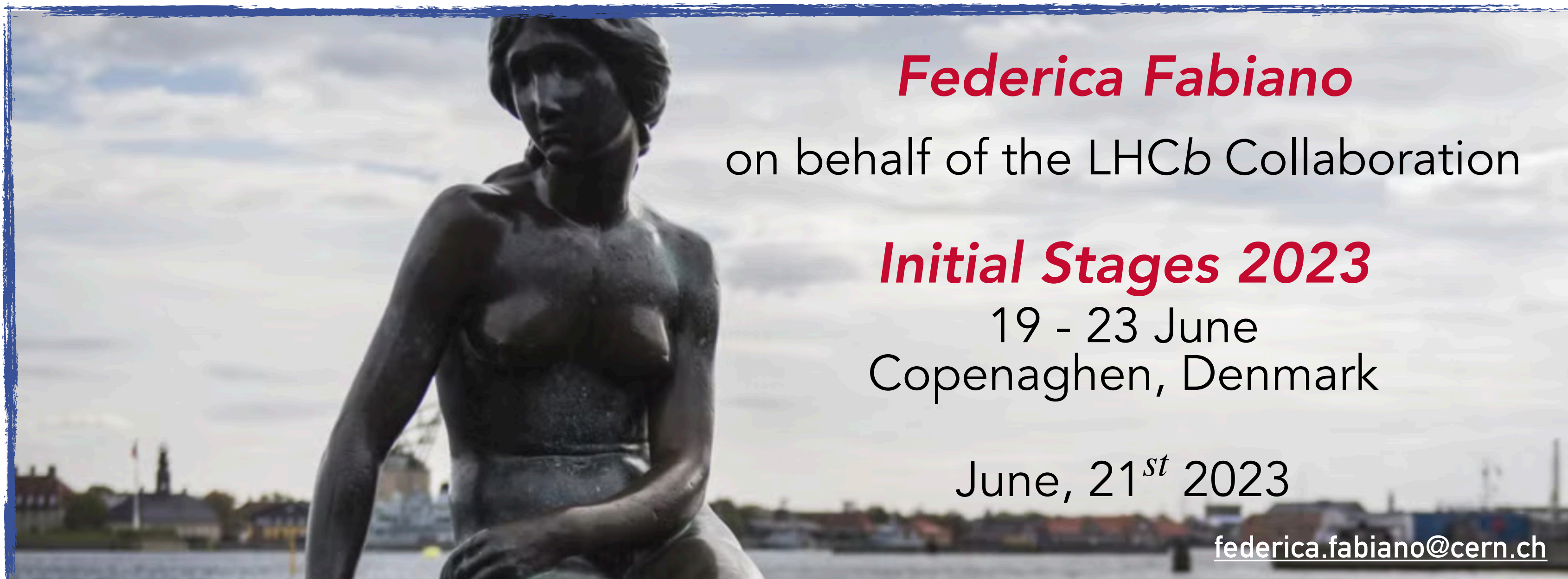# NEW CONSTRAINTS ON NUCLEON STRUCTURE FROM LHCb

Federica Fabiano

on behalf of the LHCb Collaboration

Initial Stages 2023
19 - 23 June
Copenaghen, Denmark

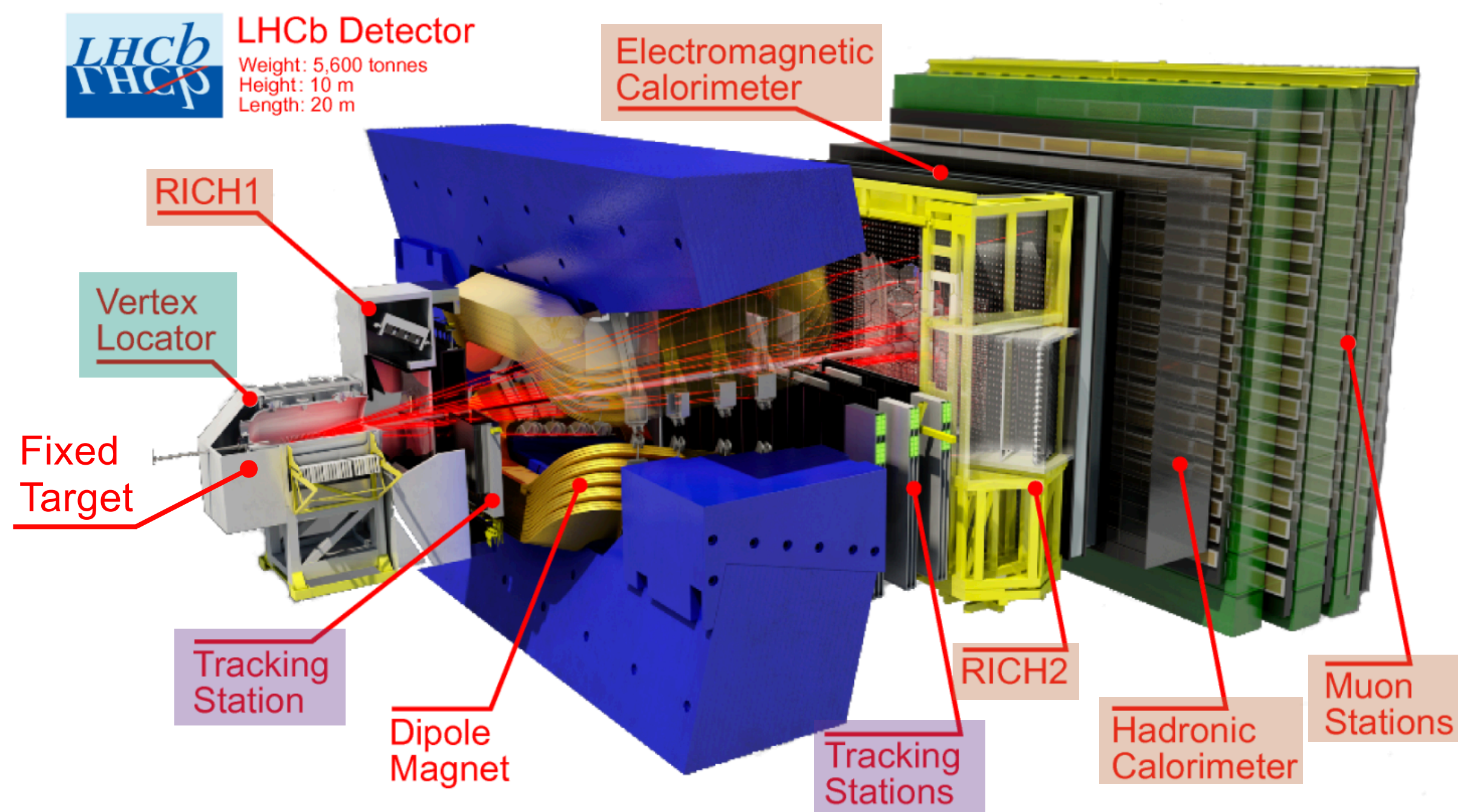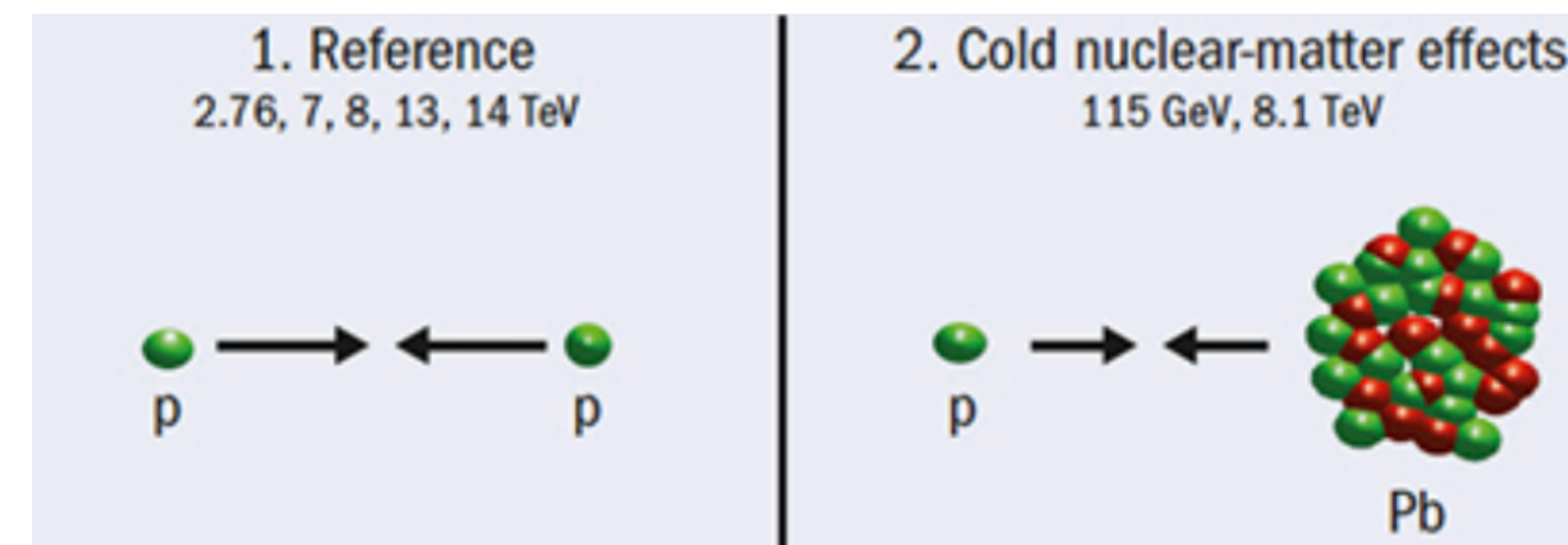June, 21st 2023

federica.fabiano@cern.ch

THE LHC*b* EXPERIMENT

▸ Single arm forward spectrometer originally devoted to *heavy flavour* physics, now a general purpose experiment with *unique* coverage $2 < \eta < 5$ (QCD, Standard Model, heavy ions and fixed-target)
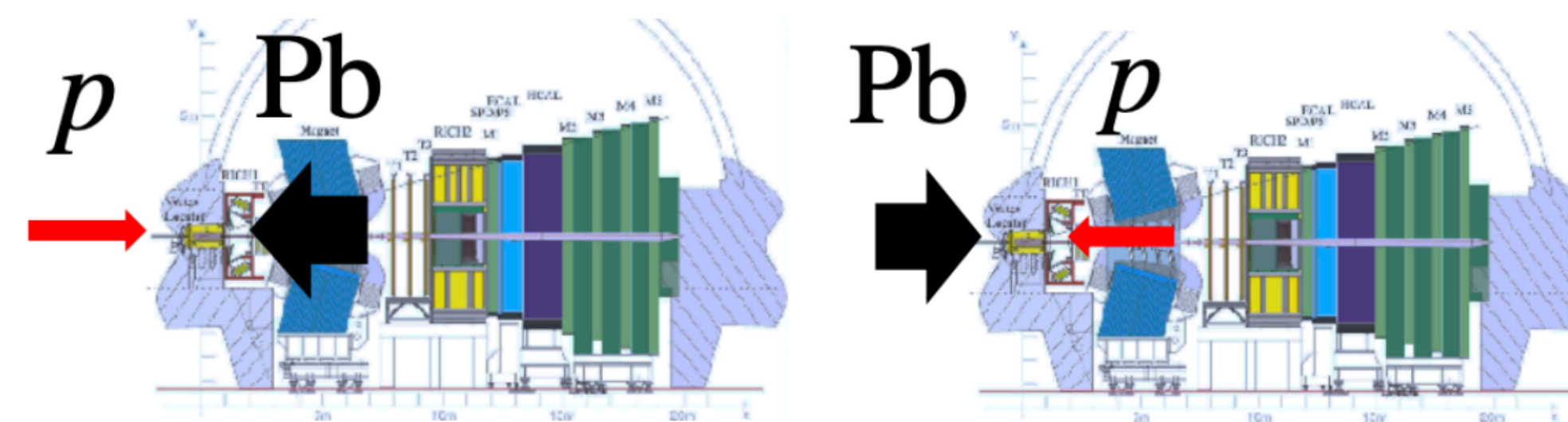
▸ *pp*/*p*Pb/PbPb and fixed-target modes available

Collider Mode

1. Reference	2. Cold nuclear-matter effects
2.76, 7, 8, 13, 14 TeV	115 GeV, 8.1 TeV

Beam Configuration for *p*Pb

$$\eta_{CM} = \eta_{Lab} - 0.465$$

Forward:
$$1.5 < y^* < 4.0$$

Backward:
$$-5.0 < y^* < -2.5$$

▸ ***Excellent*** vertexing, tracking down to very low p_T (momentum resolution 0.5-1.0% for 5-200 GeV/c), and *Particle Identification* (high precision e, μ, π, K, p, γ PID)

→ **Large variety of possible measurements!**

LHC*b* IMPACT

8.16 TeV *p*Pb — LHCb, ATLAS/CMS, ALICE, ALICE Muon; Other Collision Systems — LHCb 110 GeV, HERA

W, Z

Forward: $10^{-6} \leq x \leq 10^{-4}$

Backward: $10^{-3} \leq x \leq 10^{-1}$

Gluon saturated region

p → Gas (He,Ne, Ar...)

LHCb-PUB-2018-015

▸ Accessible range in the (x, Q^2) plane in LHC*b*

→ $Q^2 \sim m^2 + p_T^2$ is the momentum transfer between a particle and the incident particle in a collision

→ $x \sim \dfrac{Q}{\sqrt{s_{NN}}} e^{-\eta}$

nNNPDF3.0 (EPJC 82 (2022) 6, 507)   LHC*b* D^0 production in *p*Pb at 5 TeV: JHEP 1710 (2017) 090
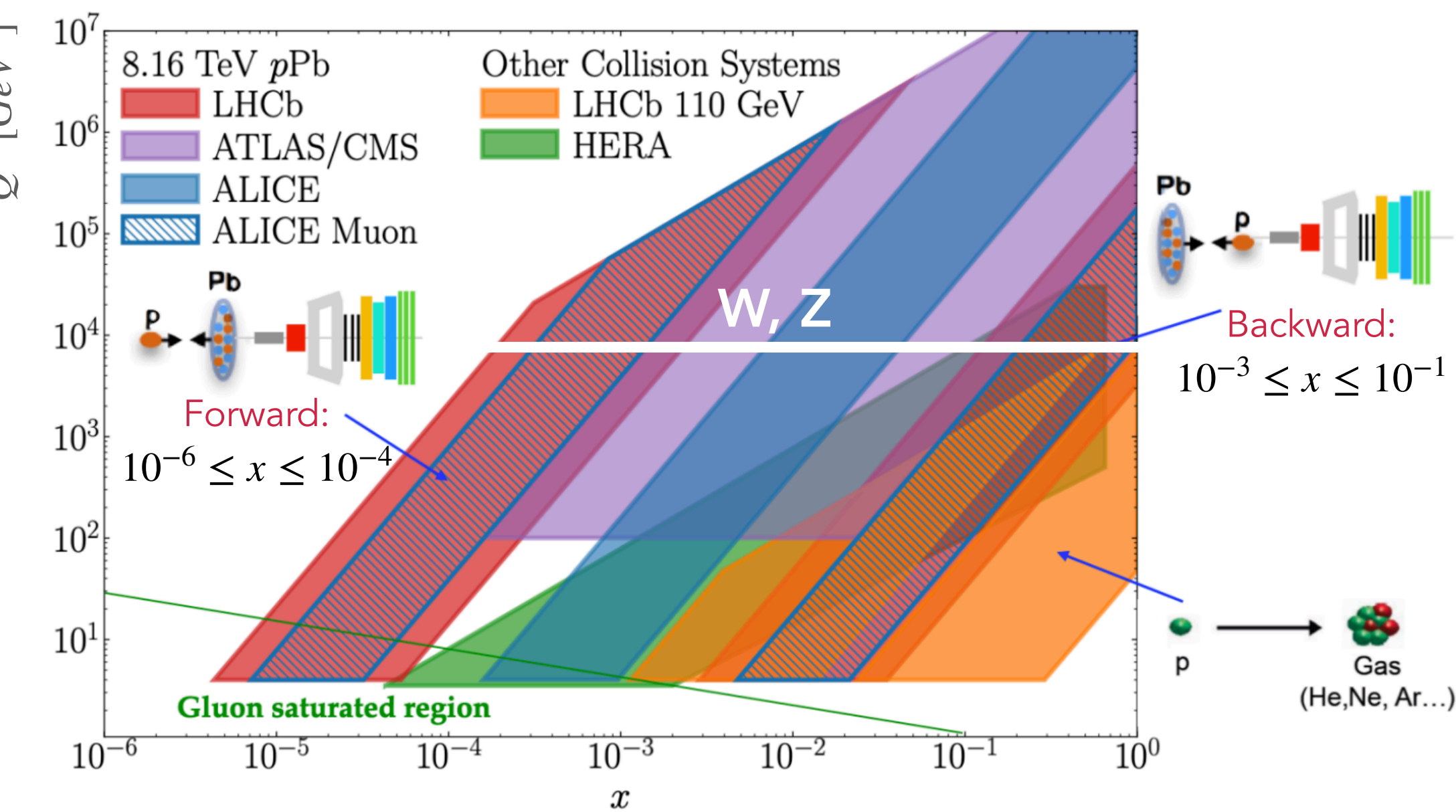
LHC*b* measurements have a significant *impact* on nPDFs fits
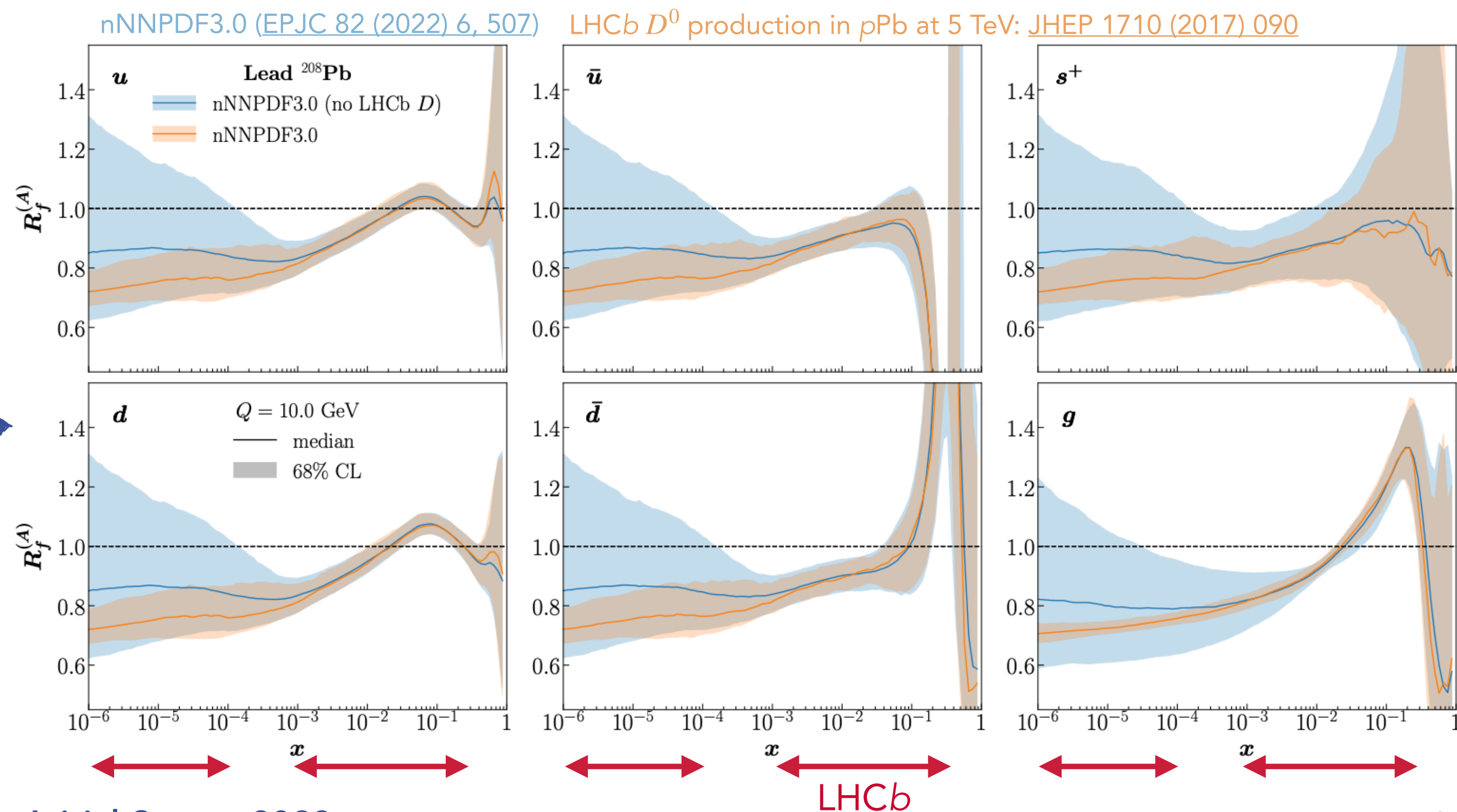
✓ *pp, p*Pb **collisions**:

- ▸ Prompt D^0 nuclear modification factor production in pPb at $\sqrt{s_{NN}}$ = 8.16 TeV   arXiv:2205.03936

  → *see Jianqiao Wang's talk (Wednesday, Parallel Session 5)*

- ▸ Charged particle production in pPb $\sqrt{s_{NN}}$ = 5 TeV   PRL 128(2022) 142004

- ▸ Neutral pion production in pPb at 8.16 TeV   arXiv:2204.10608, accepted by PRL

- ▸ Z boson production cross-section in pPb collisions at 8.16 TeV   JHEP06(2023)022

- ▸ Z bosons produced in association with charm in the forward region

 of *pp* collision at 13 TeV   Phys.Rev.Lett.128,082001

✓ **Fixed-Target collisions**:

- ▸ Charmonium production in pNe collisions at 68.9 GeV   arXiv:2211.11645, submitted to EPJC

  → *see Camilla De Angelis poster*
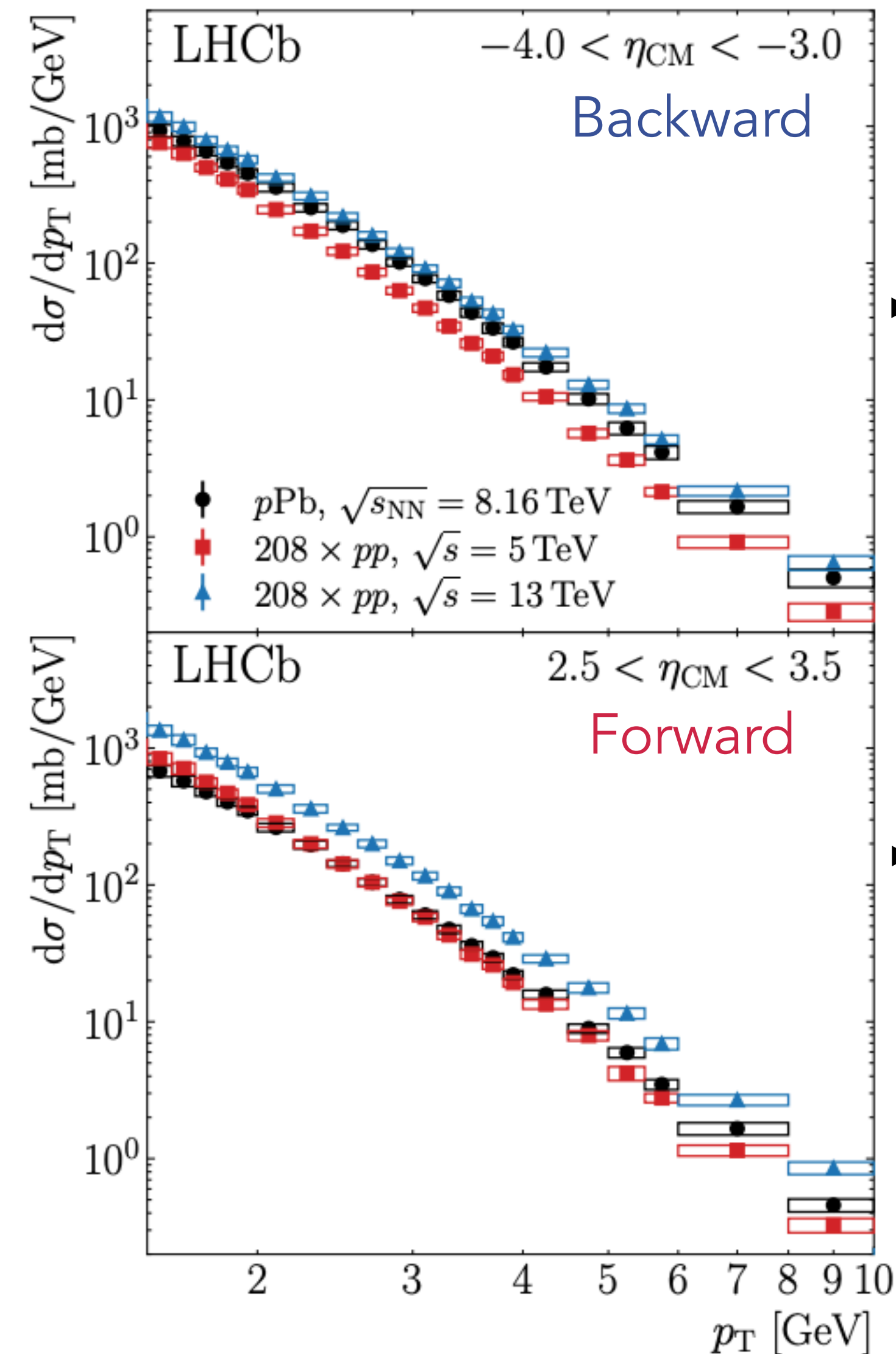
▸ *Motivation*: study Cold Nuclear Matter effects and provide coinstraints on nPDFs for $10^{-6} < x < 10^{-1}$

▸ $\pi^0 \to \gamma^{conv}\gamma^{ECAL}$ reconstructed with one converted photon and one ECAL photon for better momentum resolution
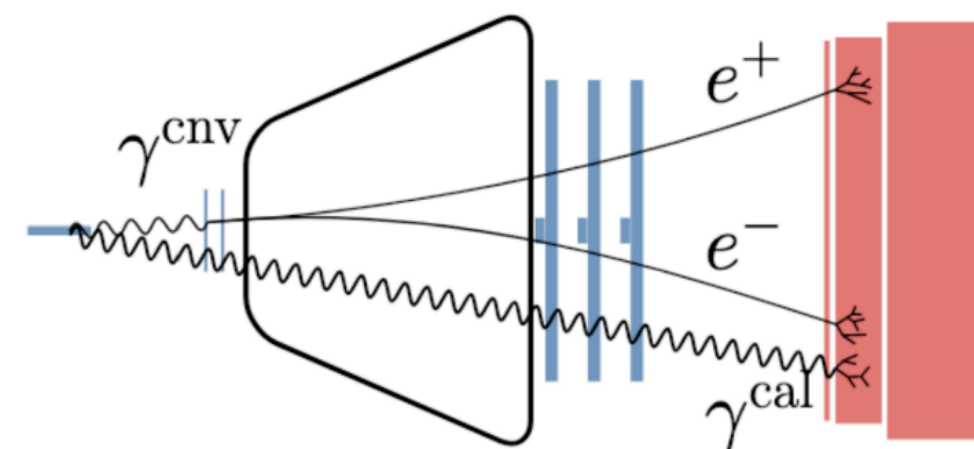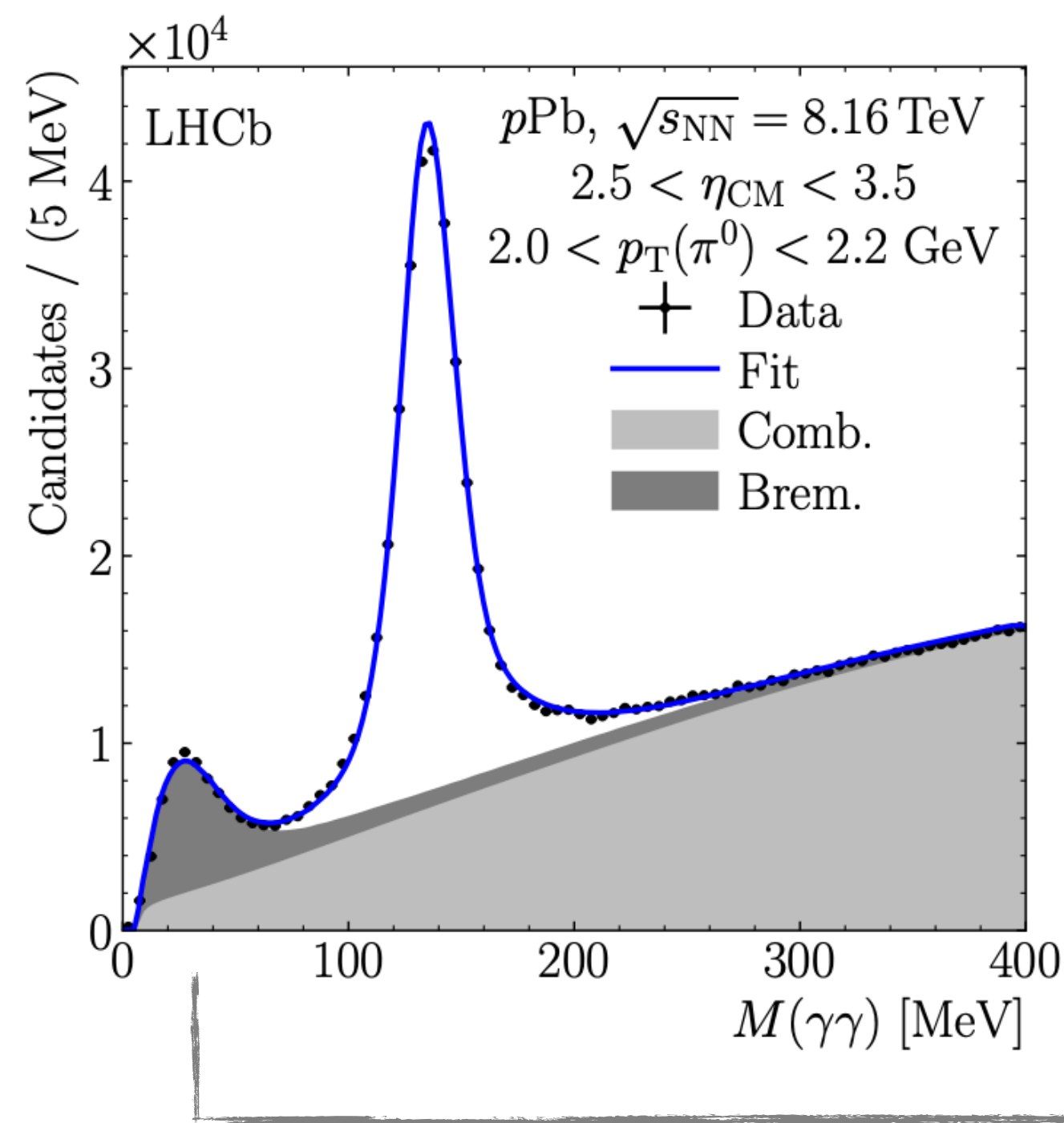
▸ Combinatorial background modelled using charged tracks from MC

▸ γ^{conv} combined with its own bremsstrahlung radiation to form a π^0

▸ π^0 cross section in bins of p_T and η_{CM}

▸ pPb data compared to $208 \times pp$ at 5 and 13 TeV

▸ Results compared to NLO pQCD → nPDFs reweighted to have LHCb D^0 production data

$$R_{p\text{Pb}} \equiv \frac{1}{A} \frac{\mathrm{d}\sigma_{p\text{Pb}}/\mathrm{d}p_{\text{T}}}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\text{T}}}$$

with A = 208

▸ **Enhancement** of π^0 production w.r.t. pp at intermediate p_T

▸ Enhancement smaller than charged particles R_{pPb} from LHCb pPb at 5 TeV

PRL 128(2022) 142004

Backward

Forward

LHCb

π^0, $\sqrt{s_{\text{NN}}} = 8.16$ TeV, $-4.0 < \eta_{\text{CM}} < -3.0$
nCTEQ15+LHCb D^0 JHEP09(2014)138
EPPS16+LHCb D^0 JHEP05(2020)037
CGC PHYS. REV. D 88, 114020 (2013)

π^0, $\sqrt{s_{\text{NN}}} = 8.16$ TeV, $-4.0 < \eta_{\text{CM}} < -3.0$
$h^{\pm}$, $\sqrt{s_{\text{NN}}} = 5$ TeV, $-3.5 < \eta_{\text{CM}} < -3.0$
$h^{\pm}$, $\sqrt{s_{\text{NN}}} = 5$ TeV, $-4.0 < \eta_{\text{CM}} < -3.5$

π^0, $\sqrt{s_{\text{NN}}} = 8.16$ TeV, $2.5 < \eta_{\text{CM}} < 3.5$

π^0, $\sqrt{s_{\text{NN}}} = 8.16$ TeV, $2.5 < \eta_{\text{CM}} < 3.5$
$h^{\pm}$, $\sqrt{s_{\text{NN}}} = 5$ TeV, $2.5 < \eta_{\text{CM}} < 3.0$
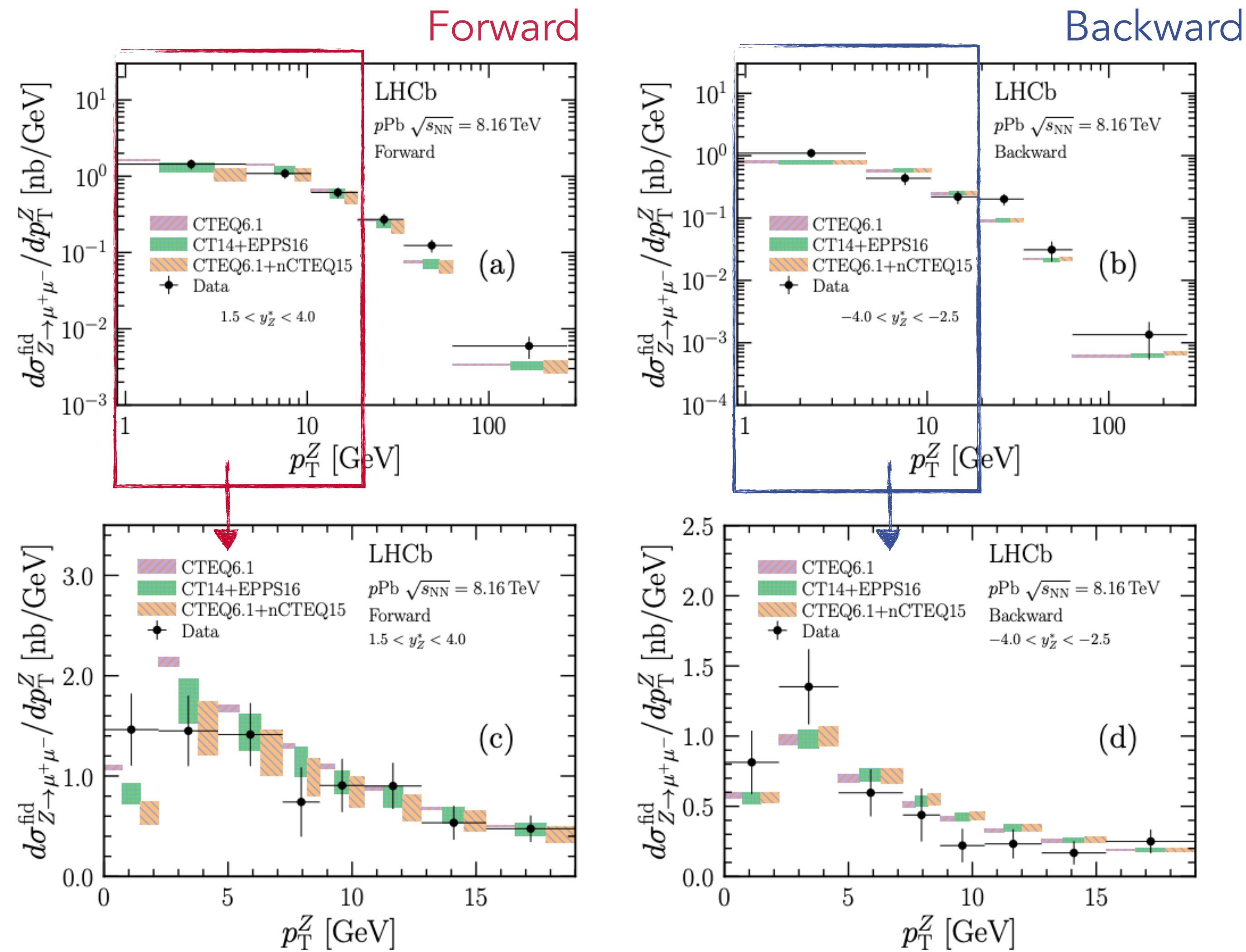$h^{\pm}$, $\sqrt{s_{\text{NN}}} = 5$ TeV, $3.0 < \eta_{\text{CM}} < 3.5$

p_{T} [GeV]
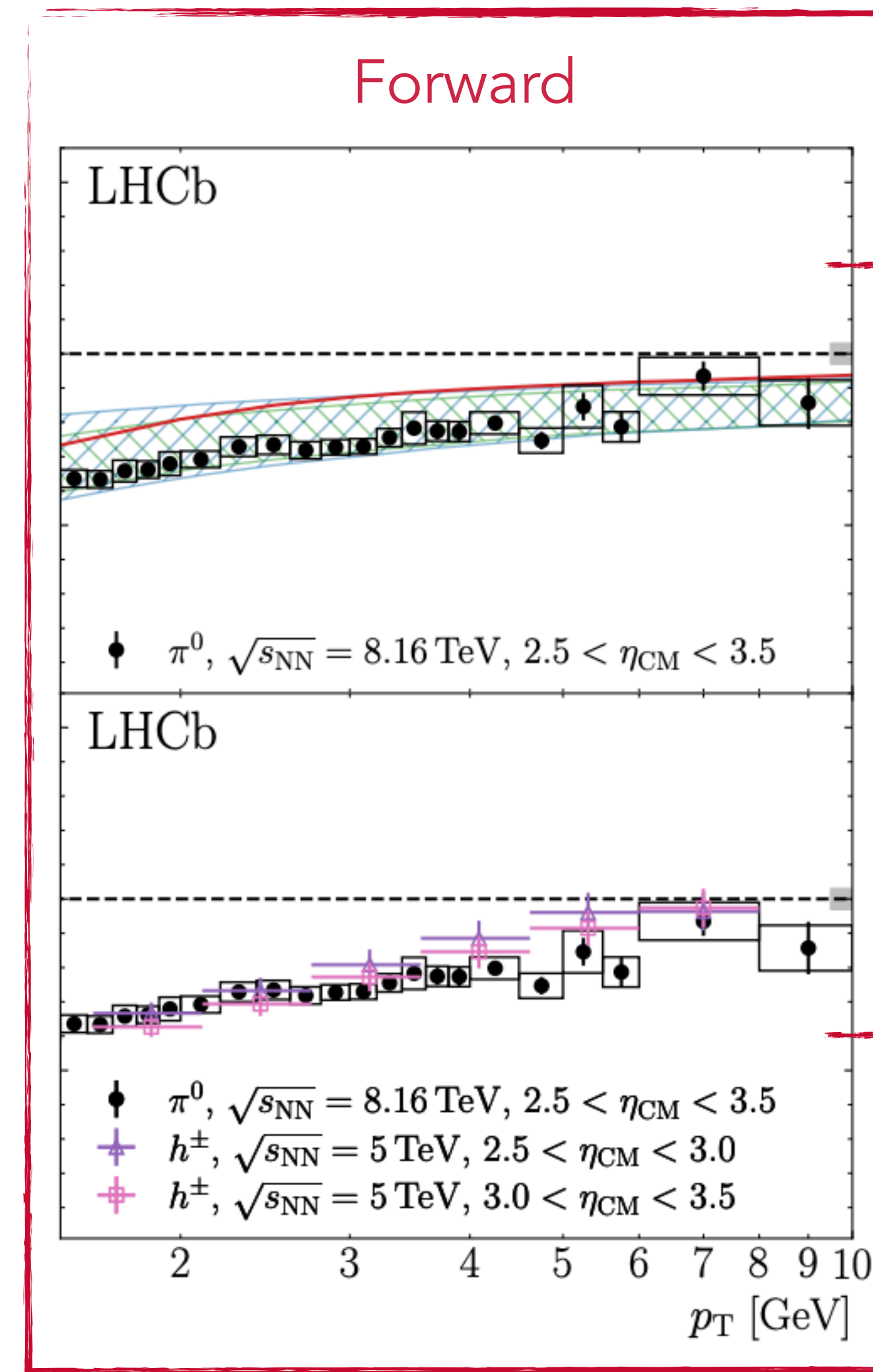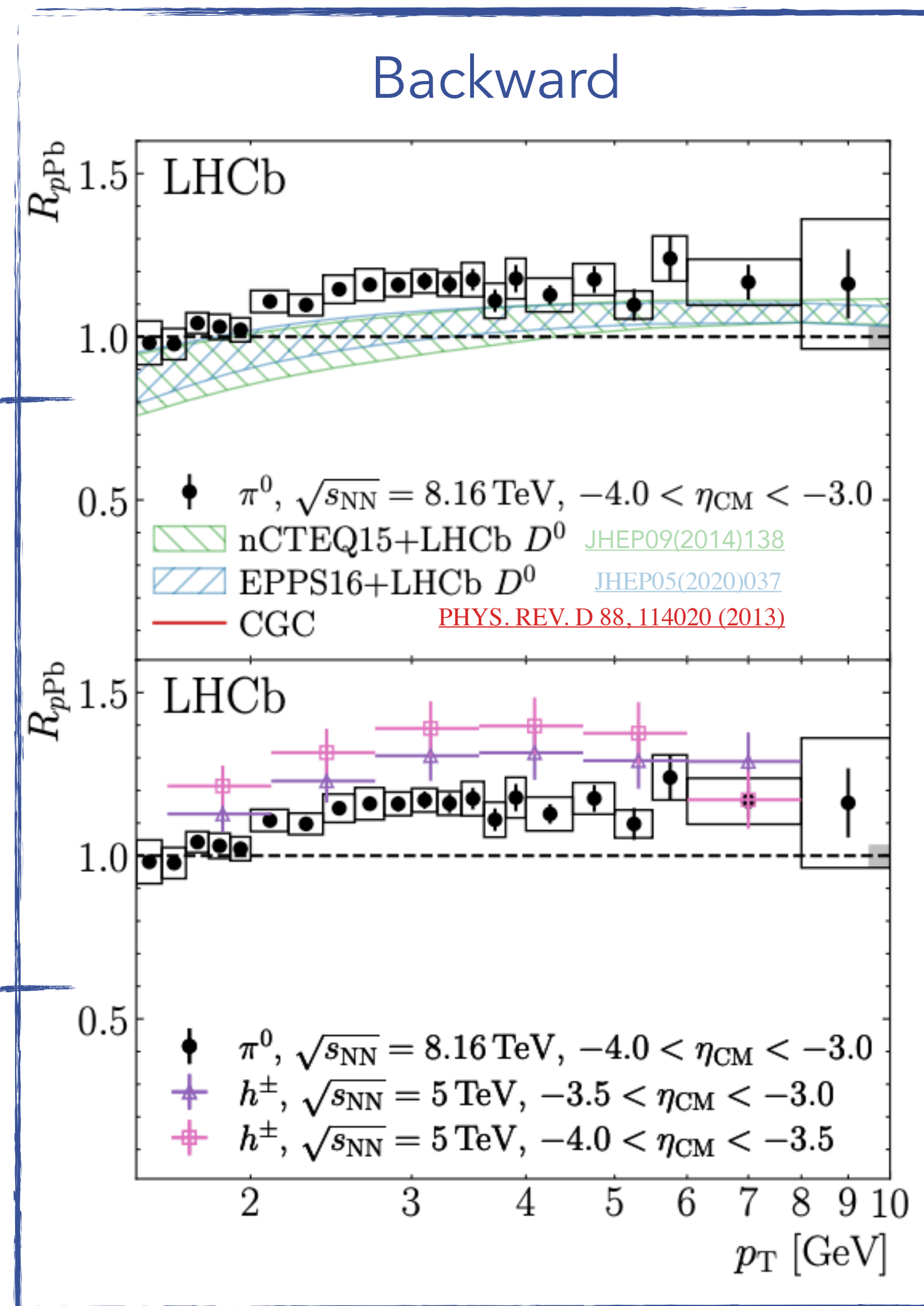
▸ Strong **suppression** of R_{pPb}

▸ LHCb uncertainties smaller than predictions → data constrain nPDFs at low-x

▸ Consistent with charged-particle R_{pPb} from LHCb pPb at 5 TeV

PRL 128(2022) 142004

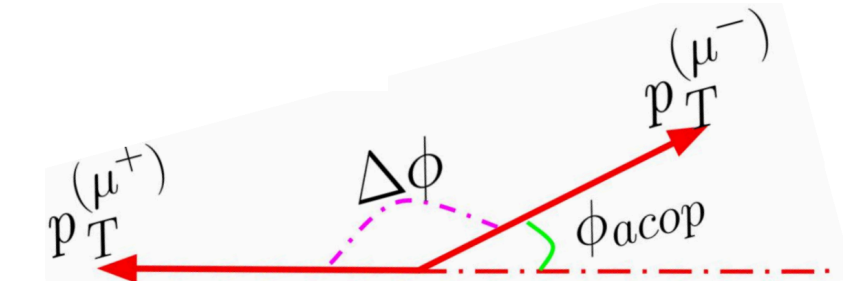# Z PRODUCTION IN pPb COLLISIONS AT 8.16 TeV

Forward

Backward

- *Motivation*: Z production helps to constrain (n)PDFs and it is a clean probe of the initial state at low- and high-x

- $Z \to \mu^+\mu^-$ reconstructed in $60 < m_{\mu^+\mu^-} < 120$ GeV

- Results are given in bins of y_Z^*, p_T^Z and ϕ^*

  where $\phi^* = \dfrac{\tan(\phi_{\mathrm{acop}}/2)}{\cos(\Delta\eta/2)}$

- Forward: data with smaller uncertainty in low-p_T^Z bins wrt PowhegBox predictions

  → strong *constraint* to nPDFs models

- Backward: uncertainties greater than theory predictions but statistically compatible

▸ **Nuclear modification factor** (R_{pPb}) and **forward-backward ratio** (R_{FB}) corrected for the different muon rapidity acceptance, and compared to PowhegBox prediction
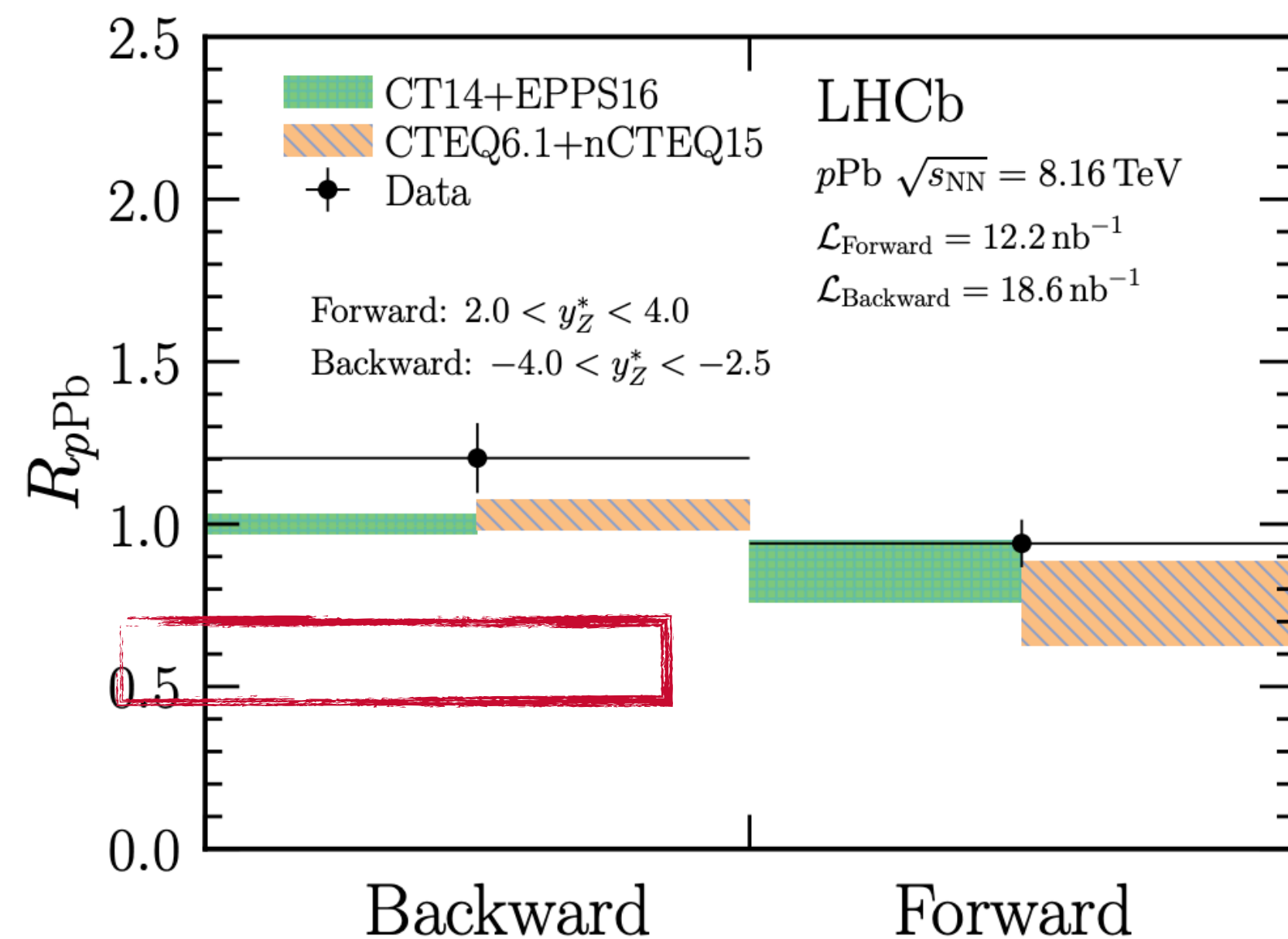

▸ Results in forward region well described by predictions with a smaller uncertainty → constrain on the current nPDFs

▸ Same trend observed in previous LHC*b* *p*Pb result at 5 TeV   arXiv:1406.2885

$$\mathrm{R}_{pPb}^{\mathrm{fw.}} = 0.94 \pm 0.07$$

$$\mathrm{R}_{pPb}^{\mathrm{bw.}} = 1.21 \pm 0.11$$

$$\mathrm{R}_{\mathrm{FB}} = 0.78 \pm 0.10$$

▸ R_{FB} **below** one: *suppression* at small Bjorken-x and *enhancement* at large-x
→ uncertainty **smaller** than predictions → constraining power on nPDFs
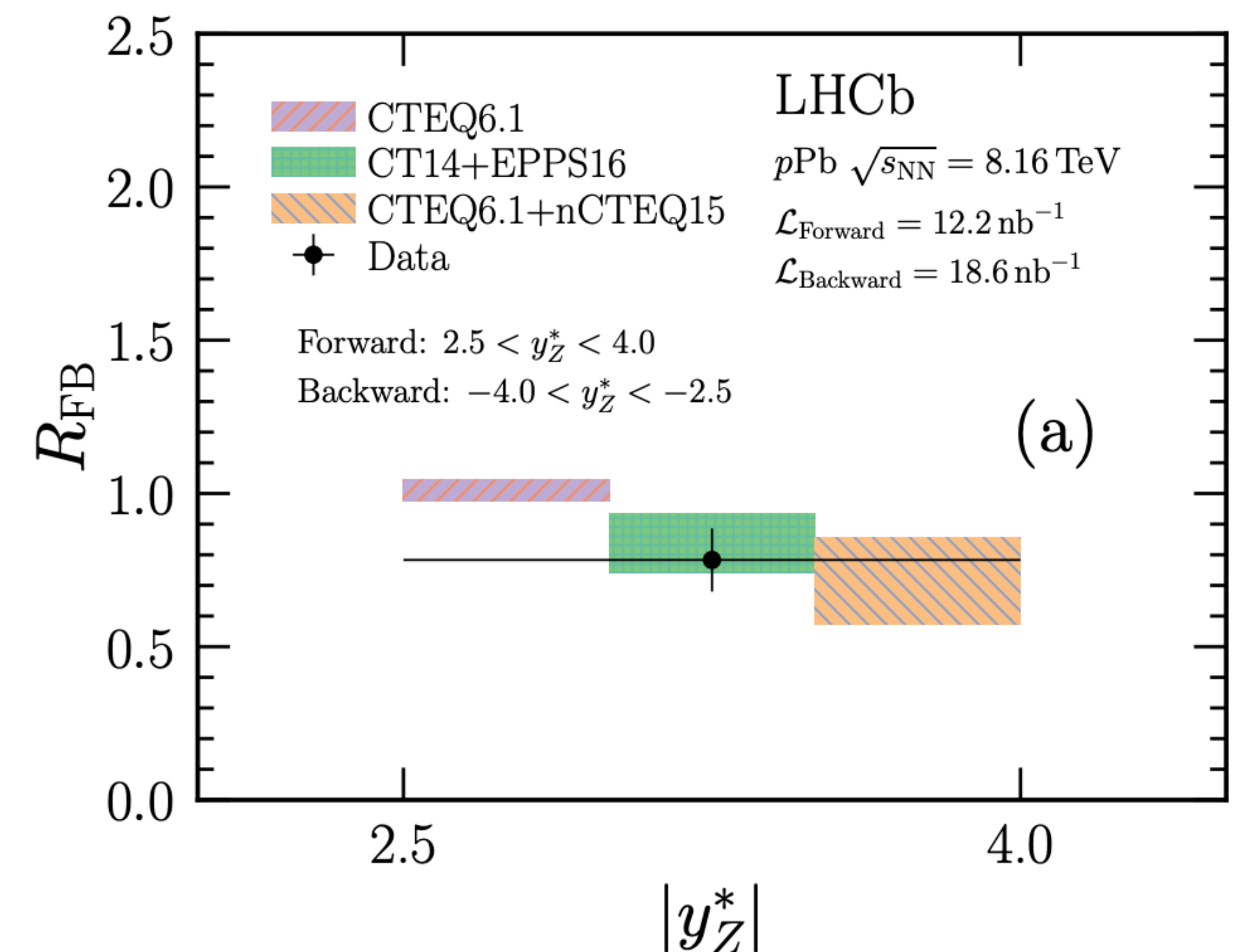
▸ *Motivation*: existence of intrinsic heavy quarks within the proton wavefunction still under debate and not yet definitively established   Phys.Lett.B 93(1980) 451-455

$$|\mathbf{proton}\rangle = |uud\rangle + \epsilon|uudc\bar{c}\rangle \text{ ?}$$
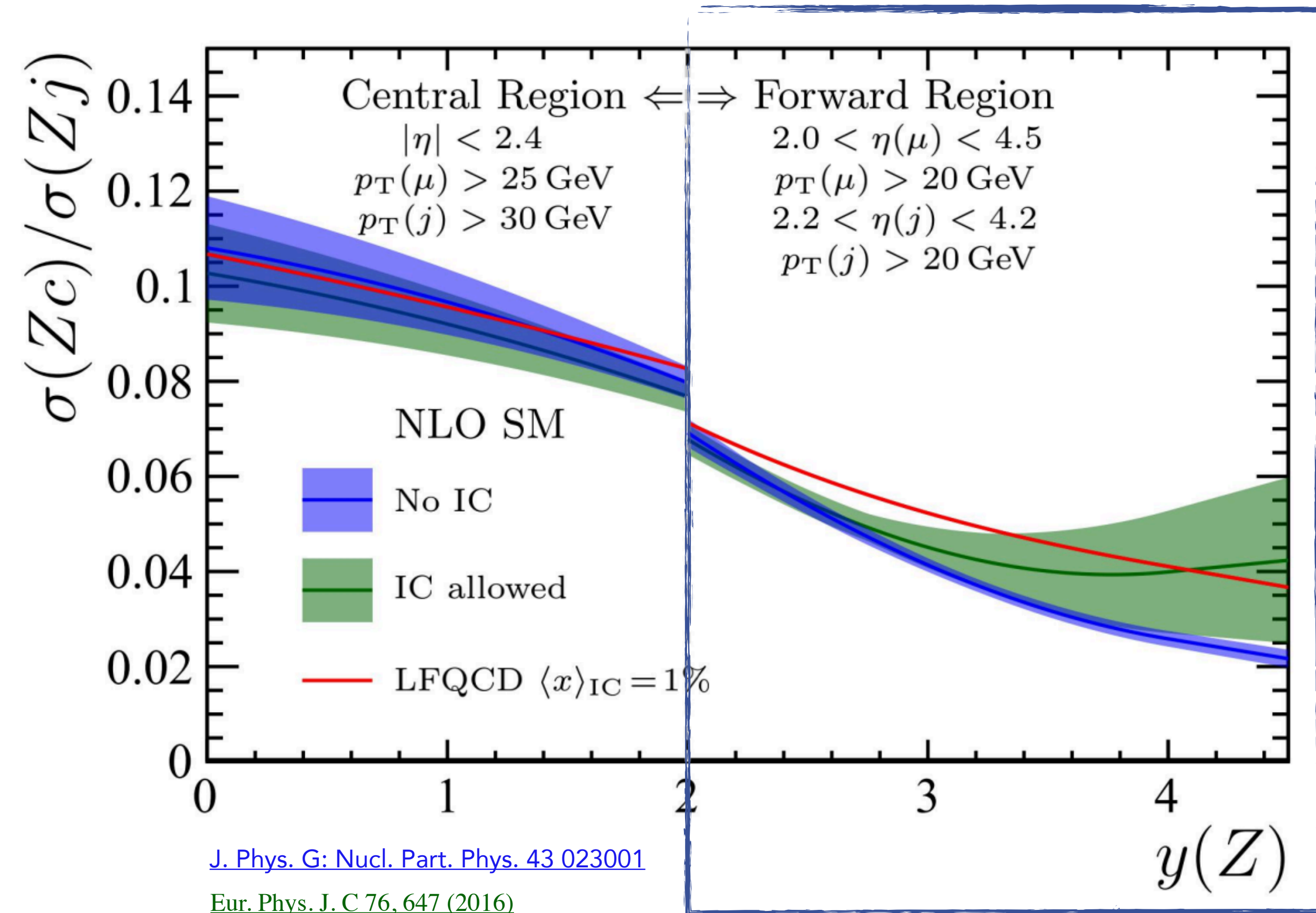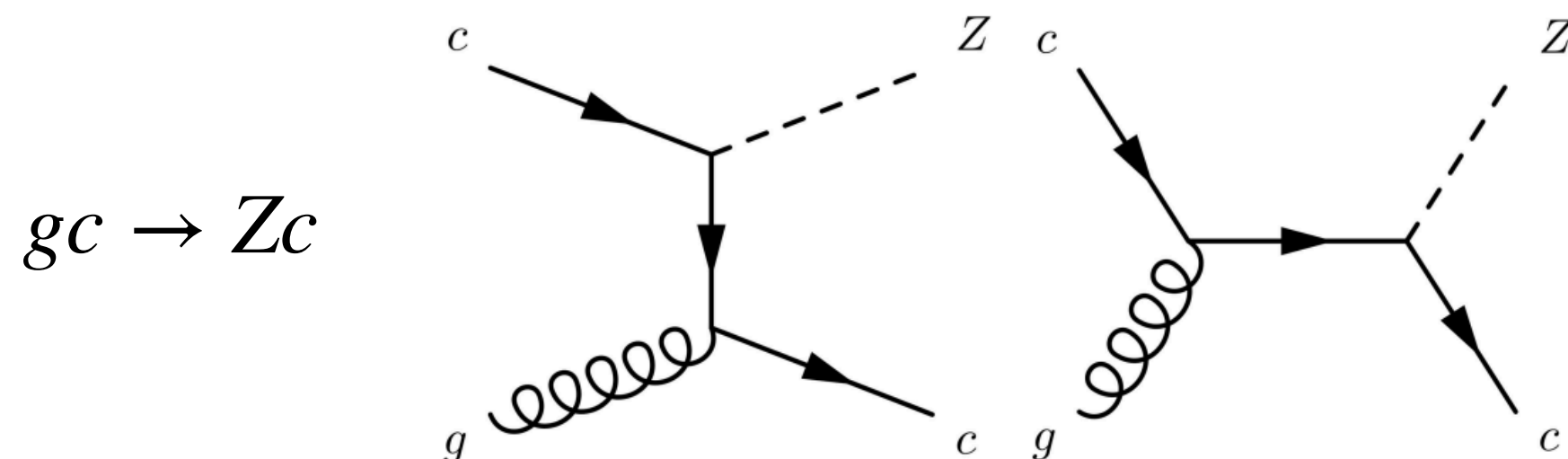$$\epsilon \lesssim \mathcal{O}(\%)$$

▸ Non-perturbative **Intrinsic Charm** (IC) manifests as **valence-like** charm content in the proton's PDF

Tool: ratio of cross section between *Zc* and *Zj* (events of a Z boson and any type jet)

$$\mathscr{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$$

Phys. Rev. D 93, 074008 (2016).

$gc \rightarrow Zc$

J. Phys. G: Nucl. Part. Phys. 43 023001
Eur. Phys. J. C 76, 647 (2016)
JHEP02(2018)059

IC contribution would produce a clear enhancement in $\mathscr{R}_j^c$ at high $y(Z)$

▸ *Procedure*:

  ▸ Z bosons reconstructed using $Z \to \mu^+\mu^-$ decay

  ▸ Jet reconstructed using anti-k_T clustering algorithm   JHEP04(2008)063

  ▸ c-jet yields determined using a c-tagging algorithm that finds a displaced vertex (DV) in the jet cone
                                           arXiv:2112.08435

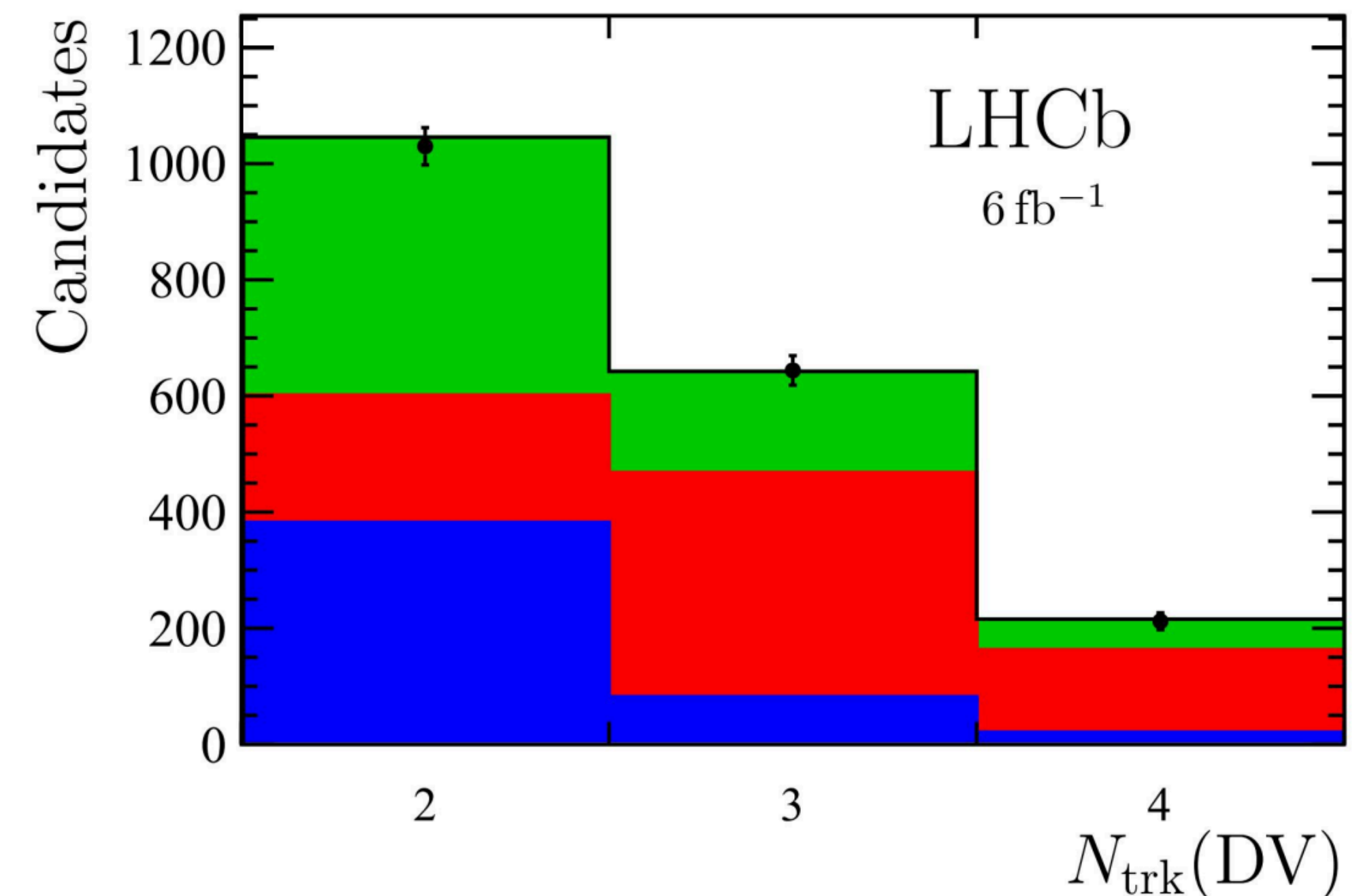 ▸ Two properties of DV used to separate charm jets from beauty and light jets:

jet

Secondary vertex(displaced-vertex)

PV
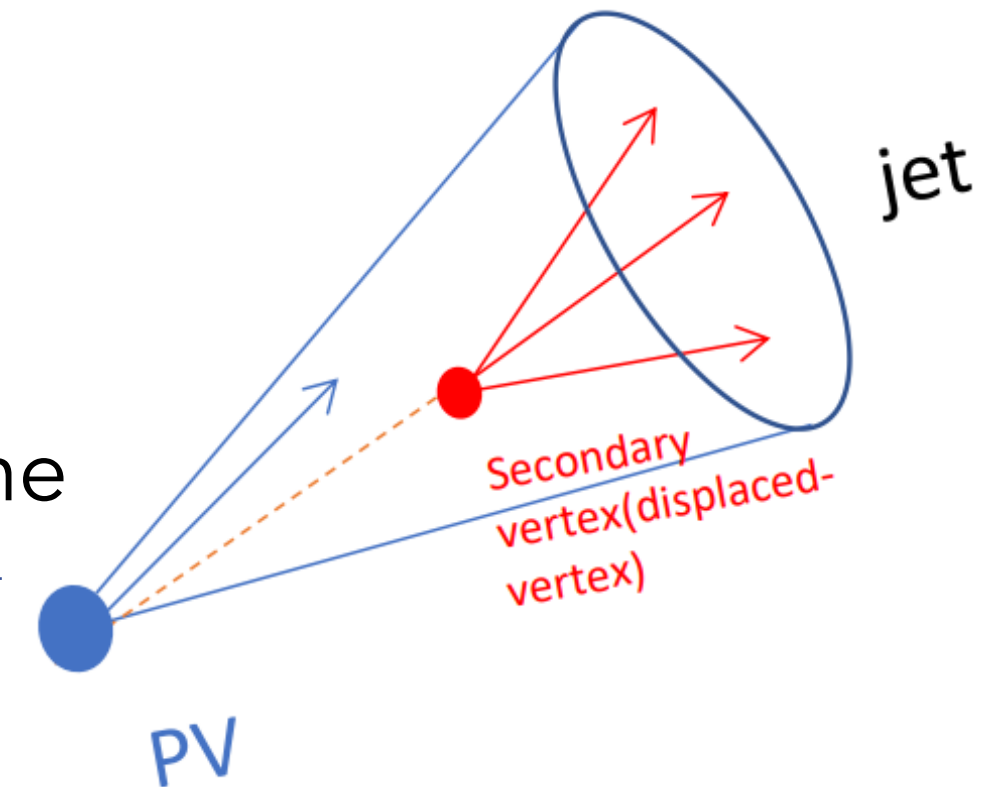
m_{cor}(DV) ≡ *corrected mass of a DV*

N_{trk}(DV) ≡ *number of tracks in the DV*
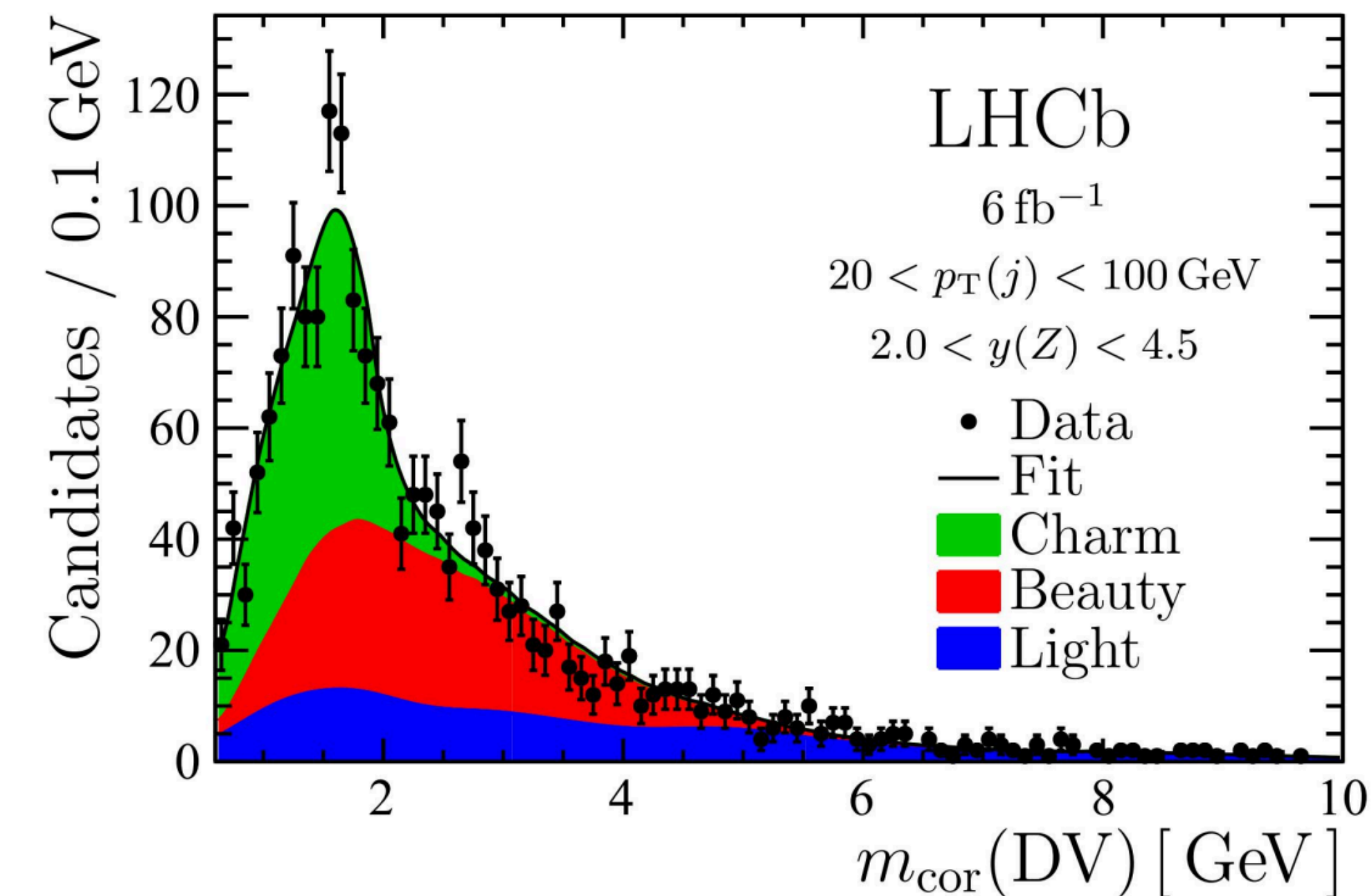
$$m_{\mathrm{cor}}(\mathrm{DV}) =$$
$$= \sqrt{m^2(\mathrm{DV}) + p^2(\mathrm{DV})\sin^2\theta}$$
$$+ p(\mathrm{DV})\sin\theta$$

where θ is the angle between the momentum and the flight direction of the DV
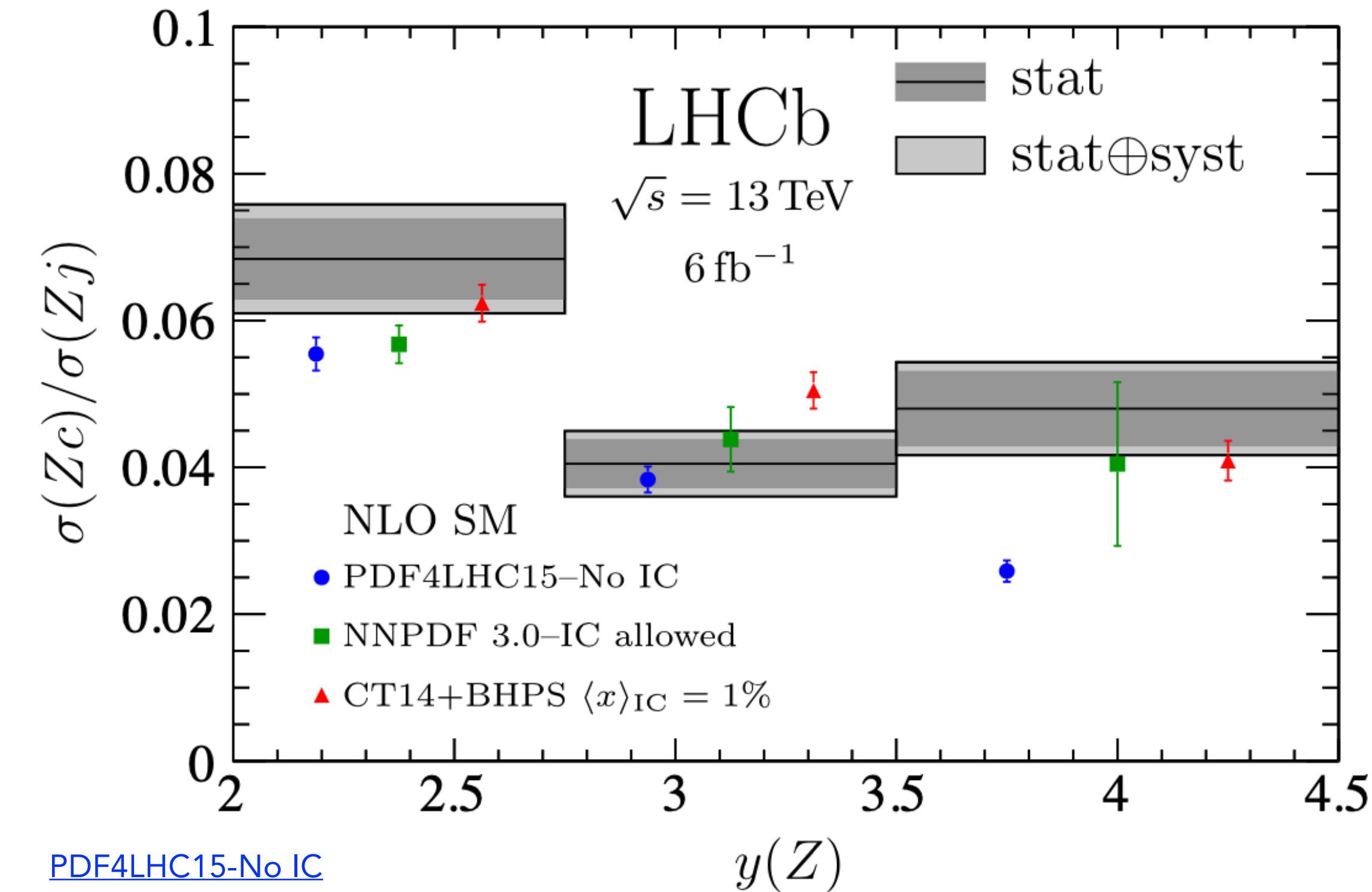
PDF4LHC15-No IC

NNPDF 3.0-IC allowed

CT14+BHPS$\langle x\rangle_{IC}$ = 1%

▸ The fraction of Zc-jet in Zjet is measured for the ***first time*** in the forward region of *pp* collisions

▸ Clear ***enhancement*** at forward $y(Z)$ observed consistent with the effect predicted by BHPS for a proton with a $|uudc\bar{c}\rangle$ component
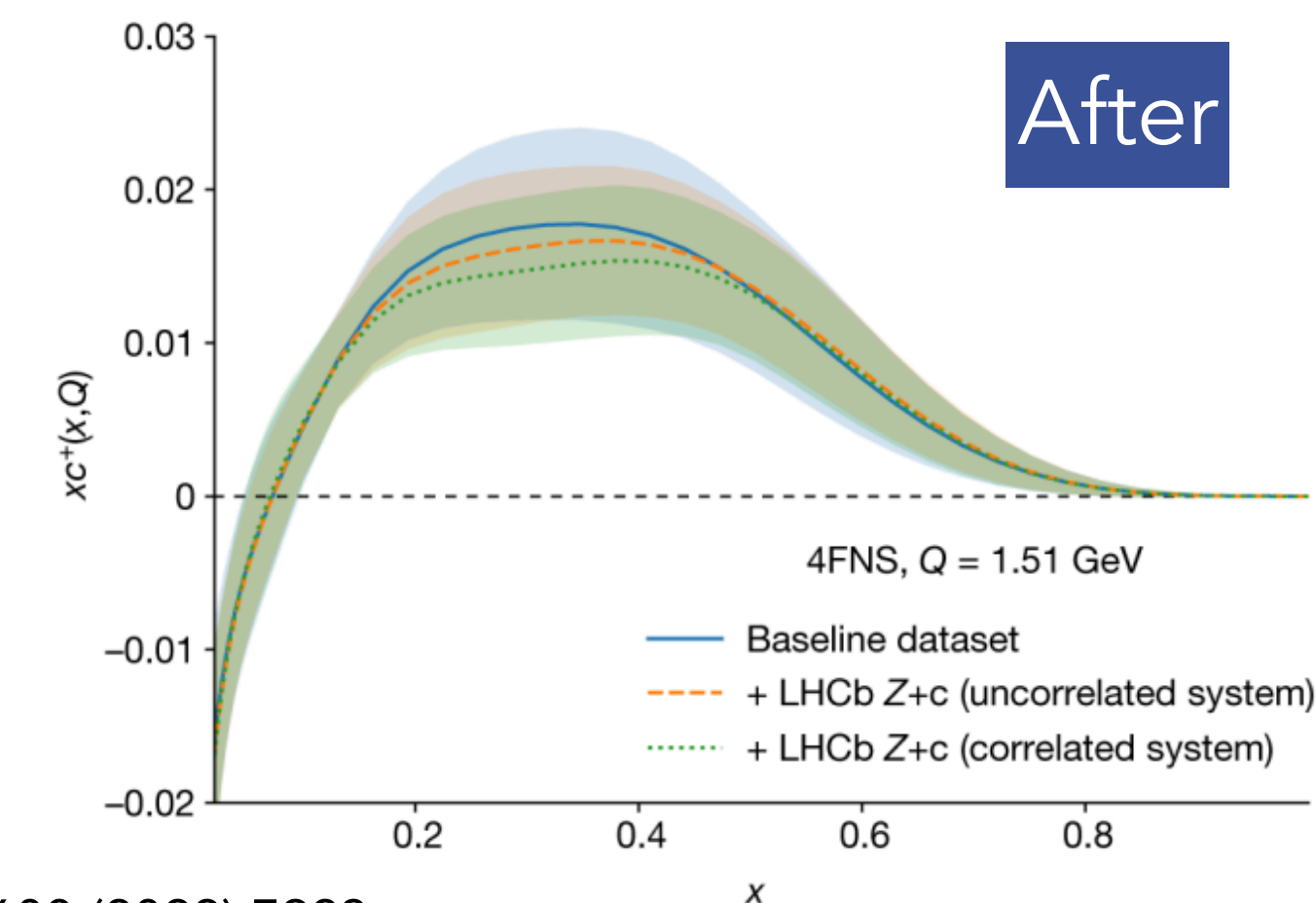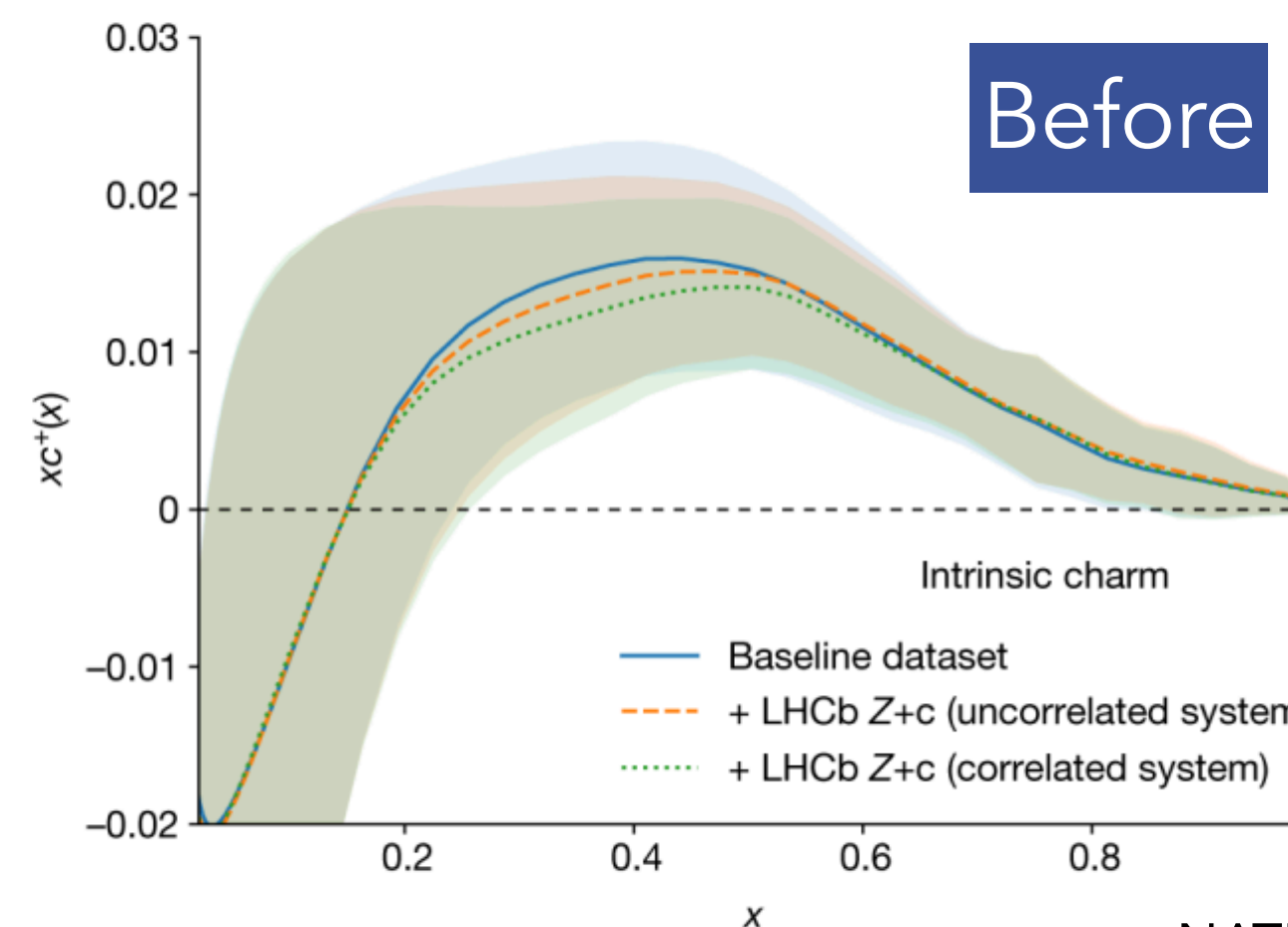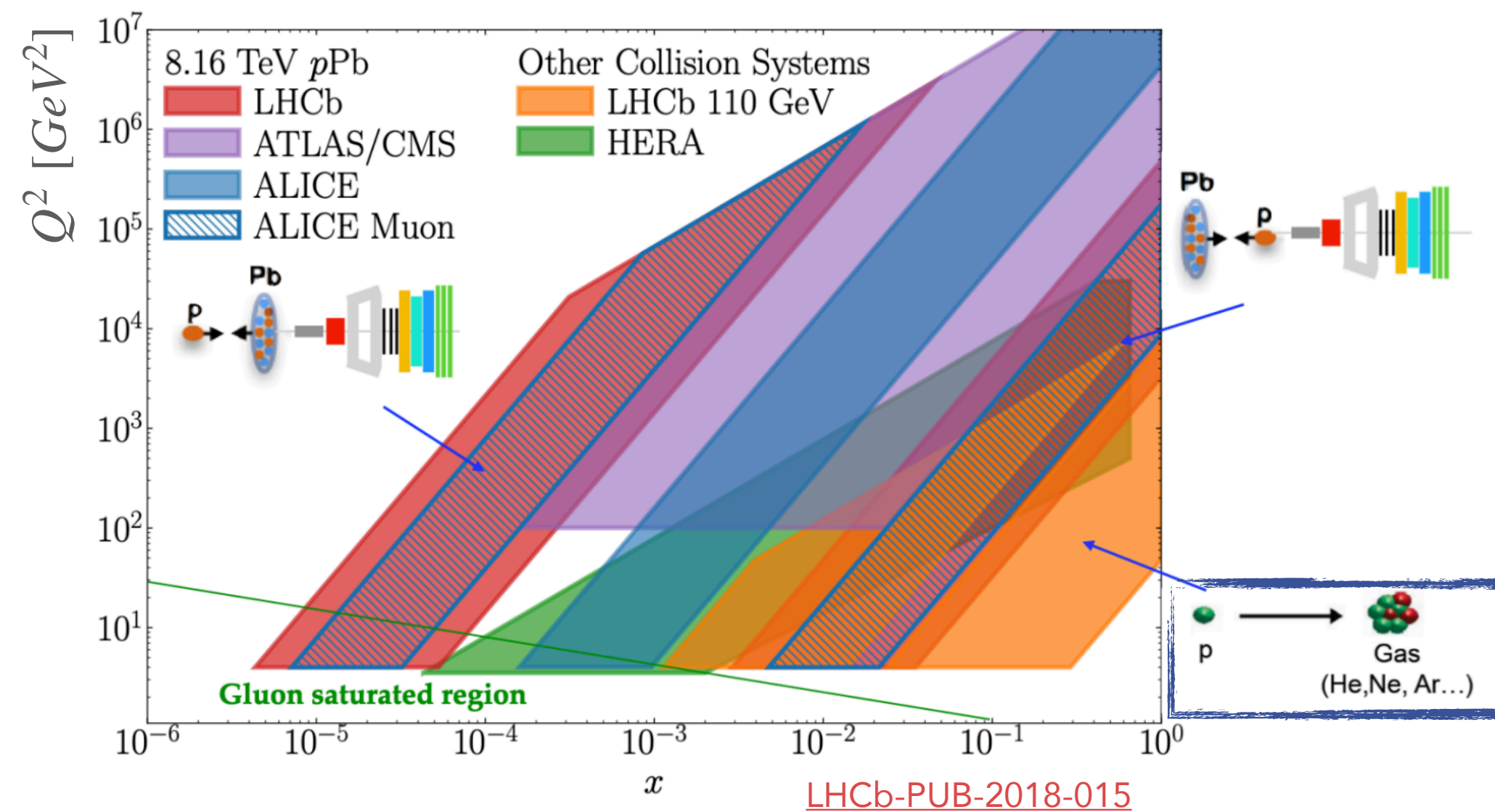
▸ Default PDFs including IC are ***compatible*** with LHC*b* measurement at high $y(Z)$

▸ Including $\mathcal{R}_j^c$ the uncertainty on the charm PDF is strongly ***reduced***

NATURE 608 (2022) 7923

‣ Fixed-target system of LHCb:

SMOG (**S**ystem for **M**easuring **O**verlap with **G**as)

LHCb-PUB-2018-015

‣ Noble gas (He, Ne, Ar) at $\sim 2 \times 10^{-7}$ mbar injected into the LHC vacuum around the LHCb interaction region

‣ Access to (x, Q^2) kinematic region, ***poorly explored*** by previous experiments

→ *Unique experimental inputs to models!*

‣ Charmonia production is an excellent probe for

Cold Nuclear Matter effects
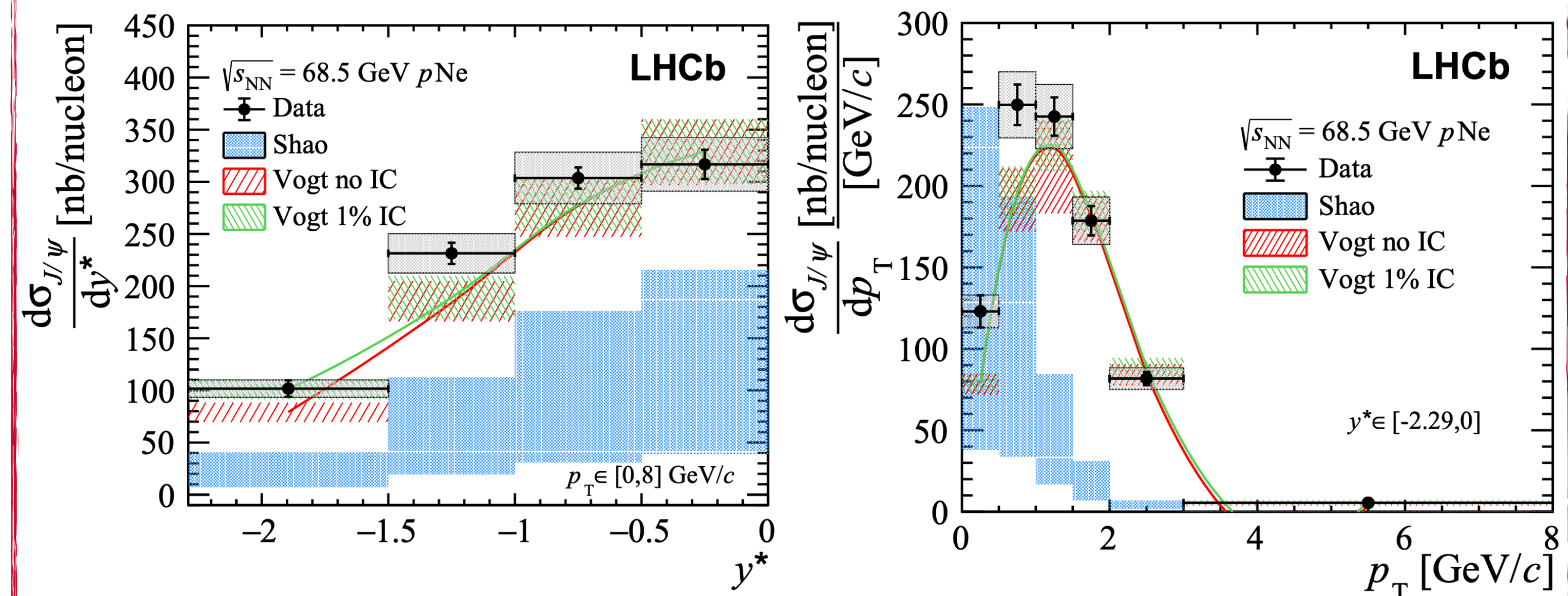
‣ J/ψ differential cross-section in bins of p_T and y^*:

→ Measurement not sensitive to Intrinsic Charm contribution

→ Tension between data and HELAC-ONIA

→ *see Giulia Manca's* talk *and Camilla De Angelis* poster *for details*

CONCLUSIONS

▸ LHCb has proved its capability to perform **high-precision** measurements of EW observables, and provides significant information for the (n)PDFs global fitting

▸ The π^0 nuclear modification factor can provide **constraints** on nPDFs at low-x in the forward region

▸ The Z boson production in pPb provides strong constraints on the nPDFs, especially at low Bjorken-x

  → Results at 8 TeV are **consistent** with previous LHCb pPb measurements at 5 TeV

▸ The fraction of Z+jet events with a c-jet is measured for the **first time** in the forward region of pp collisions

  → $\mathscr{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$ ratio shows a clear **enhancement** at forward Z rapidities

▸ Results from collisions complementary to LHCb fixed-target IC program

▸ **More** LHCb measurements to come that will help clarify the nucleon structure scenario
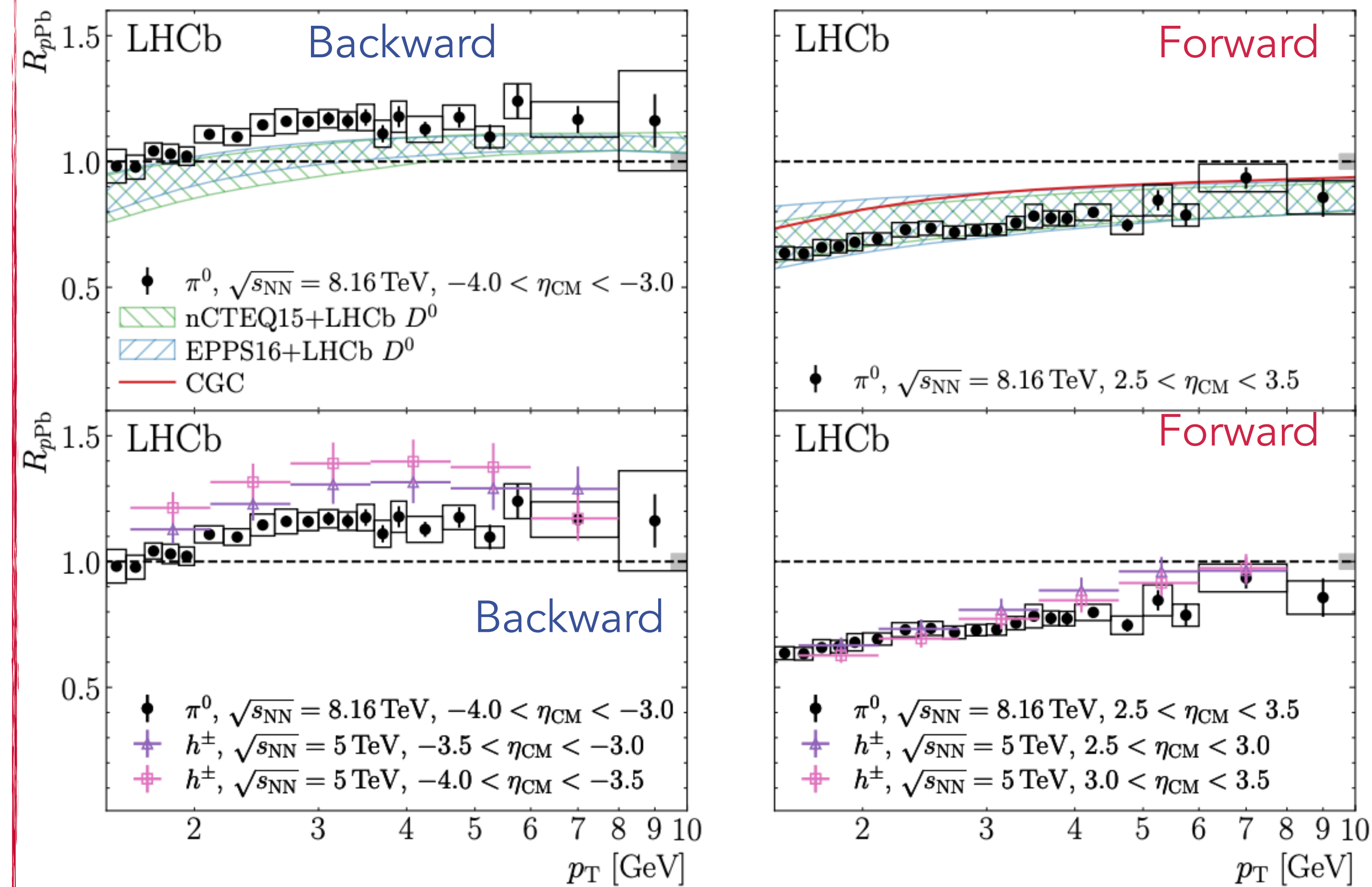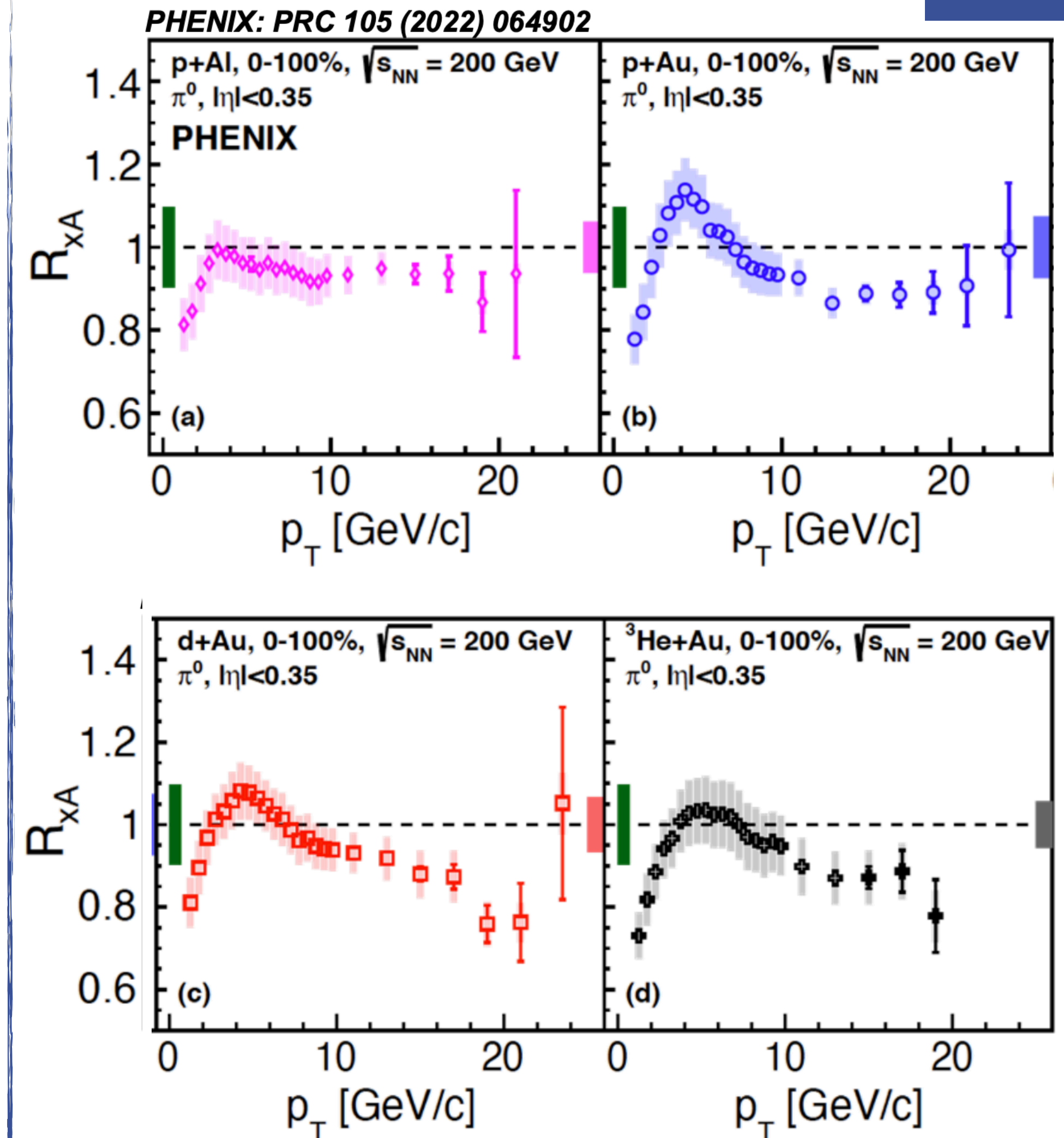
Stay Tuned!

THANK YOU! 💃

BACKUP

→ *from Alex Drees* *talk* *on Monday*

▸ Cross-section results *compatible* with previous results at 5 TeV from LHC*b* and other experiments

▸ Only experimental uncertainty shown on data/theory ratio
→ theory PDF uncertainty is a band around unity
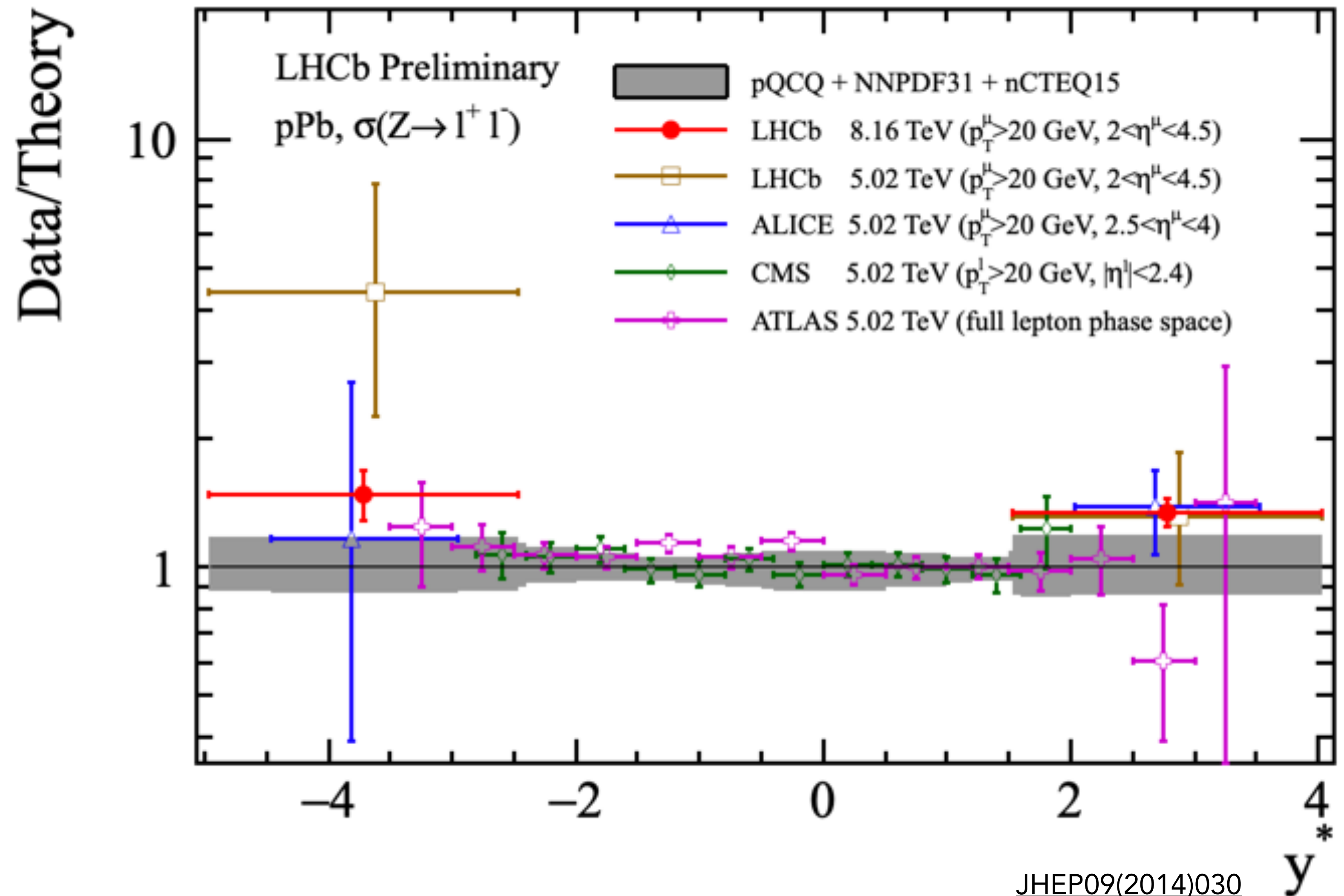
JHEP09(2014)030
LHCb-CONF-2019-003