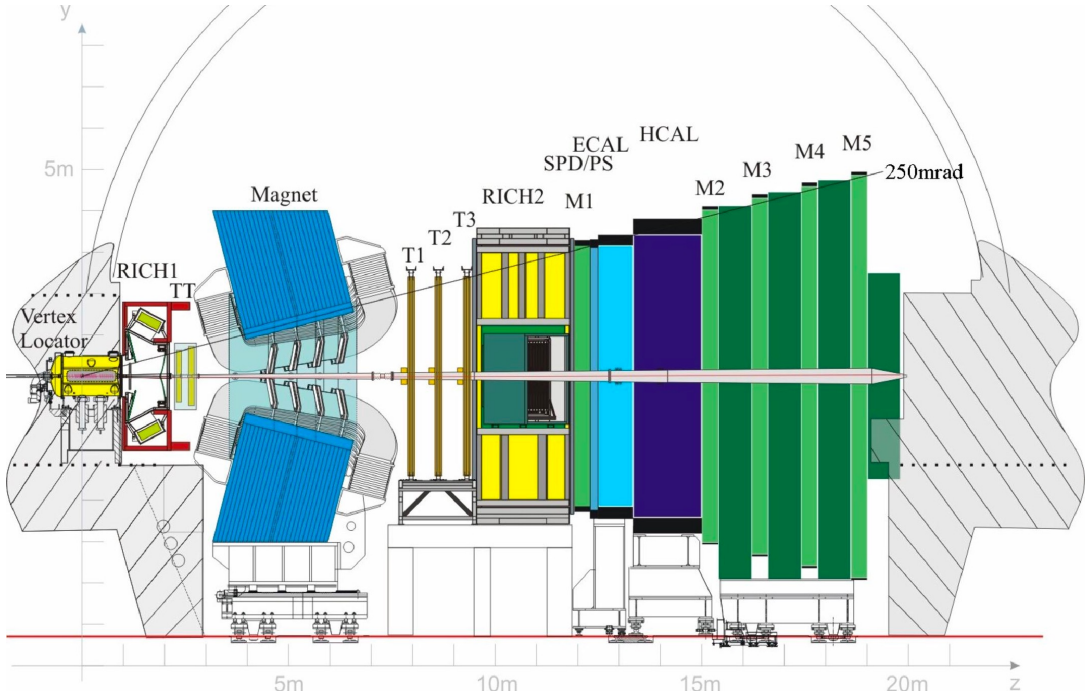
Measurements of charmonium production in Ultraperipheral PbPb collisions and Z production in pPb collisions at LHCb

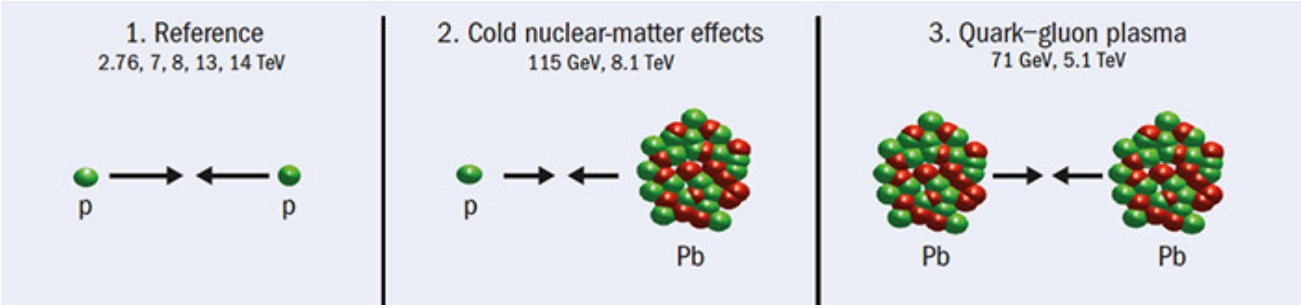
李天齐 (South China Normal University)
On behalf of LHCb Collabration
第八届中国LHC物理研讨会
23/11/2022 南京

The LHCb detector

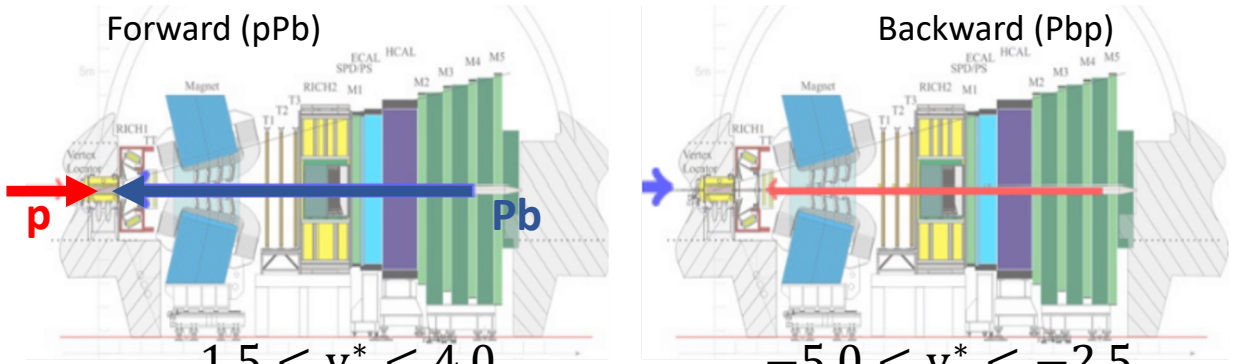
- A forward spectrometer, unique kinematic coverage: $2 < \eta < 5$
- High precision device: tracking down to $p_T = 0$, excellent particle identification, precise vertex reconstruction and tracking



- Collider mode: pp, pPb, PbPb



- Beam configurations for p-Pb collisions



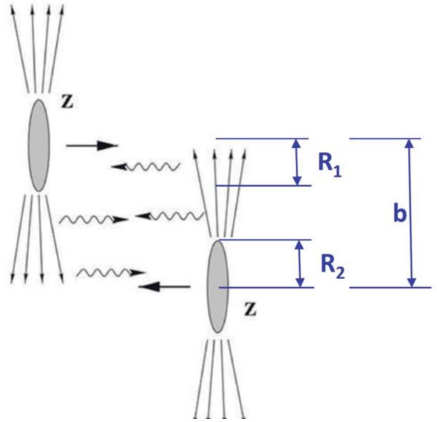
$1.5 < y^* < 4.0$ $\quad -5.0 < y^* < -2.5$

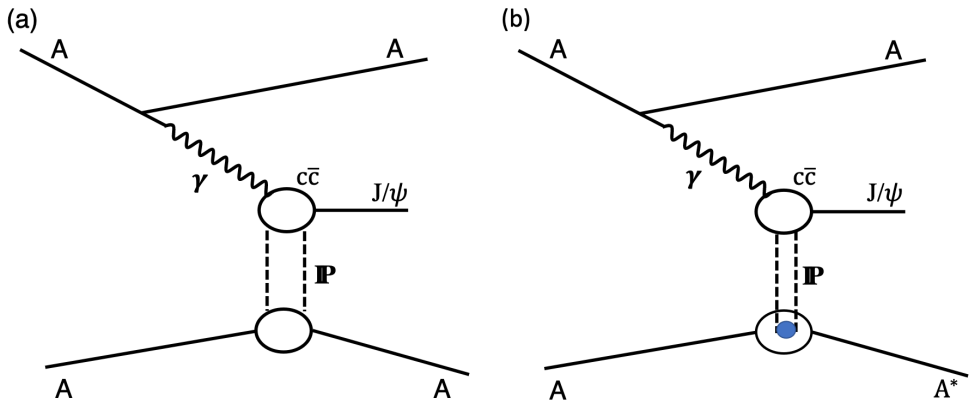
y*: rapidity in center of mass frame, required a rapidity shift of about 0.47 w.r.t. the lab frame coverage

Ultra-Peripheral PbPb Collisions

arXiv: 2206.08221

- Ultra-peripheral collisions (UPC): impact parameter $b > 2R_A$, electromagnetic interactions, strong interactions suppressed
- Exclusive vector meson production, only one vector meson is produced in the final state, clean events
- Photon-induced interactions enhanced by strong EM field of the nucleus, number of photons $\sim Z^2$, study fundamental aspects of QED and QCD
- Probing nucleon/nucleus structure: coherent J/ψ and $\psi(2S)$ production can constrain the probability density functions (PDF) of gluon in PbPb, study gluon shadowing effects, with small partonic momentum fractions $x \sim 10^{-2} - 10^{-5}$
- Measurement of $(J/\psi)/\psi(2S)$ ratio can correct the vector meson wave function in dipole scattering models [PLB 772 (2017) 832, PRC (2011) 011902]





- Coherent J/ψ production: photon interact with the whole nucleus
- Incoherent J/ψ production: photon interact with nucleons in the nucleus

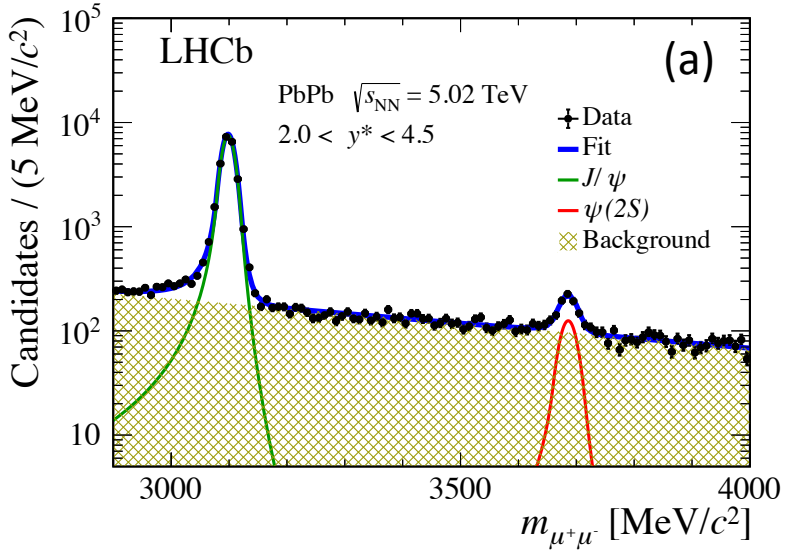
Ultra-Peripheral PbPb Collisions

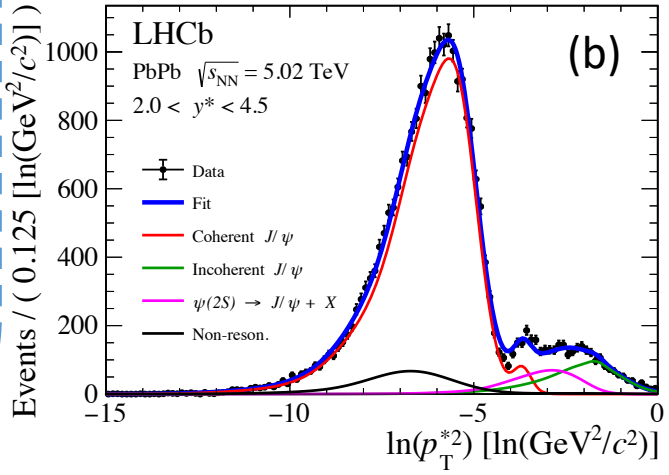
arXiv: 2206.08221

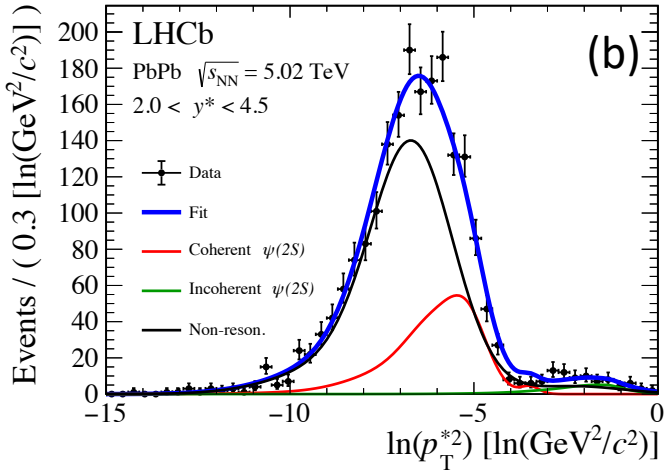
- Cross-sections:

$$\frac{\mathrm{d}\sigma_{\psi}^{\mathrm{coh}}}{\mathrm{d}x} = \frac{N_{\psi}^{\mathrm{coh}}}{\mathcal{L} \times \varepsilon_{\mathrm{tot}} \times \mathcal{B}(\psi \to \mu^{+}\mu^{-}) \times \Delta x}$$

- Event selection:
  - Signal candidates reconstructed with dimuon channel: $2.0 < \eta_{\mu^{\pm}}(\mathrm{lab}) < 4.5$, $p_T^{\mu} > 700\mathrm{MeV/c}$, $p_T^{\mu\mu} < 1\mathrm{GeV}$, $\Delta\phi_{\mu\mu} > 0.9\pi$
  - HERSCHEL detector [JINST 13 (2018) 04 P04017] providing further signal selection
- Signal extraction:
  - (a) Dimuon mass fit: Double-side Crystal Ball function and exponential
  - (b) $\ln(p_T^2)$ fit: signal pdf based on the STARLight model, shape of bkg taken from the sideband method







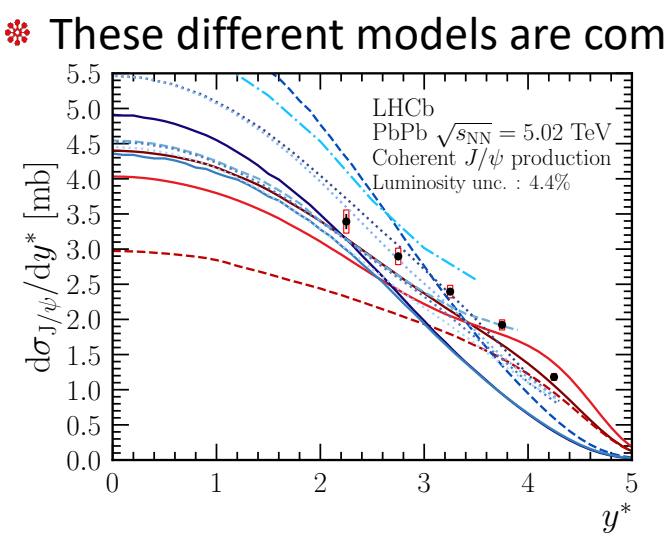
Ultra-Peripheral PbPb Collisions

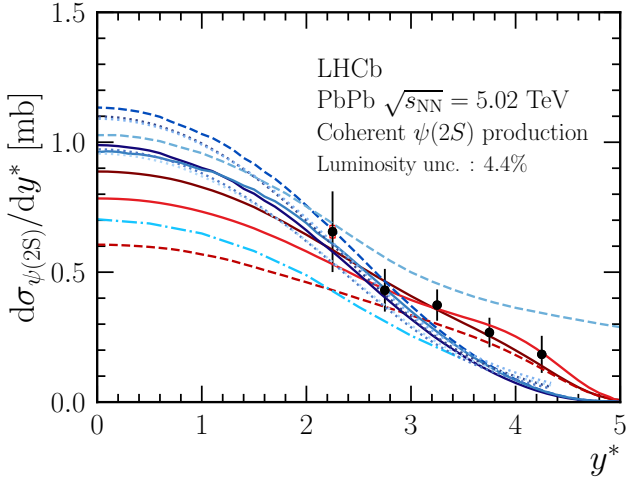
arXiv: 2206.08221

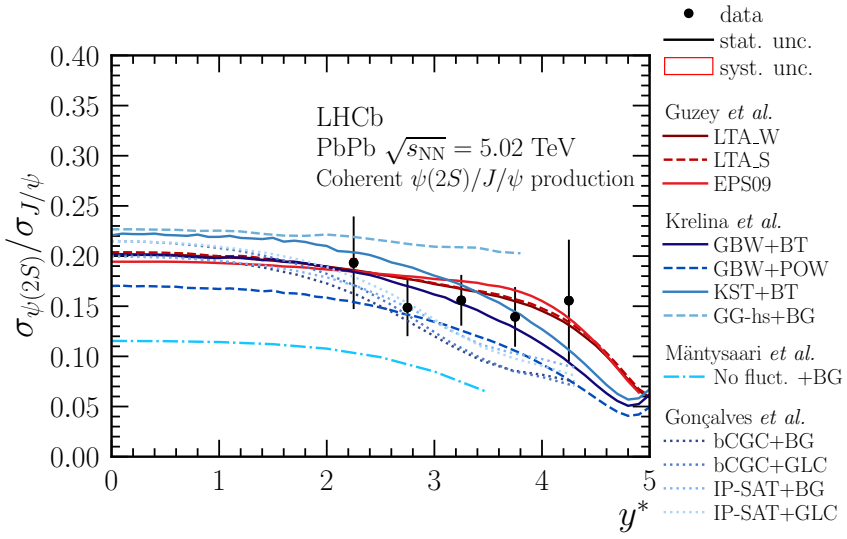
- Integrated cross-section and ratio:

$$\sigma^{coh}_{J/\psi} = 5.965 \pm 0.059(stat) \pm 0.232(syst) \pm 0.262(lumi)mb$$
$$\sigma^{coh}_{\psi(2S)} = 0.923 \pm 0.086(stat) \pm 0.028(syst) \pm 0.040(lumi)mb$$
$$\sigma^{coh}_{J/\psi}/\sigma^{coh}_{\psi(2S)} = 0.155 \pm 0.014(stat) \pm 0.003(syst)$$

- Differential cross-section as a function of rapidity (compared to pQCD and color-dipole models)
  - The most precise measurement for coherent J/ψ production in PbPb UPC in the forward rapidity today
  - The first coherent $\psi(2S)$ measurement in forward rapidity region at the LHC
  - These different models are compatible with the data

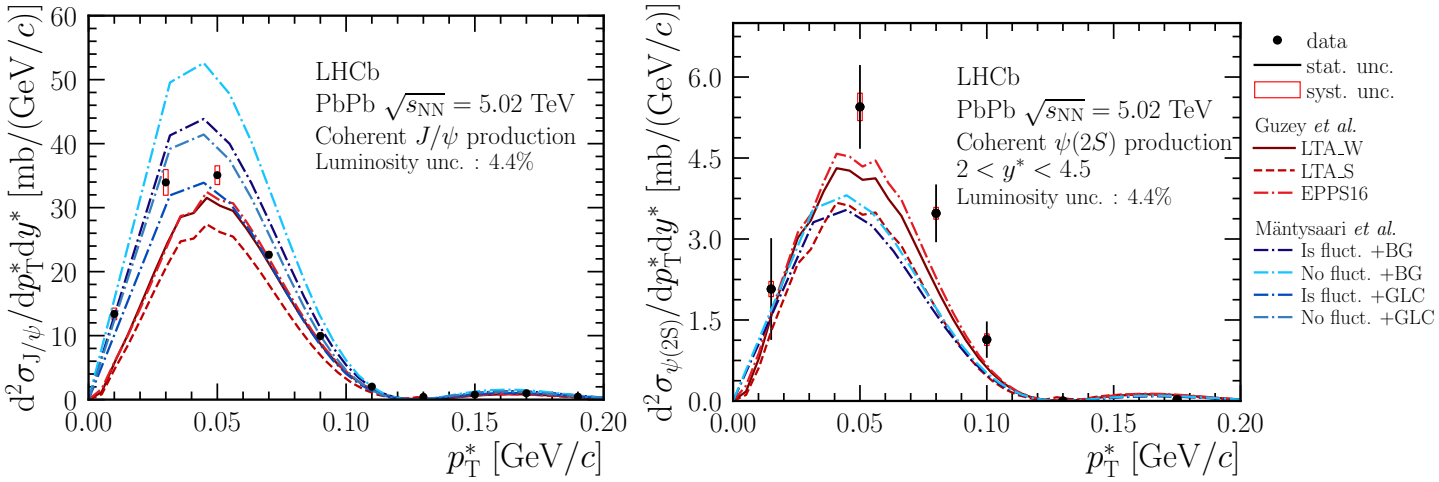






Ultra-Peripheral PbPb Collisions

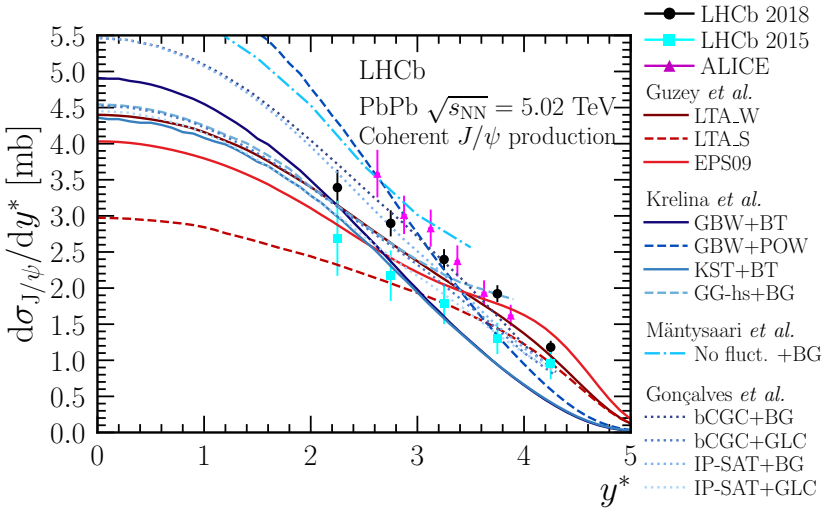
arXiv: 2206.08221



- Differential cross-section vs. charmonium p_T
  - The first and most precise measurement of the coherent J/ψ and $\psi(2S)$ production cross-section vs. p_T in PbPb UPC today.

- The LHCb 2018 J/ψ measurement is agreement with LHCb 2015 and ALICE results.
- The difference between the LHCb 2018 and LHCb 2015 measurement is about 2.0σ.
- With the inclusion of the 2018 results, further constrain theoretical model

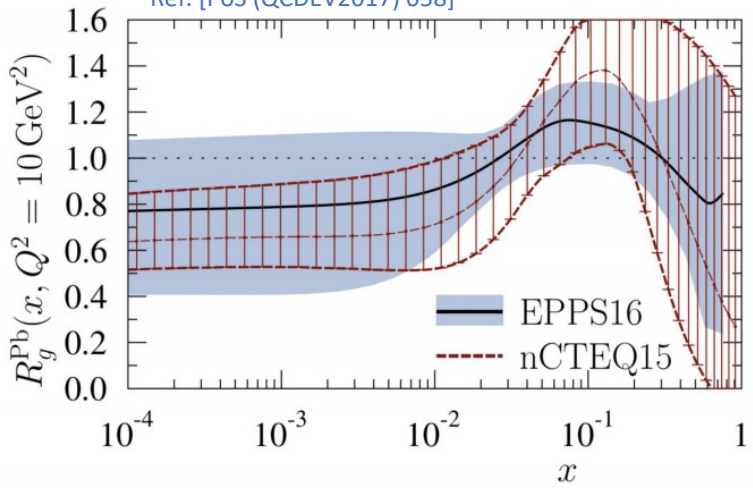
Guzey et al.: PRC 93 (2016) 055206, PRC 95 (2017) 025204,
Krelina et al.: PRC 97 (2018) 024901, arXiv:2008.05116
Mantysaari et al.: PLB 772 (2017) 832, PoS DIS2014 (2014) 069, PRD 74 (2006) 074016
Goncalves et al.: PRD 96 (2017) 094027, EPJC 40 (2005) 519,

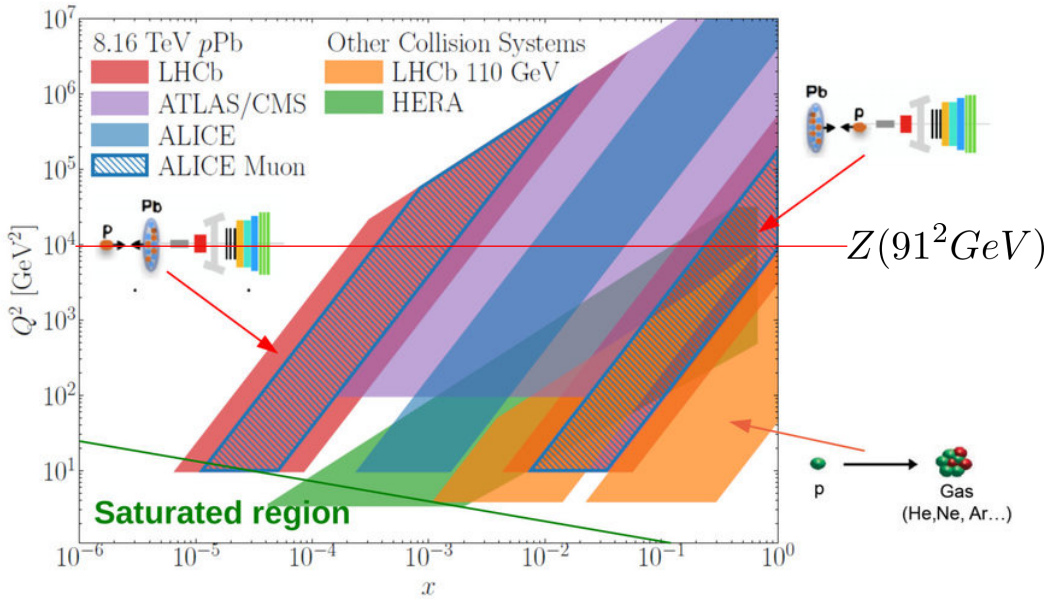


Z production in pPb collisions at 8TeV

- 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 $Q^2 = 91^2 \mathrm{GeV}^2$.
  - 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]





Z prodution in pPb collisions at 8TeV

arXiv: 2205.10213, accepted by JHEP

- Cross-section:

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

- Forward-Backward ratio

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

at the common $2.5 < |y^*_Z| < 4.0$

- Nuclear modification factor

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

- The resulting $\sigma_{Z\to\mu^+\mu^-,pp}$, given by LHCb public results [ARXIV:1511.08039]

- $\mathrm{k_{FB}}$ and $\mathrm{k_{pPb}}$ are correction factor to correct the different muon rapidity acceptance, derived using CTEQ61 free proton PDF.

- Results are estimated separately in bins of the

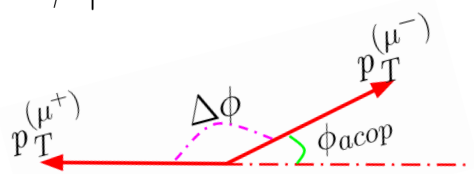
y^*_Z, p^Z_{T} and ϕ^*_η

  - ϕ^*_η is defined as $\frac{\tan(\phi_{\mathrm{acop}}/2)}{\cos(\Delta\eta/2)}$, where the acoplanarity angle

$$\phi_{\mathrm{acop}} \equiv \pi - |\,\Delta\phi\,|$$

- Fiducial volume:

$$p_{\mathrm{T}}(\mu^\pm) > 20\mathrm{GeV}/c,$$
$$2.0 < \eta_{\mu^\pm}(\mathrm{lab}) < 4.5,$$
$$60 < m_{\mu^+\mu^-} < 120\mathrm{GeV}/c^2$$



Z production in pPb collisions

arXiv: 2205.10213, accepted by JHEP

- Total fiducial cross-section

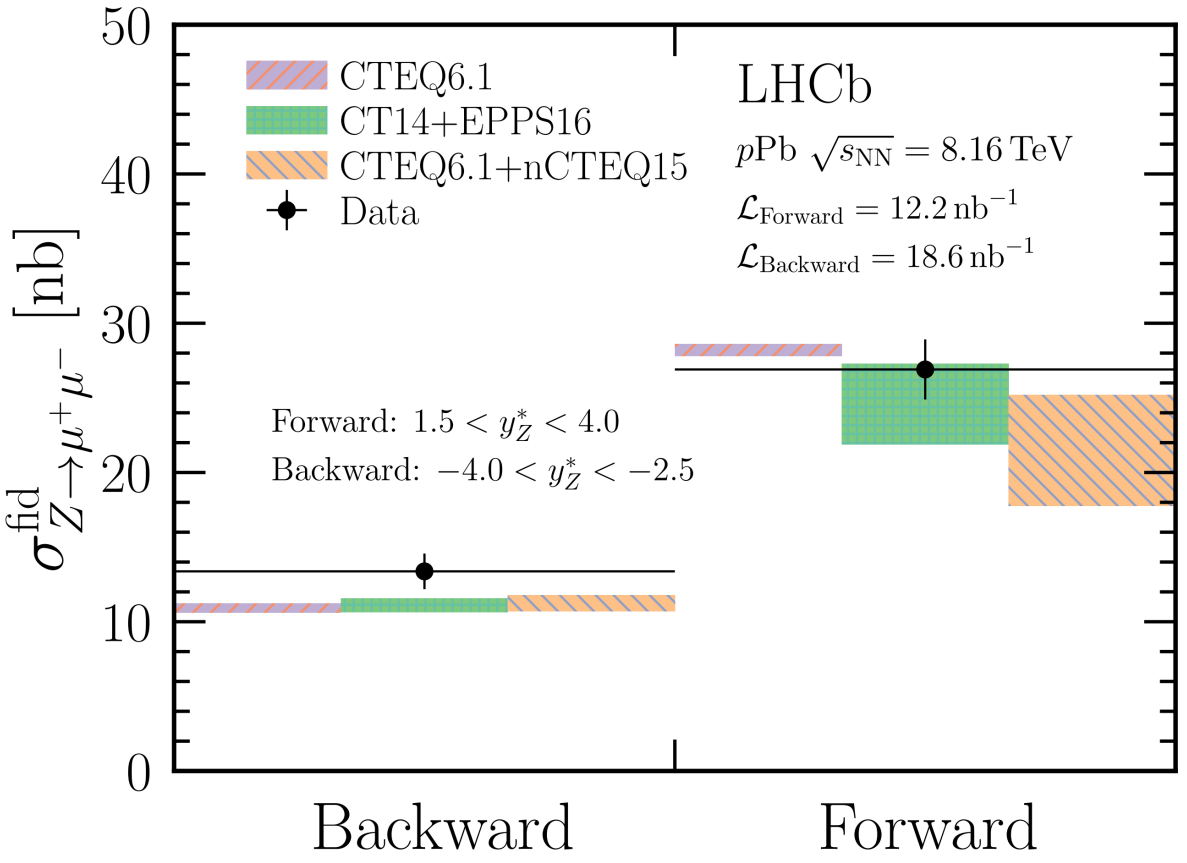
$$\sigma^{\text{fid}}_{Z\to\mu^+\mu^-,\text{pPb}} = 26.9 \pm 1.6(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.7(\text{lumi.}) \quad \text{nb}$$

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

- 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.

Events for backward: 167

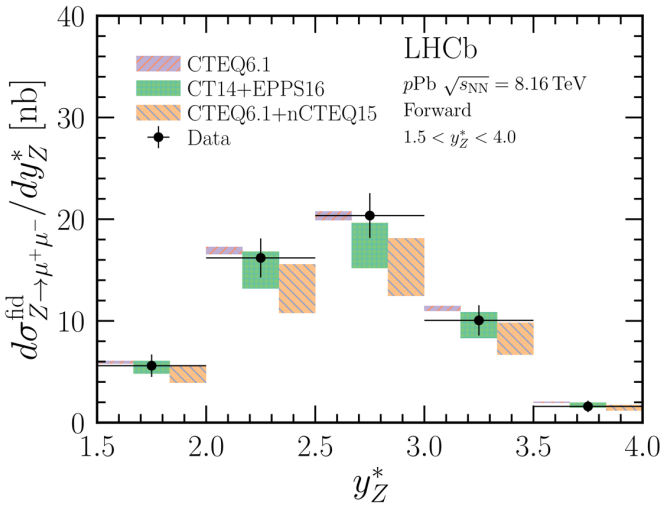
Events for forward: 268

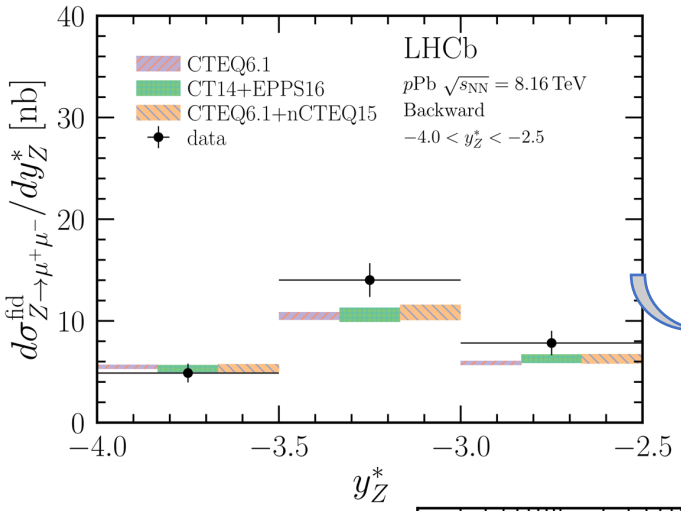


Z production in *p*Pb collisions

arXiv: 2205.10213, accepted by JHEP

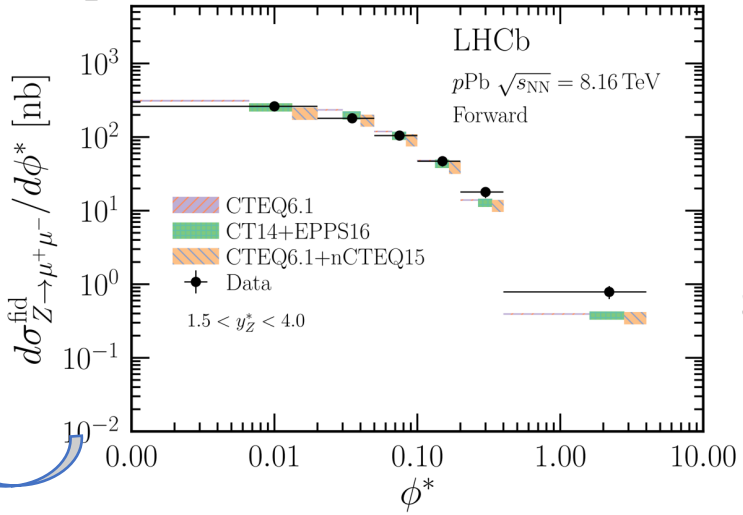
- Differential cross-section as a function of y_Z^* and ϕ_η^*, compare measured and theoretical results.

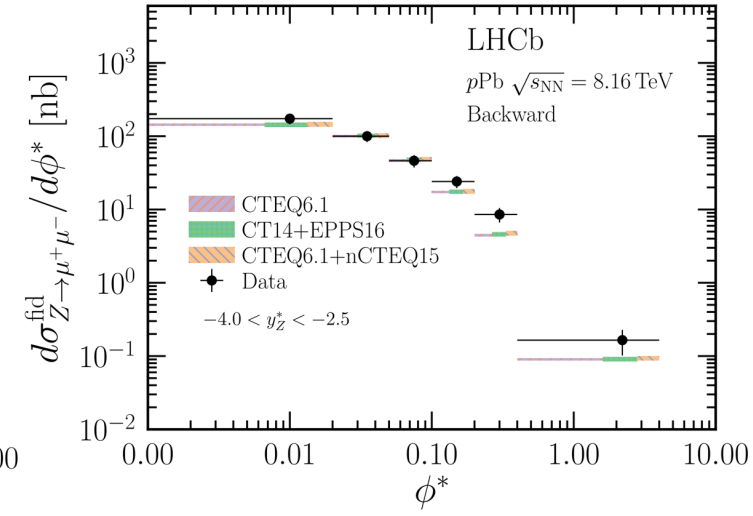




For forward: the measurements show a good agreement with predictions, a smaller uncertainty to constrain the nPDFs.
For backward: the measured results' uncertainties are greater than theoretical calculations

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

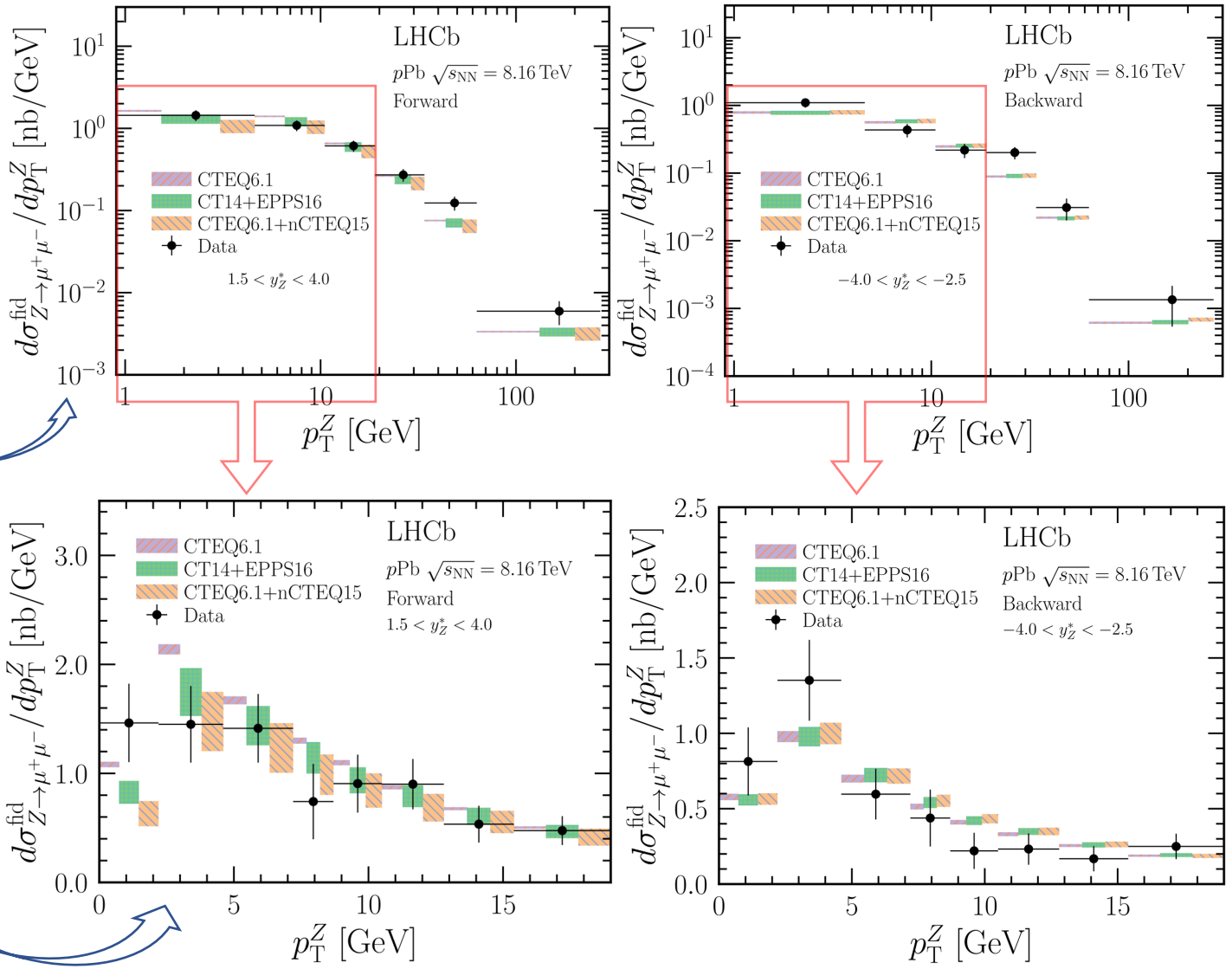




Z production in *p*Pb collisions

arXiv: 2205.10213, accepted by JHEP

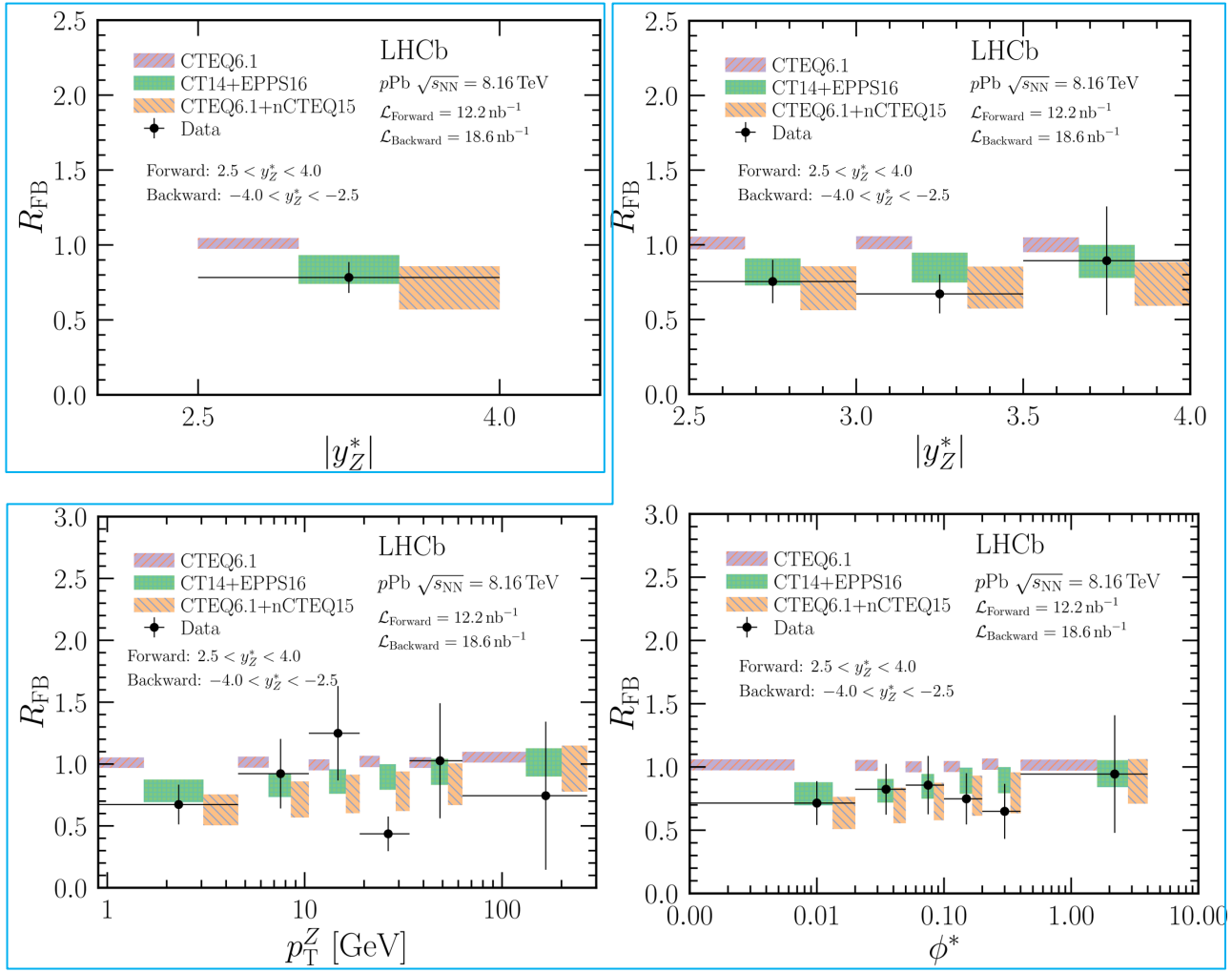
- Cross-section as a function of p_T^Z, compare measured and theoretical results.
- For forward, a smaller measured uncertainty in low-p_T^Z bins, further constrain the nPDFs
- For backward, the measured uncertainties are greater than (n)PDF calculations, the central values of measurements are compatible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



Z production in *p*Pb collisions

arXiv: 2205.10213, accepted by JHEP

- 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



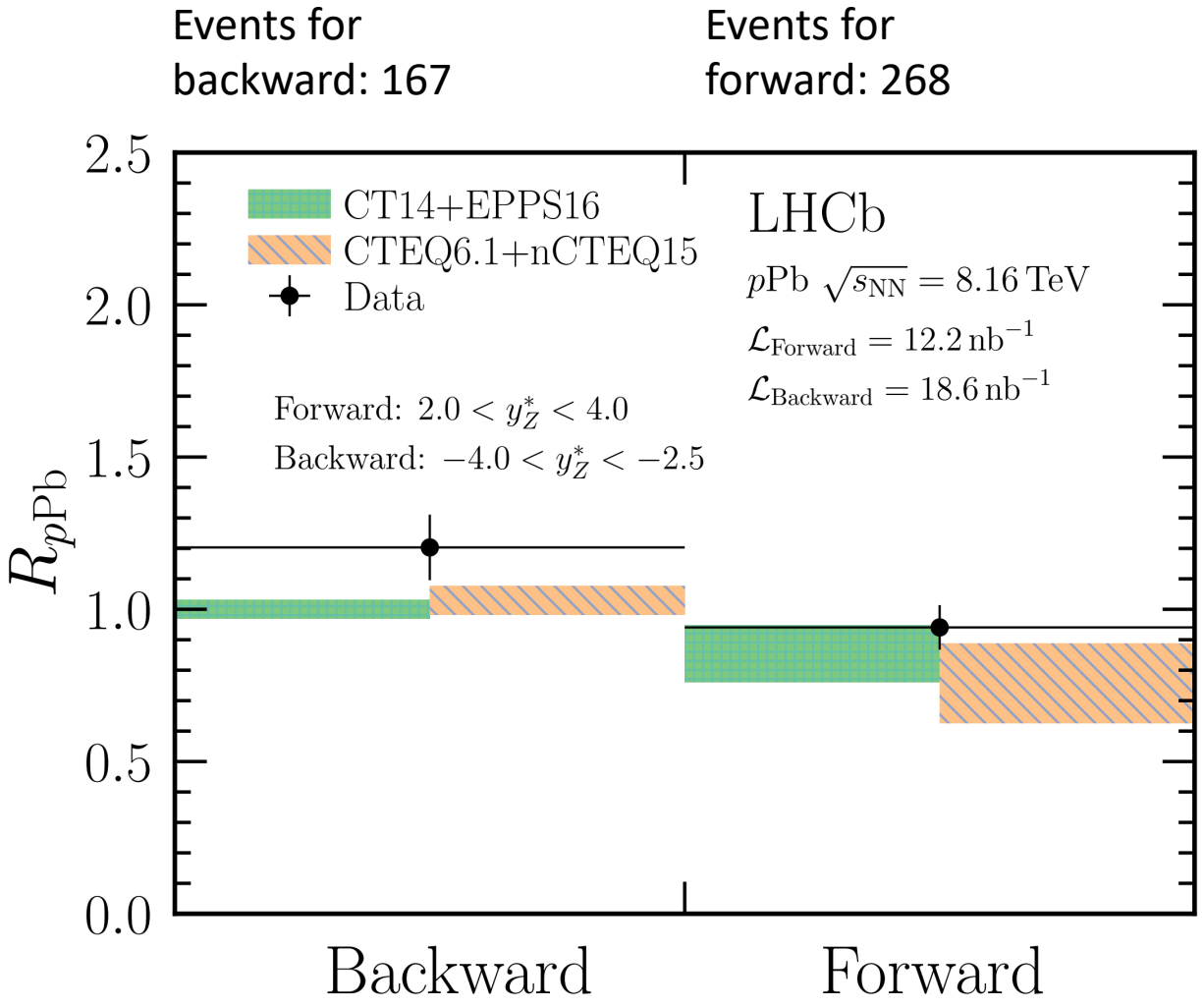
Z production in *p*Pb collisions

arXiv: 2205.10213, accepted by JHEP

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

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

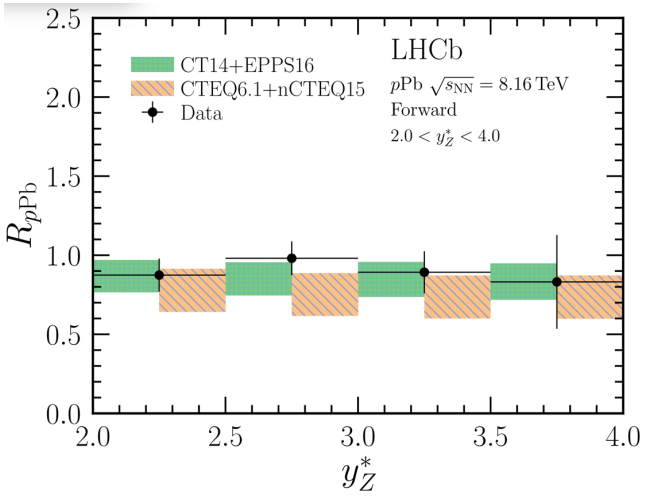
- The measurements are compatible with theoretical predictions; Results in forward region(small Bjorken-x, nuclear shadowing suppression part) give higher precision, constrain on the current nPDF sets.

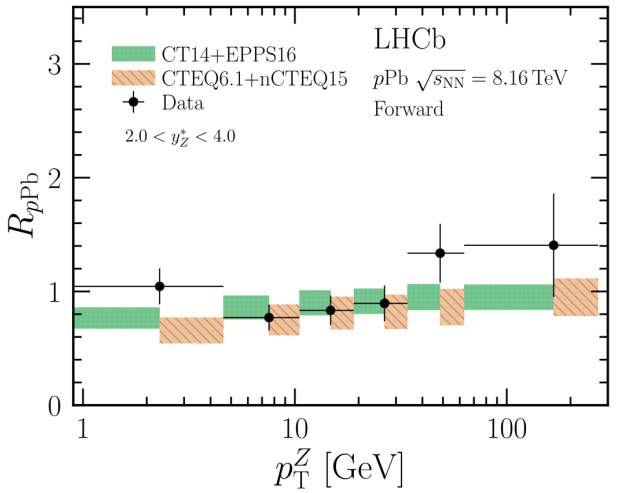


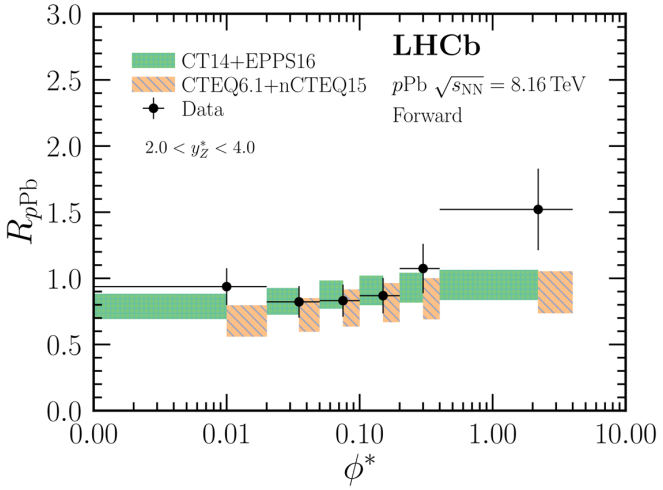
Z production in pPb collisions

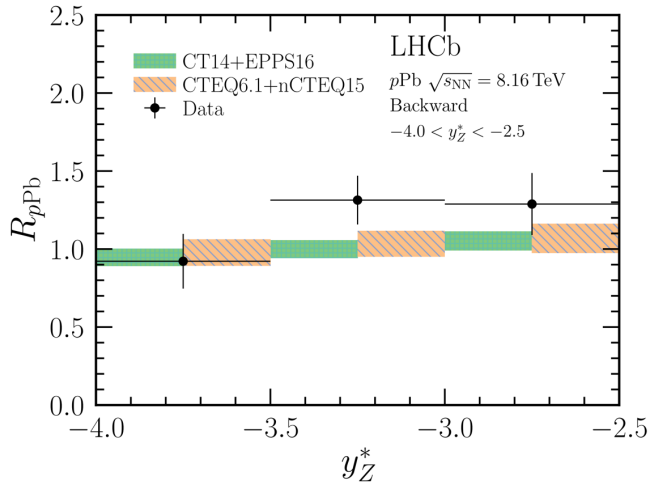
arXiv: 2205.10213, accepted by JHEP

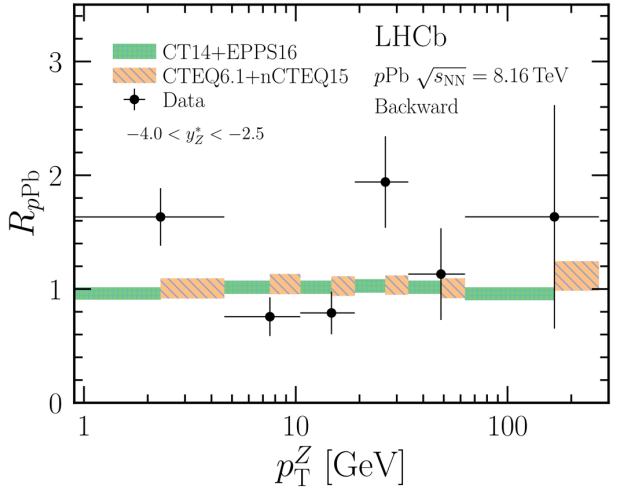
- Nuclear modification factor as a function of y_Z^*, p_T^Z and ϕ_η^*

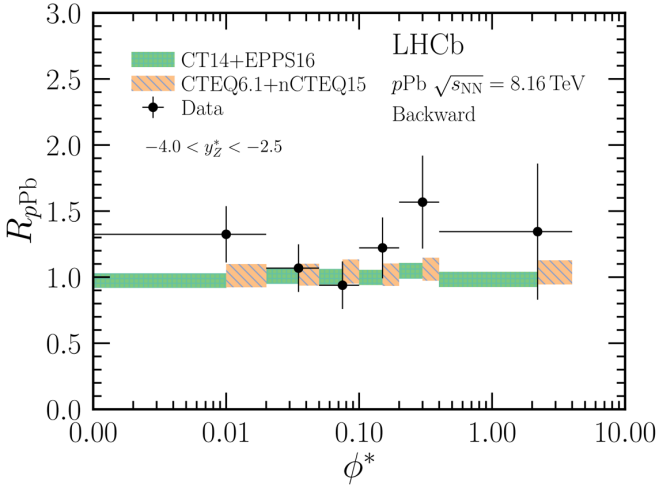












Summary

- A new measurement of the exclusive coherent J/ψ and ψ(2S) production and their cross-section ratio in UPC PbPb collisions with the 2018 dataset.
  - The most accurate coherent J/ψ production measurement and the first coherent ψ(2S) measurement in forward rapidity region in UPC at LHC to date.
  - The first measurement of coherent J/ψ and ψ(2S) production cross-section vs. p_T in the PbPb UPC.

- 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.

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)

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

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

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

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.

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

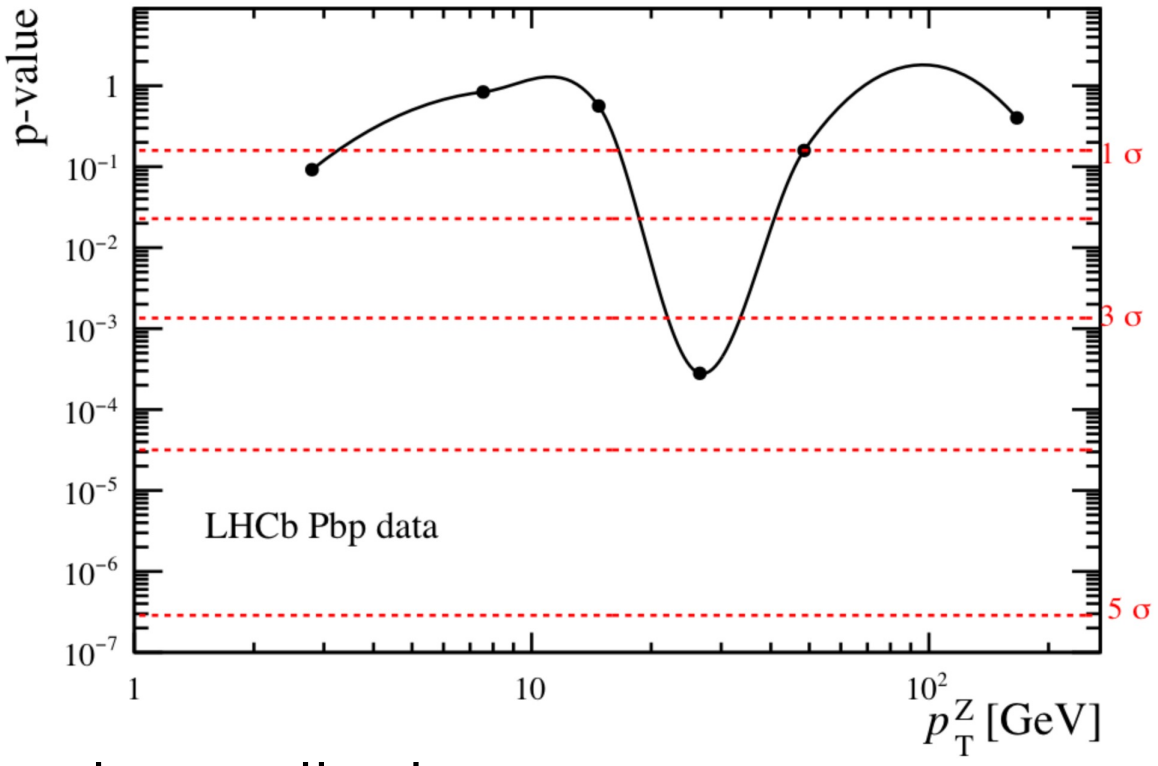
Row	runNumber	eventNumb	totCandid	nCandidat	Z0_M*1e-3	Z0_PT*1e-	Z0_Y
11009	187042	336775248	3	1	97.855408	22.998711	2.4948854
24534	187058	1.003e+09	2	0	91.837976	29.415430	3.0331178
24589	187113	1.300e+09	1	0	65.004351	25.719245	2.5533646
33356	187392	764408682	3	2	88.524788	20.137204	2.6463455
35723	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

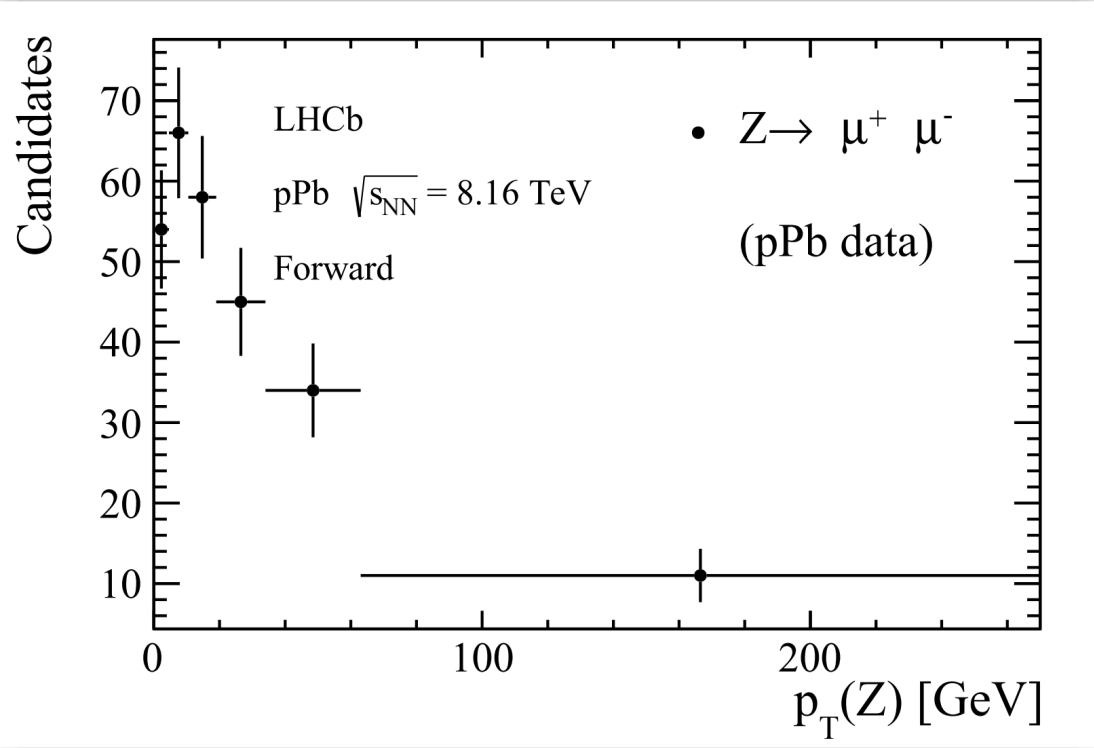
- P-value as a function of p_T^Z

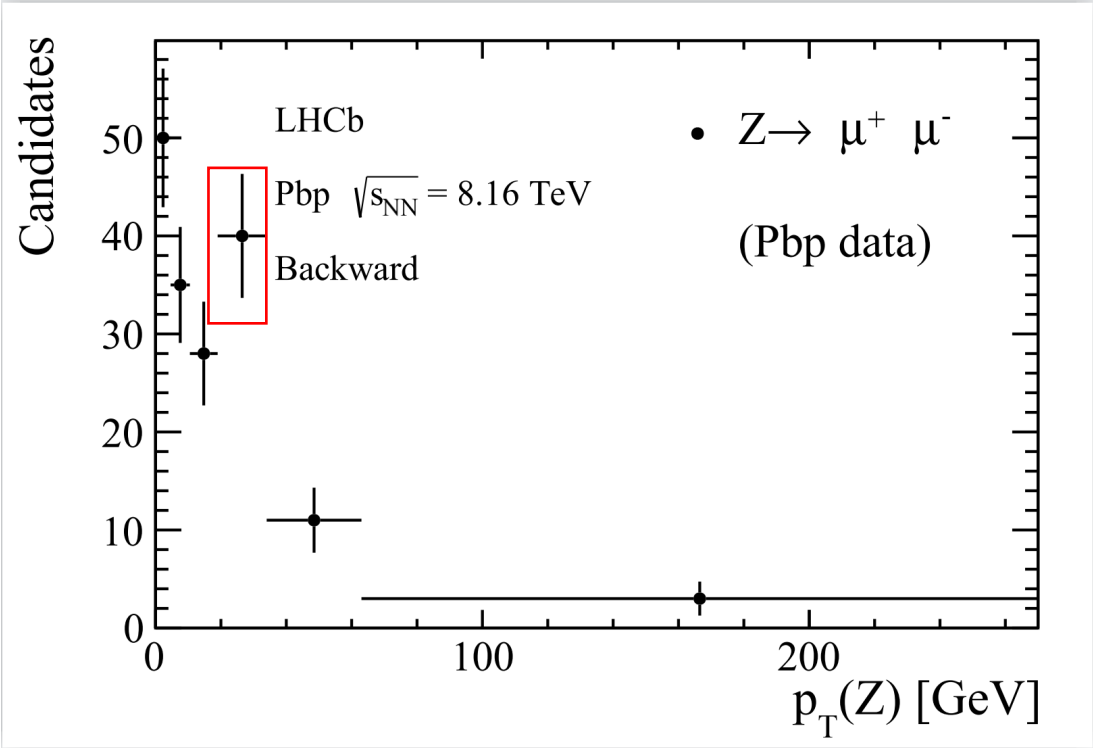


- Significance and p-value results of xsec

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