



# Ultraperipheral collisions as probes for nuclear matter

***2026 RHIC/AGS Annual Users' Meeting,  
May 11-15, 2026.***

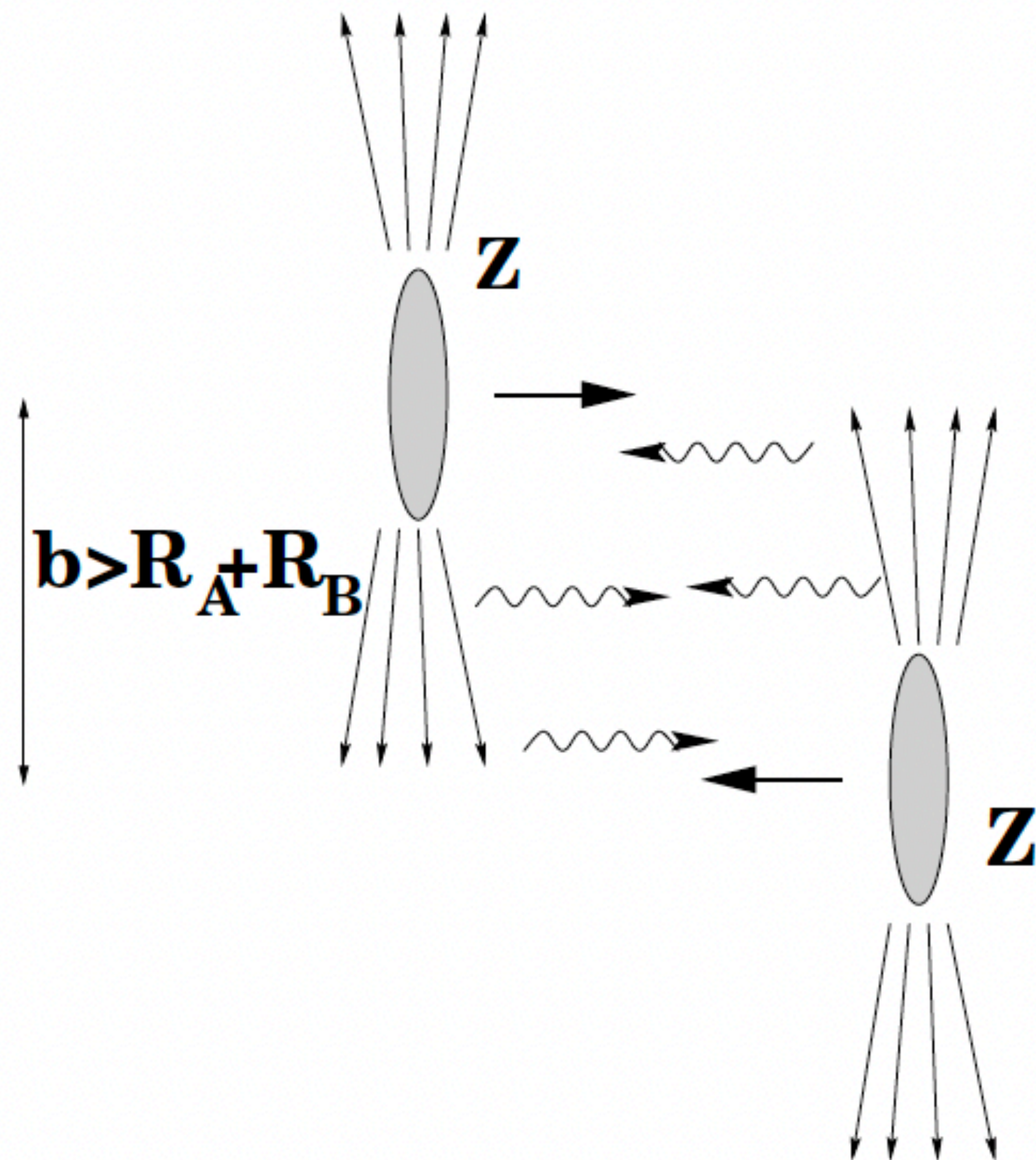
***Gian Michele Innocenti***  
*Massachusetts Institute of Technology*

*Special thanks to Cristian Baldenegro, Ben Gilbert, Vadim Guzey, Balazs Kovacs, Michael Pitt, Minjung Kim, Cristophe Royon, Anna M. Stasto, Daniel T. Takaki, Zaochen Yen, Pranjal Verma*



MIT HIG group's work is supported by the U.S. DOE Office of Nuclear Physics and by the DOE NP Early Career Award Program.

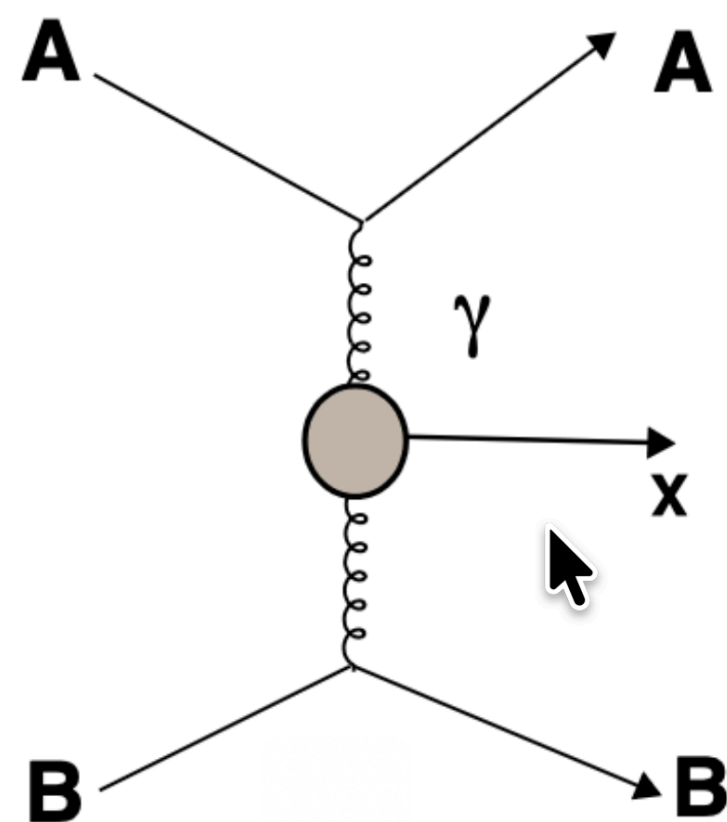
# Ultraperipheral heavy-ion collisions



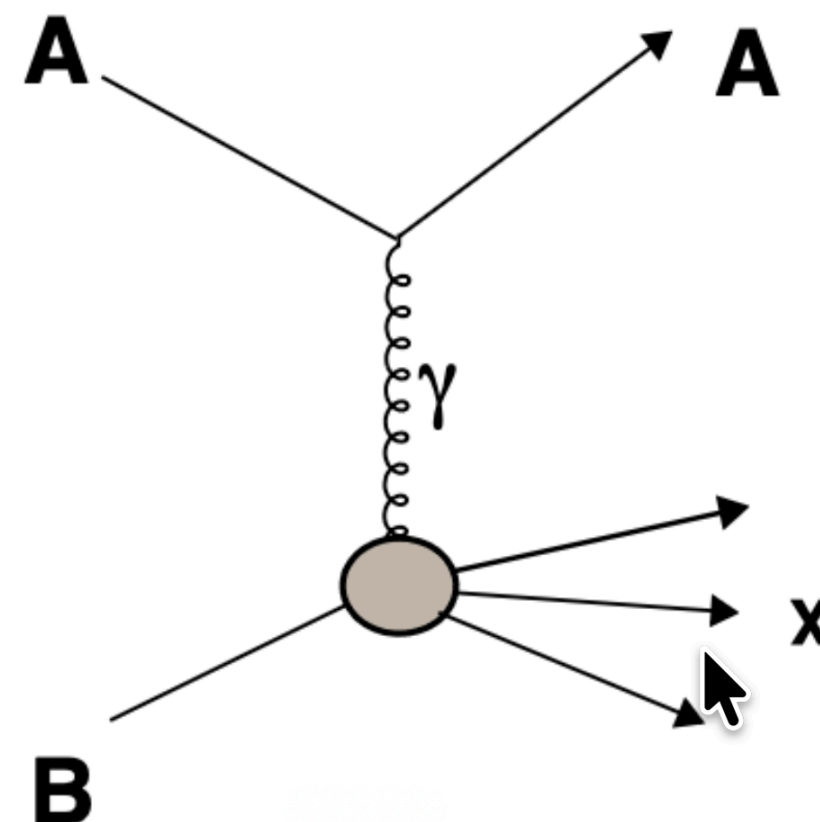
- **$b > R_A + R_B$  to avoid hadronic collision**
- Photons are quasi-real, ( $Q \sim 30$  MeV)
- The coherent photon flux scales as  $\sim Z^2$
- The maximum photon energy is  $\omega_{max} \sim \gamma/R_A$

→ UPCs at RHIC and LHC: abundant sources of high-energy  $\gamma\gamma$ ,  $\gamma$ -proton, and  $\gamma$ -nucleus collisions  
 → nuclear matter down to the very low-x, in-vacuum QCD, and BSM physics

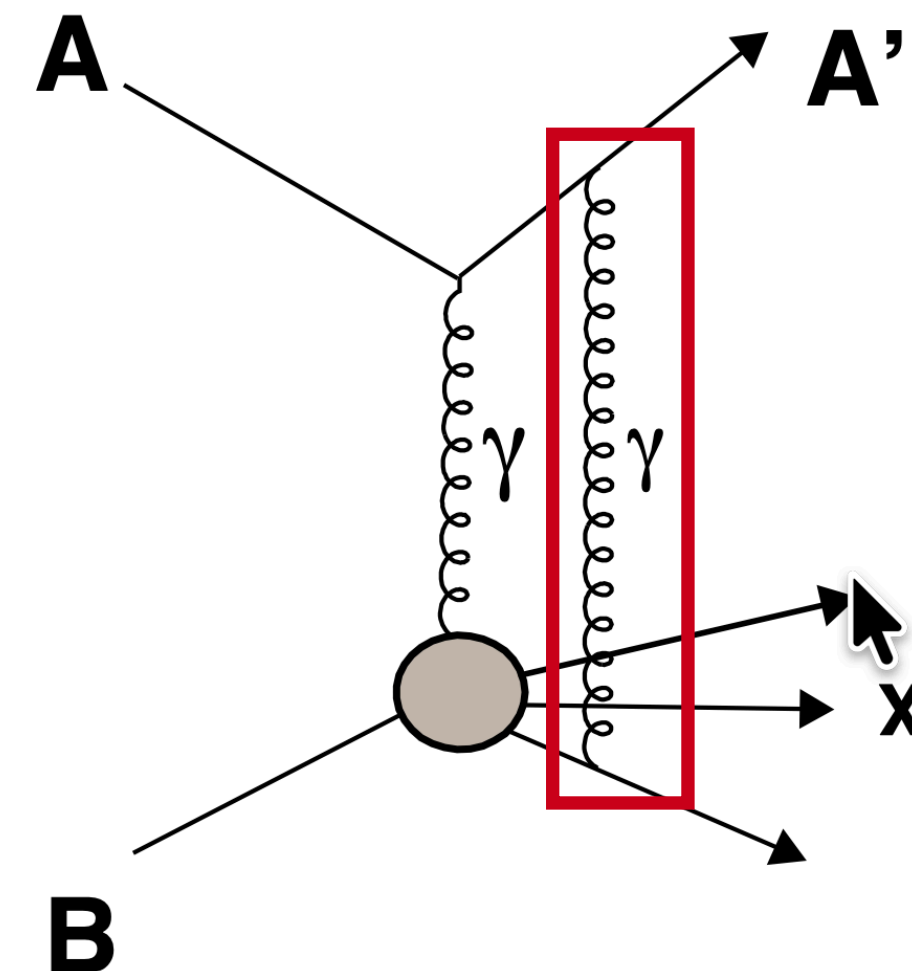
# UPC processes and nuclear-breakup tags



Photon-photon interactions

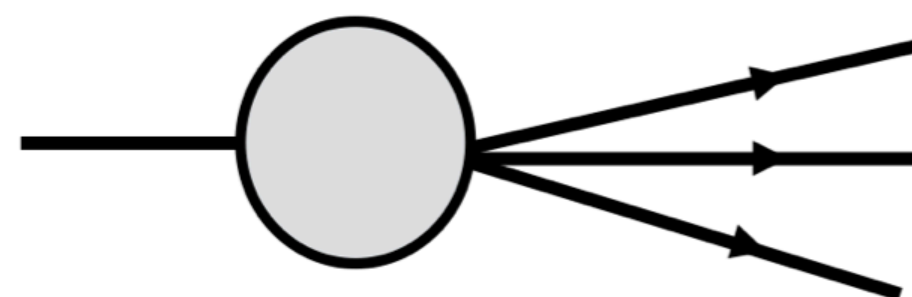


Photon-nuclear interactions  
(diffractive and non-diffractive)



Additional soft-photon exchanges:  
→ nuclear excitation/breakup

Experimental handle: **"centra" final-state reconstruction with forward neutron tagging in the Zero-Degree Calorimeter**



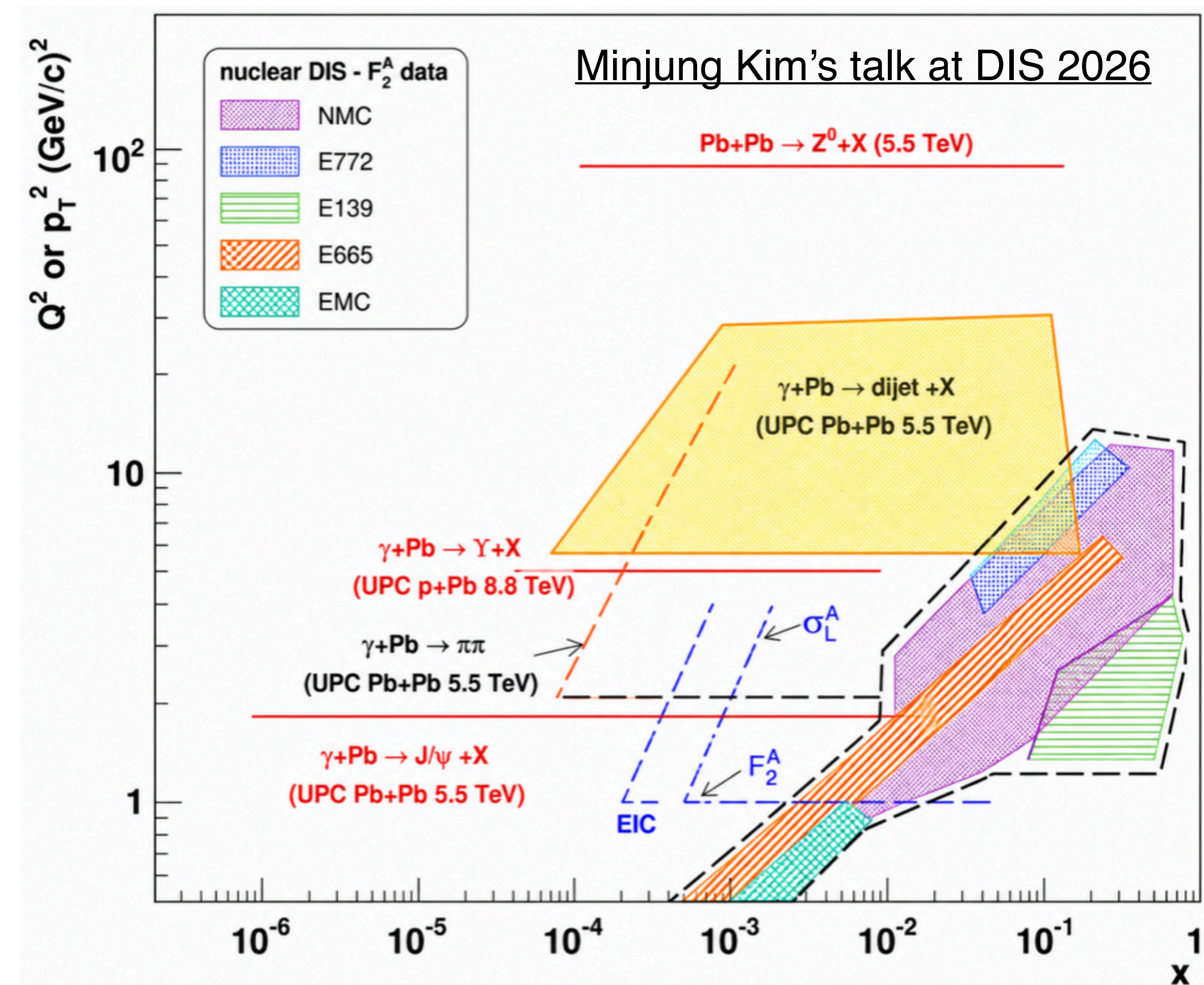
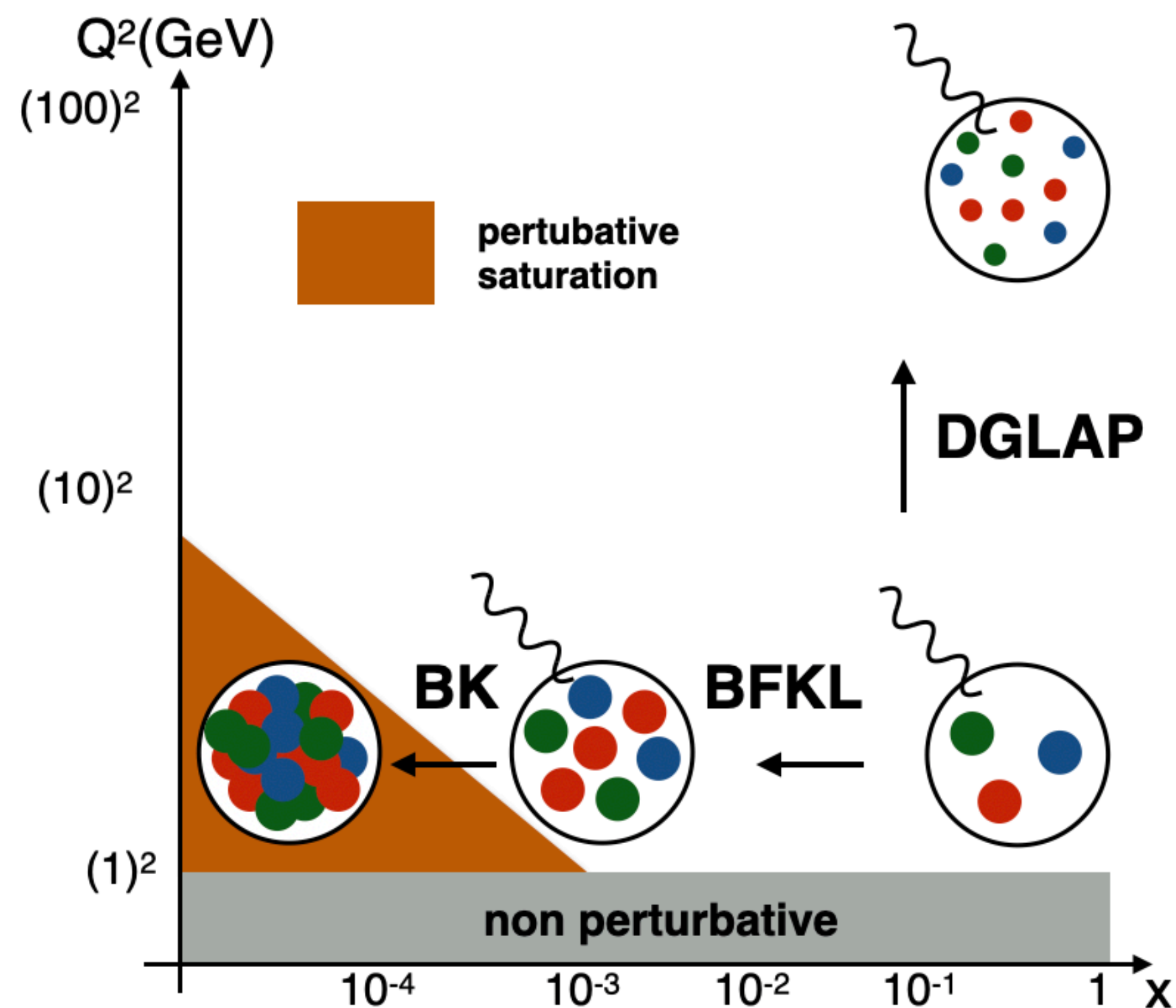
**Pb + X + neutron(s)**

**ZDC neutron tags: 0n0n, 0nXn, XnXn**

Xn → at least one neutron detected

0n → no neutron detected

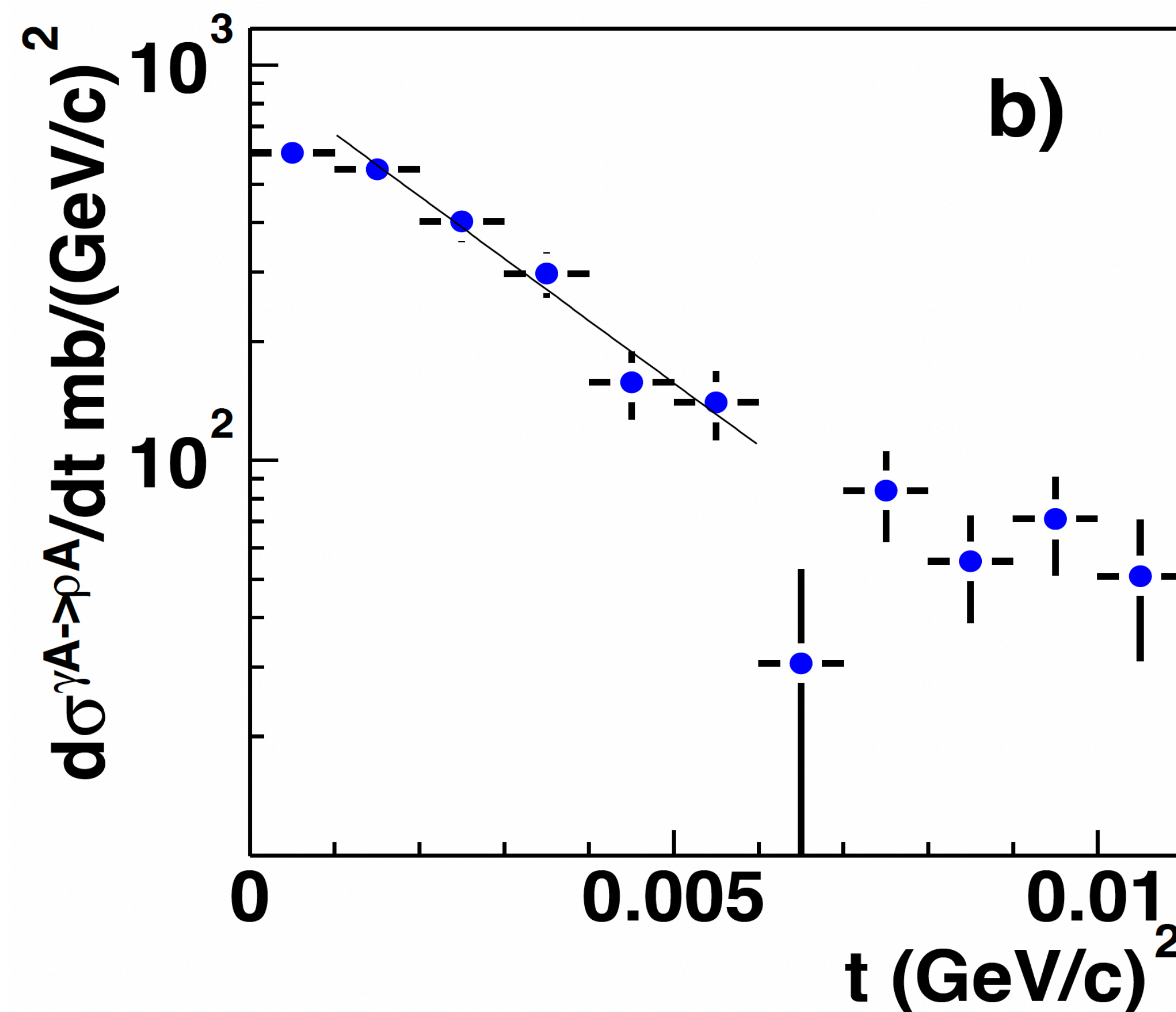
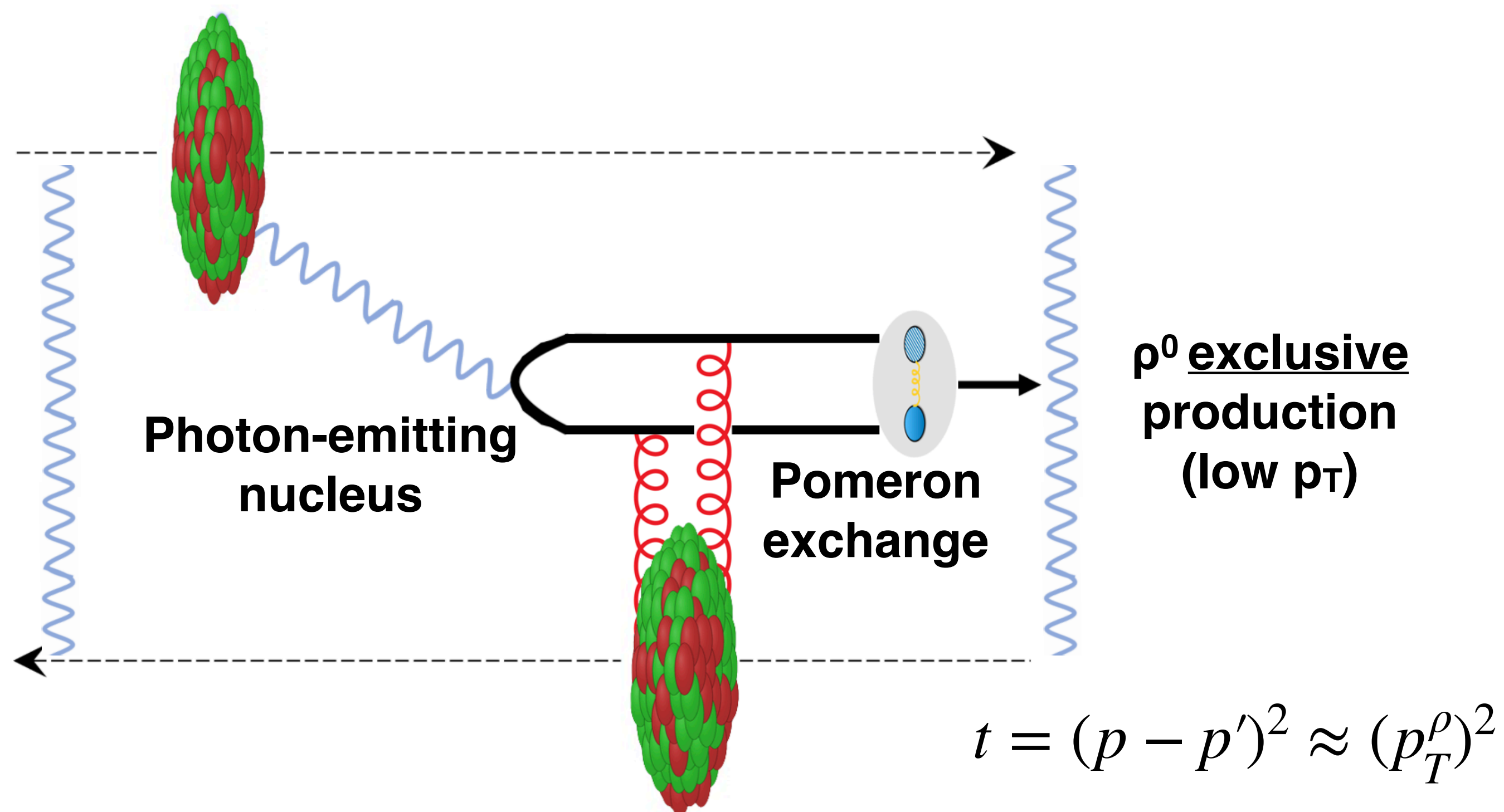
# Studying parton dynamics in protons and nuclei



- Probe quark and gluon densities versus  $x$ ,  $Q^2$ , and nuclear size
- Build a QCD-based characterization of nuclear matter at low  $x$
- Test the boundary between linear evolution equations and nonlinear small- $x$  dynamics (**saturation**)

# Coherent $\rho^0$ production at RHIC: the first UPC signal

Dipole interacting “coherently” with the target nucleus



**STAR observed exclusive coherent  $\rho^0$  photoproduction in AuAu UPCs**

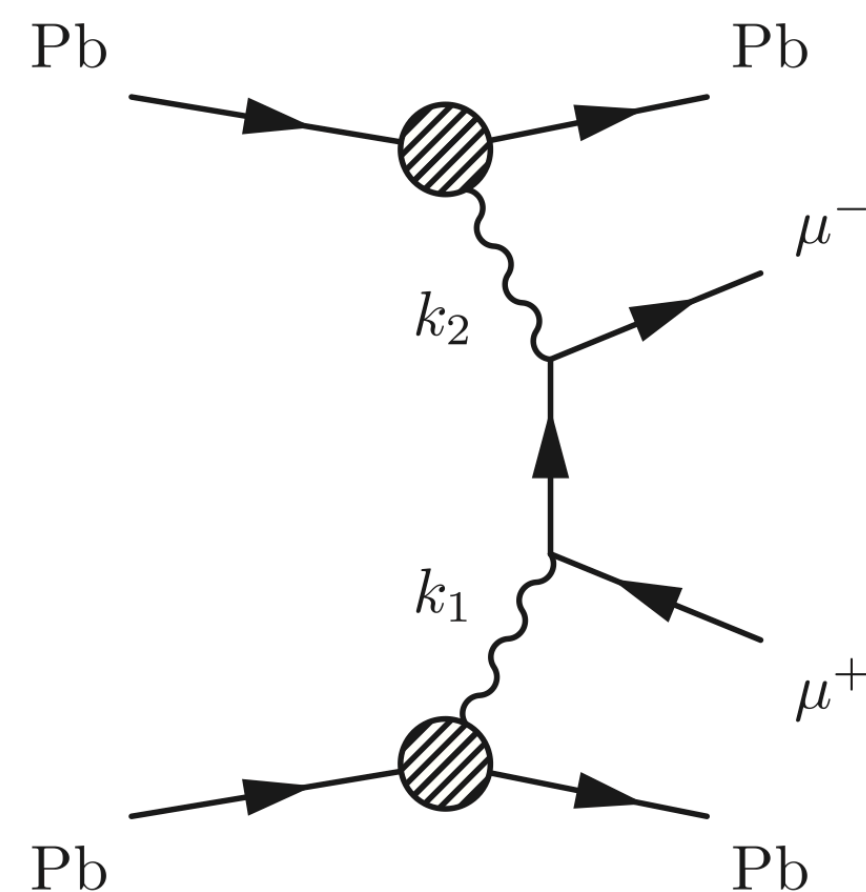
- A landmark analysis that demonstrated the feasibility and the potential of UPC measurements
- paved the way to the UPC program at RHIC and (later) at the LHC

# **Constraining the key ingredients of UPC phenomenology**

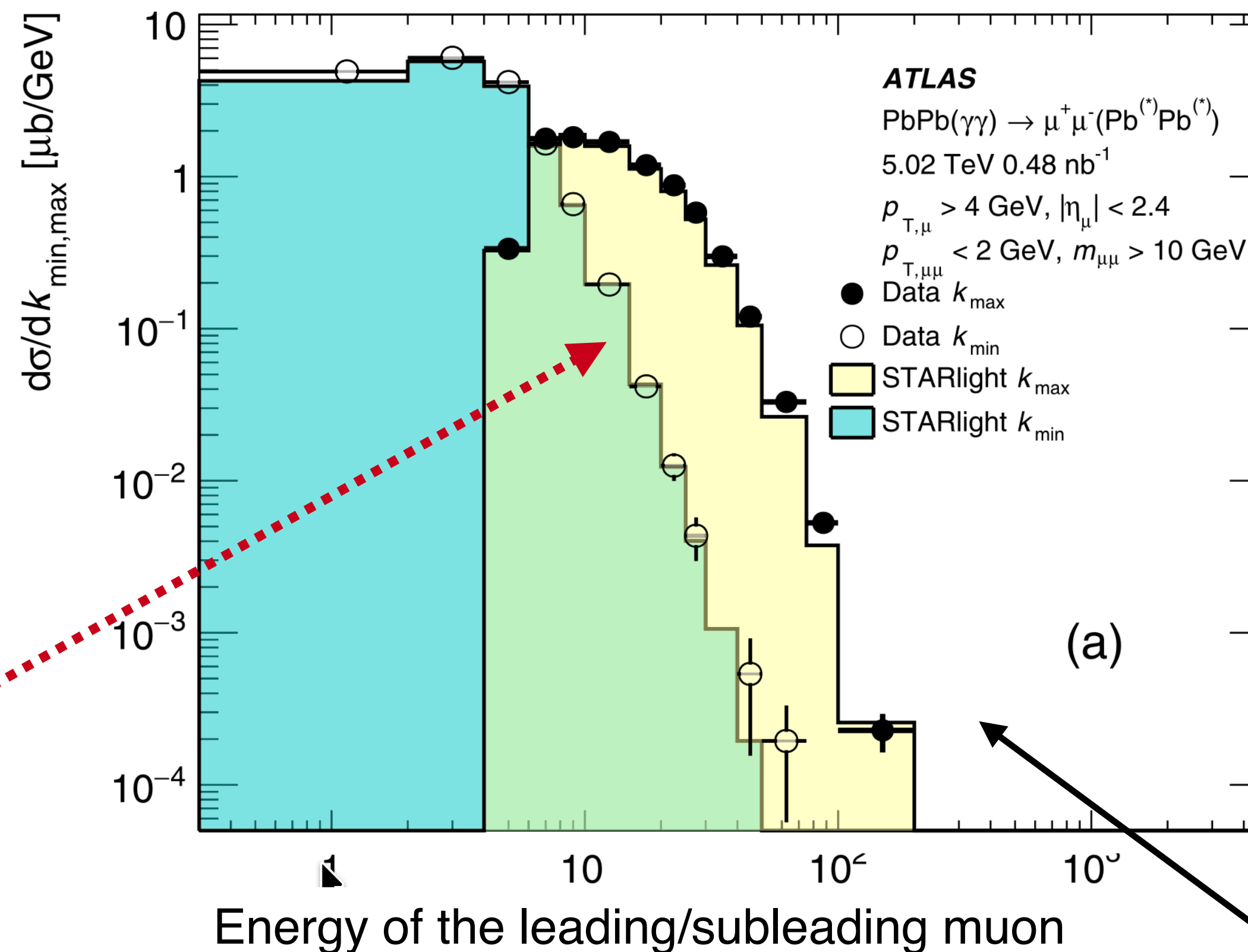
# Constraining the photon flux with $\gamma\gamma \rightarrow \mu^+\mu^-$

Pure QED process

→ **standard candle for the photon flux**



→ Photon-flux at low-moderate energies well described by models



Up to about 20% disagreement for very high E (smaller impact parameter)

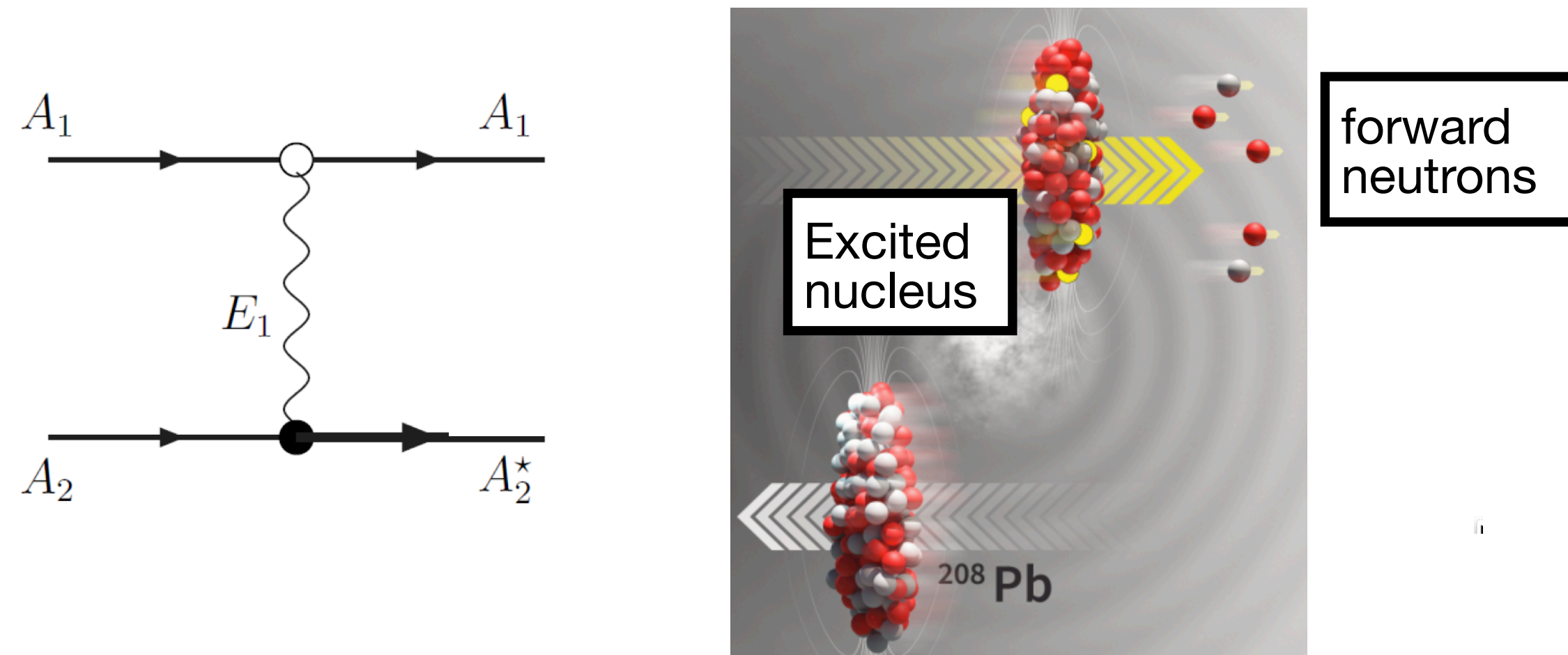
*New ALICE measurements of  $\gamma\gamma \rightarrow \mu^+\mu^-$  in an invariant mass region  $m_{\mu\mu} < 10 \text{ GeV}$  (more in backup)*

# Forward neutrons from electromagnetic dissociation (EMD)

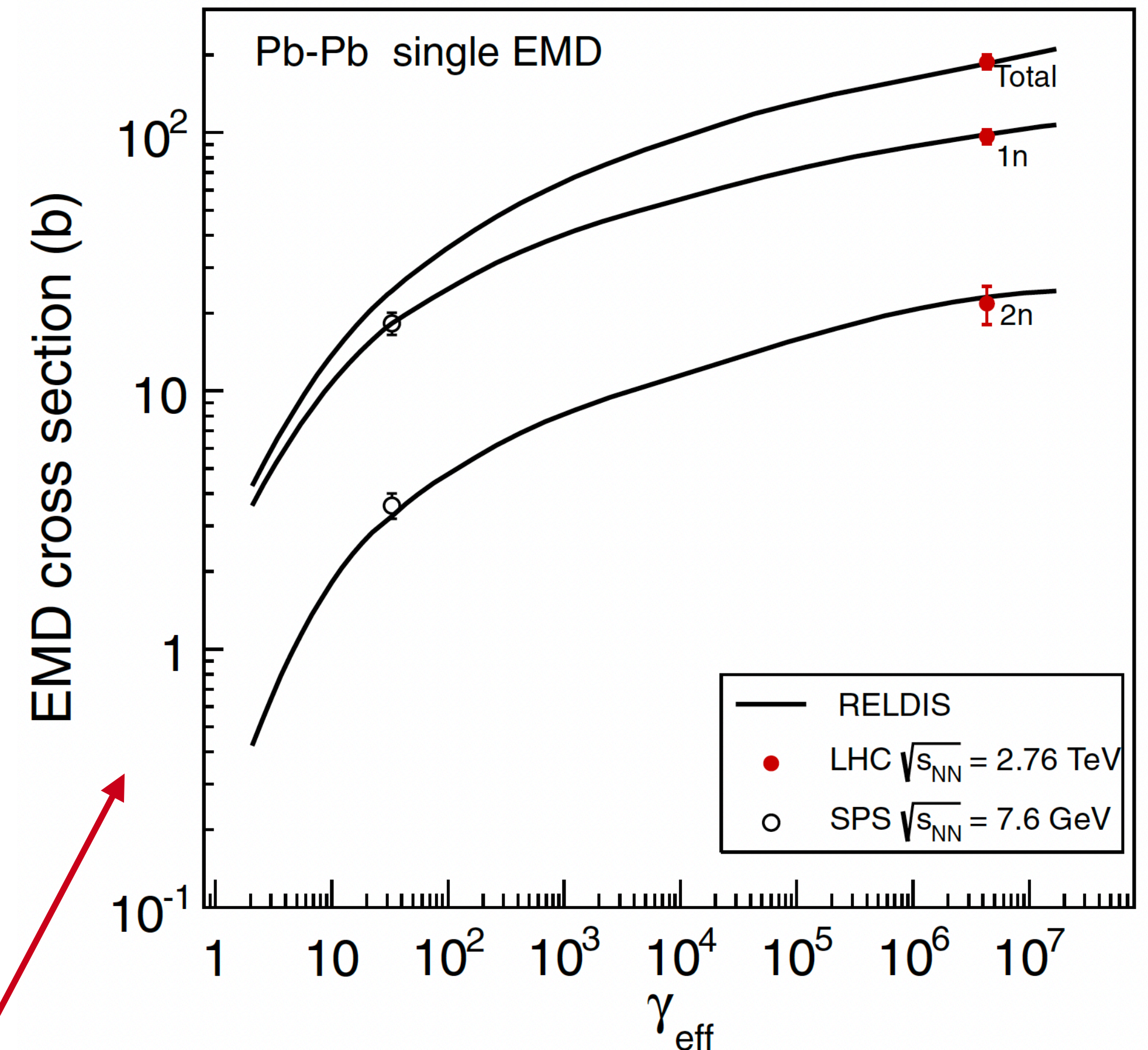
ALICE, *Phys. Rev. Lett.* 109 (2012) 252302

ALICE, *Phys. Rev. C* 111, 054906

**Soft-photon exchange, independent of the main photonuclear process, can excite one or both nuclei → forward neutrons detected by the ZDCs**



EMD is sensitive to the description of the photon flux,  
**modeling of the nuclear excitation and decay**

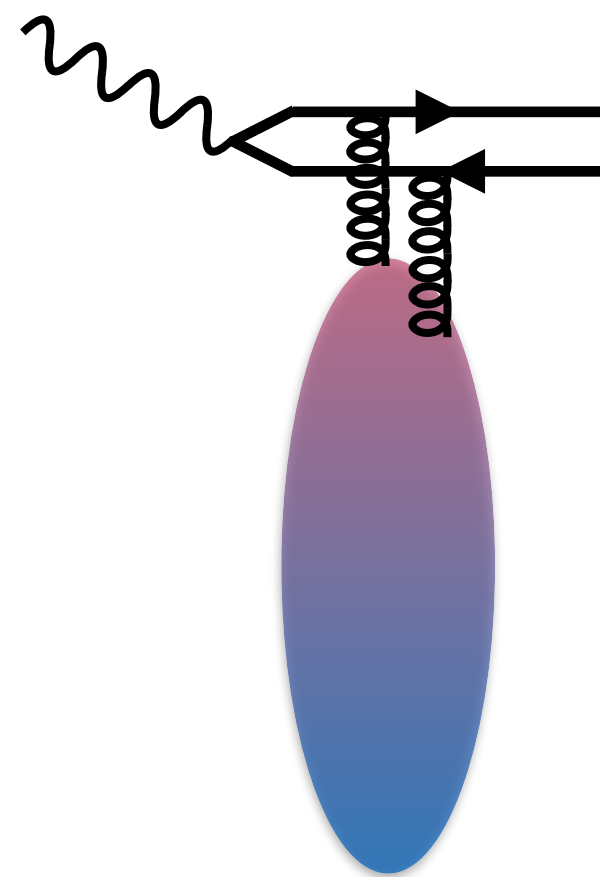


**Phenomenological models reasonably well describe the cross-section of EM dissociation**

→ The effect of EMD can be modeled well enough and was not a major obstacle for UPC analyses

→ *Newer ALICE measurements provide the first constraints on the proton production (Phys. Rev. C 111, 054906)*

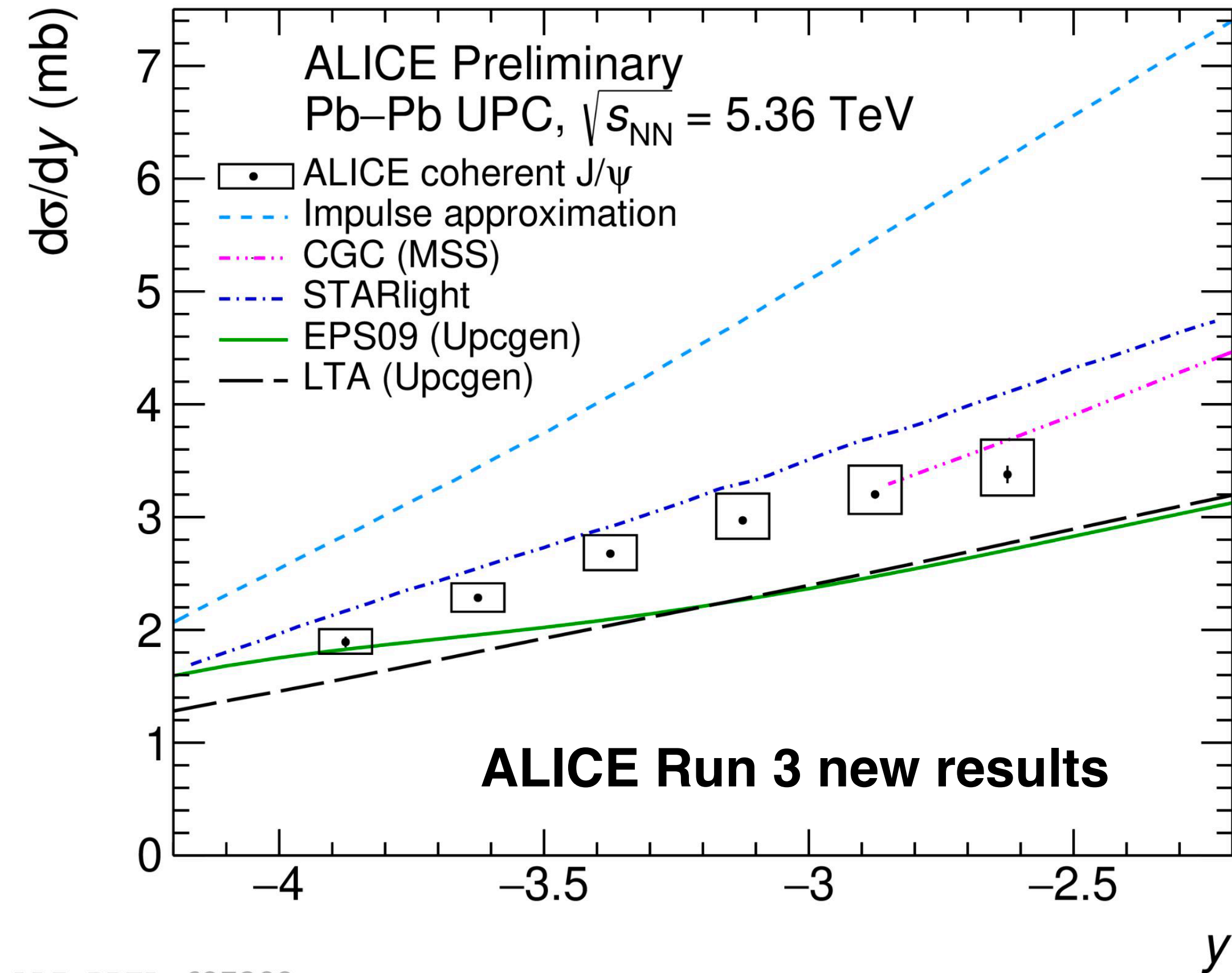
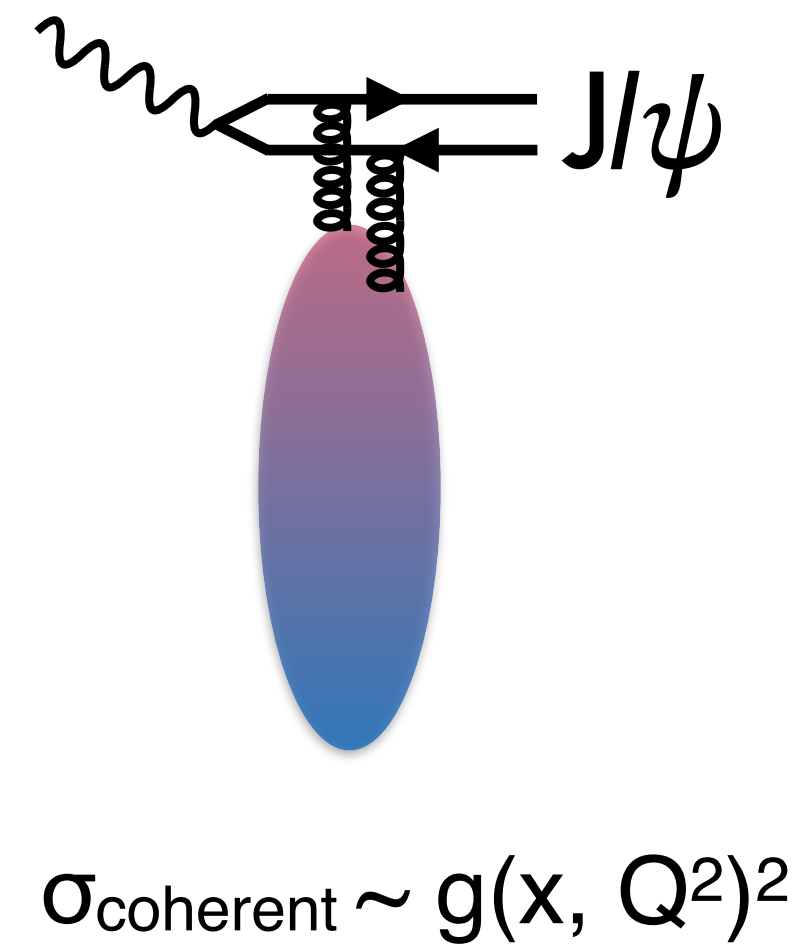
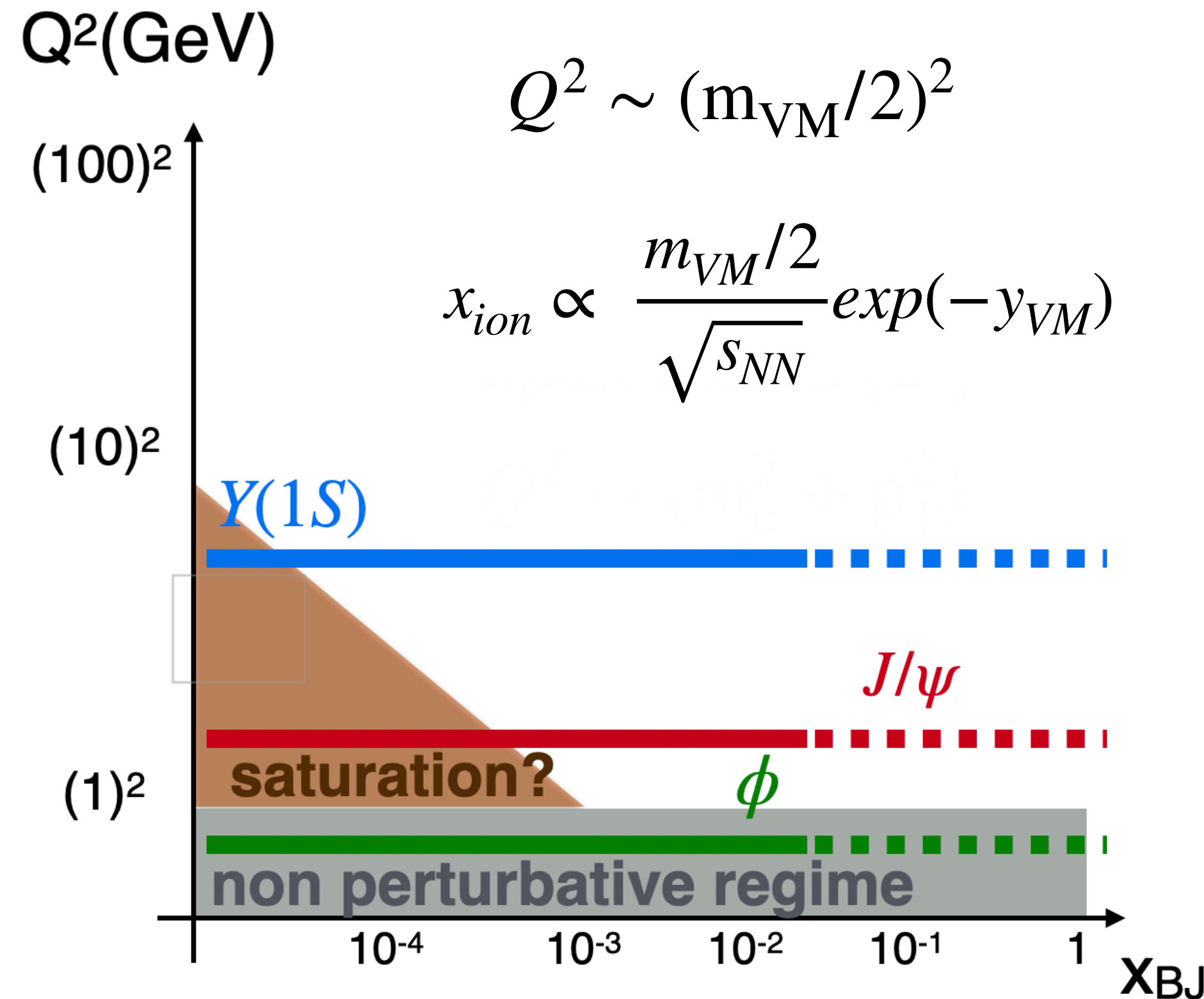
# Recent measurements of exclusive vector-meson (VM) photoproduction



# Light and heavy vector-meson coherent production

→ Heavy vector mesons provide a perturbative scale and access to small-x gluons.

ALICE, Phys. Lett. B 798 (2019) 134926  
 N. Burmasov's talk at DIS 2026  
 Minjung Kim's talk at DIS 2026

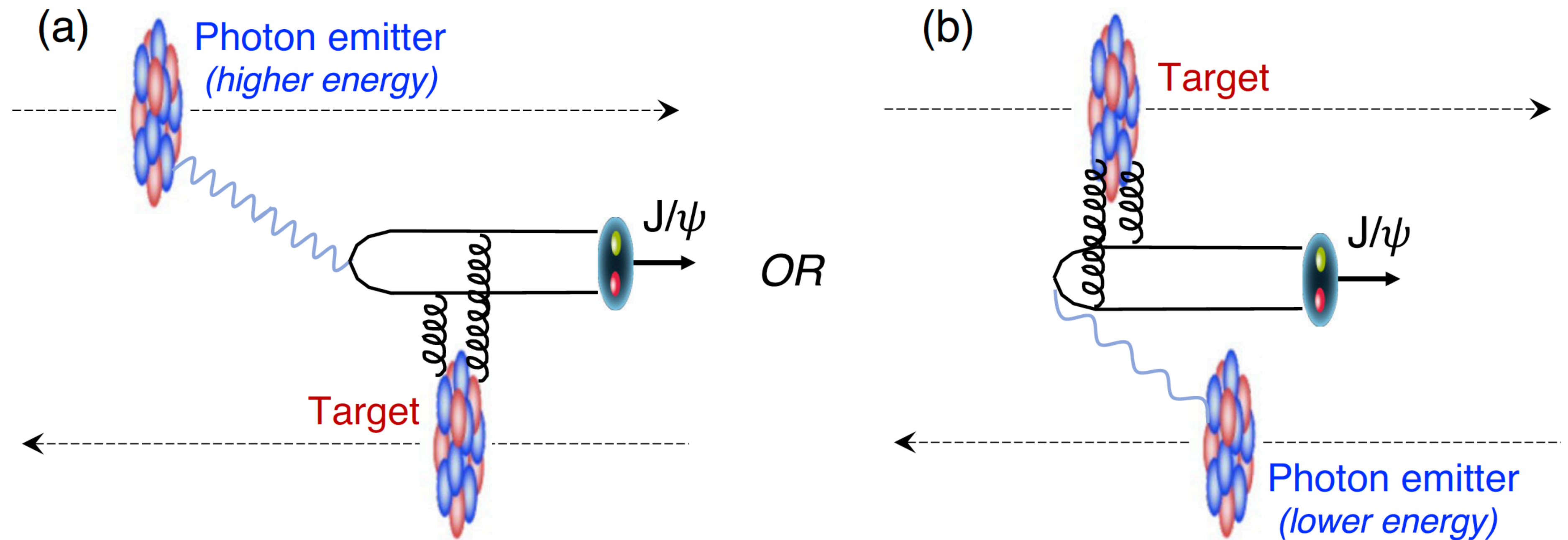


ALI-PREL-627392

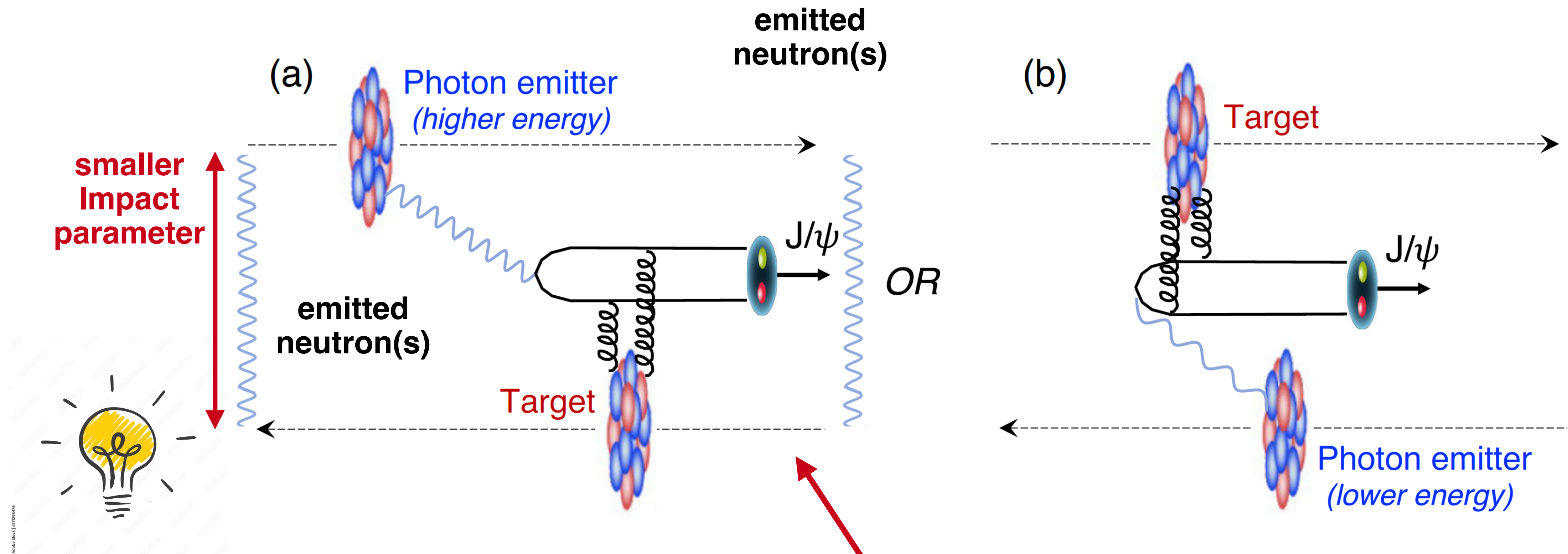
**J/ψ cross-section measured as a function of rapidity with very good experimental accuracy**  
**At a given rapidity, the cross-section receives contributions from two different x regions**

# “Two-way” photon ambiguity

A vector meson with given  $p_T$  and rapidity can be produced either by a high-energy photon or by a low-energy photon, depending on which nucleus emits the photon!



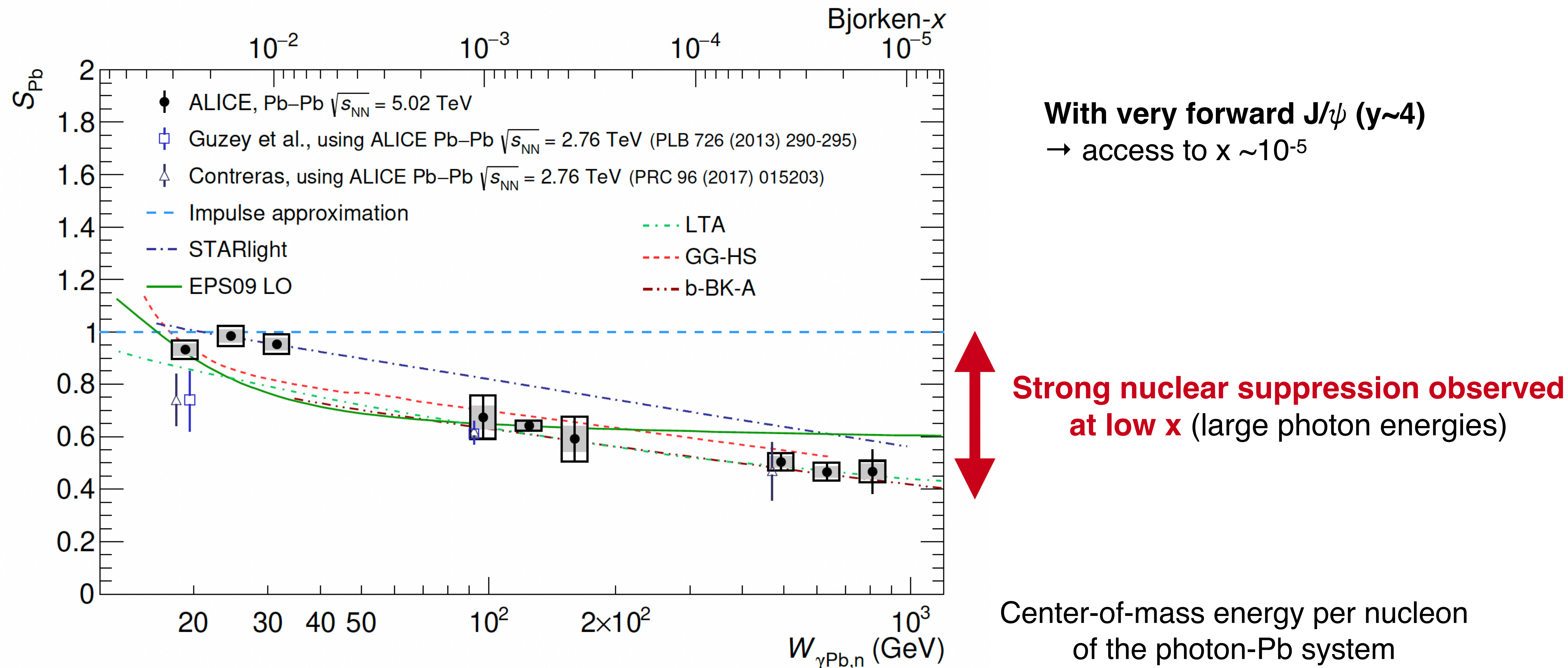
# Neutron-tagging method



## Neutron-tagging method:

- higher-energy photons correspond to smaller impact parameters
- Smaller impact parameters give larger EMD probability
- **By selecting events with forward neutrons, one can preferentially select events with high-energy photon emitters**

# Coherent $J/\psi$ production with neutron-tagging method

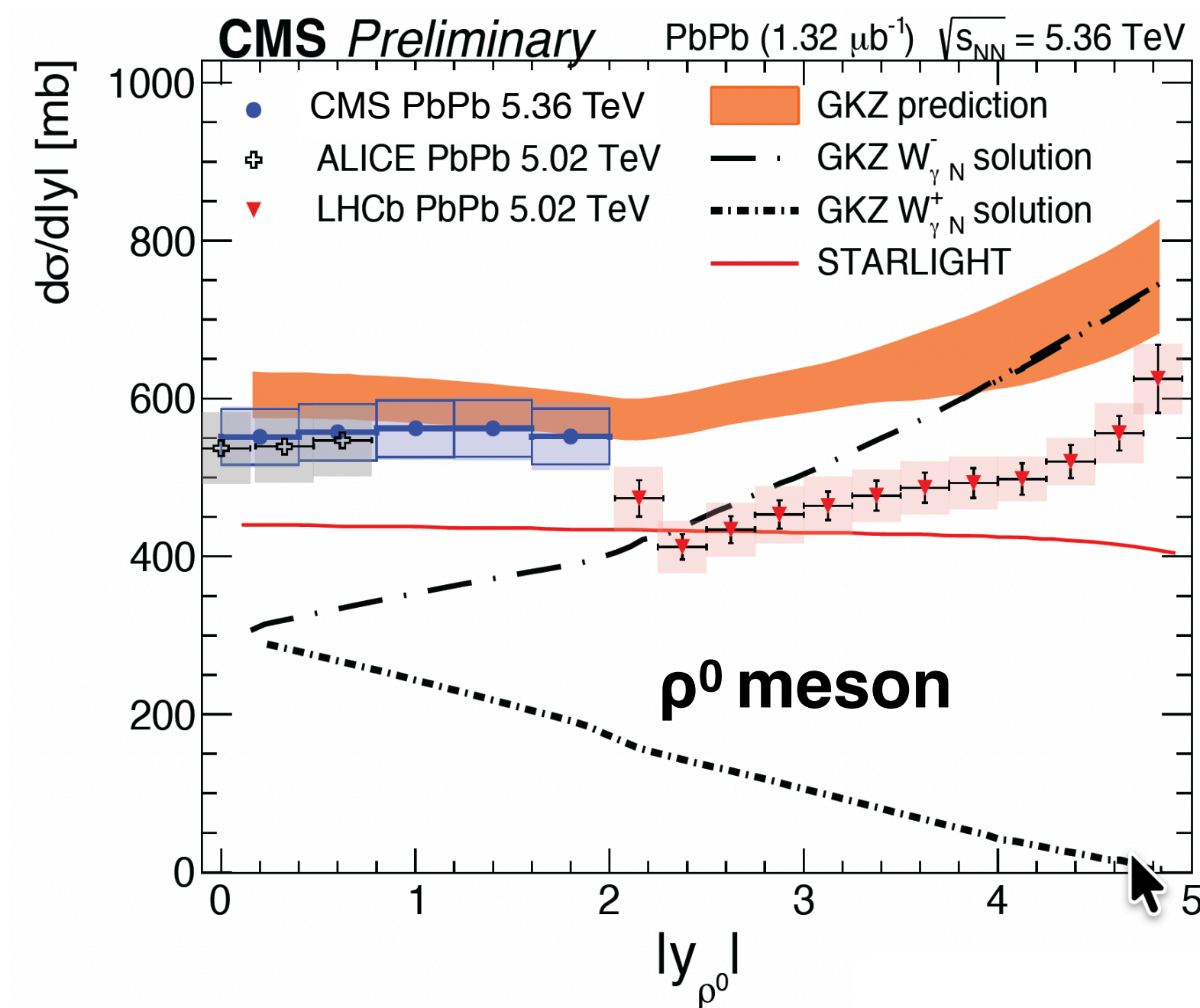


**Systematic comparison to theoretical calculations, including linear evolution with nuclear shadowing (e.g. LTA), and nonlinear small-x evolution (e.g. CGC)**

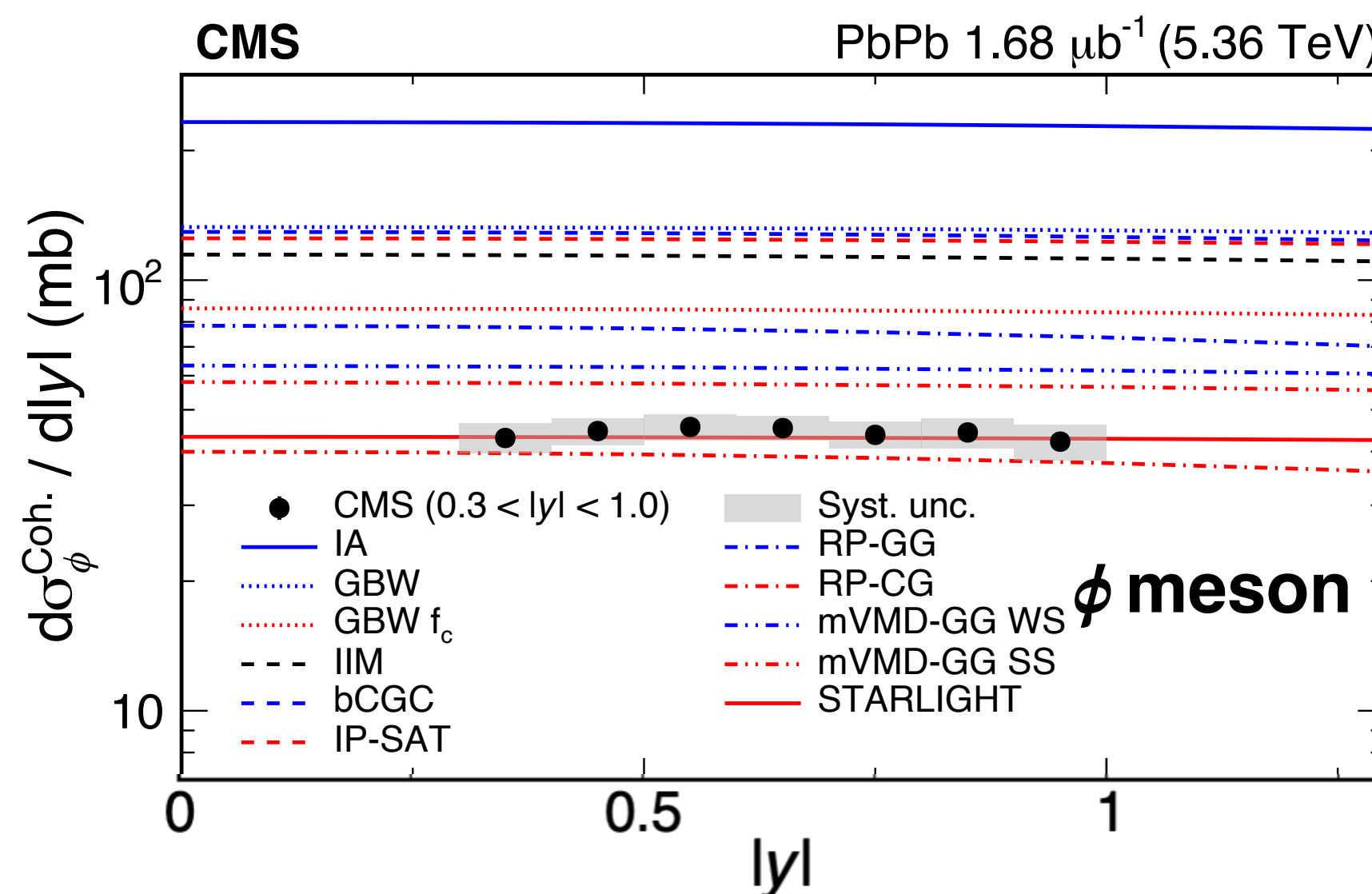
# Scanning nuclear gluon dynamics with exclusive VMs

VM mass sets the hard scale  
rapidity/energy/mass sets the probed x

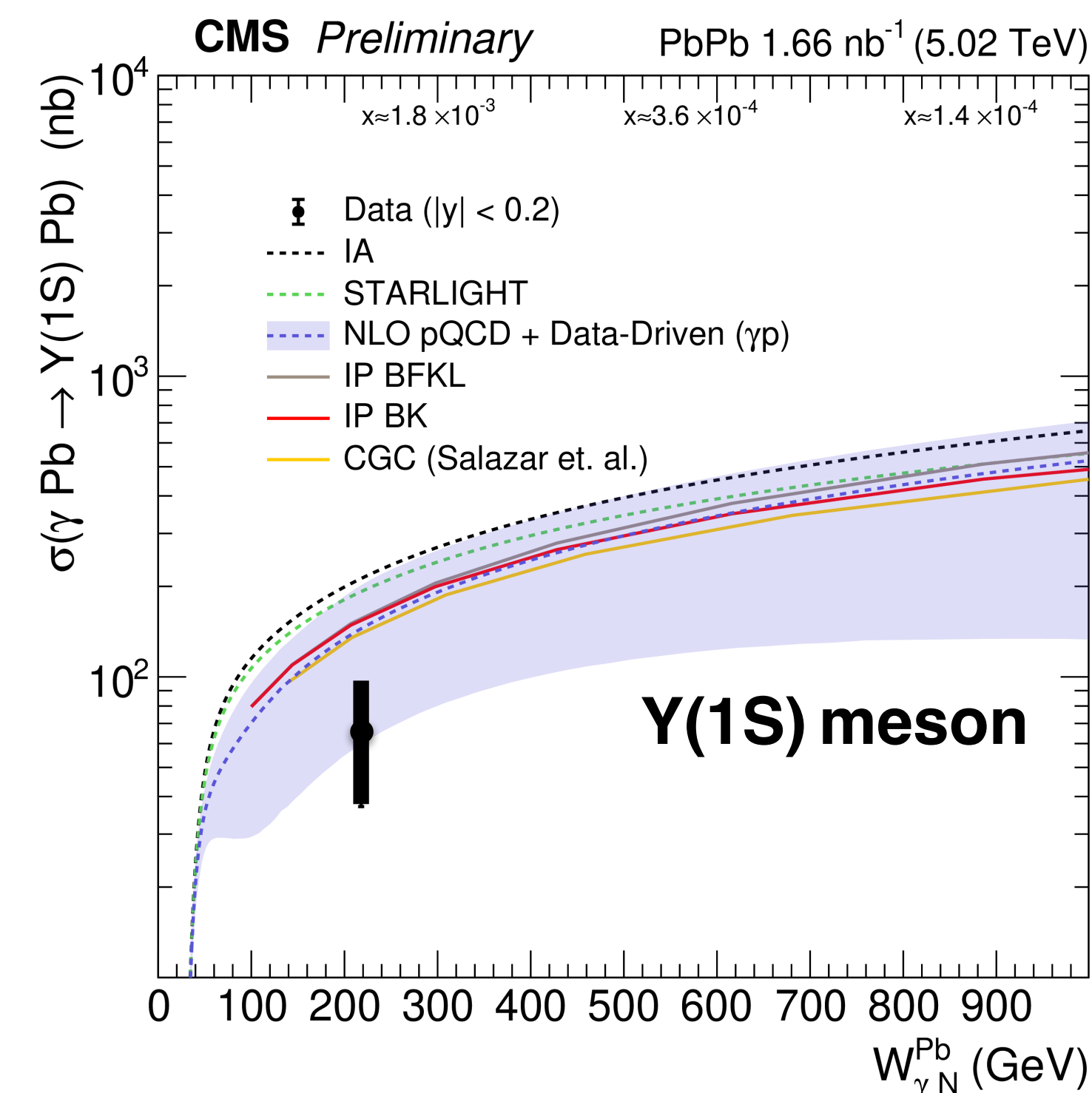
$$Q^2 \sim (m_{VM}/2)^2 \quad x_{ion} \propto \frac{m_{VM}/2}{\sqrt{s_{NN}}} \exp(-y_{VM})$$



$Q(\rho^0) \approx 0.39 \text{ GeV}$      $Q(\phi) \approx 0.51 \text{ GeV}$



$Q(J/\psi) \approx 1.55 \text{ GeV}$      $Q(Y) \approx 4.73 \text{ GeV}$

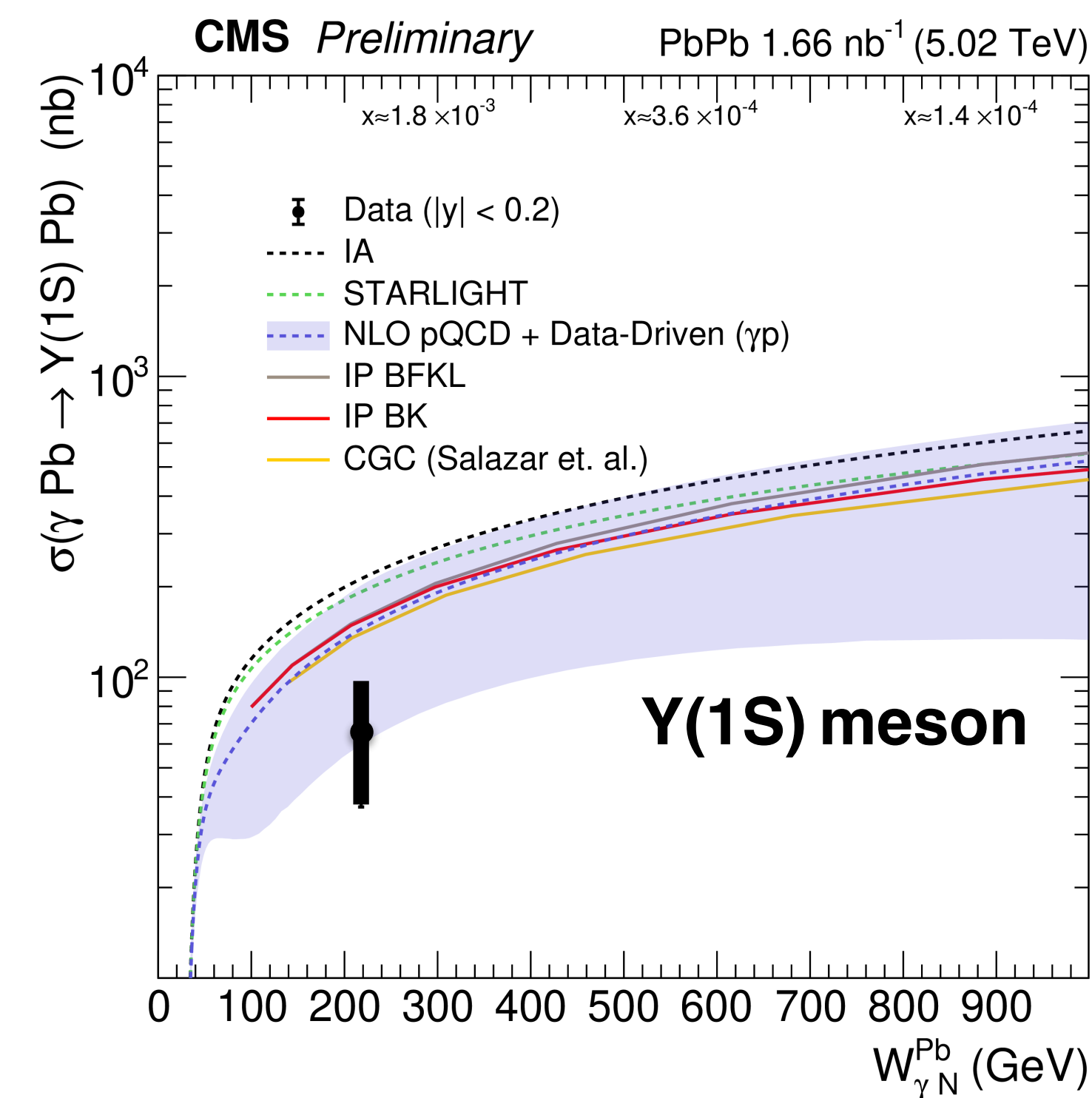
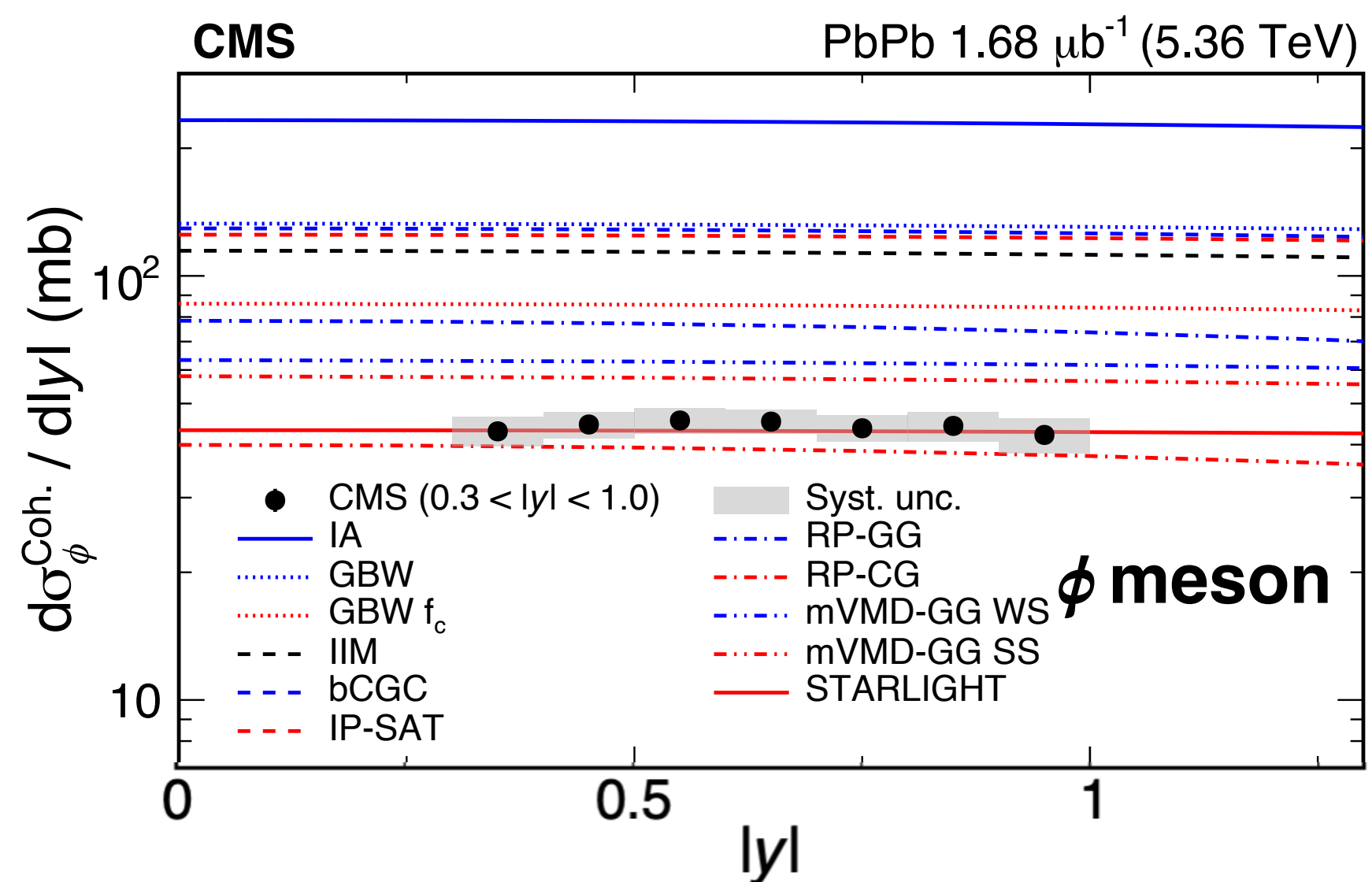
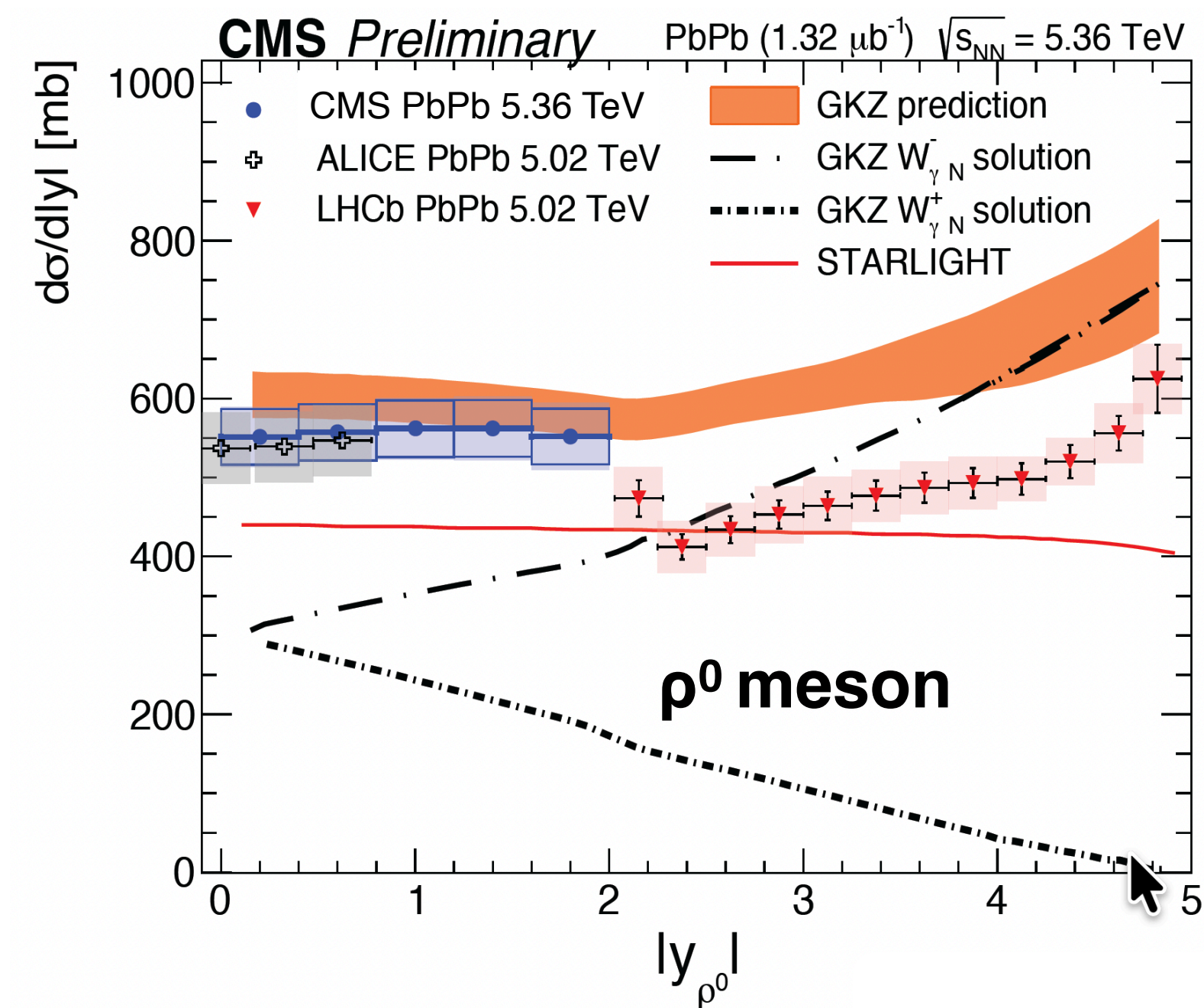


**Perturbative regime**

Non-perturbative regime  
stronger sensitivity to nonlinear dynamics

# Scanning nuclear gluon dynamics with exclusive VMs

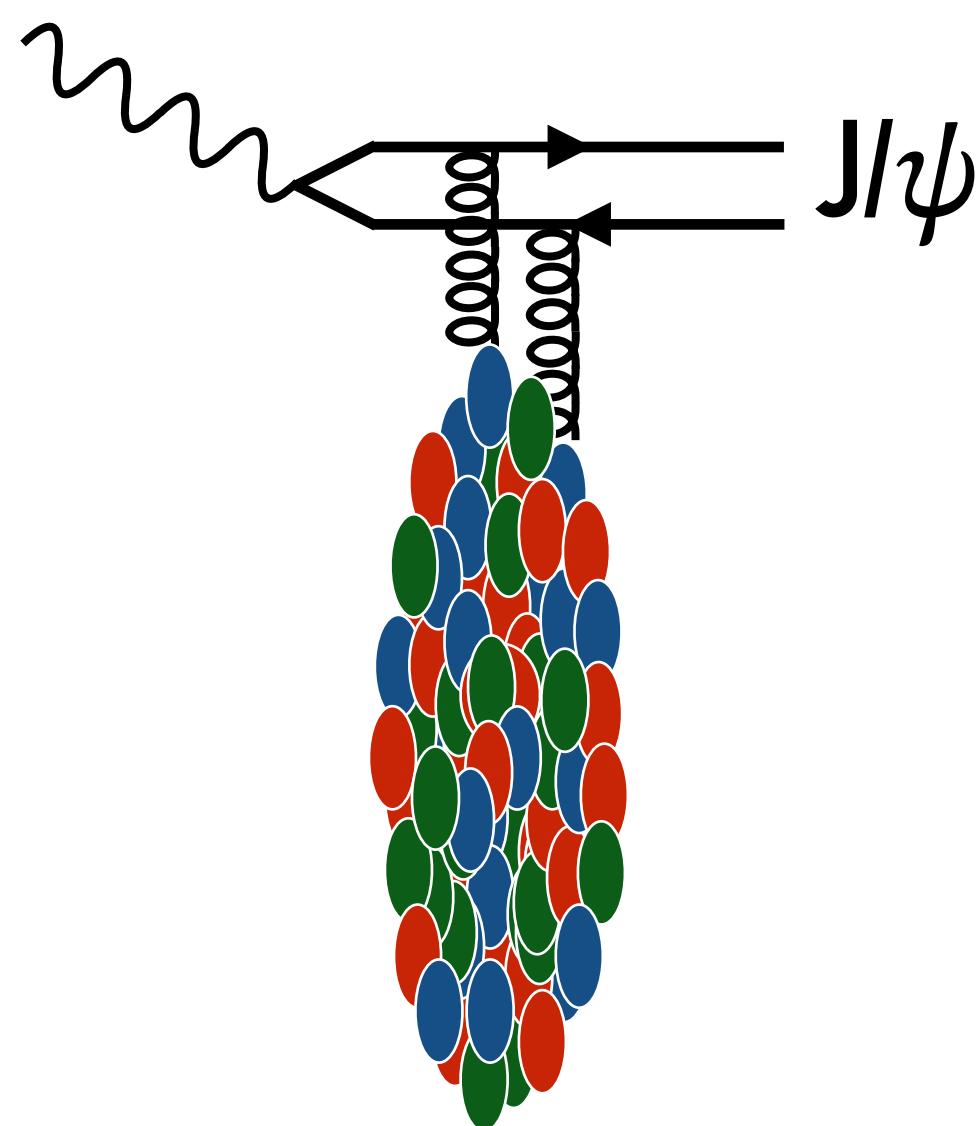
CMS, HIN-24-020, CMS-PAS-HIN-24-013,  
 CMS, Phys. Rev. Lett. 135 (2025) 262301  
 LHCb, JHEP 11 (2025) 103  
 ALICE, JHEP06 (2020) 03



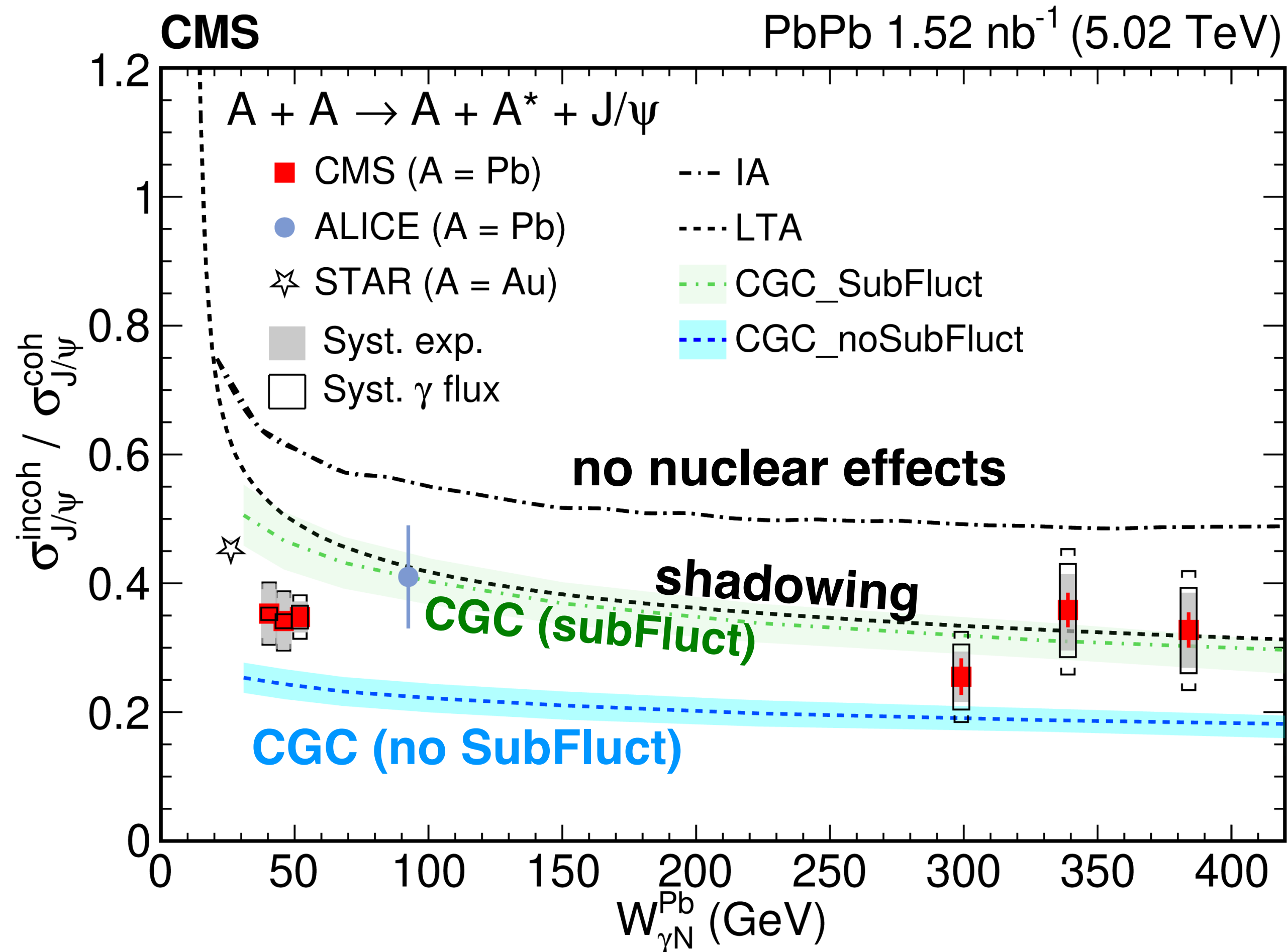
- Both light and heavy vector mesons favor a **strong suppression scenario over impulse approximation**
- **No unambiguous evidence for non-linear evolution, as encoded in saturation models**
- Challenging NLO corrections and light VMs description, and differing exclusivity selections

# Incoherent $J/\psi$ production in UPCs

**Incoherent photoproduction probes** event-by-event gluon-density fluctuations at subnucleon scales



$W_{\gamma N}$  = center-of-mass energy per nucleon of the photon-Pb system

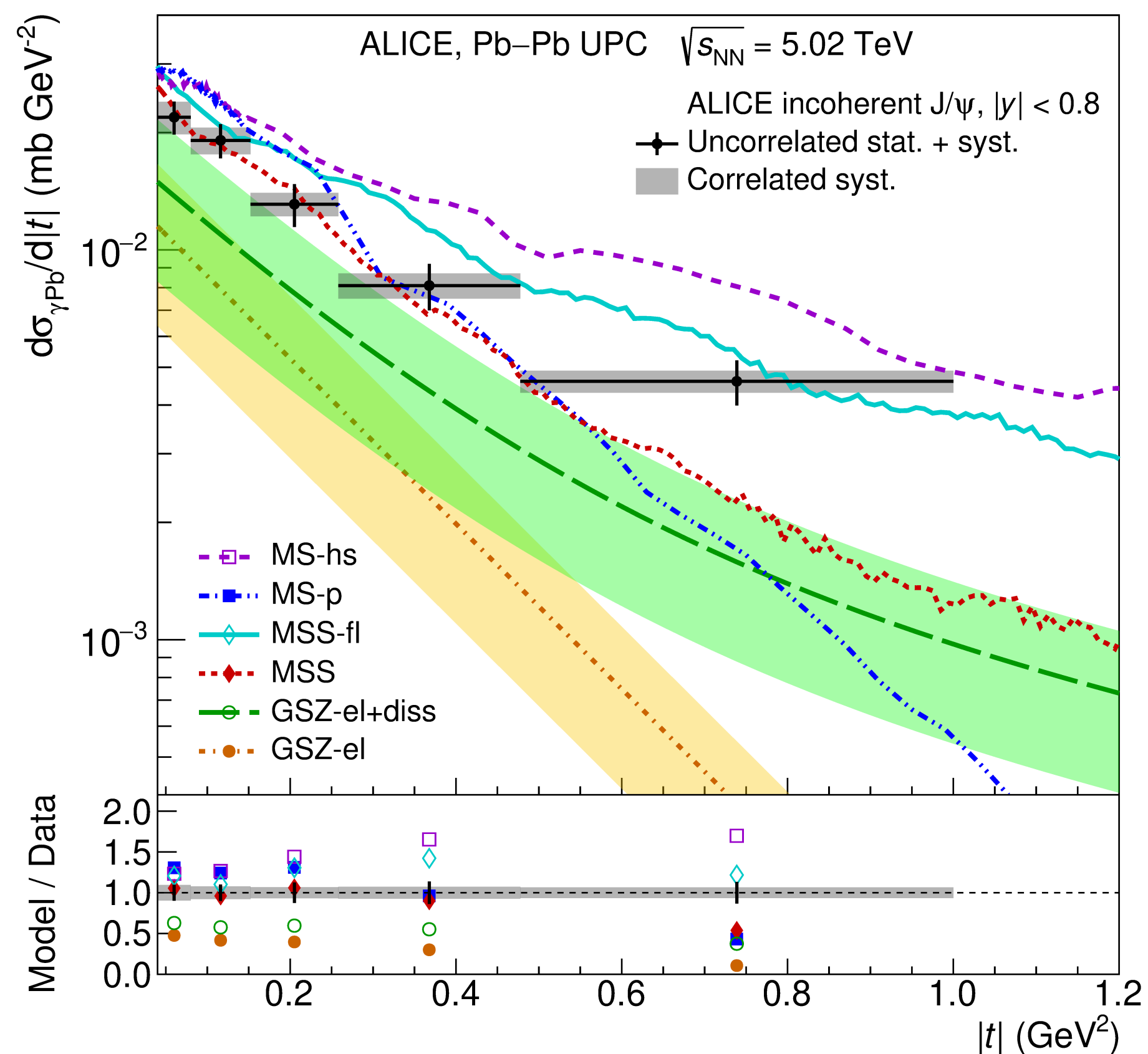


**Ratio < 1: at low x, incoherent production is suppressed relative to coherent production**

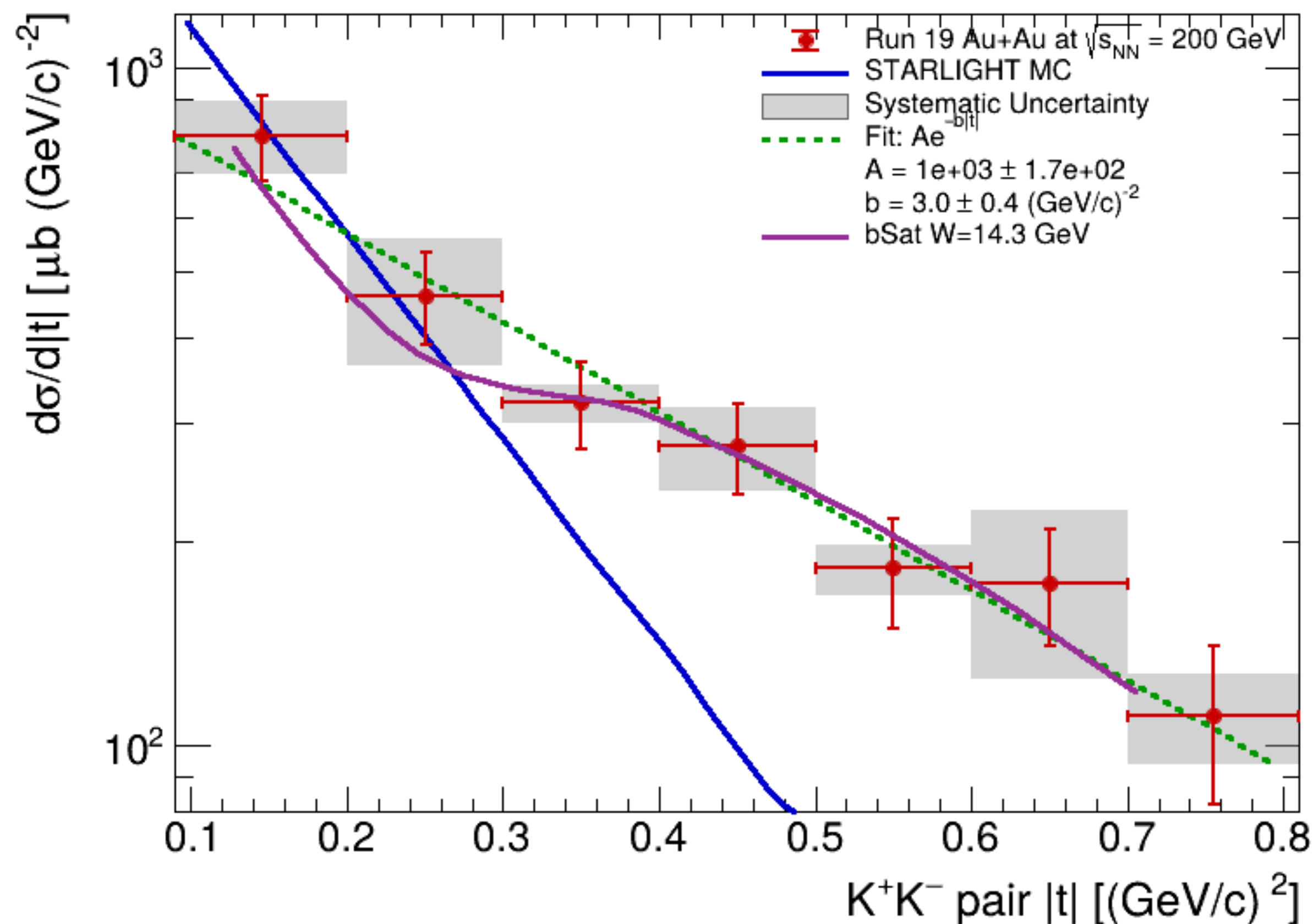
→ consistent with saturation/CGC expectations

# t-dependence of incoherent VM production

## Incoherent $J/\psi$ production at the LHC (ALICE)



## Incoherent $\phi$ production at RHIC (STAR)



## Incoherent VM production probes event-by-event gluon-density fluctuations

→ t-dependence is sensitive to the transverse scale of gluon-density fluctuations

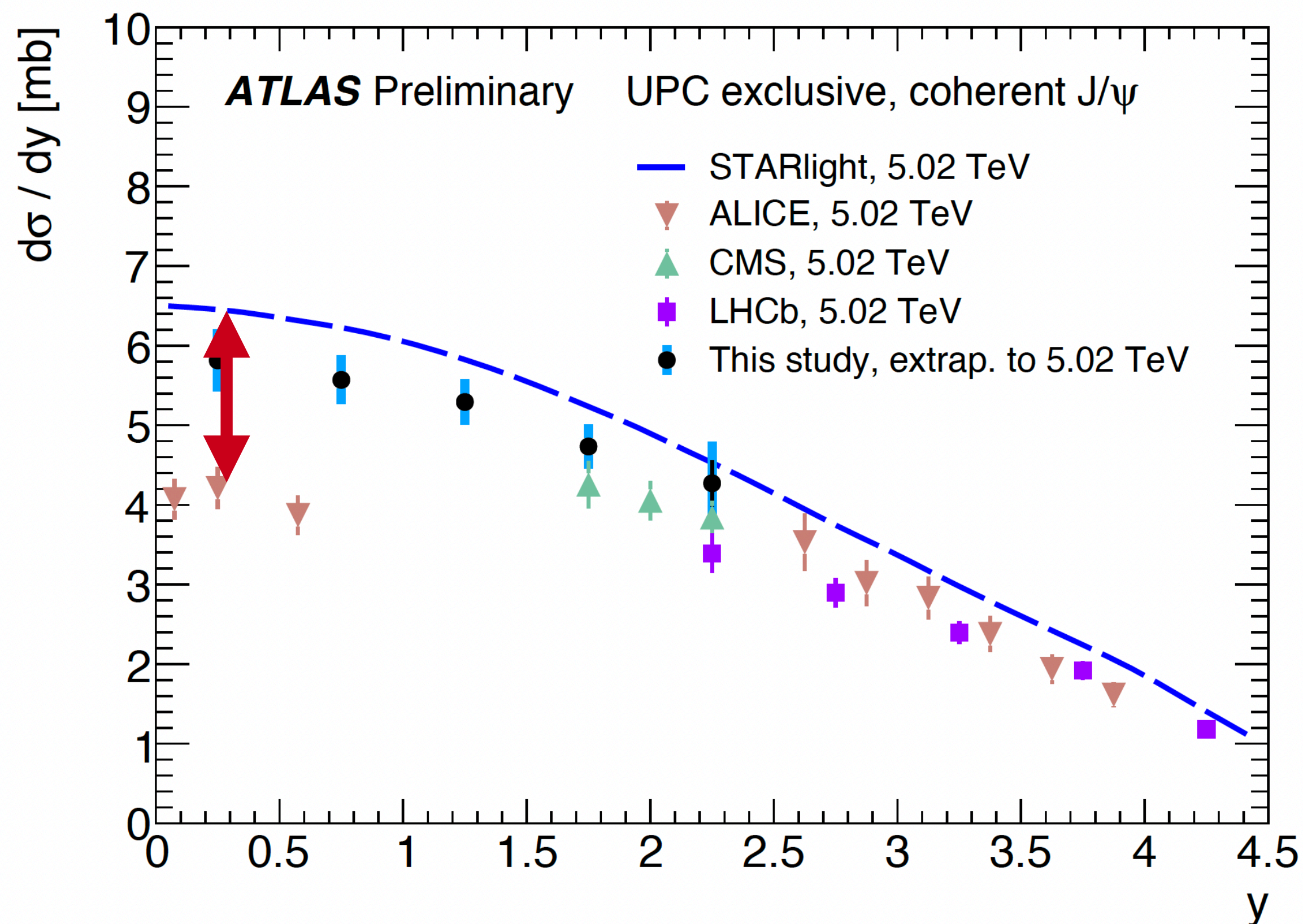
→ **Models without gluon-density fluctuations predict a much steeper t-dependence than observed**

# Defining exclusive production: an emerging issue

Comparisons of exclusive measurements across experiments can depend significantly on how exclusivity is defined.

→ “**Exclusivity**” is not a purely theoretical concept; it depends on detector veto  $\eta$ -coverage and energy thresholds

y-dependent cross section of exclusive coherent  $J/\psi$



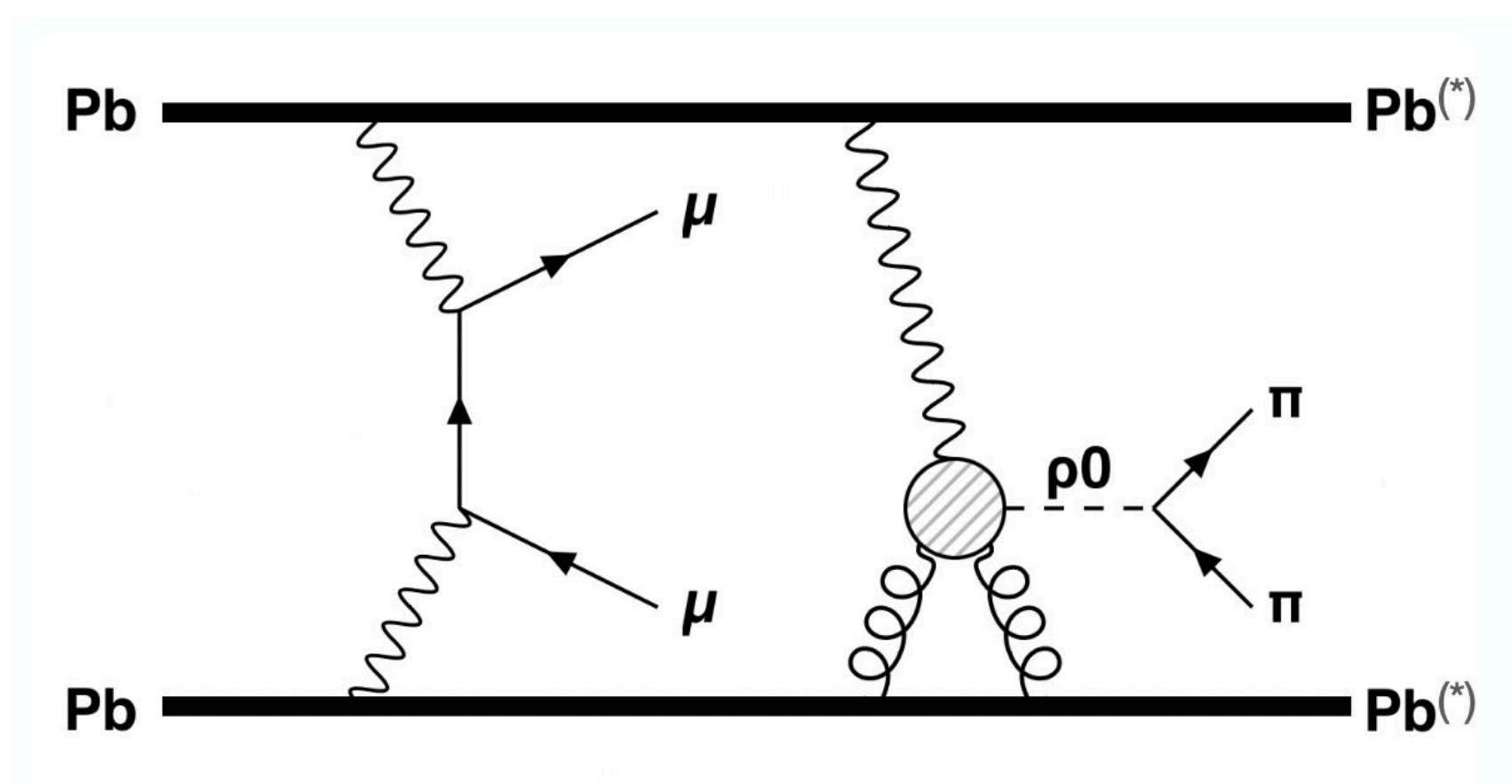
- Independent soft  $\gamma\gamma \rightarrow e^+e^-$  pair production can make (otherwise good) coherent VM events fail exclusivity cuts
- EMD-induced activity can also affect exclusivity selections

ATLAS, [ATLAS-CONF-2025-003](#)  
M. Dyndal et al., [arXiv:2604.19879](#)  
ATLAS, [arXiv:2504.07795](#)  
L.A. Harland-Lang et al, [SciPostPhys.11 \(2021\)064](#)

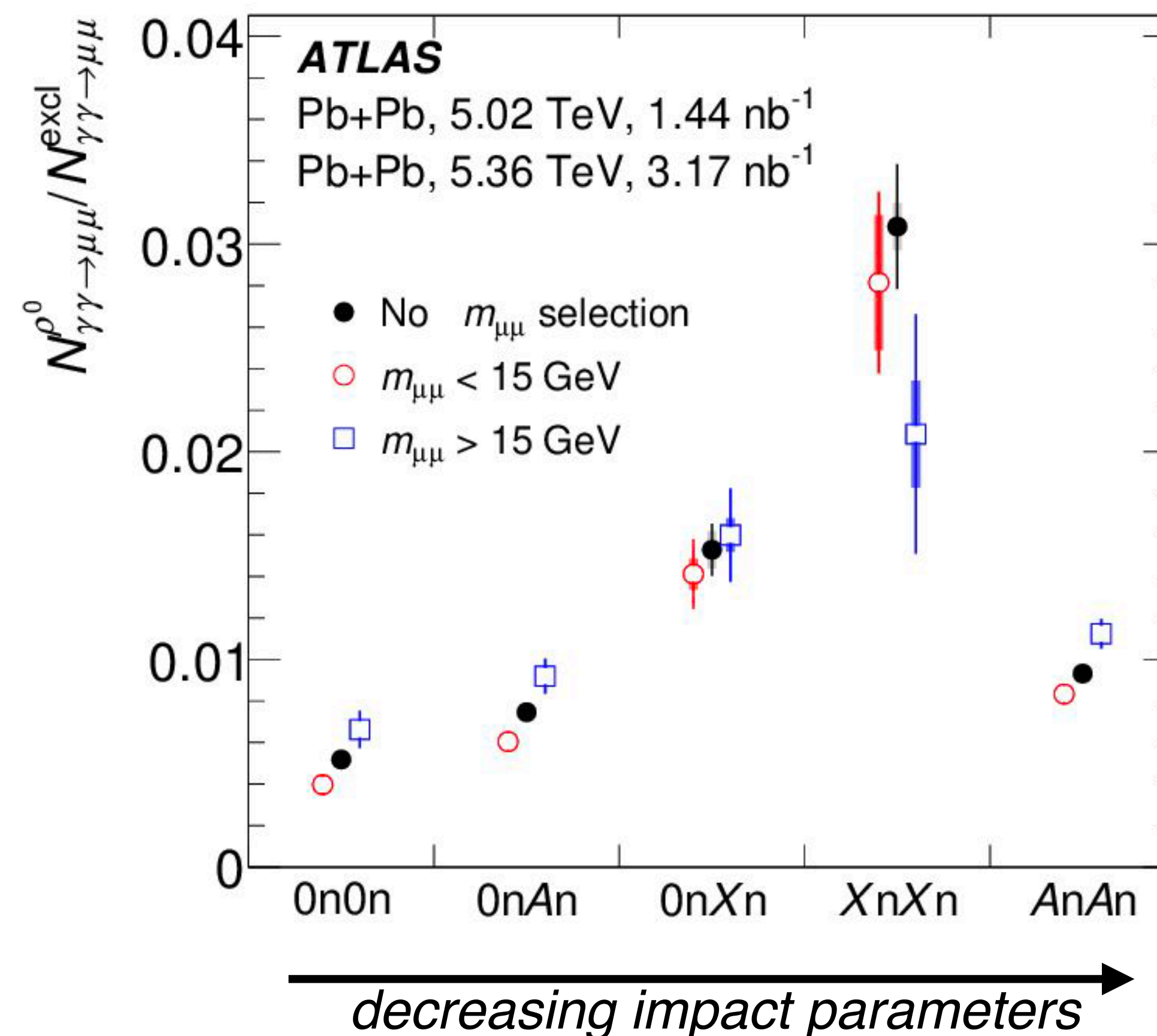
**Precision UPC comparisons require reproducible exclusivity definitions across experiments**

# $\rho^0$ production in coincidence with $\gamma\gamma \rightarrow \mu^+\mu^-$

Multiple electromagnetic interactions can occur in the same UPC event



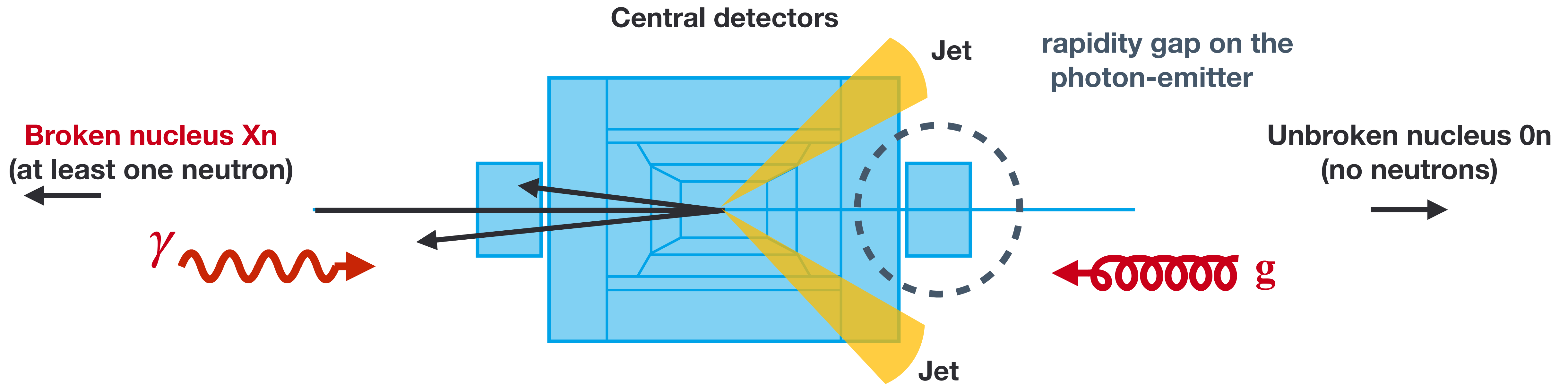
two opposite-sign back-to-back muons with  $p_T > 3.7$  GeV,  $|\eta| < 2.4$  in events with  $\rho^0$  production



**About 1% of selected dimuon events contain coincident  $\rho^0$  production in this kinematic range**

- Such coincidences can affect exclusivity vetoes and event classification
- the effect may be larger for softer  $\gamma\gamma \rightarrow \mu^+\mu^-$  or  $\gamma\gamma \rightarrow e^+e^-$  pairs

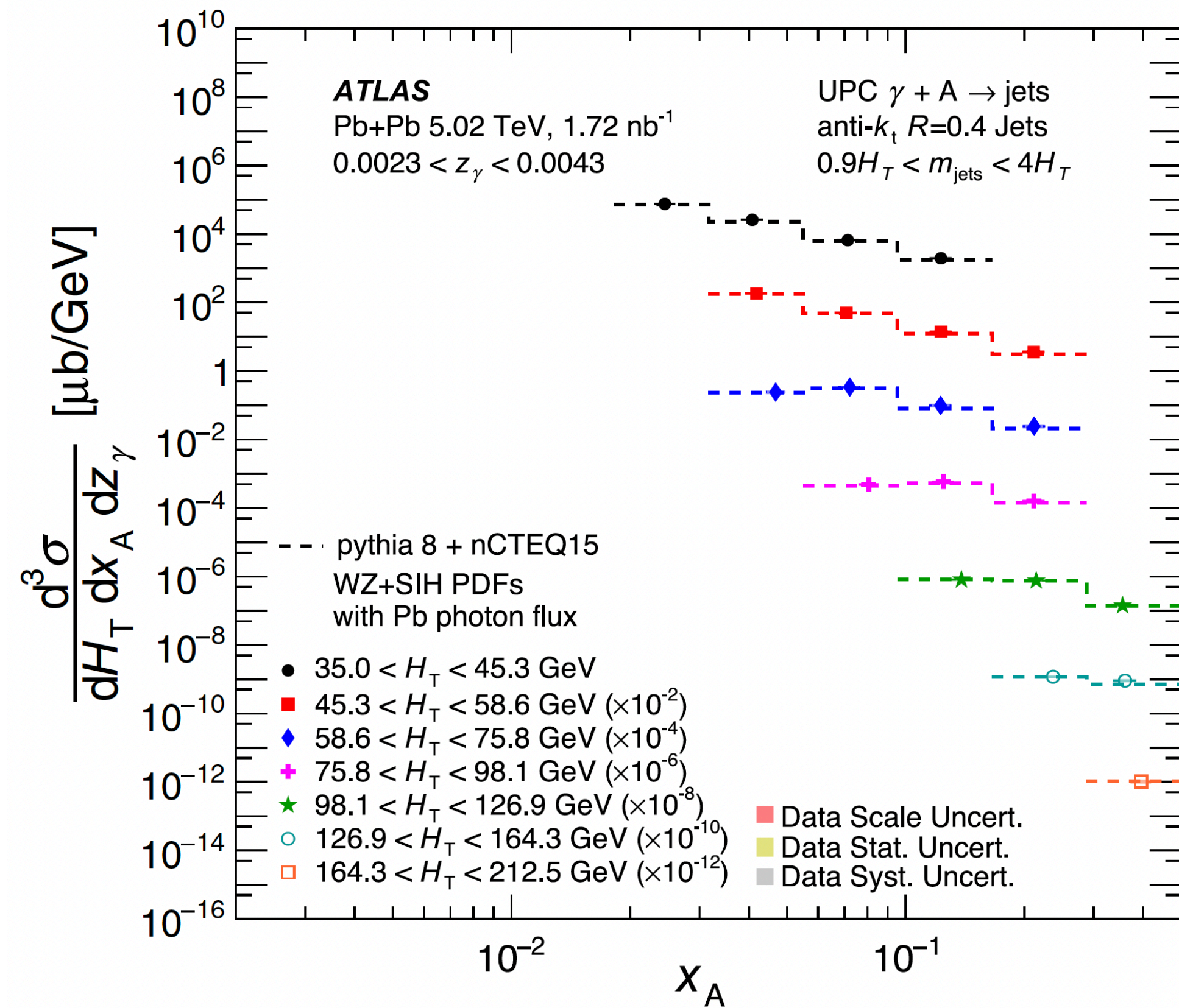
# Photonuclear jets and open heavy-flavor in UPCs



# Photonuclear jet cross sections in UPC PbPb

Xn0n → **photon-emitter direction**

**Full reconstruction of the final state → direct access to scattering kinematics**



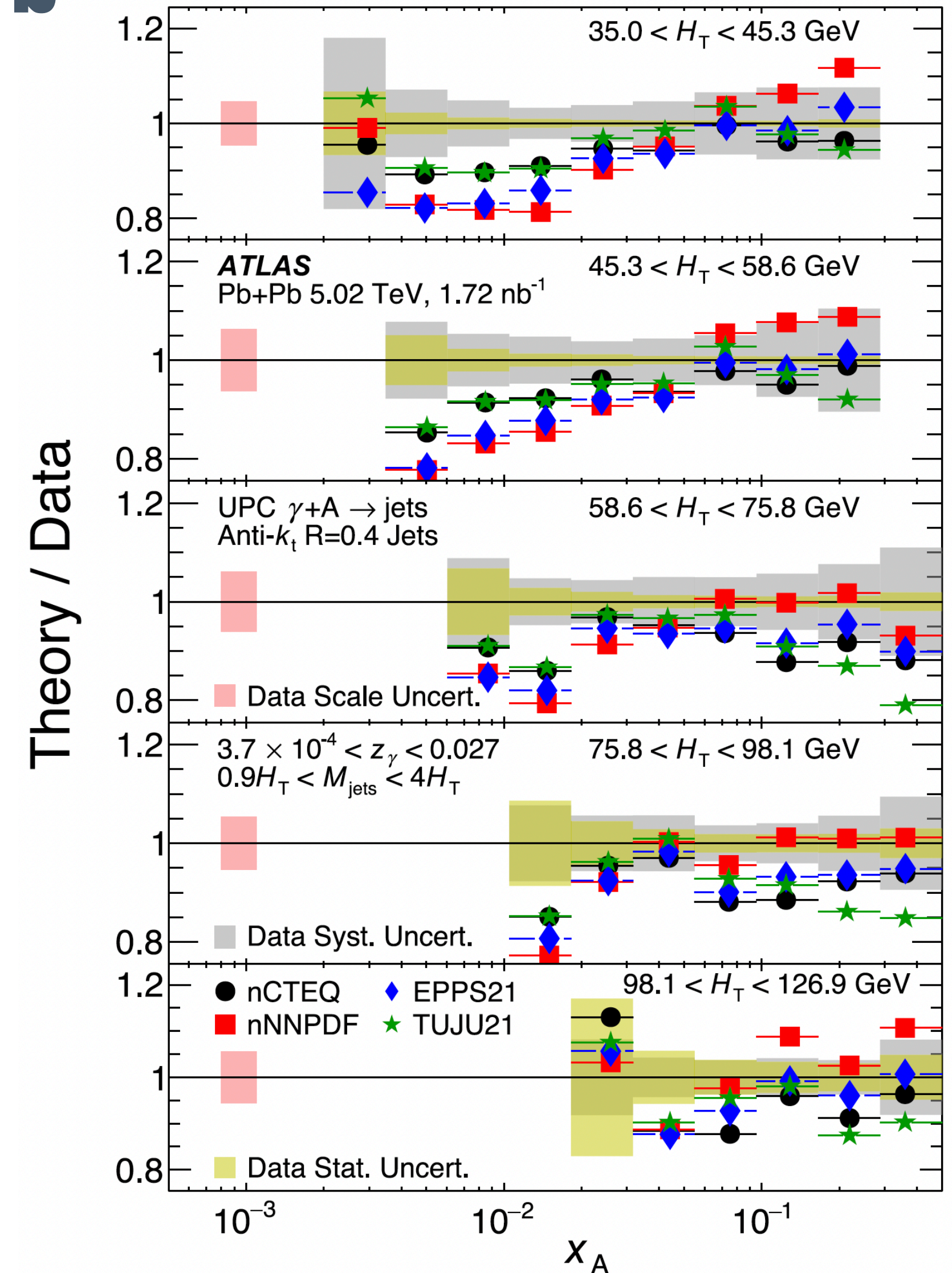
$$x_A \equiv \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$$

$$H_T \equiv \sum_i p_{Ti}$$

**Jet kinematics scan different regions of x, Q<sup>2</sup>**

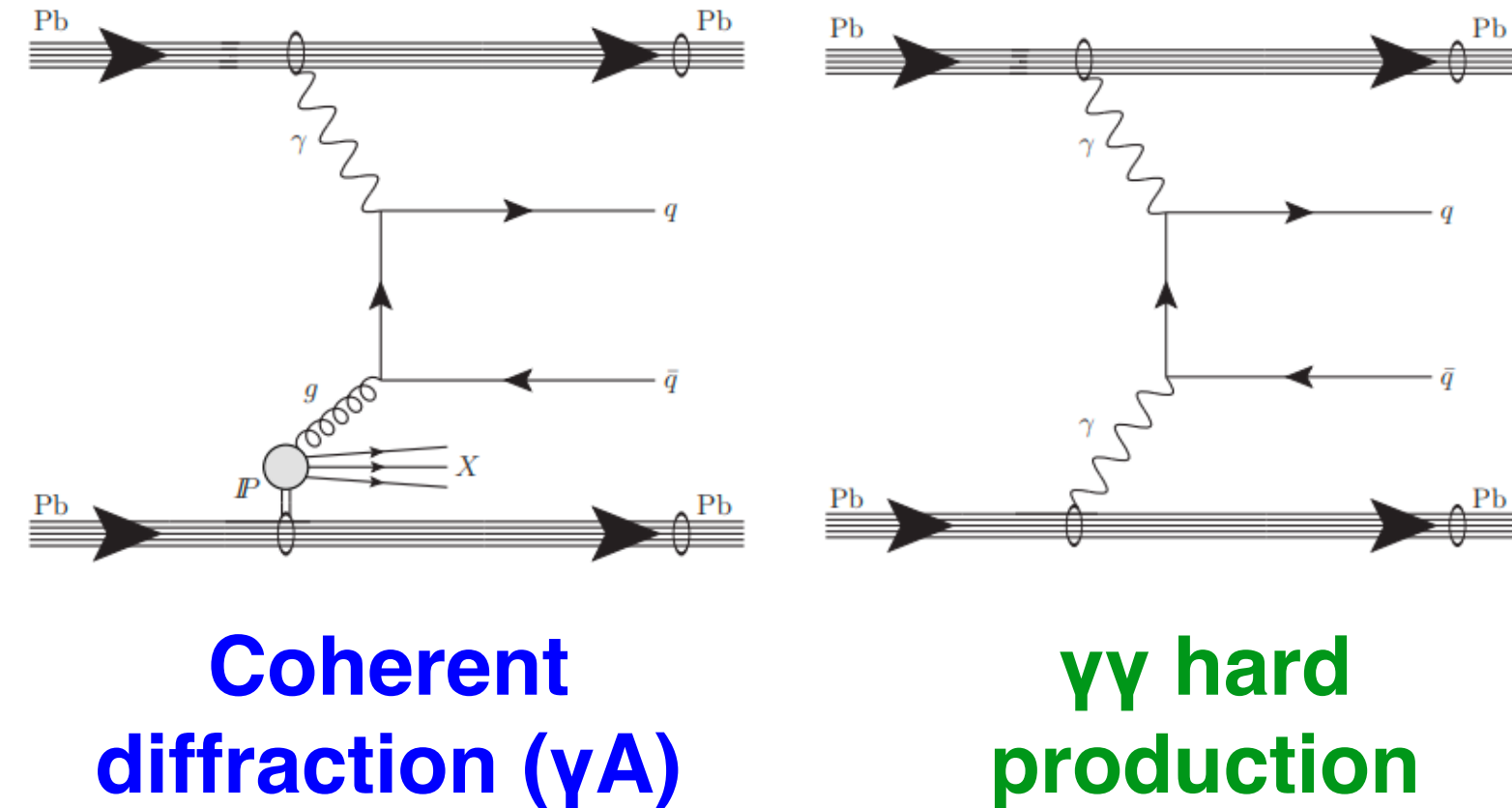
10<sup>-3</sup> ≲ x<sub>A</sub> ≲ 0.4 for H<sub>T</sub> > 30-40 GeV

→ **accesses shadowing, antishadowing, and EMC-sensitive regions**



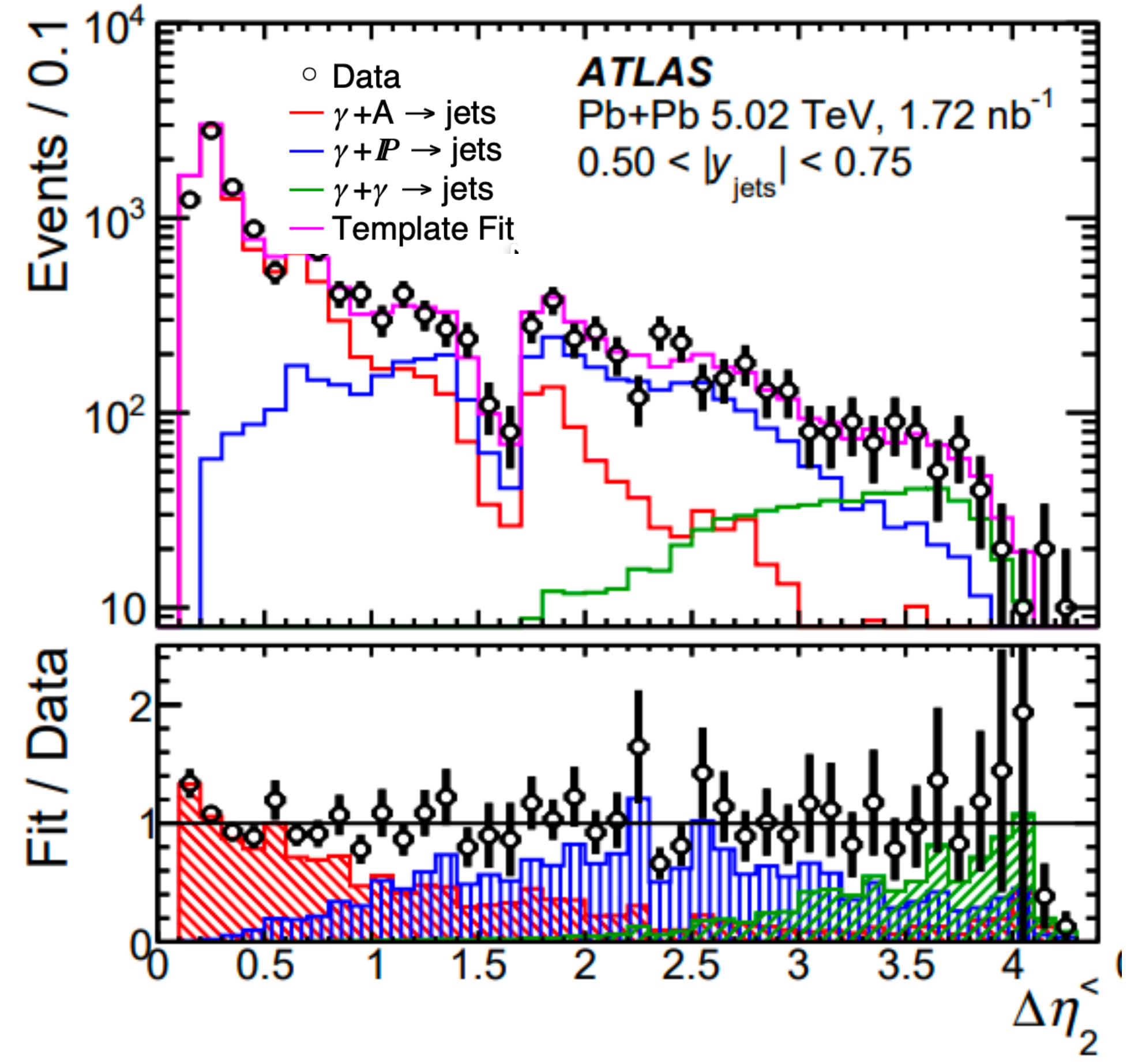
LO calculations with current nPDFs describe the main trends

# UPC jets in OnOn events



**Alvioli et al., arXiv.2402.19060**  
**Larionov et al. arXiv.812.08231**

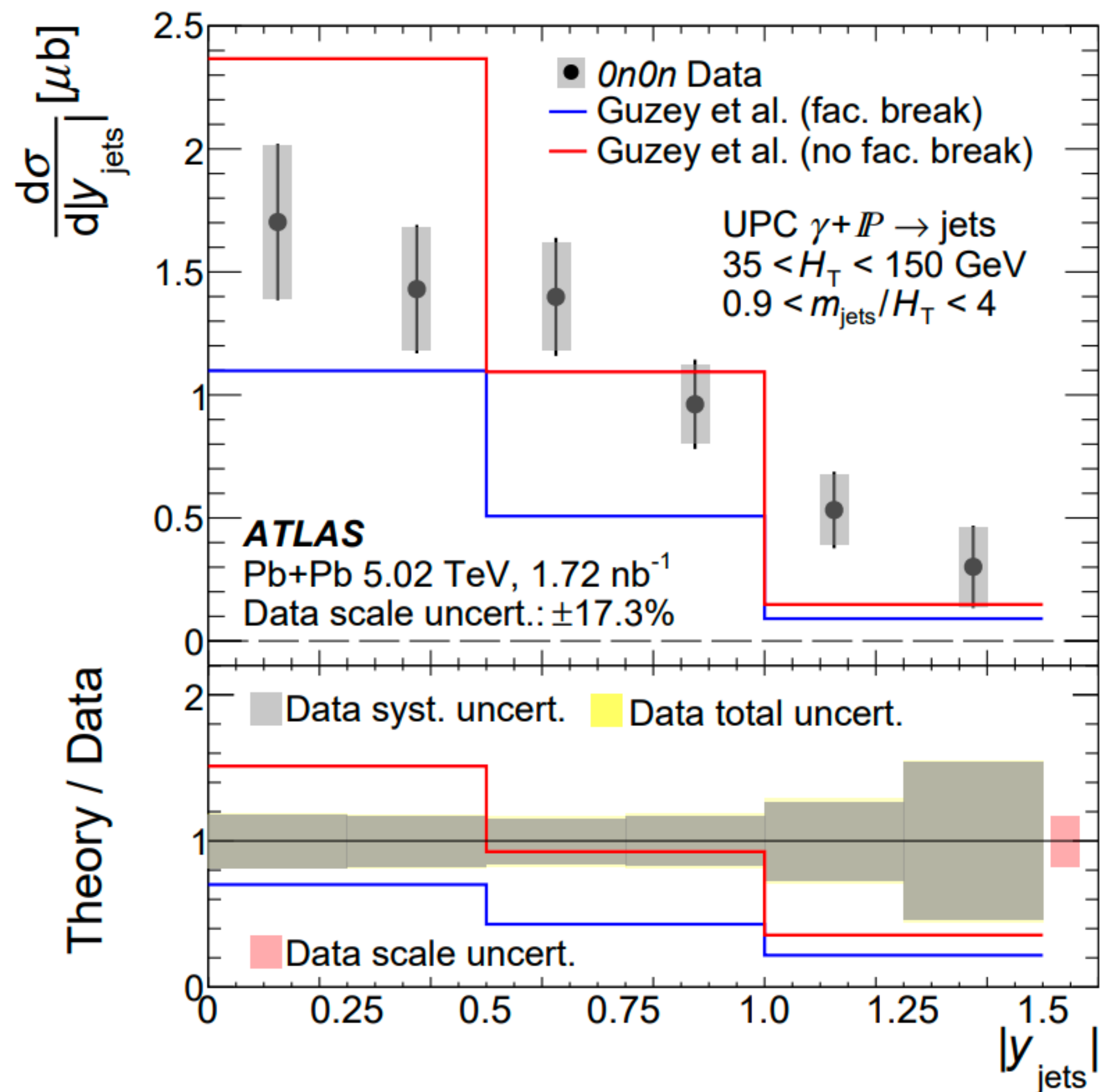
**Non-diffractive  $\gamma A$  without observed neutron emission**  
 target excitation below neutron-emission threshold  
 → **more likely to occur in “peripheral” UPCs**  
 → sensitivity to the impact-parameter dependence of nuclear PDFs



MC templates separate diffractive,  $\gamma\gamma$ , and non-diffractive  $\gamma A$  components

# Diffraction jet production in PbPb UPCs

ATLAS, arXiv:2604.24435  
 ATLAS, arXiv:2604.20559  
 M. Klasen, G. Kramer, *Eur. Phys.J. C38* (2004) 93-104  
 V. Guzey, M. Klasen, *JHEP* 04 (2016) 158



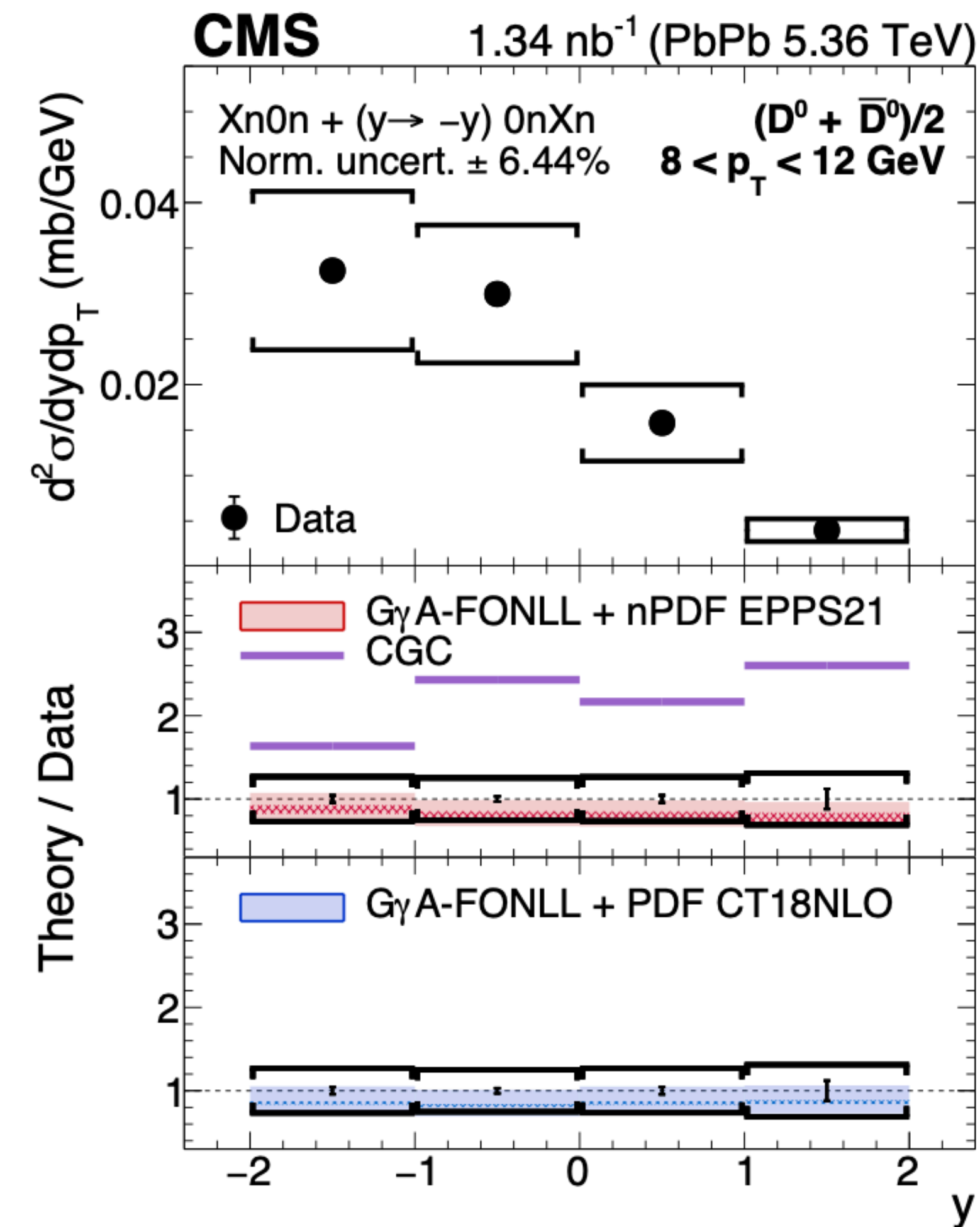
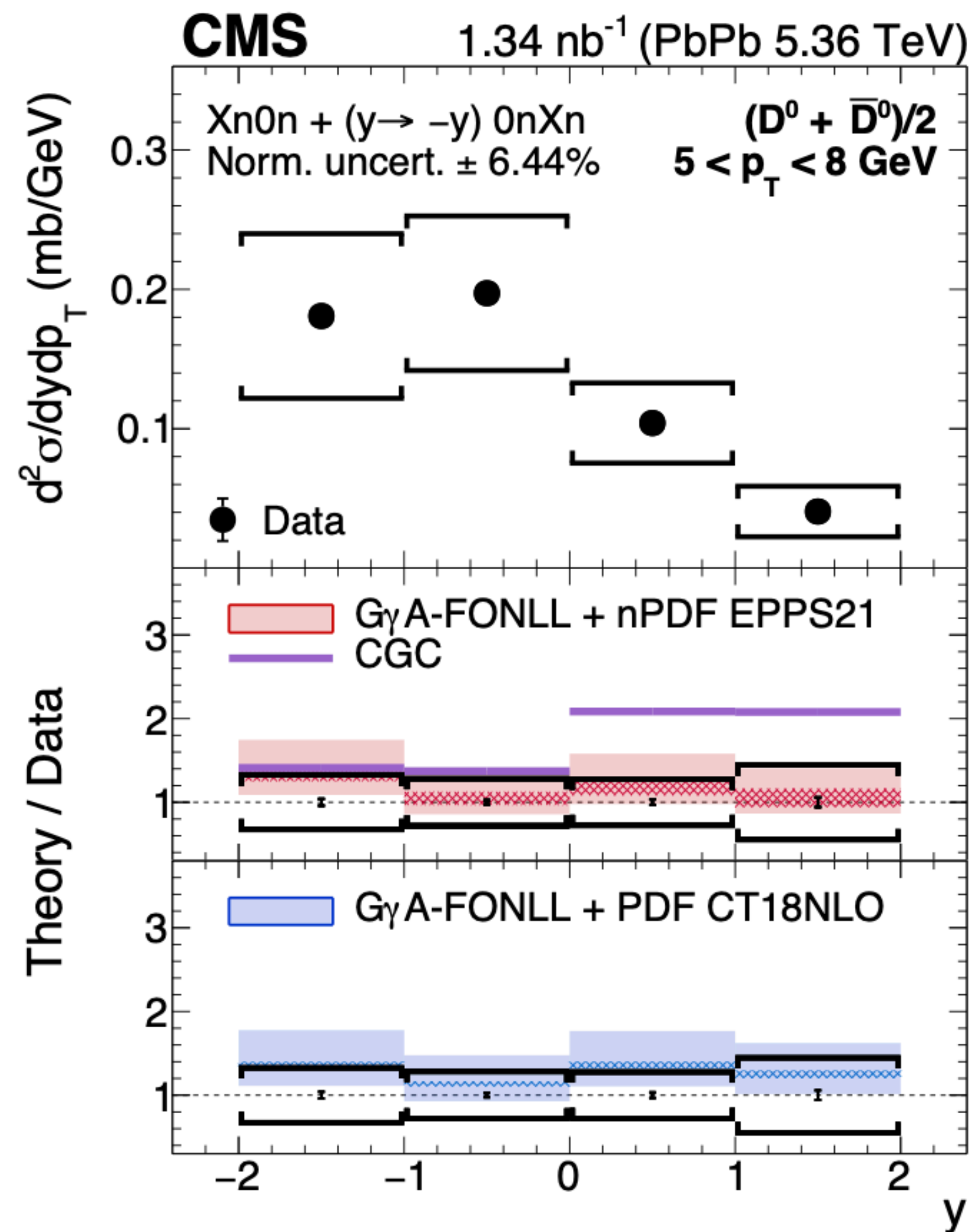
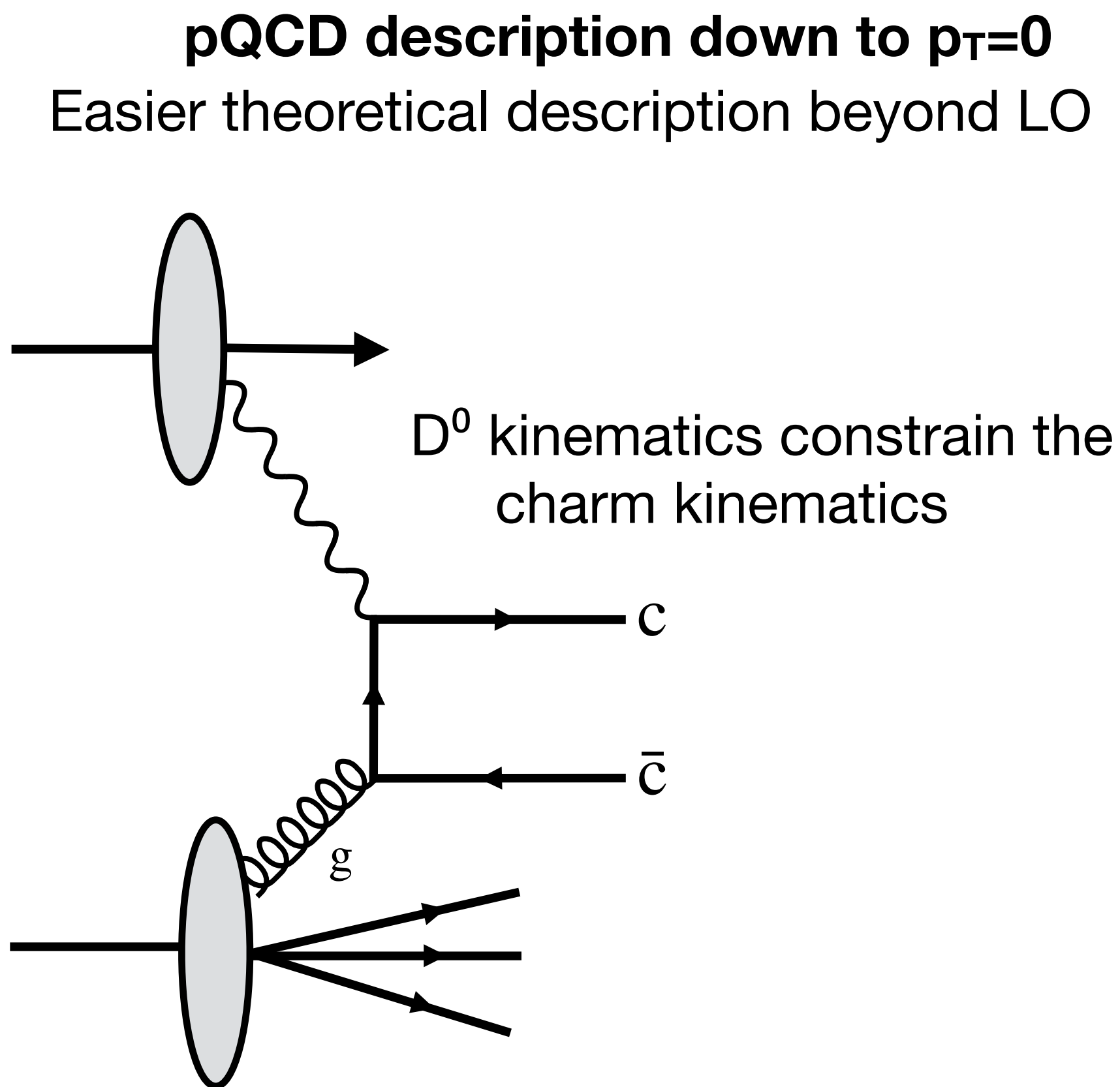
## Diffraction cross-section as a function of $|y_{\text{jets}}|$

- Compared with NLO diffractive dijet calculations under different factorization-breaking scenarios

→ **Data are qualitatively consistent with NLO predictions**

→ **Future higher-precision measurements could constrain factorization breaking in UPCs**

# D<sup>0</sup> photoproduction in PbPb Xn0n UPCs



**First open-charm UPC result, using only 2023 data for 2 < p<sub>T</sub> < 12 GeV, and |y| < 2.0**

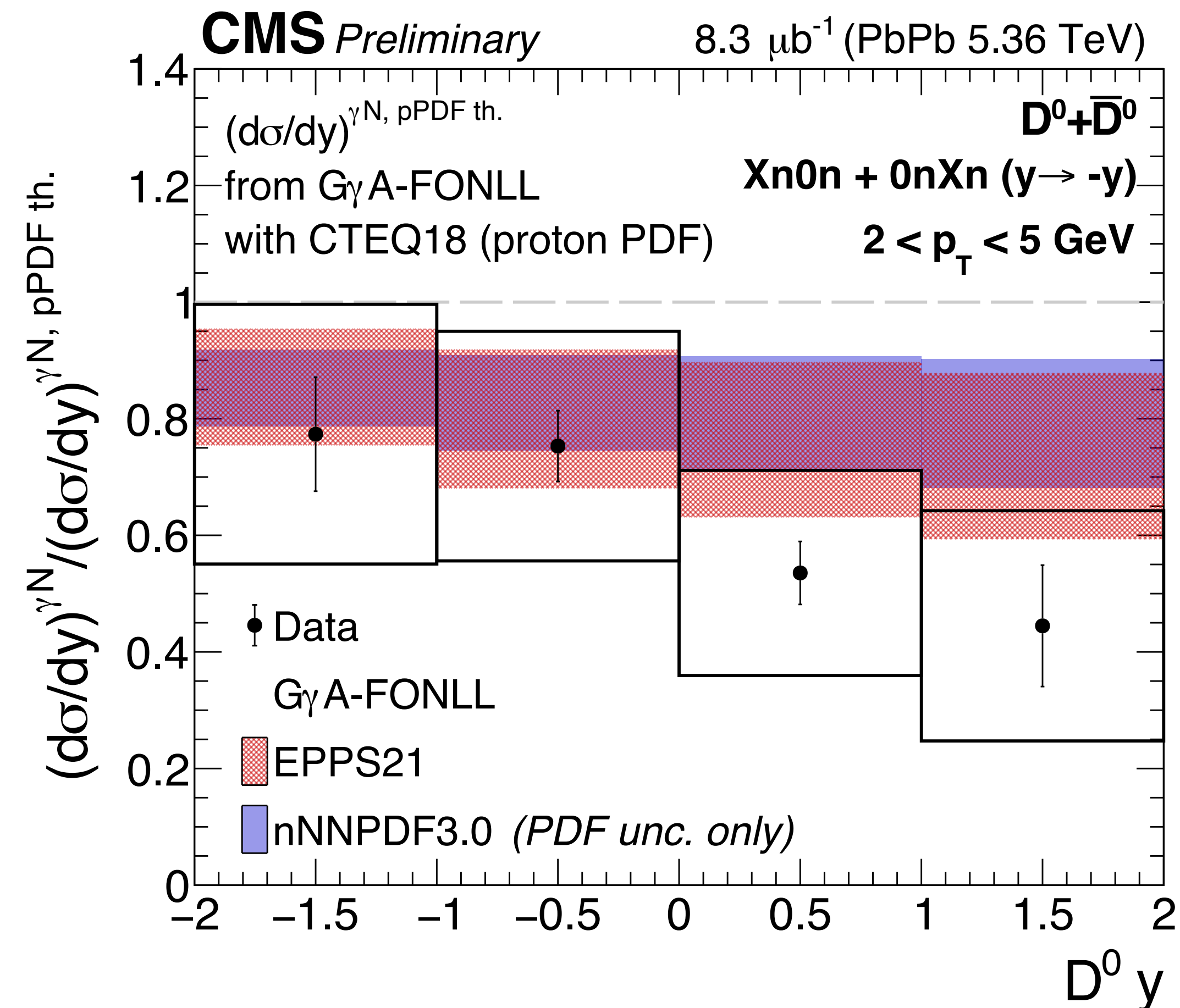
→ **G $\gamma$ A-FONLL** provides NLO+NLL pQCD predictions with state-of-the-art nPDF parametrizations

→ includes corrections to account for impact of EM dissociation of the photon-emitting nucleus

# Rapidity dependence of low- $p_T$ $D^0$ photoproduction

Ratio of the CMS UPC  $D^0$  measurement to a proton-PDF  $\gamma p$  theoretical baseline (G $\gamma$ A-FONLL)

CMS, CMS-PAS-HIN-25-002  
 M. Cacciari, GMI, A. Stasto, PRD 112, 094029  
 S. Nese (ALICE), 2509.11814



Data lie below the proton-PDF baseline, but interpretation is still limited by experimental and theoretical uncertainties

**Experimental uncertainties still sizable:**

→ 15–20× more data already recorded in 2024–2025

**Theory-based proton introduces dependence beyond nPDF:**

→ need for a high-statistics  $\gamma p$  reference from pPb

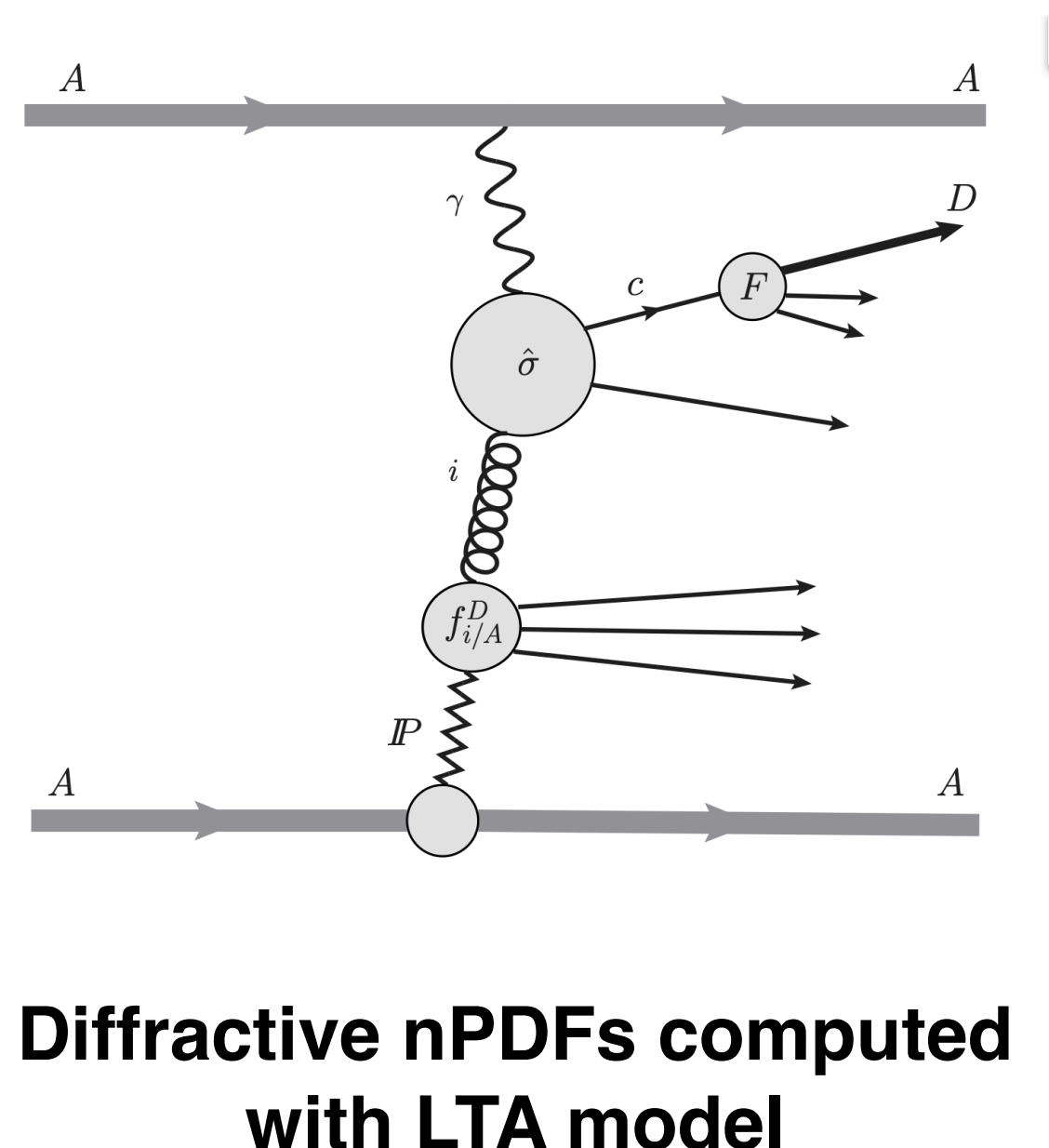
**Xn requirements select a subset of the inclusive photoproduction, while the calculation is fully inclusive**

→ magnitude of the diffractive component rejected?

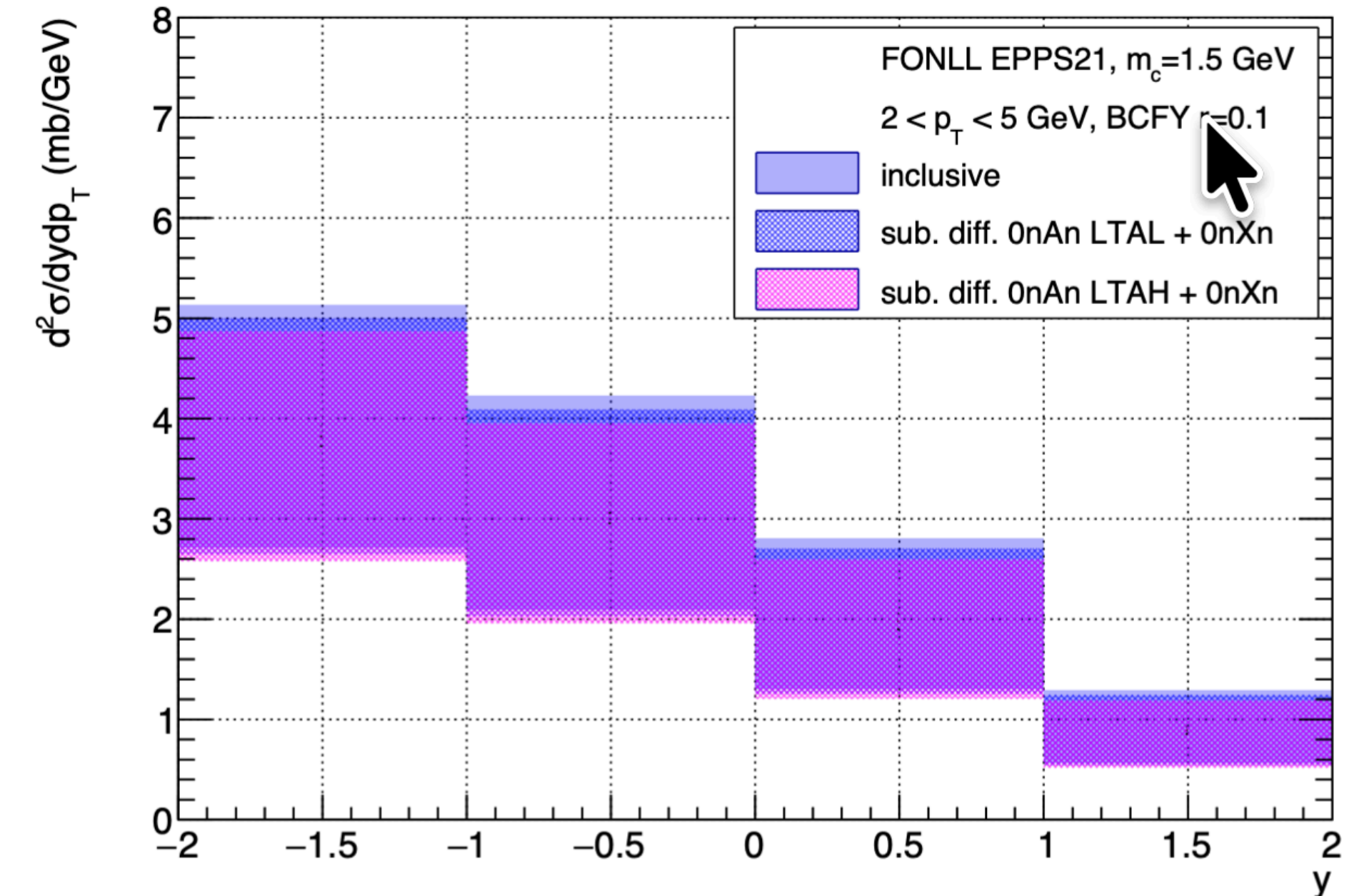
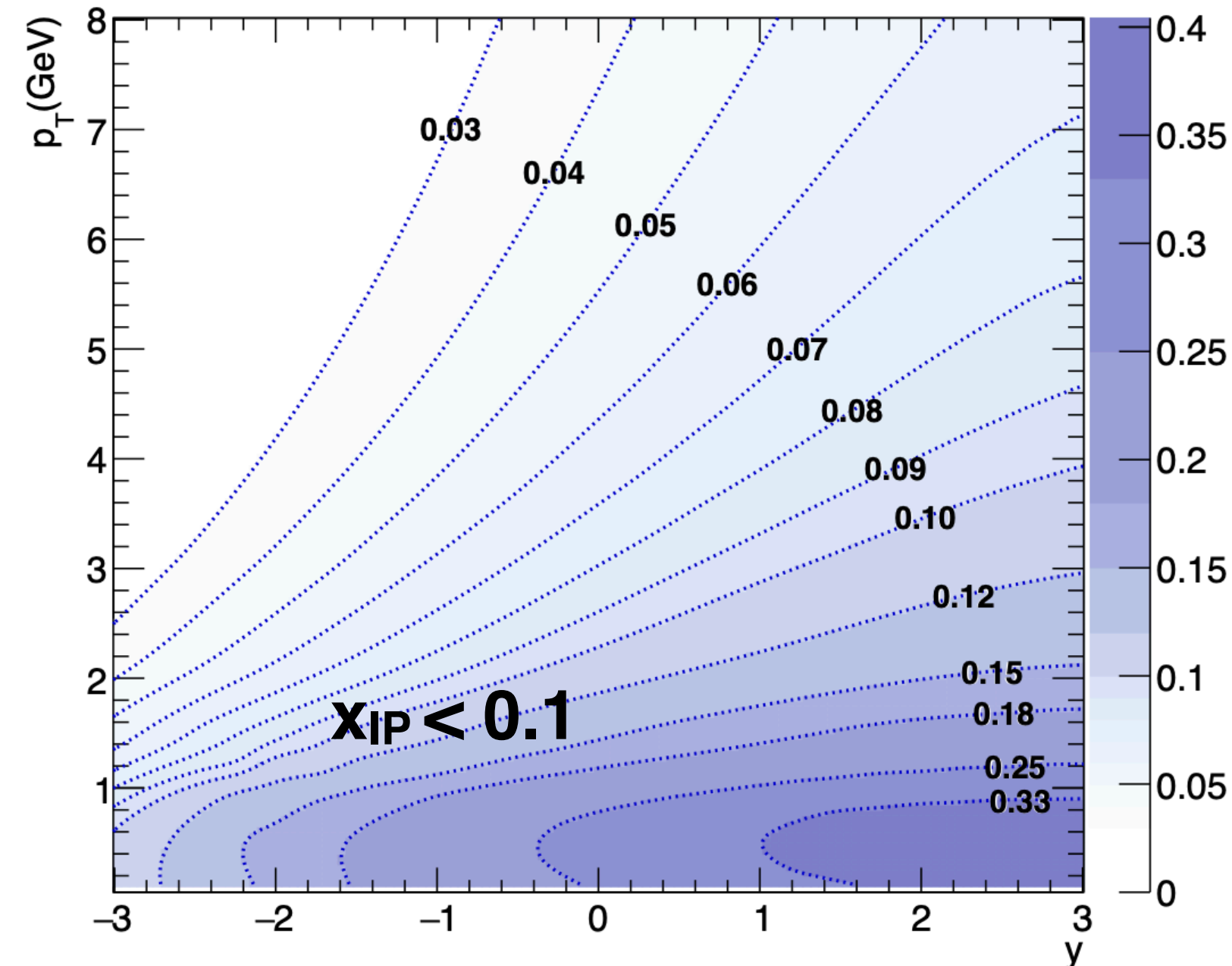
# D<sup>0</sup> diffractive production in UPCs with GyA-FONLL

M. Cacciari, A. Stasto, GMI, V. Guzey, Paper in preparation  
A. Stasto's talk in DIS2026

GyA-FONLL can now perform predictions for  $\gamma p$  and  $\gamma Pb$  coherent diffraction of open-charm and beauty measurements



Diffractive/Inclusive D<sup>0</sup> in PbPb UPCs

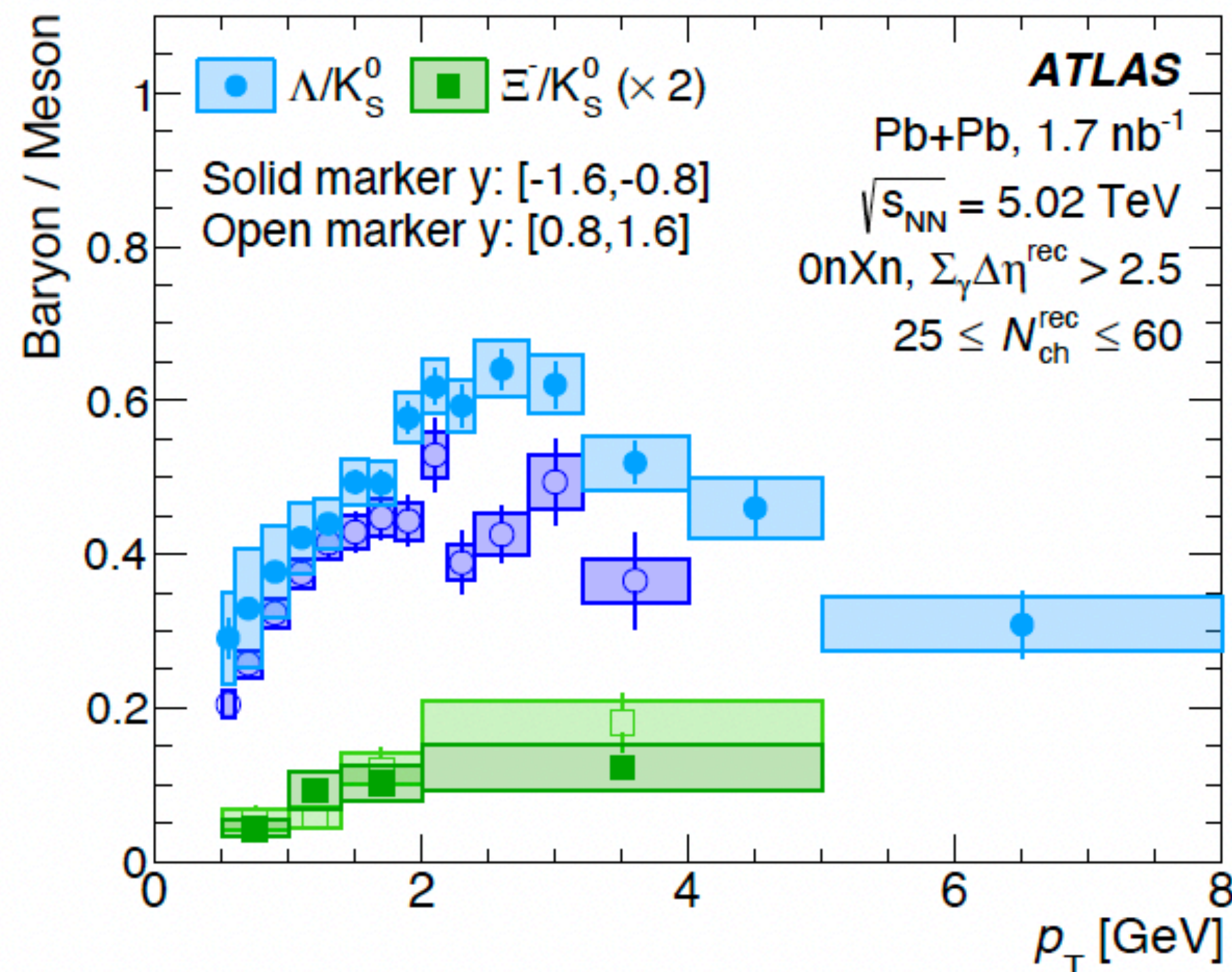


The diffractive cross section is sizable and can potentially be constrained by future measurements

The bias in the inclusive cross section induced by the Xn condition in the existing measurement is negligible

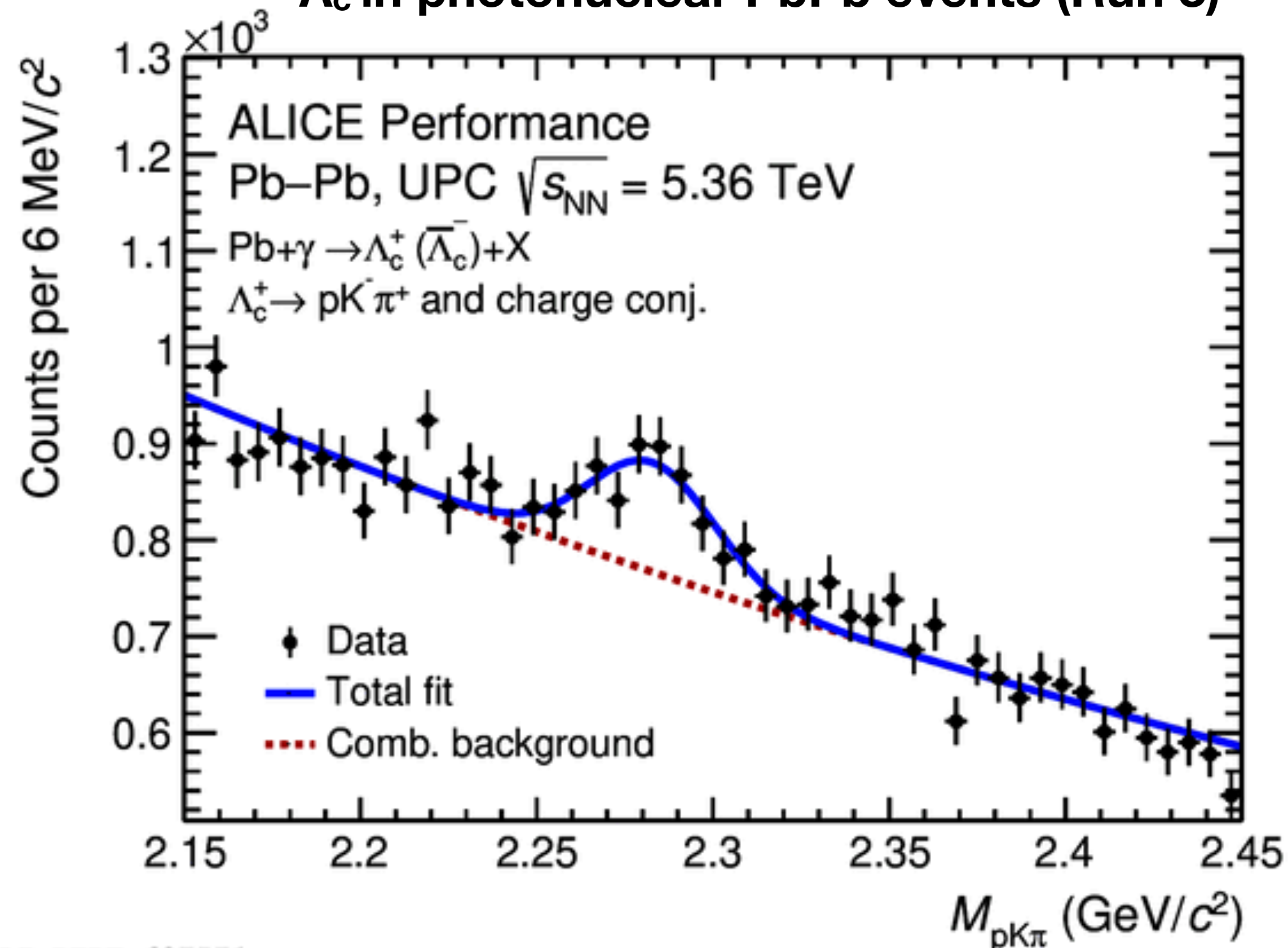
# Charm hadrochemistry in photonuclear collisions

Baryon/meson ( $\Lambda/K_S^0$ ) enhancement  
 observed in UPCs!



Enhancement quantitatively similar to  
 that observed in pPb at similar multiplicities

$\Lambda_c$  in photonuclear PbPb events (Run 3)



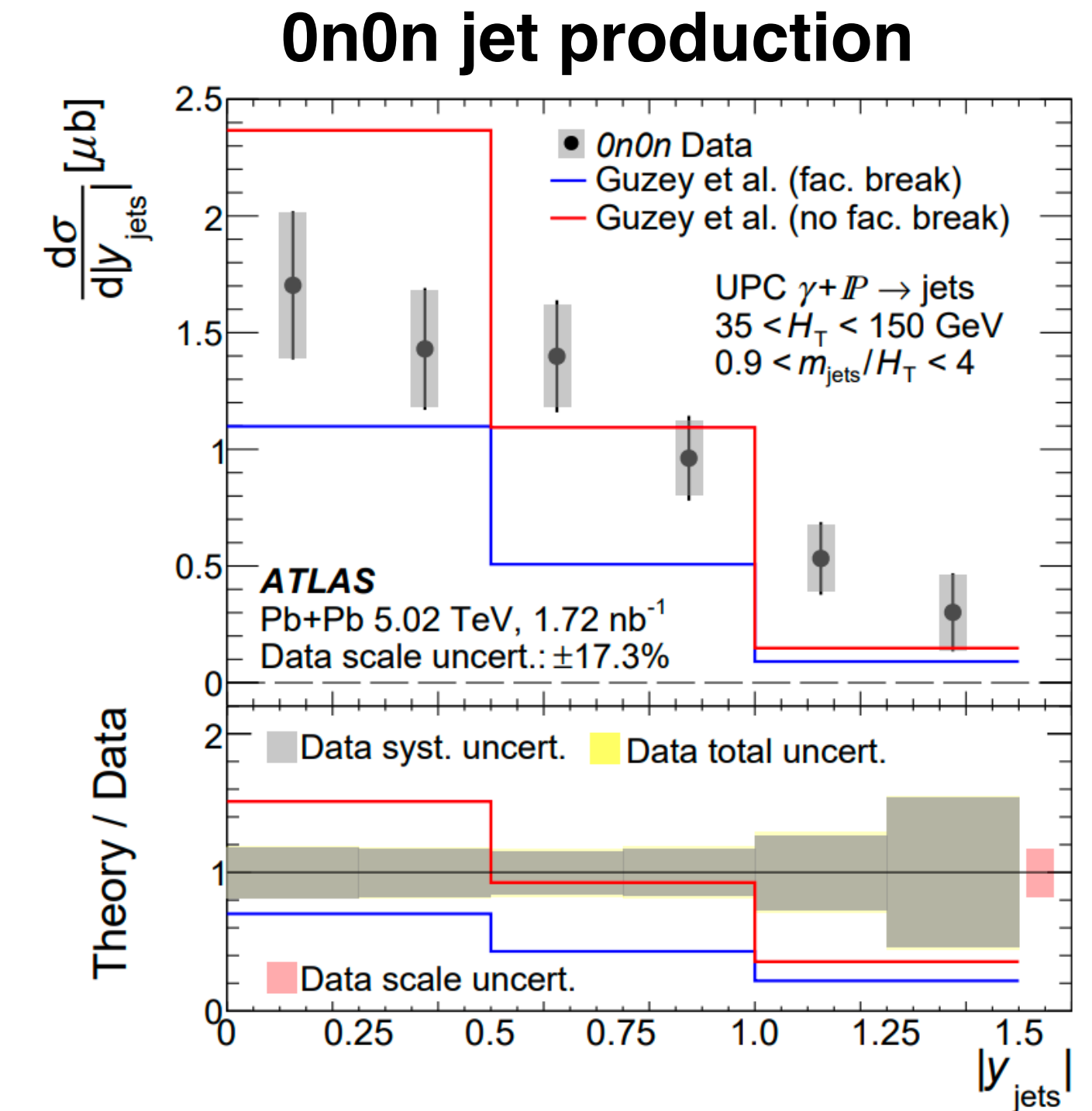
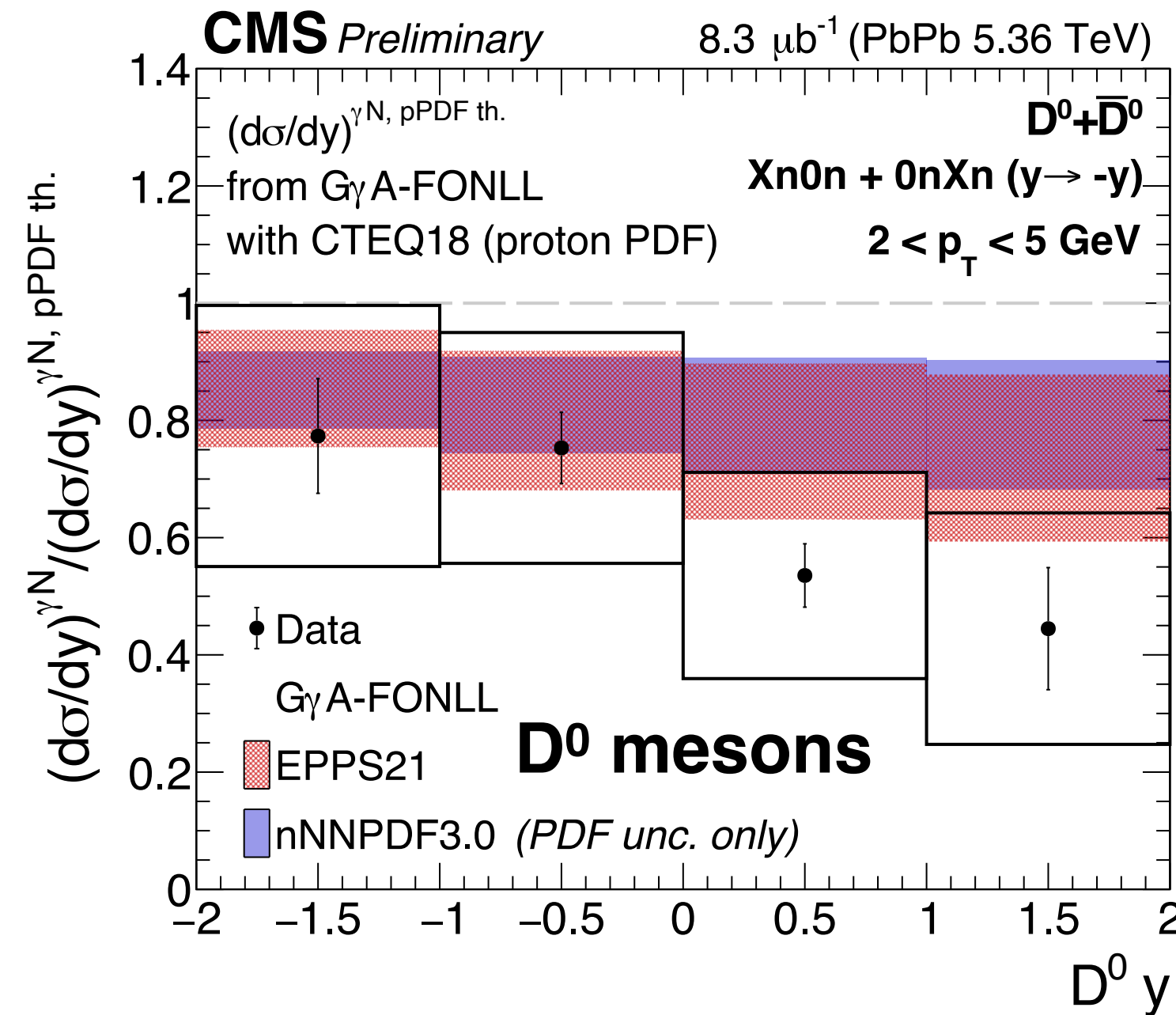
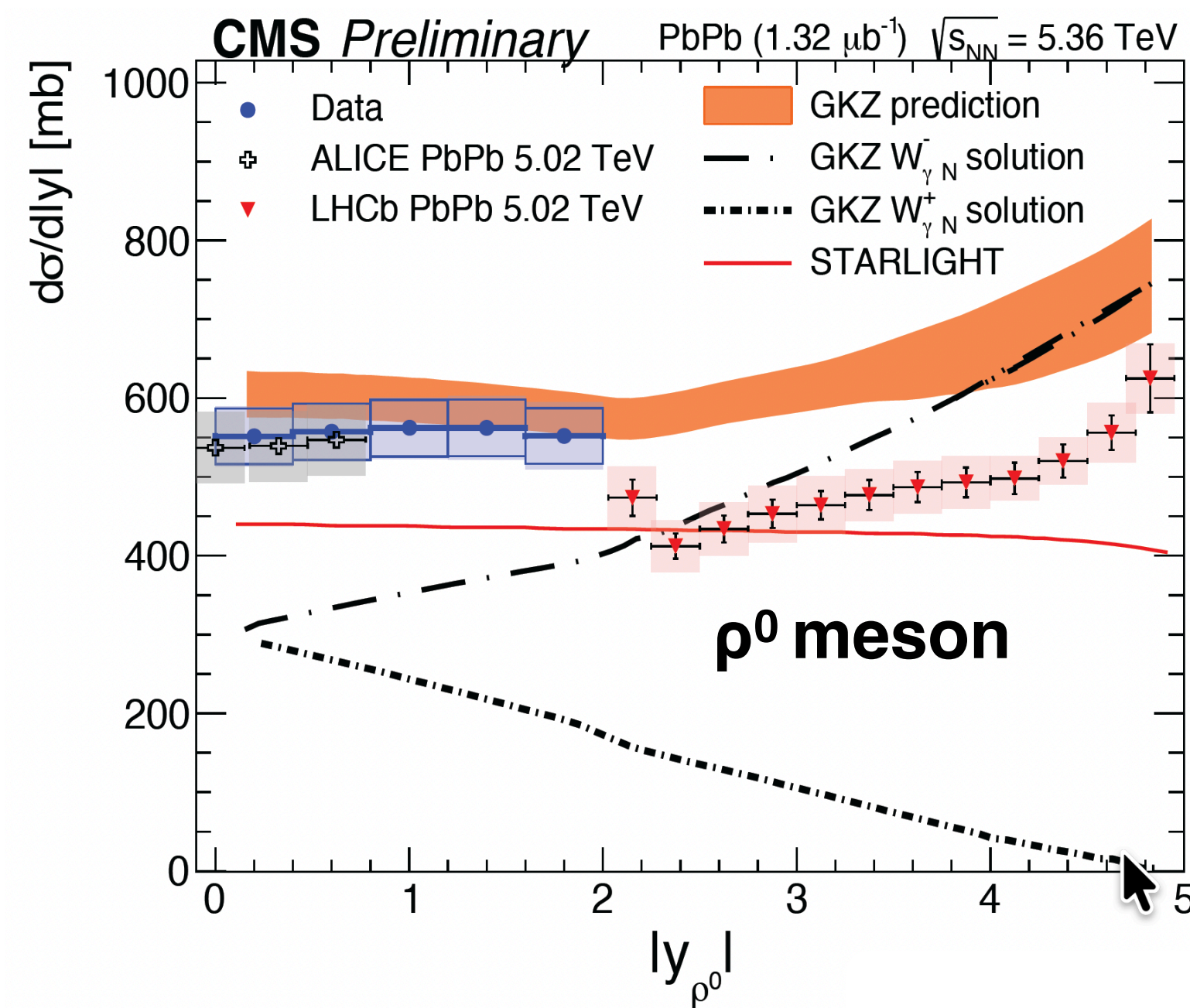
ALI-PERF-607571

**Future charm-baryon measurements can test whether fragmentation universality breaks down in  $\gamma$ Pb collisions**

# Conclusions

Fifteen years after the first measurement at RHIC, remarkable advances in both theory and experiment

→ **UPCs rapidly maturing into a precision tool for photon-induced QCD studies**



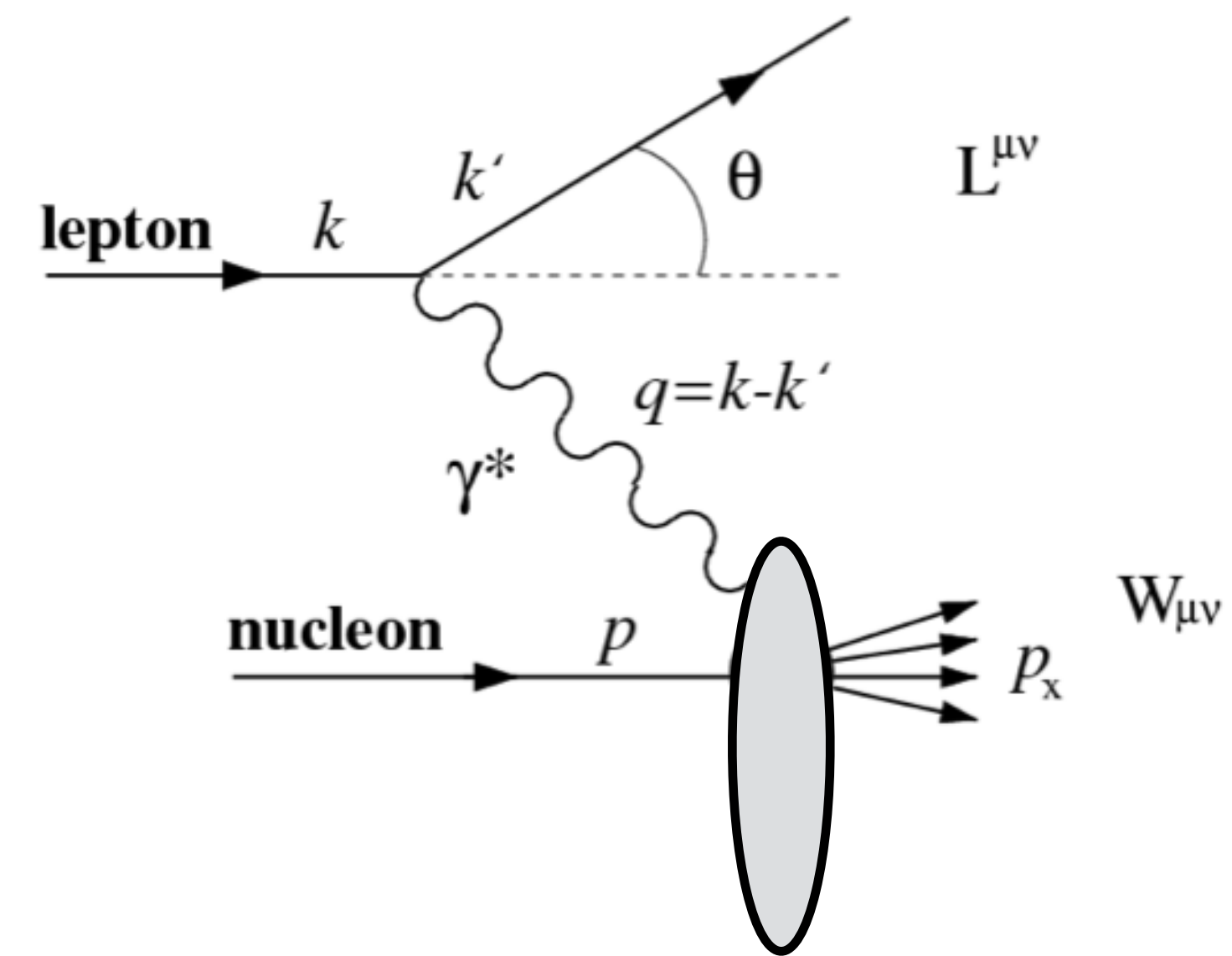
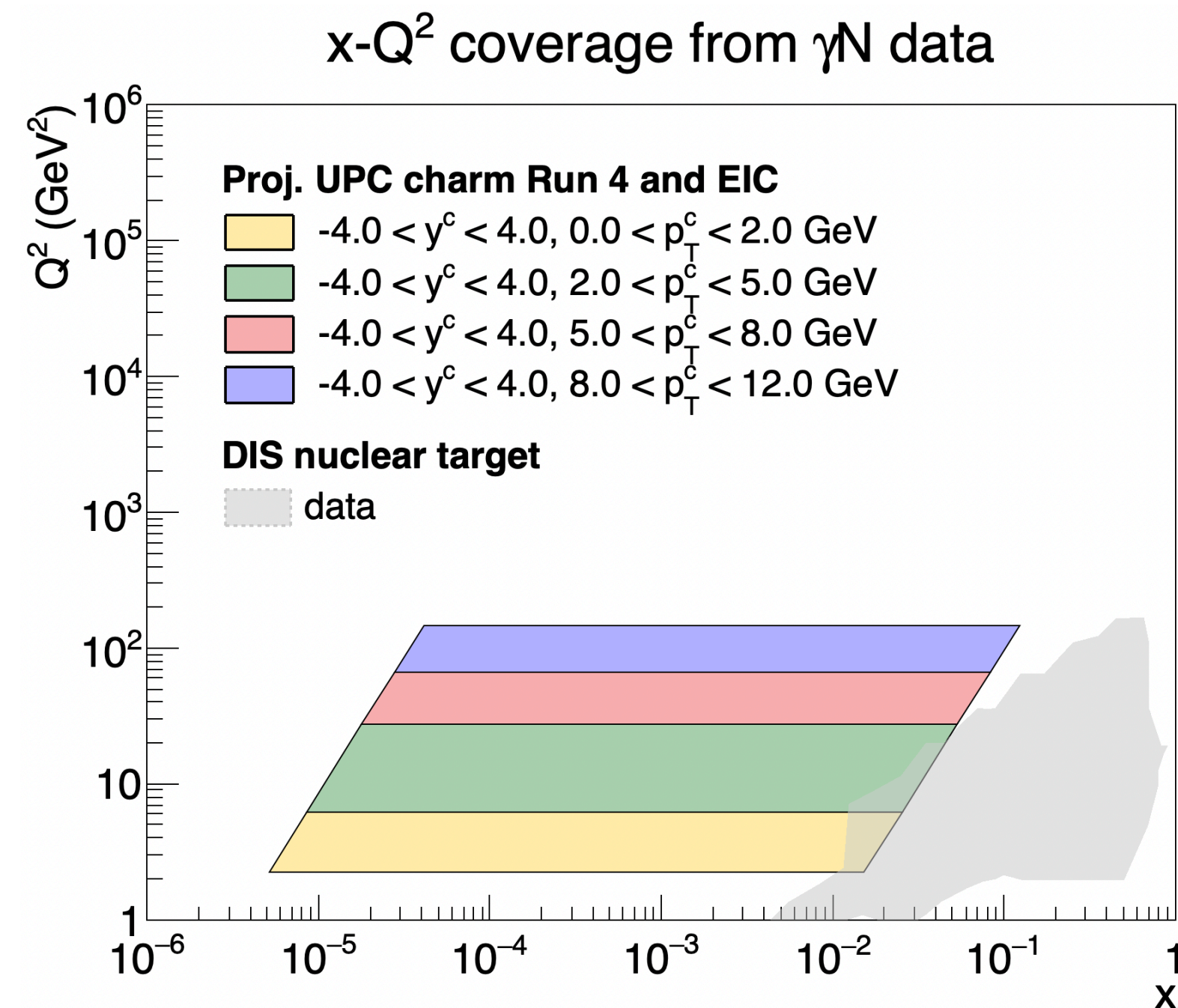
**“With great power (and small uncertainties) come great responsibility.”**

→ Precision UPC measurements now require reproducible definitions of exclusivity, neutron tagging, and photon-flux selections.

# UPCs at the LHC and electron-ion collisions at the EIC

M. Cacciari, GMI, A. Stasto,  
PRD 112, 094029

High energy reach combined with controlled kinematics → multi-scale characterization of nuclear parton dynamics



## UPCs at the LHC in Runs 4 and 5 (2032-2040)

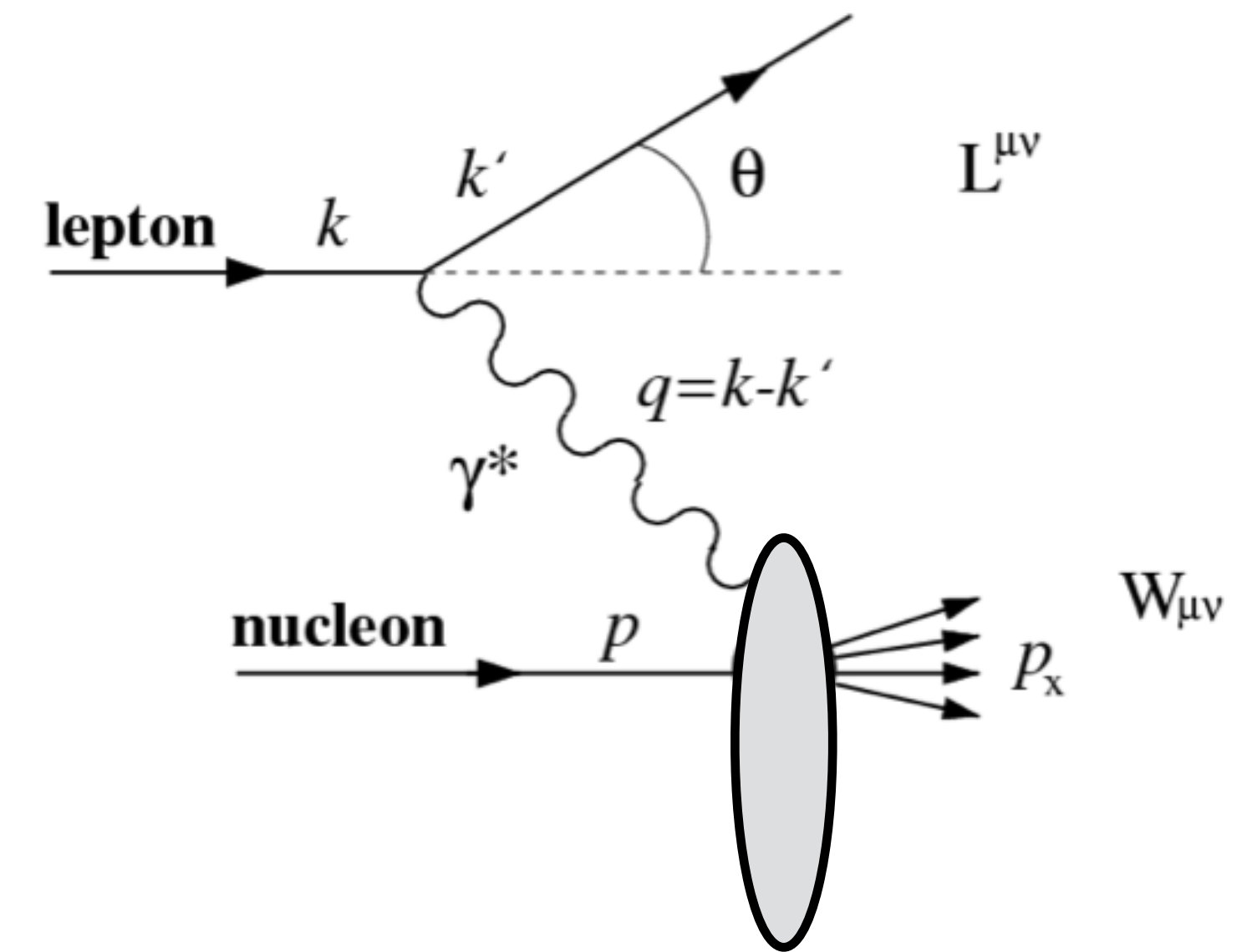
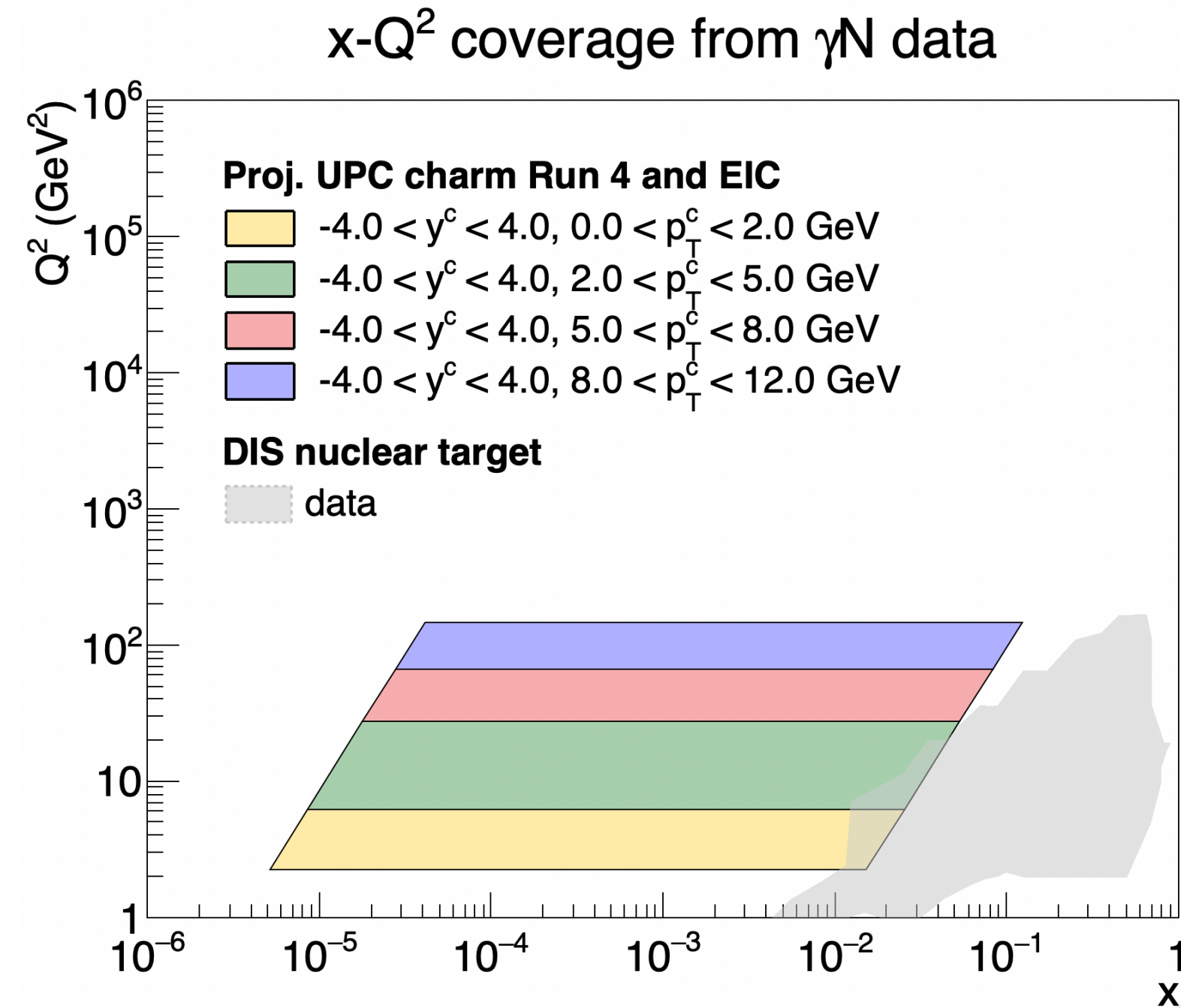
- Detector upgrades substantially expand UPC sensitivity
- Highest energies and broadest kinematic reach  
**→ for the strongest sensitivity to small-x dynamics**

## Electron-nucleus collisions at the EIC ('30s)

- Full control of the scattering kinematics
- Multidimensional, scale-dependent measurements  
**→ from longitudinal structure to 3D imaging of nuclei**

# UPCs at the LHC and electron-ion collisions at the EIC

High energy reach combined with controlled kinematics → multi-scale characterization of nuclear parton dynamics



## UPCs at the LHC in Runs 4 and 5 (2032-2040)

- Detector upgrades substantially expand UPC sensitivity
- Highest energies and broadest kinematic reach  
**for the strongest sensitivity to small-x dynamics**

## Electron-nucleus collisions at the EIC ('30s)

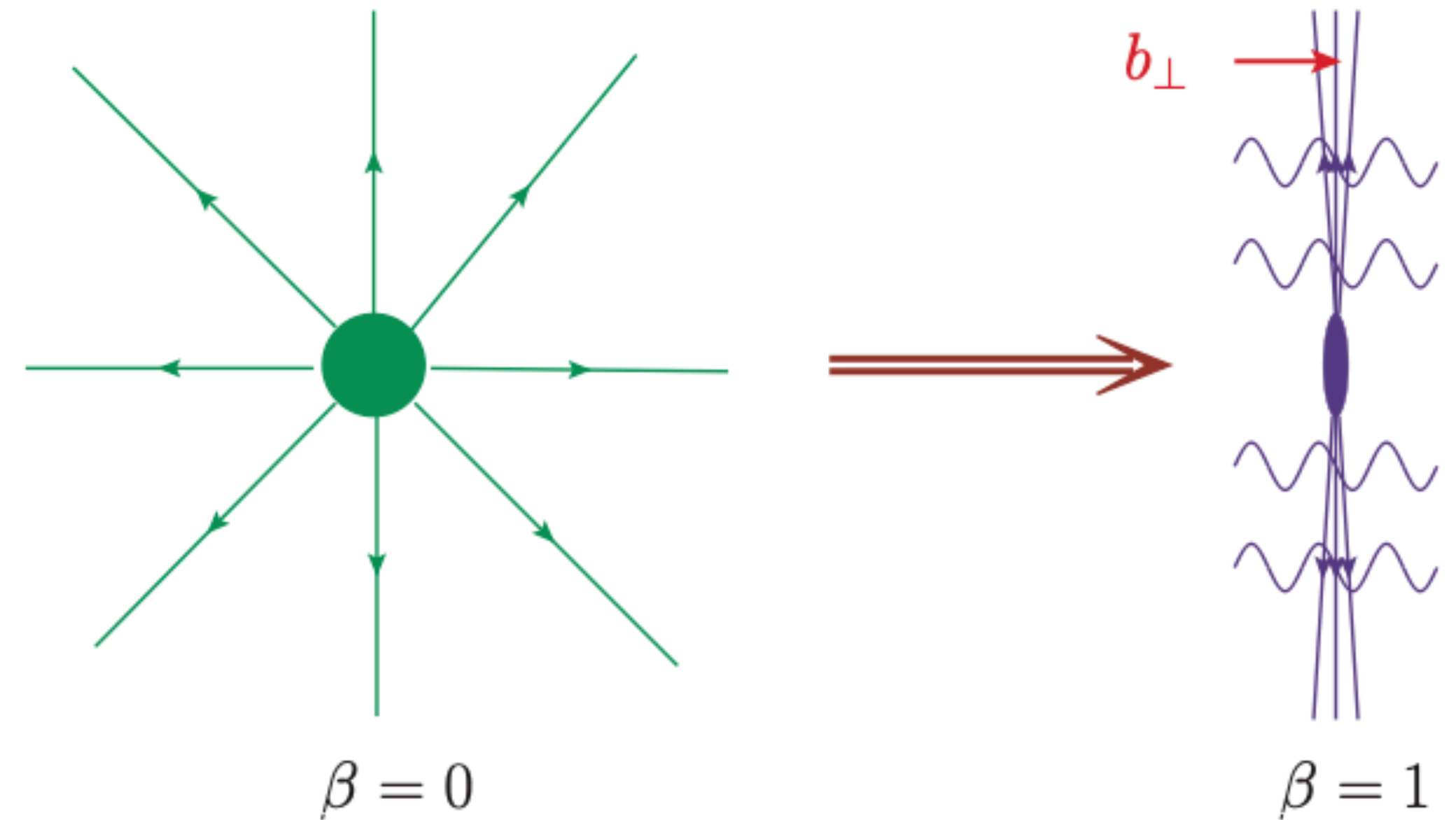
- Full control of the scattering kinematics
- Multidimensional, scale-dependent measurements  
**→ from longitudinal structure to 3D imaging of nuclei**

# Thank you for your attention

**BACKUP**

# Ultraperipheral heavy-ion collisions: the origins

**1924 (Fermi):** the electromagnetic field of a charged particle treated as an equivalent radiation spectrum



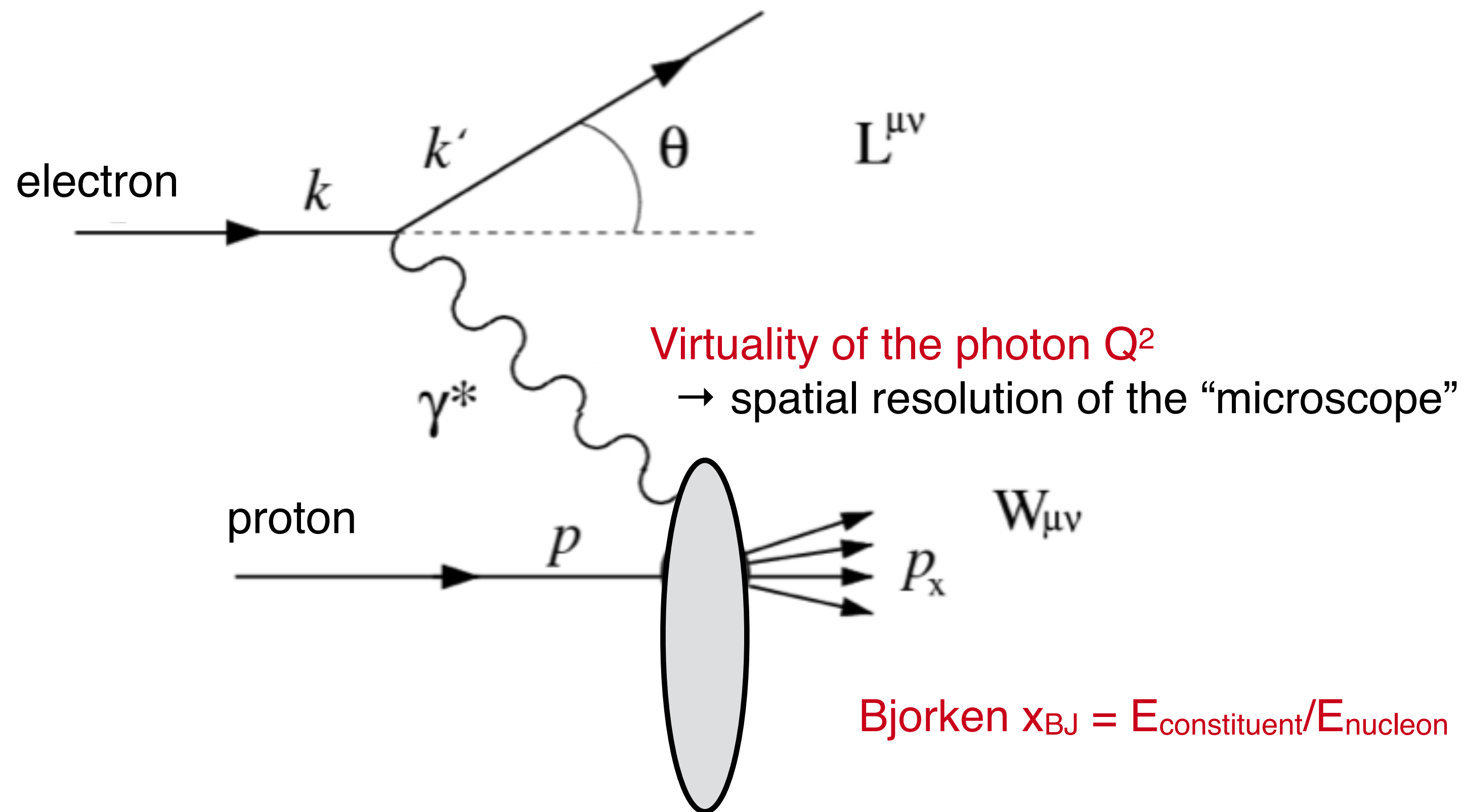
**1934 (Weizsäcker and Williams) → Equivalent Photon Approximation (EPA)**

- The field of a fast charge can be treated as a radiation field of virtual photons
- **Interactions can then be computed with standard photon-scattering methods**

**Starting in the 1970s, extending the EPA to heavy-ion ultraperipheral collisions**

# Electron-proton/ion collisions as the traditional tool

Lepton scatterings provide the cleanest access to the complex hadronic structure of protons and nuclei

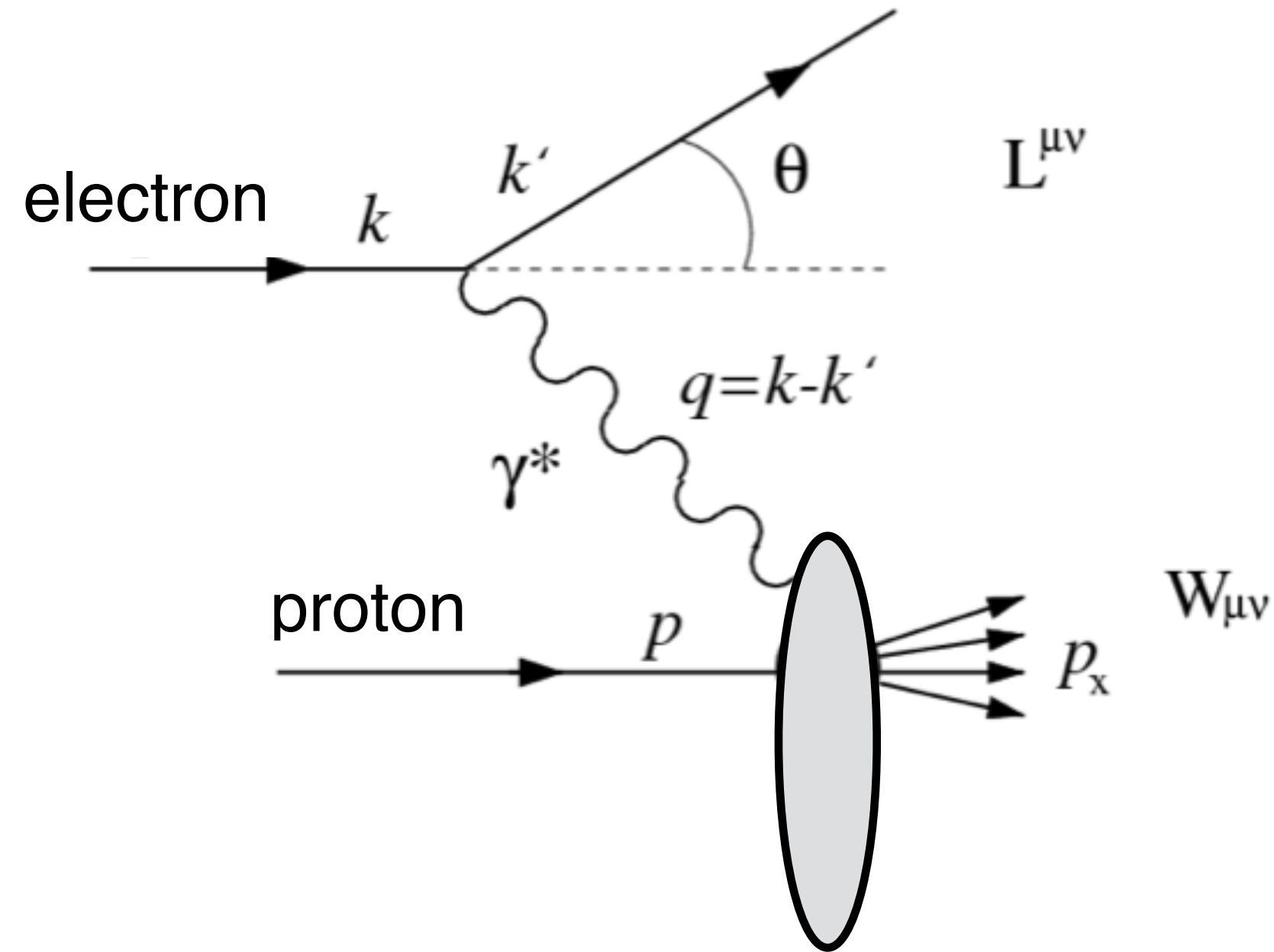


Properties of quarks and gluons parametrized by **Parton Distribution Functions for protons and nuclei**

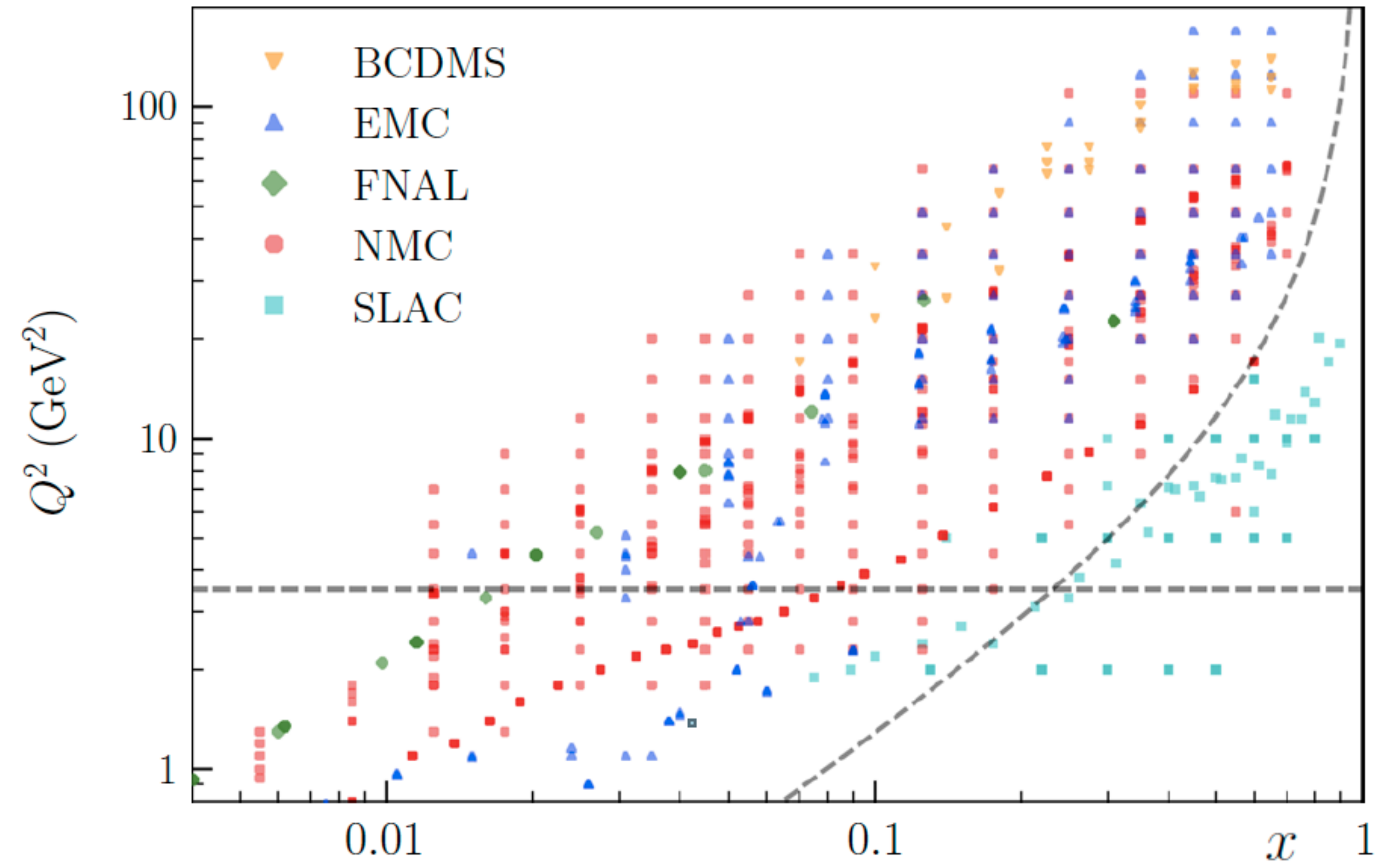
probability densities of the proton constituents (quarks and gluons) as a function of  $x, Q^2$

→ **constrained by measurements (due to their non-perturbative nature)**

# Existing data from lepton-nucleus fixed-target experiments



NNPDF Collaboration, *Eur. Phys. J. C* (2019) 79:471

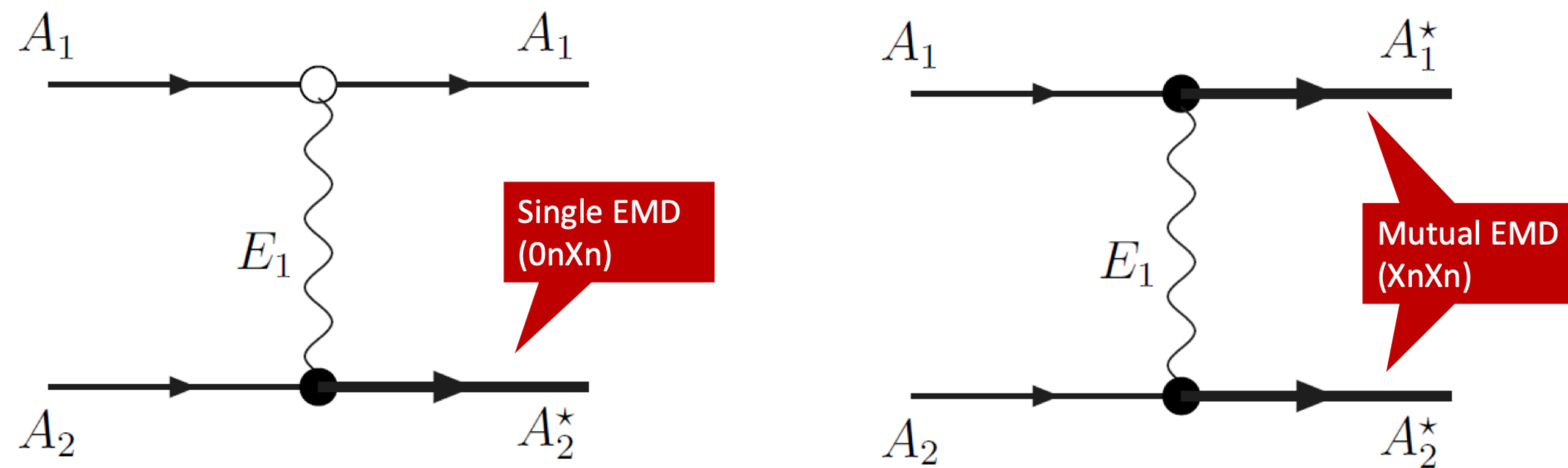


- **no access to the high-density low- $x$  region**
- low  $Q^2$  but coverage **limited to  $x > 0.005$**

**BACKUP: constraining the key ingredients  
of UPC phenomenology**

# Constraining electromagnetic dissociation in PbPb

With the first PbPb runs of the LHC, ALICE performed a quantitative measurement of the probability of single and mutual dissociation in events where no activity was measured at central rapidity

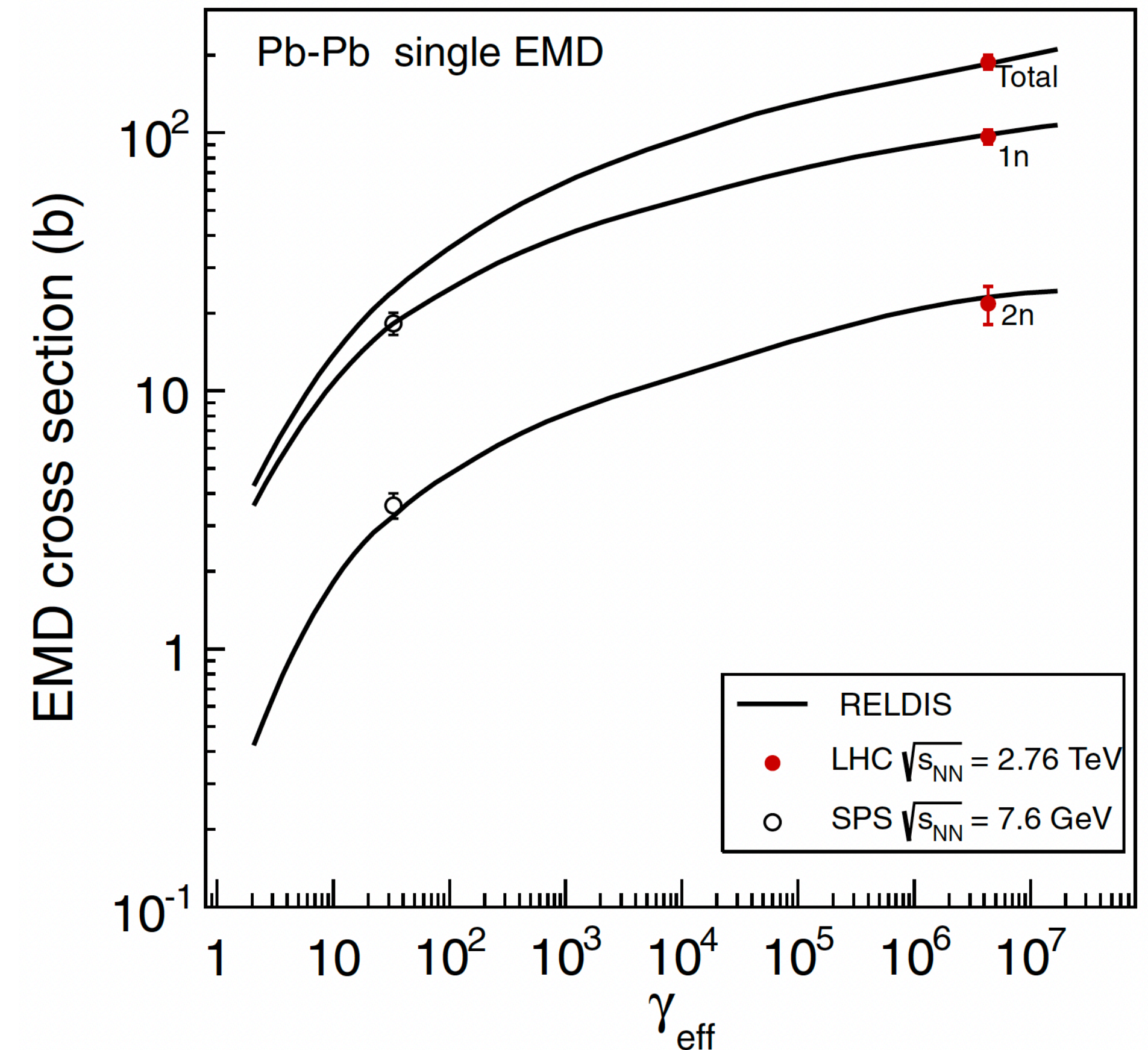


**Single EMD:** only one of the two excited nuclei emits a neutron

**Mutual EMD:** both nuclei undergoing the collisions emit at least one neutron

**Phenomenological models (e.g., RELIS) combining:**

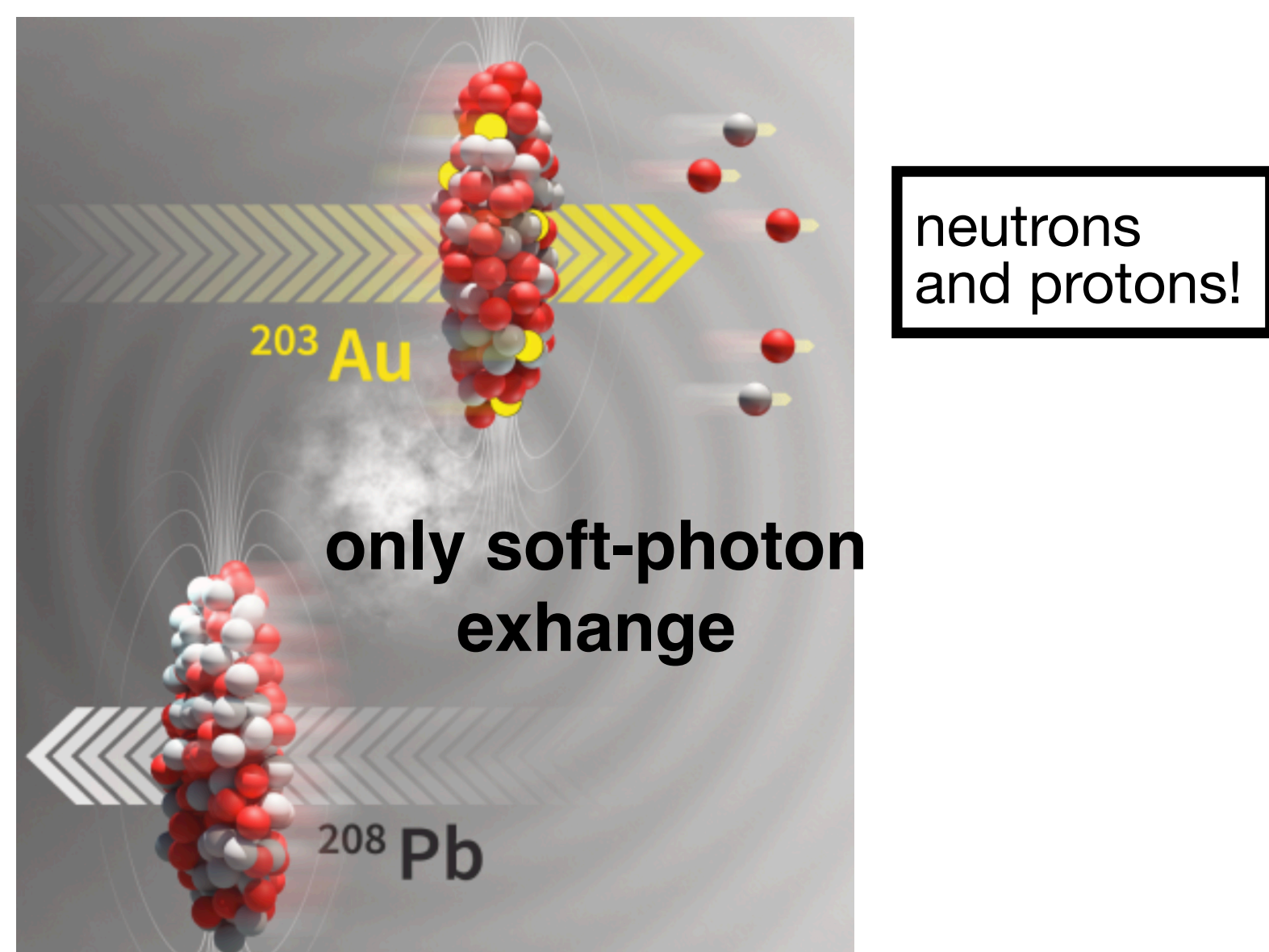
- an EPA photon flux
- photonuclear absorption probabilities
- decay model for the excited residual nucleus



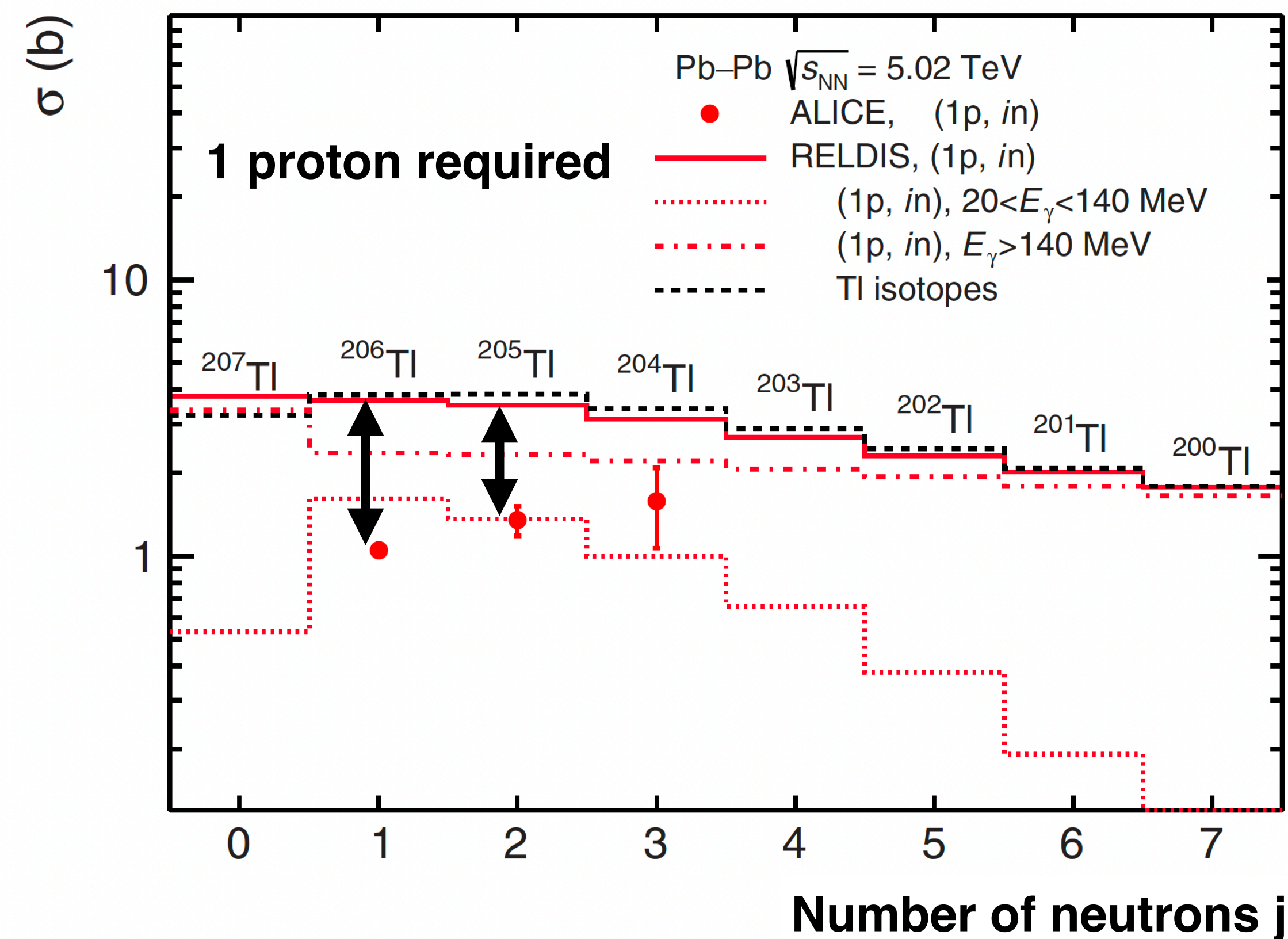
# Forward proton production in EMD

→ access to the details of nuclear excitation and decay

*CERN news: ALICE detects the conversion of lead into gold at the LHC*



By counting both neutrons and protons, we can constrain the excited nuclear species



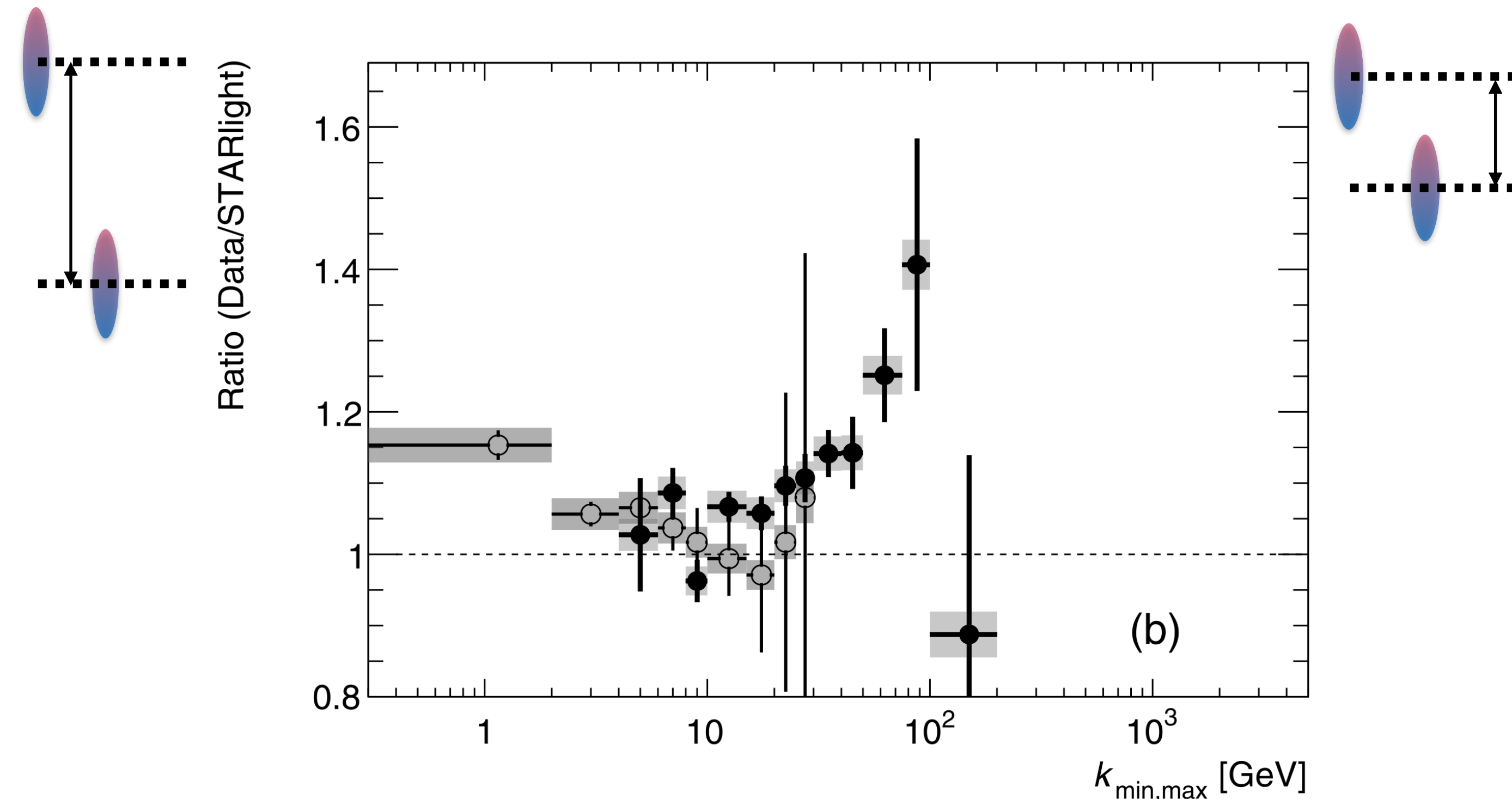
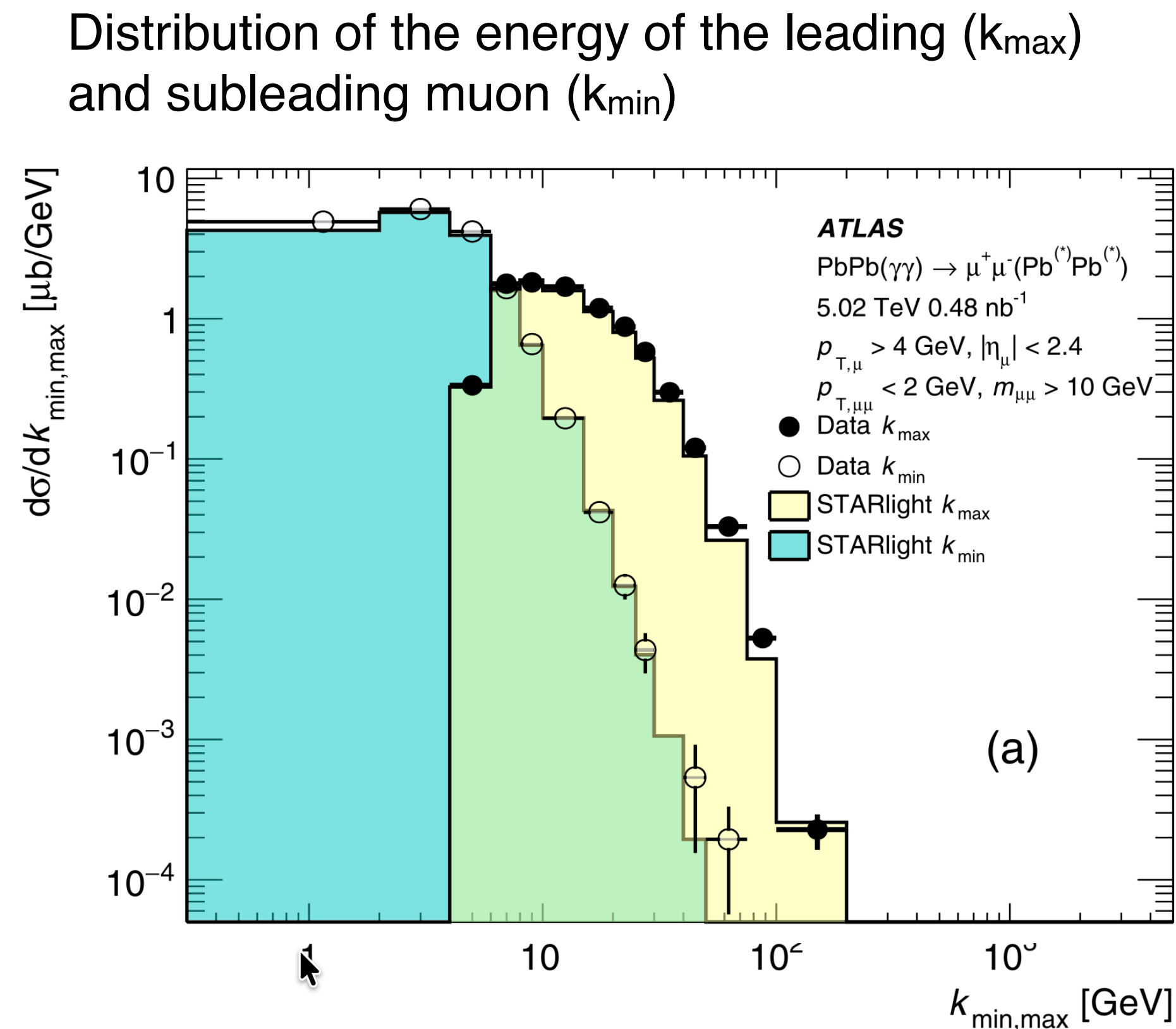
**Associated neutron-proton production shows some disagreement with simulations**

→ not yet a limiting factor for most current UPC analyses (relying on neutron counting)

→ **opportunity for interesting nuclear physics studies**

# Constraining photon-flux properties with UPC $\gamma\gamma \rightarrow \mu^+\mu^-$

QED photon-photon fusion  $\gamma\gamma \rightarrow \mu^+\mu^-$  is a clean standard candle for the UPC photon flux



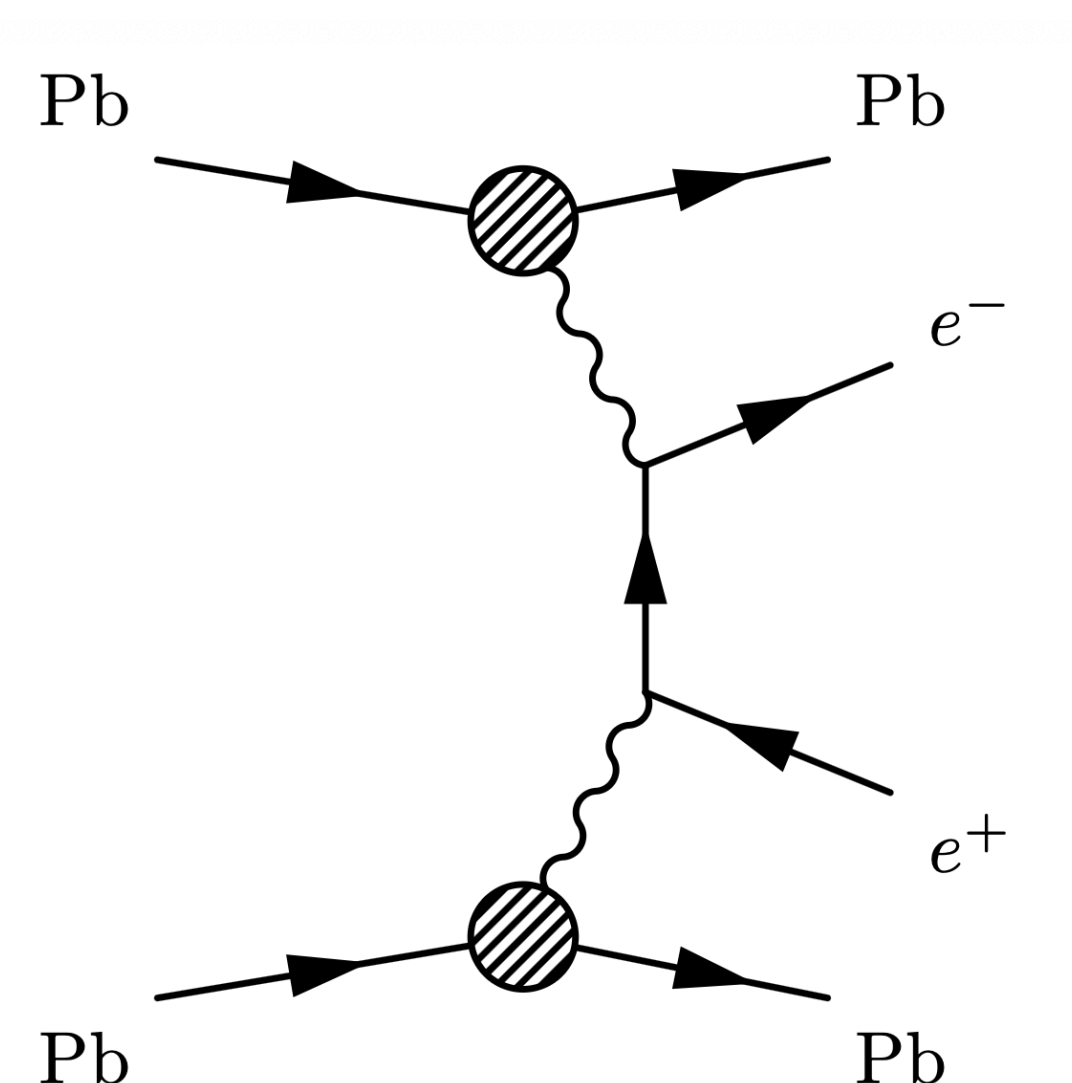
Good agreement between data and calculations (STARLight and SuperChic) in the low-moderate photon-energy regime

Stronger disagreement for very high photon energies (*smaller impact parameter*)

# Constraining photon-flux properties with UPC $\gamma\gamma \rightarrow e^+e^-$

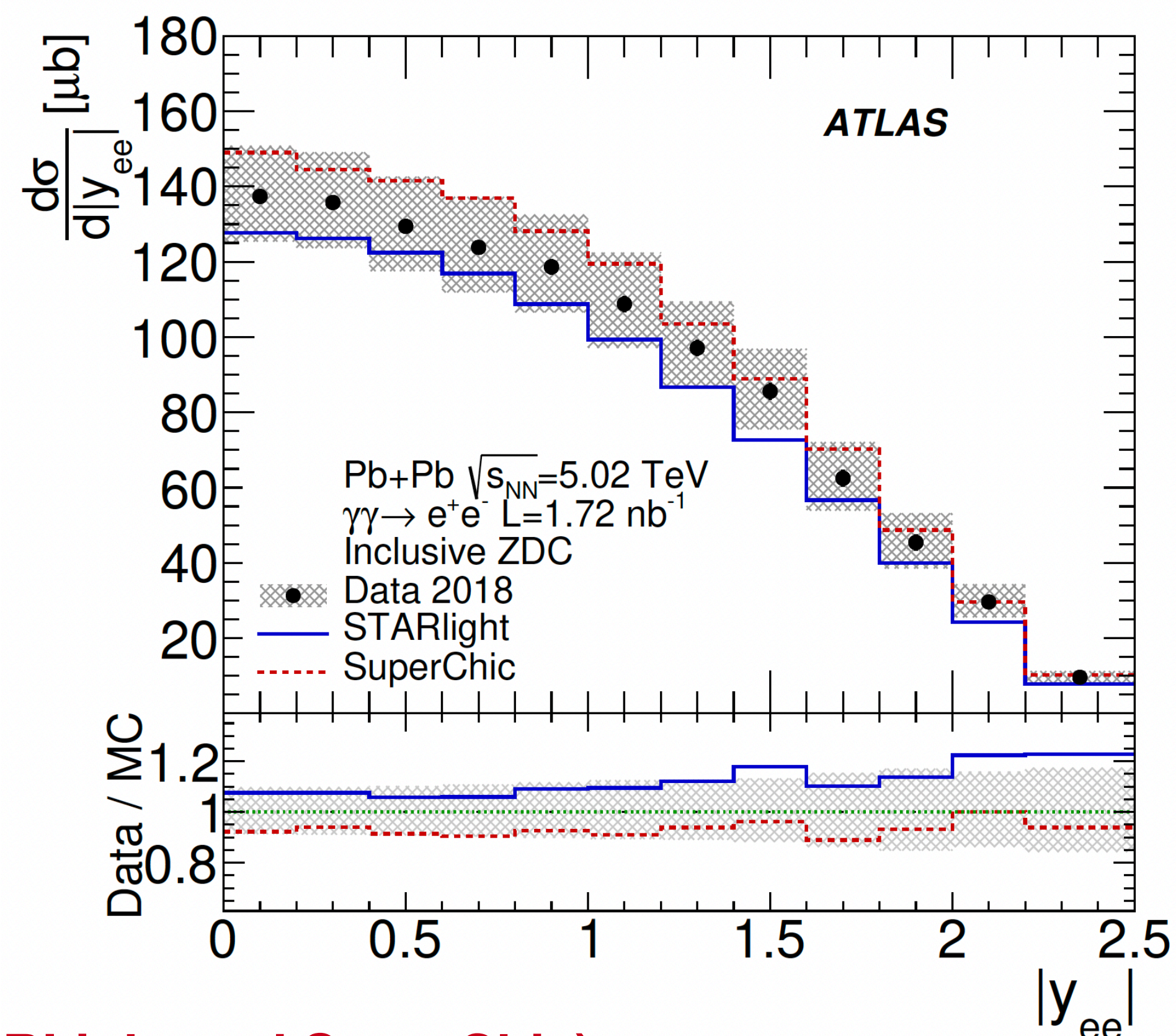
**QED photon-photon fusion  $\gamma\gamma \rightarrow e^+e^-$  is a clean standard candle for the UPC photon flux**

→ The  $y$ -dependence tests the photon-energy dependence, while the total rate fixes the overall normalization



**Only two tracks (+/-)**

- $p_T > 2.5$  GeV,
- $|\eta_{el}| < 2.5$ ,
- $m_{ee} > 5$  GeV
- $p_{T,ee} < 2$  GeV

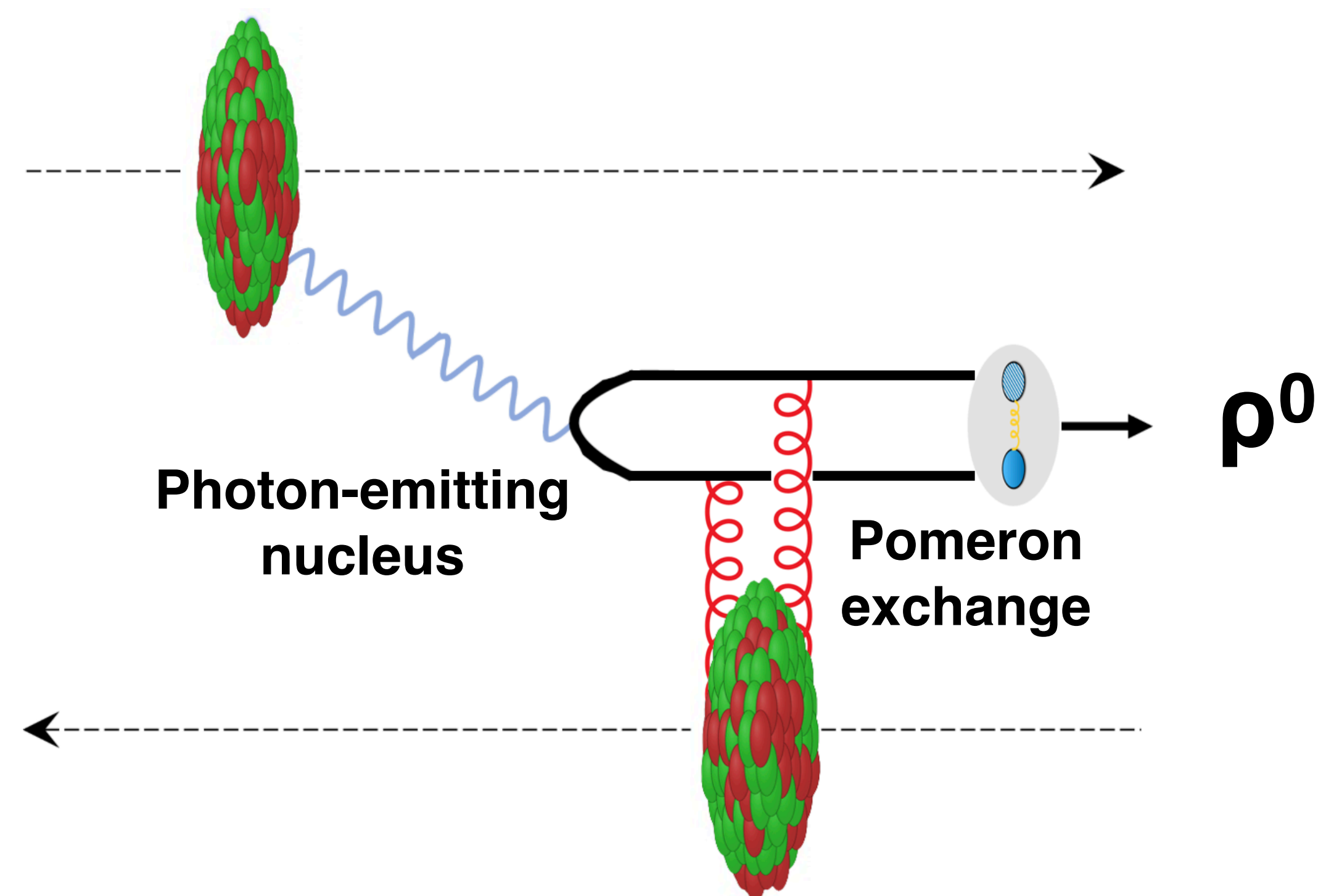


**Good agreement between data and calculations (STARLight and SuperChic)**

→ The  $y$ -dependence tests the photon-energy dependence, while the total rate fixes the overall normalization

**BACKUP: exclusive VM production**

# First UPC signal: coherent $\rho^0$ production at RHIC



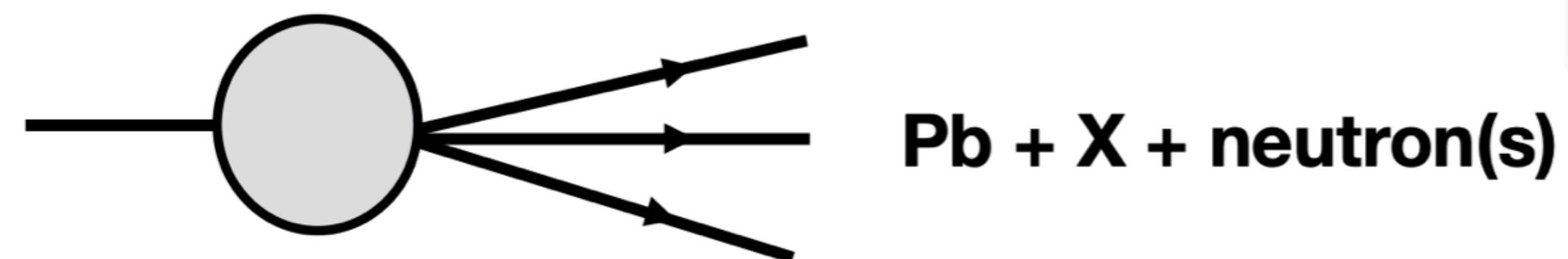
**Dipole interacting "coherently"**  
with the target nucleus

## Exclusive reconstruction

- Only two opposite-sign tracks in the entire event ( $\rho^0 \rightarrow \pi^+ \pi^-$ )

## Zero-Degree Calorimeters used to select genuine UPCs

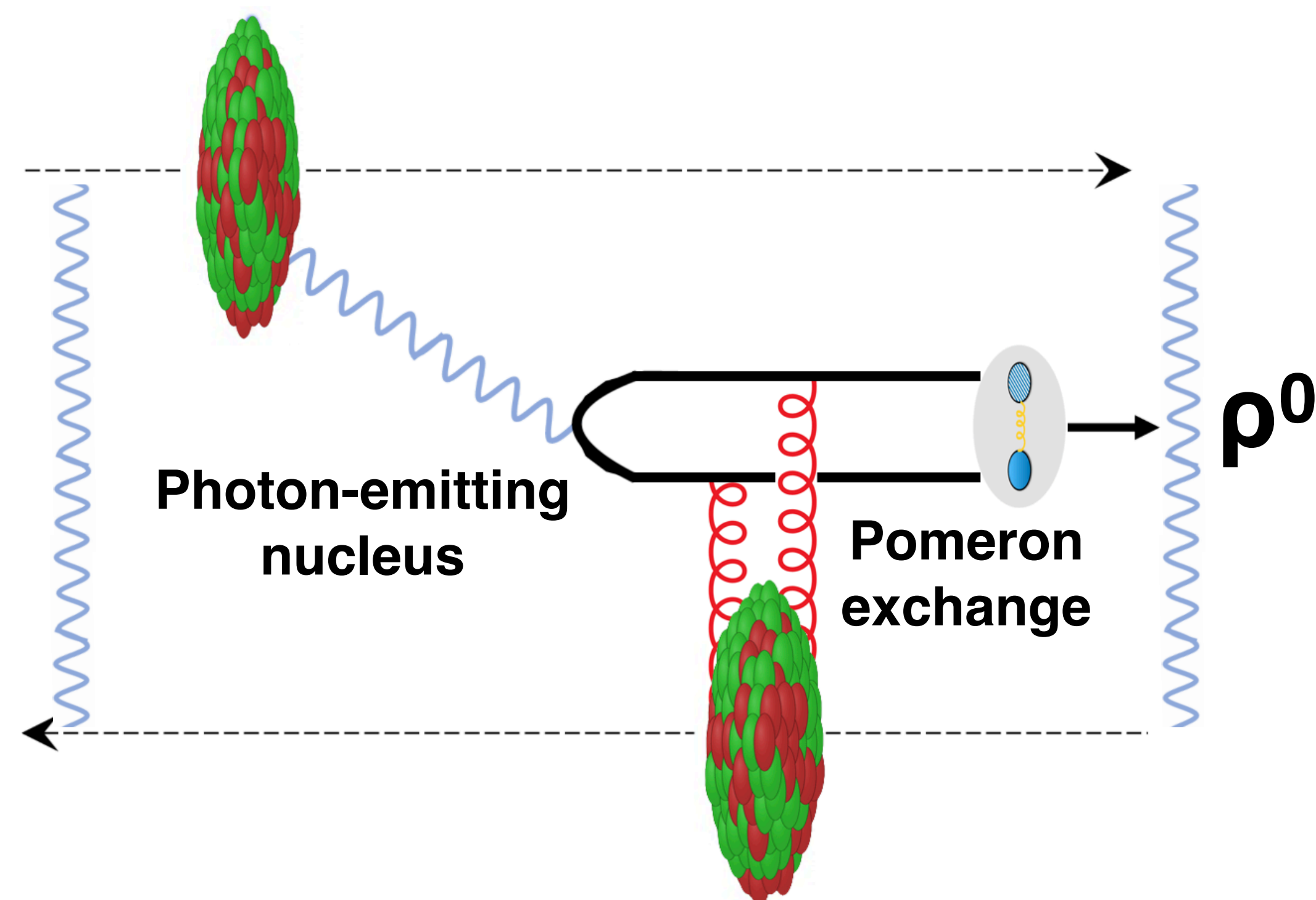
→ detects neutrons produced in the nuclear breakup



Xn → at least one neutron detected

0n → no neutron detected

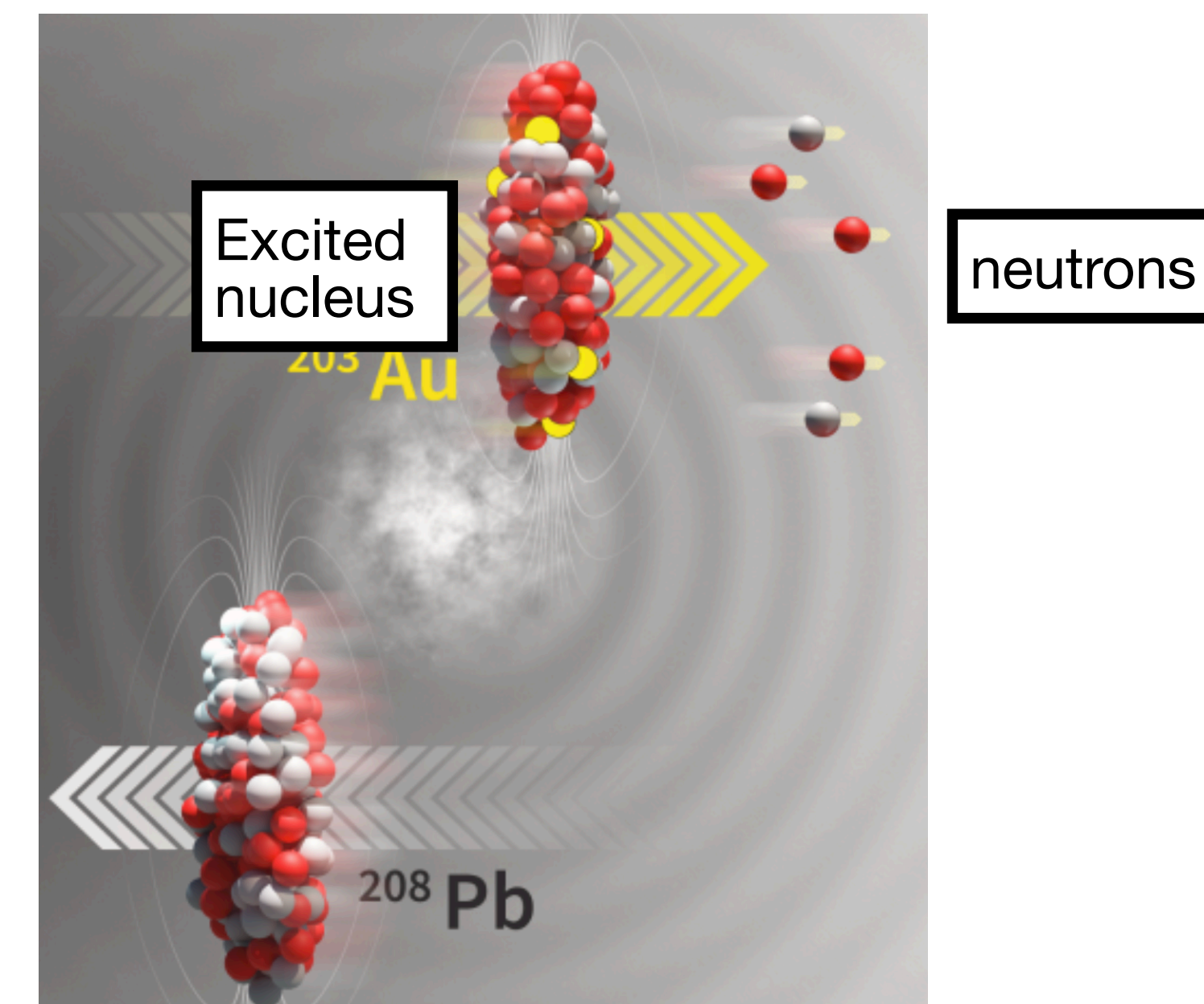
# First UPC signal: coherent $\rho^0$ production at RHIC



## Challenges:

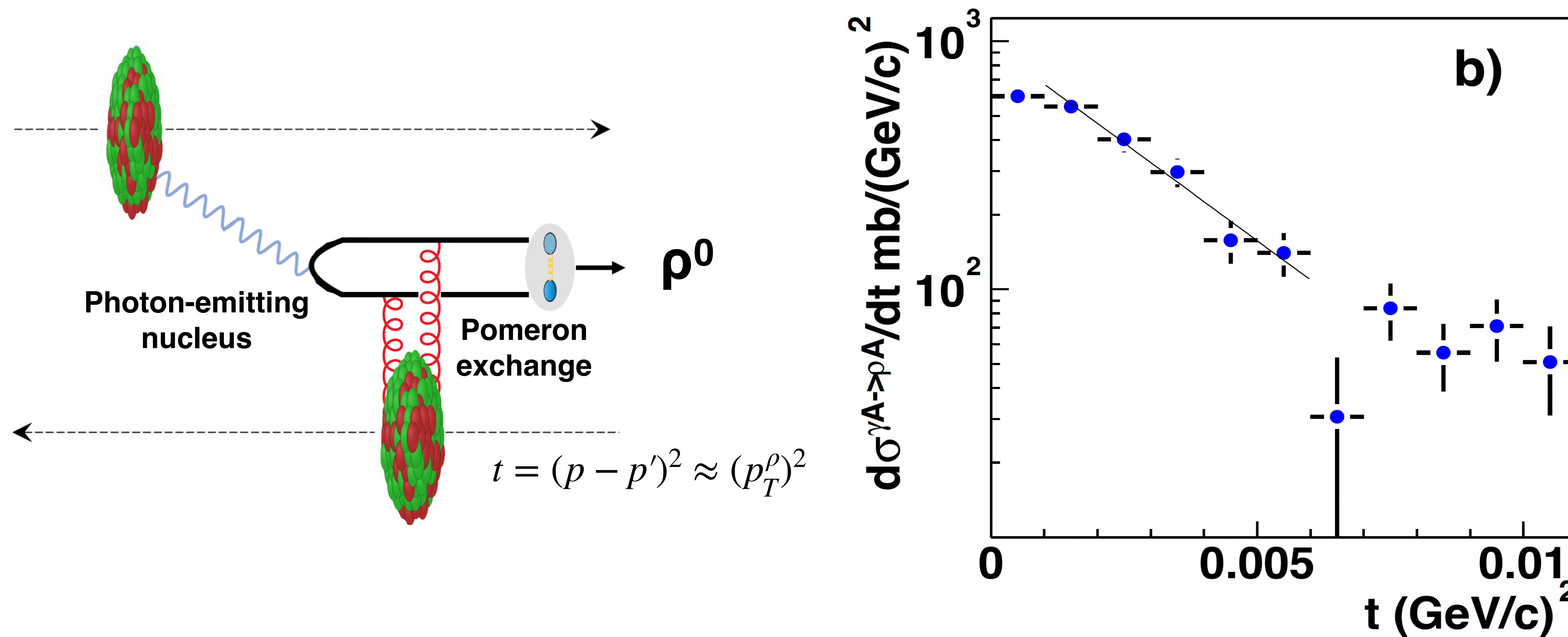
- Kinematics are inferred indirectly from the measured final state  $Q^2 \sim (m_{\rho^0}/2)^2$

## Electromagnetic dissociation



- **ZDC selection introduces sensitivity to “uncorrelated” nuclear effects**  
E.g. **electromagnetic dissociation (EMD)** caused by soft-photon exchange  
**unrelated to the hard scattering  $\rightarrow$  nucleus excitation  $\rightarrow$  neutron production**

# First UPC signal: coherent $\rho^0$ production at RHIC



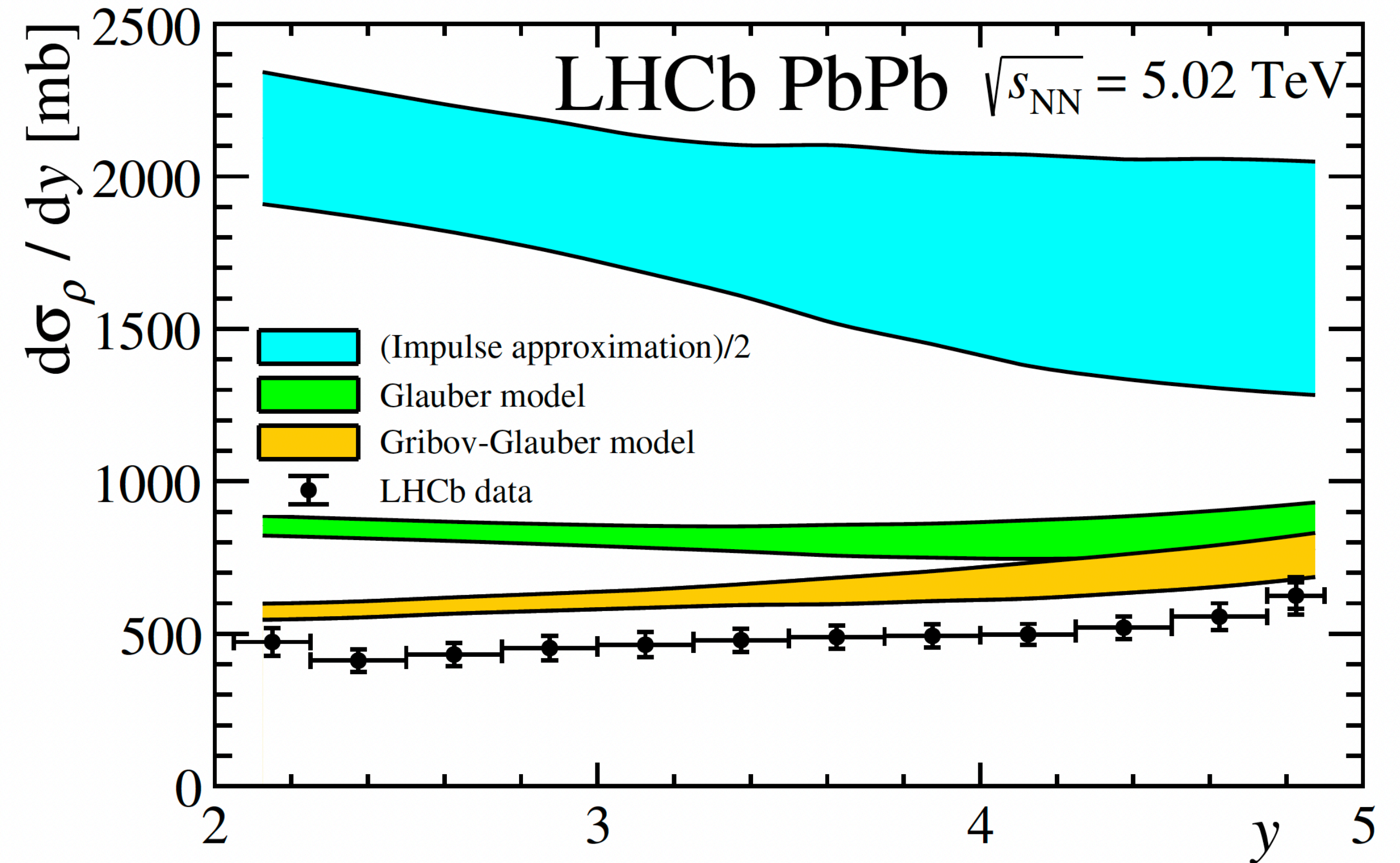
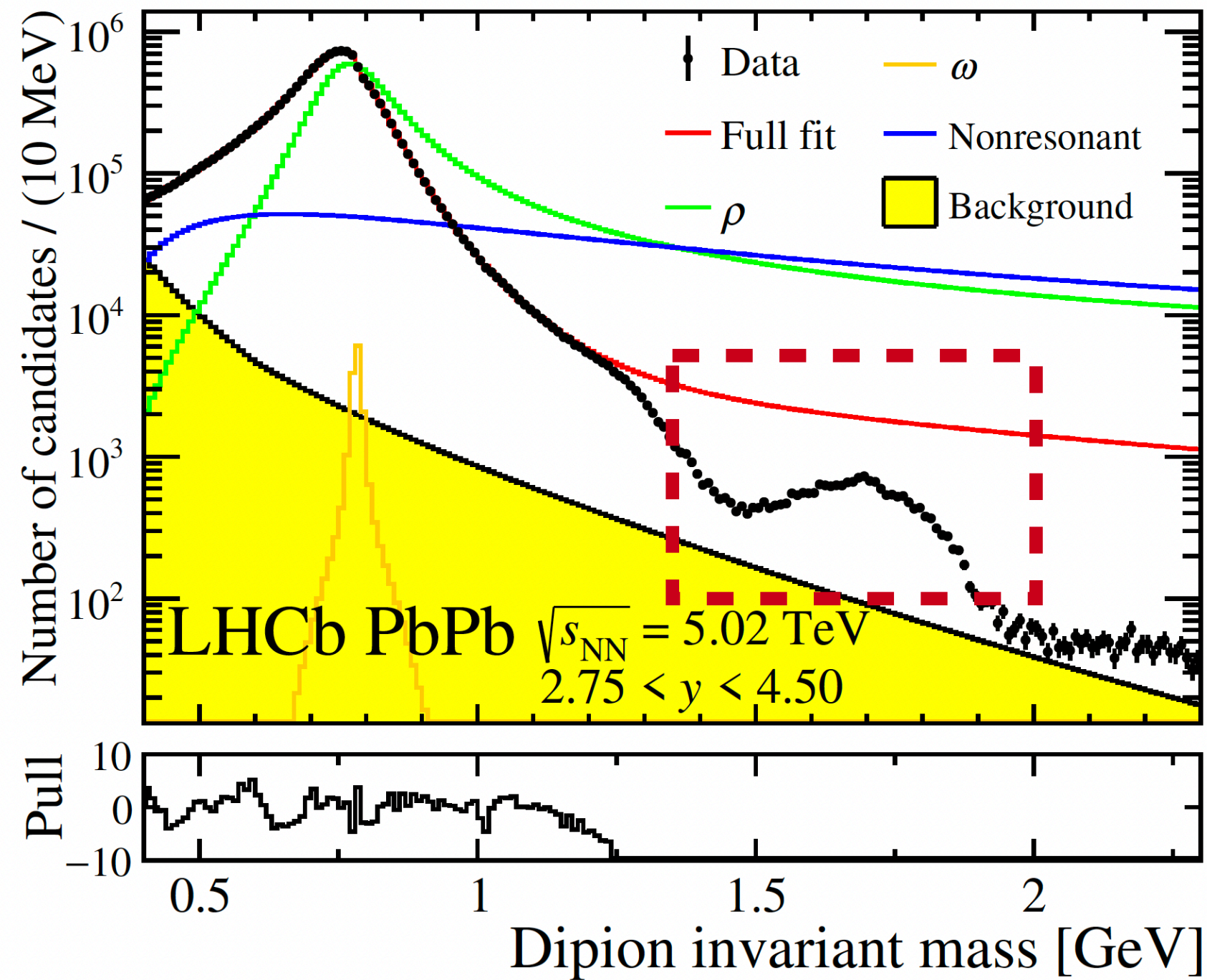
**A landmark analysis that demonstrated the feasibility and the potential of UPC measurements**

→ motivated a systematic effort to better constrain the underlying ingredients of UPC description

# Coherent photoproduction of $\rho^0$ , $\omega$ mesons in PbPb UPCs

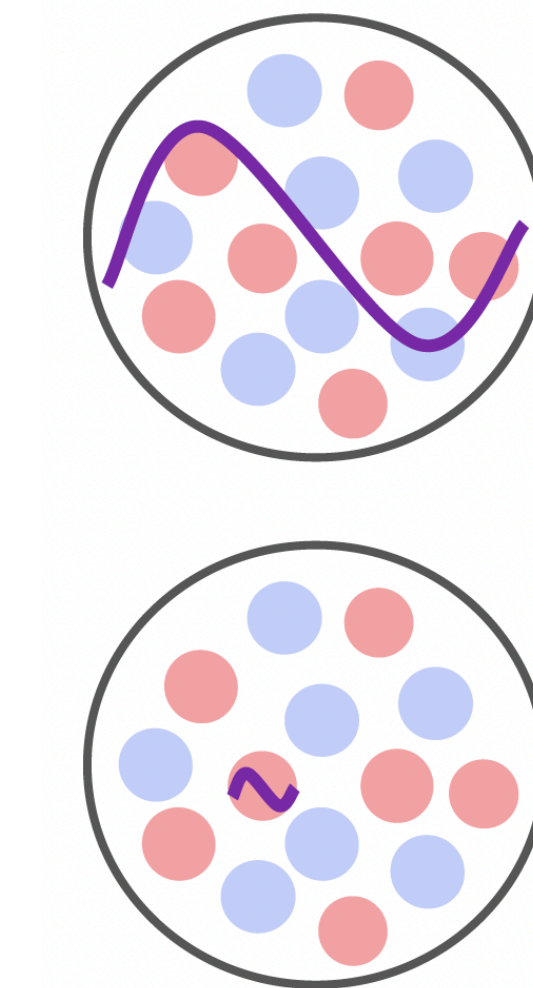
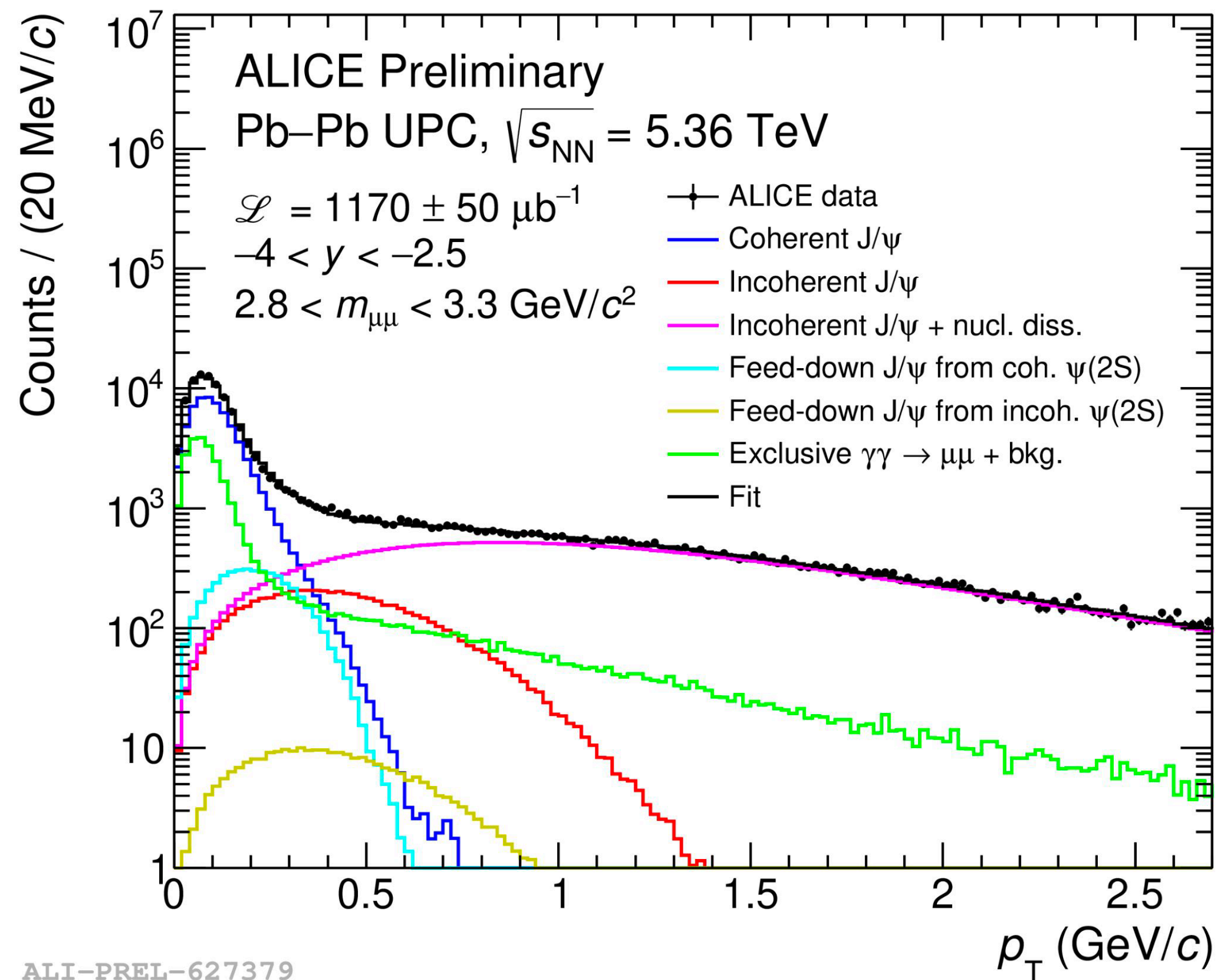
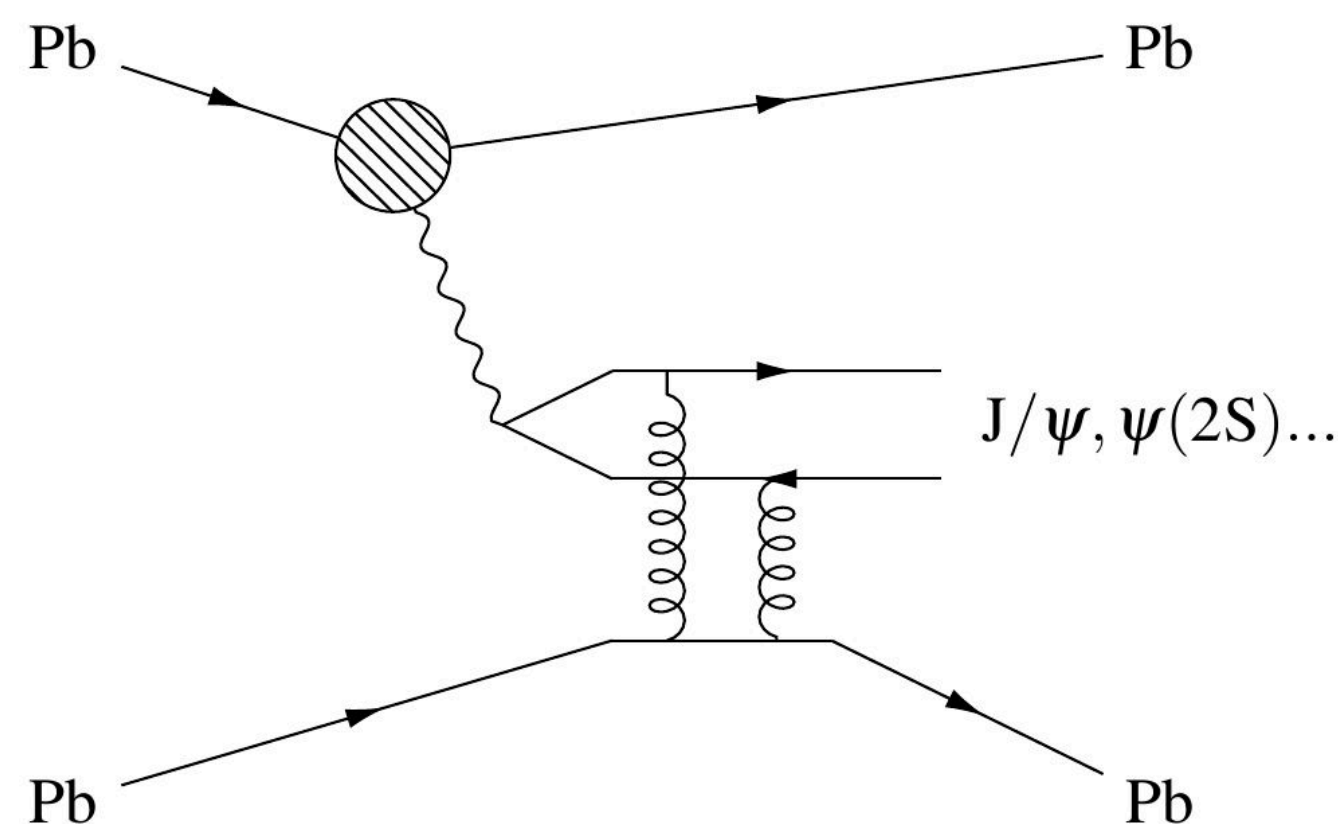
LHCb, JHEP 11 (2025) 103

Evidence for higher- $\rho$  states in UPC photoproduction (as observed by ALICE)



- **Data require strong nuclear suppression beyond impulse approximation.**
- GKZ / Gribov-Glauber captures the trend but overpredicts by  $\sim 30\%$ .
- Additional suppression may point to saturation-like effects

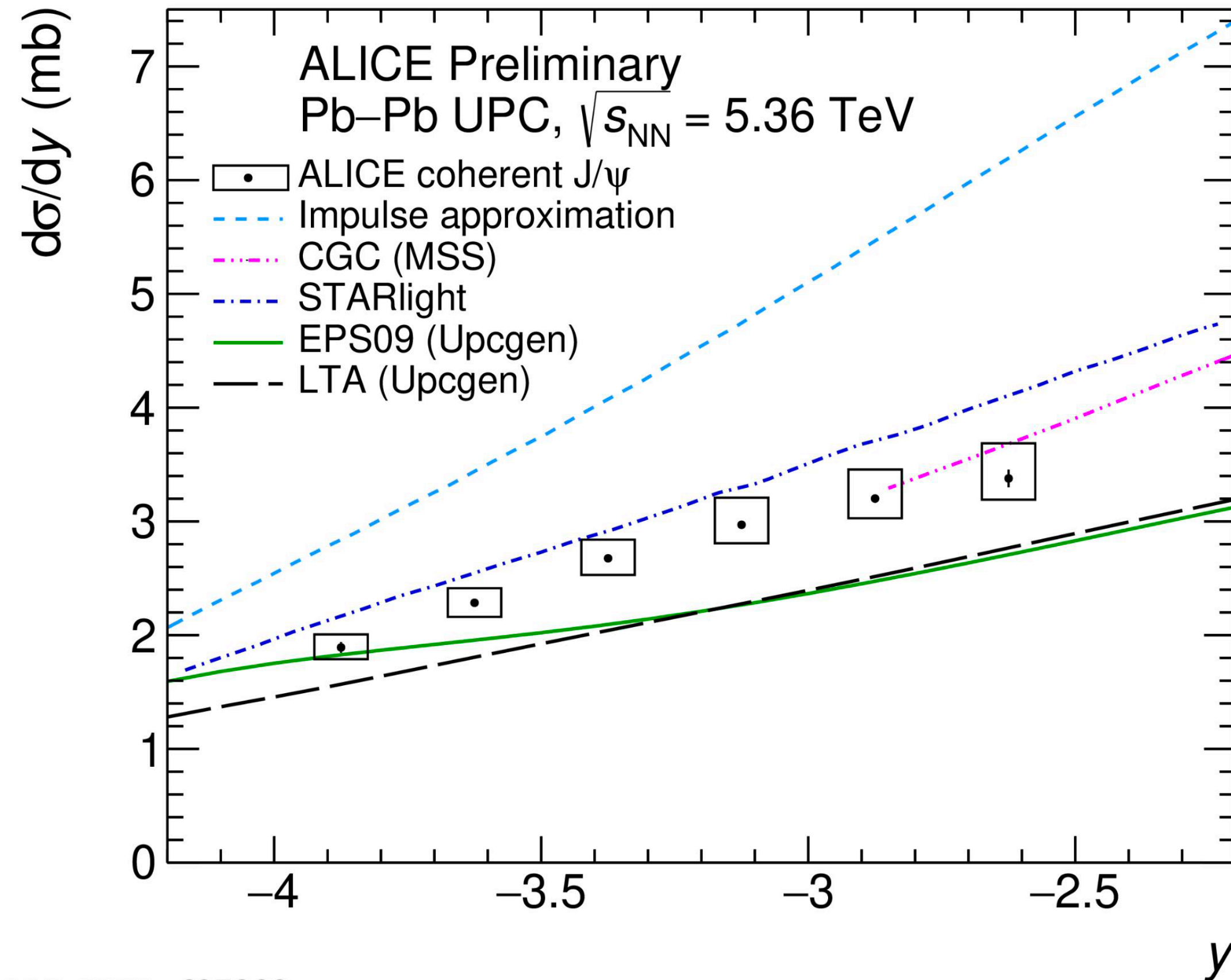
# Exclusive charmonium in UPCs with ALICE Run 3



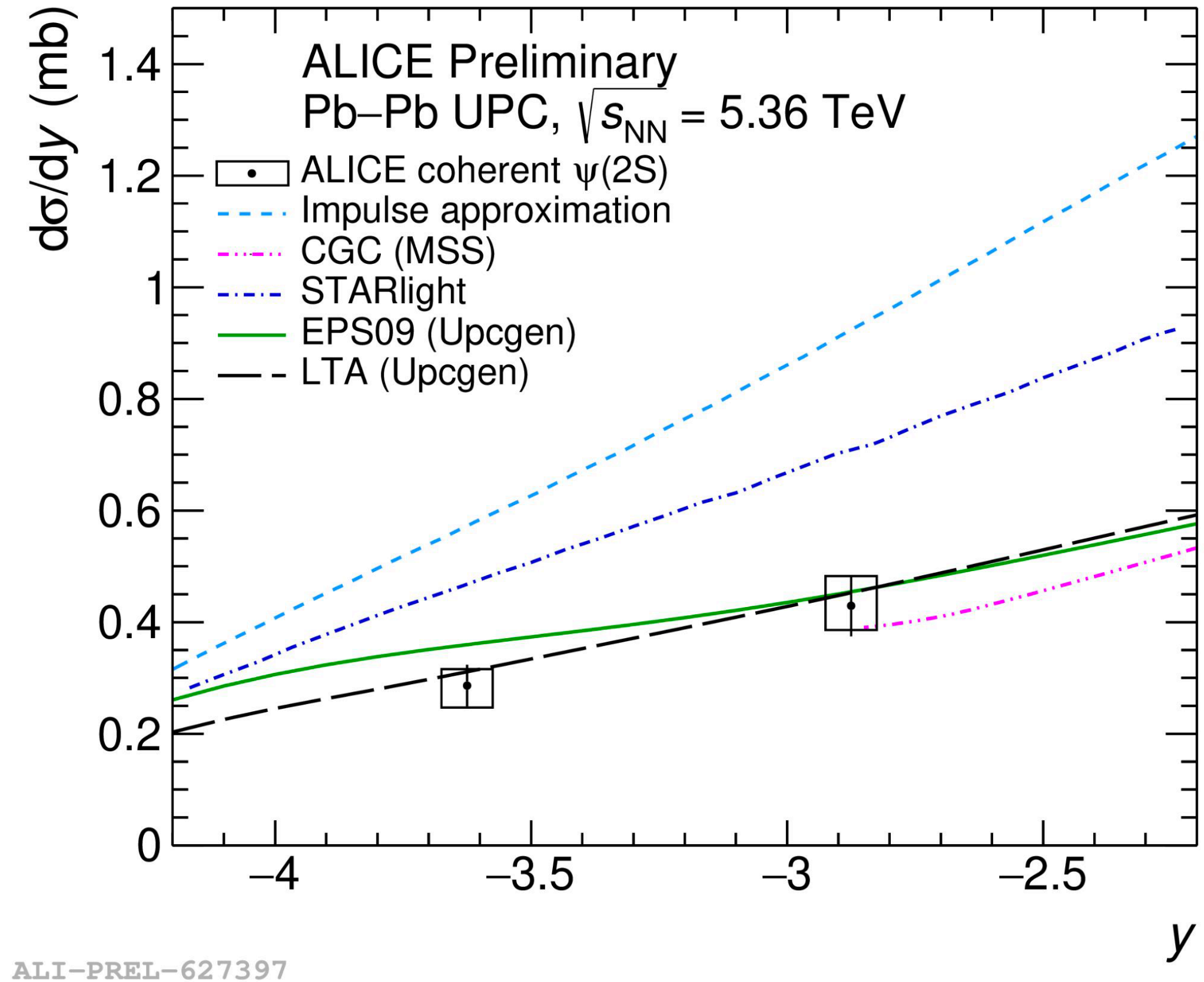
- Coherent J/ψ (MC template)
- Incoherent J/ψ (MC template)
- Incoherent J/ψ with nucleon dissociation (H1 parametrization)
- Feed-down J/ψ from coherent and incoherent  $\psi(2S)$  decays (MC template)
- $\gamma\gamma \rightarrow \mu\mu$ : data-driven template

# Coherent $J/\psi$ production in PbPb collisions with ALICE Run 3

N. Burmasov's talk at DIS 2026  
Minjung Kim's talk at DIS 2026

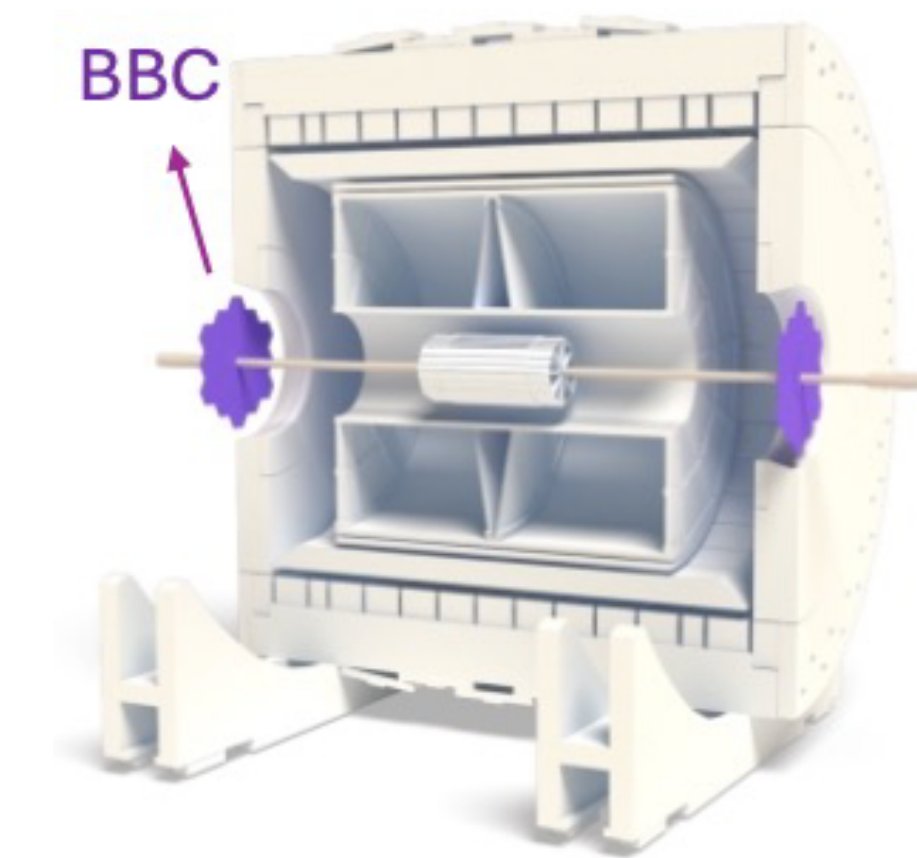
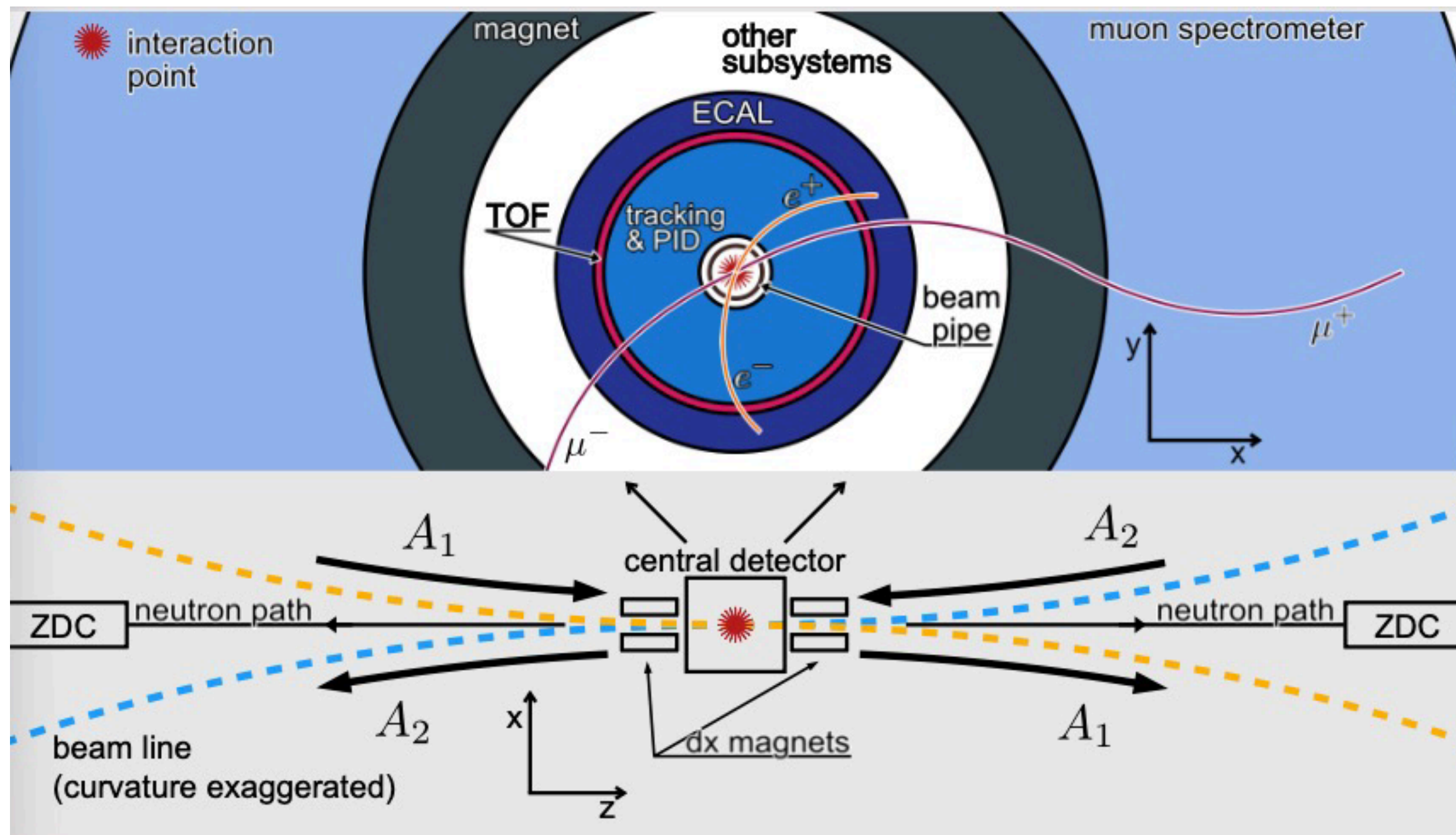


ALI-PREL-627392



ALI-PREL-627397

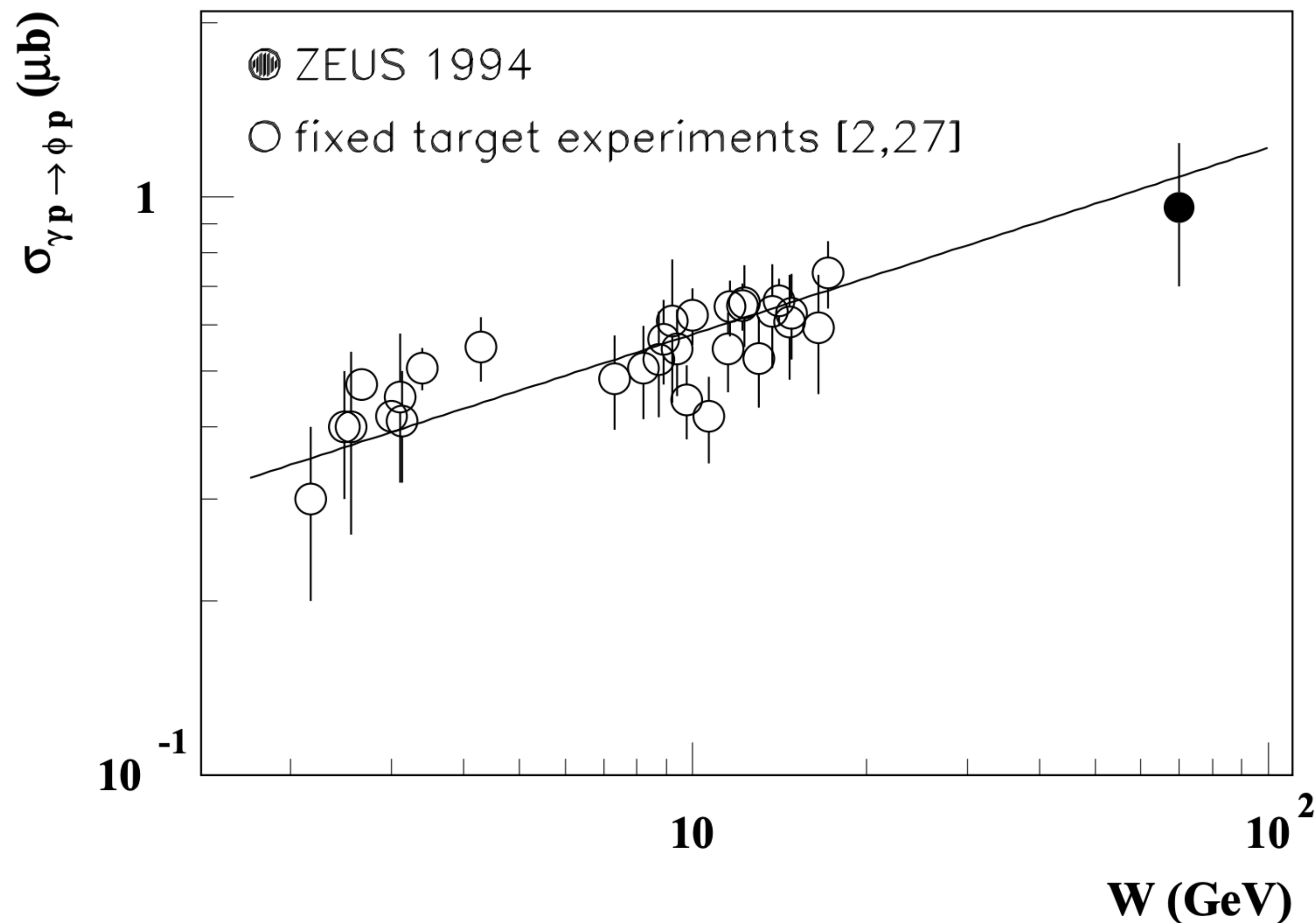
# $\phi$ exclusive photoproduction with STAR



**BBC (Beam-Beam Counter):** Vetoes hadronic interactions by requiring no forward activity, ensuring exclusivity of UPC events

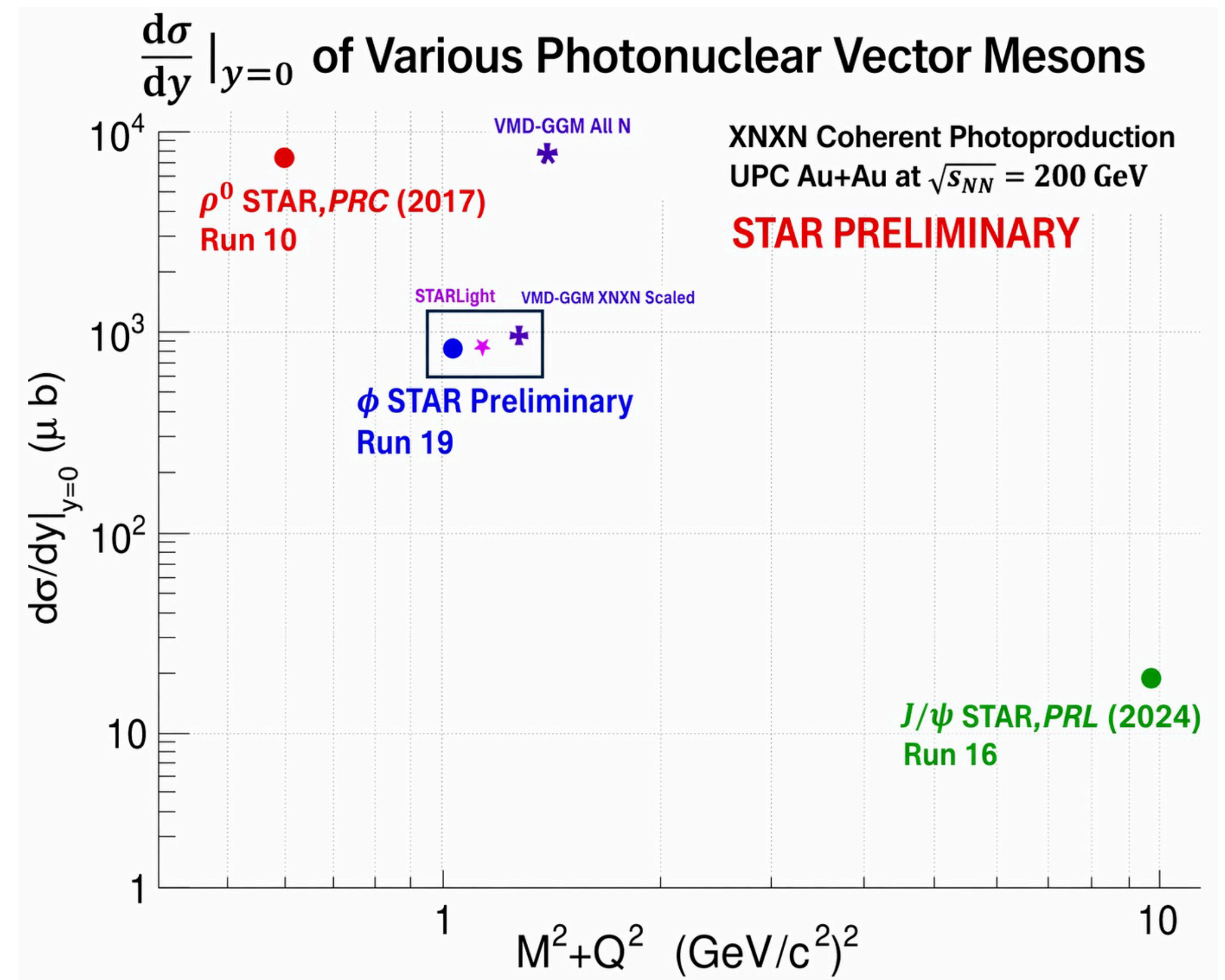
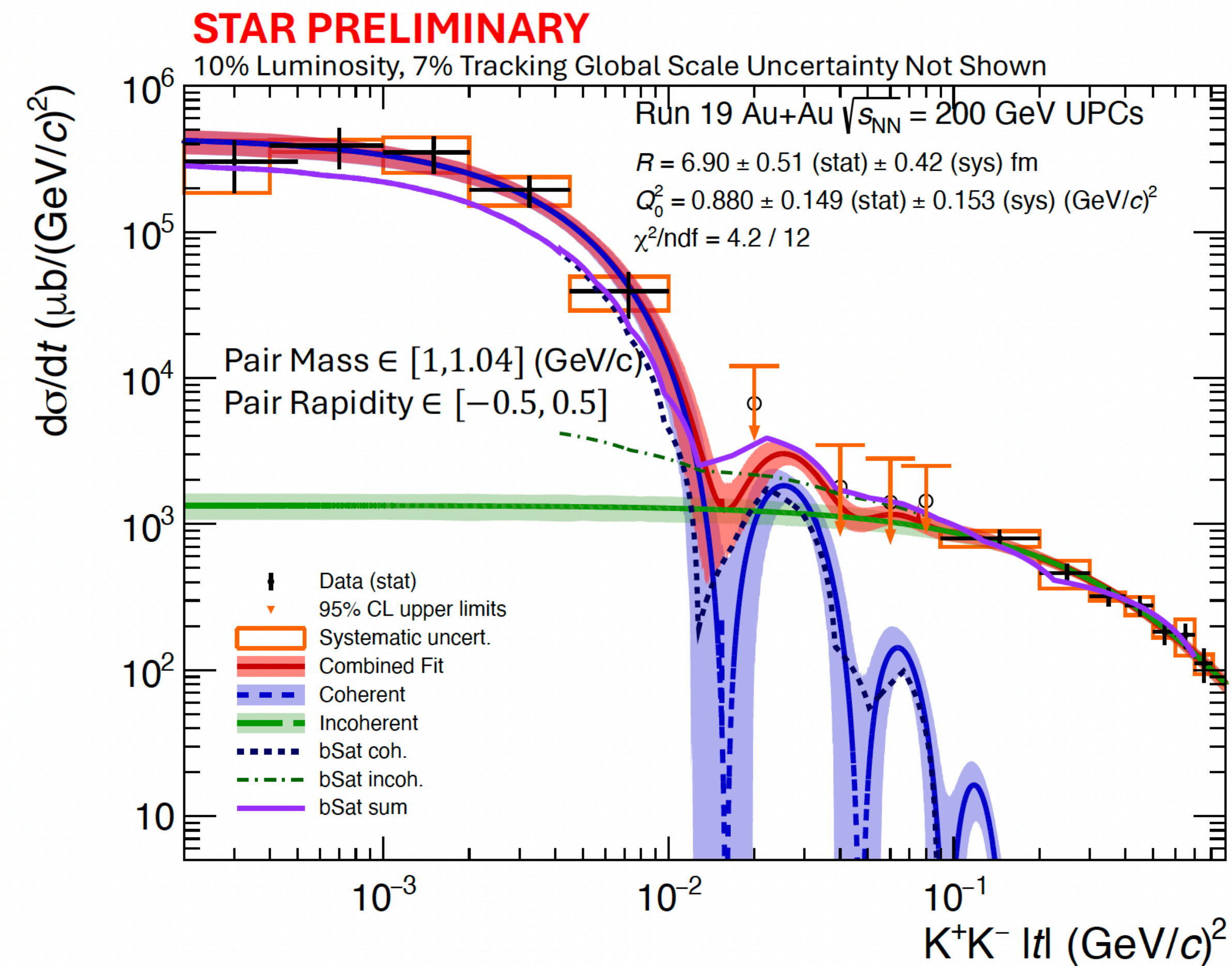
# $\phi$ -meson exclusive photoproduction at HERA (ZEUS)

**ZEUS 1994**

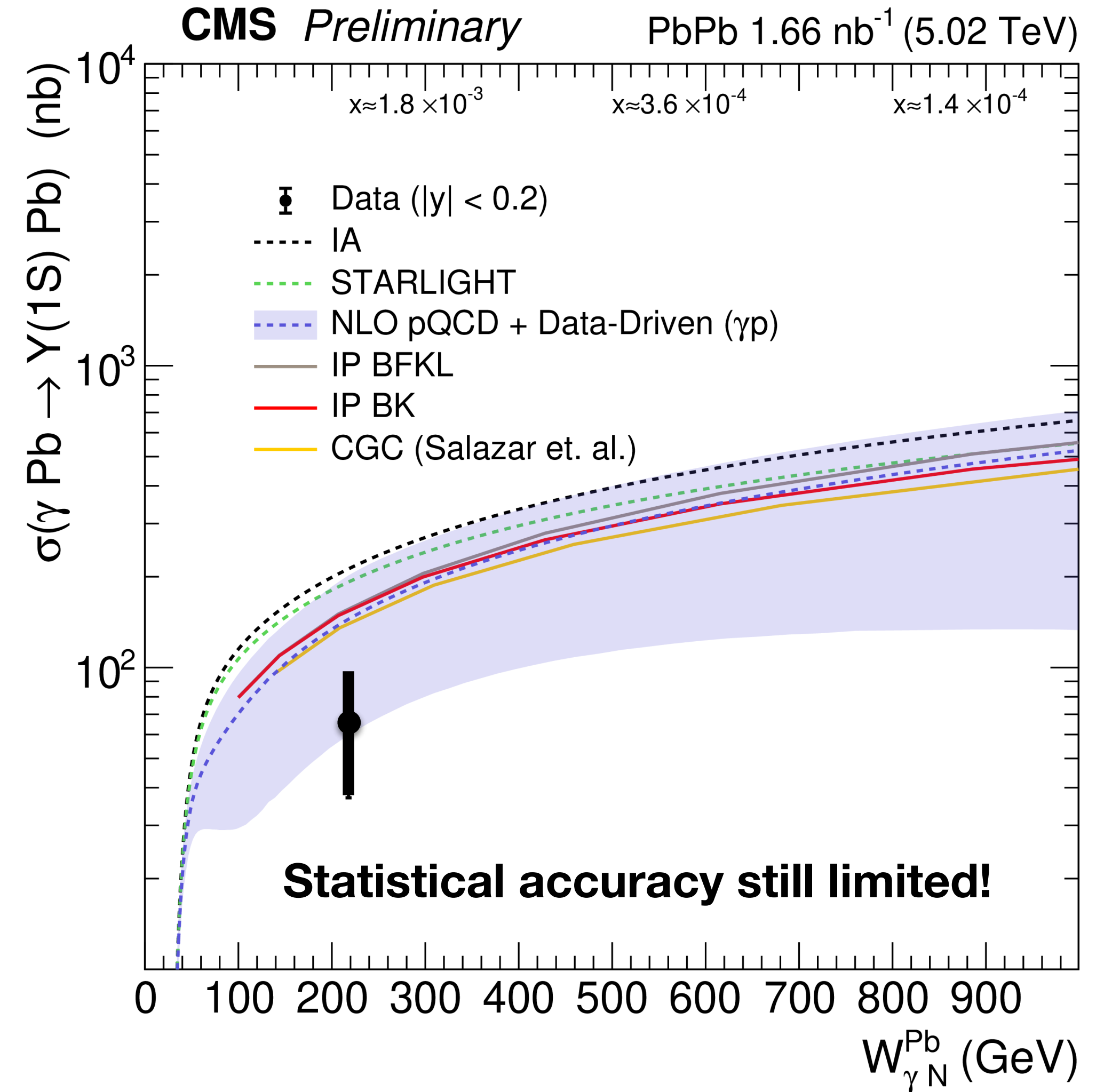
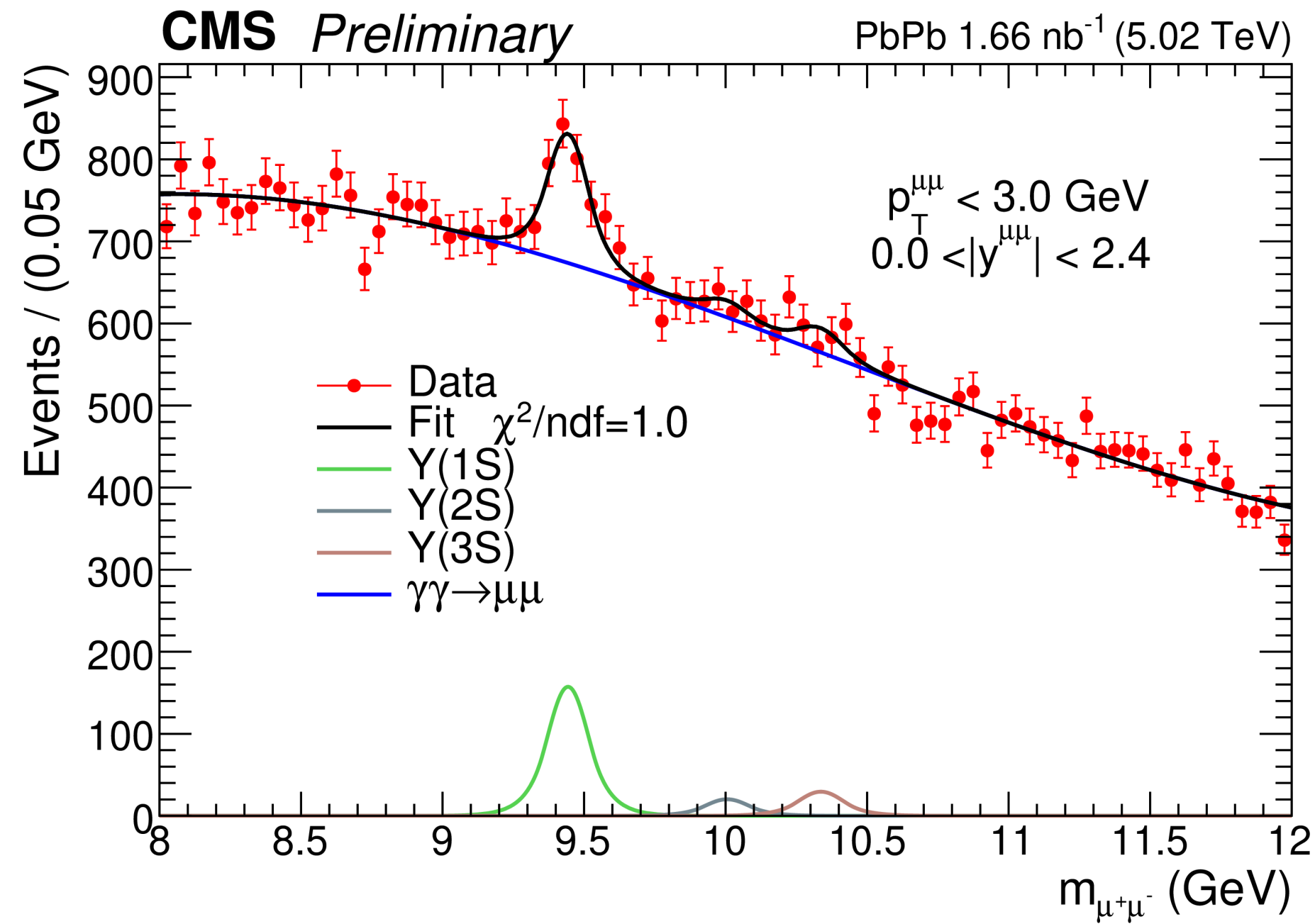
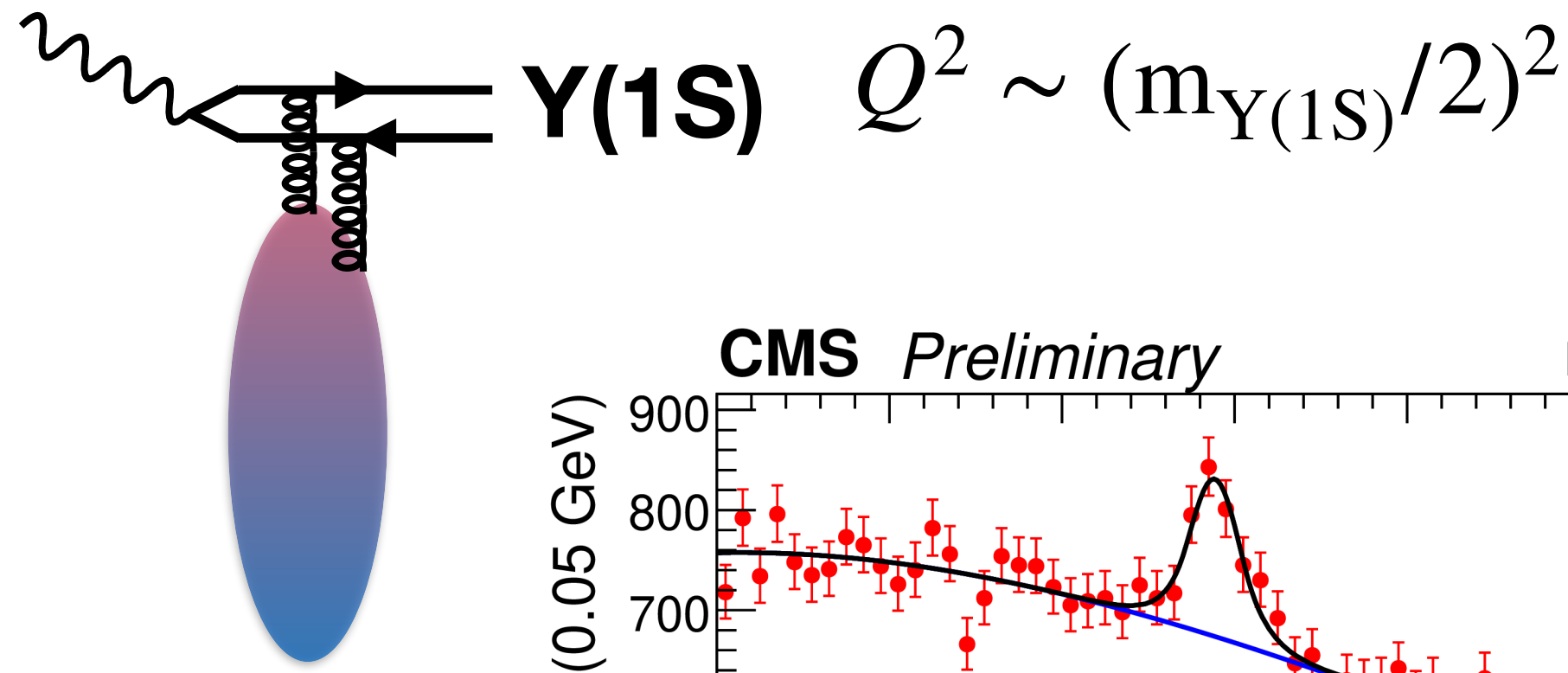


# Mass dependence for coherent VM photoproduction at RHIC

Xihe Han (STAR), DIS 2026's talk



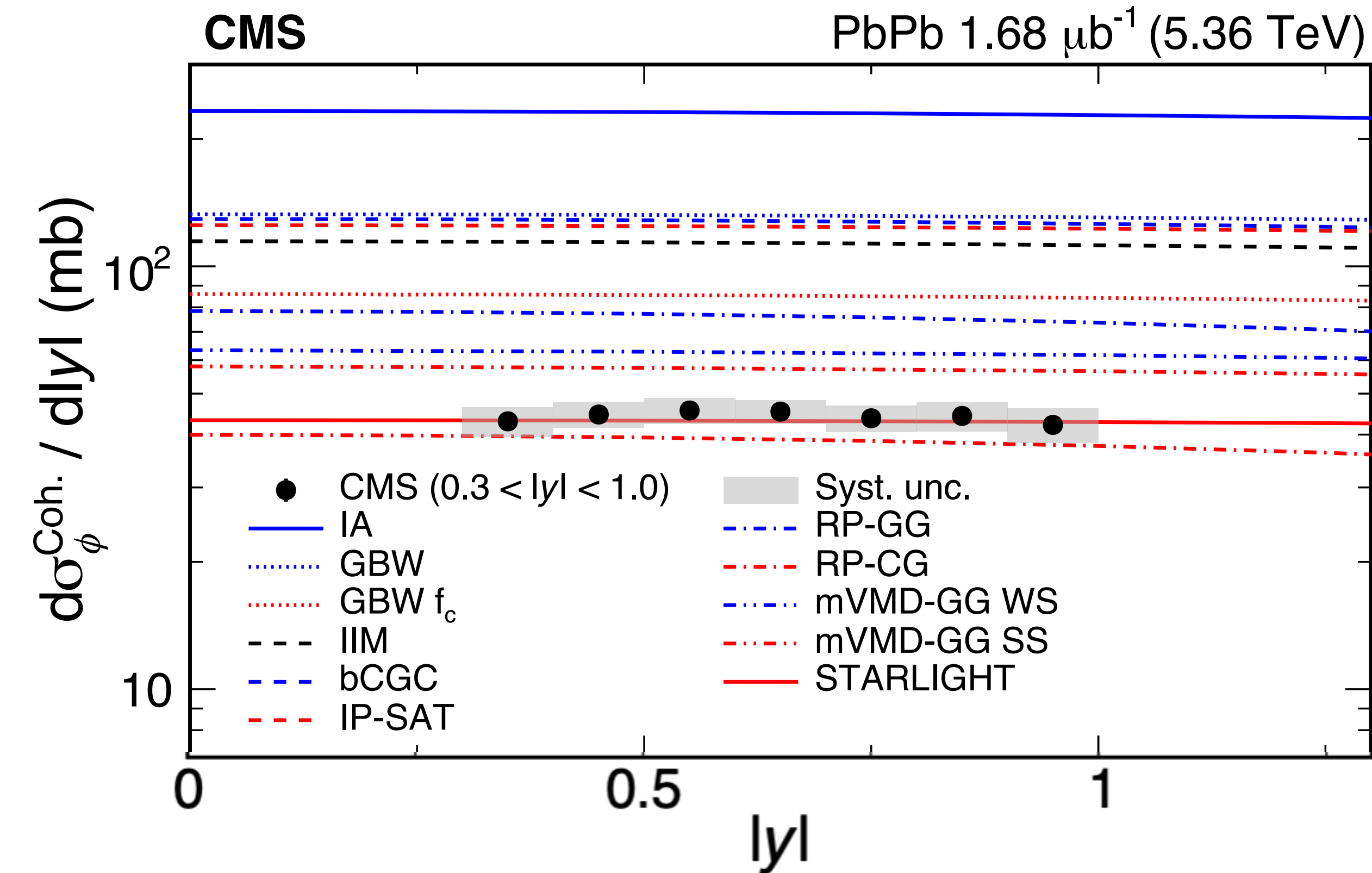
# First coherent $Y(1S)$ production in PbPb UPCs



Bound  $b\bar{b}$  with a mass of about 9.5 GeV is produced in UPCs!

- testing nuclear matter at the boundaries of the saturation region
- stronger theoretical control, “easier” NLO calculations

# First observation of coherent $\phi(1020)$ at the LHC

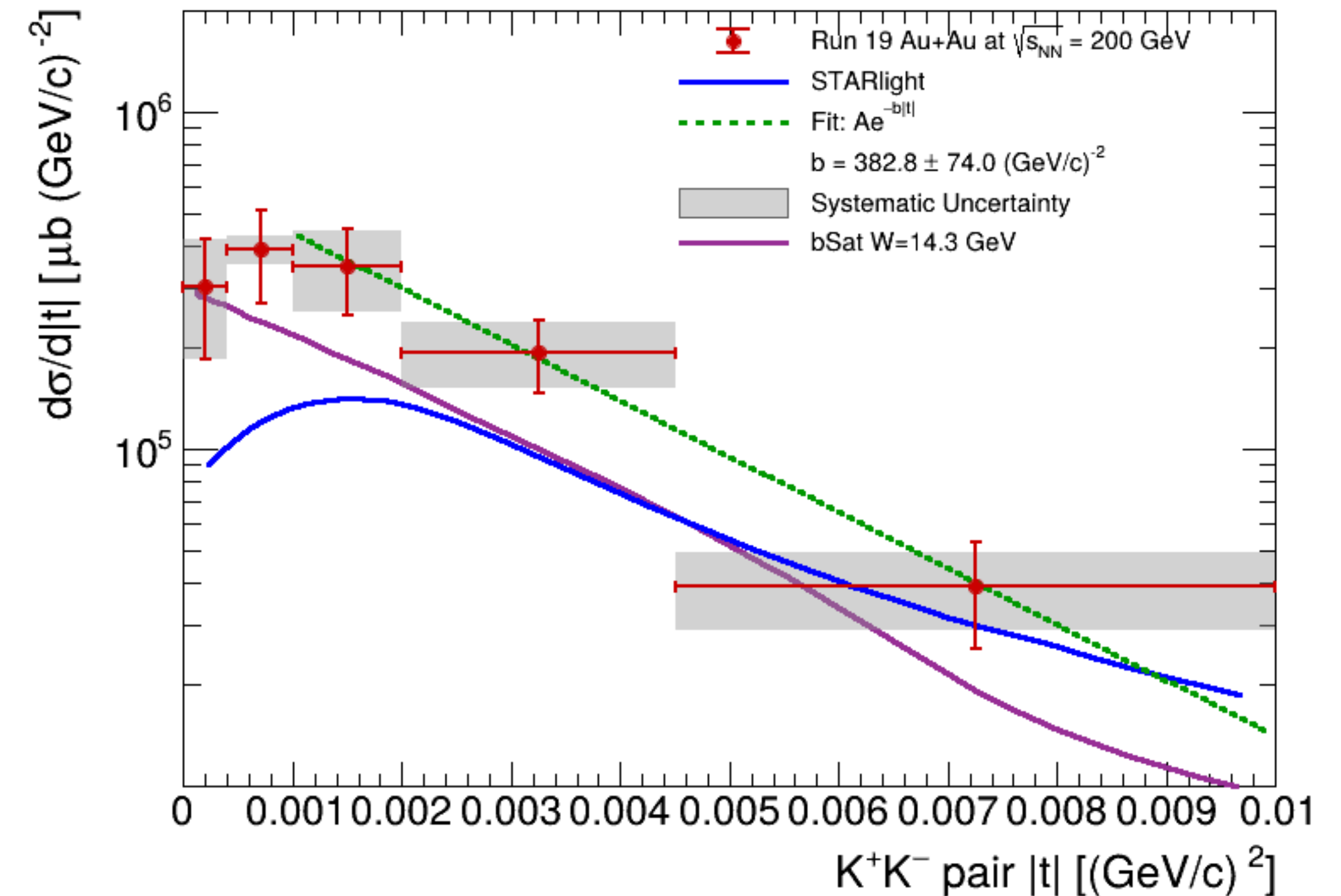
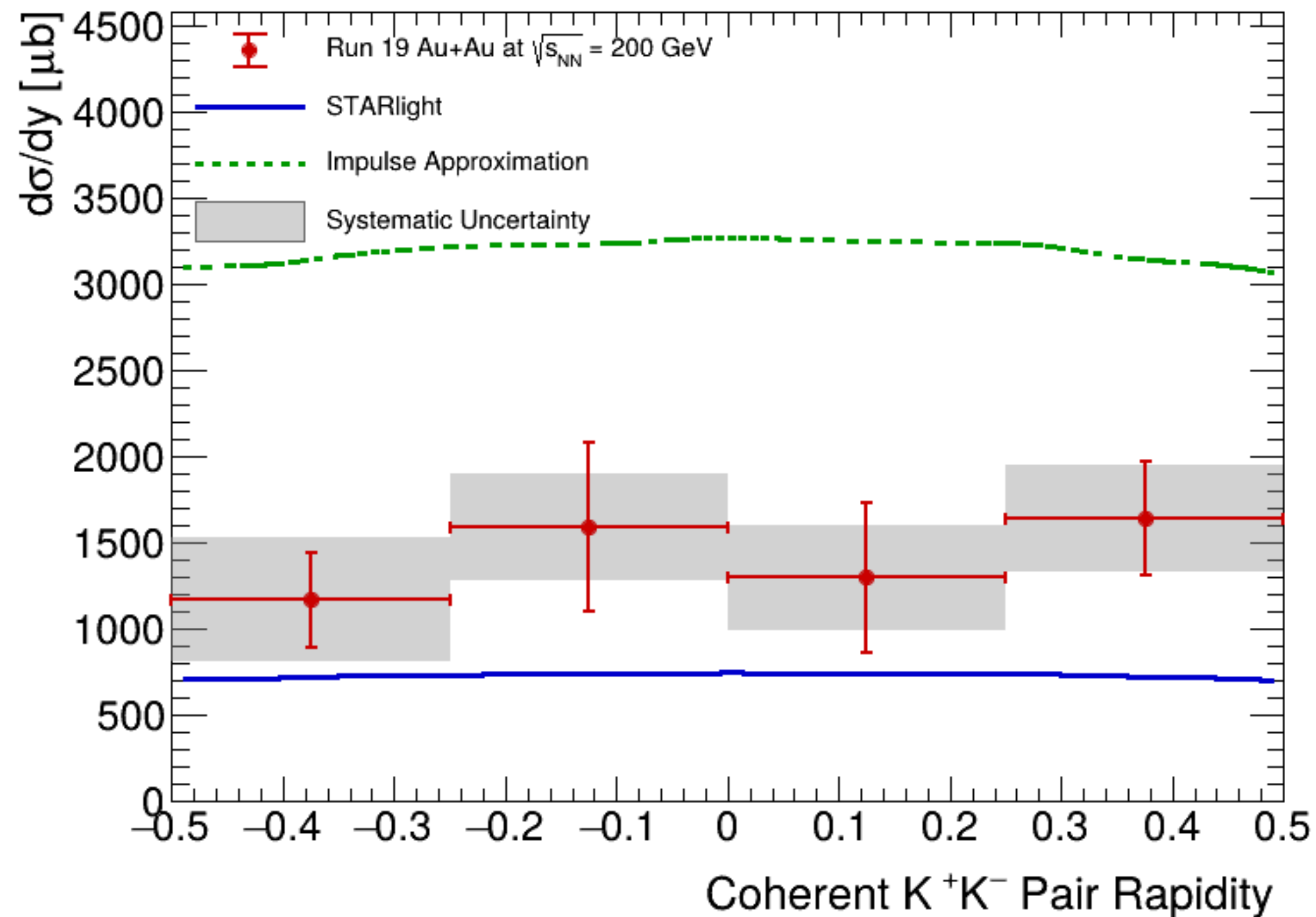


→ larger saturation effects expected (lower  $Q^2$ )  
 → **non-perturbative regime**

- **Saturation models predict much smaller suppression** (challenges due to non-perturbative corrections)
- **Much better agreement provided by shadowing models (??)**

$$\left. \frac{\sigma_{\text{coh}}}{\sigma_{\text{IA}}} \right|_{y=0} \approx 0.2$$

# Coherent $\phi$ exclusive photoproduction with STAR

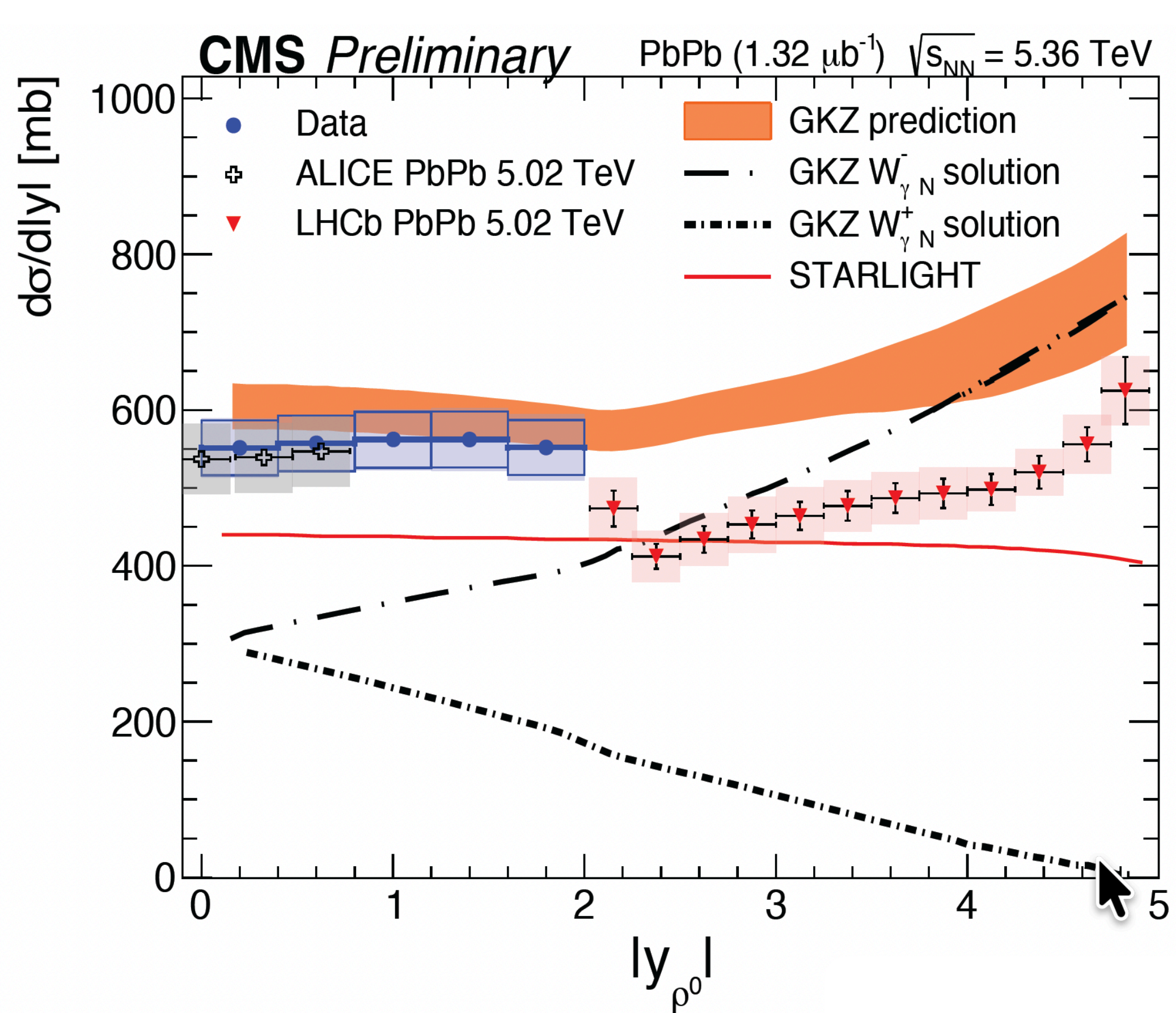


$$\left. \frac{\sigma_{\text{coh}}}{\sigma_{\text{IA}}} \right|_{y=0} \approx 0.436 \pm 0.15 \text{ (stat)} \pm 0.12 \text{ (sys)}$$

$r_{\text{rms}} \approx \sqrt{3b\hbar c} \approx 6.68 \text{ fm} \pm 0.65 \text{ fm}$   
**bSat** (impact-parameter-dependent saturation dipole model)  
**provides the best description of the t-dependence**

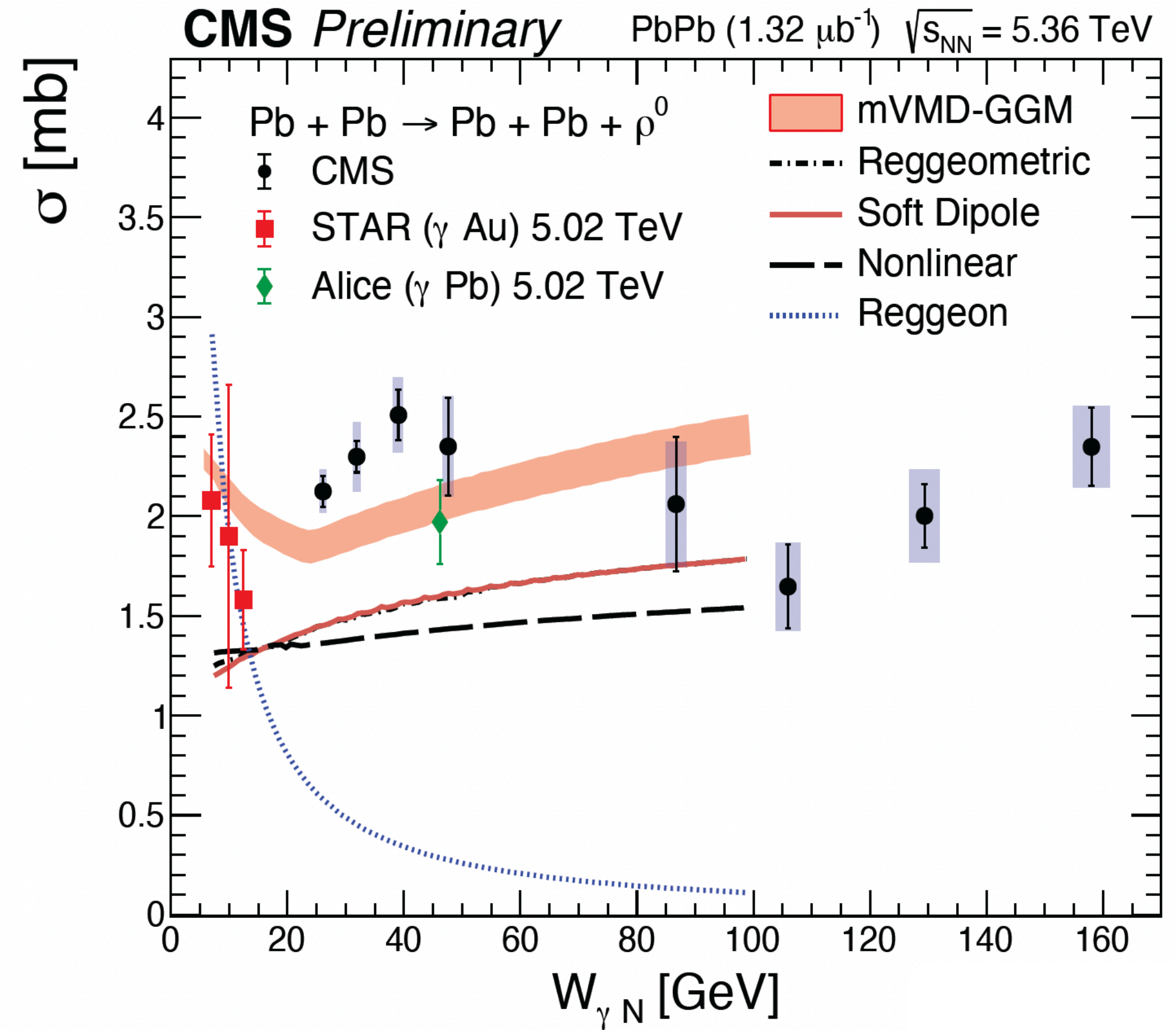
# Coherent $\rho^0$ in $\gamma$ Pb UPCs at LHC and RHIC

CMS, HIN-24-020  
 V. Guzey et al., PRC 102 (2020)1,015208  
 LHCb, JHEP 11 (2025) 103  
 ALICE, JHEP06 (2020) 03



## $d\sigma/d|y|$ including both $\gamma$ N and $N\gamma$ :

- nearly flat at central rapidity
- CMS results consistent with ALICE at mid rapidity
- LHCb removes a fraction of EM dissociated events

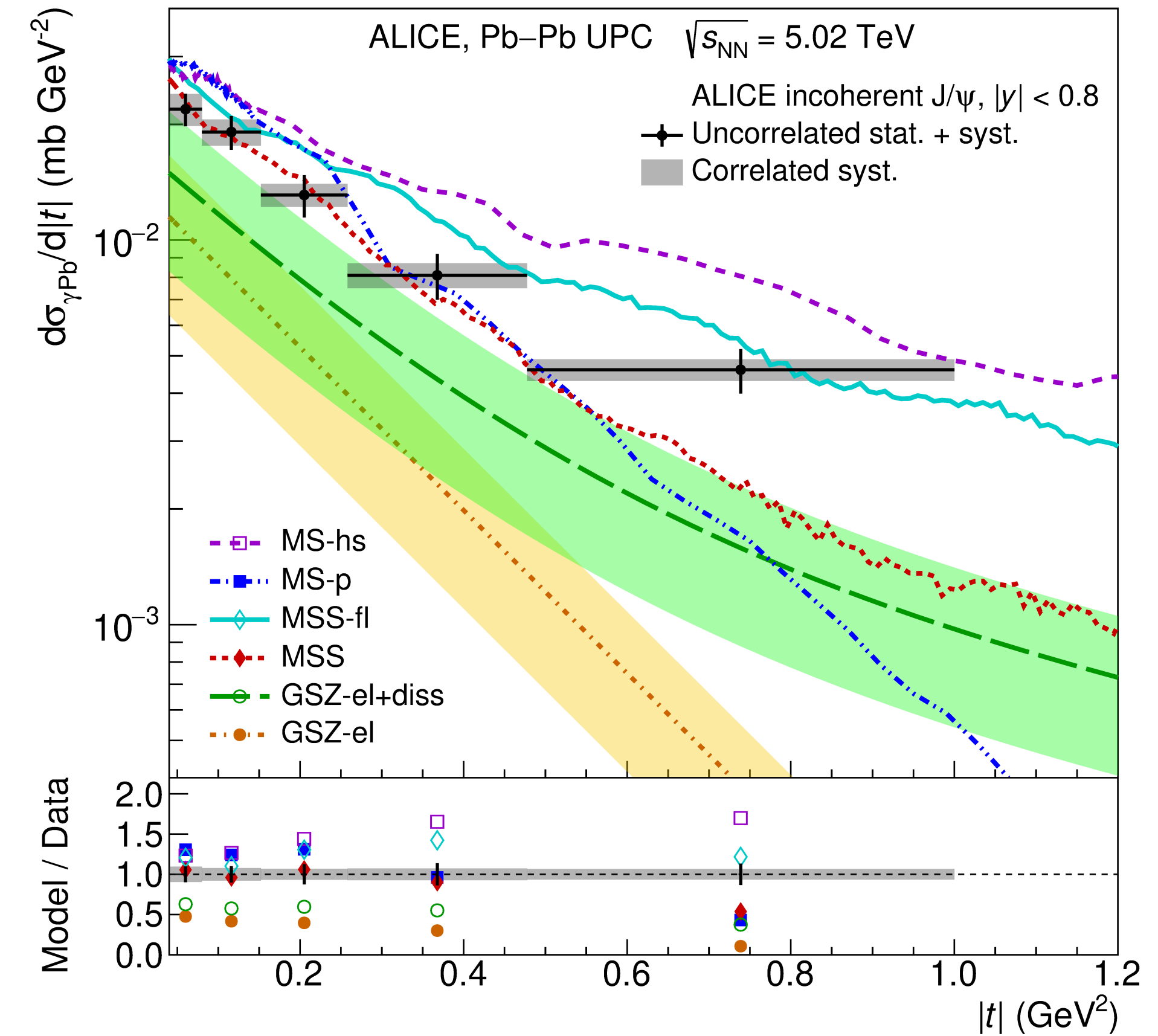
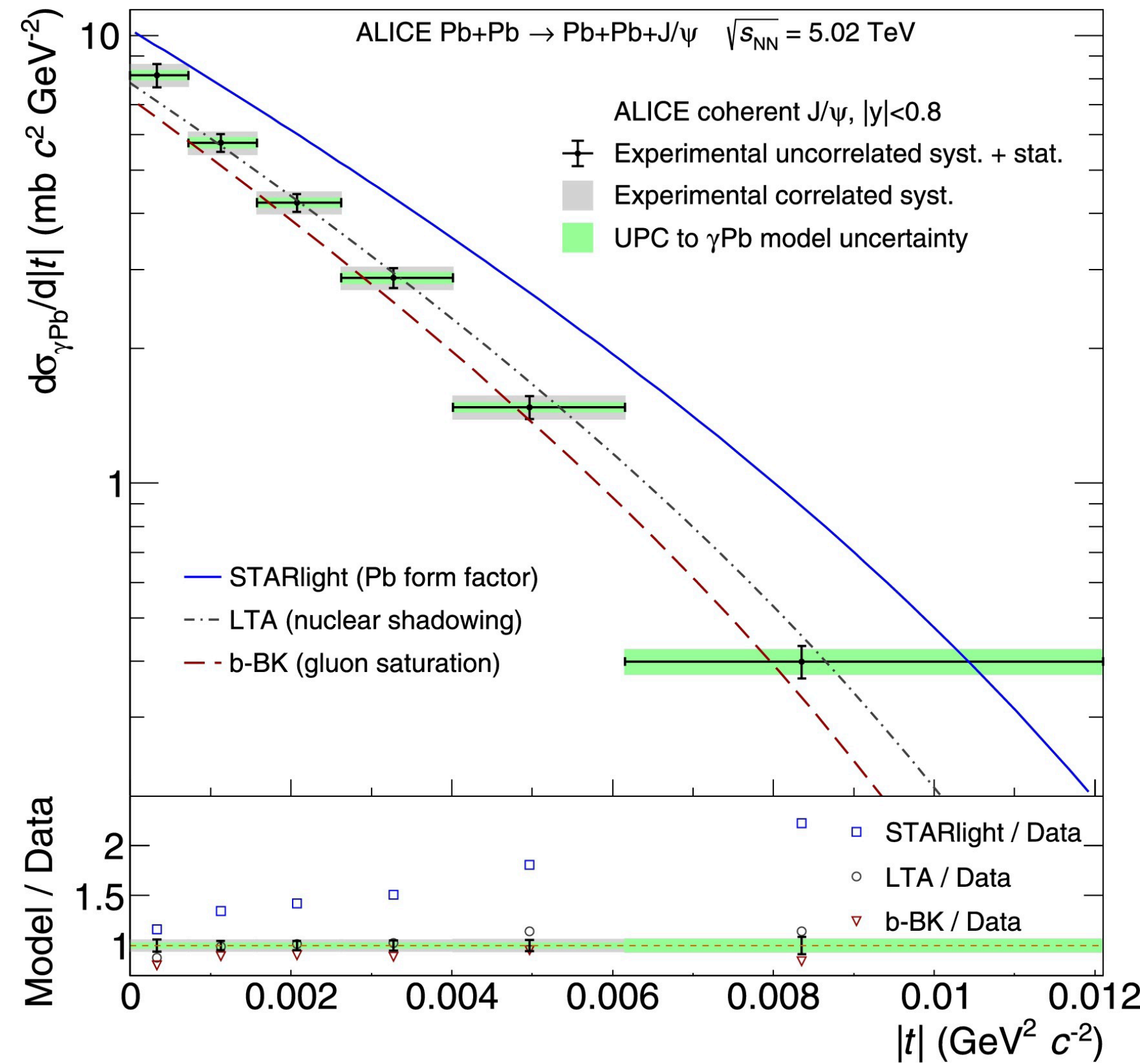
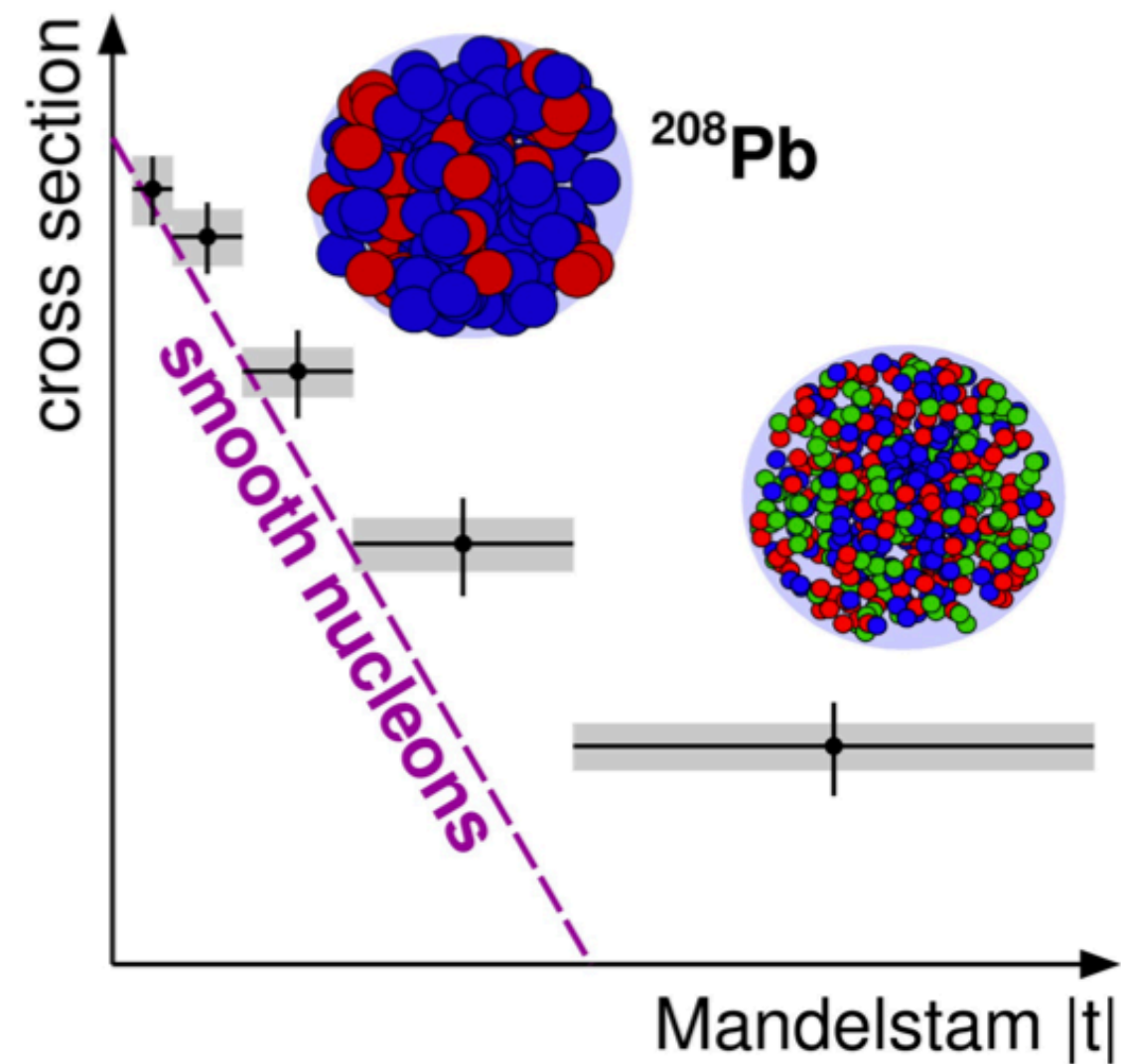


## $\sigma$ cross-section as a function of $W_{\gamma N}$

(two-way ambiguity solved with neutron counting)  
 → **mVMD-GGM** (nuclear shadowing with Gribov-Glauber)  
 provide a good description of the data

# Coherent and incoherent $J/\psi$ production with ALICE (Run 2)

ALICE, *Phys. Rev. Lett.* 132, 162302

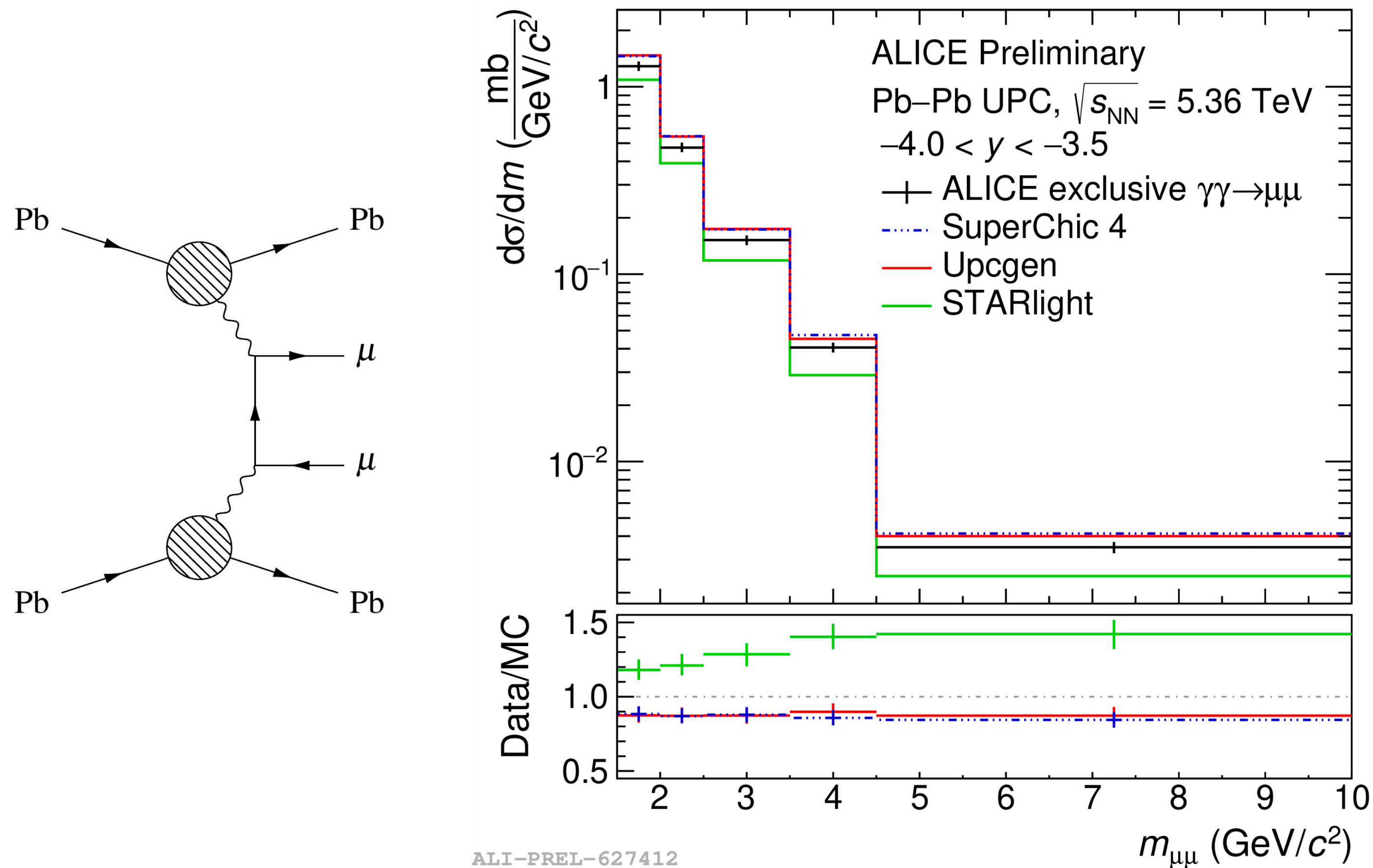


Overall distribution well described by models based on shadowing/saturation

**Slope of incoherent production is better described by models including subnucleonic degree of freedom**

# Exclusive dimuon production with ALICE Run 3

Exploiting the improved ALICE capabilities in Run 3 (e.g., continuous readout and muon-vertexing)

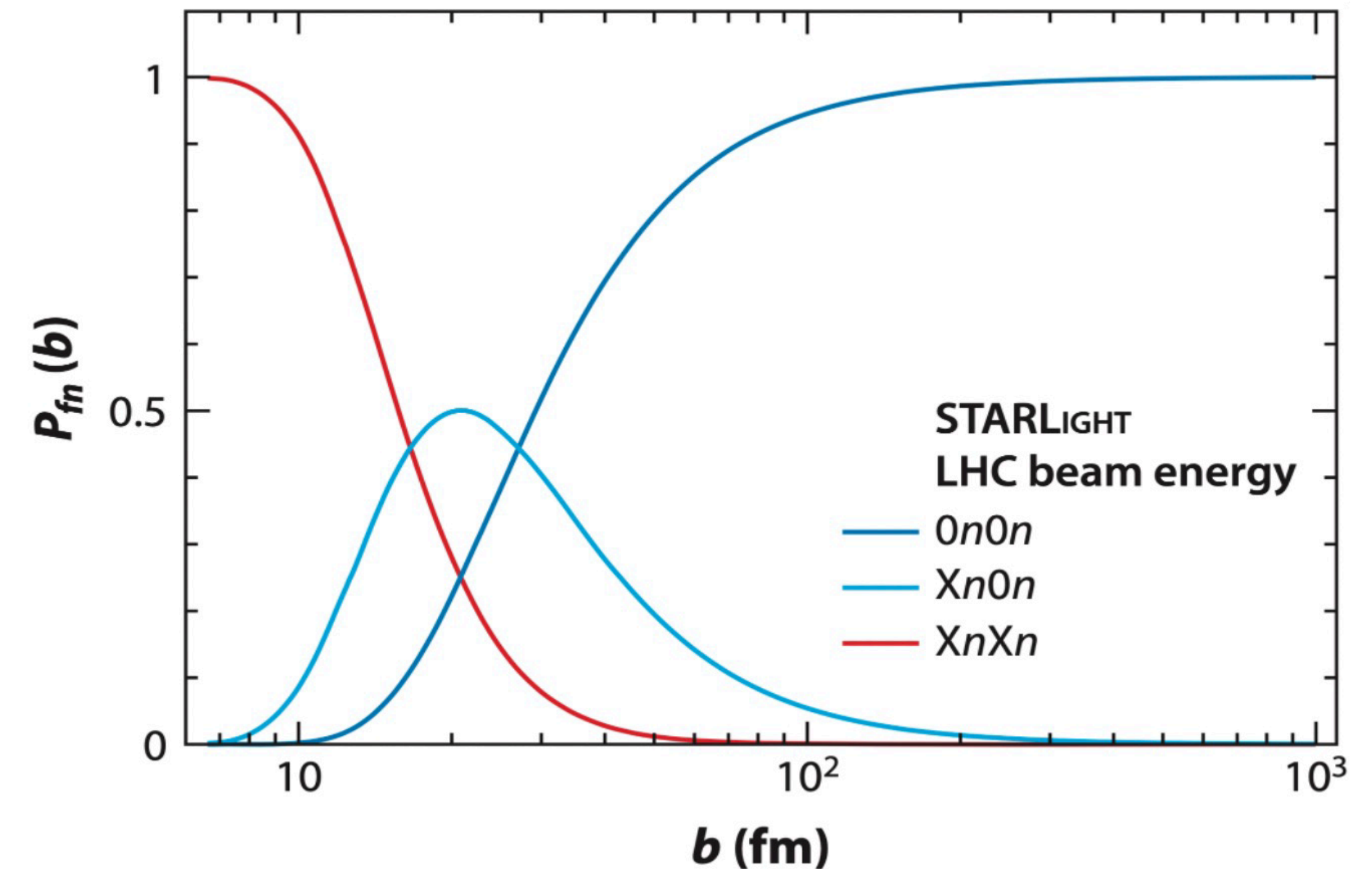
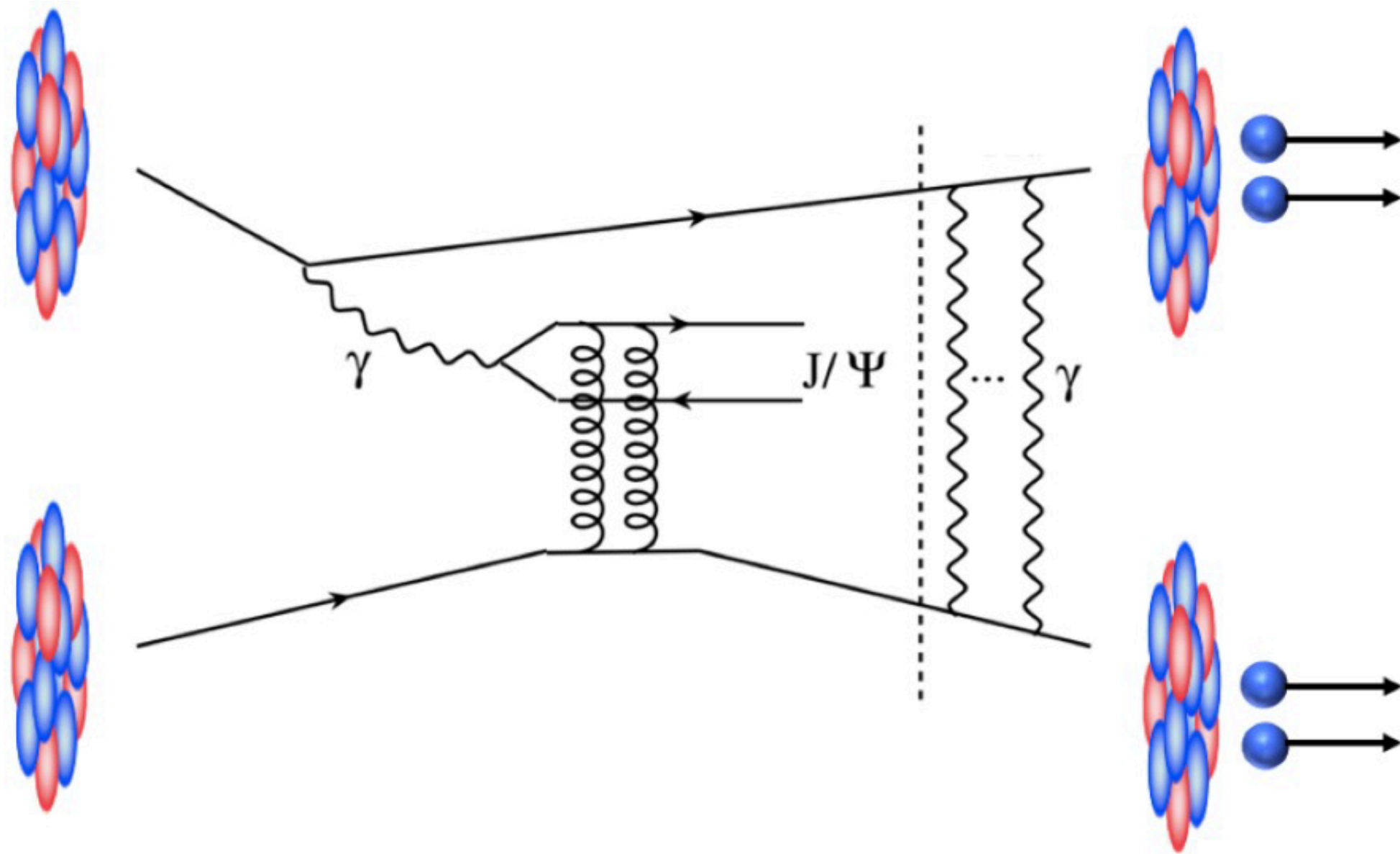


- **UPCgen and SuperChic 4** calculations overpredict the data by 10-20 %
- Significant sensitivity to the details of the photon-flux modeling

# Solving the photon ambiguity with neutron information from ZDC

**Method in a nutshell (V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942)**

- Rate of high energy photon flux is larger at smaller impact parameter
- impact parameter of the collision can be estimated by considering the magnitude of EM dissociation

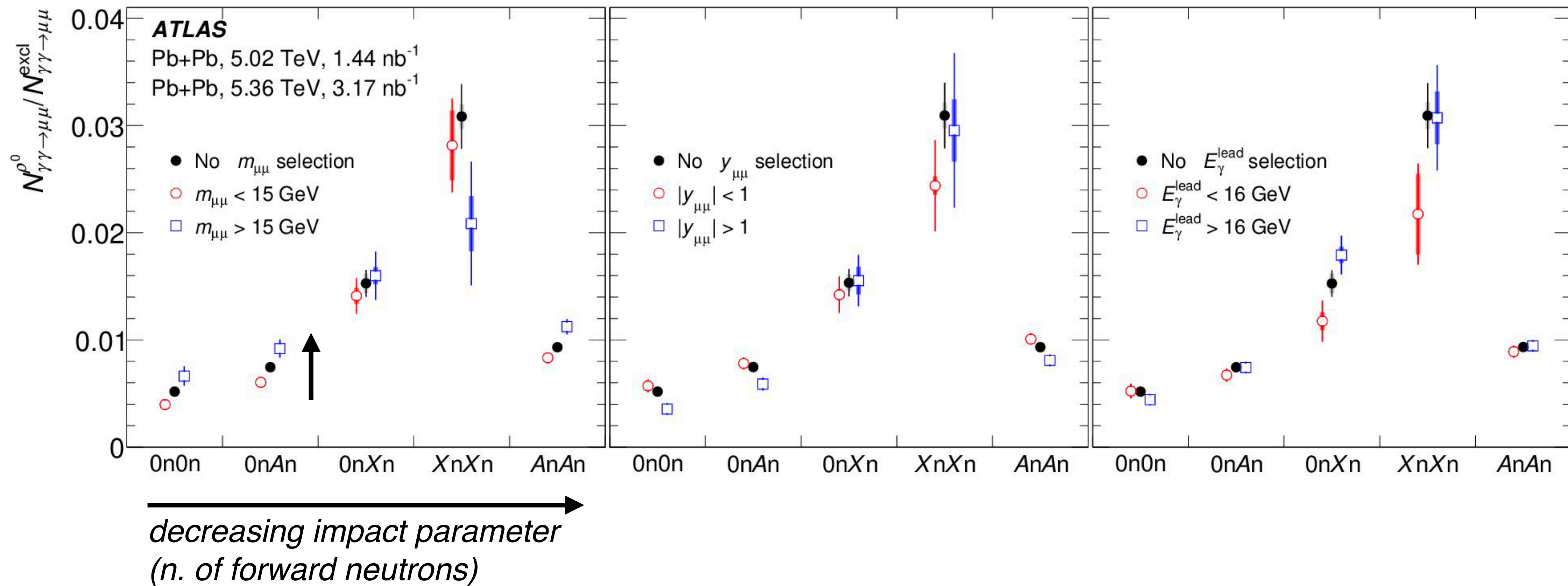


**EM dissociation (EMD) leads to neutron emission with additional photon exchange**

- Independent of interested physics process
- Large cross section  $\sim 200$  b (single EMD)

Probability of EMD is strongly correlated with the impact parameter of the collision  $\mathbf{b}$

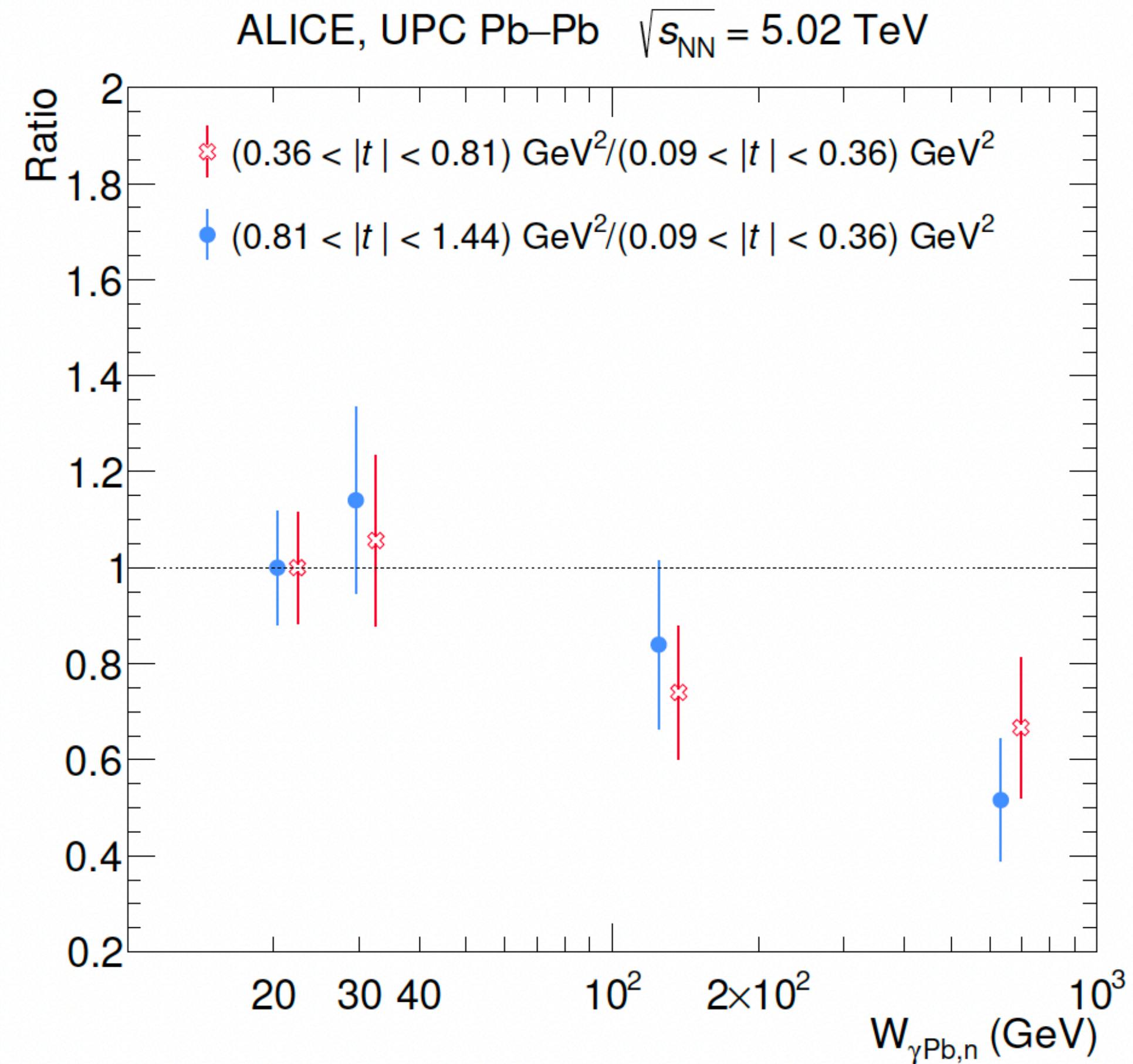
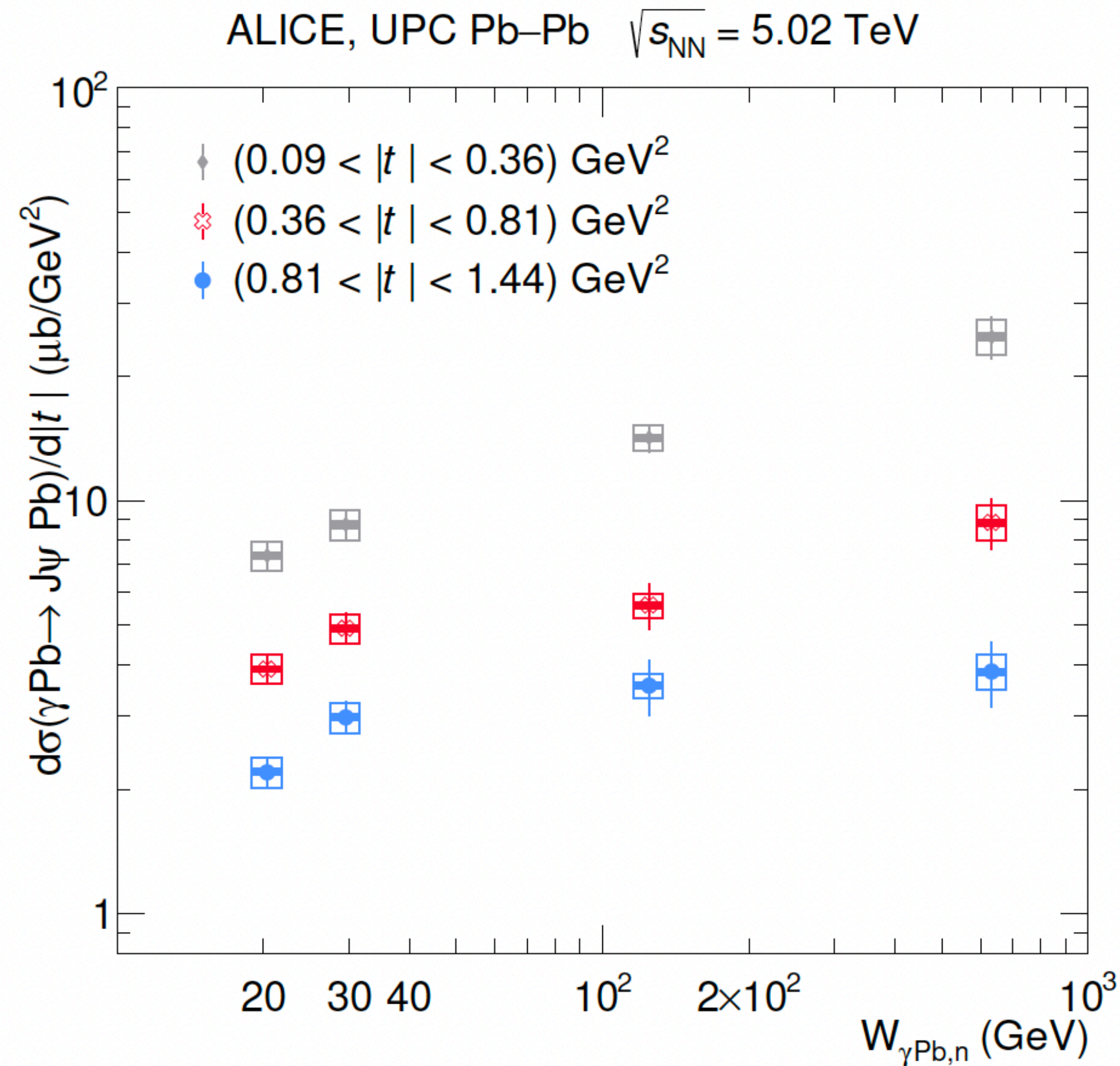
# $\rho^0$ production in coincidence with $\gamma\gamma \rightarrow \mu^+\mu^-$ events



**On average, nearly 1% of dimuon events coincide with  $\rho^0$  production in this kinematic range**  
 → **significant increase of the coincident rate for decreasing impact parameters**  
 (number of forward neutrons, dimuon invariant mass, or rapidity)

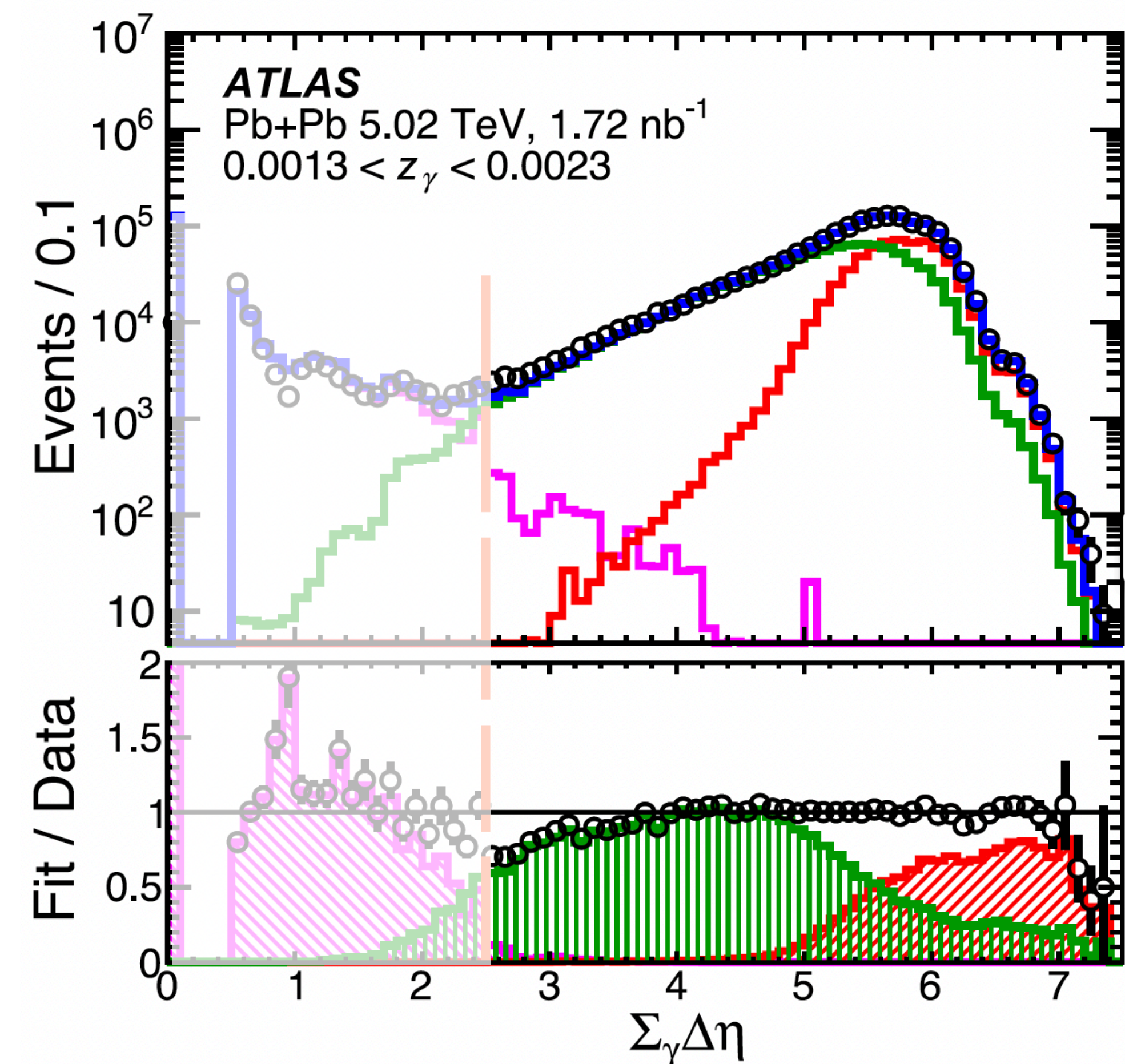
# J/ψ suppression in incoherent photonuclear production

ALICE, [arXiv.2503.18708v1](https://arxiv.org/abs/2503.18708v1)



**BACKUP: jets and open heavy-flavor  
photoproduction**

# Monte Carlo and phenomenological tools for UPCs



Total width gap in the photon-going direction

— pythia 8 Direct MC  
— pythia 8 Resolved MC  
— Hadronic Background

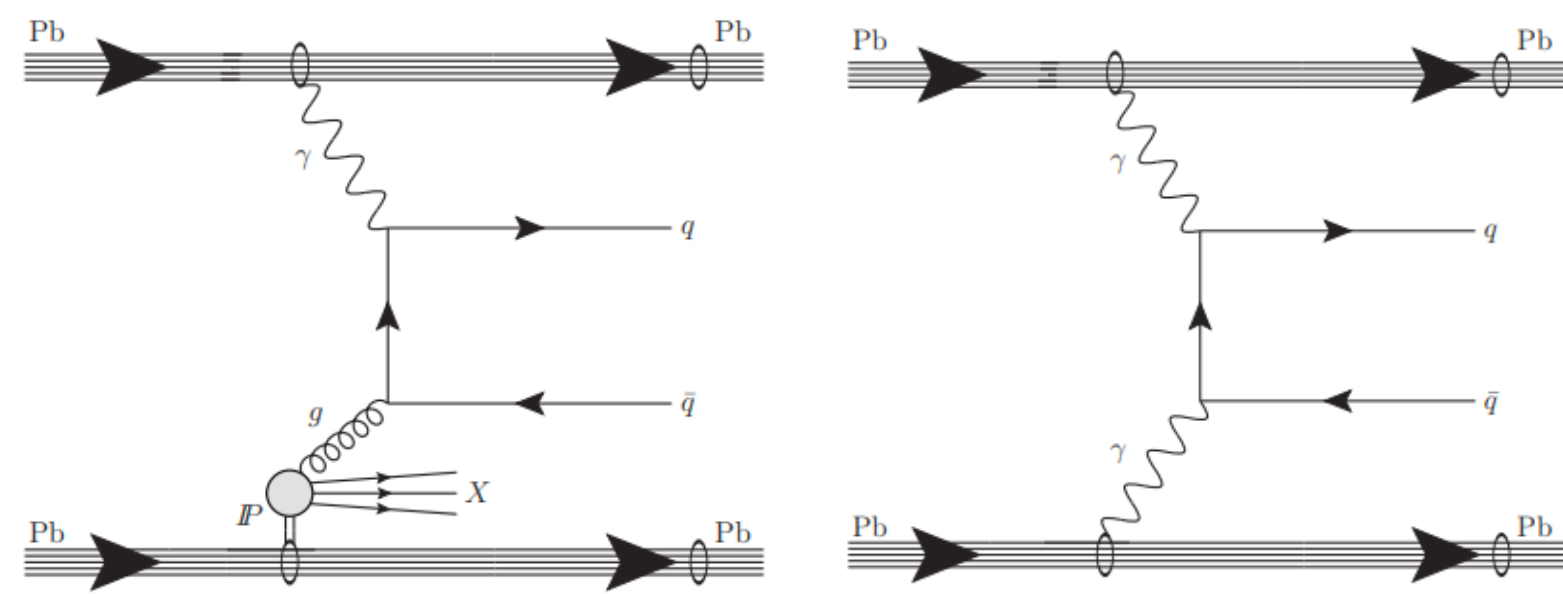
— Total  
○ Data

**Under the push of these new measurements:**

- Hard UPC processes embedded in MCs (e.g., Pythia)
- improved modeling of the photon flux, including spatial effects

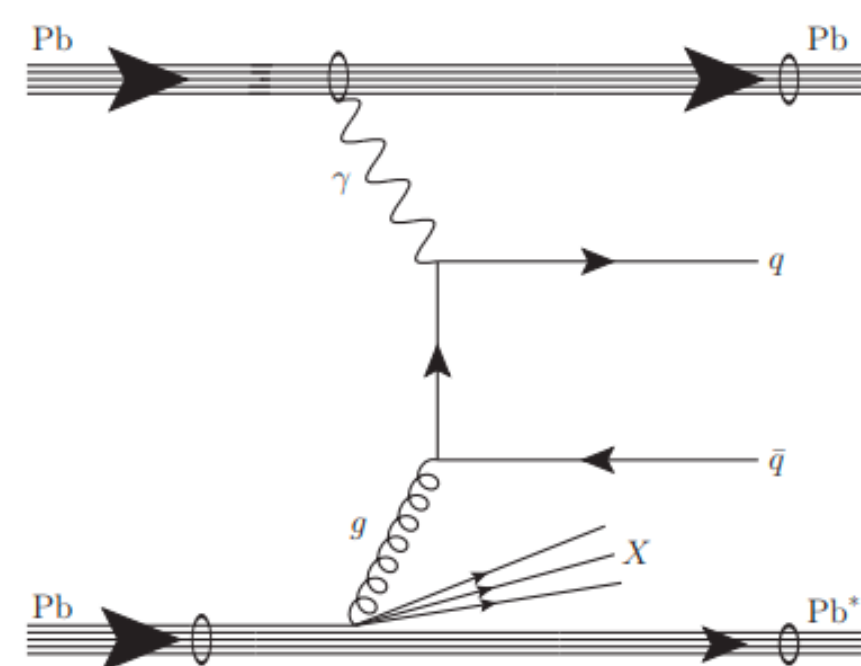
V. Guzey and M. Klasen, Phys. Rev. C 99, 065202 (2019)  
K. J. Eskola, et al., Phys. Rev. C 110, 054906 (2024)  
L. A. Harland-Lang, Phys. Rev. D 107, 093004 (2023)  
I. Helenius et al., Eur. Phys. J. C 79, 413 (2019)

# UPC jets without forward neutron production (0n0n)

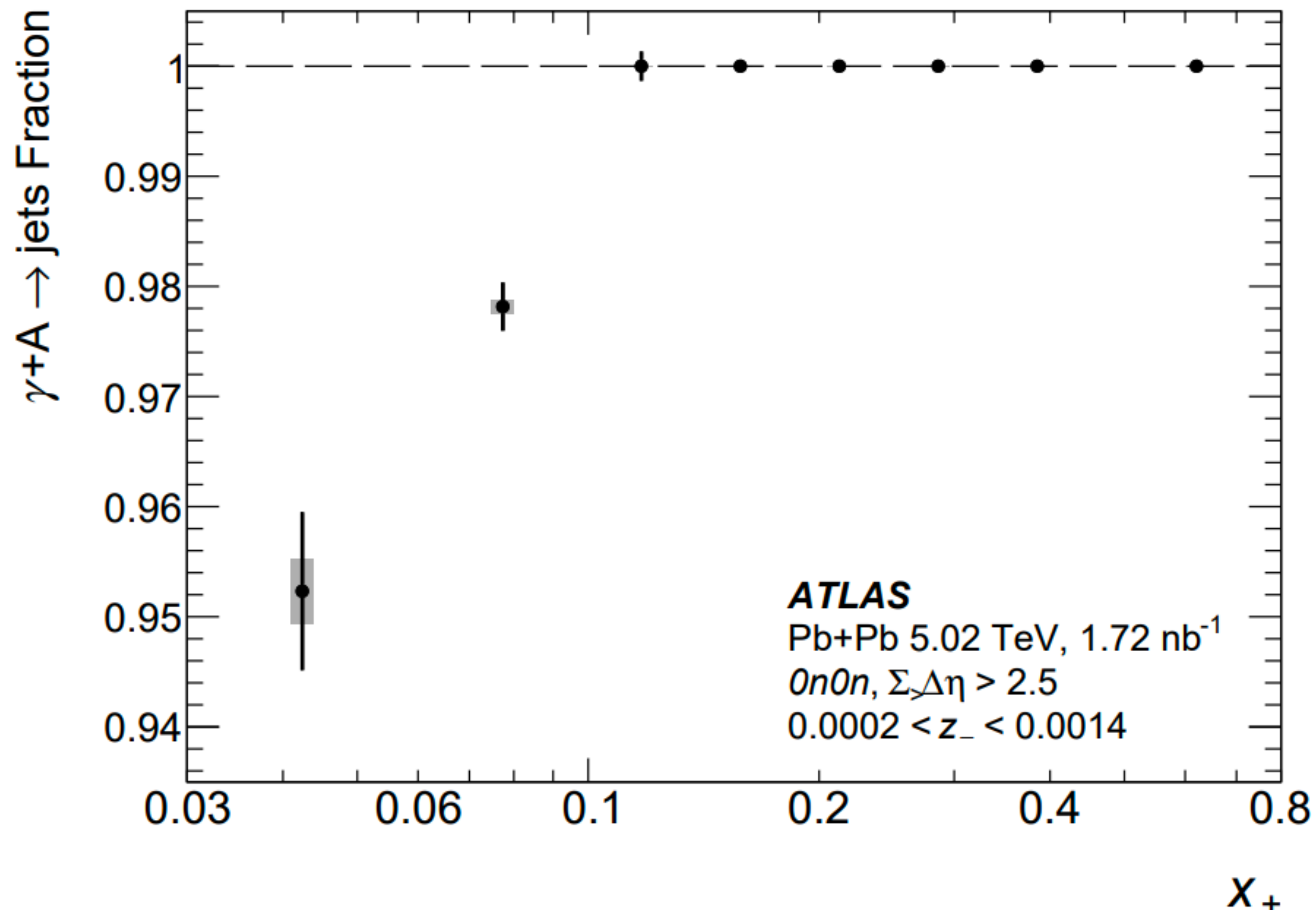


**Coherent  
diffraction ( $\gamma A$ )**

**$\gamma\gamma$  hard  
production**



Alvioli et al., arXiv.2402.19060  
 Larionov et al. arXiv.812.08231



## Non-diffractive $\gamma A$ without observed neutron emission

target excitation below neutron-emission threshold

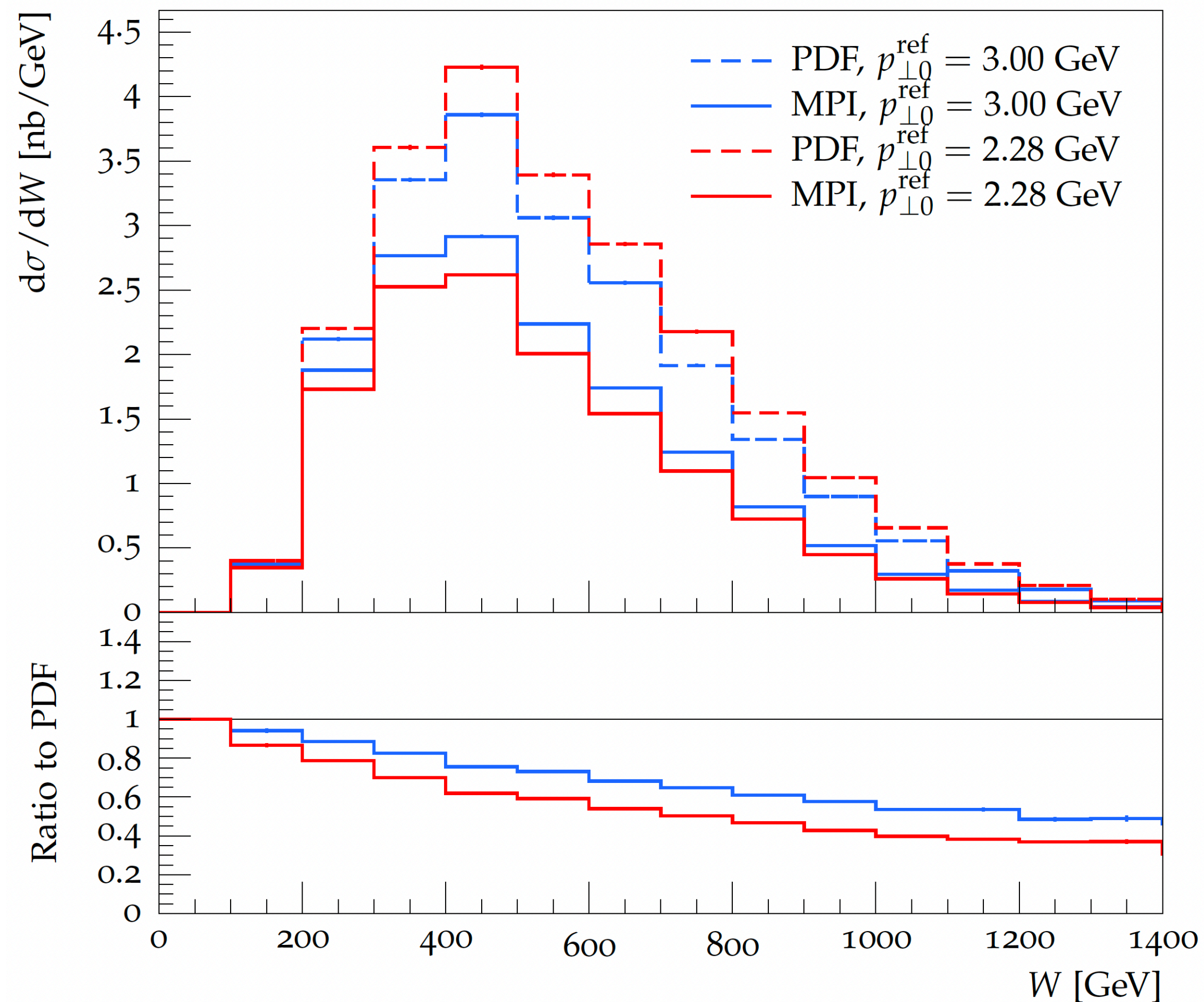
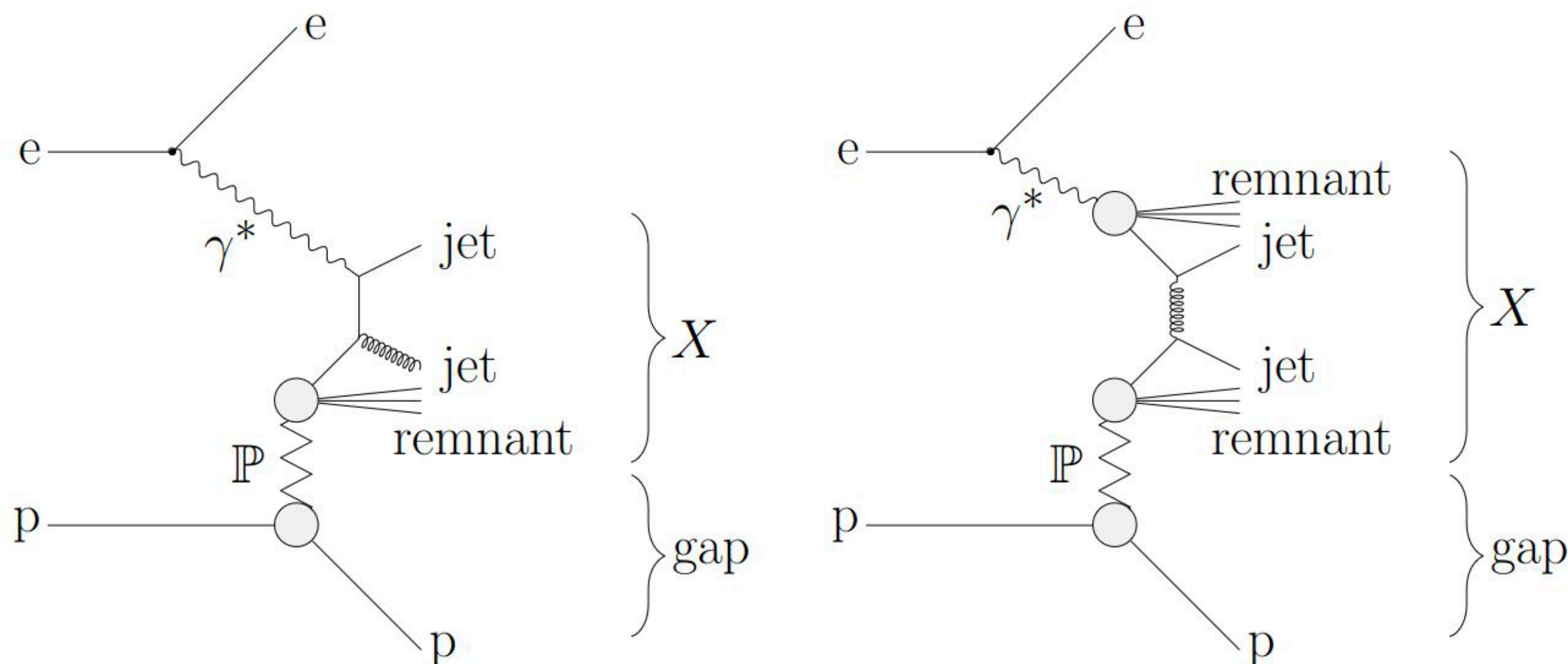
→ more likely to occur in “peripheral” UPCs

→ sensitivity to the impact-parameter dependence of nuclear PDFs

# Diffractive production of jets and heavy quarks

Ilkka Helenius, [arXiv:2107.07389](https://arxiv.org/abs/2107.07389)

C. Marquet, C. Rayon et al. [arXiv.1306.4901](https://arxiv.org/abs/1306.4901)

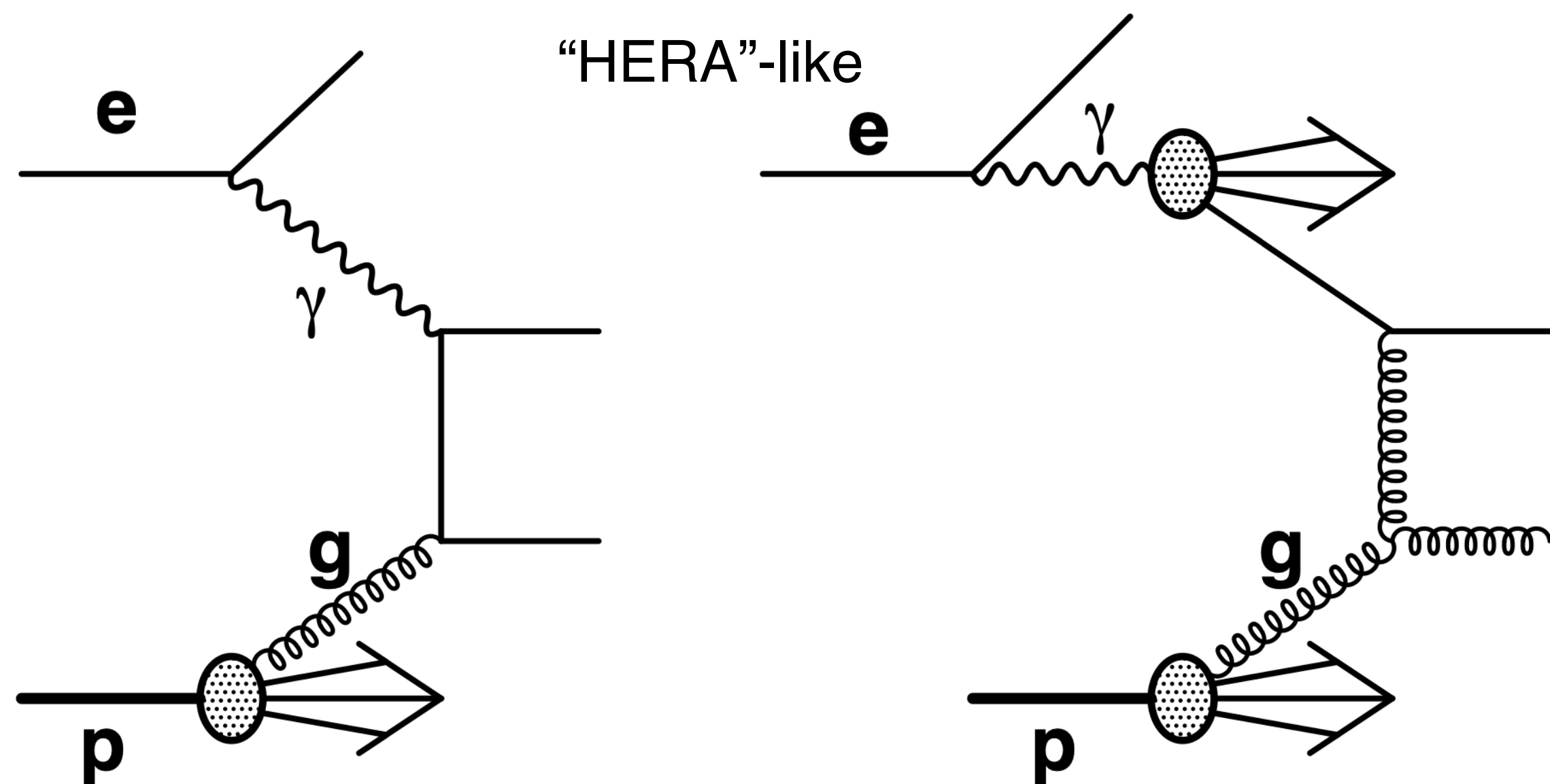


- **test for factorization**: diffractive PDFs  $\otimes$  partonic coefficient functions
- benchmark for PbPb measurements

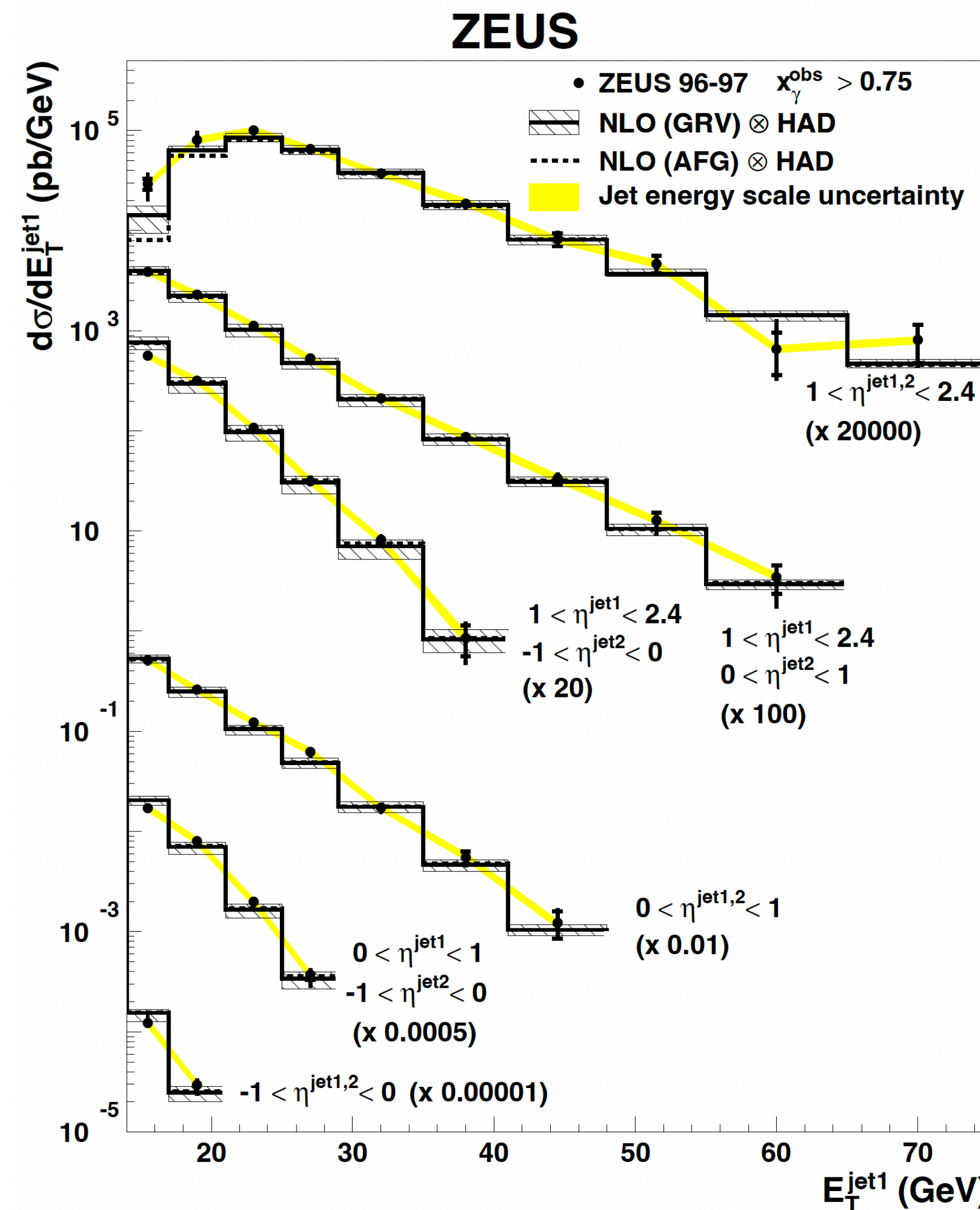
**Need for theoretical calculations and MC simulations for diffractive events in both  $\gamma p$  and  $\gamma Pb$  collisions!**

# Jets and open heavy-quarks in $\gamma p$ scatterings in pPb collisions

→  $\gamma p$  scatterings in pPb collisions as the baseline for  $\gamma Pb$  measurements



In combination with HERA and EIC measurements:  
 → **New constraints on proton PDFs, GDF, TMD**  
 at the highest  $\gamma p$  center of mass energies available

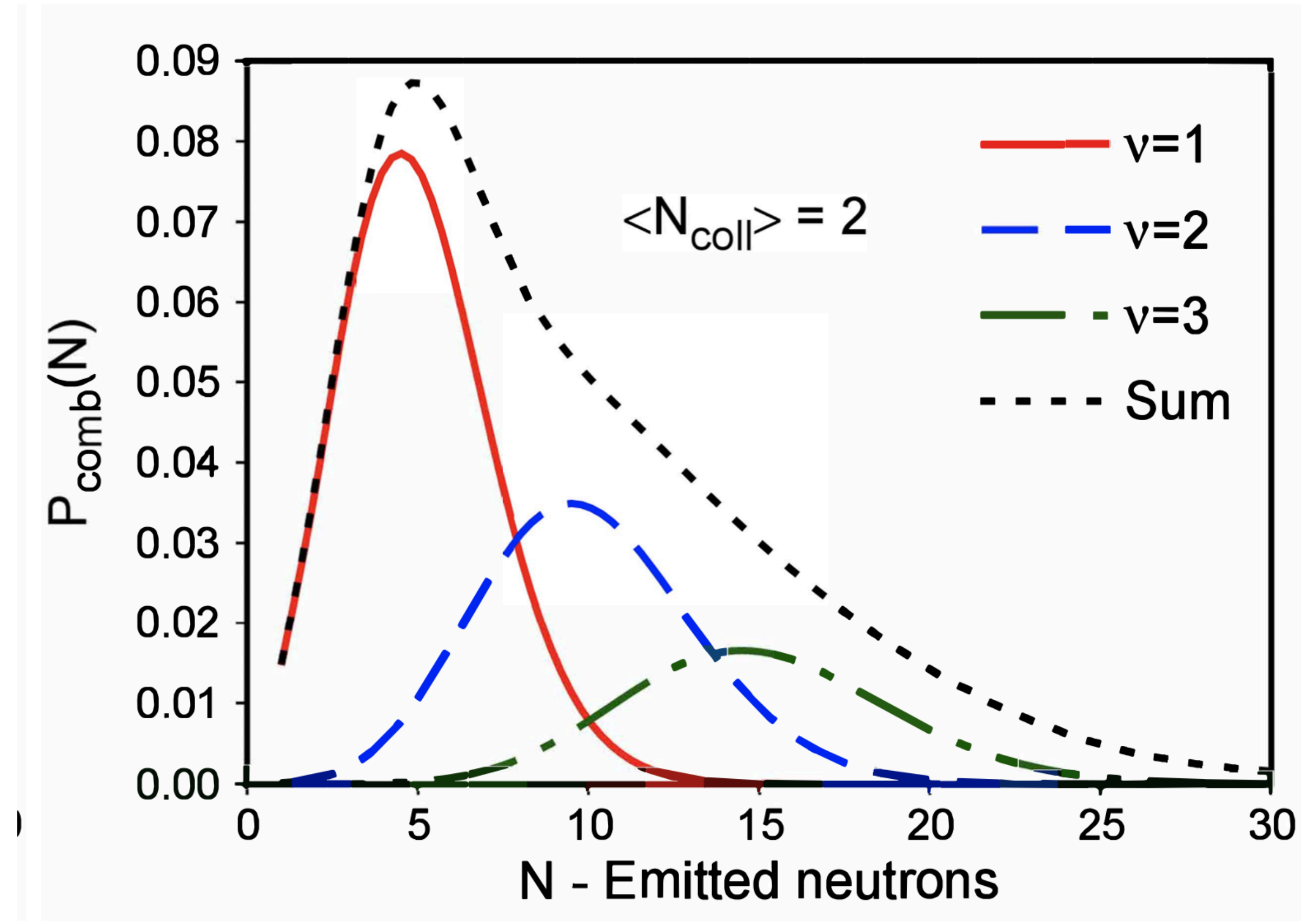
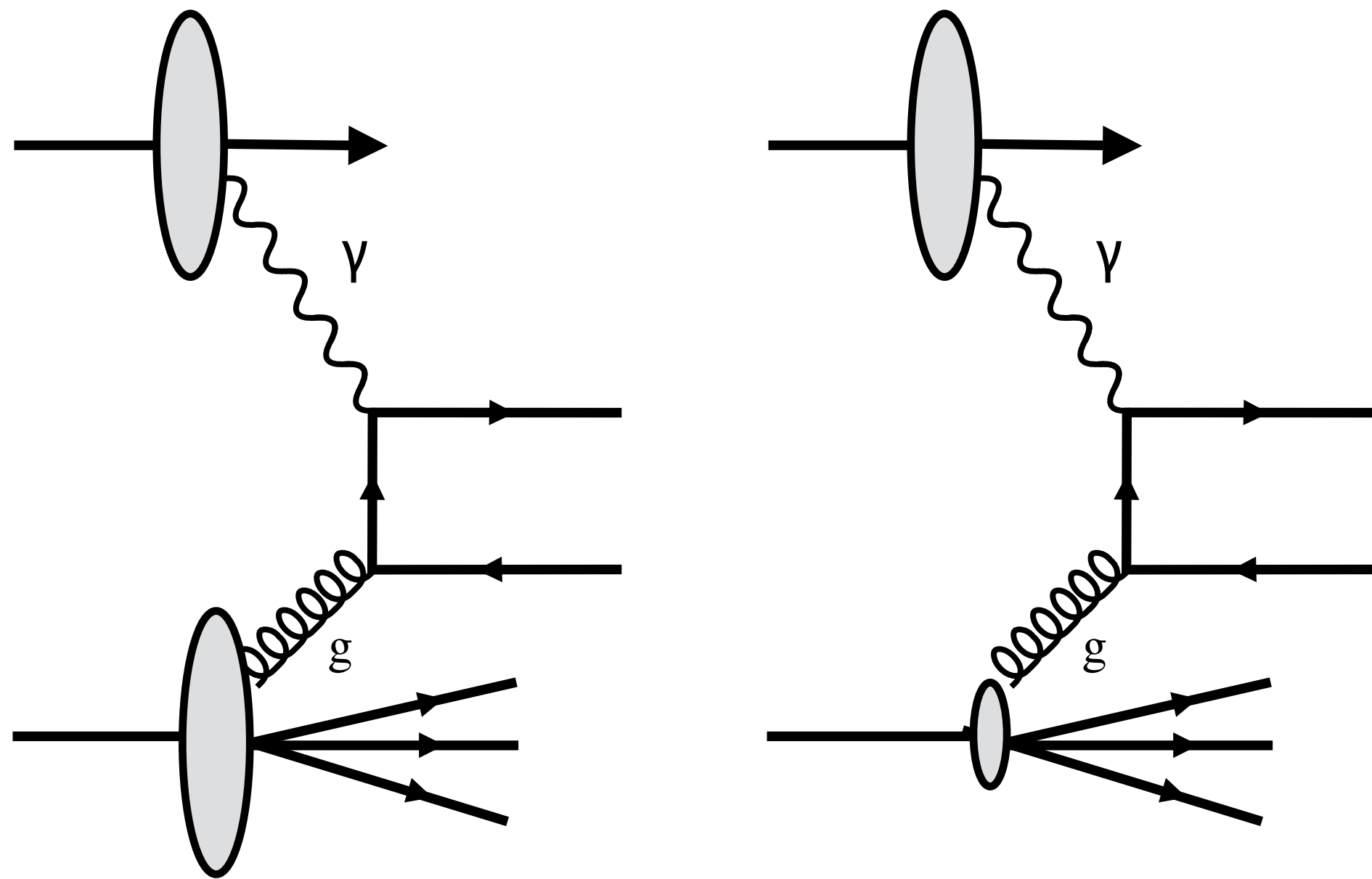


ZEUS, Eur.Phys.J.C23:615-631,2002

# New observables in $\gamma p/\gamma Pb$ collisions

**Basic concept:** “over-constraining” low-x models by measuring both barrel and very forward observables

M. Strikman, V. Guzey et al., [arXiv.2402.19060](https://arxiv.org/abs/2402.19060)



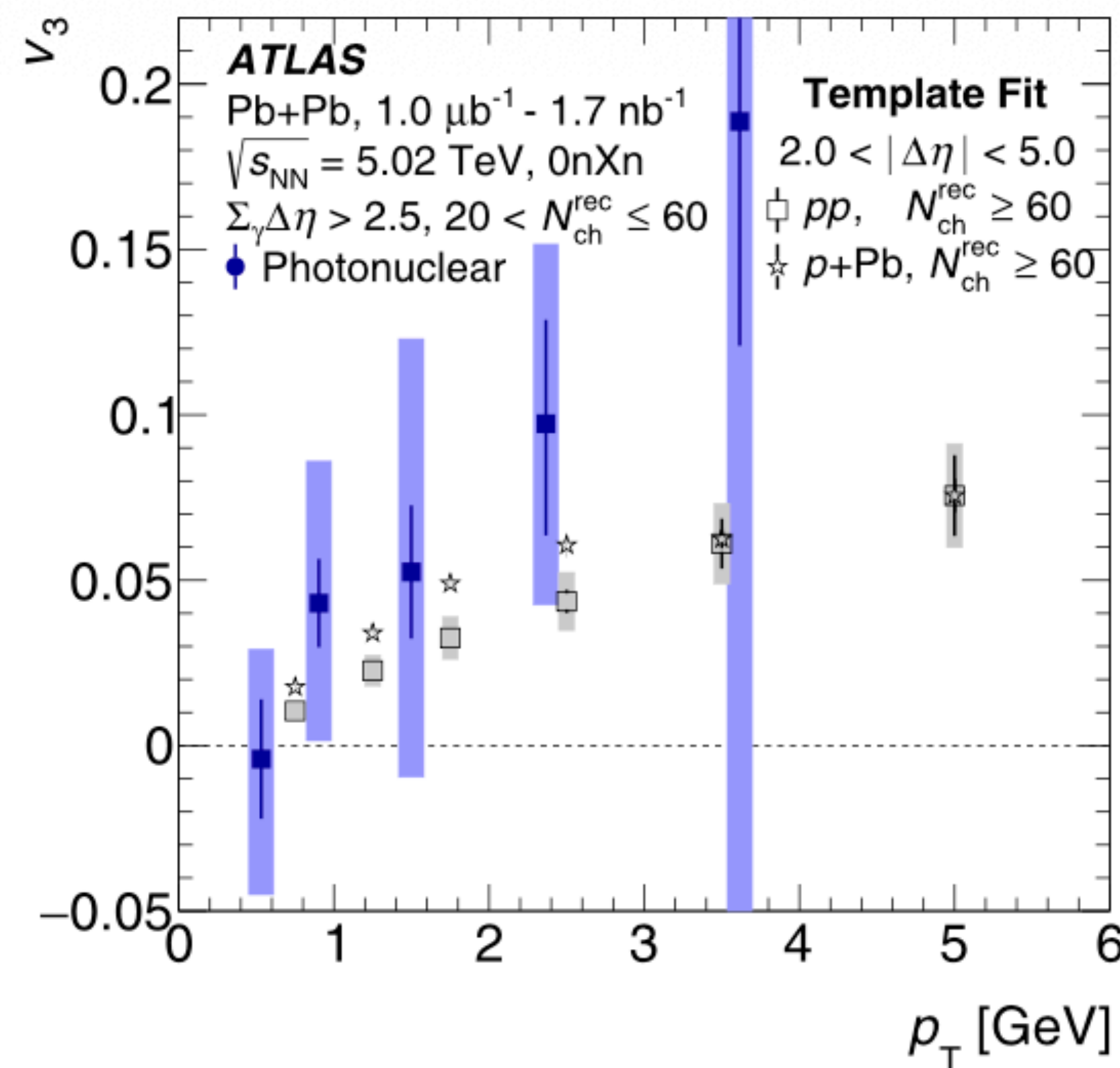
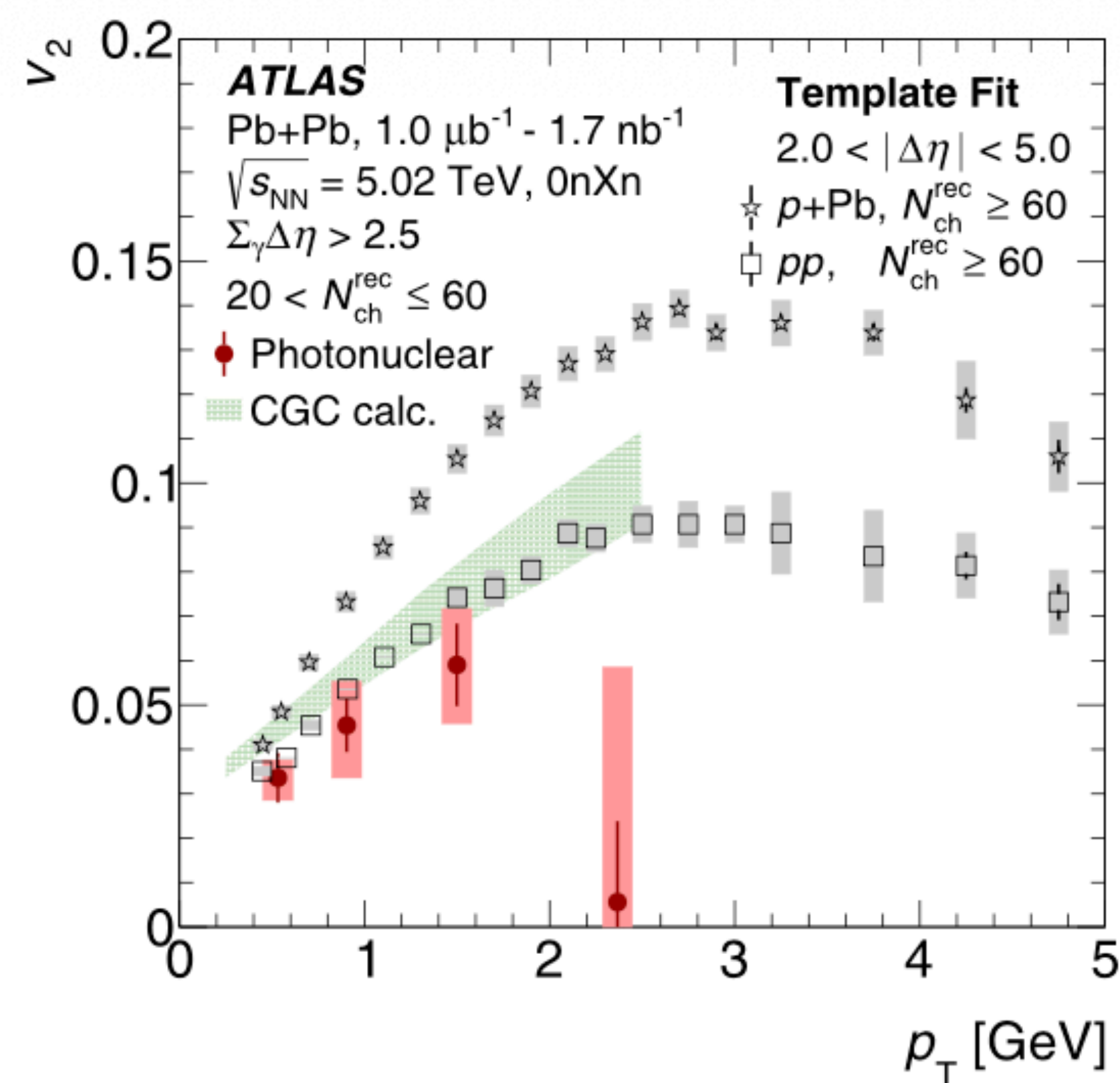
**Hard-scattering production at central rapidities with information on the number of neutrons in ZDC:**

→ stronger discrimination power on low-x nuclear matter

→ **new experimental challenges for ZDC reconstruction and calibration**

**How “cold” are UPCs?**

# An open question: flow in $\gamma$ Pb collisions?



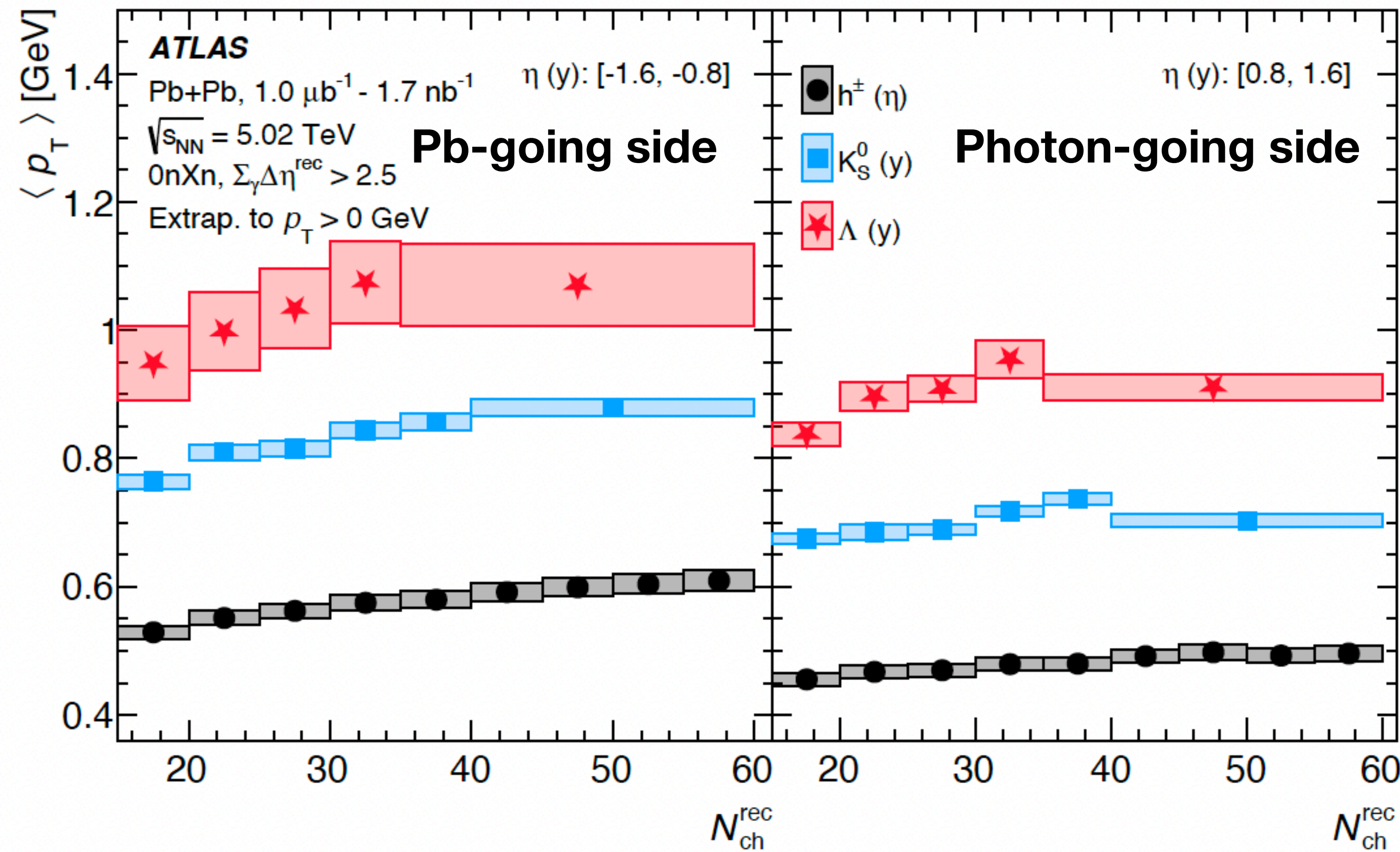
**Non-zero positive  $v_2$  and  $v_3$  observed in high-multiplicity  $\gamma$ Pb photonuclear events (with nuclear breakup Xn0n)**

- Medium-like system converting initial anisotropy generated by photon fluctuations?
- early-time correlations between gluon fields in the color glass condensate?

**Disclaimer: flow in UPCs must be handled with care!**

# Radial-flow-like signatures in photonuclear collisions?

ATLAS, Phys. Rev. C 111, 064908



$\langle p_T \rangle$  increases with  $N_{ch}$   
 for all species

**Mass ordering:**  
 $\langle p_T(\pi) \rangle < \langle p_T(K_S^0) \rangle < \langle p_T(\Lambda) \rangle$

$\langle p_T \rangle$  is larger in the direction of the outgoing broken nucleus:  
 → quantitatively consistent with the pPb  $\langle p_T \rangle$

While smaller than in hadronic collisions, **the role of final-state effects in photonuclear collisions needs to be addressed**  
 (both in UPCs at the LHC and in eA at the EIC)