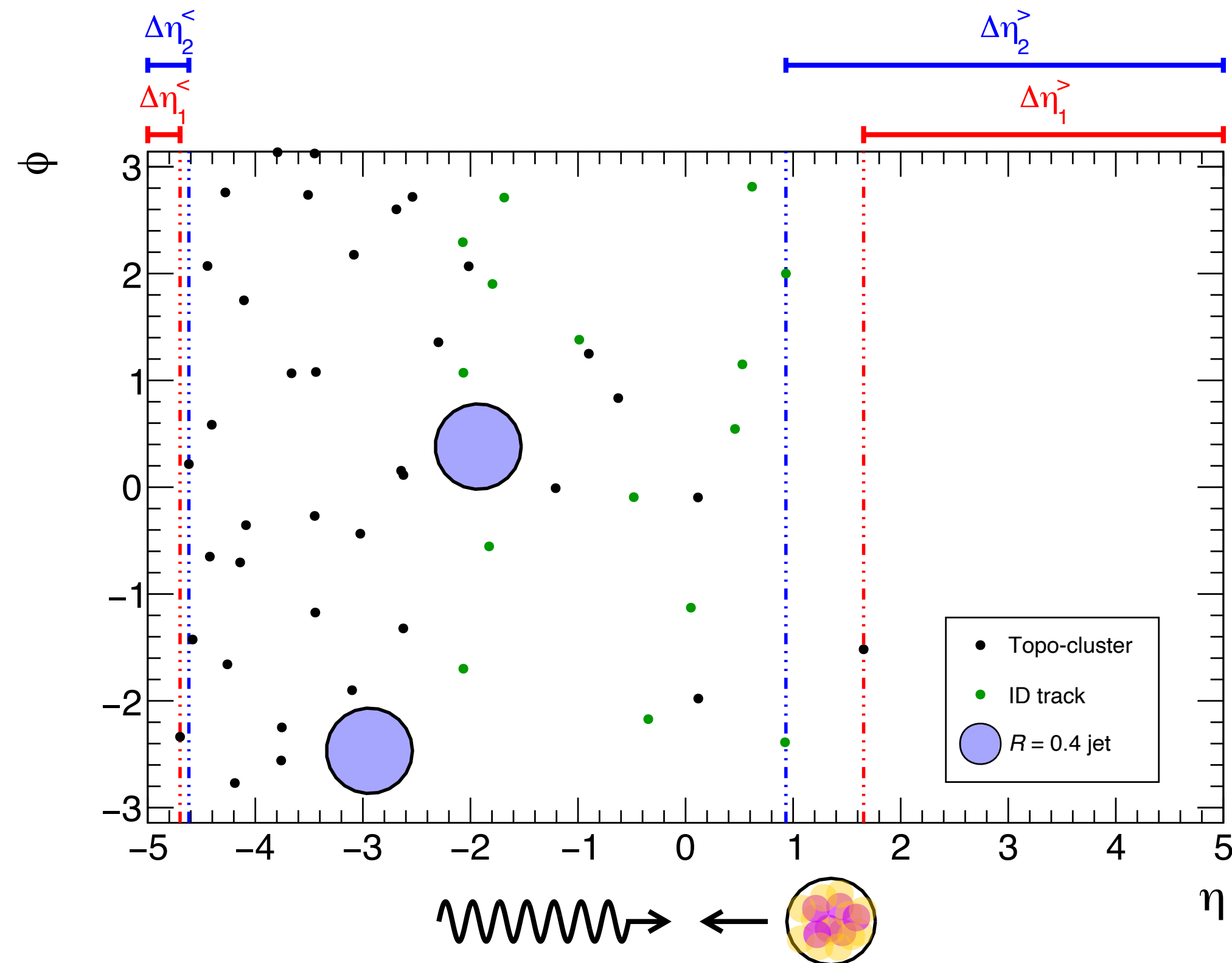


Two-photon jet
production

Only direct process shown

The photon scatters from a nucleon near the nuclear surface, producing jets without detectable nuclear break-up

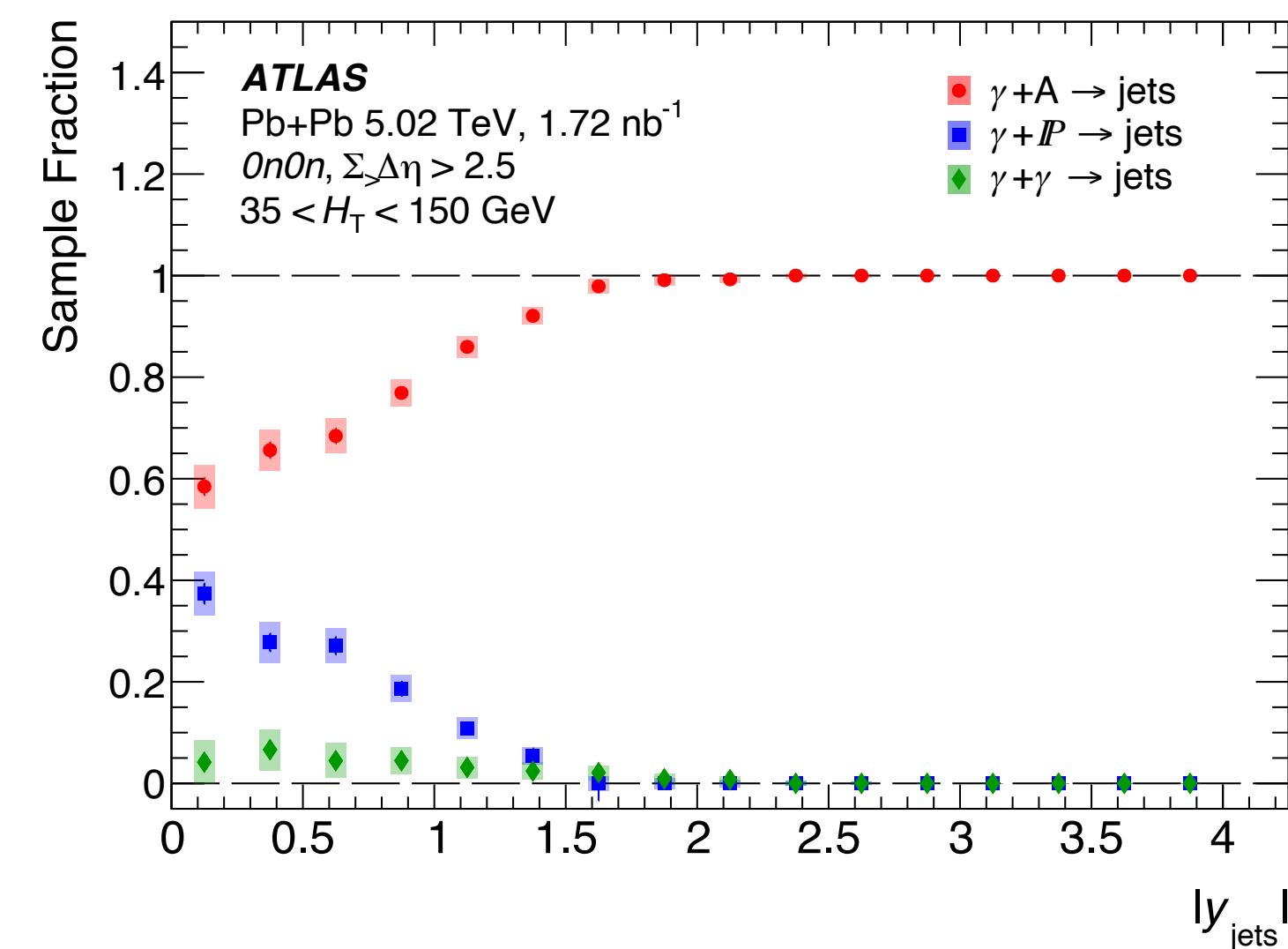
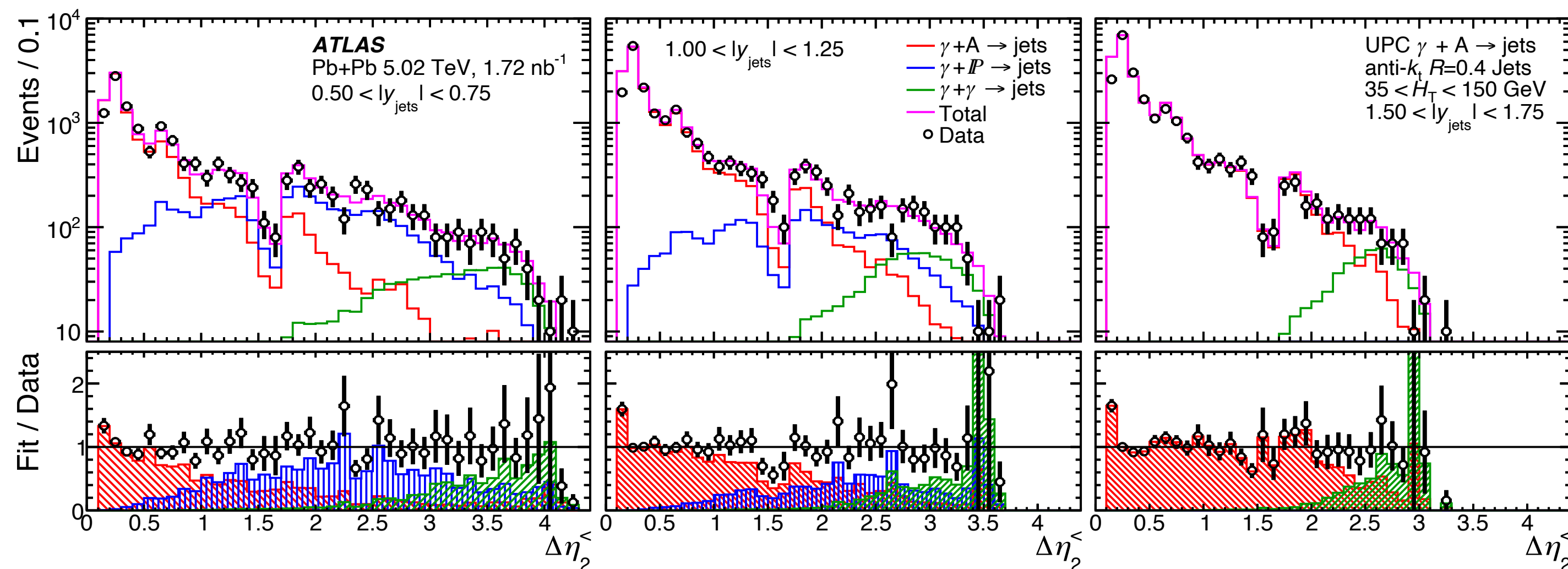
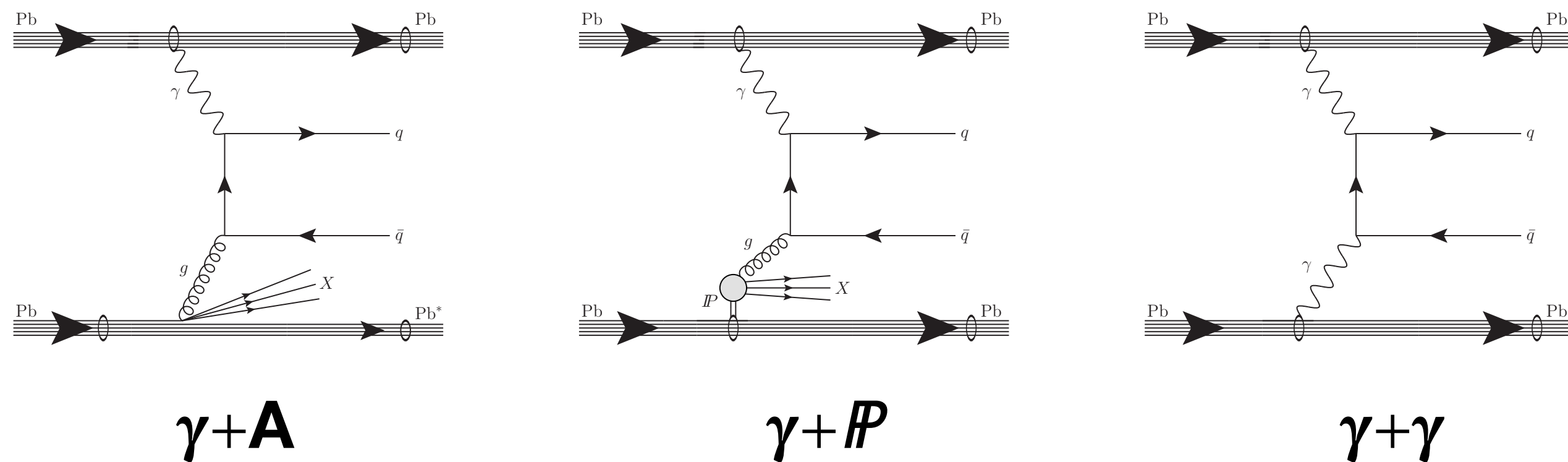
Rapidity gaps for **0n0n** UPCs



$$y_{\text{jets}} \equiv \frac{1}{2} \ln \left(\frac{\sum_i E_i + \sum_i p_{zi}}{\sum_i E_i - \sum_i p_{zi}} \right)$$

The sign of y_{jets} can be used to infer the photon direction without using ZDC tagging

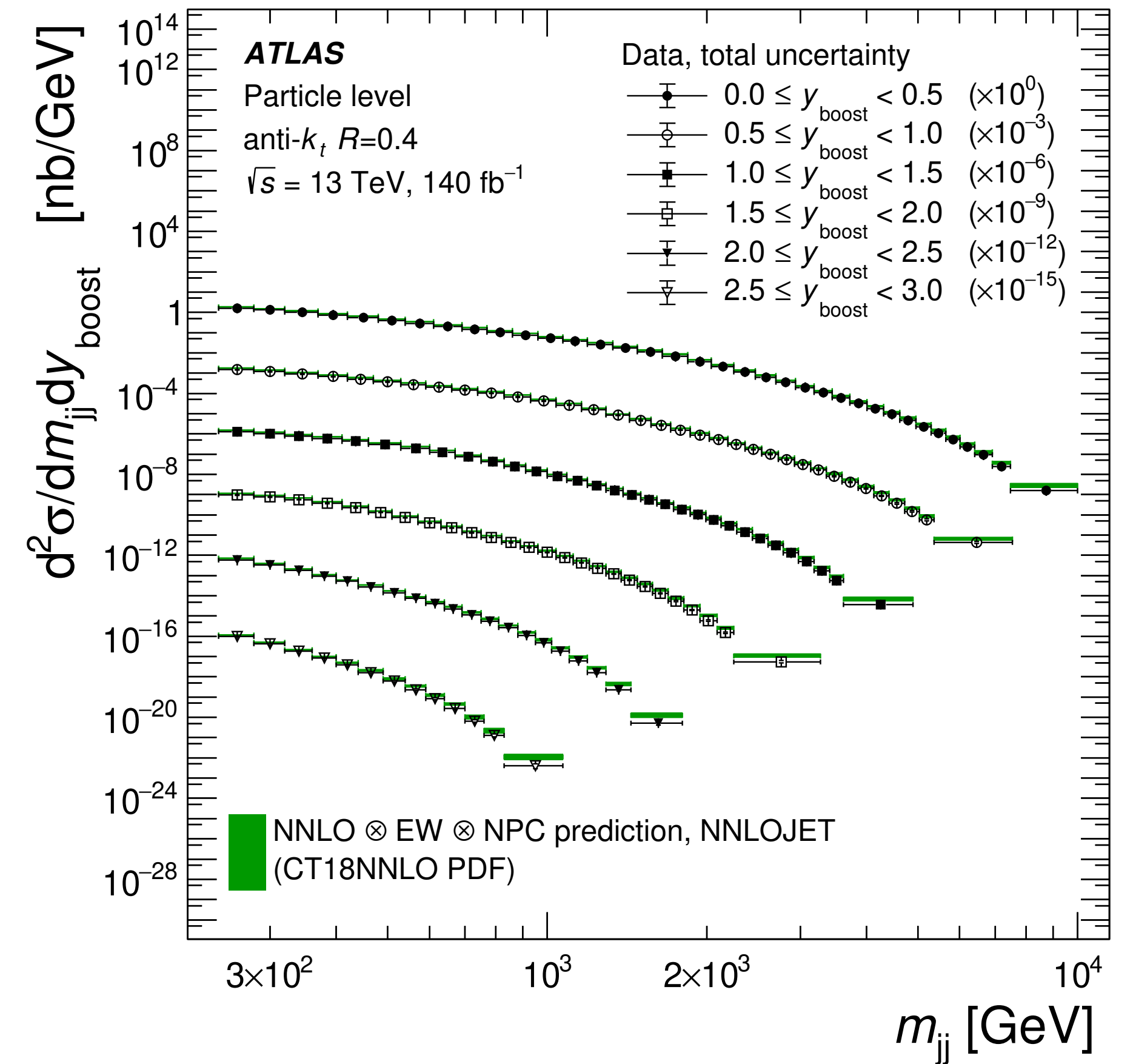
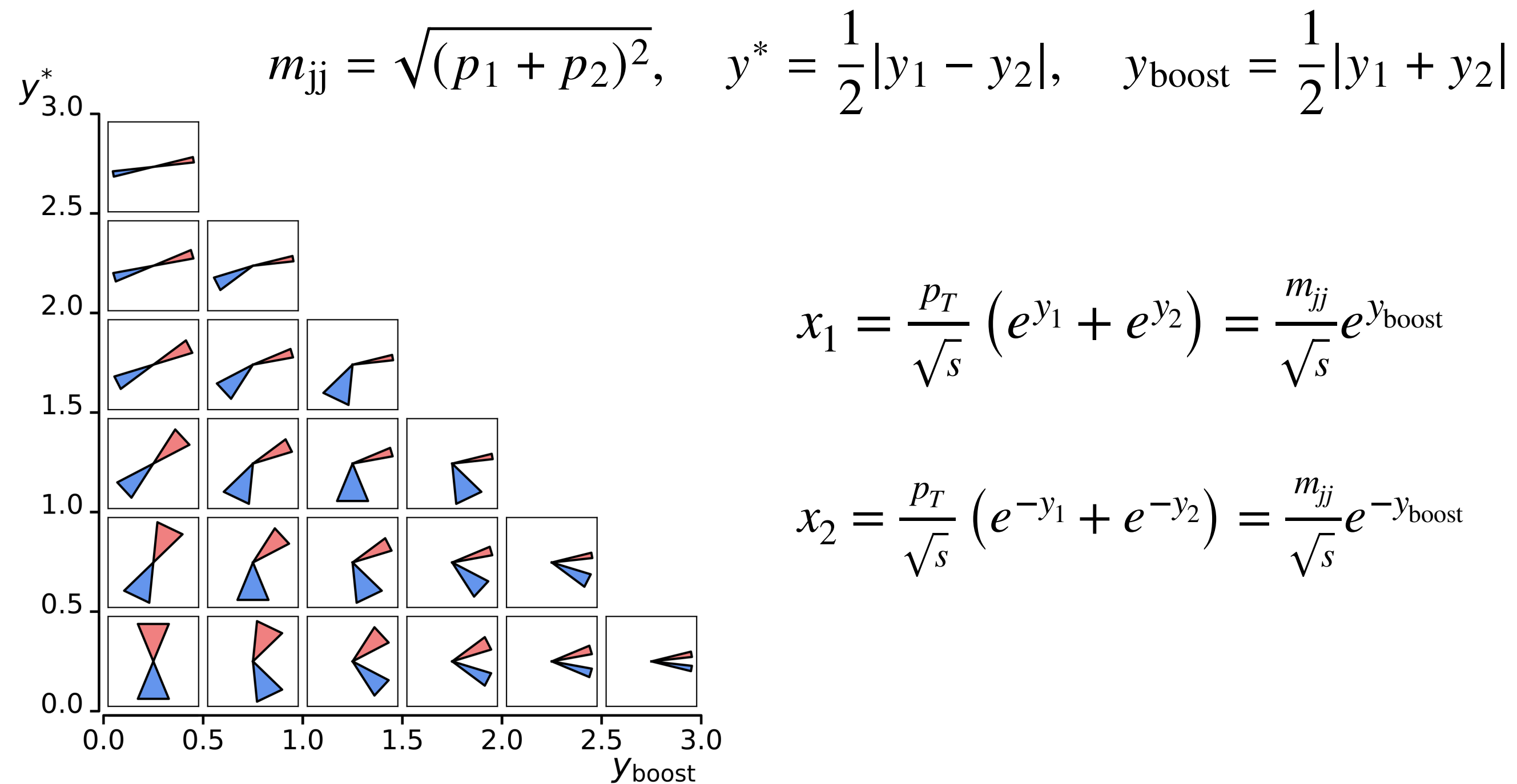
Component separation in **0n0n** UPC events



pp dijet kinematics and parton-x baseline

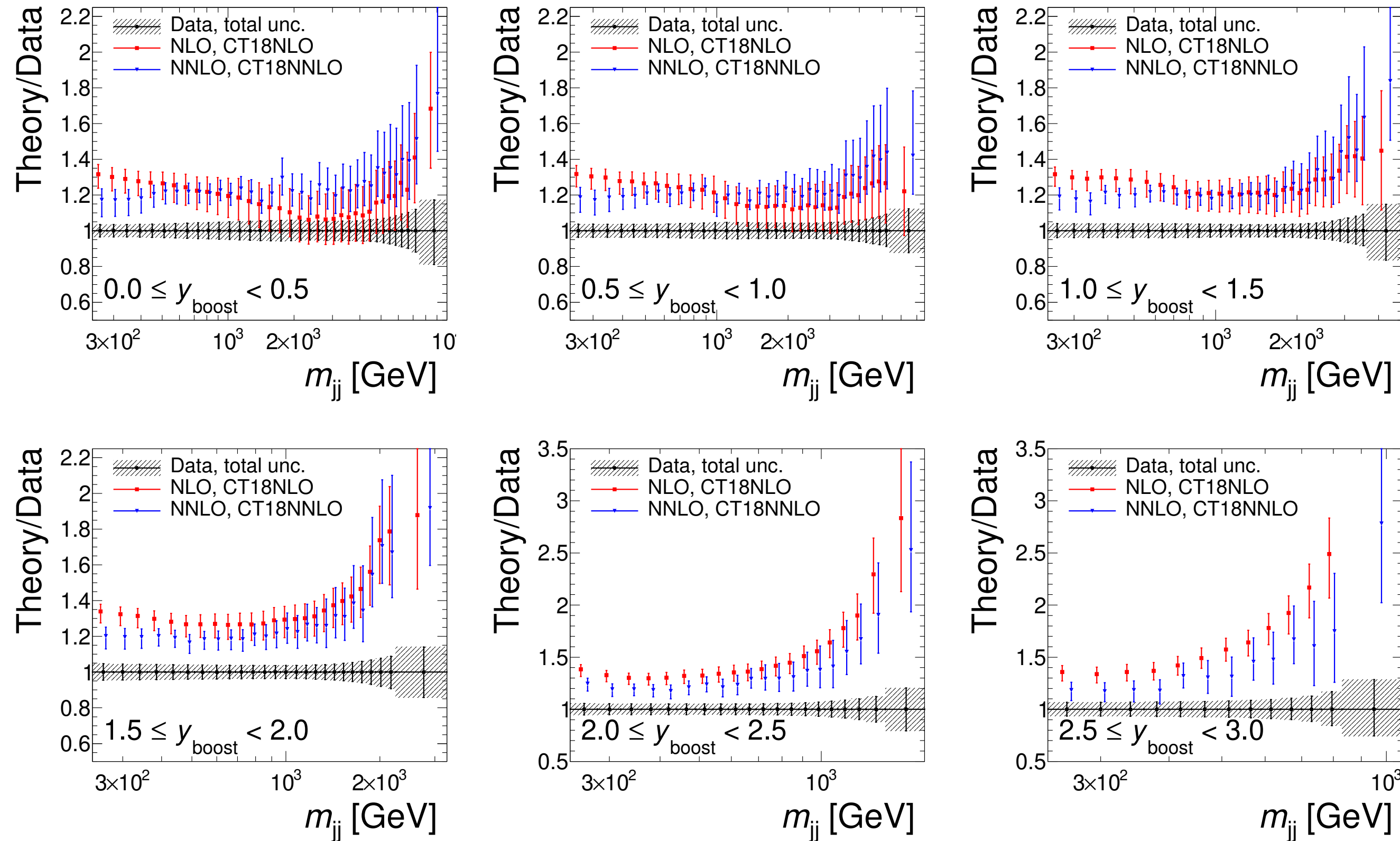
ATLAS: arXiv:2512.19073

- Full Run2 pp collision data at 13 TeV
- Dijet mass ranges from 240 GeV to 10 TeV (at least two jets with $p_T > 75$ GeV)



pp dijets as a PDF baseline

ATLAS: arXiv:2512.19073



- ATLAS pp jets constrain the gluon PDF over a broad (x, Q^2) range
- Compared with state-of-the-art full-color NNLO pQCD calculations, with EM and non-perturbative corrections
- The NNLO theoretical predictions tend to overestimate the data by about 15–20%

ATLAS
Particle level

$\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$
anti- k_t $R=0.4$

$\mu_R = \mu_F = m_{jj}$
 $\alpha_s(m_Z) = 0.118$

pQCD
 $\otimes \text{EW} \otimes \text{NPC}$

Kinematic observables in 0nXn UPC jets

ATLAS: PRD 111 (2025) 052006

Total scalar p_T :

$$H_T = \sum_i p_T^i$$

Q^2 : $Q \sim H_T/2$

Pb momentum fraction:

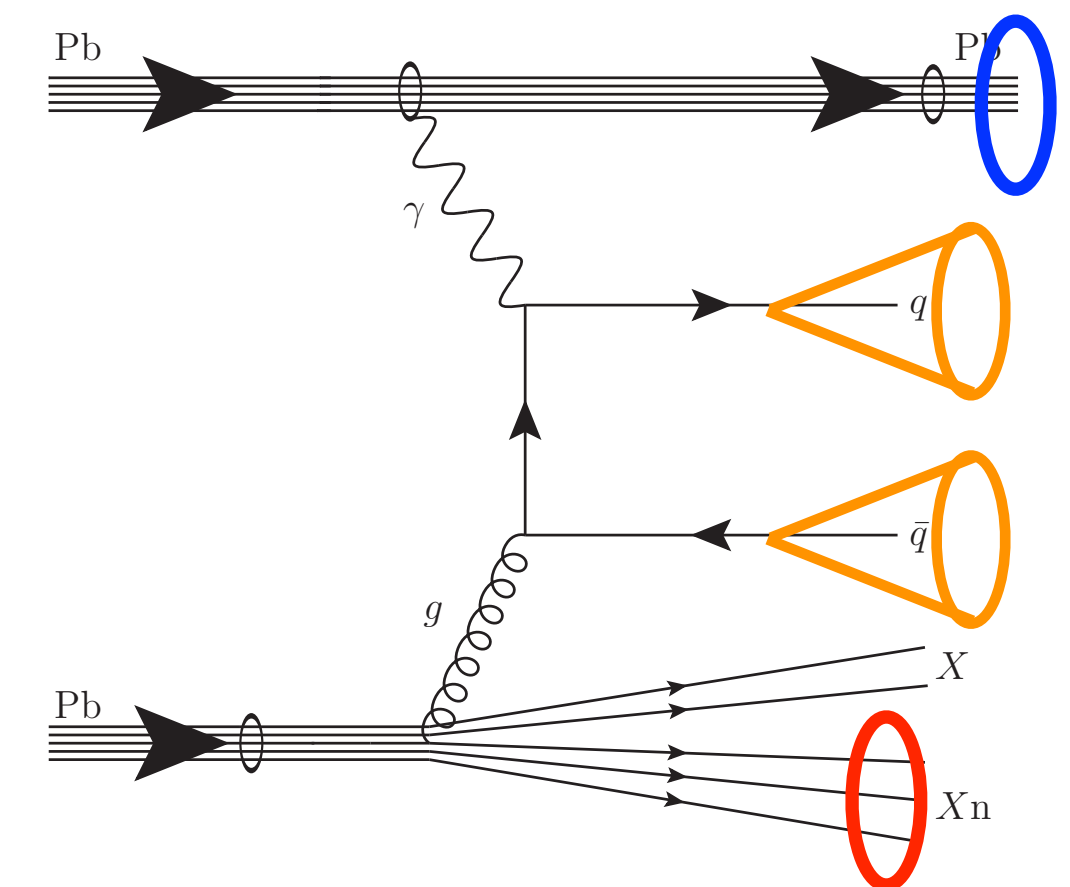
$$x_A = \frac{m_{\text{jets}} e^{-y_{\text{jets}}}}{\sqrt{s_{\text{NN}}}}$$

Bjorken- x : x_A at LO

Photon momentum fraction:

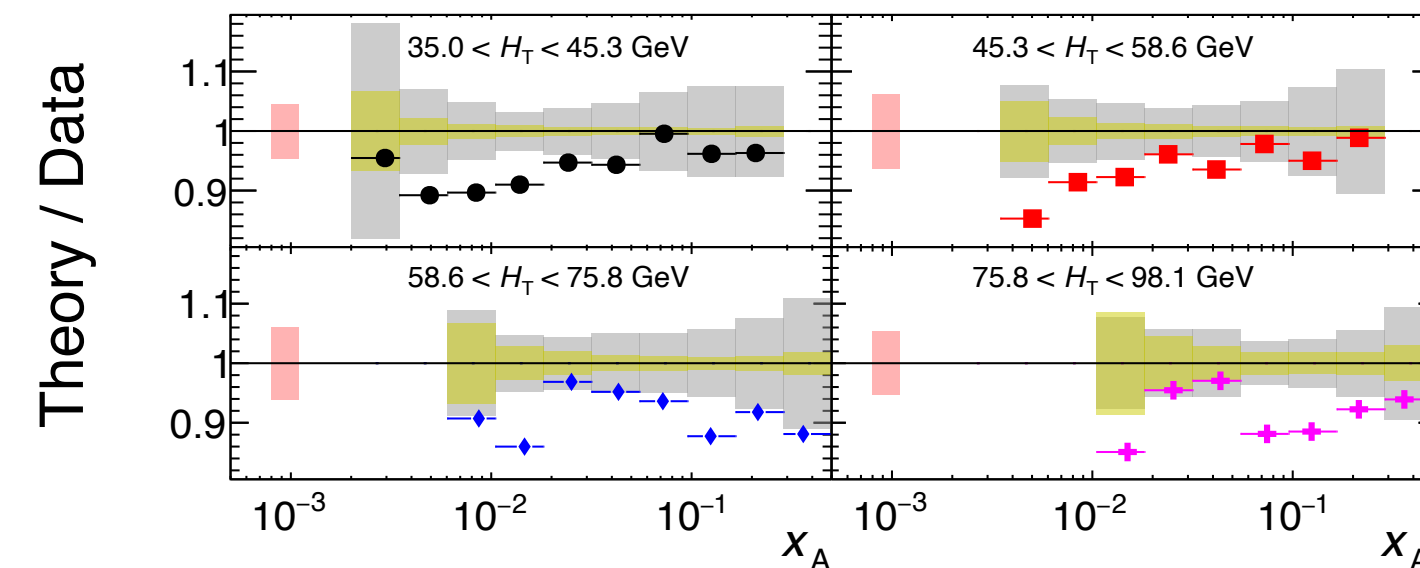
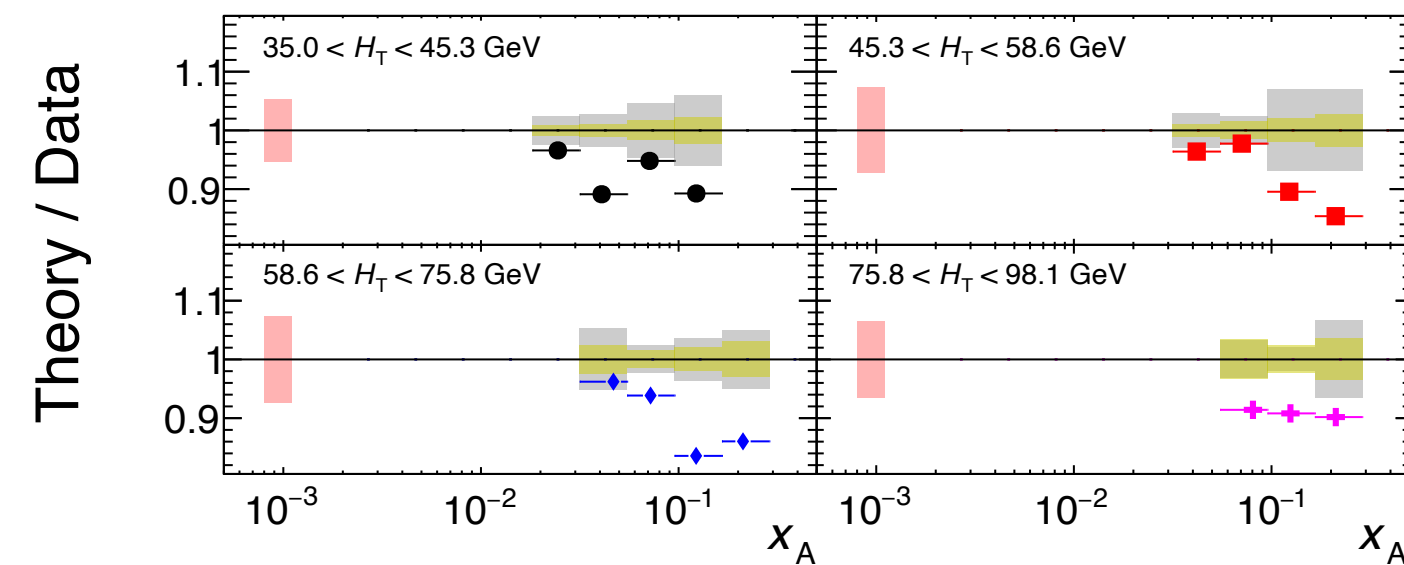
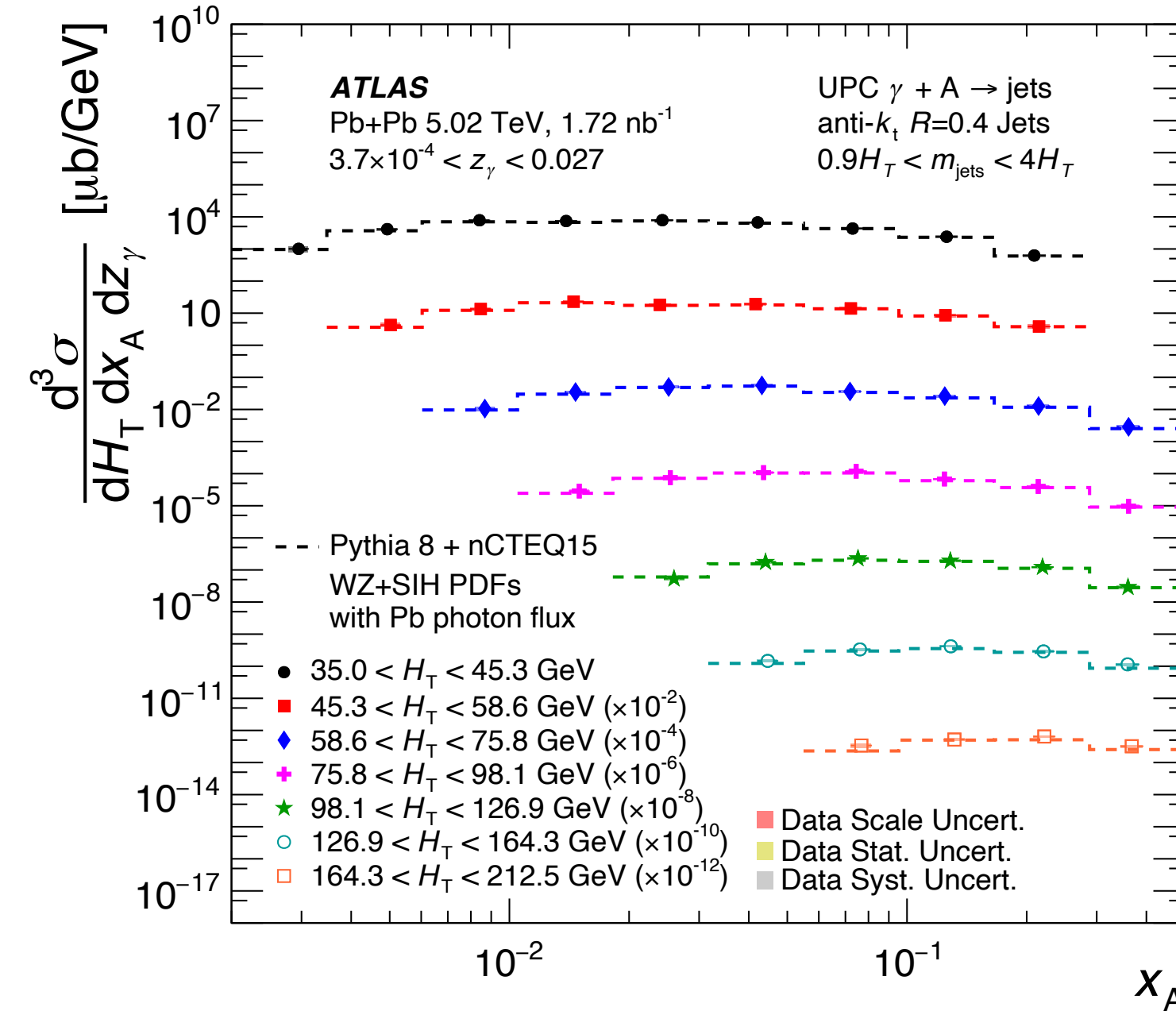
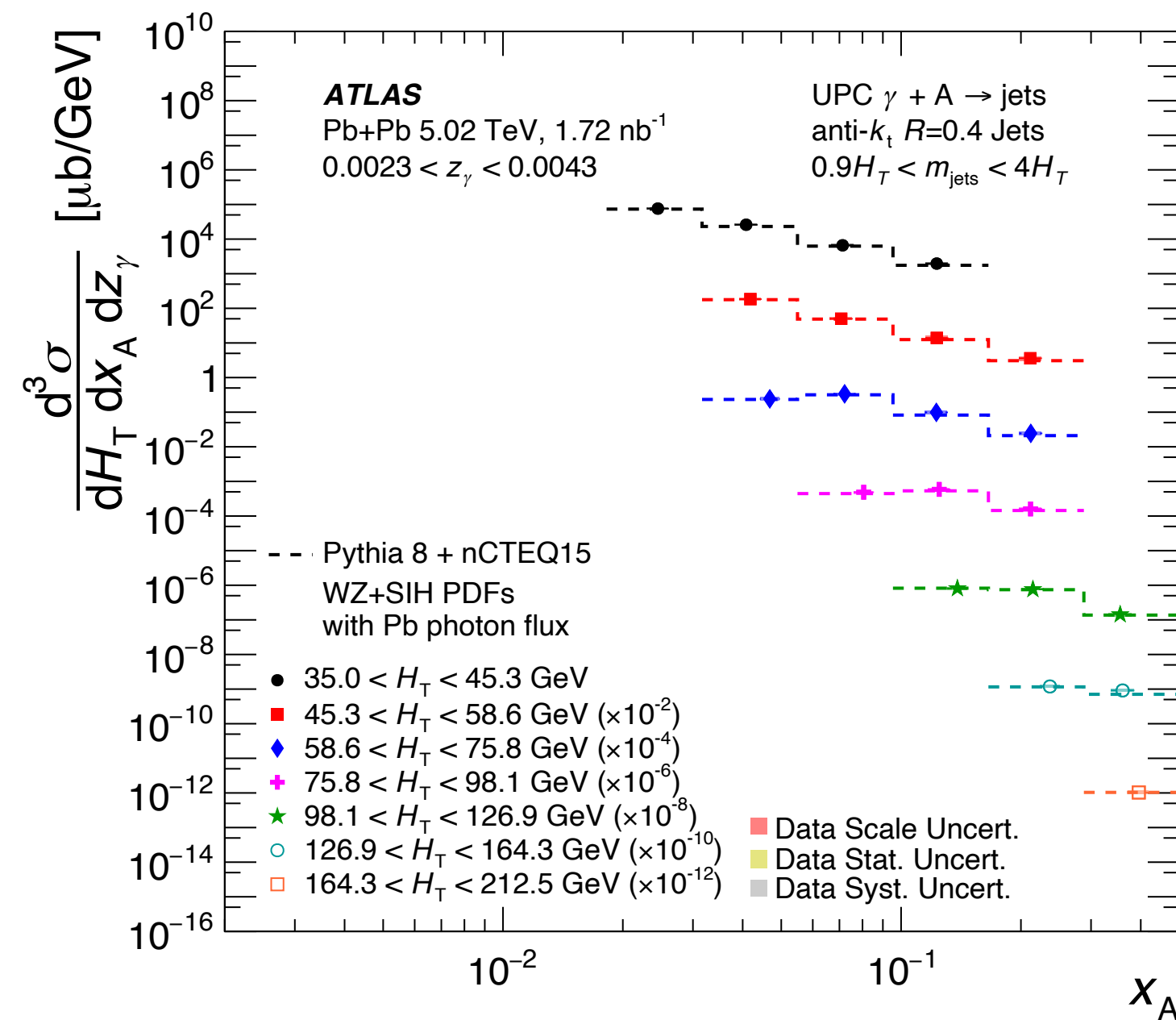
$$z_\gamma = \frac{m_{\text{jets}} e^{+y_{\text{jets}}}}{\sqrt{s_{\text{NN}}}}$$

E_γ : $z_\gamma \sim E_\gamma / E_A$ at LO



Triple-differential UPC $\gamma+A \rightarrow \text{jets}$ cross sections

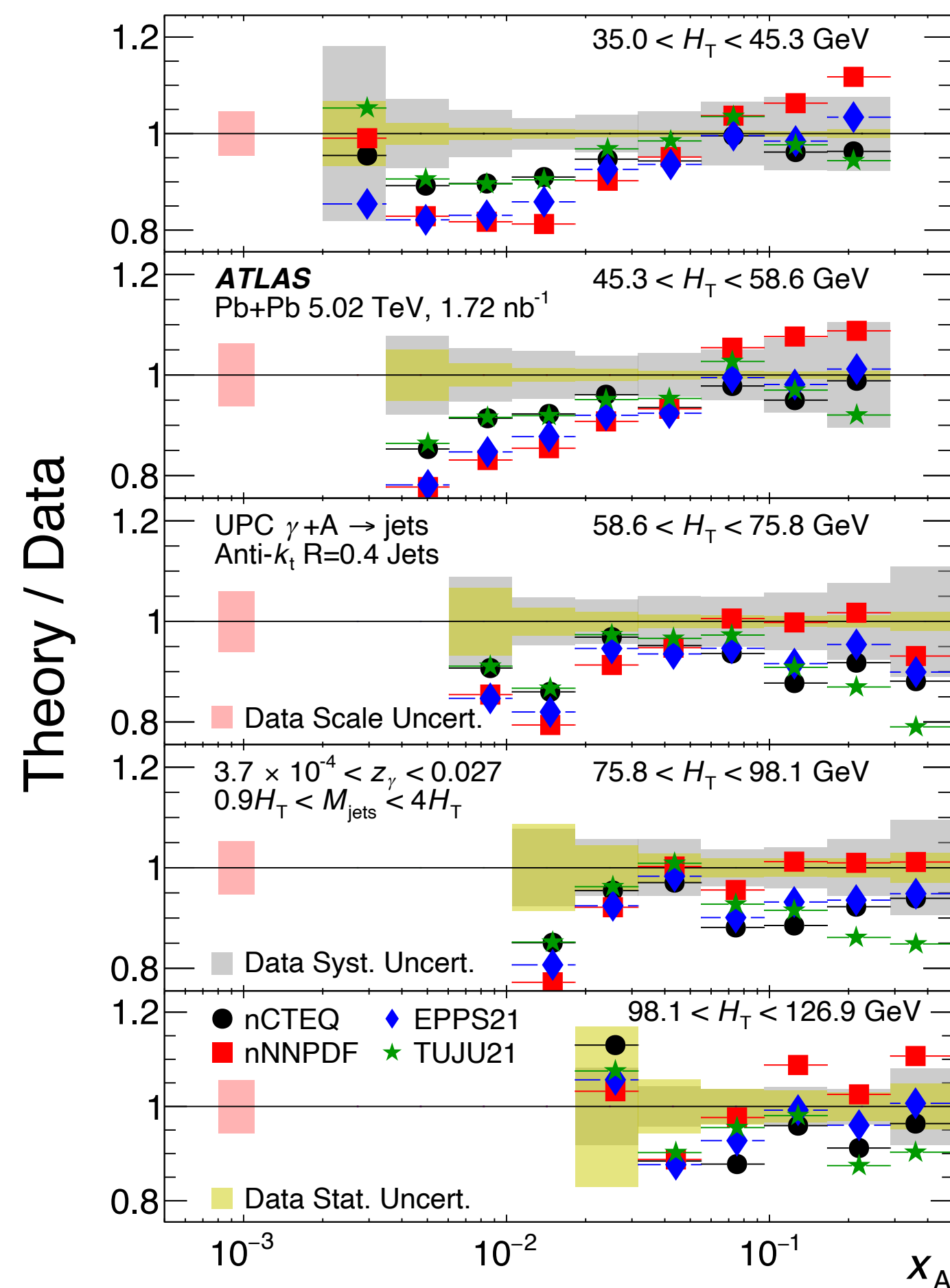
ATLAS: PRD 111 (2025) 052006



- Differential in H_T , x_A and z_γ
- Precision better than 5% over a broad range of x_A from 10⁻³ to 10⁻¹, and intermediate-to-high Q^2

Constraining nPDFs with UPC jets

ATLAS: PRD 111 (2025) 052006



Ratios of measured triple-differential cross-sections to predictions using different nPDF fits; photon-flux uncertainties are not included:

- **nCTEQ15** WZ+SIH
 - **nNNPDF3.0**
 - **EPPS21**
 - **TUJU21**
- nCTEQ gives the best overall agreement. While TUJU agrees well with data at higher H_T .
 - nNNPDF overpredicts the cross sections at high H_T and large x_A

Kinematic observables in 0n0n UPC jets

ATLAS: arXiv:2604.24435

ATLAS: arXiv:2604.20559

Total scalar p_T :

$$H_T = \sum_i p_T^i$$

Q^2 : $Q \sim H_T/2$

Pb momentum fraction:

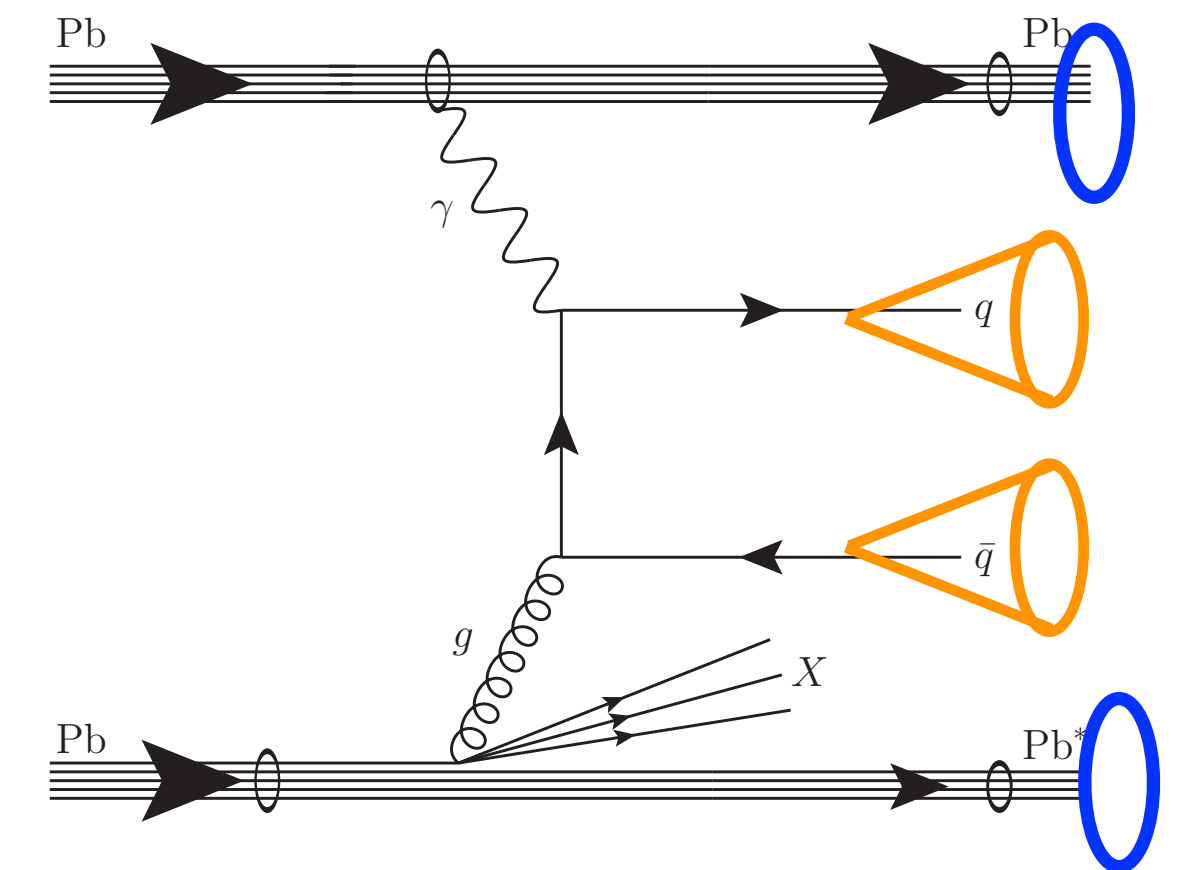
$$x_+ = \frac{m_{\text{jets}} e^{+|y_{\text{jets}}|}}{\sqrt{s_{\text{NN}}}}$$

Bjorken- x : x_+ at LO

Photon momentum fraction:

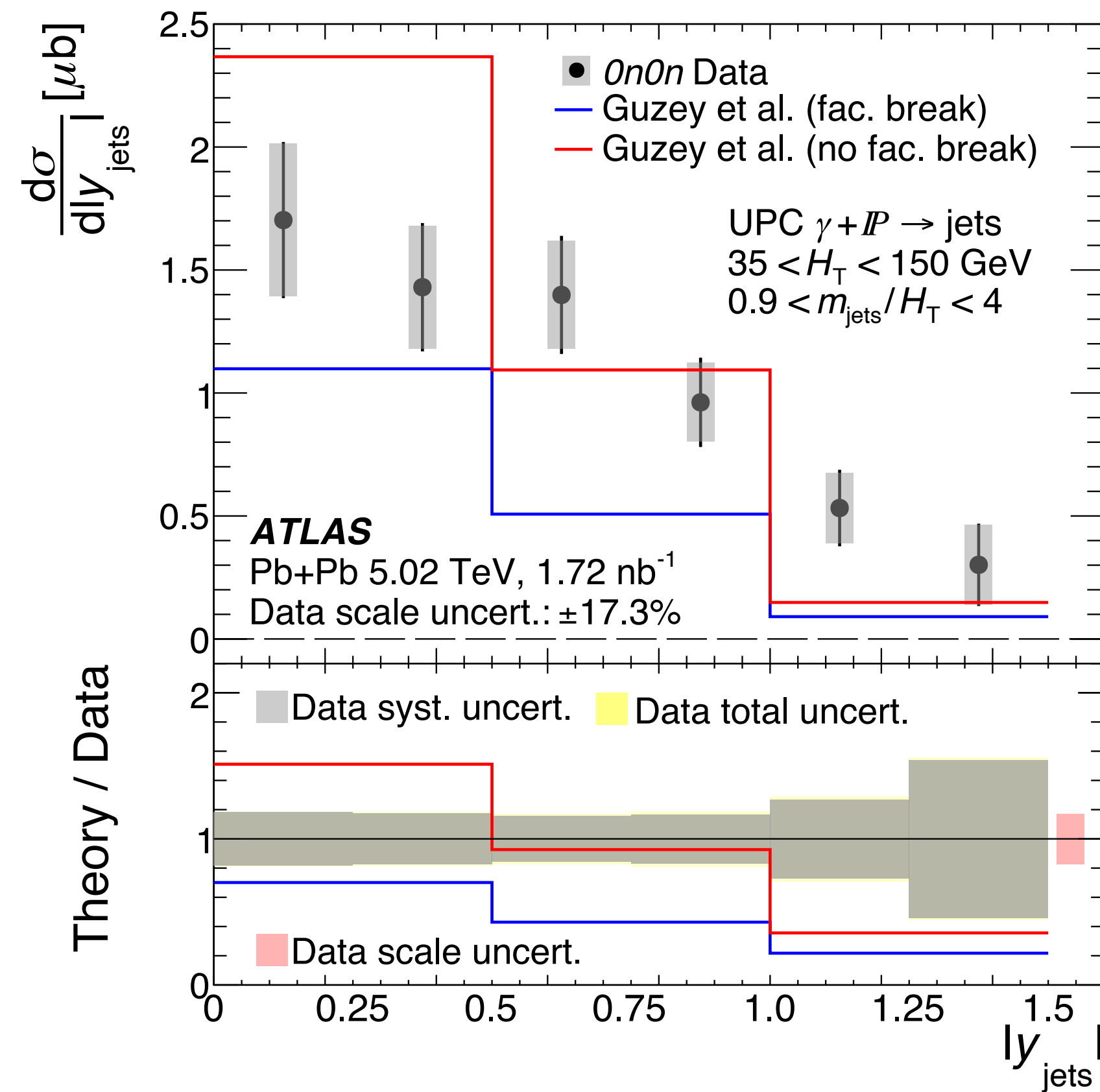
$$z_- = \frac{m_{\text{jets}} e^{-|y_{\text{jets}}|}}{\sqrt{s_{\text{NN}}}}$$

E_γ : $z_- \sim E_\gamma / E_A$ at LO



$\gamma + P \rightarrow \text{jets}$ cross section

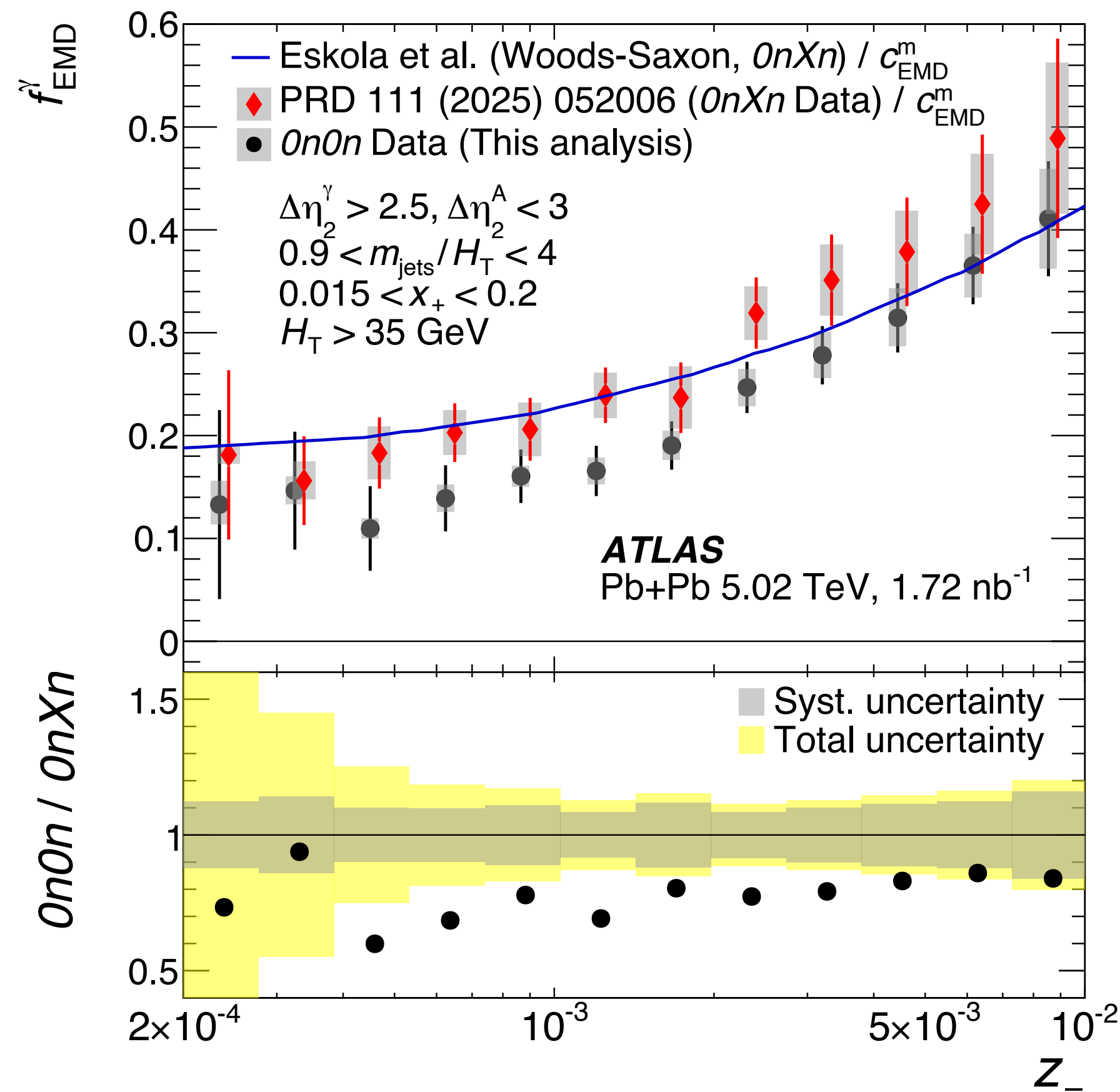
ATLAS: arXiv:2604.24435



- First measurement of diffractive jets in 0n0n UPCs
- The H_T -integrated cross sections are compared to NLO predictions (JHEP 04 (2016) 158)
- The model without diffractive QCD factorization breaking predicts the normalization reasonably well, but not the shape

EMD rate as an impact-parameter proxy

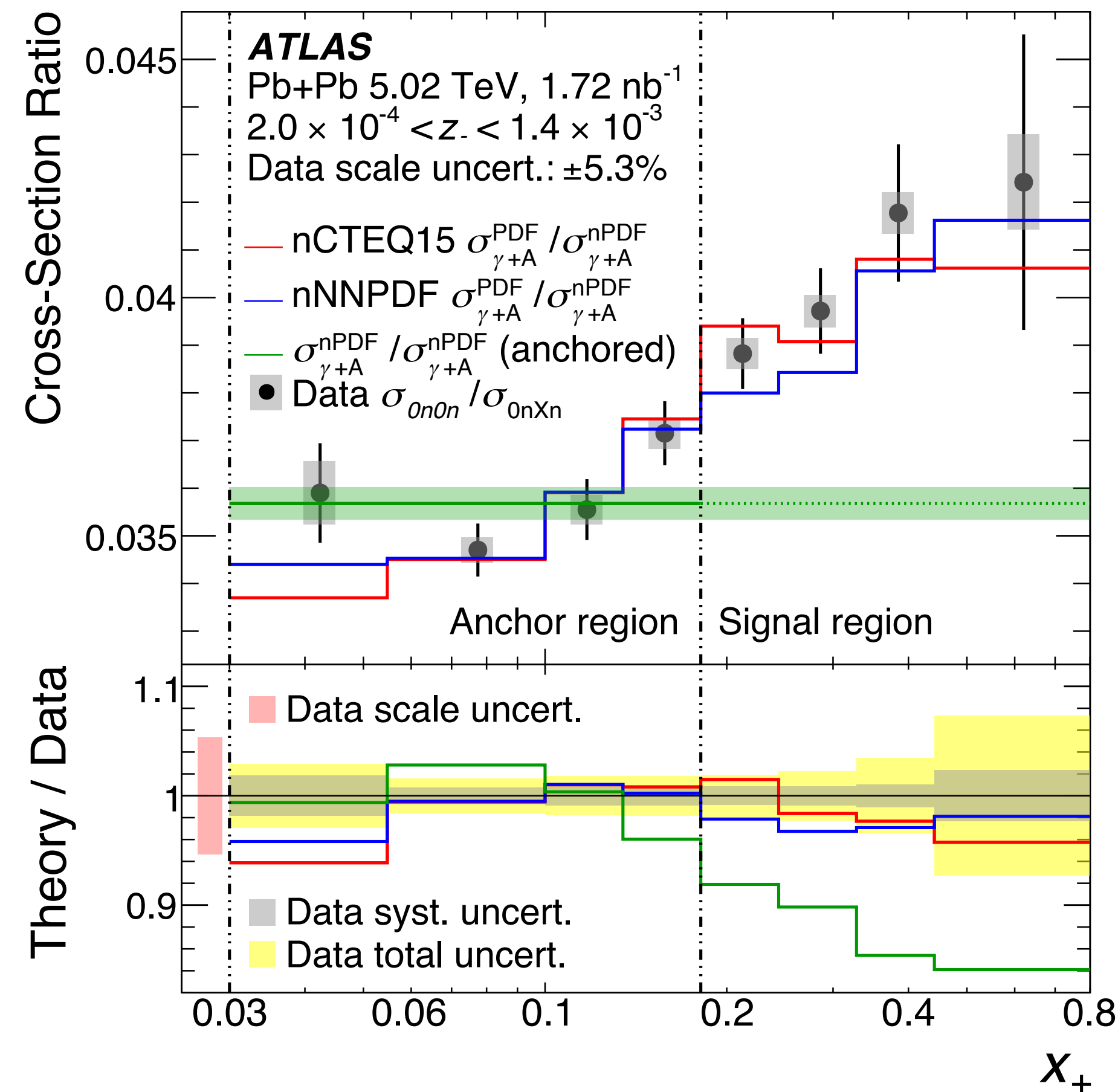
ATLAS: arXiv:2604.20559



$$f_{\text{EMD}}^\gamma = \text{[Diagram 1]} + \text{[Diagram 2]}$$

The diagram illustrates the EMD rate as a sum of two processes. The first process (top) shows a Pb nucleus emitting a photon γ which interacts with a quark q and antiquark $\bar{q}$ in a Pb nucleus, producing a quark q and antiquark $\bar{q}$ and a photon γ . The second process (bottom) shows a Pb nucleus emitting a photon γ which interacts with a quark q and antiquark $\bar{q}$ in a Pb nucleus, producing a quark q and antiquark $\bar{q}$ and a photon γ .

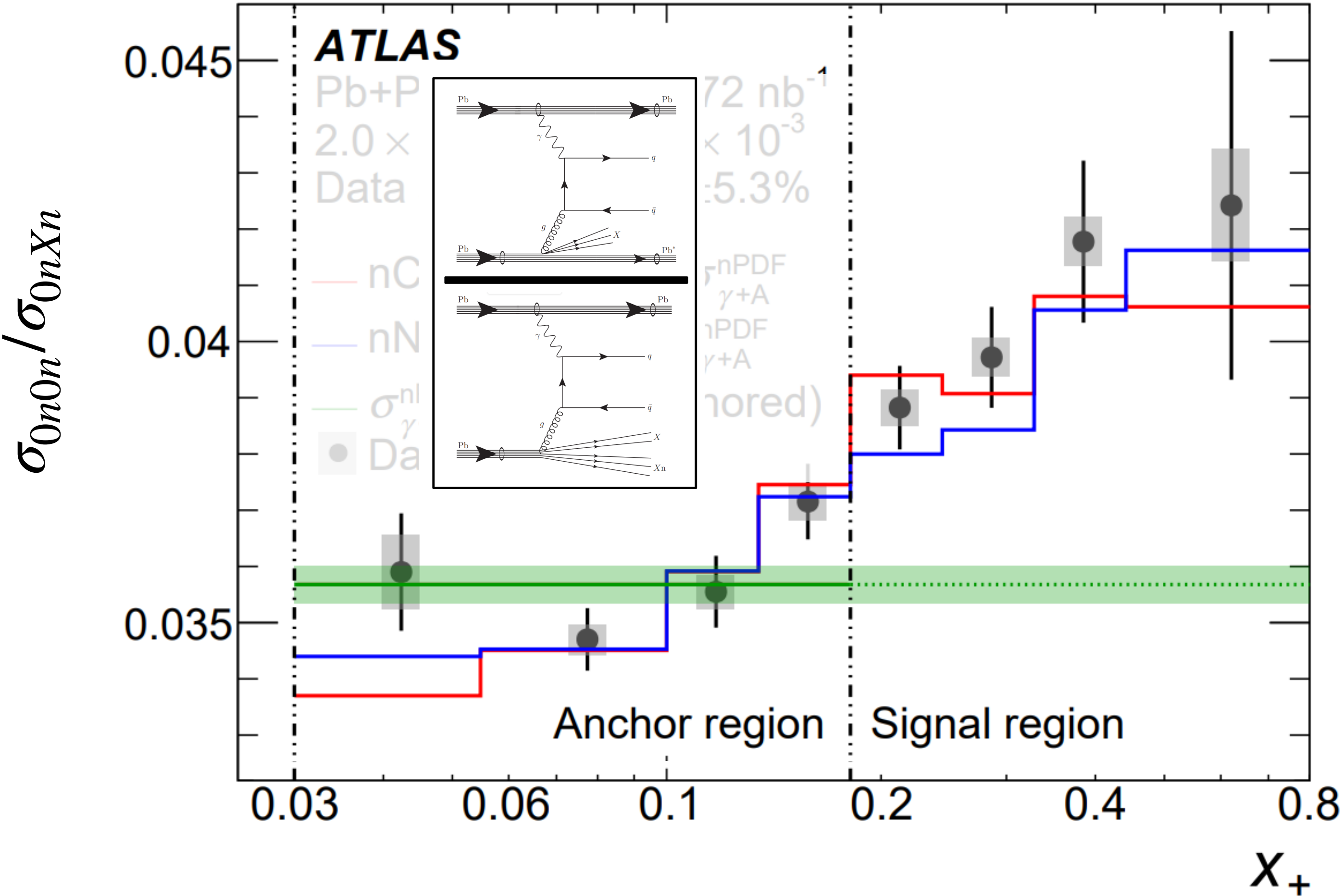
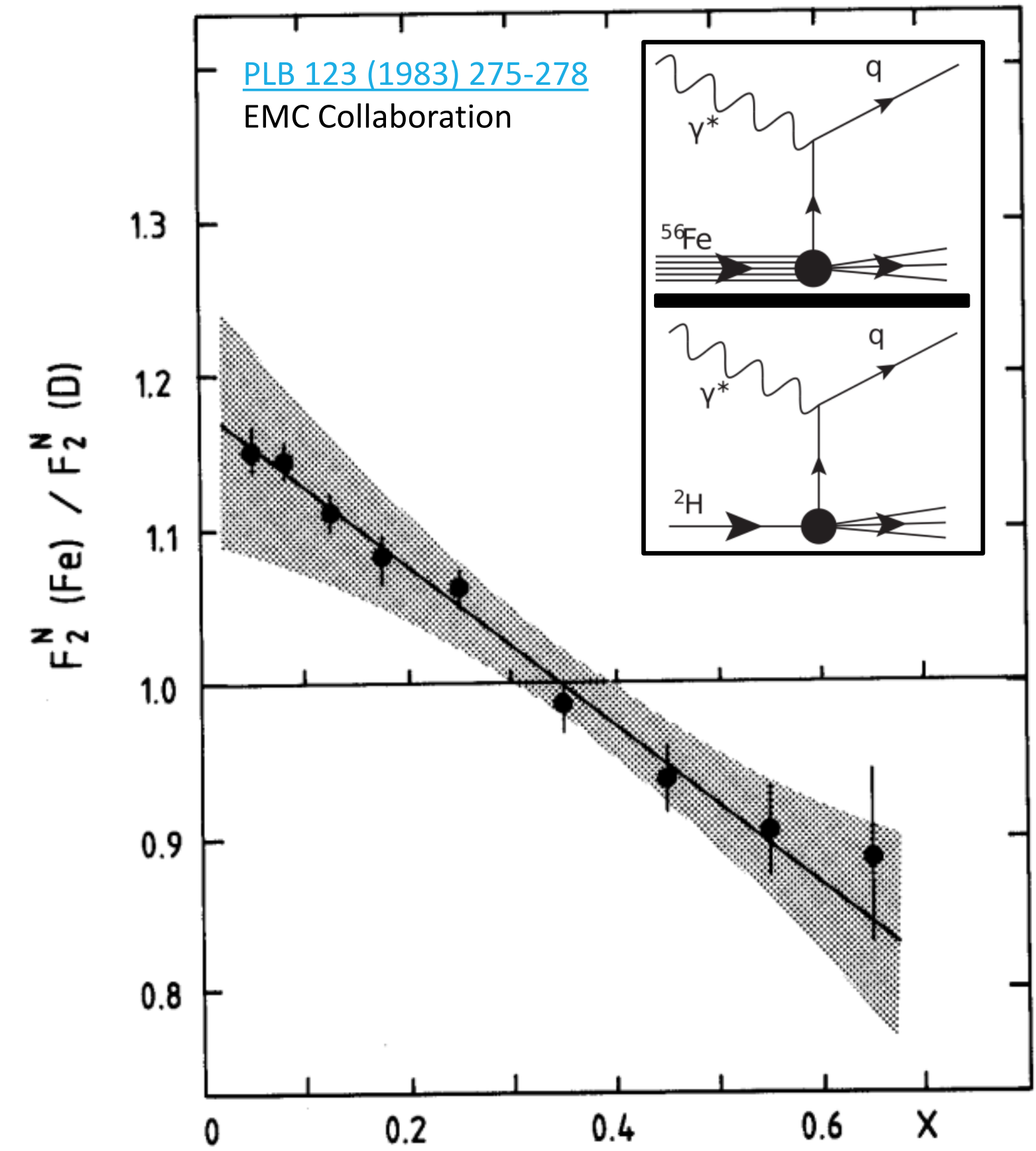
- The $0n0n$ events exhibit a systematically lower EMD rate than $0nXn$ events
- Evidence that $0n0n$ collisions probe large impact-parameter, corresponding to more peripheral UPCs



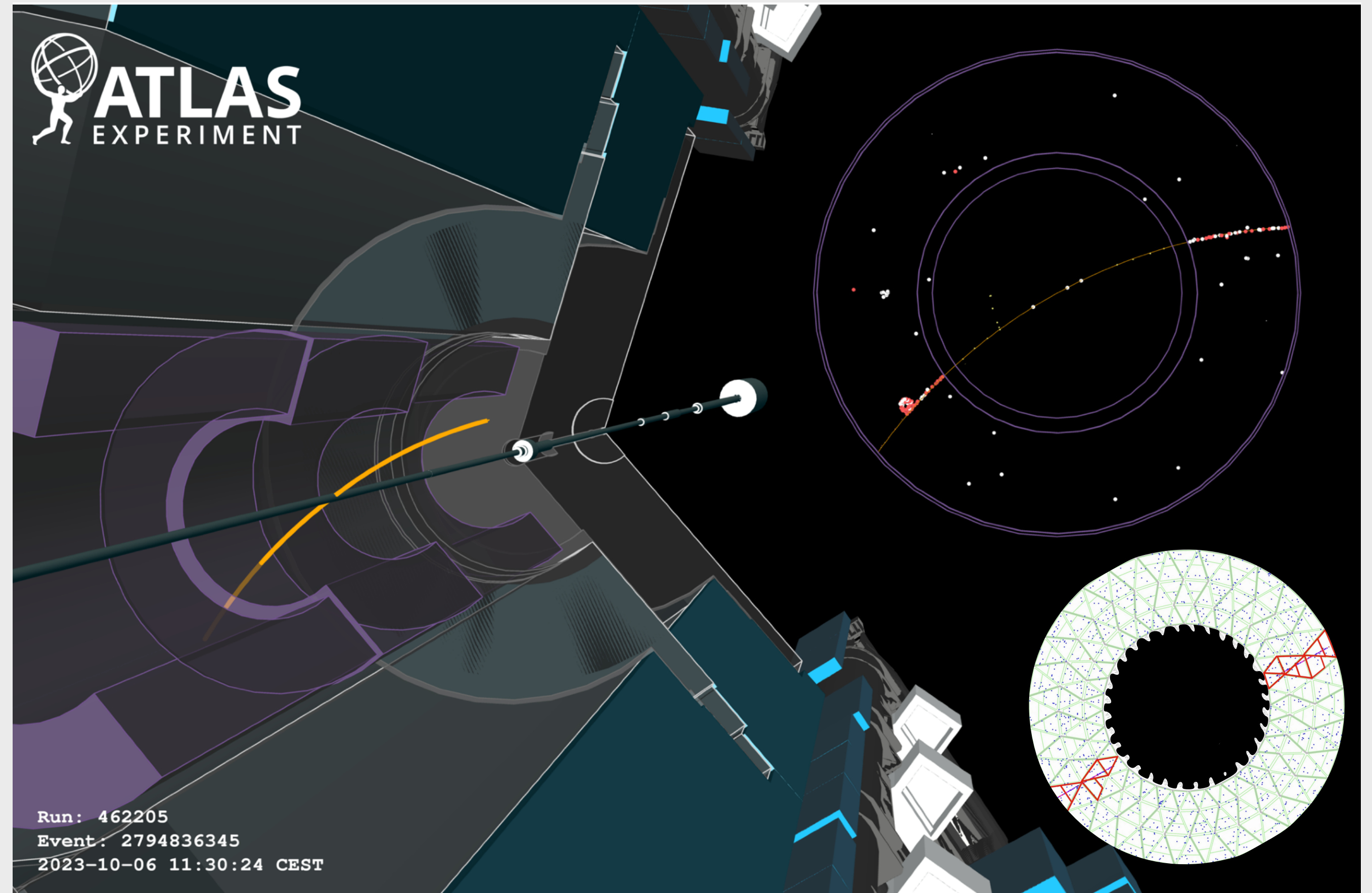
- $0n0n/0nXn$ ratio shows a clear increasing trend with x_+ (x in Pb)
- Theoretical comparisons are constructed using nCTEQ and nNNPDF: free nucleon PDF / nPDF
- Significance of the slope: **6.0 σ**

$$x_+ \equiv \frac{m_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{+|y_{\text{jets}}|}$$

Reversing the EMC Effect

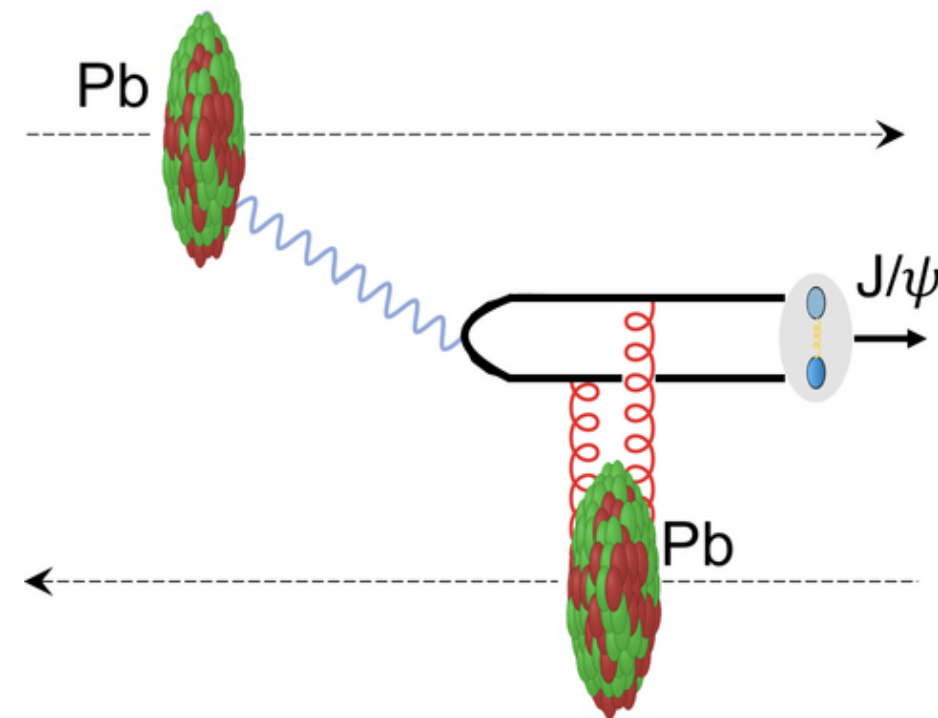


Coherent J/ψ

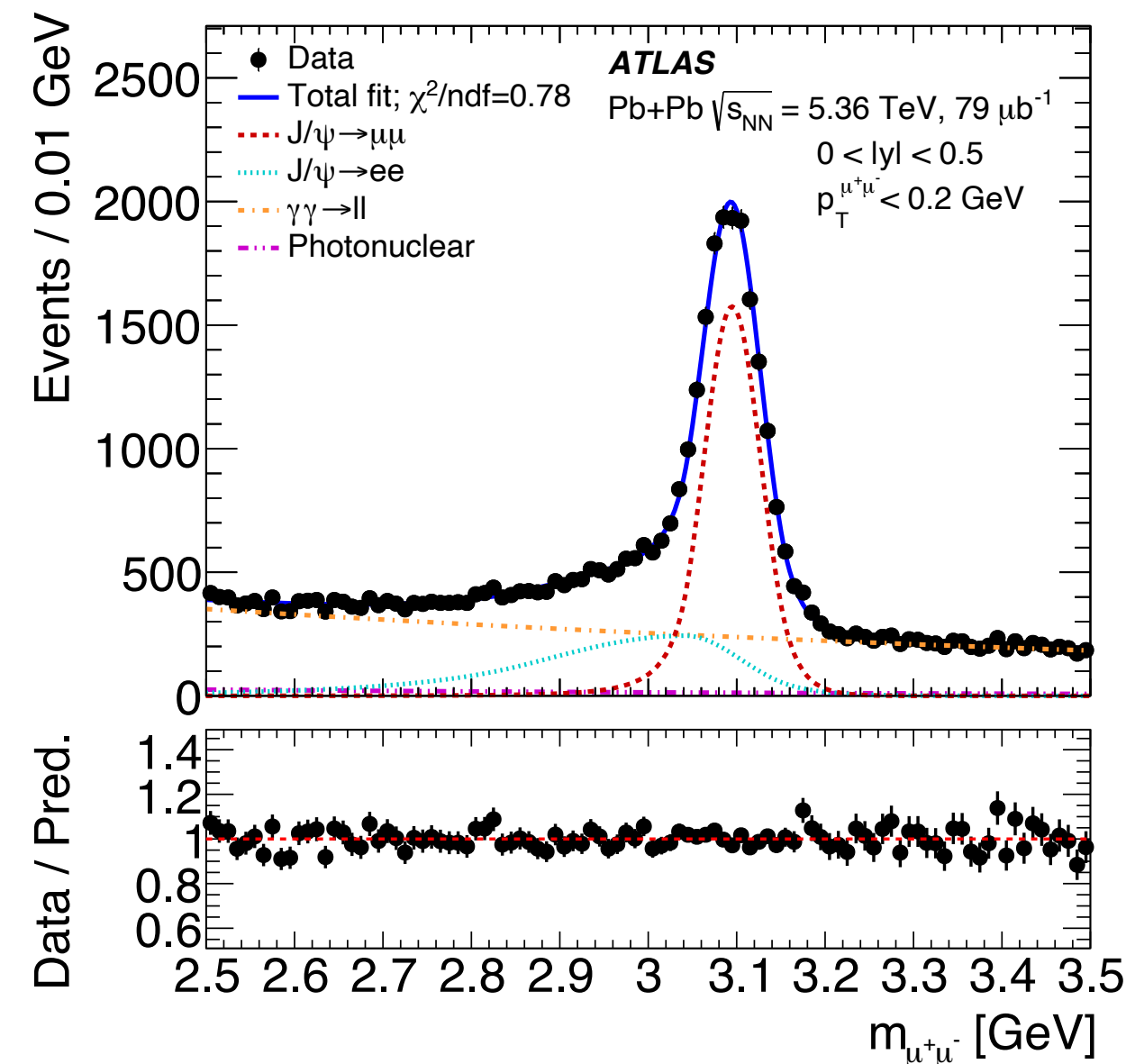
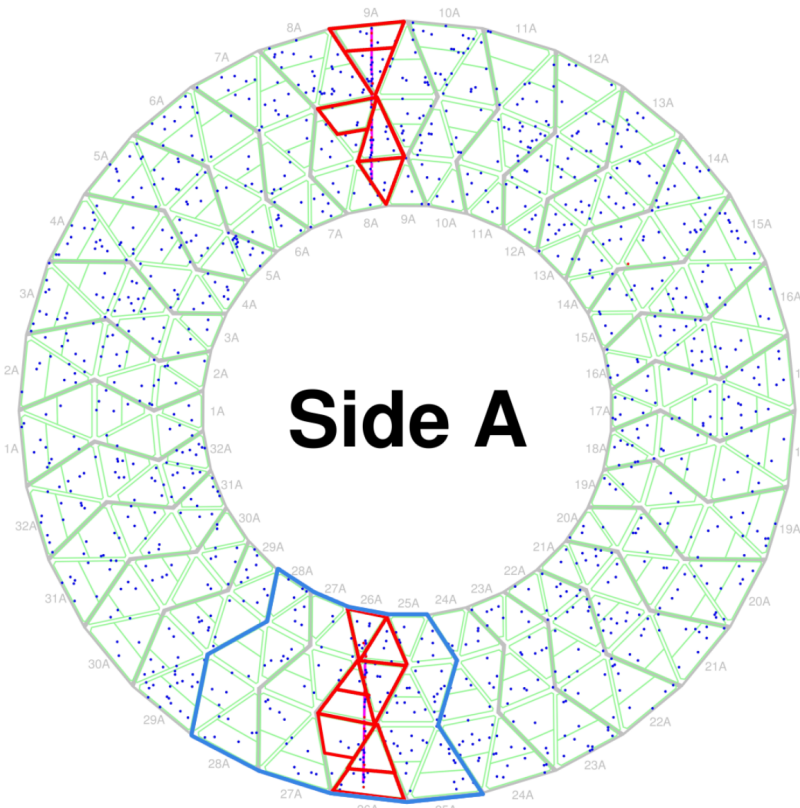
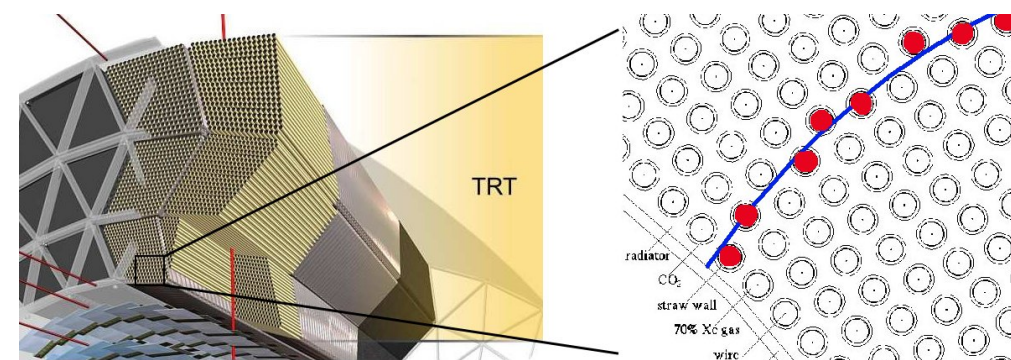


Coherent exclusive vector meson photoproduction

ATLAS: JHEP 04 (2026) 020



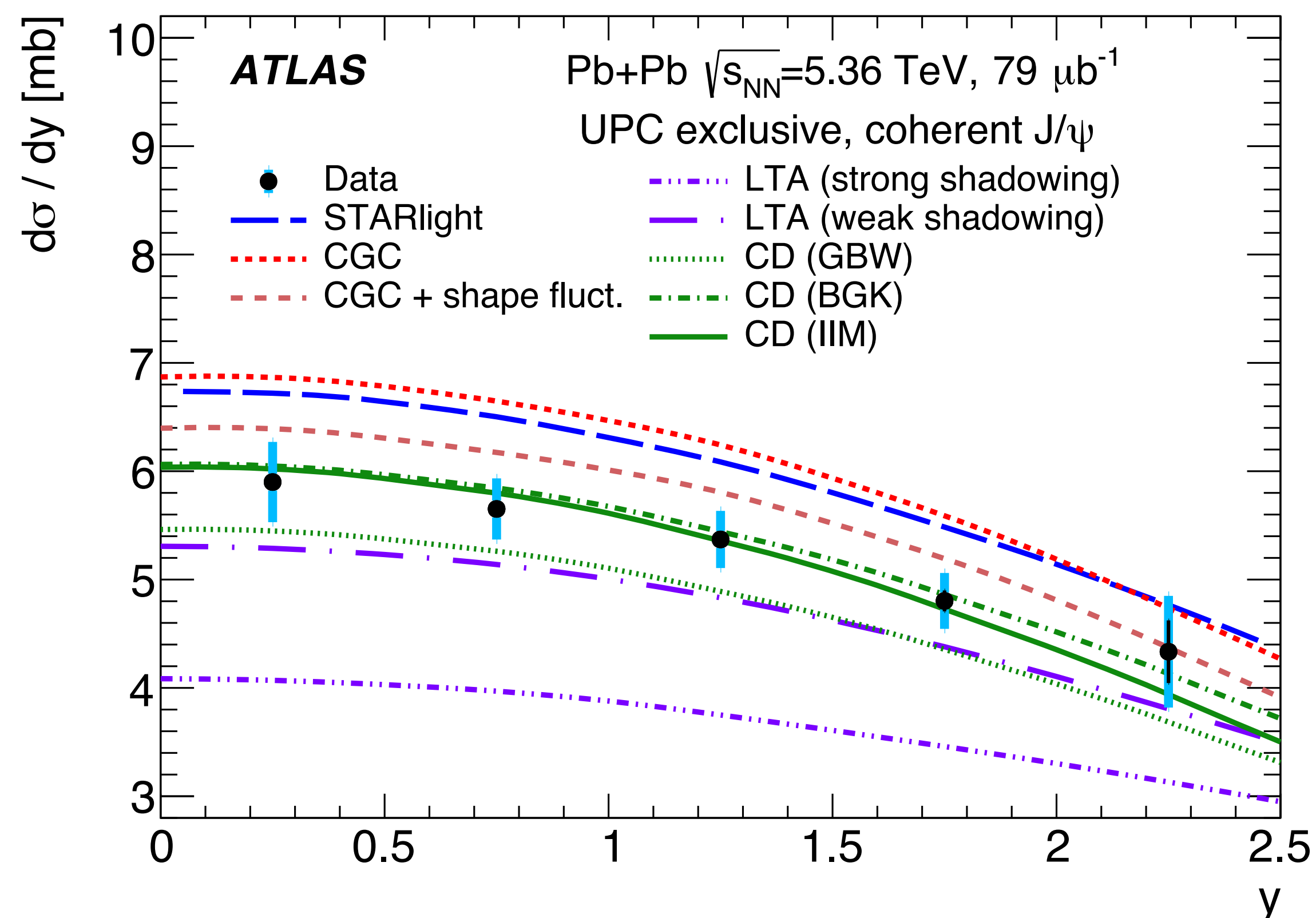
- Coherent exclusive heavy vector meson production provides perturbative and direct access to parton x in Pb. Sensitivity to nuclear gluon dynamics, shadowing, and saturation at small- x
- Has been extensively studied by STAR, ALICE, CMS and LHCb



- A dedicated hardware track trigger enables ATLAS low p_T measurements at mid-rapidity, filling the gap for $0.8 < |y| < 1.6$ to discriminate among models

Model comparisons

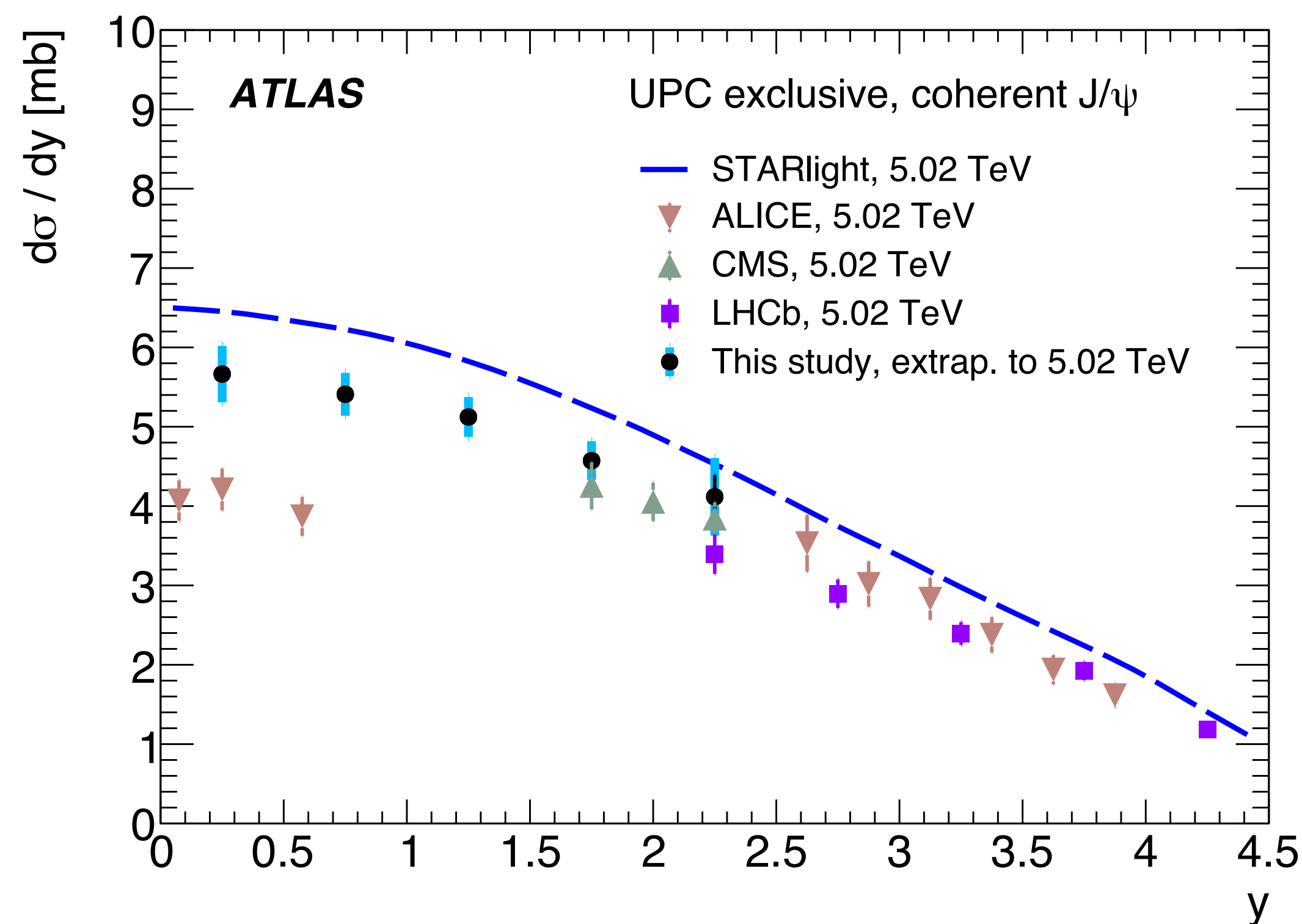
ATLAS: JHEP 04 (2026) 020



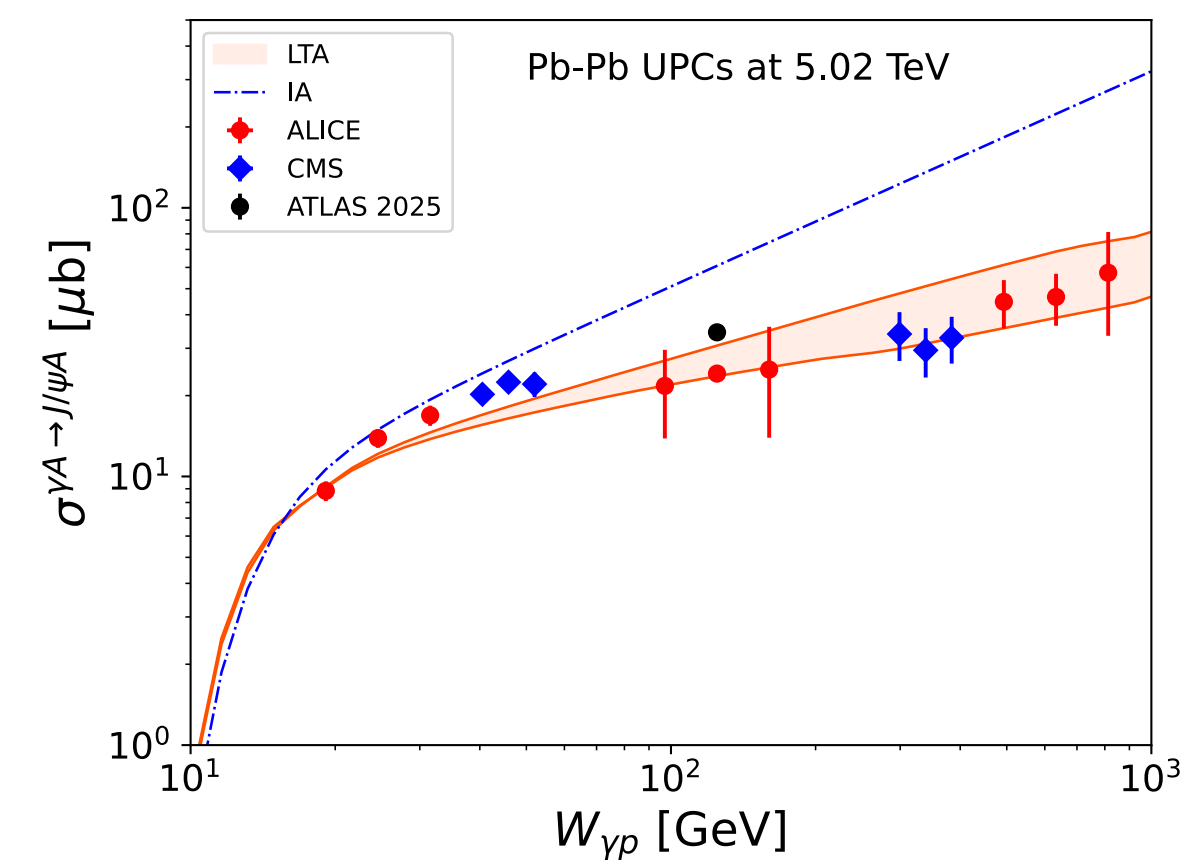
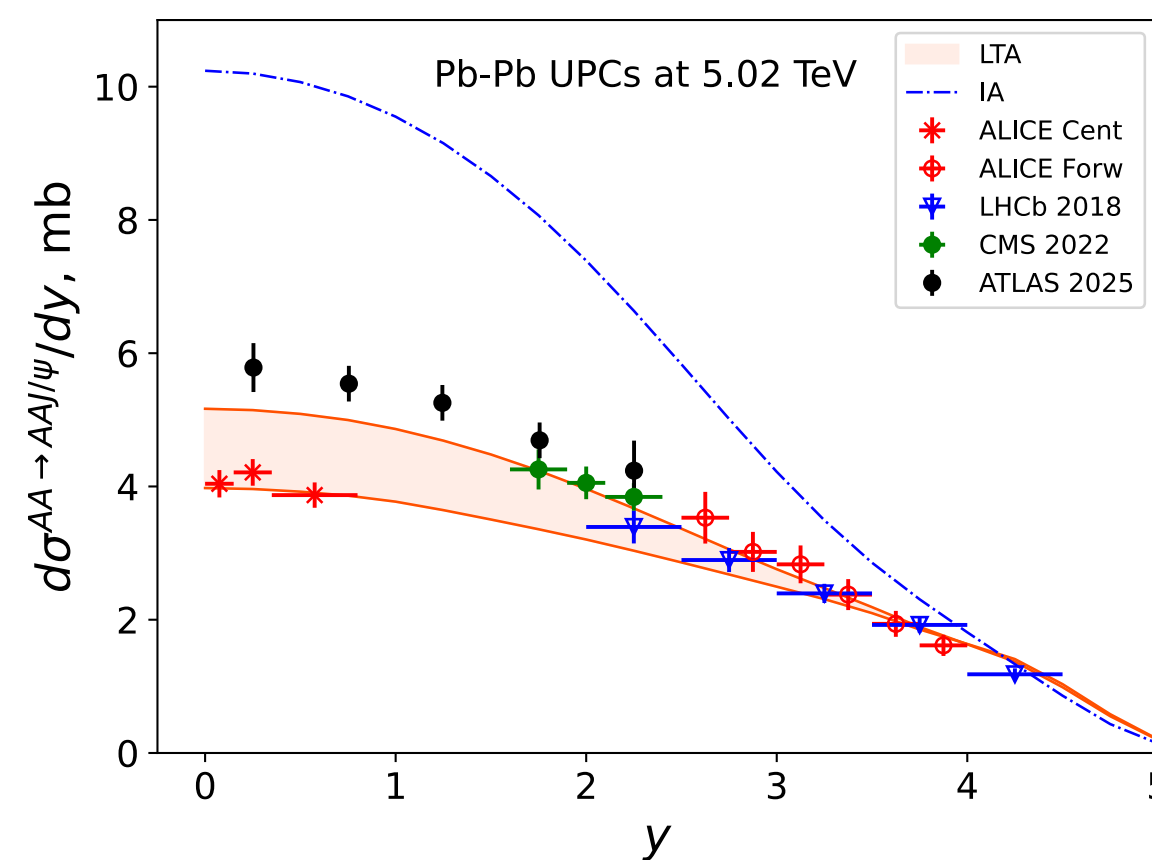
- Differential cross-section measured as a function of J/ψ rapidity
- Compared with CGC, LTA (Leading-Twist Approximation) and CD (Color Dipole) model predictions
- Among the models considered, the CD models provide the best data description

Comparison with existing measurements

ATLAS: JHEP 04 (2026) 020

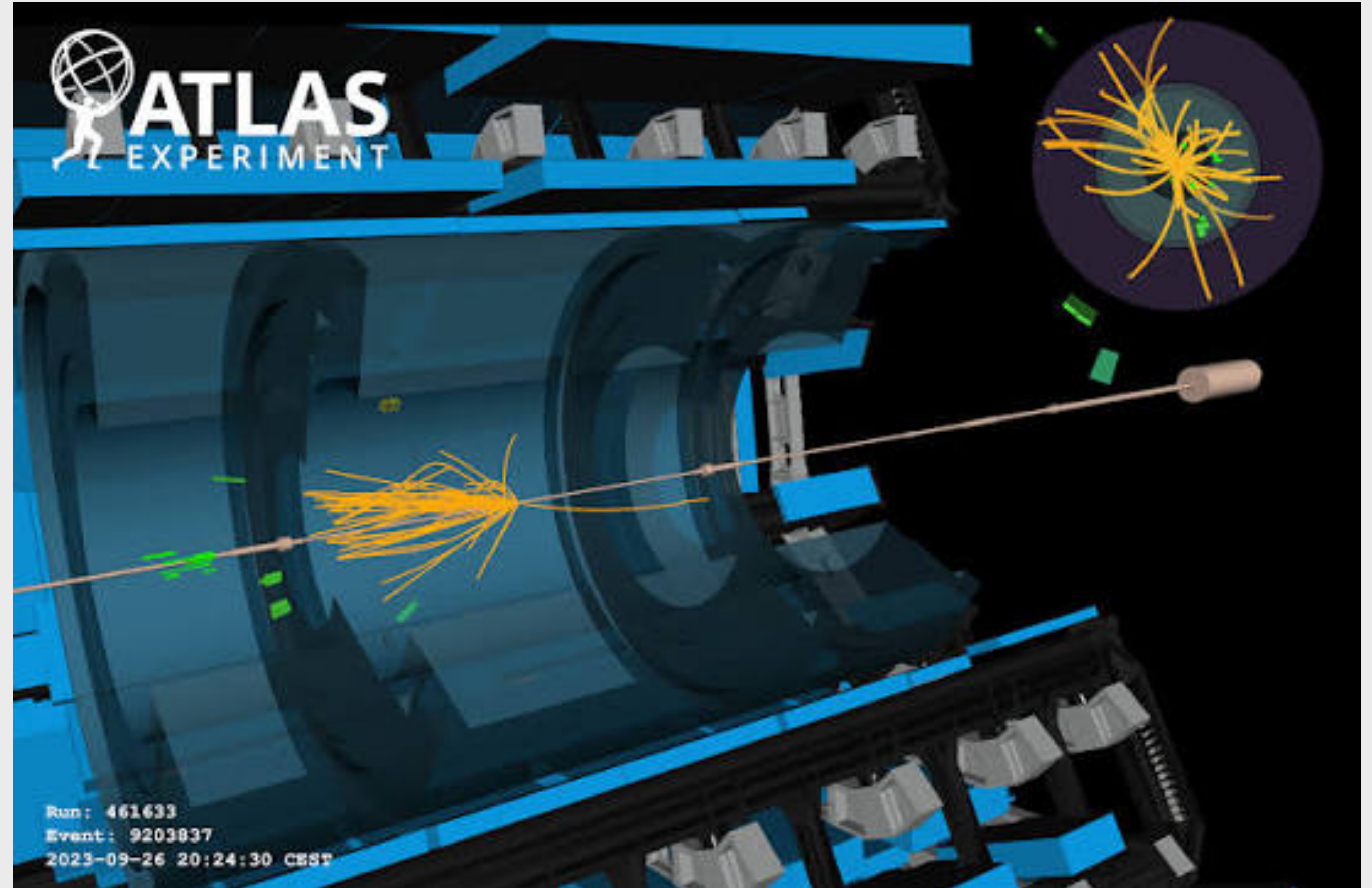


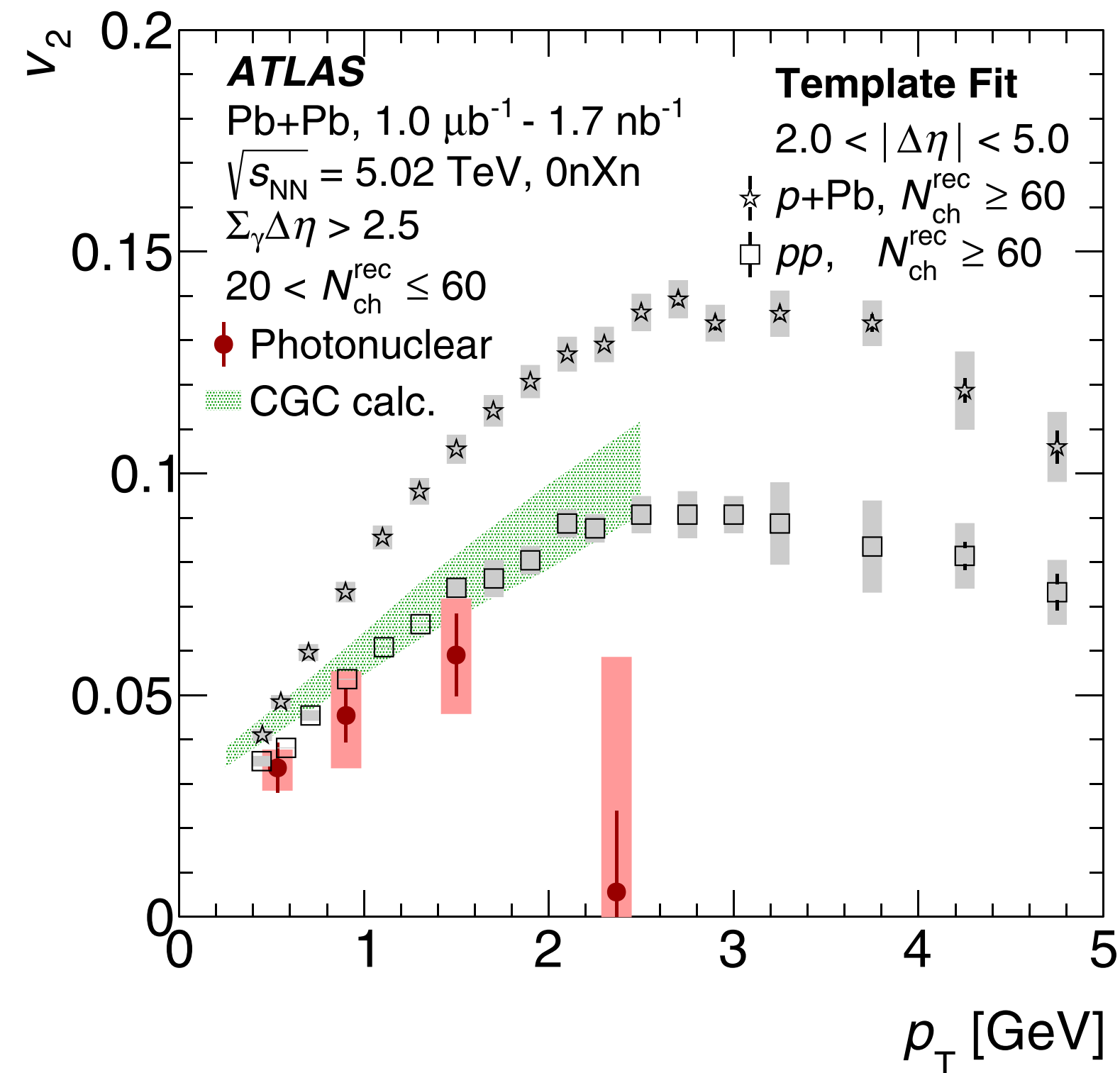
- Scaled to lower collision energy (5%)
- Good agreement at forward rapidities
- Tension with ALICE at mid-rapidity



Vadim Guzey, EMMI Workshop

$\gamma + \mathbf{A}$ collectivity





Photonuclear collisions are not only probes of nPDFs; at high multiplicity, they bridge small-x initial-state dynamics and final-state response

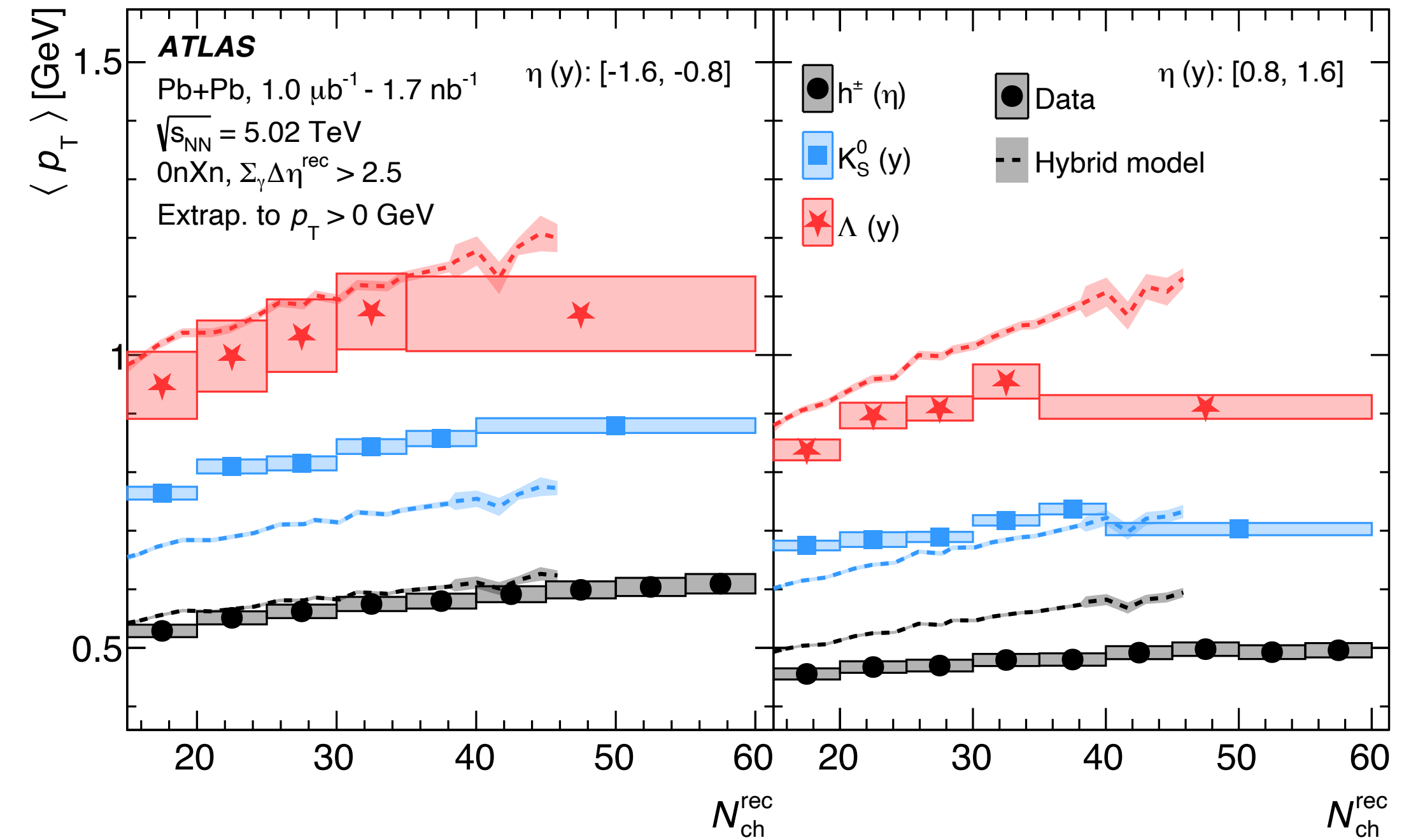
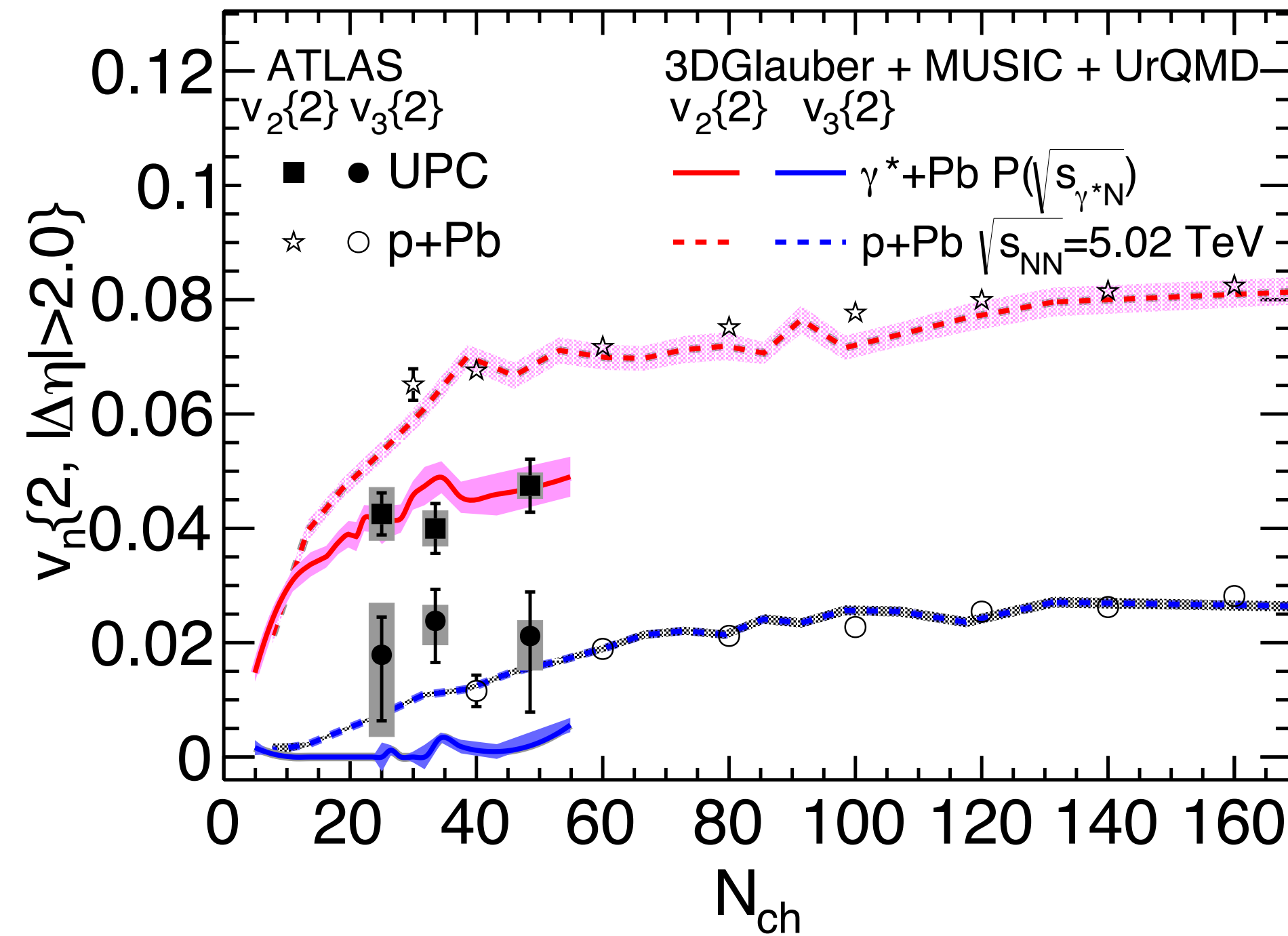
Two-particle correlation in 2018 Pb+Pb MinBias UPC events, **non-zero v_2 observed**

Reasonable agreement with CGC-based v_2 predictions

Comparison with hydrodynamic models

ATLAS: RPC 104 (2021) 014903

ATLAS: PRC 111 (2025) 064908



Reasonable description of measured v_n and $\langle p_T \rangle$ in $\gamma + A$, by 3D Glauber + MUSIC + UrQMD model

W. Zhao, C. Shen, and B. Schenke, PRL 129 (2022) 252302

p +Pb dijets

Photon+multiphoton event

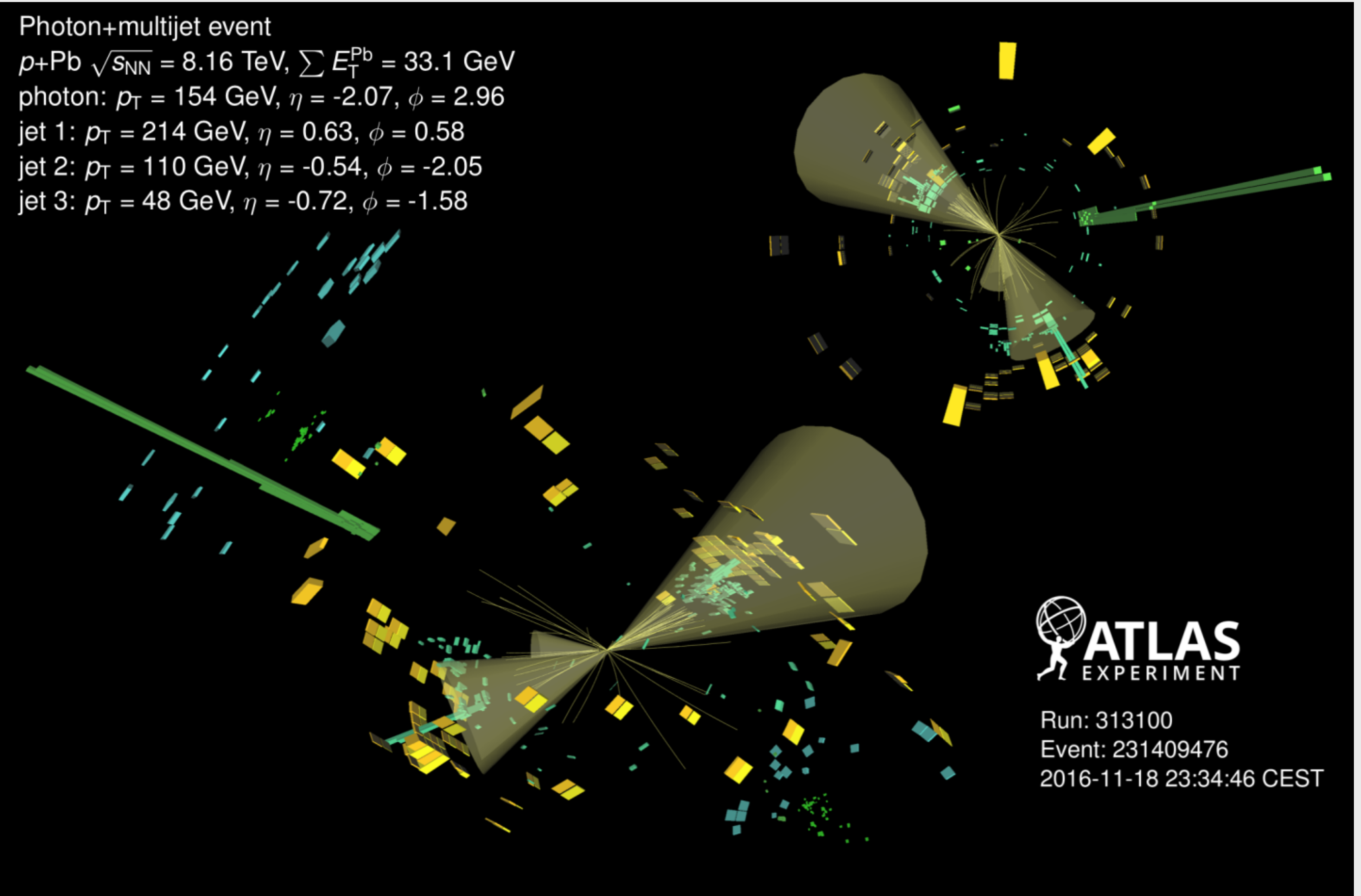
p +Pb $\sqrt{s_{NN}} = 8.16$ TeV, $\sum E_T^{Pb} = 33.1$ GeV

photon: $p_T = 154$ GeV, $\eta = -2.07$, $\phi = 2.96$

jet 1: $p_T = 214$ GeV, $\eta = 0.63$, $\phi = 0.58$

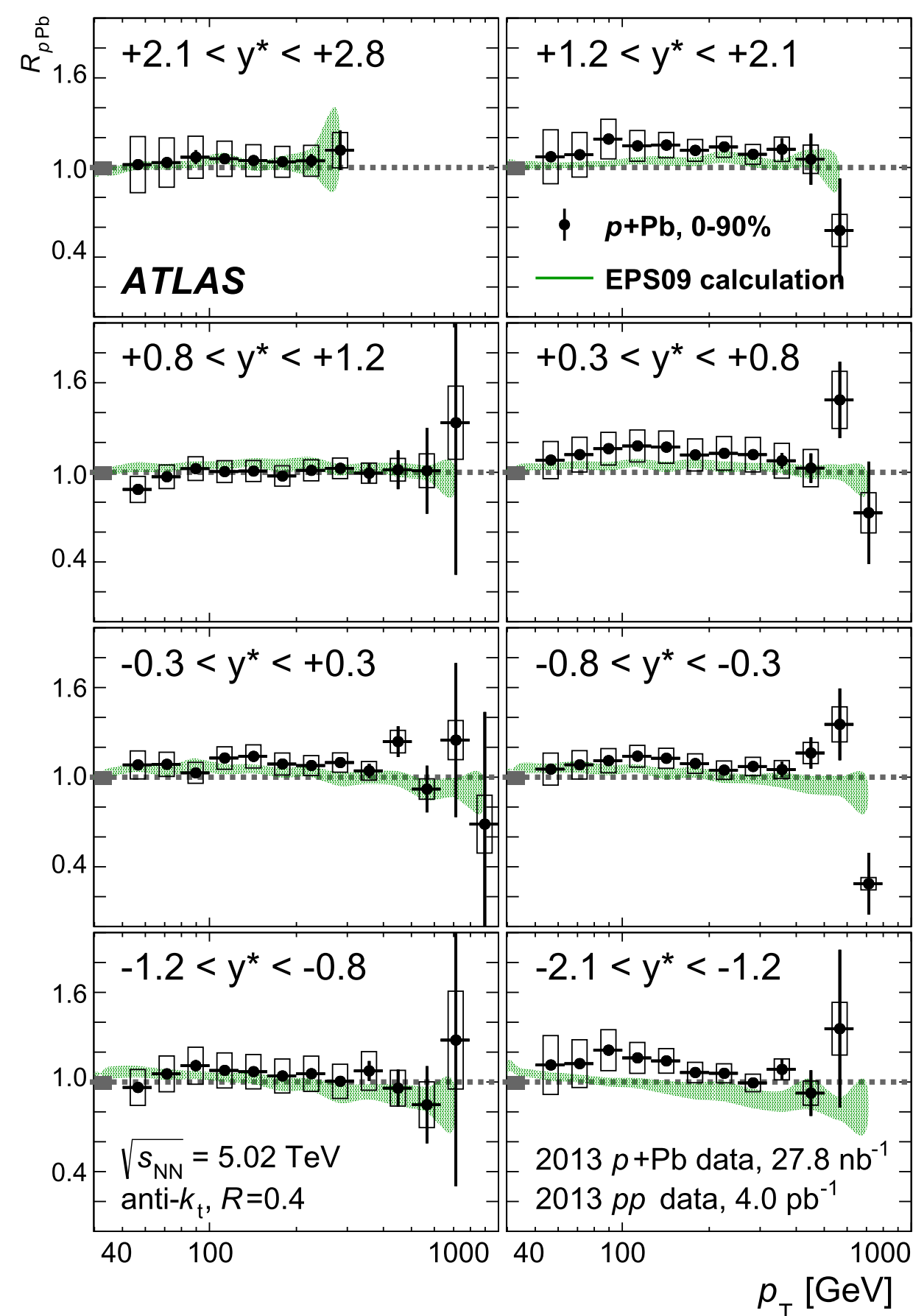
jet 2: $p_T = 110$ GeV, $\eta = -0.54$, $\phi = -2.05$

jet 3: $p_T = 48$ GeV, $\eta = -0.72$, $\phi = -1.58$

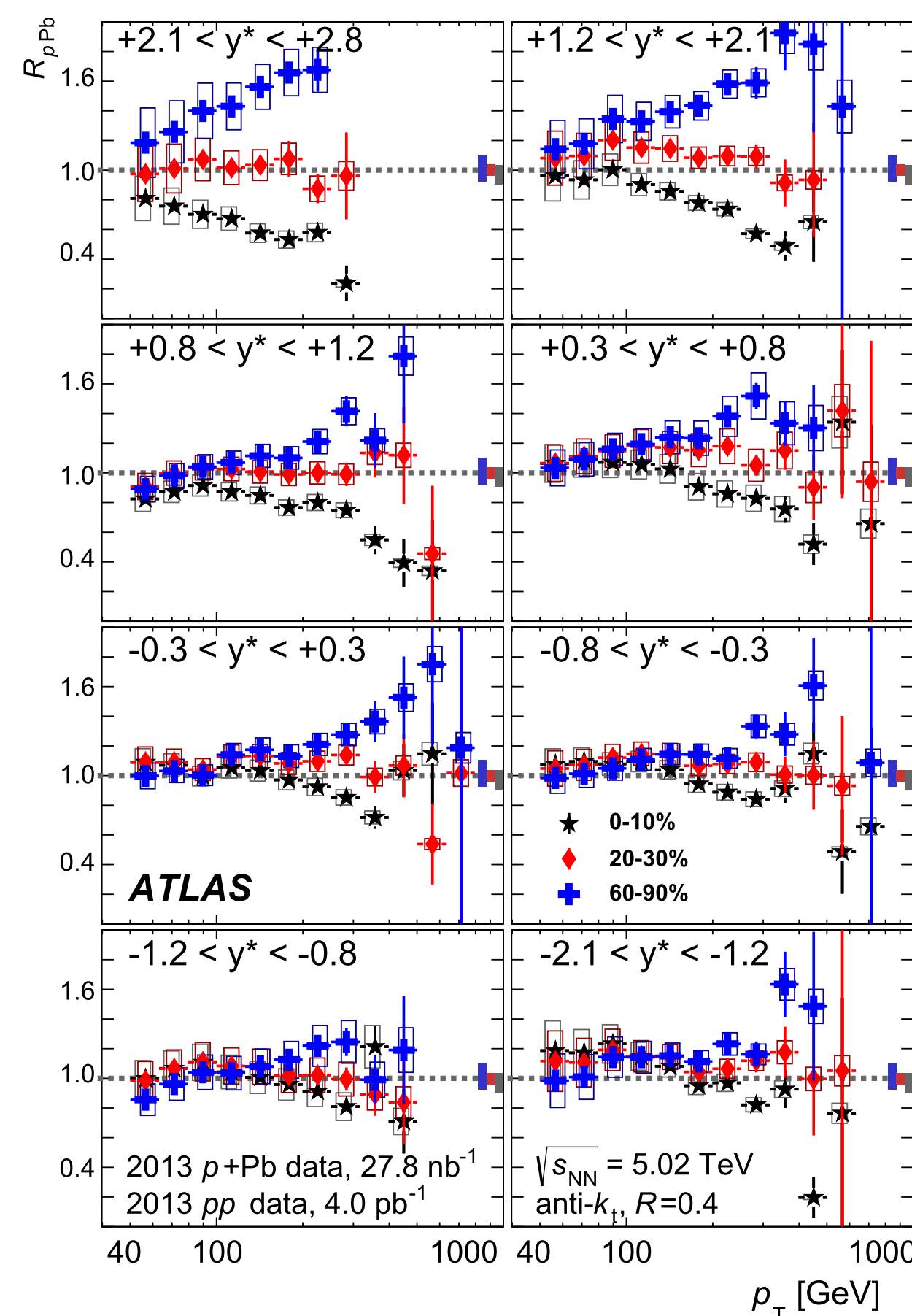


Centrality-dependent jet production in p+Pb

ATLAS: PLB 748 (2015) 392



0-90%



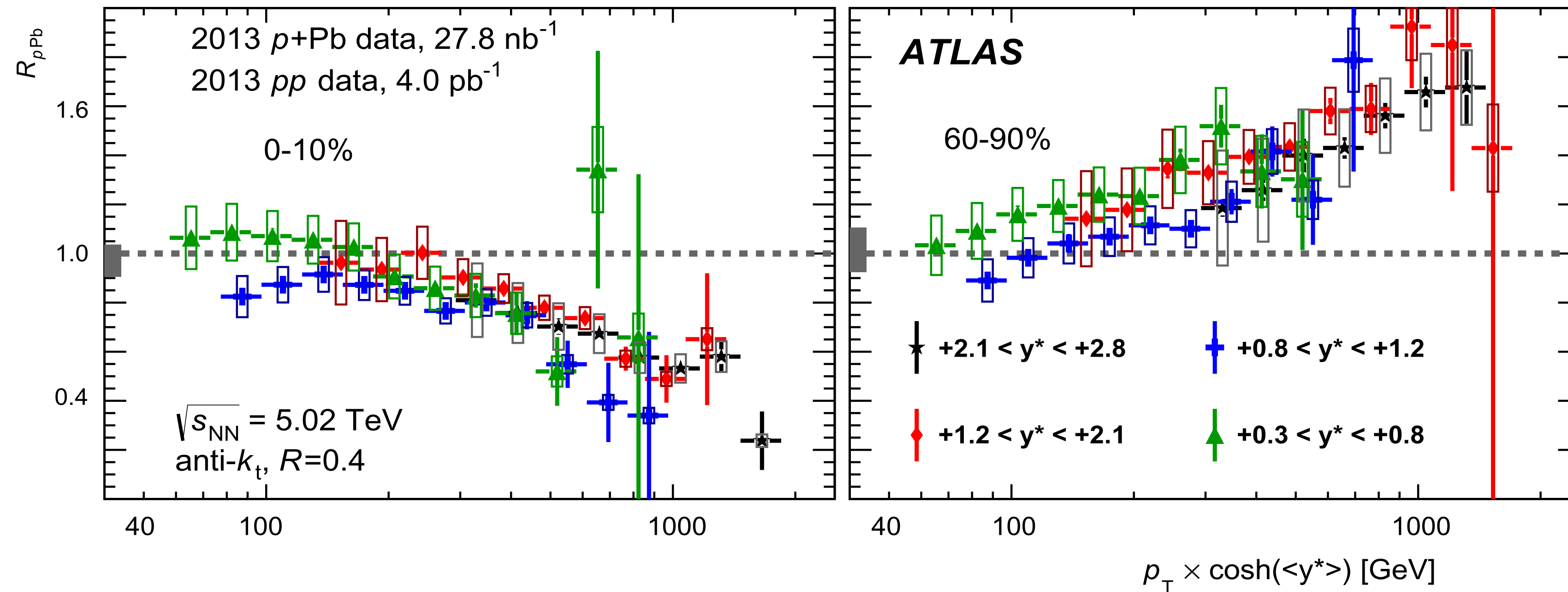
Centrality dependent

Inclusive jets in 5.02 TeV p+Pb data

Centrality-integrated: $R_{pPb} \sim 1$

Centrality-dependent:

- Suppression in central events
- Enhancement in peripheral events

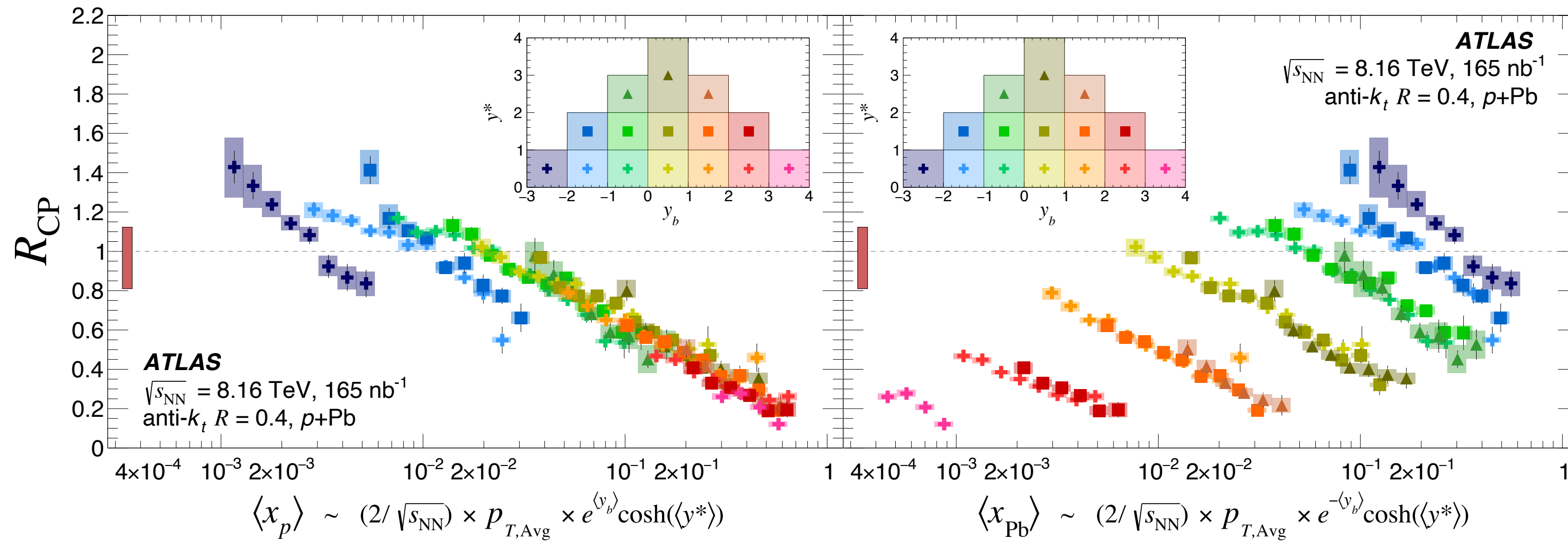


- When plotted as a function of $p_T \times \cosh(\langle y^* \rangle)$, an approximate jet energy, results from different rapidity intervals follow a similar trend
- The observed effect may depend mainly on the total jet energy, or more generally on the underlying parton-parton kinematics

Parton-x dependence of p+Pb dijets

ATLAS: PRL 132 (2024) 102301

Dijet events in 8.16 TeV p+Pb data



$$p_{T,Avg} = \frac{p_{T,1} + p_{T,2}}{2}$$

$$y_b = \frac{y_1^{c.m.} + y_2^{c.m.}}{2} \quad y^* = \frac{|y_1^{c.m.} - y_2^{c.m.}|}{2}$$

$$x_p = \frac{p_{T,1} e^{y_1^{c.m.}} + p_{T,2} e^{y_2^{c.m.}}}{\sqrt{s_{NN}}} \simeq \frac{2p_{T,Avg}}{\sqrt{s_{NN}}} e^{y_b} \cosh(y^*)$$

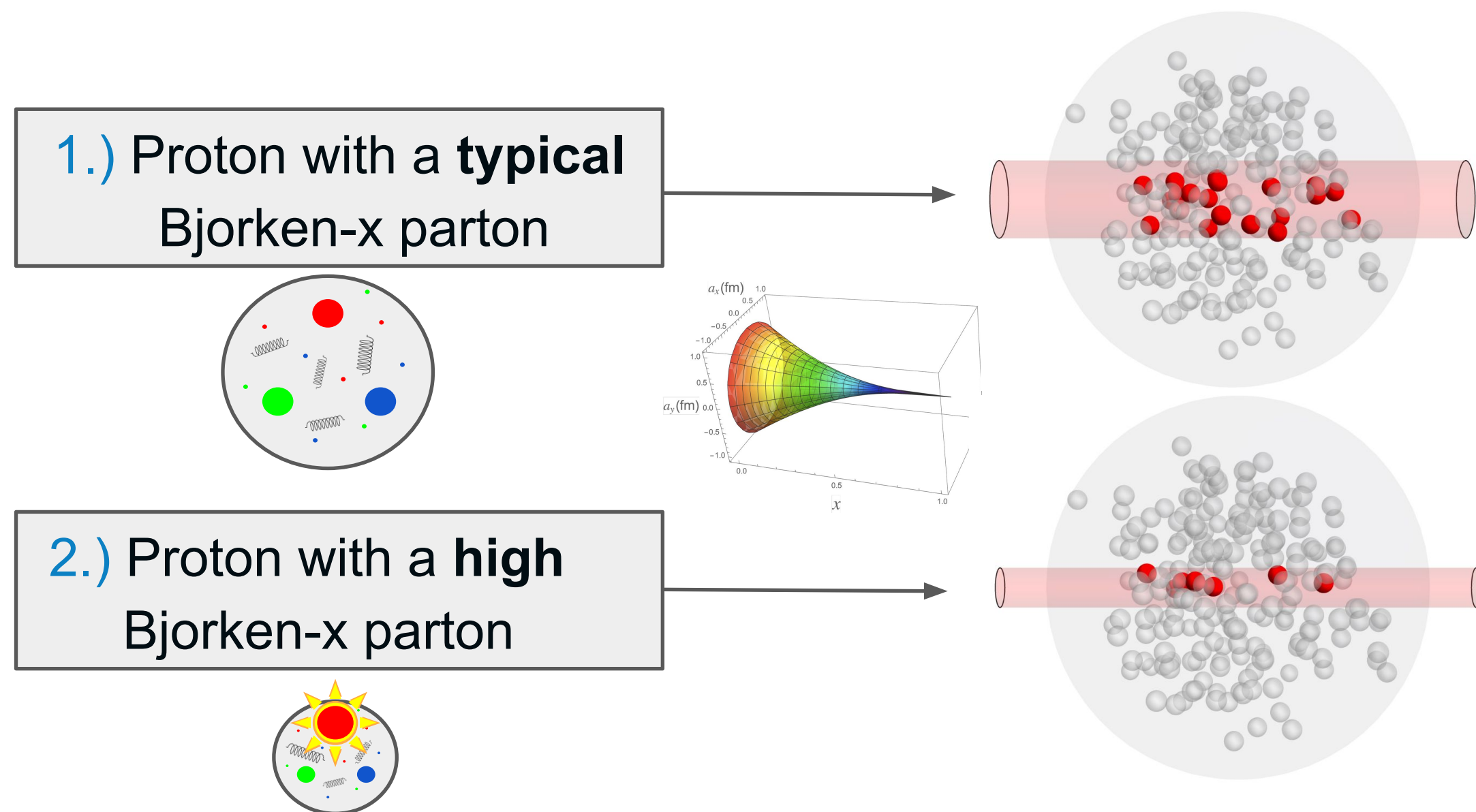
$$x_{Pb} = \frac{p_{T,1} e^{-y_1^{c.m.}} + p_{T,2} e^{-y_2^{c.m.}}}{\sqrt{s_{NN}}} \simeq \frac{2p_{T,Avg}}{\sqrt{s_{NN}}} e^{-y_b} \cosh(y^*)$$

- Observed x_p -scaling at large x_p
- Centrality dependences of jet p_T - and rapidity- yields in p+Pb are directly correlated with x_p biases
- The lack of monotonic scaling with decreasing x_{Pb} suggests that gluon saturation is unlikely to be the dominant source of the observed effect

Possible explanation — color fluctuations

Same p+Pb impact parameter

Different Bjorken-x



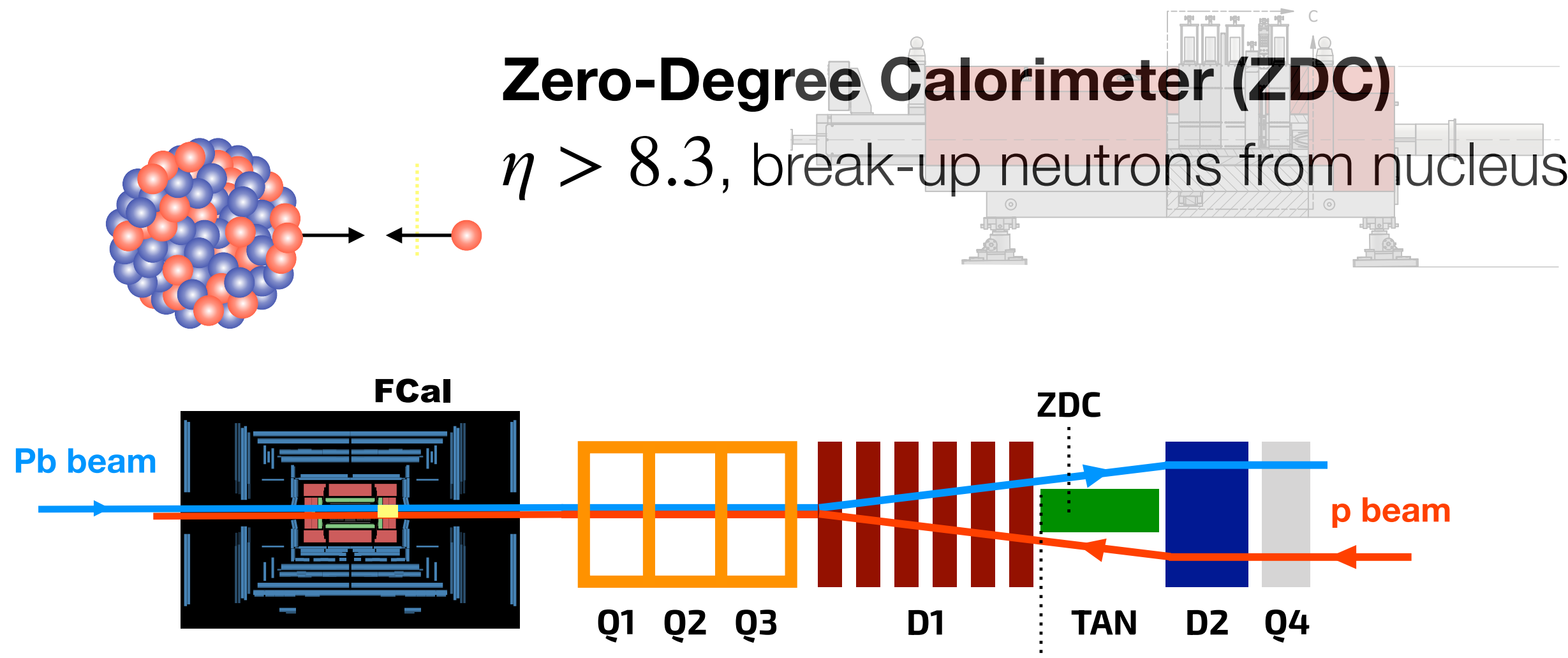
- **Color fluctuations:** the effective size of proton depends on the Bjorken-x of its partons
- Frozen configuration: at TeV energies, the proton traverses the Pb nucleus before its color configuration can change
- Forward activity, such as FCal or ZDC energy, can be correlated with the hard scattering, rather than only with collision geometry

Centrality bias in p+Pb with hard scattering

ATLAS: PLB 877 (2026) 140440

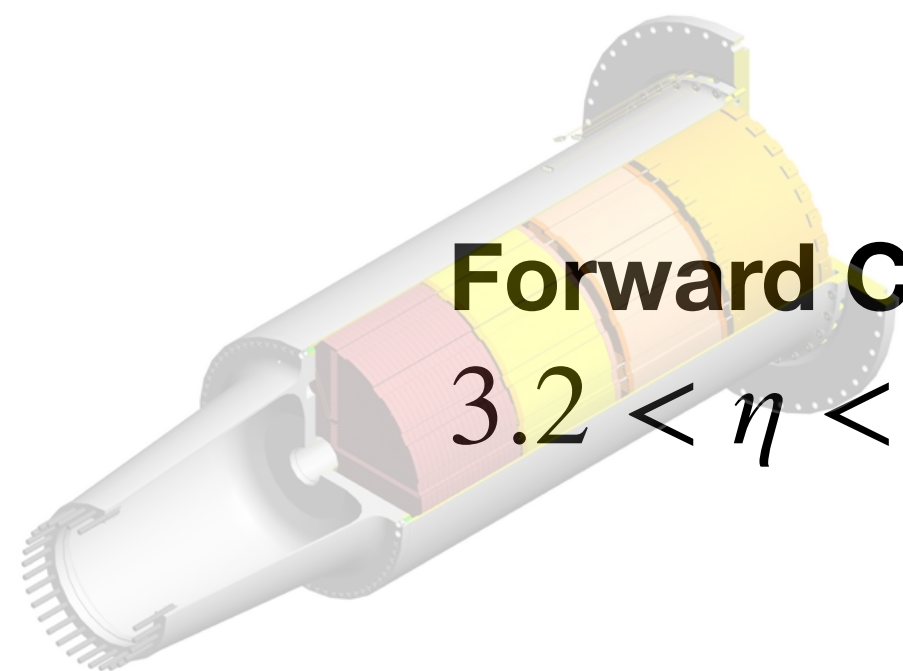
Zero-Degree Calorimeter (ZDC)

$\eta > 8.3$, break-up neutrons from nucleus

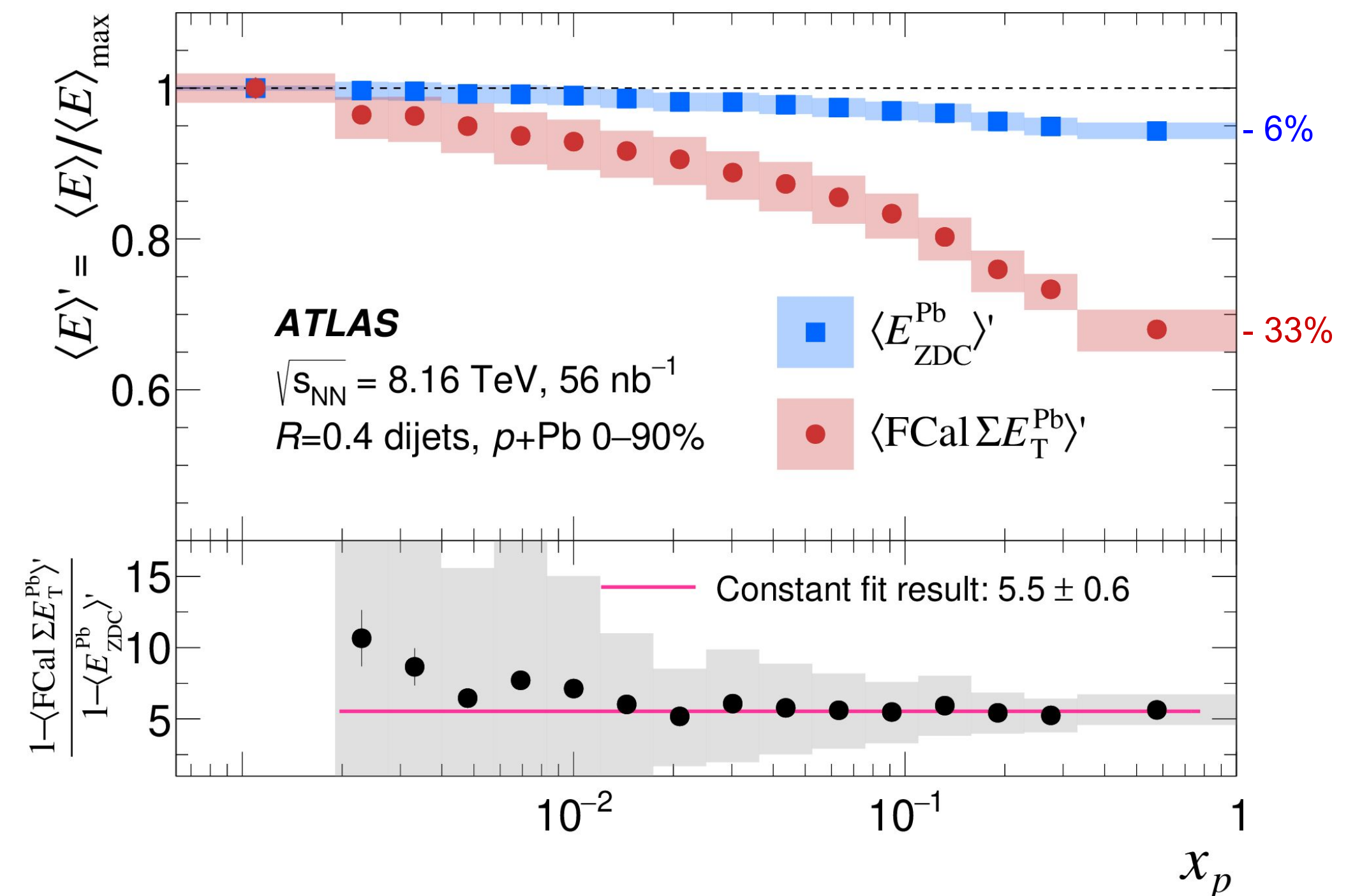


Forward Calorimeter (FCal)

$3.2 < \eta < 4.9$, underlying events activity



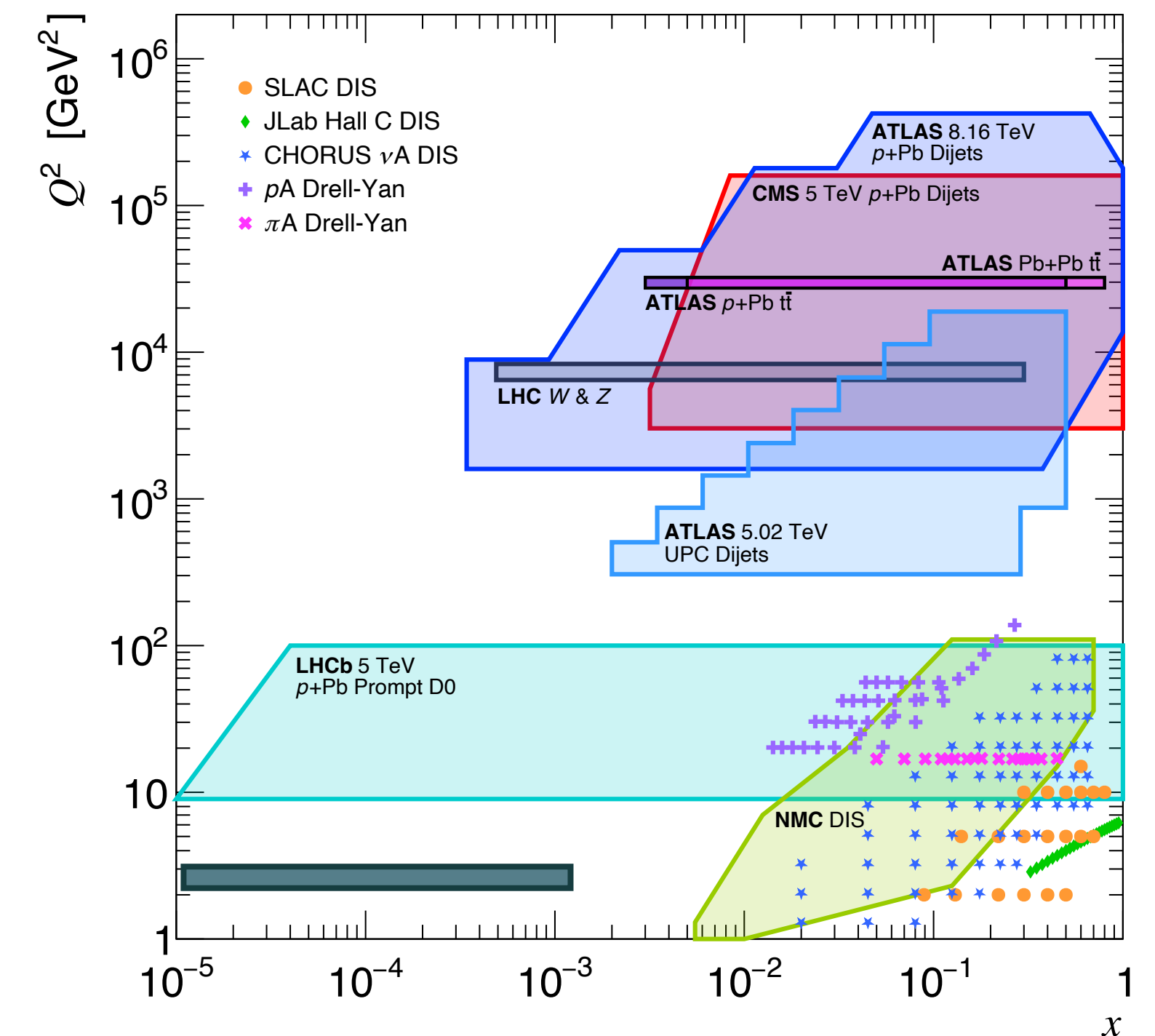
$$x_p = \frac{p_{T,1} e^{y_1^{c.m.}} + p_{T,2} e^{y_2^{c.m.}}}{\sqrt{s_{NN}}} \simeq \frac{2p_{T,Avg}}{\sqrt{s_{NN}}} e^{y_b} \cosh(y^*)$$



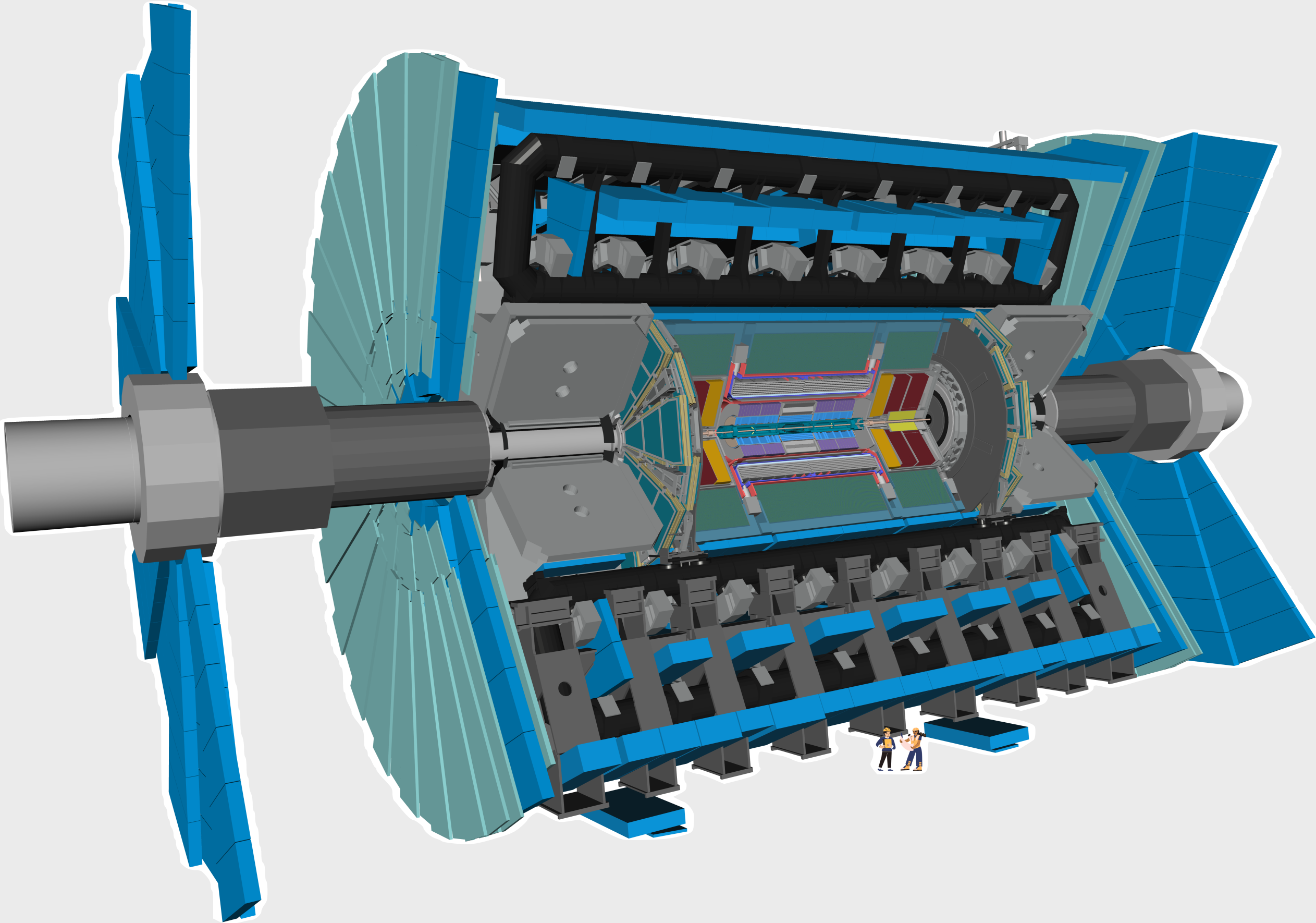
- Decreasing UE energy and break-up neutrons with increasing x_p
- UE is more sensitive to the change in x_p

Summary

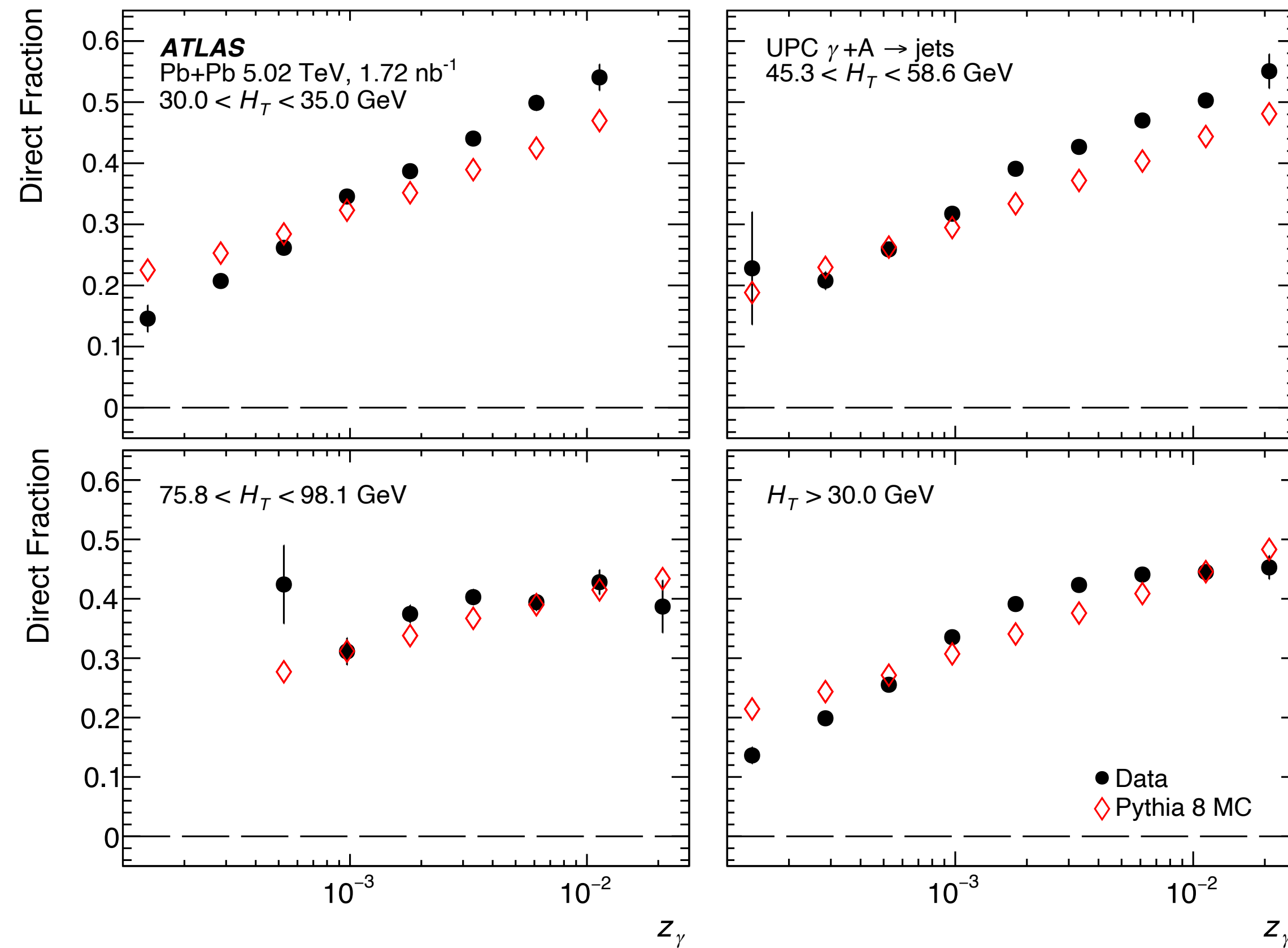
- **UPC photonuclear collisions are ATLAS's small-x heavy-ion frontier:** jets constrain high- Q^2 nPDFs, and adds geometry sensitivity, and coherent J/ψ probes low-x gluons
- **p+Pb dijets provide the essential baseline:** their centrality dependence scales with x_p , but not x_{Pb} , highlighting centrality bias and color-fluctuation effects
- **High-multiplicity photonuclear events connect small-x to collectivity:** correlations and identified-hadron yields test the link between initial-state dynamics and final-state response



Backup



Direct and resolved separation

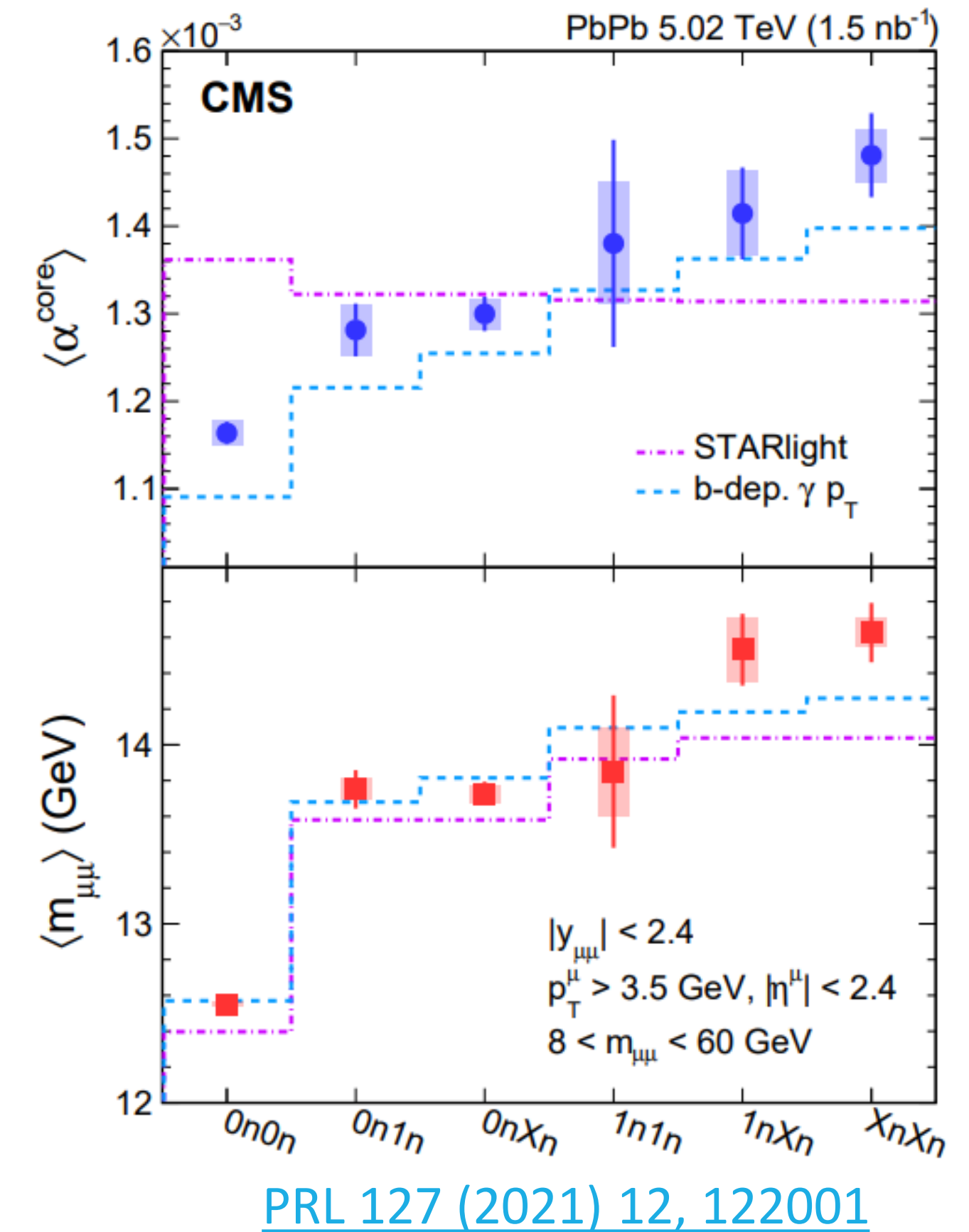
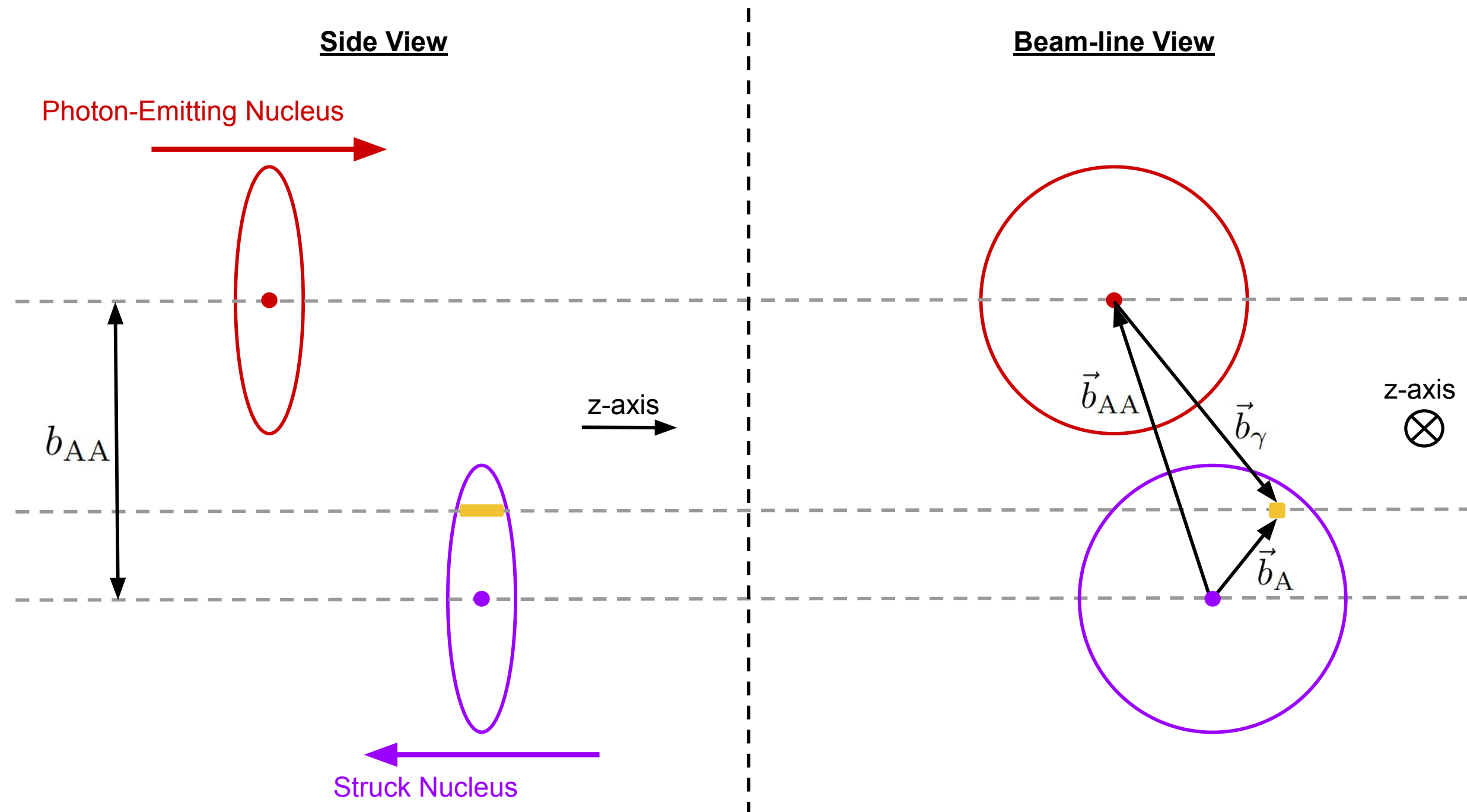


- Decomposition of direct and resolved processes based on sum of rapidity gaps $\Sigma_\gamma \Delta\eta$
- Good consistency with Pythia 8 using CJKL photon PDFs

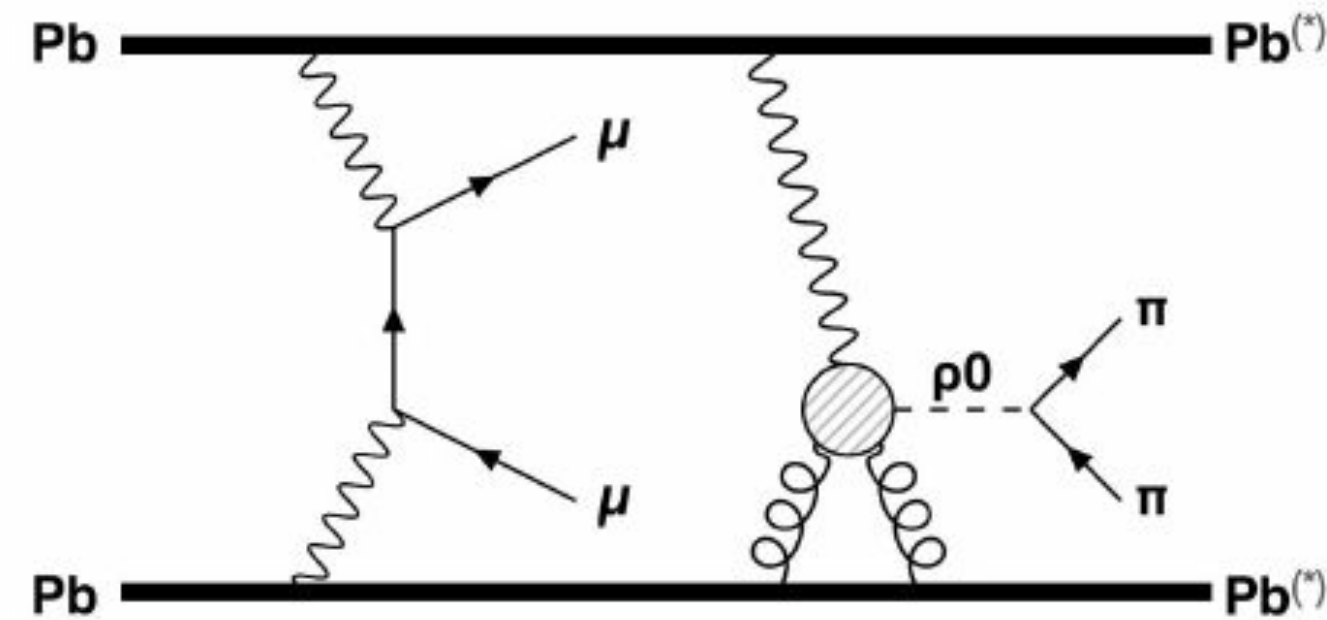
EMD and Impact Parameter

Closer-passing (smaller b_{AA}) UPCs expose each nucleus to a larger flux of soft photons. This yields a correlation between b_{AA} and the EMD rate

Results from CMS (and others) indicate that forward neutrons correlate with b_{AA}



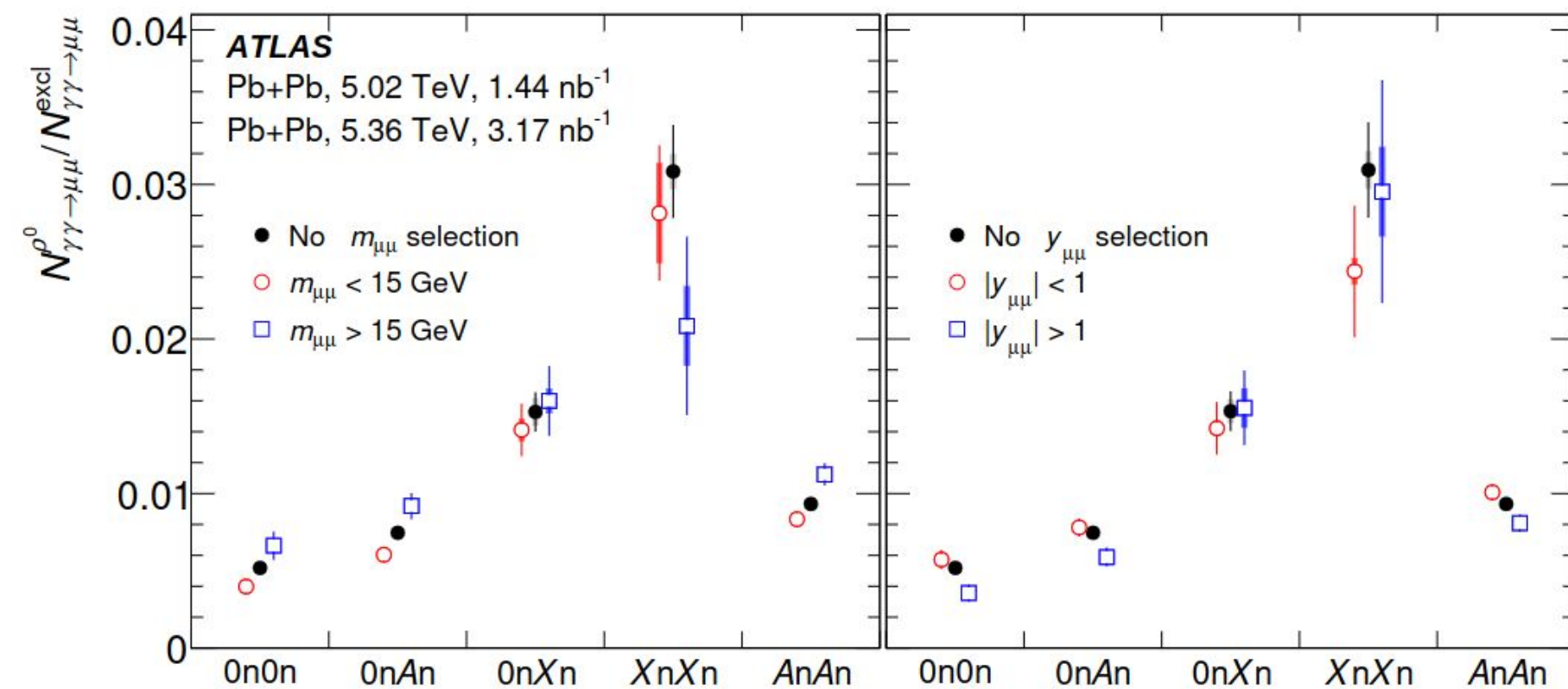
Coincident UPC processes



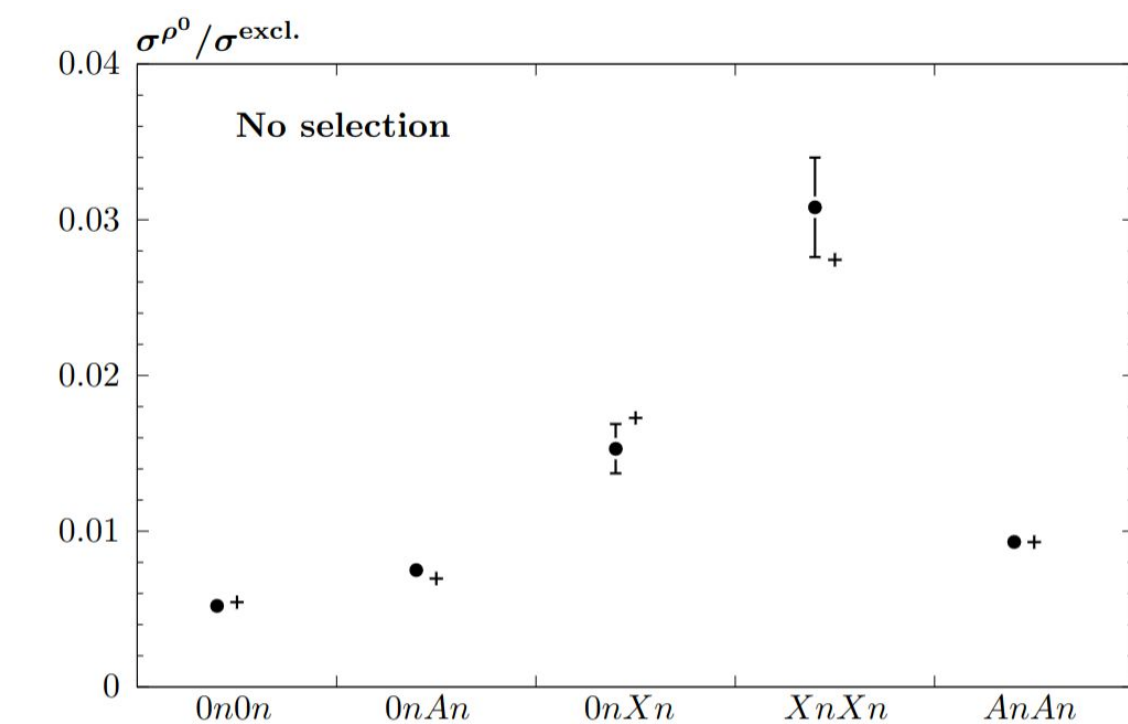
Multiple scattering within one UPC collision? Multiple photon-induced processes measured for the first time:

- Rate of coincident $\gamma\gamma \rightarrow \mu\mu$ and $\gamma+A \rightarrow \rho^0+A$ measured
- Coincidence rate: 0.93 ± 0.04 (stat) ± 0.03 (syst) %
- Rate increases with increasing dimuon mass and ZDC activity, i.e. correlated with impact parameter

Implemented in SuperChic generators, PRD 112 (2025) 5

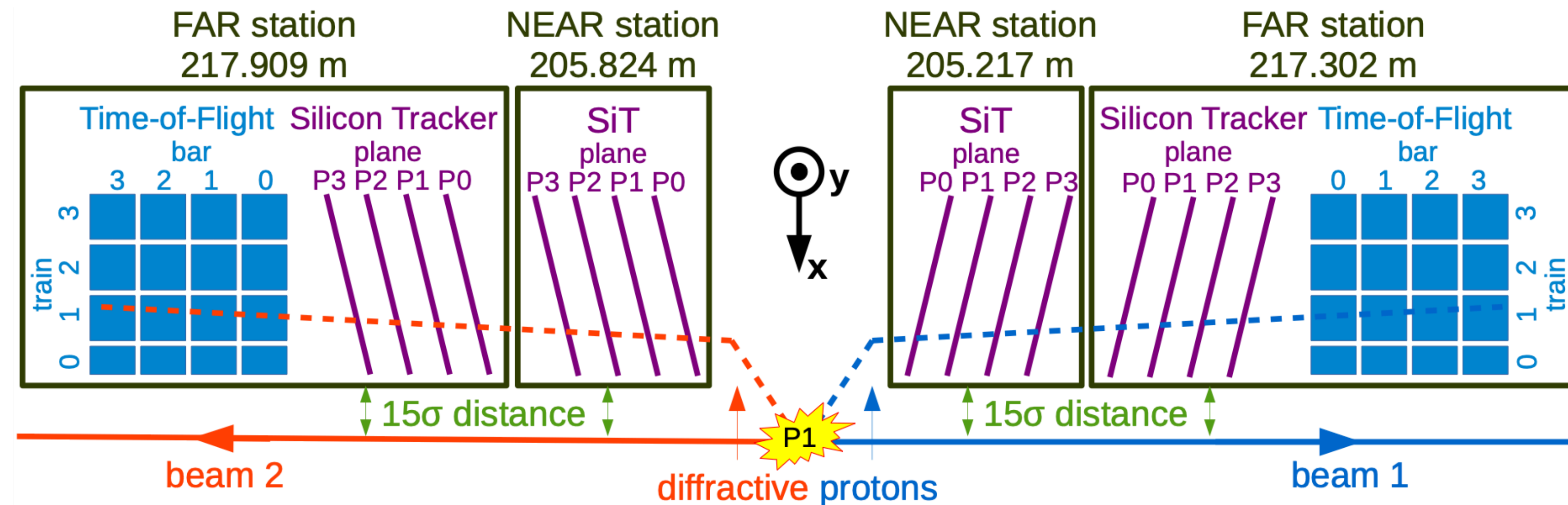


$$An = 0n + Xn$$



- ATLAS data
- + SuperChic predictions

ATLAS Forward Proton (AFP) Detector



- NEAR stations consist of **Silicon Tracker Planes**
- FAR stations additionally have **Time-of-Flight detectors**
- Housed in Roman Pots: $\sim 2\text{mm}$ from the beam during operation