Z production measurments in proton-lead collisions at LHCb

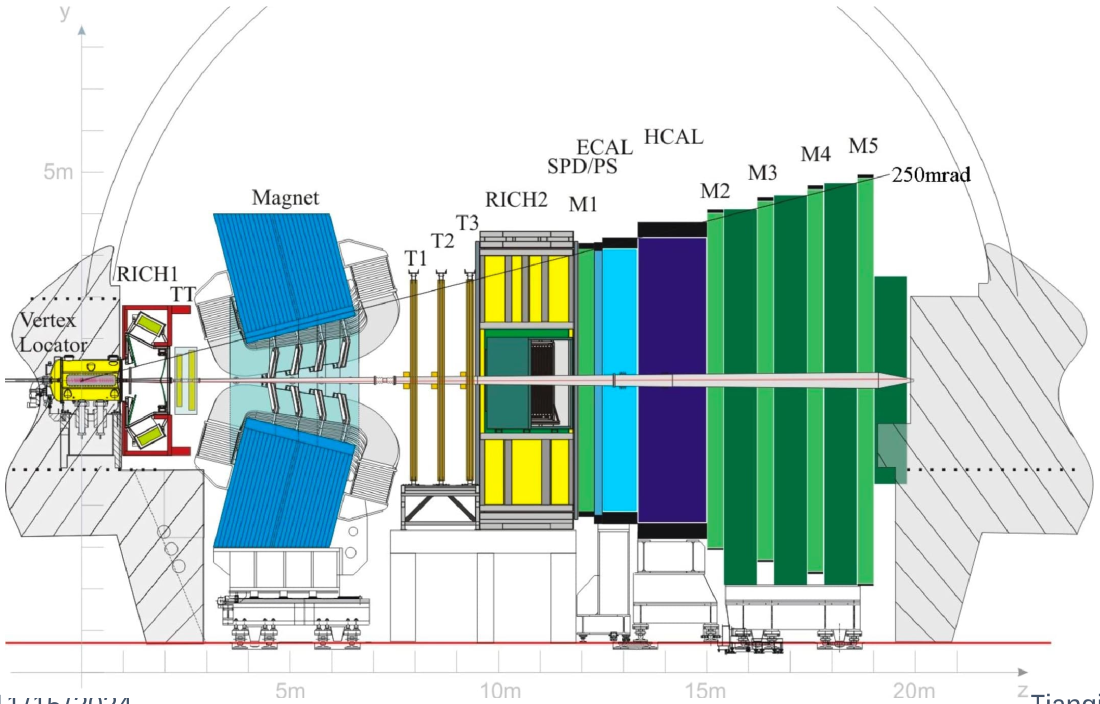
李天齐 (South China Normal University)
On behalf of LHCb Collabration

第十届中国LHC物理会议

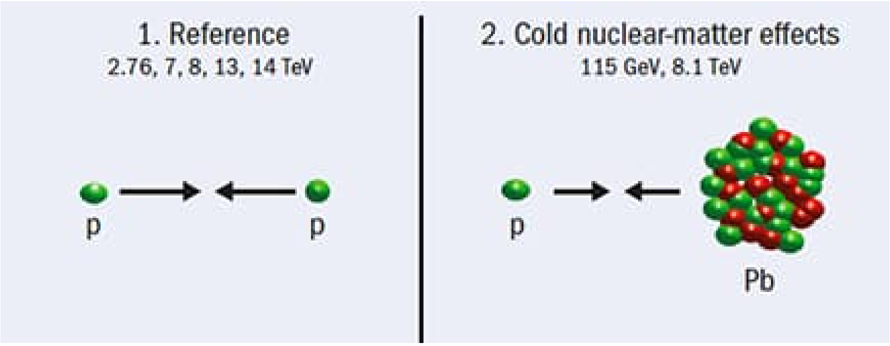
2024.11 青岛

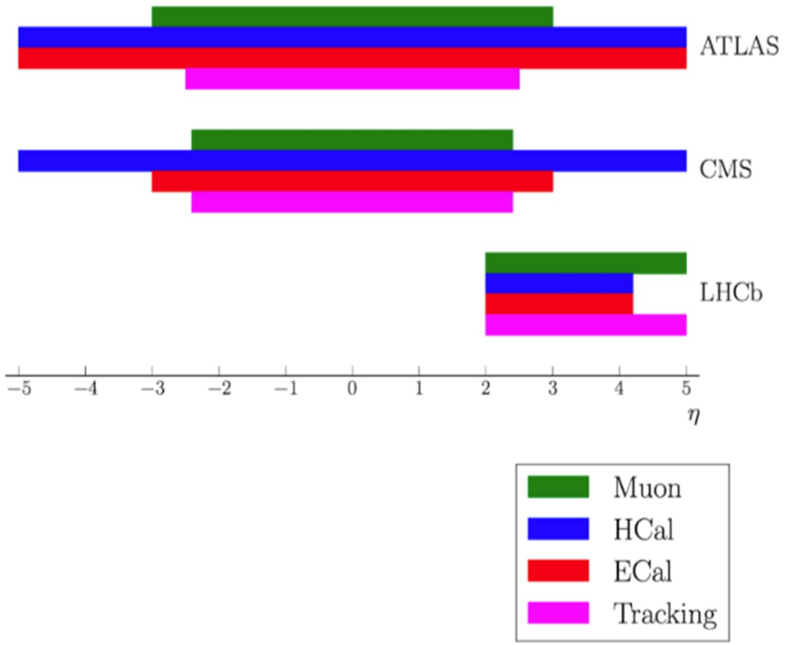
The LHCb detector

- A forward spectrometer, unique kinematic coverage: $2 < \eta < 5$,
  - equipped in forward with tracking, hadron ID, muon ID, ECAL/HCAL
- High precision device: tracking down to $p_T = 0$, excellent particle identification, precise vertex reconstruction and tracking



- Collider mode for probing bosons: pp, pPb

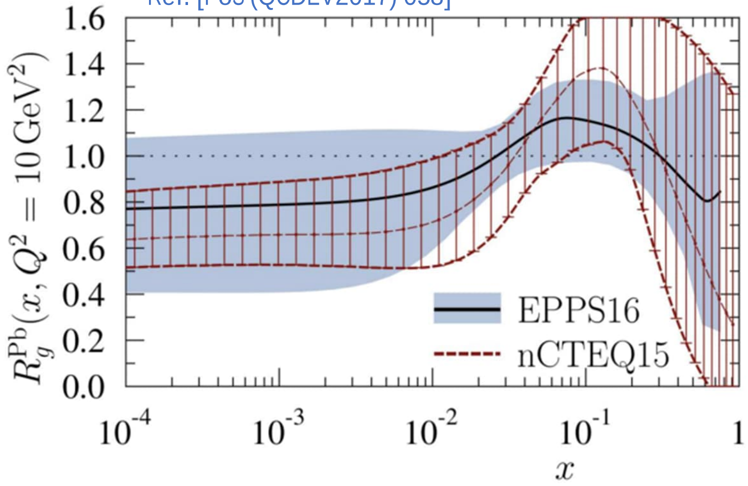


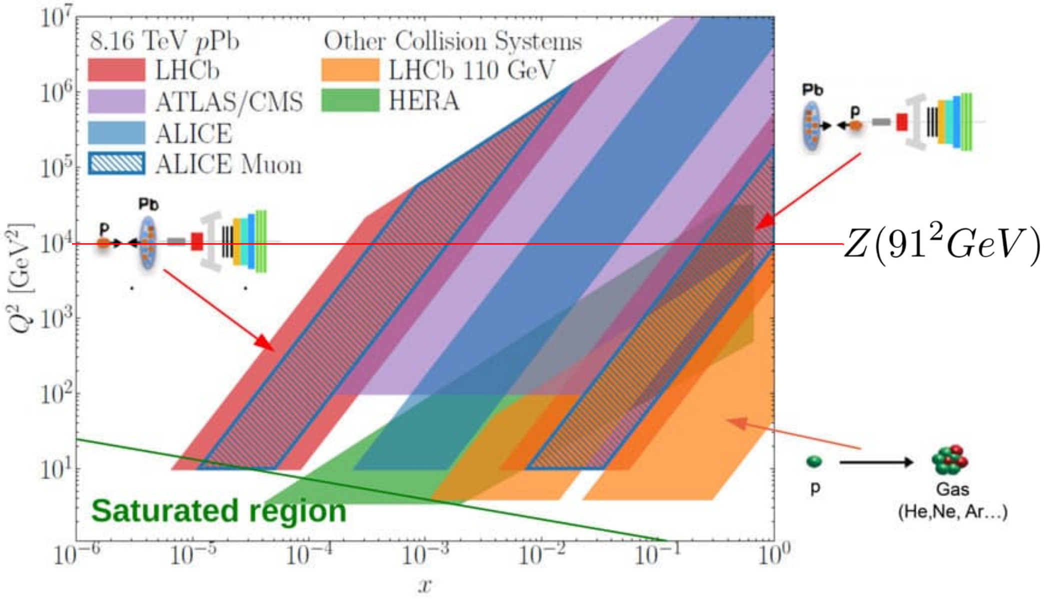


Z boson as probe to nucleon structures

- Study cold nuclear matter effects
  - Modification of PDF for the nucleon confined in nucleus w.r.t. free nucleon
- Z production in pPb/Pbp collisions can be used to constrain nPDF at $Q^2 = 91^2 GeV^2$.
  - sensitive to effects at low and high values of Bjorken-x
- Z boson lifetime is ~ the QGP formation time in Heavy Ions collisions
  - do not participate strong interaction - clearly probe initial state, can be used to differentiate between initial and final state effects.
- LHCb results are complementary to other LHC experiments

Ref. [PoS (QCDEV2017) 058]





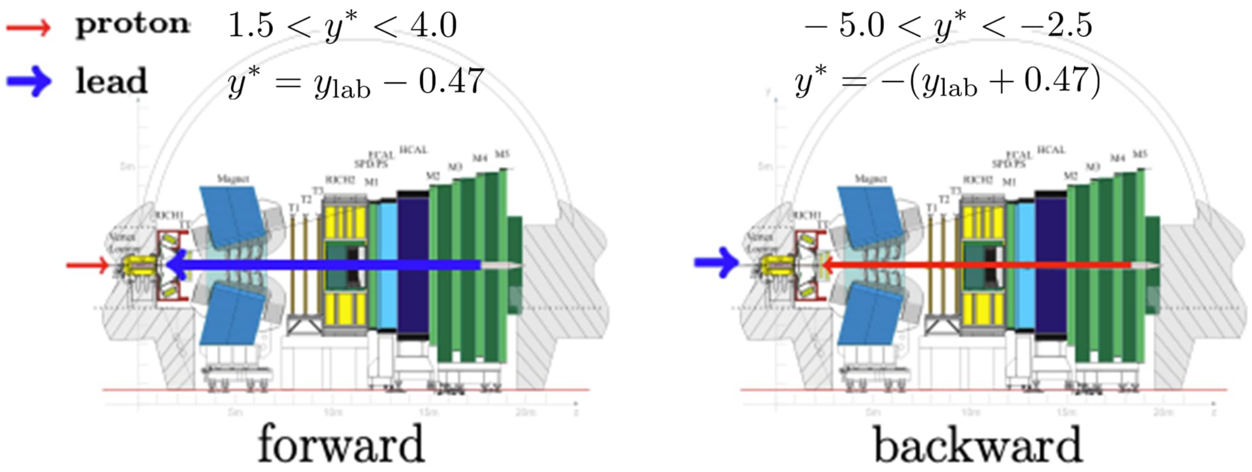
Analysis strategy

arXiv: 2205.10213

- Cross-section:

$$\sigma_{Z\to\mu^+\mu^-,\,pPb/Pbp} = \frac{N_{cand}\cdot\rho\cdot f_{FSR}}{\mathcal{L}\cdot\epsilon_{tot}}$$

  - $N_{\rm cand}$ is the number of selected Z candidates
  - $\mathcal{L}$ is the integrated luminosity
  - ρ is the purity (the fraction of actual signal events)
  - $f_{\rm FSR}$ is final state radiation correction
  - $\epsilon_{\rm tot}$ is the total signal efficiency
  - Fiducial volume: $p_T(\mu^\pm) > 20GeV/c,\ 2.0 < \eta_{\mu^\pm}(lab) < 4.5,\ 60 < m_{\mu^+\mu^-} < 120GeV/c^2$



- Beam configurations for p-Pb collisions
  - y*: rapidity in center of mass frame, required a rapidity shift of about 0.47 w.r.t. the lab frame coverage

Analysis strategy

arXiv: 2205.10213

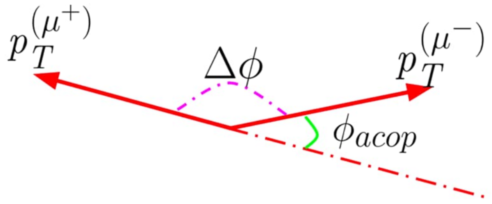
- Forward-Backward ratio

$$R_{FB} = \frac{\sigma_{(pPb,1.53<y^*_\mu<4.03)}}{\sigma_{(Pbp,-4.97<y^*_\mu<-2.47)}} \cdot k_{FB}$$

  - Cross-section in pPb over that in Pbp at the common $2.5 < |y^*_Z| < 4.0$
  - k_{FB} is correction factor to correct the different muon rapidity acceptance, derived using CTEQ61 free proton PDF.
- Nuclear modification factor

$$R^{fw.}_{pPb} = \frac{1}{208} \cdot \frac{\sigma_{(pPb,1.53<y^*_\mu<4.03)}}{\sigma_{(pp,2.0<y^*_\mu<4.5)}} \cdot k_{pPb}$$

  - k_{pPb} is to correct the different muon rapidity acceptance between pp and pPb collisions, derived using CTEQ61.
  - The resulting $\sigma_{Z\to\mu^+\mu^-,pp}$, given by LHCb public results [ARXIV:1511.08039]
- Results are estimated separately in bins of the y^*_Z, p^Z_T and ϕ^*_η
  - ϕ^*_η is defined as $\frac{\tan(\phi_{acop}/2)}{\cos(\Delta\eta/2)}$, where the acoplanarity angle $\phi_{acop} \equiv \pi - |\Delta\phi|$



Data, MC samples, Selection

arXiv: 2205.10213

- Data samples in 2016 Heavy Ion run:

Sample	Collision	lumi.
$Z \to \mu^+\mu^-$	pPb 8.16	12.18 nb^{-1}
$Z \to \mu^+\mu^-$	Pbp 8.16	18.58 nb^{-1}
$Z \to \mu^+\mu^-$	pp 13TeV	2.0 fb^{-1}

- MC samples:
  - with correct multiplicity profile (JIRA ticket):
  - generator level: Sim09i - v49r17
  - Pythia8 ($Z \to \mu^+\mu^-$) + EPOS (Mini-Bias)

Sample	Collision	Event Type
$Z \to \mu^+\mu^-$	pPb 8.16 TeV	42112000
$Z \to \mu^+\mu^-$	Pbp 8.16	42112000

- Selection criteria for pPb and Pbp:

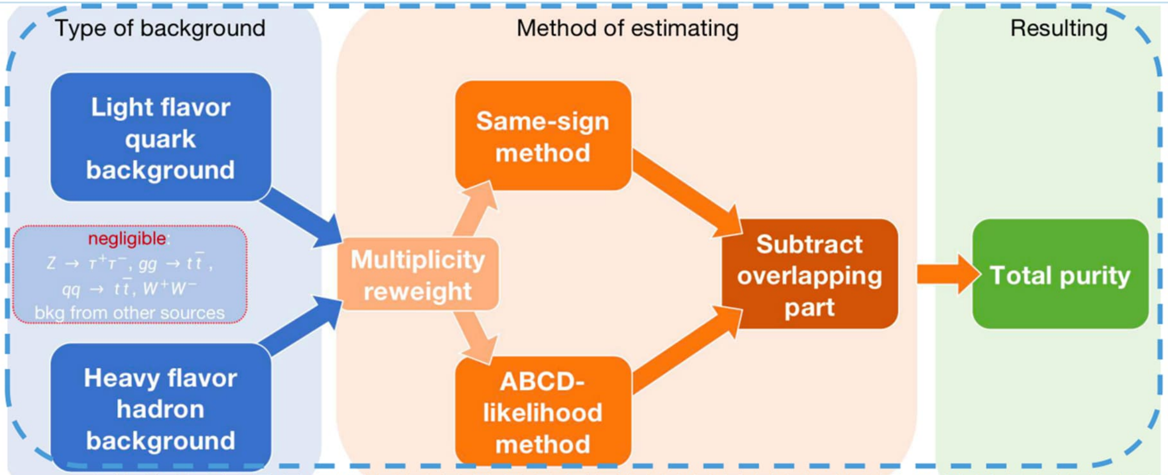
	Condition
Turbo line:	Hlt2DiMuonBTurbo
Fiducial region:	60 < $M(\mu^+\mu^-)$ < 120 GeV/c^2, 2 < η^μ < 4.5, p_T^μ > 20G eV/c^2
Selection cuts:	$\Delta p/p < 0.1$, track χ^2 probability > 0.01, LongTrack, isMuon, at least one $\mu^\pm$ pass L0Muon_TOS, at least one $\mu^\pm$ pass Hlt1SingleMuonHighPT_TOS.

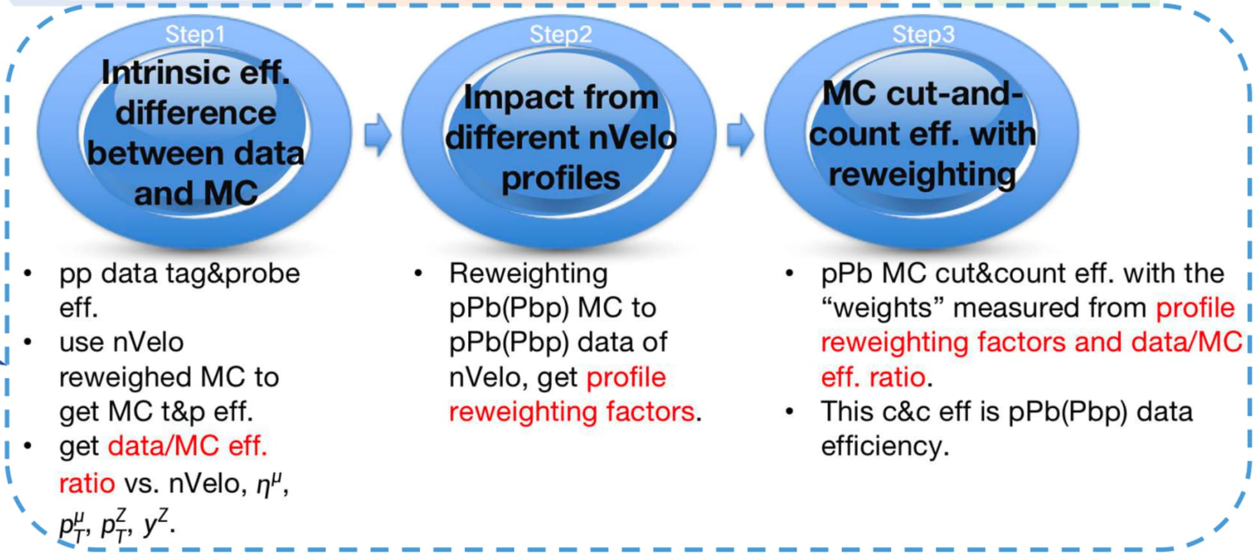
Systematic uncertainty

arXiv: 2205.10213

- Major systematic uncertainties
  - Uncertainties from background modeling (purity)
  - Uncertainties from efficiency: reco&select (tracking, largest), muon-id, and trigger efficiencies
  - Uncertainties from fsr corrections
  - Luminosity: directly propagated
- Rapidity coverage is different for xsec, R_{FB} and R_{pA} measurements, uncertainties are shown in table.

Quantity	Forward	Backward
N_{cand} (for σ^{fid})	268	166
N_{cand} (for R_{FB})	160	166
N_{cand} (for R_{pPb})	241	166
ρ [%]	99.69 ± 0.07	99.75 ± 0.08
$\epsilon^{reco\&sel}$ [%]	87.2 ± 2.9	72.0 ± 2.5
$\epsilon^{muon\text{-}id}$ [%]	97.3 ± 0.3	97.3 ± 0.3
ϵ^{trig} [%]	98.3 ± 0.6	97.1 ± 0.6
$\mathcal{L}$ [nb^{-1}]	12.2 ± 0.3	18.6 ± 0.5
f_{FSR}	1.02 ± 0.01	1.02 ± 0.01
k_{FB} (for R_{FB})	0.65 ± 0.02	–
k_{pPb} (for R_{pPb})	0.706 ± 0.002	1.518 ± 0.003





Fiducial cross-section results

arXiv: 2205.10213

- Total fiducial cross-section

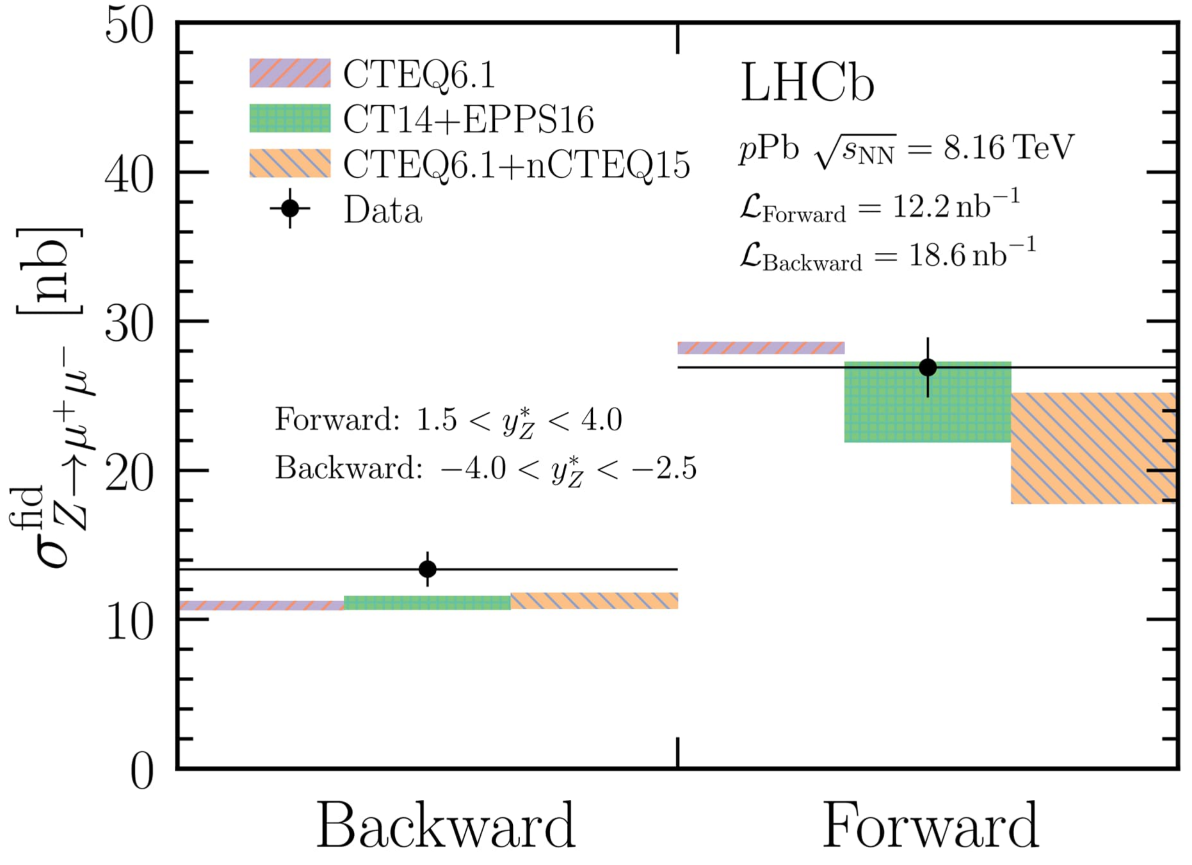
$$\sigma^{\mathrm{fid}}_{Z\to\mu^+\mu^-,\mathrm{pPb}} = 26.9 \pm 1.6(\mathrm{stat.}) \pm 0.9(\mathrm{syst.}) \pm 0.7(\mathrm{lumi.}) \quad \mathrm{nb}$$

$$\sigma^{\mathrm{fid}}_{Z\to\mu^+\mu^-,\mathrm{Pbp}} = 13.4 \pm 1.0(\mathrm{stat.}) \pm 0.5(\mathrm{syst.}) \pm 0.3(\mathrm{lumi.}) \quad \mathrm{nb}$$

- Measured results compatible with the theoretical calculations within current uncertainties:
  - CTEQ61(PDF) for both p and Pb
  - CT14(PDF) for p and EPPS16(nPDF) for Pb
  - CTEQ61 for p and nCTEQ15(nPDF) for Pb
- Forward result(at small Bjorken-x) shows strong constraining power on the nPDF.

Events for backward: 167

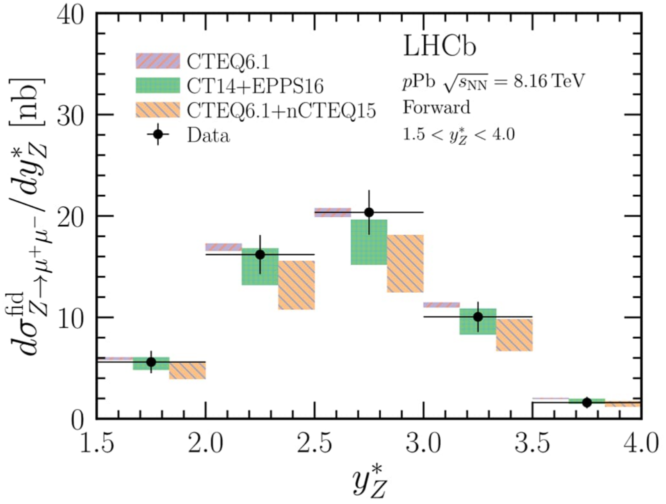
Events for forward: 268

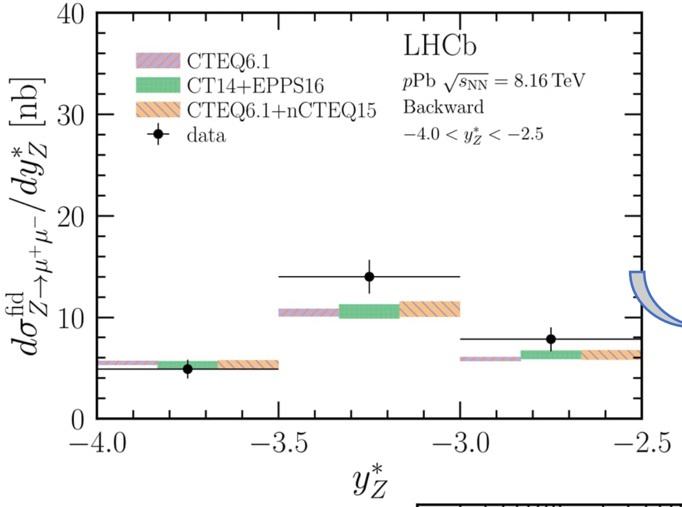


Cross-section result: y_Z^*, ϕ_η^*

arXiv: 2205.10213

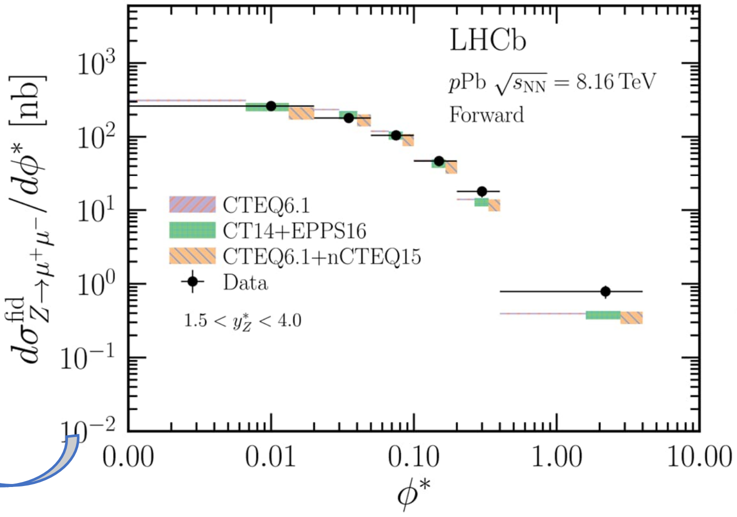
- Differential cross-section as a function of y_Z^* and ϕ_η^*, compare measured and theoretical results.

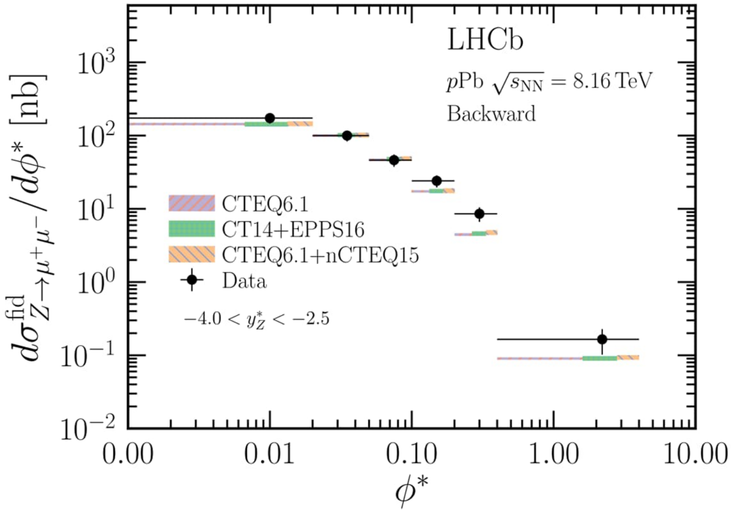




For forward: the measurements show a good agreement with predictions, a smaller uncertainty to constrain the nPDFs.
For backward: the measured results' uncertainties are greater than theoretical calculations

In general, the measurements are also in good agreement with the theoretical predictions.
For forward: the measured values give a smaller uncertainty in low-ϕ_η^*, showing a strong constraining power.
For backward: a certain excess for the two bins in range from 0.1 to 0.4, but less than 2-sigma effect

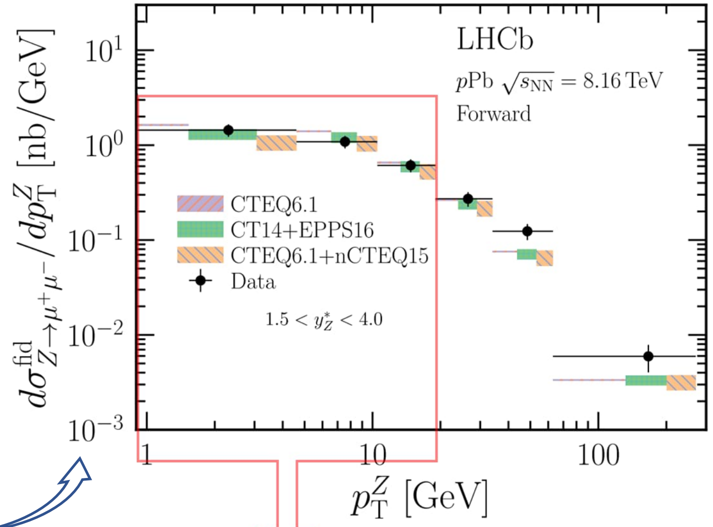


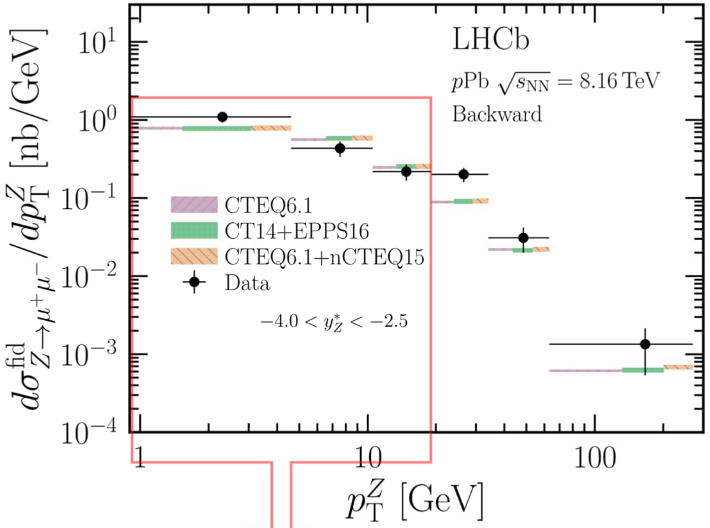


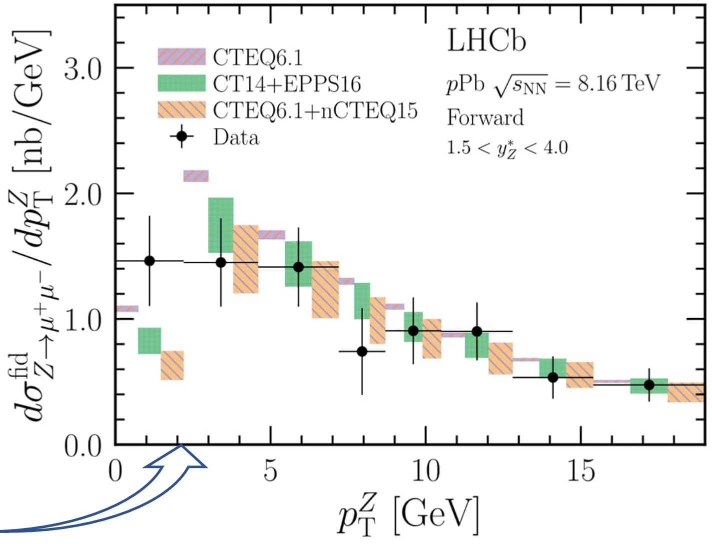
Cross-section result: p_T^Z

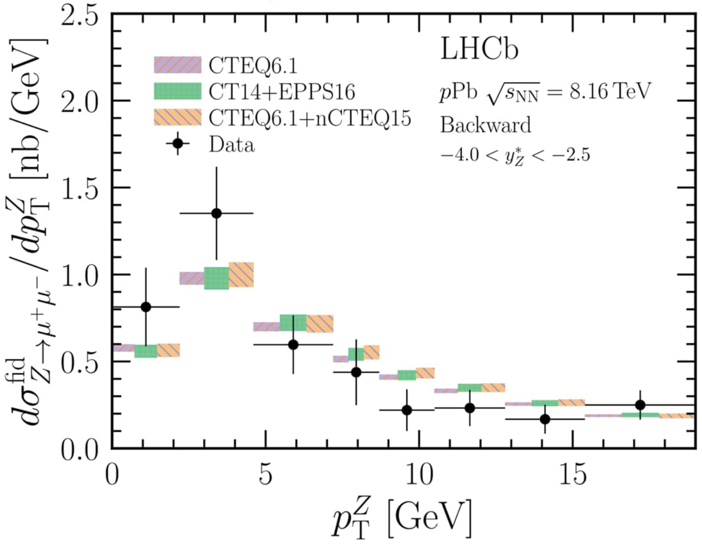
arXiv: 2205.10213

- Cross-section as a function of p_T^Z, compare measured and theoretical results.
- For forward, a smaller measured uncertainty in low-p_T^Z bins, further constrain the nPDFs
- For backward, the measured uncertainties are greater than (n)PDF calculations, the central values of measurements are compatible with theoretical predictions.
- Cross-section shown in low-p_T^Z









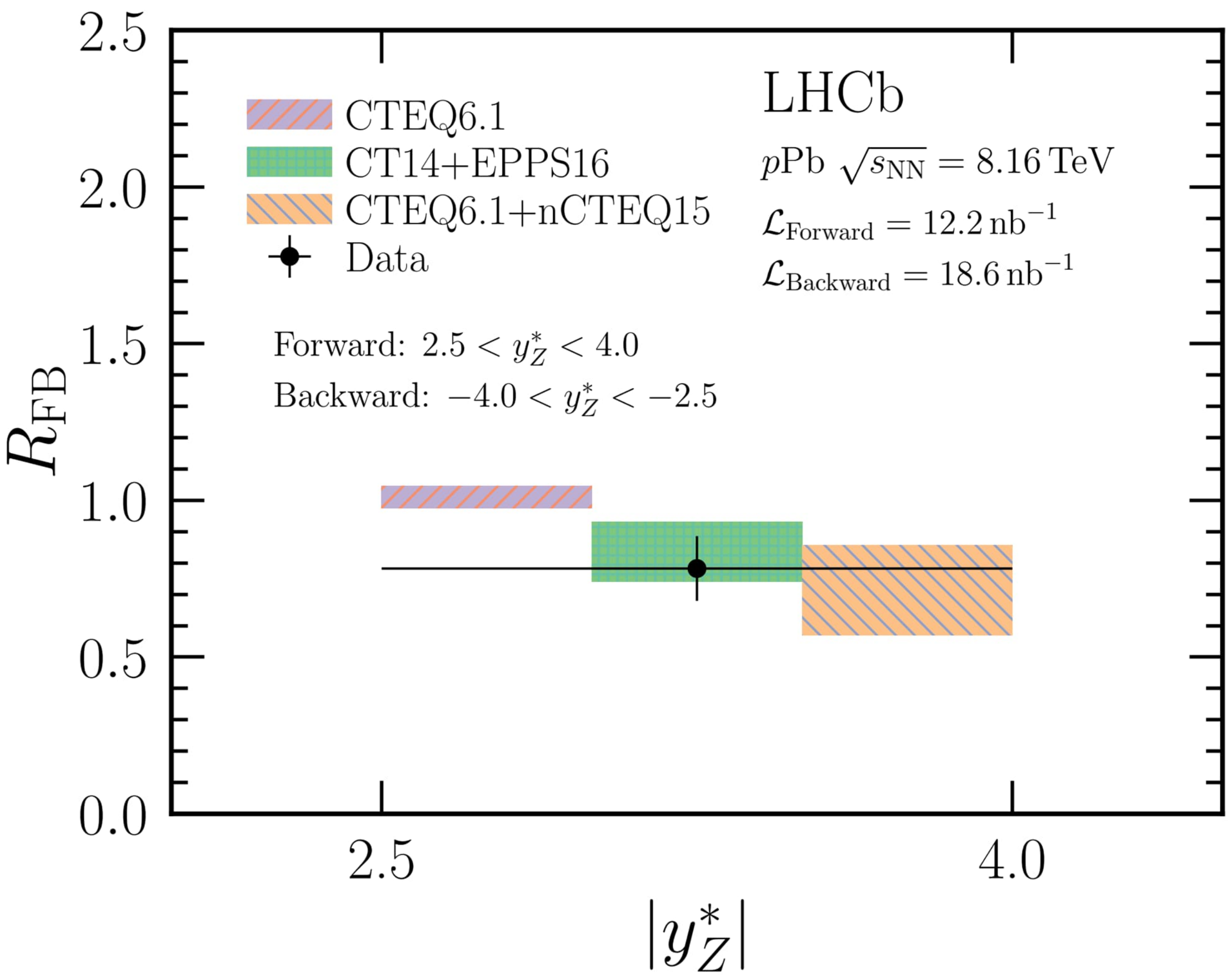
Forward-backward ratio R_{FB}

arXiv: 2205.10213

- Forward and backward ratio is sensitive to nuclear effects in the Z production, probe the nuclear matter effects
- Measured result:

$$R_{FB} = 0.78 \pm 0.10$$

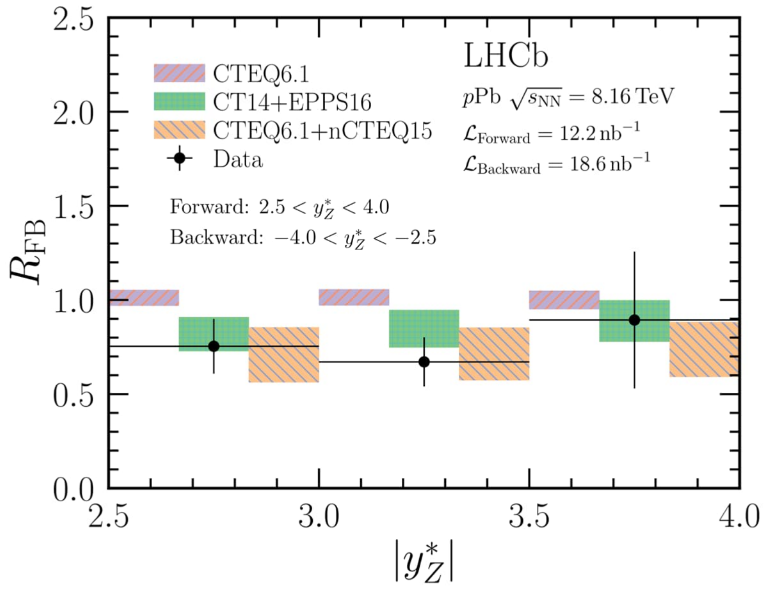
- The measurement shows a general suppression below one, is consistent with theoretical predictions, smaller uncertainty provide constraining power on the nPDFs.

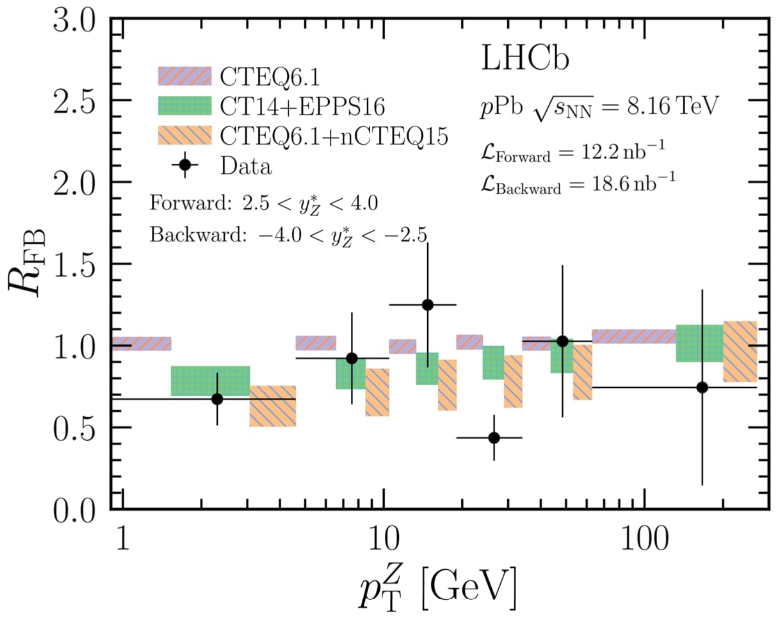


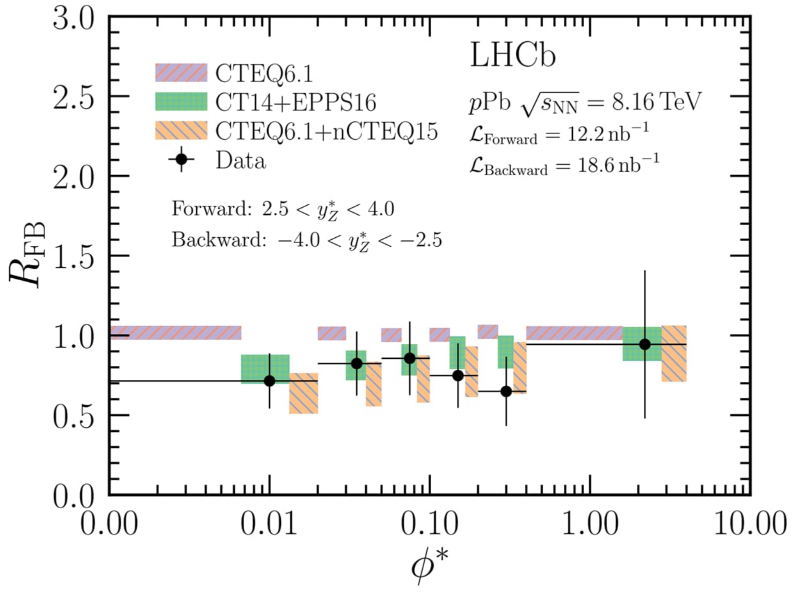
Forward-backward ratio: vs. y_Z^* , p_T^Z , ϕ_η^*

arXiv: 2205.10213

- Forward and backward ratio as a function of y_Z^*, p_T^Z and ϕ_η^*, compare measured and theoretical results.
- Measured in common rapidity window $2.5 < |y_Z^*| < 4.0$
- The measurements show a good agreement with the theoretical predictions







Nuclear modification R_{pA} : overall

arXiv: 2205.10213

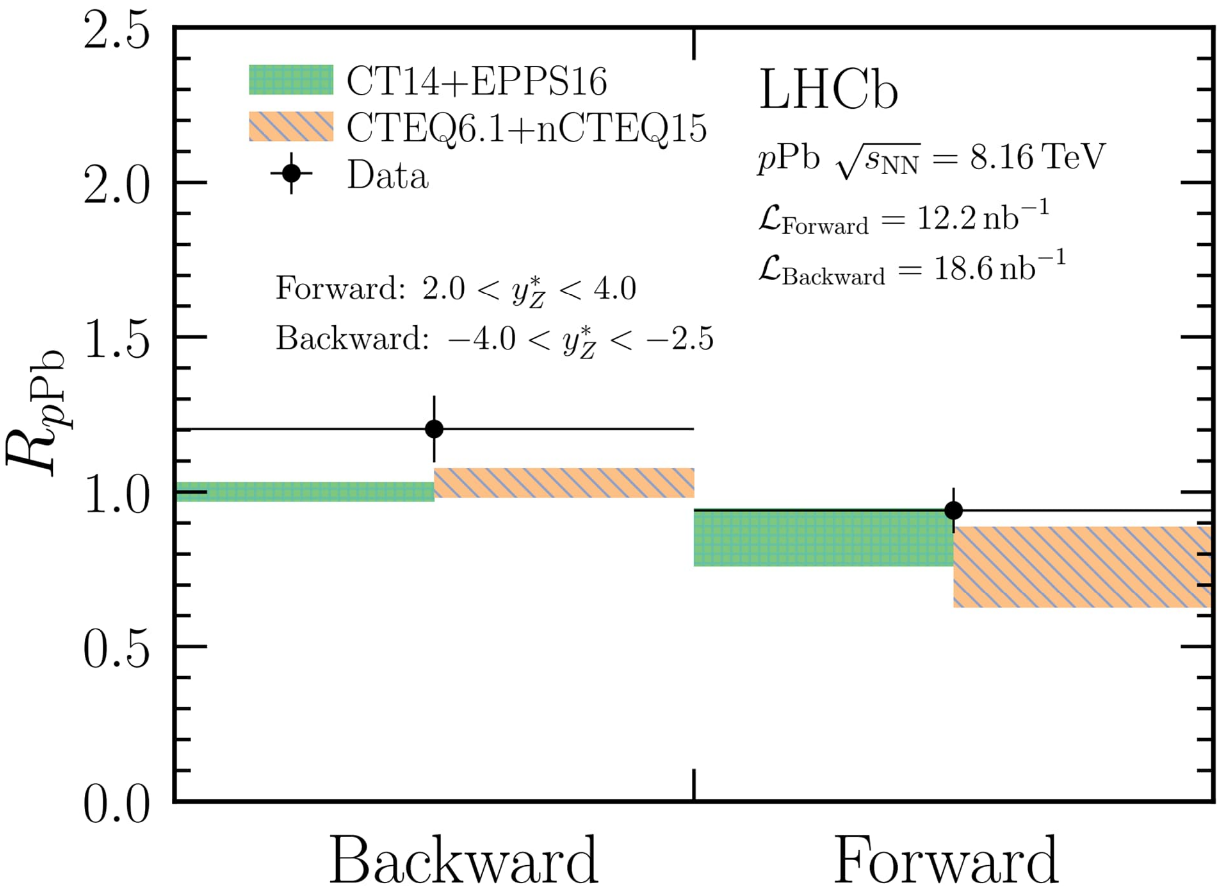
- Nuclear modification factor R_{pPb} directly probes the cold nuclear matter effects.
- The measured results:

$$R_{pPb}^{fw.} = 0.94 \pm 0.07$$
$$R_{pPb}^{bw.} = 1.21 \pm 0.11$$

- The measurements are compatible with theoretical predictions; Results in forward region(small Bjorken-x, nuclear shadowing suppression part) give higher precision, constrain on the current nPDF sets.

Events for backward: 167

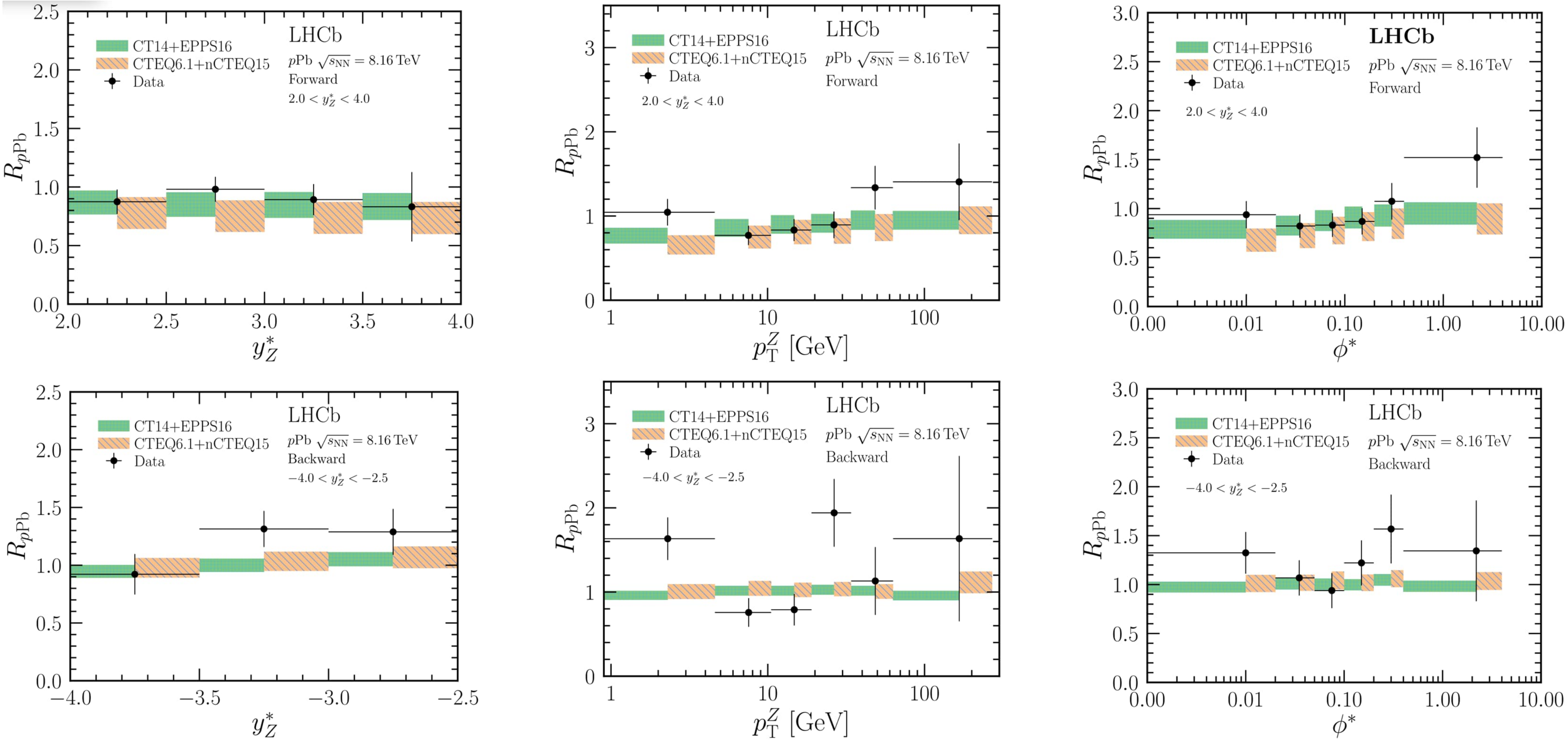
Events for forward: 268



Nuclear modification factor

arXiv: 2205.10213

- Nuclear modification factor as a function of $y_Z^*,\ p_{\mathrm{T}}^Z$ and ϕ_η^*



Summary

- A new Z boson production measurement in pPb collisions at 8.16 TeV.
- The differential cross-section, R_{FB} and R_{pPb} as a function of y^*_Z, p^Z_T 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.

Thanks for your attention!

Back up

Rapidity shift

1. Because the per-nucleon energy in the proton beam is larger than that in the lead beam, the proton-lead system is not at rest in the laboratory frame($2.0 < y < 4.5$). In case of pPb configuration, the proton-lead system is boosted to the forward direction, while in case of Pbp configuration, the proton-lead system is boosted to the backward direction.

rapidity: $y_{cm} = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ total energy: $E = E_p + E_N = \frac{N_A+N_Z}{N_A} \cdot E_p$

total momentum: $p_z = E_p - E_N = \frac{N_A-N_Z}{N_A} \cdot E_p$ (neglecting the masses)

$E + p_z = 2 \cdot E_p \qquad E - p_z = 2 \cdot \frac{N_Z}{N_A} \cdot E_p$

$y_{cm} = \frac{1}{2} \ln \frac{E+p_z}{E-p_z} = \frac{1}{2} \ln \frac{N_A}{N_Z} = \frac{1}{2} \ln \frac{208}{82} = 0.4654 = \Delta y$

$y = y^* + y_{cm}$

2. Hence the rapidity of a particle in the laboratory system is equal to the sum of the rapidity of the particle in the center of mass system and the rapidity of the center of mass in the laboratory system.

Z prodution in pPb collisions at 5 TeV

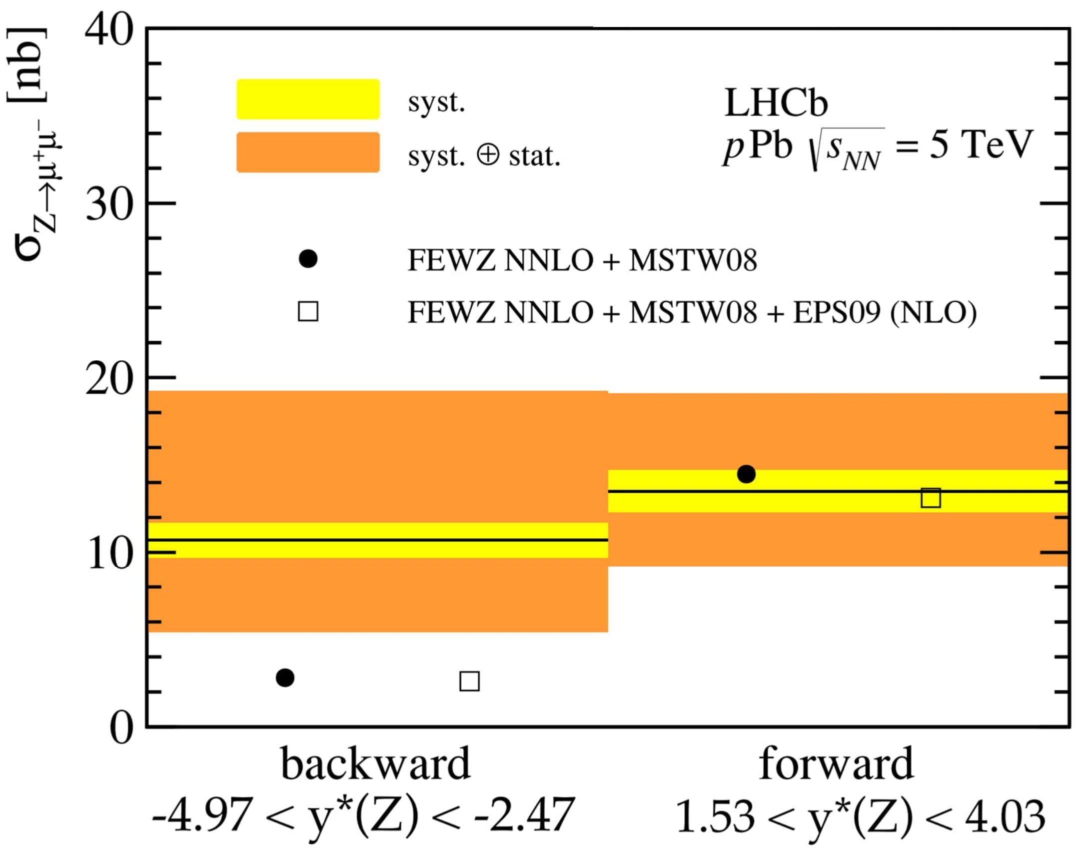
JHEP09(2014)030

- Fiducial cross-section results:

$$\sigma^{\text{fid}}_{Z\to\mu^+\mu^-,\text{pPb}} = 13.5^{+5.4}_{-4.0}(\text{stat.}) \pm 1.2(\text{syst.}) \quad \text{nb}$$

$$\sigma^{\text{fid}}_{Z\to\mu^+\mu^-,\text{Pbp}} = 10.7^{+8.4}_{-5.1}(\text{stat.}) \pm 1.4(\text{syst.}) \quad \text{nb}$$

- Compatible with theoretical calculations using FEWZ:
  - MSTW08 for both p and Pb
  - MSTW08 for p and EPS09 for Pb



Print Event List of forward p_T^Z bin at 19-34 region

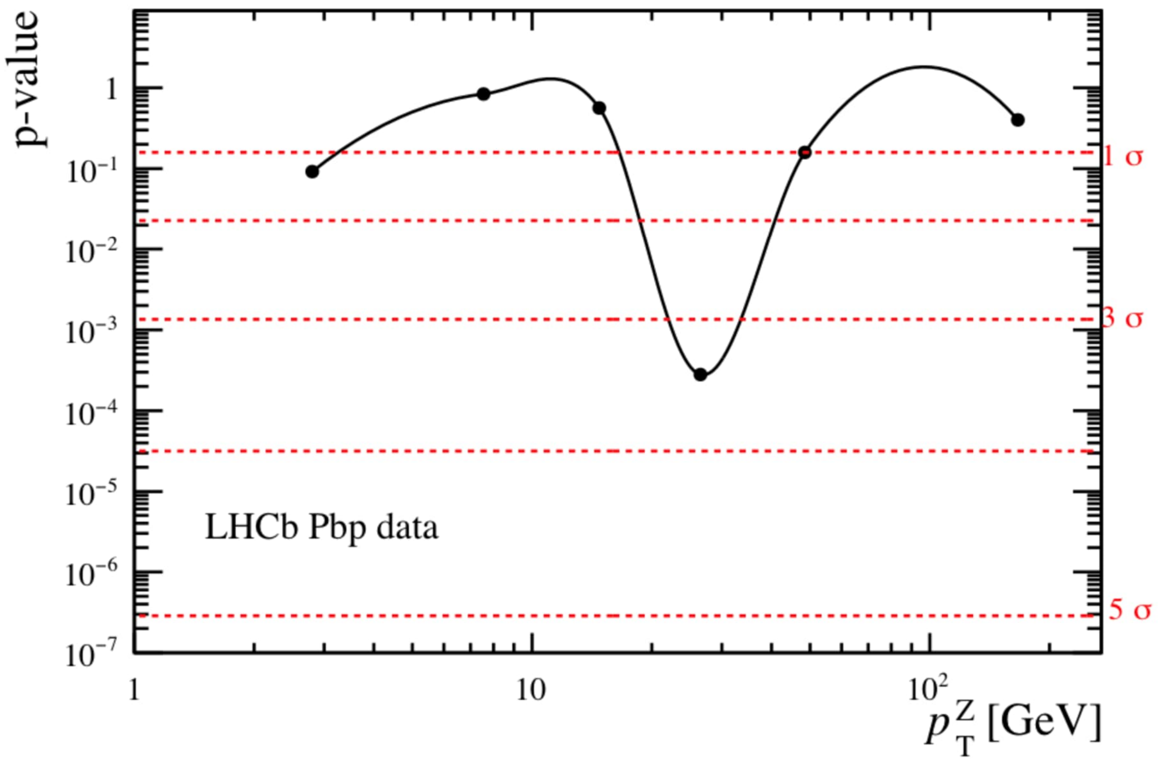
Row	runNumber	eventNumb	totCandid	nCandidat	Z0_M*1e-3	Z0_PT*1e-	Z0_Y
11009	187042	336775248	3	1	97.855408	22.998711	2.4948854
24534	187058	1.003e+09	2	0	91.837976	29.415430	3.0331178
24589	187113	1.300e+09	1	0	65.004351	25.719245	2.5533646
33356	187392	764408682	3	2	88.524788	20.137204	2.6463455
35723	187064	61189625	1	0	92.993134	30.466417	3.1630365
39482	187058	943324610	1	0	78.068202	19.741248	2.6437083
52139	187040	1.319e+09	2	1	94.130049	29.615294	3.0829156
53586	187084	657247672	1	0	90.293414	33.533806	2.8929272
60300	187375	426626028	1	0	91.686726	26.067810	2.8060159
61071	187058	1.077e+09	1	0	92.671234	31.246519	2.8460642
61999	187377	730661584	2	1	92.740764	24.045402	2.1518478
67170	187074	233951165	3	1	87.615141	27.131514	2.9590507
105283	187182	1.388e+09	2	1	90.539913	26.133607	2.3568860
105834	187110	602969520	4	1	90.341843	23.605301	2.0345614
106563	187247	854332469	3	1	92.763772	25.260032	2.8696536
110647	187203	445080031	1	0	89.679179	31.655364	2.7419204
124715	187018	1.513e+09	1	0	79.138804	26.715565	3.0396327
130626	187106	290909673	2	0	77.678383	22.520191	2.4252934
131044	187021	88835280	2	0	90.497499	24.069802	2.5421882
136326	187244	1.030e+09	1	0	90.011898	22.096279	3.0419518
139545	187045	337153303	1	0	70.201826	20.342807	2.6253993
142191	187015	983797759	1	0	87.250750	21.279852	2.6226207

Print Event List of forward p_T^Z bin at 19-34 region

Row	runNumber	eventNumb	totCandid	nCandidat	Z0_M*1e-3	Z0_PT*1e-	Z0_Y
153024	187266	396404324	1	0	87.827508	22.270386	2.2540266
154765	187182	951084122	1	0	89.929030	23.803096	2.5372449
155765	187058	1.021e+09	1	0	90.936782	23.206777	2.7358255
160684	187086	422838925	2	1	107.43587	27.409773	2.7013636
176565	187078	253793531	2	0	98.148846	26.520806	2.2898459
182468	187018	1.167e+09	1	0	90.868399	22.750585	2.3299417
196402	187082	1.227e+09	1	0	86.162844	24.719267	2.6657607
210948	187266	34303770	3	1	94.474091	26.836842	2.6912913
211911	187061	431432067	2	1	86.066696	26.415777	2.6698646
220645	187074	897443085	2	1	91.597374	21.165782	2.3826714
225541	187355	375768881	3	2	91.103499	20.644773	2.3043086
226222	187182	128884550	1	0	90.961391	20.613841	2.6468129
234381	187062	247698042	4	1	85.978405	28.557926	2.7866309
236472	187394	240977315	2	0	88.995656	22.763857	3.1805306
236601	187394	669353862	1	0	91.225256	30.164516	2.8572145
246471	187204	102471537	3	2	94.301030	33.439505	2.2263164
273917	187199	1.125e+09	2	1	93.867935	32.145872	2.5239332
288857	187184	1.062e+09	2	1	90.817719	22.358488	2.4893033

p-value in p_T^Z bin for forward

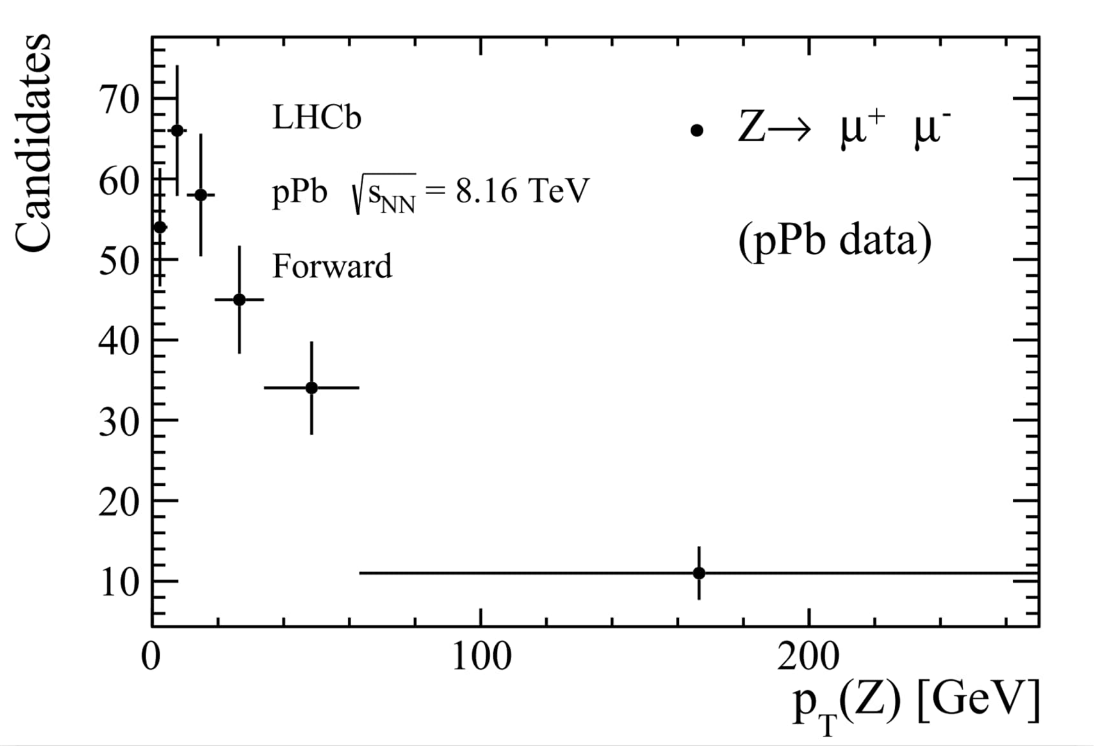
- P-value as a function of p_T^Z

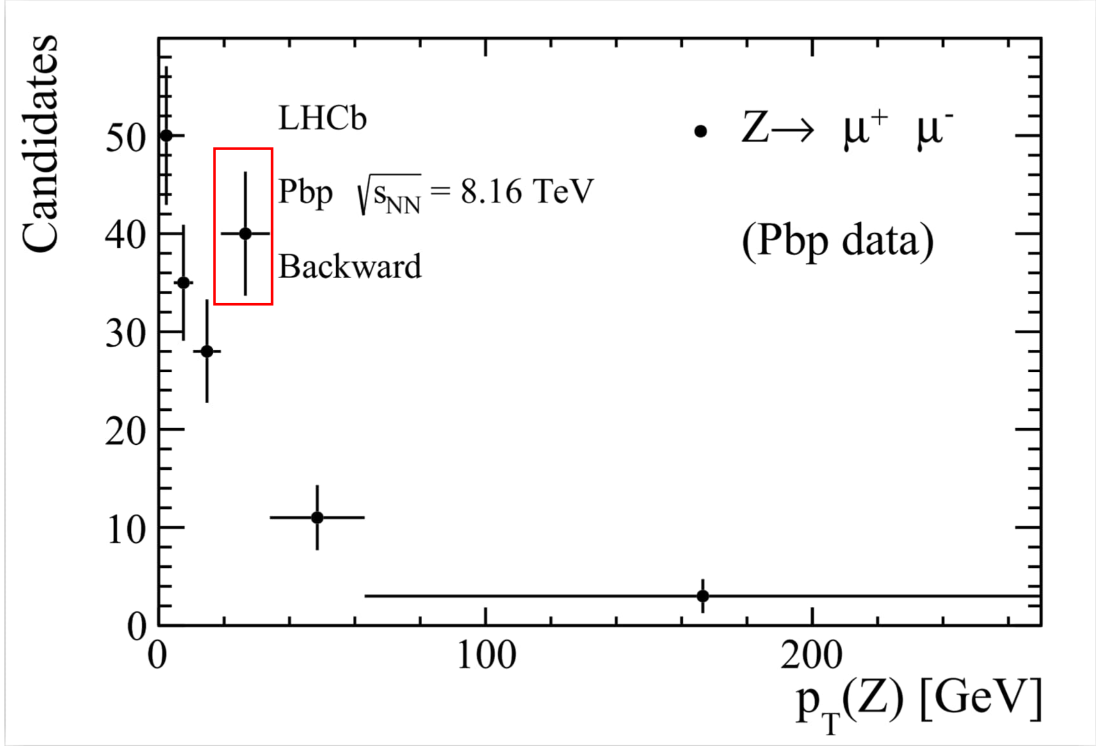


- Significance and p-value results of xsec

significance	1.3286092	-0.98333581	-0.15782034	3.45010288	0.99996401	0.25099433
p-value	9.19885e-02	8.37279e-01	5.62701e-01	2.80186e-04	1.58664e-01	4.00910e-01

Data yields in bins of p_T^Z





- Debugging one bin excess: : https://indico.cern.ch/event/1001006/#3-debugging-the-bump-in-ptz-sp