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Probing the valence quark region of nucleons with Z bosons at LHCb

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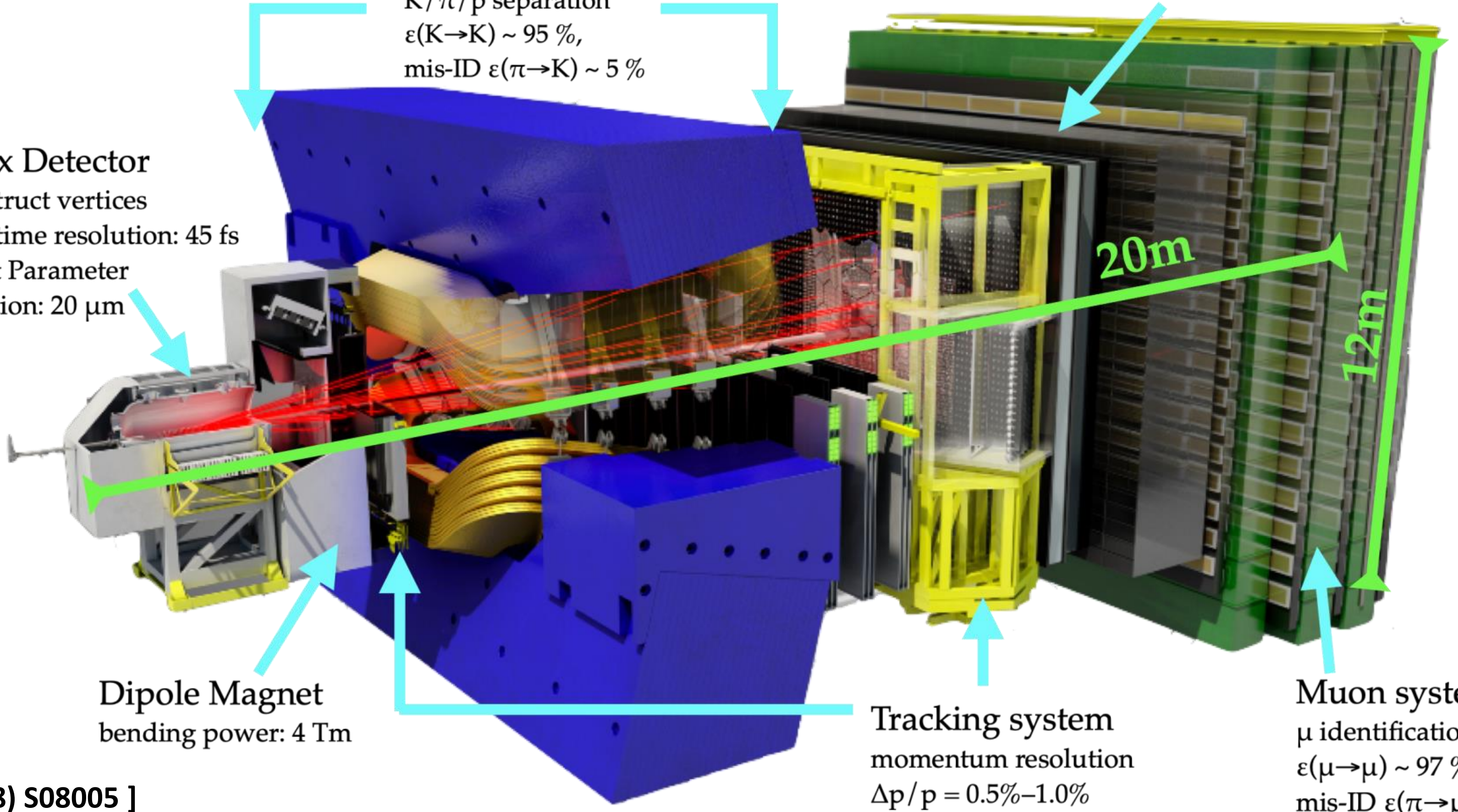
on behalf of the LHCb collaboration

The LHCb detector

- LHCb is the only dedicated detector (at LHC) fully instrumented in forward region
- Unique kinematic coverage

  $2 < \eta < 5$

- A high precision device, down to very low-p_T, excellent particle ID, precise vertex and track reconstruction.

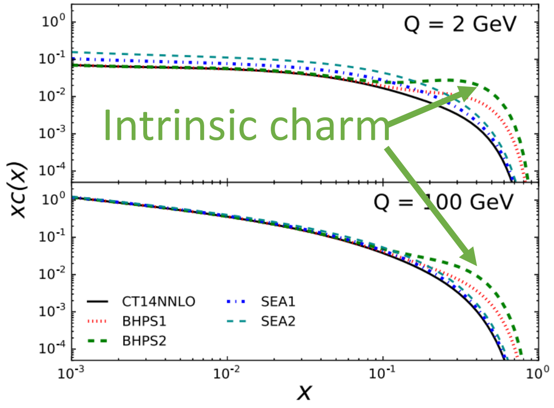


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

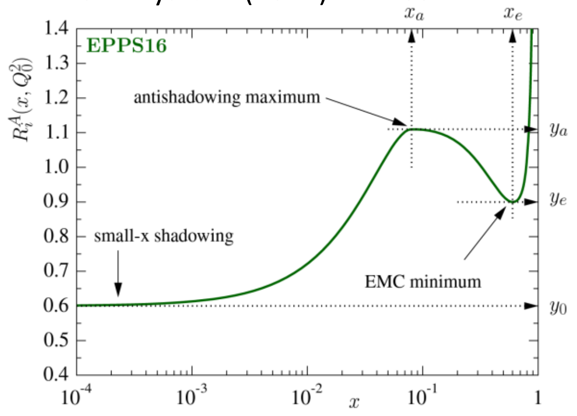
Z boson as probe to nuclear/nucleon structures at LHCb

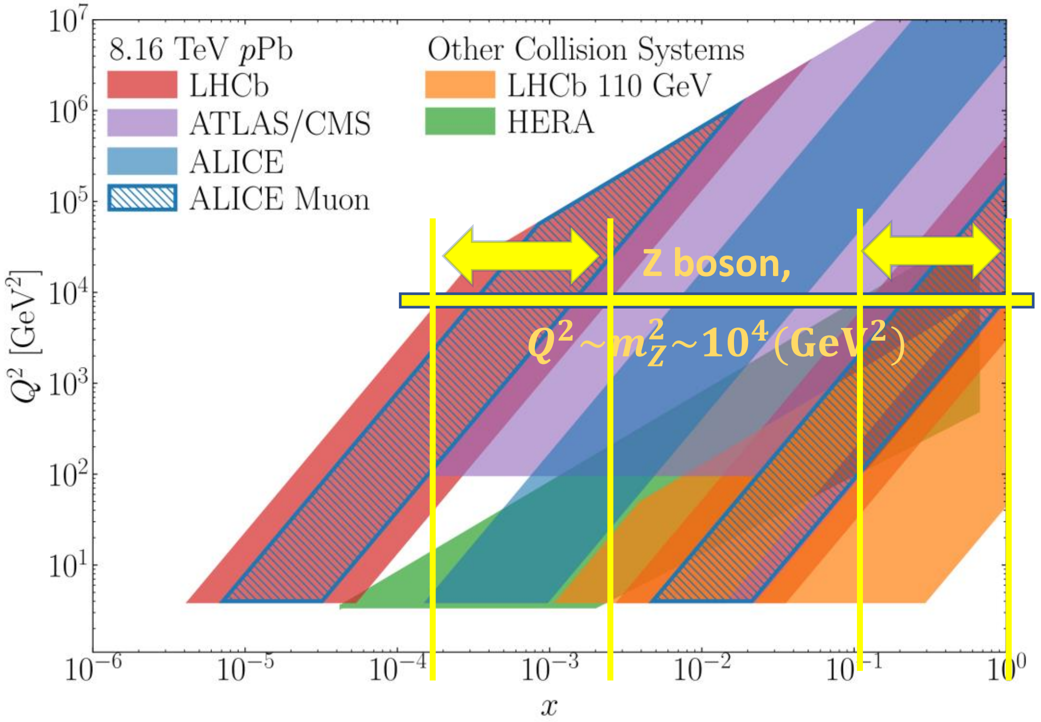
- Z boson production at LHCb allows to probe the non-perturbative initial-state effects in kinematic window
    - Bjorken-x in $10^{-4} < x < 10^{-3}$ and $10^{-1} < x < 1$,
    - with $Q^2 \sim m_Z \sim 10^4 \text{GeV}^2$.
- EW Z boson with leptonic decay: once created, do not participate in hadronic interactions, preserves the initial-state information.
- Two recent results:
    - Z + cjets production (PRL 128 (2022) 08200): probe intrinsic (valence-like) charm contents in protons
    - Z in pPb collisions (arXiv:2205.10213 [hep-ex]): Probe cold nuclear matter effects in initial states

Phys. Rev. D 93 (2016) 074008



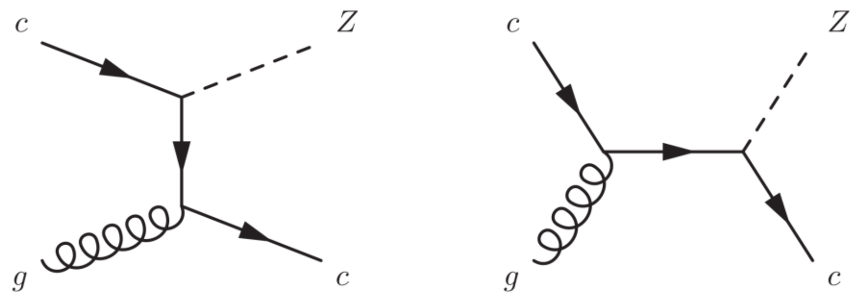
Eur. Phys. J. C (2017) 77 :163





Probe intrinsic charm

- Intrinsic-charm vs. extrinsic-charm.
- Z + c-jets production:

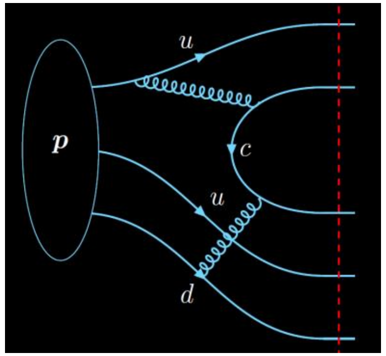


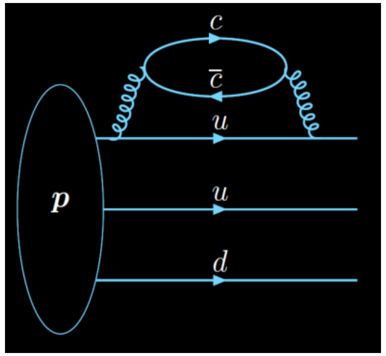
Leading-order Feynman diagrams for $gc \to Zc$

- Valence-like intrinsic charm contents in proton PDFs can enhance c-jet production especially at high Bjorken-x

Intrinsic-charm:
Non-perturbative
valence-quark-like
long time scale

Extrinsic-charm:
Perturbative
short time scale





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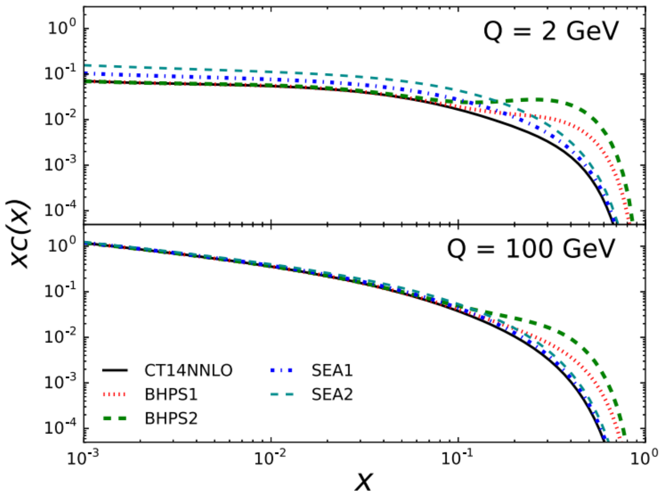


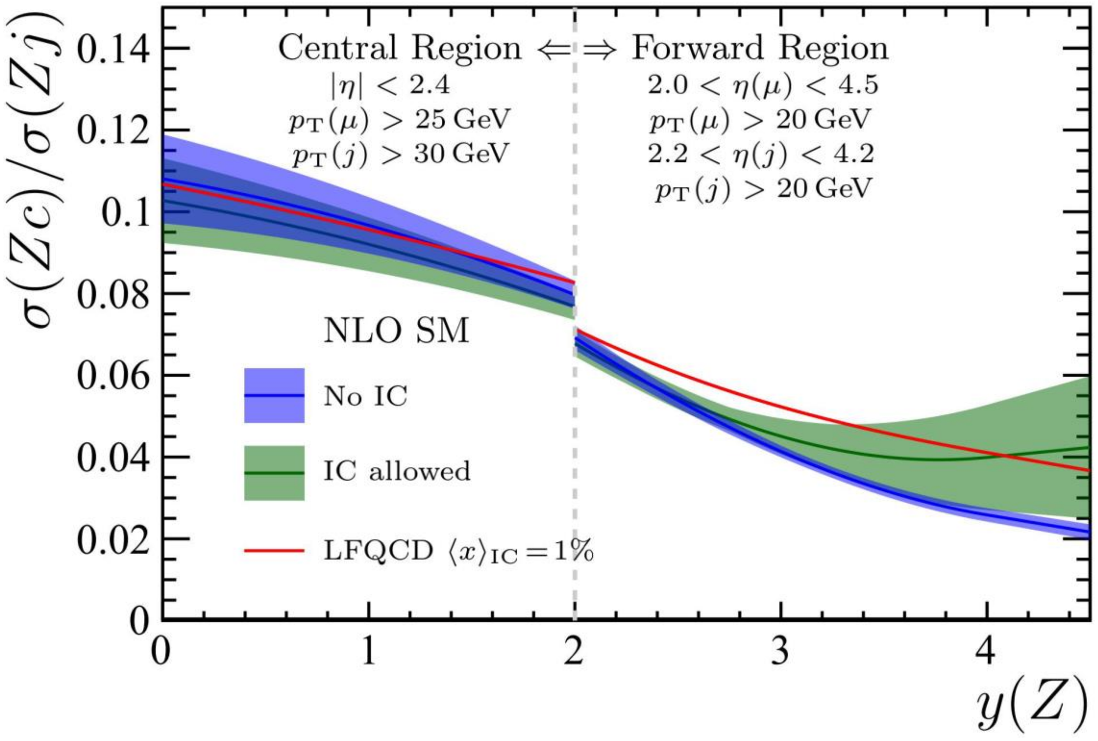
Probe intrinsic charm

- First study of Z + c-jets in the forward region, with optimized c-tagging.
- Measure ratio:

$$\sigma(Z + c \text{ jets})/\sigma(Z + \text{all jets})$$

  - Percent-level intrinsic-charm contribution would significantly enhance the ratio at high $y(Z)$.
  - Models allowing intrinsic-charm are largely unconstrained at high $y(Z)$.
  - Jet-related systematic uncertainties can largely cancel in the ratio.

PRL 128 (2022) 08200



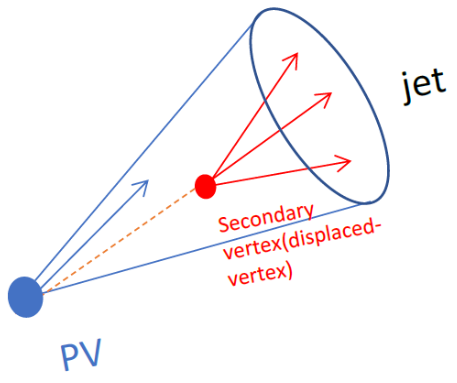
Z + c-jets

PRL 128 (2022) 08200

- LHCb Run2 (2015 – 2018) pp collisions at 13 TeV, about 6 fb^{-1}, using $Z \to \mu^+\mu^-$ events:

$$R_j^c = \frac{N(Z + c\text{ jets})}{N(Z + \text{all jets})\epsilon(c - \text{tag})}$$

- C-jet is tagged using method based on displaced-vertex (DV, or secondary vertex)



Fiduclal region/event selection

Z bosons	$p_T(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120$ GeV
Jets	$20 < p_T(j) < 100$ GeV, $2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c\,\text{hadron}) > 5$ GeV, $\Delta R(j, c\,\text{hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

Systematic uncertainties

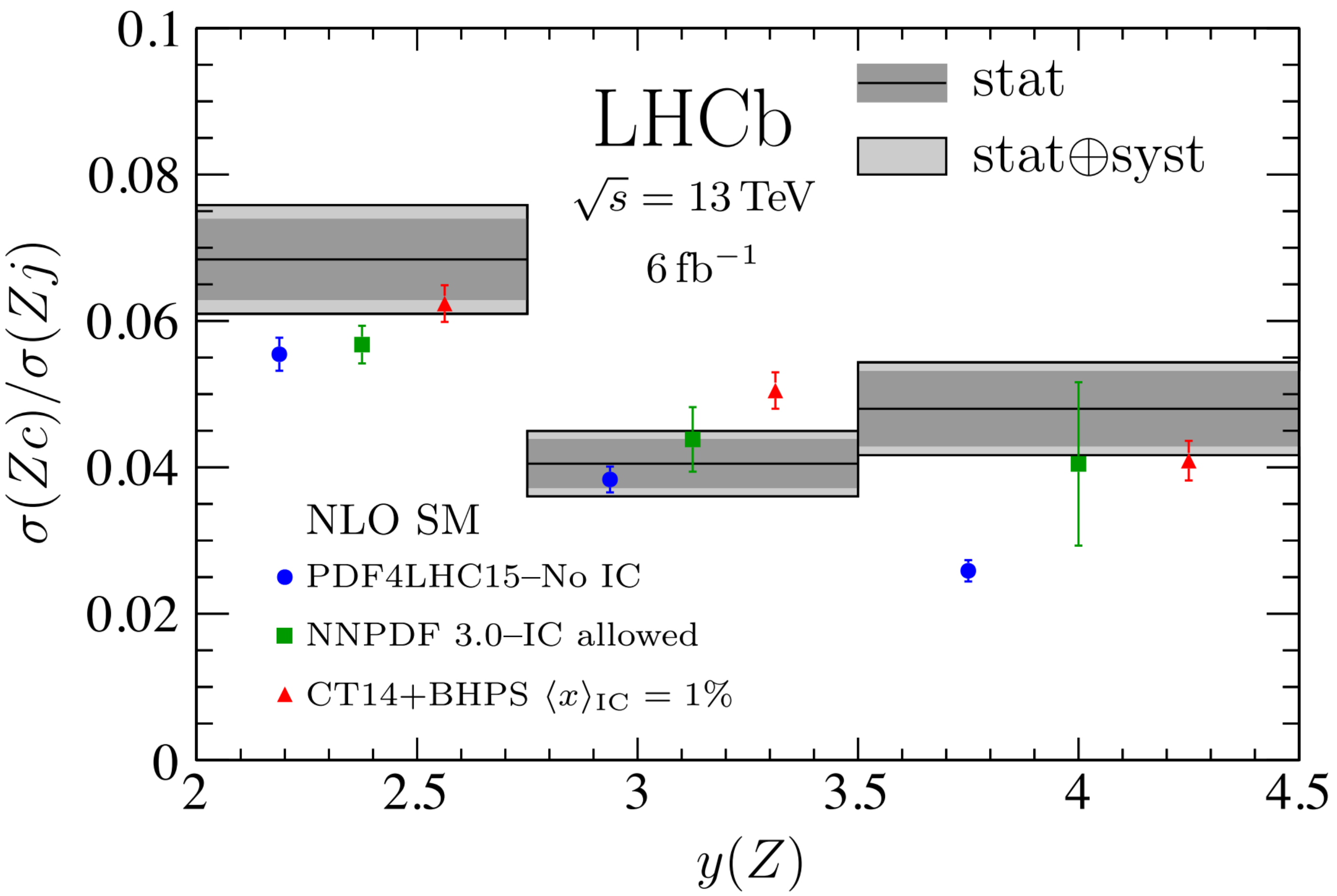
- Leading systematic uncertainty due to c-tagging calibration
  LHCb-DP-2021-006
- Other systematic uncertainties almost cancelled in the ratio.

Source	Relative uncertainty
c tagging	6%–7%
DV-fit templates	3%–4%
Jet reconstruction	1%
Jet p_T scale and resolution	1%
Total	8%

Z + c-jets

PRL 128 (2022) 08200

- Clear enhancement in highest $\boldsymbol{y}$ bin.
- Inconsistent with No-Intrinsic-Charm theory at >$\boldsymbol{3\sigma}$.
- More consistent with intrinsic-charm-allowed predictions, such as the BHPS model based on light front QCD.
- High rapidity results should strongly constrain the large-$\boldsymbol{x}$ charm PDF.
- Current results are statistically limited, Run3 dataset will allow for finer binning.



Probe nuclear modification with Z boson

- Z bosons are unmodified by the hot and dense medium created in heavy ion collisions,
  - Their leptonic decays pass through the medium without being affected by the strong interaction.
  - “conserved” the initial conditions of the collisions.
- Ideal probe of cold nuclear matter effects at Bjorken-x in $10^{-4} < x < 10^{-3}$ and $10^{-1} < x < 1$, with $Q^2 \sim 10^4 \mathrm{GeV}^2$.
- A calibration channel for probing the nuclear modification using other processes such as heavy quark production.

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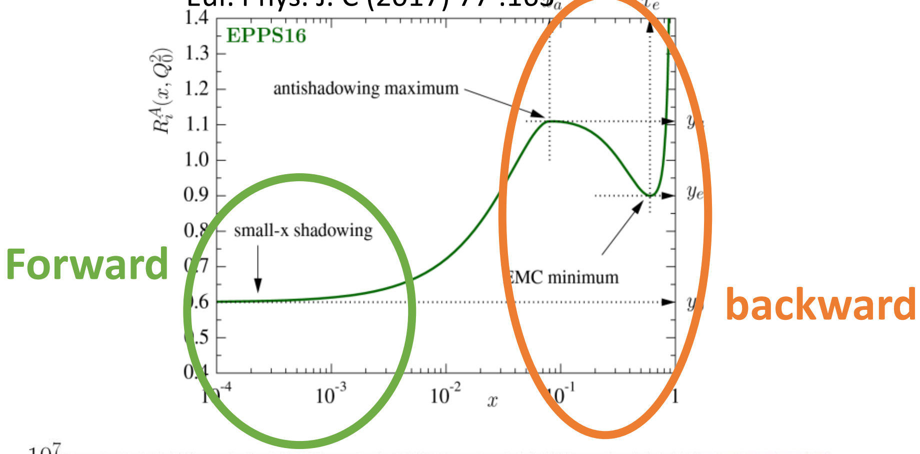
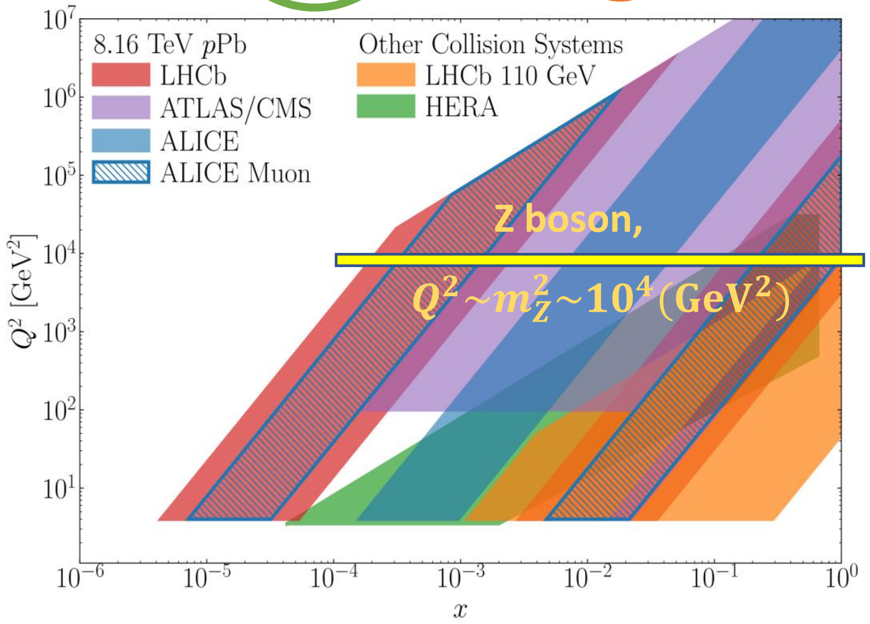




Z production in pPb collisions

arXiv:2205.10213 [hep-ex]

- **LHCb pPb dataset at 8.16 TeV about 30 nb^{-1}.**
- **Fiducial volume:**

$$p_{\mathrm{T}}^{\mu} > 20\ \mathrm{GeV},\ 2.0 < \eta_{\mu} < 4.5,$$
$$60 < m_{\mu\mu} < 120\ \mathrm{GeV}$$

- **Cross-section**:

$$\sigma_{Z\to\mu\mu} = \frac{N_{\mathrm{cand}} \cdot \rho \cdot f_{\mathrm{FSR}}}{\mathcal{L} \cdot \epsilon}$$

- **Forward-backward ratio:**

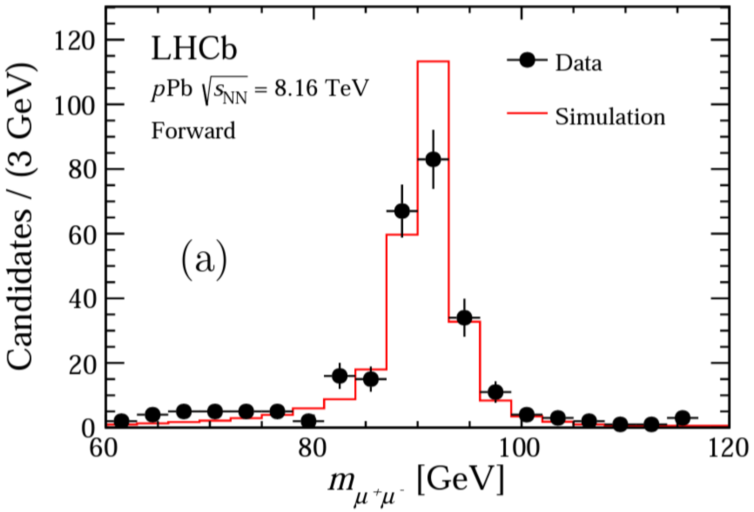
$$R_{\mathrm{FB}} = \frac{\sigma_{(1.53<y_{\mu}^{*}<4.03)}}{\sigma_{(-4.97<y_{\mu}^{*}<-2.47)}} \cdot k_{\mathrm{FB}}$$

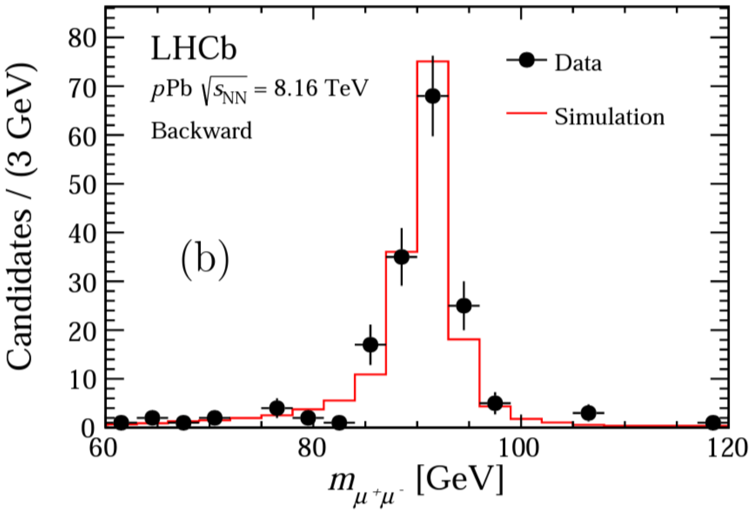
- **Nuclear modification factors:**

$$R_{p\mathrm{Pb}}^{\mathrm{fw.}} = \frac{1}{208} \cdot \frac{\sigma_{(p\mathrm{Pb},\,1.53<y_{\mu}^{*}<4.03)}}{\sigma_{(pp,\,2.0<y_{\mu}^{*}<4.5)}} \cdot k_{p\mathrm{Pb}}$$

Forward: 268 events

Backward: 167 events





- The cross-section, R_{FB} and $R_{p\mathrm{Pb}}$ are measured as a function of y_{Z}^{*}, p_{T}^{Z}, and $\phi_{\eta}^{*} = \tan(\phi_{\mathrm{acop}}/2)/\cos(\Delta\eta/2)$ (an angular variable equivalent to p_{T}^{Z} w/o uncertainty from momentum calibration).
- k_{FB} and $k_{p\mathrm{Pb}}$ are the corresponding muon rapidity acceptance correction factors.
- pp reference cross-section at 8.16 TeV is interpolated from LHCb 7, 8 and 13 TeV results.

Z production in *p*Pb collisions

arXiv:2205.10213 [hep-ex]

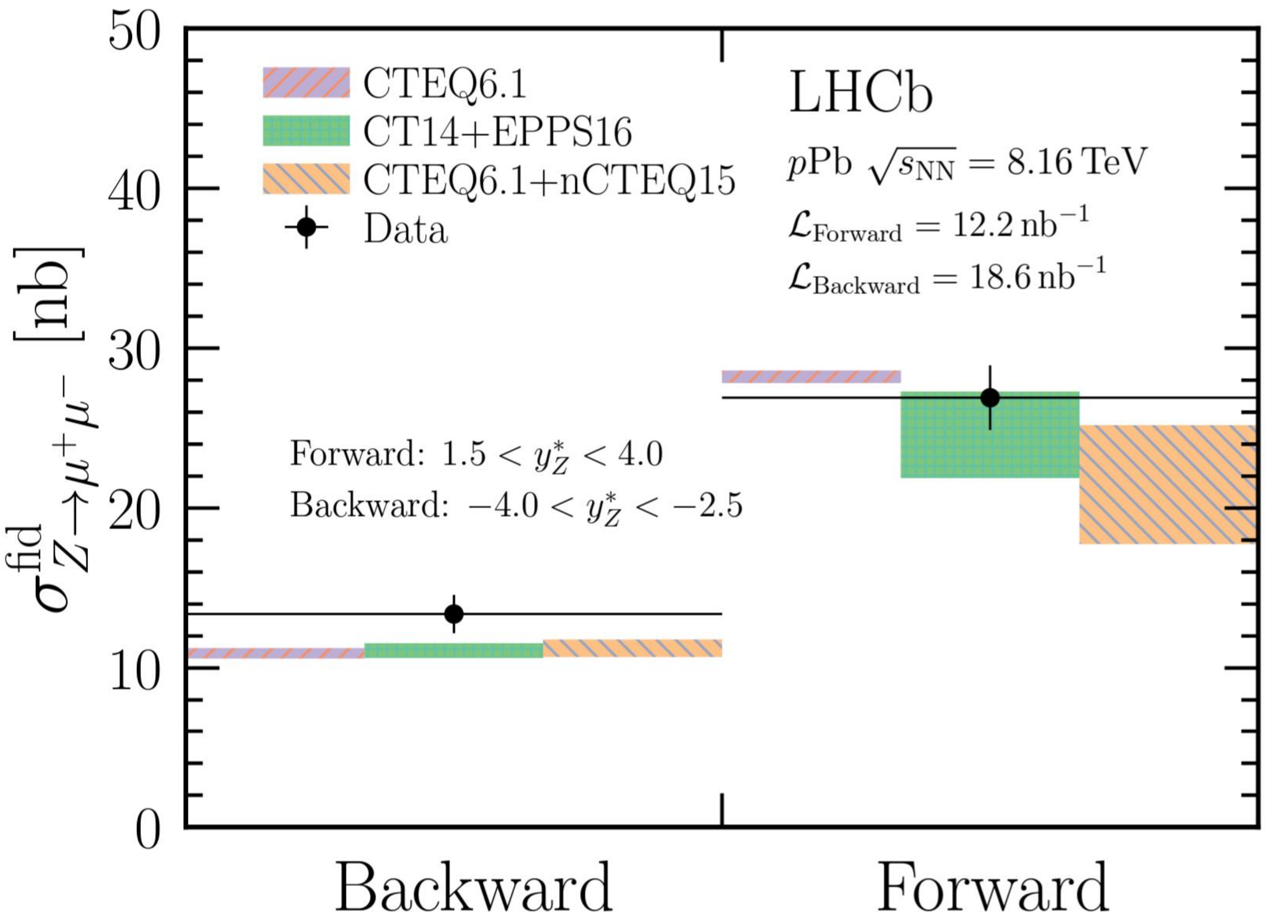
- **Total fiducial cross-section**:

  $\sigma_{Z\to\mu\mu,\,\text{fwd.}}$
  $= 26.9 \pm 1.6(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.7(\text{lumi.})\text{nb}$

  $\sigma_{Z\to\mu\mu,\,\text{bwd.}}$
  $= 13.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.3(\text{lumi.})\ \text{nb}$

- Compatible with theoretical calculations using POWHEG v2:
  - CTEQ61 (PDF) for both ***p*** and **Pb**
  - CT14 (PDF) for ***p*** and EPPS16 (nPDF) for **Pb**
  - CTEQ61 (PDF) for ***p*** and nCTEQ15 (nPDF) for **Pb**

- Forward (small Bjorken-x) results show strong constraining power on the nPDFs.



Z production in *p*Pb collisions

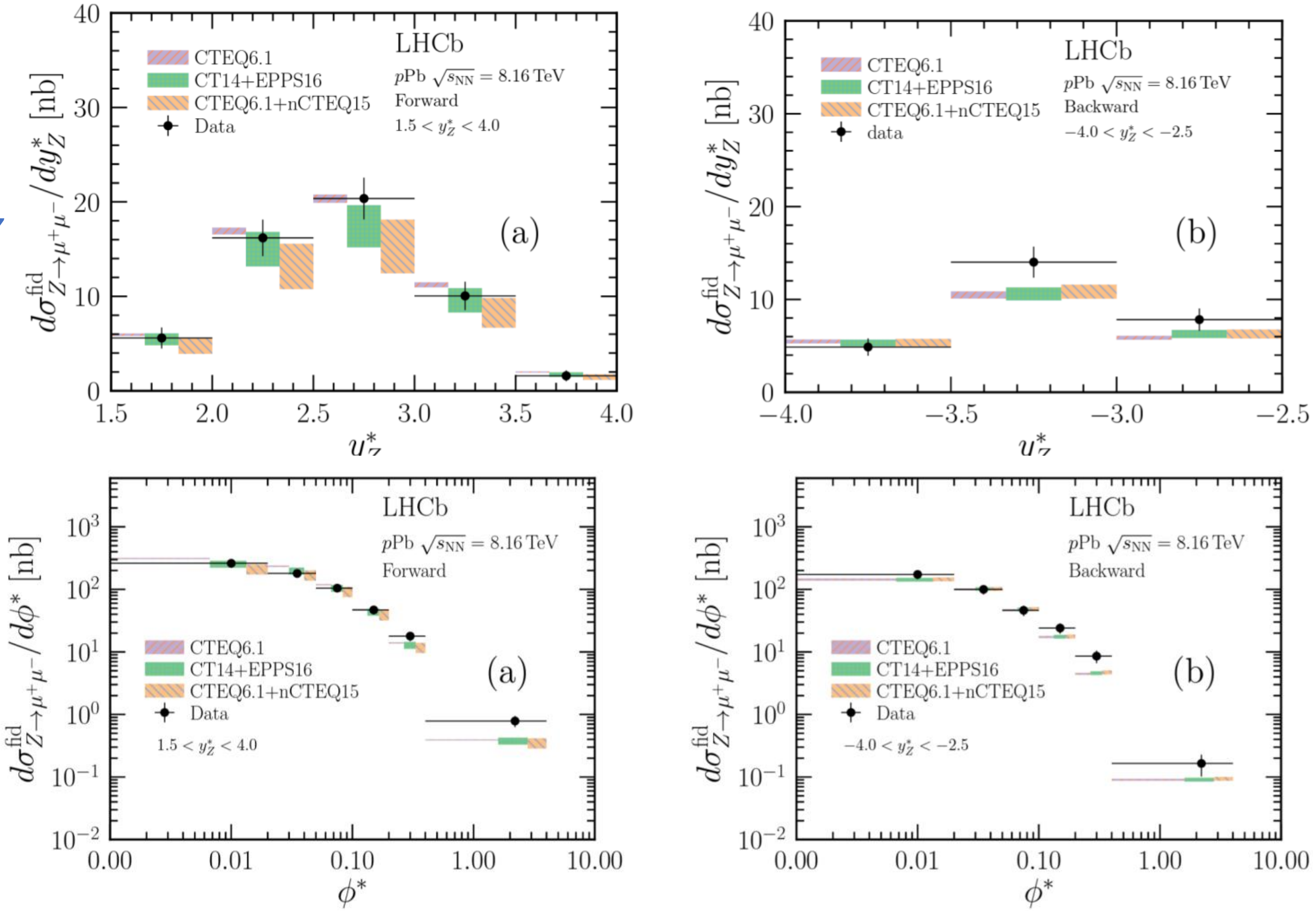
arXiv:2205.10213 [hep-ex]

- **Differential cross-section as a function of y_Z^* and ϕ_η^* :**
  - In good agreement with theoretical predictions.
  - Forward: smaller uncertainty than prediction, constraints on nPDFs.
  - Backward: larger uncertainty than predictions.

Forward | backward

y_Z^*

ϕ_η^*



Z production in pPb collisions

arXiv:2205.10213 [hep-ex]

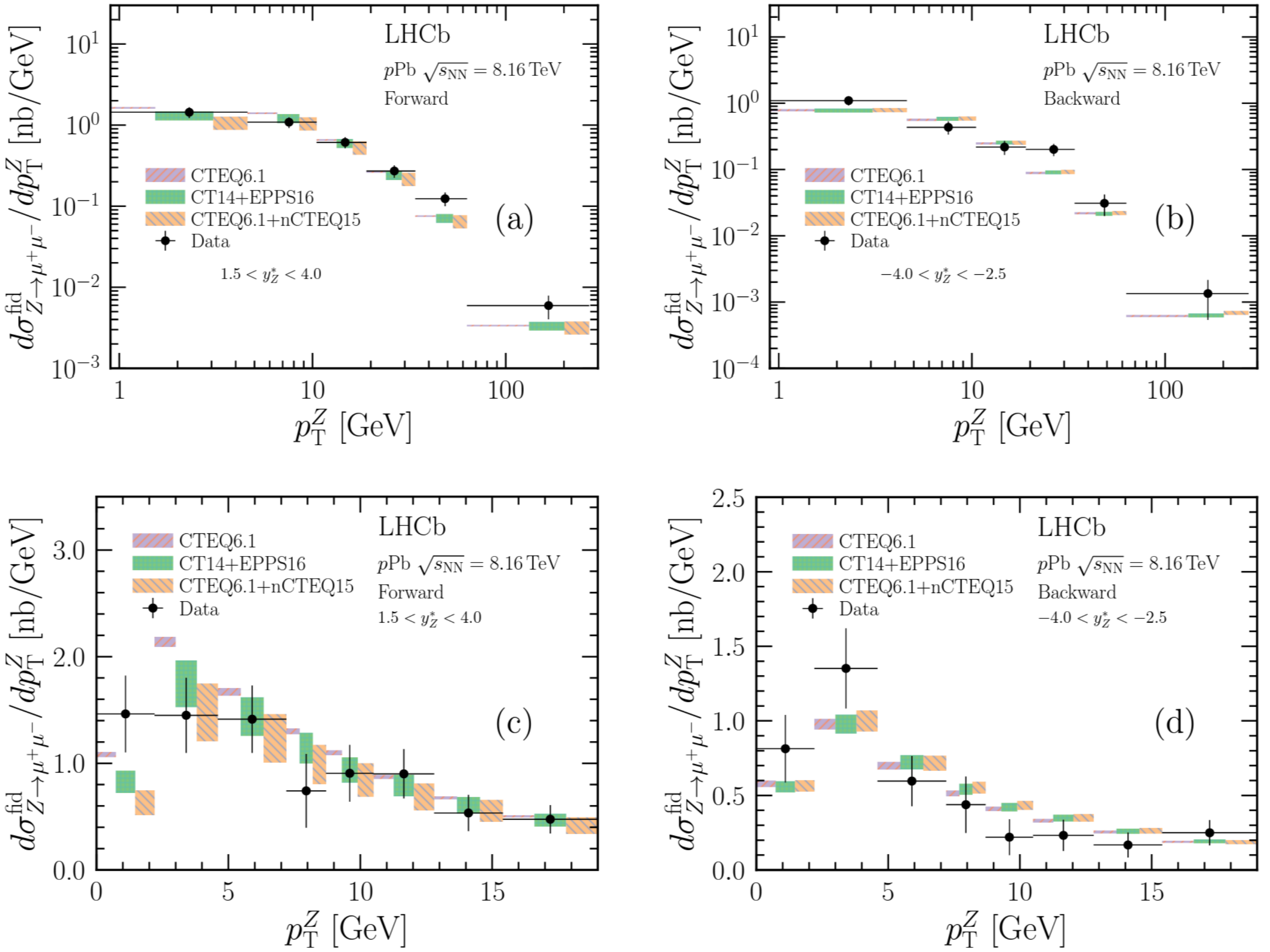
- **Differential cross-section as a function of p_T^Z :**
  - Compatible with theoretical predictions.
  - Smaller uncertainty than prediction for forward collisions, showing constraints on nPDFs.
  - Low-p_T^Z results are given, useful for TMD (transverse-momentum-dependent PDFs) studies.

Forward

backward

p_T^Z

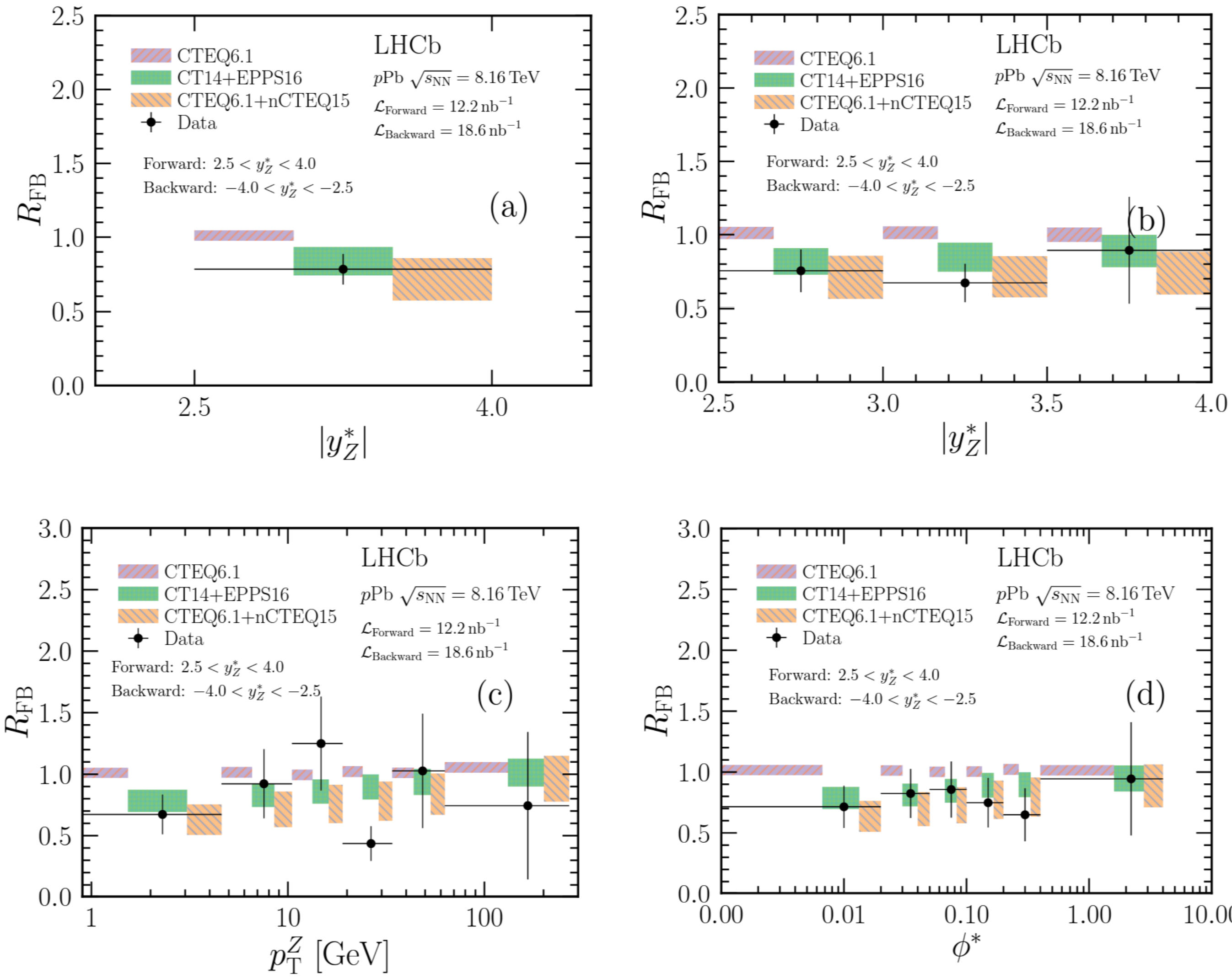
Low-p_T^Z



Z production in pPb collisions

arXiv:2205.10213 [hep-ex]

- **Forward-backward ratio** measured in common rapidity window $2.5 < |y_Z^*| < 4.0$:
  - **Total $R_{\mathrm{FB}} = 0.78 \pm 0.10$**
  - **As a function of y_Z^*, p_{T}^Z, and ϕ_η^* , see plots**
- A general suppression below unity.
- Compatible with theoretical predictions.
- Higher precision in total R_{FB} and certain bins as a function y_Z^*, p_T^Z, and ϕ_η^* can constrain the nPDFs.



Z production in pPb collisions

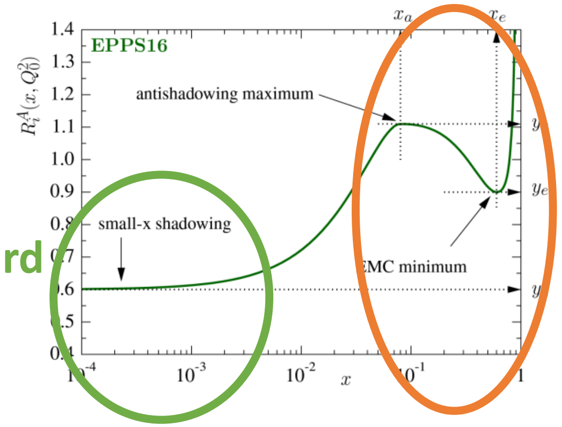
arXiv:2205.10213 [hep-ex]

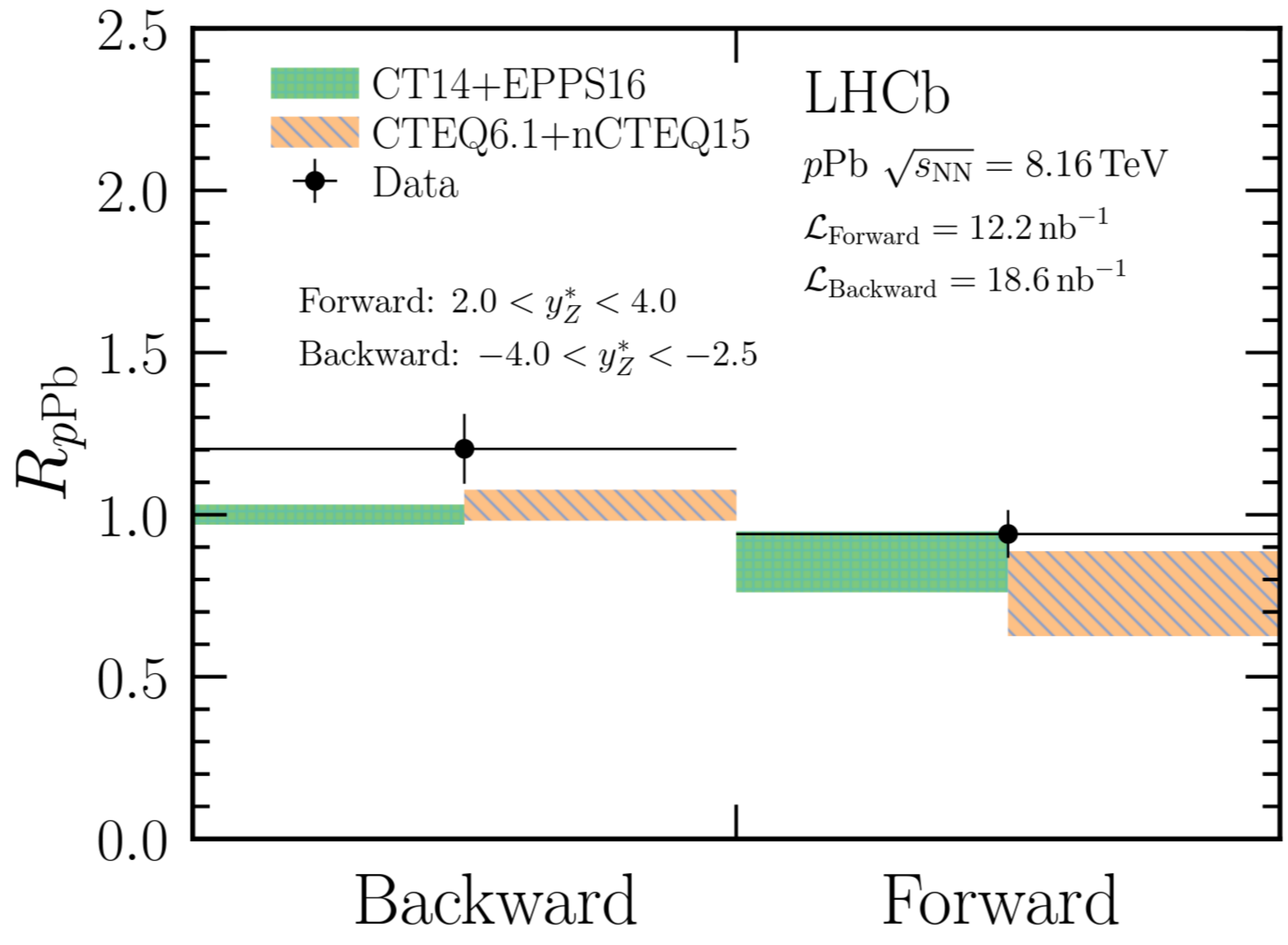
- **Inclusive nuclear modification factors:**

$$R_{p\mathrm{Pb}}^{\mathrm{fw.}} = 0.94 \pm 0.07$$

$$R_{p\mathrm{Pb}}^{\mathrm{bw.}} = 1.21 \pm 0.11$$

- Compatible with theoretical predictions.
- Suppression in the forward and enhancement in the backward are visible.
- Forward (small Bjorken-x) results show strong constraining power on the nPDFs.

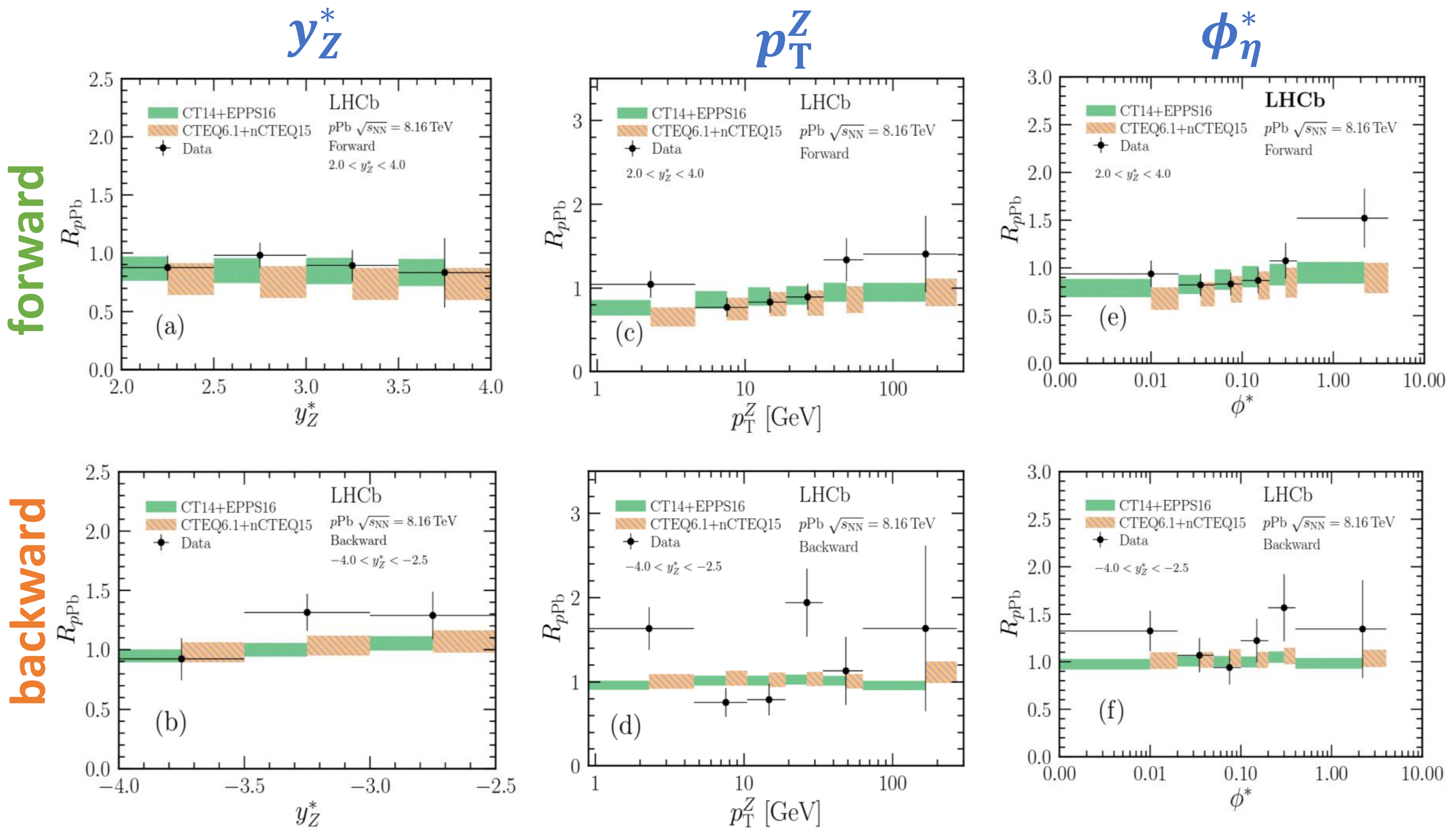




Z production in pPb collisions

arXiv:2205.10213 [hep-ex]

- **Nuclear modification factors as a function of y_Z^*, p_T^Z, and ϕ_η^***
- Compatible with theoretical predictions.
- Constraints on nPDFs are visible in certain bins in case of forward collisions.



Conclusion

- The fraction of Z boson production associated with charm jets is measured for the first time in the forward region at LHCb using pp collisions at 13 TeV
  - Considerable enhancement observed at the large Z boson rapidity.
  - Consistent with predictions assuming existence of intrinsic (valence-like) charm contents.
- A new Z boson production measurement in pPb collisions at 8.16 TeV
  - The differential cross-section, R_{FB} and $R_{p\mathrm{Pb}}$ as a function of y_Z^*, p_{T}^Z, and ϕ_η^* are measured for the first time in the forward region at LHCb.
  - The new results are compatible with nCTEQ15 or EPPS16 nPDFs calculations.
  - Forward (small Bjorken-x) results show strong constraining power on the nPDFs.

Backups

Supplementary material for LHCb-PAPER-2022-009

https://lhcbproject.web.cern.ch/Publications/p/LHCb-PAPER-2022-009.html

- Concerning the difference between the fourth data point (19 < pZ T < 34GeV) and the corresponding theoretical prediction in the differential fiducial cross-section measurement as a function of Z boson pT, a detailed study has been performed.
- This study excludes possible bugs from data quality, efficiency estimation, beam crossing angle, geometry acceptance, track reconstruction quality, and possible contributions from missing backgrounds such as standard model ZZ.
- Therefore, it is concluded as a statistical fluctuation.
- The p-value and the corresponding local significance of differences between the measurements and the PowhegBox predictions are shown in Fig. 1. The p-value of the fourth data point corresponds to about a 3-σ significance.