Implications of LHCb measurements and future prospects, 19-21, October 2022

Z boson production in pp and pPb collisions

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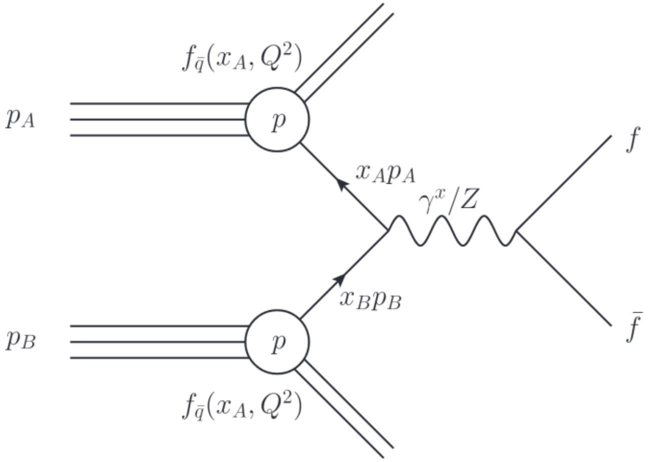
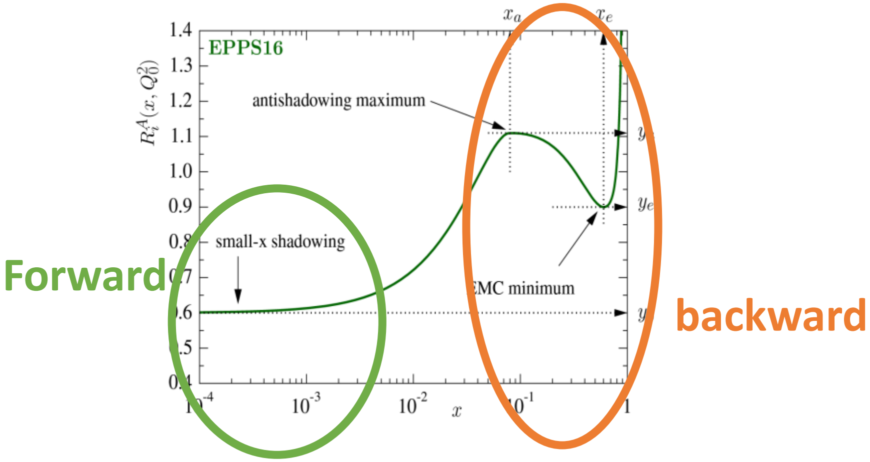
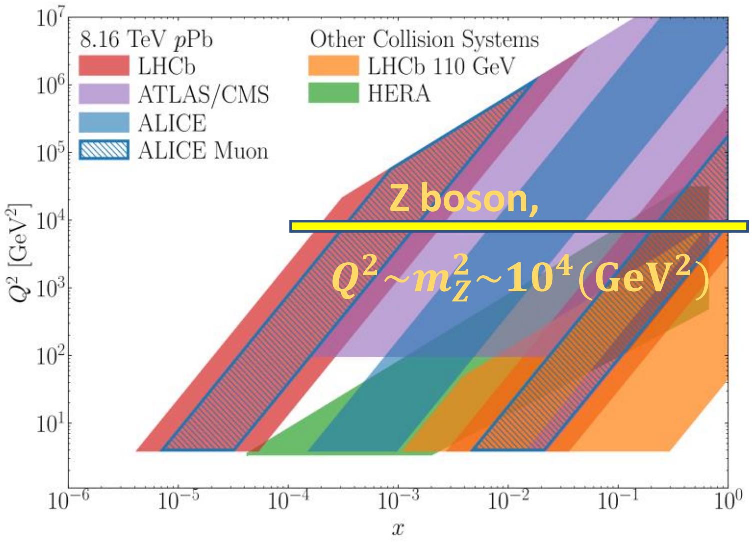
on behalf of the LHCb collaboration

Motivation

- Z boson production is an ideal probe of the initial conditions, such as proton PDFs, nuclear modifications, etc.
- Can be precisely predicted by factorization theory.
- Do not participate in strong interaction, unaffected by hadronic activities in the final states.



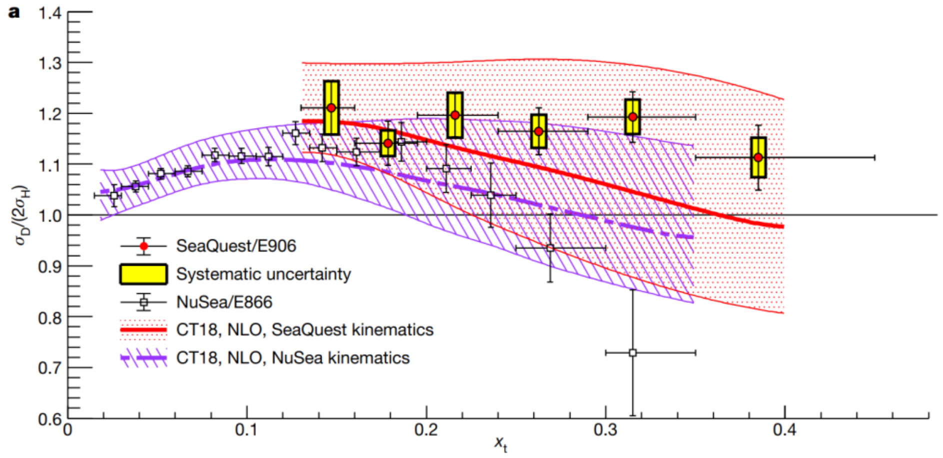


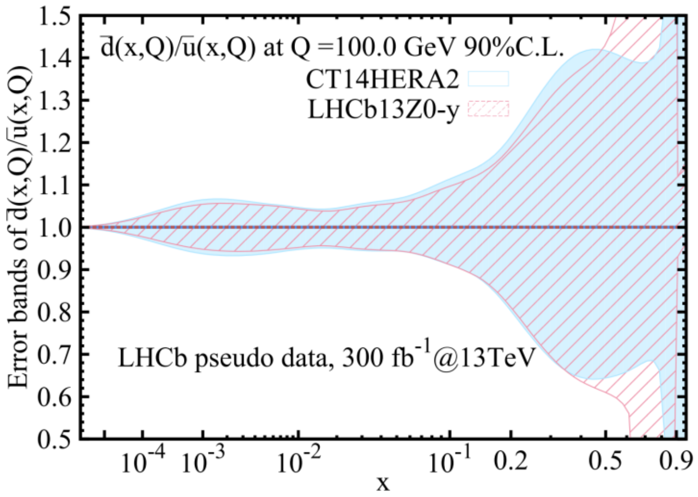


Motivation

- Z boson production is of particular interest in constraining u/d quark PDFs
  - Inconsistency show up in SeaQuest and NuSea results, LHCb data will be the only clean data to clarify it.
- Z production at LHC are also sensitive to the intrinsic heavier quark flavors [Eur. Phys. J. C (2017) 77:488]
- A calibration channel for probing the nuclear modification using other processes such as heavy quark production.

Nature **volume 590**, pages561–565 (2021)





Chinese Phys. C 45 (2021) 023110

Z production in pp collisions at 13 TeV

JHEP 07(2022)026

Z production in pp collisions

JHEP 07(2022)026

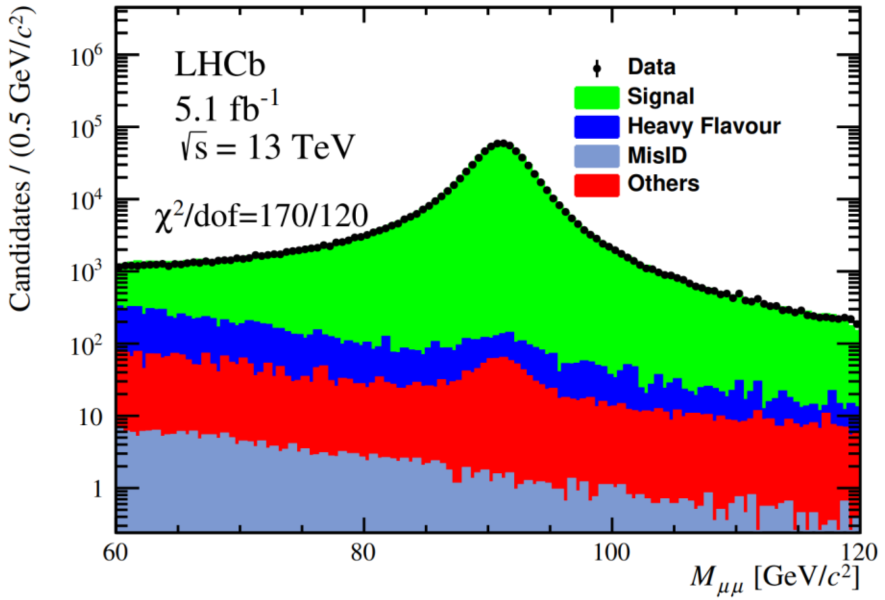
- LHCb pp data@13 TeV： $5.1 \pm 0.1\ \text{fb}^{-1}$ (2016-2018).
  - Very high purity: $N_{bkg}/N_{sig} \sim 2\%$
- Fiducial volume:

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

- Differential Cross-section:

$$\frac{d\sigma_{Z\to\mu\mu}}{dy} = \frac{\Delta N_{\mathrm{Z}}(y)\cdot f_{\mathrm{FSR}}(y)}{\mathcal{L}\cdot\epsilon(y)\cdot\Delta y}$$

in bins of Z rapidity, p_T^Z, and φ^*.



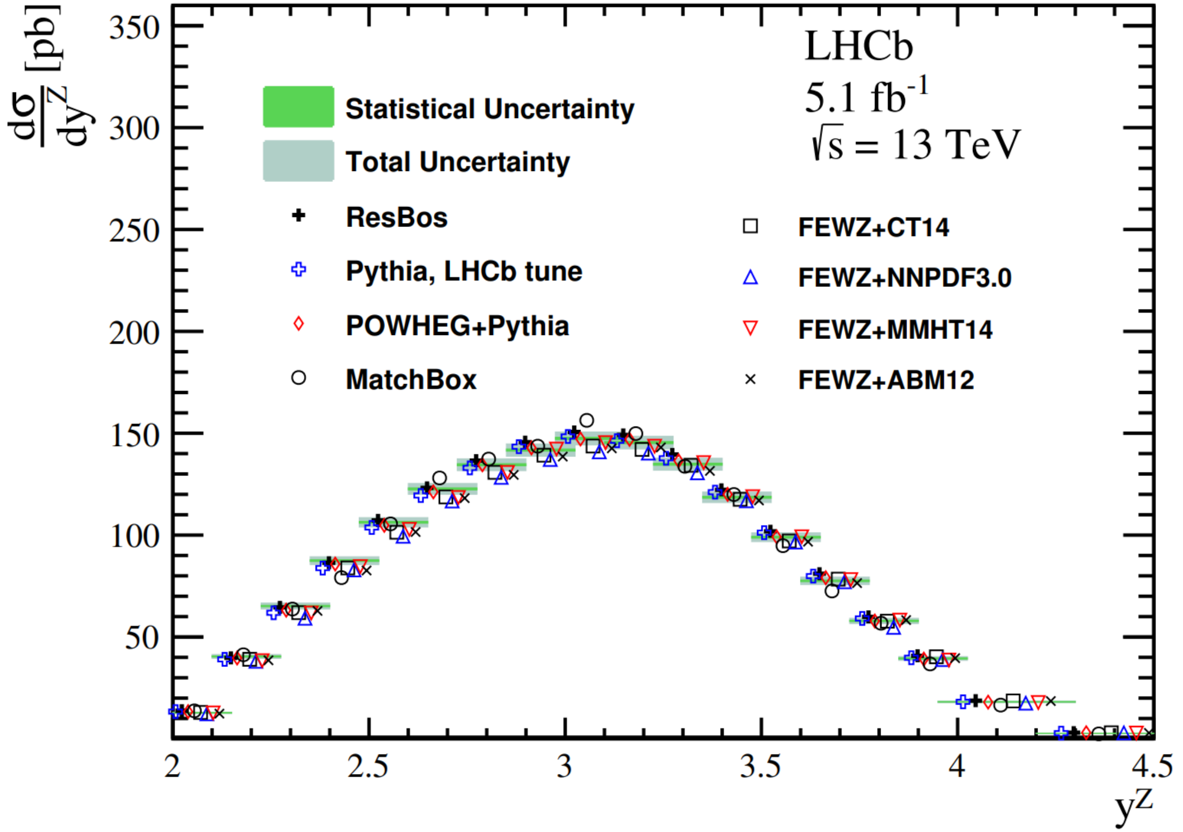
Systematic uncertainties

Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.06
Alignment & calibration	—
Efficiency	0.77
Closure	0.23
FSR	0.15
Total Systematic (excl. lumi.)	0.82
Luminosity	2.00
Total	2.16

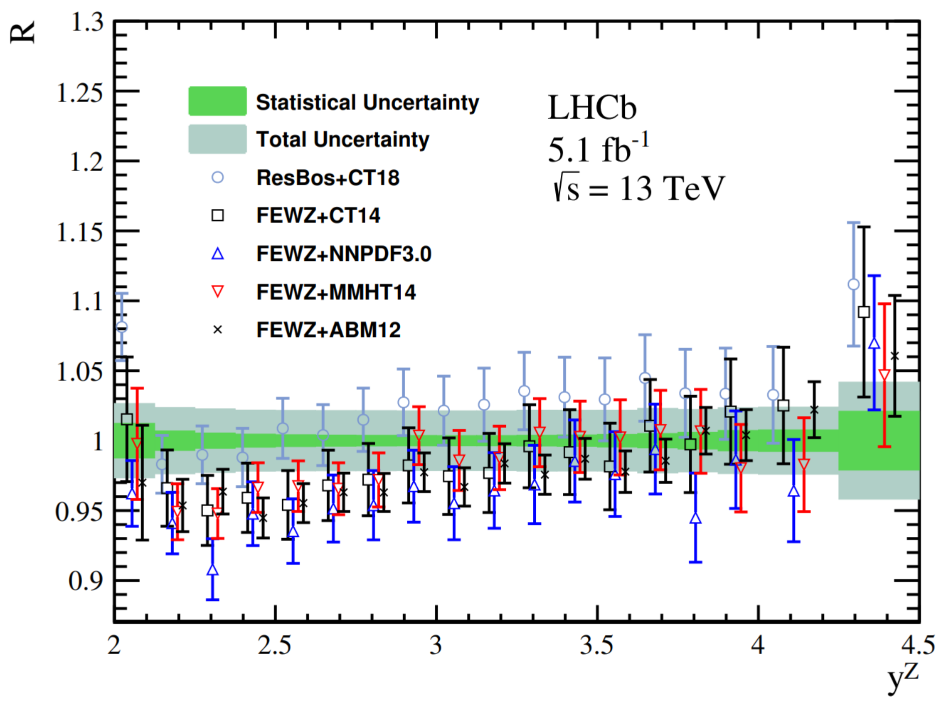
Z production in pp collisions

JHEP 07(2022)026

- Single differential cross-section vs Z boson rapidity
  - Compatible with theory prediction, difference observed at rapidity from 2 to 3



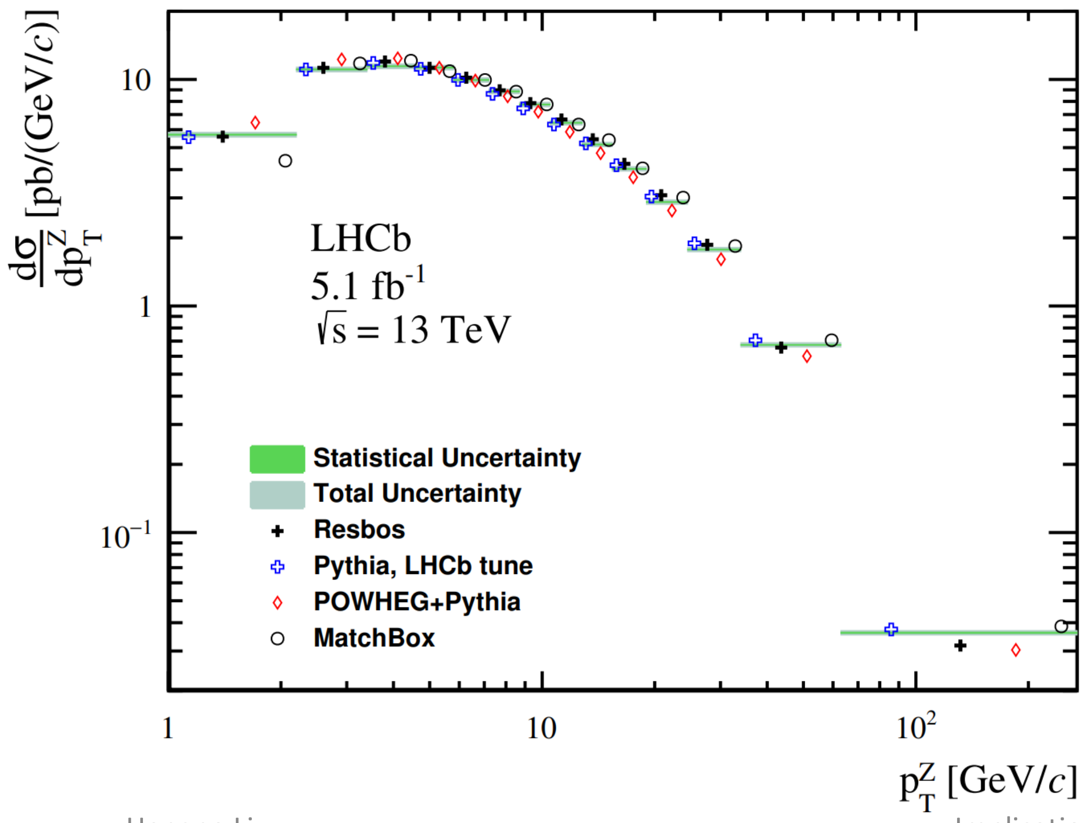
Prediction/data ratio



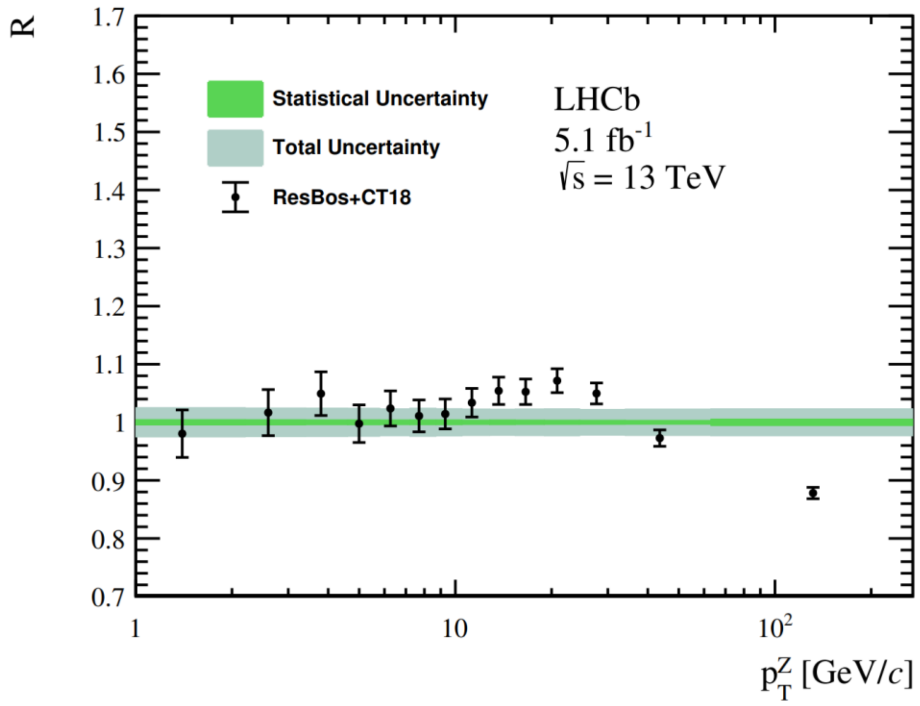
Z production in pp collisions

JHEP 07(2022)026

- Single differential cross-section vs. p_{T}^{Z}
  - Compatible with theory prediction, difference observed in large p_{T}^{Z}



Prediction/data ratio

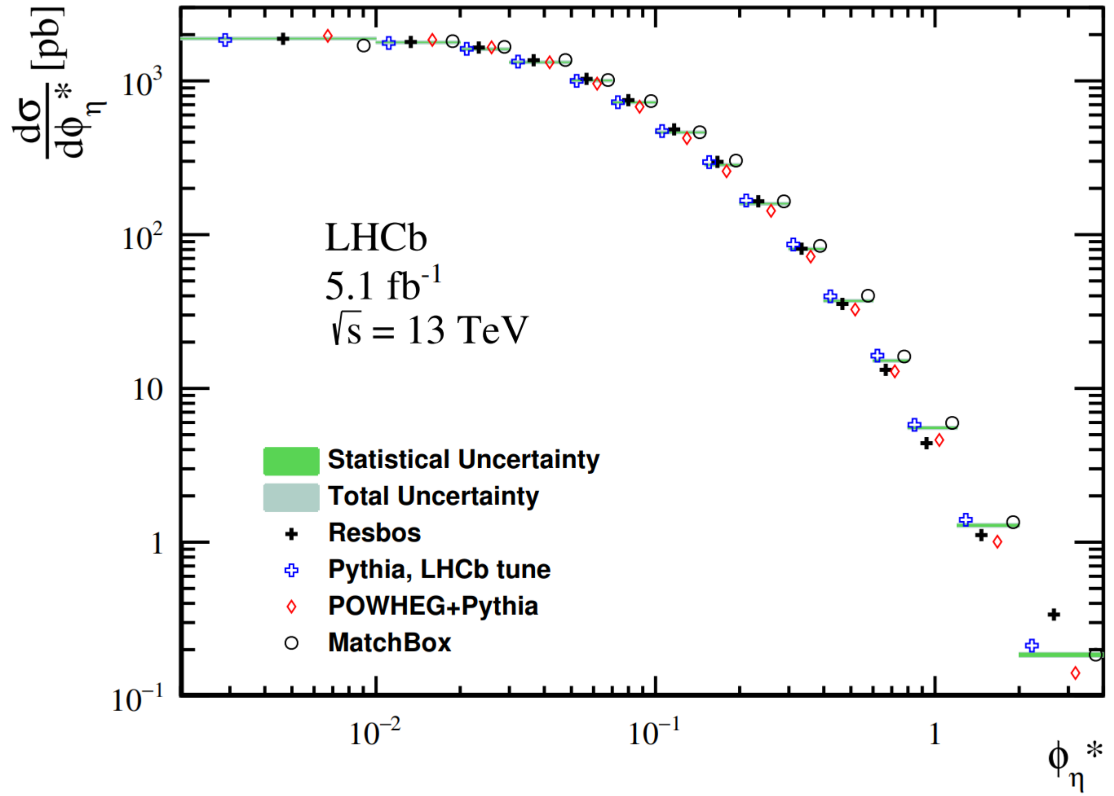


Z production in pp collisions

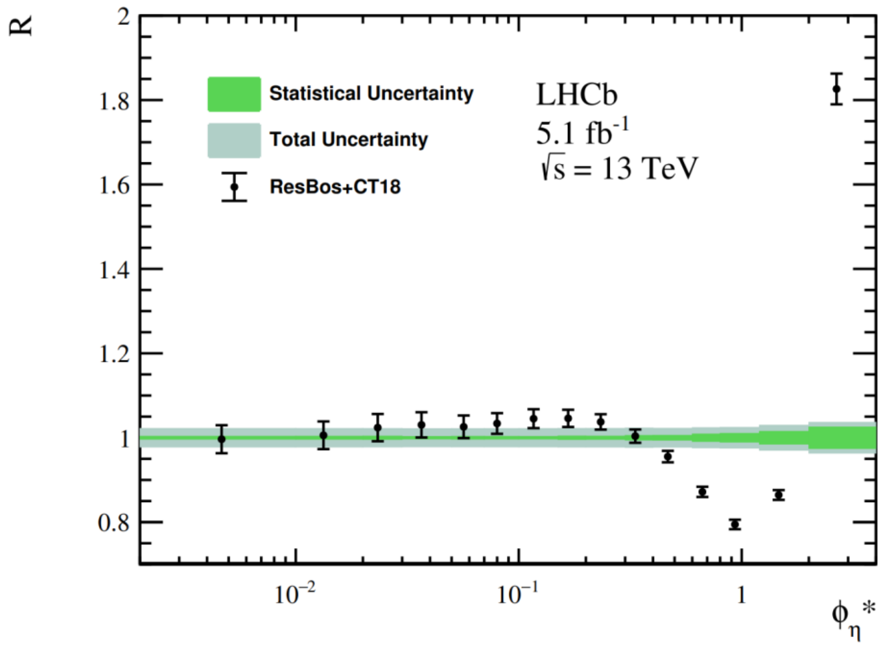
JHEP 07(2022)026

- Single differential cross-section vs. ϕ^*
  - Compatible with theory prediction,
  - Difference observed at large ϕ^* corresponds to large p_T^Z

$\phi^* = \tan(\phi_{acop}/2)\,/\,\cos(\Delta\eta/2)$, equivalent to p_T^Z, less impacted by detector resolution effects.



Prediction/data ratio



Z production in pp collisions

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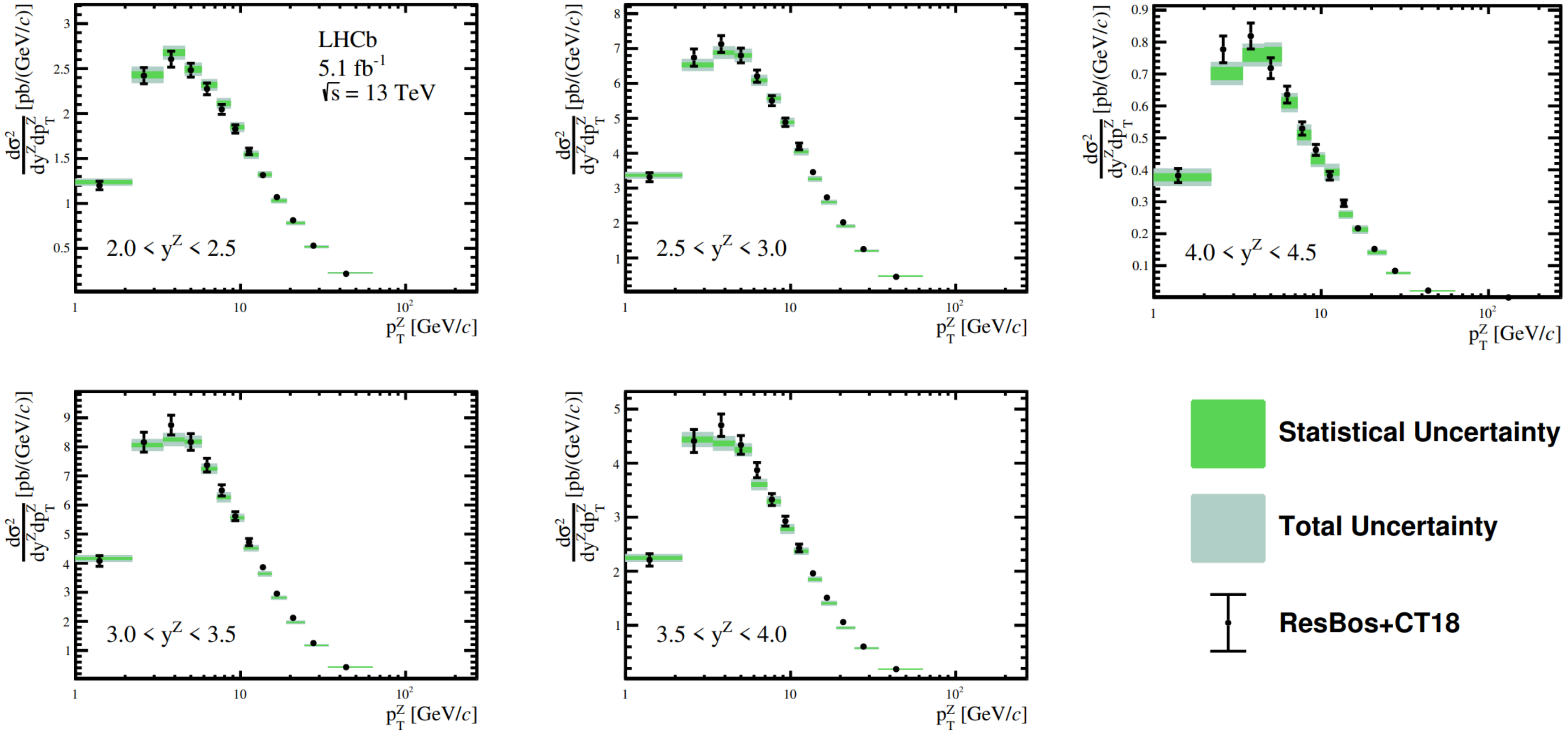
- Double differential cross-section: $y_Z - p_{\mathrm{T}}^{Z}$
  - Compatible with theoretical prediction



First double differential measurements in the forward region

Z production in pp collisions

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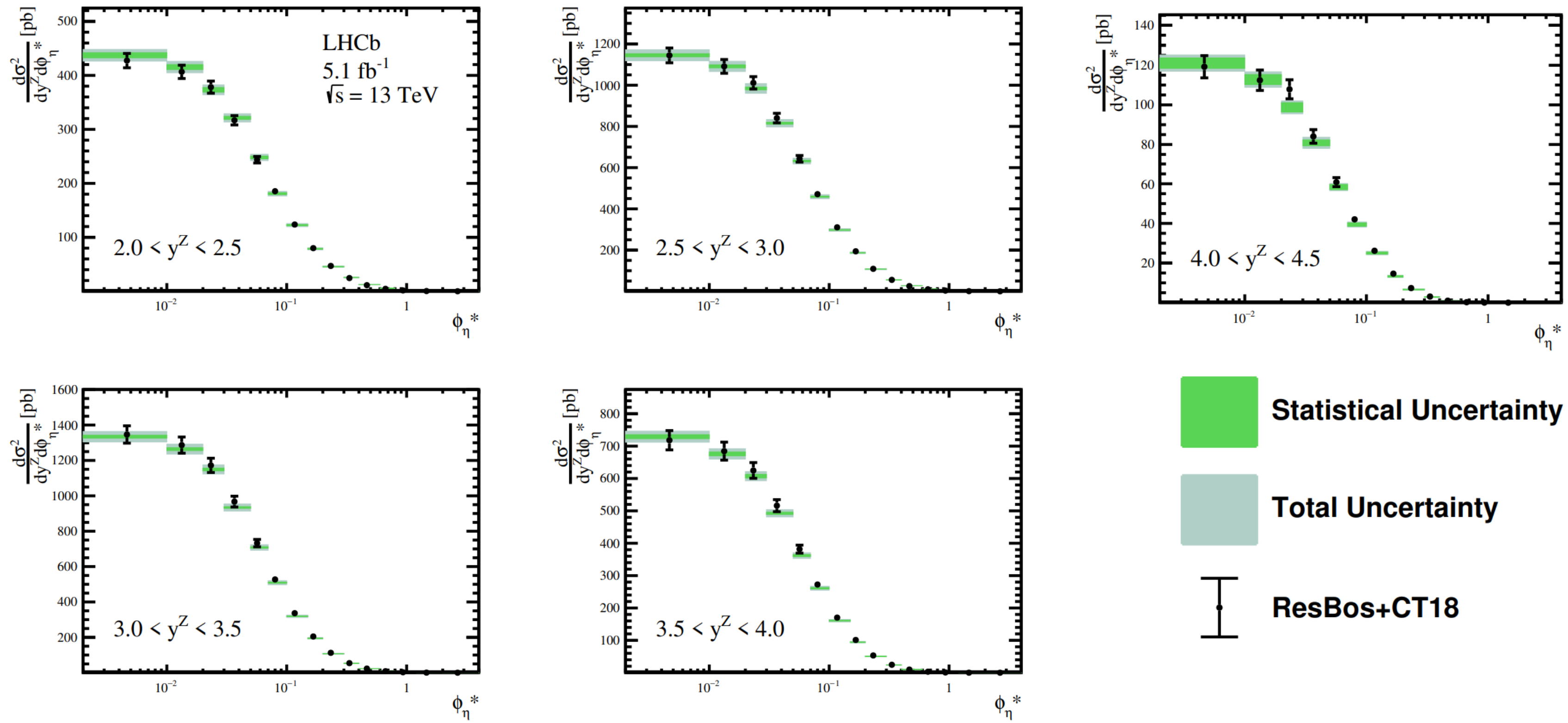
- Double differential cross-section: $y_Z - \varphi^*$
  - Compatible with theoretical prediction

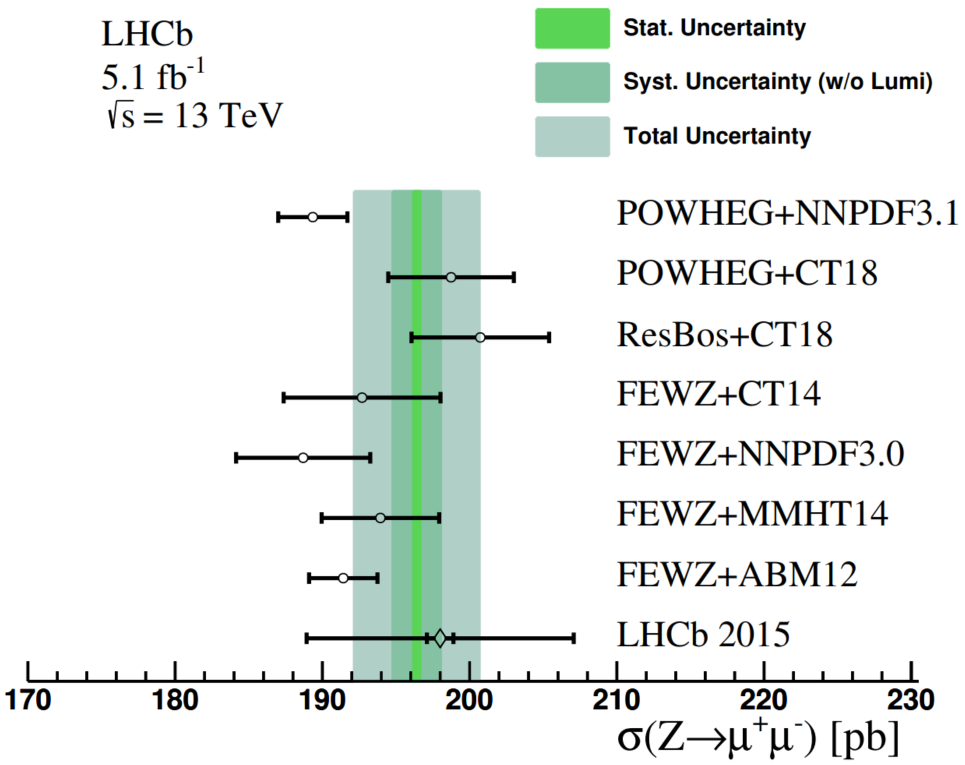
First double differential measurements in the forward region



Z production in pp collisions

- Integrated cross-section Run2:

$$\sigma_{(Z\to\mu^+\mu^-)} = 196.4 \pm 0.2(stat.) \pm 1.6(syst) \pm 3.9(lumi)\ \text{pb},$$



Most precise measurement in the forward region at the moment.

Combined using “BLUE” method:
[NIM A270(1988) 110, NIM A500(2003) 391]

- Uncertainties from Lumi., FSR corr., background, closure test, are treated as 100% correlated.
- Other uncertainties are treated as not correlated.

Z production in pPb collisions at 8.16 TeV

LHCb-PAPER-2022-009, arXiv:2205.10213, accepted by JHEP.

Z production in pPb collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

pPb data 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**:

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

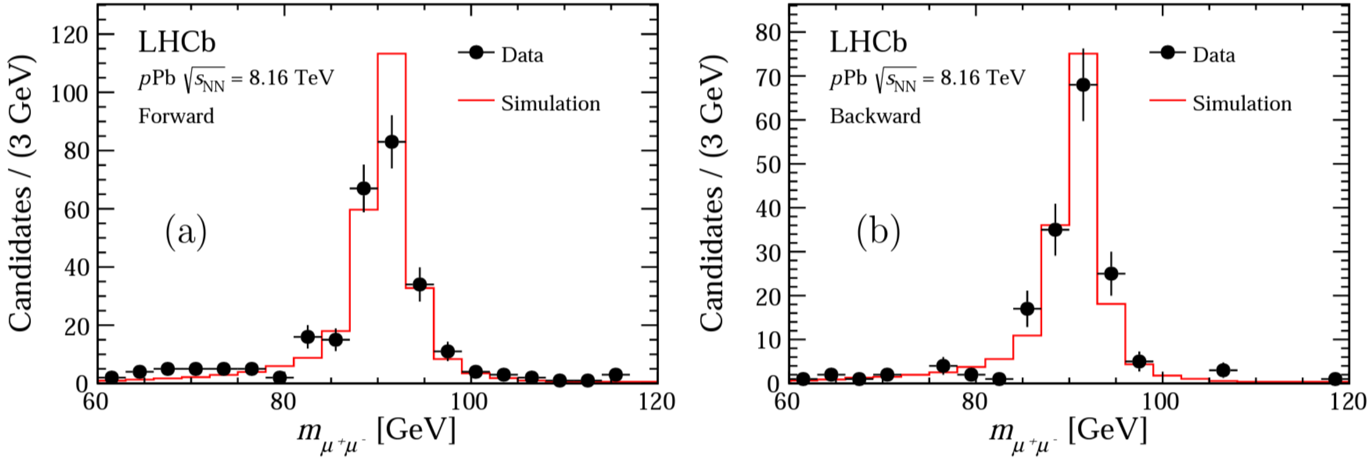
- **Forward-backward ratio:**

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

- **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 ϕ_{η}^{*}
  - k_{FB} and $k_{p\mathrm{Pb}}$: 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

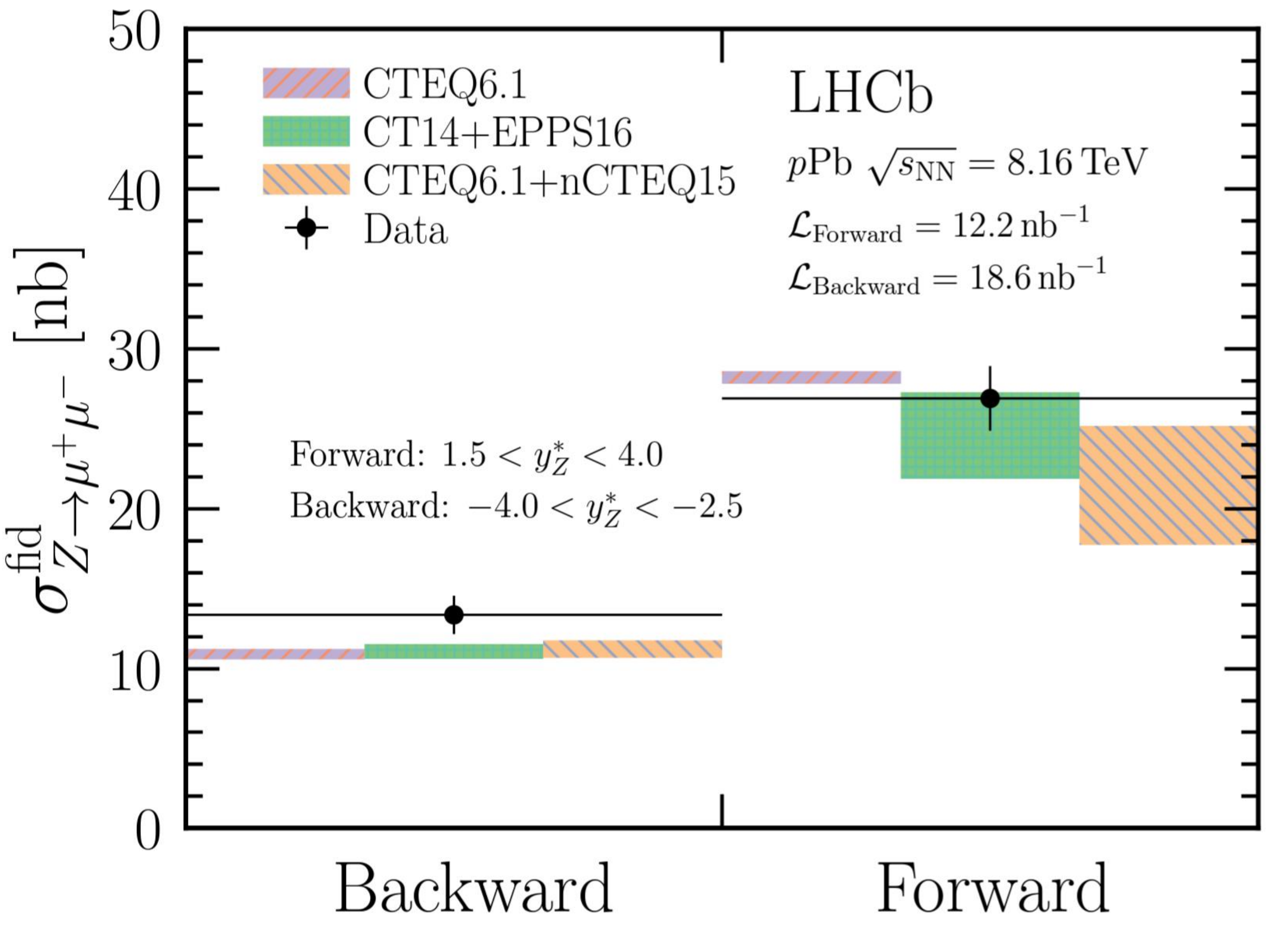
LHCb-PAPER-2022-009, arXiv:2205.10213

- **Total fiducial cross-section**:

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

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

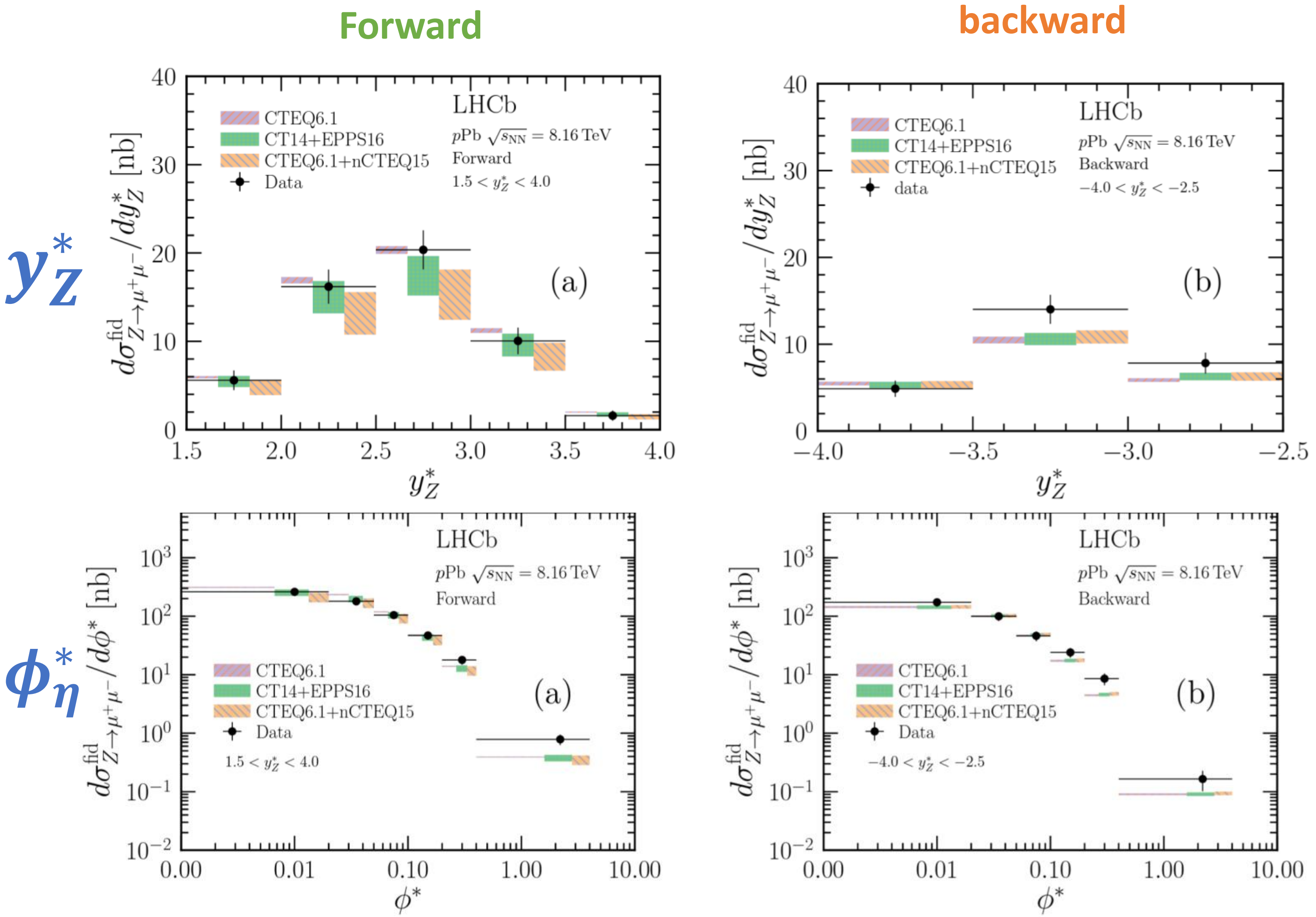
- Compatible with theoretical calculations using POWHEG v2:
  - CTEQ61 (PDF) for both ***p*** and **Pb**
  - CT14 (PDF) for ***p*** and EPPS16 (nPDF) for **Pb**
  - CTEQ61 (PDF) for ***p*** and nCTEQ15 (nPDF) for **Pb**
- Forward (small Bjorken-x) results show strong constraining power on the nPDFs.



Z production in pPb collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

- **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.



Z production in pPb collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

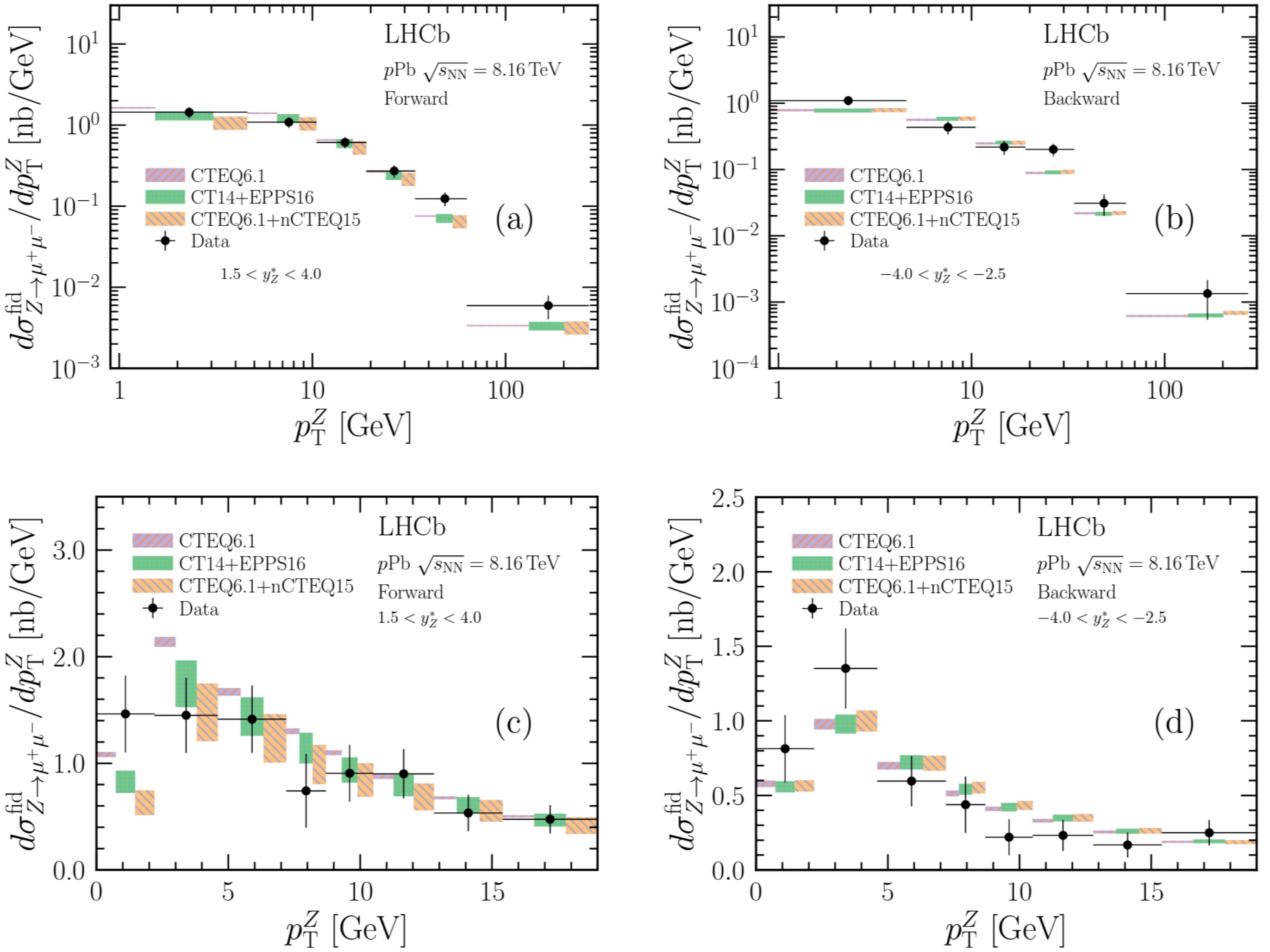
- **Differential cross-section as a function of p_T^Z :**
  - Compatible with theoretical predictions.
  - Smaller uncertainty than prediction for **forward** collisions, showing constraints on nPDFs.
  - **Low-p_T^Z** results are given, useful for TMD (transverse-momentum-dependent PDFs) studies.

Forward

backward

p_T^Z

Low-p_T^Z

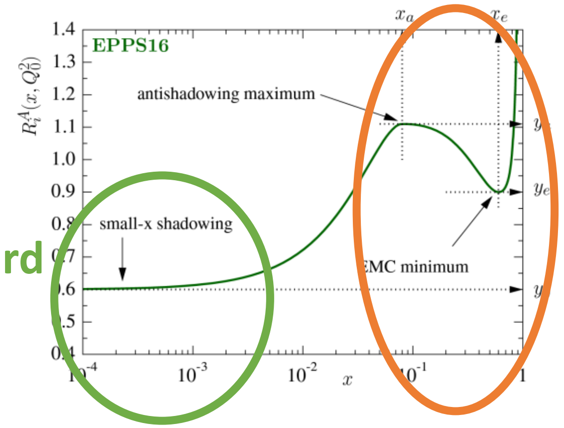


Z production in pPb collisions

- **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.



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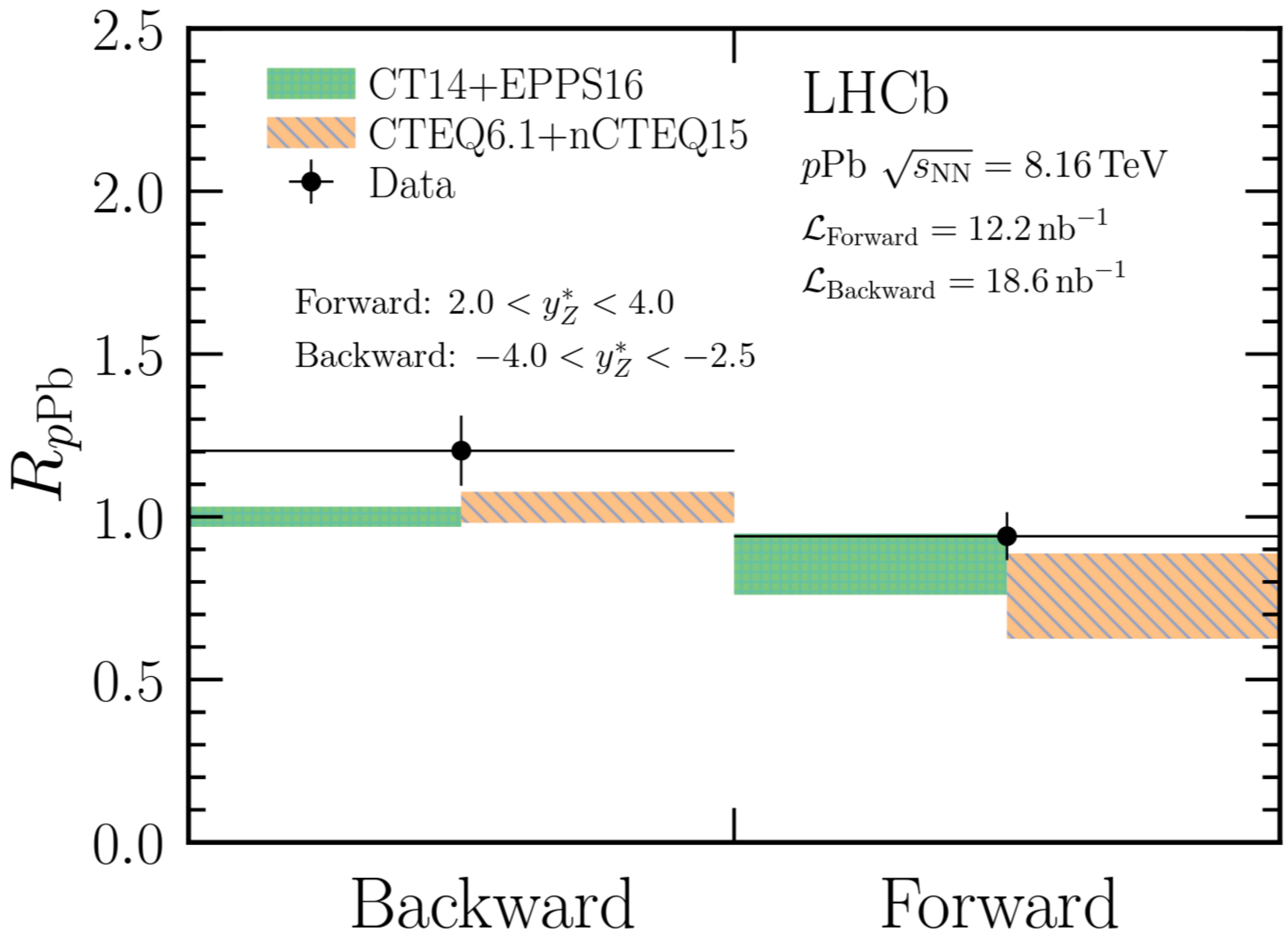
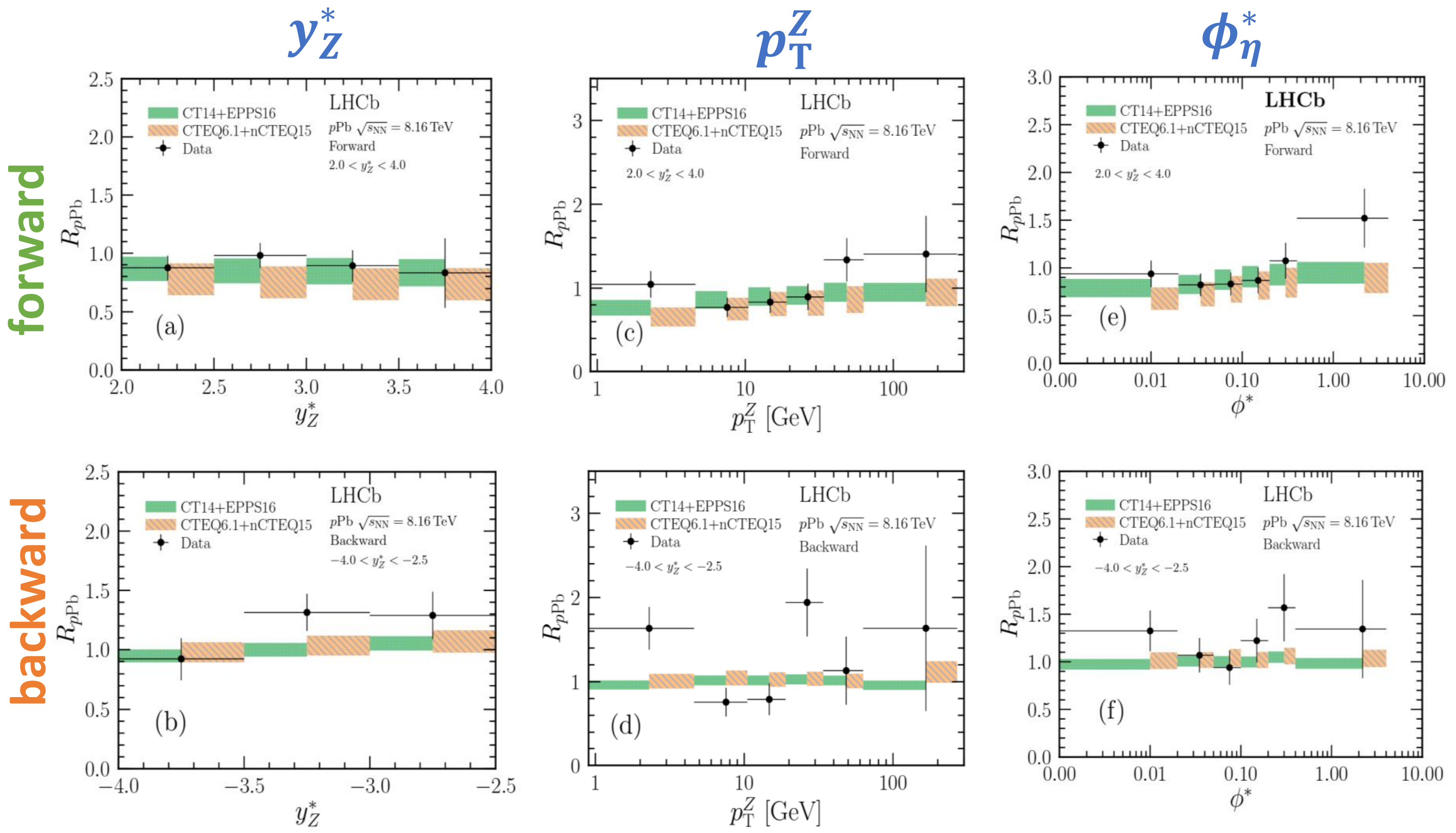


Z production in pPb collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

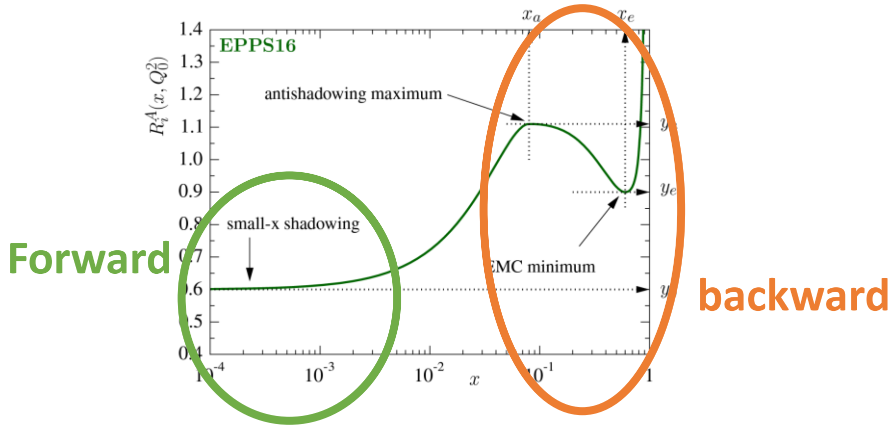
- **Nuclear modification factors as a function of y_Z^*, p_T^Z, and ϕ_η^***
- Compatible with theoretical predictions.
- Constraints on nPDFs are visible in certain bins in case of forward collisions.

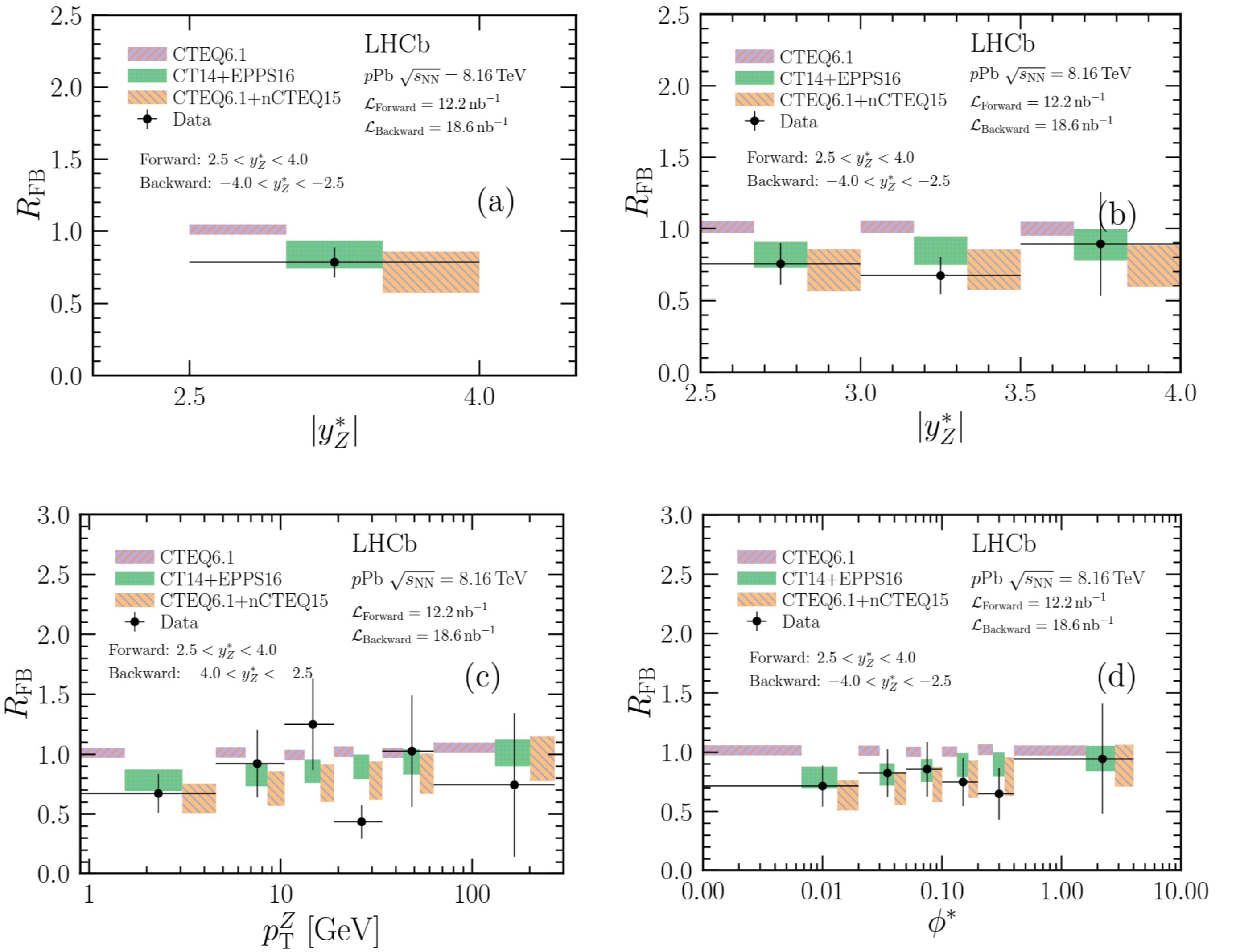


Z production in pPb collisions

LHCb-PAPER-2022-009, arXiv:2205.10213

- **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.





Conclusion/Outlook

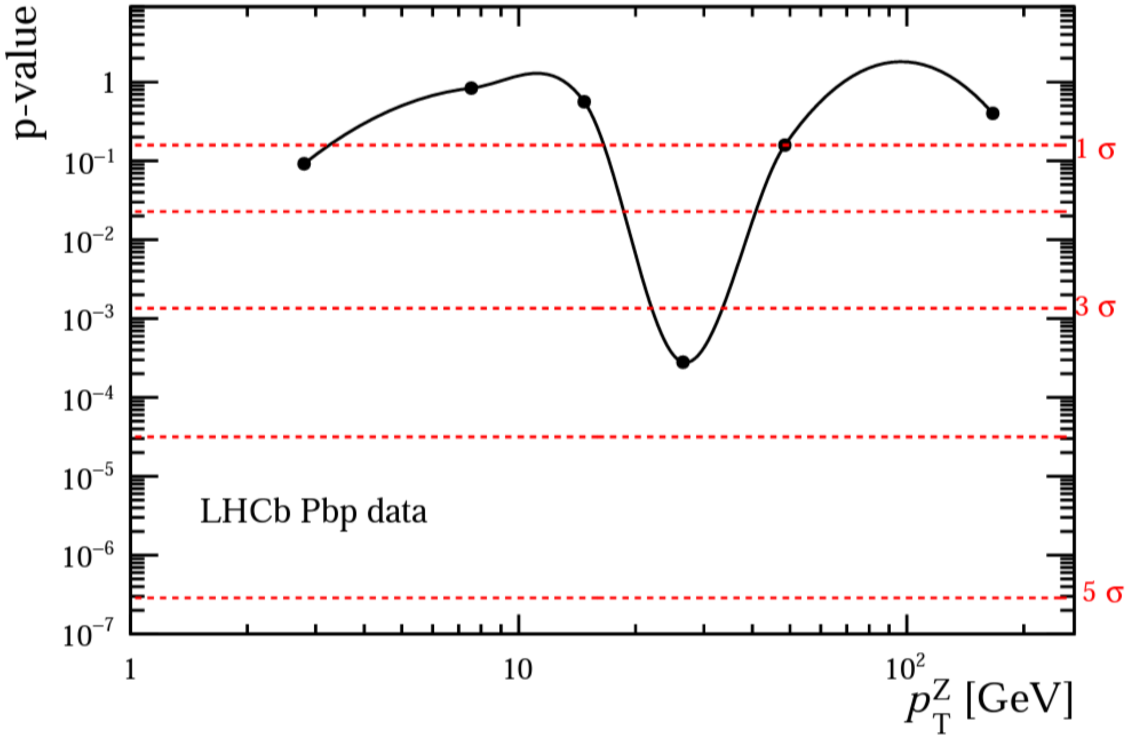
- The most precise measurement of the Z boson production in pp collisions at 13 TeV in the forward region.
  - First double differential measurements ($y_Z - p_{\mathrm{T}}^{Z}$, $y_Z - \varphi^*$) in the forward region
  - Reasonable agreement between data and theoretical predictions
  - Provide important/unique constraints to the PDFs at small and large Bjorken-x
- 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.
  - Compatible with nCTEQ15 or EPPS16 nPDFs calculations.
  - Forward (small Bjorken-x) results show strong constraining power on the nPDFs.
- The Z production serves as a very important benchmark process to many physics topics; this series of measurements will always be carried out in future datasets. Stay tuned!

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.

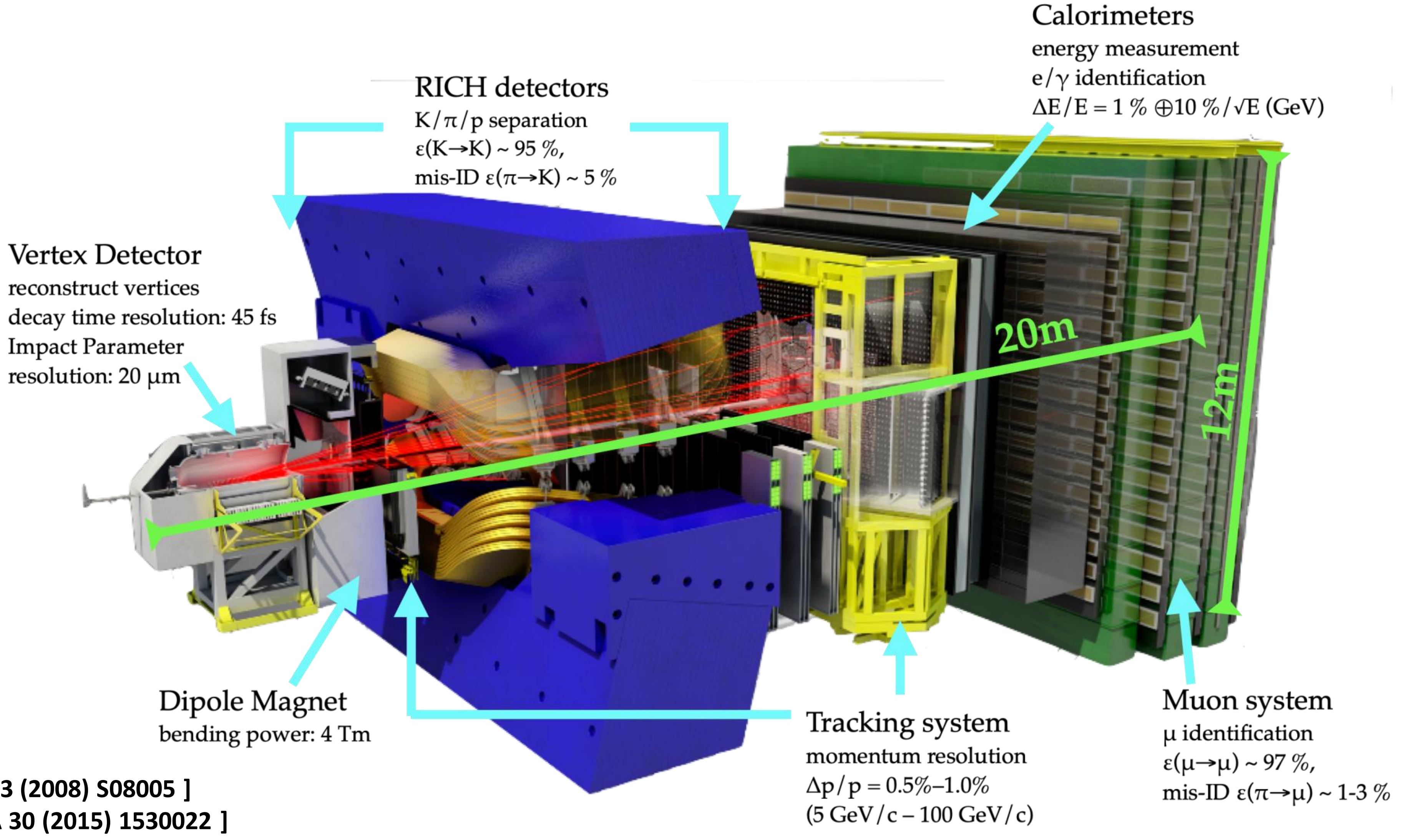


The LHCb detector

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

  $2 < \eta < 5$

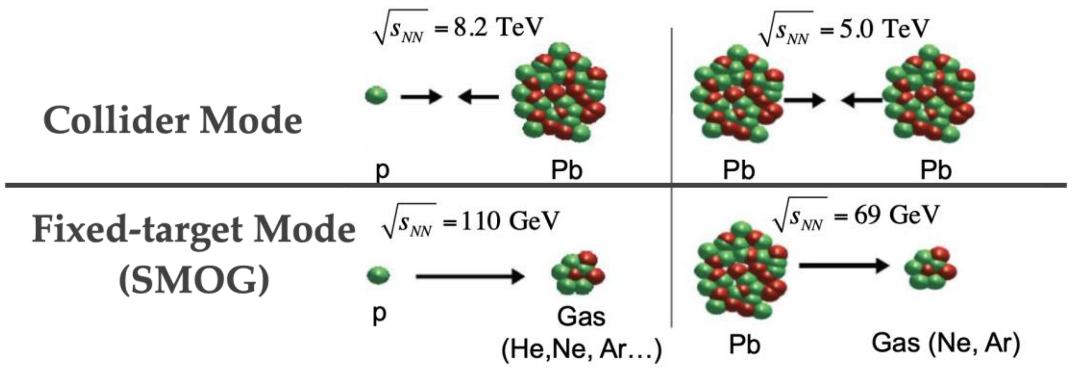
- A high precision device, down to very low-p_T, excellent particle ID, precise vertex and track reconstruction.



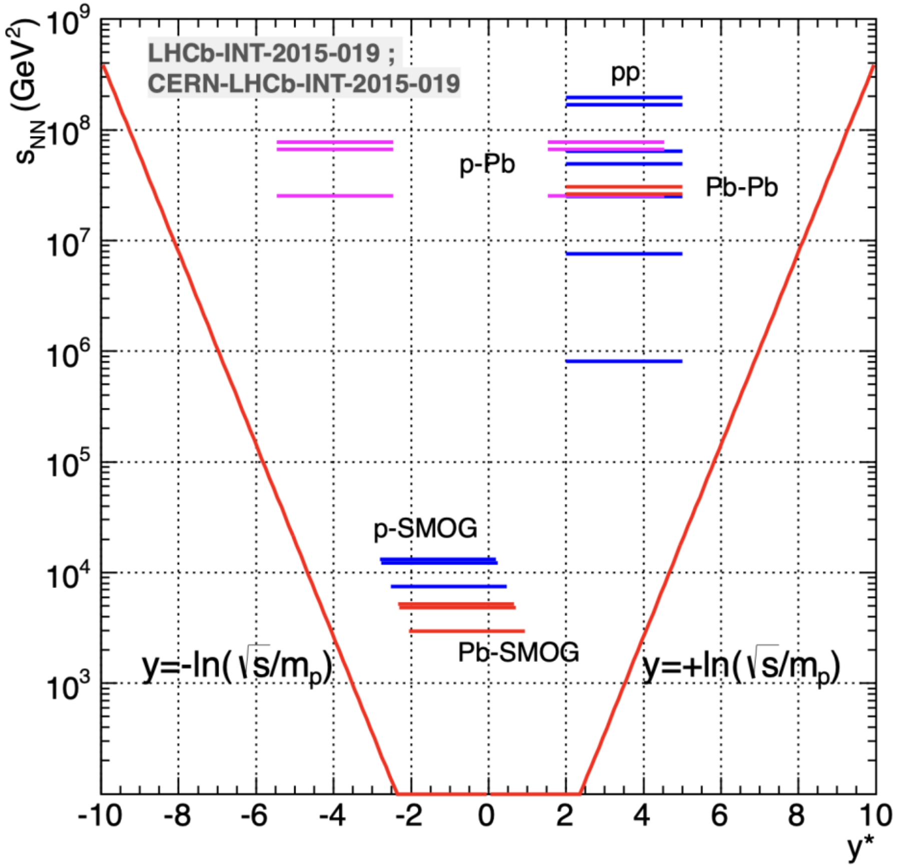
[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

LHCb running modes and kinematic coverage

Both the collider mode and fixed-target mode running at the same time



Kinematic acceptance

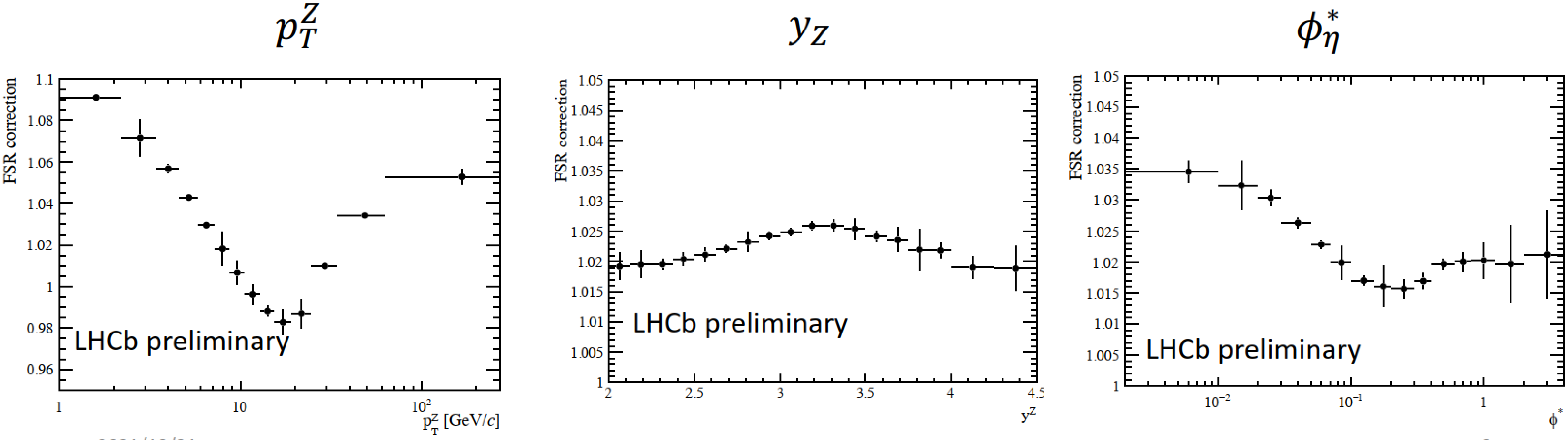


Collider mode datasets:

$\sqrt{s_{NN}}$	2013 5.02 TeV		2016 8.16 TeV		2015 5.02 TeV	2017 5.02 TeV	2018 5.02 TeV
	pPb	Pbp	pPb	Pbp	PbPb	XeXe	PbPb
$\mathcal{L}$	1.1 nb^{-1}	0.5 nb^{-1}	13.6 nb^{-1}	20.8 nb^{-1}	10 $\mu\mathrm{b}^{-1}$	0.4 $\mu\mathrm{b}^{-1}$	$\sim$ 210 $\mu\mathrm{b}^{-1}$

FSR

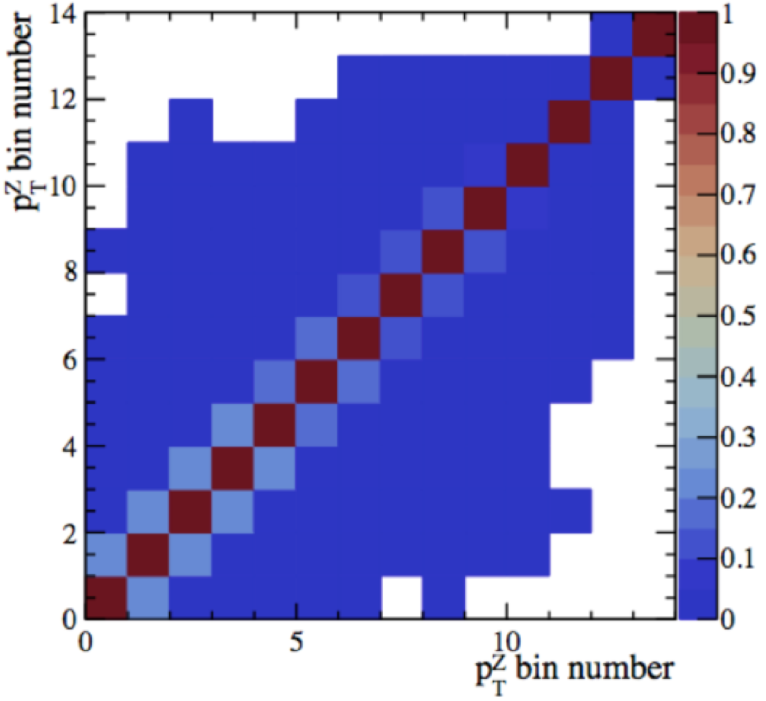
- In order to be directly compared with different theoretical predictions, the measured cross-section is corrected to the **Born level**
- QED FSR correction evaluated through ResBos
- Taking differences of FSR corrections between ResBos+Photos and Powheg+Pythia as a systematic uncertainty



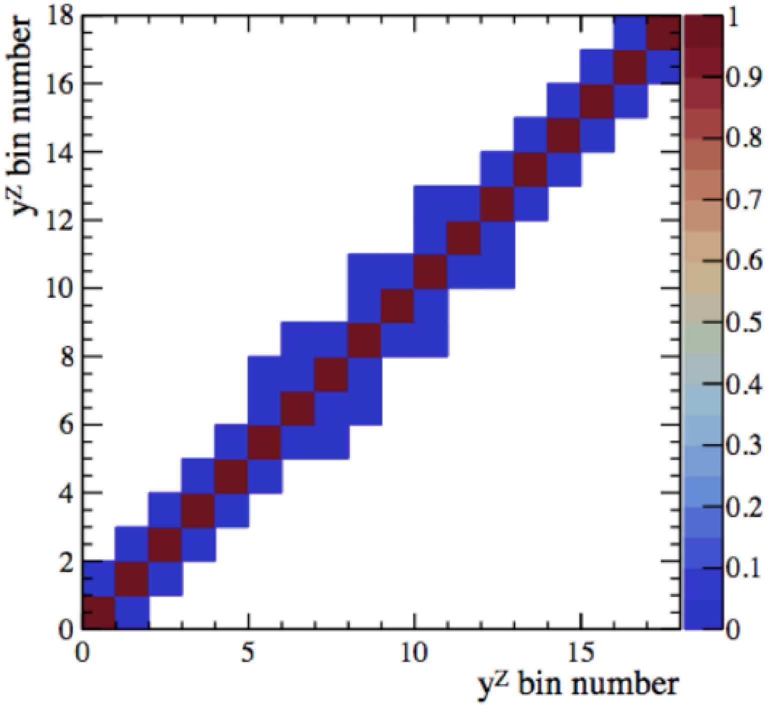
Statistical correlation matrix

- Determined using the simulation events
- Large correlations between events in low p_T^Z region, small correlations in the high p_T^Z region
- For y_Z and ϕ_η^*, the correlations between different bins are negligible

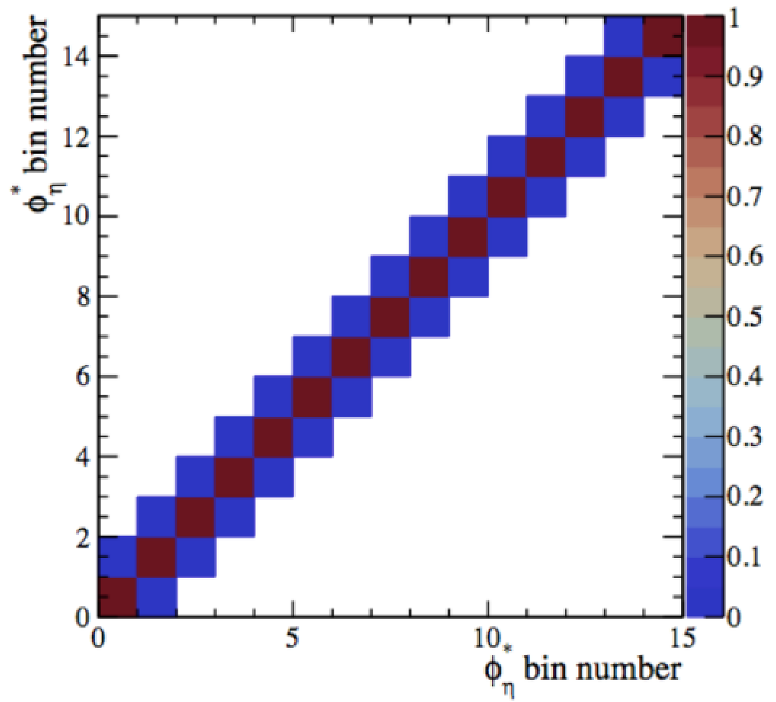
p_T^Z LHCb preliminary



y_Z LHCb preliminary



ϕ_η^* LHCb preliminary

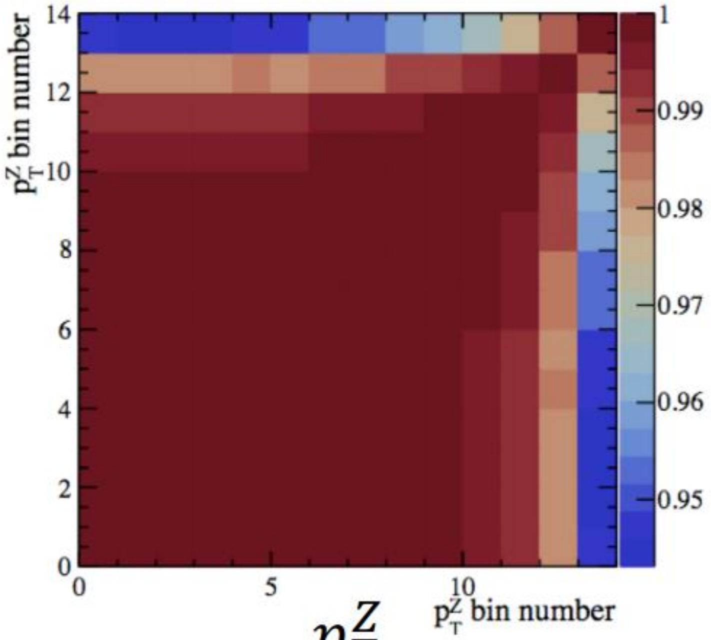


Systematic correlation matrix

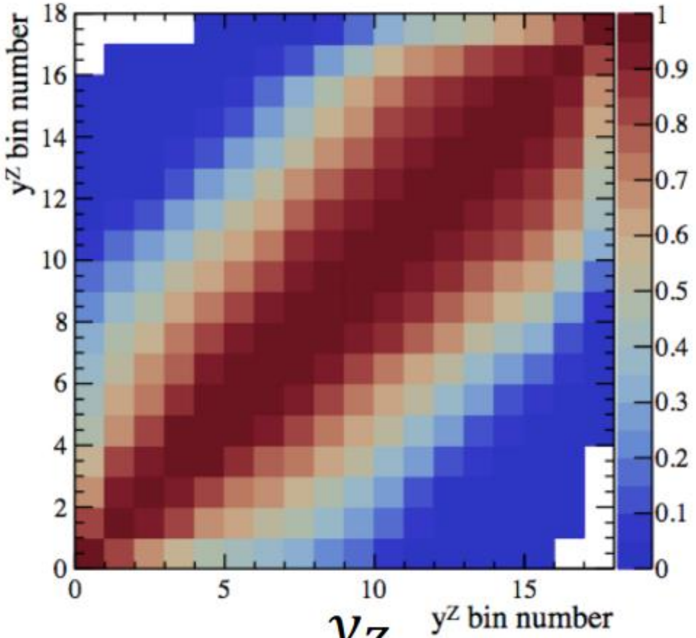
- Systematic uncertainties from background, alignment, efficiency closure test, and FSR are considered to be uncorrelated
- Luminosity uncertainties are considered to be 100% correlated

Efficiency systematic

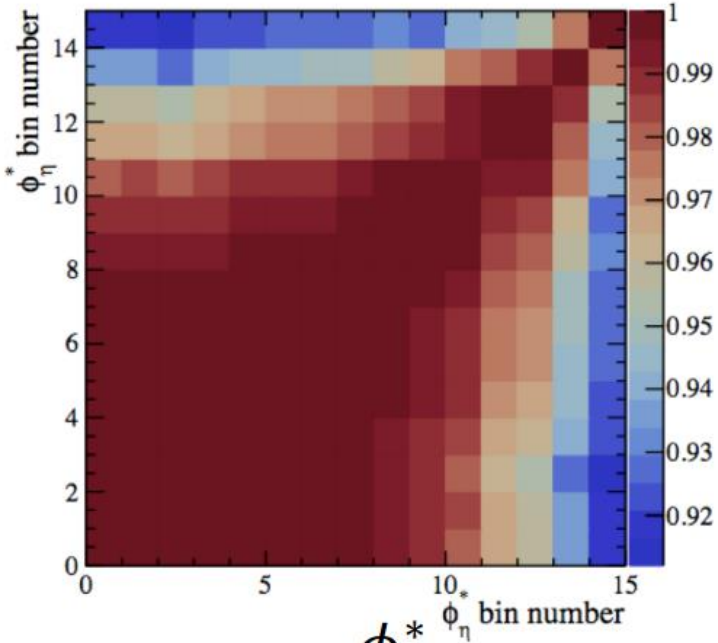
LHCb preliminary



p_T^Z



y_Z



ϕ_η^*