Laboratory for Nuclear Science

Cold nuclear matter in CMS

→ *focus on recent UPC measurements*

Cold Nuclear Matter Effects: from the LHC to the EIC

January 13th 2025

Gian Michele Innocenti (MIT)

MIT HIG group's work was supported by US DOE-NP

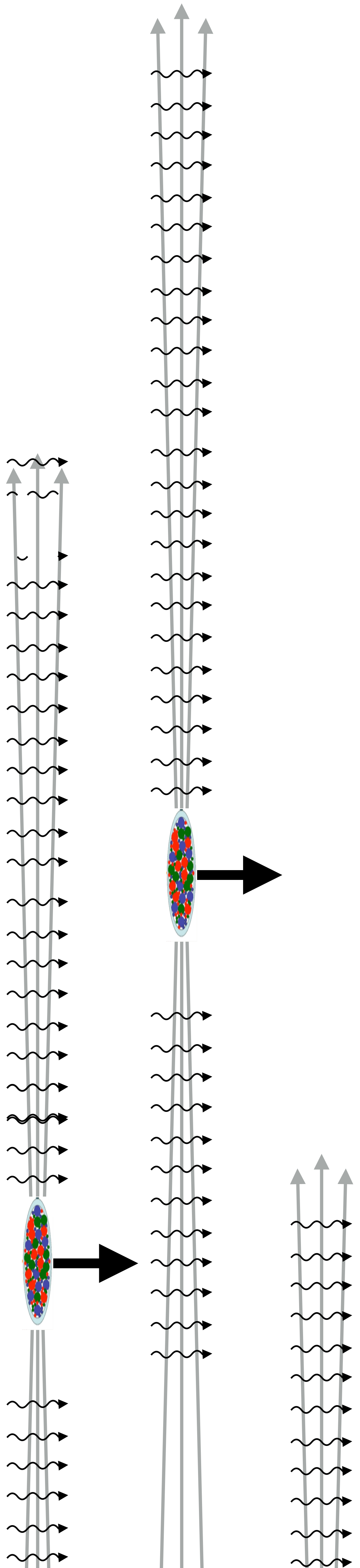
Focus of this talk

LHC as a photon-hadron collider

Coherent and incoherent J/ψ production in PbPb UPCs

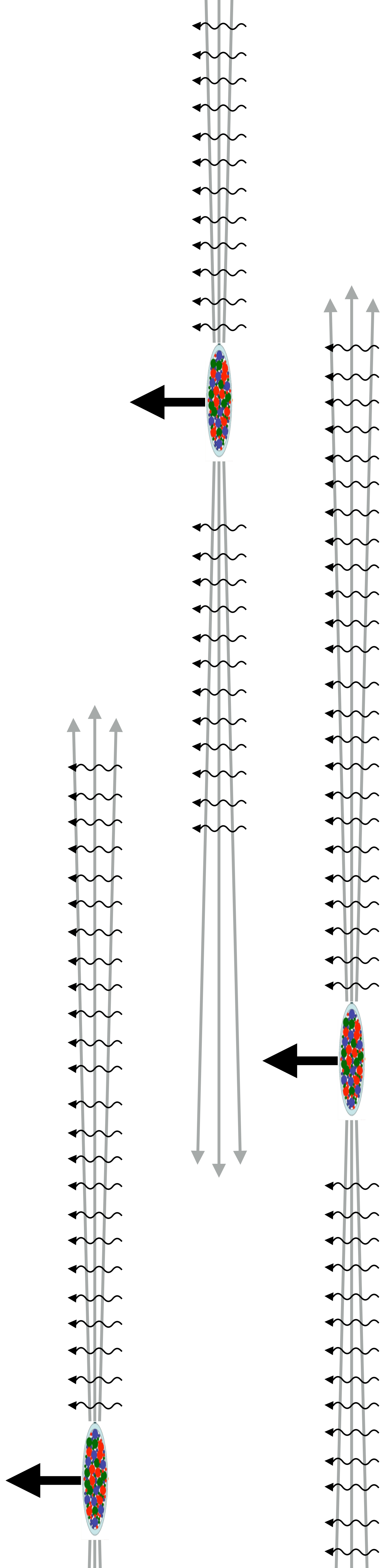
Open heavy-flavor production in UPCs:
→a new tool for high-precision characterization of cold-nuclear matter
- first results on photonuclear D^0 production in PbPb collisions with CMS
- near and long-term prospects

Collisions of heavy-ion "bunches" at the LHC



Pb "bunch" 1

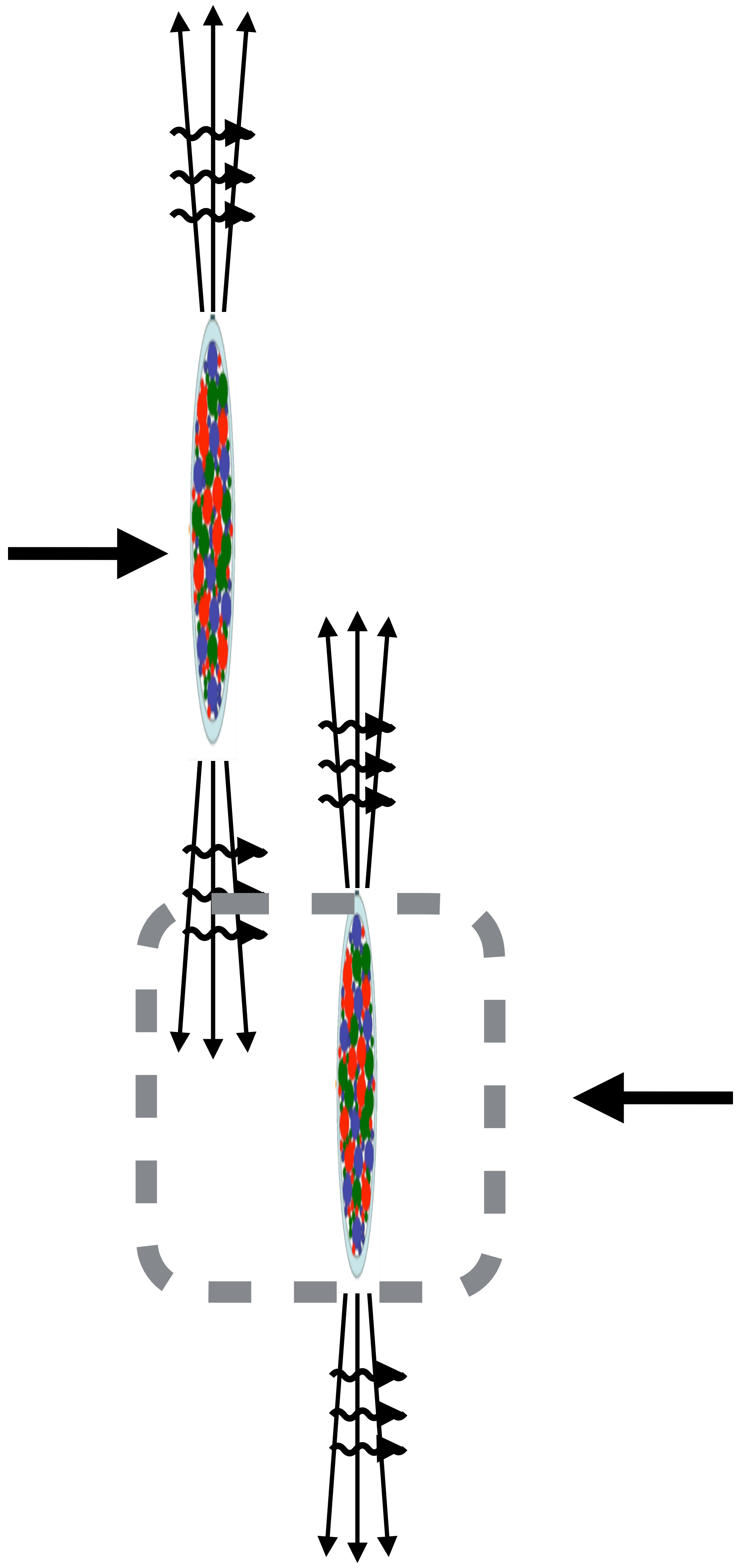
Pb "bunch" 2

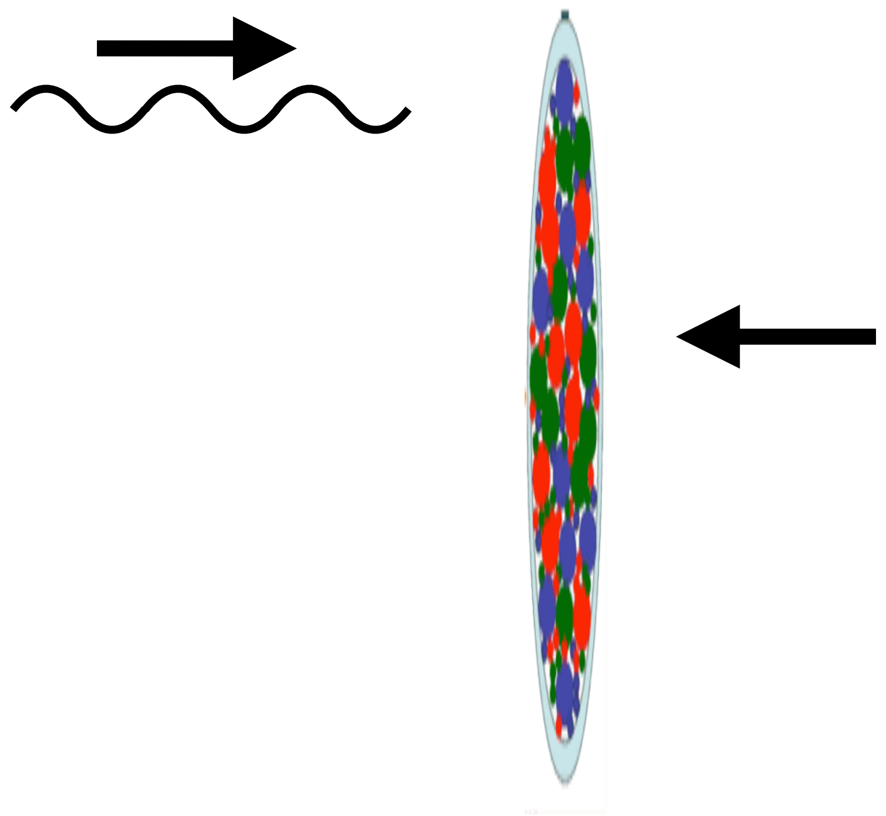


1 bunch-bunch interaction (crossing) every 50 nanoseconds
→ ***less than 1% of the collisions are "hadronic"!***

The Large Hadron "Photon" Collider

→ many photon-photon or photon nucleus collisions in so-called **ultraperipheral heavy-ion collisions (UPCs)**





Photon-nucleus collision in UPCs:

- highest γ-nucleon center-of-mass energy accessible
- large flux of photons (~Z^2)

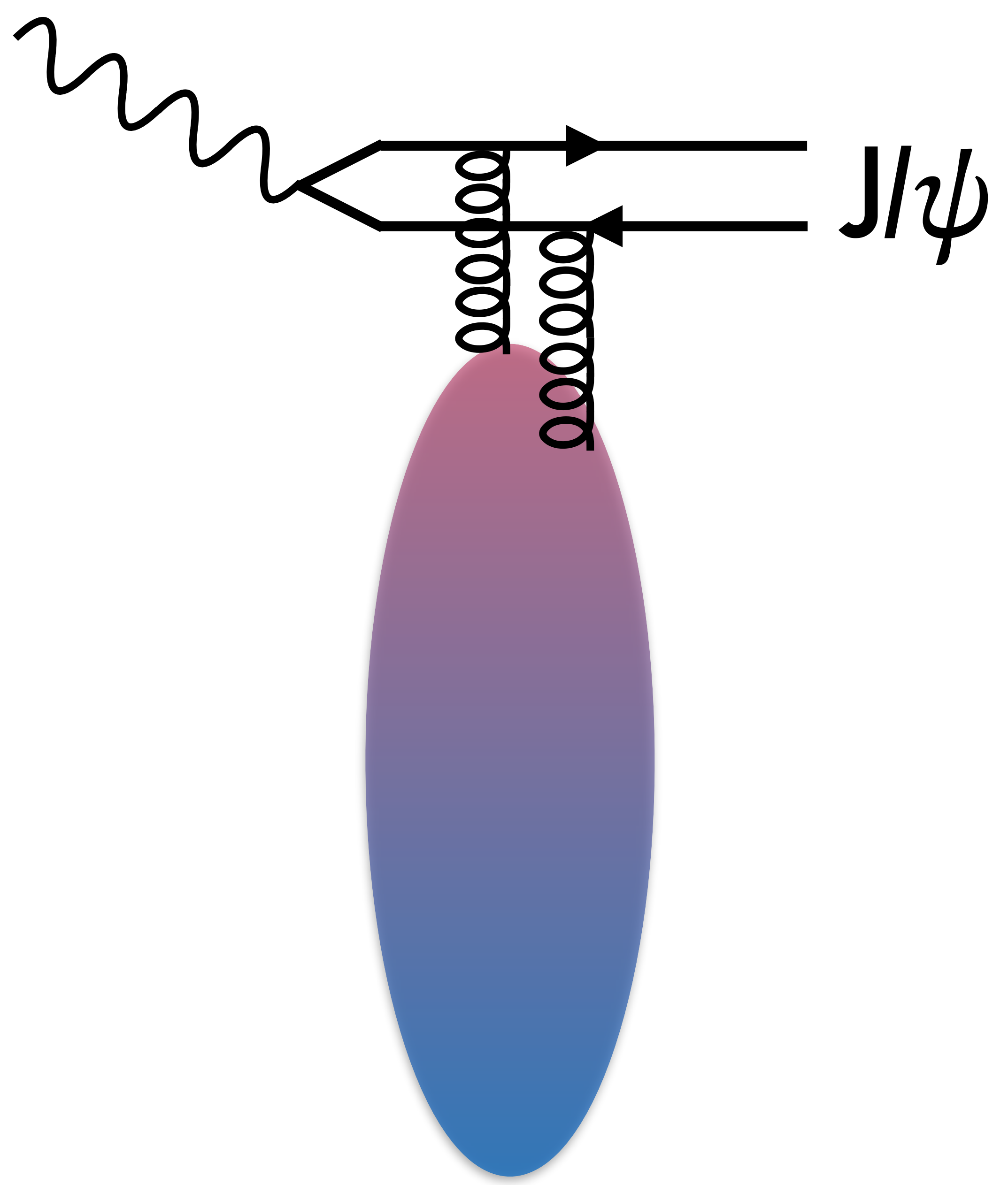
→ unique tools to study the **properties of quarks and gluons in nuclei at extremely high partonic densities**

CMS, Phys. Rev. Lett. 131 (2023) 262301

Coherent J/ψ production in PbPb UPCs

Low p_T J/ψ (~50 MeV)

- Photon interacts coherently with the nucleus
  → **average gluon density at fixed Q^2**



Two-way ambiguity solved by using ZDC information (V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942) → **see backup**

CMS, Phys. Rev. Lett. 131 (2023) 262301

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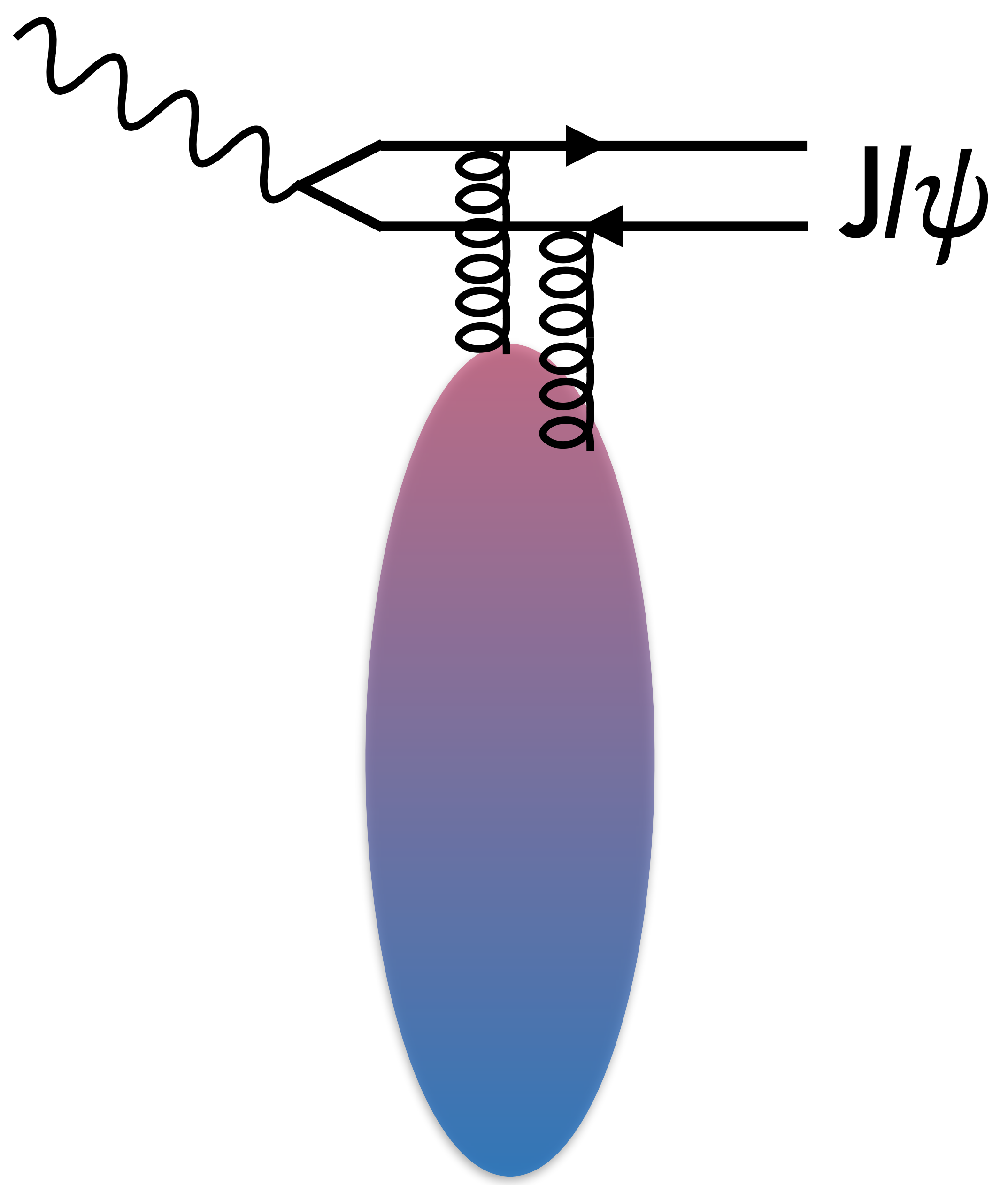
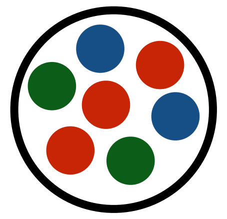
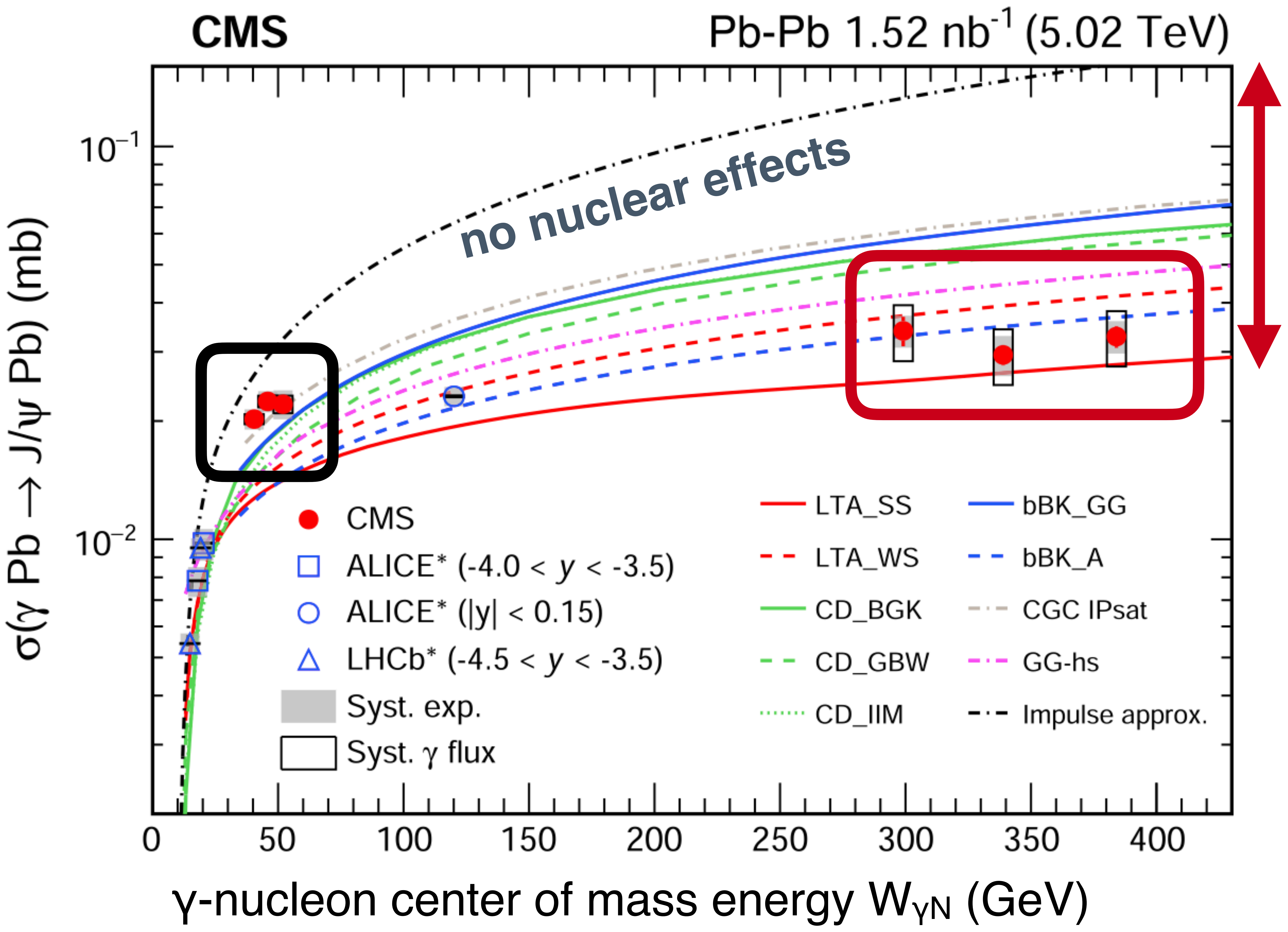


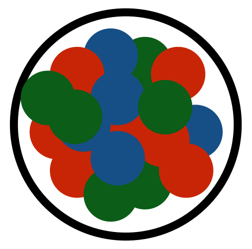
large x_{BJ}





$x_{BJ} < 10^{-4}$
$Q^2 \sim m^2_{c\bar{c}}$

small x_{BJ}



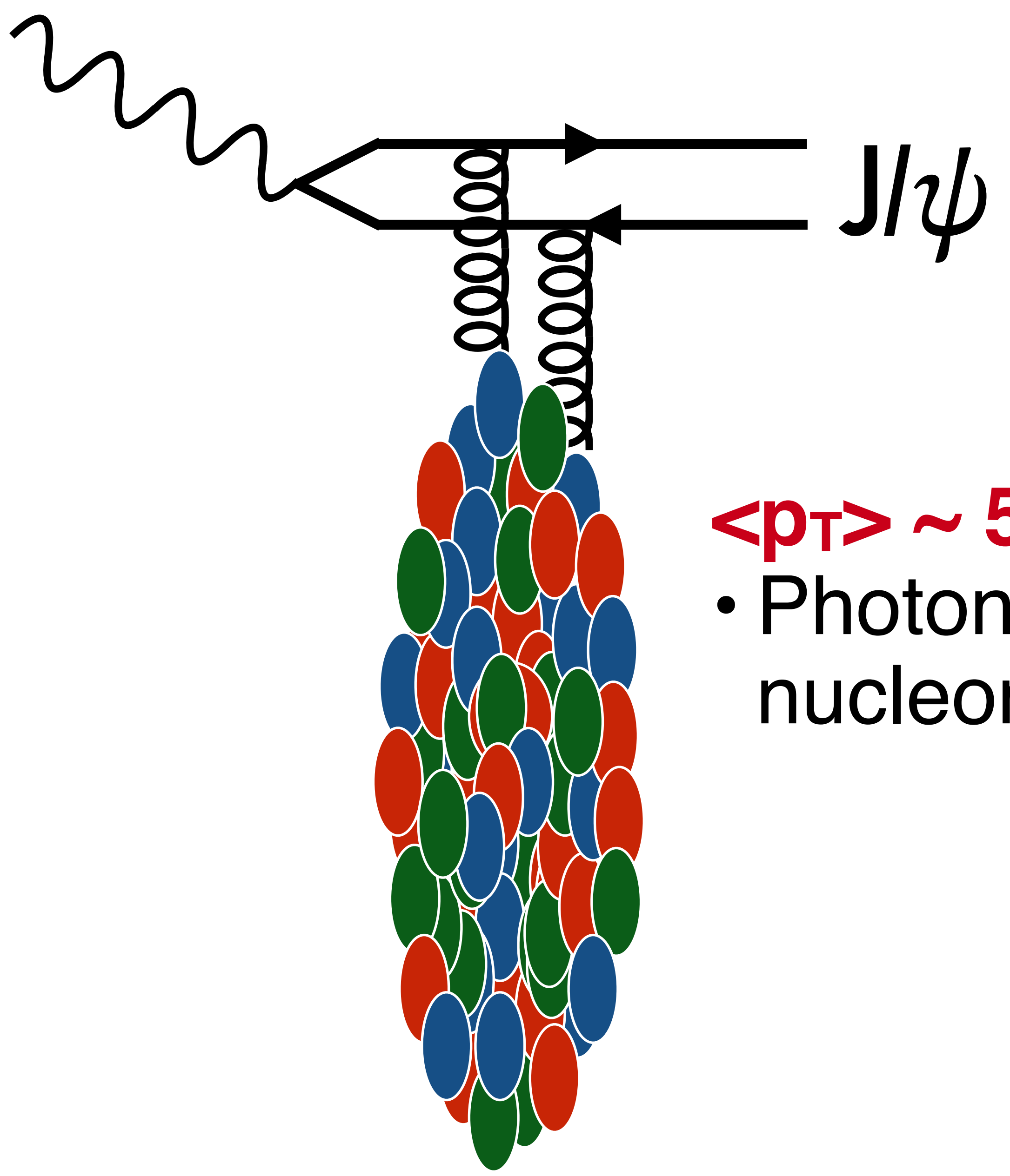
→ **strong suppression at high $W_{\gamma N}$ values (small x_{BJ})** compared to scenarios without nuclear effect (IA)

→ **both shadowing models (*linear evolution*) and saturation (non-linear) fail in describing the observed $W_{\gamma N}$ dependence**

First measurement of incoherent J/ψ in UPCs vs $W_{\gamma N}$

CMS-PAS-HIN-23-009

→ **Probing the local gluon density and fluctuations**



$\langle p_T \rangle$ ~ 500 MeV

- Photon interacts with a single nucleon or sub-nucleon

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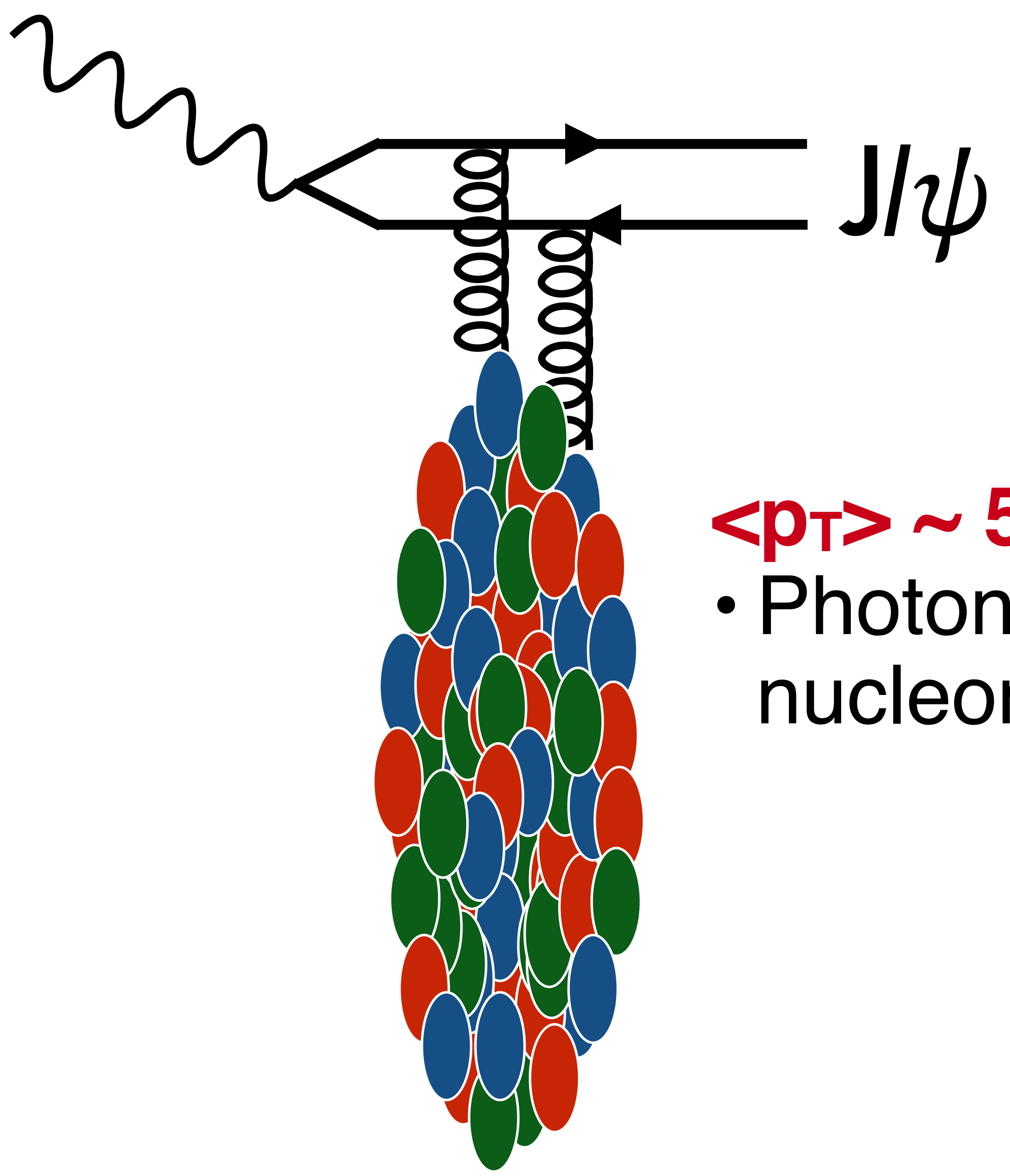

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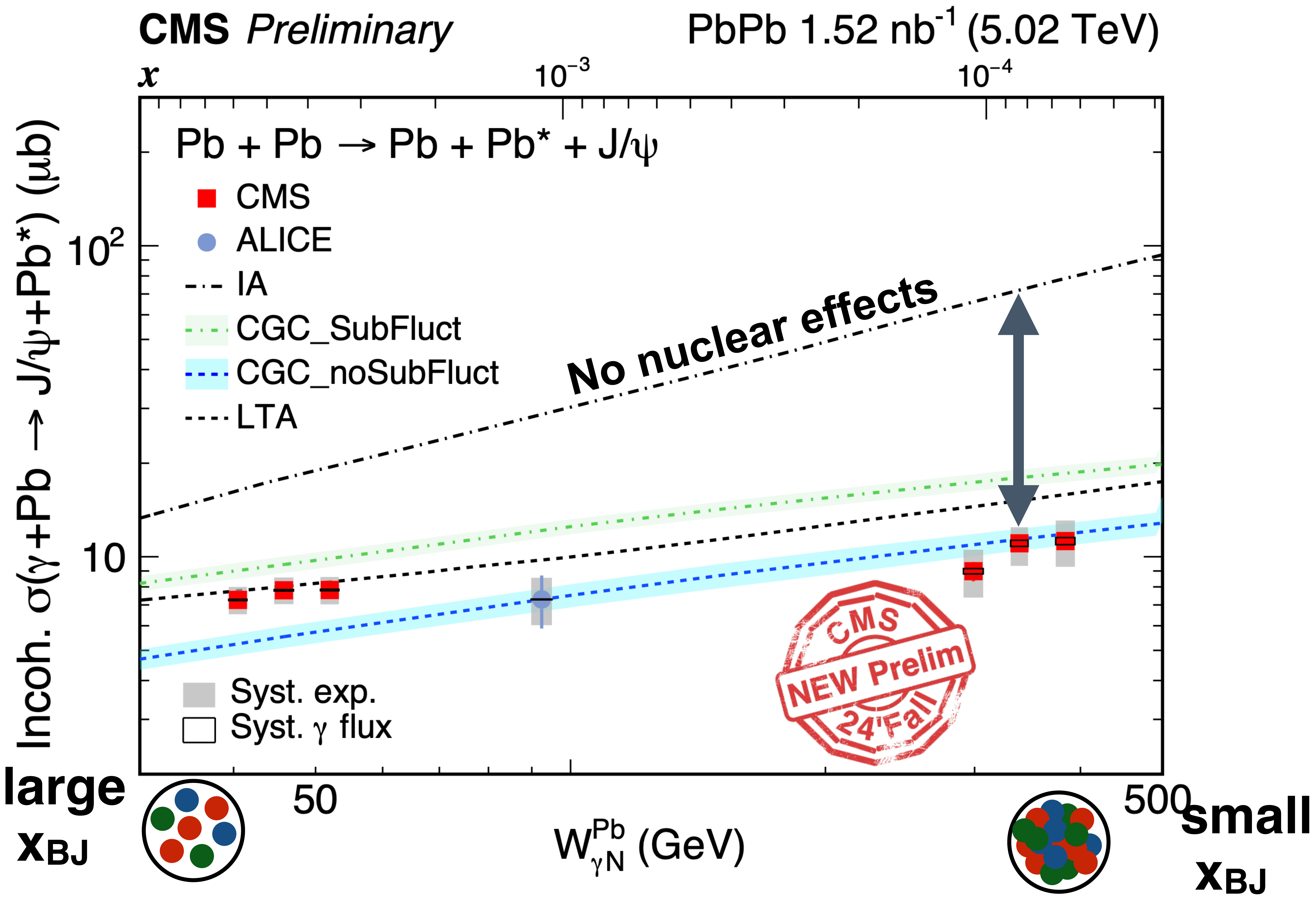
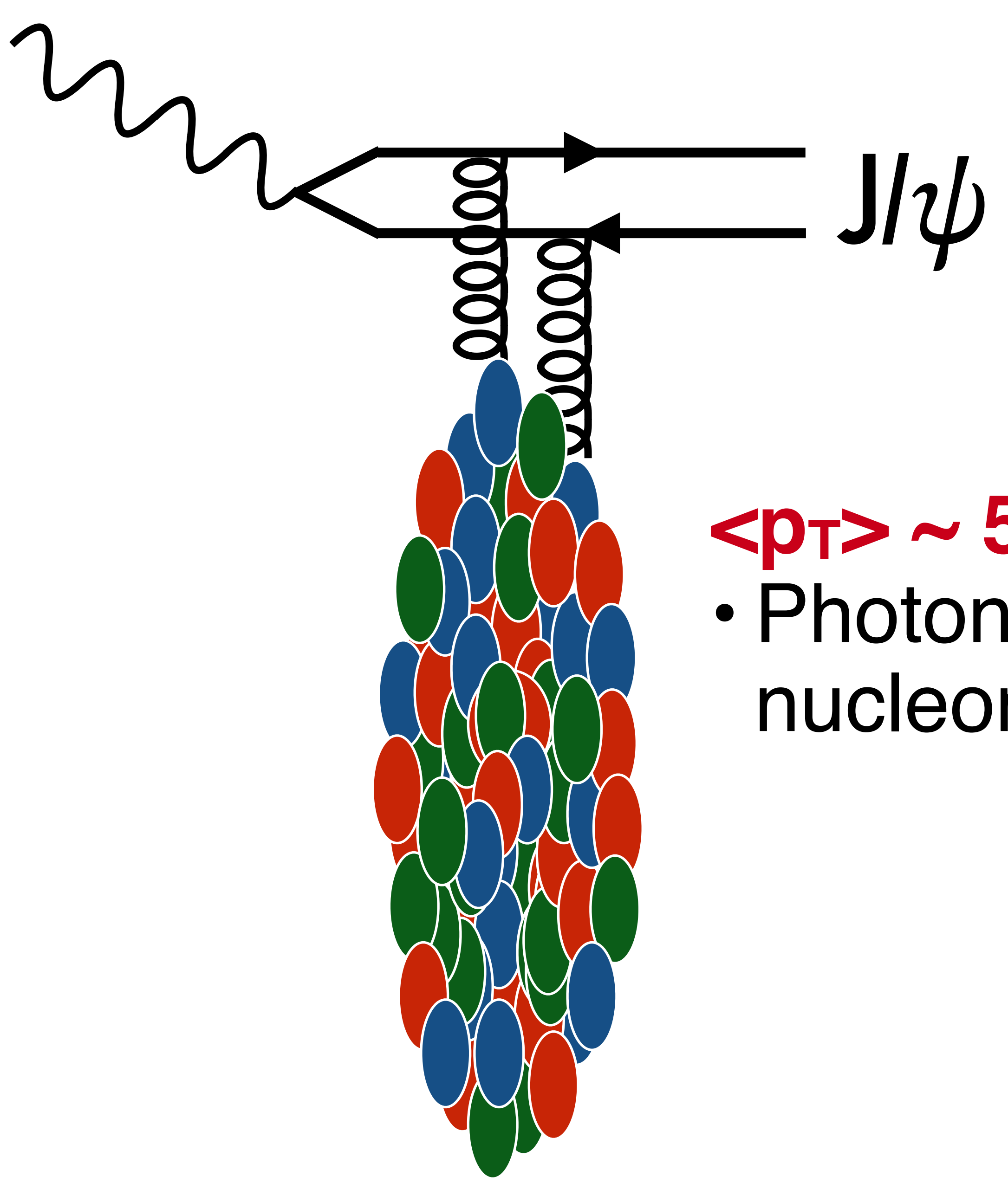


Strong suppression observed at large $W_{\gamma N}$ (small x) w.r.t. no-nuclear effects predictions

- **CMS data "challenge" both shadowing and saturation descriptions**

Incoherent/coherent J/ψ in UPCs

CMS-PAS-HIN-23-009



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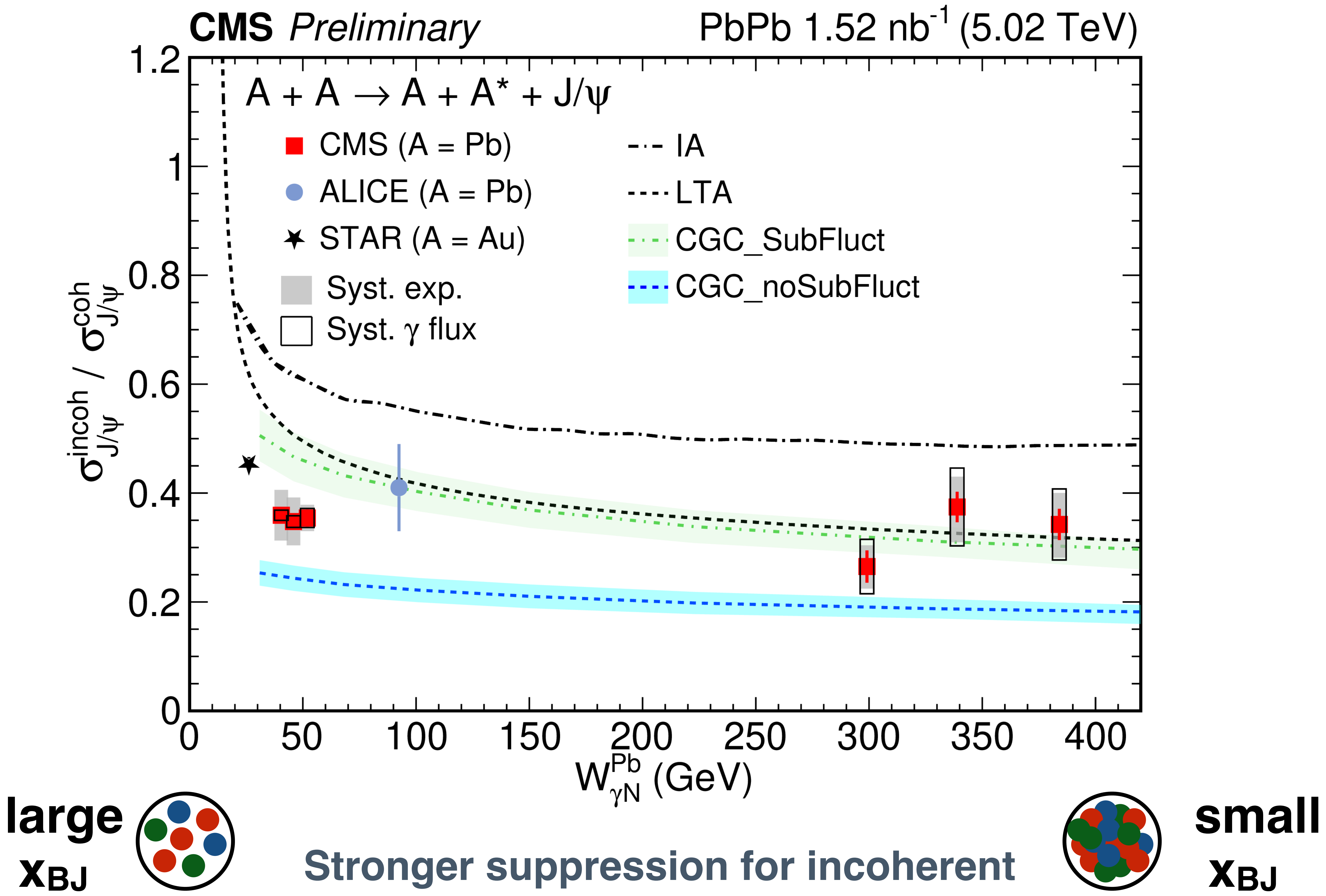


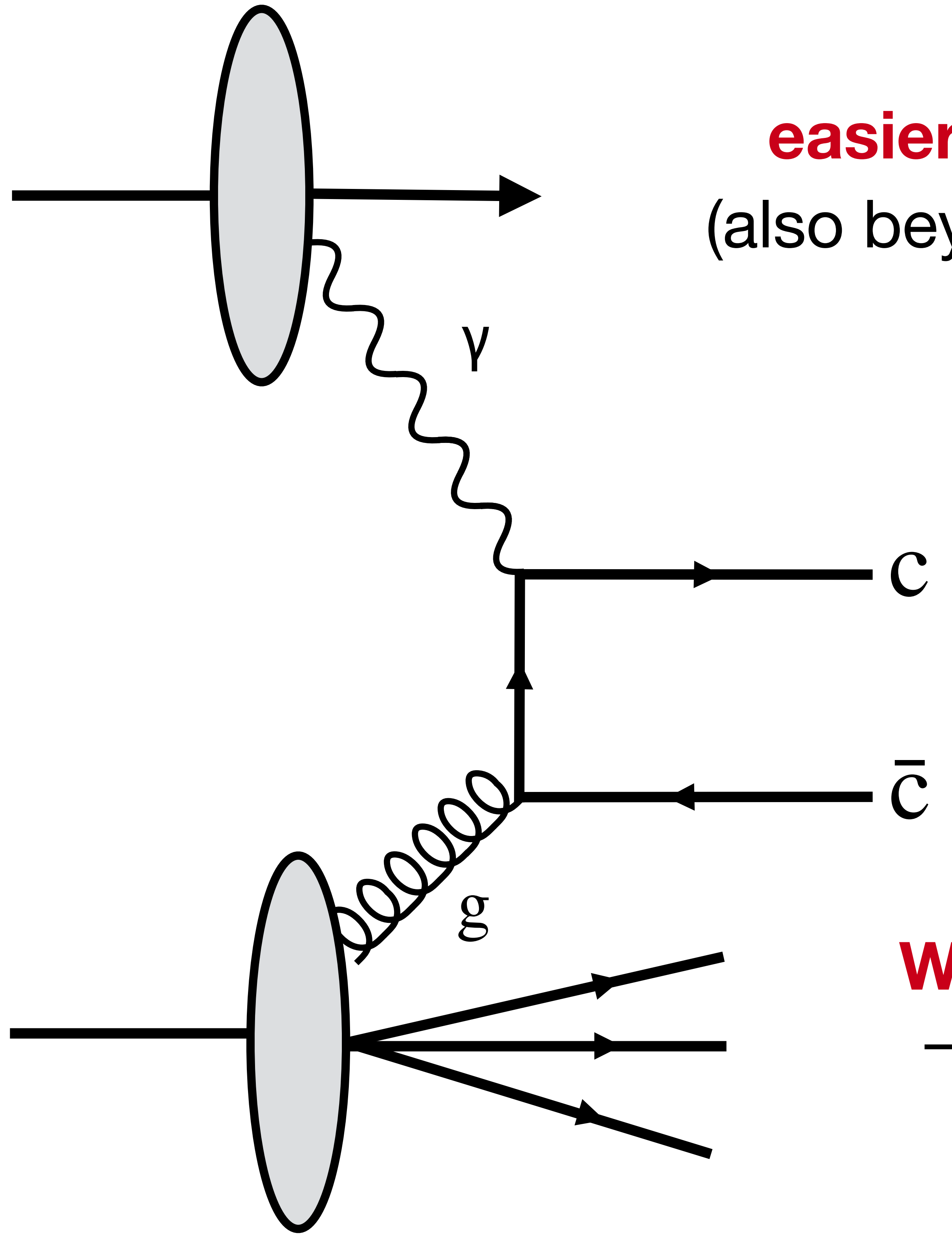
Stronger suppression for incoherent than coherent production

- **No clear W dependent observed within 40<W<400 GeV)**

→ New high-accuracy constraints on theoretical calculations, which fail to provide a comprehensive description

→ Need to "over-constrain" calculations with new probes that provide additional/complementary constraints

Open charm production in UPCs



easier pQCD description at any p_T
(also beyond LO) due to **simple 1-gluon exchange channel**

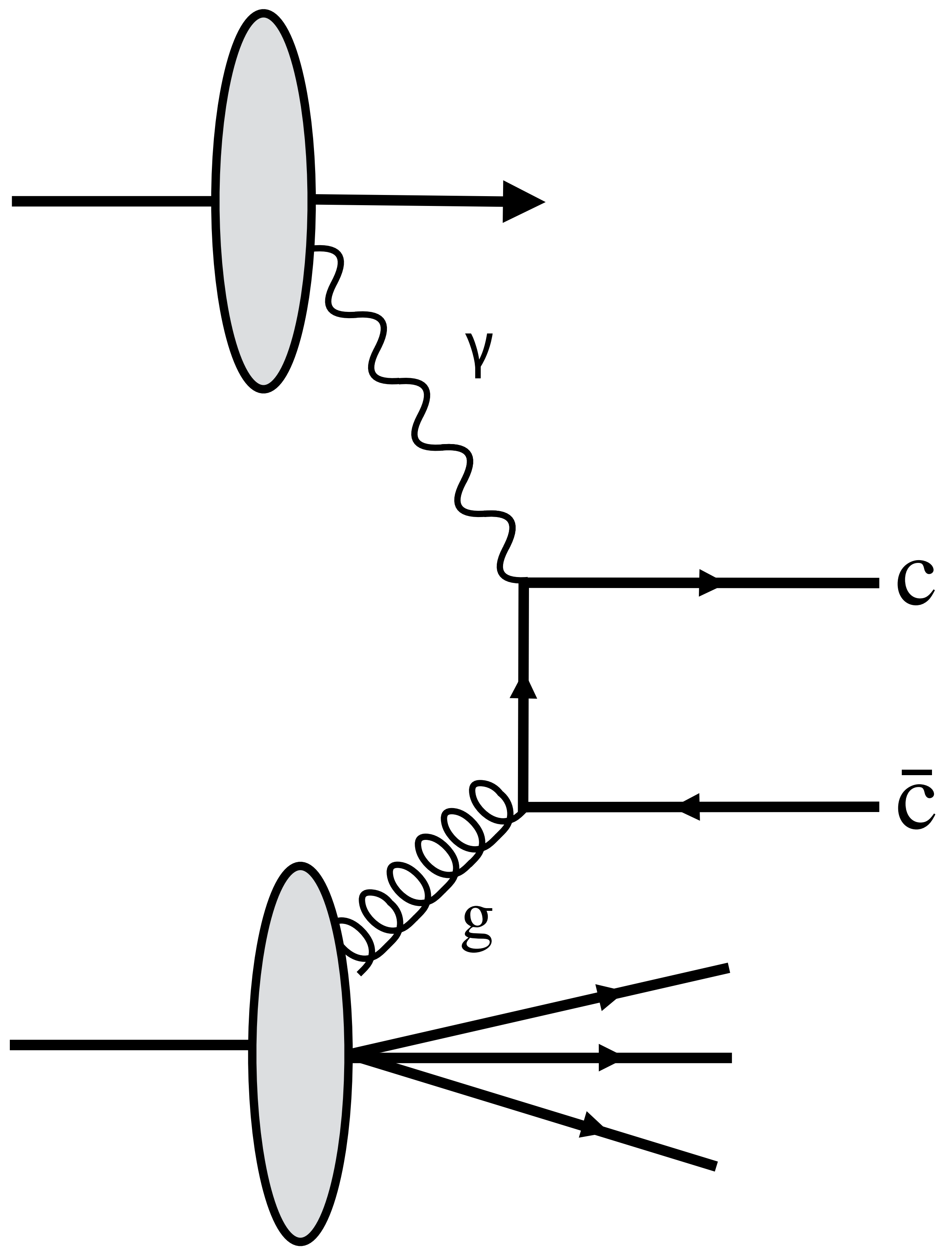
Accurate final state reconstruction
(e.g. $D^0 \rightarrow K^-\pi^+$ or HF jets)

Wide x, Q^2 coverage
→ differential measurements in y and p_T of the heavy hadron:

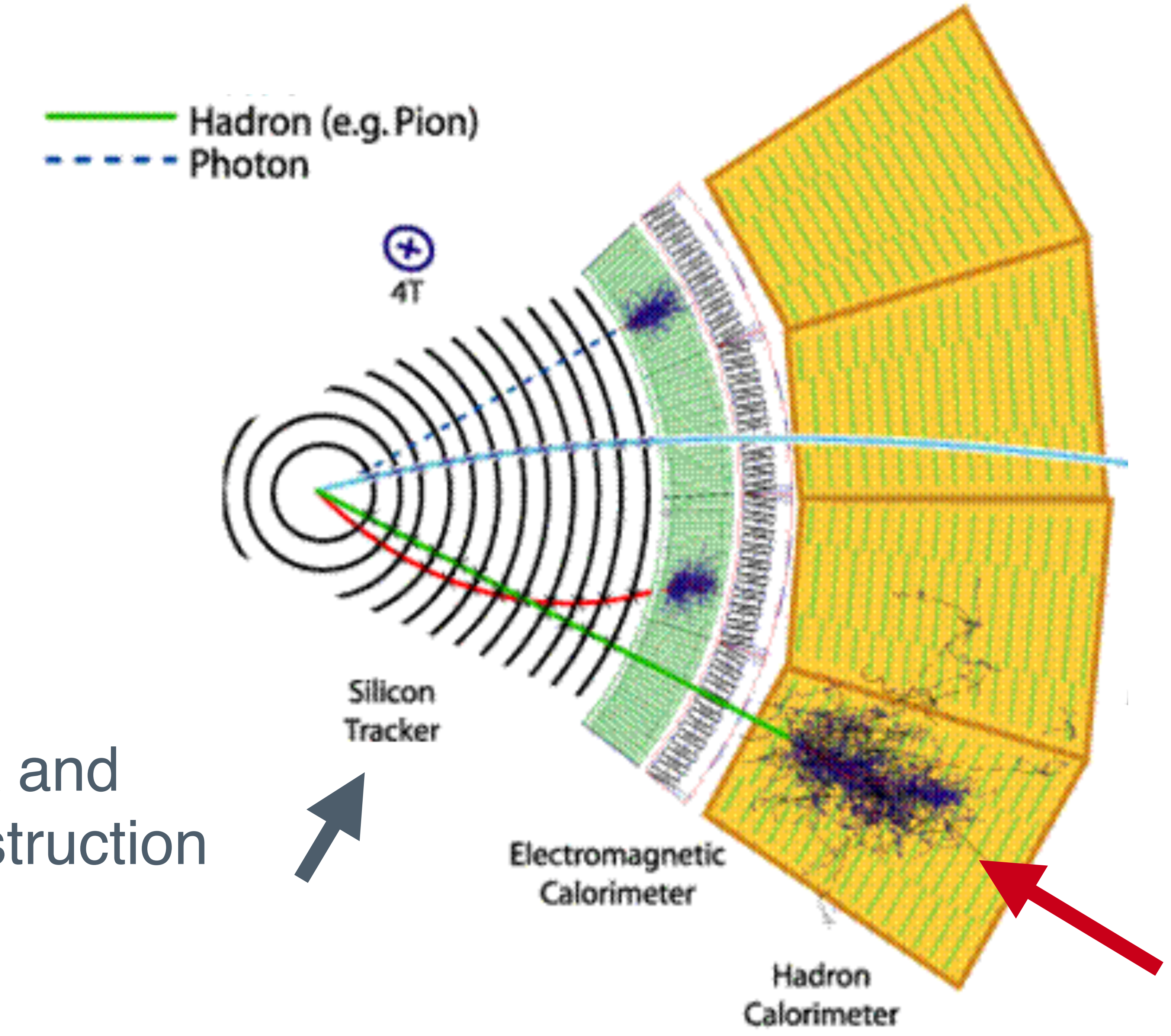
→ ideal probe to test the transition towards low-x nuclear matter in absence of sizable final state effects

S. Klein, R. Vogt et al: Phys. Rev. C, v66, 2002

Experimental strategy with CMS

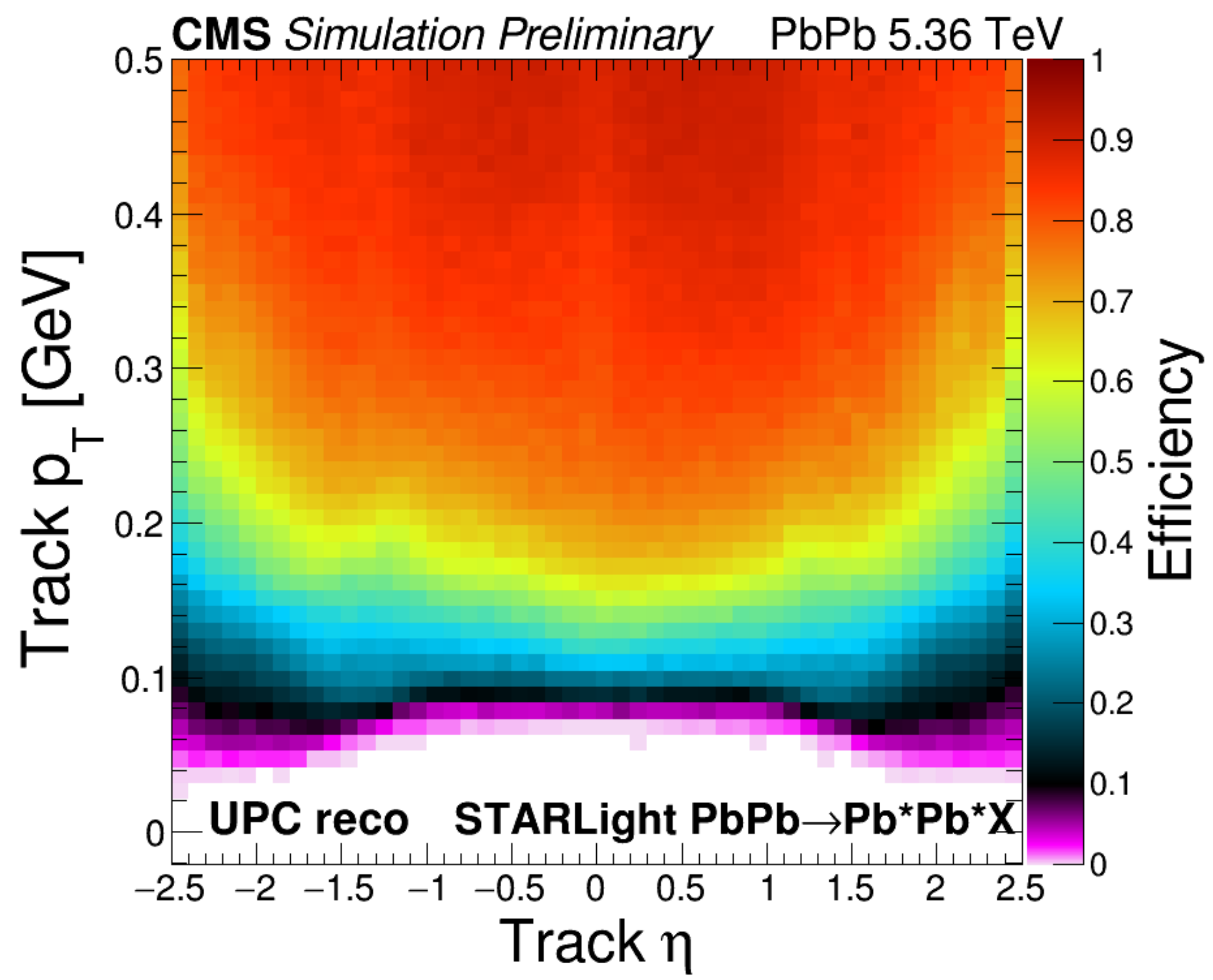


$D^0 \rightarrow K^-\pi^+$ with charged tracks in the tracker



Track and D reconstruction

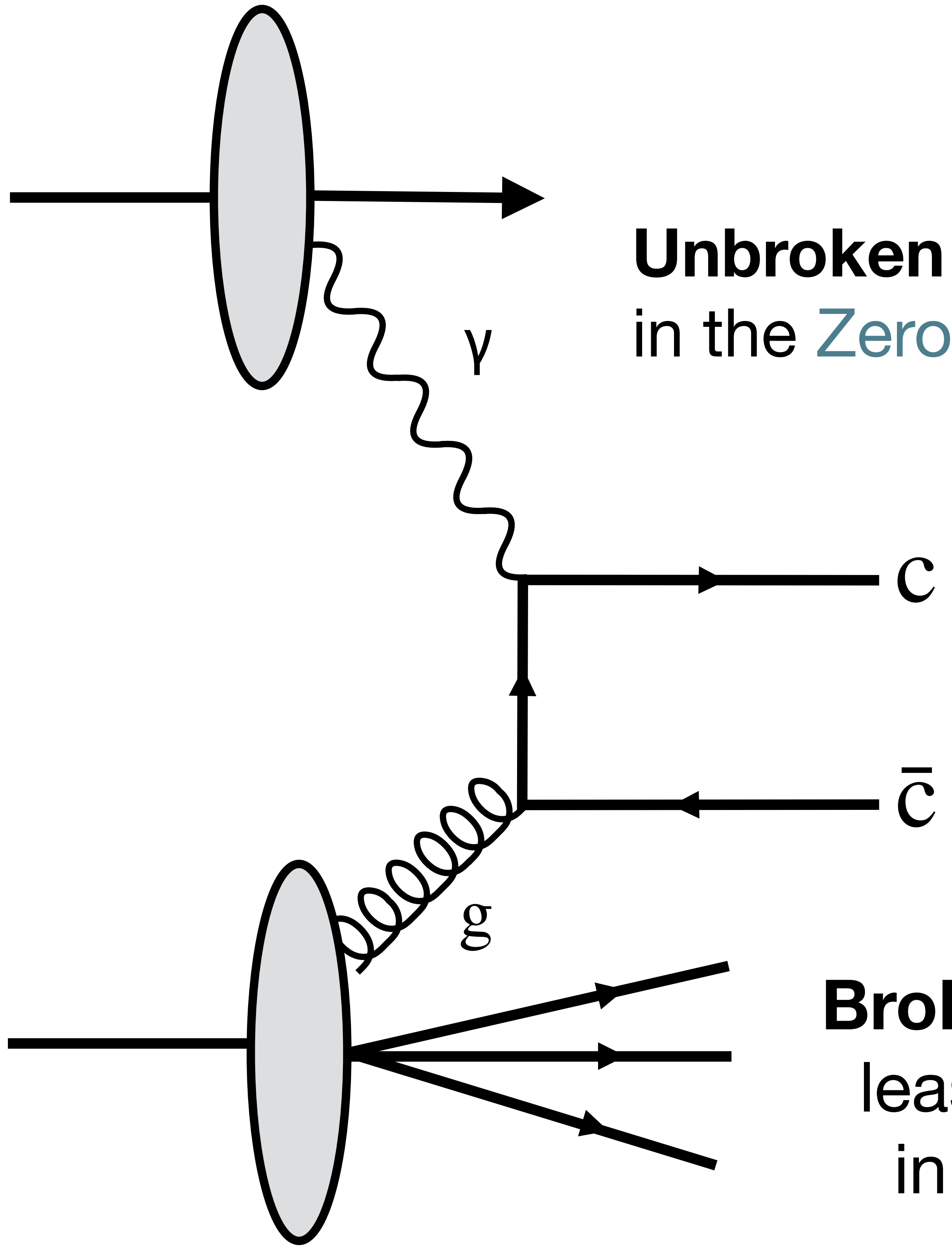
Improved low-p_T tracking and vertexing performance



CMS Collaboration, CMS HIN-24-003

Experimental strategy with CMS

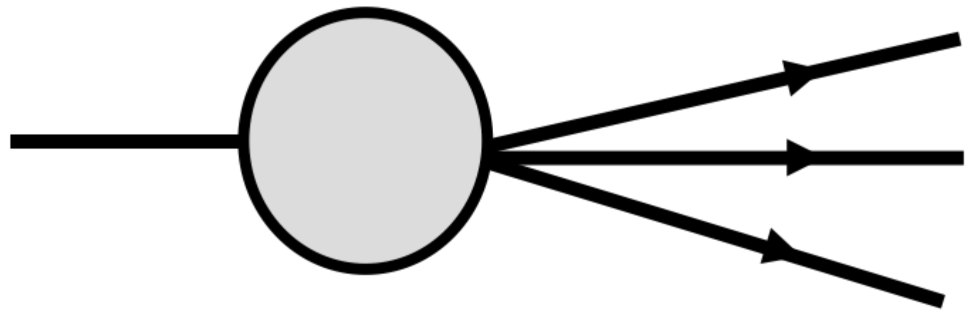
→ **select events in which one nucleus breaks and the other stays intact**



Unbroken nucleus: no neutrons (0n) in the Zero Degree Calorimeter (ZDC)

Broken nucleus: at least one neutron in the ZDC (Xn)

Zero-Degree Calorimeters |η| > 8.3 (0.5 mrad)
→ detect neutrons produced in the nuclear break-up process



Pb + X + neutron(s)

Located at about 140 meters from the PbPb interaction point!

A new trigger and readout strategy for UPCs with CMS

Rate of electromagnetic processes is huge (~10MhZ) and our signal represents only a small fraction of it

Improved readout and HLT compression for increased high-rate capabilities

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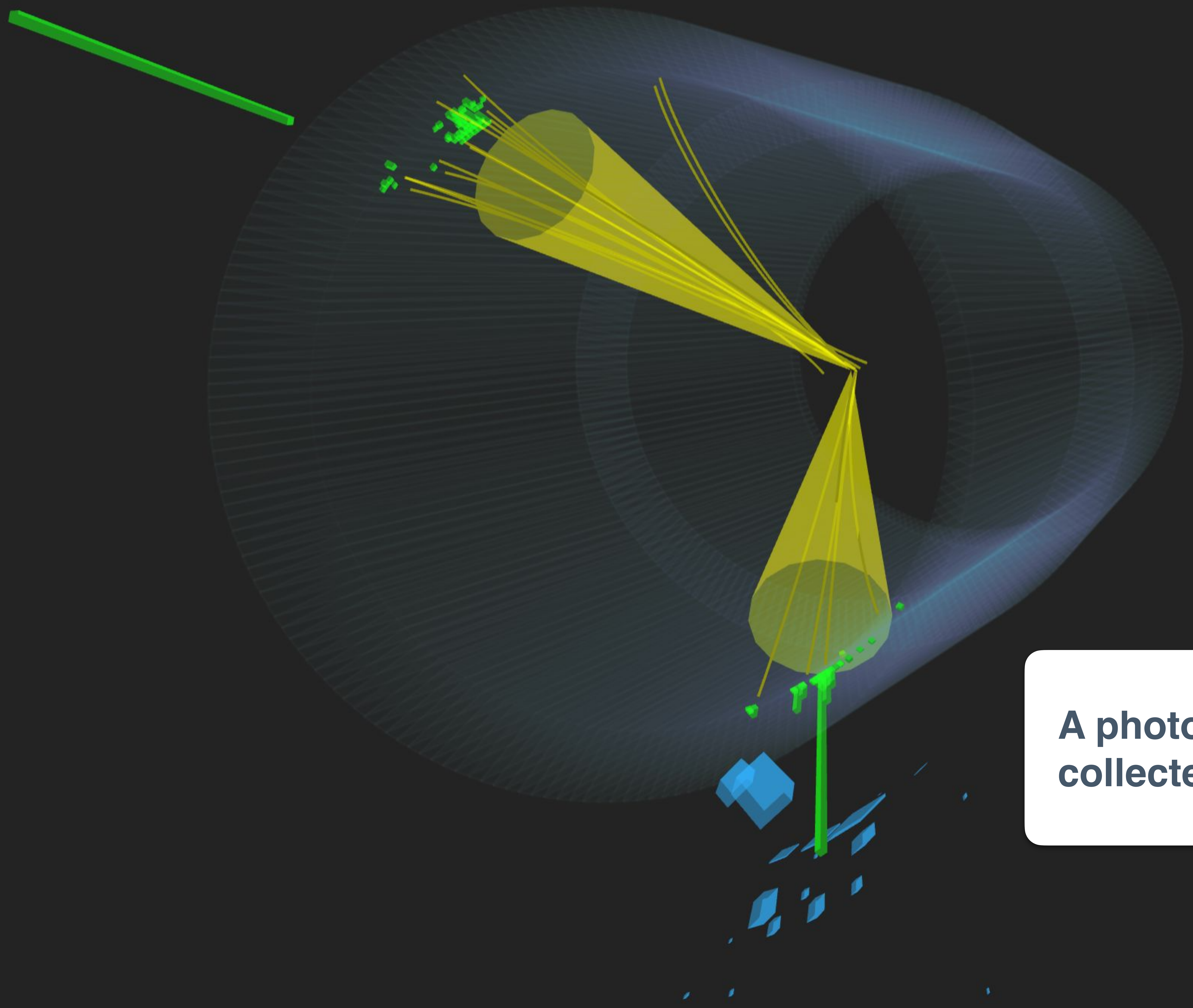
First triggers for low-p_T heavy-flavor and jets in UPCs with CMS
using the Zero-Degree Calorimeter (ZDC) **as a trigger detector**

→ “a long-distance” trigger challenge!

From a few millions (2018) to about 10 billions (2023) of UPC photonuclear events collected!

CMS Experiment at the LHC, CERN
Data recorded: 2023-Oct-10 05:24:04.000512 GMT
Run / Event / LS: 374925 / 591414336 / 646

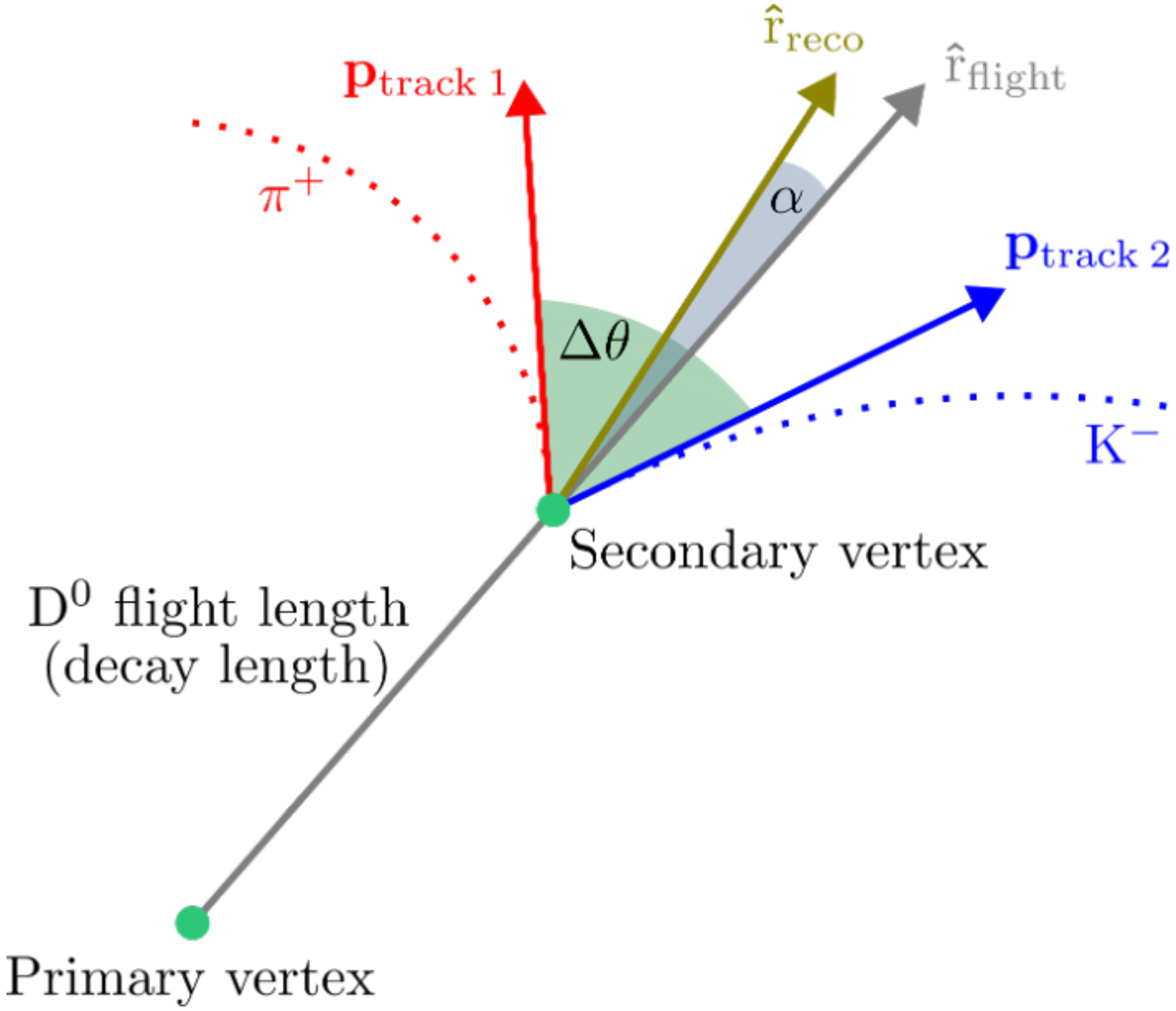


A photonuclear dijet candidate in PbPb UPCs ‘23 collected with the new triggering algorithms

The first D^0 signal in UPCs!

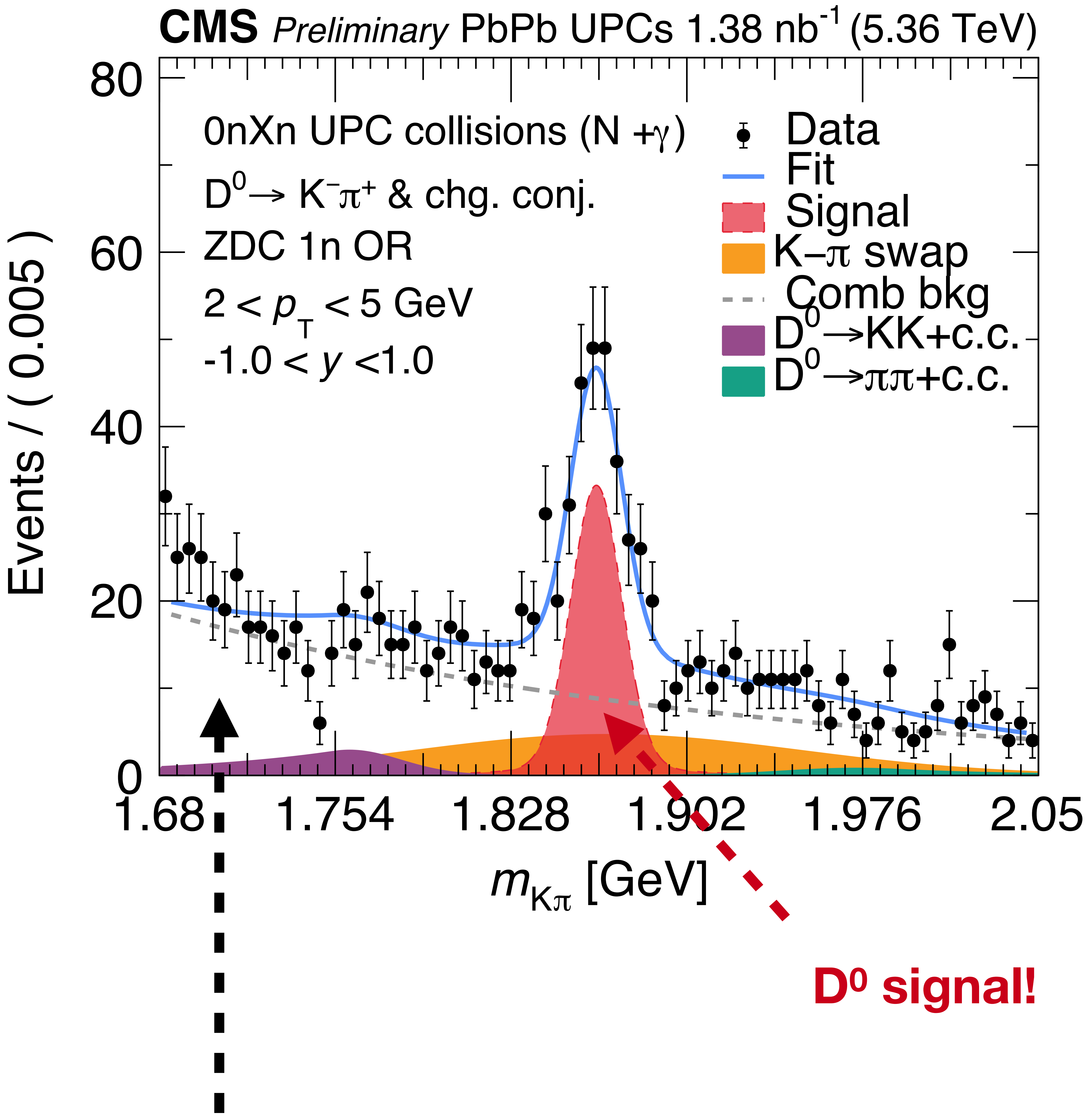
CERN News October 2024

$D^0 \to K^-\pi^+$ with charged tracks in the tracker



D^0 kinematics:
$2 < p_T < 5$ GeV
$-1 < y < 1$

Invariant mass of pairs of selected D^0 candidates



CMS Collaboration, CMS HIN-24-003

→ Very low combinatorial background, even for very low D^0 p_T

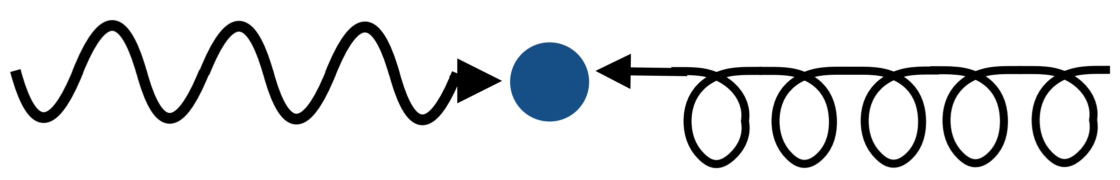
Invariant mass distributions in intervals of D^0 p_T and y

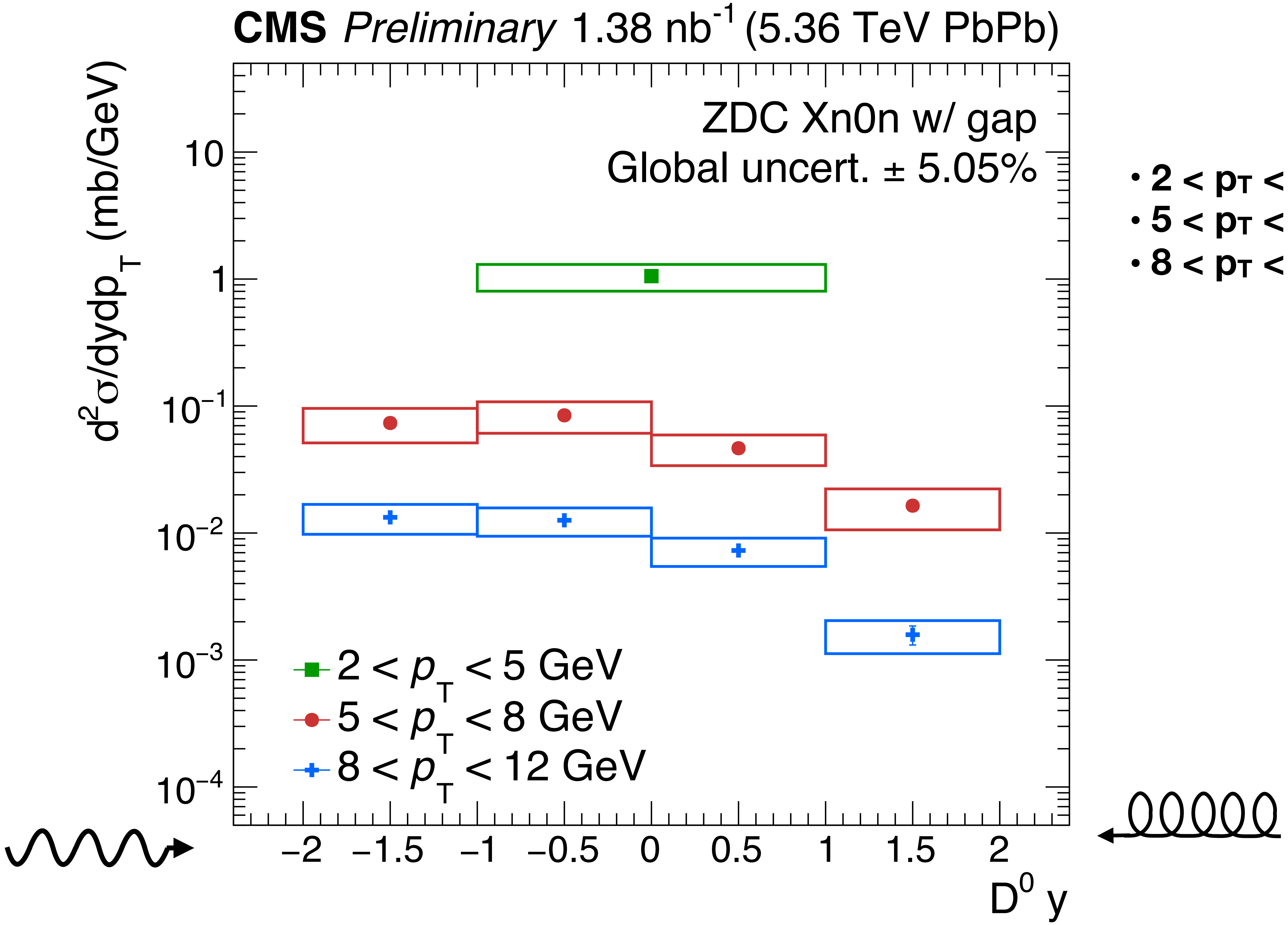
→ **very clean signals extracted in nine intervals of D^0 pT and y!**
→ **statistical uncertainties around 5-7 %!**

$$x_{gluon} \sim \frac{p_{T,D^0}}{\sqrt{s_{NN}}} exp(-y^*_{D^0})$$

** with respect to the incoming photon direction*

CMS Collaboration, CMS HIN-24-003

D^0 production in UPC collisions vs p_T and y ()

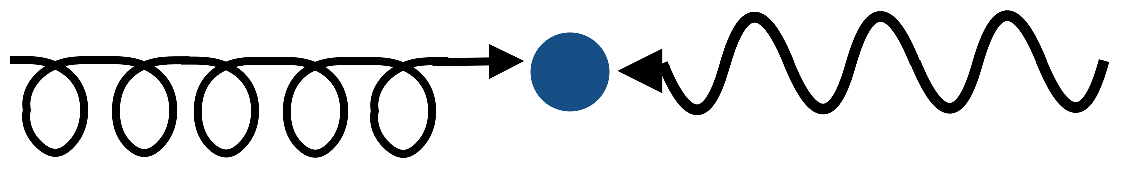


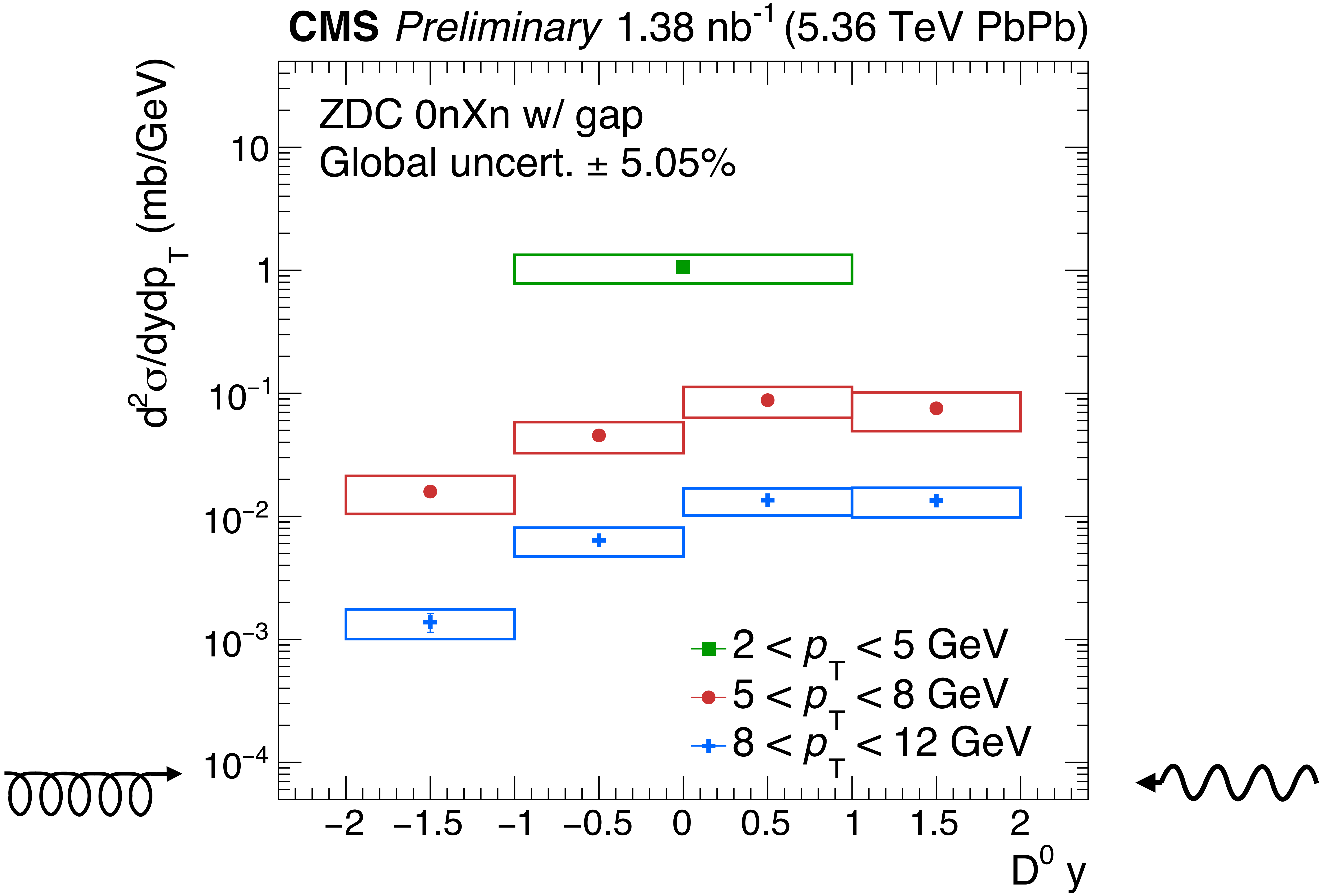
- **$2 < p_T < 5$ GeV** and **$-1 < y < 1$**
- **$5 < p_T < 8$ GeV** with y ∊[-2, -1, 0, 1, 2]
- **$8 < p_T < 12$ GeV** with y ∊ [-2, -1, 0, 1, 2]

D^0 production peaks at negative rapidities

→ photons (although very energetic) have on average less energy than the gluons

CMS Collaboration, CMS HIN-24-003

D^0 production in UPC collisions vs p_T and y ()

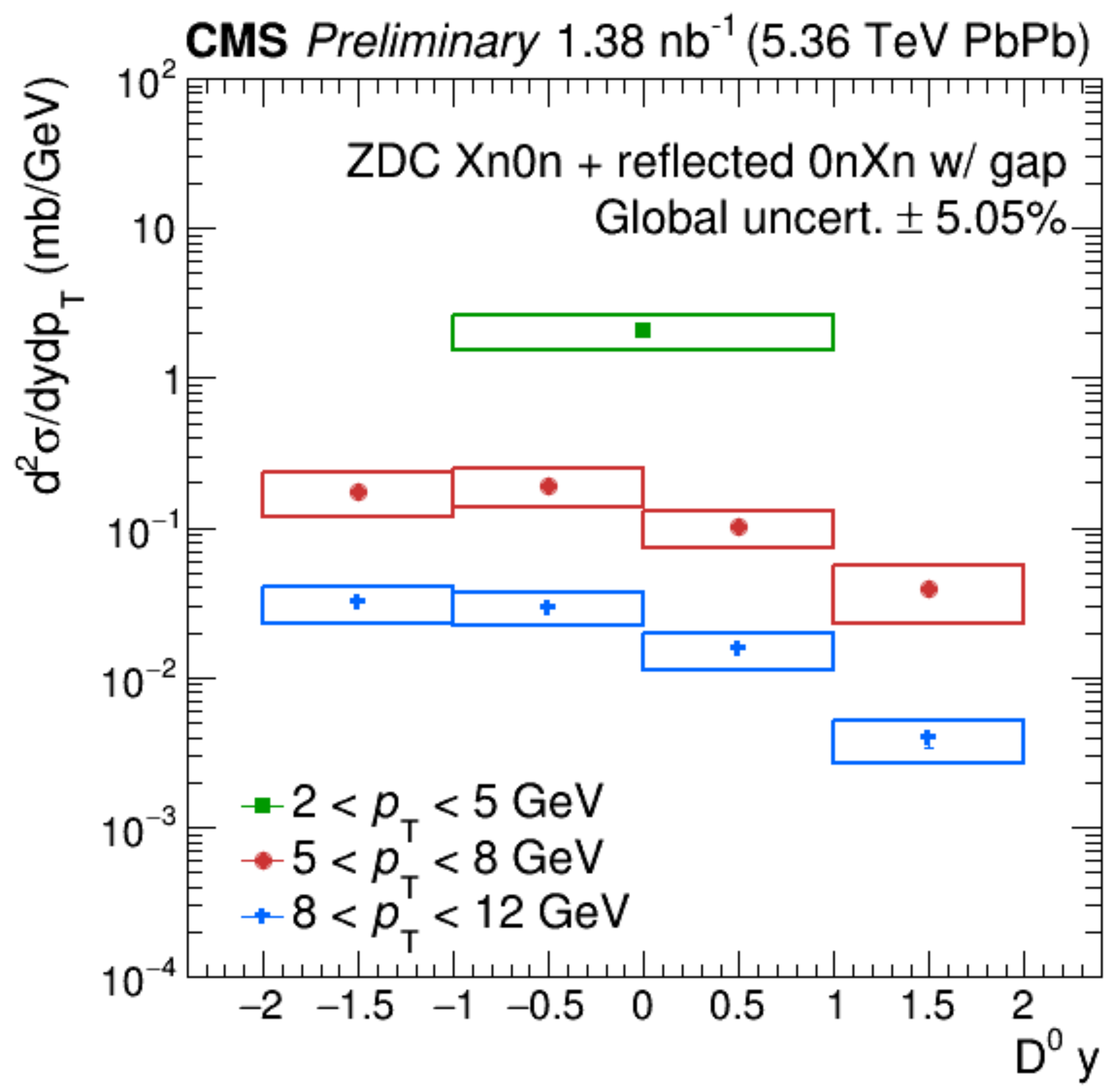


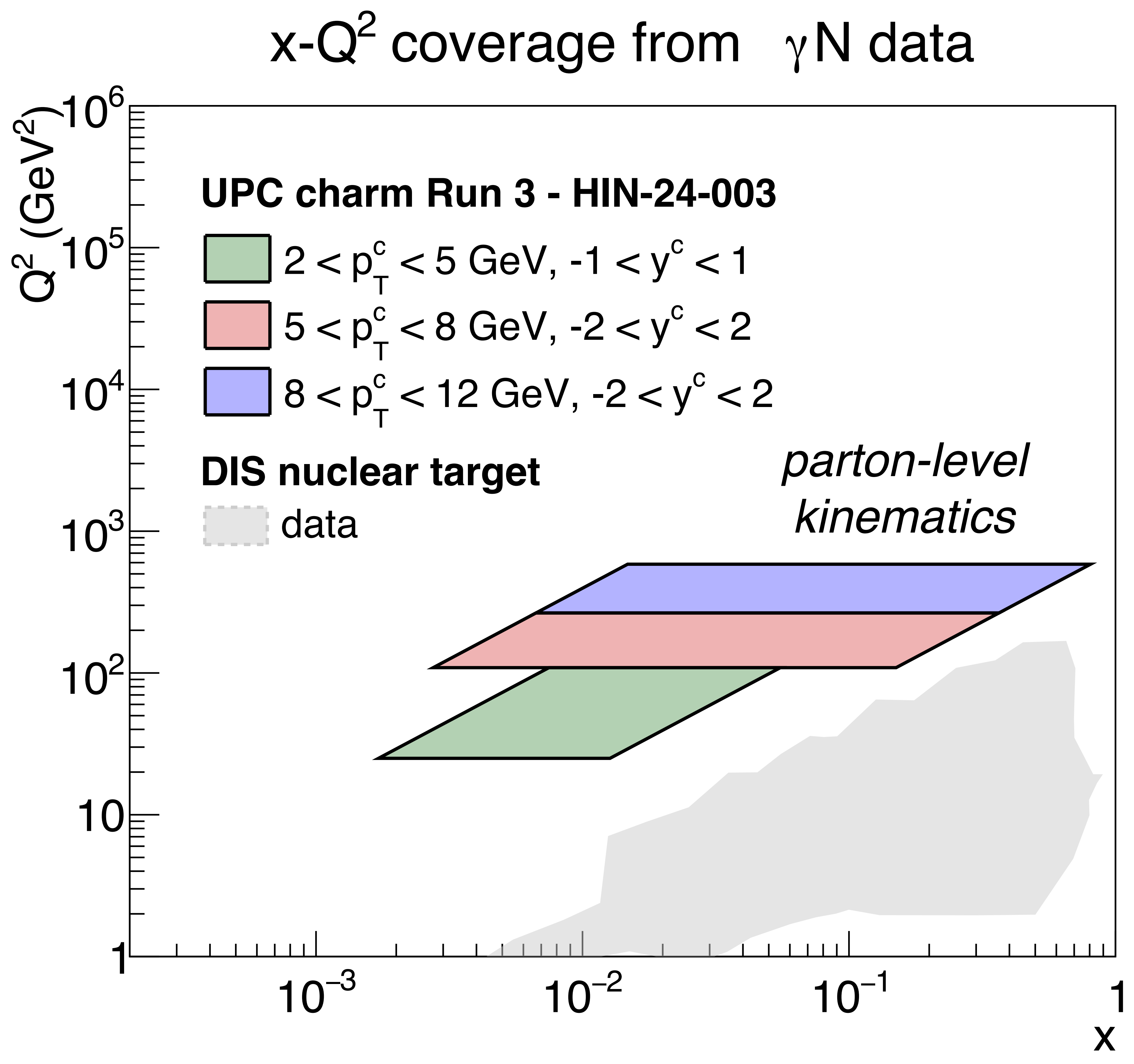
The production cross section for "gluon-photon" is the y-reflected version of the "photon-nucleus" one!

→ for this first measurement, we have measured the two results separately and merged them

CMS Collaboration, CMS HIN-24-003

First measurement of the D^0 photonuclear production in UPCs

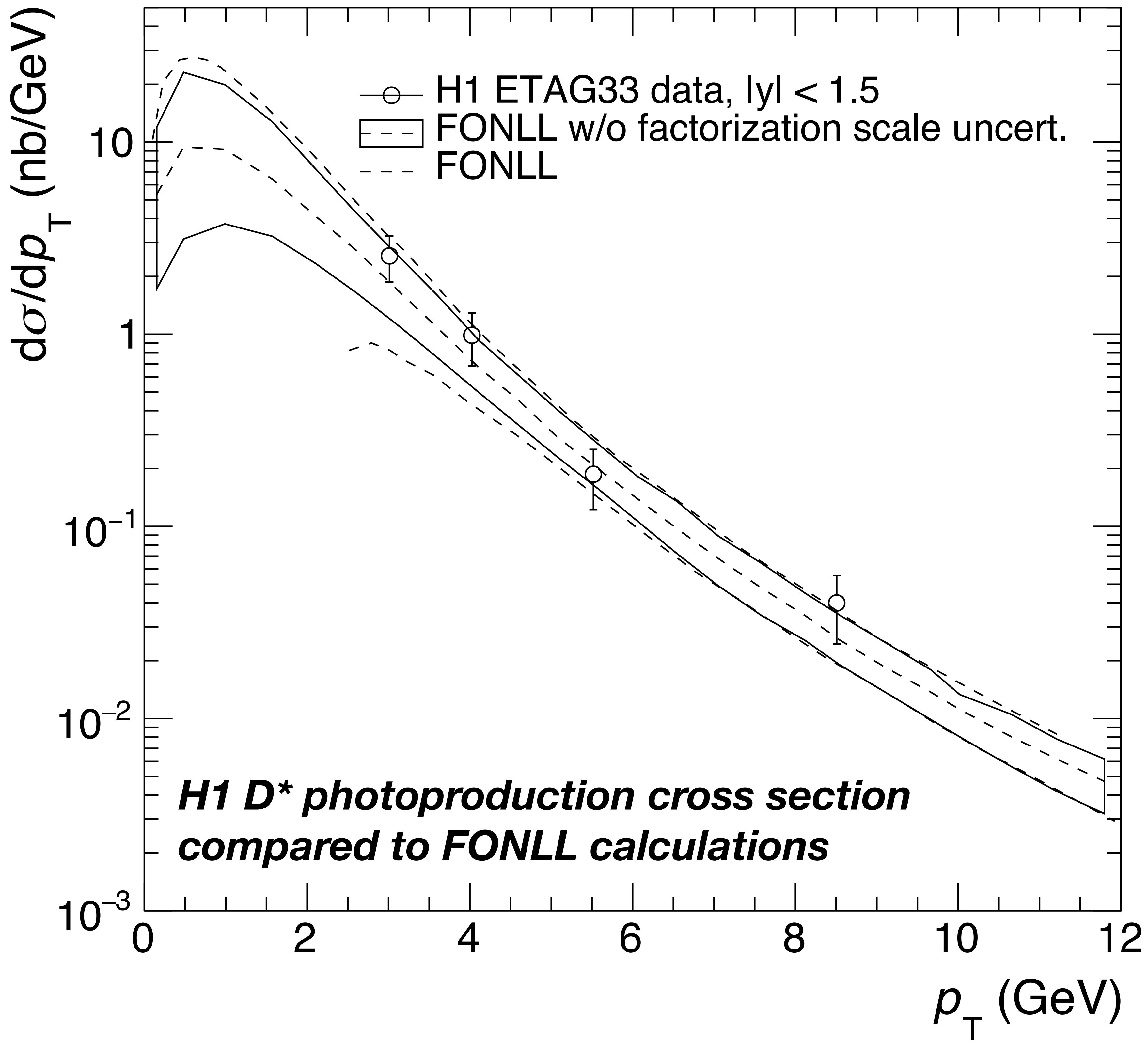




Constraints on gluon nPDFs for about $10^{-3} < x < 10^{-2}$ for $20 < Q^2 <$ hundreds GeV^2 <u>from photon-nucleus collisions:</u>

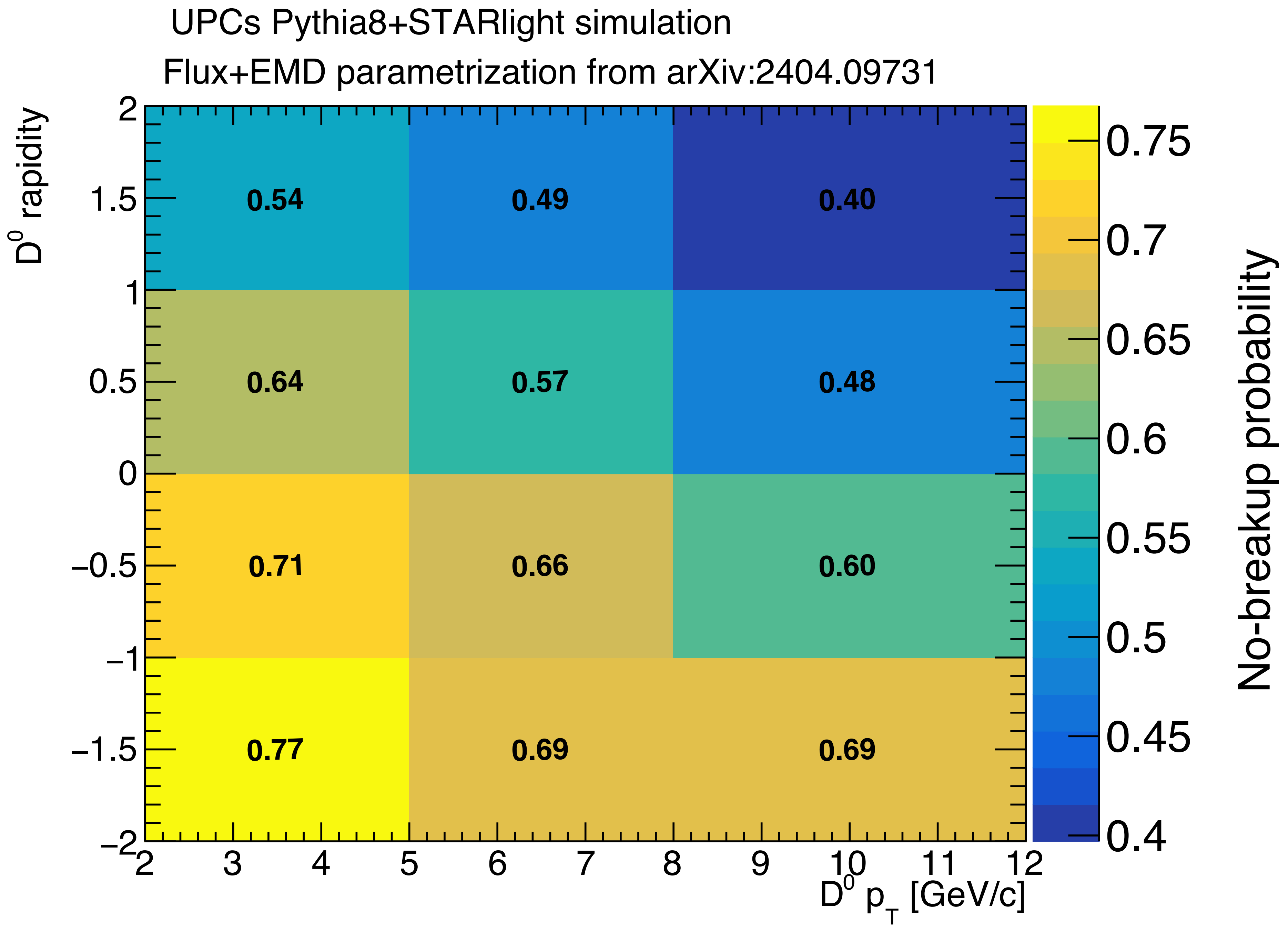
“Building” FONLL-based predictions for D^0 in UPCs at the LHC

FONLL for prompt inclusive charm photoproduction
→ *full agreement with existing predictions for ZEUS/H1*



ATLAS, ATLAS-CONF-2017-011
K. J. Eskola et al., https://arxiv.org/pdf/2404.09731

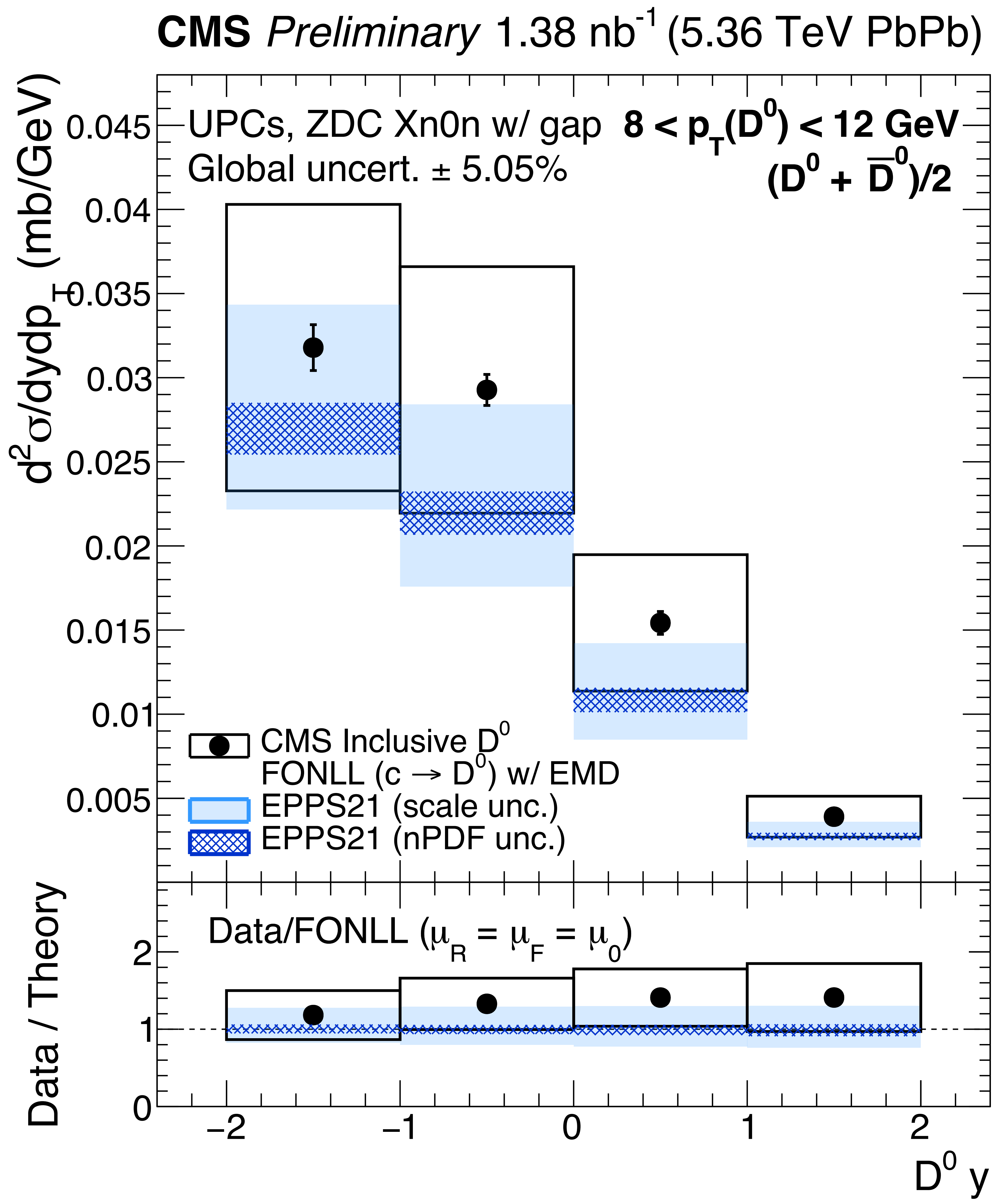
Reweight photon flux to match those expected in UPCs



Multiply for the predicted Xn0n “survival” probability in the presence of EM dissociation (EMD)
- estimated by reweighting gen-level Pythia events by the EMD-corrected photon flux for 0nXn topologies

A. M. Stasto, GMI, Paper in preparation

Comparison with FONLL with EPPS21 nPDFs



- **CMS D^0 ($c \to D^0$ and $b \to D^0$) Xn0n with rapidity gap**

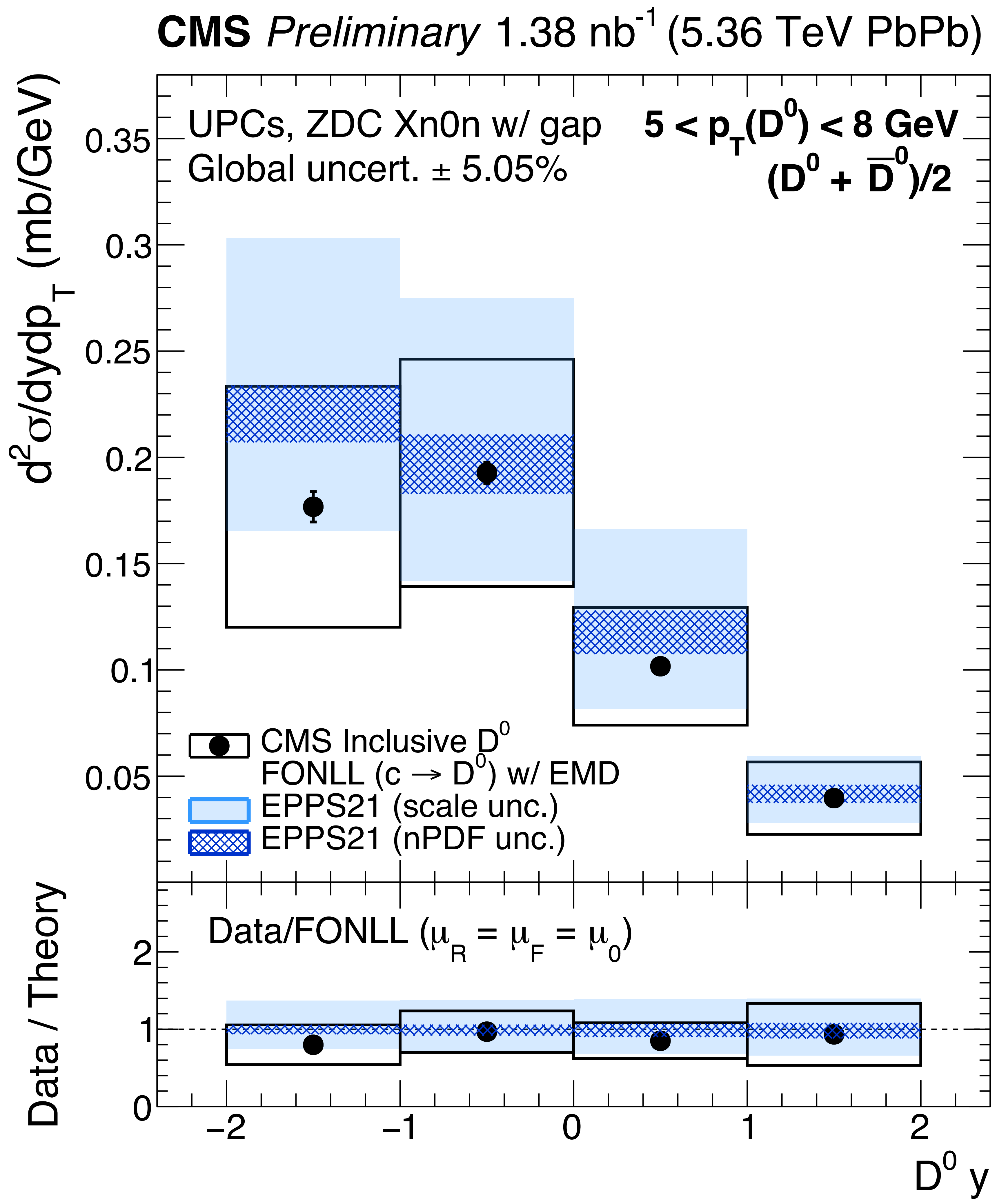
- **Light blue band**: **prompt FONLL predictions with scale variations**
- **Dotted blue band**: EPPS21Pb nPDF uncertainty only
- FONLL+EPPS21nPb scaled for the probability of no-breakup (EMD)

D^0 $8 < p_T < 12$ GeV:

→at higher p_T, data are overall above the central values of the predictions

A. M. Stasto, GMI, Paper in preparation

Comparison with FONLL with EPPS21 nPDFs



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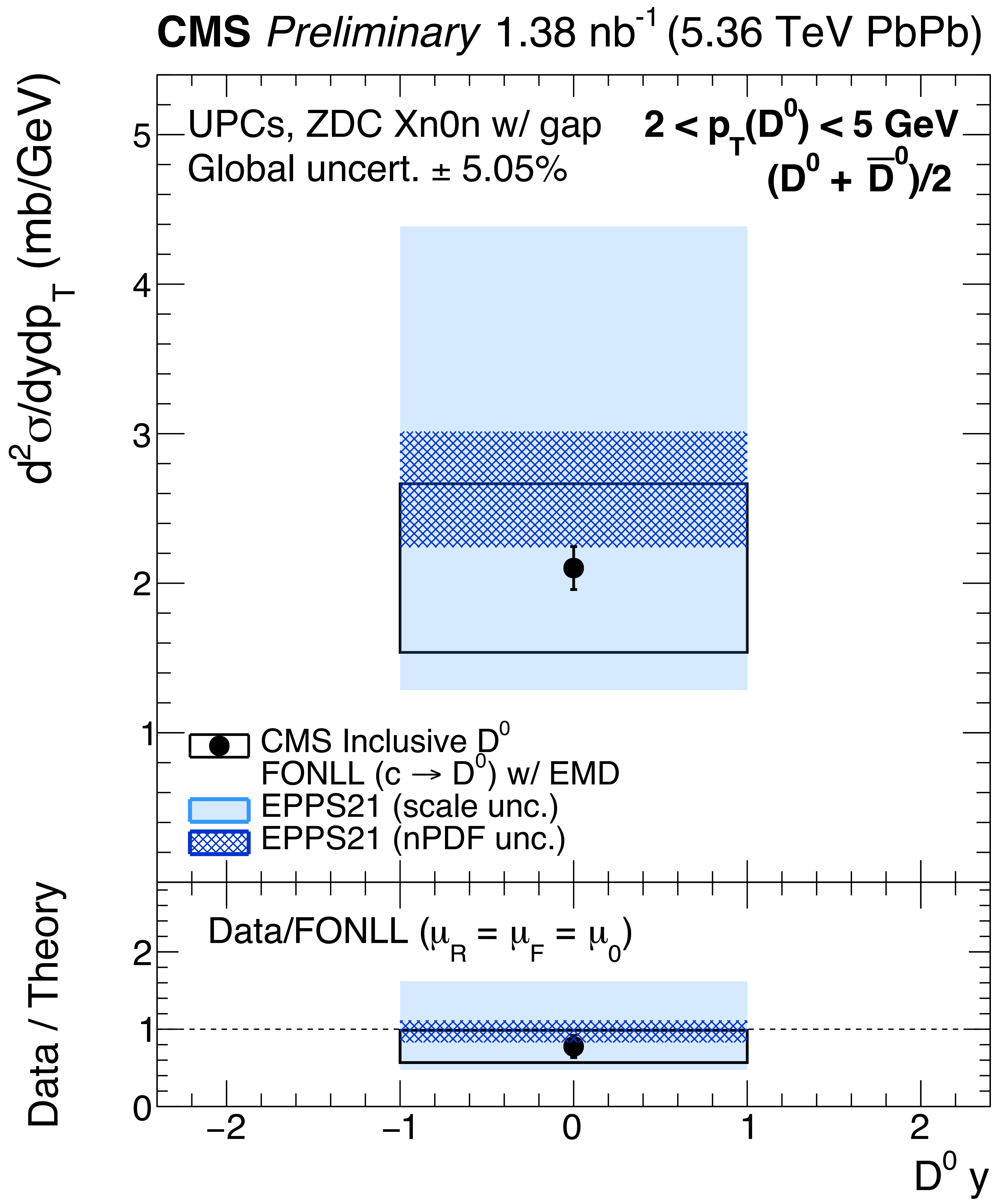
D^0 $5 < p_T < 8$ GeV:

→data consistent with central values of the FONLL-based predictions

Comparison with FONLL with EPPS21 nPDFs



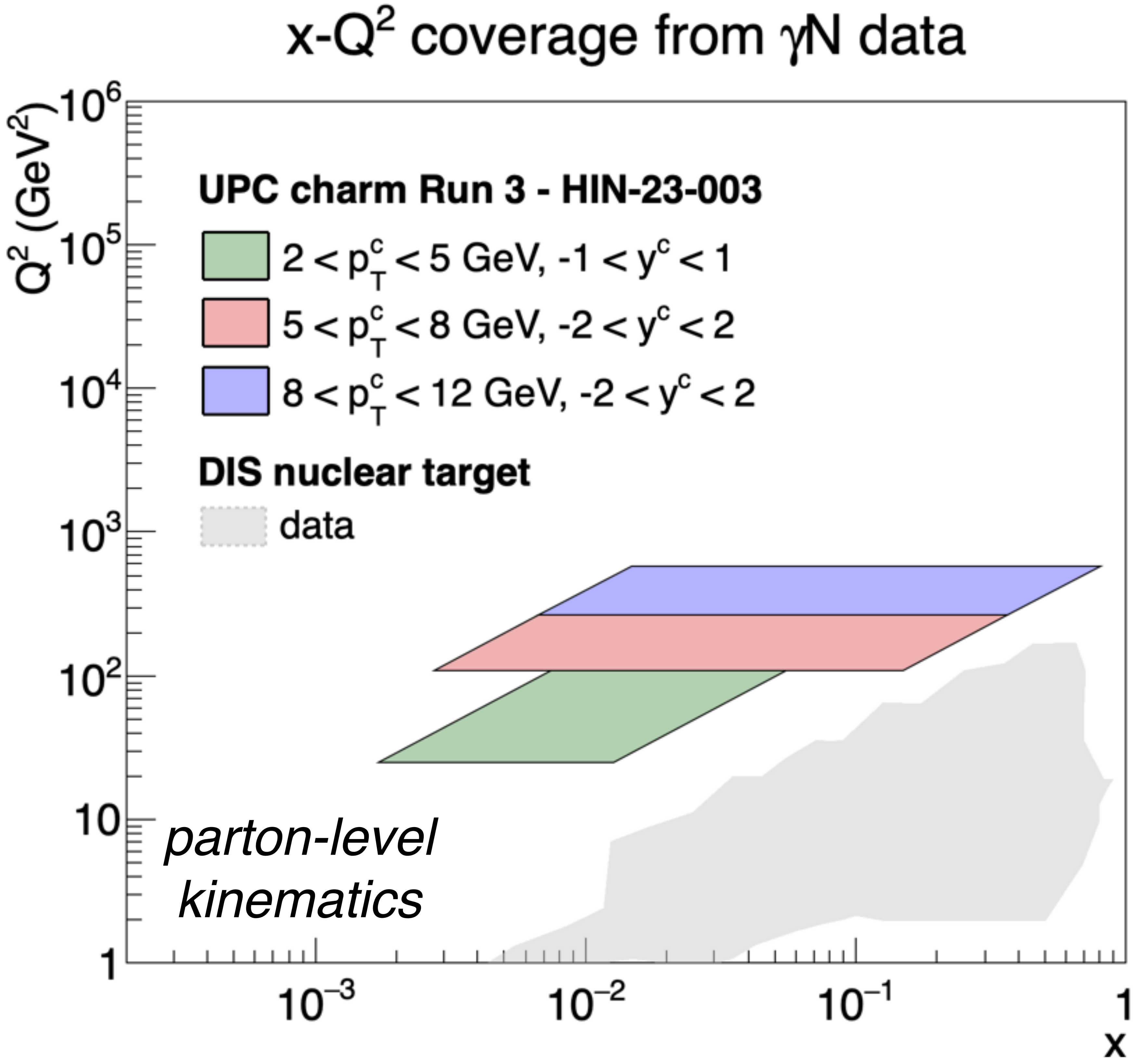
D^0 $2 < p_T < 5$ GeV:

- x_{BJ} down to about 2 * 10^{-3}
- Q^2 down to ≈ 20-30 GeV^2

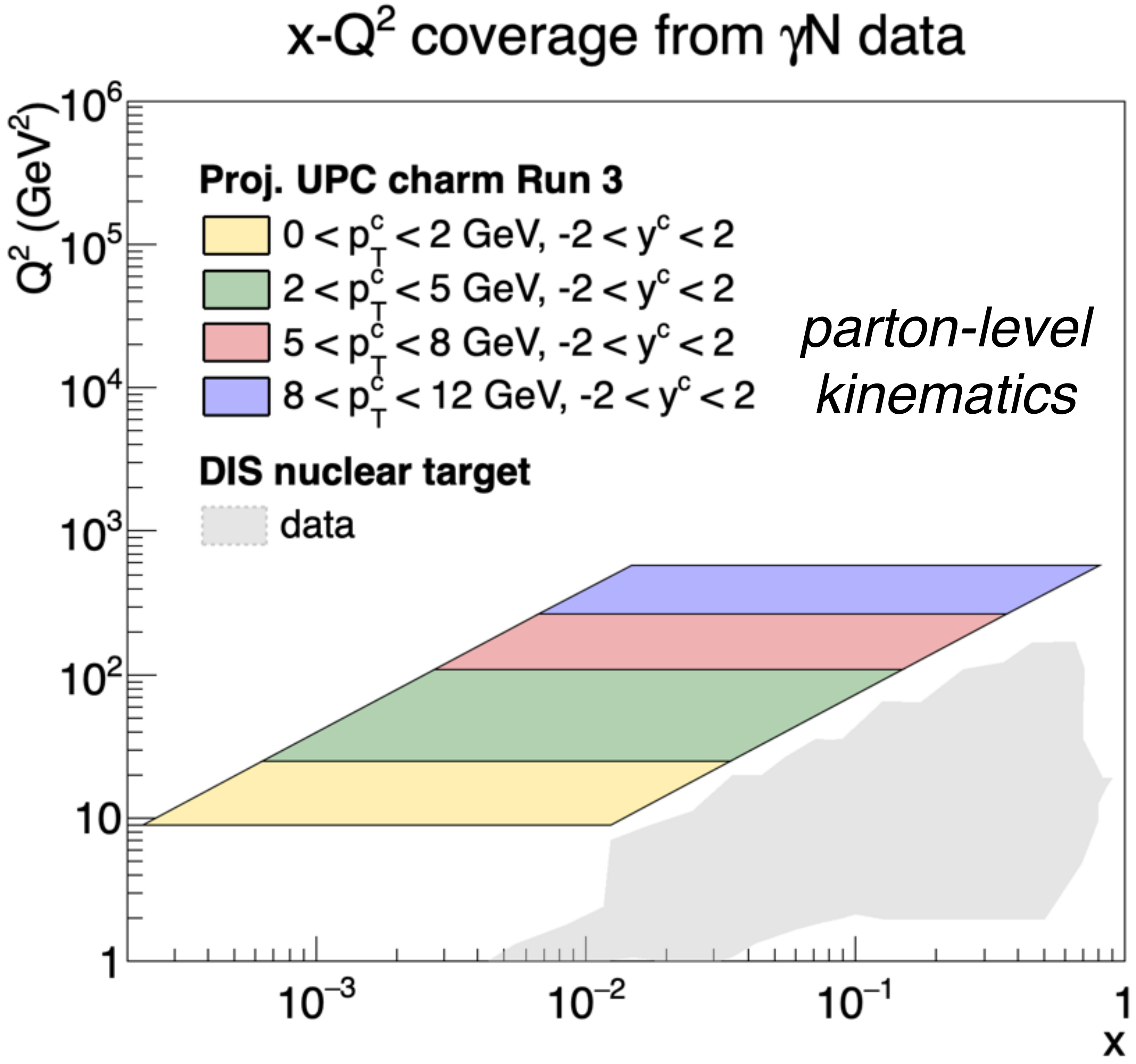
→ **Constraints in the saturation region at low Q^2**
→ **At low p_T, the data/FONLL ratio is below unity.**

Ongoing analysis: extend the measurement to D^0 $p_T = 0$

Existing analysis:
- $p_T > 2$ GeV
- limited y range at low p_T

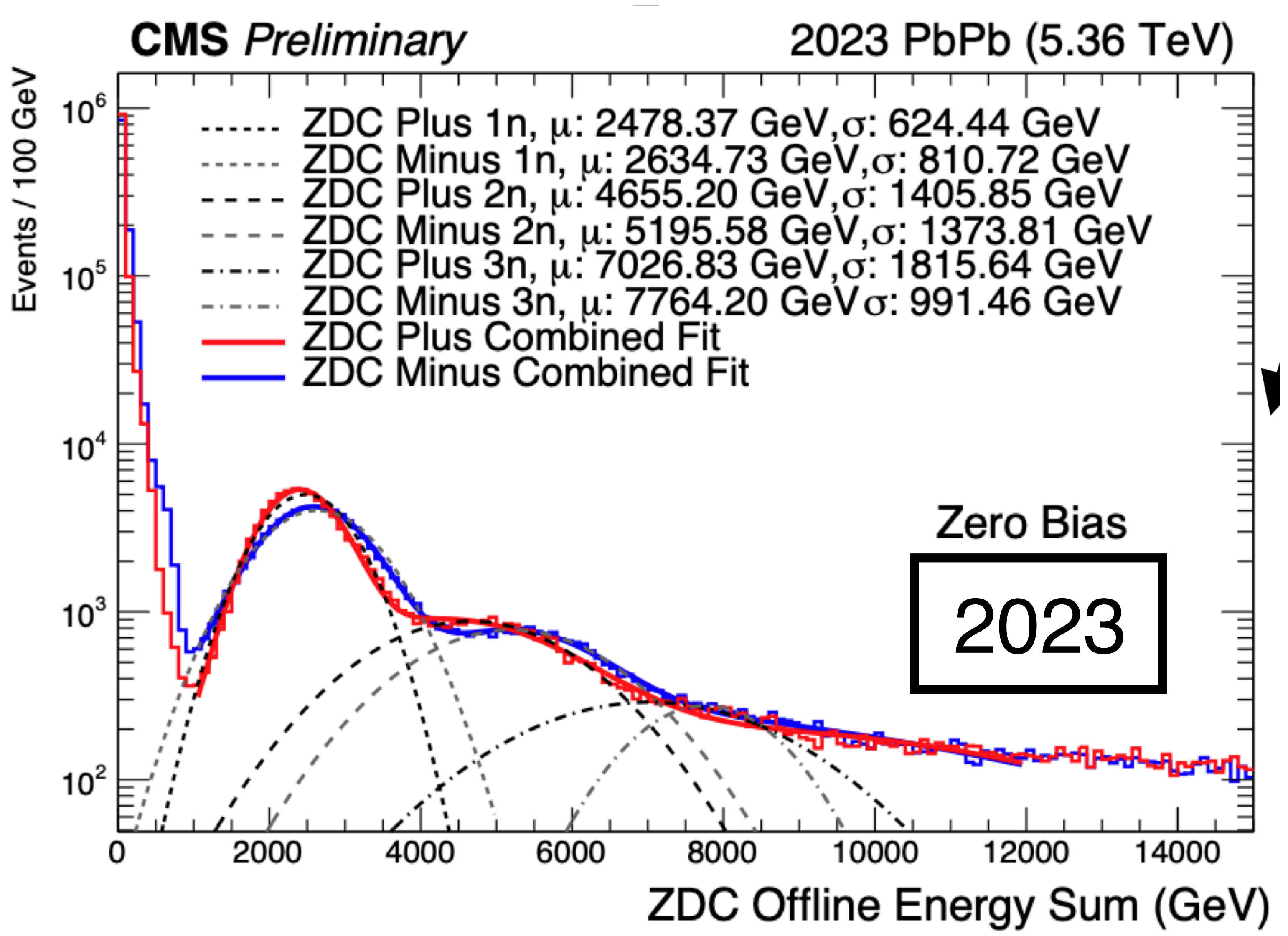


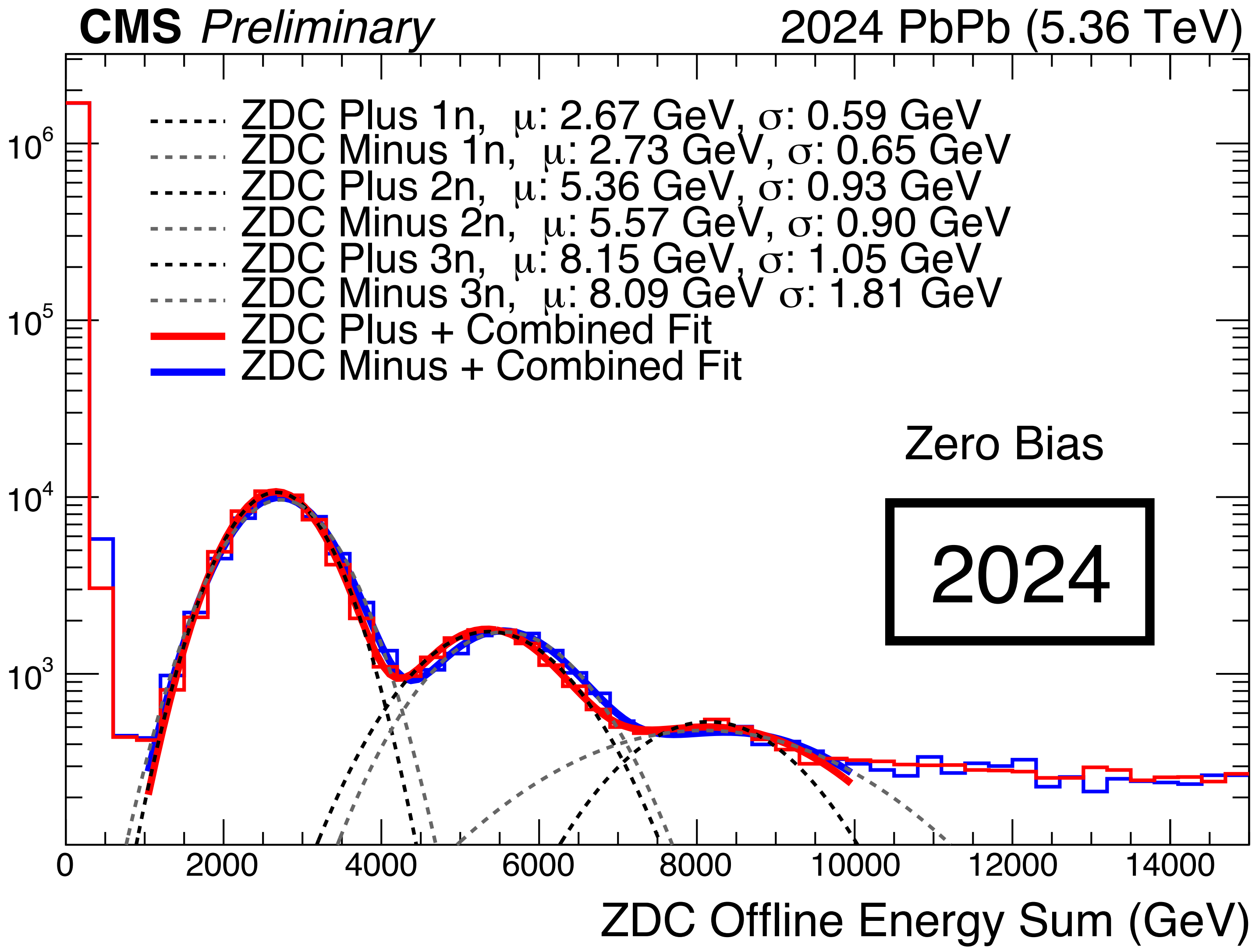
New ongoing analysis (including 2024 data)
- down to $p_T = 0$ in intervals of y
- **reduced systematic uncertainty**
- **forward-backward ratios** (substantial cancellation of systematics)

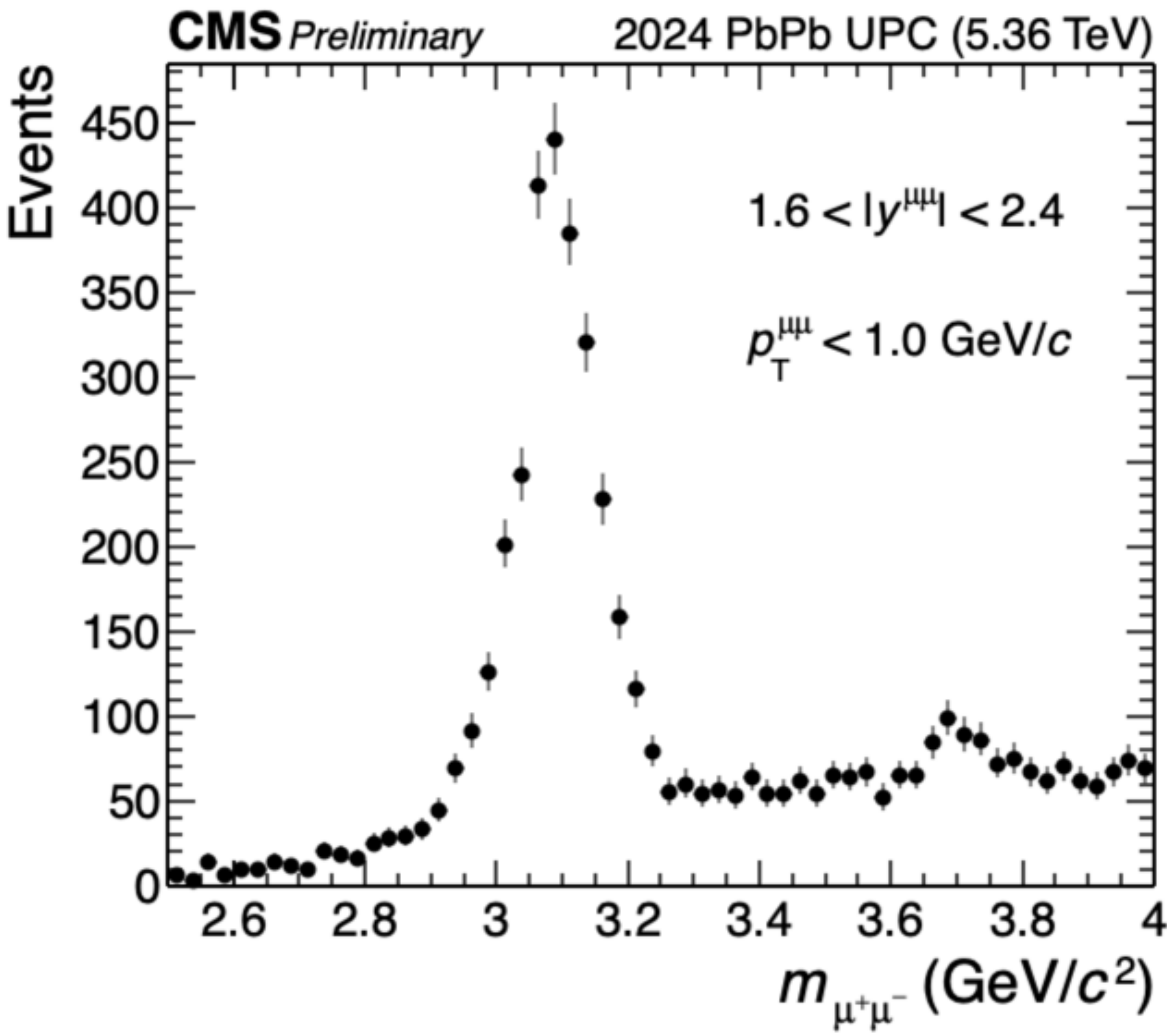


Prospects:
- diffractive heavy-flavor productions
- measurements as a function of the number of neutrons
- ..

New high-quality data from the latest PbPb run (November ’24)





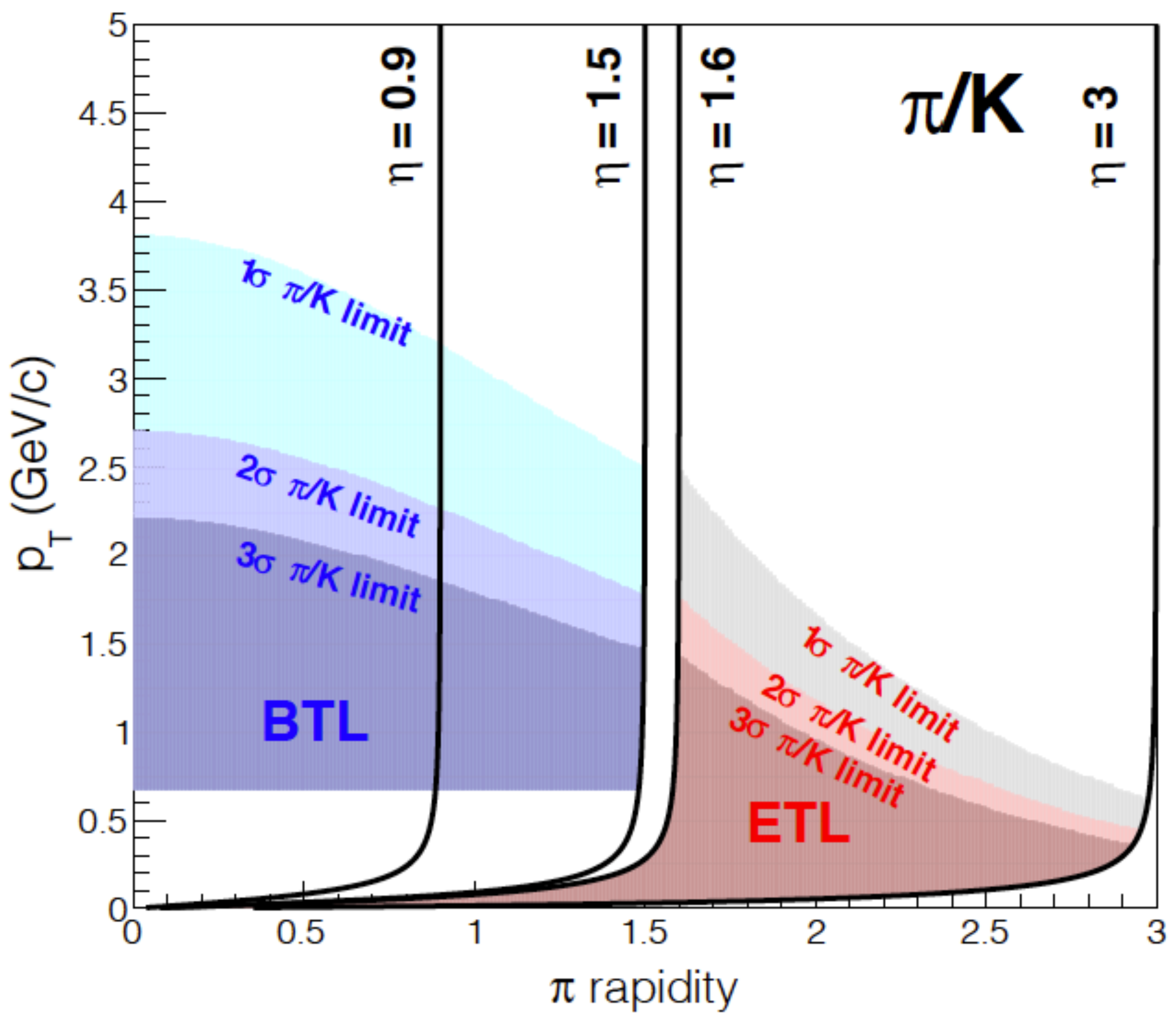


→ substantial increase in the number of collected photonuclear events!
→ improved the performance of the ZDC detector

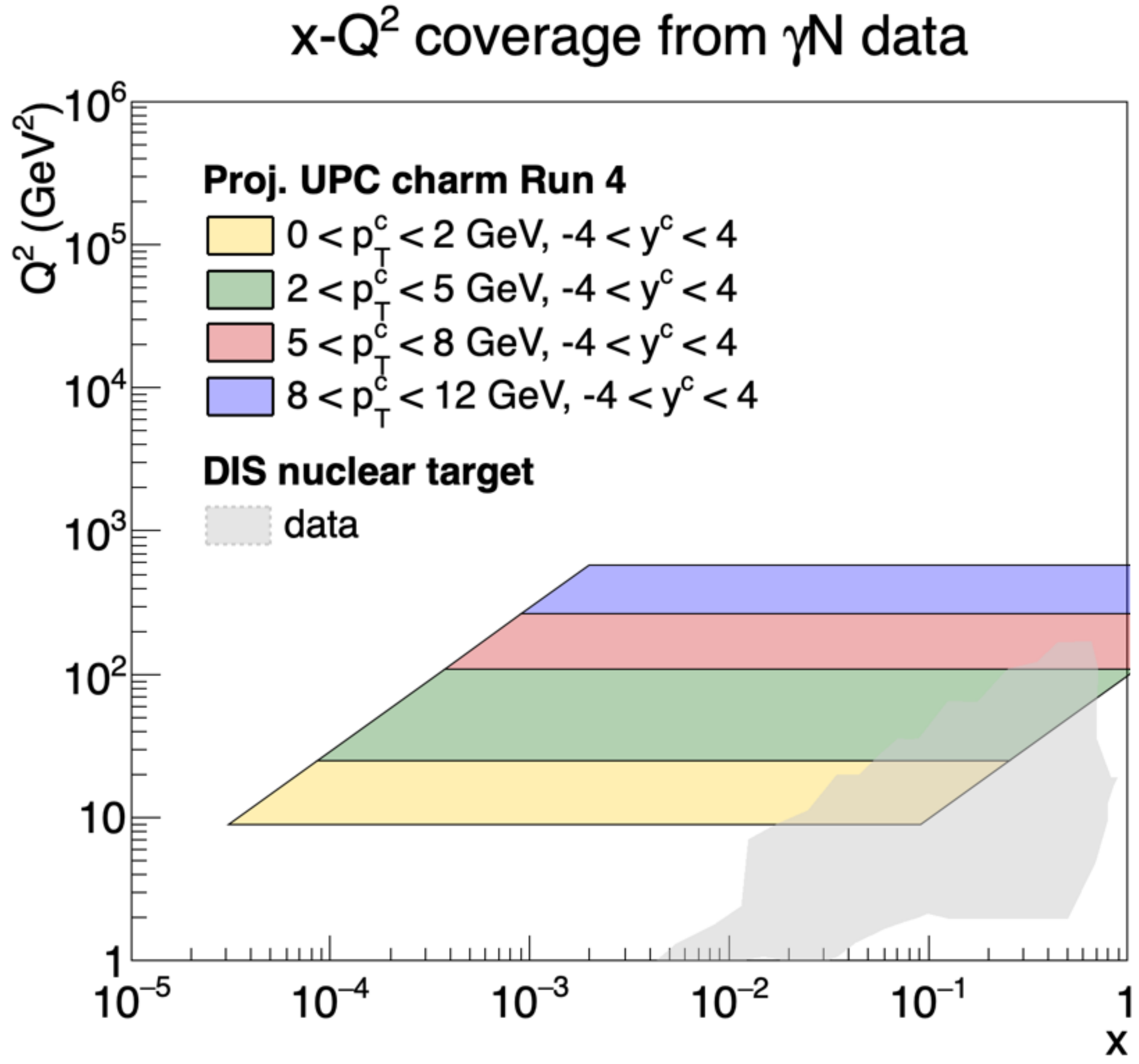
Processing of the ’24 dataset well advanced:
→ first UPC signals obtained with a new reconstruction

CMS at the LHC in Run 4 and 5 (2030–2041)

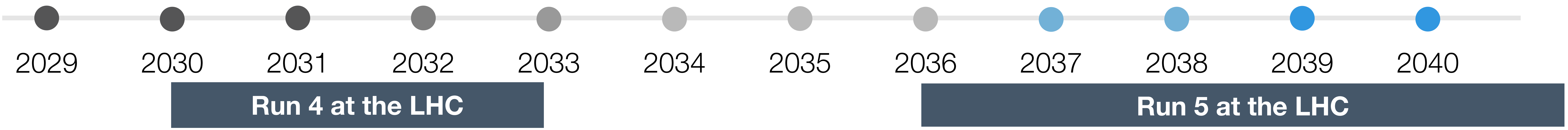
- **New tracker with |η|<4**
- PID for low p_T hadrons



CMS Phase-II tracker: CMS-TDR-014
CMS: Phys. Rev. D 96, 112003
CMS: CMS-TDR-020

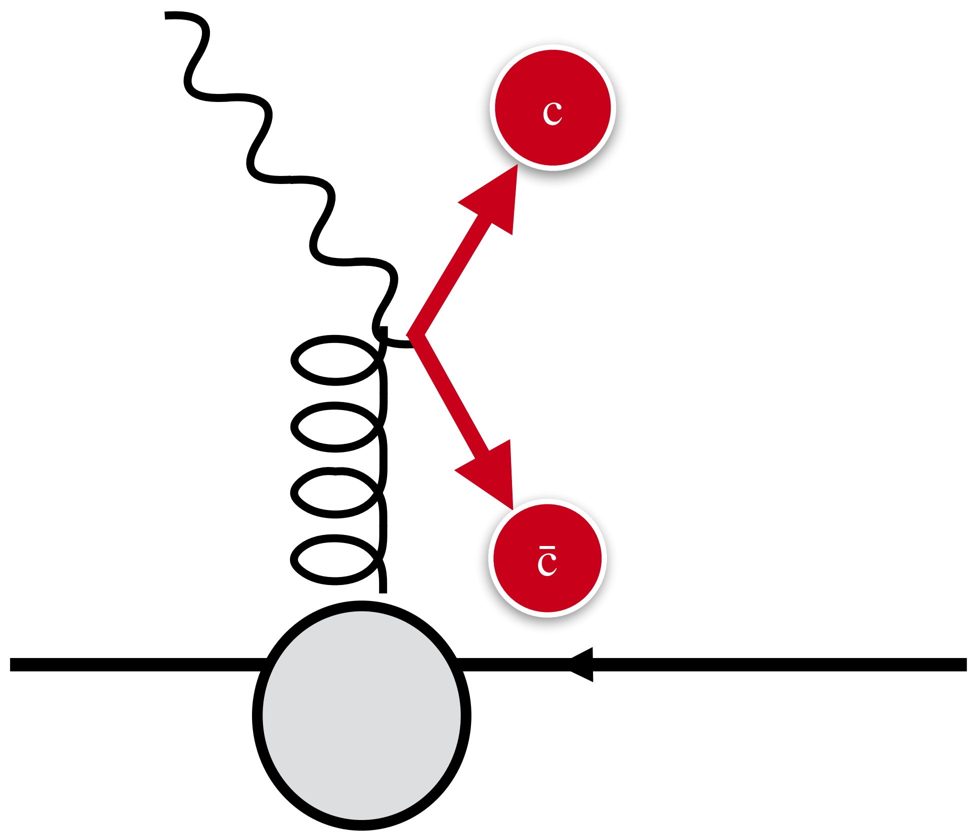


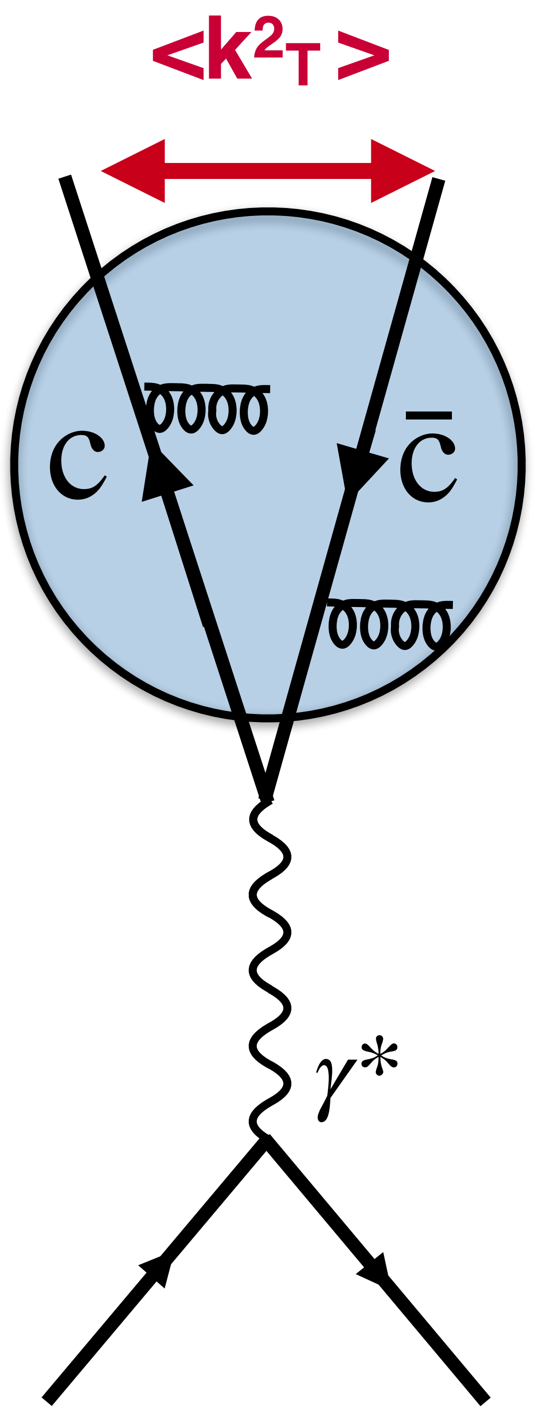
→ **Close to $x\sim10^{-5}$** with $\gamma N \rightarrow c\bar{c}$ observables



Photonuclear charm and beauty production at the EIC

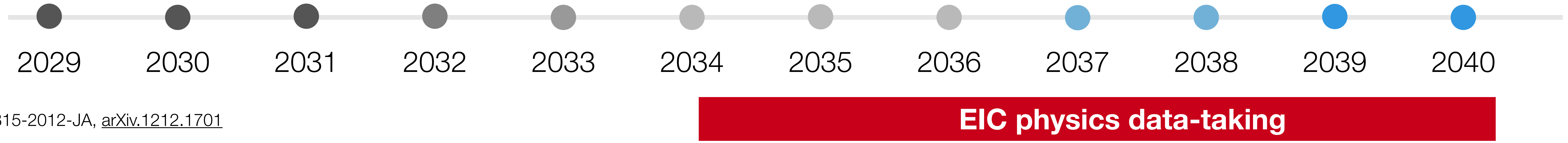
→ control on the photon virtuality Q^2 and x





Complement and expand the ongoing UPC program at the LHC:

- Transition to low-x regime with different nuclei and tunable energy
- Propagation inside the cold nuclear matter
- “Timescale” of the hadronization process for heavy quarks



EIC: BNL-98815-2012-JA, arXiv.1212.1701

Conclusions

Ultra-peripheral heavy-ion collisions

- abundant source of γN interactions at the highest energies accessible
- access to new highly-constraining signals (e.g. UPC open-charm photoproduction)

Quantitative constraints from J/ψ production in coherent and incoherent processes

→ challenging both shadowing and saturation models

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New opportunities with open heavy-flavor and jets observables:
- "fully calculable" and ready for nPDF fits, with wide reach in x, Q^2

→ developing the experimental and theoretical toolbox for a broad program at the EIC

EIC data taking will start right before LHC Run 5:
→ maximizing the physics impacts of both programs also rely on synergies in the choices of ion species

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Thank you for your attention

BACKUP