Laboratory for Nuclear Science

# First measurement of $D^0$ photonuclear production in ultraperipheral PbPb collisions with CMS

**The 11th biennial workshop of the APS Topical Group on Hadronic Physics (GHP2025)**

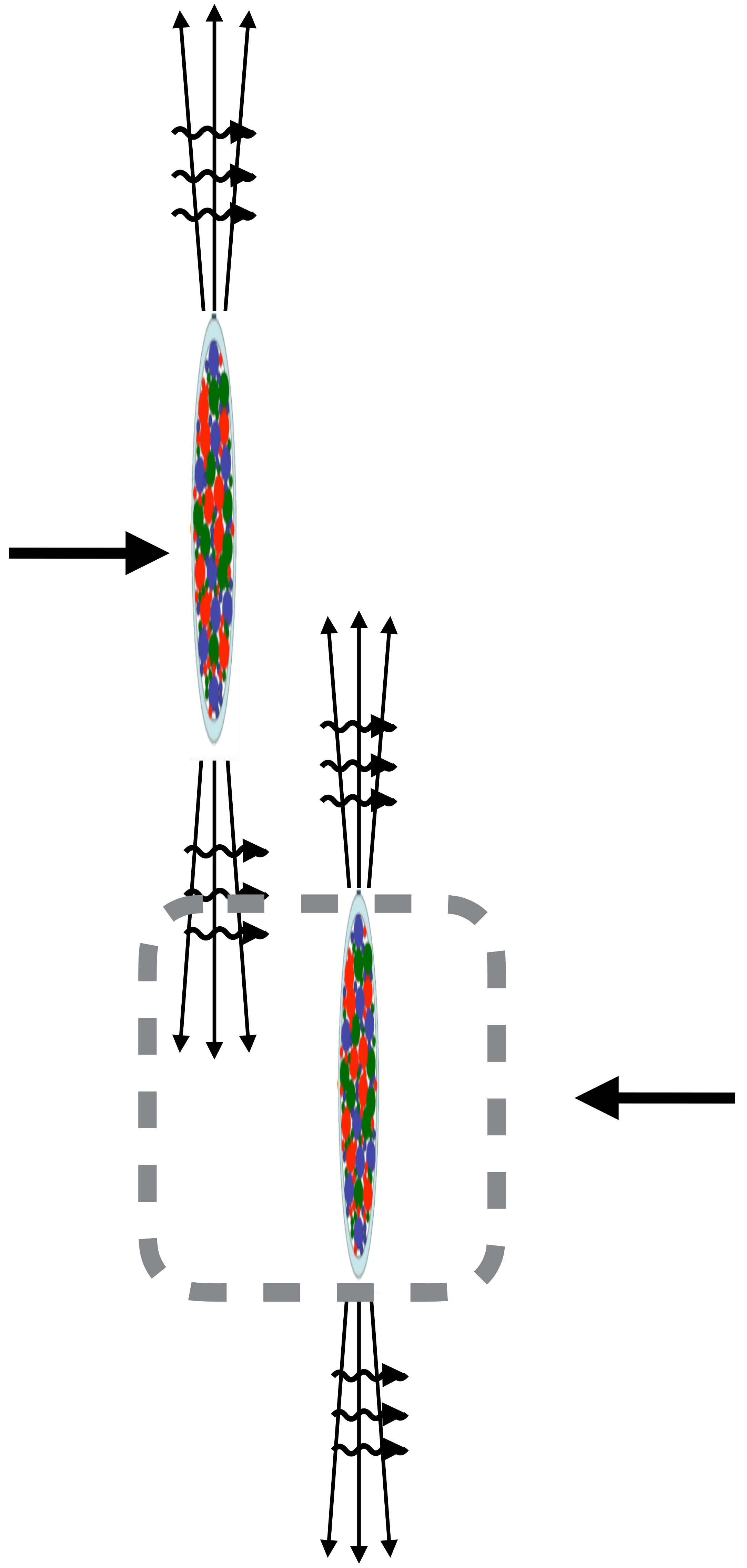
*March 14–16, 2025, Anaheim Convention Center*

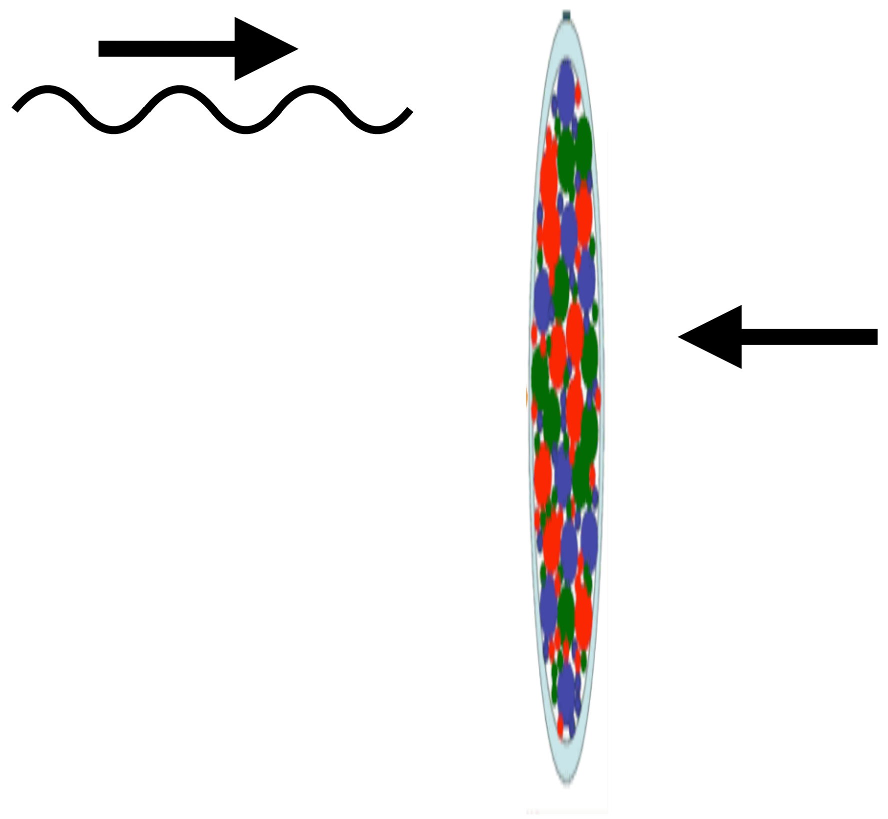
***Gian Michele Innocenti (MIT)***

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

**CMS Collaboration**, CMS HIN-24-003

# The Large Hadron “Photon” Collider



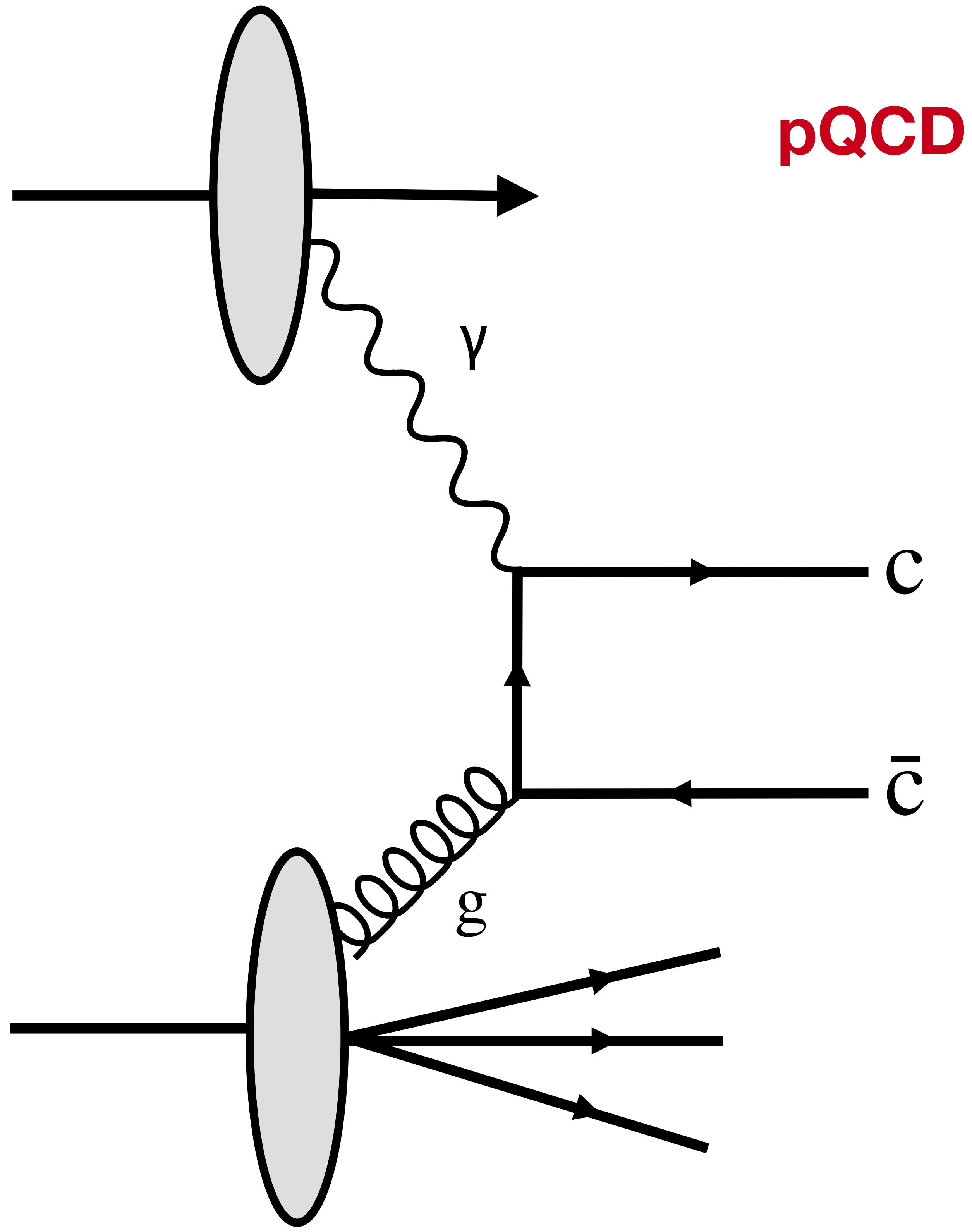


**Photon-nucleus collision in UPCs:**
- highest γ-nucleon center-of-mass energy experimentally accessible
- large flux of photons (~$Z^2$)

→ unique experimental tools to study the **properties of quarks and gluons in nuclei**

# Open charm production in UPCs

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




**pQCD description down to $p_T$=0**

($m_c > \Lambda_{QCD}$)

**Accurate final state reconstruction**

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

**Wide x, $Q^2$ coverage**

→ differential measurements in the y and $p_T$ of the heavy hadron

**Absence of sizable final-state effects** (which strongly affect hadronic collisions, e.g pPb)

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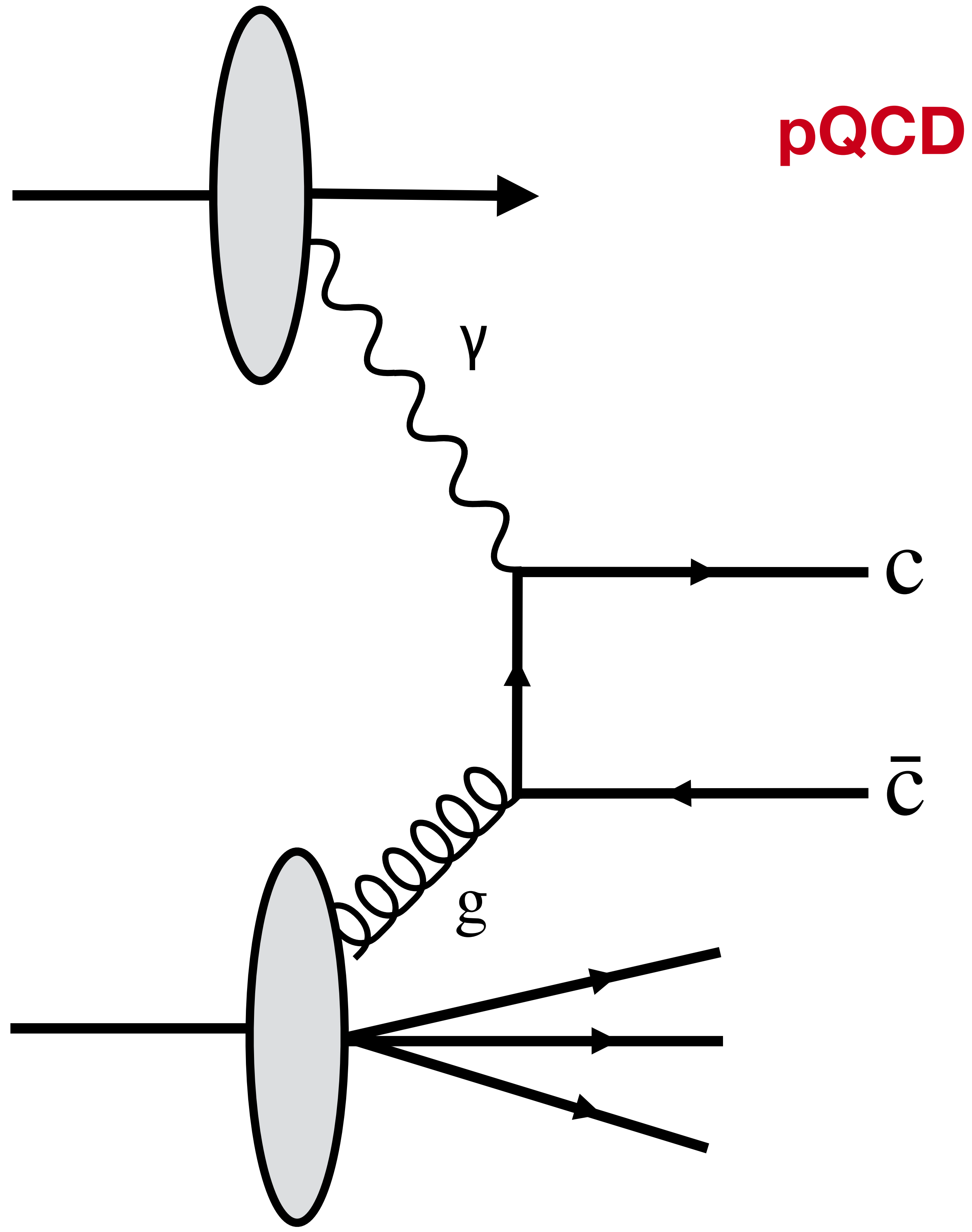
# Open charm production in UPCs

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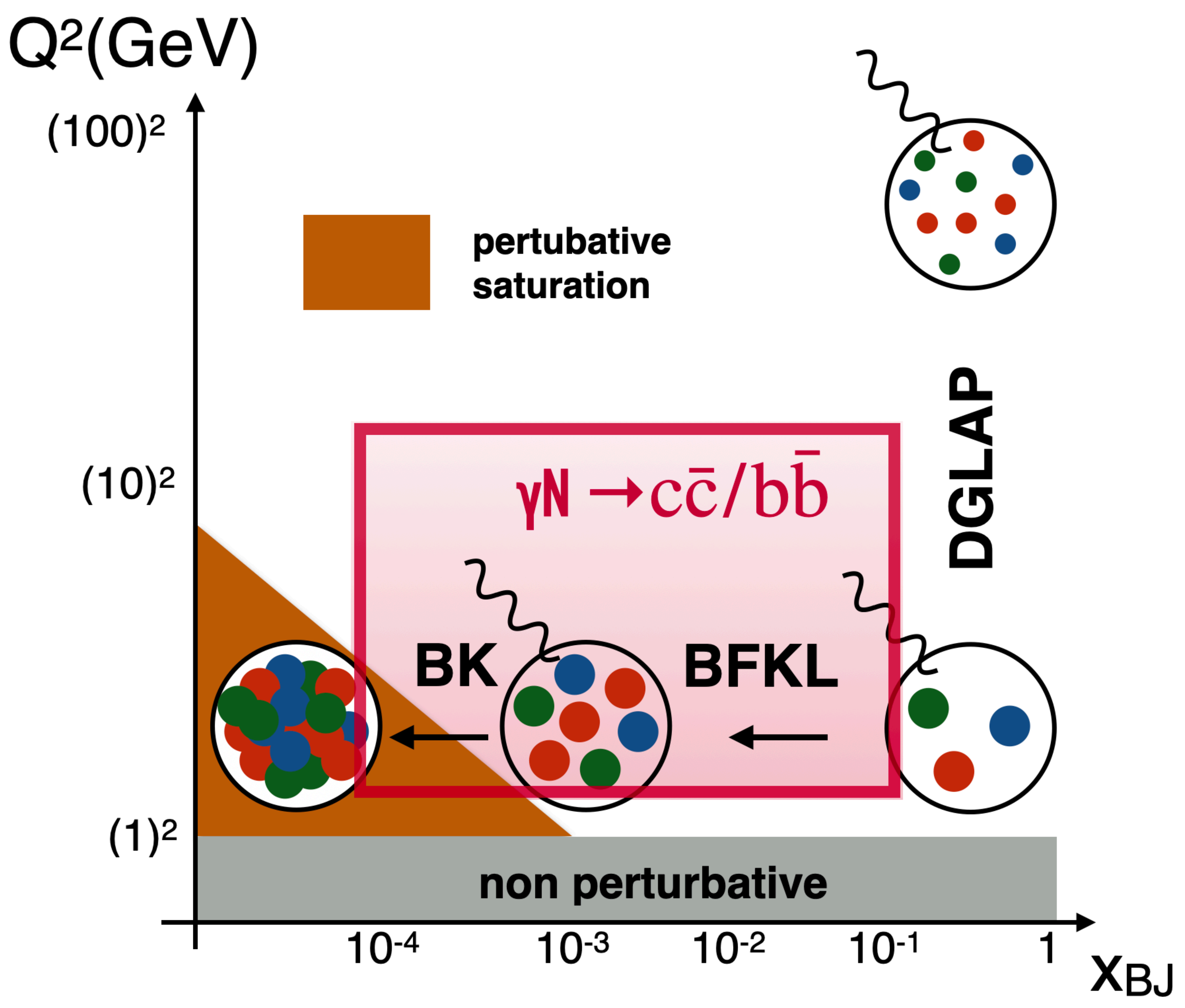


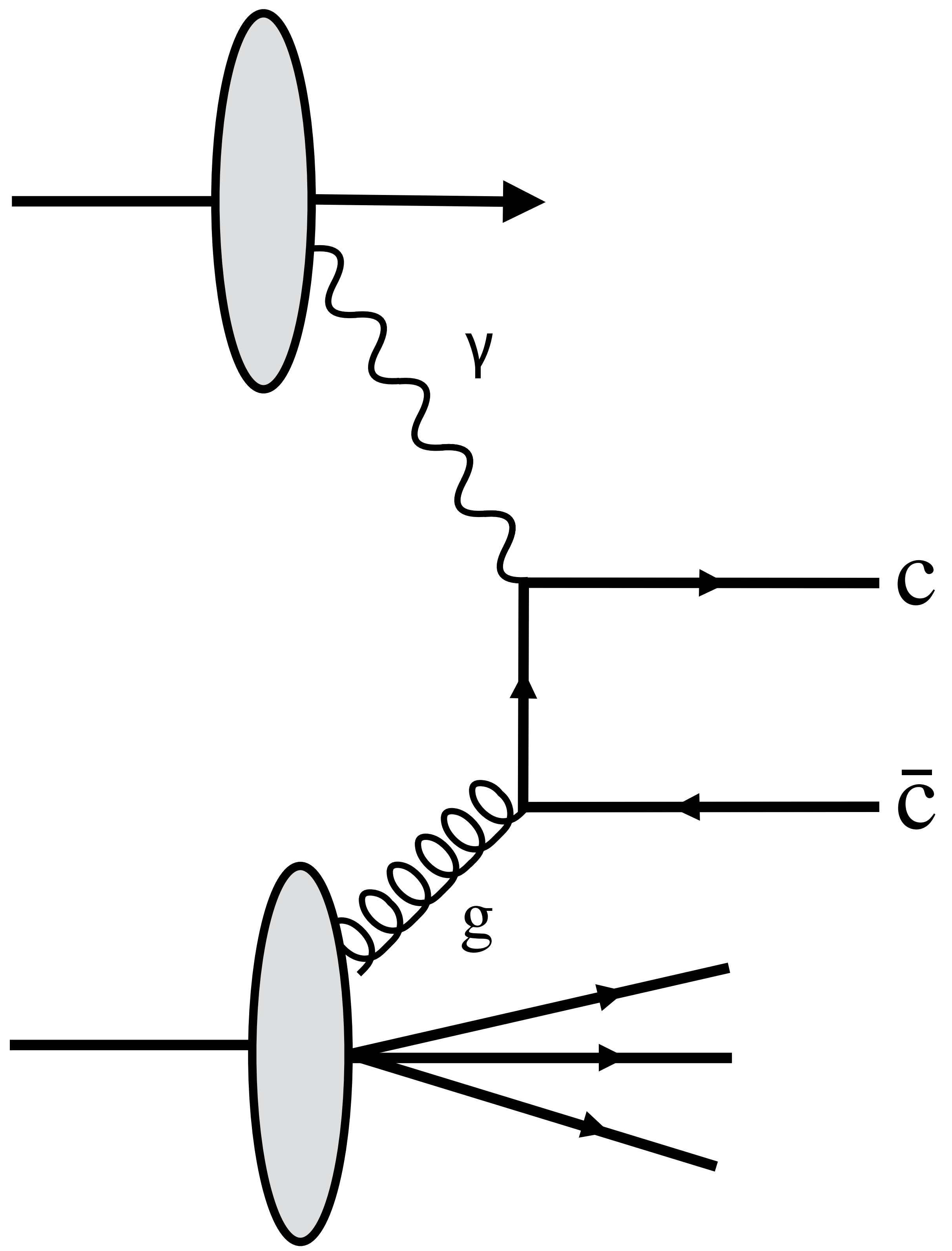

**→ test the emergence of low-x phenomena in absence of sizable final state effects**

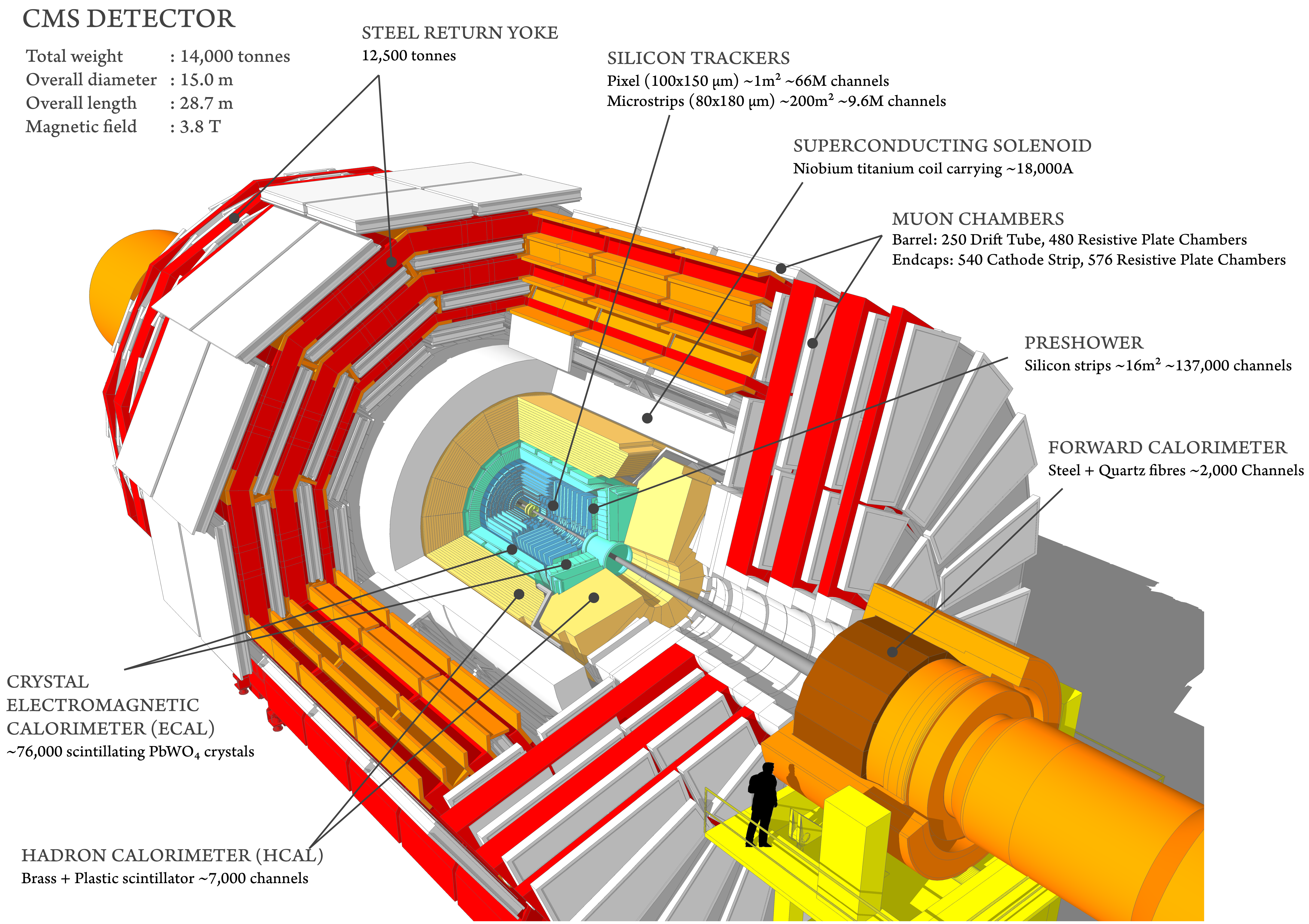
# Experimental strategy with CMS

**High-rate and large acceptance general purpose detector at the Large Hadron Collider**

→ charged particle, photons, muons

→ from low to high transverse momentum ($p_T$)

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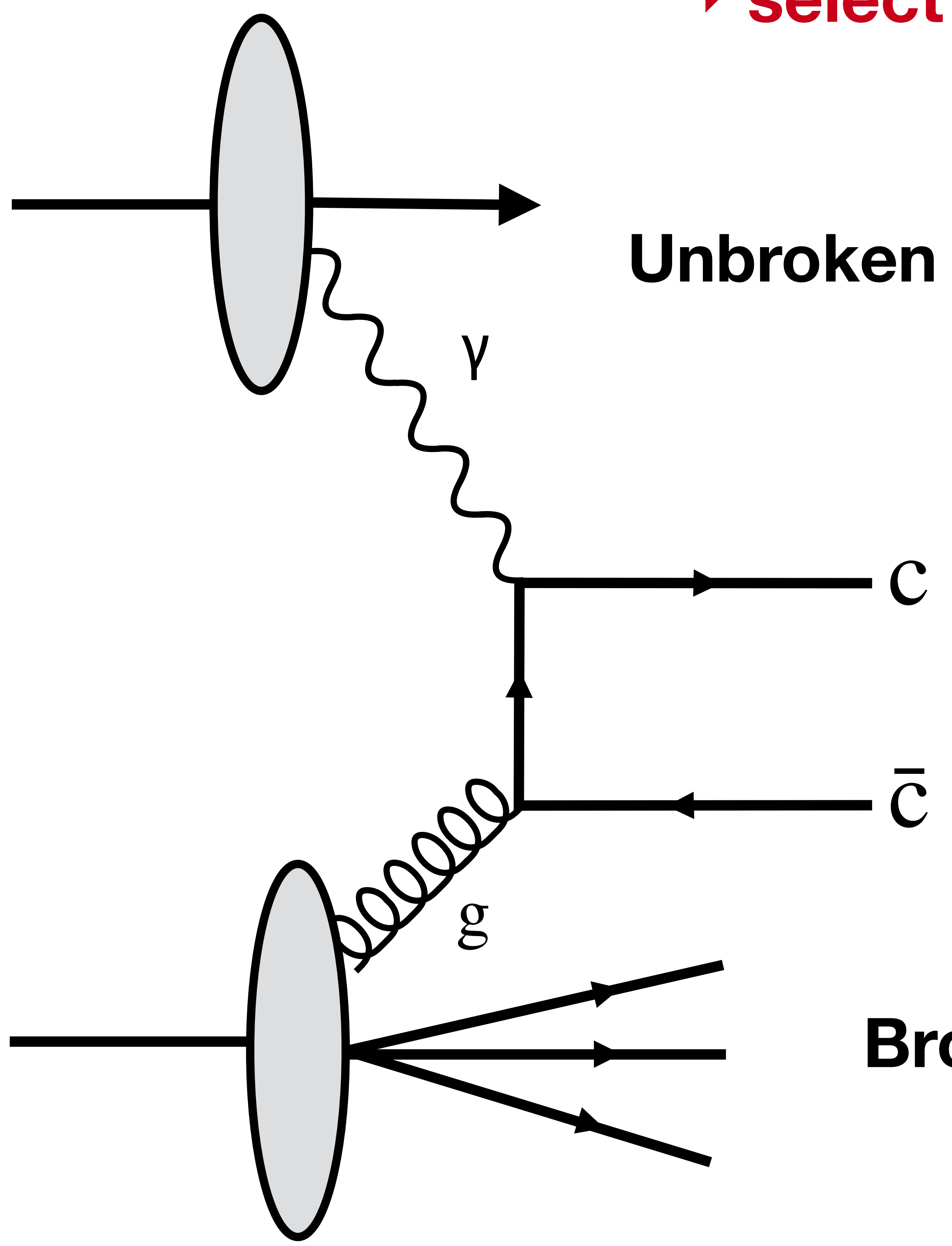
# Experimental strategy: event selection

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




**Unbroken nucleus**

**Broken nucleus**

# Experimental strategy: event selection

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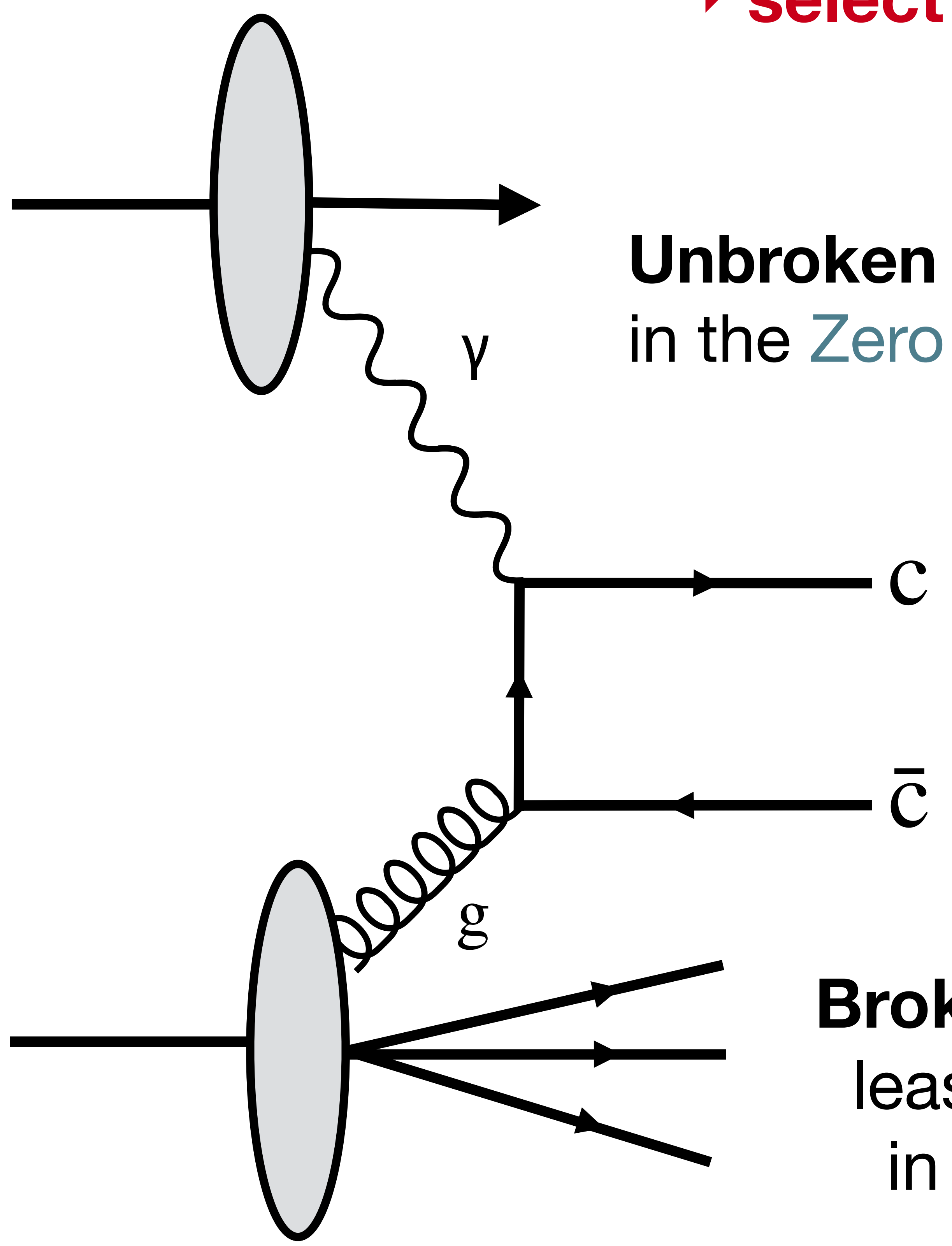
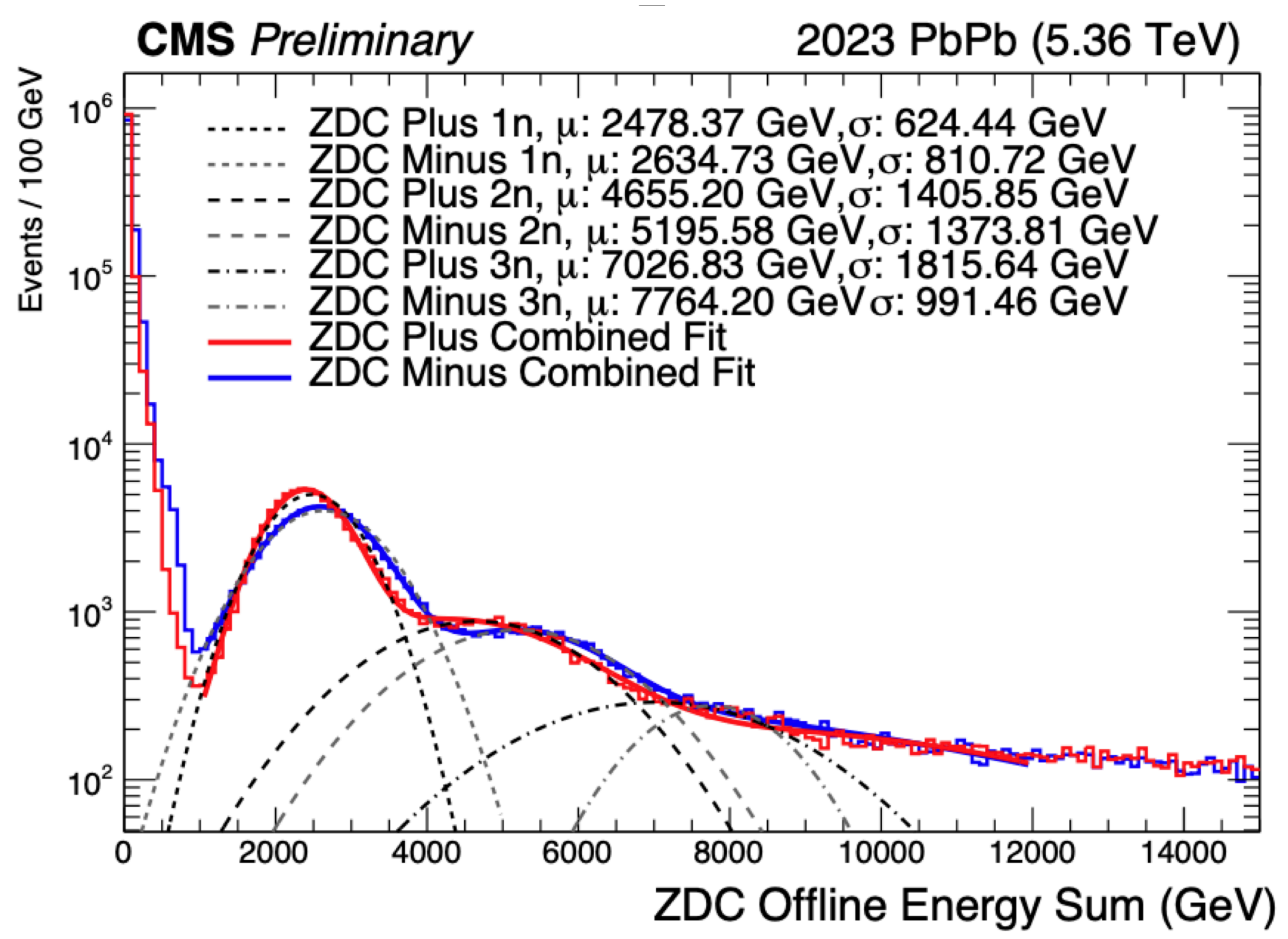
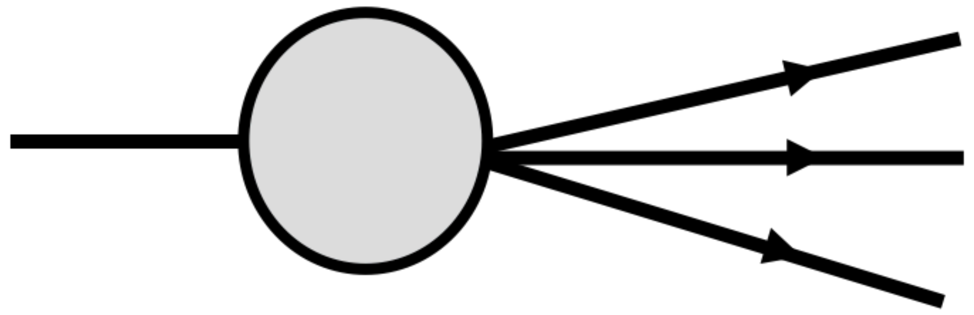



**Unbroken nucleus**: no neutrons (0n) in the Zero Degree Calorimeter (ZDC)

**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)**

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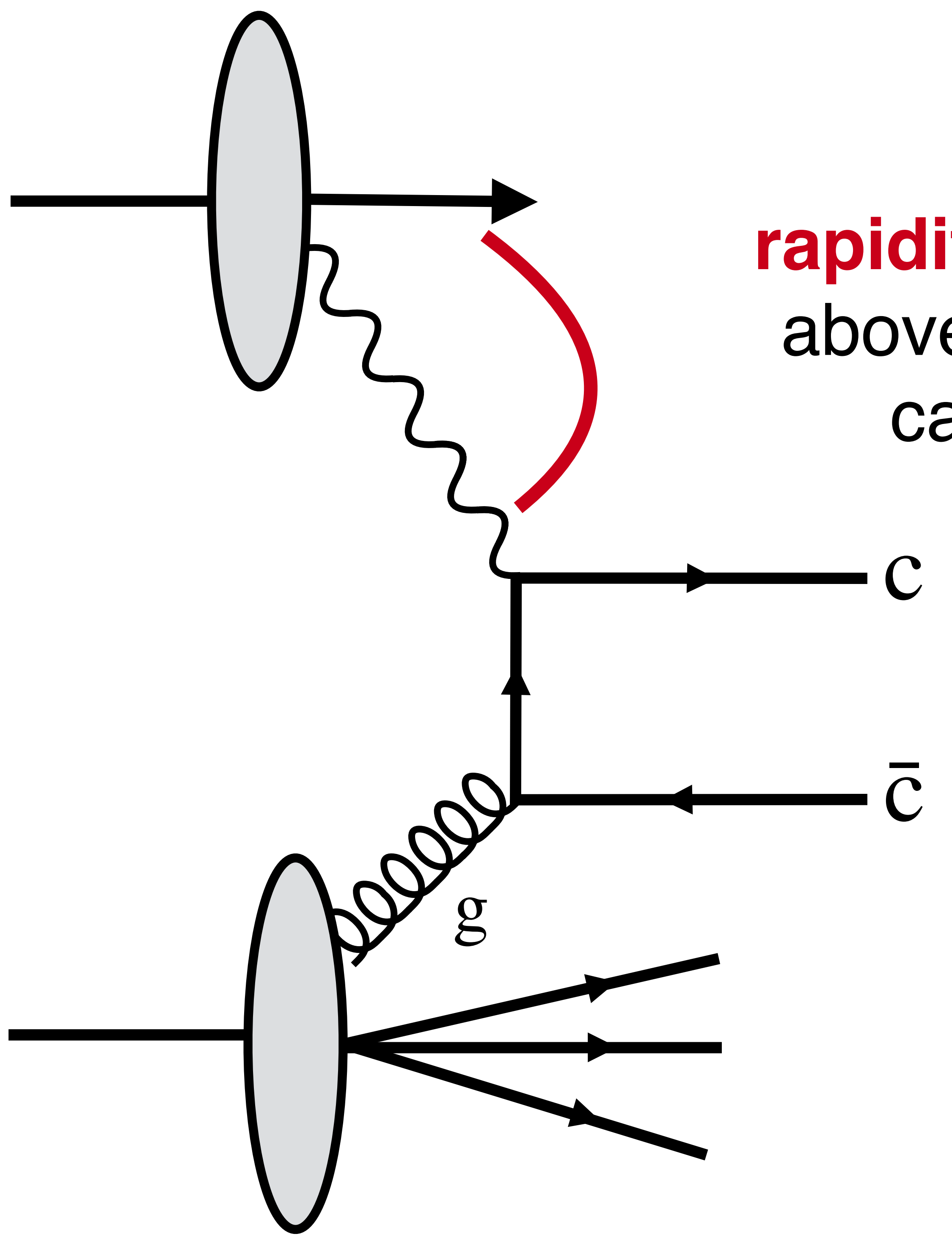
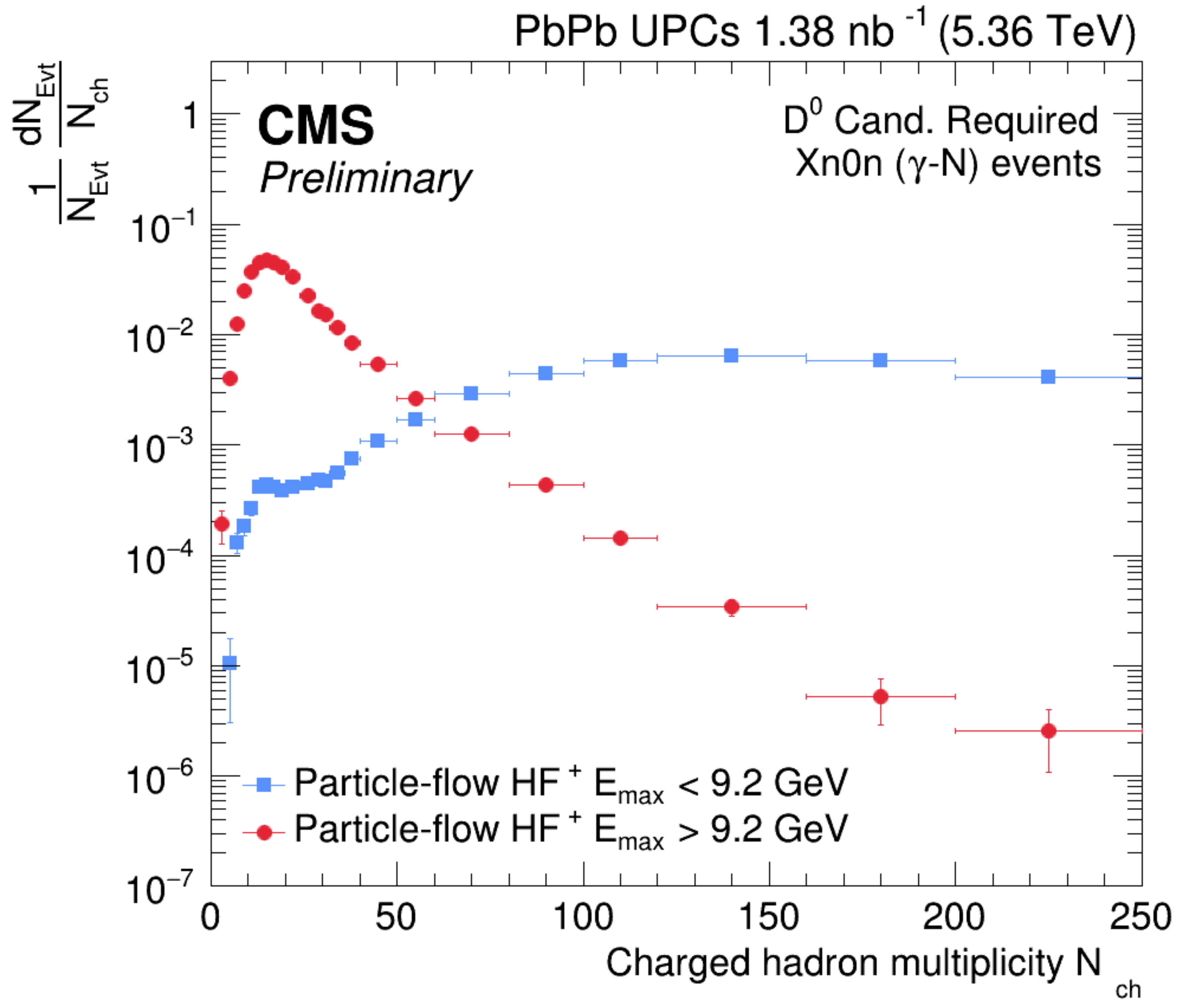
# Experimental strategy: event selection



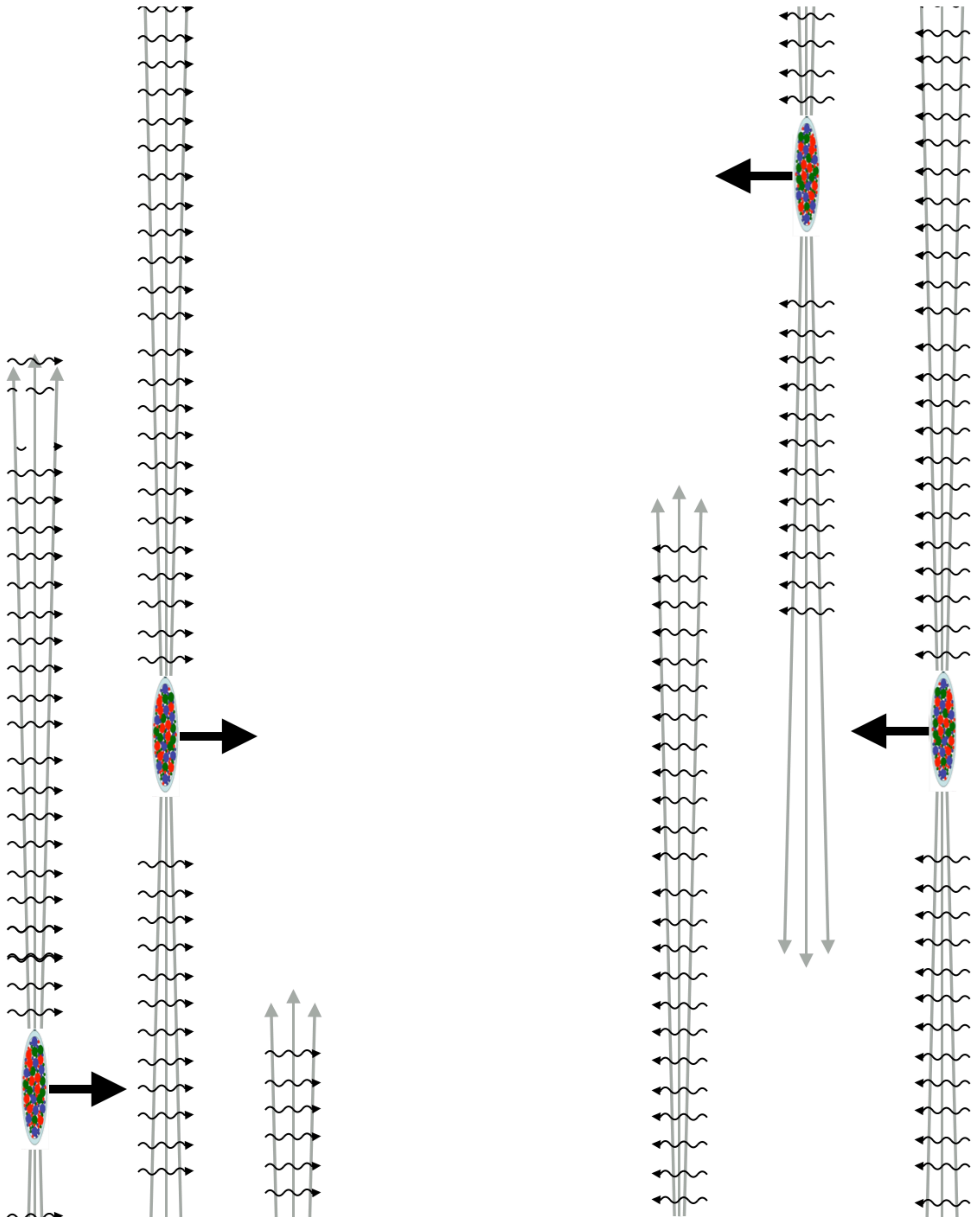

**rapidity gap condition** no deposit above $E^{th}$ in the forward hadronic calorimeter (**$3.0 < \eta < 5.2$**)




**Events passing the rapidity gap condition**
**Events failing the rapidity gap condition (high $N_{ch}$)**
(mostly coming from "hadronic" PbPb collisions)

- With simultaneous requirements on ZDC Xn0n and rapidity gap
  → **negligible contamination from "hadronic" events**

# Experimental strategy: trigger selection

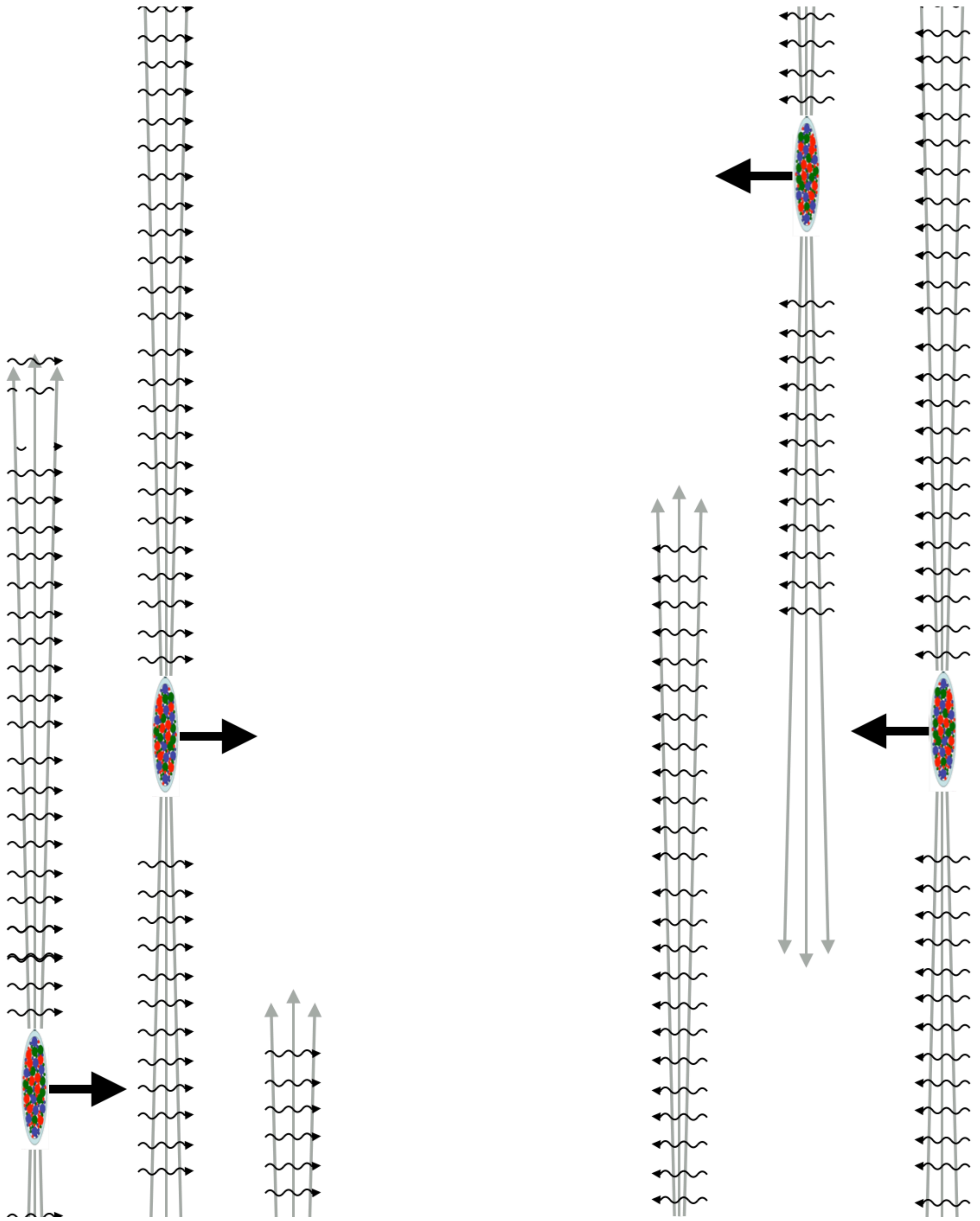


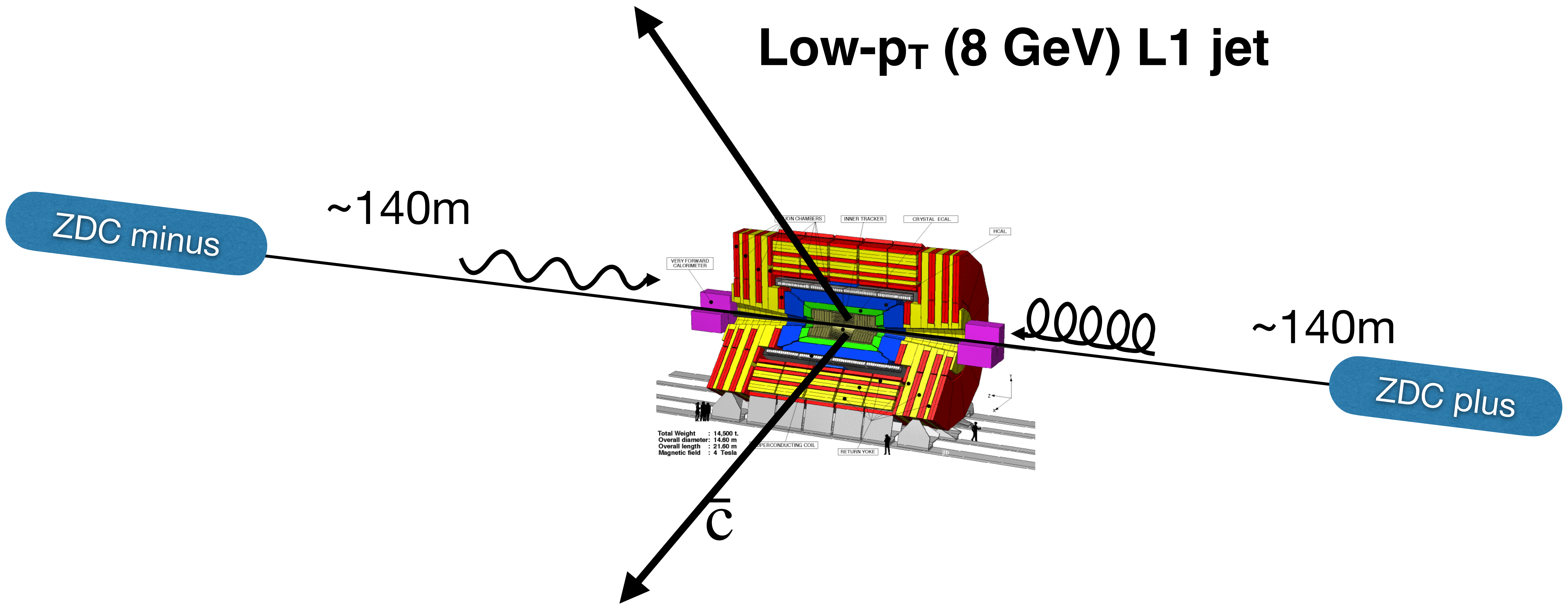
**Rate of photonuclear events ~10 MHz:**

→ much higher than CMS L1 trigger bandwidth!

→ **need for a highly-selective "hardware" L1 trigger strategy**

# A new trigger “hardware” strategy for UPCs with CMS



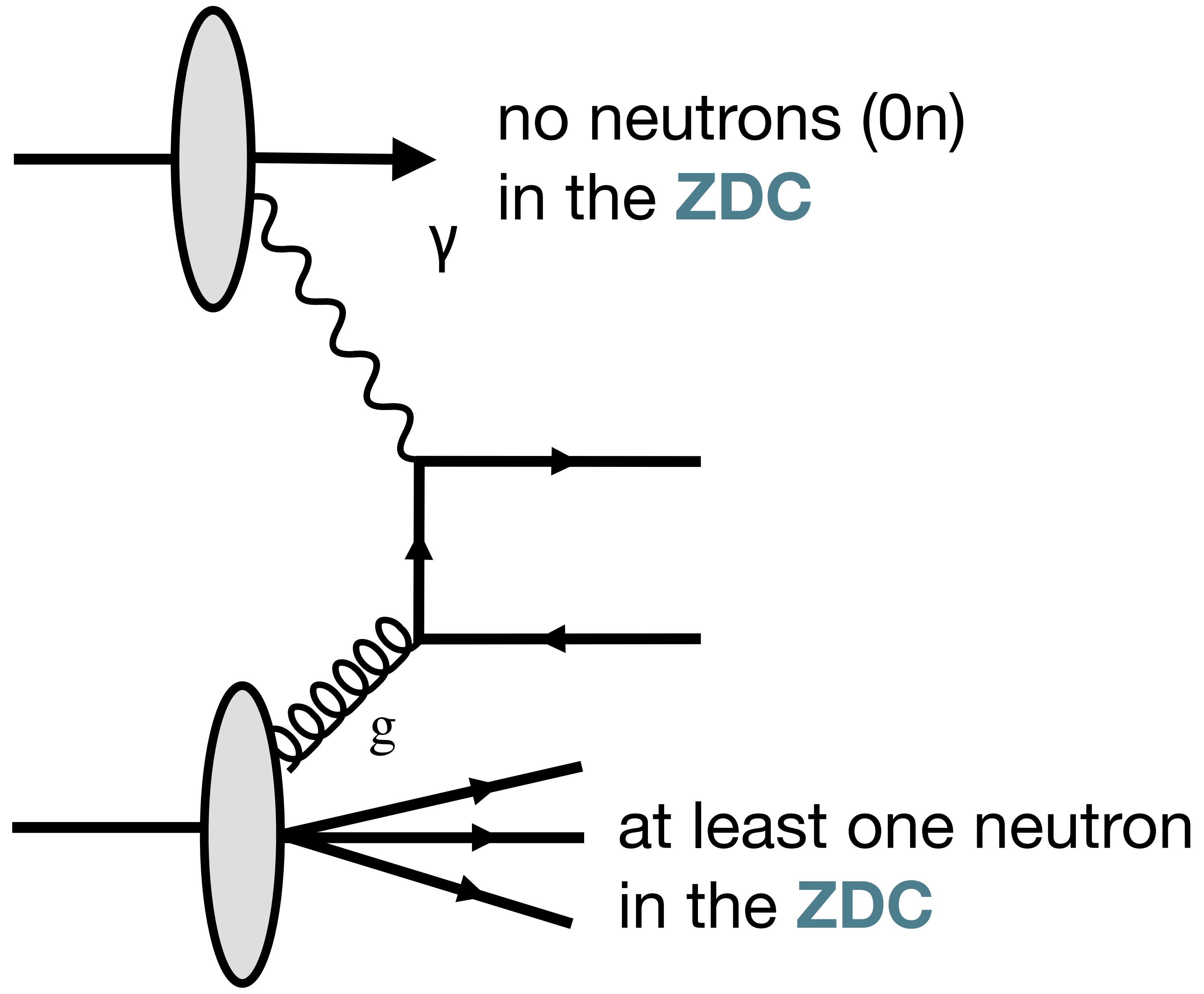



**New (L1) hardware triggers exploiting:**
- Zero-Degree Calorimeters (first time in “trigger” mode)
- ECAL and HCAL for tagging soft jets

**→Converting CMS into a high-rate photonuclear detector!**

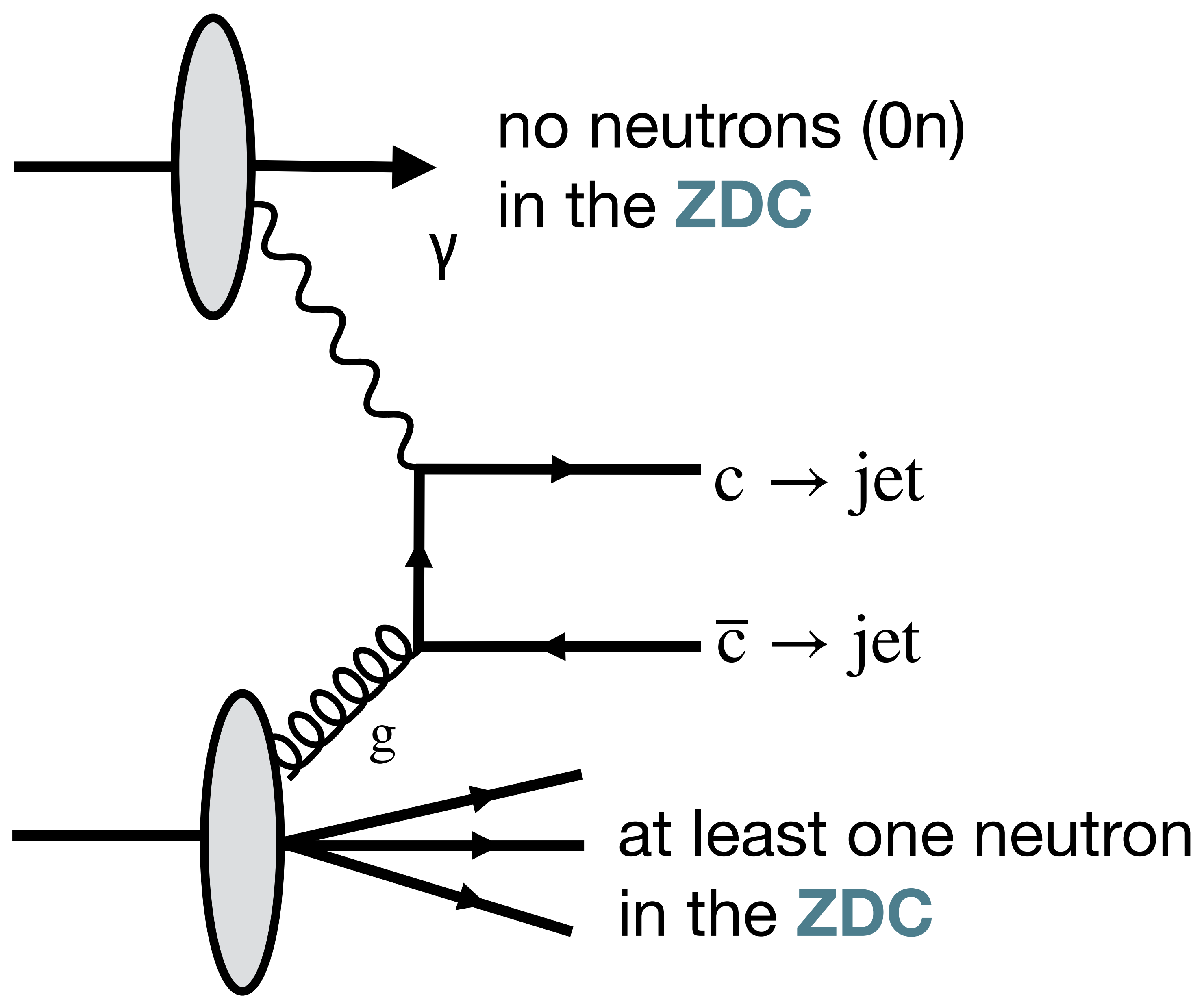
**→ From a few million (2018) to about 10 billion (2023) of UPC photonuclear events collected!**

# Photonuclear triggers for low $p_T$ $D^0$

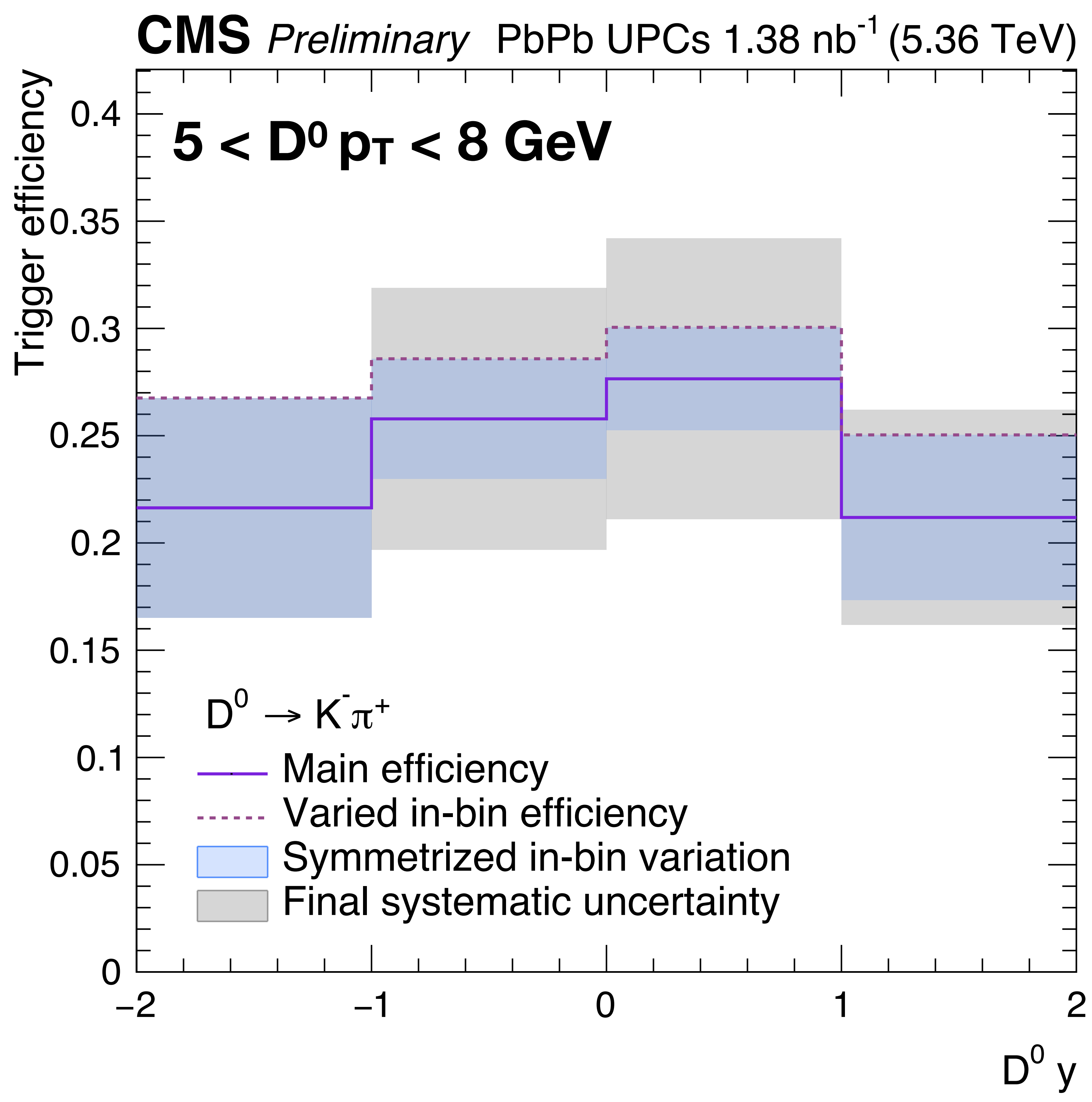



**For low-$p_T$ $D^0$ mesons ( < 5 GeV)**
→ at least one ZDC with >1n signal (**ZDCOR)**

# Photonuclear triggers for high $p_T$ $D^0$

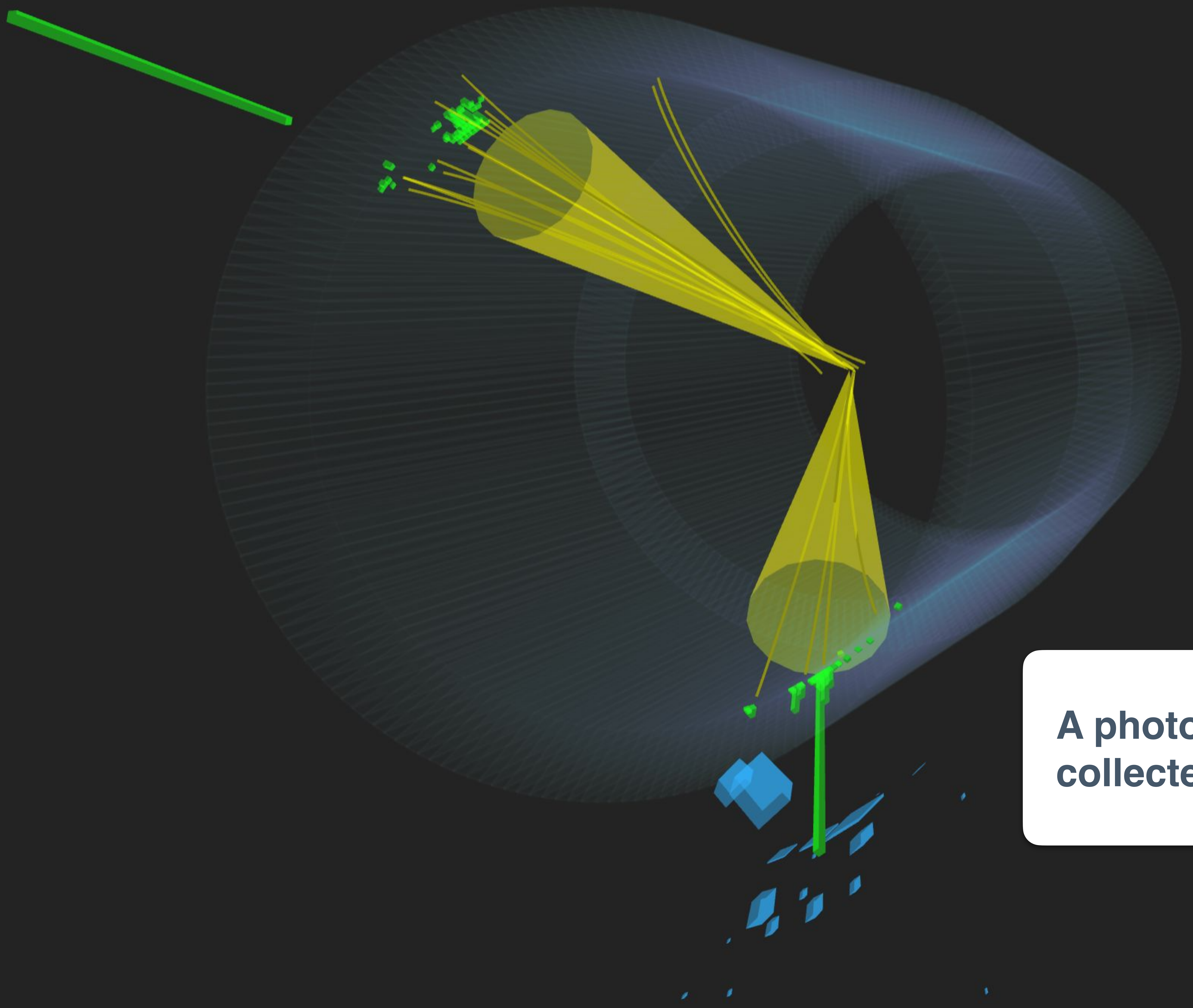



**For high-$p_T$ $D^0$ mesons ( > 5 GeV)**
→ **ZDCOR in coincidence with a Level-1 jet** ($E_{jet}$ > 8 GeV)




**"Data-driven" trigger efficiency vs $D^0$ $p_T$ and y**
→ **Good control of the trigger efficiency**
also for low $p_T$ $D^0$ mesons ($p_T$>5 GeV)

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

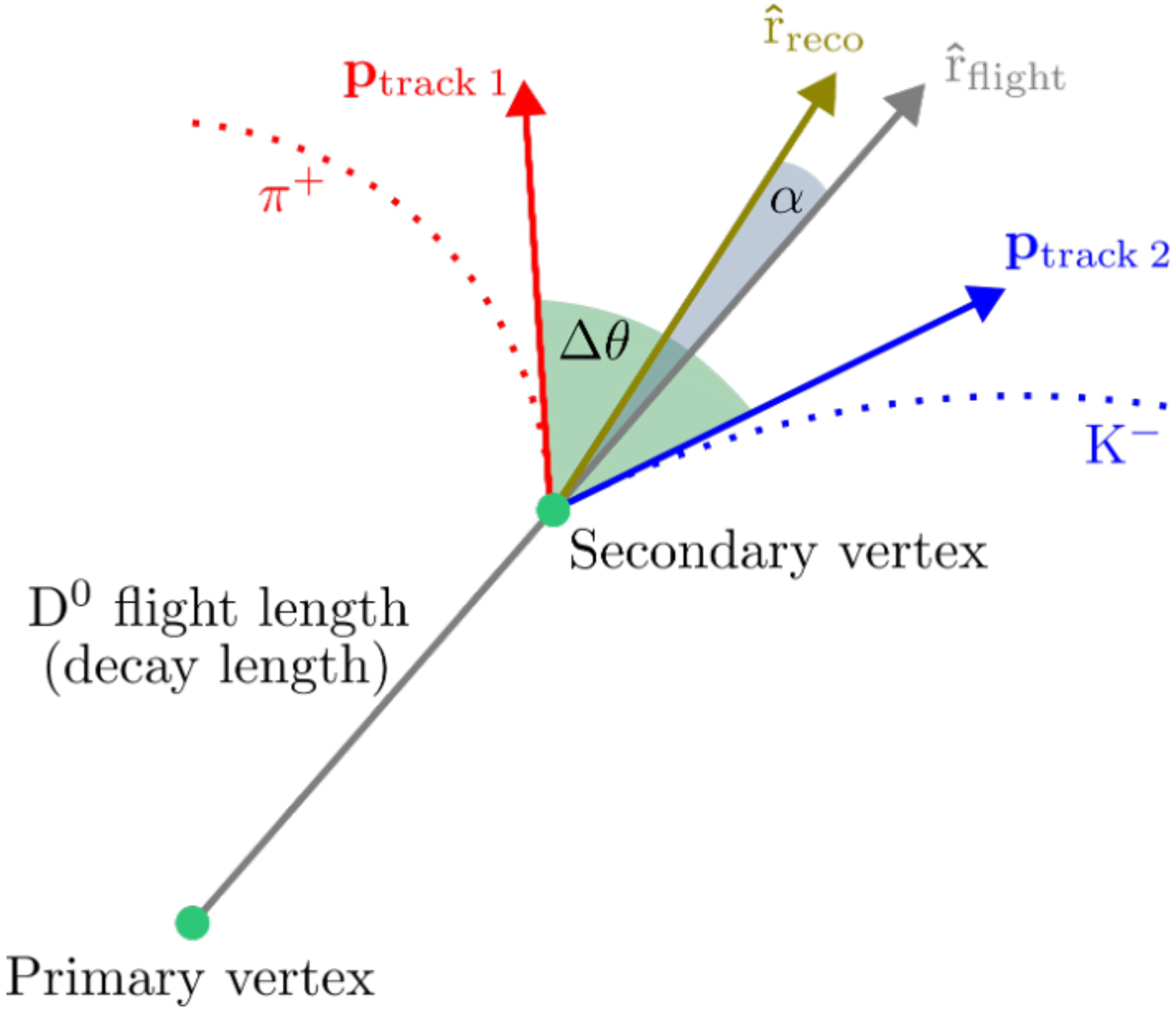


**A photonuclear dijet candidate in PbPb UPCs '23 collected with the new triggering algorithms**

# The first $D^0$ signal in UPCs!

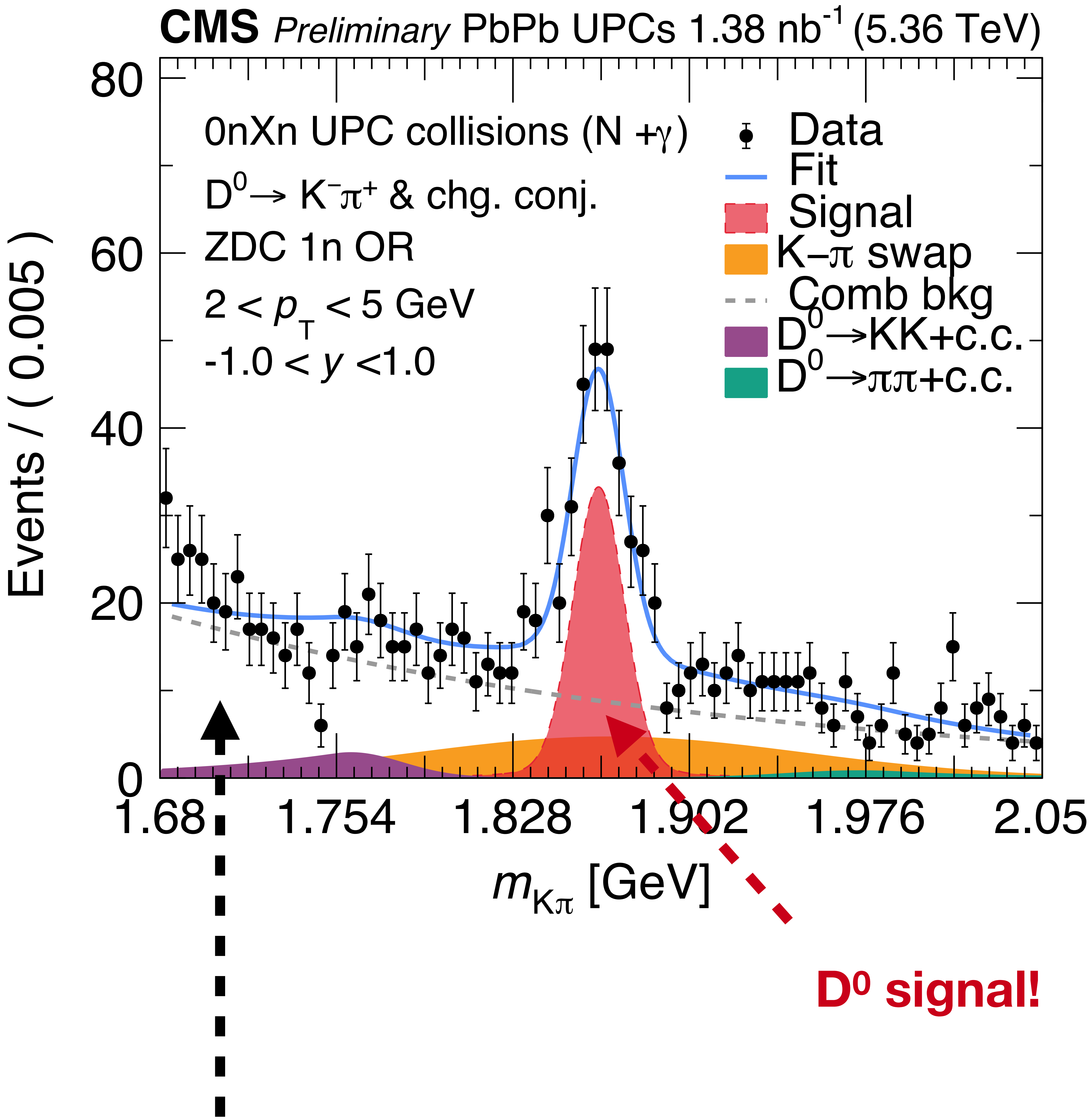
CERN News October 2024

**$D^0 \to K^- \pi^+$** 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**

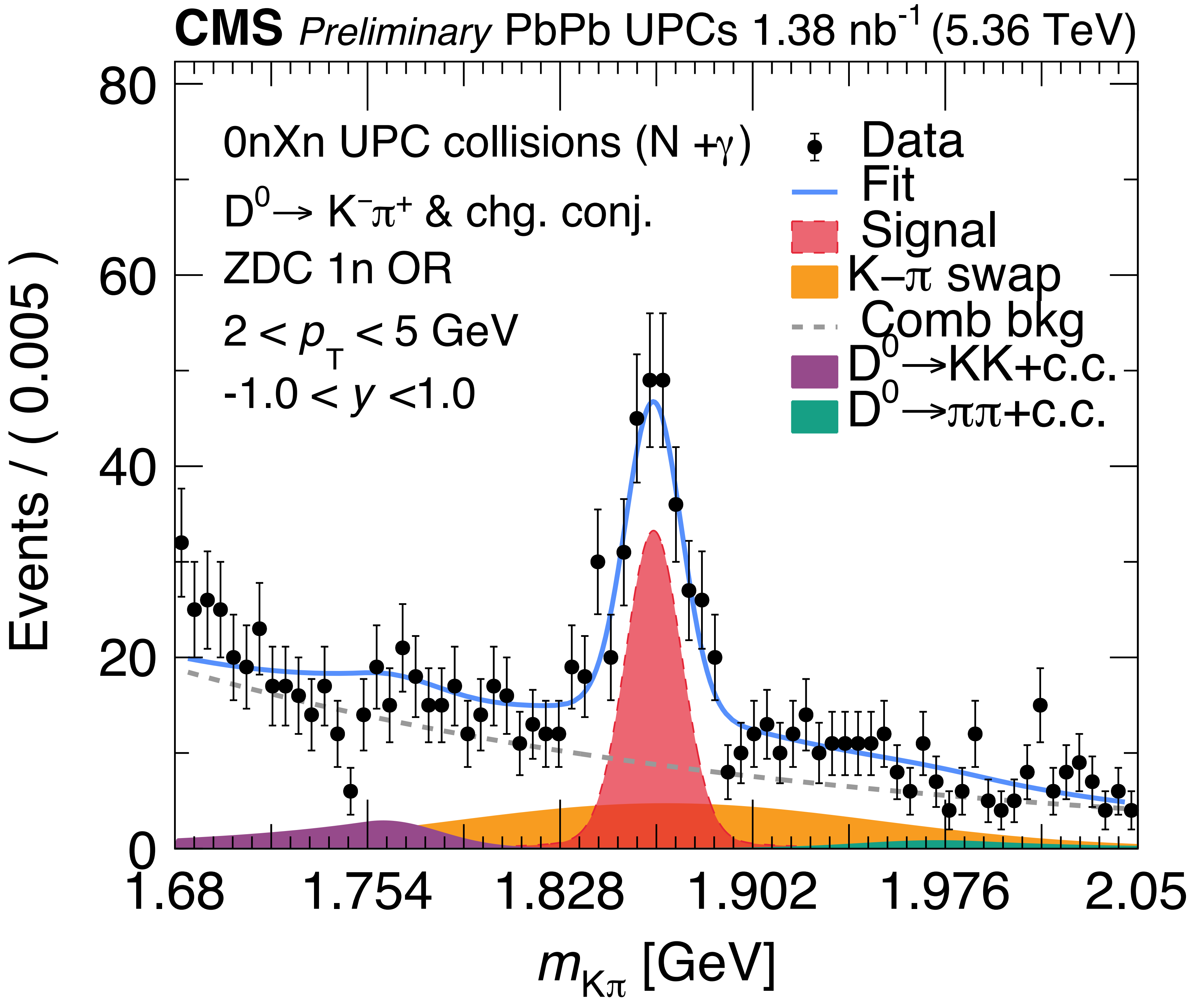


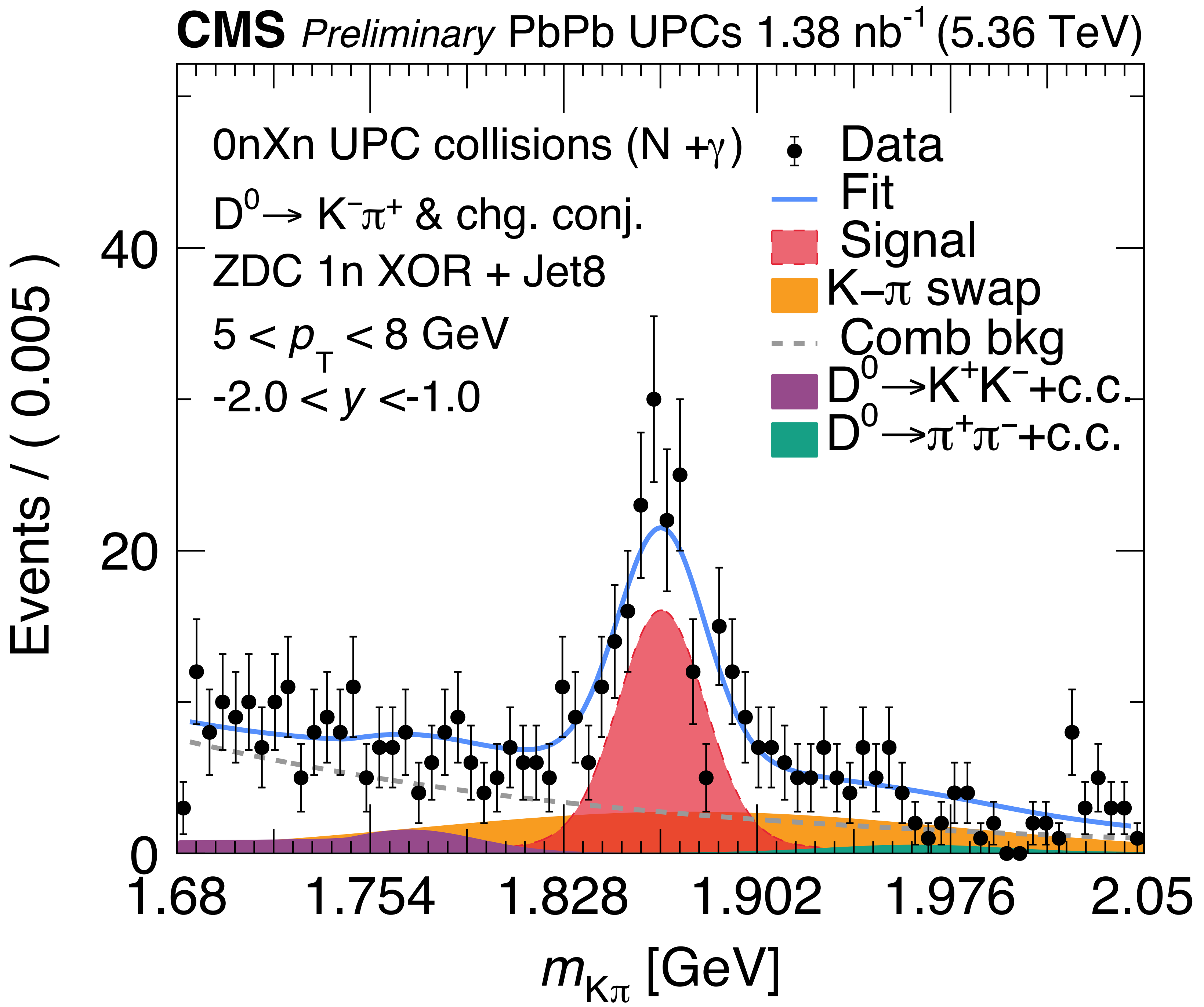

→ **Very low combinatorial background, even for very low $D^0$ $p_T$**

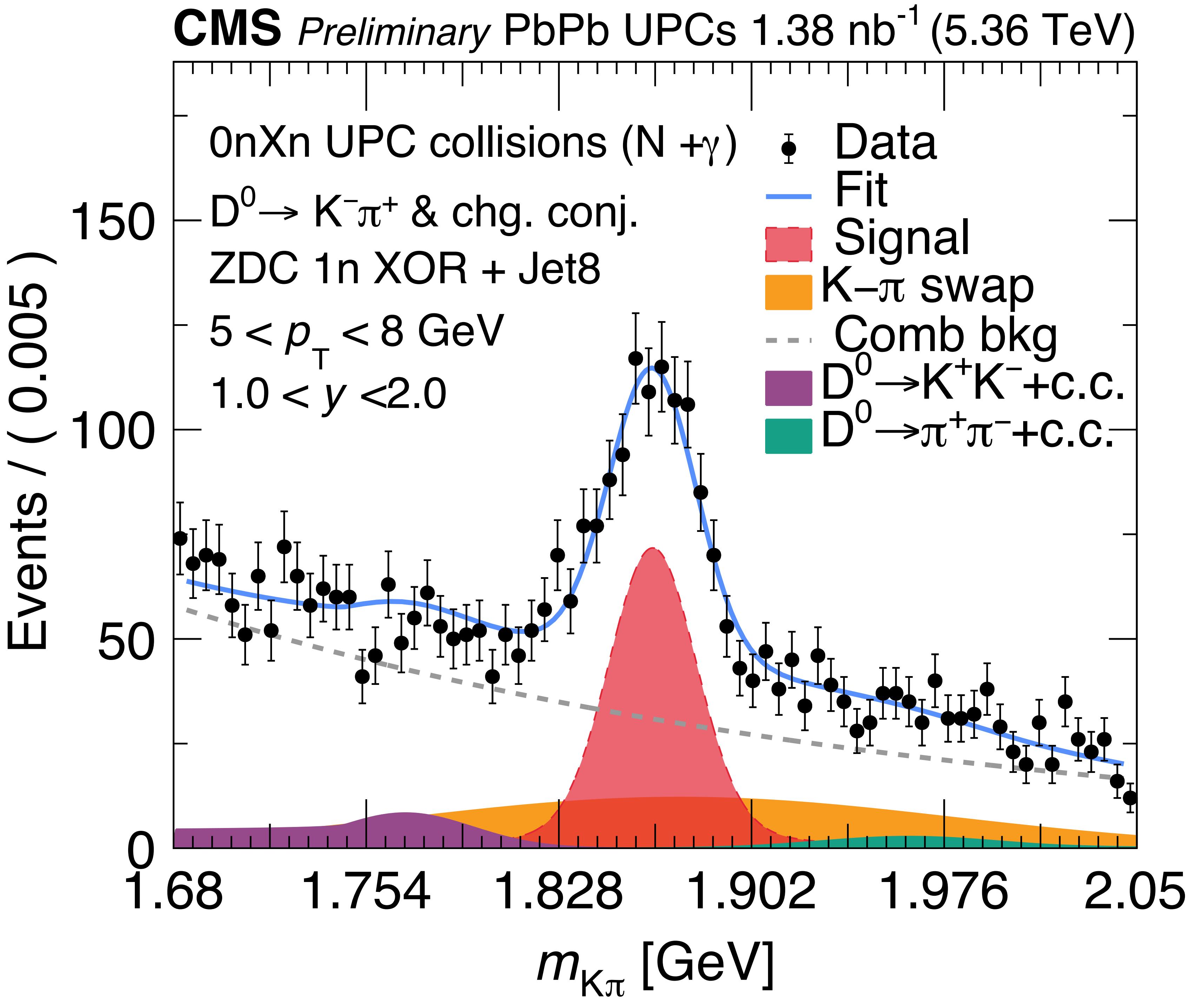
**CMS Collaboration**, CMS HIN-24-003

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

→ **very clean signals extracted in nine intervals of $D^0$ $p_T$ and y!**



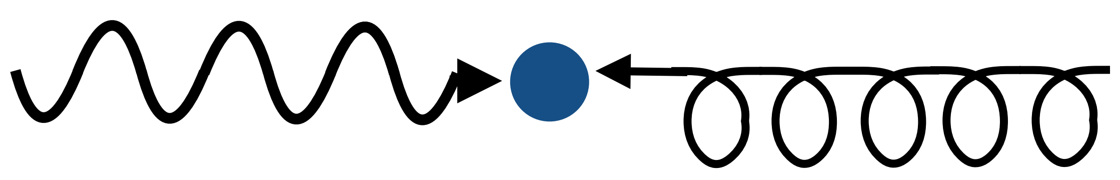



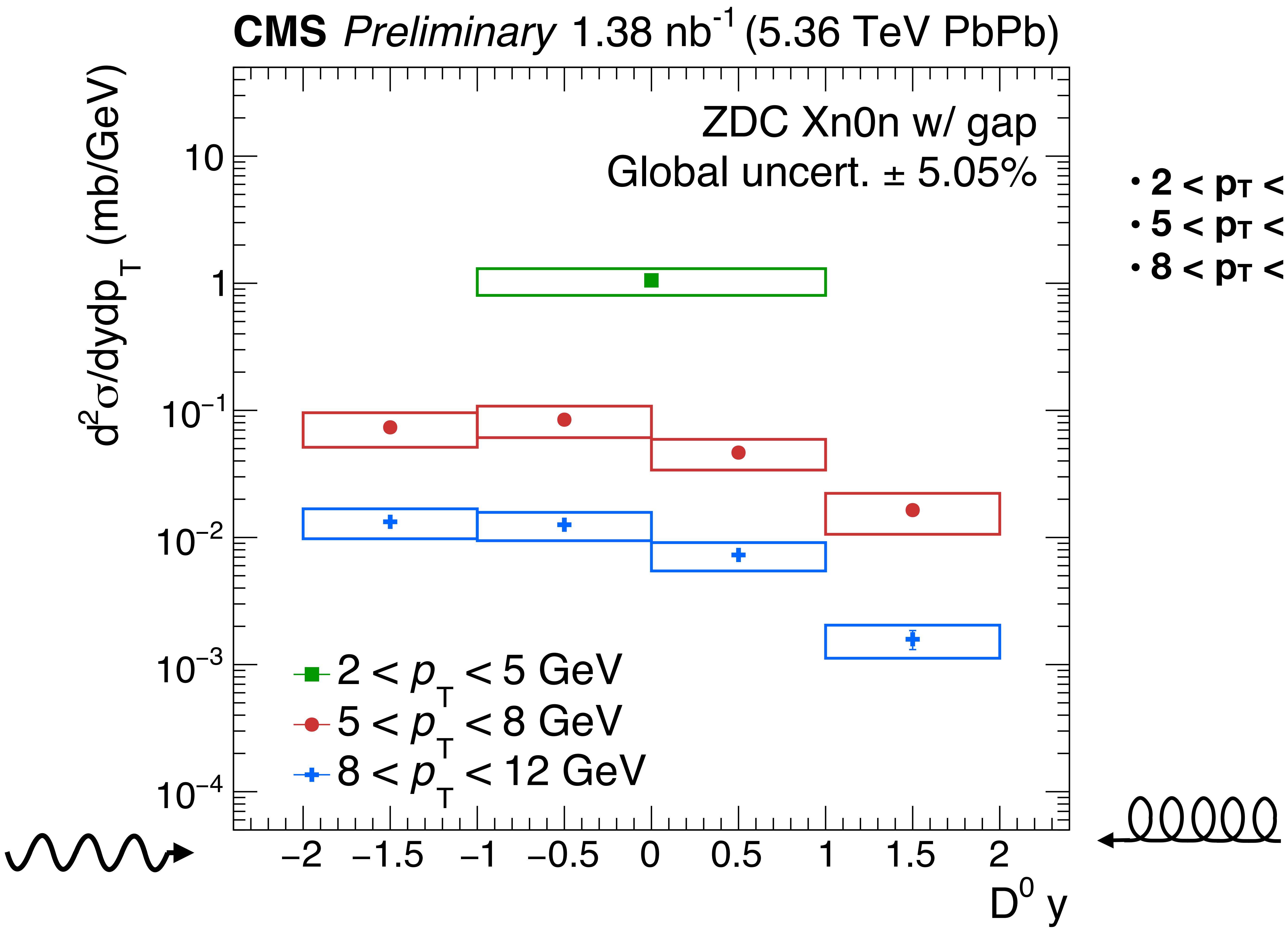




$$x_{gluon} \sim \frac{p_{T,D^0}}{\sqrt{s_{NN}}} exp(-y^*_{D^0})$$

** with respect to the incoming photon direction*

**CMS Collaboration**, CMS HIN-24-003

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



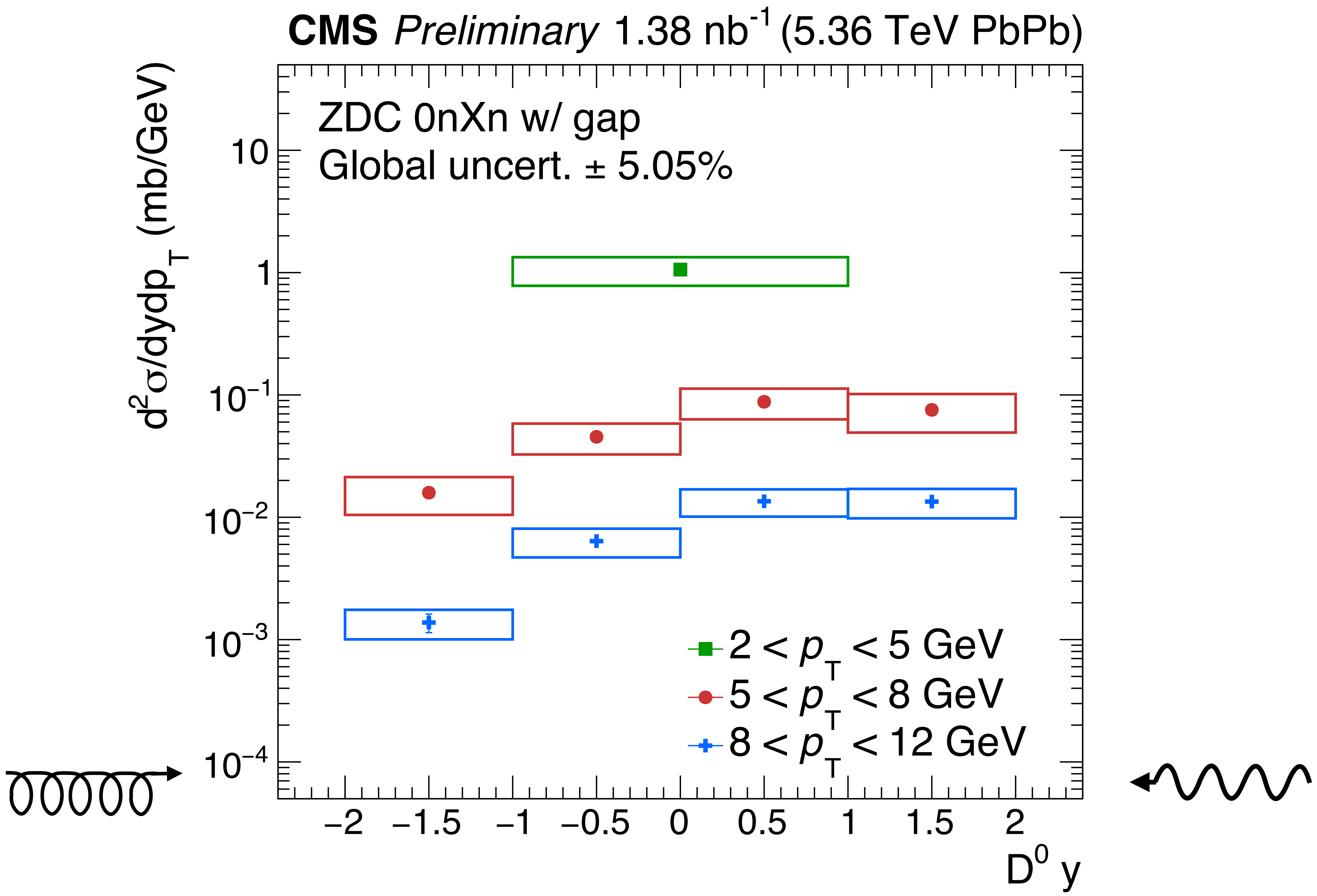

- **2 < $p_T$ < 5 GeV** and **-1 < y < 1**
- **5 < $p_T$ < 8 GeV** with y ∊[-2, -1, 0, 1, 2]
- **8 < $p_T$ < 12 GeV** with y ∊ [-2, -1, 0, 1, 2]

**$D^0$ 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

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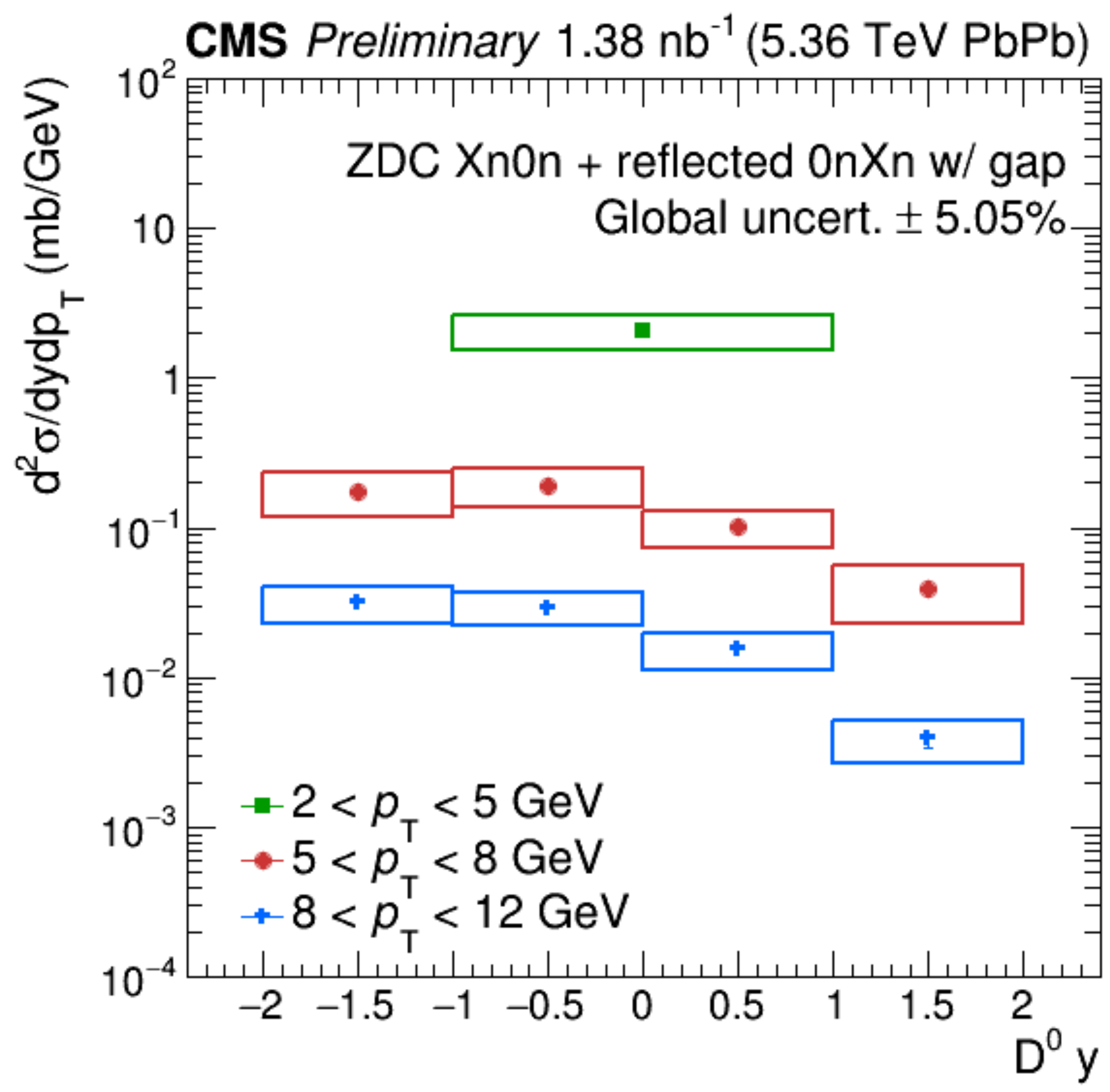
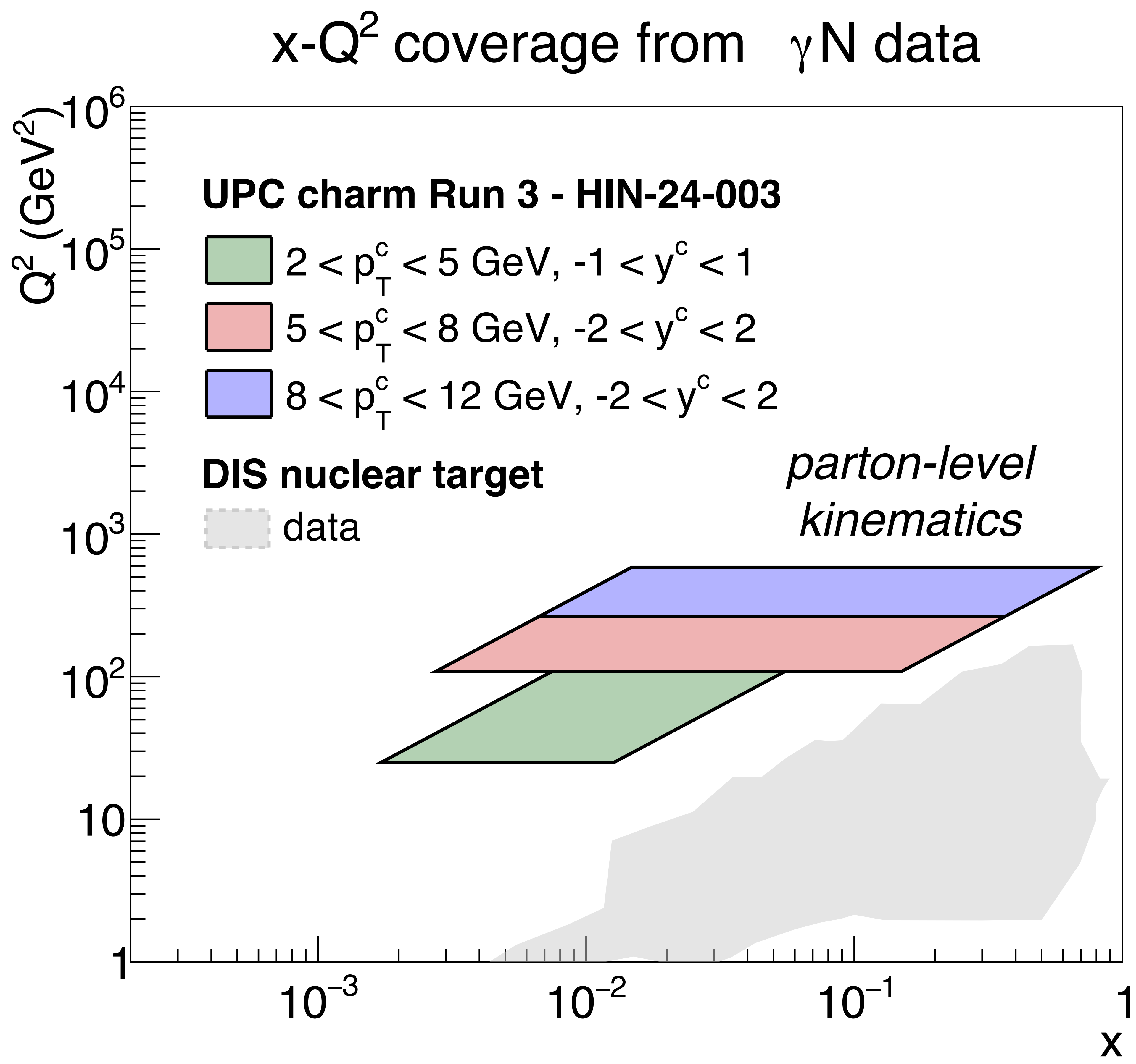
# Estimated x,$Q^2$ coverage



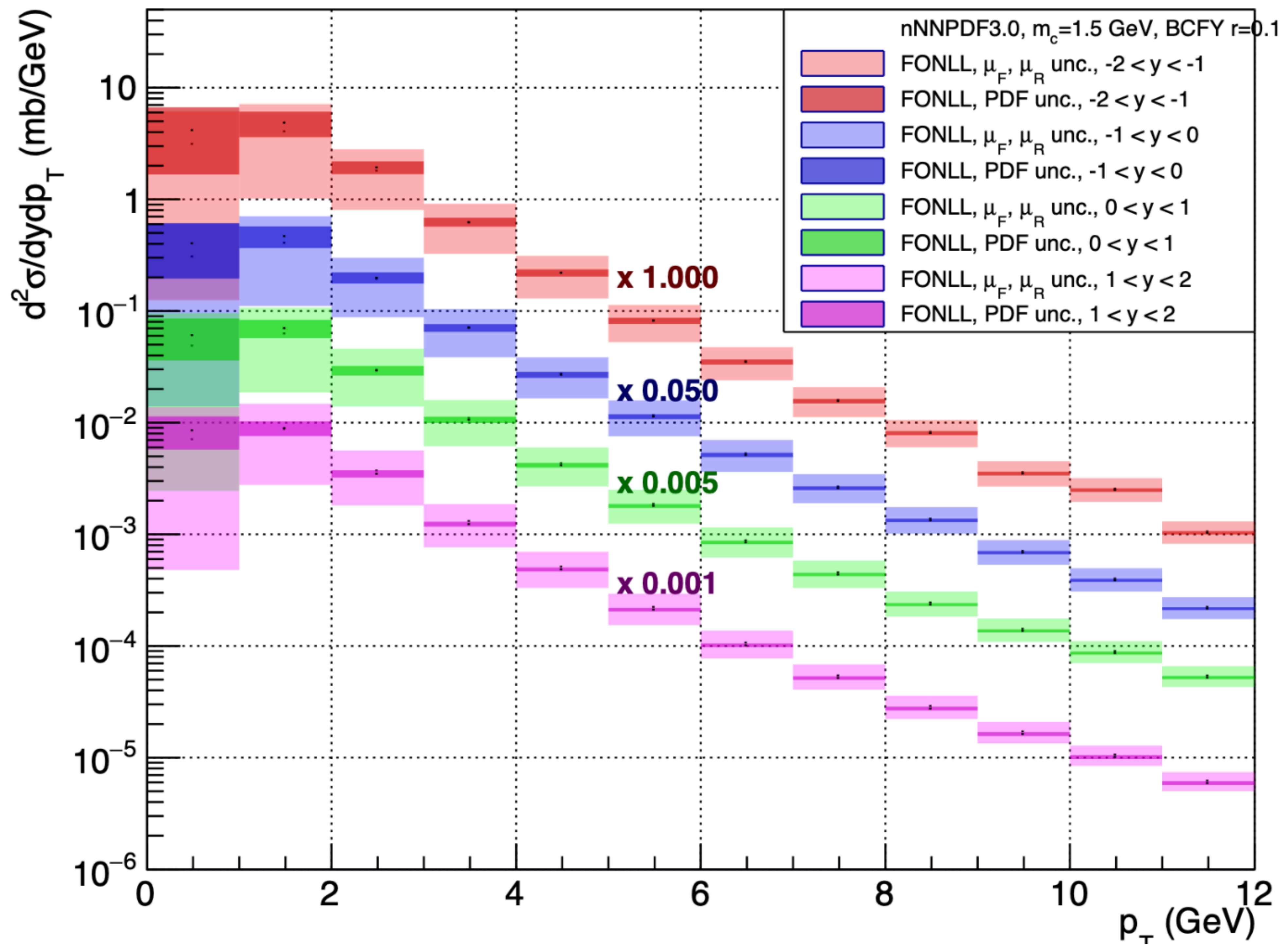




**Testing gluon properties for $10^{-3} < x < 10^{-2}$ for $20 < Q^2 <$ hundreds $GeV^2$ <u>from photon-nucleus collisions</u>**

# FONLL-based predictions for $D^0$ in UPCs

**Ingredients:**

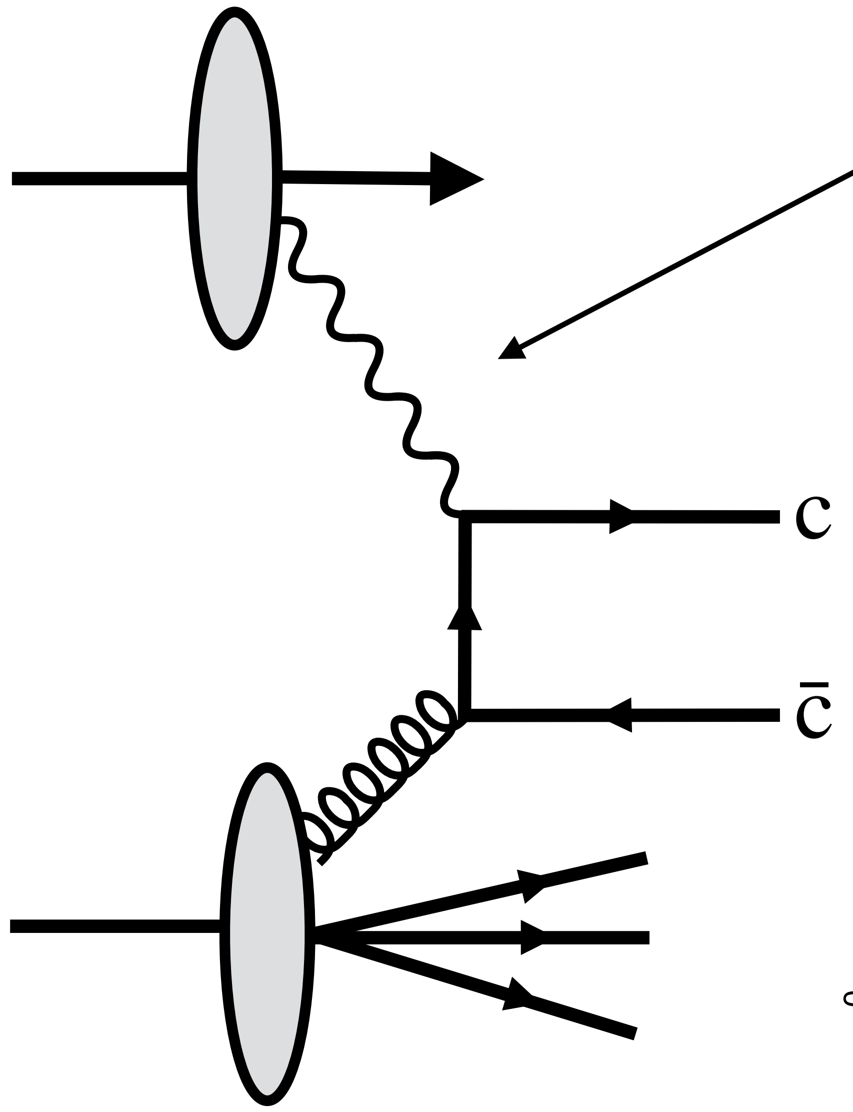
- FONLL partonic cross section for $D^0$ in ep collisions
- Photon flux expected in PbPb UPC collisions
- lead nPDF from EPPS21 and NNPDF3.0

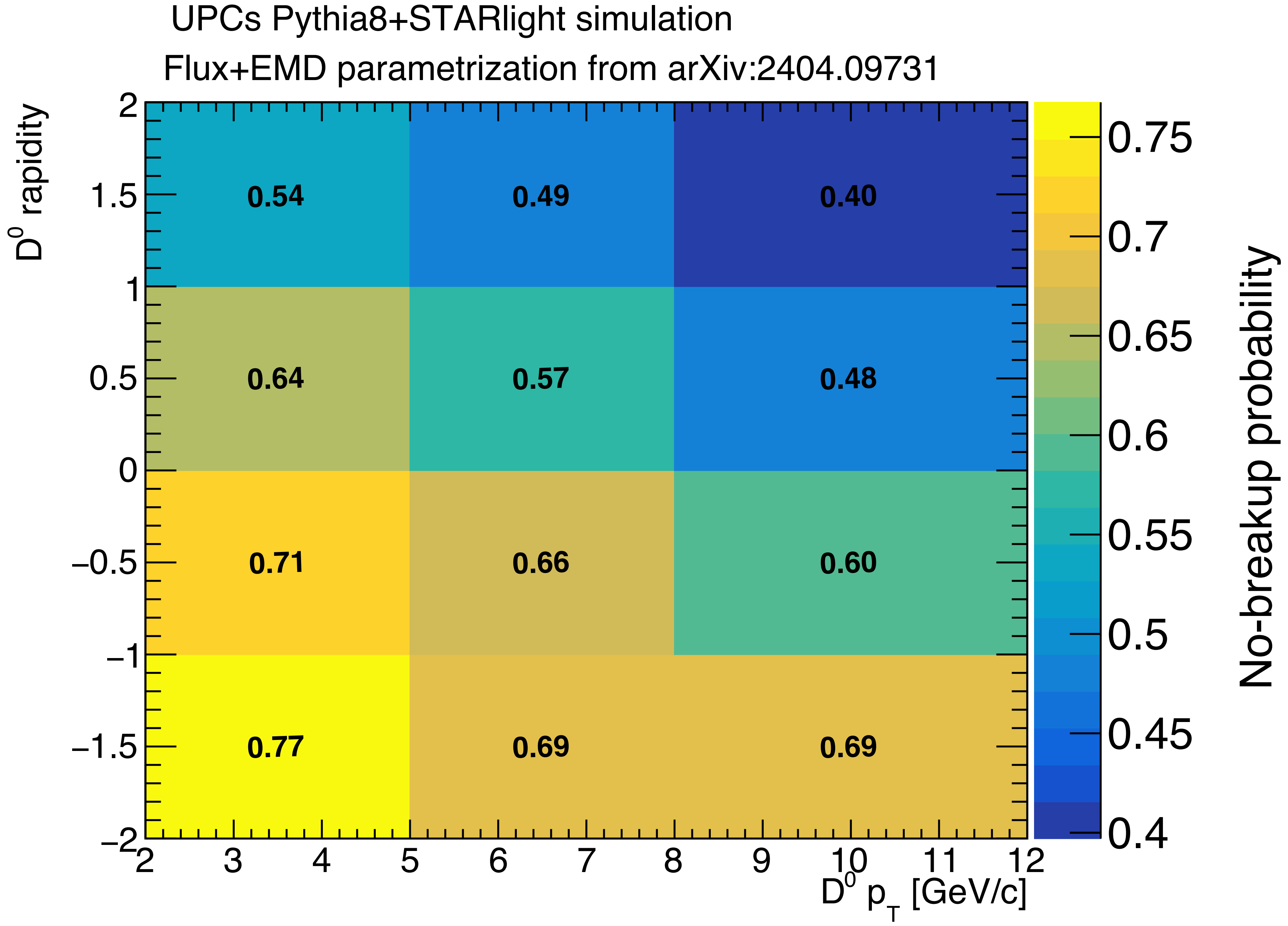



**A. M. Stasto, GMI**, Paper in preparation

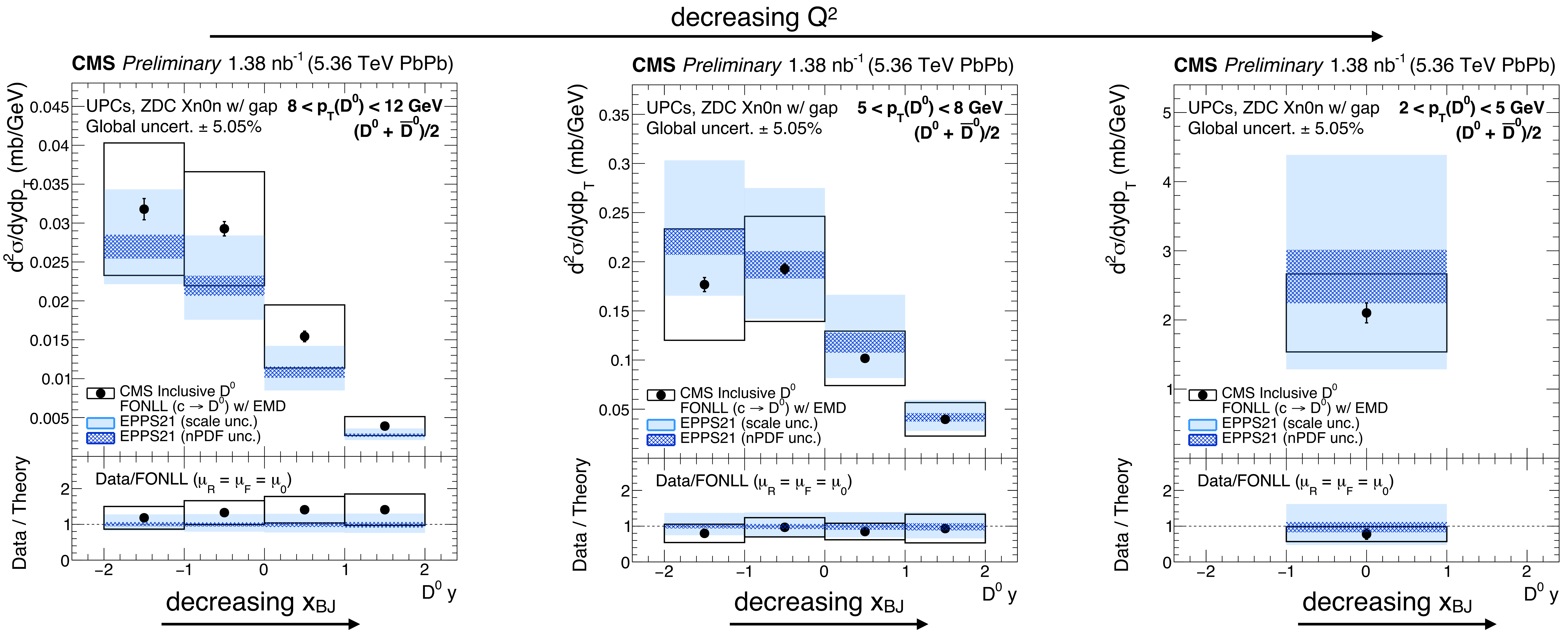
### Correction for electro-magnetic dissociation

EMD of the photon-emitting can reduce the rate of selected 0nXn events



# Comparison with FONLL-based predictions (EPPS21 nPDFs)

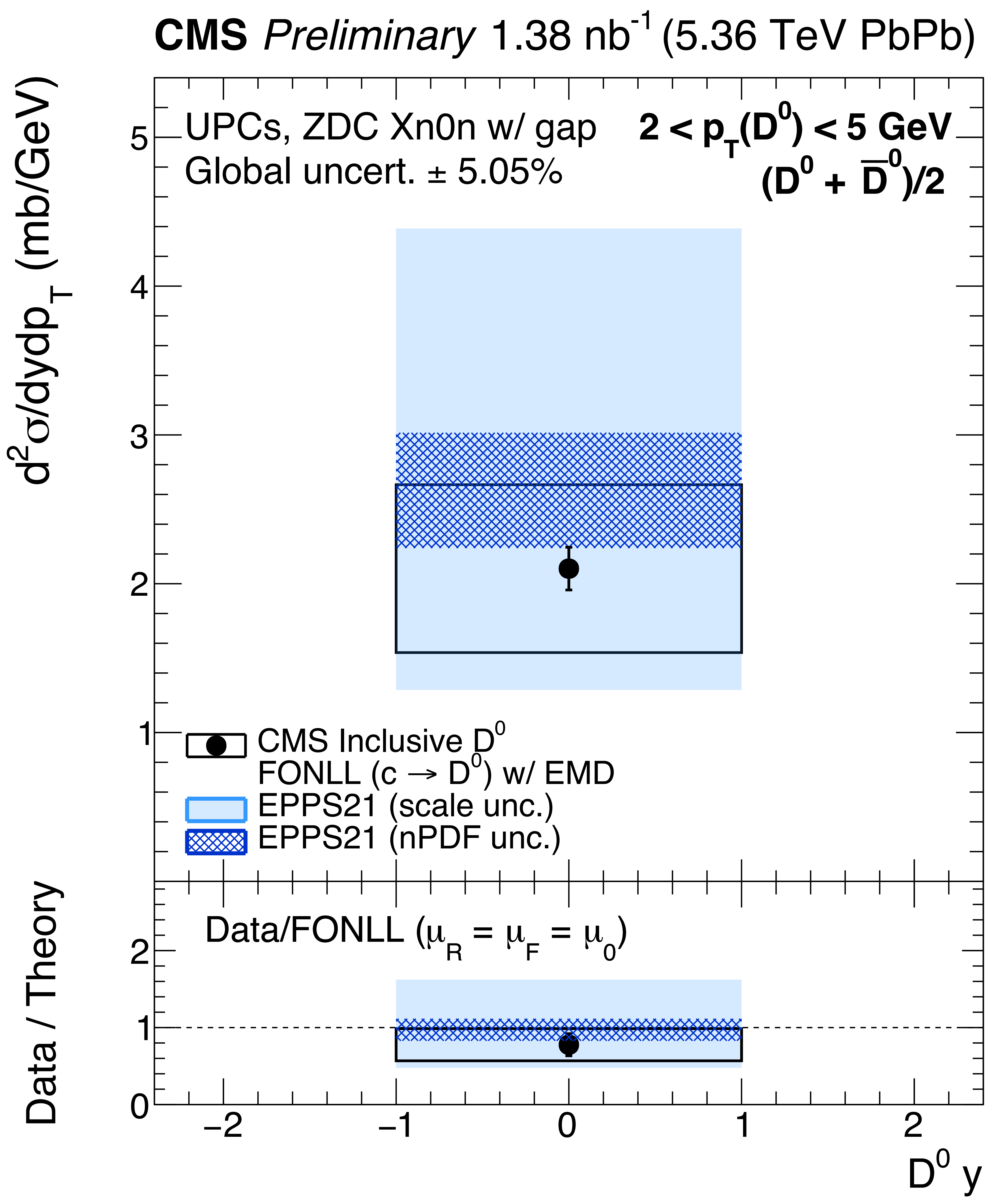



→ **dynamic constraints gluon dynamics in a large regime of $(x,Q^2)$**

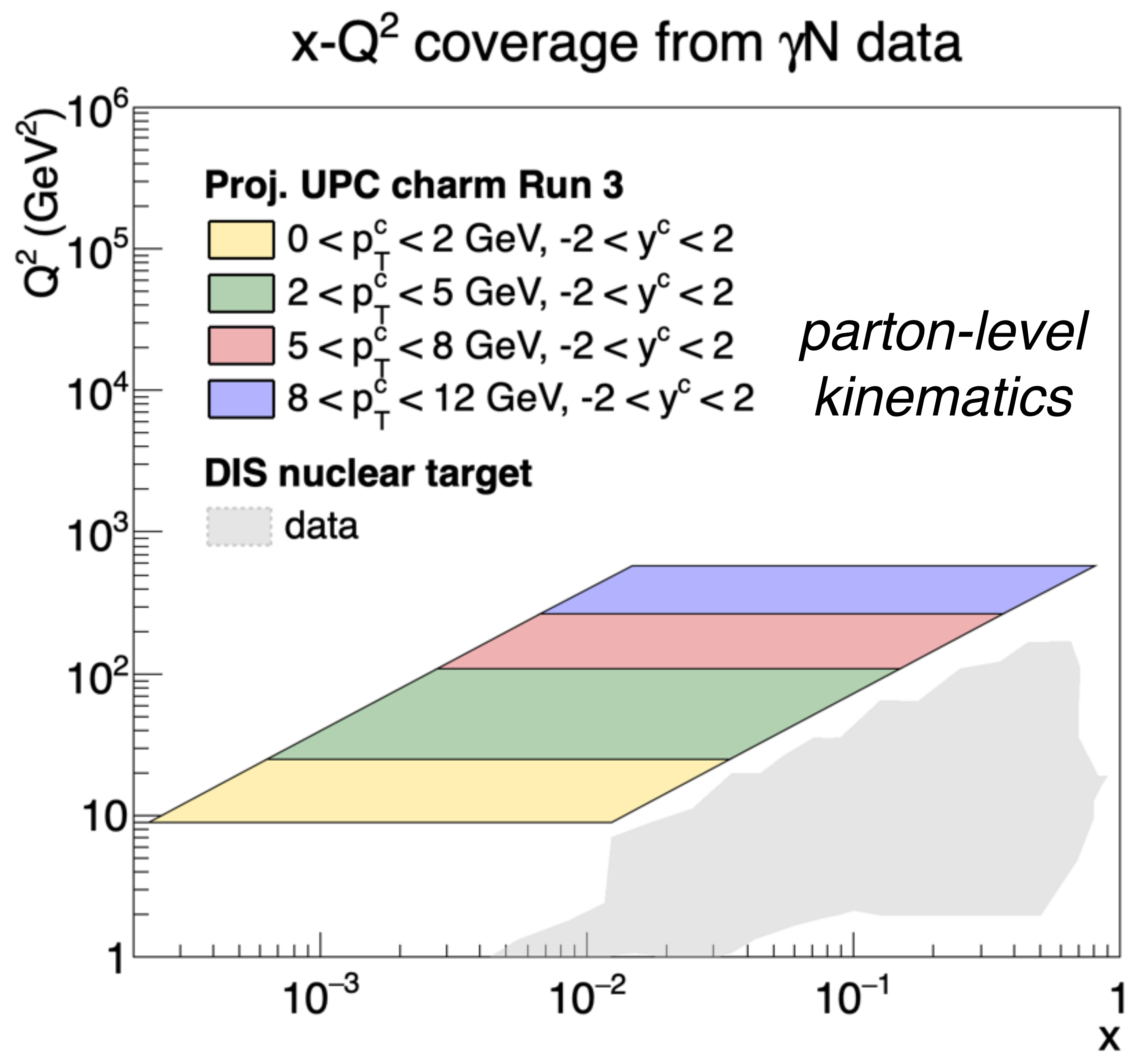
→"ready" for being included in nPDF fits!

**EPSS21:** Eur. Phys. J. C 82 (2022) 5, 413

# Prospects: photonuclear $D^0$ cross section down to $p_T$=0

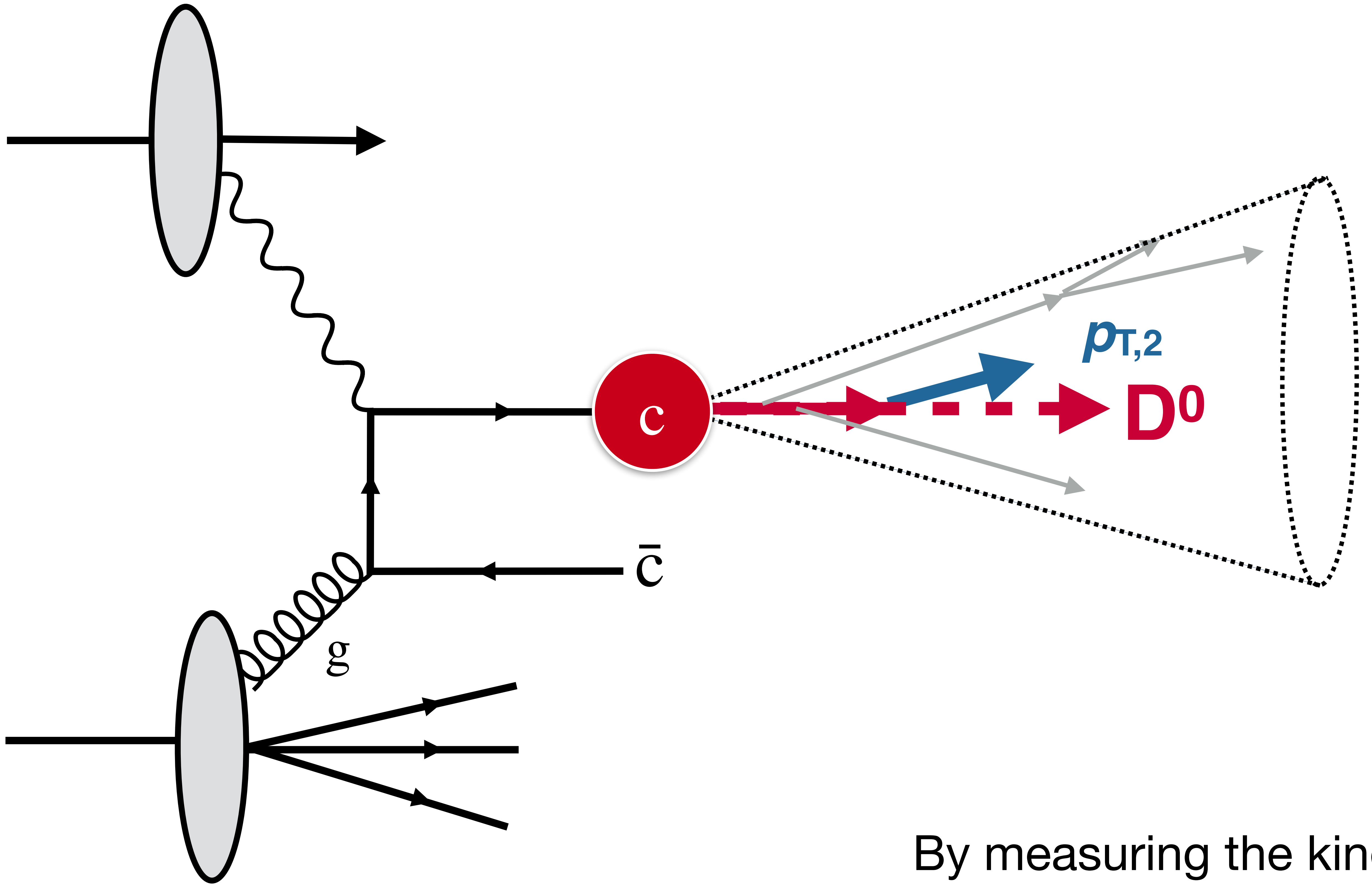



**Ongoing analysis:**
- down to $p_T = 0$ in intervals of y
- **reduced systematic uncertainty**
- **forward-backward ratios** (substantial cancellation of systematics)



# Prospects: heavy-flavor tagged jets in UPCs

In UPC photoproduction, **$x,Q^2$ are estimated via the kinematic properties of the reconstructed final states**



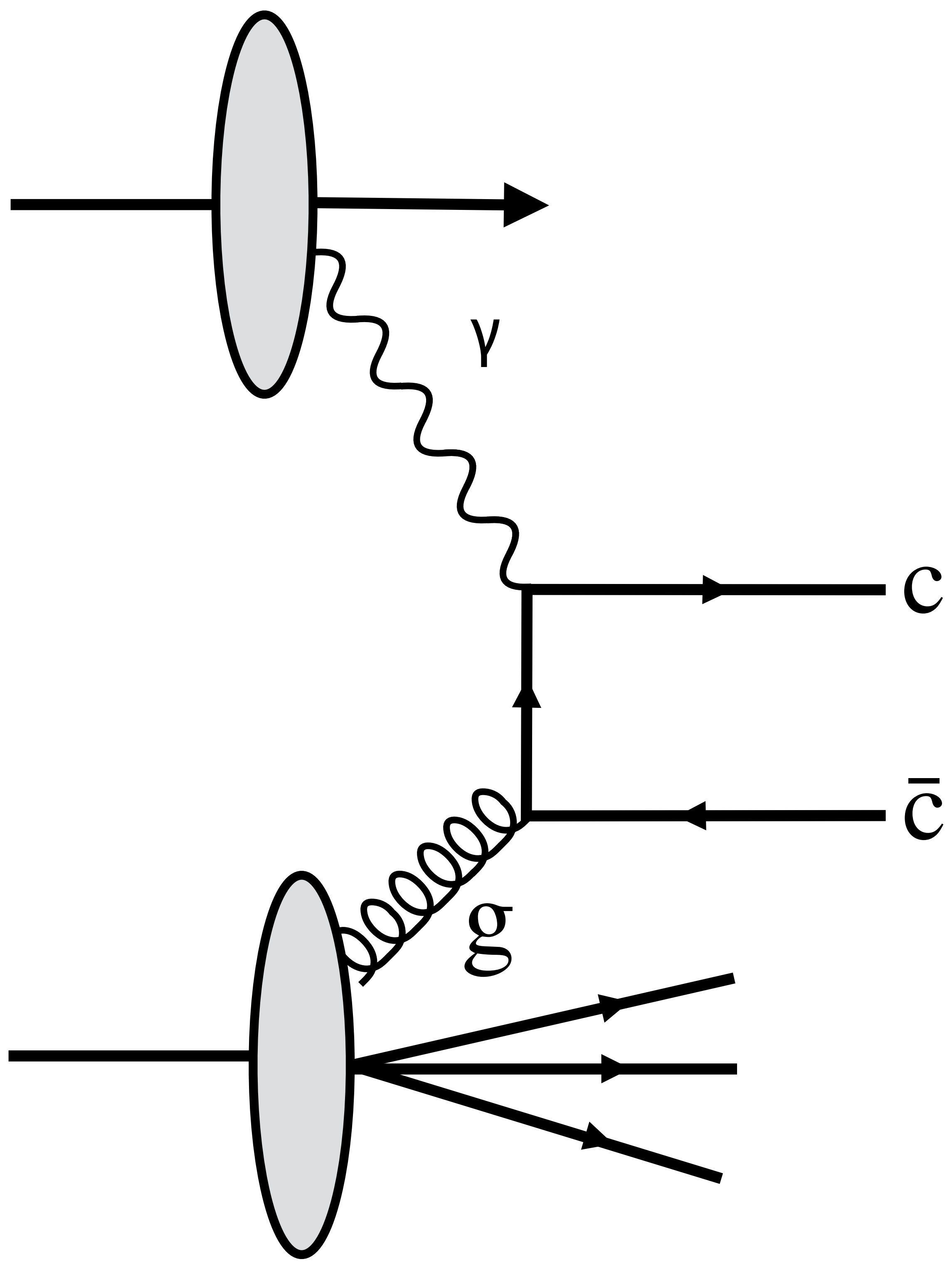

**Jet-"reclustering" techniques to access with high accuracy the $p_T$ of the associated charm jets**

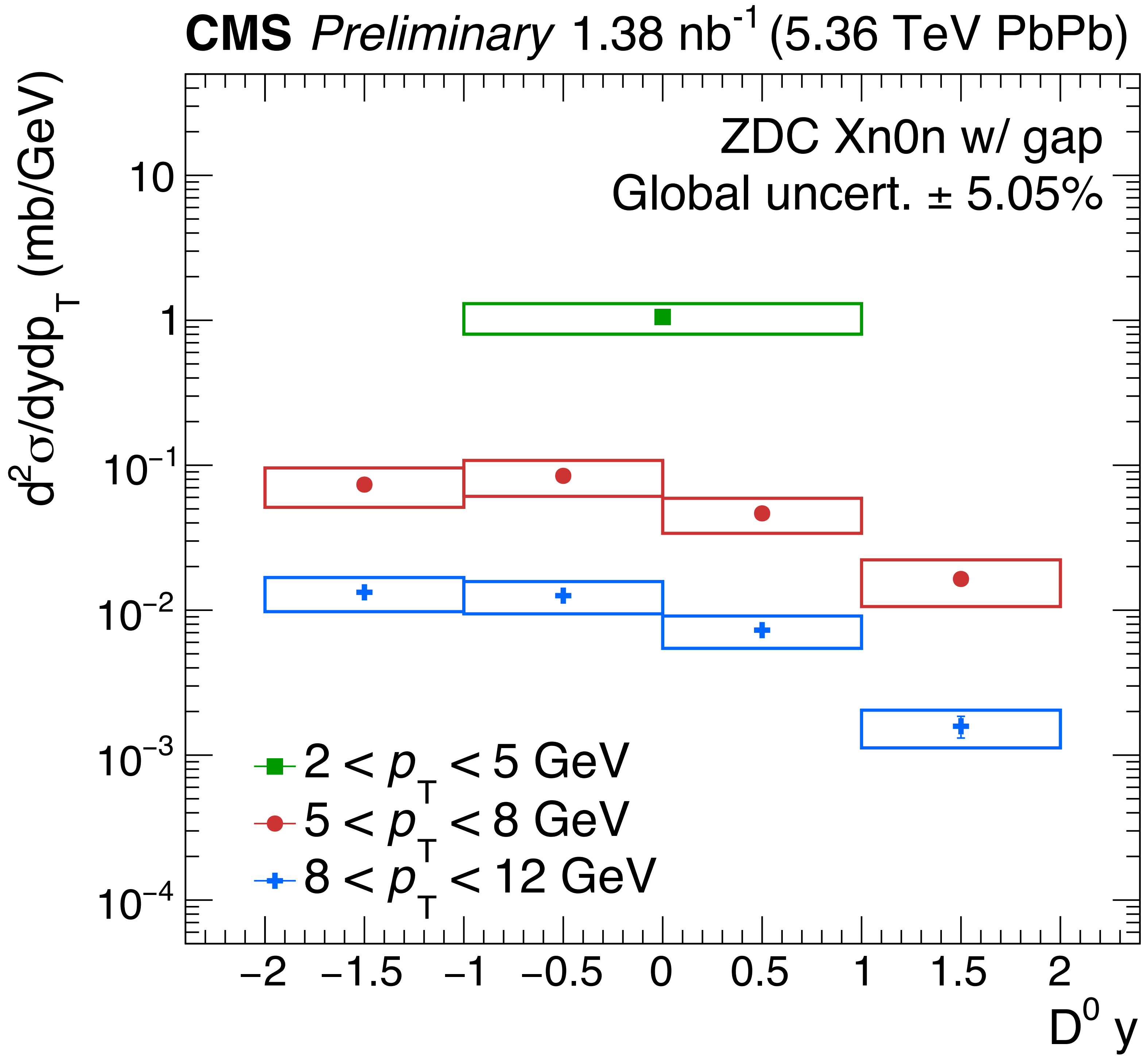
By measuring the kinematics of the two charm jets:
→ **improved control on $x,Q^2$**
→ **strongest constraints on lead nPDFs**

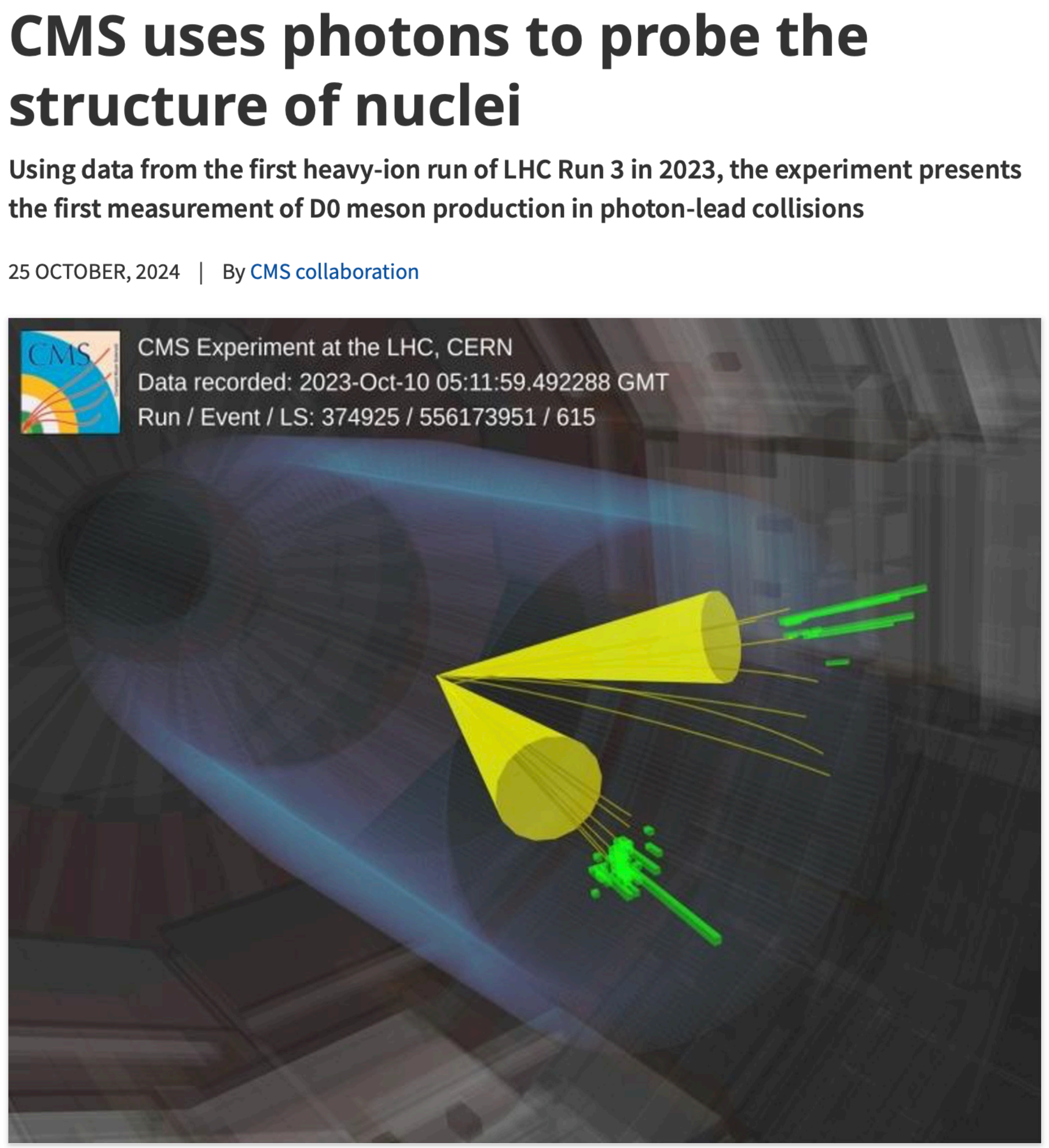
# Conclusions

**First measurement of the $D^0$ photonuclear production in Xn0n UPC collisions with 2023 PbPb data at $\sqrt{s_{NN}}$= 5.36 TeV**

→ dynamic constraints on low-x gluons in a large regime of $(x,Q^2)$ with limited final-state interactions



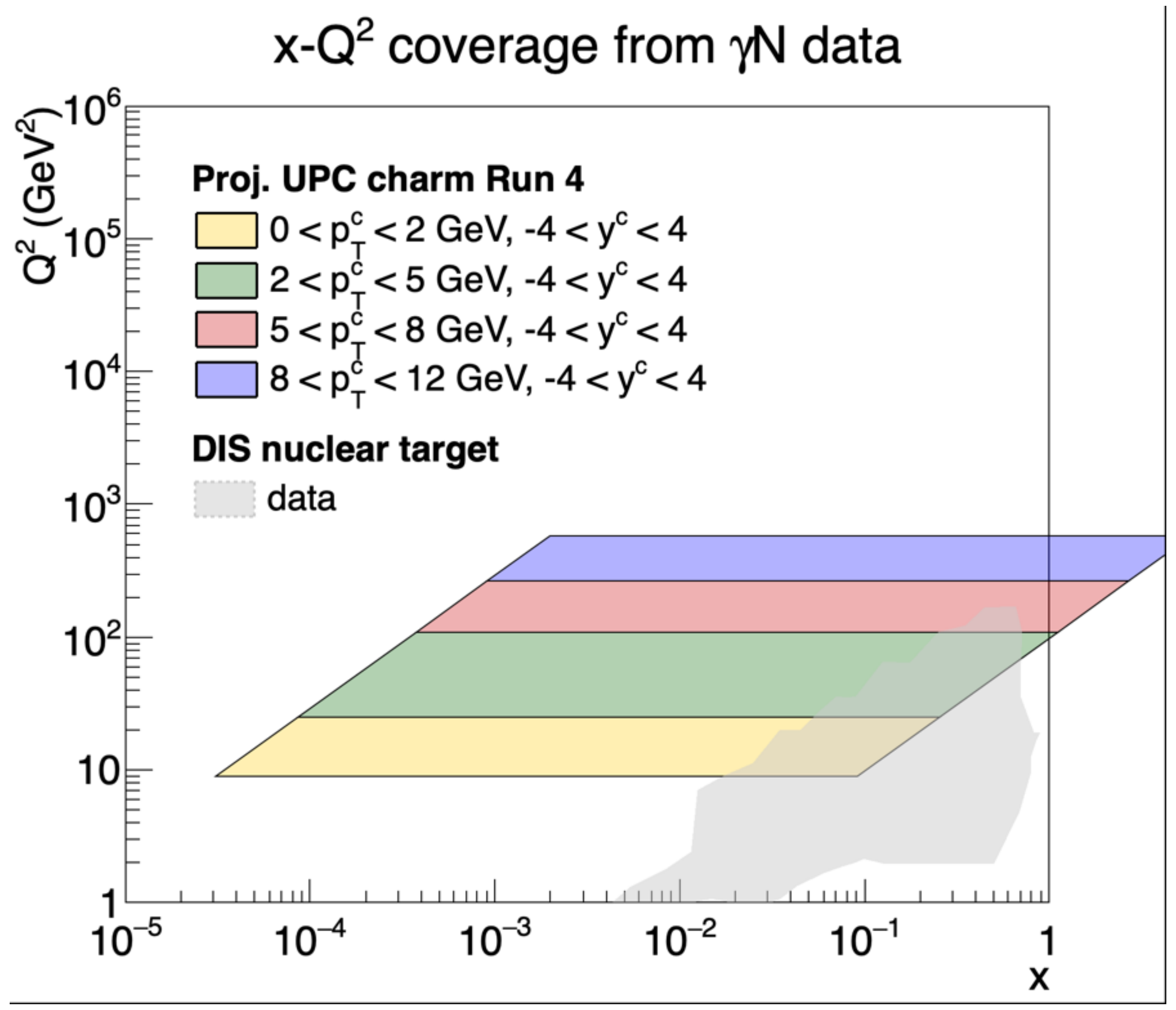




CERN News October 2024

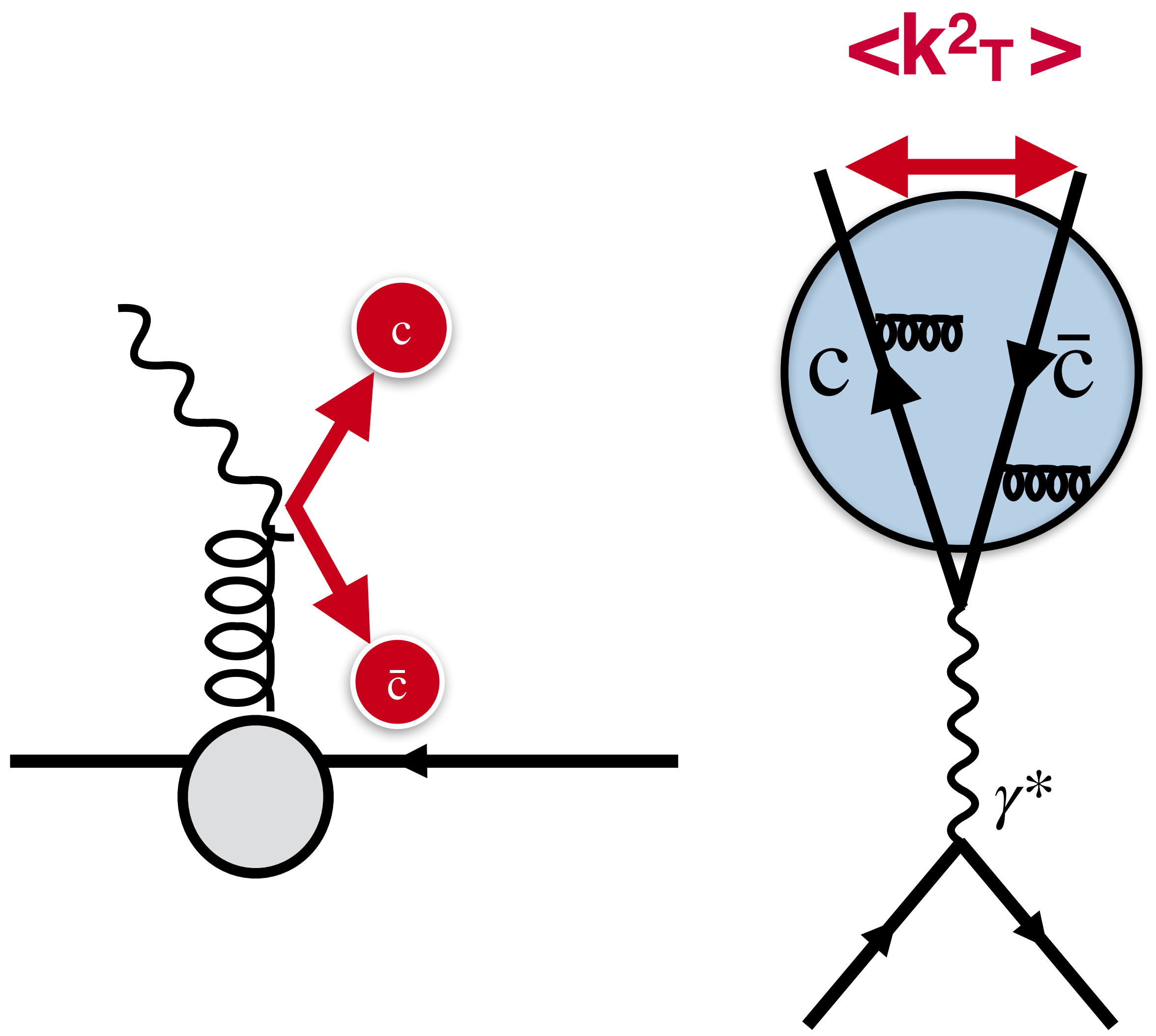
→ **proves the feasibility and the potential of these new observables!**

→ first step toward a broad program of heavy-flavor hadrons, jets and correlations in UPCs

# Conclusions: EIC + UPCs at the LHC



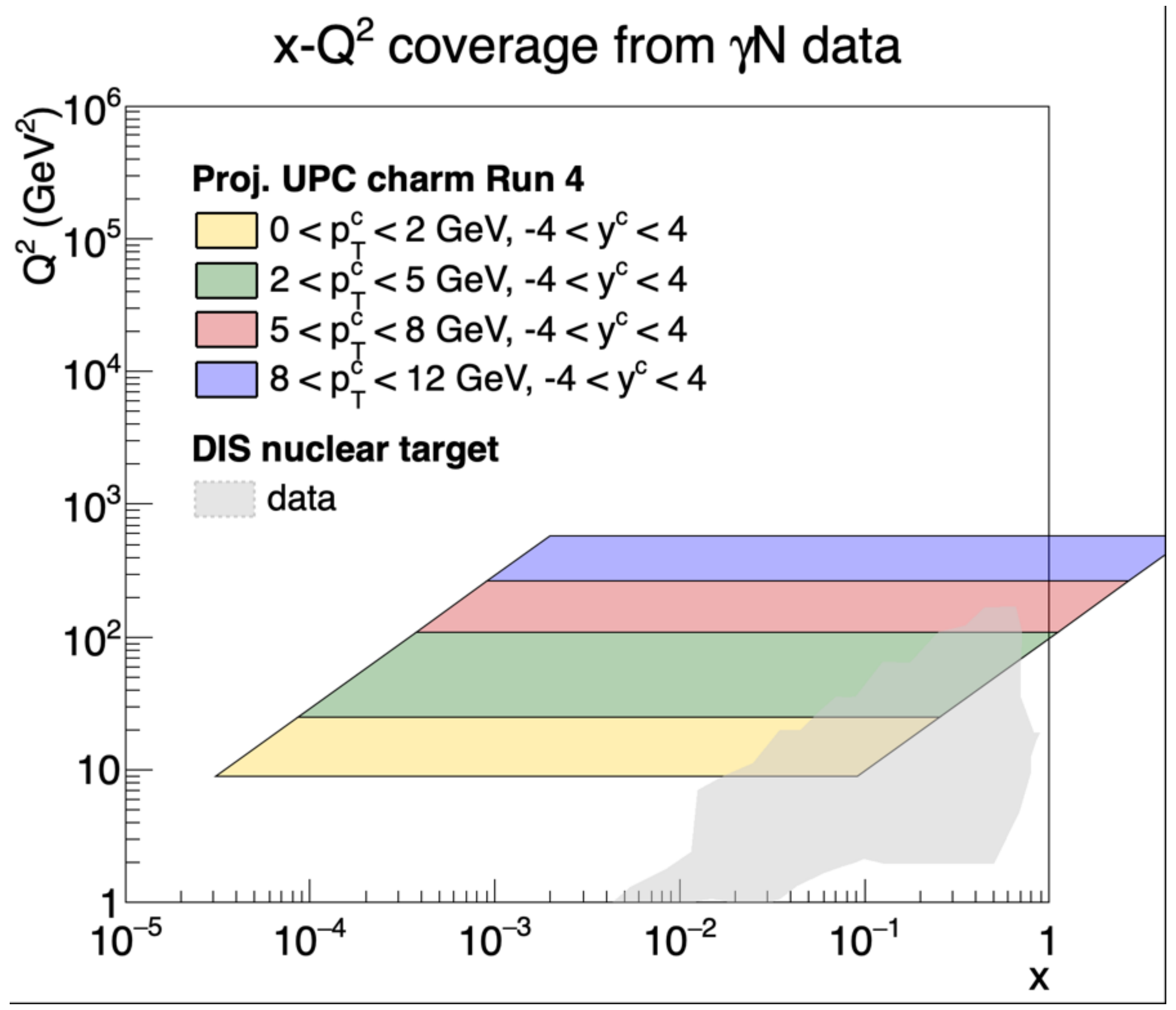

**Upgraded CMS in LHC Run 4**
→ x close to $10^{-5}$

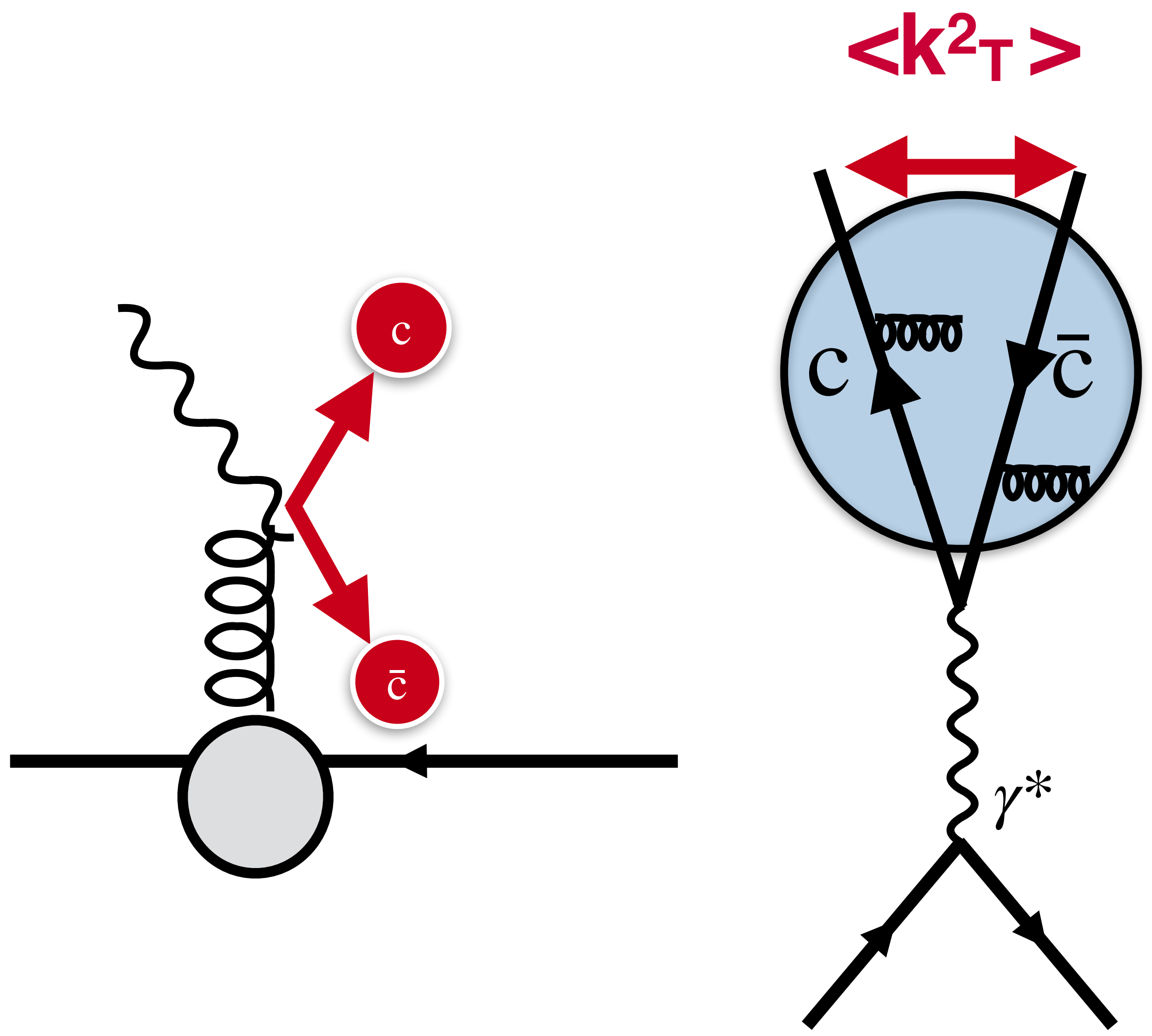



**Complement and expand the ongoing UPC program at the LHC:**

- 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

# Conclusions: EIC + UPCs at the LHC

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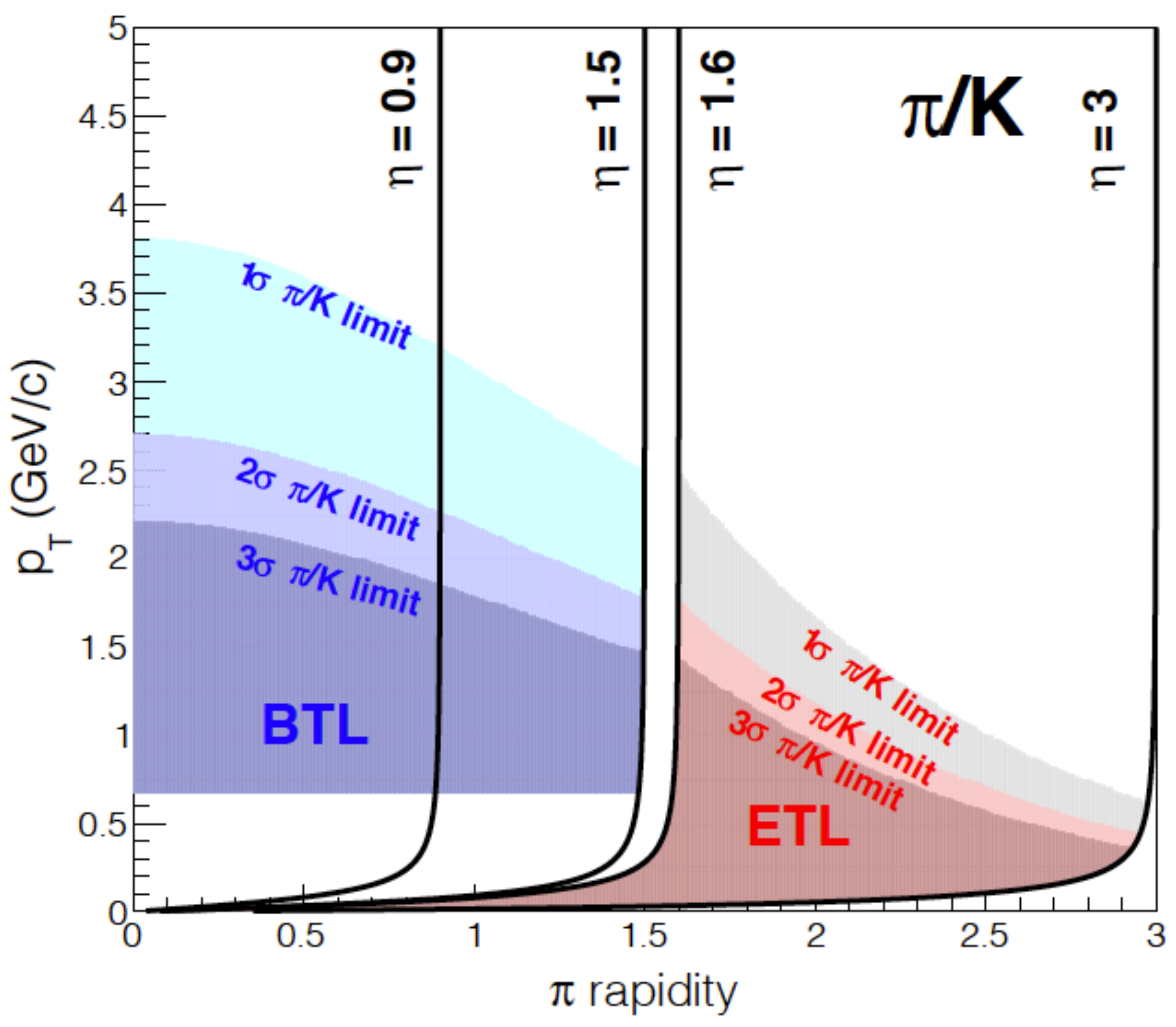
# Thank you for your attention

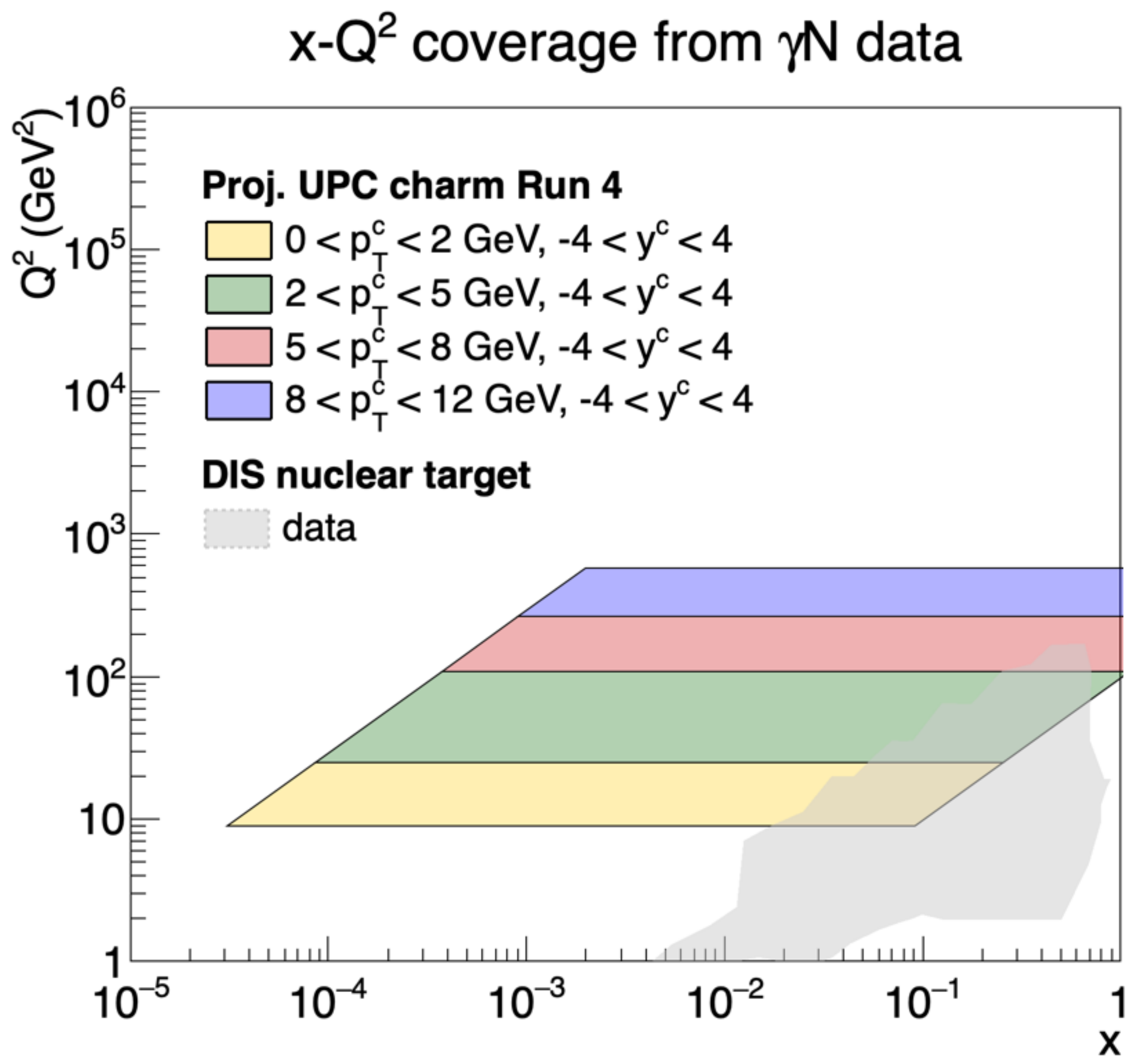
# BACKUP

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

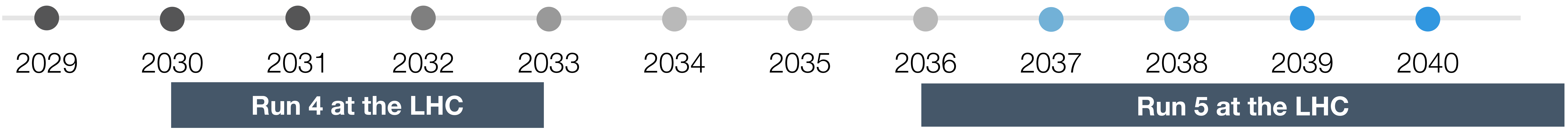
- **New tracker with |η|<4**
- PID for low $p_T$ hadrons
- Tracking capabilities for hardware triggers




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

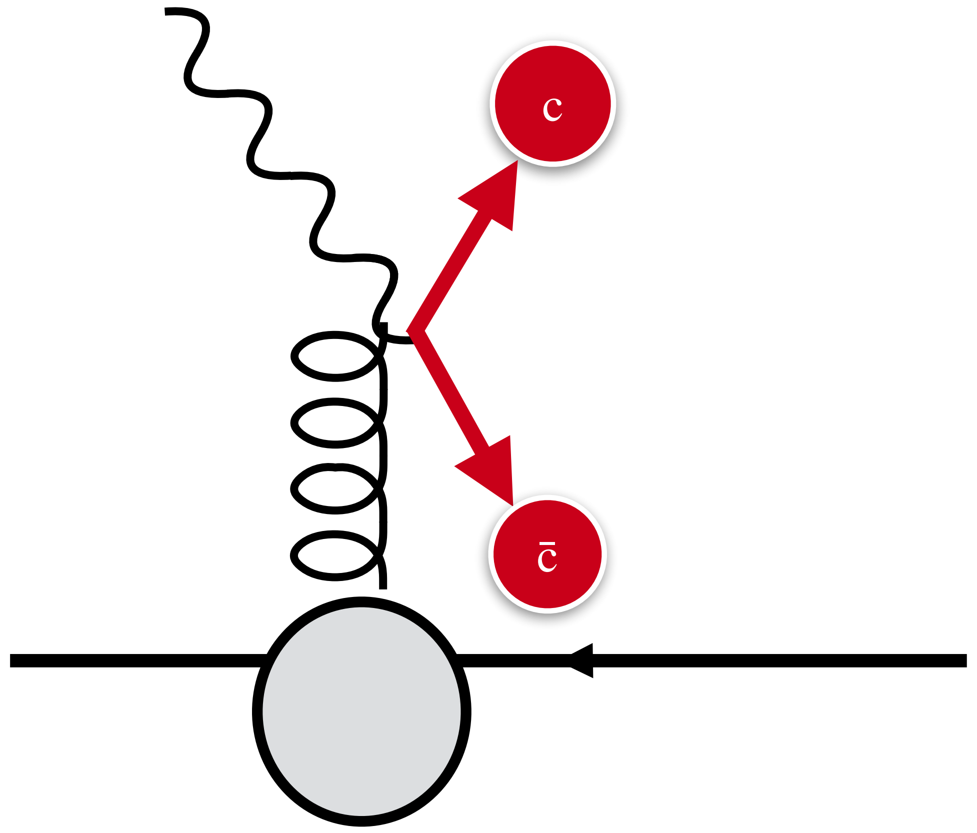


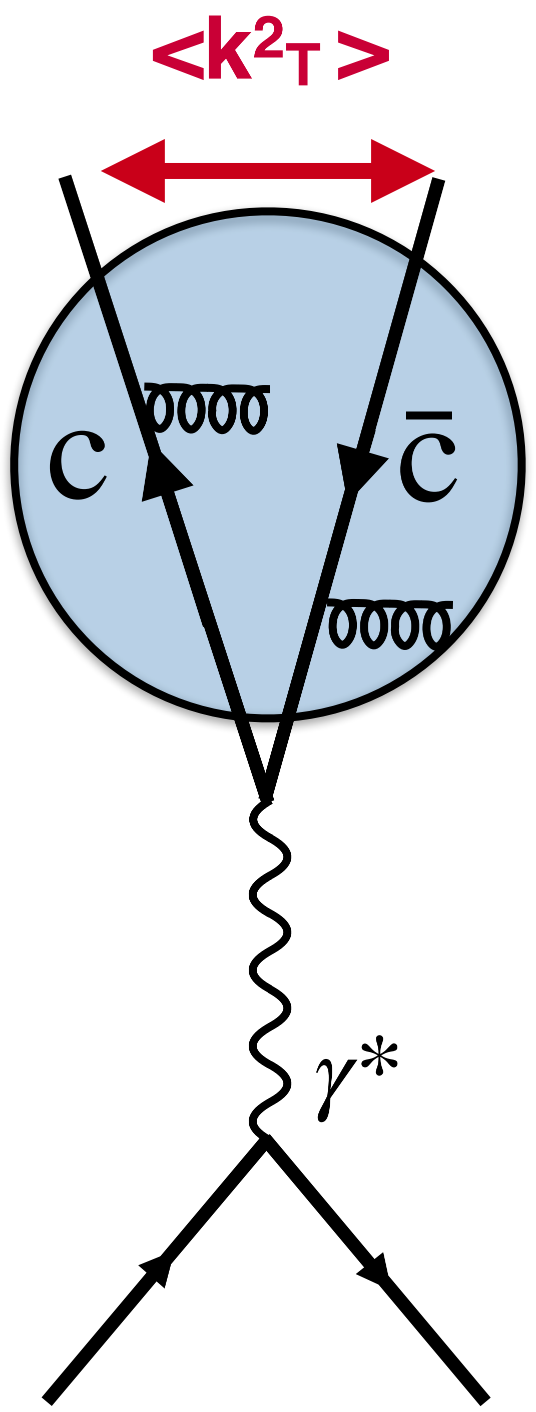

→ **Close to $x \sim 10^{-5}$** with $\gamma N \rightarrow c\bar{c}$ observables



# Photonuclear charm and beauty production at the EIC

→ control on the photon virtuality $Q^2$ and x

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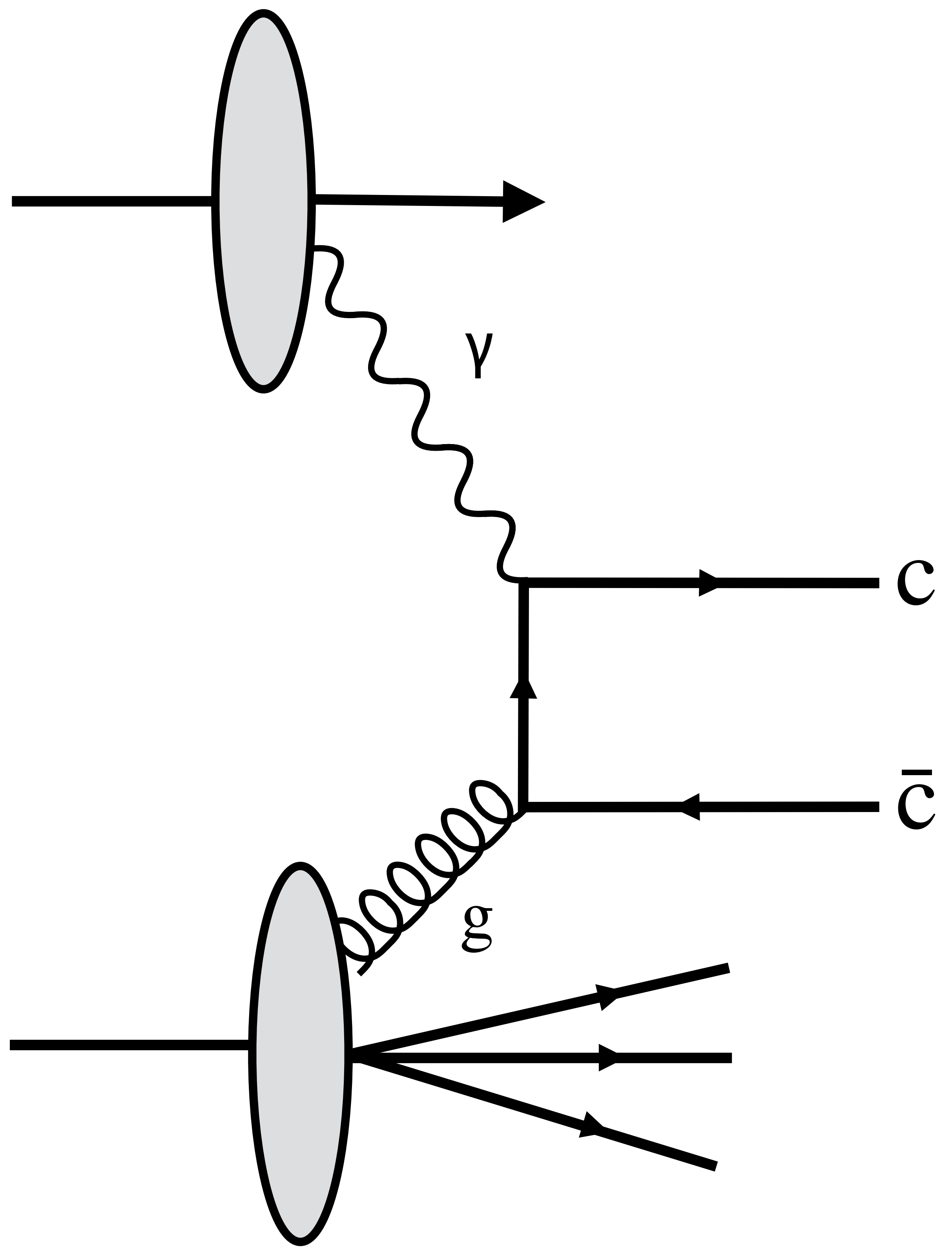
2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040

**EIC physics data-taking**

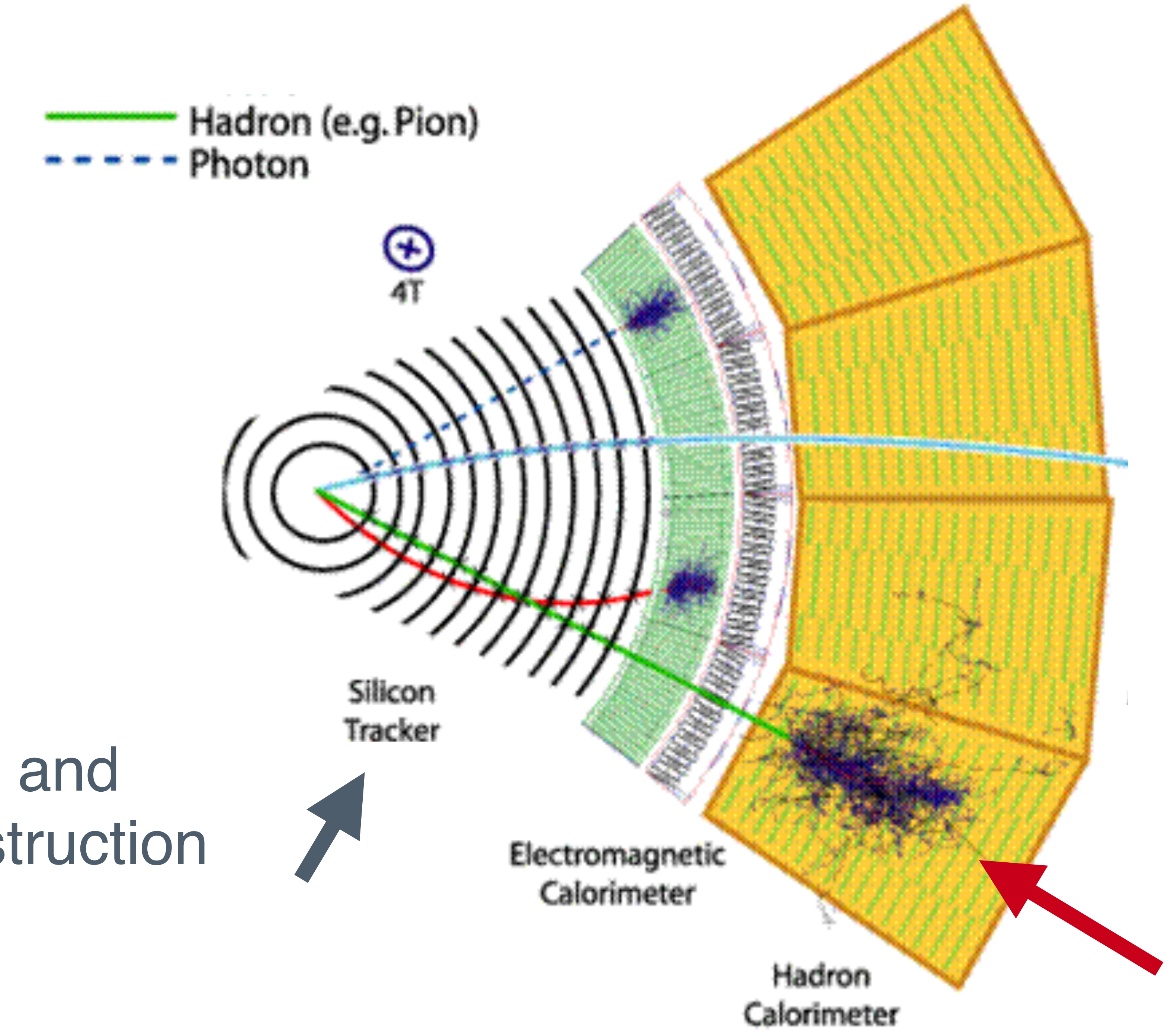
**EIC:** BNL-98815-2012-JA, arXiv.1212.1701

# Experimental strategy: $D^0$ reconstruction

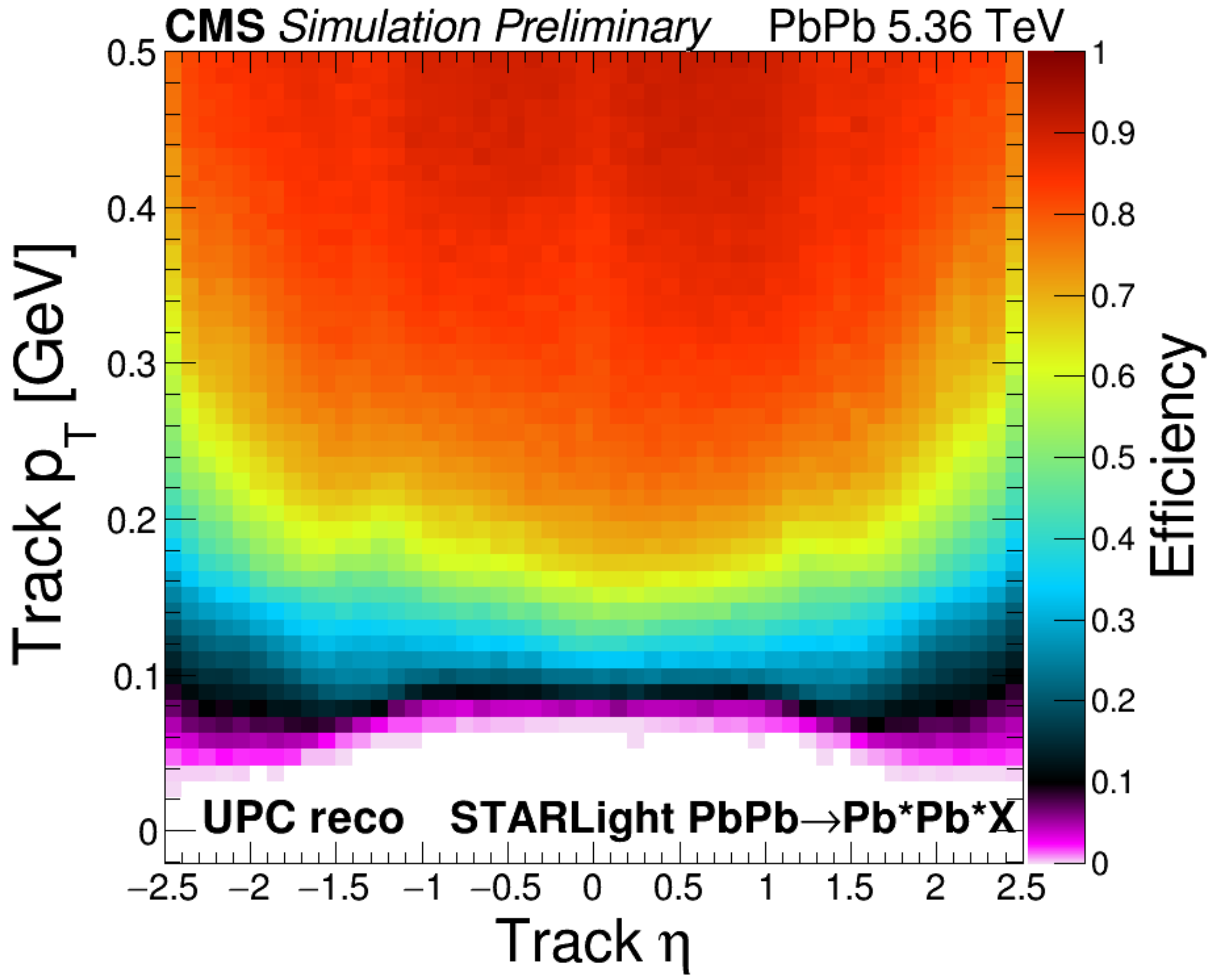



$D^0 \rightarrow K^-\pi^+$ with charged tracks in the tracker

Track and D reconstruction




Improved low-$p_T$ tracking and vertexing performance




**CMS Collaboration**, CMS HIN-24-003

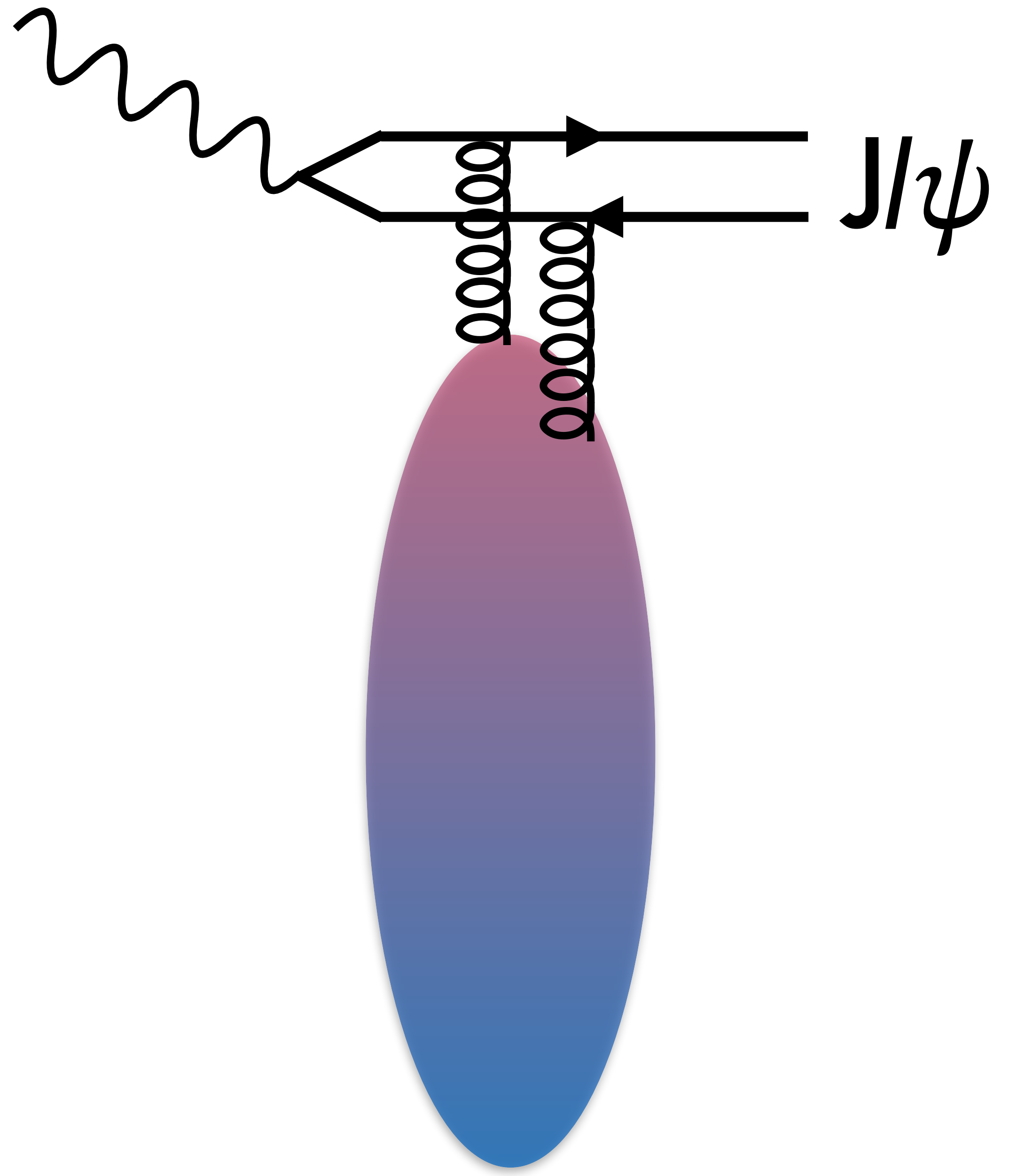
# BACKUP: UPCs

# Coherent J/$\psi$ production in PbPb UPCs

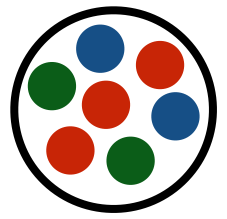
CMS, Phys. Rev. Lett. 131 (2023) 262301

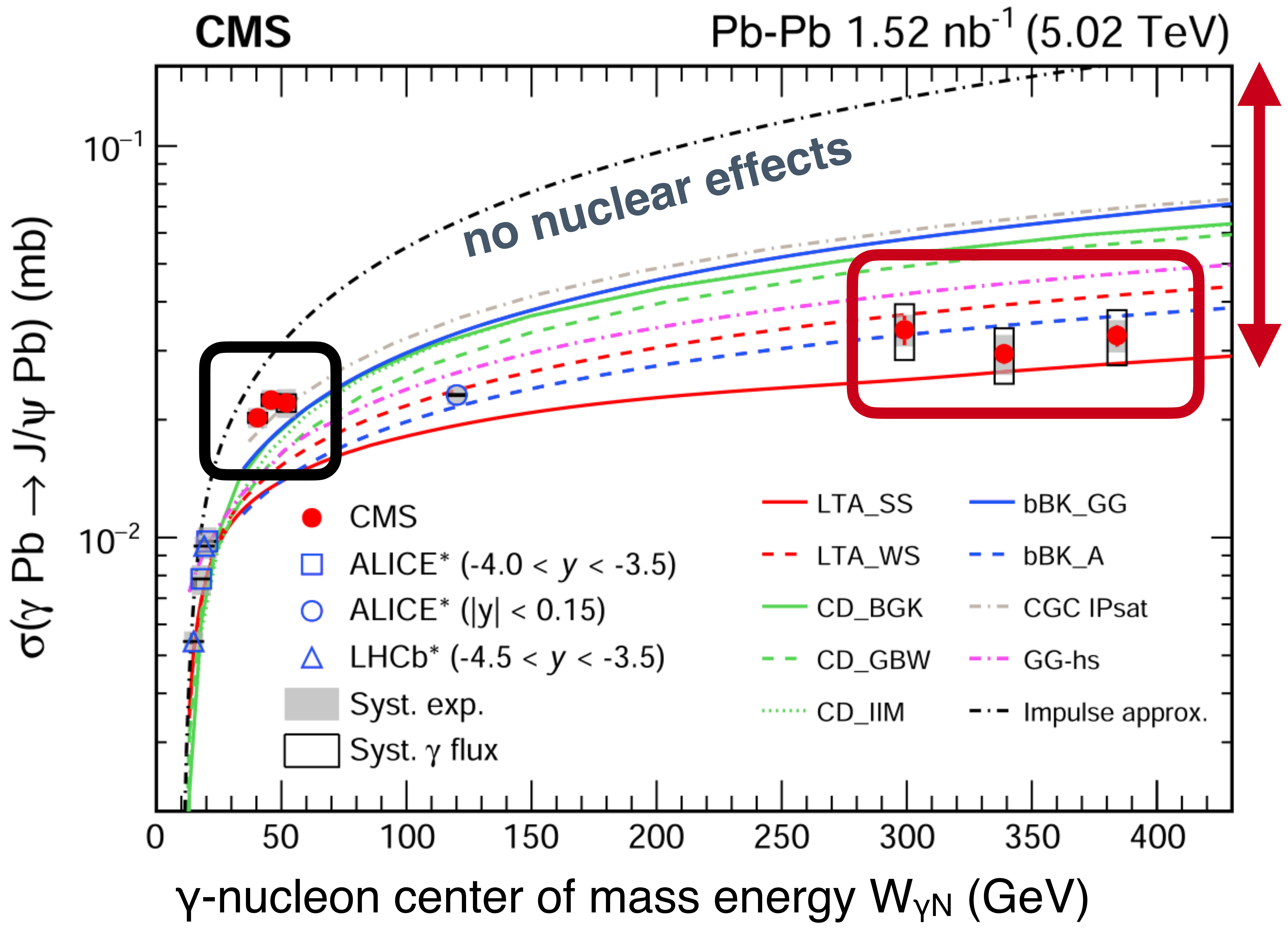
Low $p_T$ J/$\psi$ (~50 MeV)

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



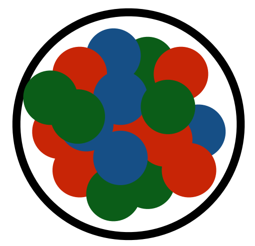

**large $x_{BJ}$**






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

**small $x_{BJ}$**



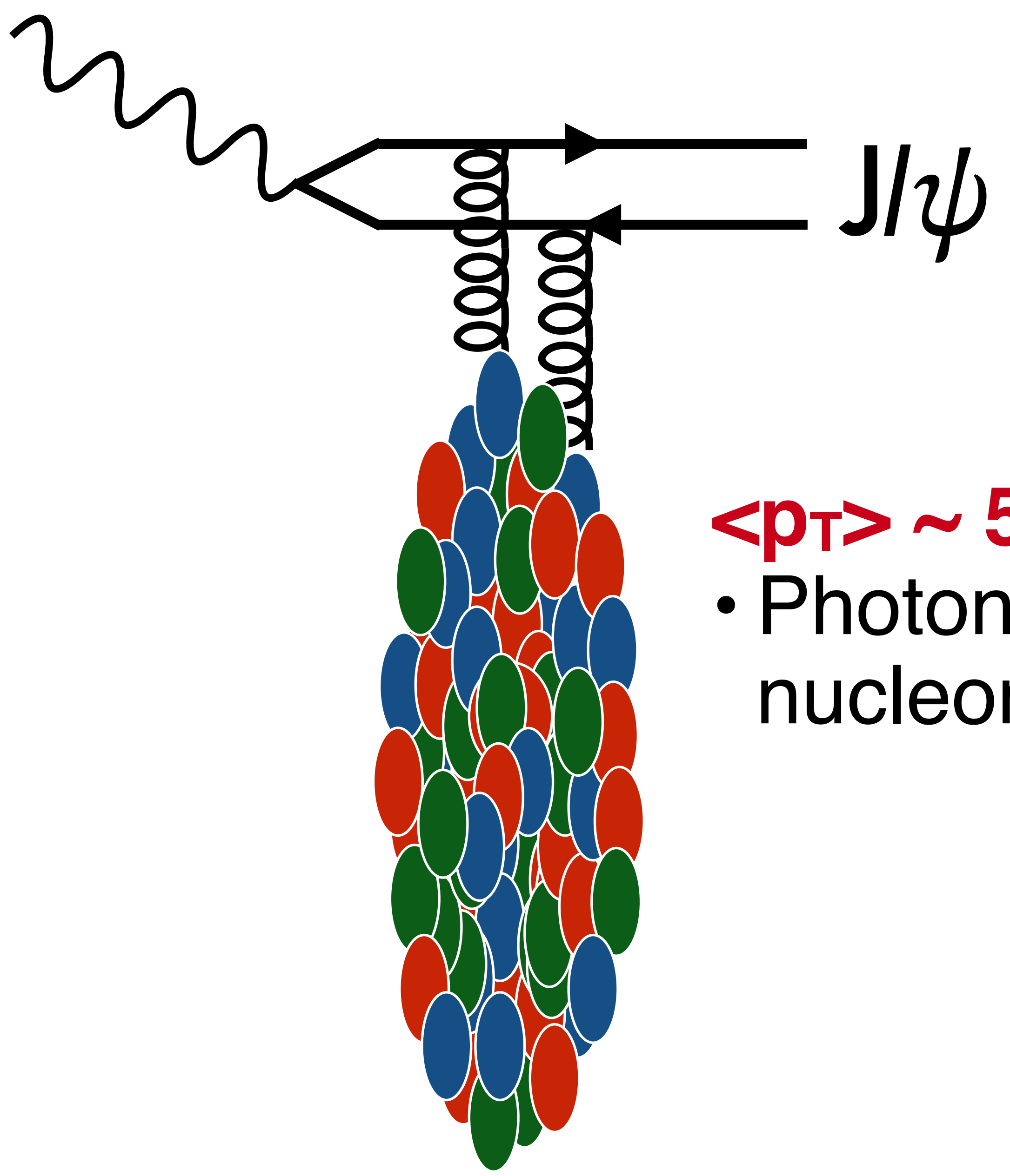
→ **strong suppression at high $W_{\gamma N}$ values (small $x_{BJ}$)** compared to scenarios without nuclear effect (IA)

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

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

CMS-PAS-HIN-23-009

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




**$\langle p_T \rangle \sim 500$ MeV**

- Photon interacts with a single nucleon or sub-nucleon

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

CMS-PAS-HIN-23-009

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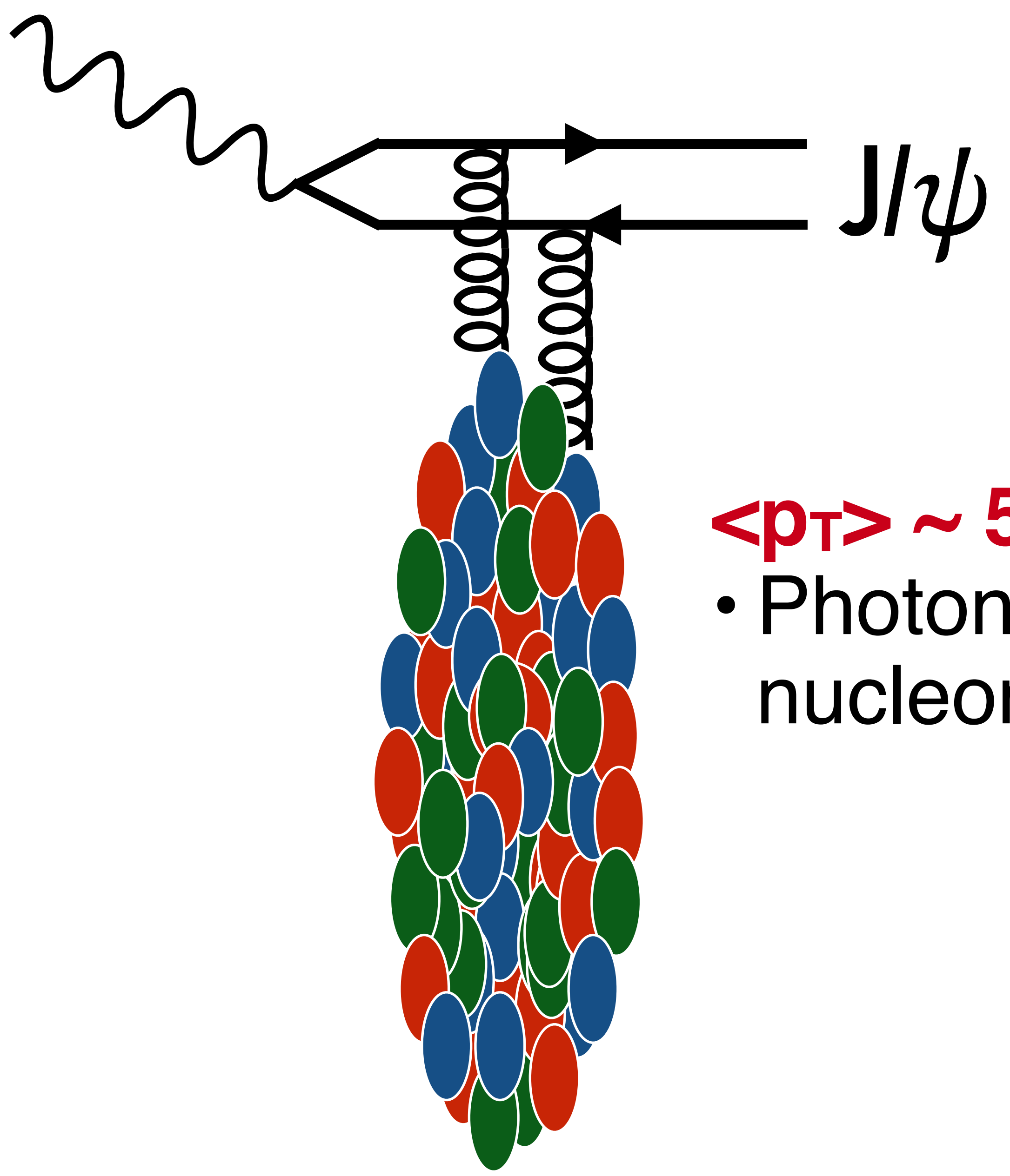
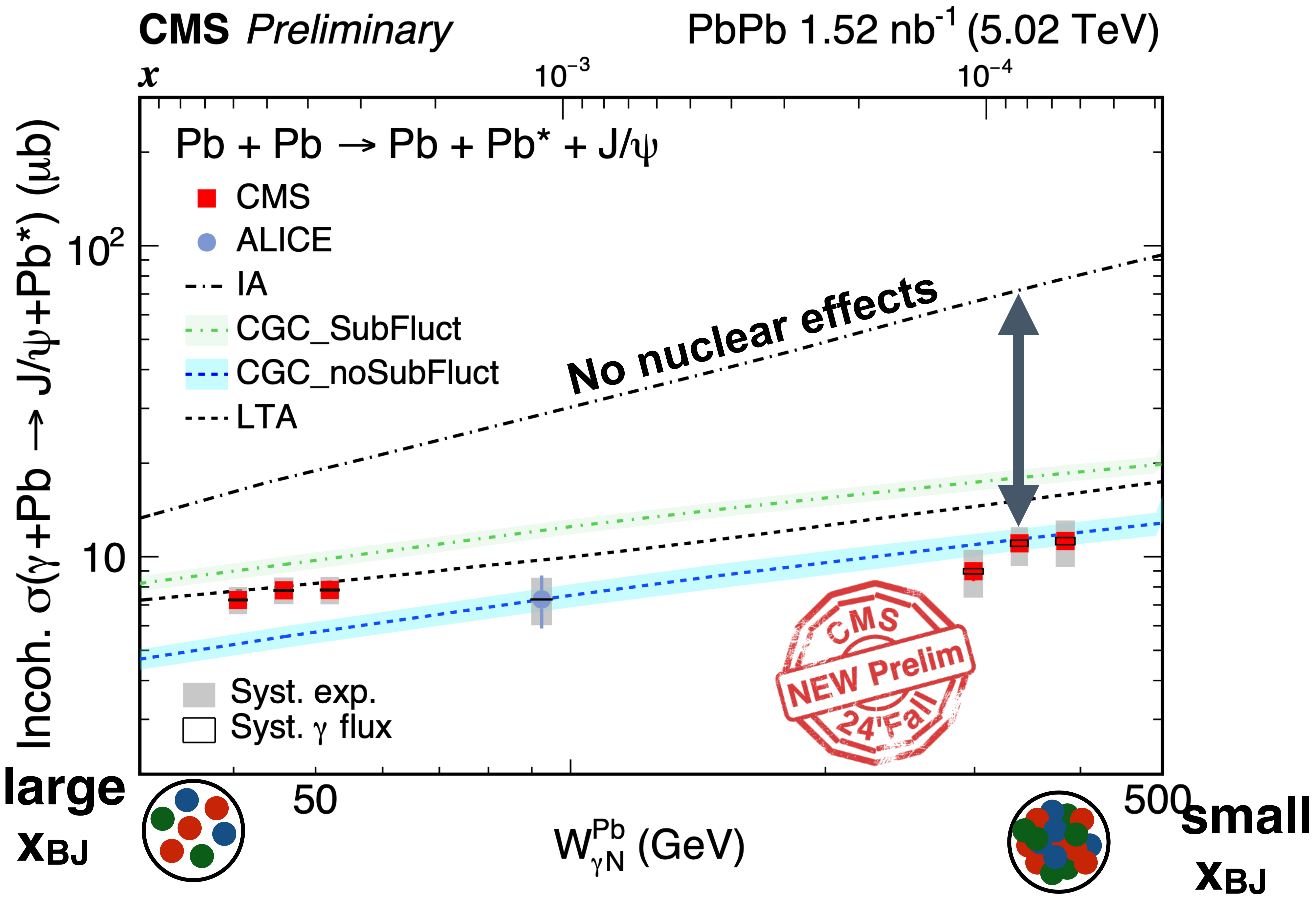



**<$p_T$> ~ 500 MeV**

- Photon interacts with a single nucleon or sub-nucleon

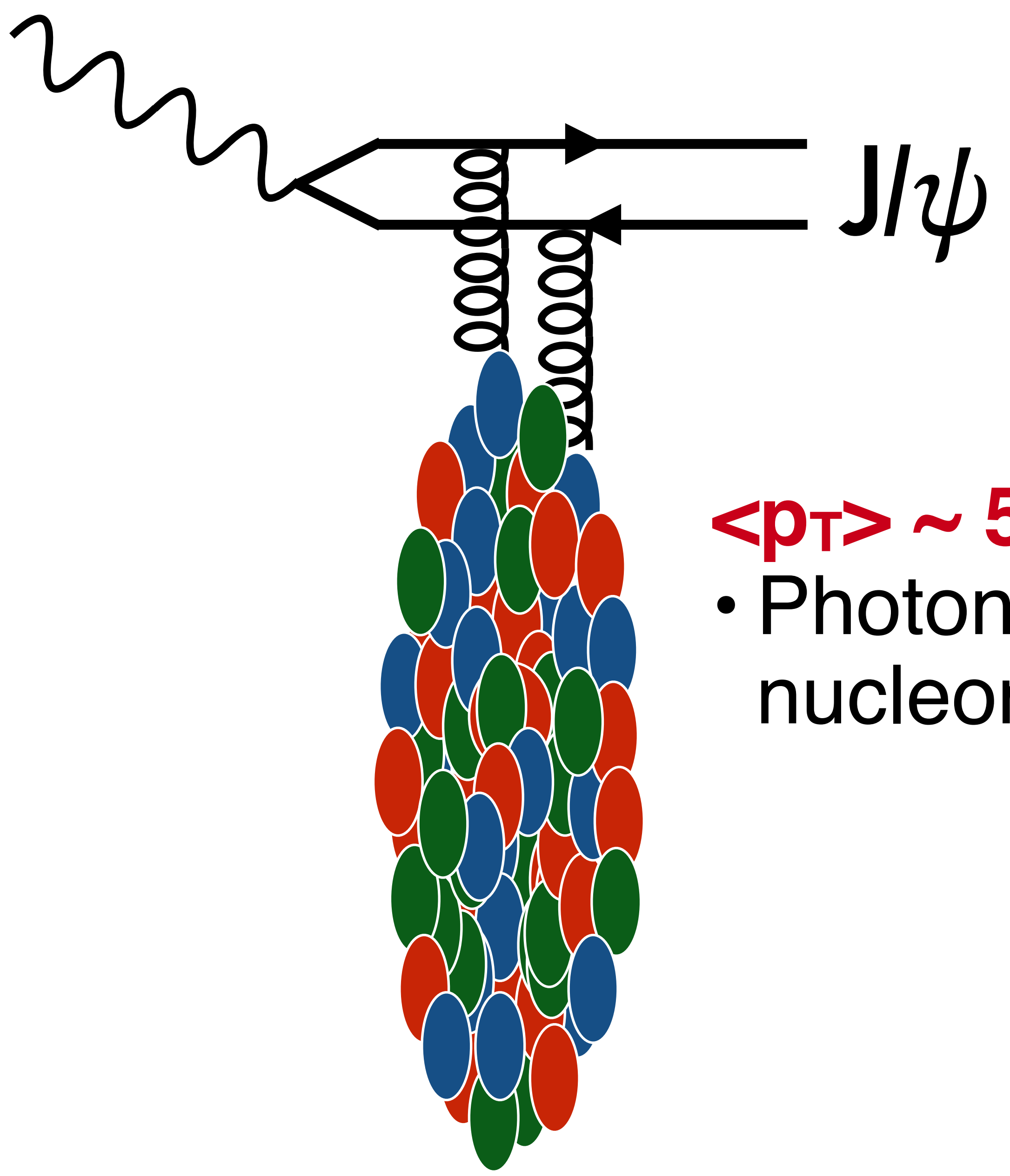



**Strong suppression observed at large $W_{\gamma N}$ (small x) w.r.t. no-nuclear effects predictions**

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

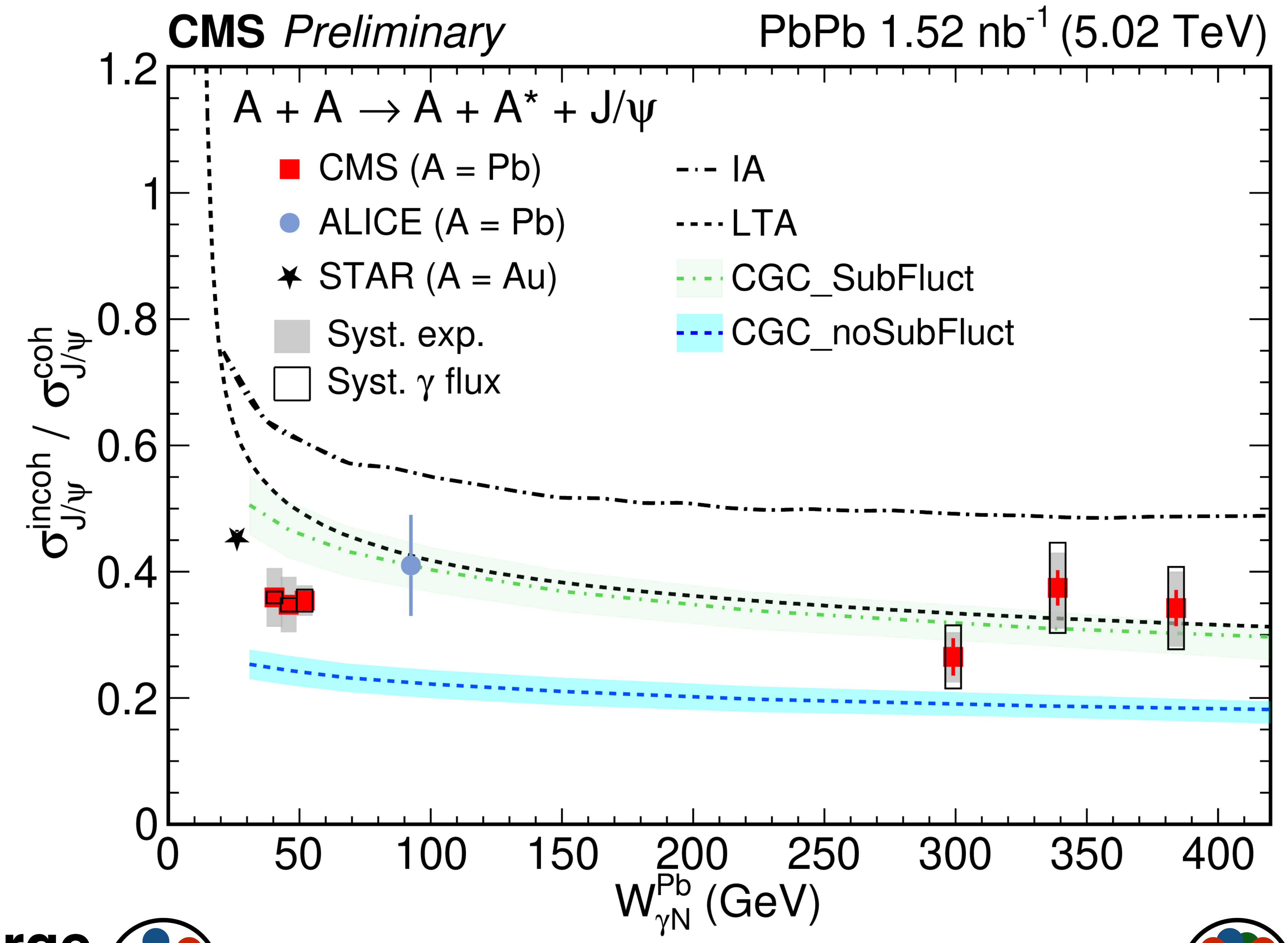
# Incoherent/coherent J/$\psi$ in UPCs

CMS-PAS-HIN-23-009

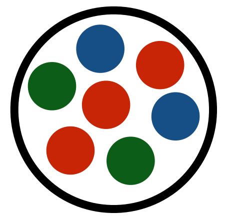



**<$p_T$> ~ 500 MeV**

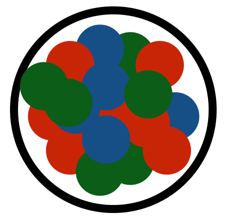
- Photon interacts with a single nucleon or sub-nucleon




**large $x_{BJ}$**



**Stronger suppression for incoherent than coherent production**



**small $x_{BJ}$**

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

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

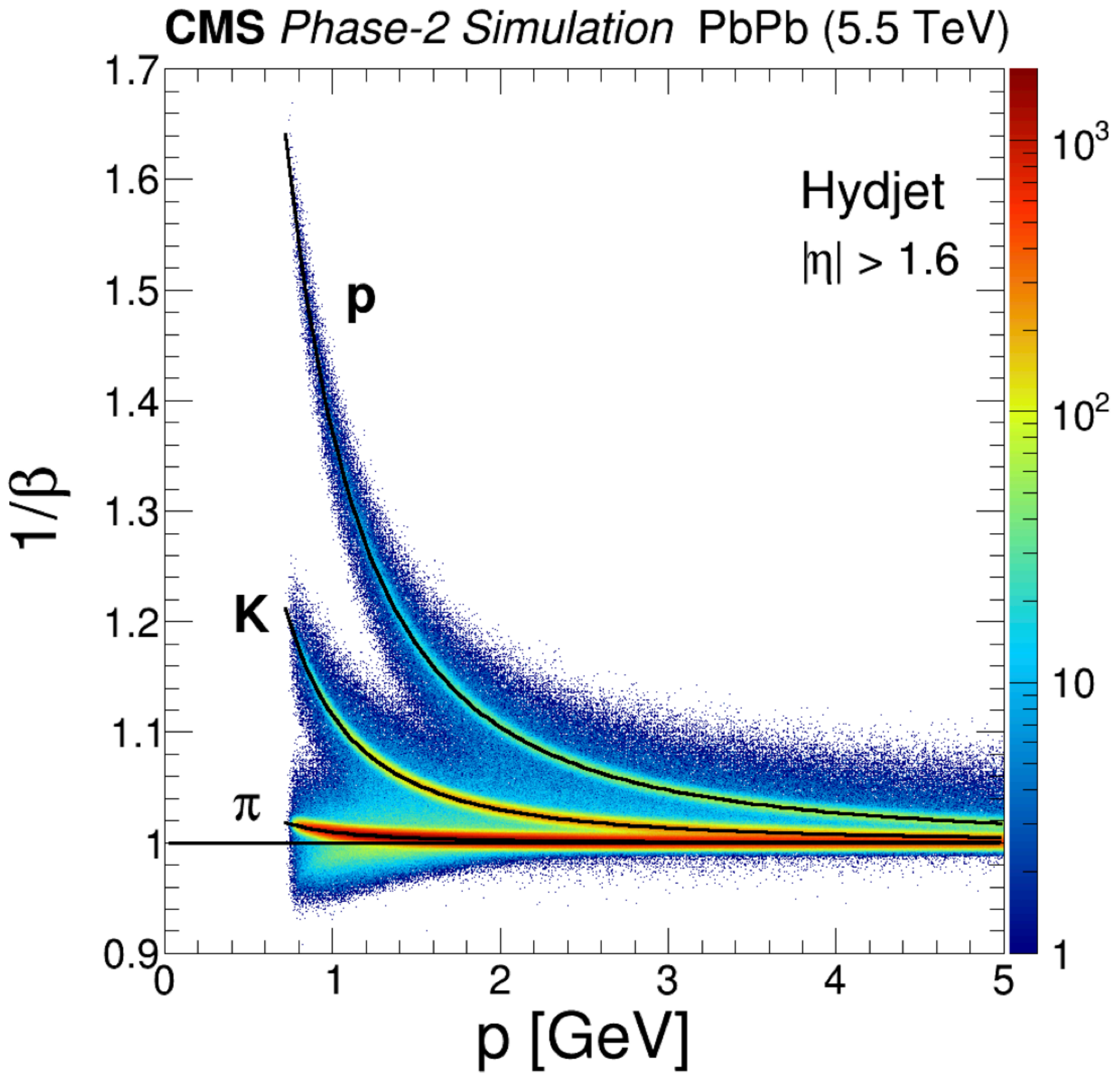
→ Need to "over-constrain" calculations with new probes that provide additional/complementary constraints

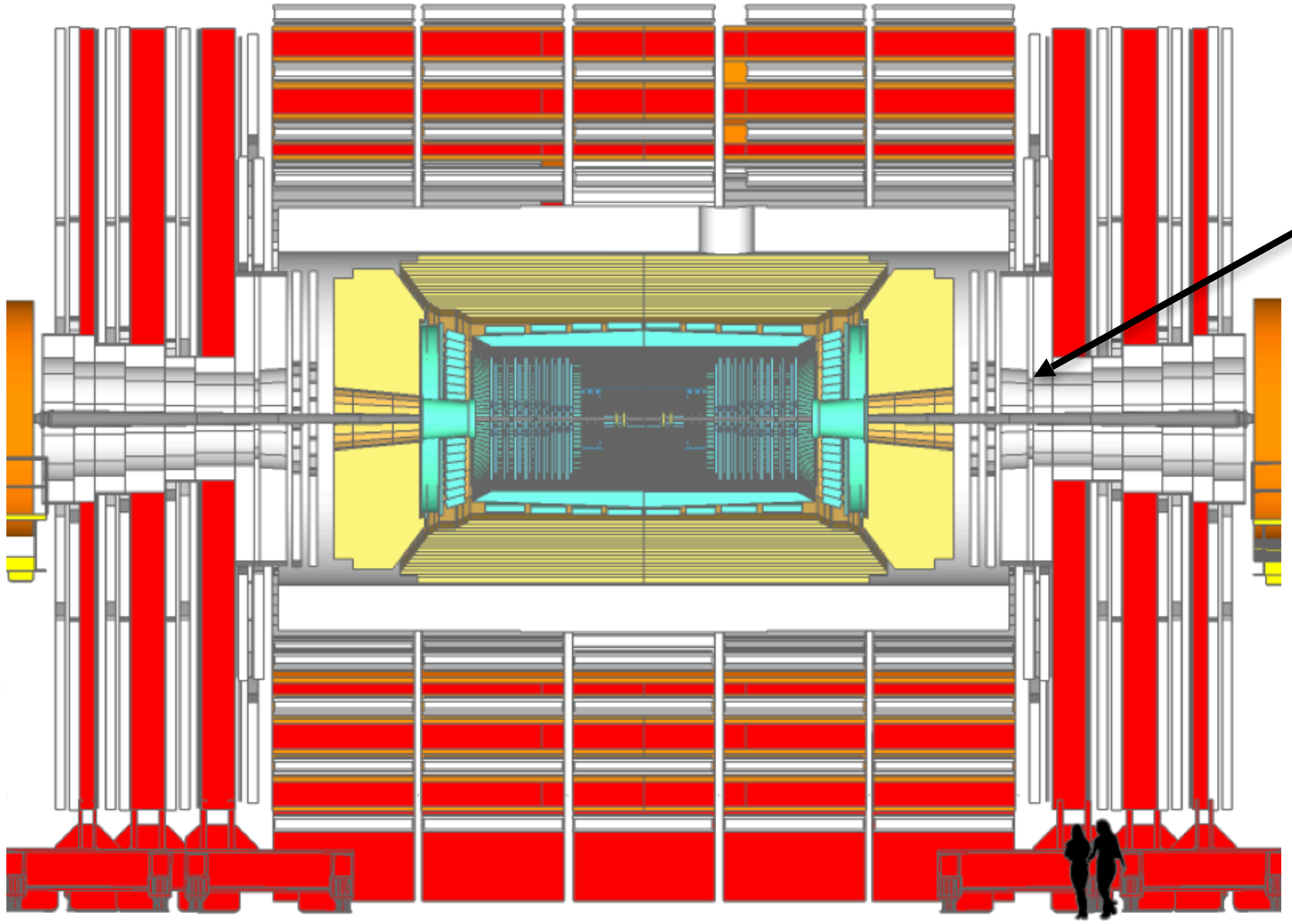
# BACKUP: future

# The upgraded CMS detector for Run 4 (Phase II)

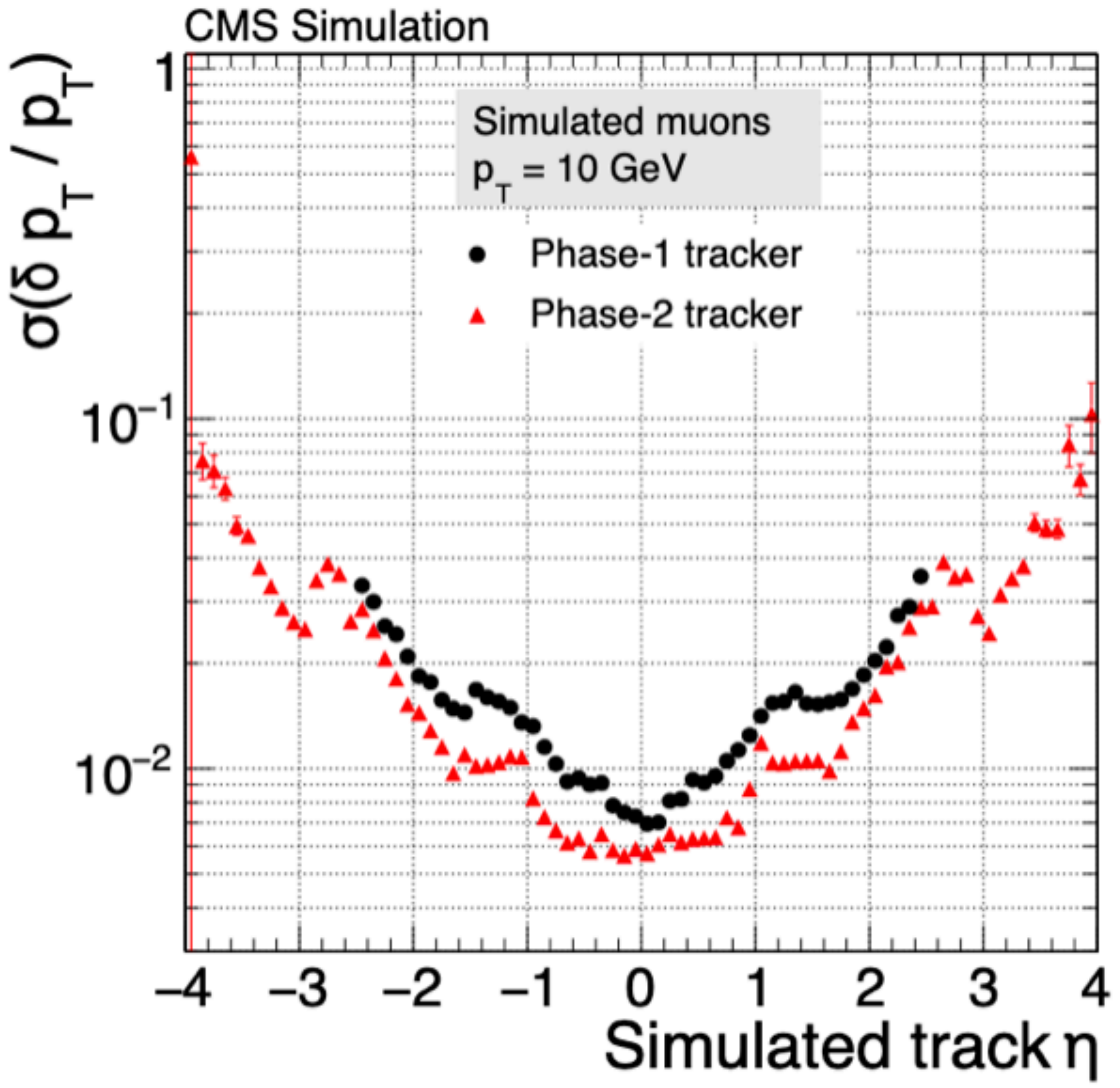
**CMS**, CERN-LHCC-2019-003
**CMS**, CMS-TDR-014

**New MIP Timing Detector** (MTD)
Precision timing $|\eta| < 3$
**Particle Identification over several units of $\eta$!**



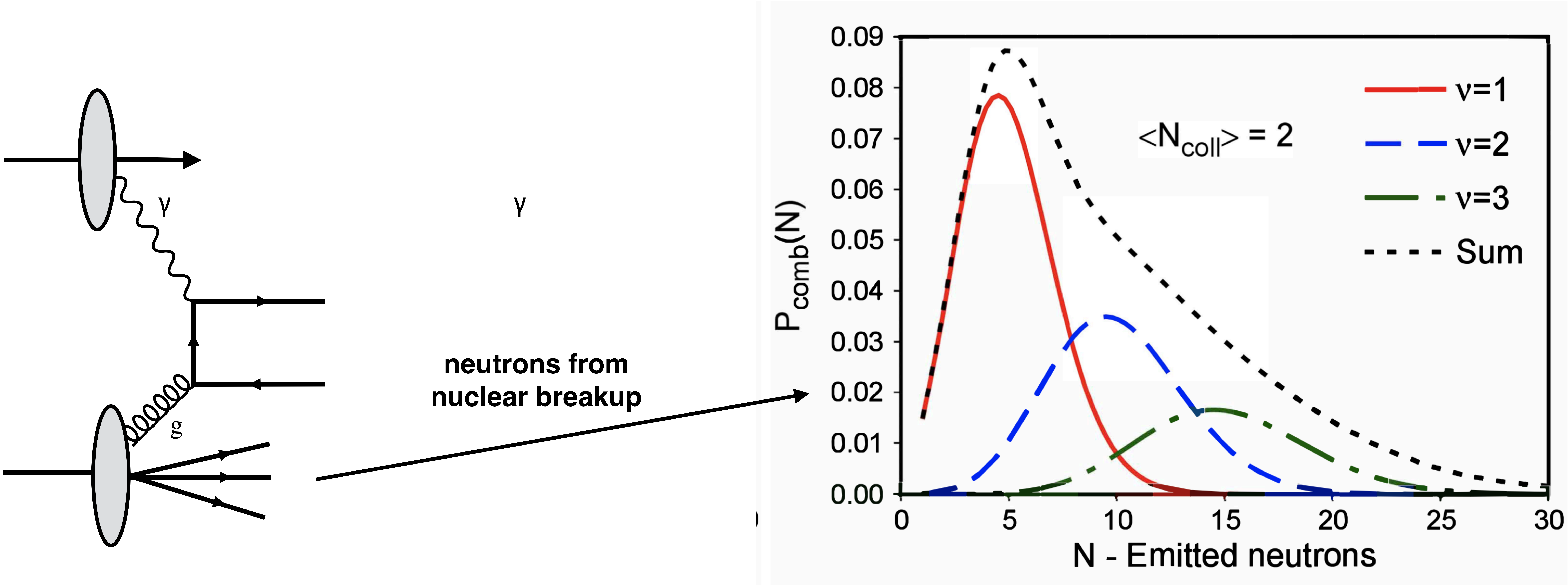



**New silicon tracker**
**Improved granularity**
Lighter material budget
$|\eta| < 2.4 \rightarrow |\eta| < 4$



# Over-constraining models with barrel and forward observables

**Basic concept**: "over-constraining" low-x models by measuring both barrel and very forward observables
**M. Strikman, V. Guzey et al.,** arXiv.2402.19060

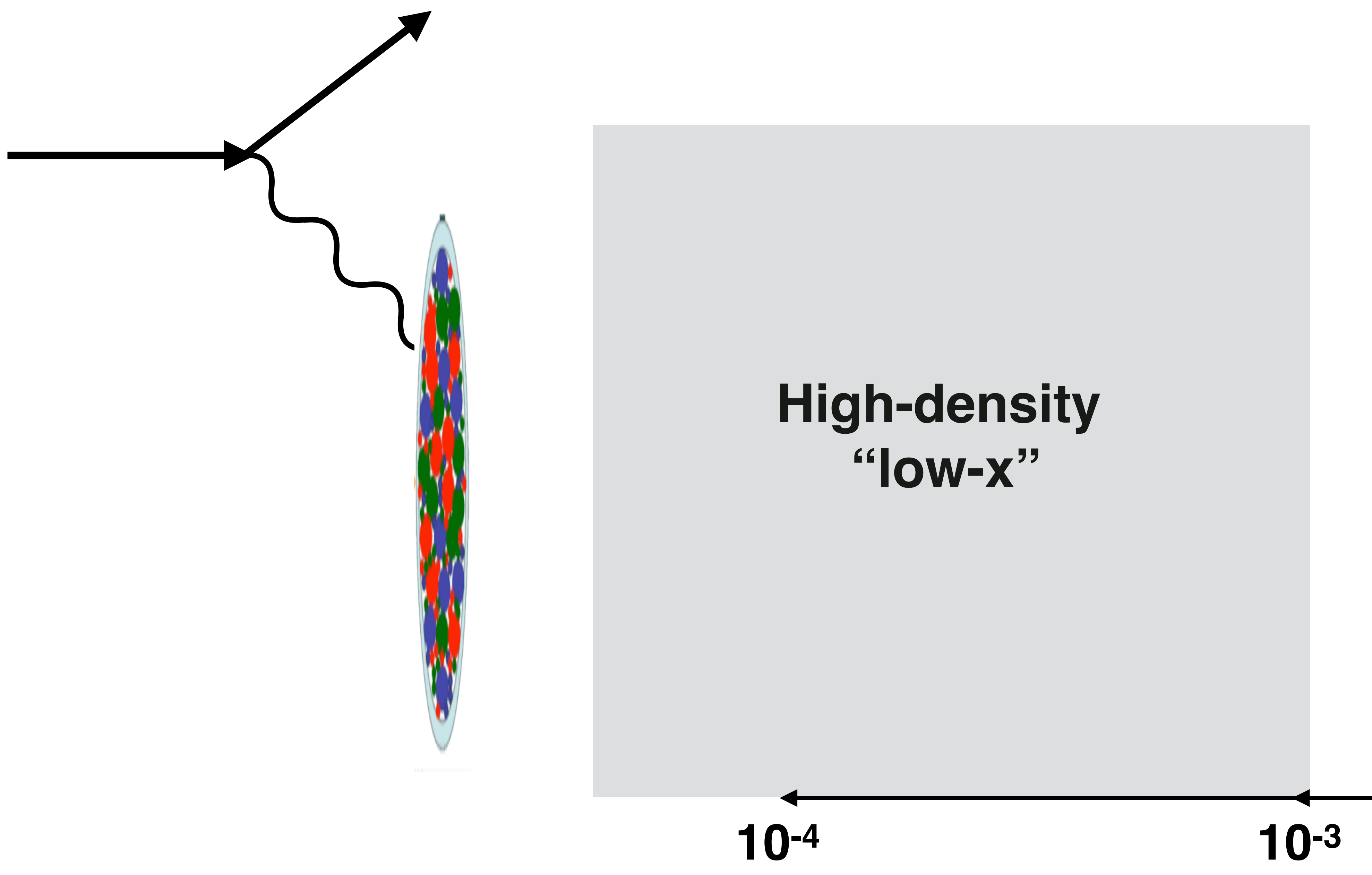



**Hard-scattering production at central rapidities with information on the number of neutrons in ZDC:**
**→ what can we learn from measuring the properties of the nuclear breakup?**

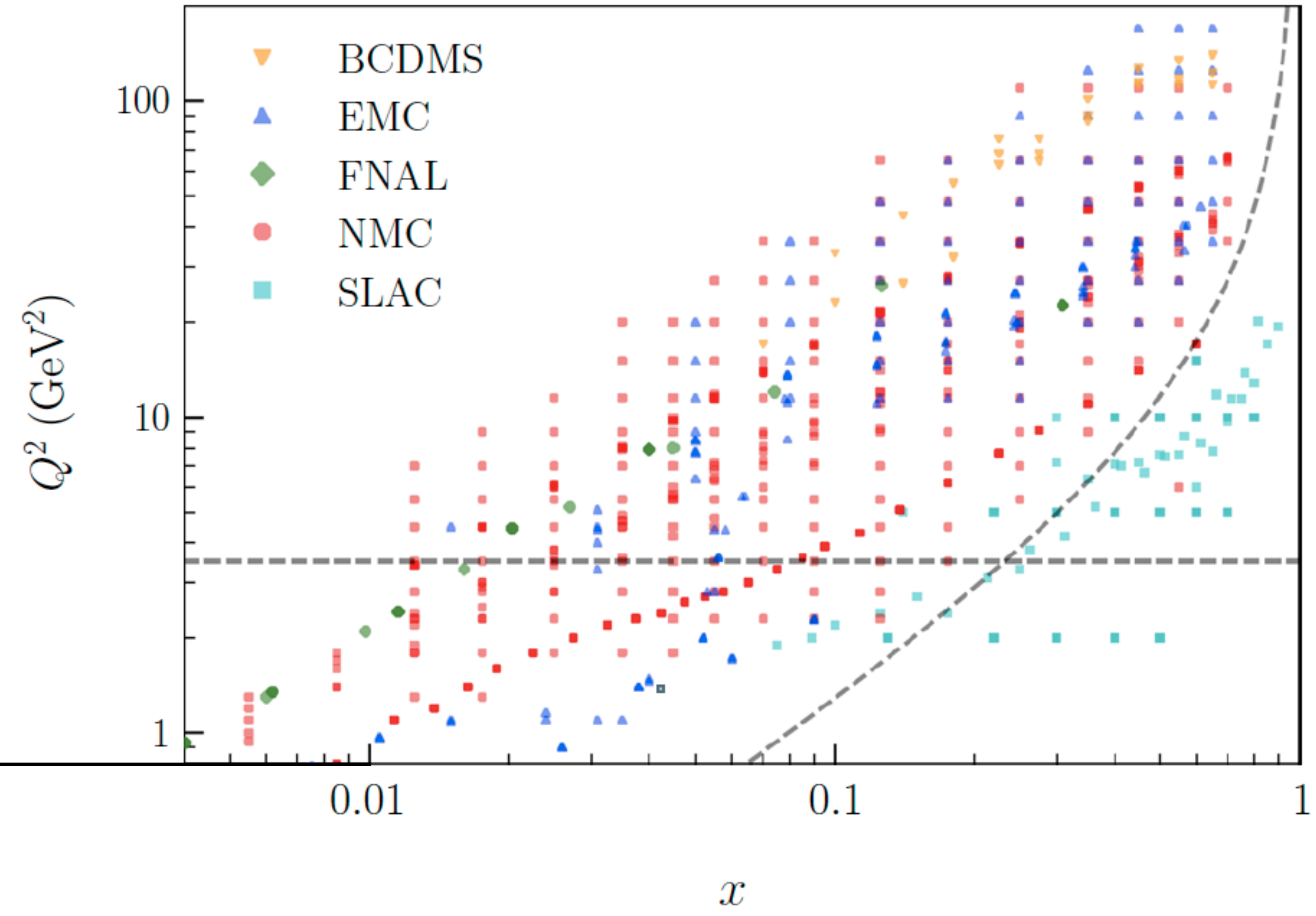
# BACKUP: exp. constraints

# Existing constraints from lepton-nucleus scatterings

→ DIS measurements (neutral-current) on **nuclear fixed-targets**




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




**Limited low-x reach due to:**
→ **difficulty in accelerating leptons at high energy**
→ lower center-of-mass achievable in fixed target experiments

→ **Electron-Ion Collider and ePIC at BNL as the high-energy frontier for electron-ion collisions**

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