Heavy-quark production in hadronic and UPC heavy-ion collisions

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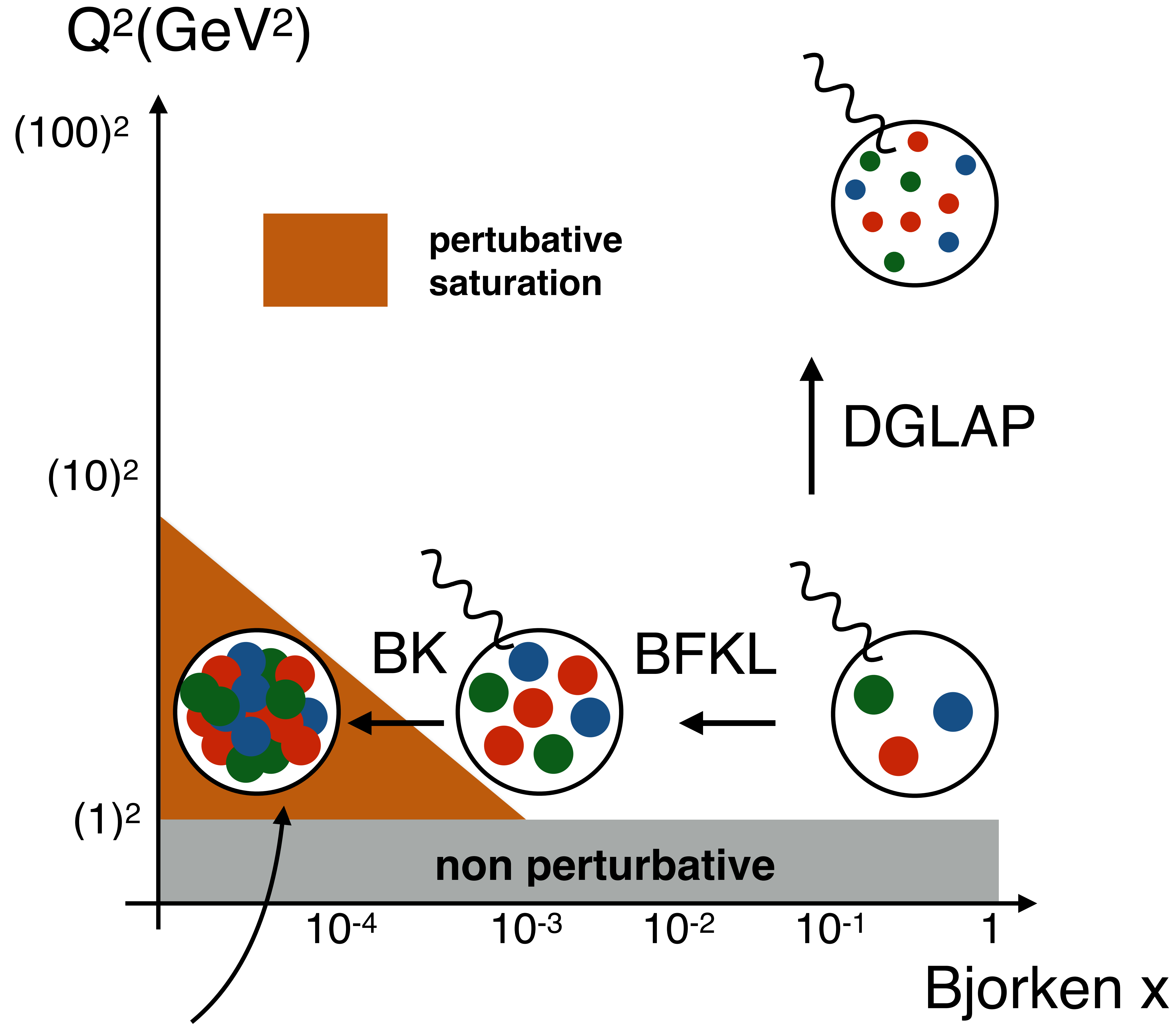
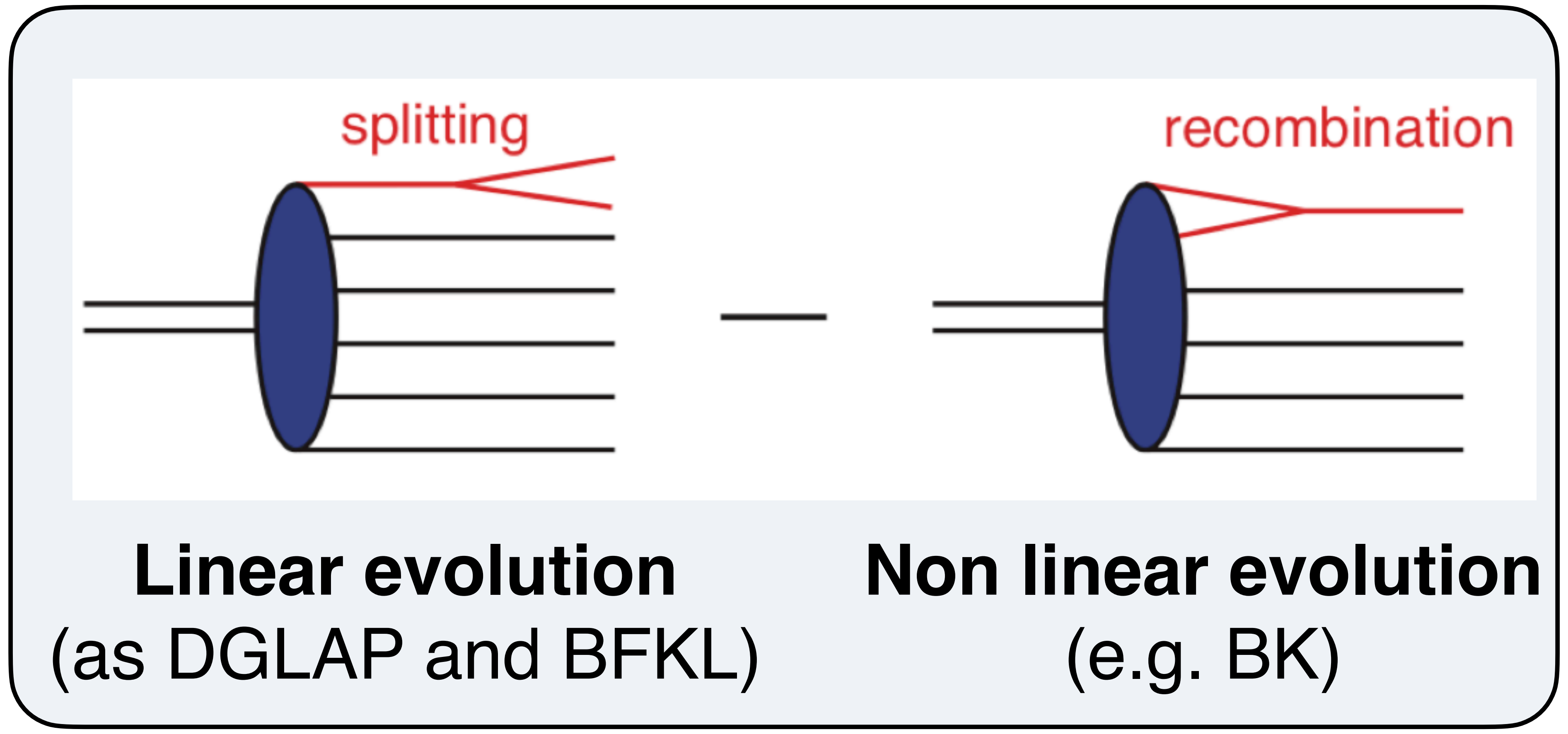
DIFFRACTION AND GLUON SATURATION AT THE LHC AND THE EIC
10 June 2024 - 14 June 2024

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?

Heavy quarks are well-calibrated/perturbative probes to explore this regime

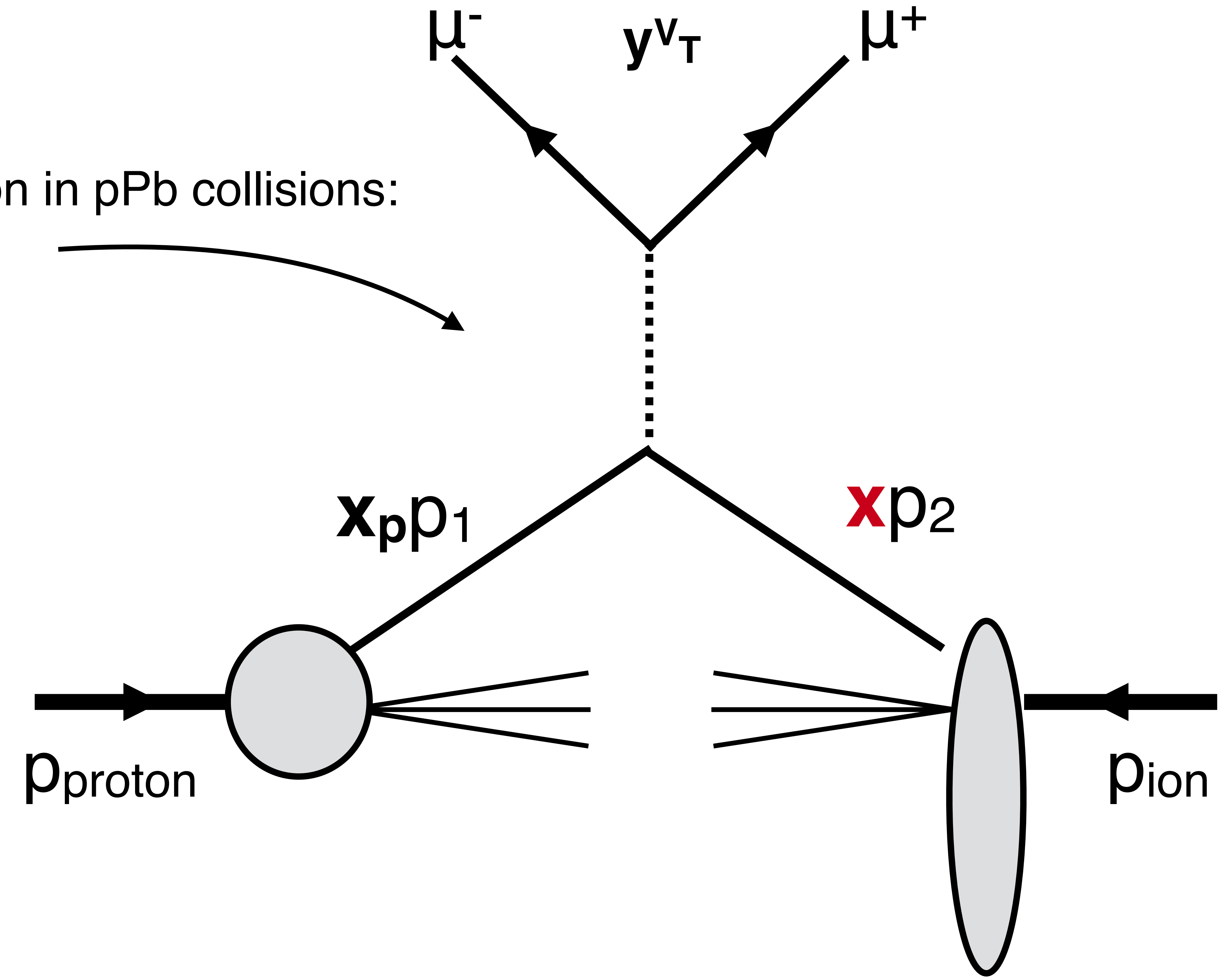
EIC: BNL-98815-2012-JA, arXiv.1212.1701
J.Albacete, C. Marquet, Prog. Part. Nucl. Phys. 76, 1 (2014)

Constraining nuclear PDFs at the LHC with "hadronic" pPb collisions

Constraining nuclear PDFs in hadronic collisions

σ_V = Parton Distribution Function (**x**,**Q²**) ⊗ σ_{parton}(pQCD) ⊗ Fragmentation functions

Example: Drell-Yan Z-boson production in pPb collisions:
→ **quark PDFs at high Q²**

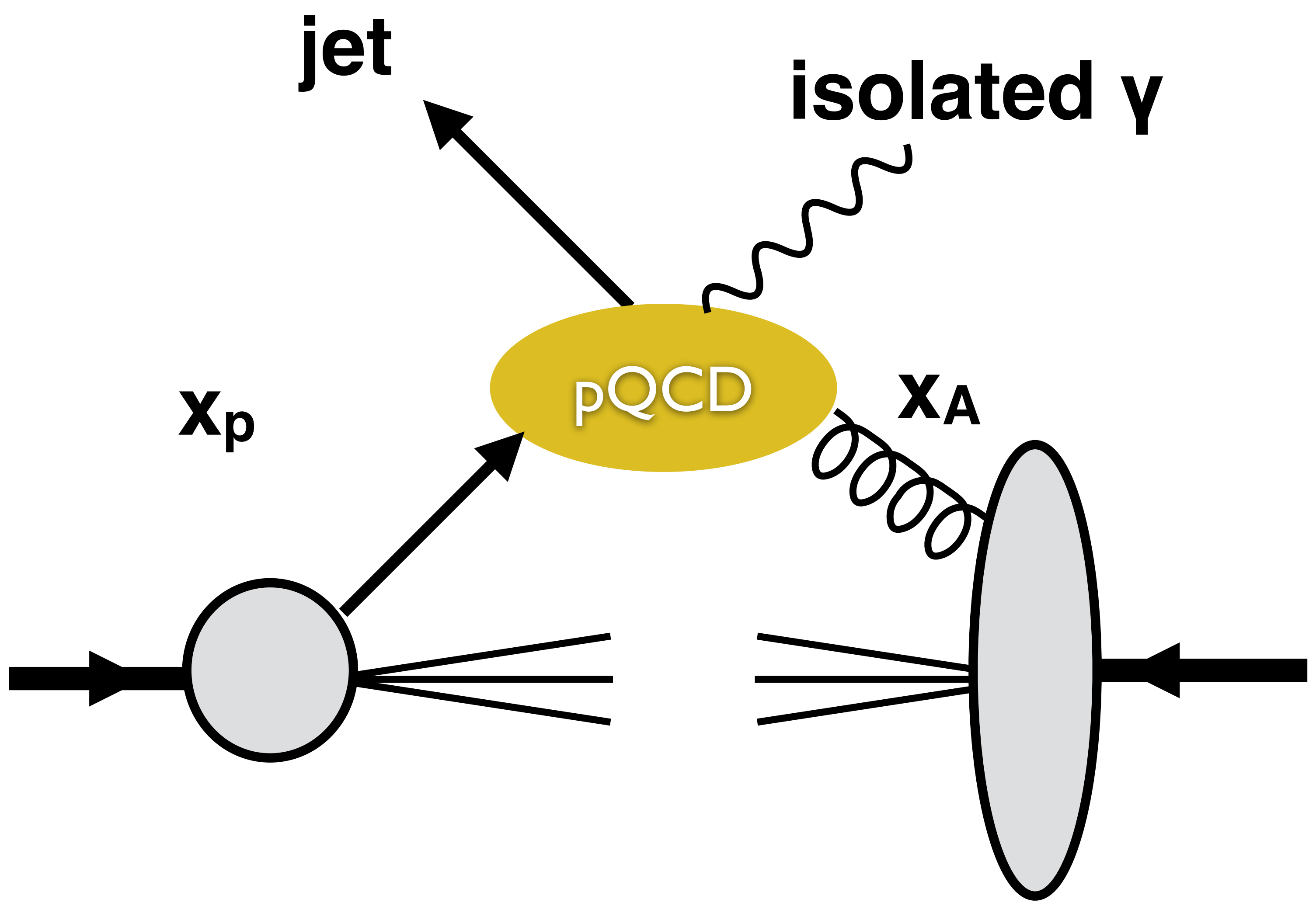


To sample different region of x and Q² for gluons and quarks:

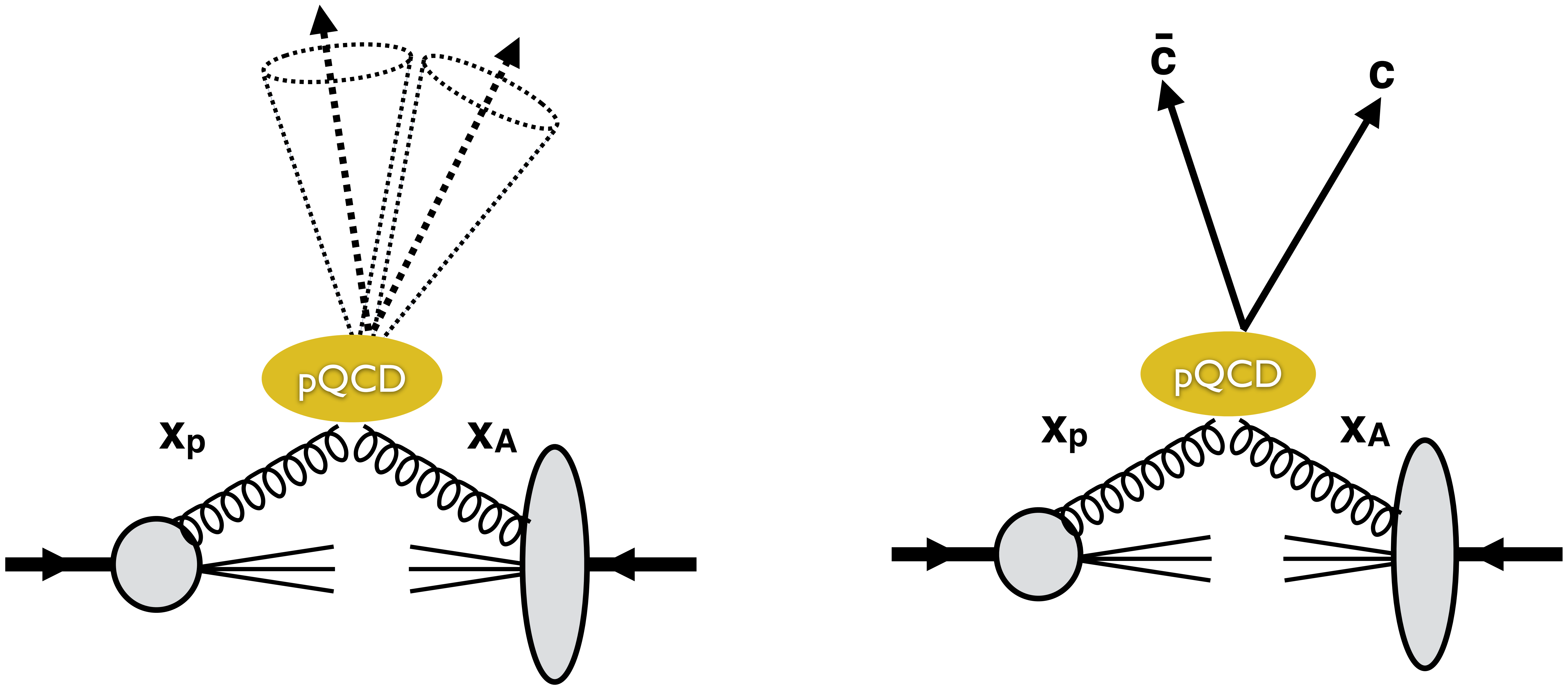
- **vary kinematic properties of the scattering and of the final-state products**
- change the partonic process to change the initial parton species

$$x_{ion} \sim \frac{M_V}{\sqrt{s_{NN}}} exp(-y_V)$$

Constraining nuclear PDFs: changing partonic “process”



Prompt-photon production
Sensitive to both quark and gluon PDFs.



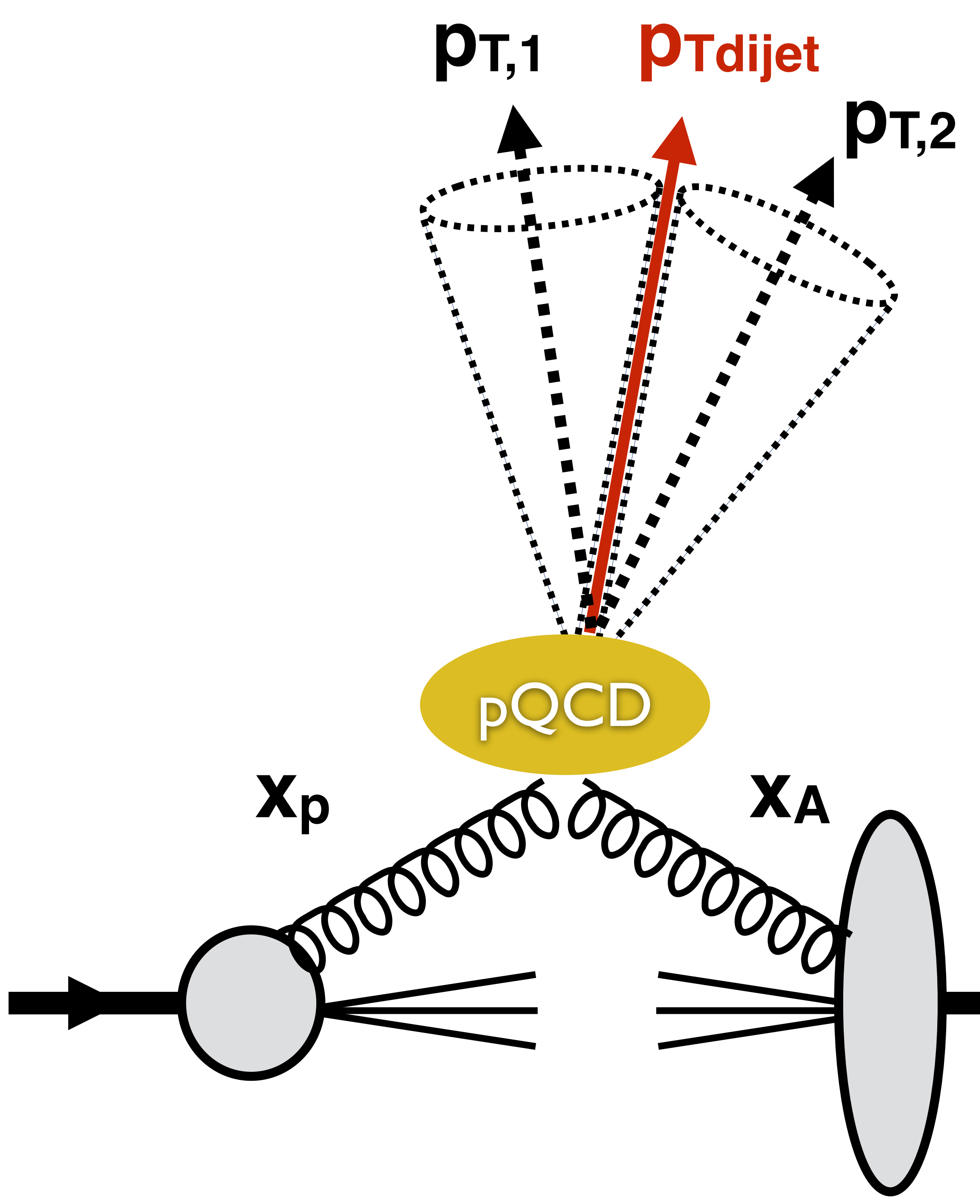
Di-jet production and heavy-quark production
Mostly sensitive to gluon PDFs

Di-jet production in pA collisions with CMS

CMS: Phys. Rev. Lett. 121.062002
Eskola et al. arXiv.1812.05438

$55^2 < Q^2 < 400^2$ GeV, $0.005 < x_A <\sim 0.8$,
gluon PDFs
mid-rapidity

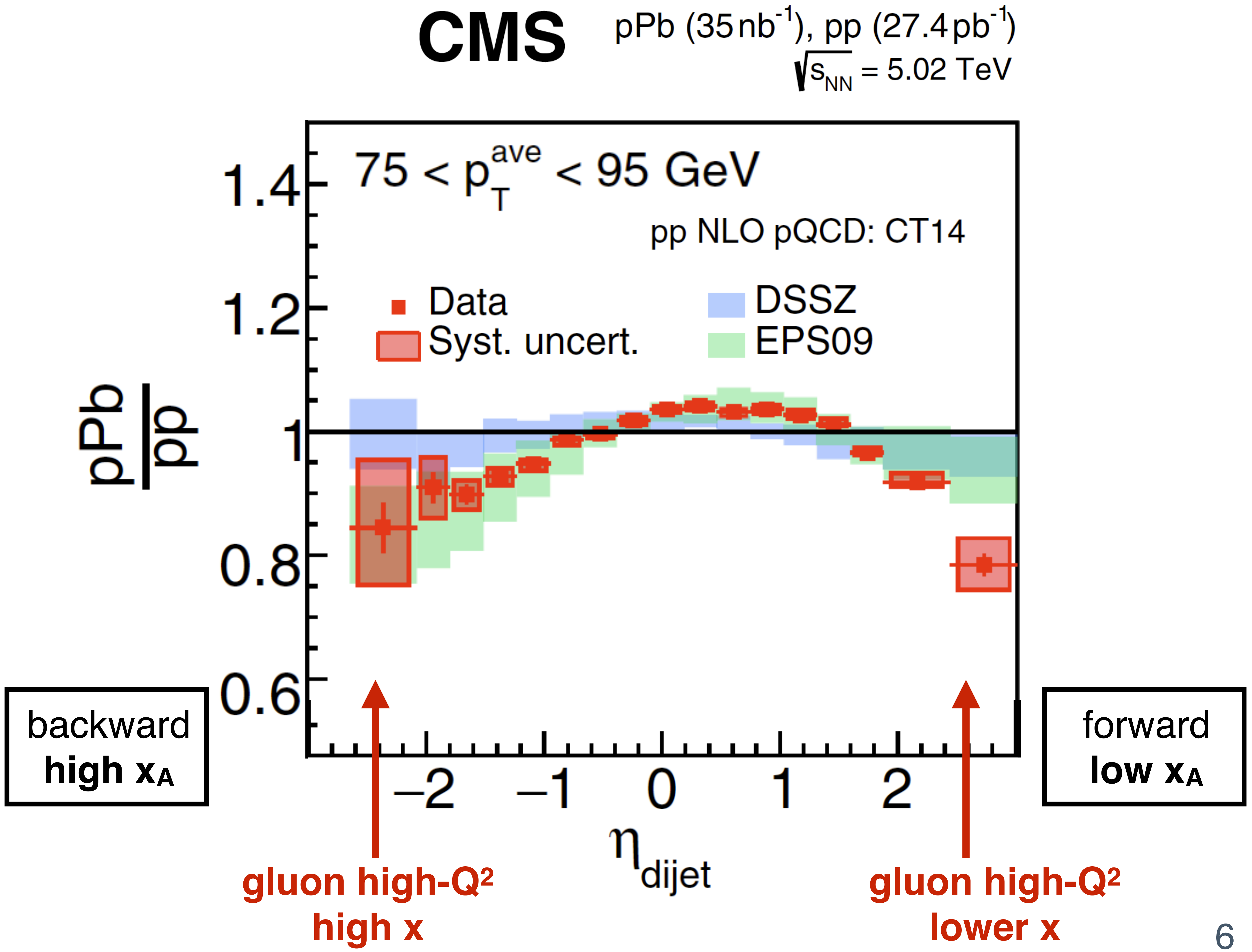
→ **QCD probe**, sensitive to gluon nPDF (gluon-gluon production)



"Averaged" dijet

$\eta_{dijet} = ½ (\eta_1 + \eta_2)$

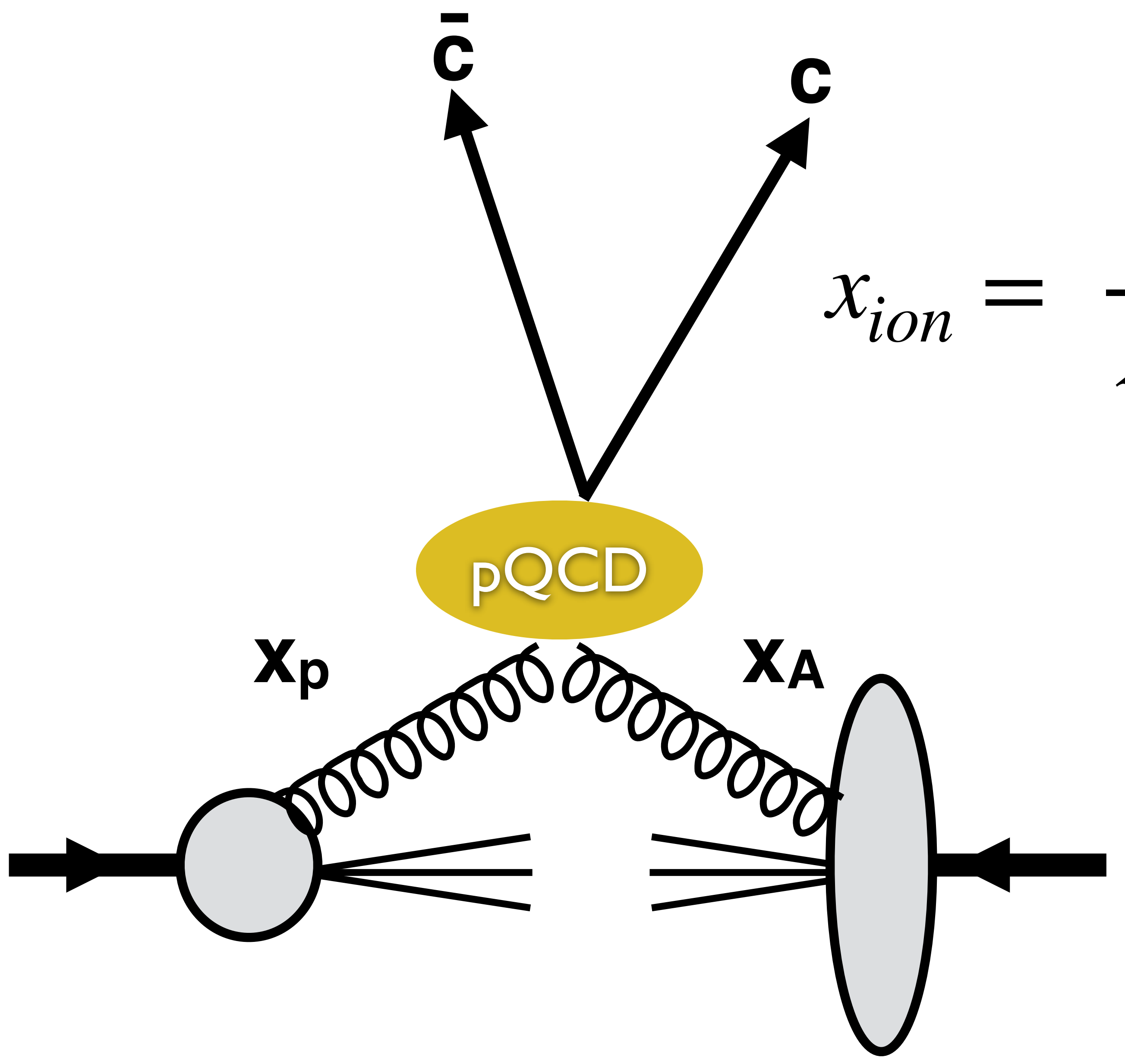
$p_{T,dijet} = ½ (p_{T,1} + p_{T,1}) \sim Q$



D^0 mesons in pA collisions at mid rapidity

ALICE: Phys. RevC. 94.054908

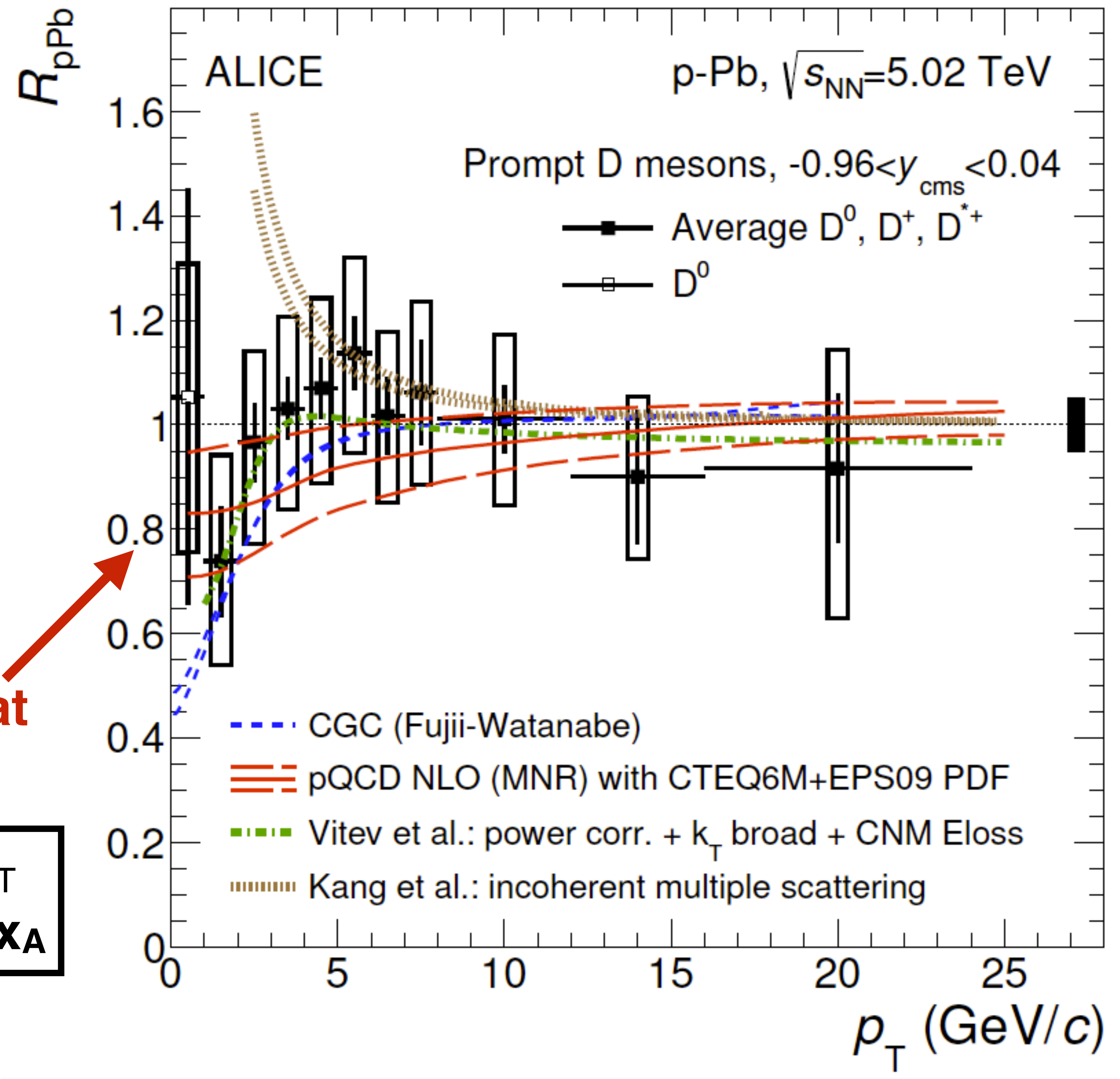
$Q^2 \sim M^2_{cc}$ GeV, x_A down to 10^{-4}
gluon PDFs
mid-rapidity



$$x_{ion} = \frac{M_{c\bar{c}}}{\sqrt{s_{NN}}} exp(-y_{c\bar{c}})$$

gluons at low-x

low p_T
lower x_A



high p_T
higher x_A

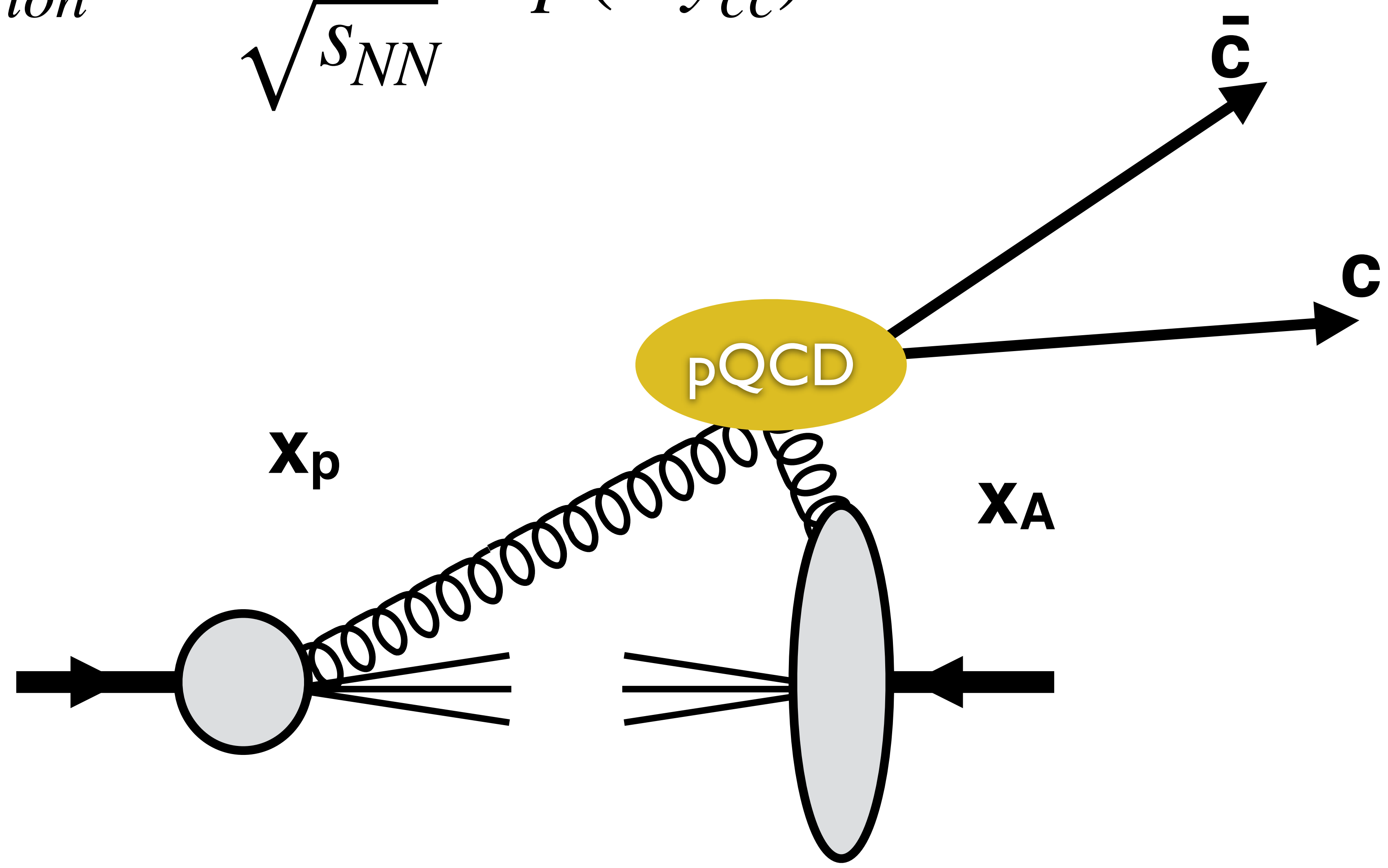
D^0 production in pA collisions at forward-y with LHCb

LHCb, JHEP 10 (2017) 090

$Q^2 \sim M^2_{cc}$ GeV, x_A down to 10^{-6}
gluon PDFs
1.5<y*<4.0

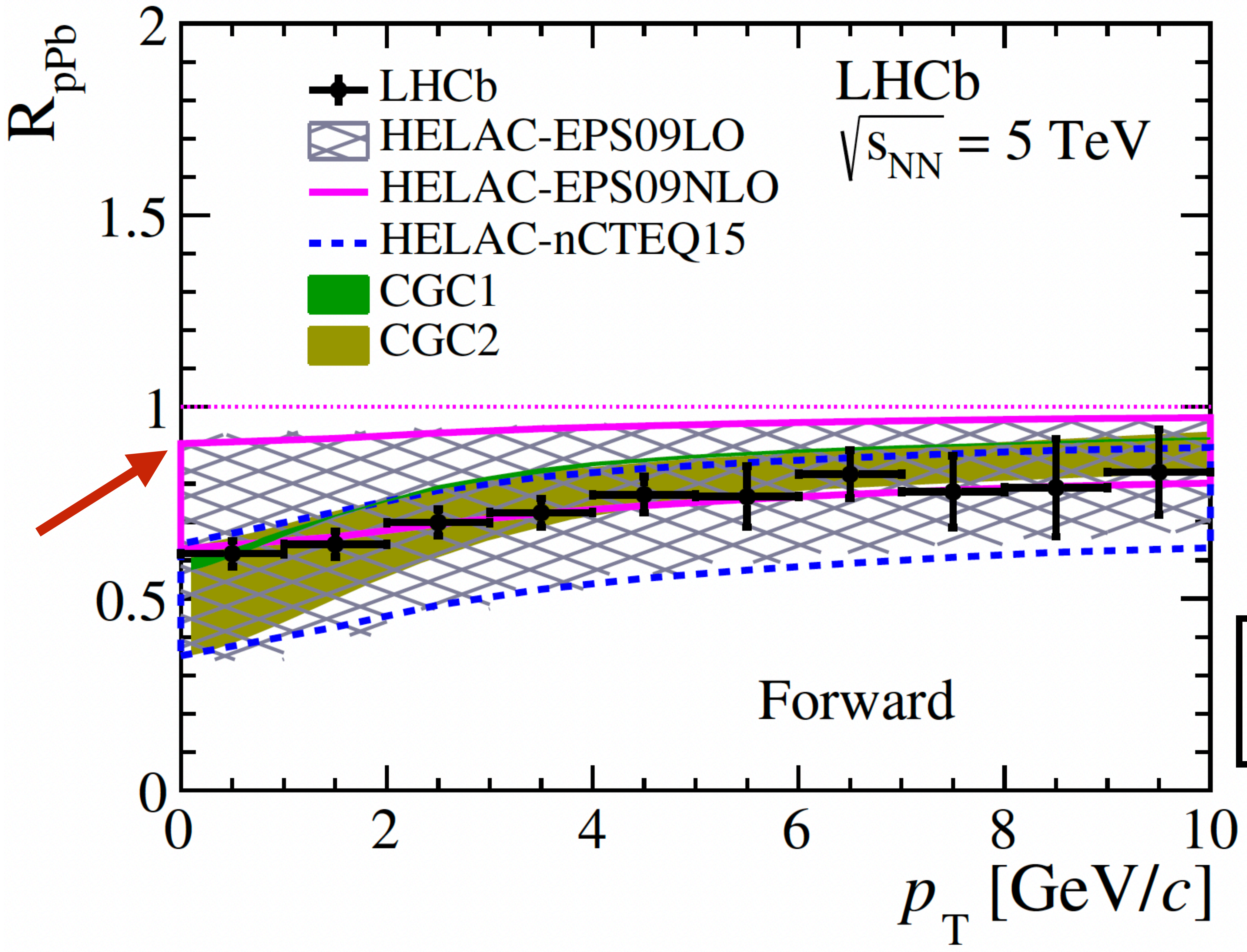
→ **QCD probe** for low-x, low-Q^2 regime

$$x_{ion} = \frac{M_{c\bar{c}}}{\sqrt{s_{NN}}} exp(-y_{c\bar{c}})$$



low-Q^2 gluon shadowing

low p_T
very low x_A

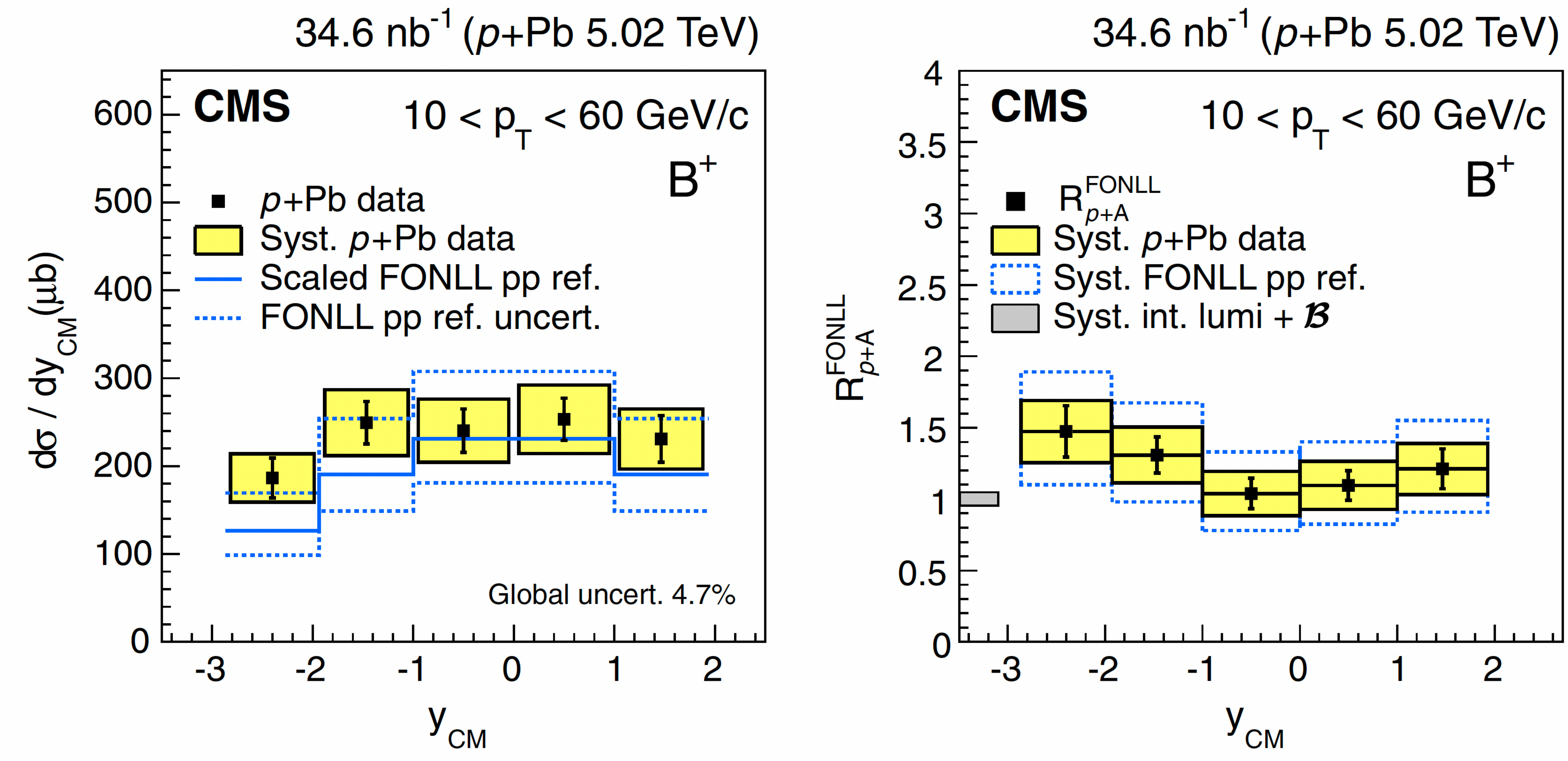


high p_T
higher x_A

- effect of final state on the nPDF?

- very good accuracy down to 0 GeV
- **unique access to the extreme low-x low-Q^2 region (saturation regime?)**

B-meson production in pPb collisions at 5.02 TeV



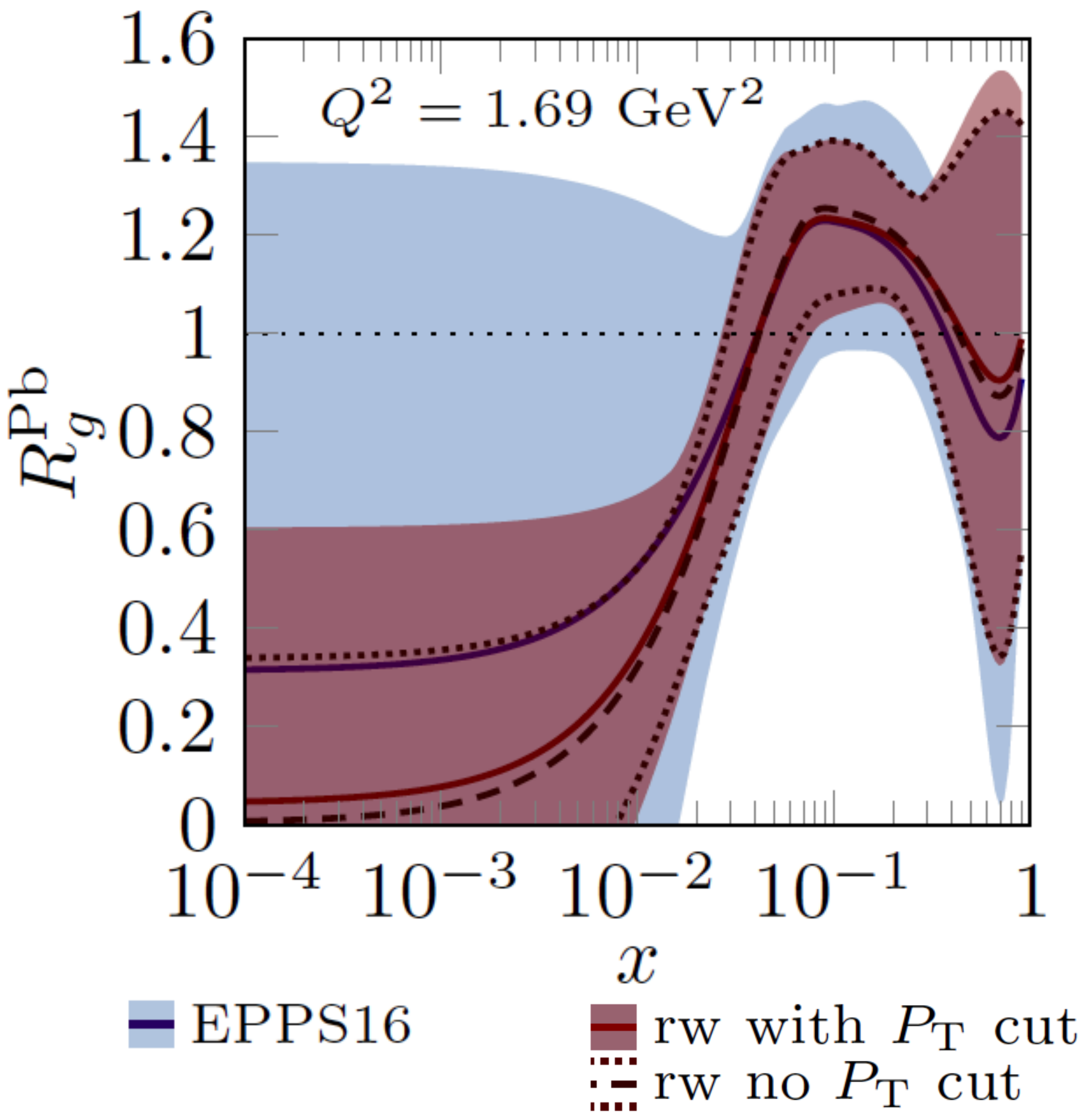
First attempt to use beauty quarks to study nPDF modifications of gluons (limited experimental accuracy)
- lack of proton-proton reference (RpA built w.r.t. to FONLL predictions)
- limited pPb statistics → **larger pPb samples needed!**

From measurements to nPDF constraints

→**Using a non-quadratic Hessian PDF reweighting**, K. J. Eskola et al., EPJC 79, 511 (2019)

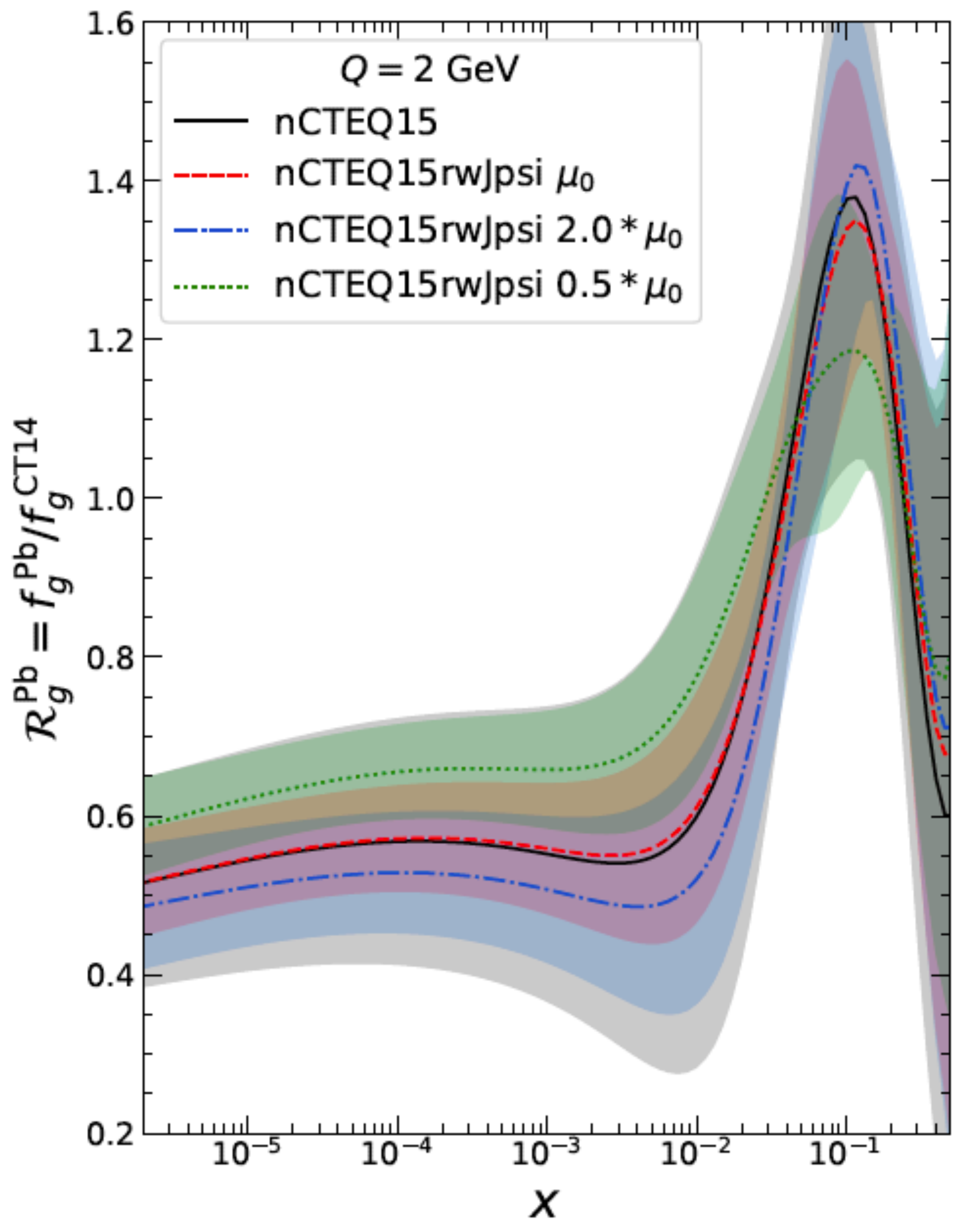
K. J. Eskola et al., JHEP 2020 37 (2020)

With D meson LHCb data at 5.02 TeV

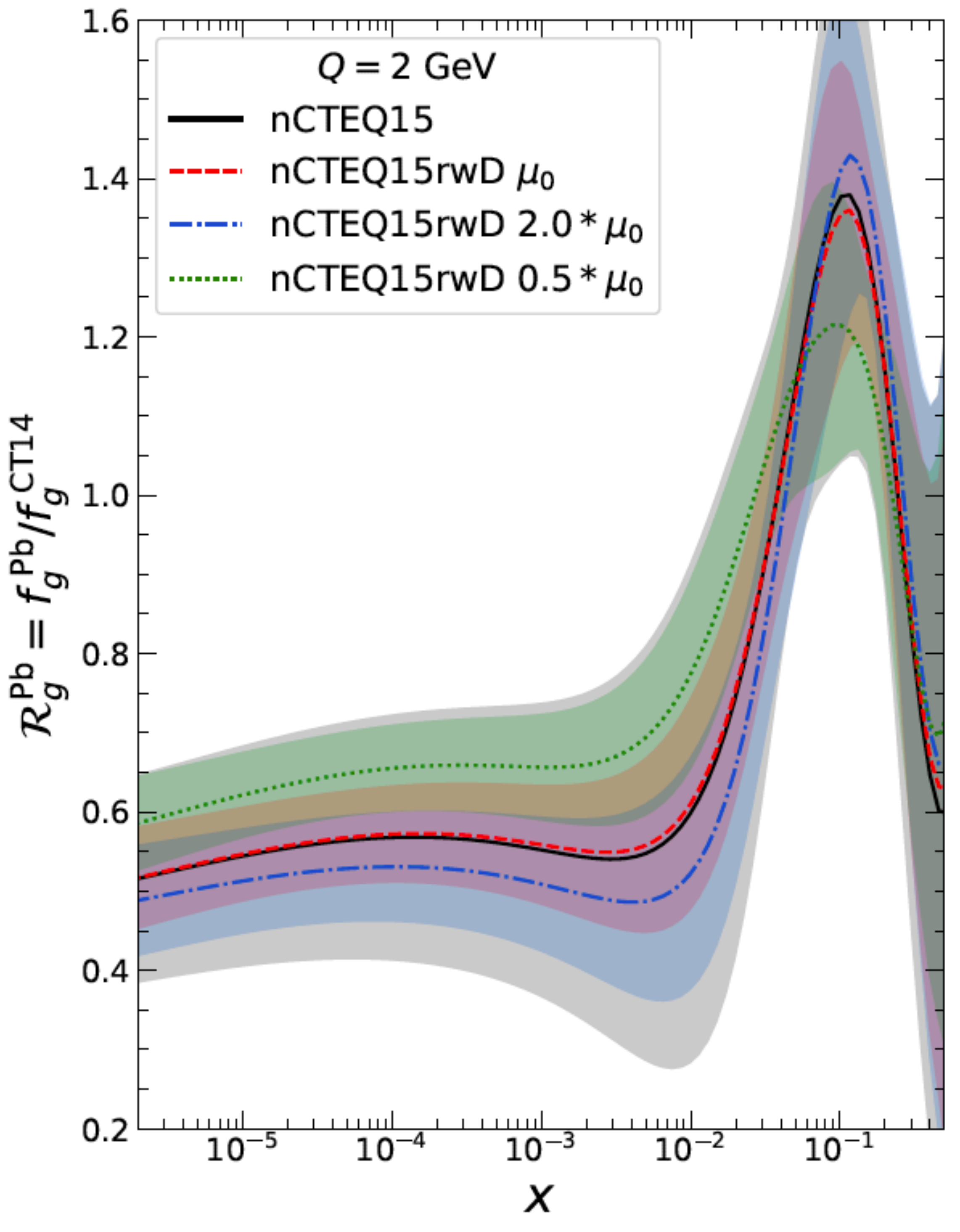


A. Kusina et al. arXIv.2012.11462

ALICE+LHCb D mesons in pPb



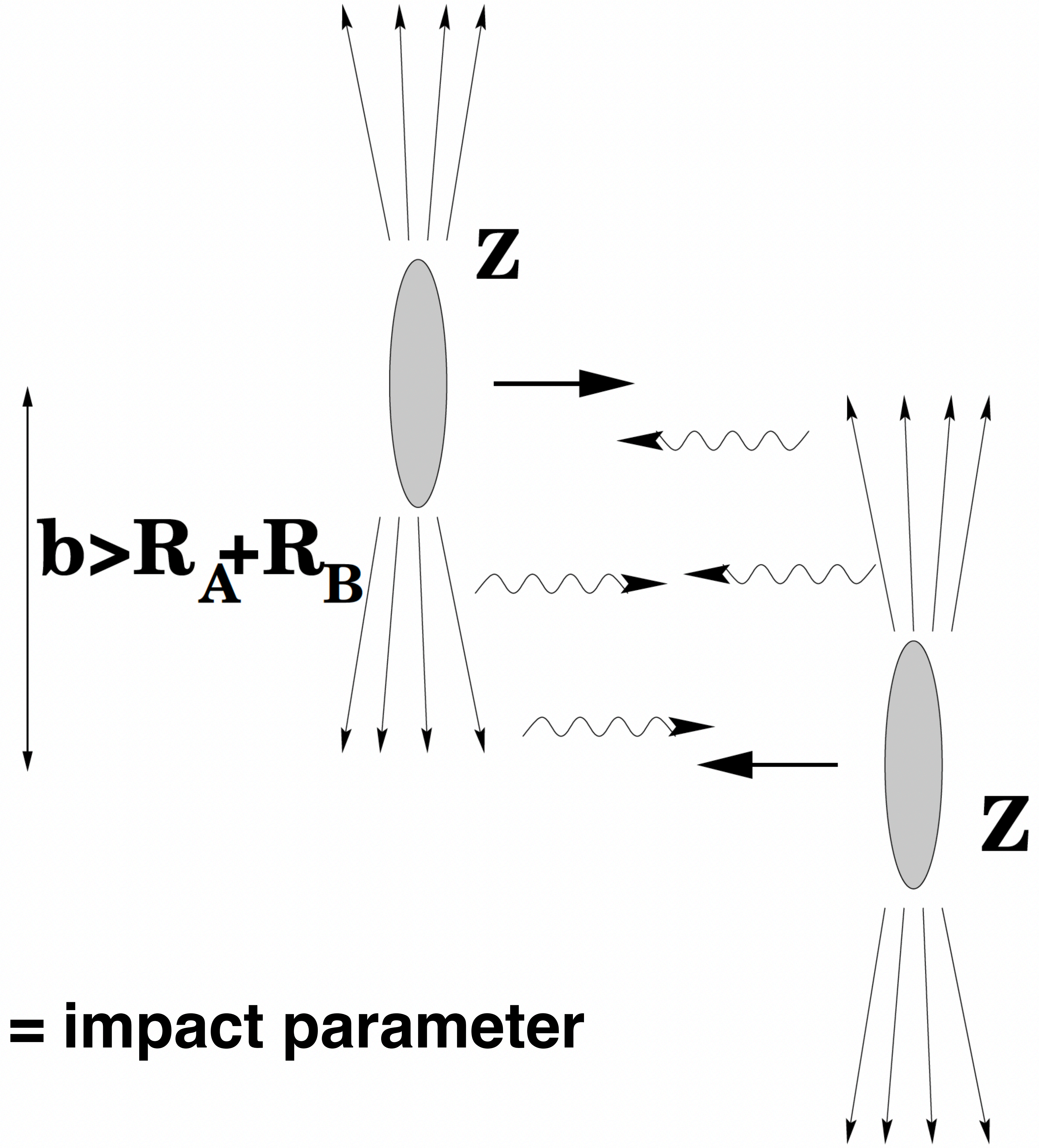
ALICE+LHCb J/ψ mesons in pPb



Significant constraints from inclusion of charm data from the LHC. Some caveats:

- **what is the influence of final state effects (e.g. D meson flow or hadronization)?**
- **can we account for them in the nPDF fits?**

Constraining nuclear PDFs at the LHC with Ultra-Peripheral HI collisions



b = impact parameter

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

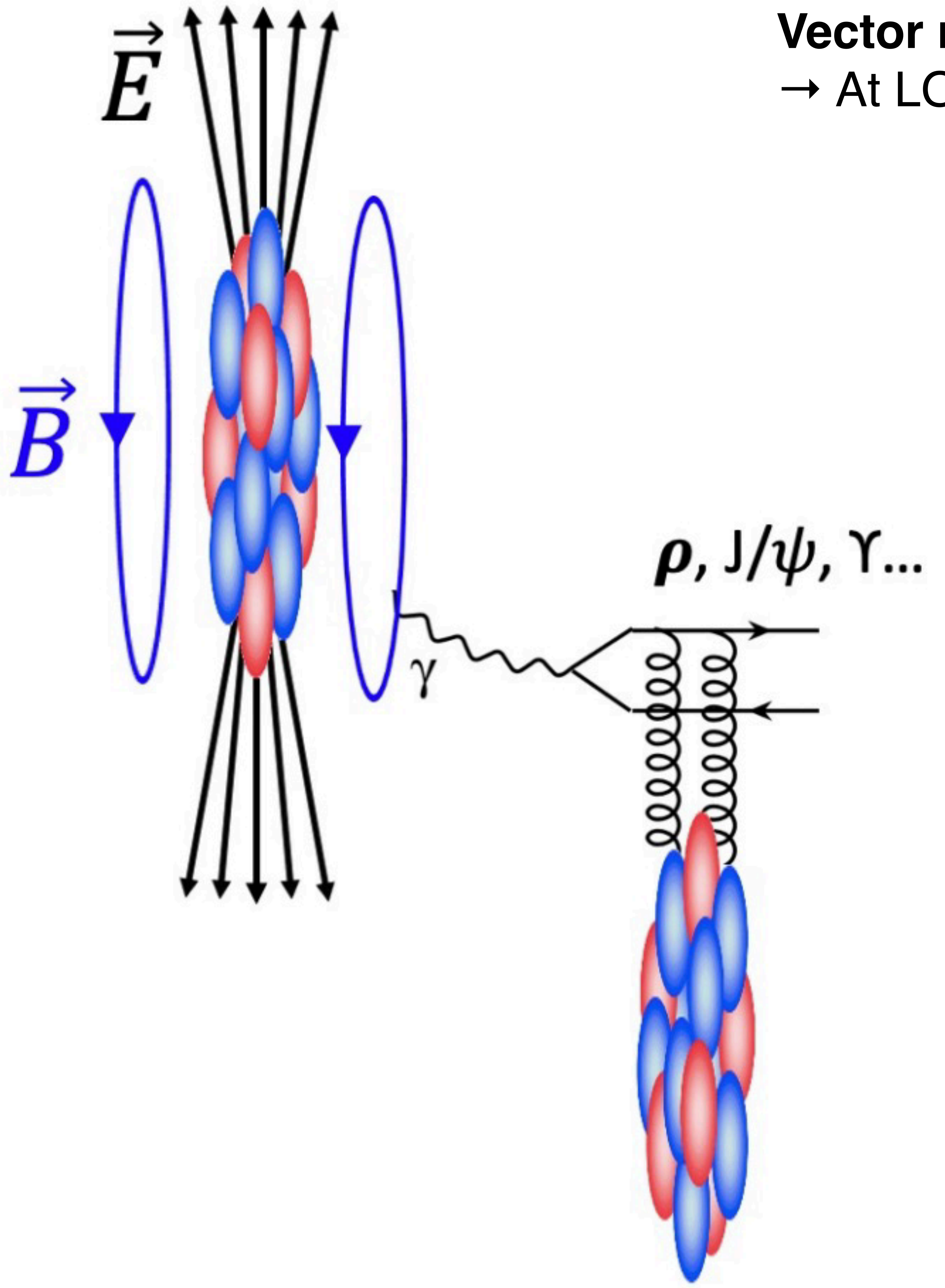
- Flux of photon is proportional to Z^2

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

When running on PbPb, LHC is effectively a γγ and γN collider!
→ probability of having a hadronic PbPb collisions in a bunch crossing in is < 0.1%!

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

Vector-meson photoproduction in UPC



Vector mesons (VM) probe gluonic structure of nucleus and nucleon.
→ At LO in pQCD, cross section ~ photon flux ⊗ [xG(x)]2

Coherent production (<p_T> ~ 50 MeV)
- Photon fluctuated dipole couples coherently to entire nucleus
- Target nucleus remains intact
- VM <p_T> ~ 50 MeV
- Probing the averaged gluon density

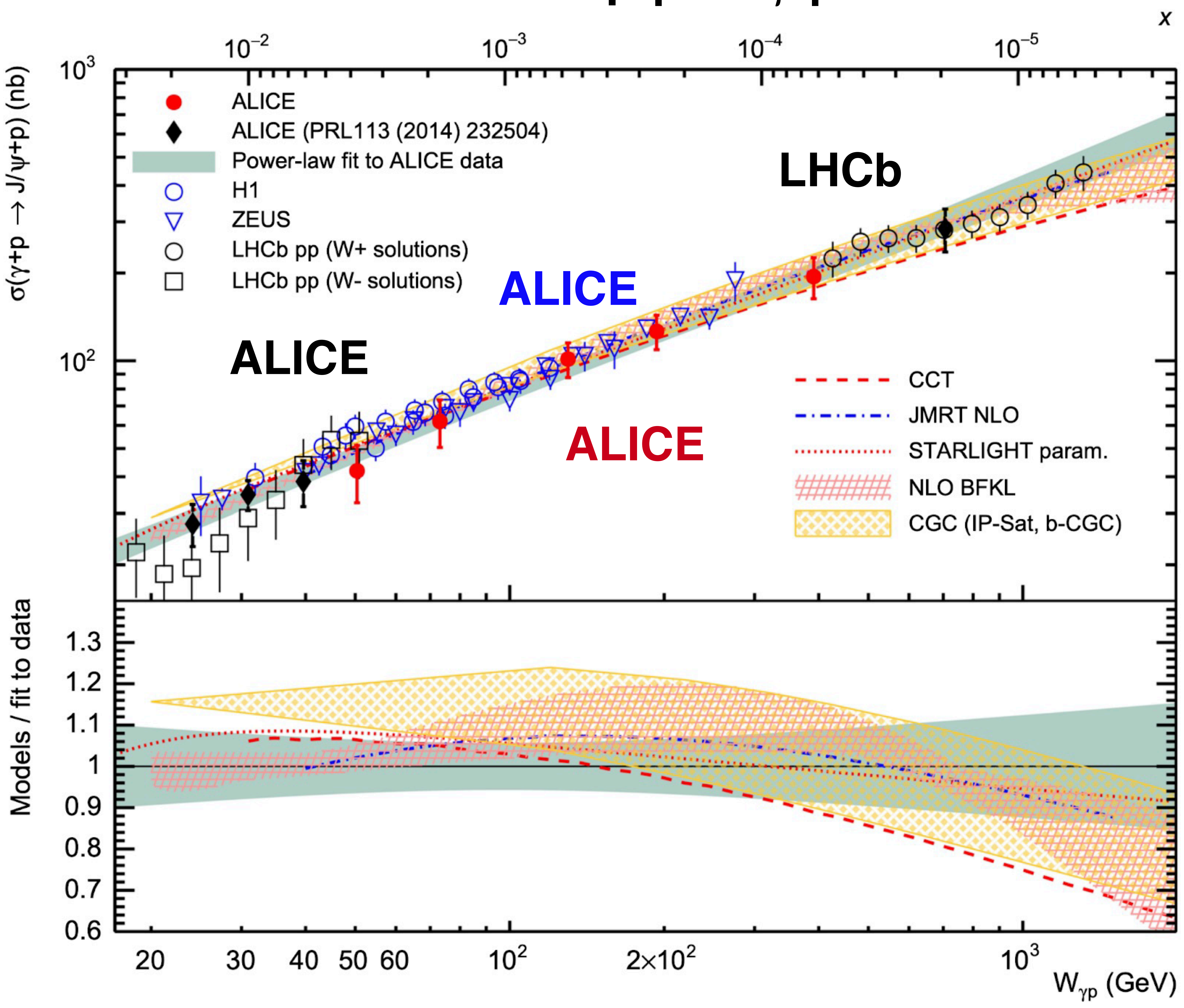
Incoherent production VM (<p_T> ~ 500 MeV)
- Photon fluctuated dipole couples to individual nucleons
- Target nucleus usually breaks
- Probing the local gluon density fluctuation

*Sketches from **Zaochen Ye's** talk at GHP2023*


CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-12 21:48:04.525285 GMT
Run / Event / LS: 326619 / 2320827 / 8
Y
Z
X

Coherent J/ψ photoproduction in UPC Pbp collisions

γ+p→J/ψ p collisions:

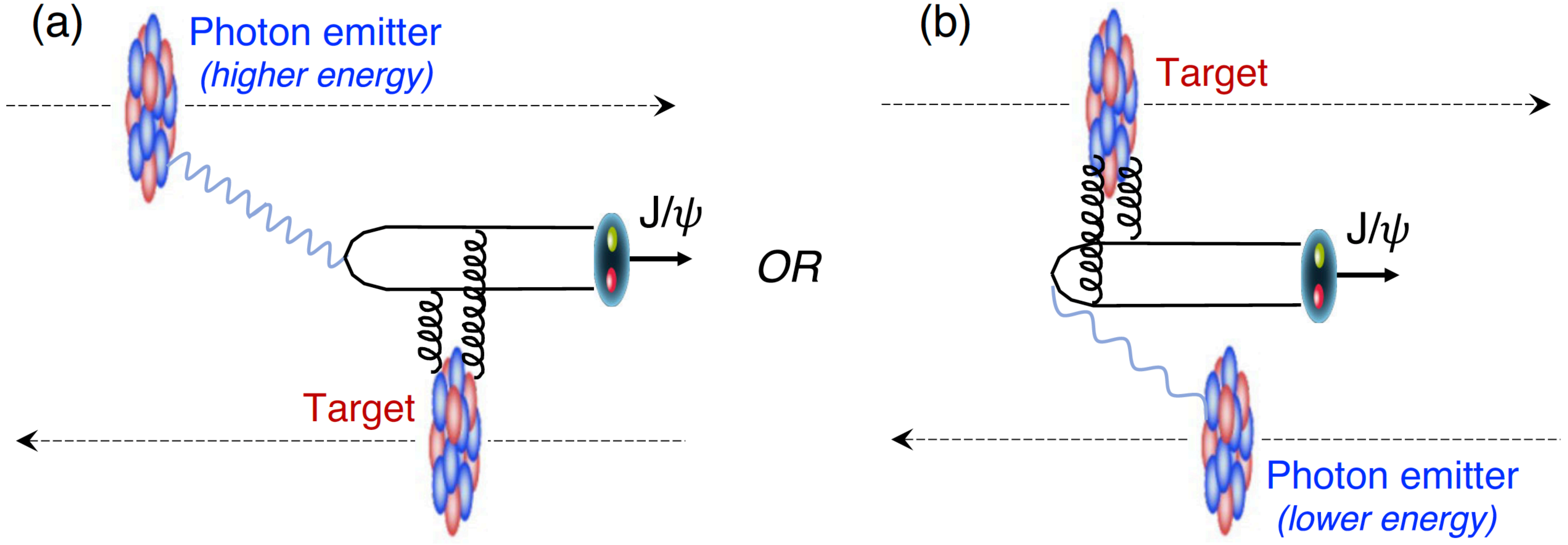


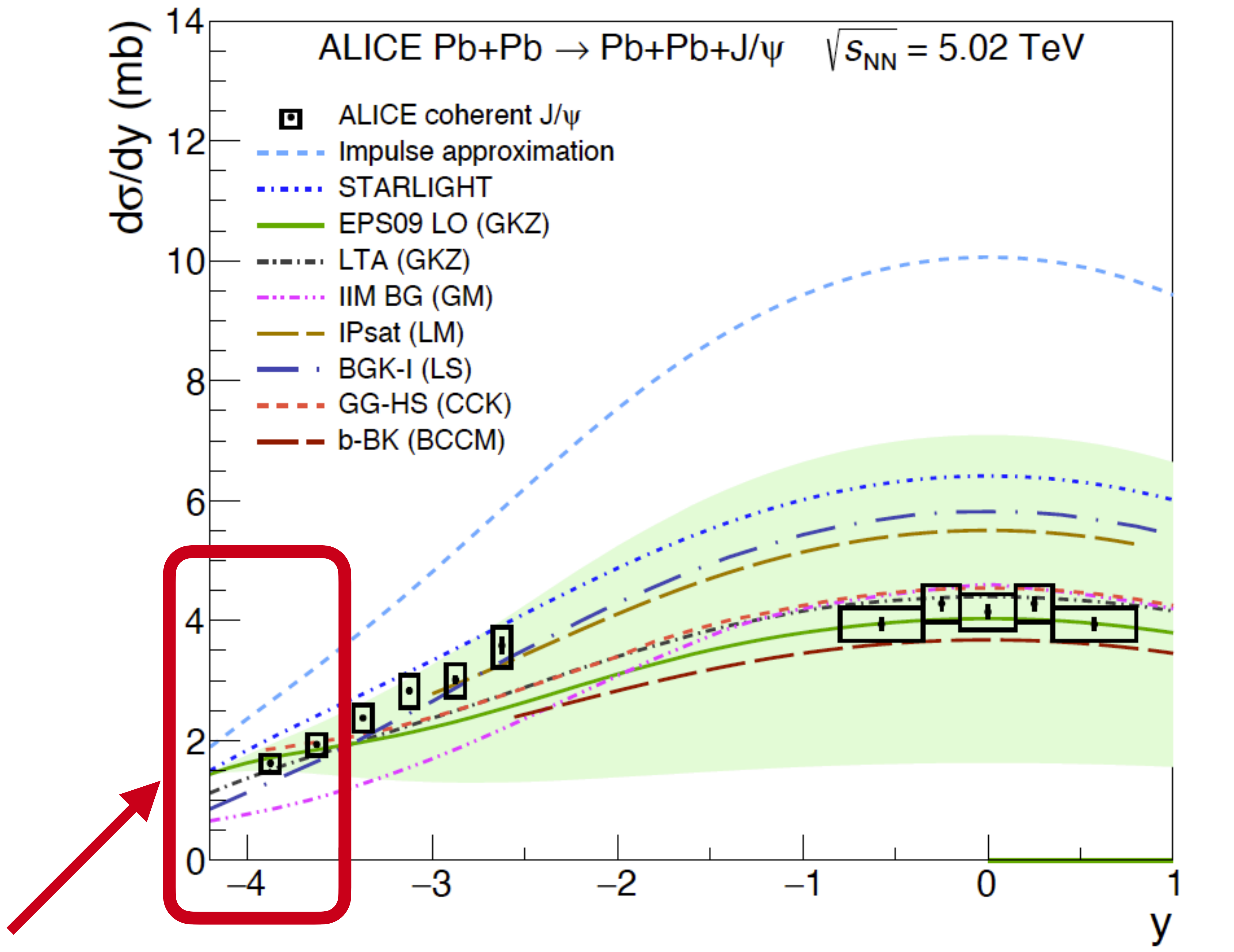
$$W_{\gamma p} = 2\sqrt{\omega \cdot E_{beam}}$$

UPC γp from LHC and ep from HERA well described by models that include a strong increase of the gluon density

No indication of gluon saturation, even down to x~10^{-5} in a free nucleon.

Coherent J/ψ photoproduction in UPC PbPb collisions





$$x = \frac{M_{VM}}{\sqrt{s_{\rm NN}}} e^{\mp y}$$

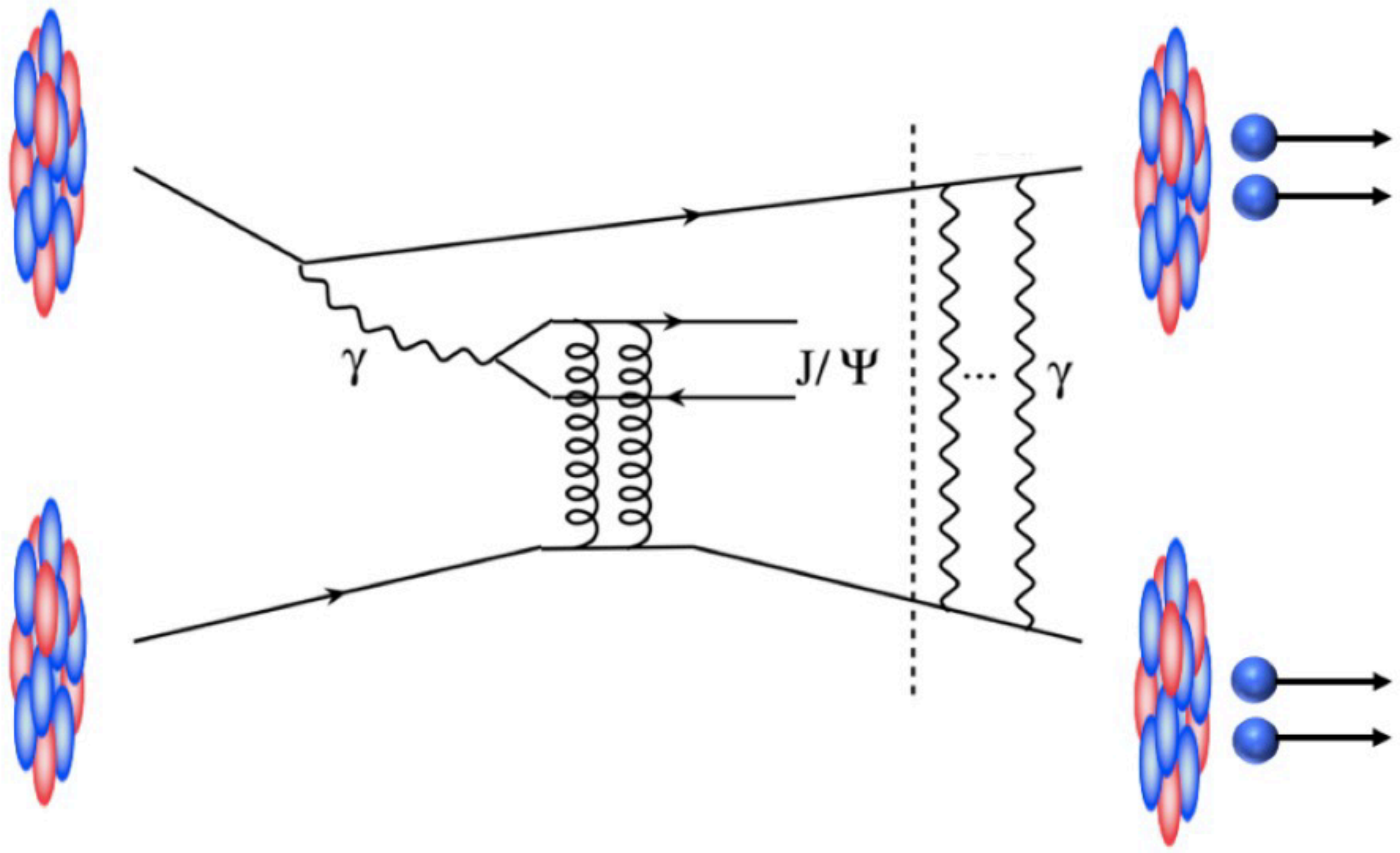
Two-Way Ambiguity in A-A UPC: the initial direction of the photon is not fully defined
At fixed y, contributions from two different photon energies $w_{1,2} = M_{J/\psi}\exp(\mp y)$

ALICE: PLB 798 (2019) 134926

Solving the photon ambiguity with neutron information from ZDC

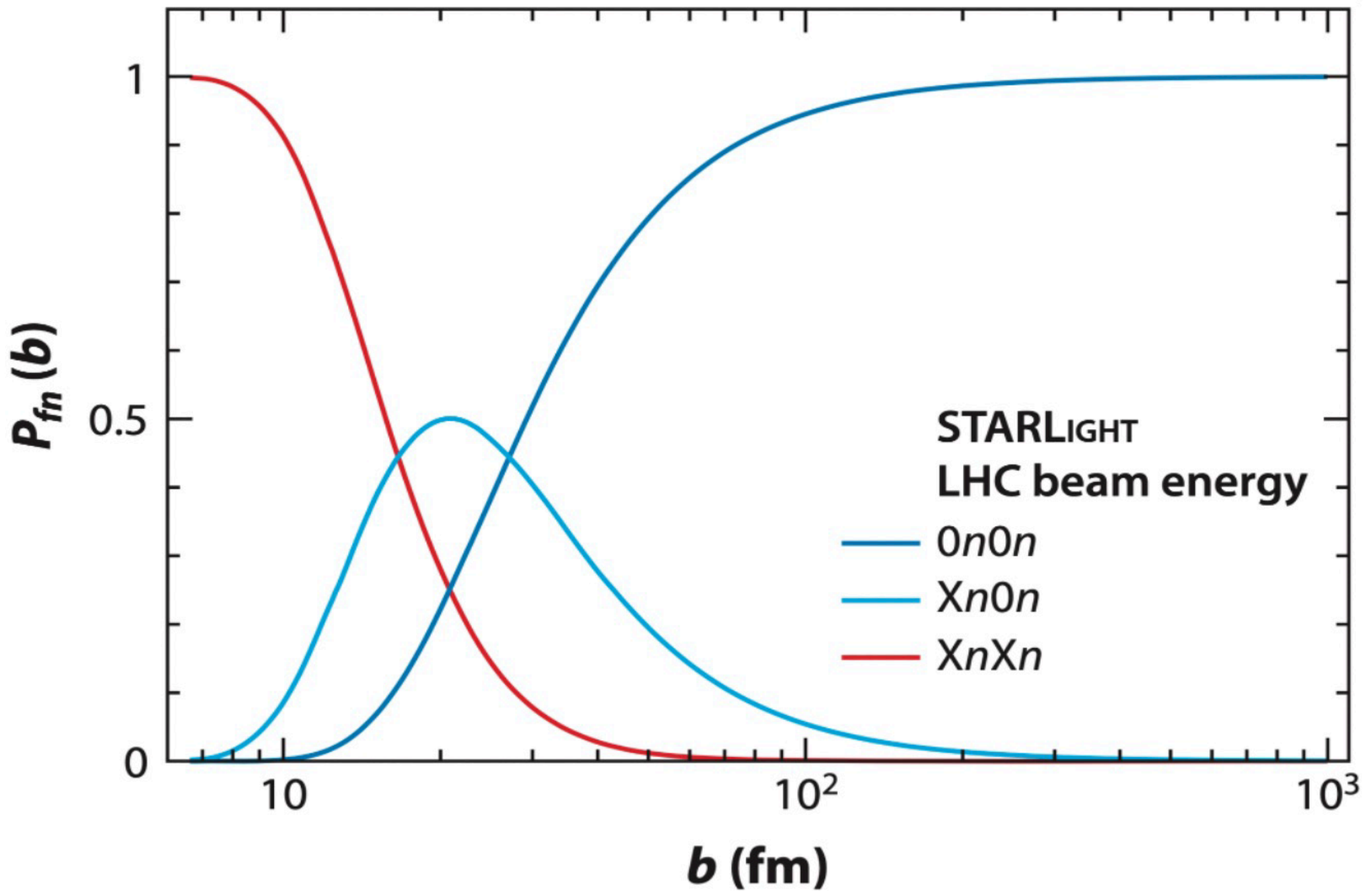
Method in a nutshell (V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942)

- 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 ~200 b (single EMD)

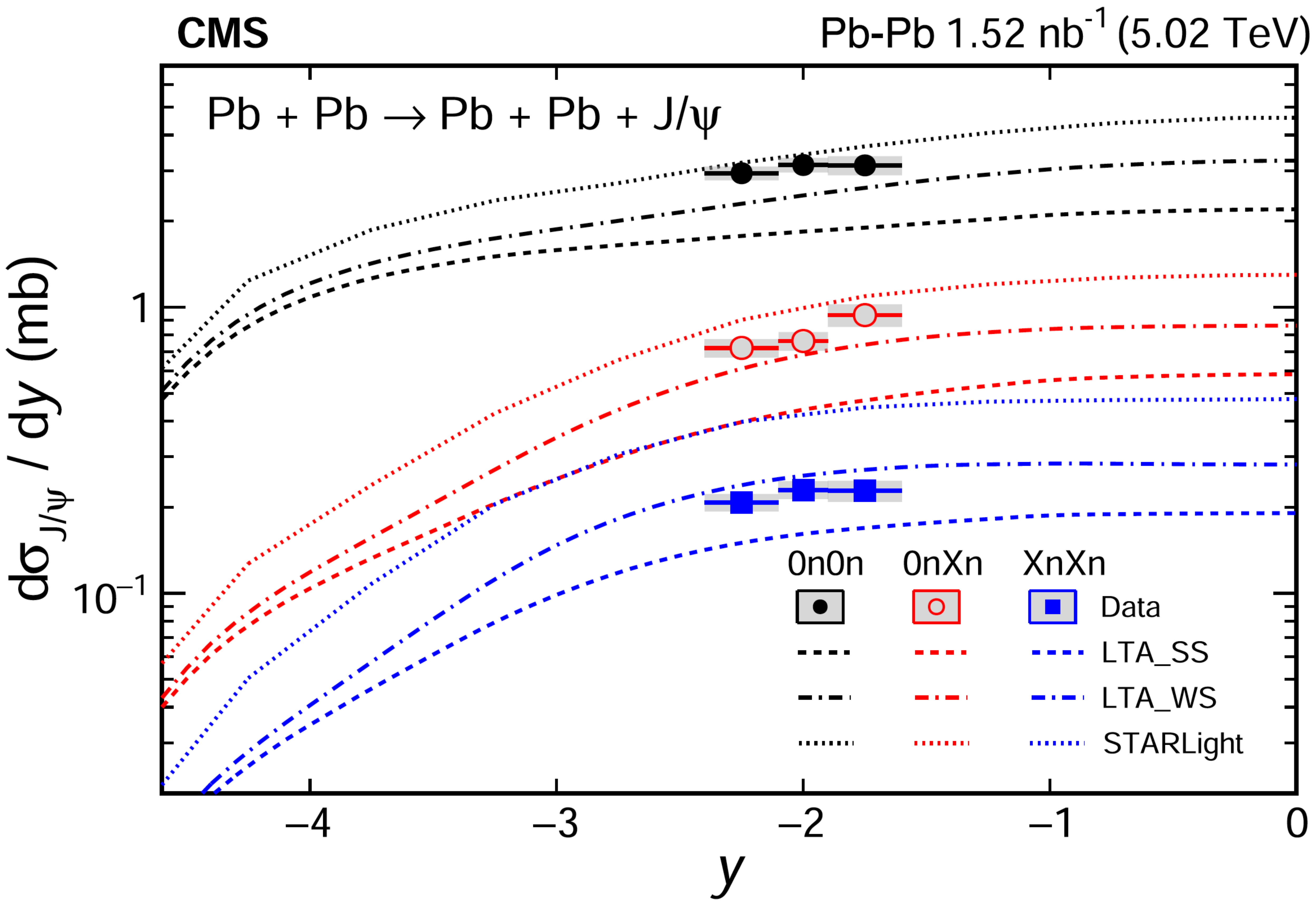


Probability of EMD is strongly correlated with the impact parameter of the collision **b**

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***

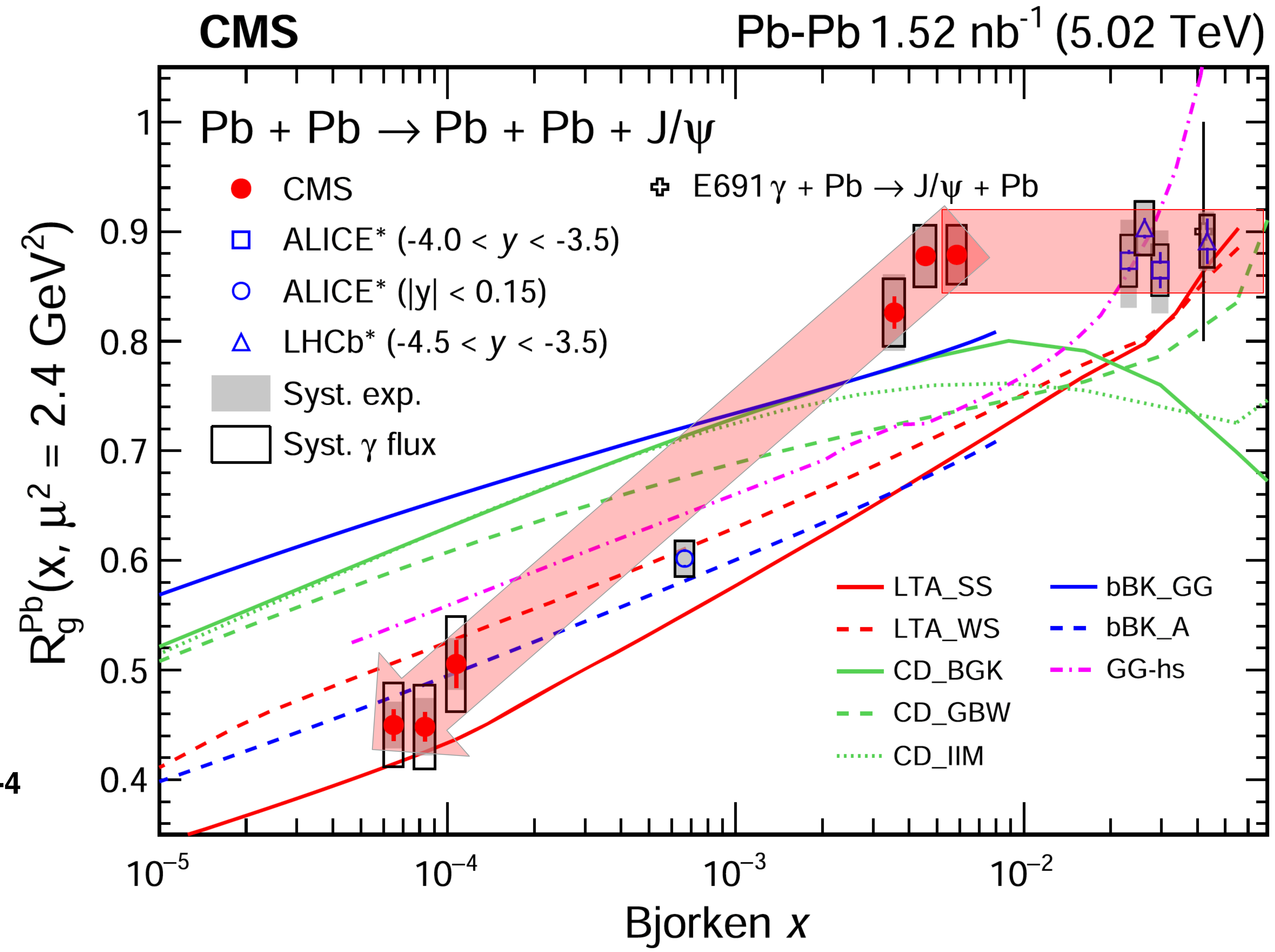


$$\frac{d\sigma^{in\,jn}_{J/\psi}(y)}{dy} = n^{in\,jn}_{\gamma A}(\omega_1)\,\sigma_{J/\psi}(\omega_1) + n^{in\,jn}_{\gamma A}(\omega_2)\,\sigma_{J/\psi}(\omega_2)$$

- *i*n *j*n = (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

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

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



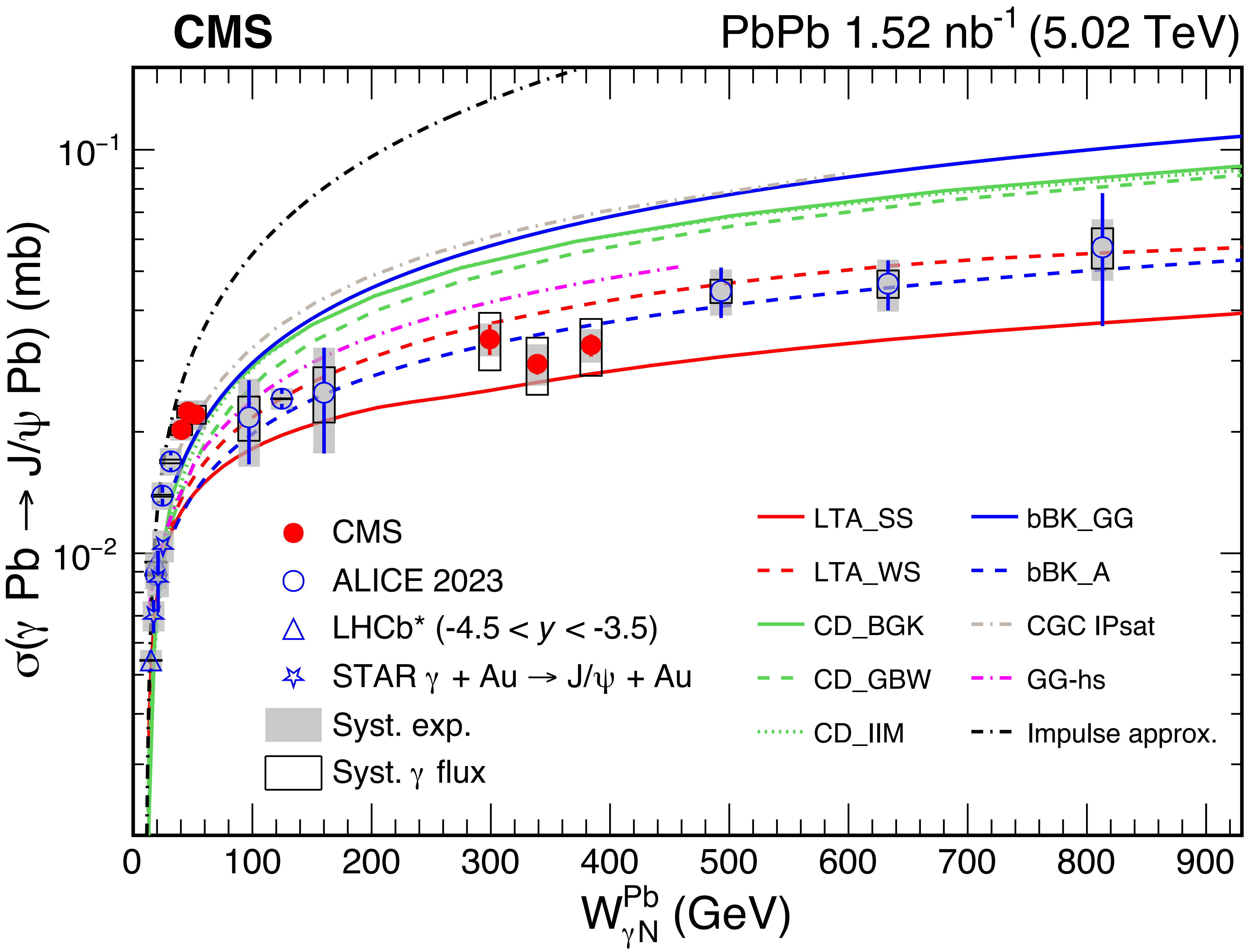
R_g ~ 0.8-0.9 for x > 10^{-3}
(low $W_{\gamma N}^{Pb}$)

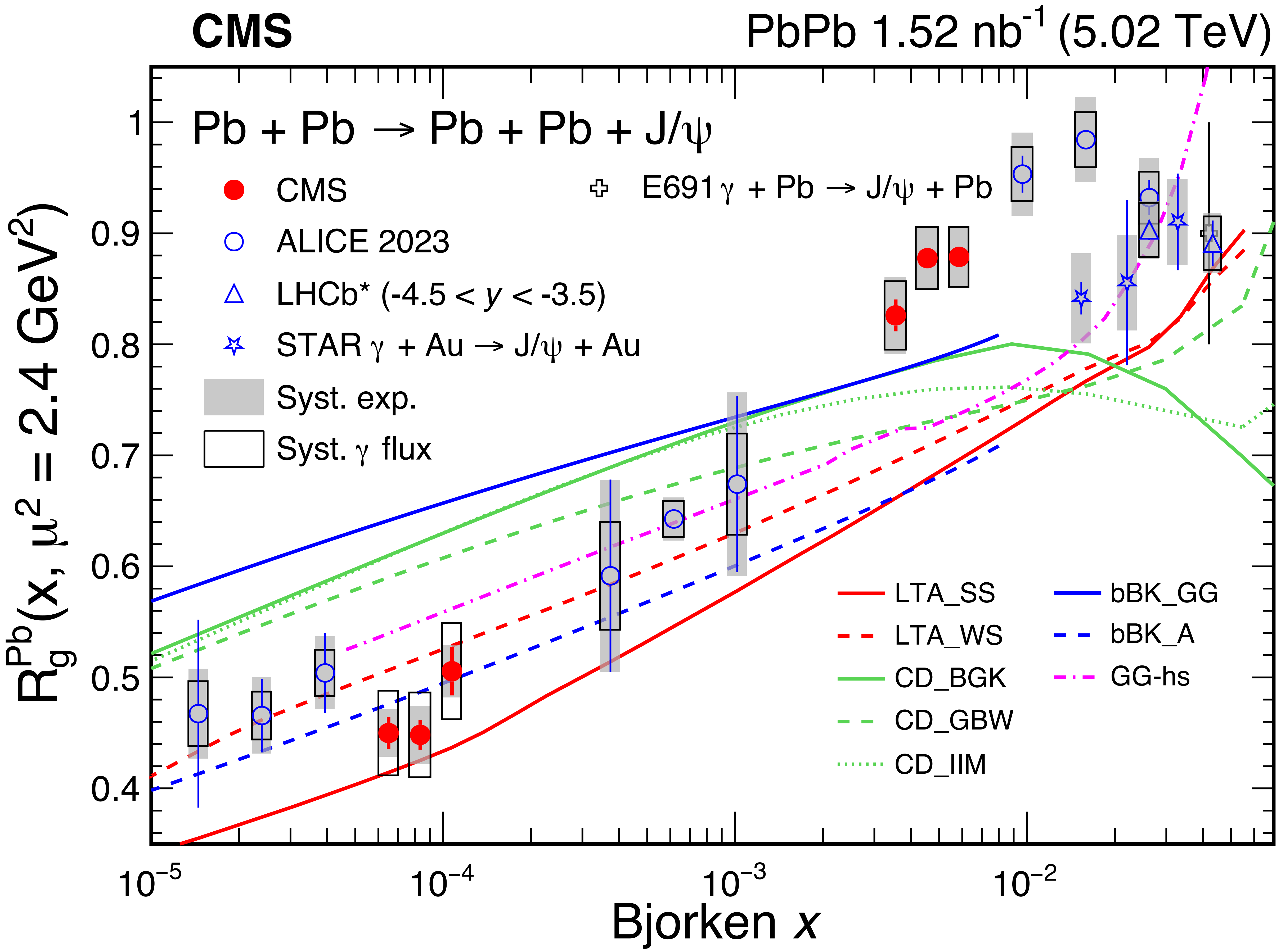
R_g ~ 0.4 for x < 10^{-4}
(high $W_{\gamma N}^{Pb}$)

No theoretical model predicts the observed values and x dependence of R_g over the wide x range reported

Coherent J/ψ in PbPb UPCs: CMS vs ALICE

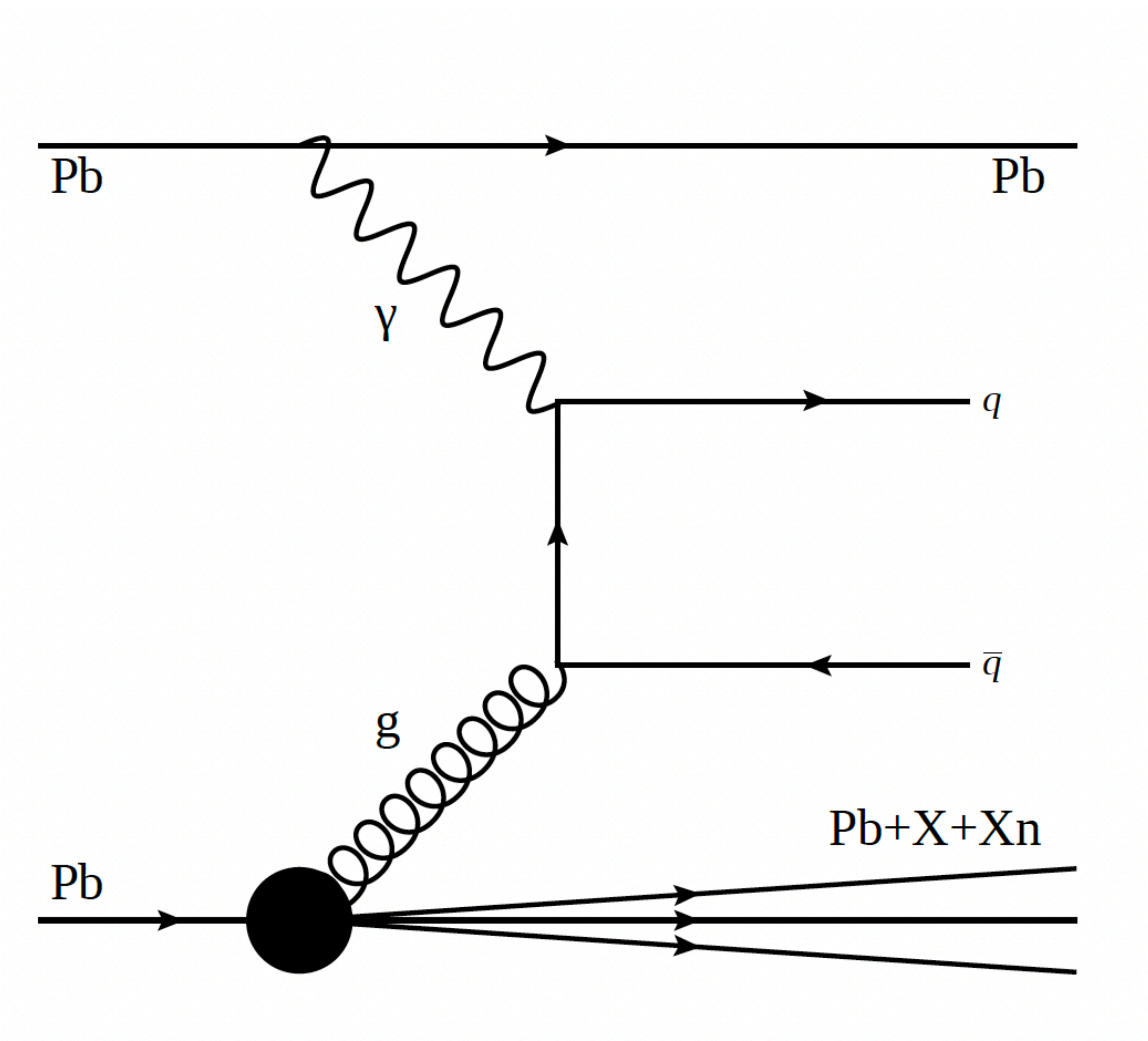
ALICE, JHEP 10 (2023) 119
CMS, Phys. Rev. Lett. 131 (2023) 262301





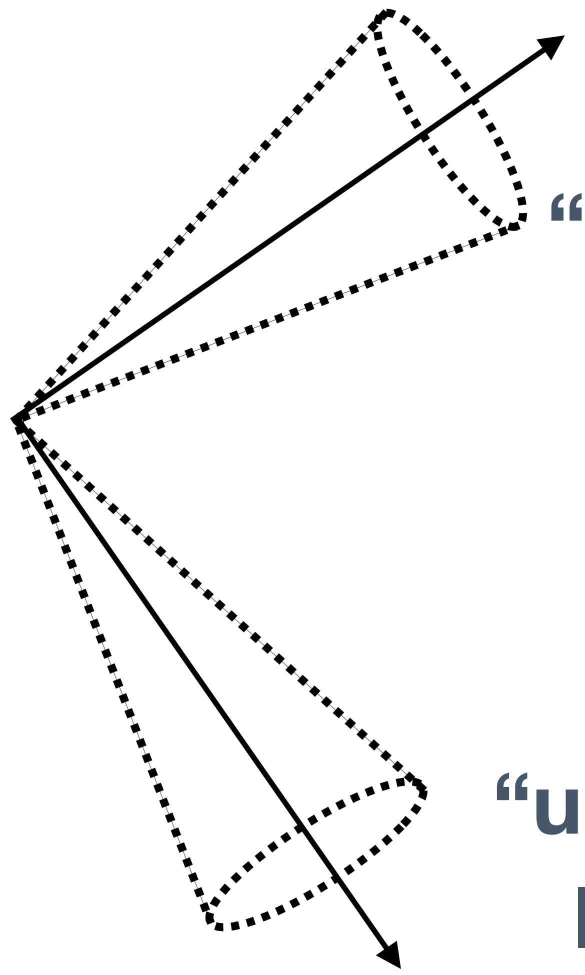
Open heavy flavors
in UPC events at the LHC

Untagged di-jets in γN scatterings



Dynamic constraints on (x, Q^2)

by varying dijet kinematics

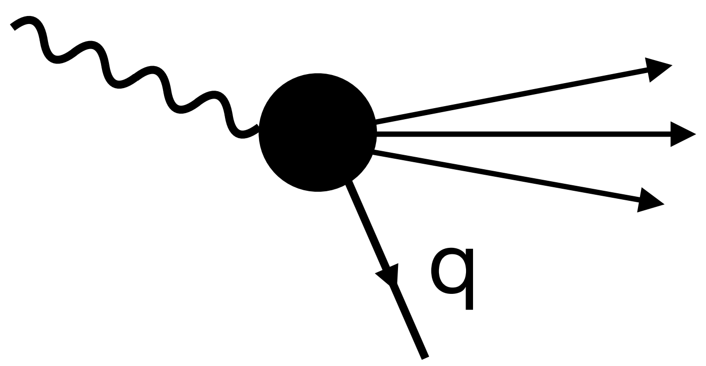


"untagged" light jet

"untagged" light jet

Limited access to low x and Q^2

→ jets limited to p_T >~15 GeV/c

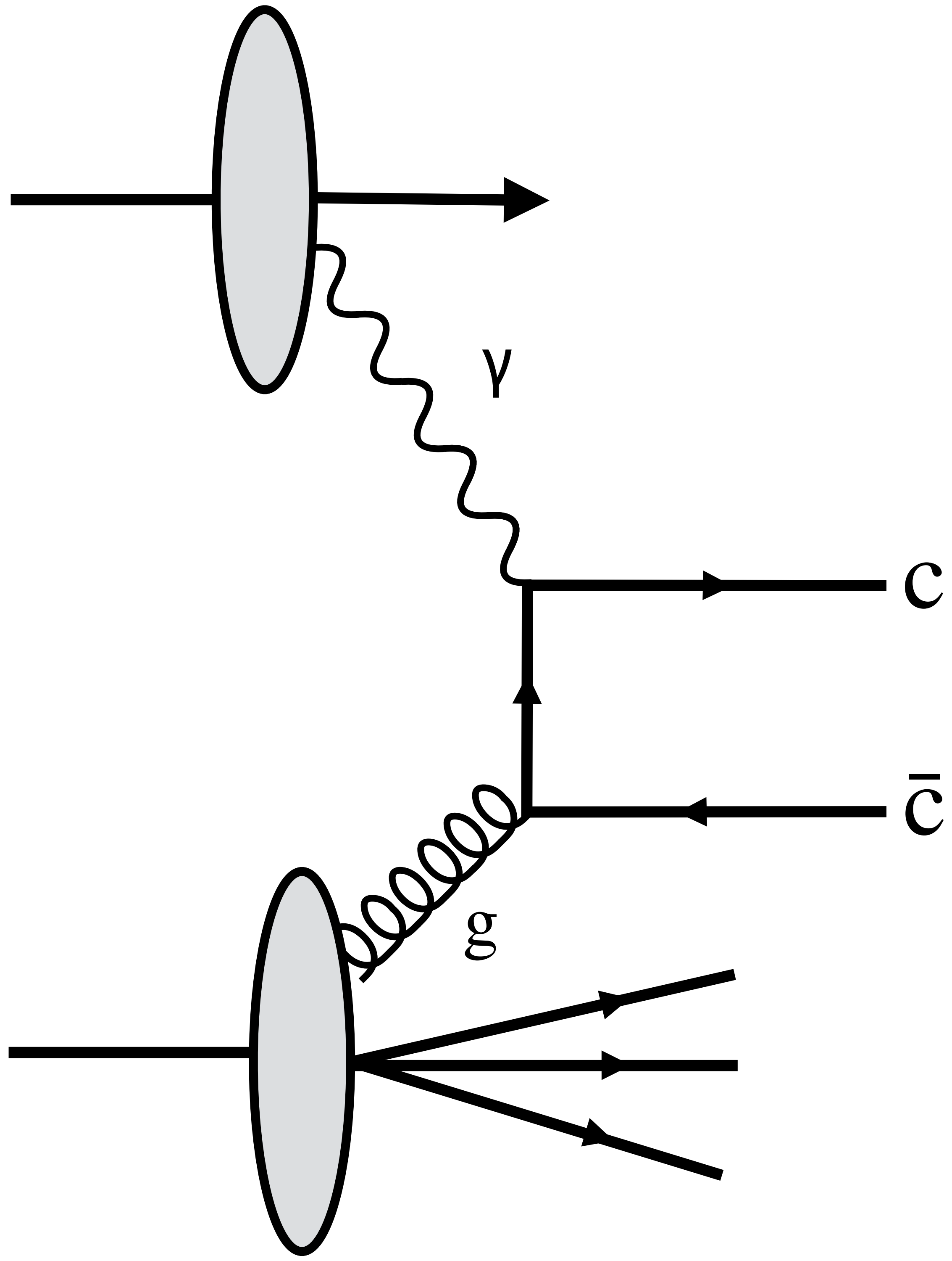


Sizeable contamination from "resolved"-photon processes:

→ complex theoretical description

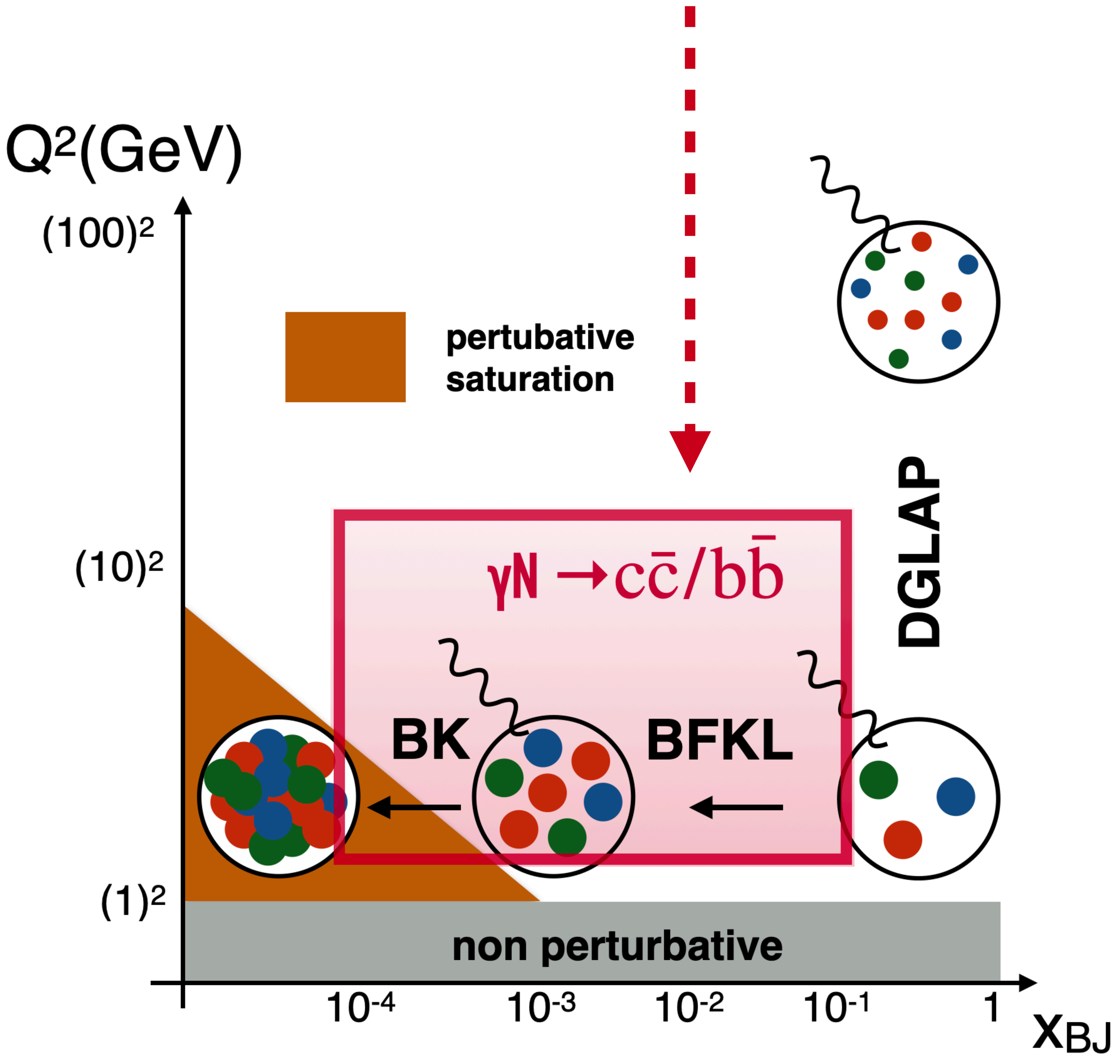
ATLAS, ATLAS-CONF-2017-011

"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)
- $Q^2_{min} \approx m^2_{c\bar{c}}$

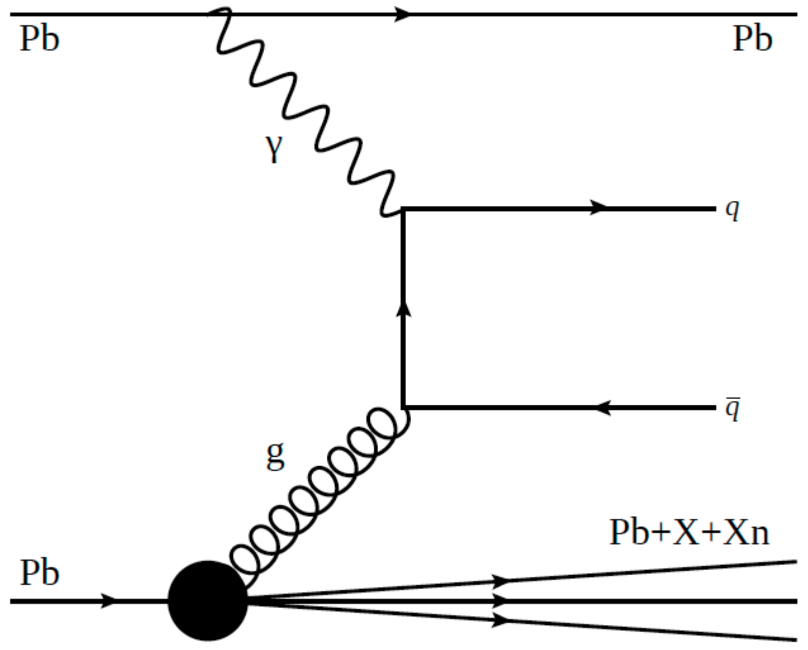
S. Klein, R. Vogt et al: Phys. Rev. C, v66, 2002

EM open heavy-quark production in UPC

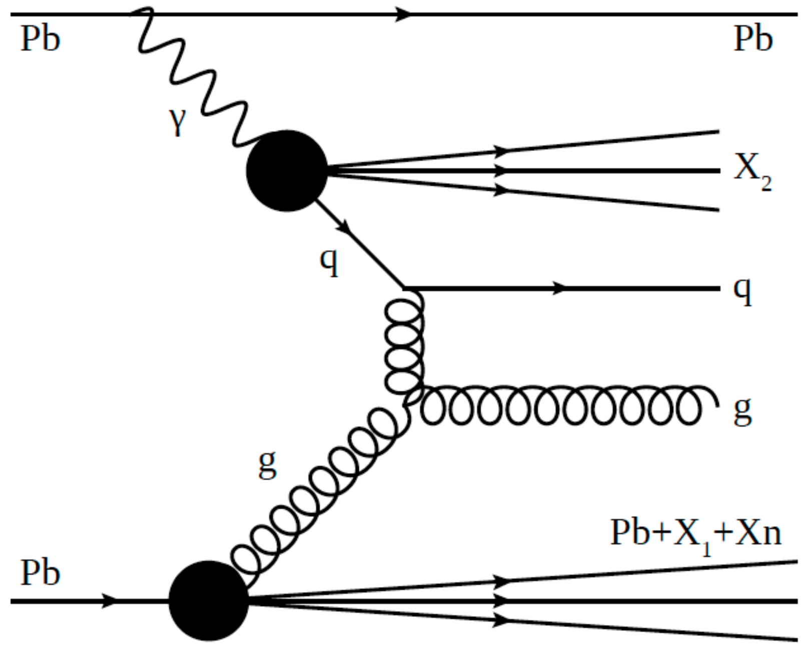
Inclusive photoproduction γg (signal):

Exclusive photoproduction

“Direct” photons



“Resolved” photons



Diffractive events

- Unbroken nuclei
- exchanging pomerons
- could be selected if in overlap with electromagnetic dissociation

EM open heavy-quark production in UPC

Background sources

$\gamma\gamma$ (purely EM)

- Not probing nucleus structure (background
- 0n0n events with both two gaps
- **can "pass" γN event selection if in overlap with electromagnetic dissociation**

Contamination from hadronic peripheral events (background)

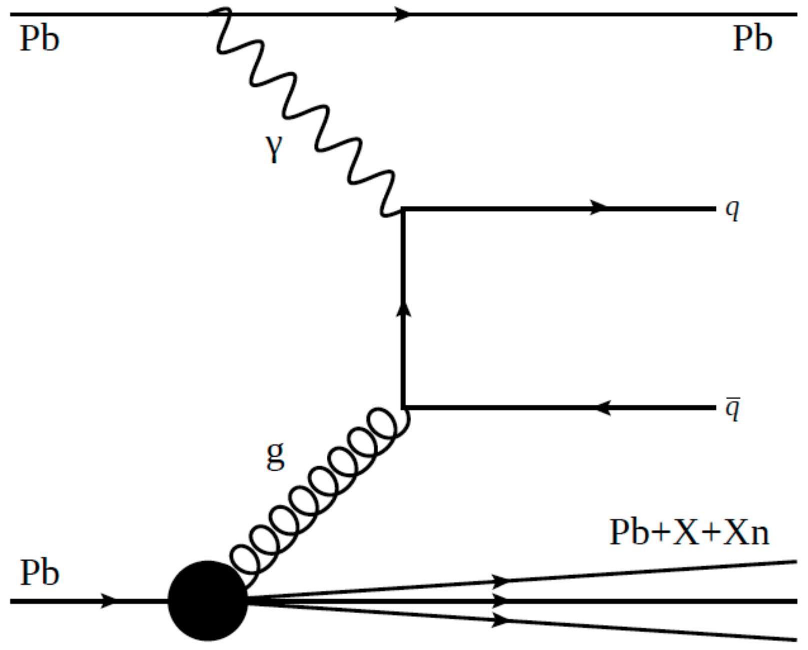
- XnXn events
- **can "pass" γN event selection in the presence of ZDC inefficiencies**

Beam-gas/beam halo events (background)

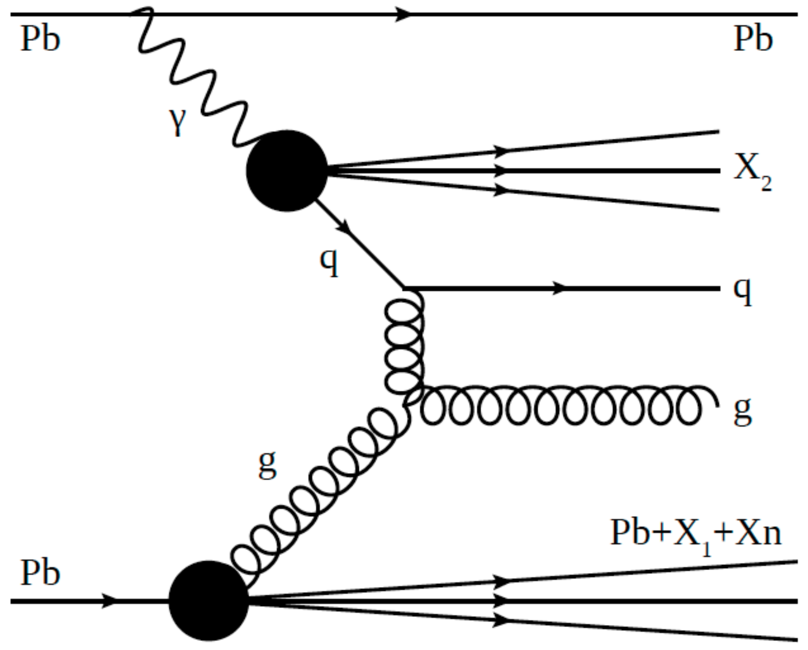
Inclusive photoproduction γg (signal):

Exclusive photoproduction

"Direct" photons



"Resolved" photons



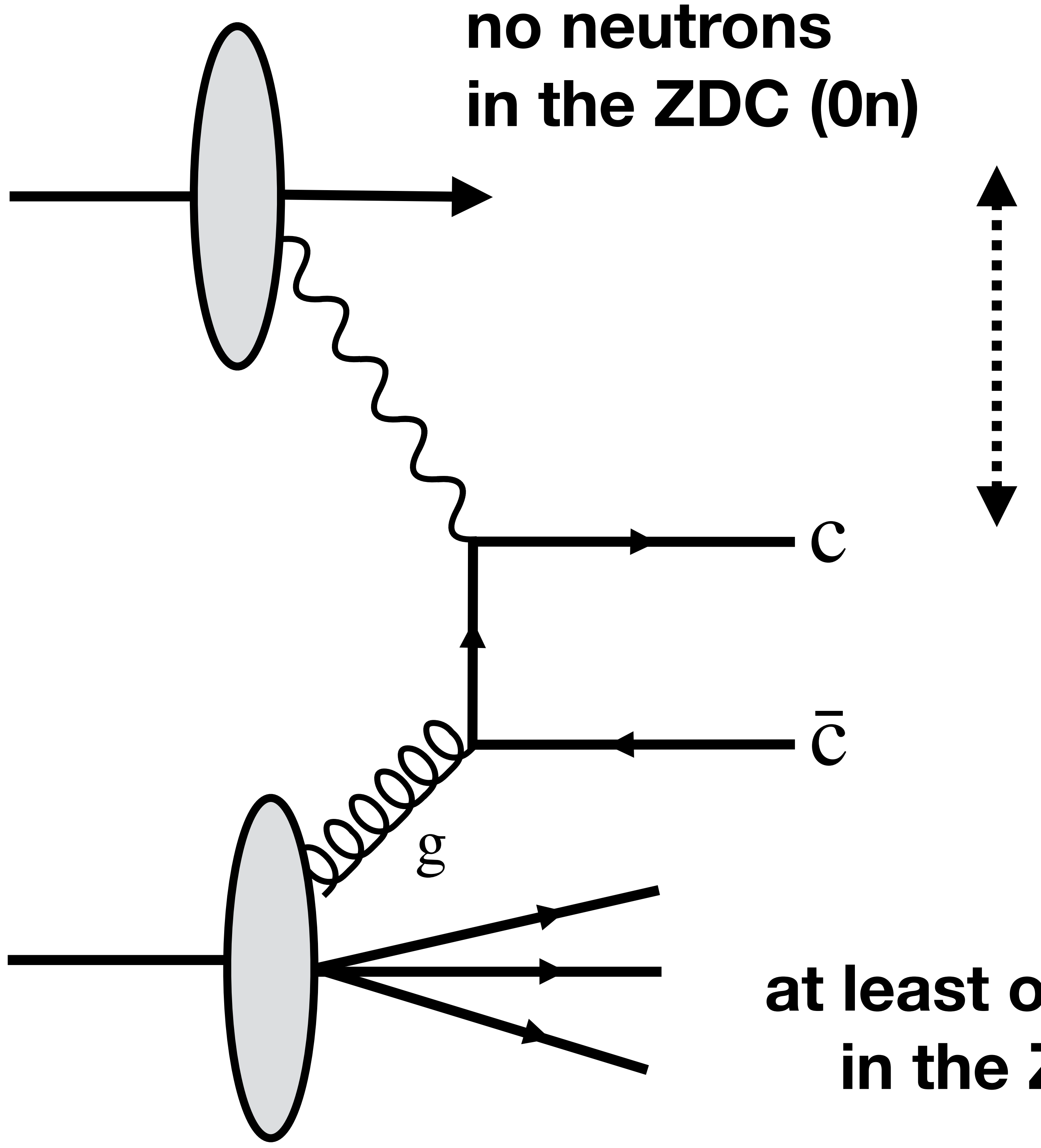
Diffractive events

- Unbroken nuclei
- exchanging pomerons
- could be selected if in overlap with electromagnetic dissociation

Experimental strategy for “hard” inclusive photoproduction

Event selection: Xn0n events with “rapidity gap”.

no neutrons in the ZDC (0n)

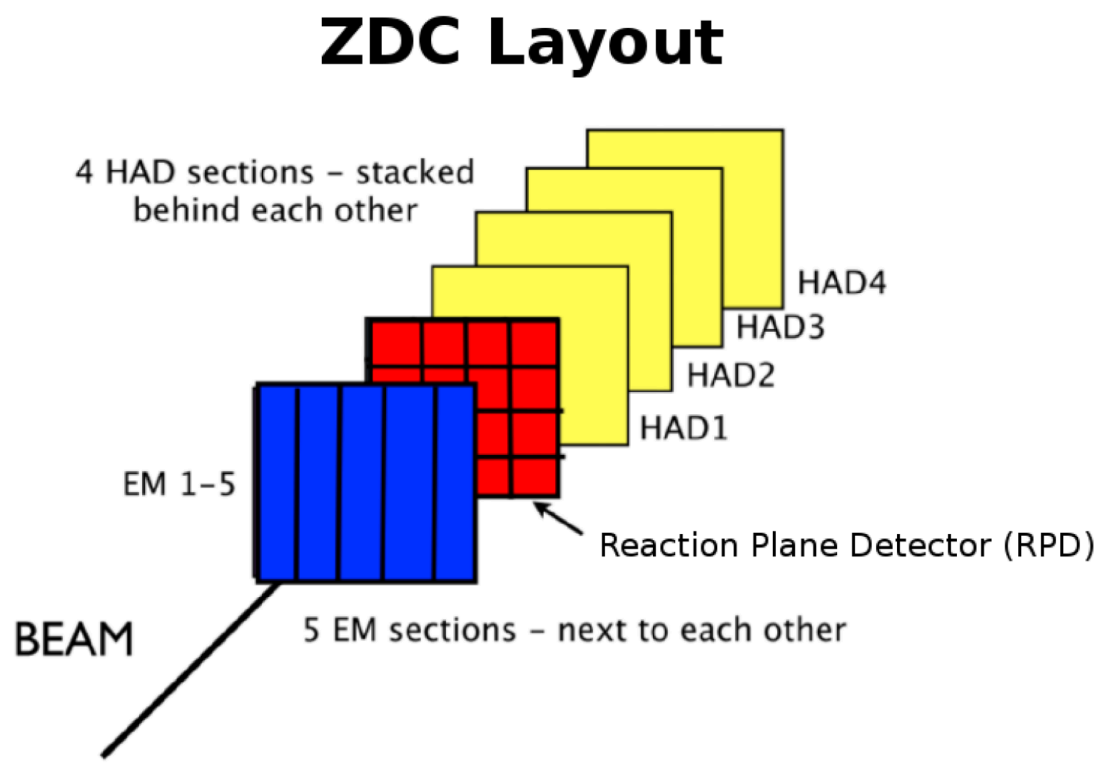


Rapidity gap in the direction of outgoing photon

Heavy-quark tagged jets:
→ high-statistics up to high-p_T

$D^0 \rightarrow K^-\pi^+$ reconstruction:
→ Trace charm quark down to low p_T

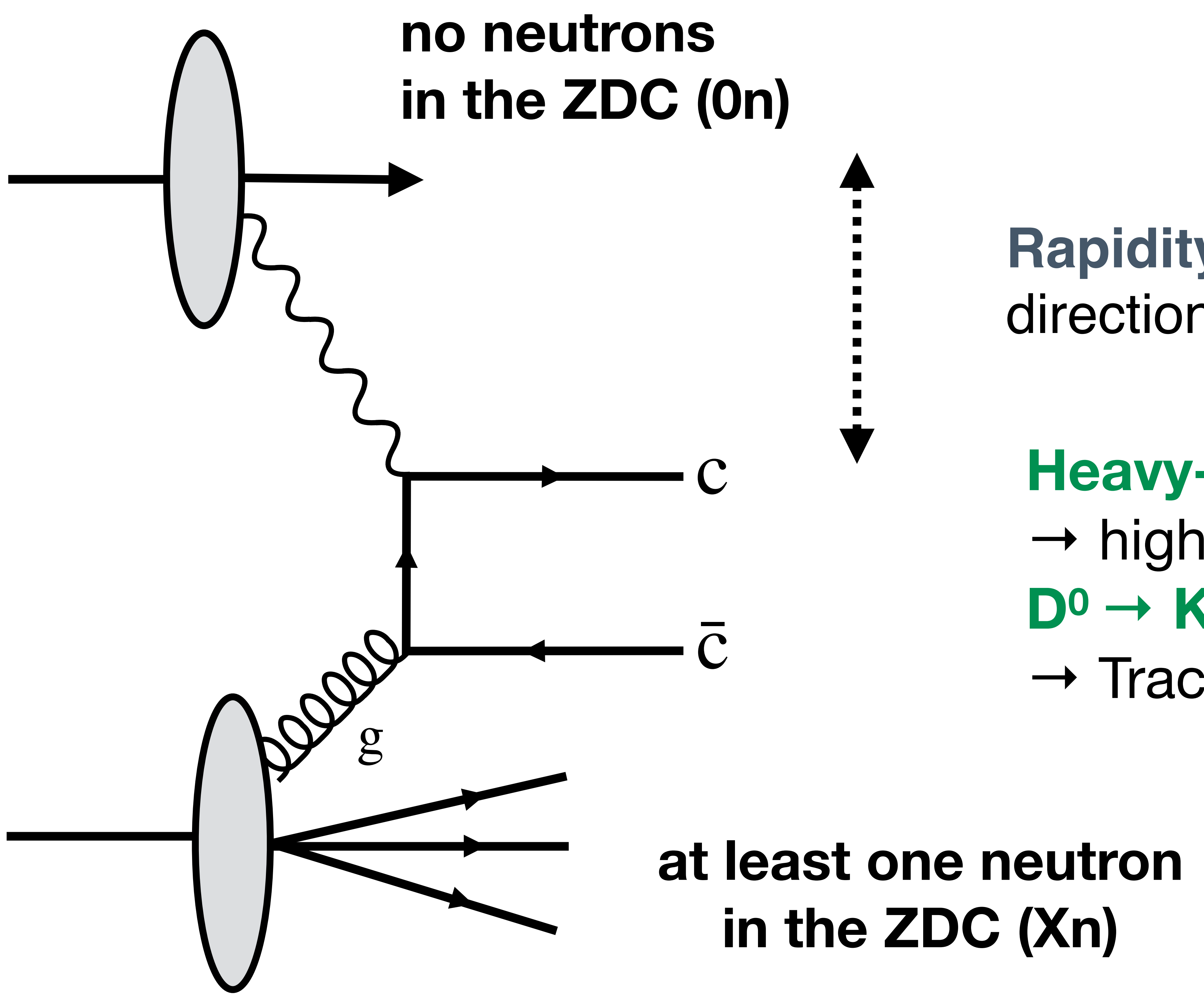
at least one neutron in the ZDC (Xn)



Questions for theorists: should we call this process inclusive photoproduction or semi-inclusive photoproduction due to the requirement on the Xn?

Experimental strategy for "hard" inclusive photoproduction

Event selection: Xn0n events with "rapidity gap".



Rapidity gap in the direction of outgoing photon

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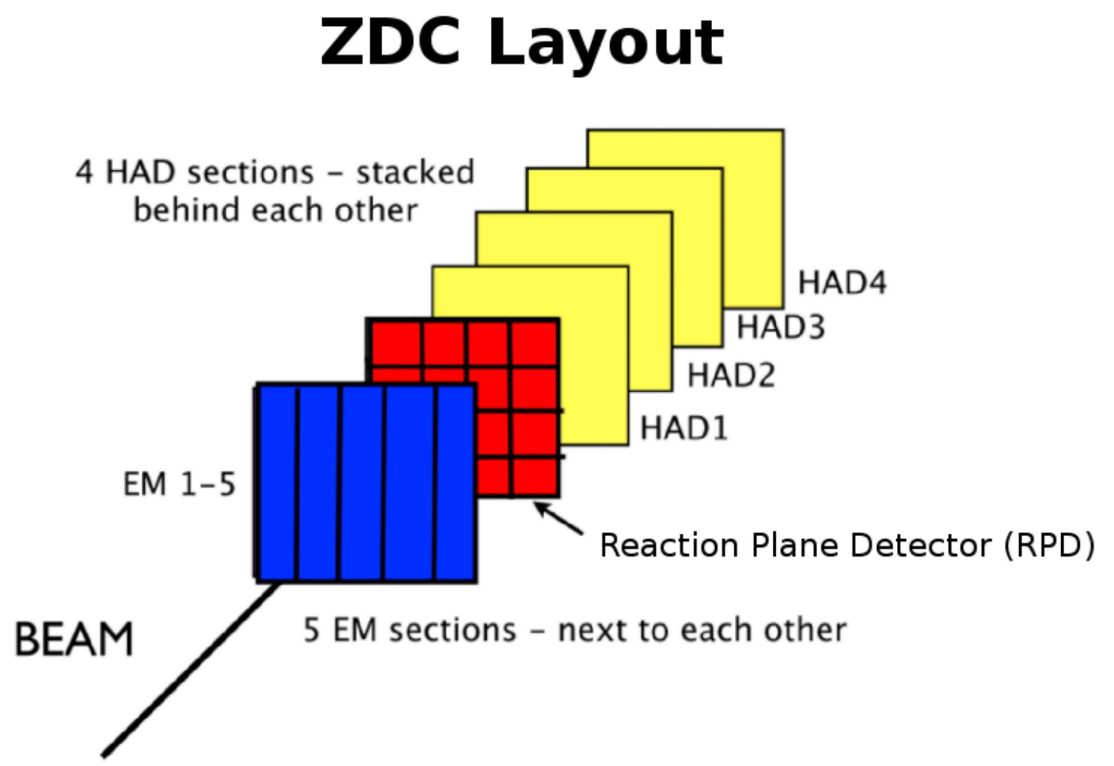
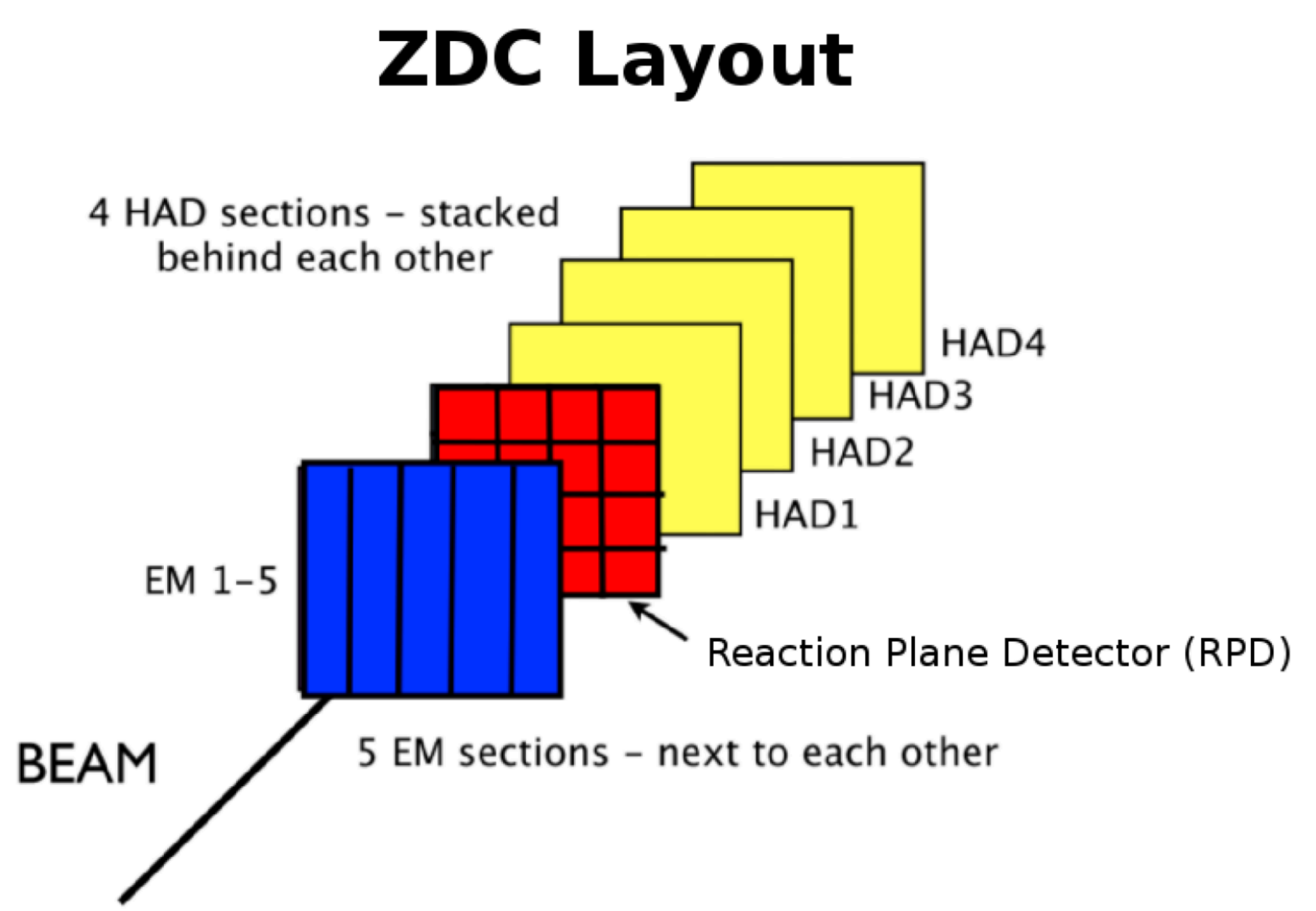


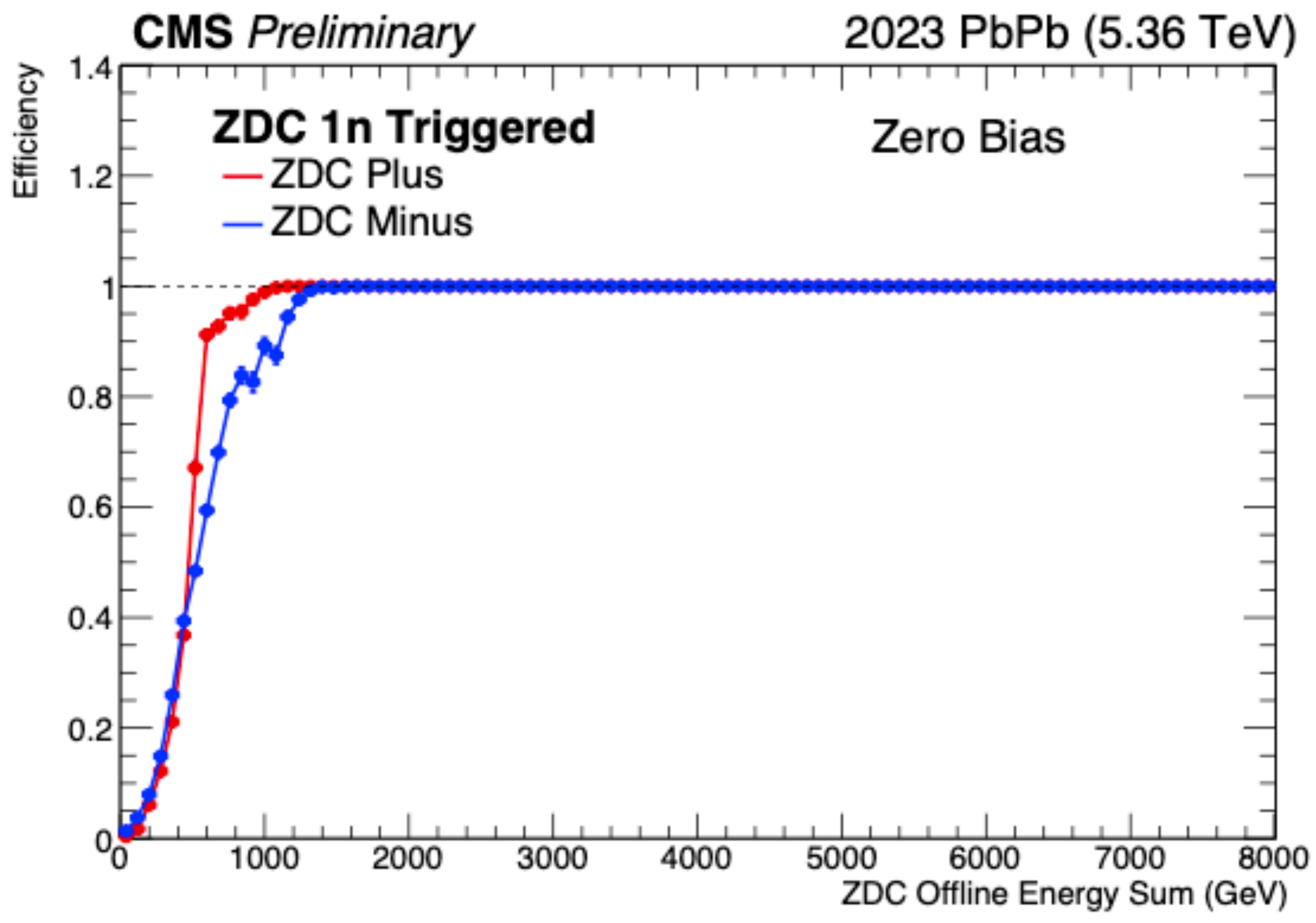
Triggering on γγ, γN events as a big experimental challenge!
- Hardware trigger system (Level-1 has max accepted rate in heavy-ions about 20-30 kHz)
- Interaction rate of γγ, γN in heavy-ions $\mathcal{O}$(MHz)!!

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

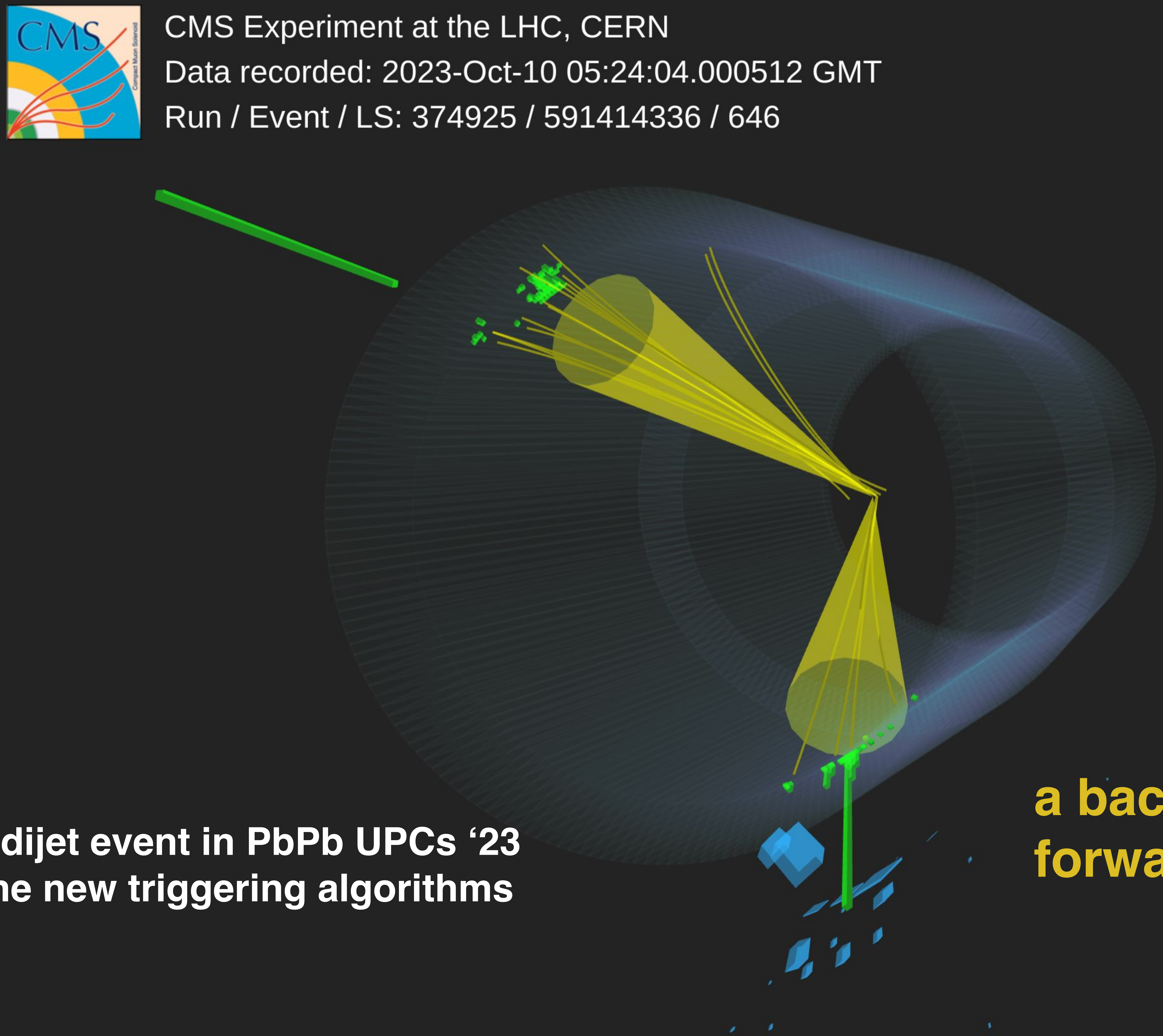


Zero-Degree Calorimeter (ZDC) as a trigger detector
→ integrate ZDC in the Level-1 (hardware) trigger-emulation chain
→ develop a strategy for fast online calibration

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



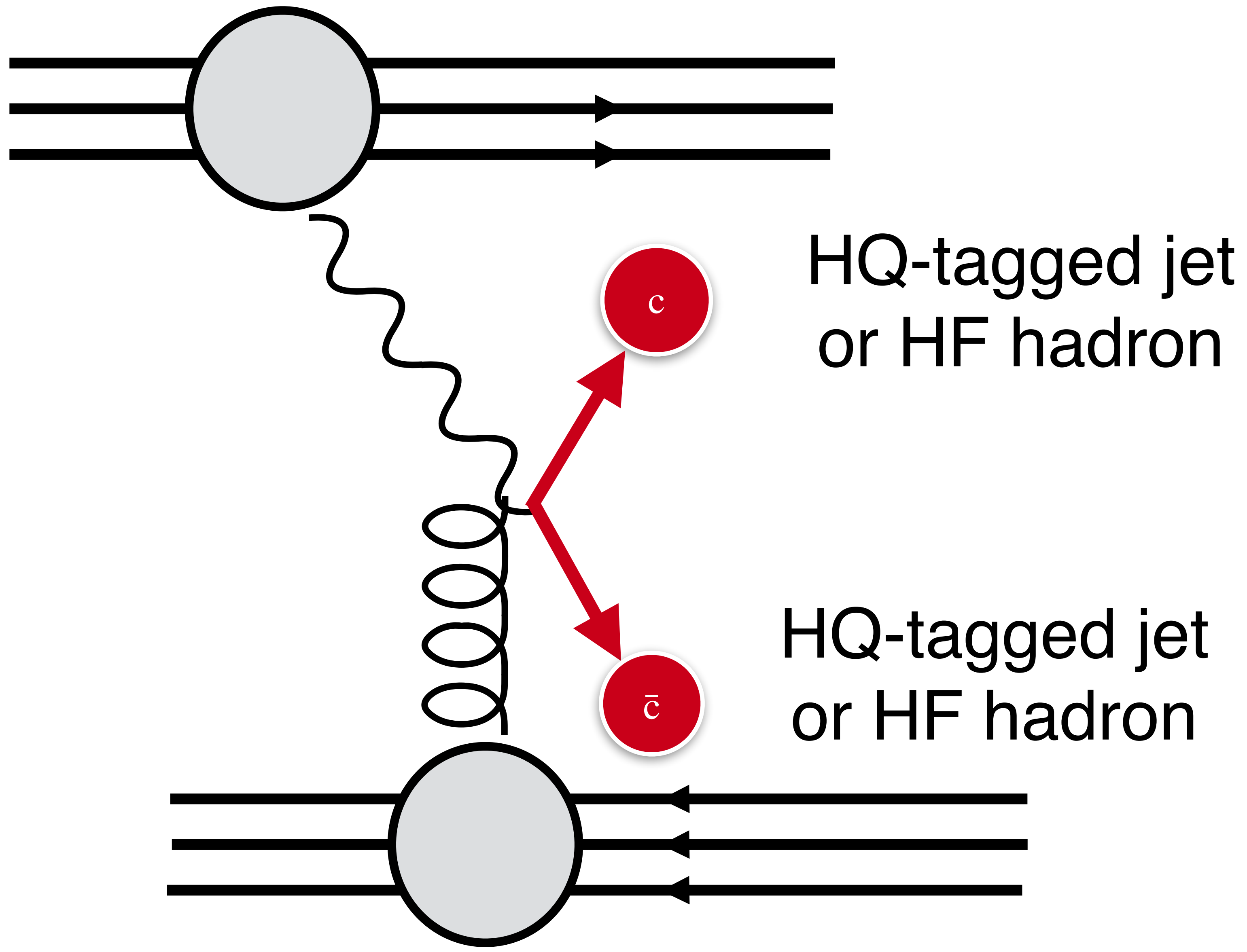
New trigger algorithms for γγ and γN "hard" events
→ **photonuclear high-Q^2 triggers** (ZDCXOR && L1 jet)
→ **photonuclear low-Q^2 triggers** (ZDCXOR)
→ **γγ and diffractive triggers**



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

a background-less forward dijet event!

Measurement of di-cjets and di-bjets in γN scatterings

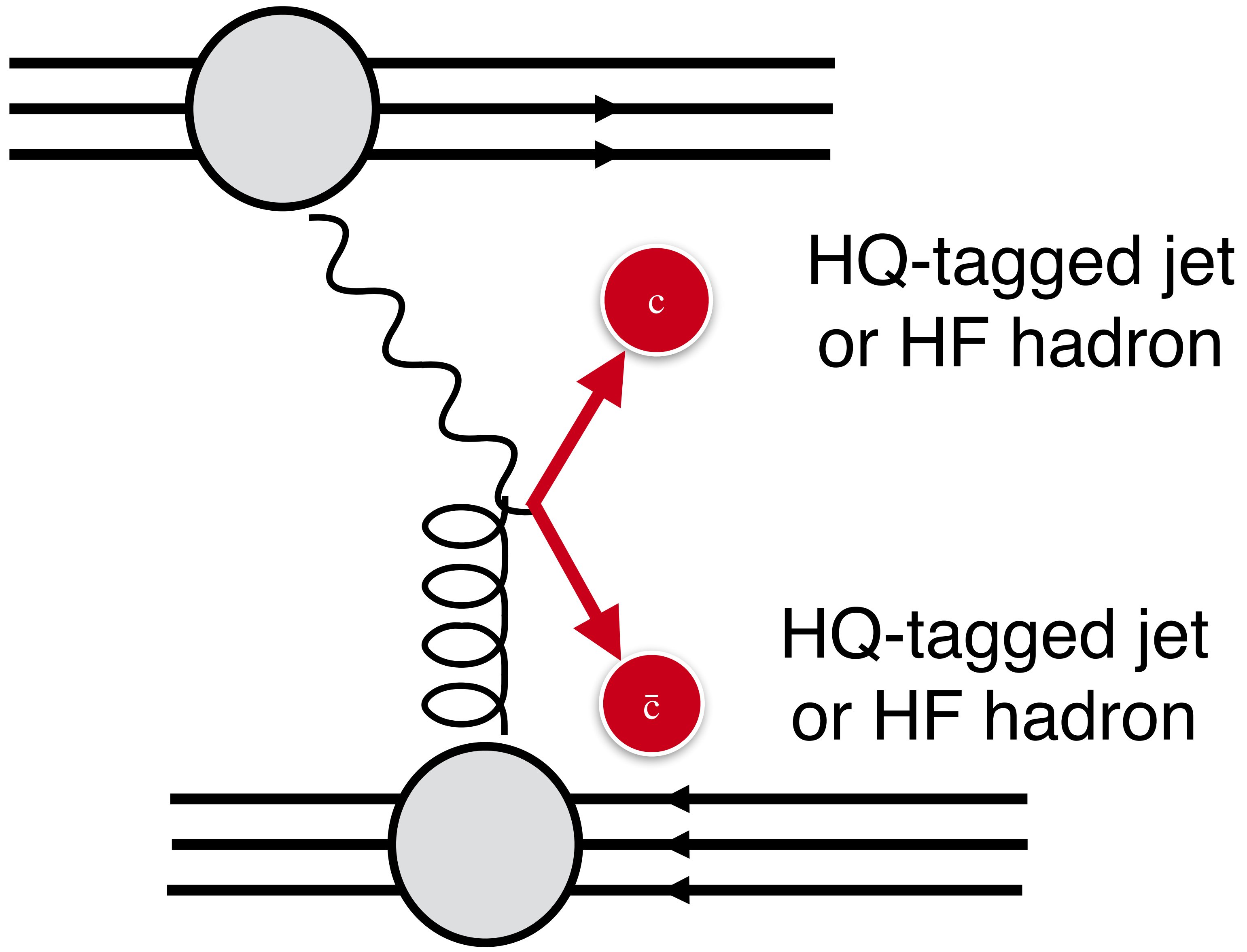


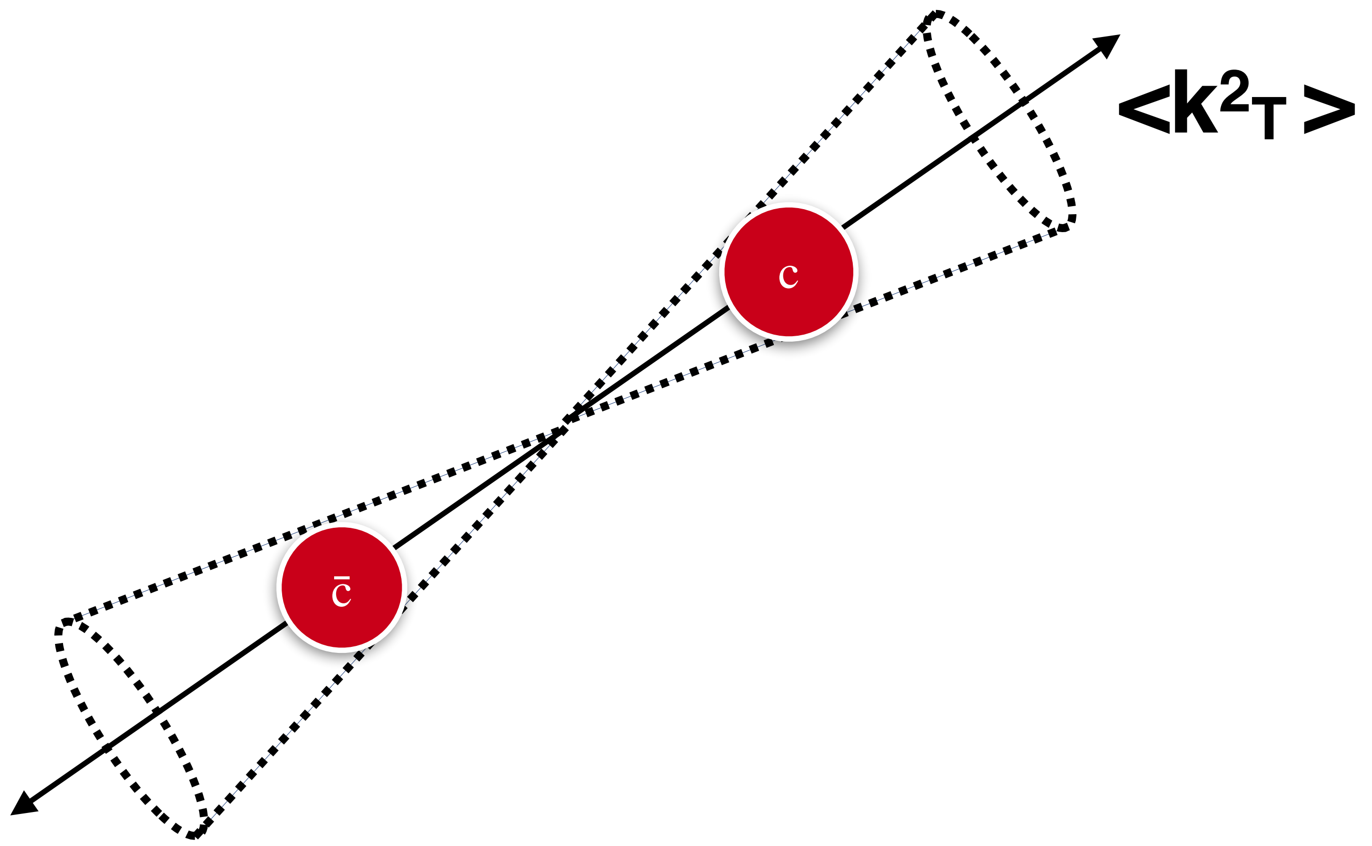
Measurement of charm and beauty tagged dijet system in pp, PbPb, AuAu

→ stronger constraints on x,Q^2

→ **enable the study of low-p_T dijet decorrelation!**

Measurement of di-cjets and di-bjets in γN scatterings





$\Delta\varphi$ correlations of di-HQ jets or hadrons:

→ strong sensitivity to the Q_s scale via $<k^2_T>$ broadening

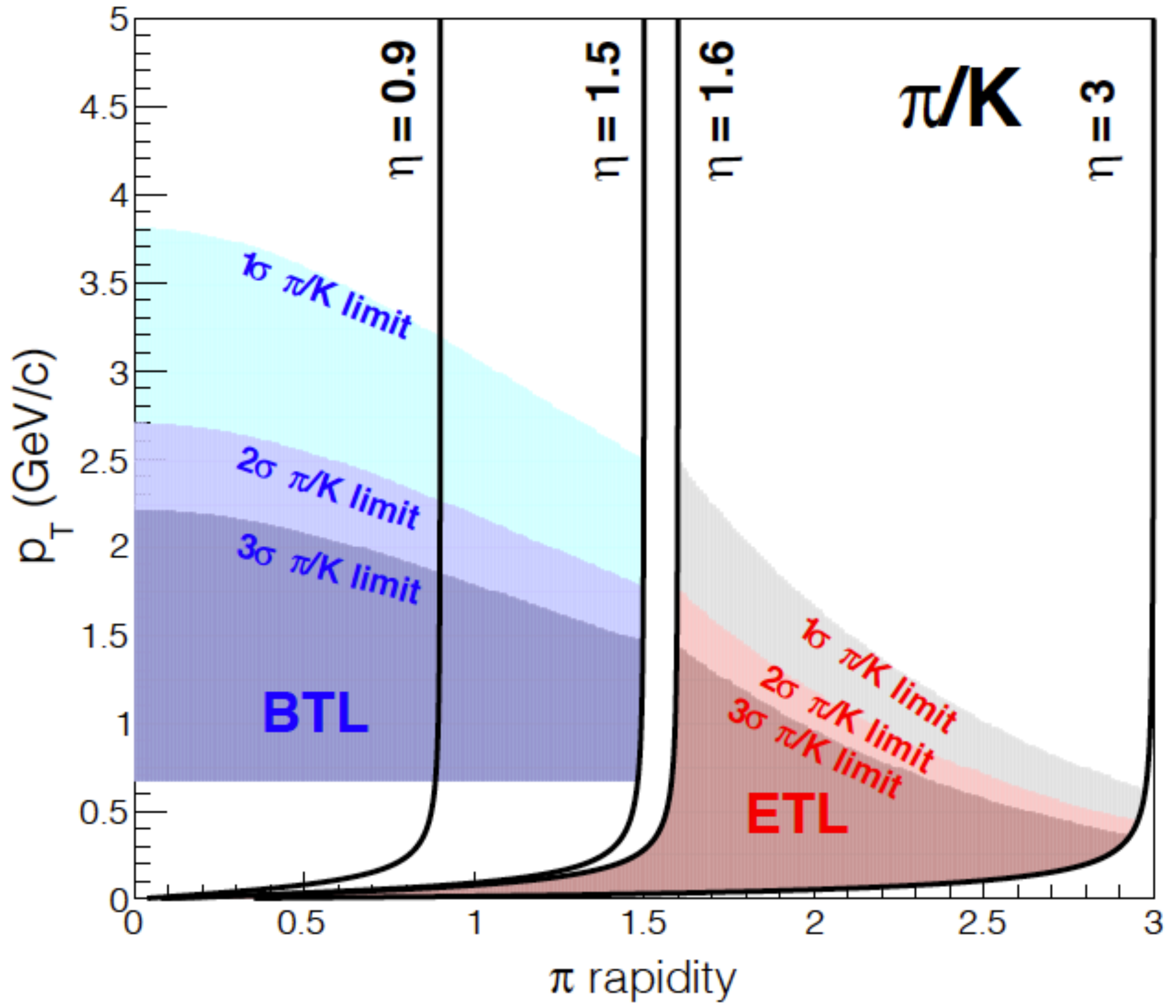
Measurement of charm and beauty tagged dijet system in pp, PbPb, AuAu

→ stronger constraints on x,Q^2

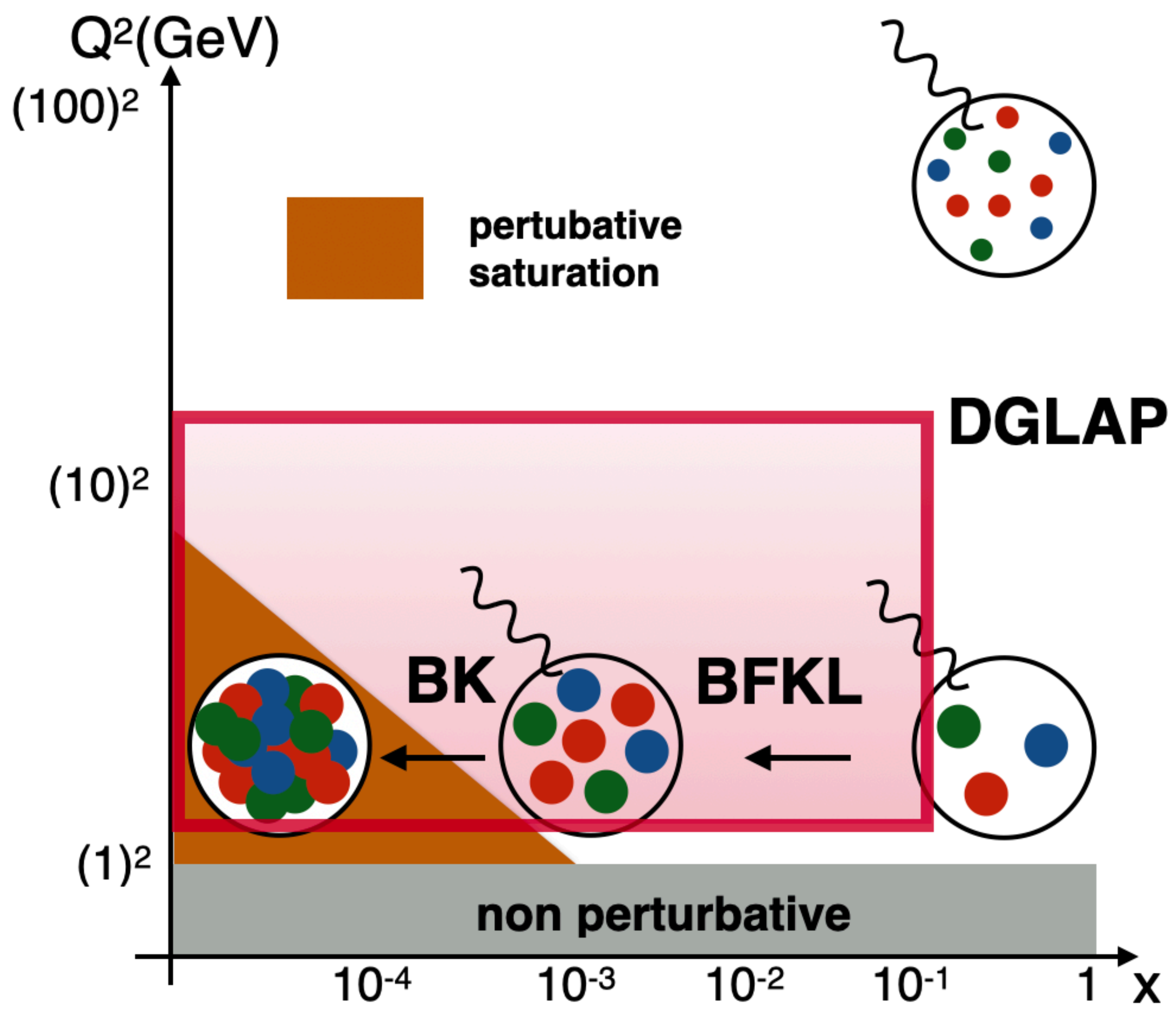
→ enable the study of low-p_T dijet decorrelation!

CMS at the LHC in Run 4 (2029–2032) and beyond

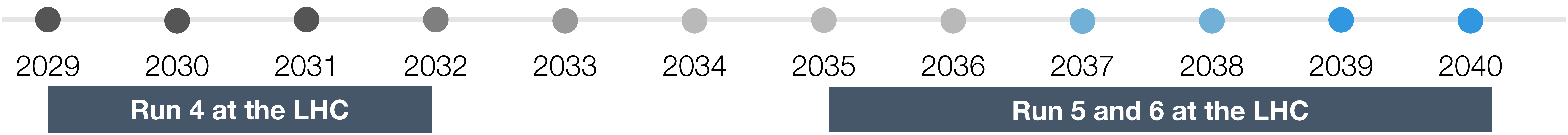
- **New tracker with |η|<4**
- PID for low p_T hadrons



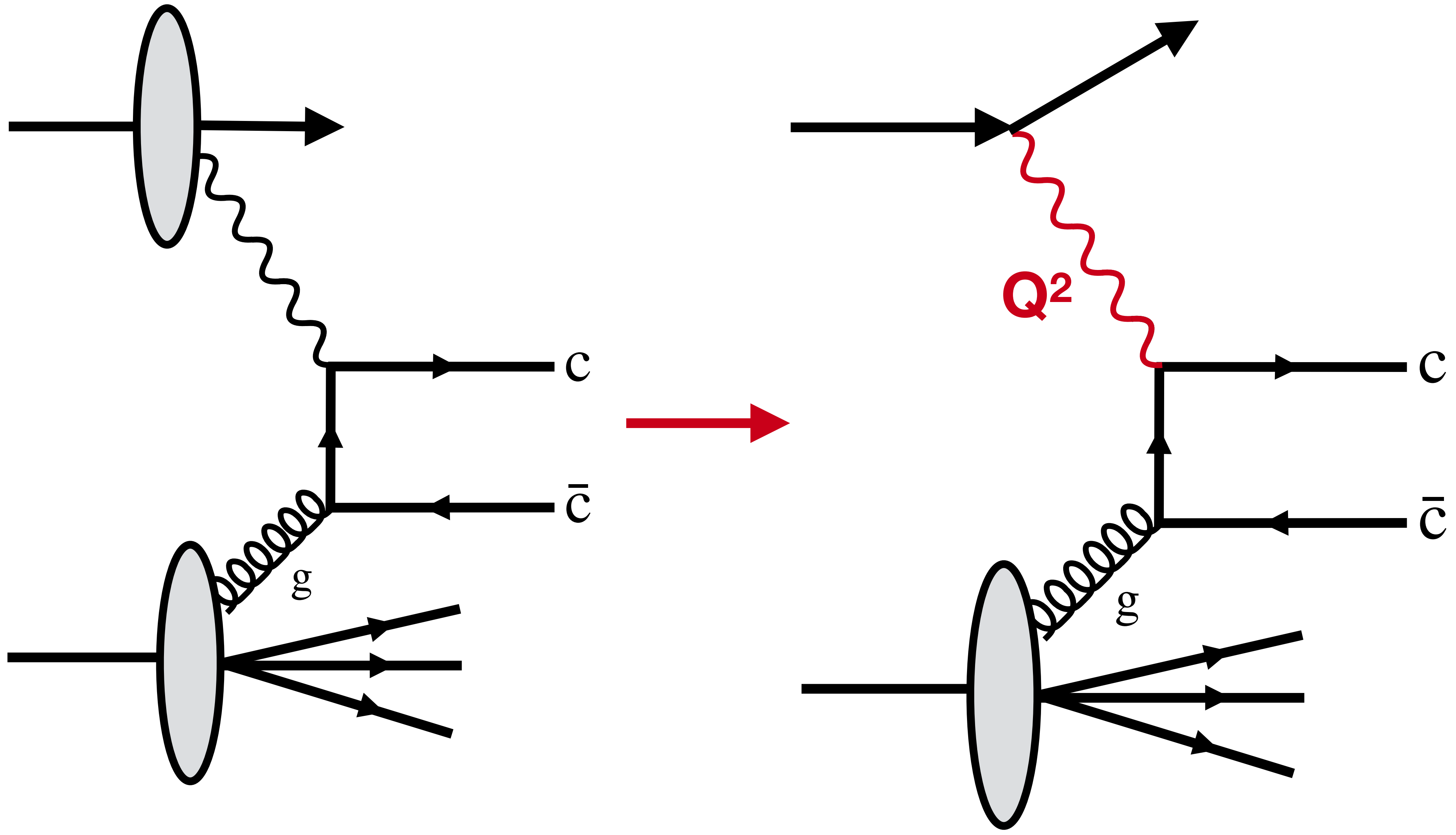
CMS Phase-II tracker: CMS-TDR-014
CMS: Phys. Rev. D 96, 112003
CMS: CMS-TDR-020



→ **Down to x ~ 10^{-5}** with $\gamma N \rightarrow c\bar{c}$ observables
→ New observables for nPDF studies (e.g. double-parton scatterings)



From UPCs at LHC/RHIC to 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

Highlights from the future EIC heavy-flavor program:

Inclusive heavy-flavors and $D\bar{D}$ correlations:
→ gluon (n)PDFs down to moderate/low x_{BJ}
→ beyond the collinear limit (TMDs)

Heavy-quark jet and substructure:
→ parton-propagation in "cold" vs "hot" matter

Heavy-flavor hadrochemistry and collectivity:
→ what is the time scale of hadronization?

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

CMS at the LHC

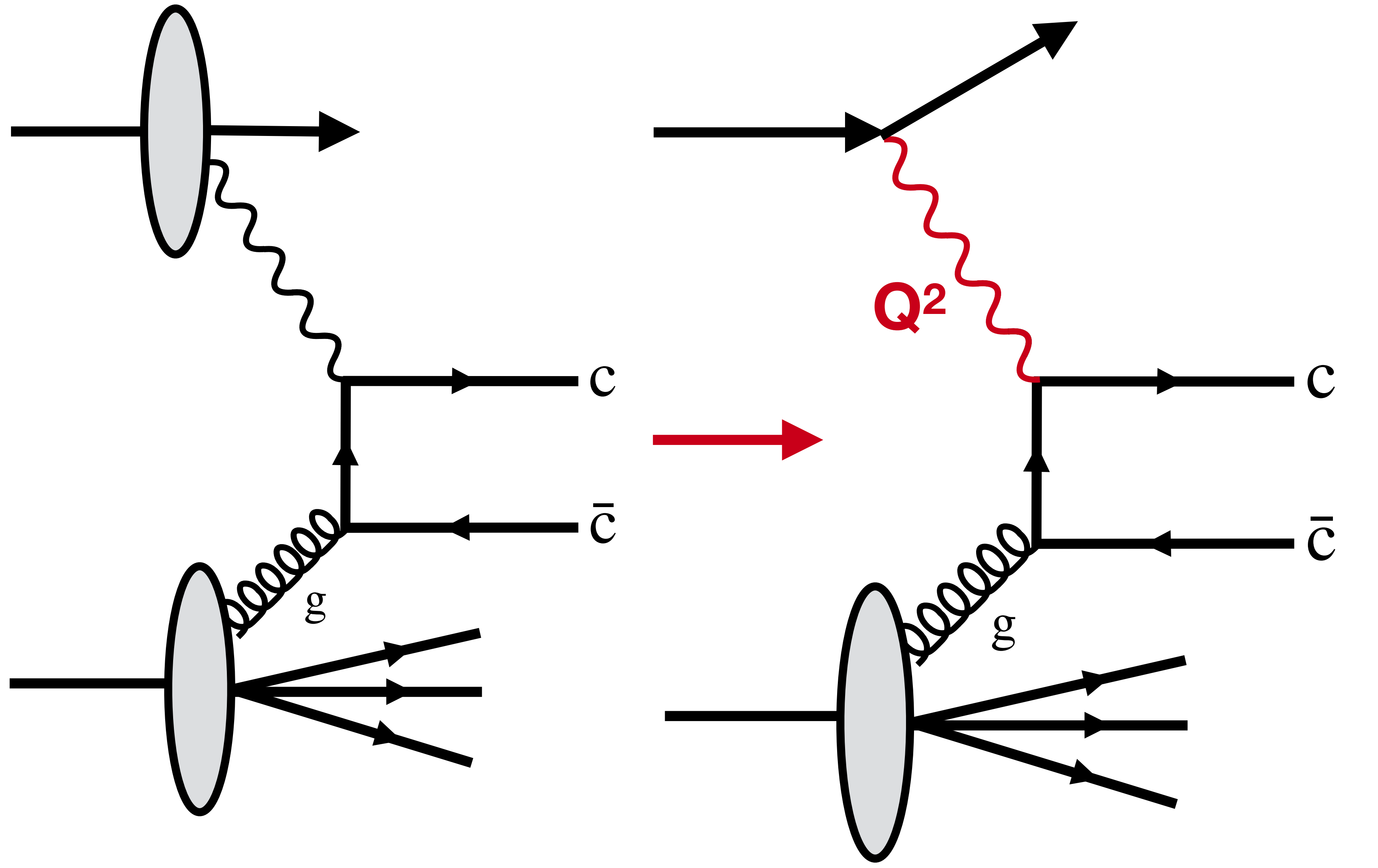
Upgraded CMS at the LHC (|η| up to 4 + PID with MTD)

Run 5 and 6 at the LHC

sPHENIX at RHIC

EIC physics data-taking

Summary and outlook



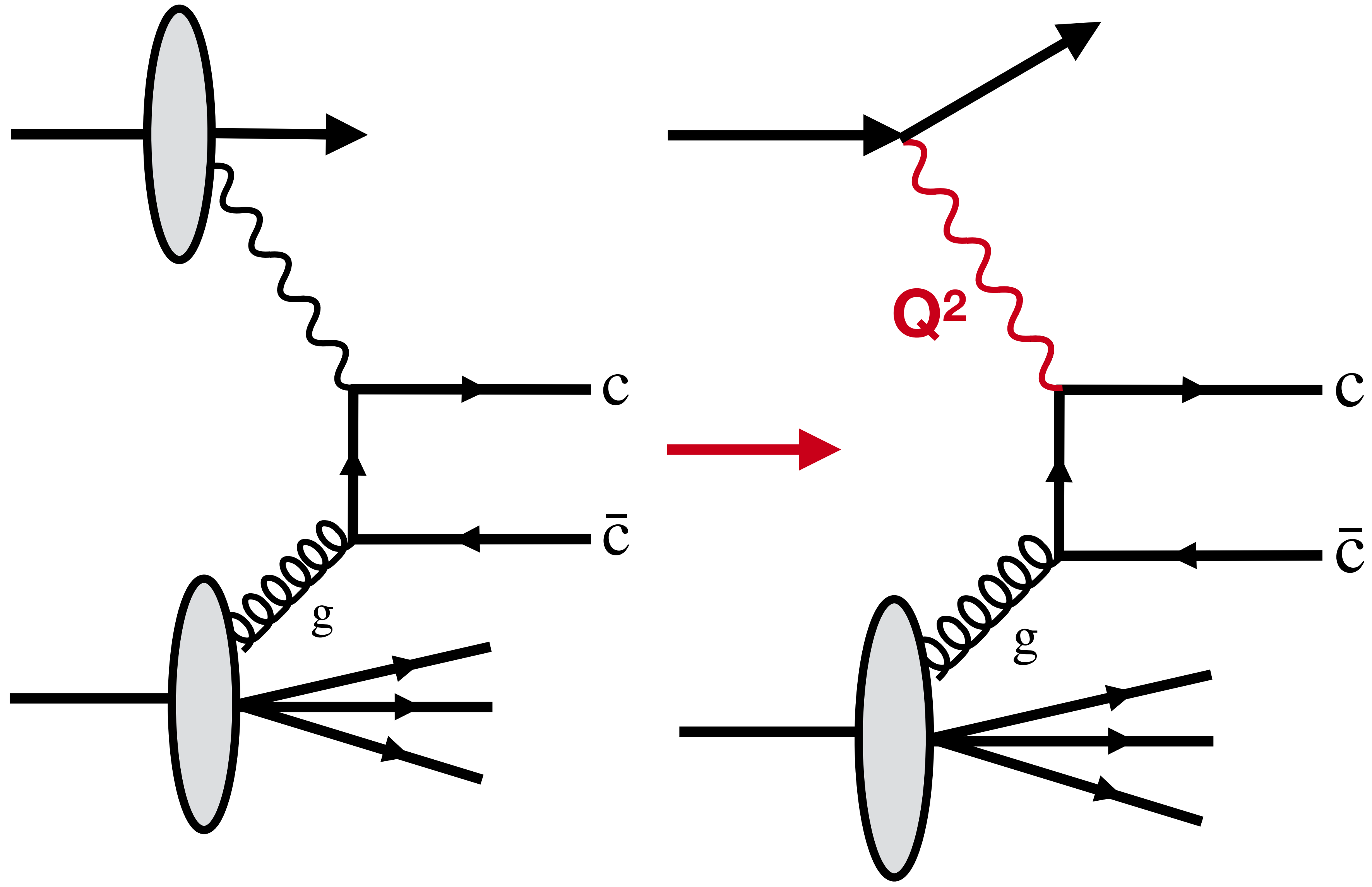
With jets and open-heavy flavor measurements in UPC collisions at LHC:

- dynamic access to a large (x,Q^2) region with the same experimental probe
- access to low-x, low-Q^2 region

Need for theoretical guidance and calculations for both LHC/RHIC and EIC:

- **"Correct" definition of the physics process**
- **Need for theoretical predictions:**
  - $dN/dp_T dy$ for charm and beauty hadrons, heavy-flavor tagged jets for inclusive photoproduction, diffractive production, …)
  - dijet measurements and correlations
- **And MC calculations for photonuclear events, diffractive events, and γγ:**
  → estimate contaminations or relative magnitude of the various subprocesses

Summary and outlook



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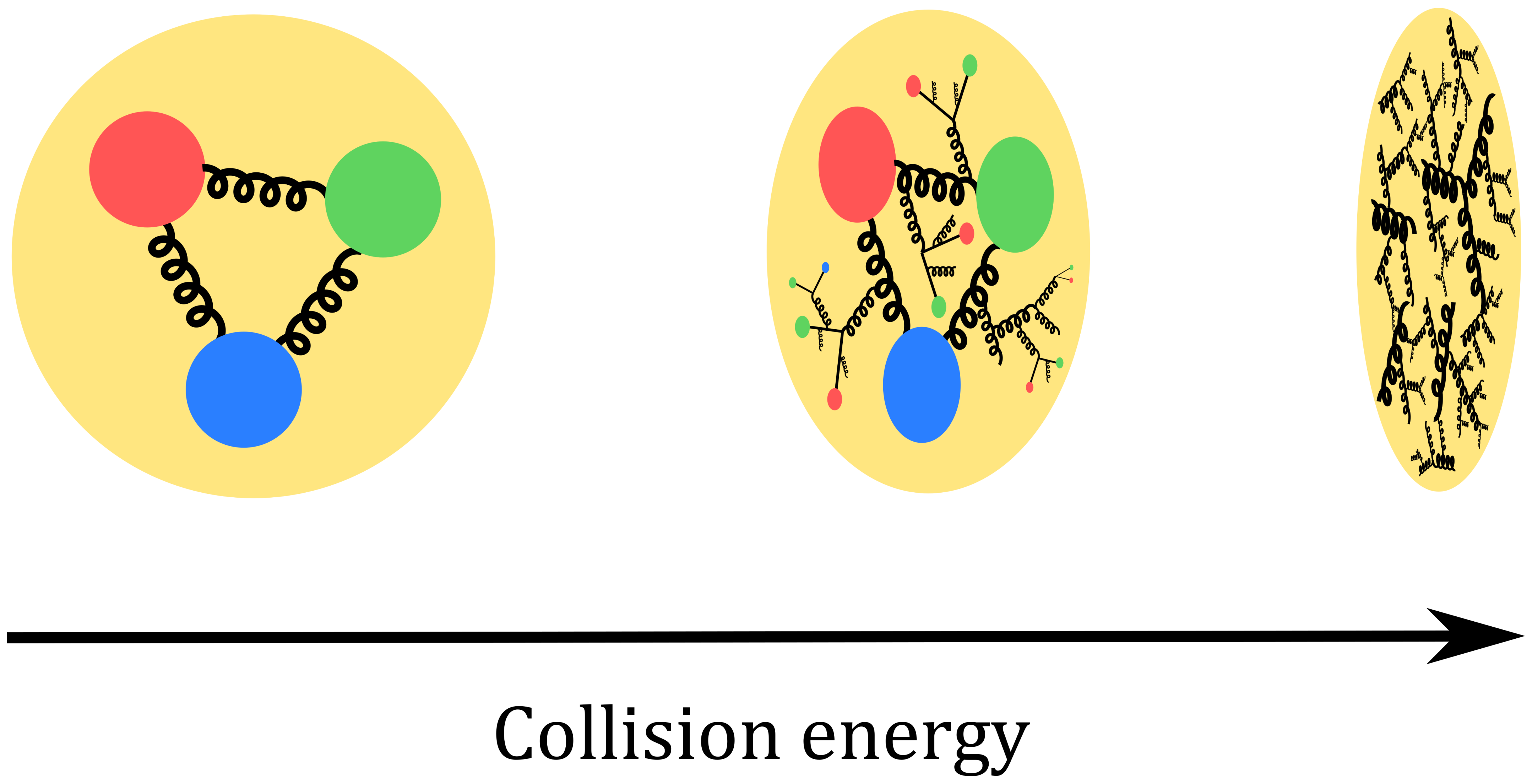
- **And MC calculations for photonuclear events, diffractive events, and γγ:**
  → estimate contaminations or relative magnitude of the various subprocesses

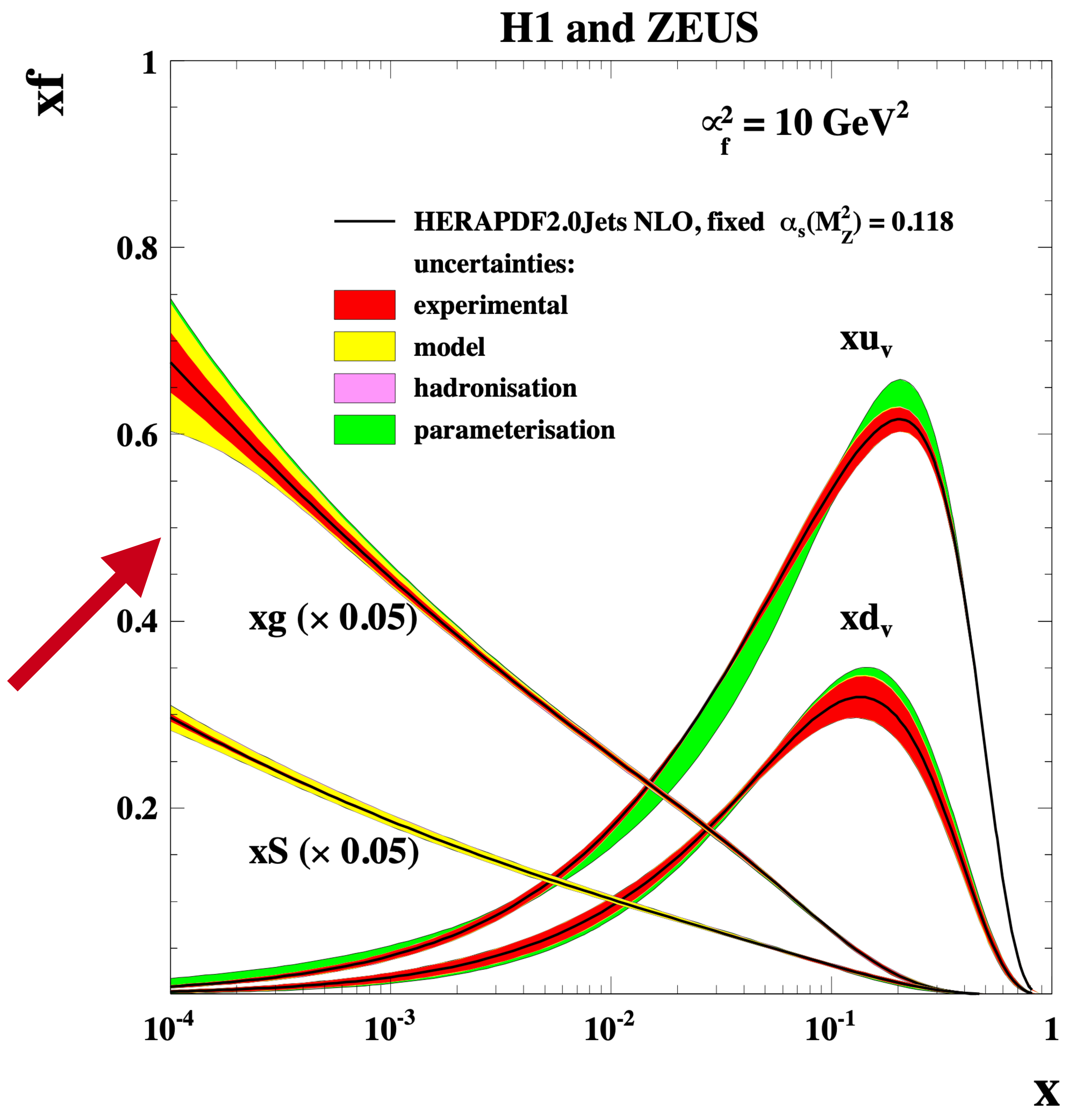
In the long term, exploit the possibility of performing analogous measurements at EIC and at the LHC/RHIC:

- running different ion species in both AA and pA collisions b

BACKUP

A new program to study cold "extreme" partonic matter





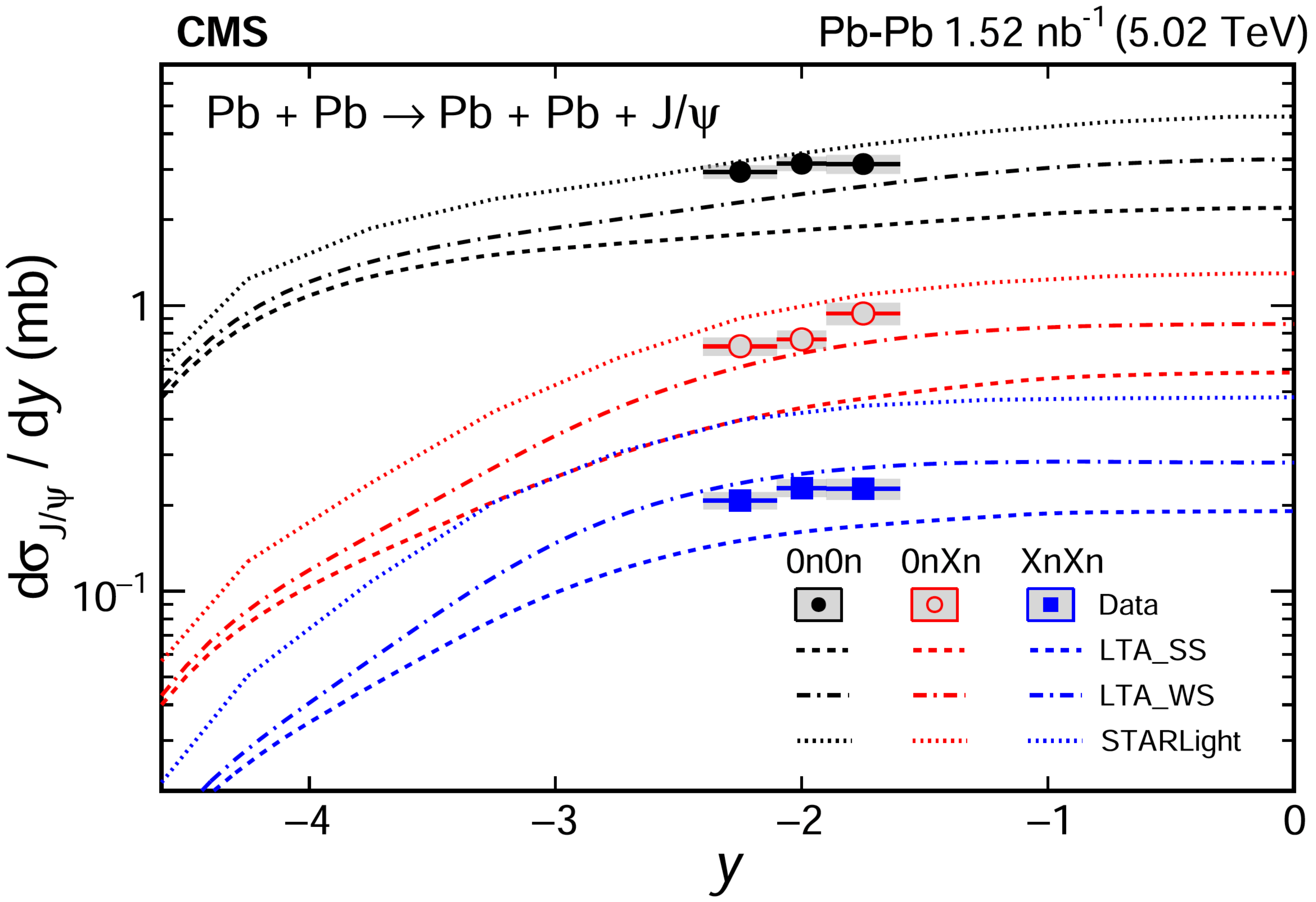
What happens to nuclear matter in the presence of very large densities of low-x gluons?

→ **Can we observe a new phase of matter characterized by the so-called gluon saturation?**

→ **"Gluon saturation" is also at the core of the program of the future Electron-Ion Collider**

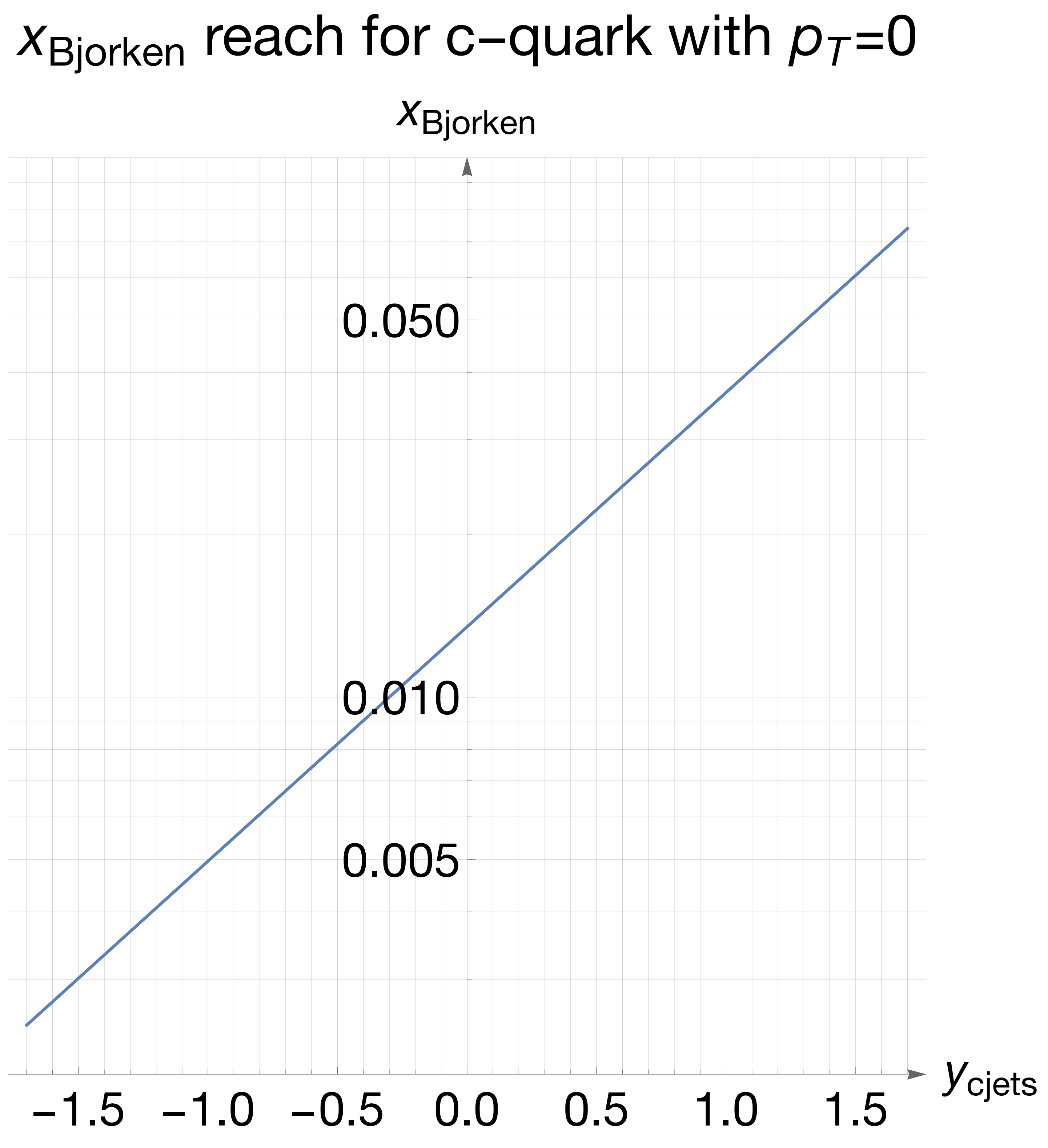
Coherent J/ψ in PbPb UPCs with forward-neutron tag

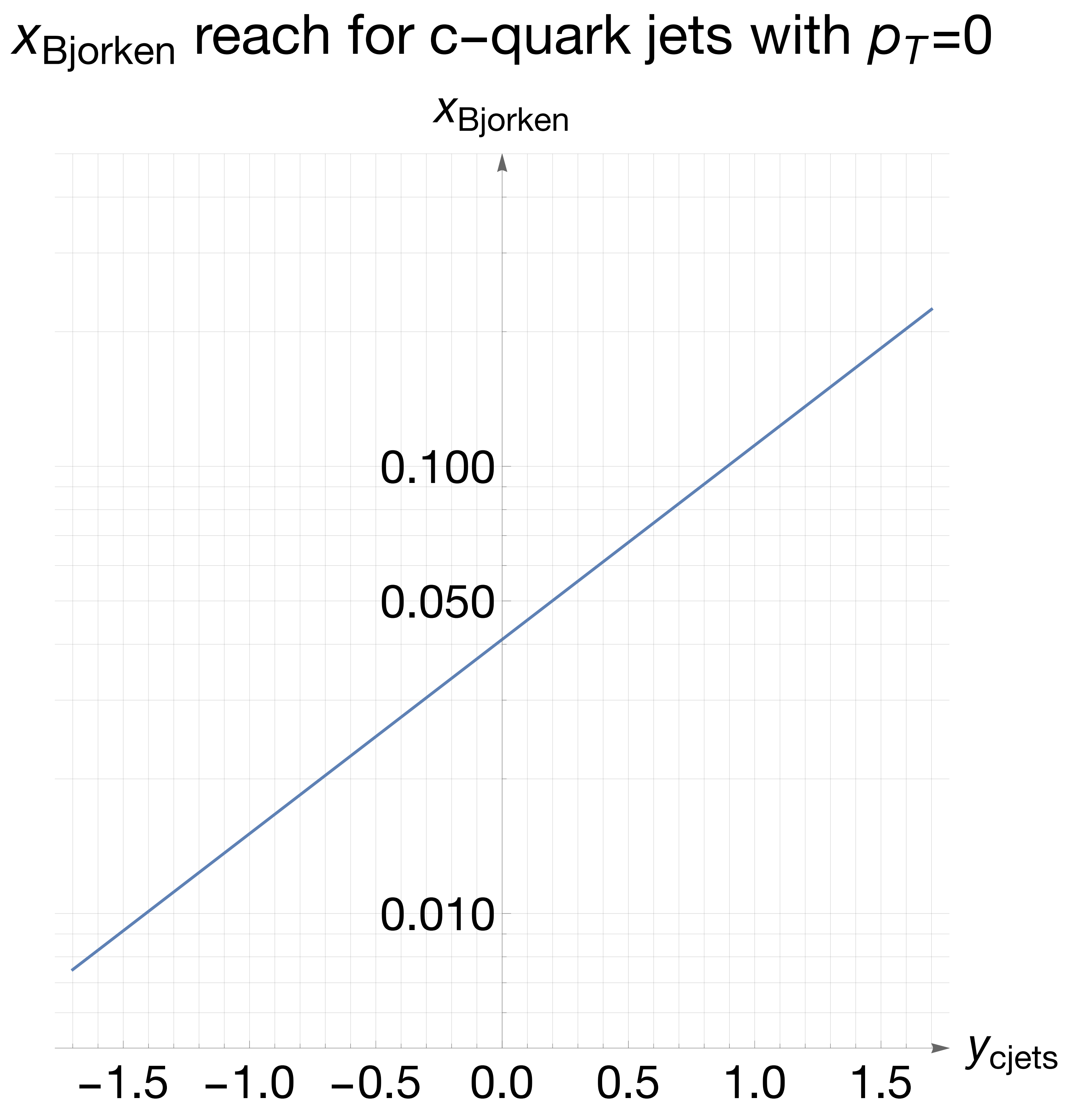
First coherent measurement in different neutron classes → ***inputs to disentangle low from high energy γN events***



Leading twist approximation (LTA) *- pQCD calculation with nuclear shadowing effects from multinucleon interference (both weak and strong shadowing scenarios are shown)*
Color dipole (CD) *with different model parameters (BGK, BGW, IIM)*
→ *assume quark-antiquark dipole scattering from the nuclear targets*

Low-x reach of HF γN at LHC



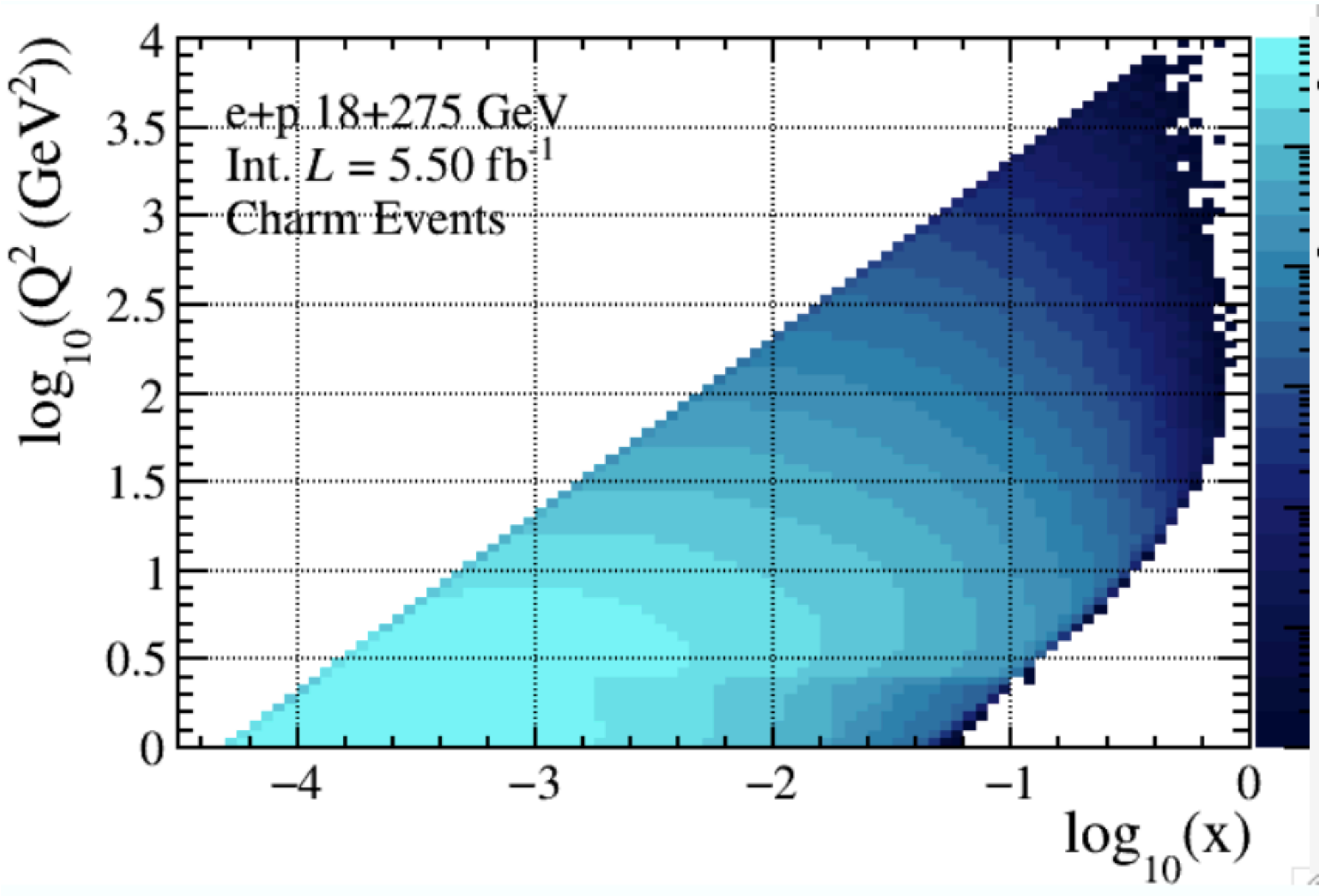


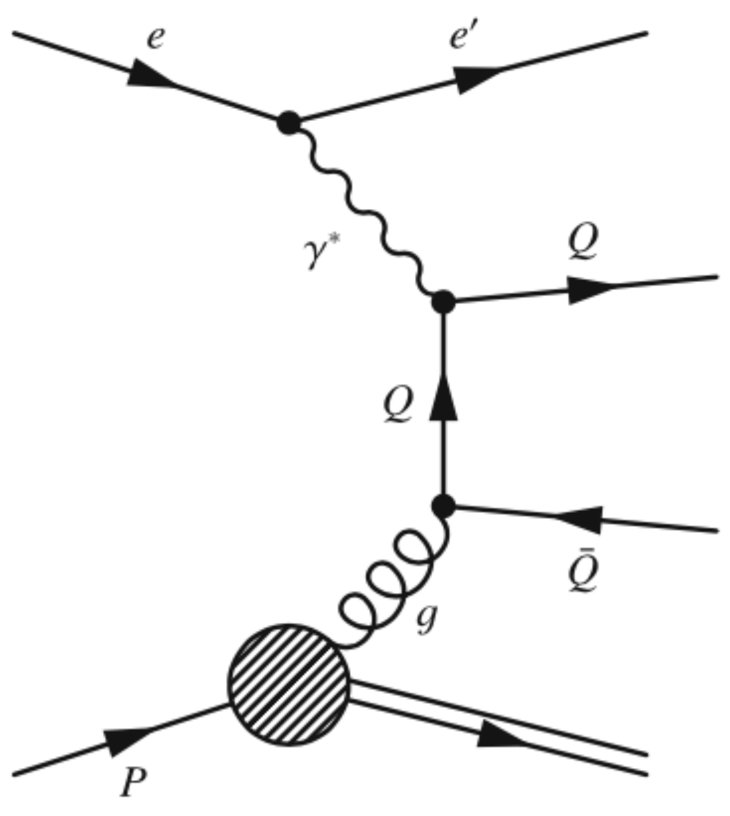
	min x	max x
charm LHC |η| < 2.0	$6.64 \cdot 10^{-5}$	$3.63 \cdot 10^{-3}$
charm LHC |η| < 4.0	$2.07 \cdot 10^{-4}$	$1.13 \cdot 10^{-2}$
beauty LHC |η| < 2.0	$8.99 \cdot 10^{-6}$	$2.68 \cdot 10^{-2}$
beauty LHC |η| < 4.0	$2.8 \cdot 10^{-5}$	$8.34 \cdot 10^{-2}$
charm RHIC |η| < 1.1	$4.49 \cdot 10^{-3}$	$4.06 \cdot 10^{-2}$
beauty RHIC |η| < 1.1	$1.4 \cdot 10^{-2}$	$1.26 \cdot 10^{-1}$

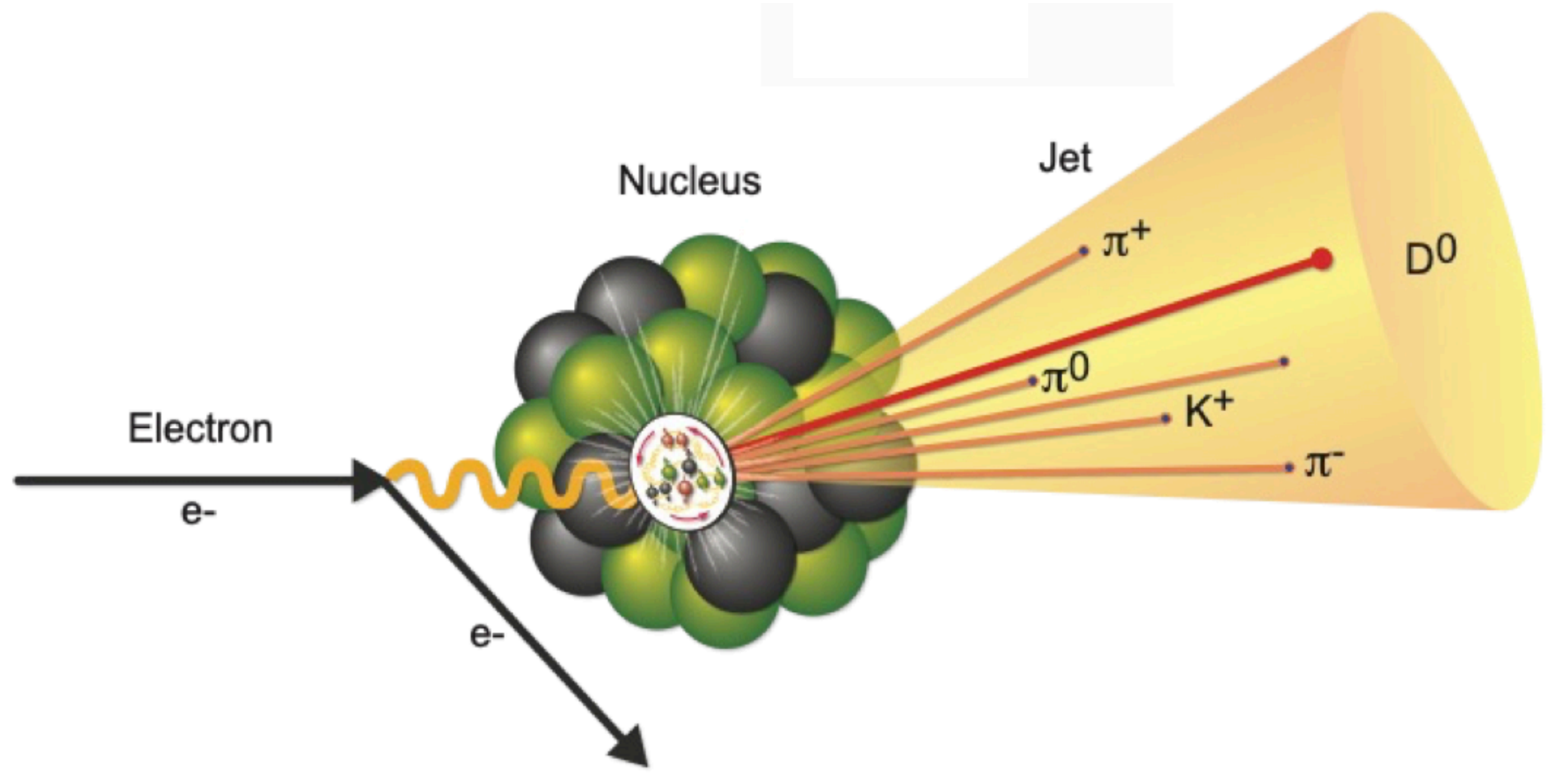
Heavy-flavor physics at the Electron-Ion Collider

B.S. Page et al. Phys. Rev. D 101, 072003
H. T. Li and I. Vitev, Phys. Rev. Lett. 126, 252001
EIC , BNL-98815-2012, arXiv:1212.1701

→ **Heavy-flavor observables are crucial to address the key physics questions of the EIC physics program**







Inclusive heavy-flavor measurements in ep/eA collisions:

→ gluon (n)PDFs down to moderate/low x_{BJ}

→ **evolution equations beyond DGLAP?**

$D\bar{D}$ correlations:

→ access to gluon TMDs

→ **nuclear structure beyond the collinear limit**

Heavy-quark jet production and substructure in ep/eA:

→ **parton-propagation inside the "cold" nuclear matter**

→ parton-shower evolution in a vacuum-like environment

Heavy-flavor hadrochemistry and collectivity:

→ hadronization modification in cold-nuclear matter

→ **what is the time scale of hadronization?**