



Z production measurements in proton-lead collisions at LHCb

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On behalf of LHCb Collaboration

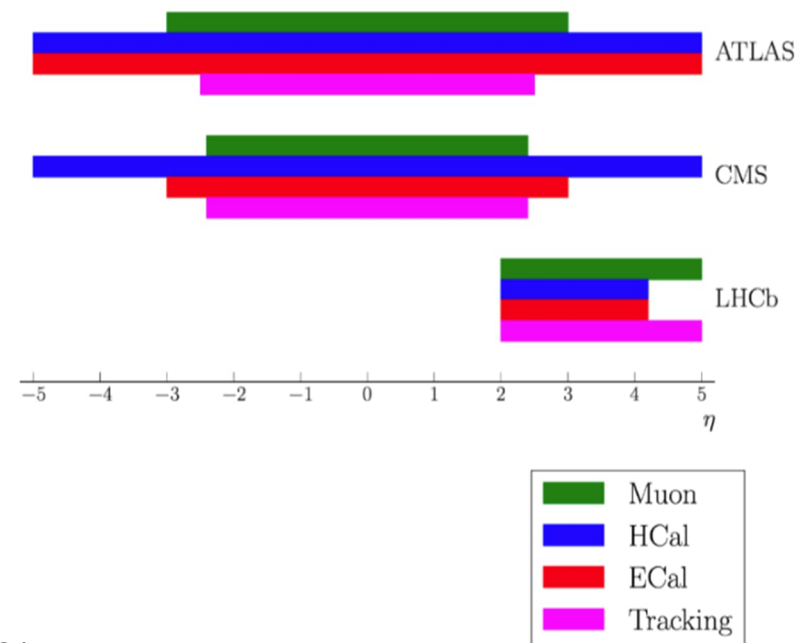
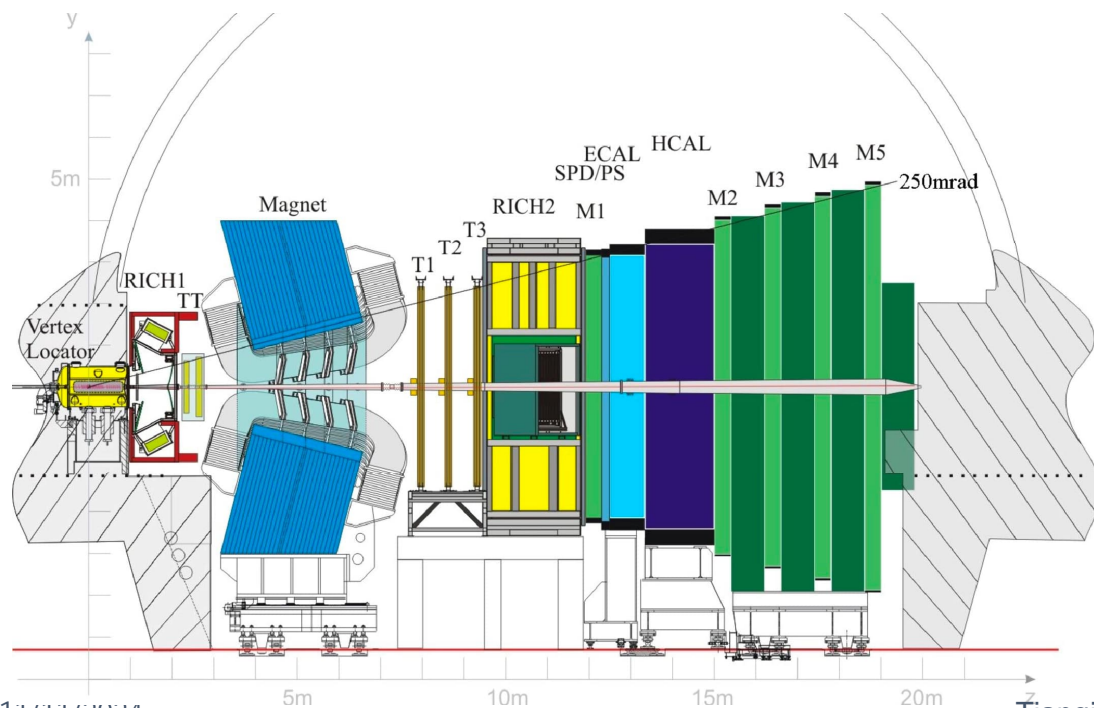
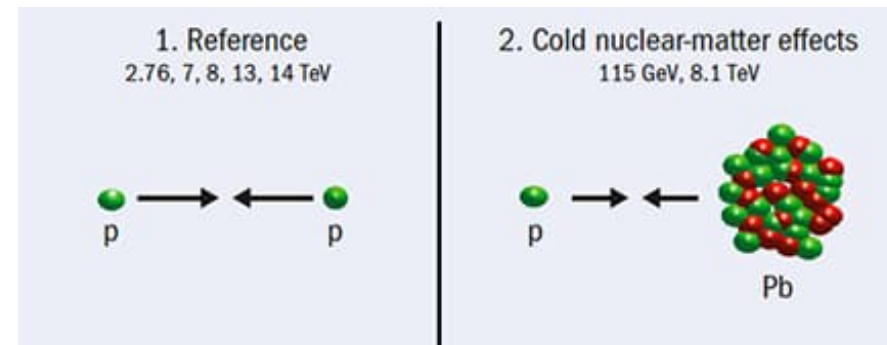
第十届中国LHC物理会议

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The LHCb detector

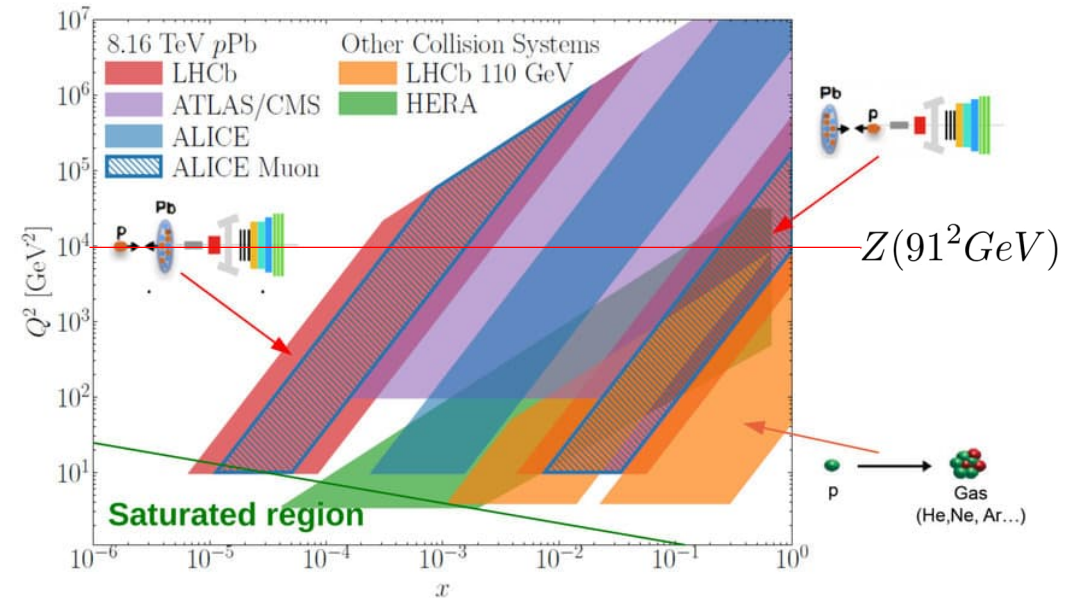
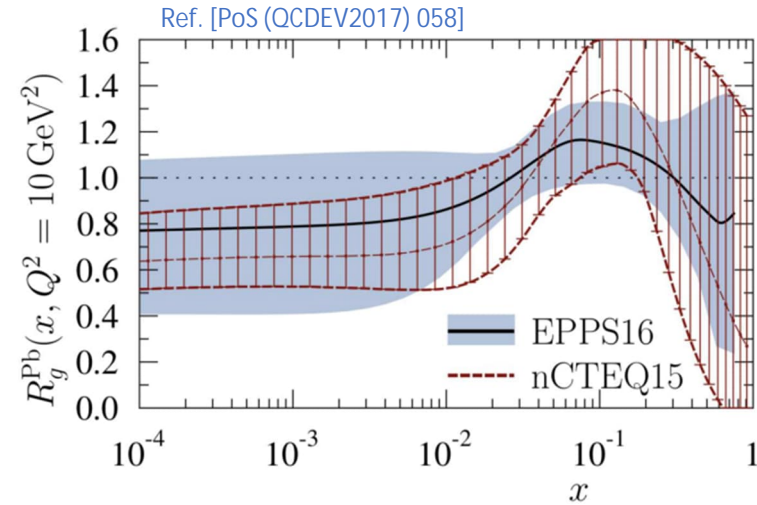
- * A forward spectrometer, unique kinematic coverage: $2 < \eta < 5$,
 - * equipped in forward with tracking, hadron ID, muon ID, ECAL/HCAL
- * High precision device: tracking down to $p_T = 0$, excellent particle identification, precise vertex reconstruction and tracking

- * Collider mode for probing bosons: pp, pPb



Z boson as probe to nucleon structures

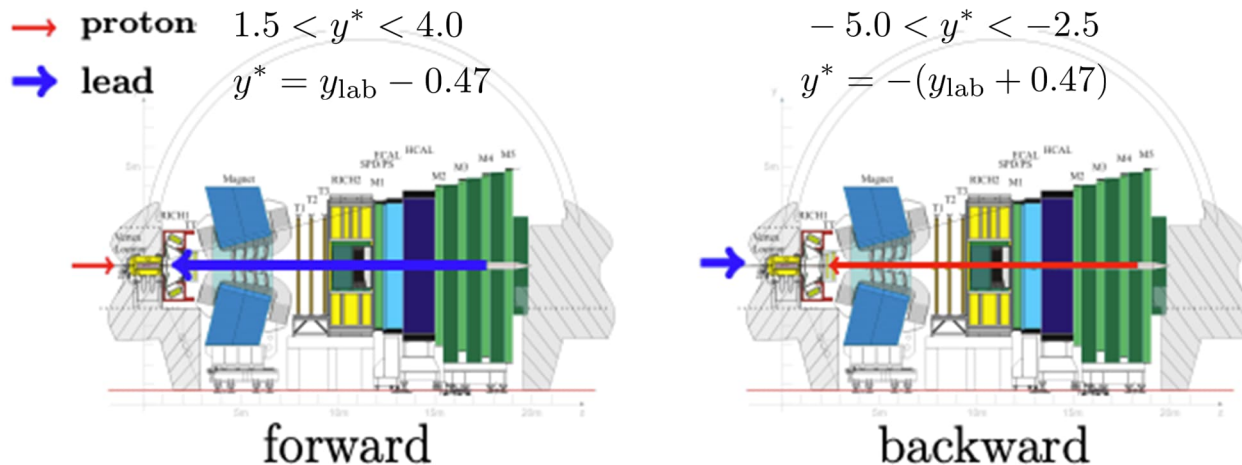
- * Study cold nuclear matter effects
 - * Modification of PDF for the nucleon confined in nucleus w.r.t. free nucleon
- * **Z production in pPb/Pbp collisions** can be used to constrain nPDF at $Q^2 = 91^2 \text{GeV}^2$.
 - * sensitive to effects at low and high values of Bjorken-x
- * Z boson lifetime 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



* Cross-section:

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

- * N_{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_{FSR} is final state radiation correction
- * ϵ_{tot} is the total signal efficiency
- * Fiducial volume: $p_T(\mu^\pm) > 20 GeV/c, 2.0 < \eta_{\mu^\pm}(lab) < 4.5, 60 < m_{\mu^+ \mu^-} < 120 GeV/c^2$



- * 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

* Forward-Backward ratio

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

* Cross-section in pPb over that in Pbp at the common $2.5 < |y_{\text{Z}}^*| < 4.0$

* k_{FB} is correction factor to correct the different muon rapidity acceptance, derived using CTEQ61 free proton PDF.

* Nuclear modification factor

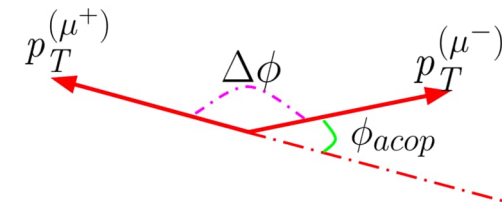
$$R_{\text{pPb}}^{\text{fw.}} = \frac{1}{208} \cdot \frac{\sigma(\text{pPb}, 1.53 < y_{\mu}^* < 4.03)}{\sigma(\text{pp}, 2.0 < y_{\mu}^* < 4.5)} \cdot k_{\text{pPb}}$$

* k_{pPb} is to correct the different muon rapidity acceptance between pp and pPb collisions, derived using CTEQ61.

* The resulting $\sigma_{\text{Z} \rightarrow \mu^+ \mu^-}$, given by LHCb public results [[ARXIV:1511.08039](https://arxiv.org/abs/1511.08039)]

* Results are estimated separately in bins of the y_{Z}^* , p_{T}^{Z} and ϕ_{η}^*

* ϕ_{η}^* is defined as $\frac{\tan(\phi_{\text{acop}}/2)}{\cos(\Delta\eta/2)}$, where the acoplanarity angle $\phi_{\text{acop}} \equiv \pi - |\Delta\phi|$



❁ Data samples in 2016 Heavy Ion run:

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

❁ MC samples:

- ❁ with correct multiplicity profile ([JIRA ticket](#)):
- ❁ generator level: Sim09i - v49r17
- ❁ Pythia8 ($Z \rightarrow \mu^+ \mu^-$) + EPOS (Mini-Bias)

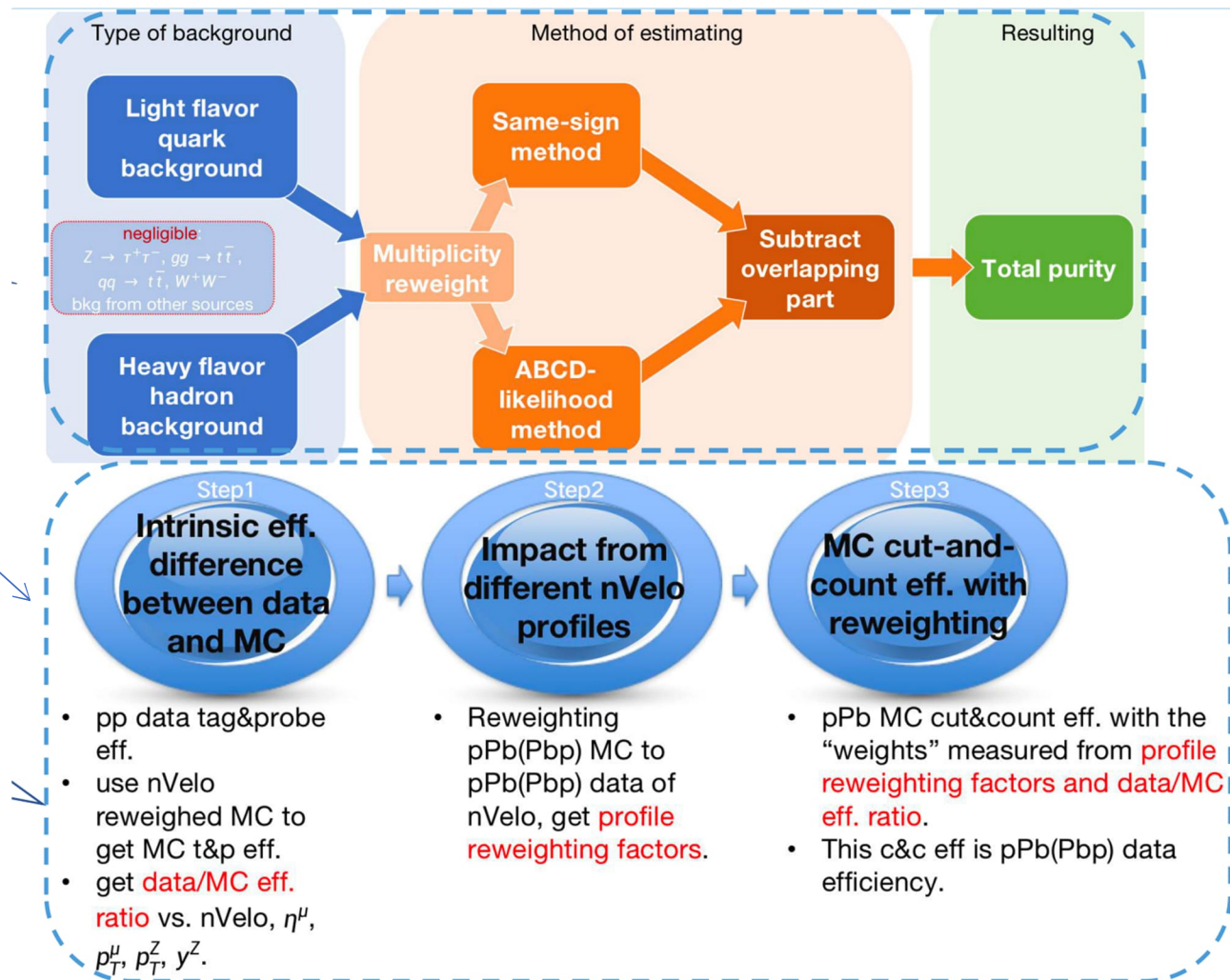
Sample	Collision	Event Type
$Z \rightarrow \mu^+ \mu^-$	pPb 8.16 TeV	42112000
$Z \rightarrow \mu^+ \mu^-$	Pbp 8.16	42112000

❁ Selection criteria for pPb and Pbp:

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

- 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 x_{sec} , 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
$\epsilon^{muon-id}$ [%]	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



* Total fiducial cross-section

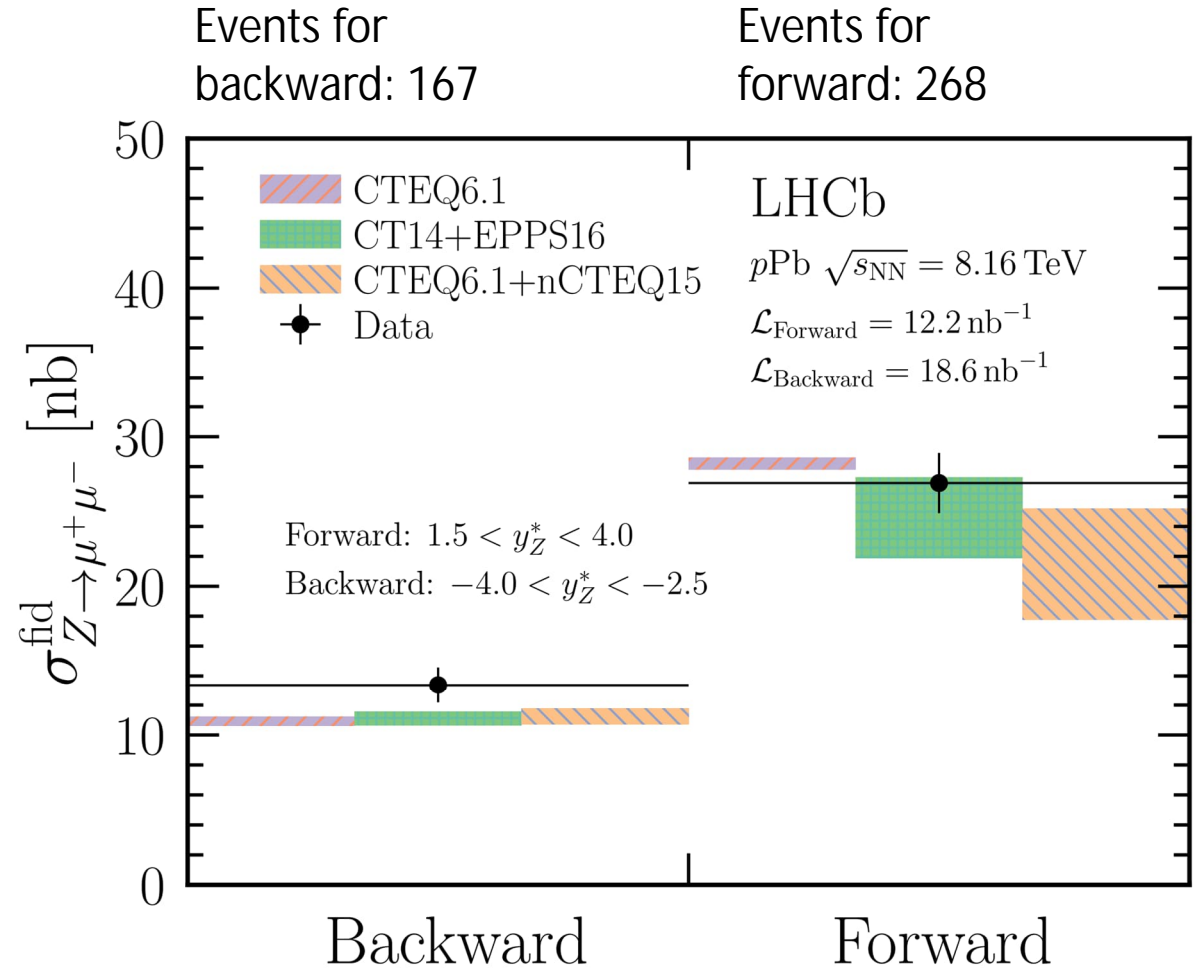
$$\sigma_{Z \rightarrow \mu^+ \mu^-, pPb}^{\text{fid}} = 26.9 \pm 1.6(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.7(\text{lumi.}) \text{ nb}$$

$$\sigma_{Z \rightarrow \mu^+ \mu^-, Pb p}^{\text{fid}} = 13.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.3(\text{lumi.}) \text{ nb}$$

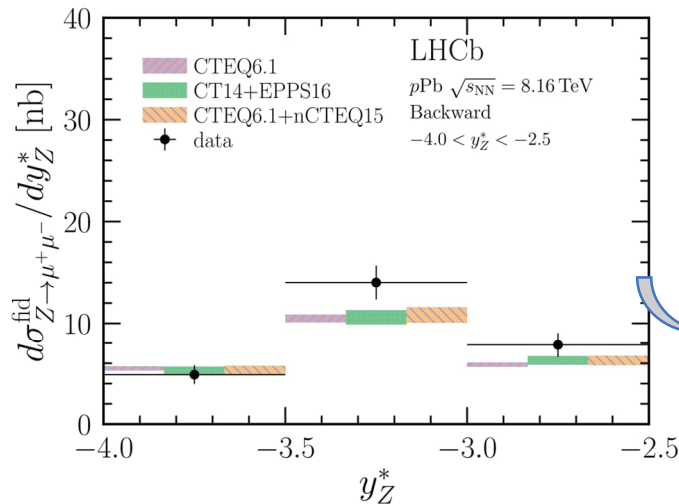
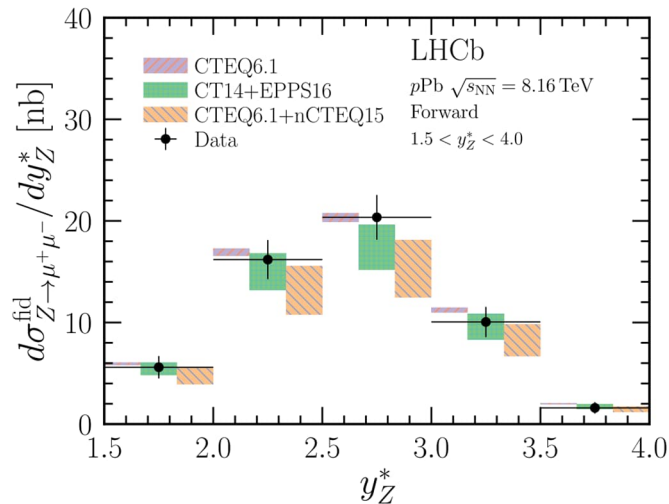
* Measured results compatible with the theoretical calculations within current uncertainties:

- * 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.

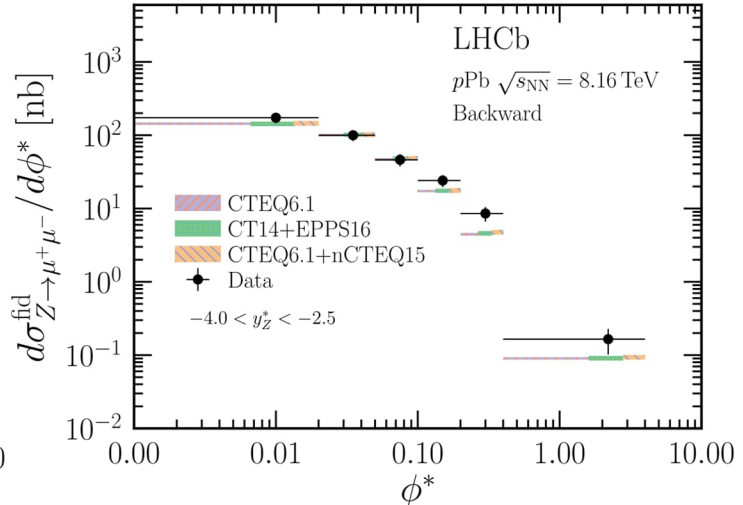
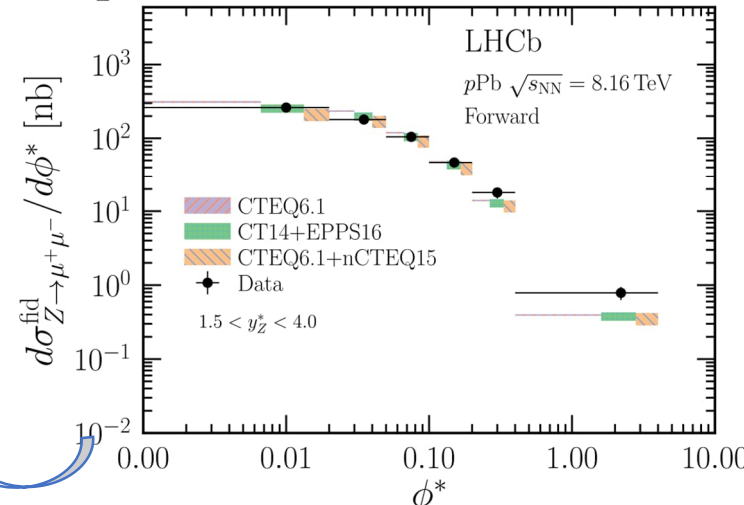


✿ Differential cross-section as a function of y_Z^* and ϕ_η^* , compare measured and theoretical results.



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

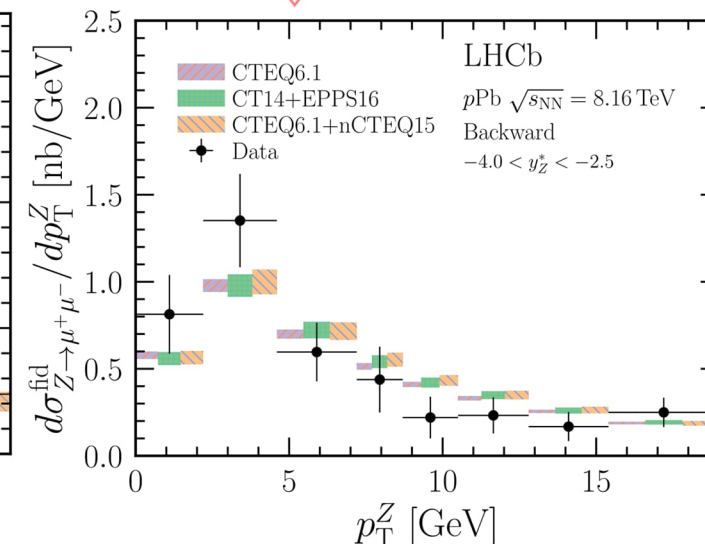
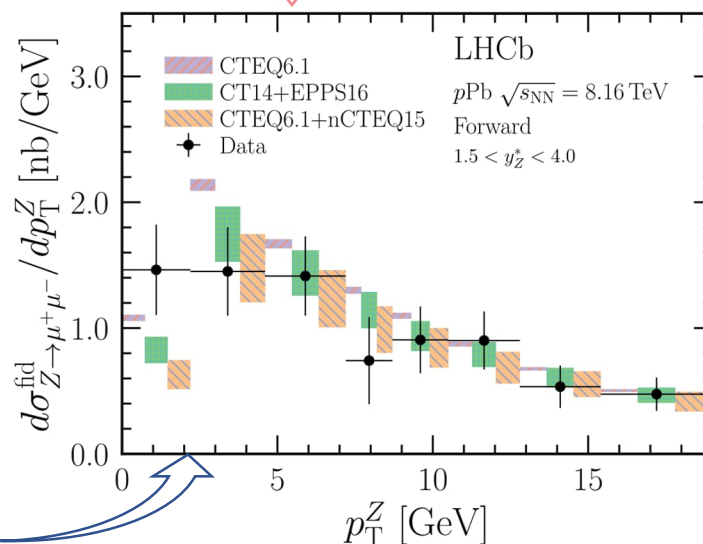
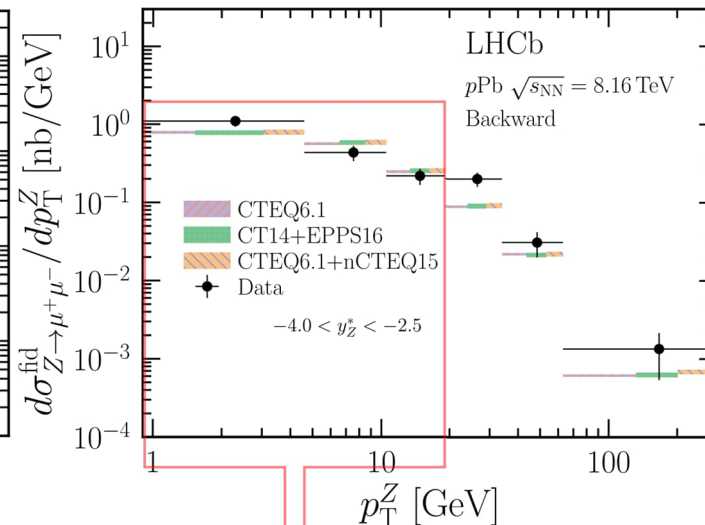
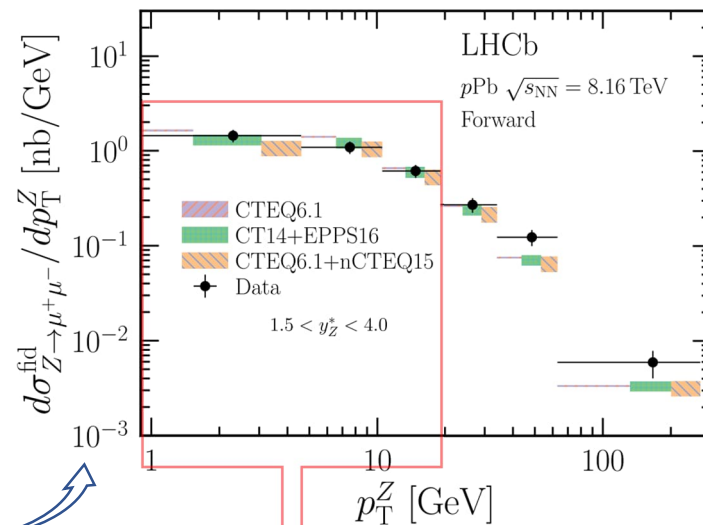
arXiv: 2205.10213

- ❁ 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

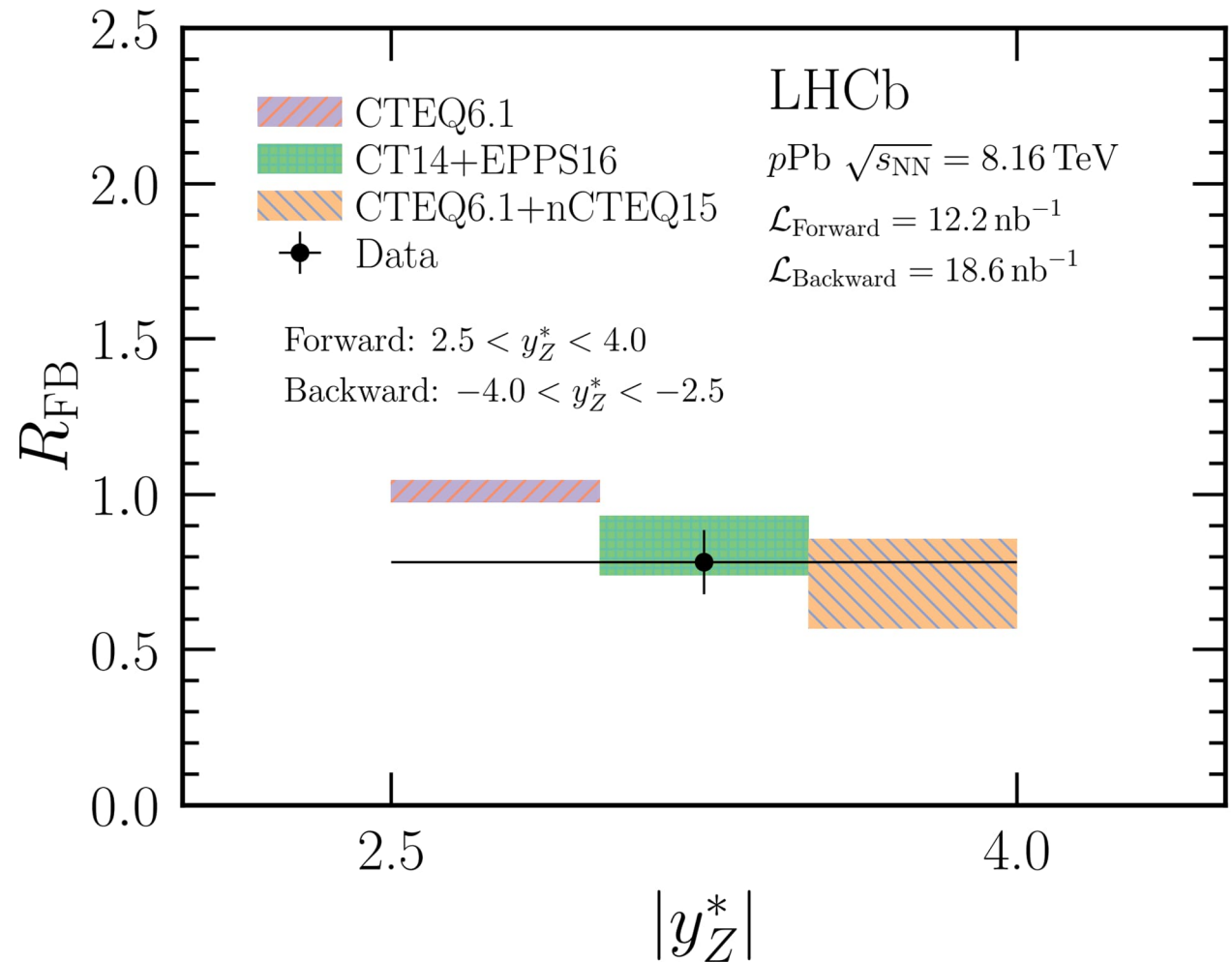


* Forward and backward ratio is sensitive to nuclear effects in the Z production, probe the nuclear matter effects

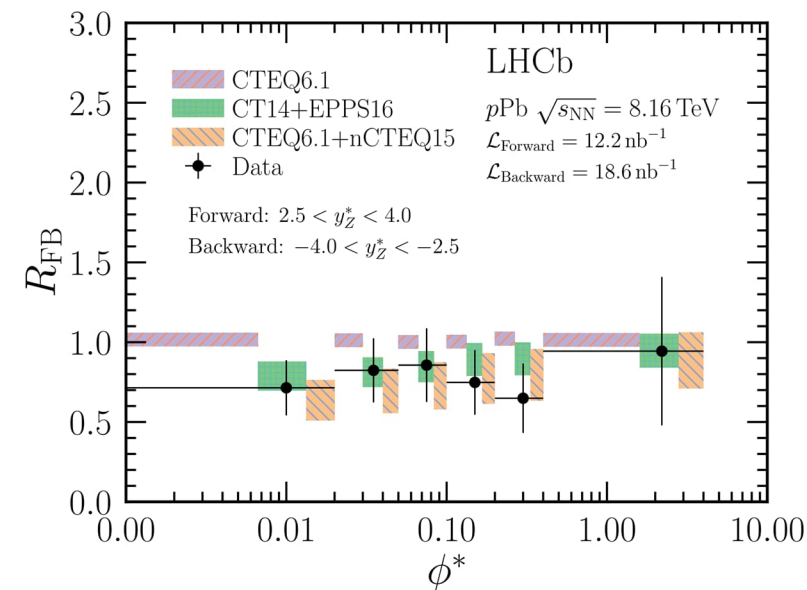
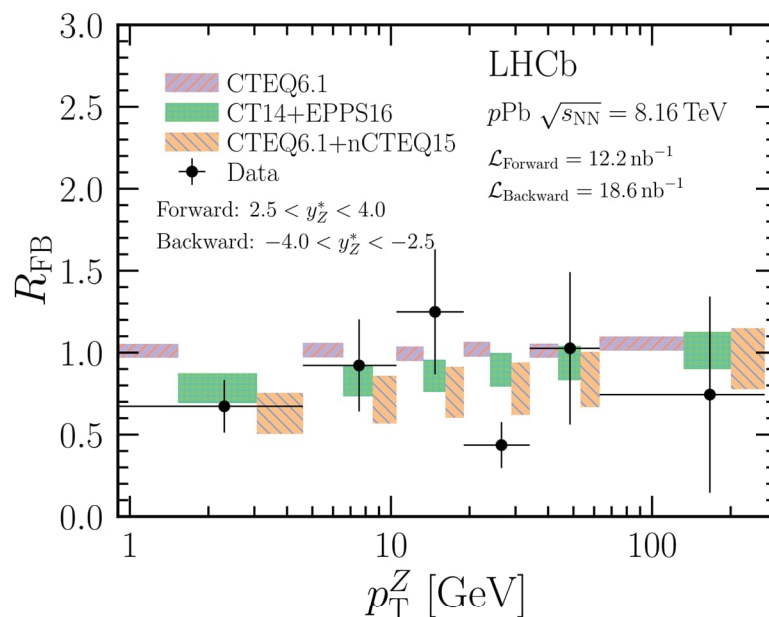
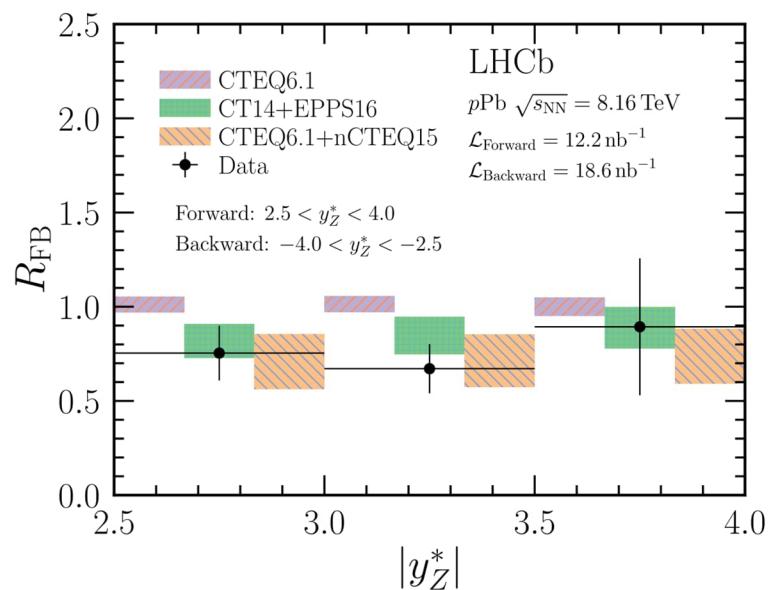
* Measured result:

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

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



- * Forward 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



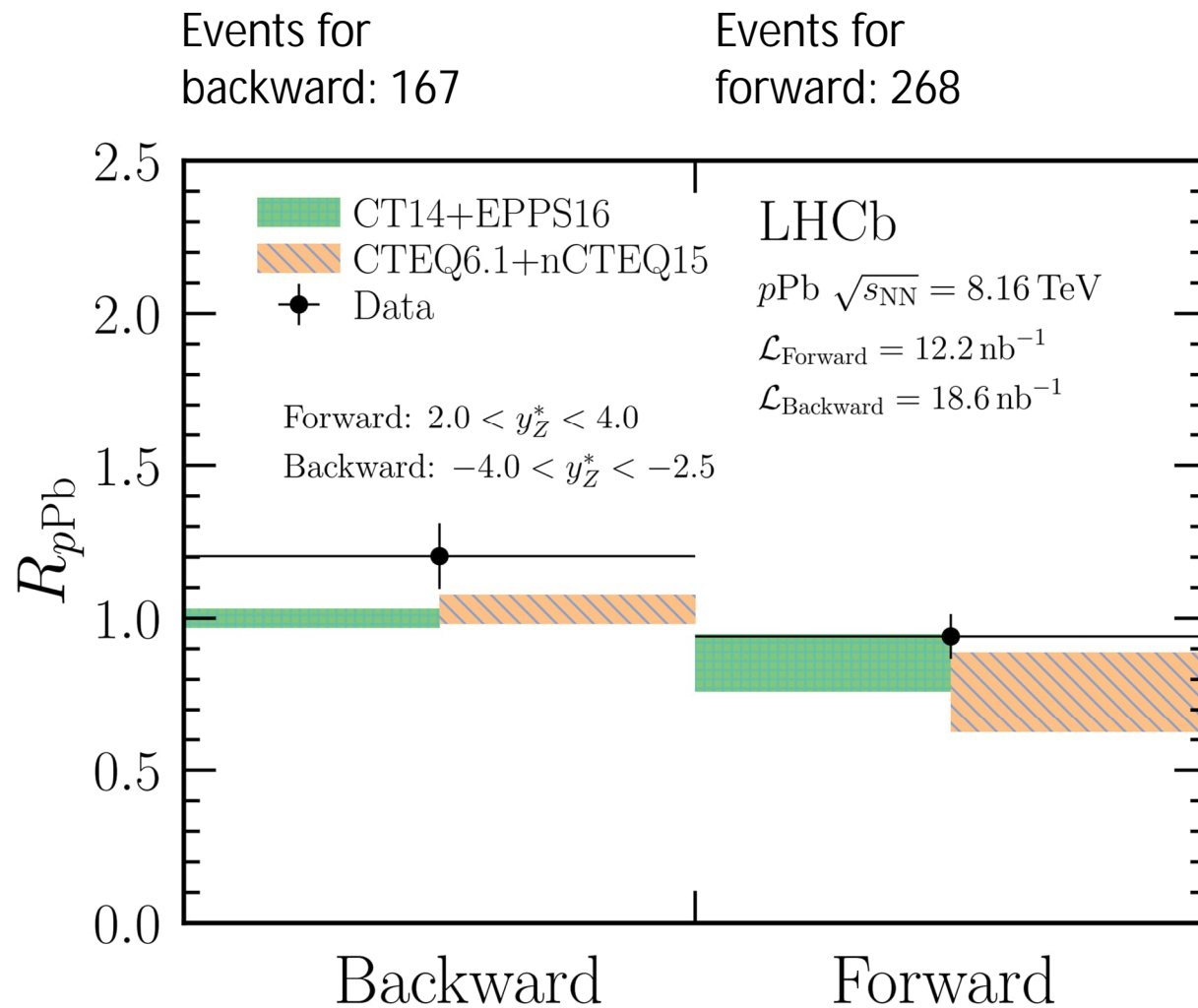
* Nuclear modification factor R_{pPb} directly probes the cold nuclear matter effects.

* The measured results:

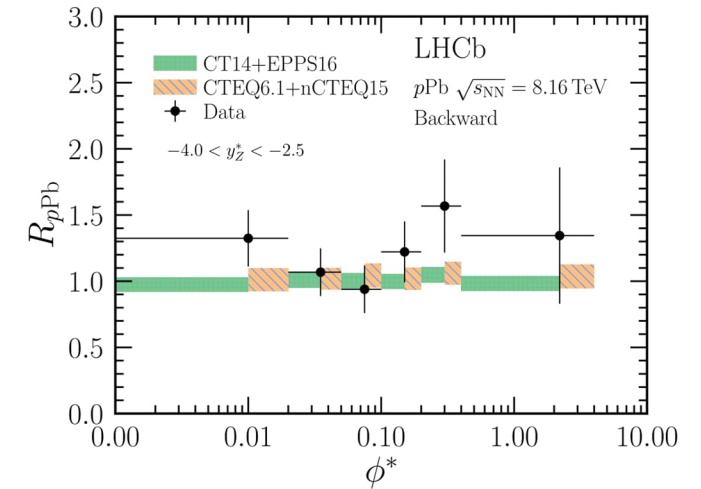
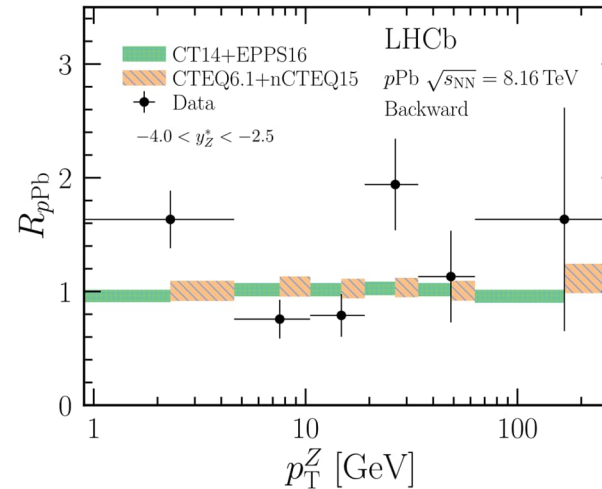
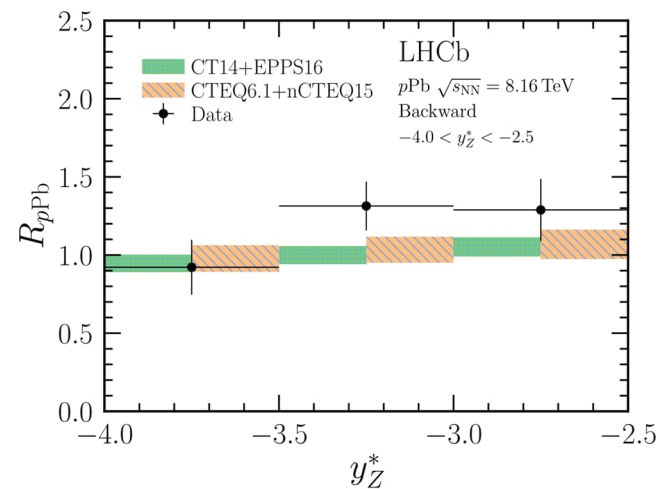
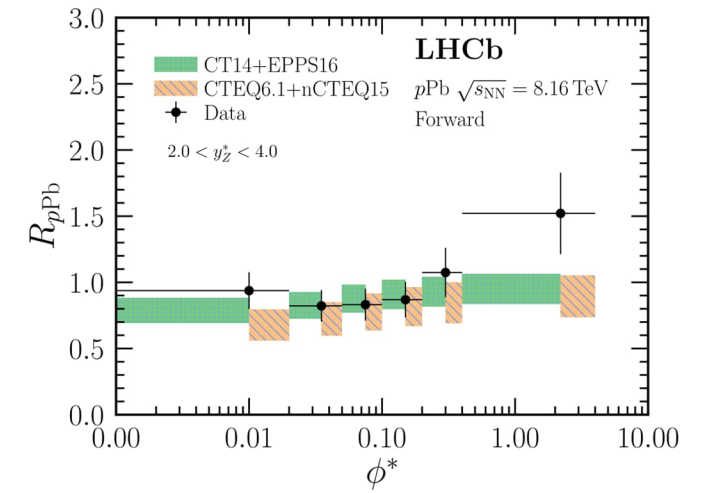
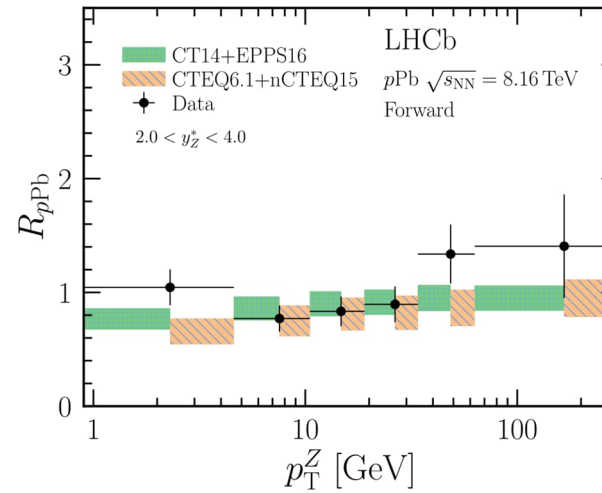
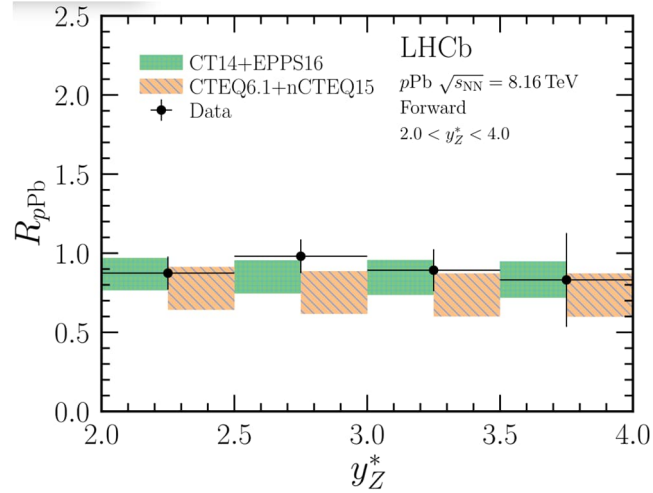
$$R_{pPb}^{\text{fw.}} = 0.94 \pm 0.07$$

$$R_{pPb}^{\text{bw.}} = 1.21 \pm 0.11$$

* 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.



* Nuclear modification factor as a function of y_Z^* , p_T^Z and ϕ_η^*



- ❁ 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_{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.

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.

$$\begin{aligned} \text{rapidity: } y_{cm} &= \frac{1}{2} \ln \frac{E+p_z}{E-p_z} & \text{total energy: } E &= E_p + E_N = \frac{N_A+N_Z}{N_A} \cdot E_p \\ \text{total momentum: } p_z &= E_p - E_N = \frac{N_A-N_Z}{N_A} \cdot E_p \text{ (neglecting the masses)} \\ E + p_z &= 2 \cdot E_p & E - p_z &= 2 \cdot \frac{N_Z}{N_A} \cdot E_p \\ y_{cm} &= \frac{1}{2} \ln \frac{E+p_z}{E-p_z} = \frac{1}{2} \ln \frac{N_A}{N_Z} = \frac{1}{2} \ln \frac{208}{82} = 0.4654 = \Delta y \\ y &= y^* + y_{cm} \end{aligned}$$

- 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.

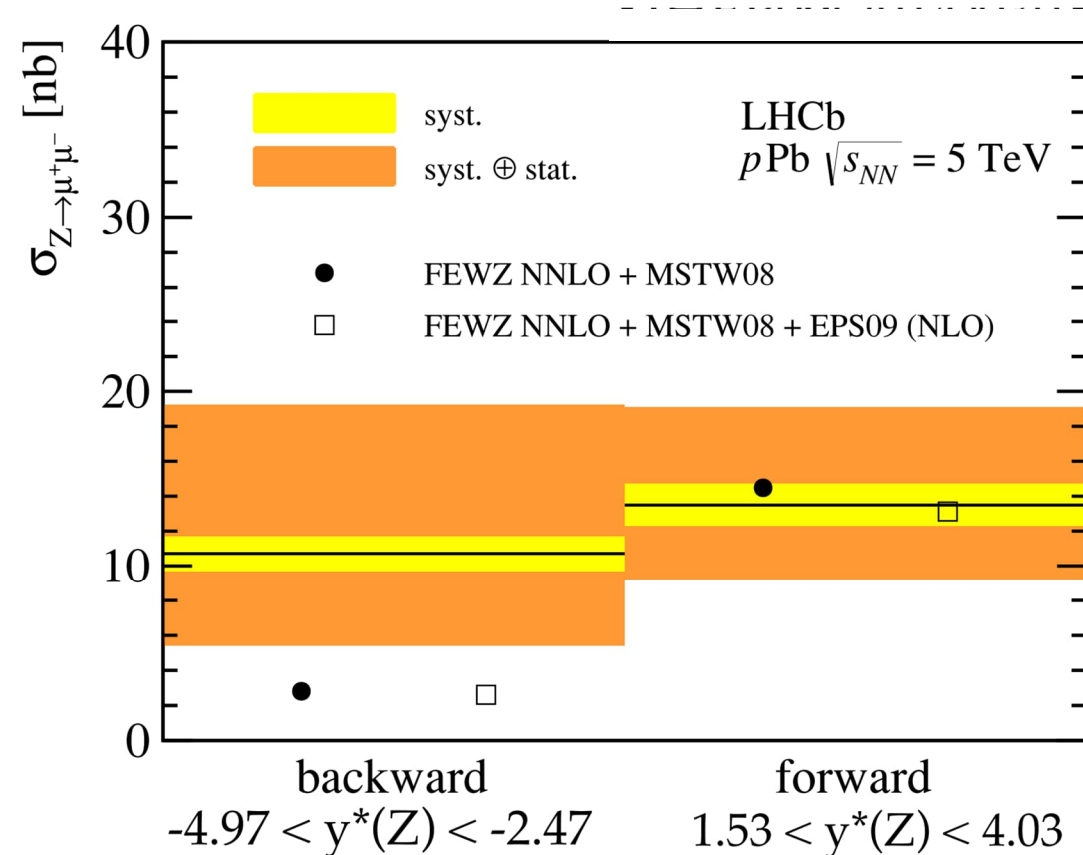
* Fiducial cross-section results:

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

$$\sigma_{Z \rightarrow \mu^+ \mu^-, Pb p}^{\text{fid}} = 10.7_{-5.1}^{+8.4}(\text{stat.}) \pm 1.4(\text{syst.}) \text{ nb}$$

* 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 *

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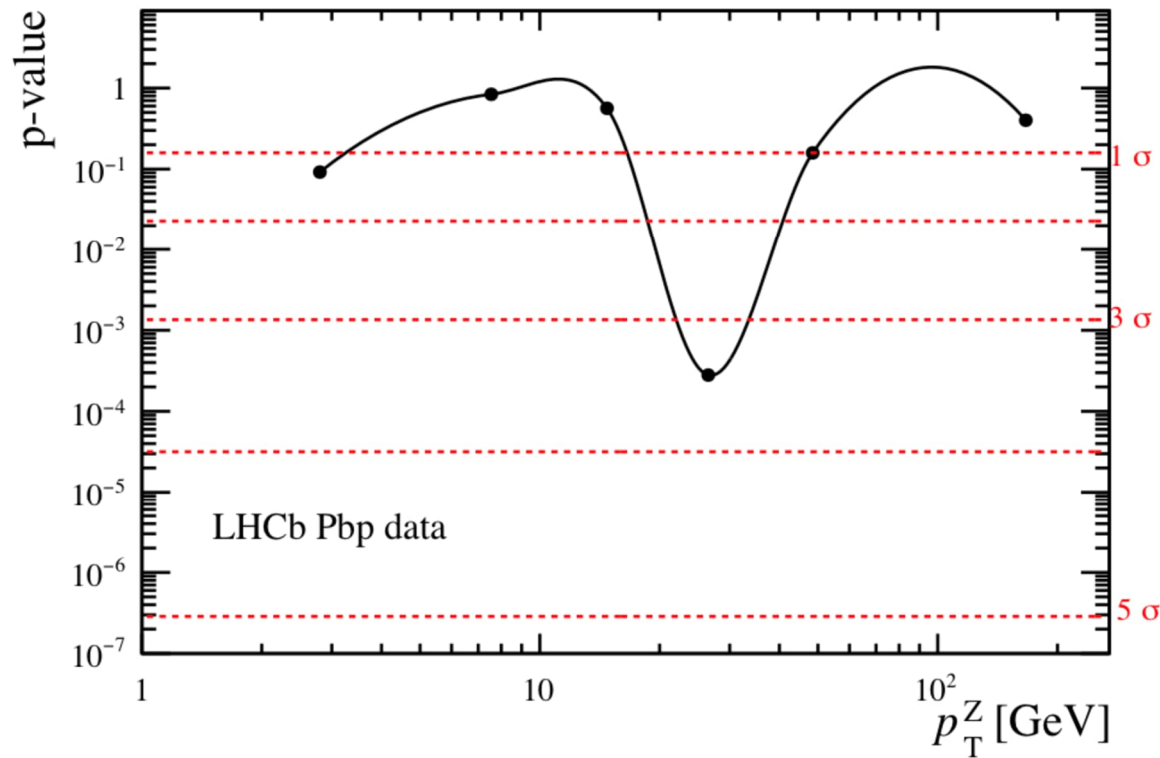
Print Event List of forward p_T^Z bin at 19-34 region

```
*****
* Row * runNumber * eventNum * 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

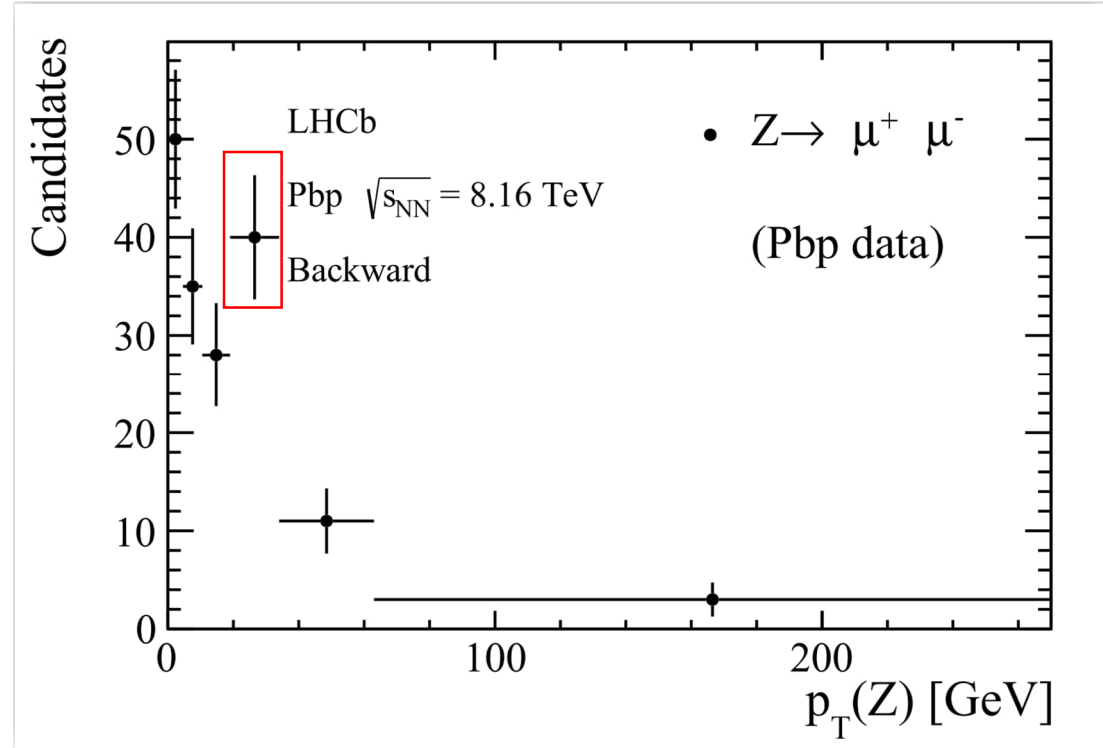
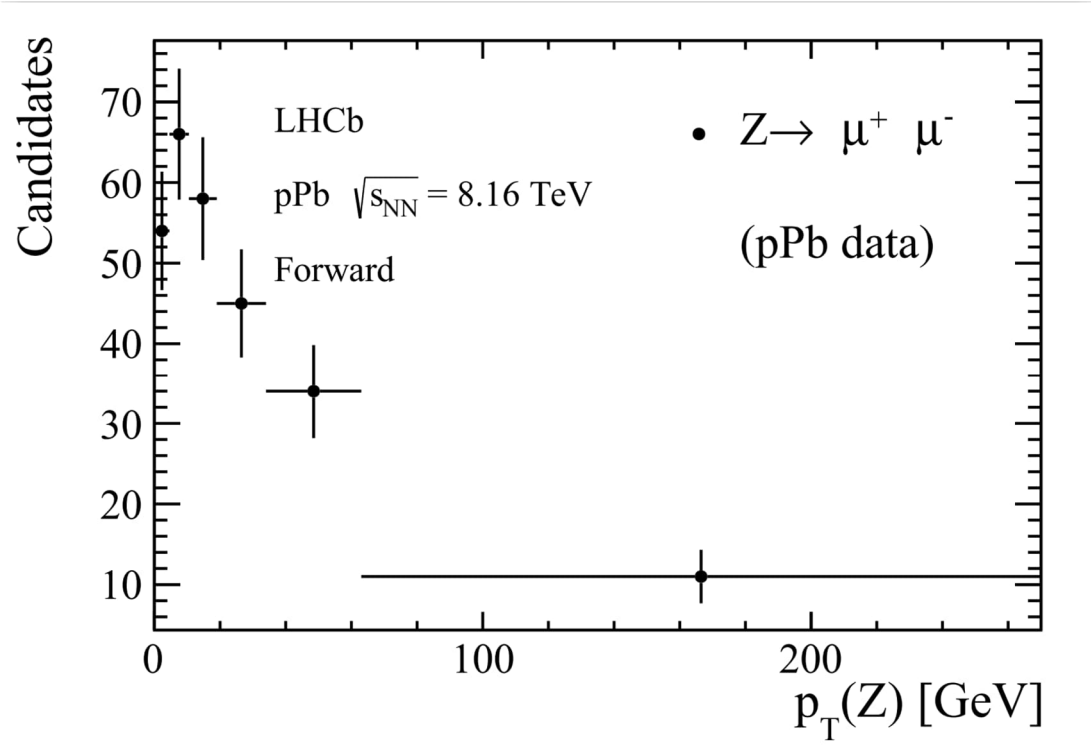
* P-value as a function of p_T^Z



* 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>