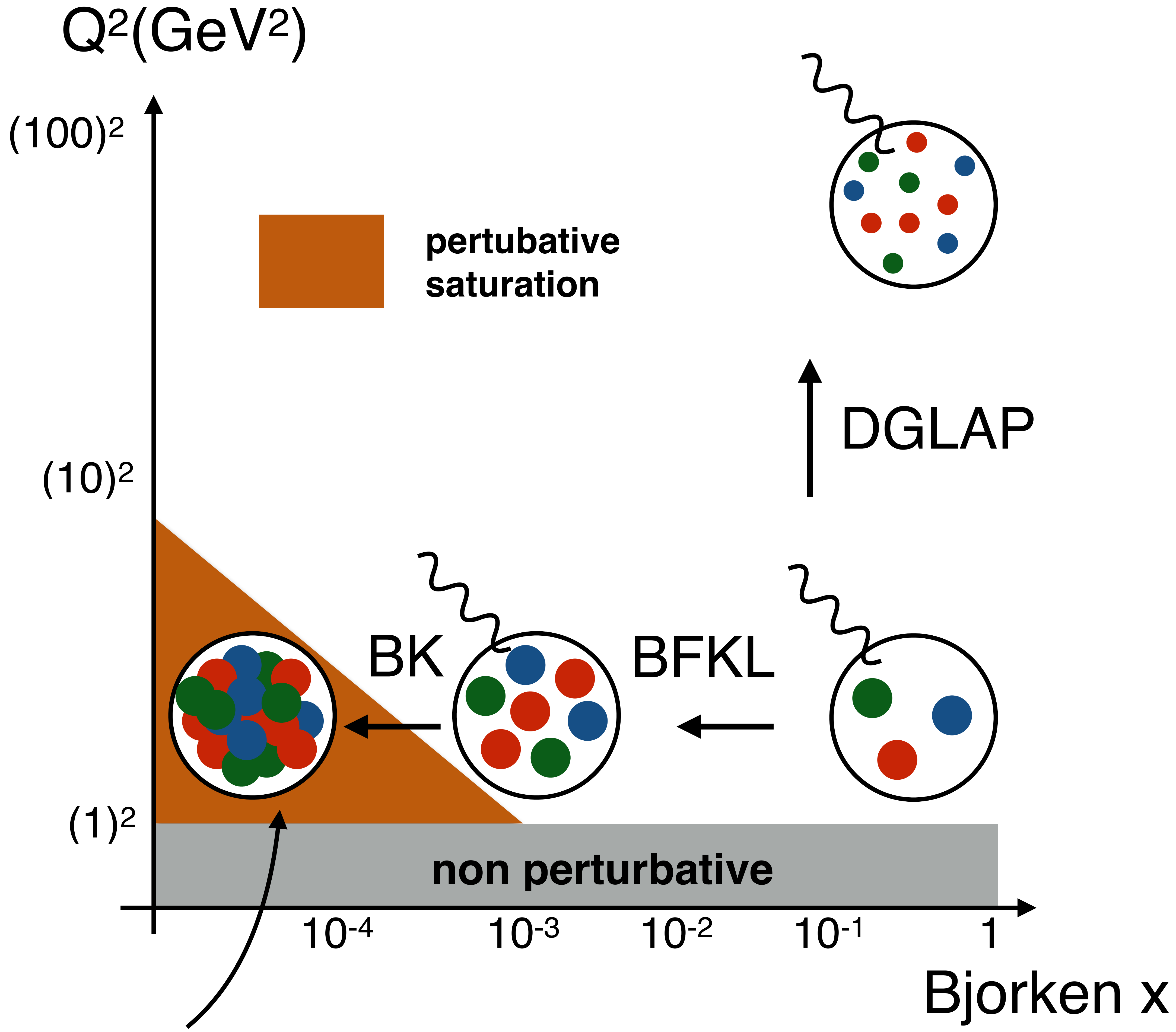
CMS studies and plans in photon-induced pPb at the LHC

(and connections to the UPC PbPb program)

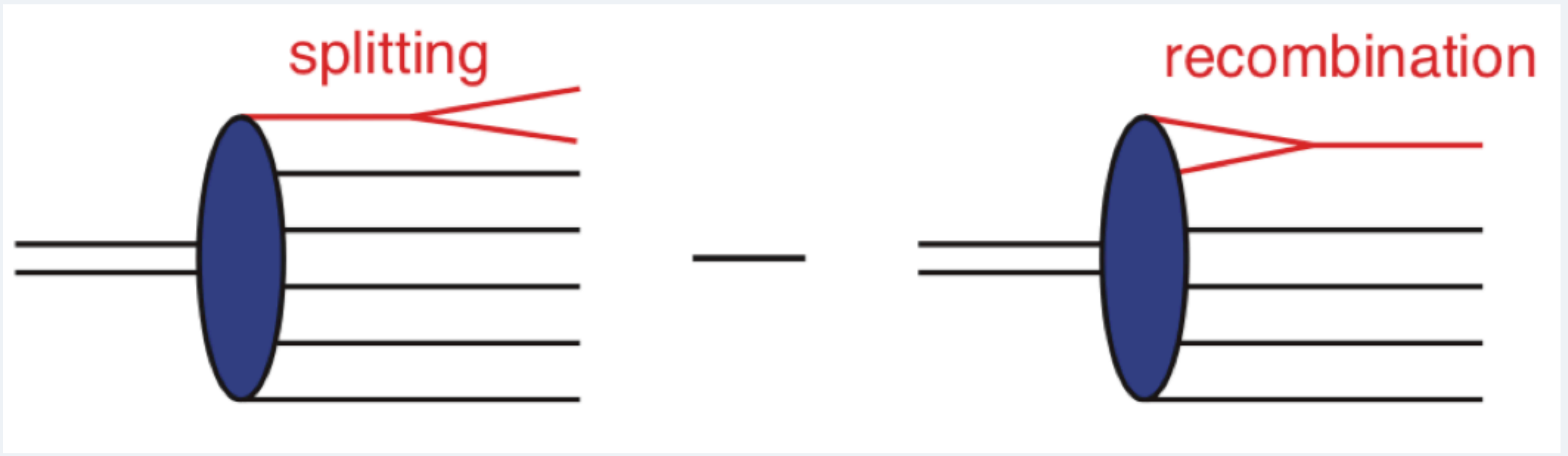
Gian Michele Innocenti for the CMS collaboration
Massachusetts Institute of Technology

Physics with high-luminosity proton-nucleus collisions at the LHC
Jul 4-5, 2024, CERN

Constraining parton dynamics in nuclei in (x,Q^2)



Accessing the saturation scale is expected to be easier in nuclei (due to the higher initial partonic density)

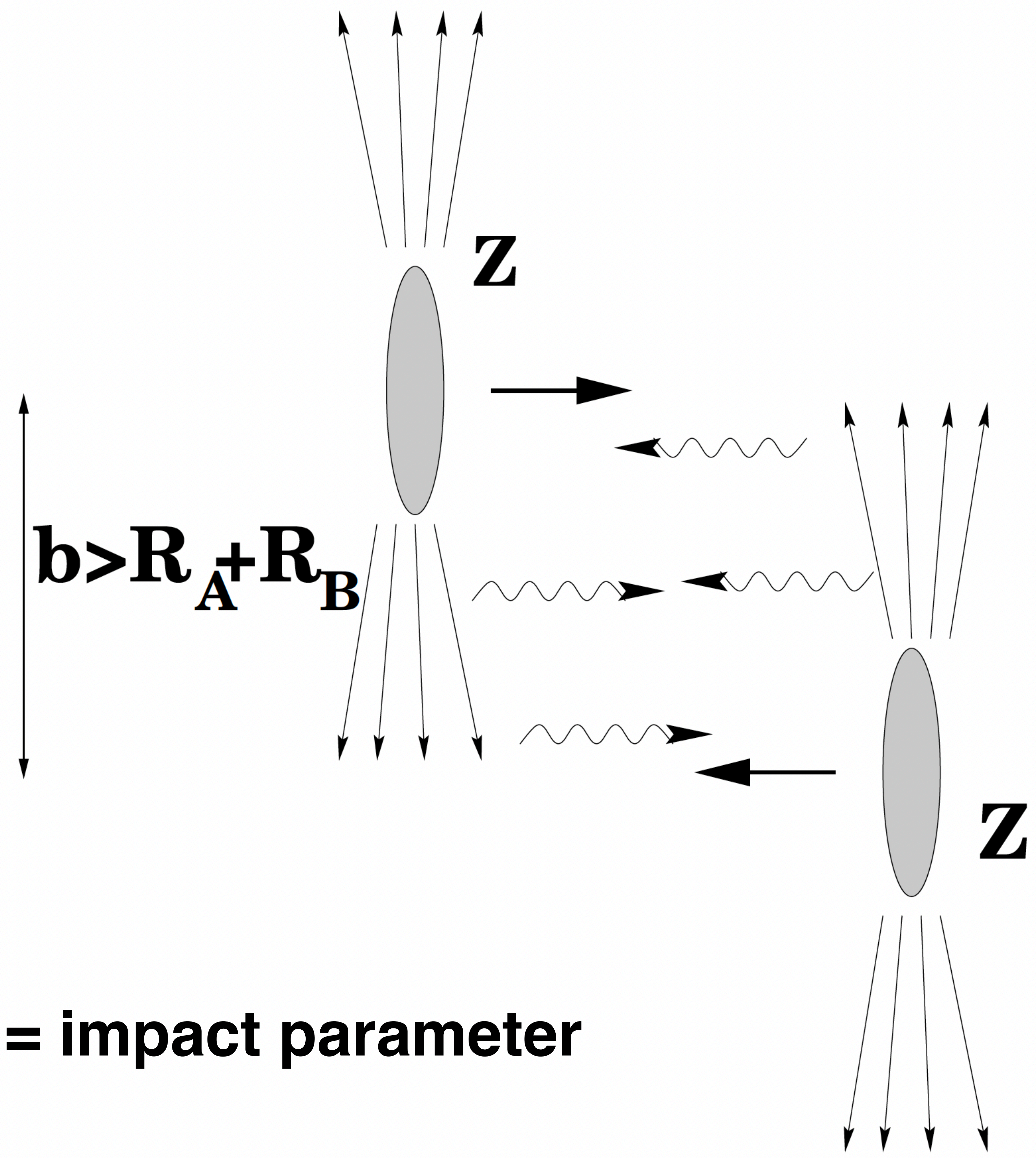


In nuclei, saturation expected at higher x

- does it exist? is it experimentally reachable?
- what is its shape in (x,Q^2)?
- what is the dependence on A?

EIC: BNL-98815-2012-JA, arXiv.1212.1701
J.Albacete, C. Marquet, Prog. Part. Nucl. Phys. 76, 1 (2014)

Ultra-Peripheral heavy-ion collisions



b = impact parameter

Ultra-peripheral collisions (impact parameter b > R_A+R_b)

- Flux of photon is proportional to Z^2

- **Photon kinematics**:
  - $p_T < \hbar/R_A \sim 30$ MeV
  - $E_{max} \sim O(100)$ GeV at LHC.

<u>When running on PbPb, LHC is effectively a γγ and γN collider!</u>

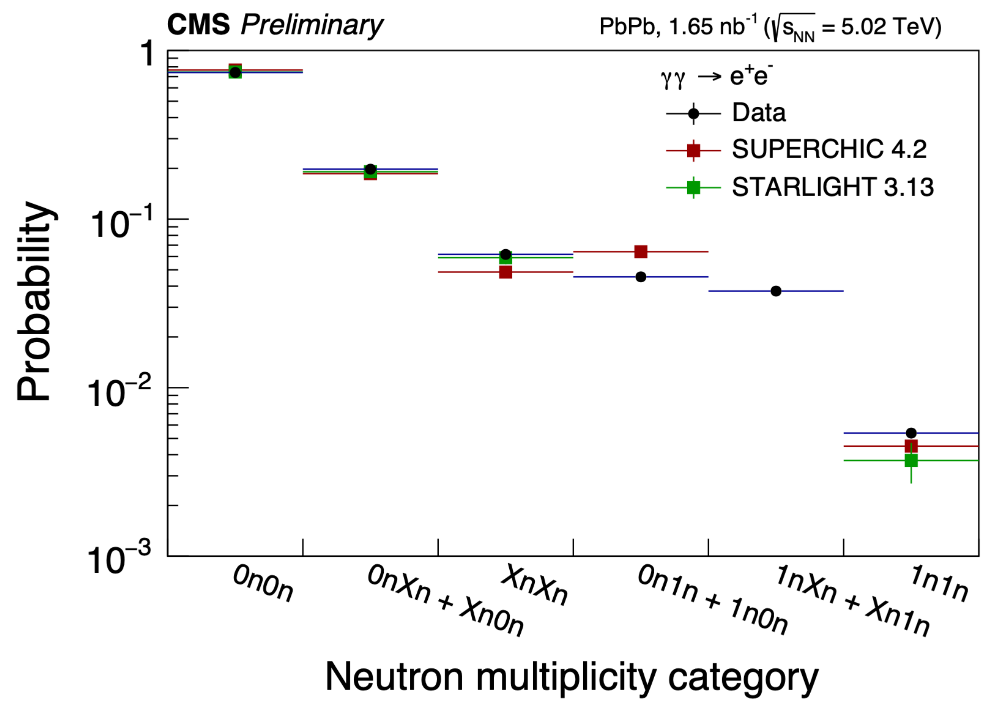
→ access to high-energy photon-nuclear collisions to test nuclear matter effect in abscence of final-state effects (as in pPb)

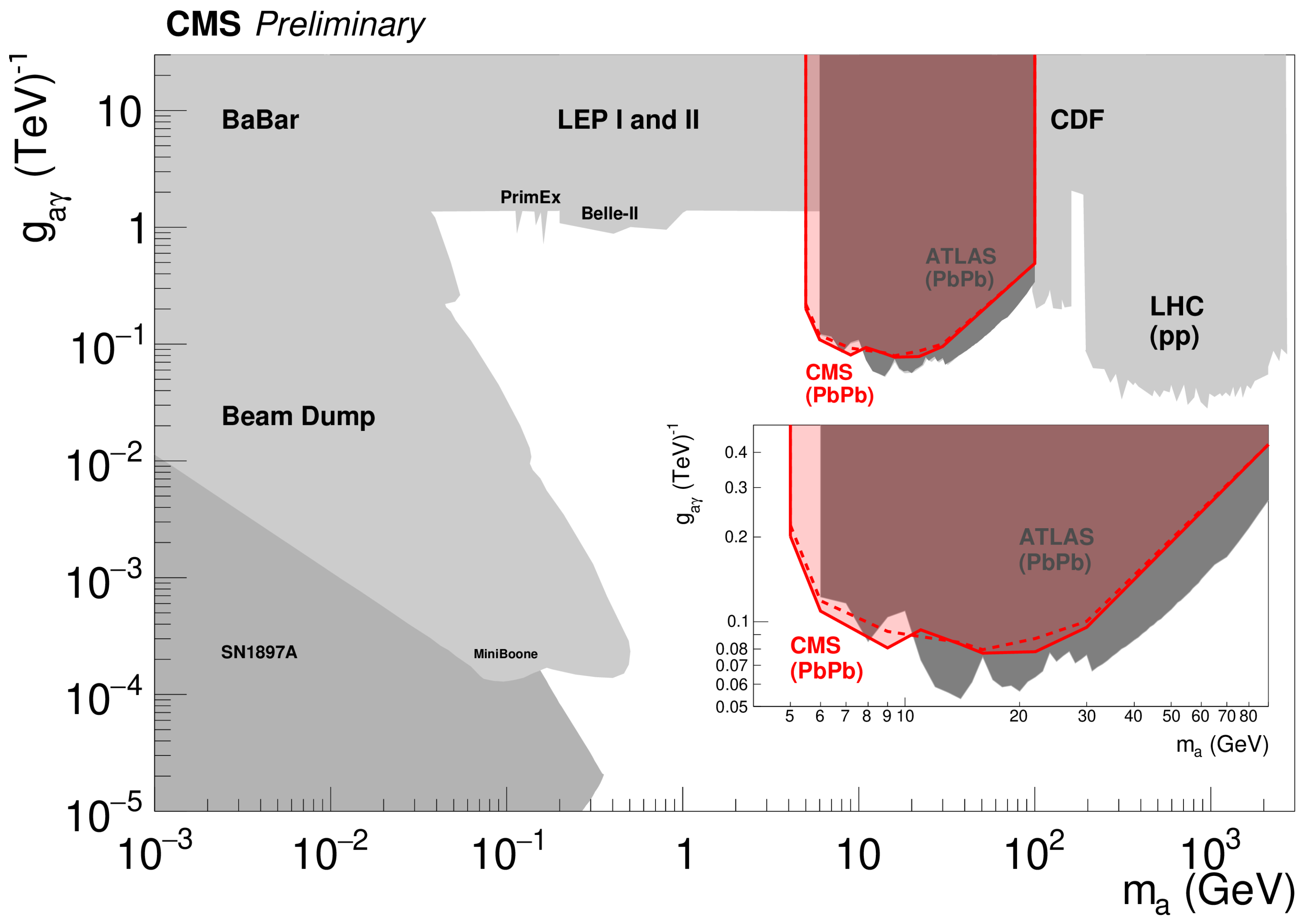
K. Hencken, M. Strikman, R. Vogt, P. Yepes, Phys. Rept. 458:1-171, 2008

Recent QCD UPC measurements in PbPb collisions with CMS and highlights for Run 3

CMS-HIN-21-015

Neutron multiplicity category	Data	SUPERCHIC 4.2	STARLIGHT 3.13
		Probability (%)	
0n0n	74.0 ± 0.7	76.6 ± 1.0	74.5 ± 1.0
0nXn + Xn0n	19.8 ± 0.5	18.6 ± 0.2	19.1 ± 1.0
XnXn	6.2 ± 0.2	4.9 ± 0.1	5.9 ± 0.5
0n1n + 1n0n	4.5 ± 0.2	6.4 ± 0.1	—
1nXn + Xn1n	3.7 ± 0.1	—	—
1n1n	0.54 ± 0.04	0.5 ± 0.0	0.4 ± 0.1



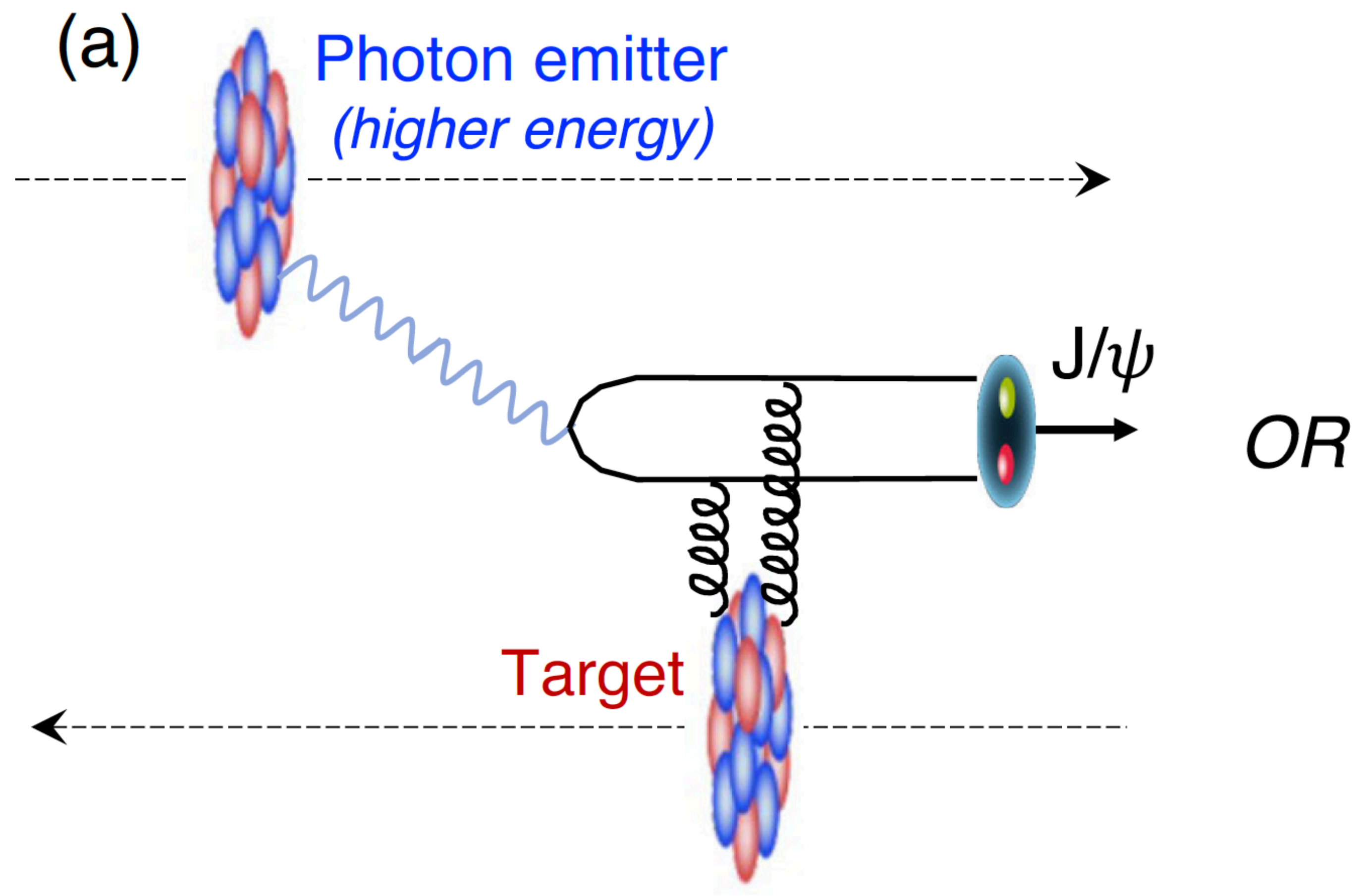


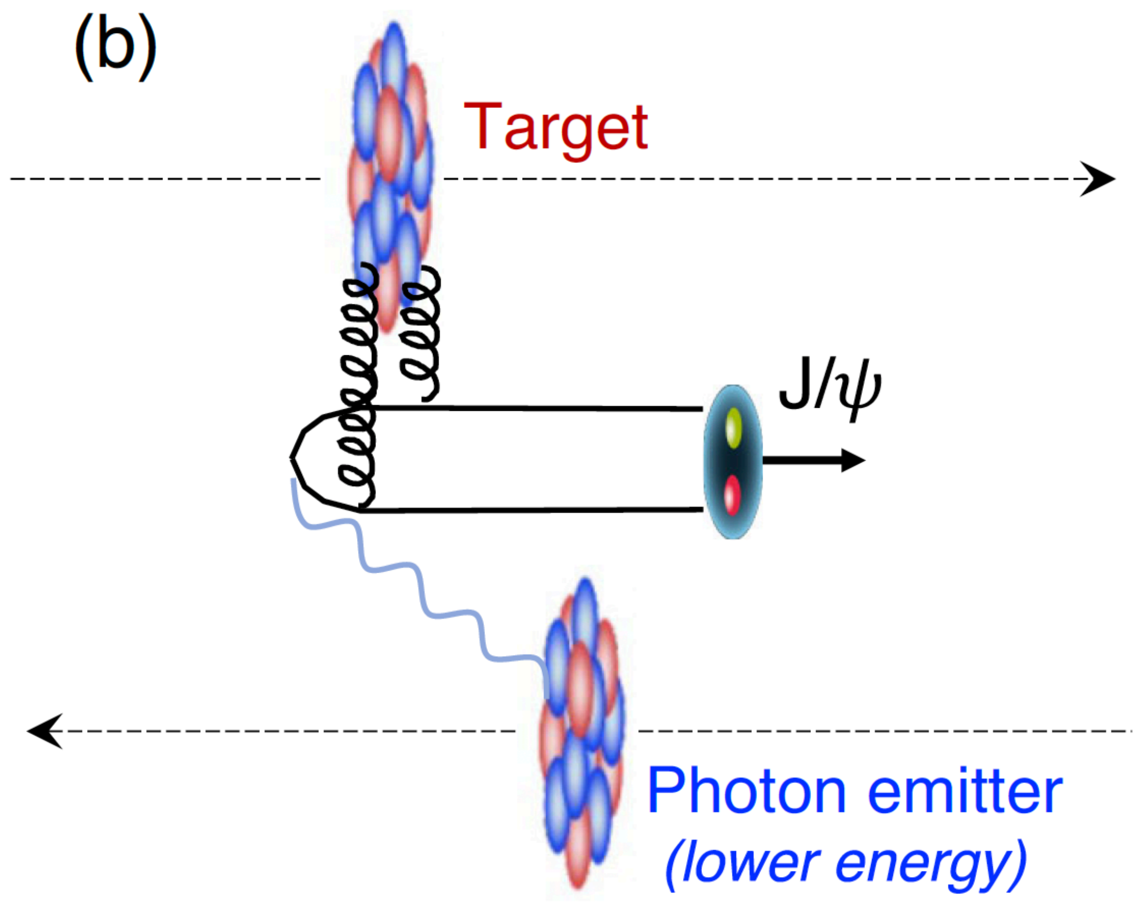
See d'Enterria's talk at Moriond QCD 2024 (link)

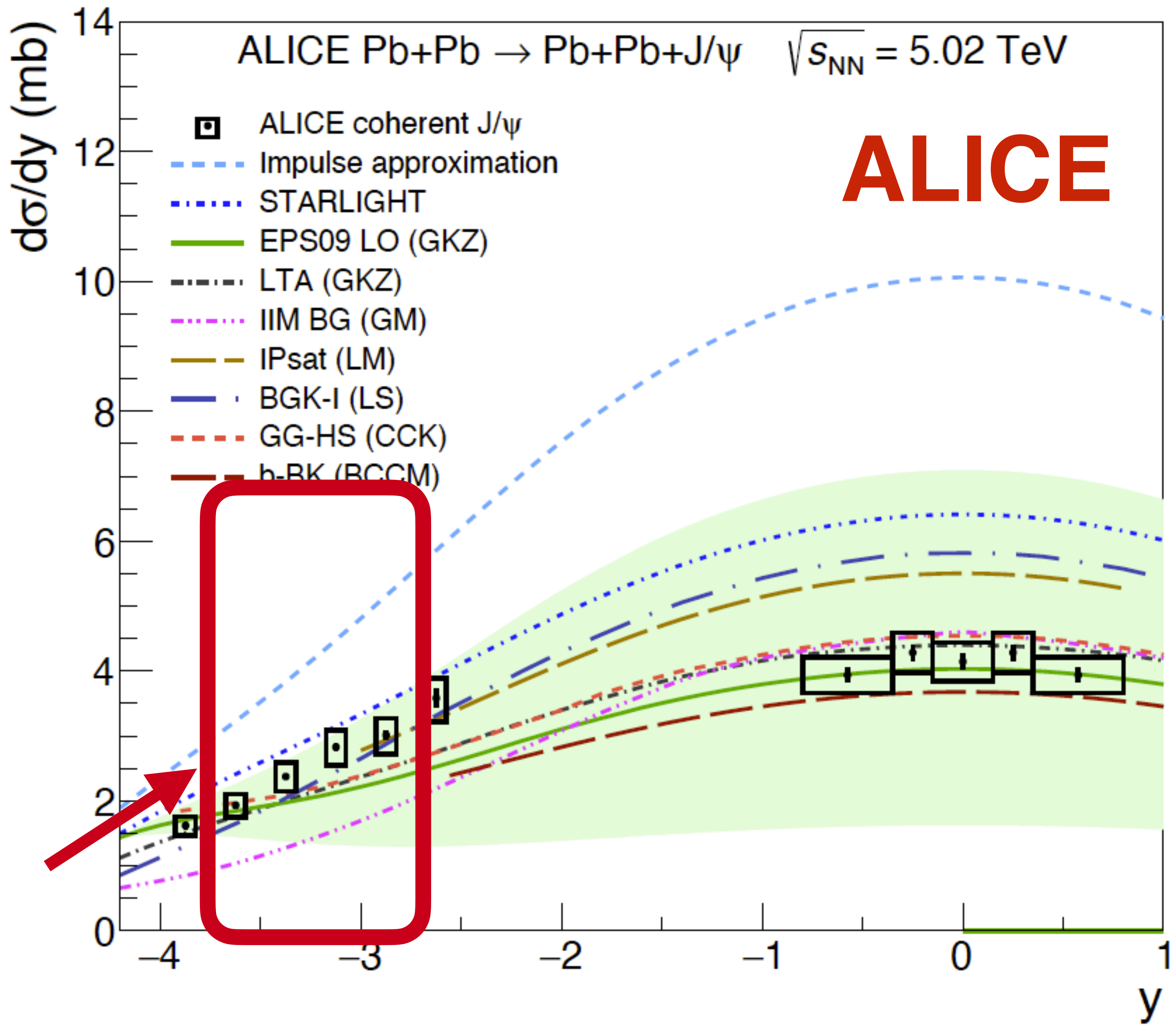
Coherent J/ψ photoproduction in UPC PbPb collisions

$Q^2 \sim M^2_{cc}$ GeV , x_A ~shadowing
(gluon PDFs)²
- 4.0< y*< -2.5 (forward)

→ access to gluon PDF in **absence of hadronic interactions**





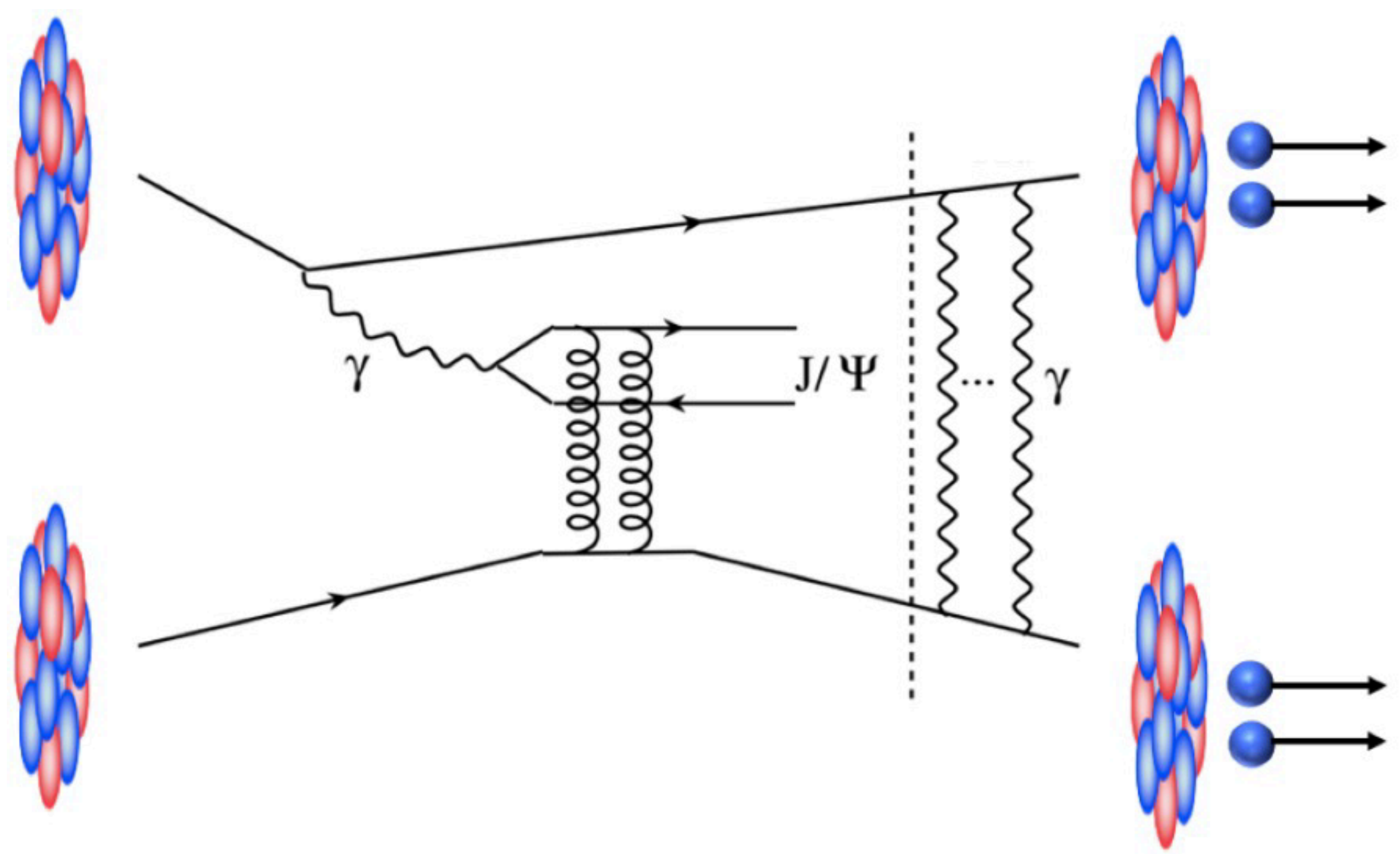


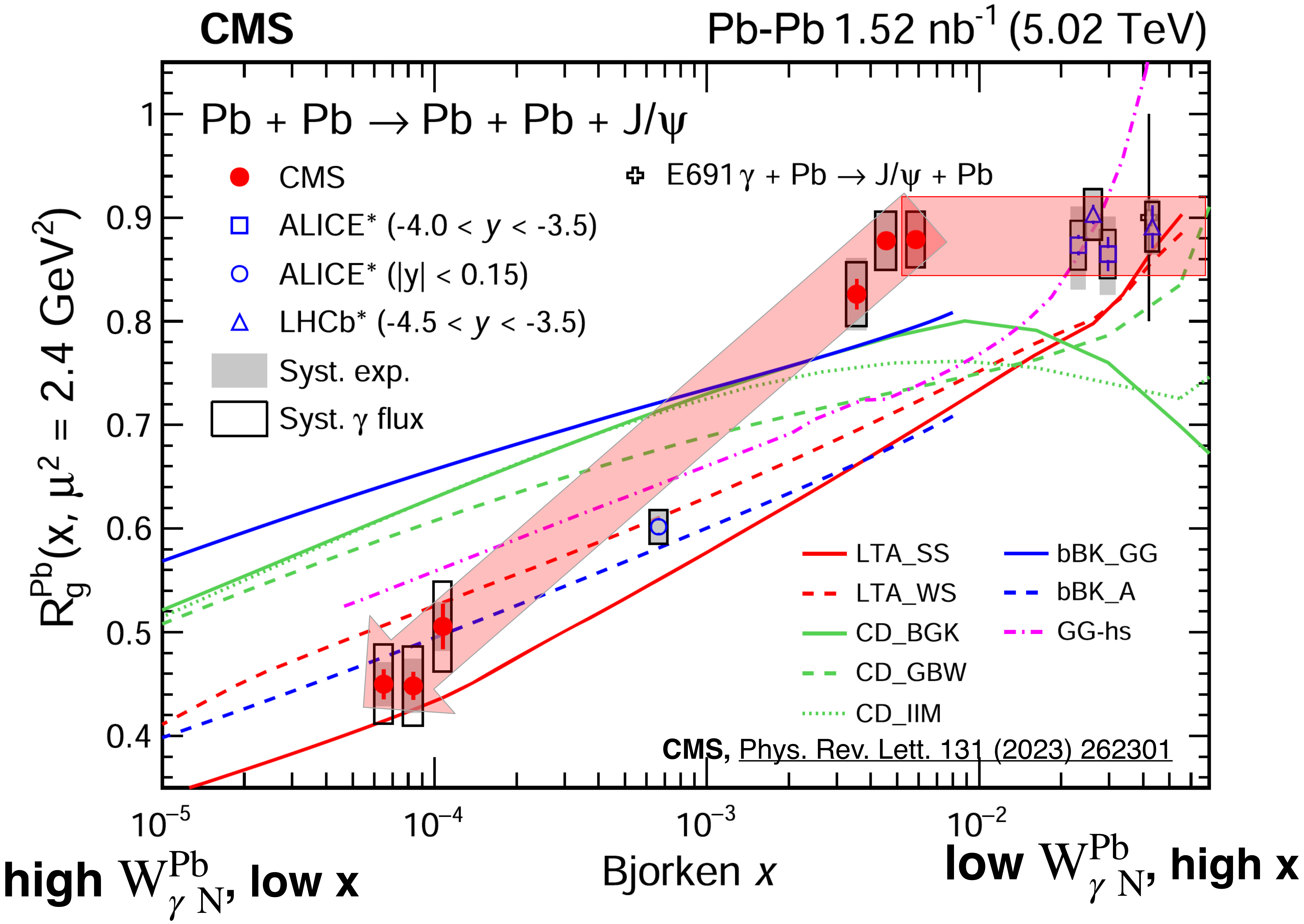
At fixed y, contributions from different x regions (higher and lower)

Two-way ambiguity can limit the constraining power due to large uncertainty on the determination of x!

- The initial direction of the photon is not fully defined

Coherent J/ψ in PbPb UPCs with forward-neutron tag with CMS





For events with Xn "on the same side" of the J/ψ:

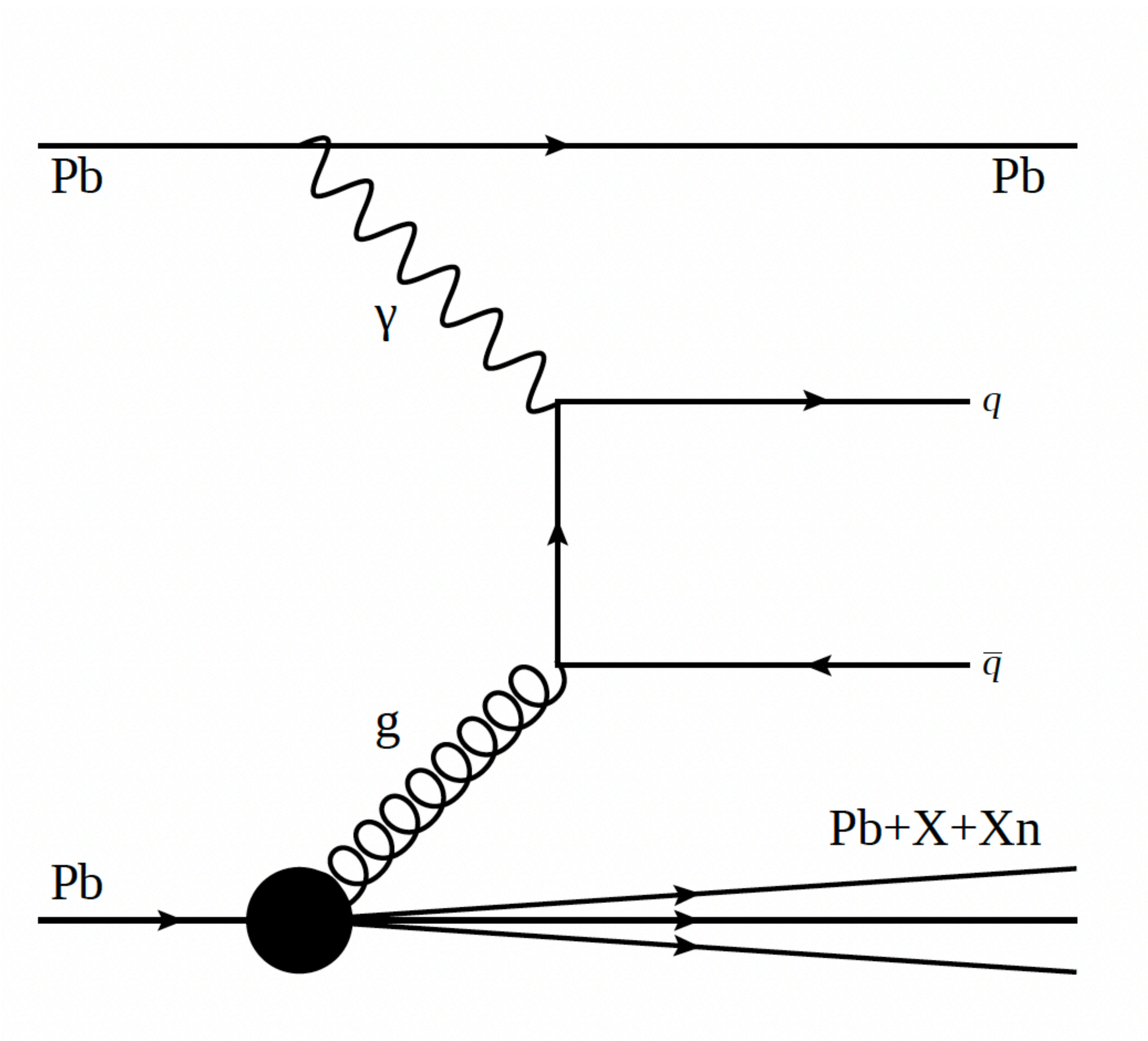
→ select low impact-parameter events ($P_{EMD} \sim 1/b^2$)

→ **high-energy photon, low-x events**

→ **increased sensitivity to low-x effects without "W+W-" ambiguities**

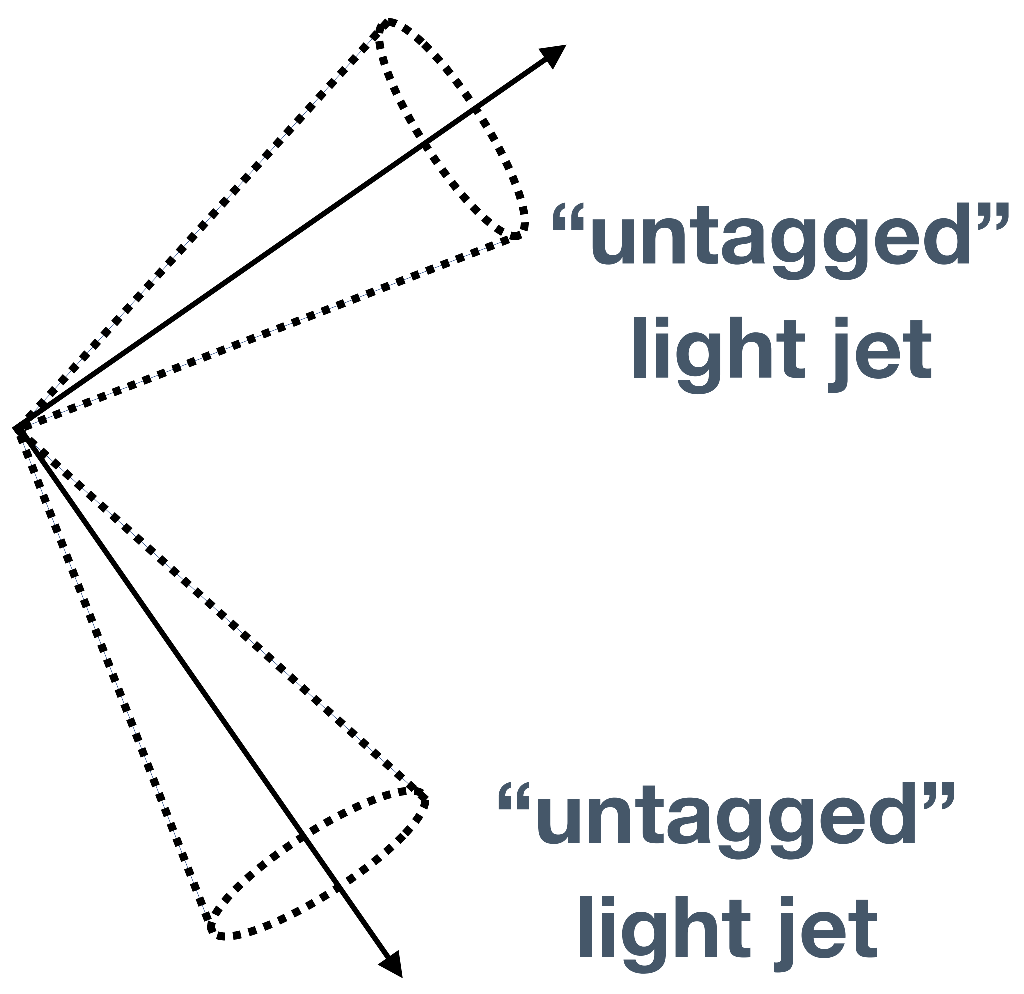
→ **<u>Have we observed saturation?!</u>**

Untagged di-jets in γN scatterings



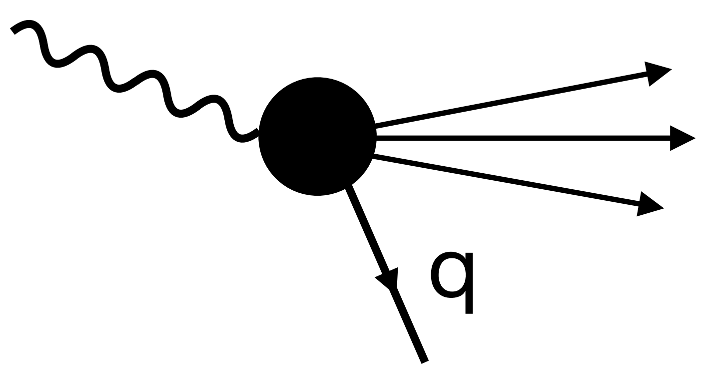
Dynamic constraints on (x, Q^2)

by varying dijet kinematics



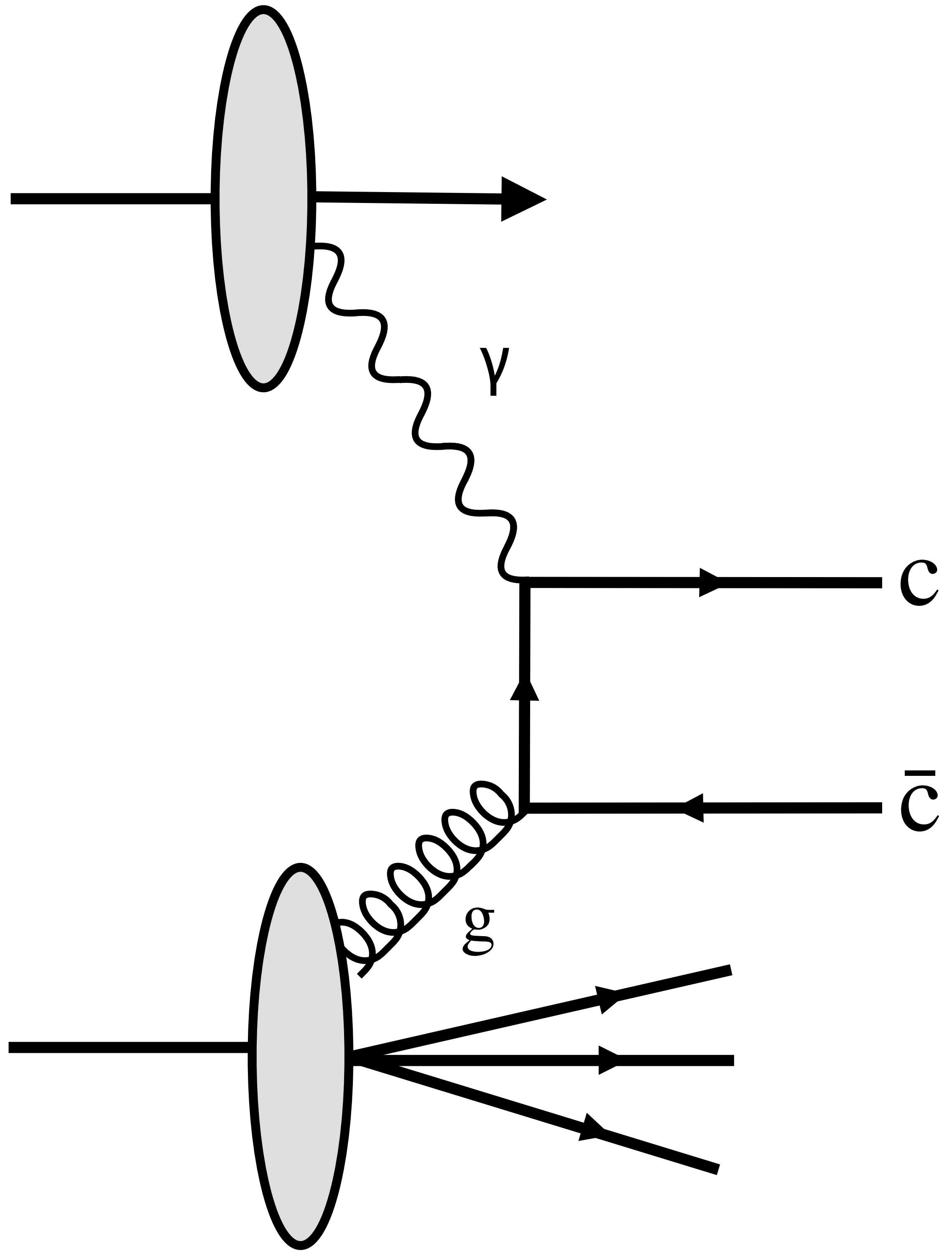
Limited access to low x and Q^2

→ jets limited to p_T >~15 GeV/c



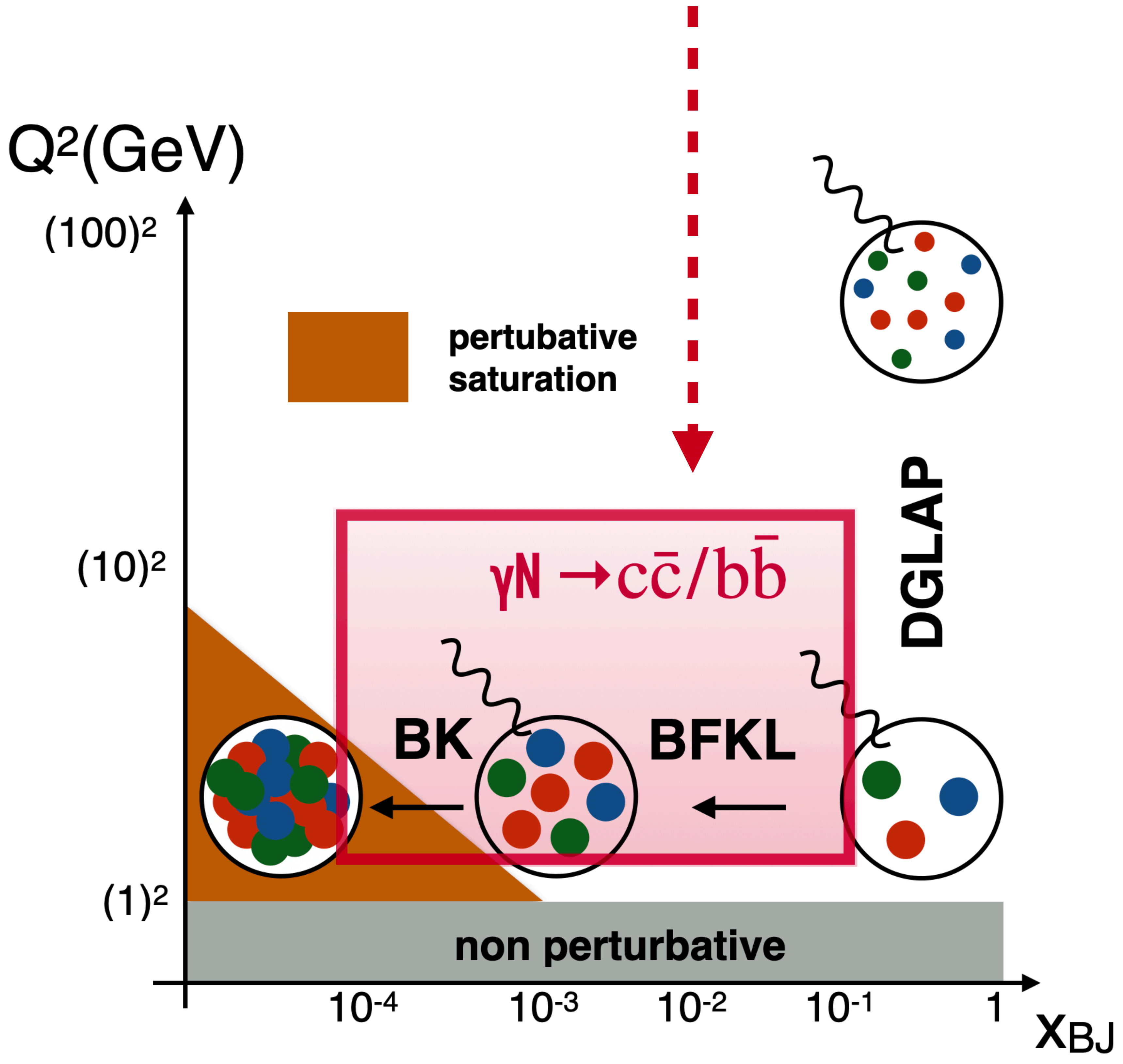
Sizeable contamination from "resolved"-photon processes:

“Open” heavy-flavor and jet photoproduction in UPCs



- Simple pQCD description down to $p_T=0$
- “in-vacuum” environment with limited final-state effects
- dynamical acces to a wide region of x, Q^2 region down to low x_{BJ}

→ **scan the region where high-density effects should emerge**



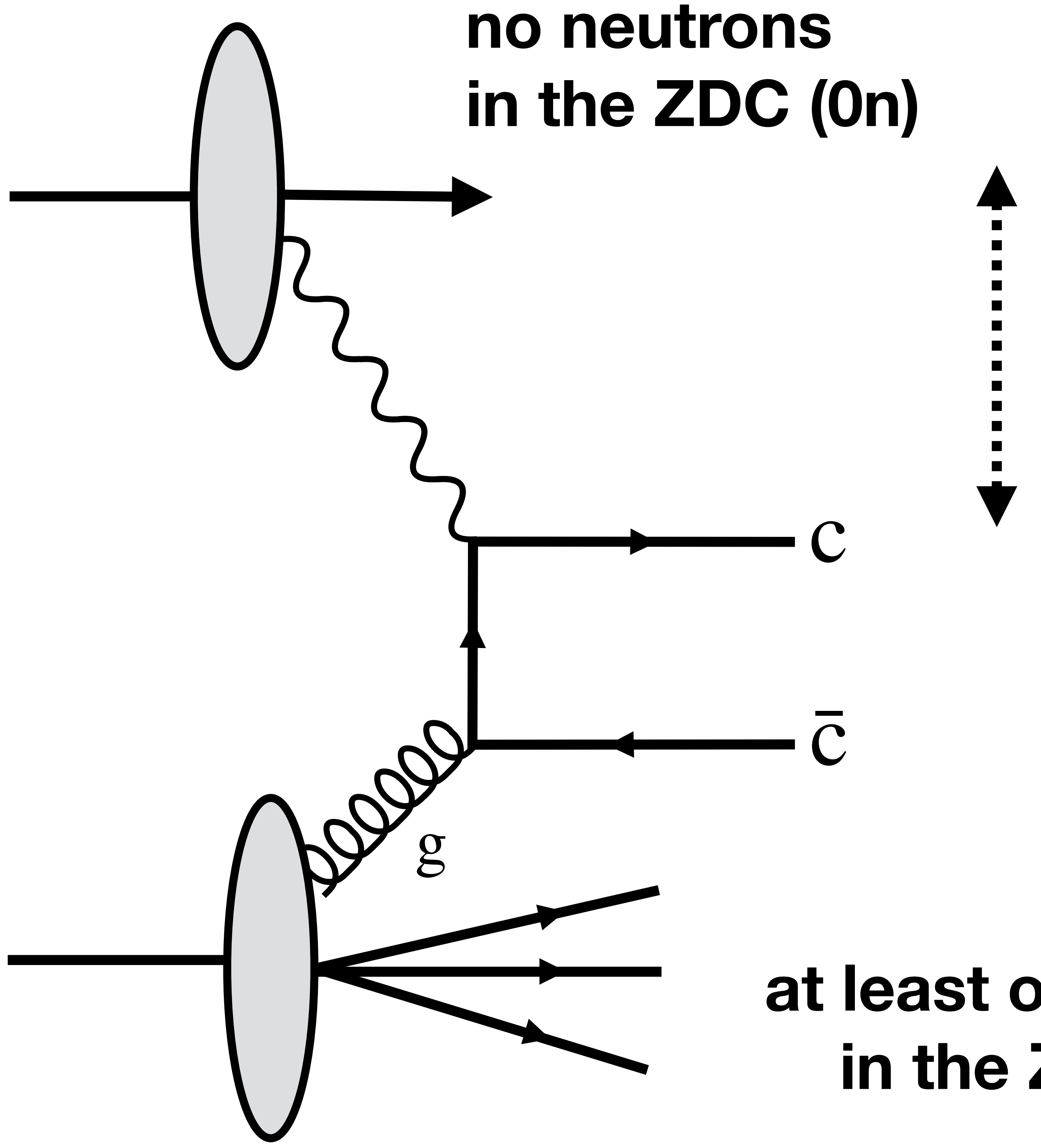
- $x_{min} \approx 10^{-4}$ with low $p_{T,}$ forward probes (LHC)
- $Q^2_{min} \approx m^2_{c\bar{c}}$

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

Experimental strategy for “hard” inclusive photoproduction

Event selection: Xn0n events with “rapidity gap”.

no neutrons
in the ZDC (0n)

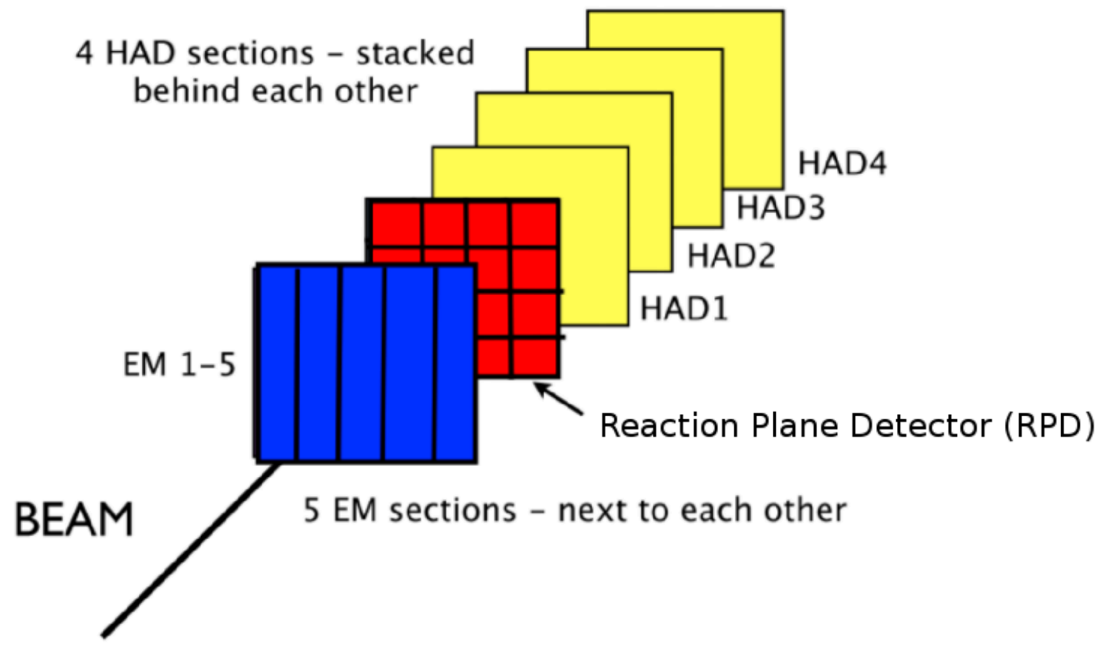


at least one neutron
in the ZDC (Xn)

Rapidity gap in the
direction of outgoing photon

Heavy-quark tagged jets:
→ high-statistics up to high-p_T
$D^0 \to K^-\pi^+$ reconstruction:
→ Trace charm quark down to low p_T

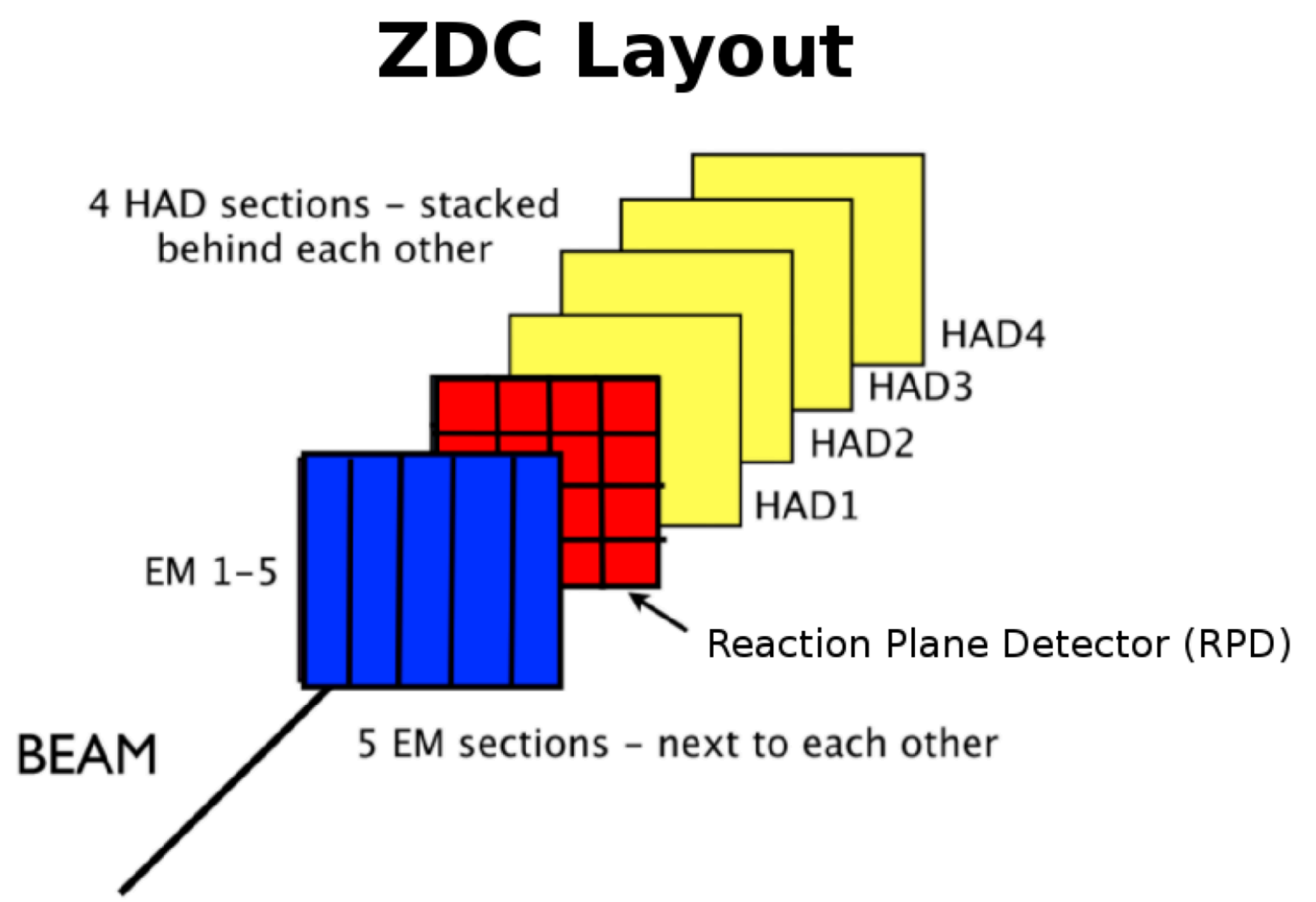
ZDC Layout



Triggering on γγ, γN events as a big experimental challenge!

- Hardware trigger system (Level-1 has max accepted rate in heavy-ions about 20-30 kHz)
- Interaction rate of γγ, γN in heavy-ions $\mathcal{O}$(MHz)!!

Converting CMS into a γγ, γN detector for the "LHγC"

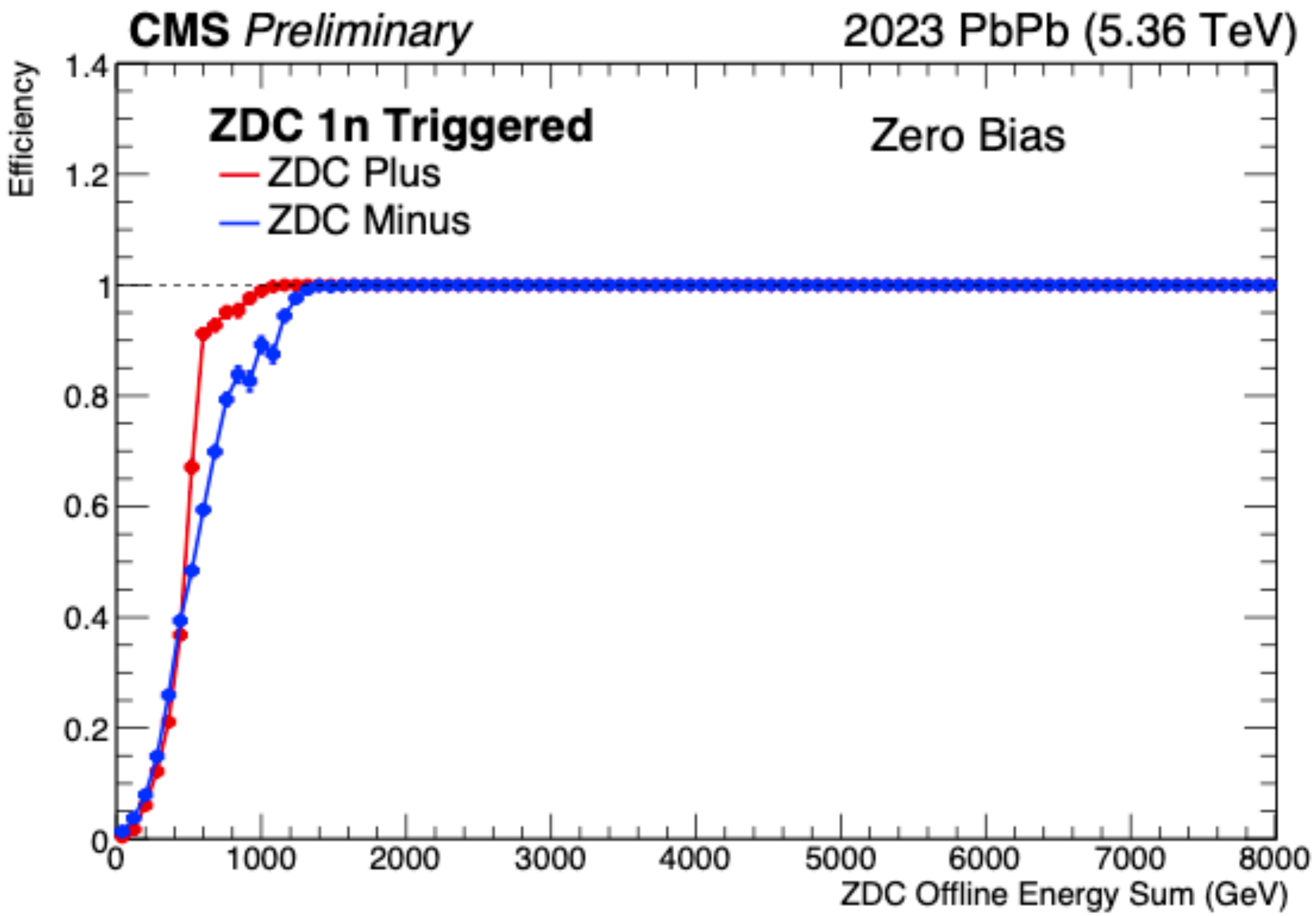


Zero-Degree Calorimeter (ZDC) as a trigger detector

→ integrate ZDC in the Level-1 (hardware) trigger-emulation chain

→ develop a strategy for fast online calibration

L1 trigger efficiency vs D^0 p_T (2023 data)



New trigger algorithms for γγ and γN "hard" events

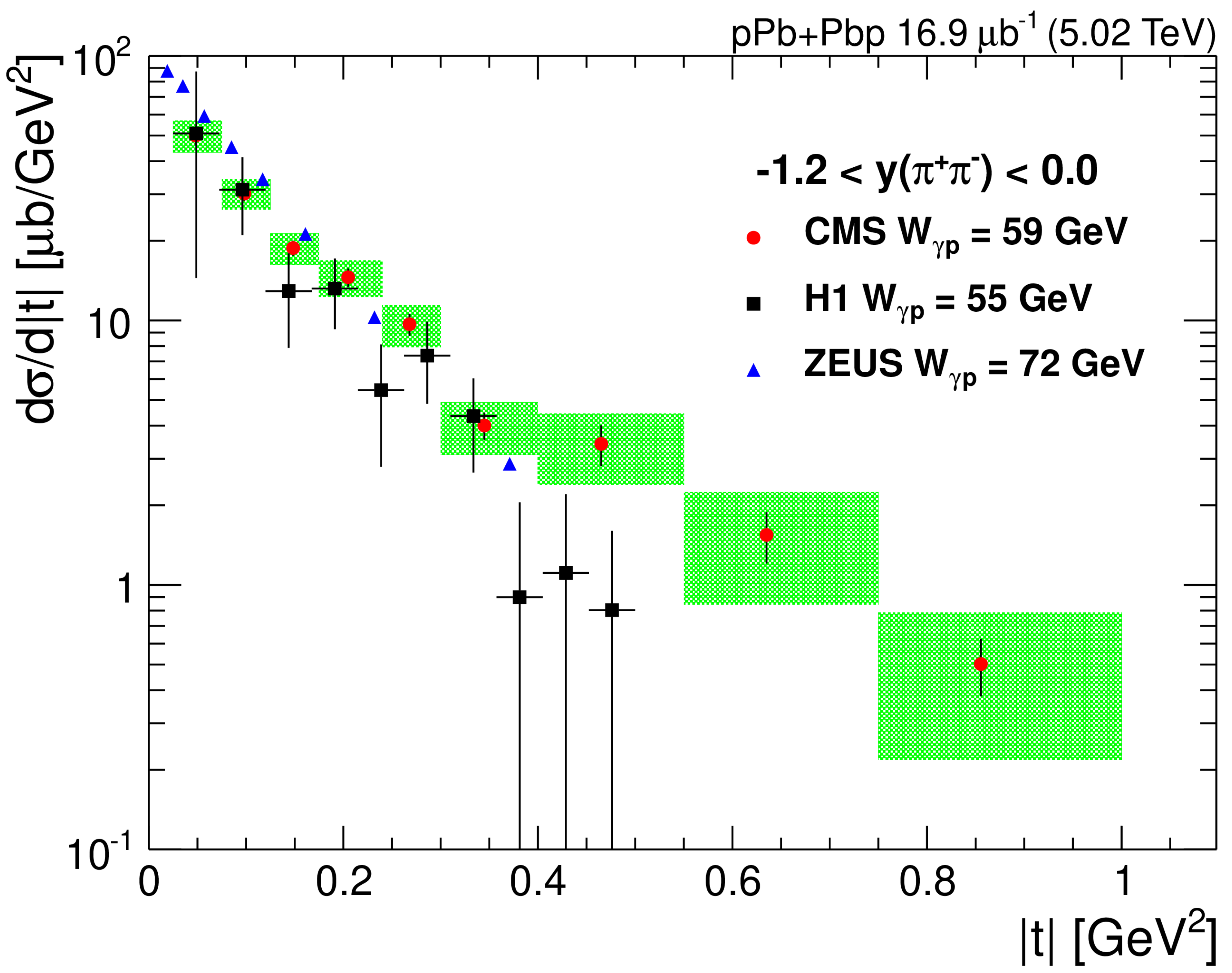
→ **photonuclear high-Q^2 triggers** (ZDCXOR && L1 jet)

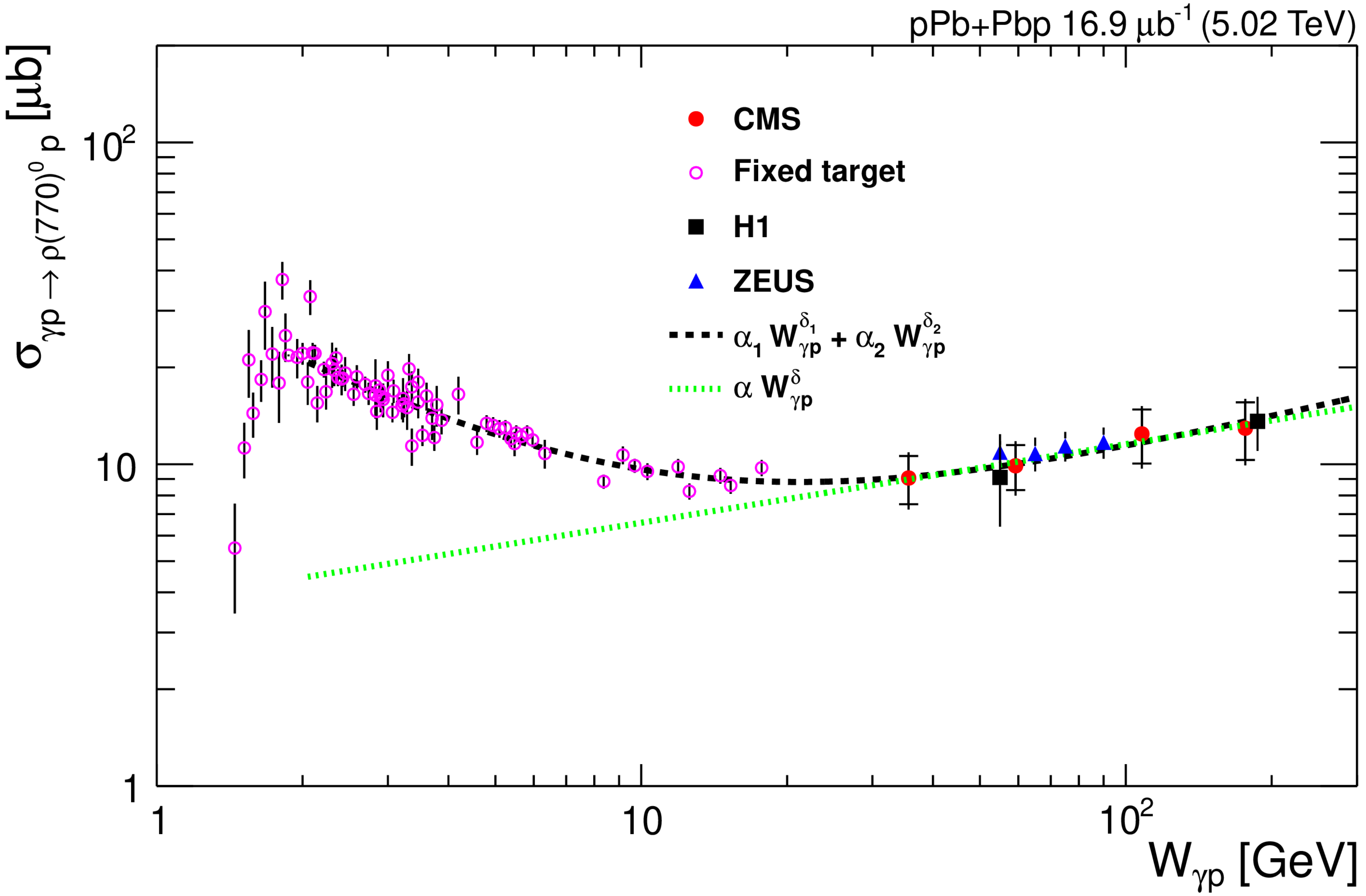
→ **photonuclear low-Q^2 triggers** (ZDCXOR)

→ **γγ and diffractive triggers**

Recent UPC measurements in pPb collisions: a few highlights

$\rho_0(770)$ photoproduction in pPb UPC collisions at 5.02 TeV



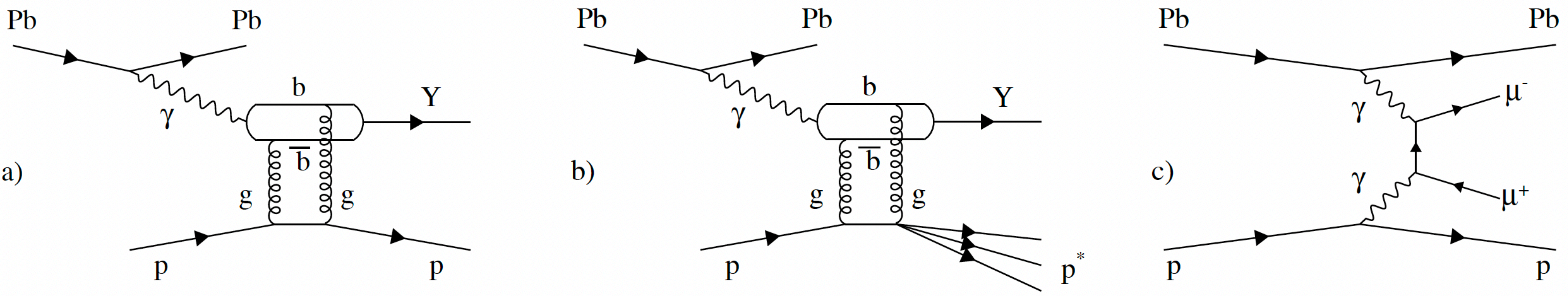


Results are consistent with those of the H1 and ZEUS Collaborations at HERA
→ **ion–proton collisions can be used in the same way as electron–proton ones, with ions acting as a source of quasi-real photons.**

CMS, Eur. Phys. J. C 79 (2019) 702, CMS-FSQ-16-007

Upsilon production in exclusive photonuclear pPb events

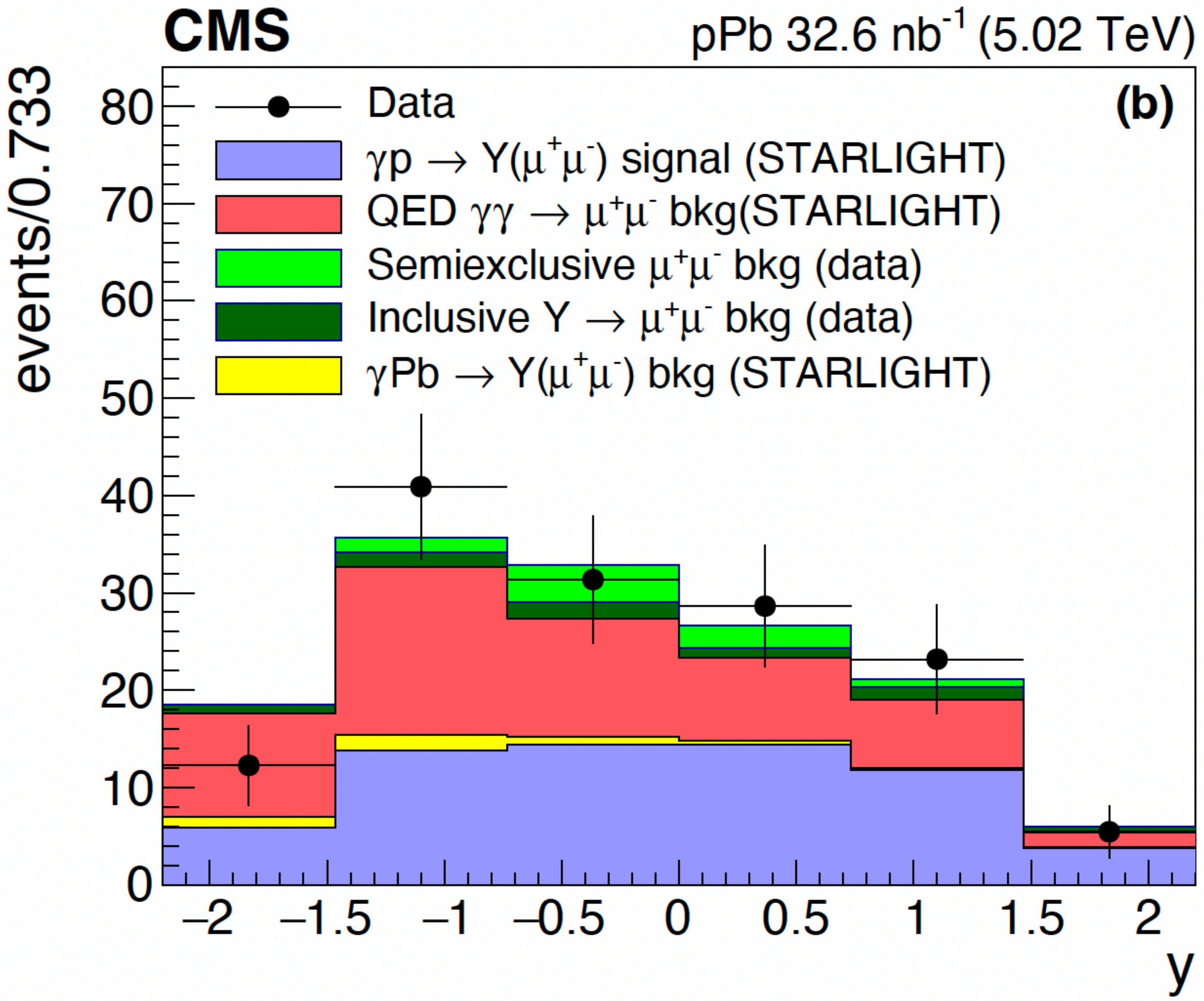
→ **sensitive to generalized parton distributions (GPDs) in the proton for $10^{-4} < x < 10^{-2}$**

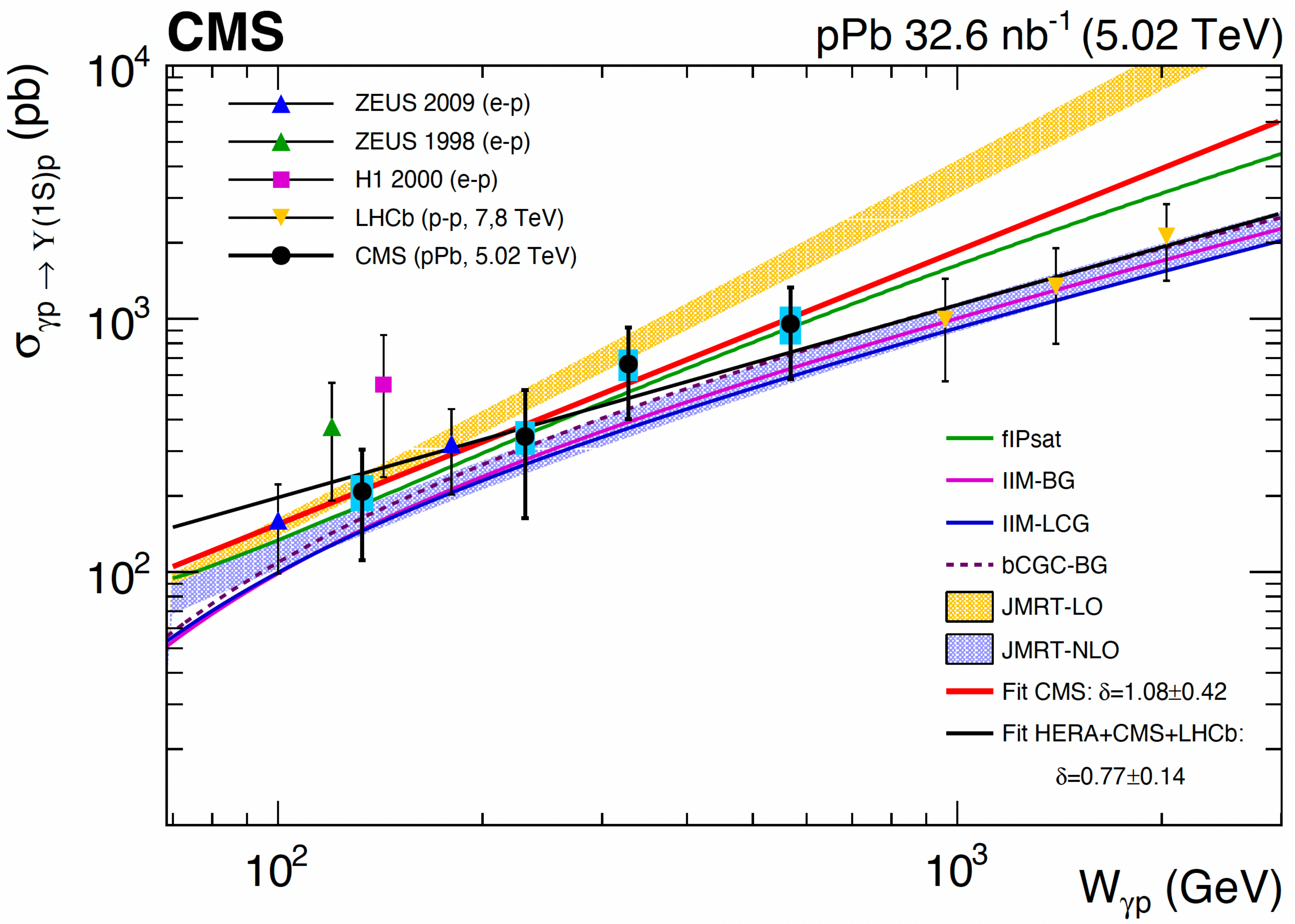


exclusive photoproduction

semiexclusive photoproduction

exclusive dimuon QED continuum

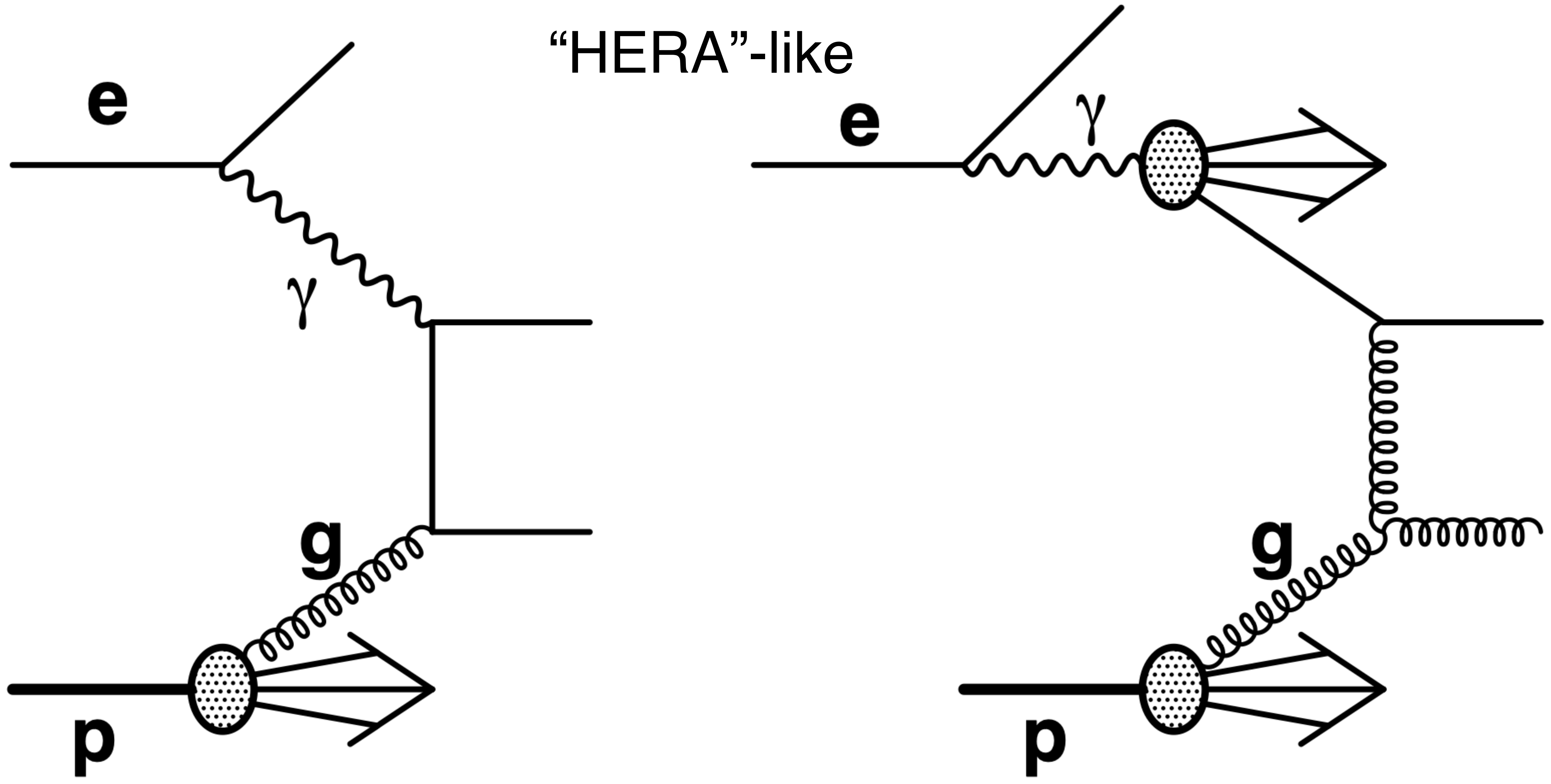




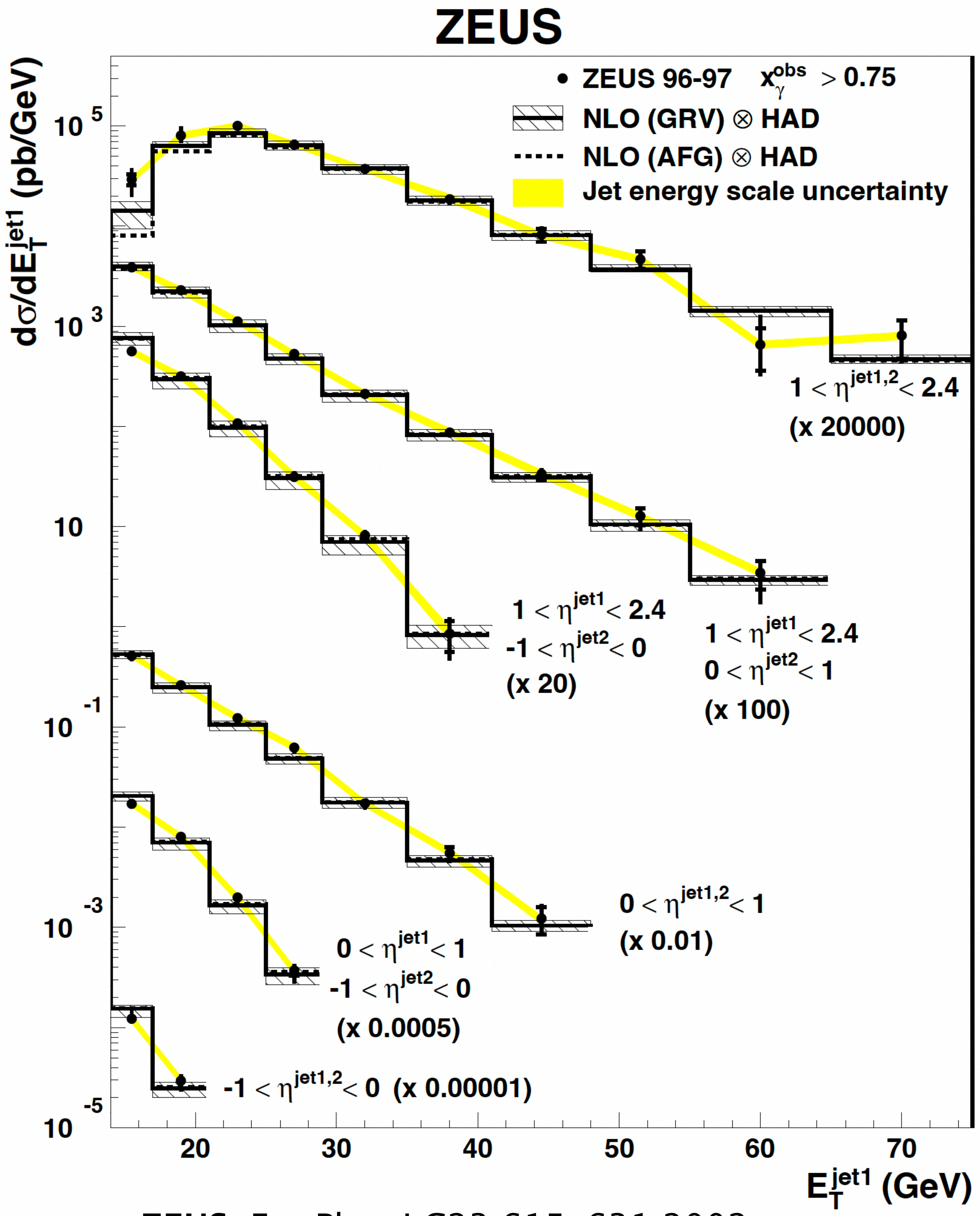
CMS, Eur. Phys. J. C 79 (2019) 277

Prospects for photon-induced measurements in Run 3 and Run 4: some highlights

Jets and open heavy-quarks in photonuclear γp scatterings

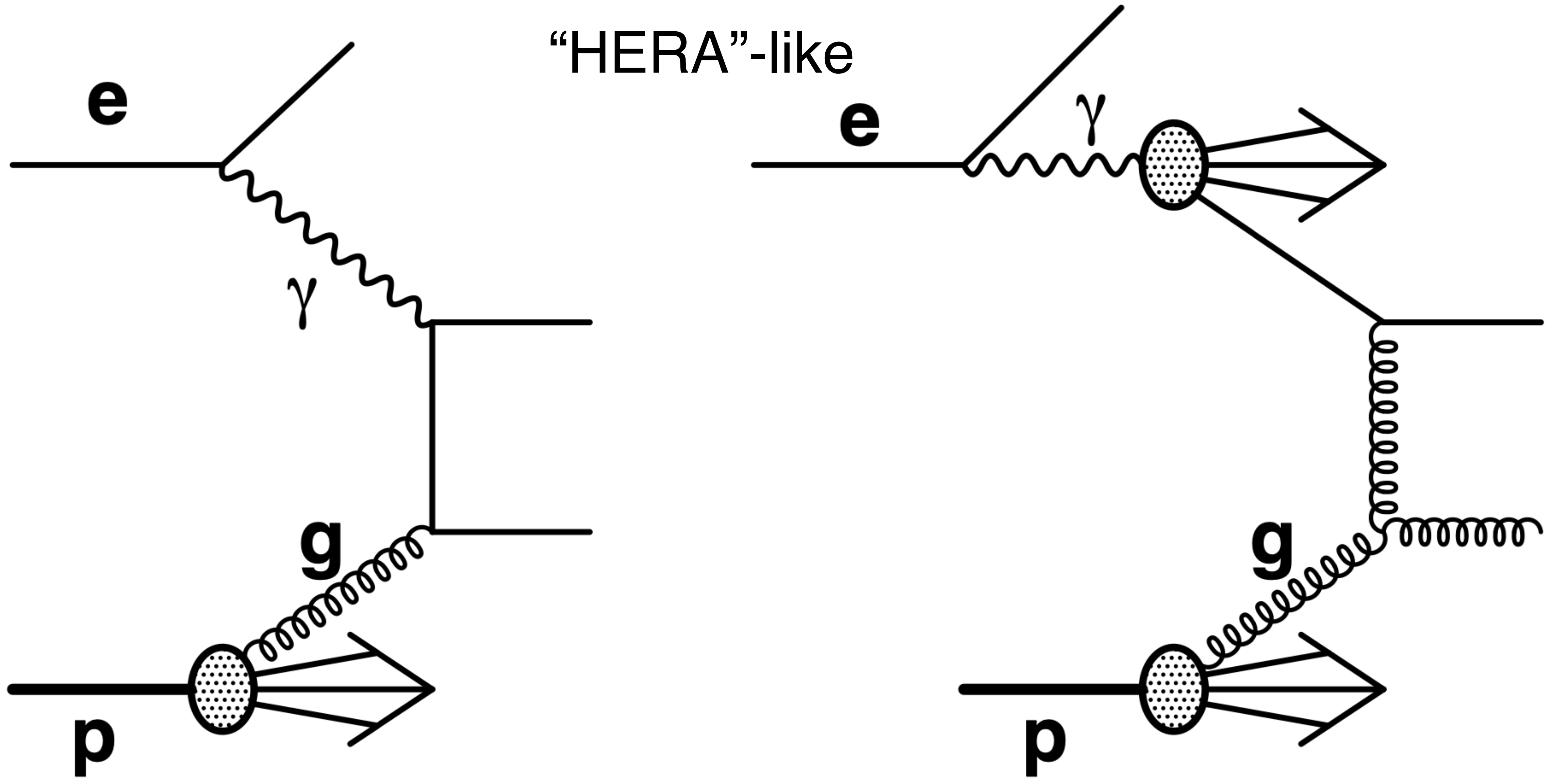


- **New constraints on proton nPDFs, GDF, TMD at the highest γp center of mass energies available**
- Baseline for γPb measurements (searches for beyond DGLAP evolution)

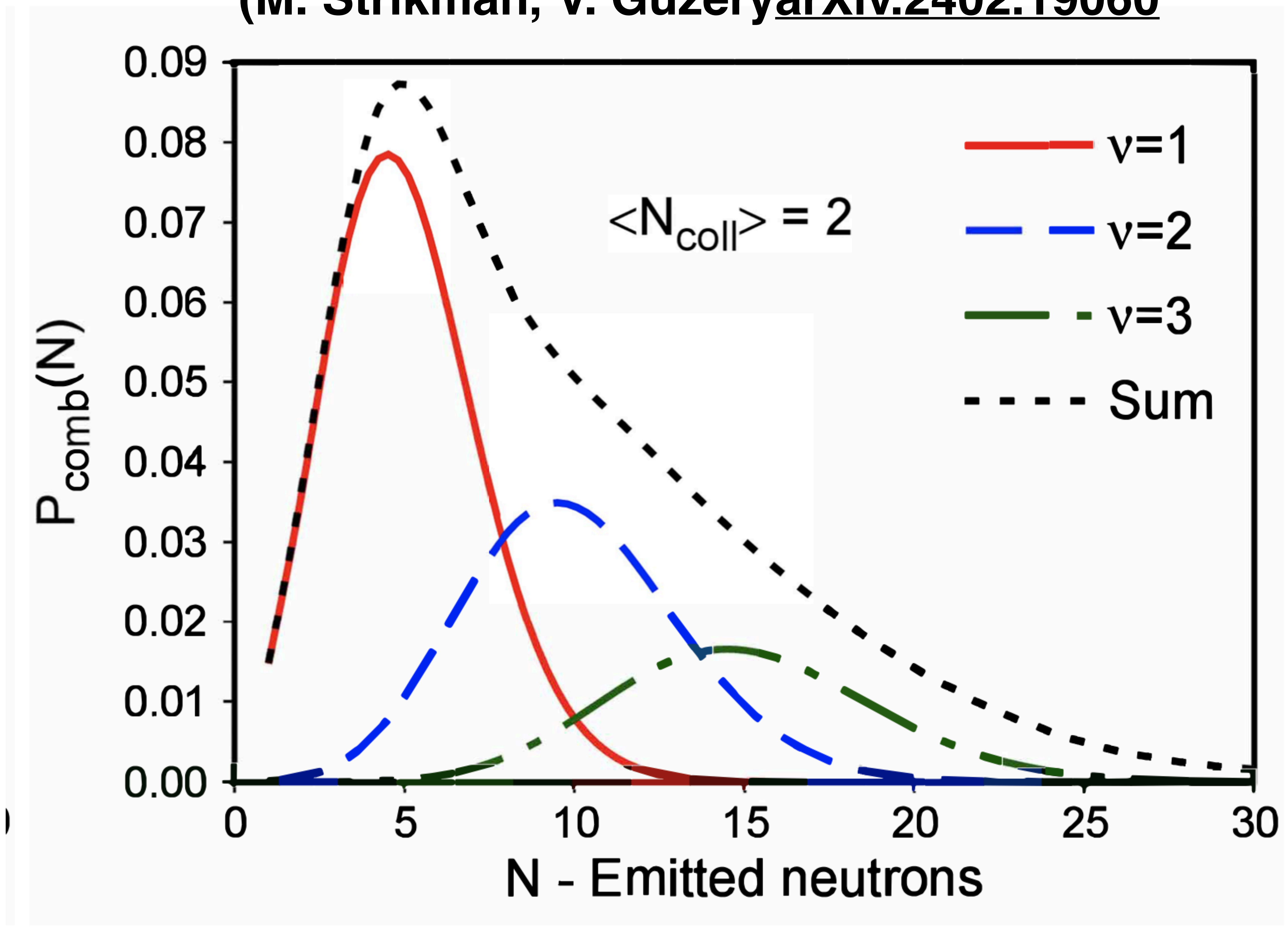


ZEUS, Eur.Phys.J.C23:615-631,2002
Dijet photoproduction at HERA and the structure of the photon

Jets and open heavy-quarks in photonuclear γp/γPb scatterings



See Mark Strikman's talk and paper(s)
(M. Strikman, V. Guzeryar Xiv.2402.19060

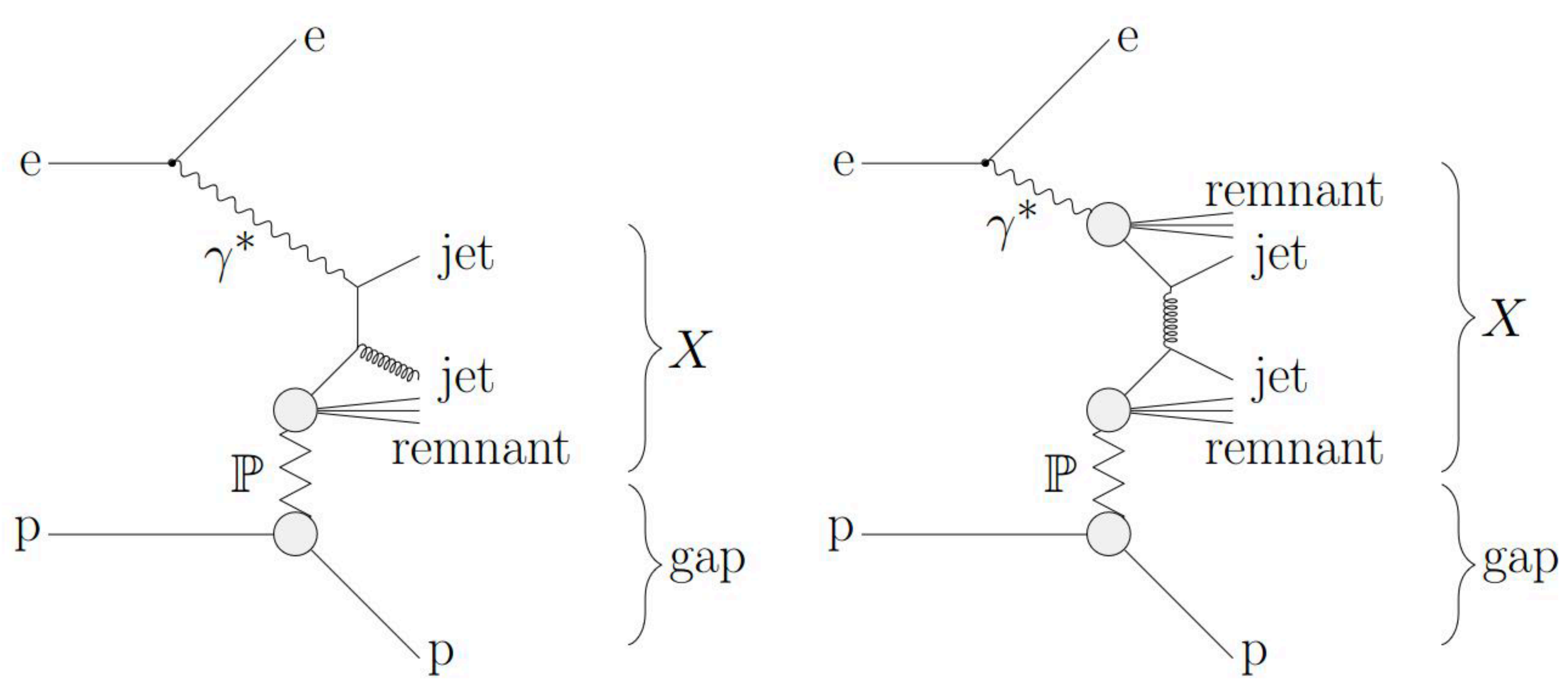


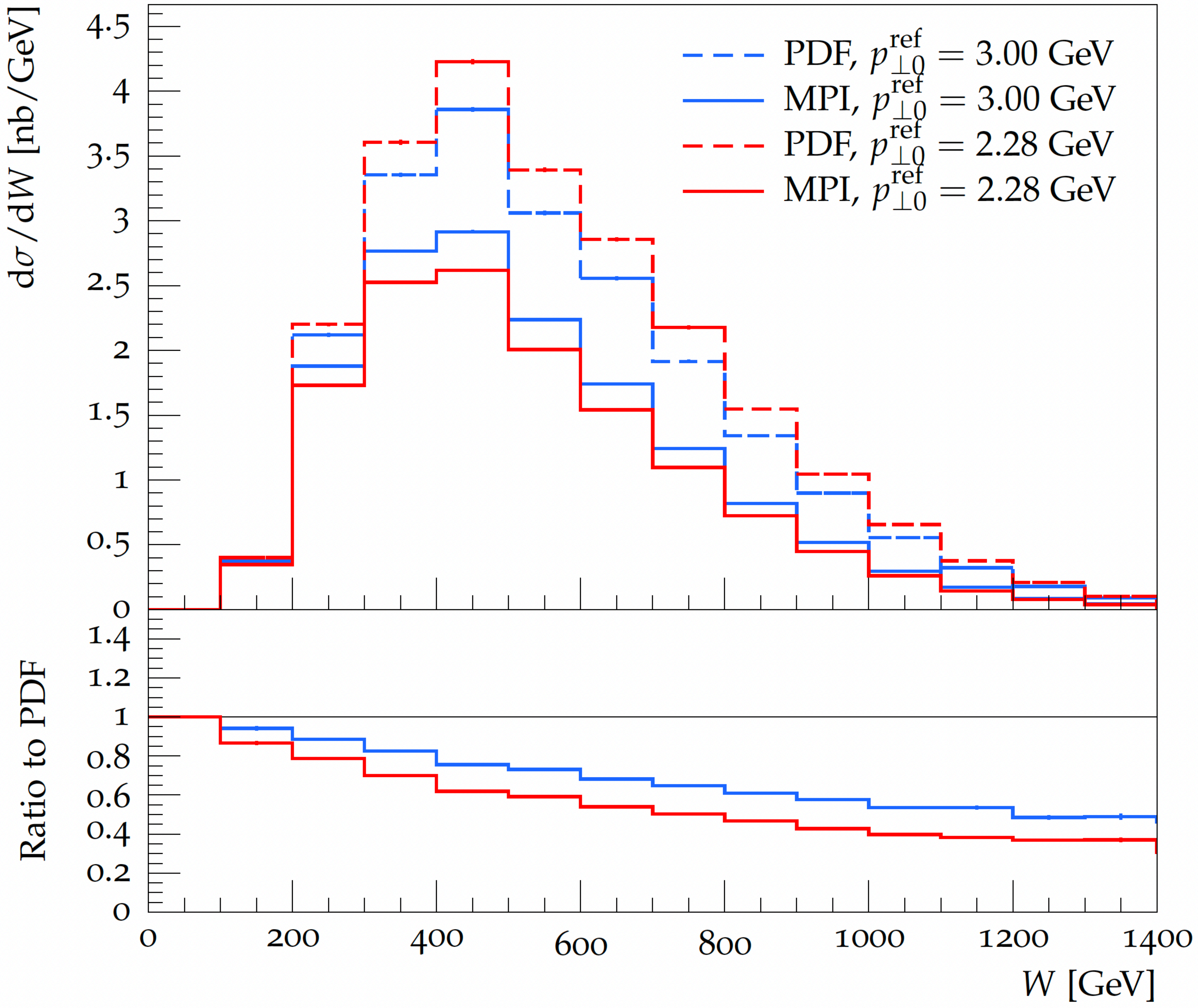
- **New constraints on proton nPDFs, GDF, TMD at the highest γp center of mass energies available**
- Baseline for γPb measurements (searches for beyond DGLAP evolution)

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

Diffractive production of jets and heavy quarks

Ilkka Helenius, arXiv:2107.07389
C. Marquet, C. Rayon et al. arXiv.1306.4901





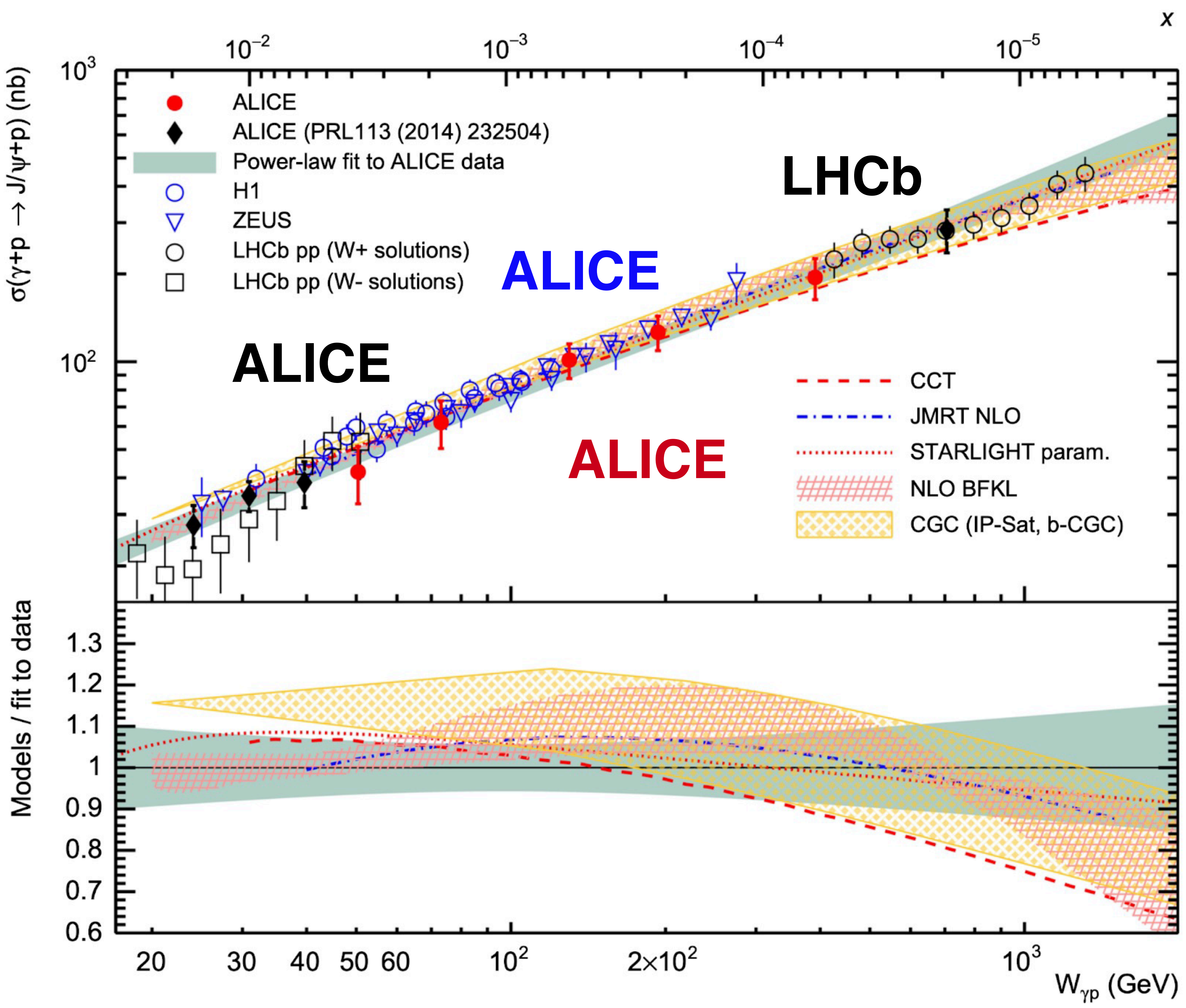
→ **test for fractorization**: **diffractive** PDFs ⊗ **partonic coefficient functions**

- **LHC vs HERA**
- **hadronic vs photoproduction**
- **direct vs resolved photoproduction ..**

→ **benchmark for PbPb measurements**

Exclusive and inclusive quarkonium photoproduction

γ+p→J/ψ p collisions:

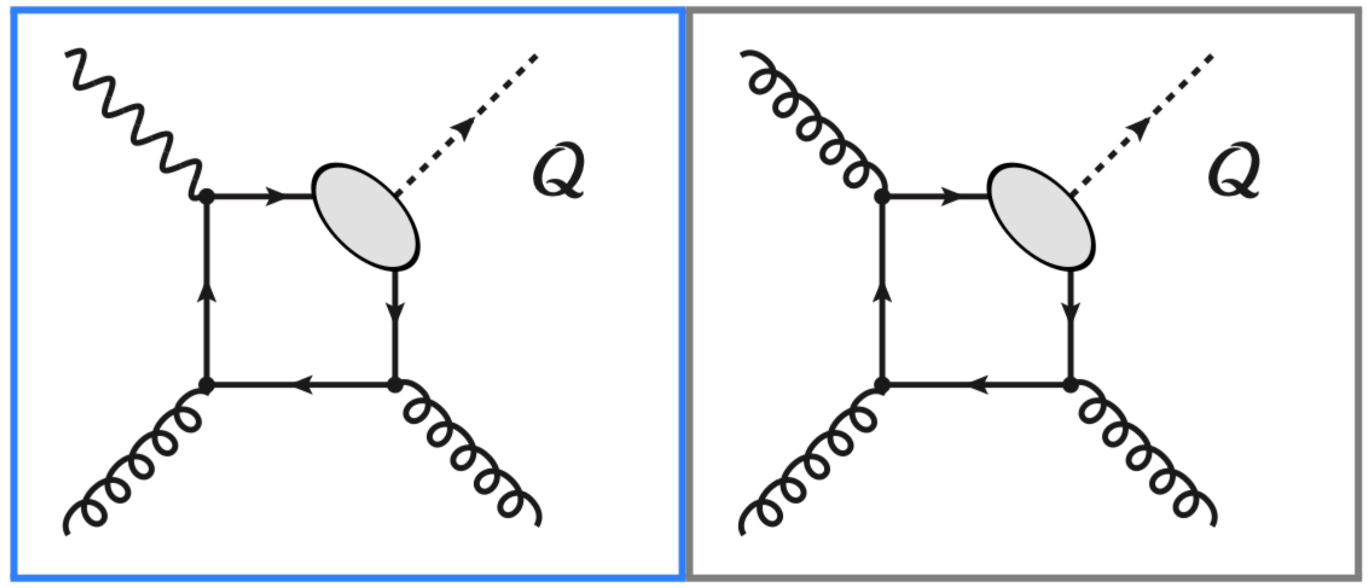


$$W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

Sensitive to the proton structure at high-gluon densities
(So far, no indication of gluon saturation, even down to $x \sim 10^{-5}$ in a free nucleon)

From Kate Lynch's talk Jean-Philippe Lansberg (IJCLab), Charlotte Van Hulse (UAH), Ronan McNulty (UCD)

- Anticipate sizeable photoproduction yield
- Large hadronic background must be shown to be suppressed



Proton-lead is the ideal collision system

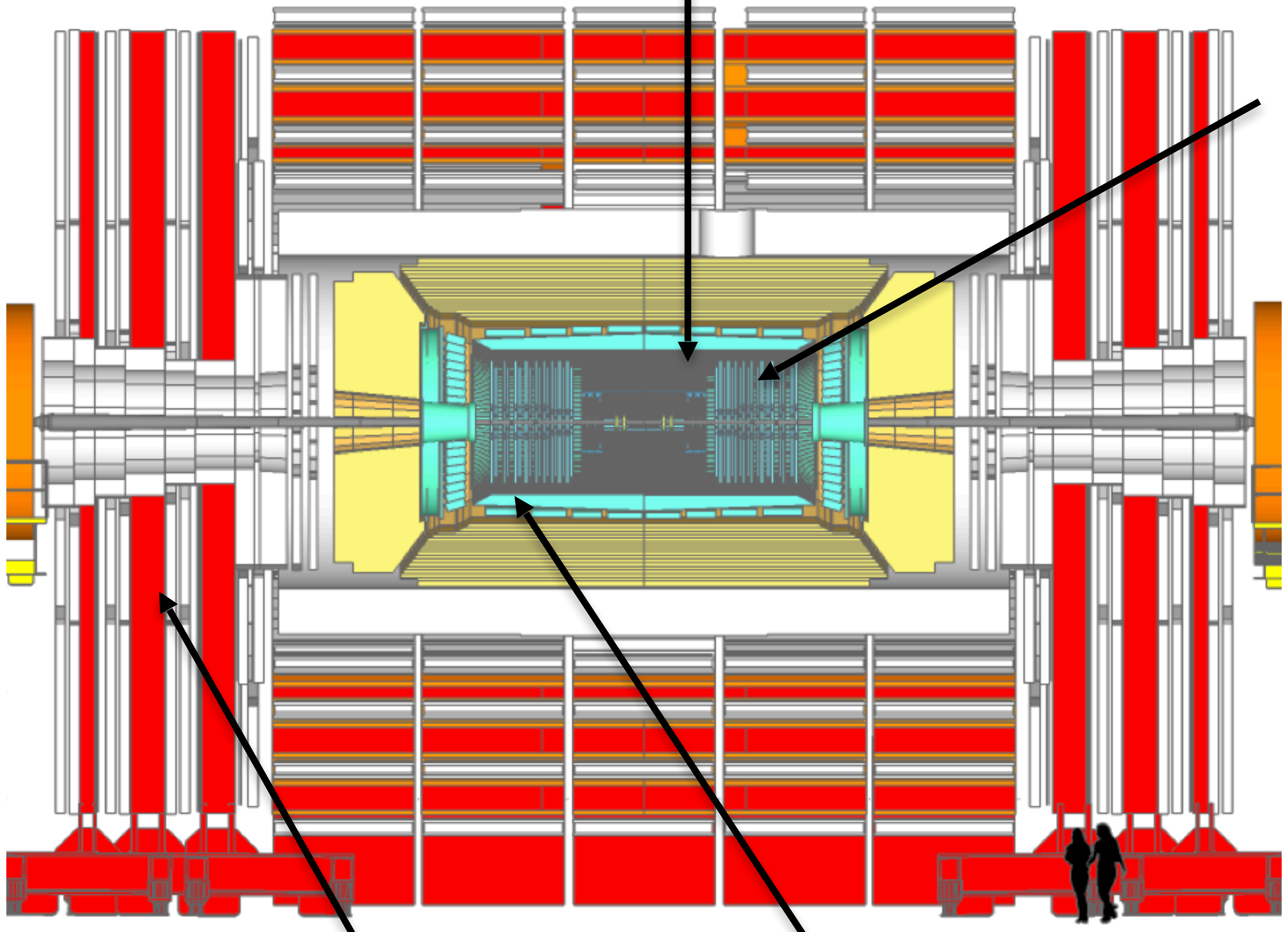
- No ambiguity as to the photon emitter
- Enhanced photon flux w.r.t. *pp* $\propto z^2$
- Less pileup than *pp*

The upgraded CMS detector for Run 4 (Phase II)

Trigger / HLT / DAQ
- L1/HLT rate x7.5
- DAQ: 6 → 60 GB/s
- **tracking capabilities at Level-1:**
  - sample the **entire cross section of photon-induced collisions** in both pPb and PbPb events

New endcap calorimeters (HGCal)
Unprecedented granularity $|\eta| < 3$

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



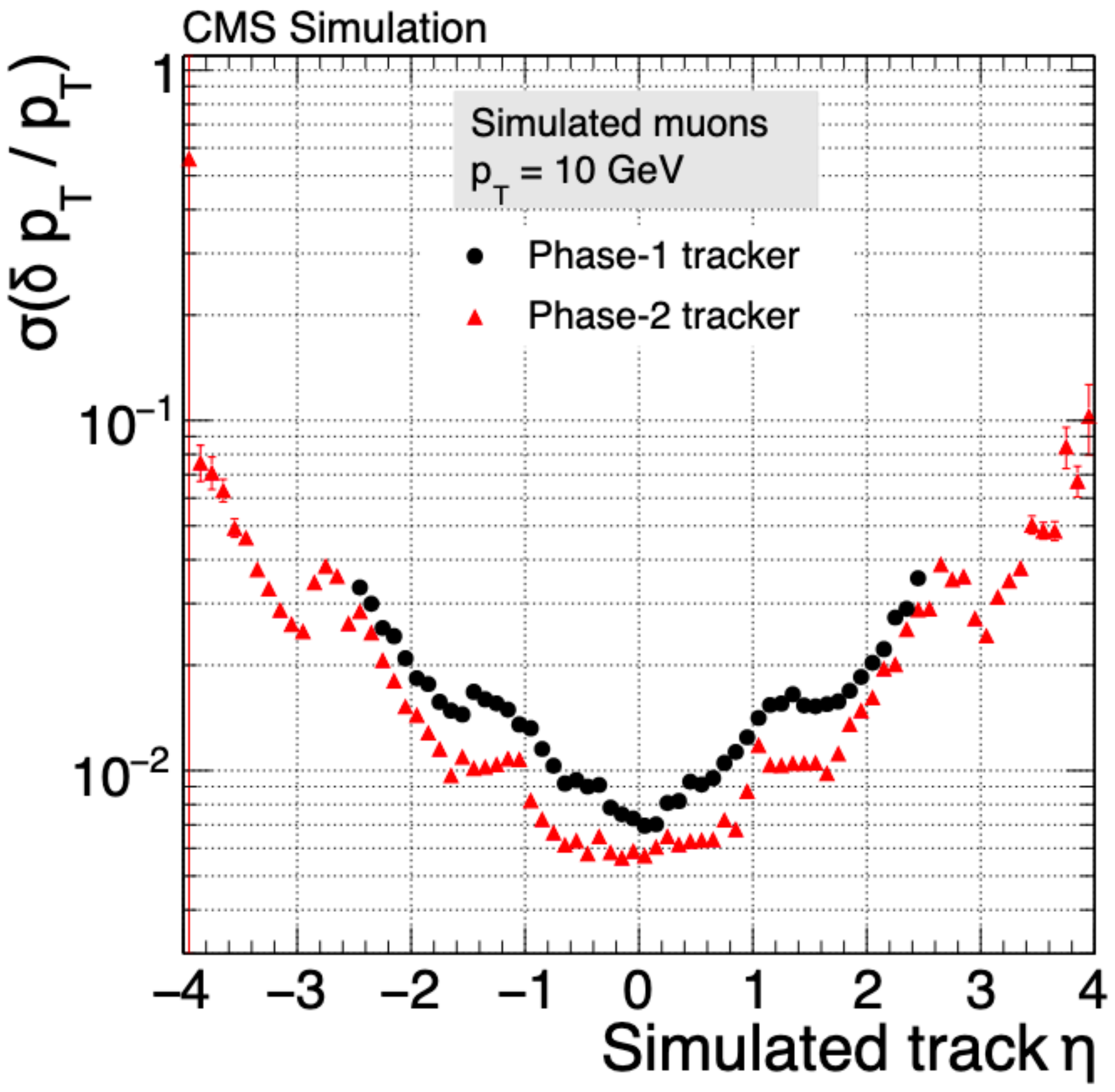
Radiation-hard ZDC + PPS upgrades
ξ down to ~ 1.5%

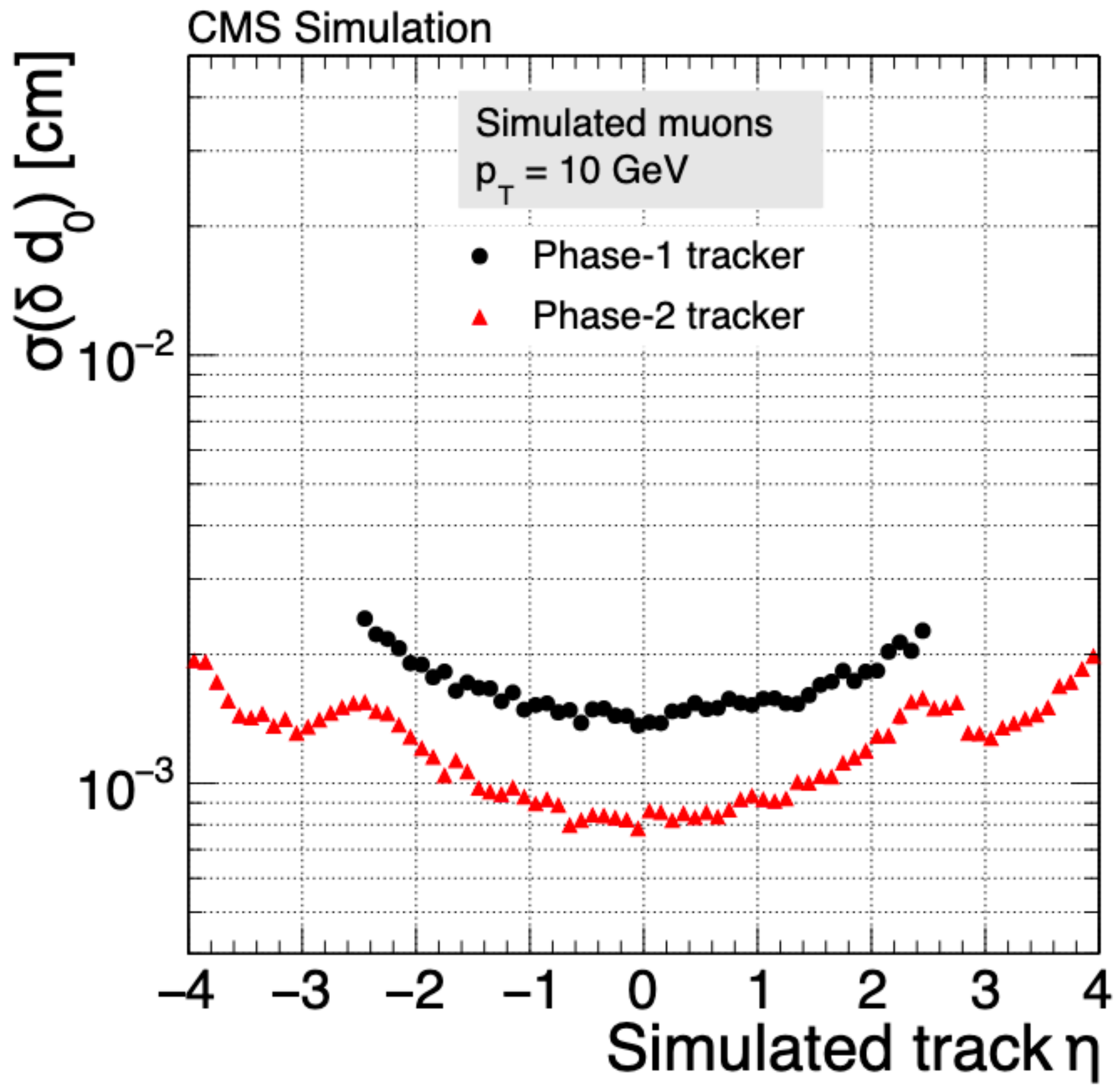
Extended muon coverage
$|\eta| < 2.4$ → $|\eta| < 2.8$

New MIP Timing Detector (MTD)
Precision timing $|\eta| < 3$
Particle Identification!

High-resolution, large acceptance silicon tracker ($|\eta| < 4$)

from 100 x 150 to 50 x 50 μm^2 pixel size
Tracking out to $|\eta| < 4$!!
Reduced material budget by up to 2x





Improved p_T resolution by about 25%
- Improved mass resolution for resonances

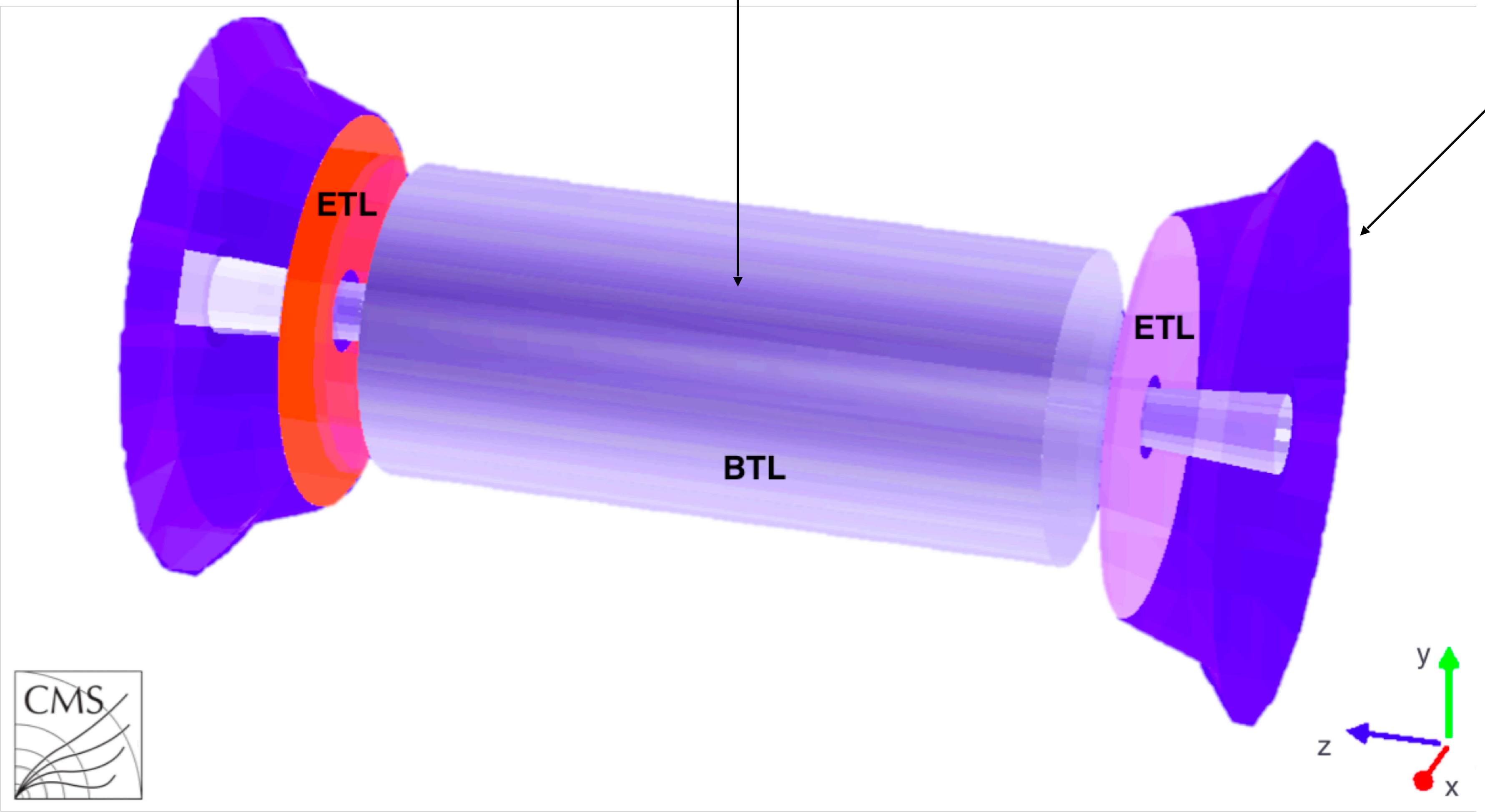
Impact parameter resolution improved by 40%
- Improved heavy flavor measurements (B/D hadrons & b/c-jet tagging)

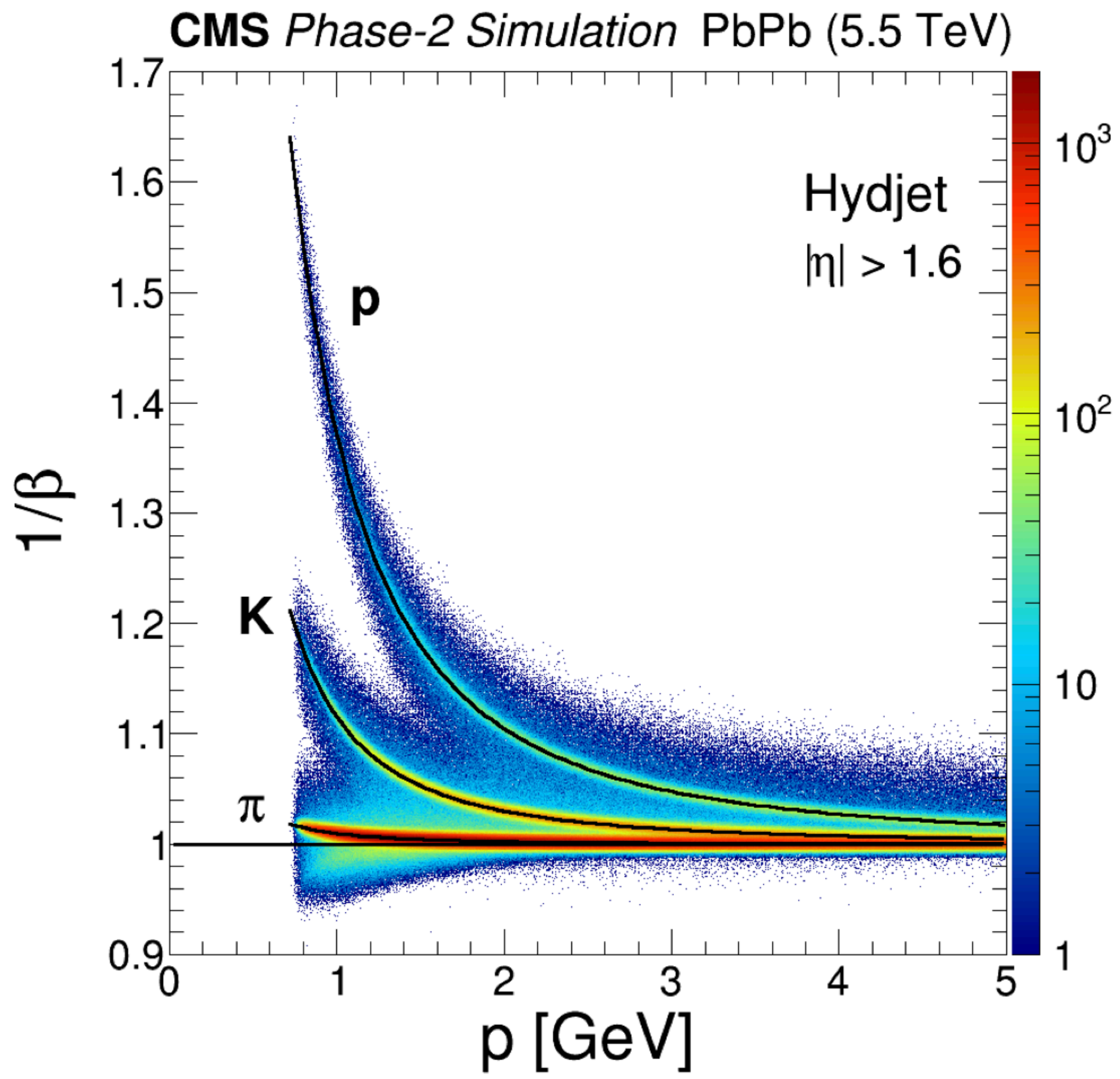
CMS, CMS-TDR-014

MIP timing detector (MTD)

Barrel Timing Layer (BTL)
- Coverage: |η| < 1.45 , p_T > 0.7 GeV
- Timing resolution: ~ 30 ps
- Tech: Scintillator + Si photo-multiplier

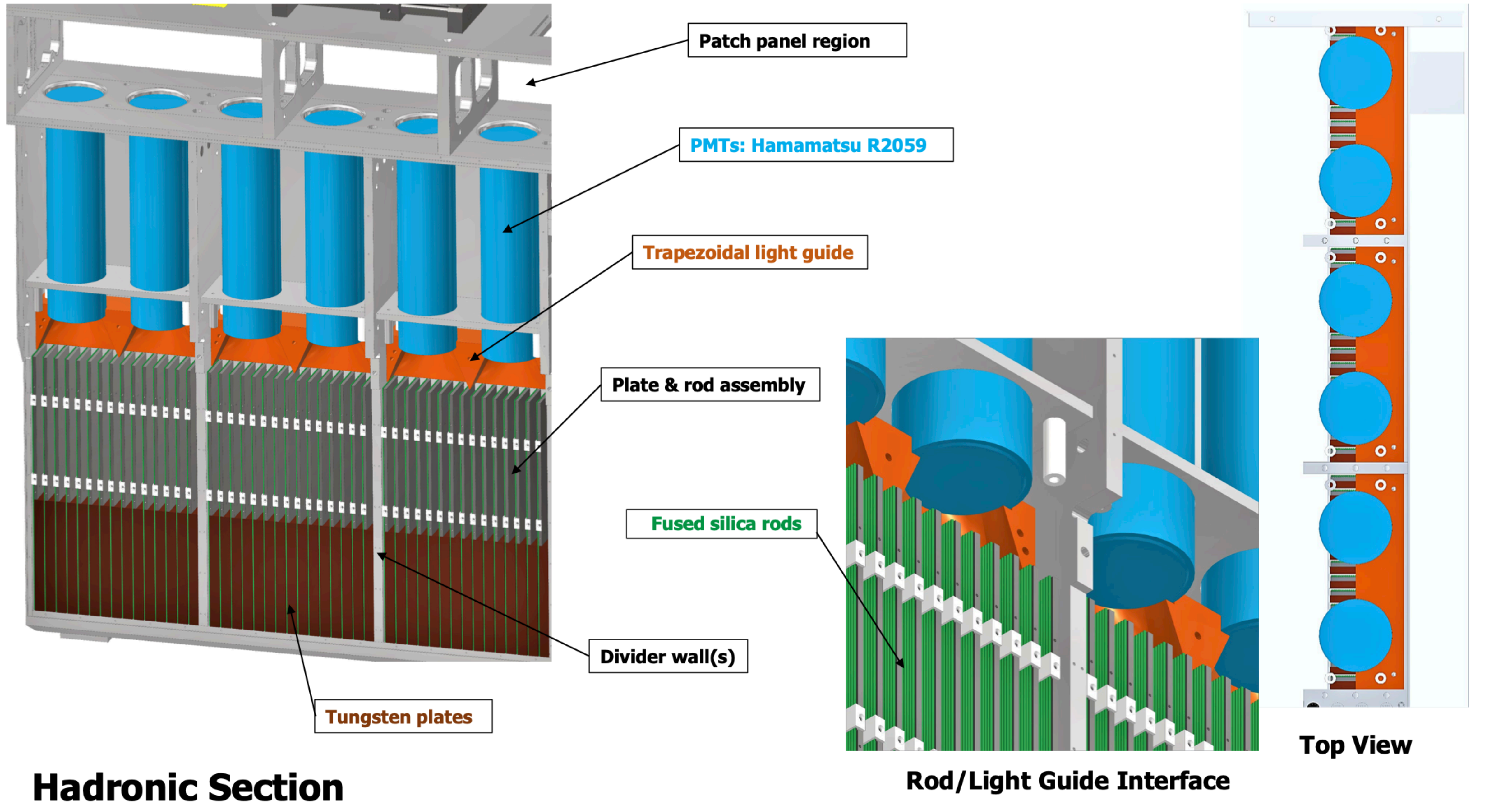
Endcap timing layer (ETL)
- Coverage: 1.6 < |η| < 3.0 , p > 0.7 GeV
- Timing resolution: ~ 30 – 40 ps
- Tech: Silicon w/ internal gain (LGAD)



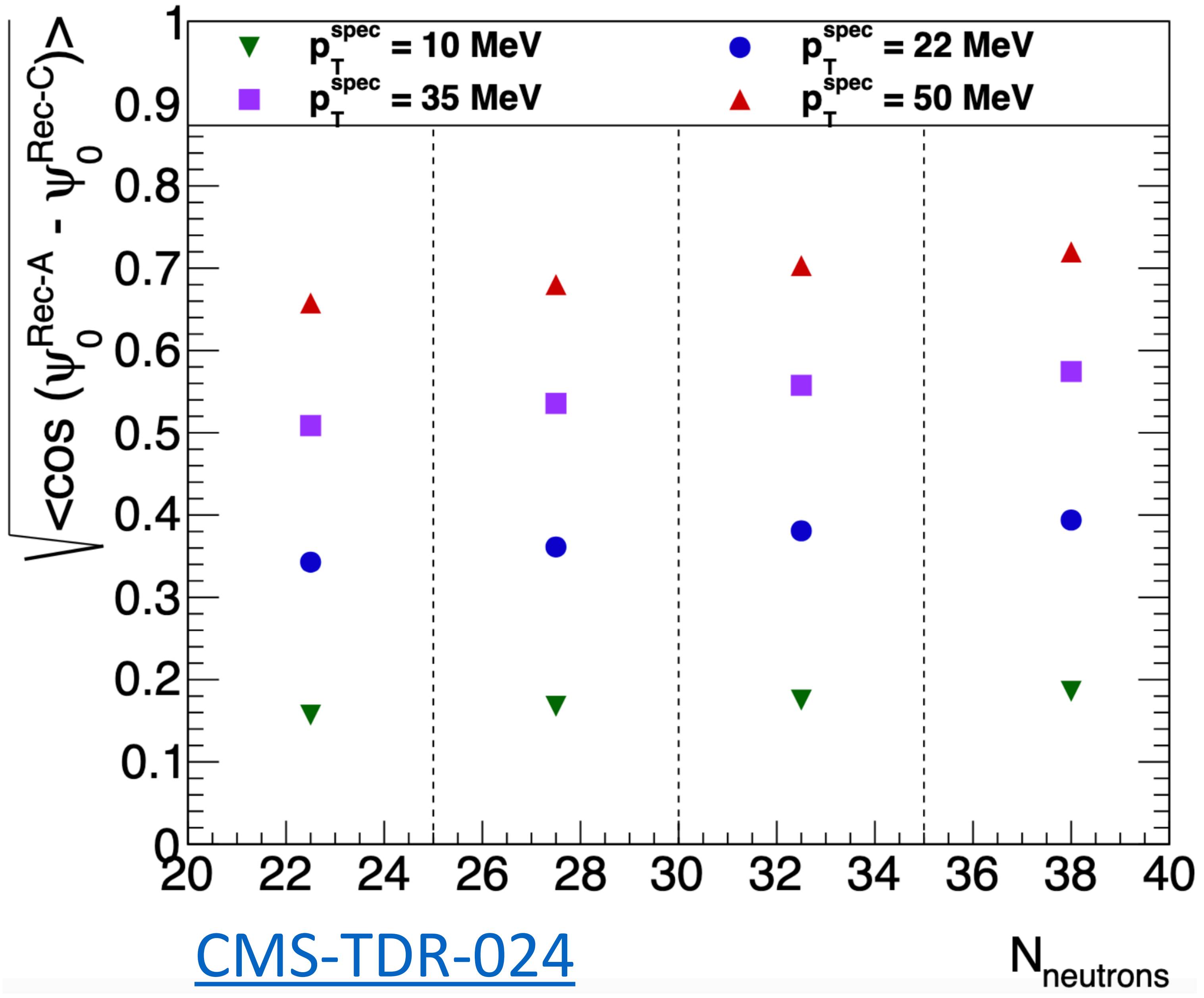


Unlock a wide set of semi-inclusive "DIS-like" measurements with identified hadrons with CMS

A new ZDC CMS detector



- **Joint ATLAS & CMS effort: radiation-hard ZDCs for Run 4**
- Crucial part of heavy-ion min. bias trigger from Run 3 onwards
  - Used to identify & characterize ultra-peripheral collisions
  - Bias estimation for centrality, especially in small systems
  - Exclusively HI detector (removed for high-lumi pp)

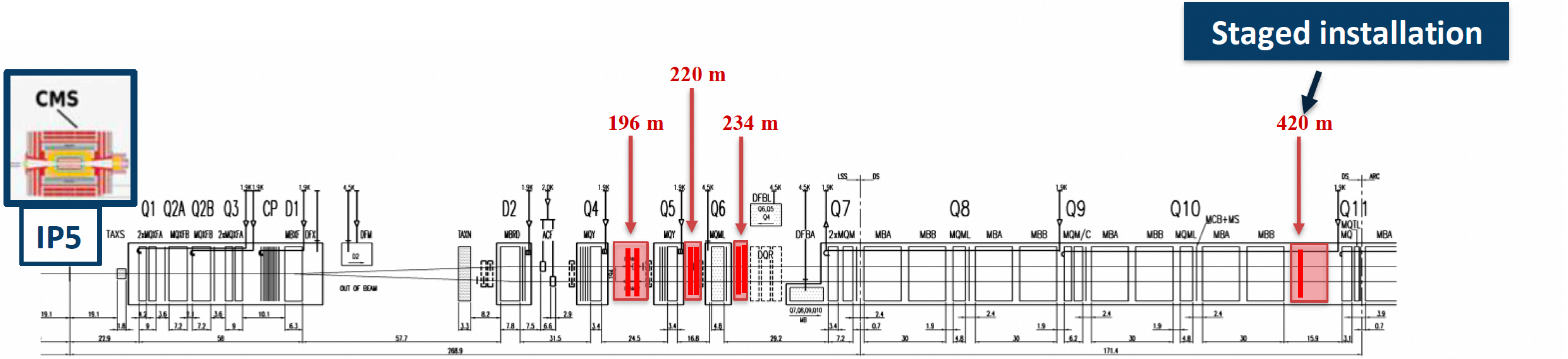


[CMS-TDR-024](CMS-TDR-024)

Upgraded Precision Proton Spectrometer (Run 4 and 5)

See Michael Pitt's talk

Basic working principle:
Protons which lose a fraction of momentum at the interaction point ($\xi = \Delta p/p$) are deflected away from the beam and measured by PPS
→ **direct measure of the $\xi = \Delta p/p$**

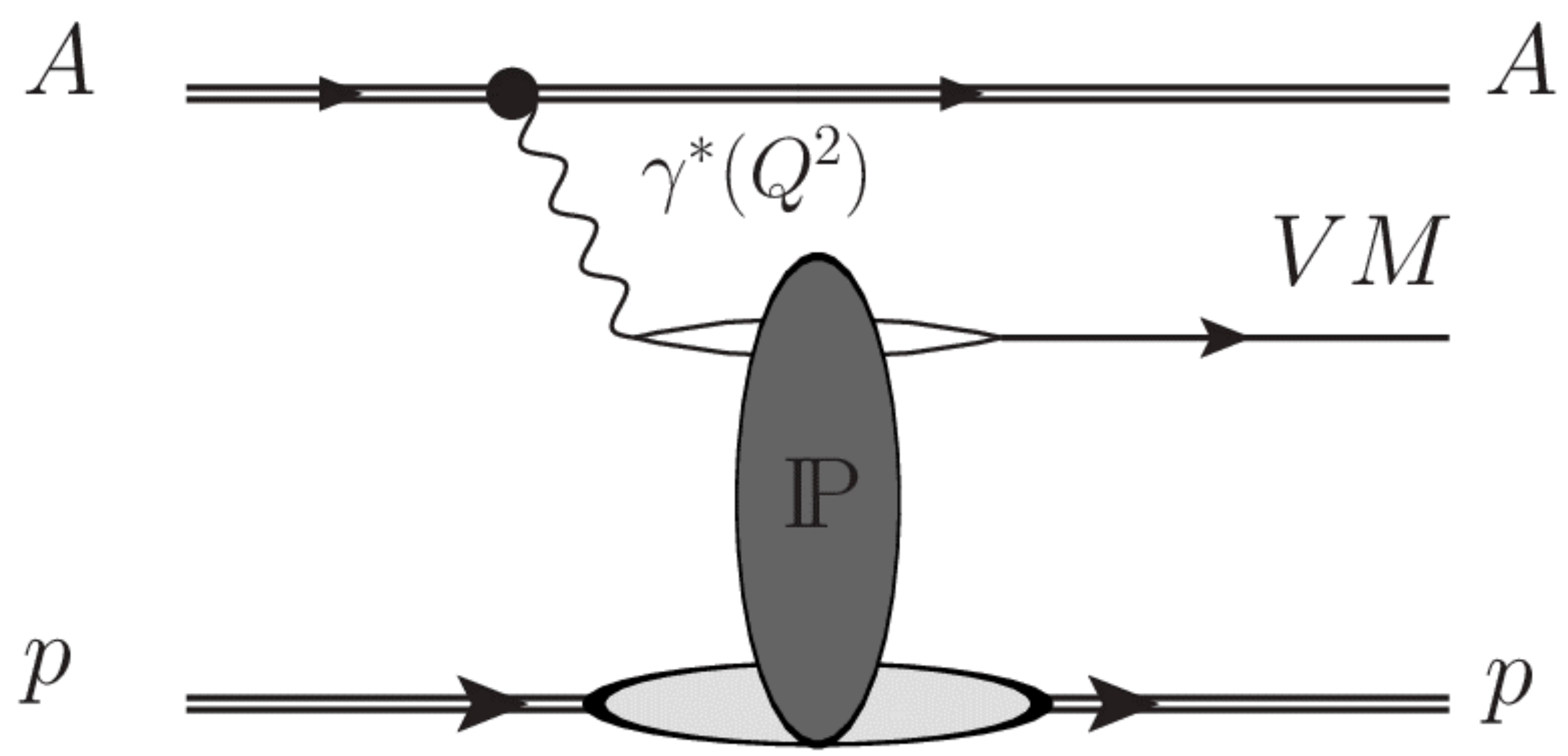


PPS upgrade will further extend the ξ acceptance of the legacy PPS:

- $1.42 < \xi < 20$ % for the first 3 stations (from Run 4)
- $0.33 < \xi < 20$ % for the first 3 stations (from Run 5)

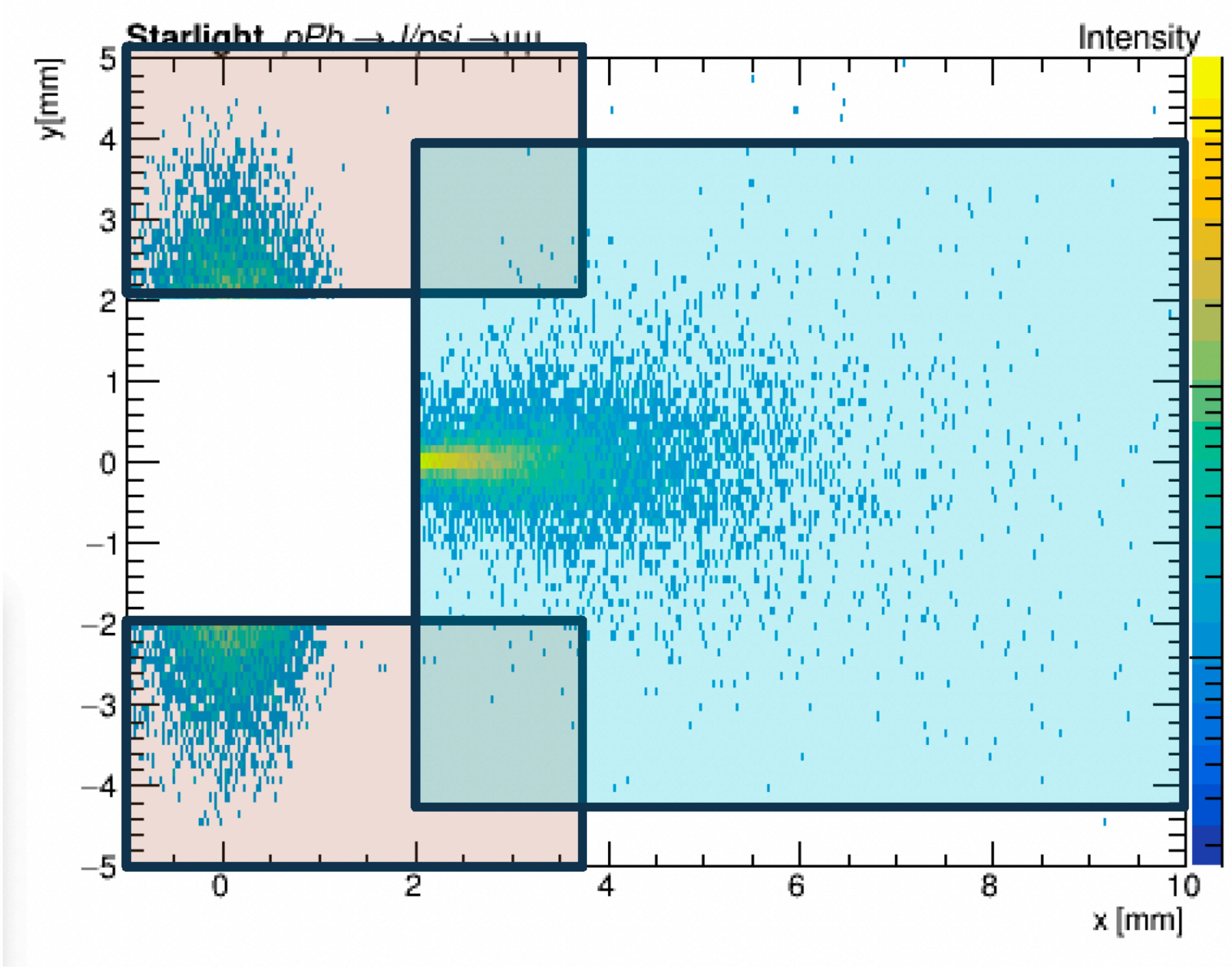
CMS NOTE -2020/008

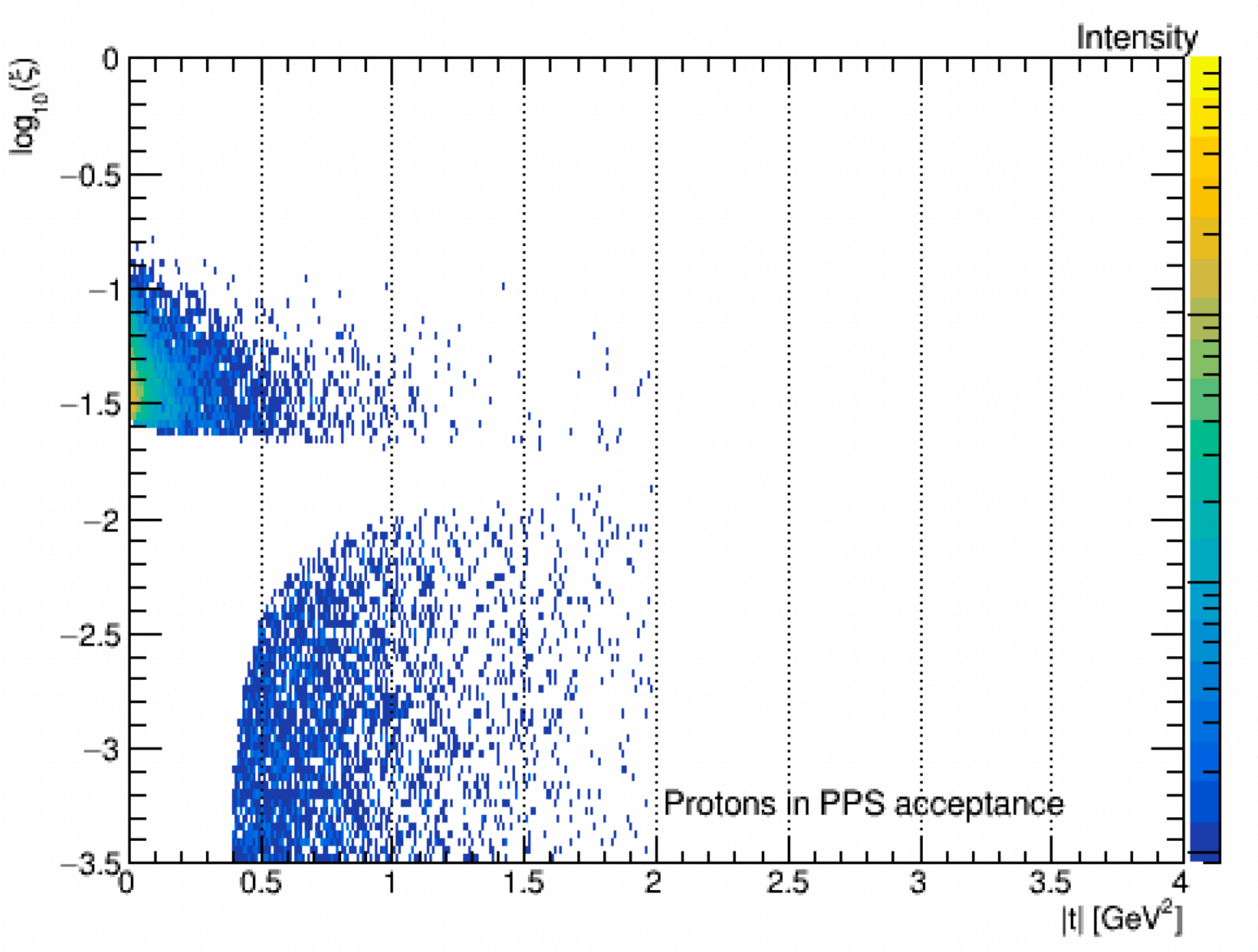
Highlight: exclusive vector-meson production in pA

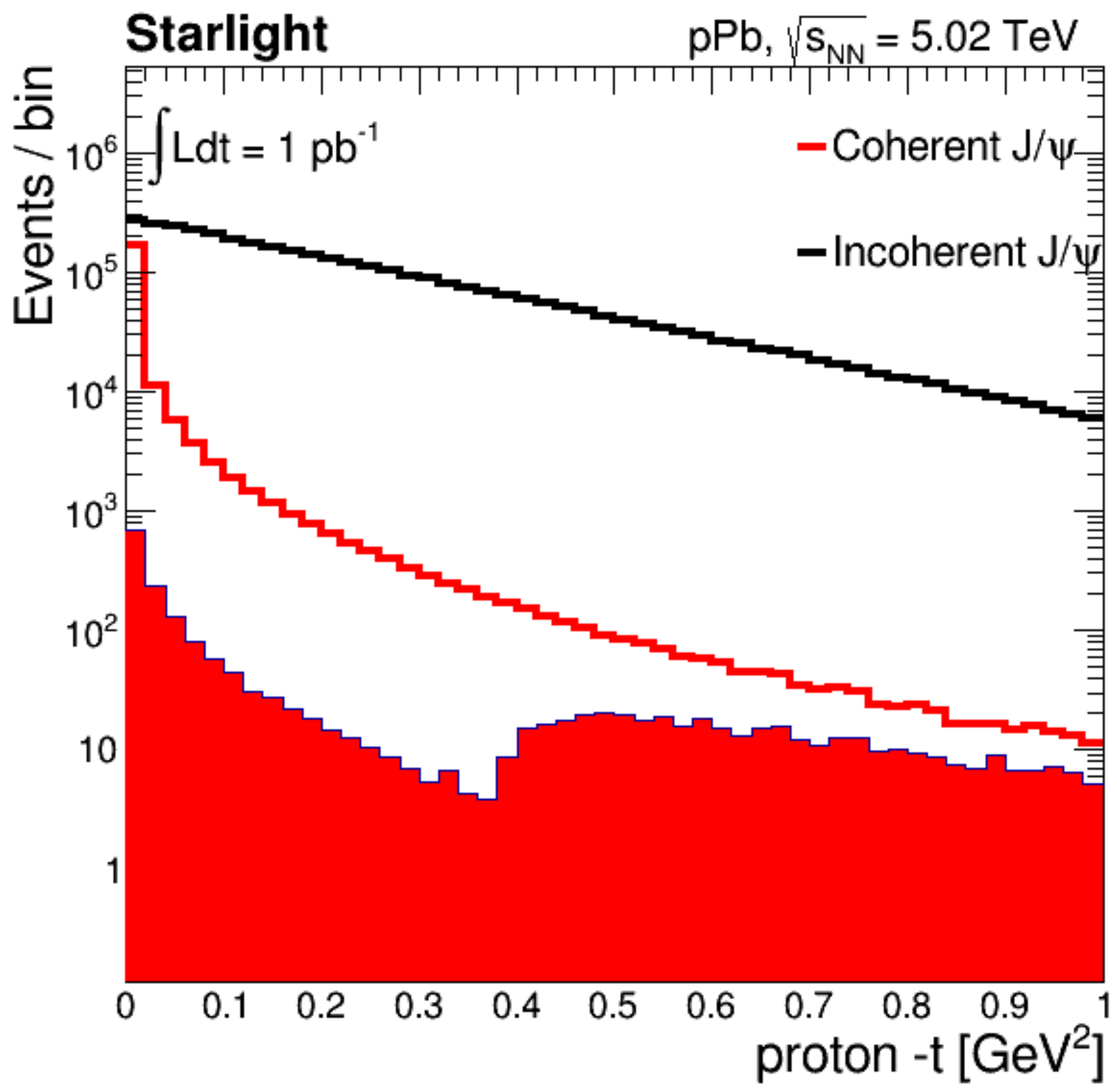


- Vector mesons (Spin 1) are produced in $\gamma - IP$ interactions
- Ions emit a photon at Q^2~0
- **In coherent production proton remain intact:**

→ PPS would provide high-accuracy tagging of coherent processes
→ Similar technique applicable to exclusive dijet production

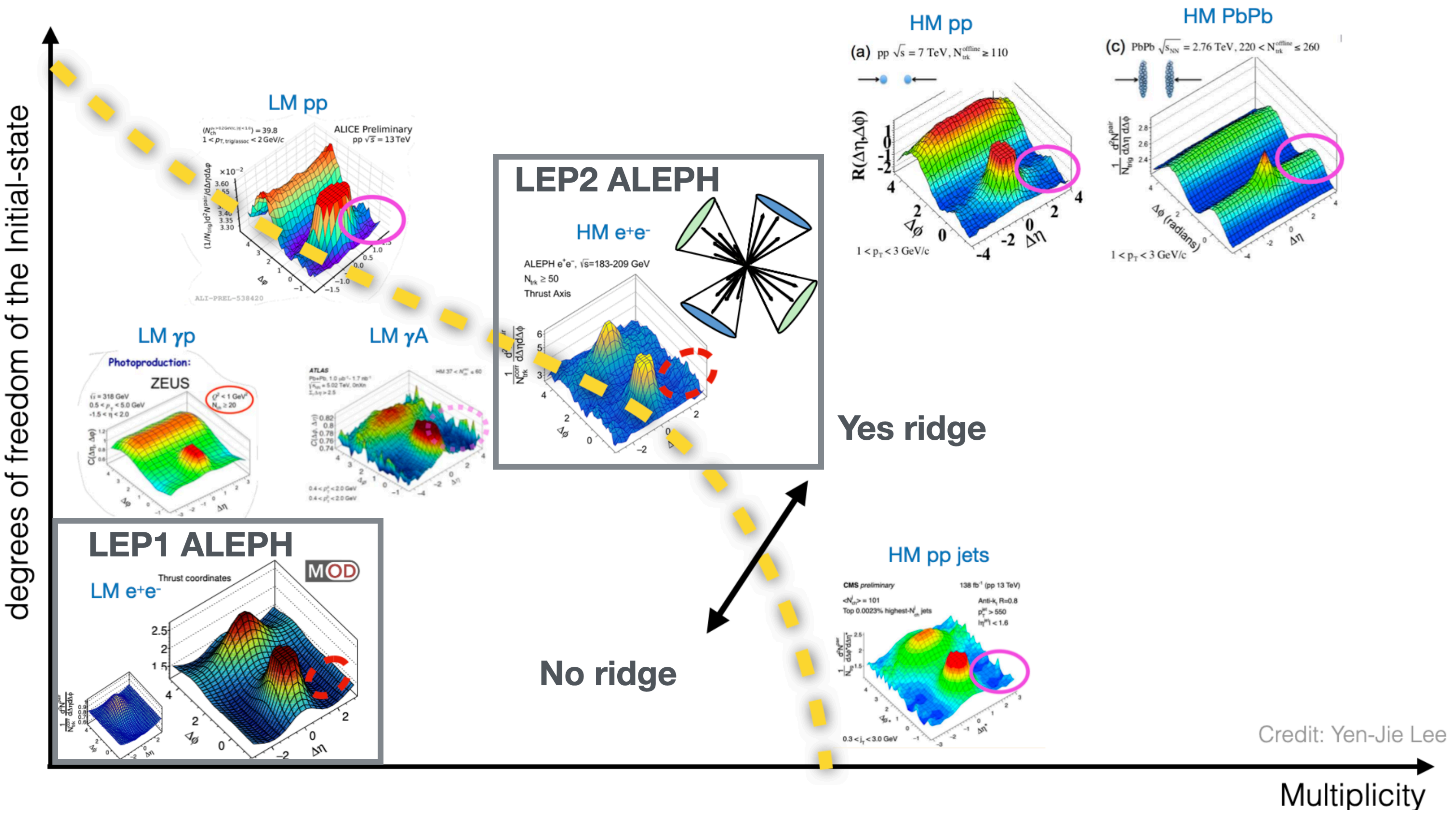






→ Proof of principle for proton (and ion) tagging with the upcoming pO/OO run (scheduled for 2025)

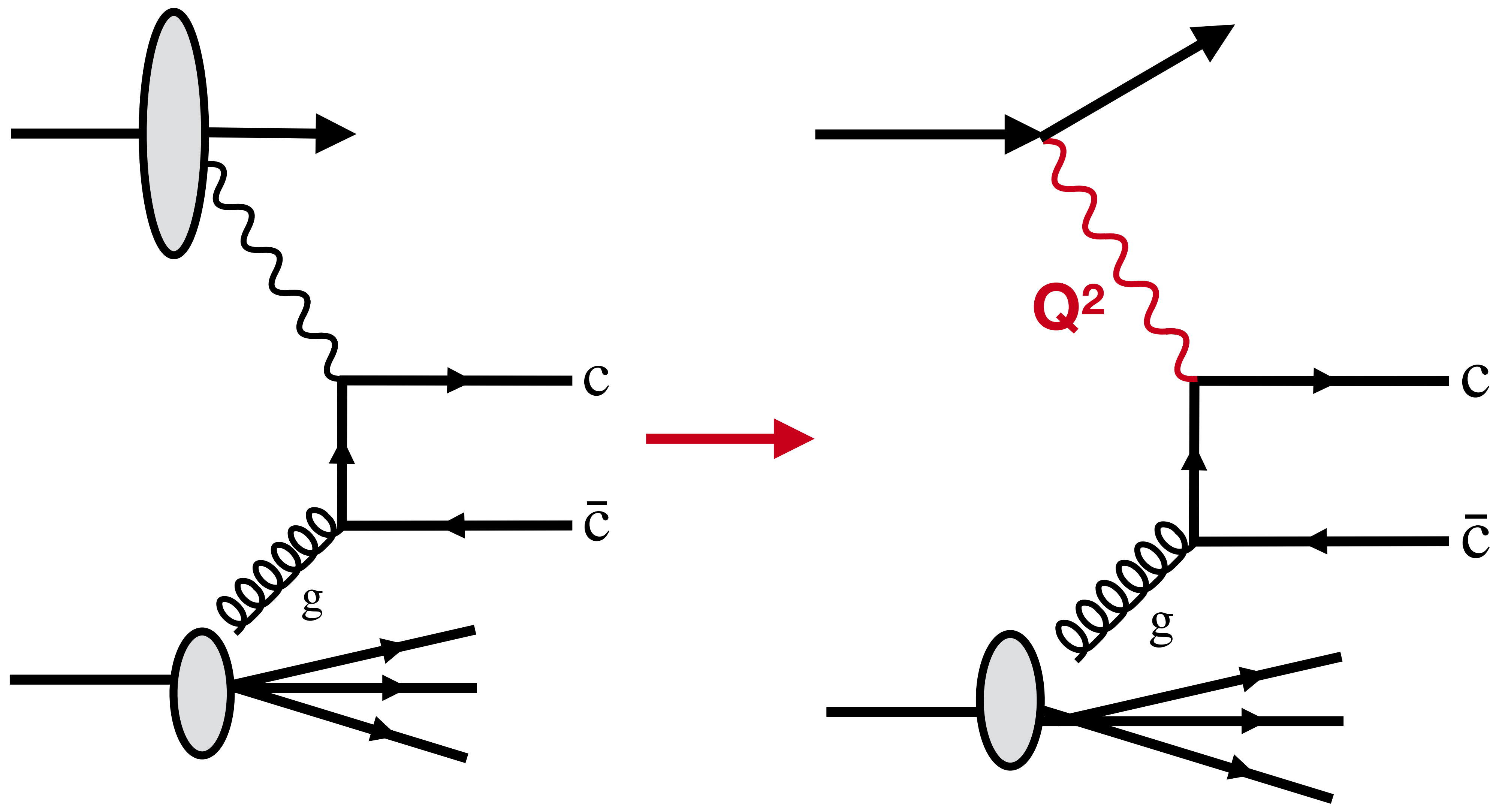
Characterizing the emergence of collective phenomenon



New insights into collective phenomena in “small” systems as well as high color-density hadronization:

- push for the highest γp multiplicities, exploiting the extended pseudorapidity coverage and PID capabilities

Synergies with the physics program at the Electron–Ion Collider



UPC at the LHC
→ very low x reach

EIC → **control on the photon virtuality (Q^2) and on the scale of the interaction**

We think is essential to have a strong pA and AA program at the LHC also in Run 5/6 to while EIC will be taking data!

2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038

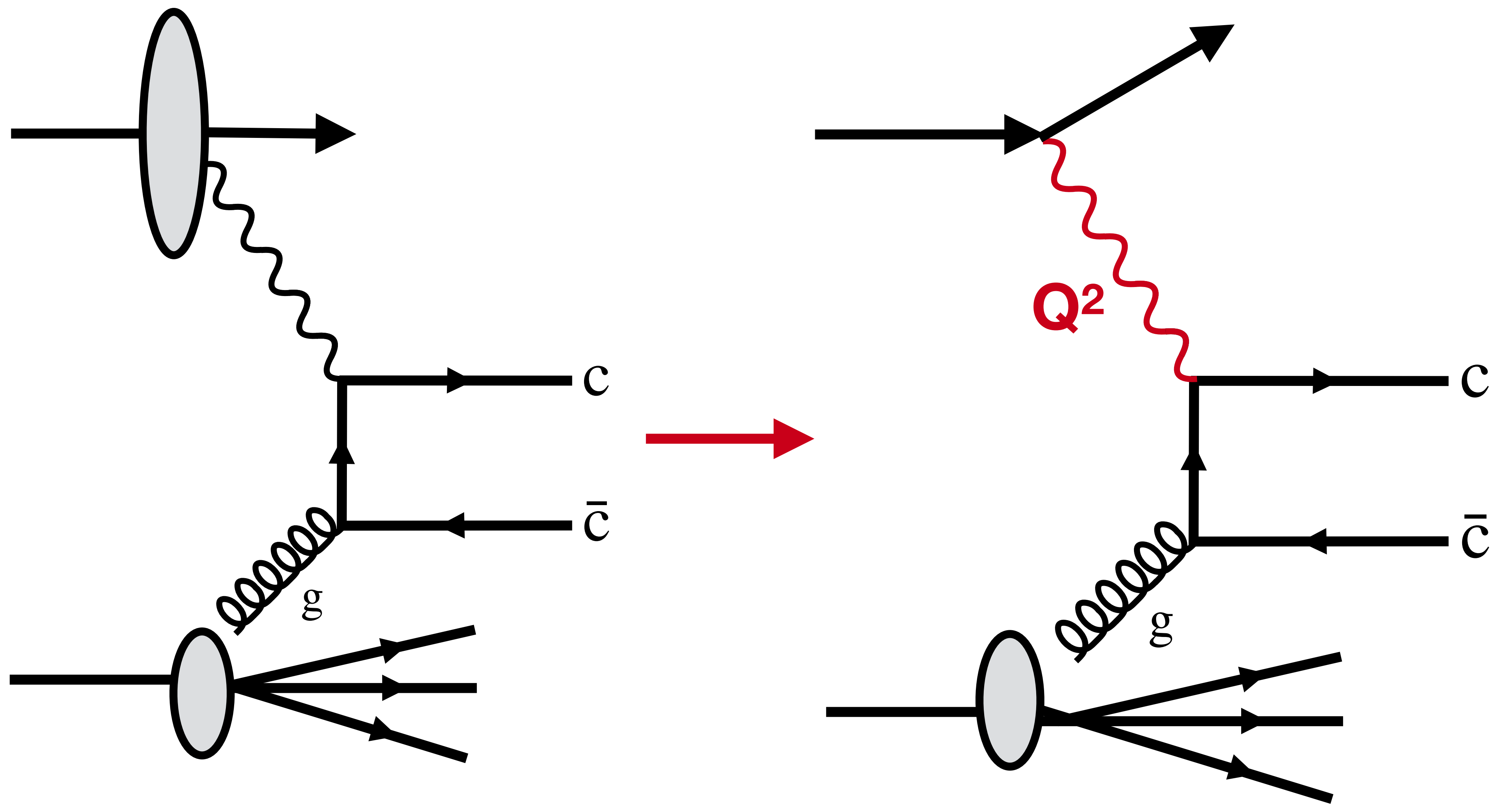
CMS at the LHC

Upgraded CMS at the LHC (|η| up to 4 + PID with MTD)

Run 5 and 6 at the LHC

EIC physics data-taking

Synergies with the physics program at the Electron–Ion Collider



UPC at the LHC
→ very low x reach

EIC → control on the photon virtuality (Q^2) and on the scale of the interaction

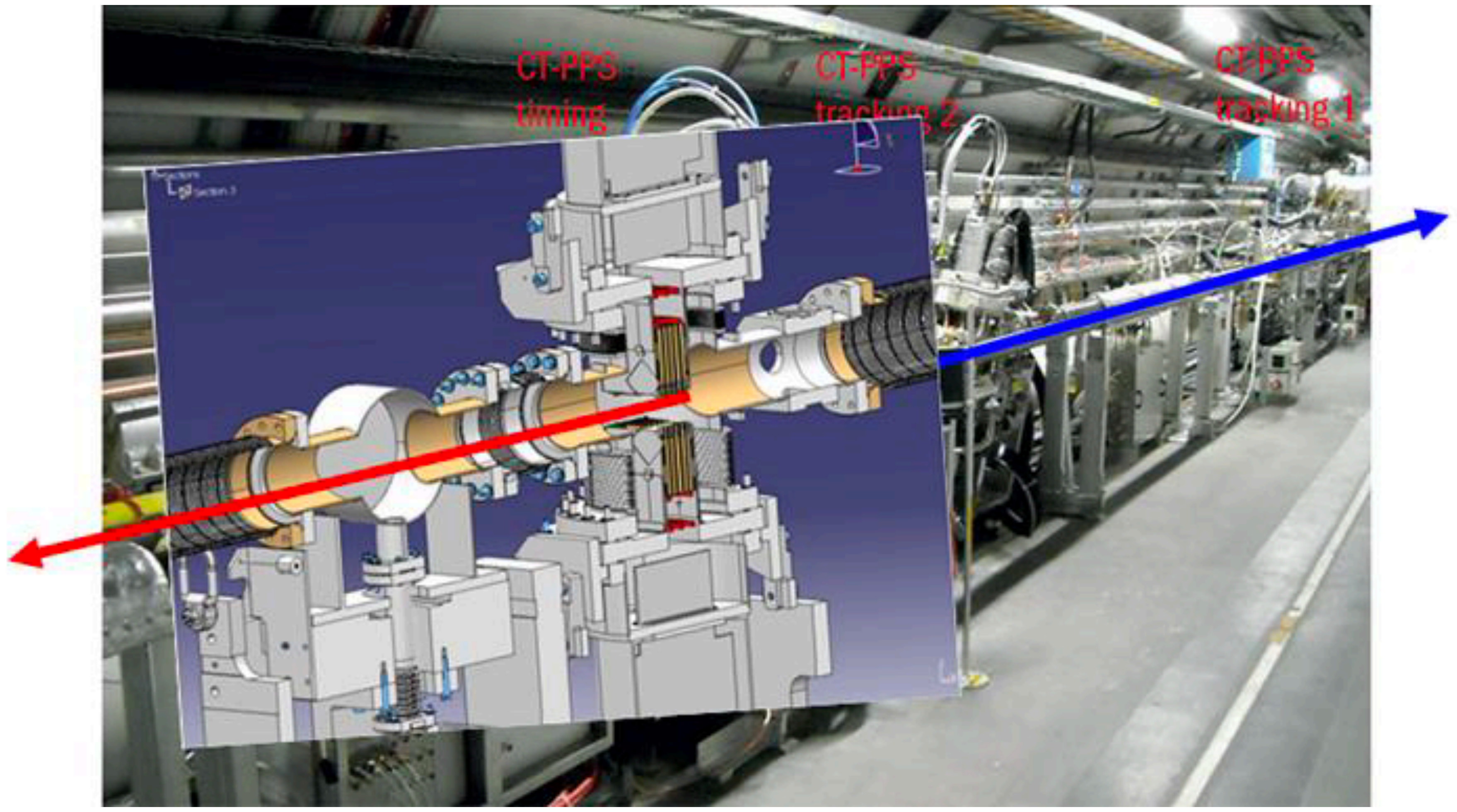
We think is essential to have a strong pA and AA program at the LHC also in Run 5/6 to while EIC will be taking data!

Thank you for your attention!

BACKUP

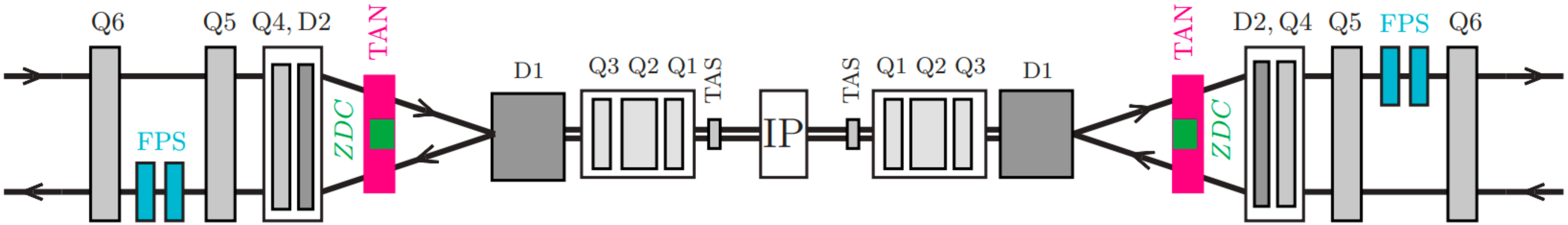
CMS Precision Proton Spectrometer (Run 2 and 3)

Since 2016 operated in standard *pp* runs, PPS TDR (TOTEM-TDR-003)
• Located ~ 200m from the interaction point in both arms, approach the beam down to a few mm



Basic working principle:
Protons which lose a fraction of momentum at the interaction point ($\xi = \Delta p/p$) are deflected away from the beam and measured by PPS

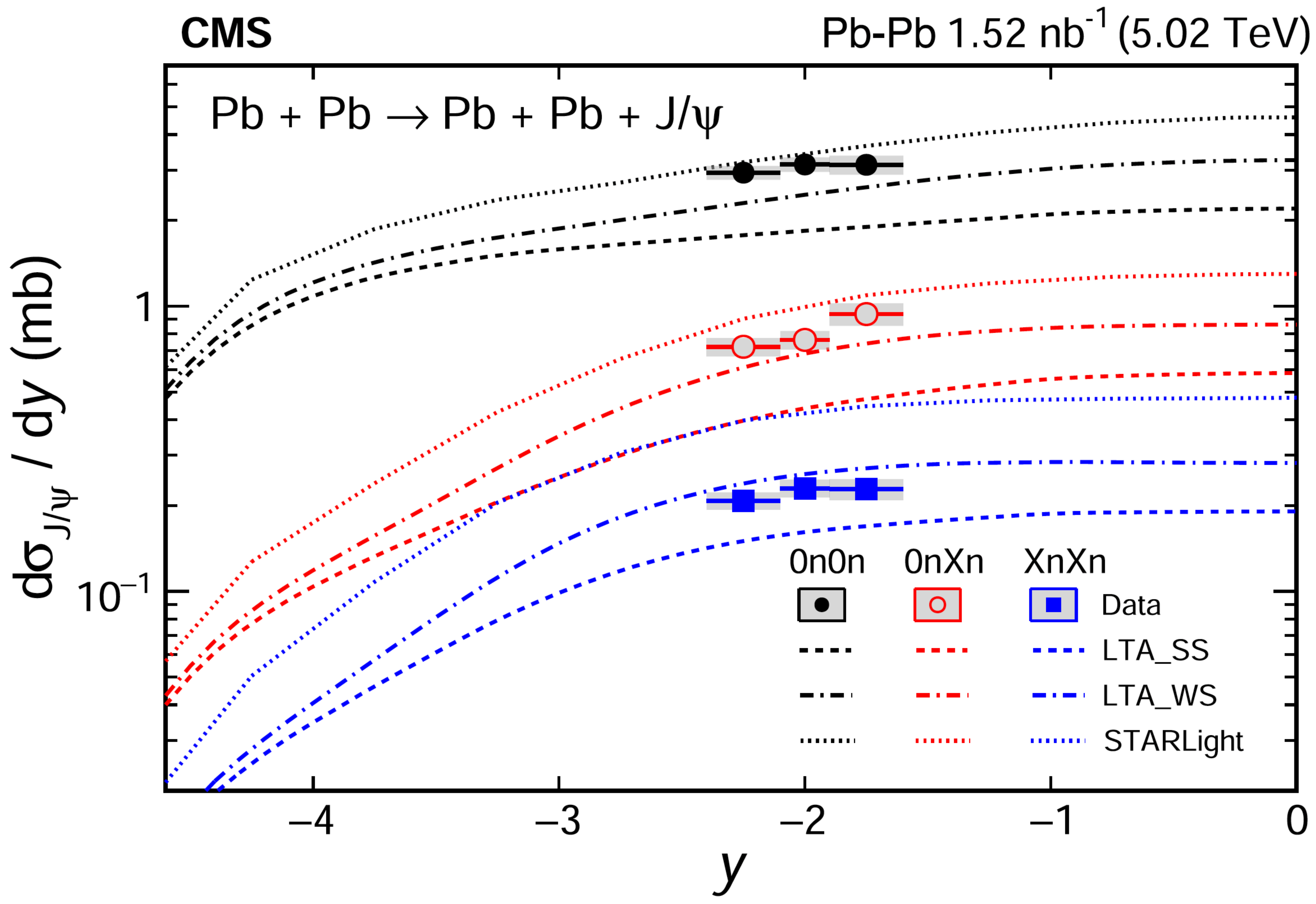
In Run 2 and 3: PPS sensitive to proton's Δp/p in the range 3 - 15 %



Coherent J/ψ in PbPb UPCs with forward-neutron tag with CMS

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

First coherent measurement in different neutron classes → ***inputs to disentangle low from high energy γN events***



$$\frac{d\sigma^{in\,jn}_{J/\psi}(y)}{dy} = n^{in\,jn}_{\gamma A}(\omega_1)\,\sigma_{J/\psi}(\omega_1) + n^{in\,jn}_{\gamma A}(\omega_2)\,\sigma_{J/\psi}(\omega_2)$$

- in jn = (0n0n, 0nXn, XnXn)
- $\omega_{1,2} = \omega_{1,2}(y)$ two possible photon energies
- $n_{\gamma A}(\omega)$ is the photon flux (from theory)
- $\sigma_{J/\psi}(\omega)$ the coherent photoproduction cross section for a single γA interaction, averaged over a range of y