W and Z cross section measurements at LHCb

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On behalf of the LHCb Collaboration

Weak Interactions and Neutrinos

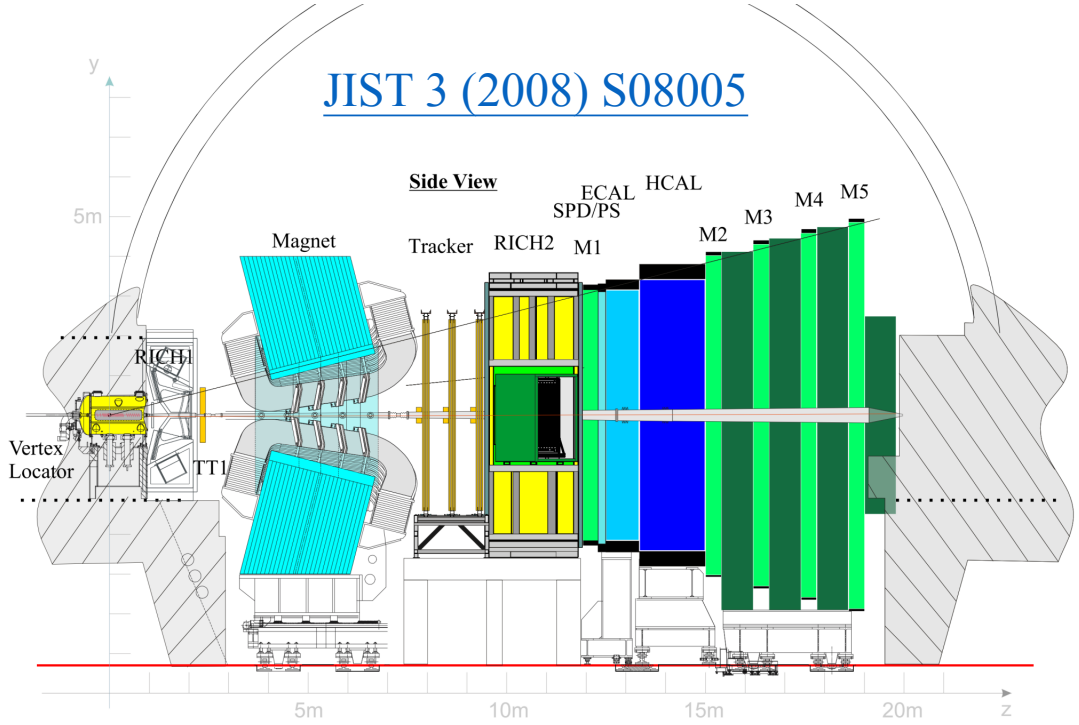
Zhuhai 2023

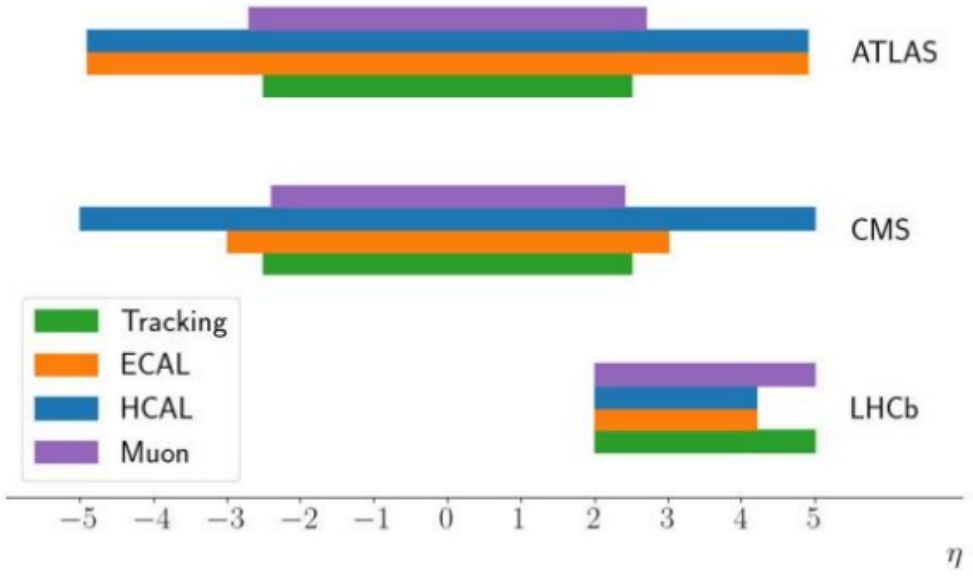
Outline

- LHCb detector
- WZ Cross-section measurement at LHCb
  - $Z \rightarrow \mu\mu$ Cross-Section at 13 TeV
  - $Z \rightarrow \mu\mu$ Cross-Section at 5.02 TeV
  - Z angular coefficient
  - Progress in W Cross-Section
- Summary and outlook

LHCb detector

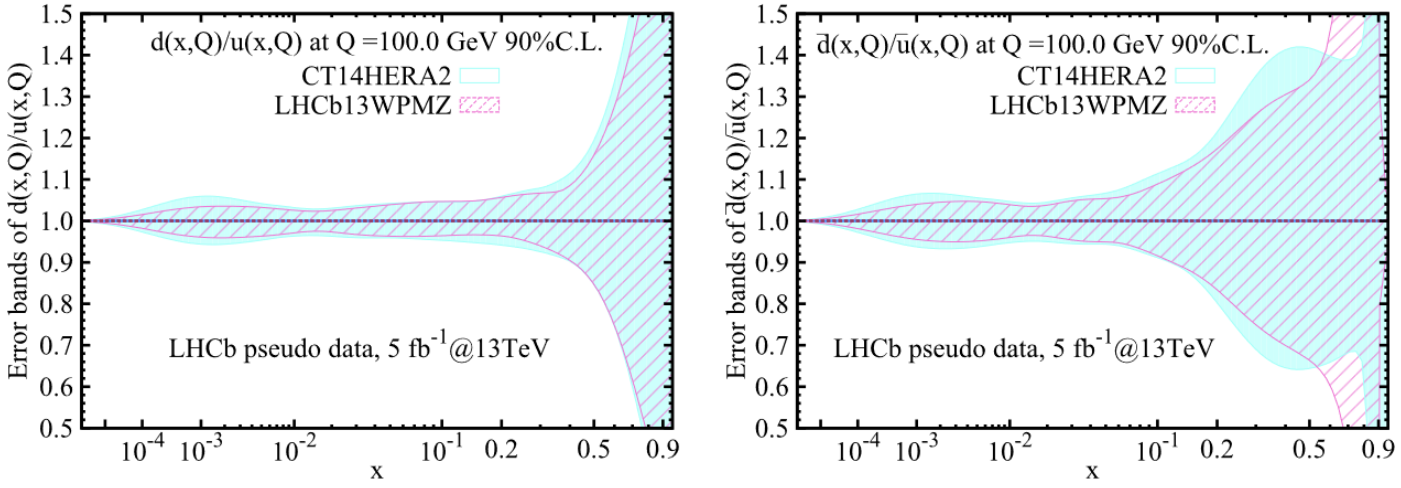
- LHCb detector: Single-arm forward spectrometer
  - Cover the pseudorapidity range $2 < \eta < 5$
- Designed for the heavy quark physics, but extended into the EW physics
  - Unique coverage compare with ATLAS and CMS
  - Perfect performance of tracking and muon detector



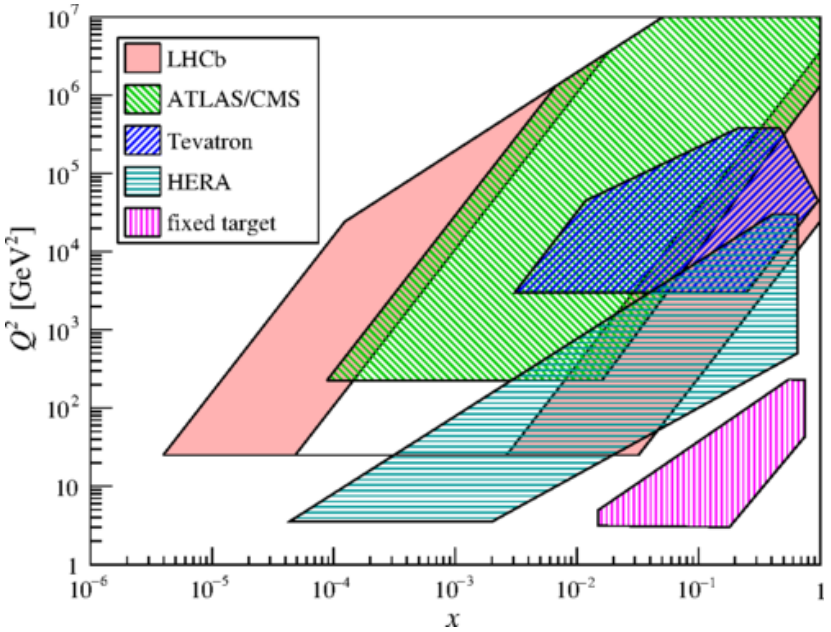


WZ Cross-section measurement at LHCb

- The LHCb data is sensitive to the PDFs (Parton Distribution Functions) at very low Bjorken-x region
  - Provide unique information for the PDFs fit, complementary to ATLAS and CMS results
  - W and Z data have the potential to reduce the PDFs error at high and low x region



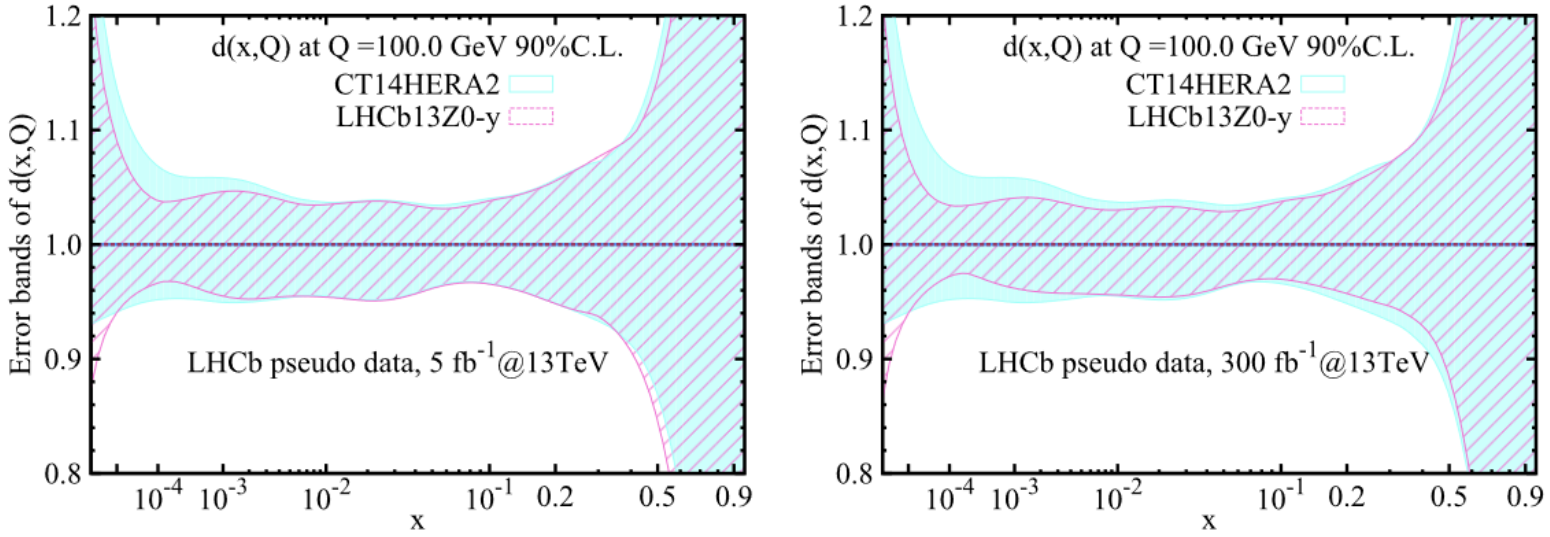
Chinese Phys. C 45 (2021) 023110



Phys. Rev. D 93, 074008 (2016)

Motivation

- Test the QCD and EW sectors of the standard model
- Compare with the different theoretical predictions at higher order
- Improve the constraints on the PDFs, especially u-, d-quark



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Analysis Strategy

- Dataset: LHCb 2016, 2017 and 2018 pp collision data: $5.1 \pm 0.1\ \mathrm{fb}^{-1}$
- Fiducial region: $P_T^{\mu} > 20GeV,\ 2 < \eta_{\mu} < 4.5,\ 60 < M_{\mu^+\mu^-} < 120GeV$

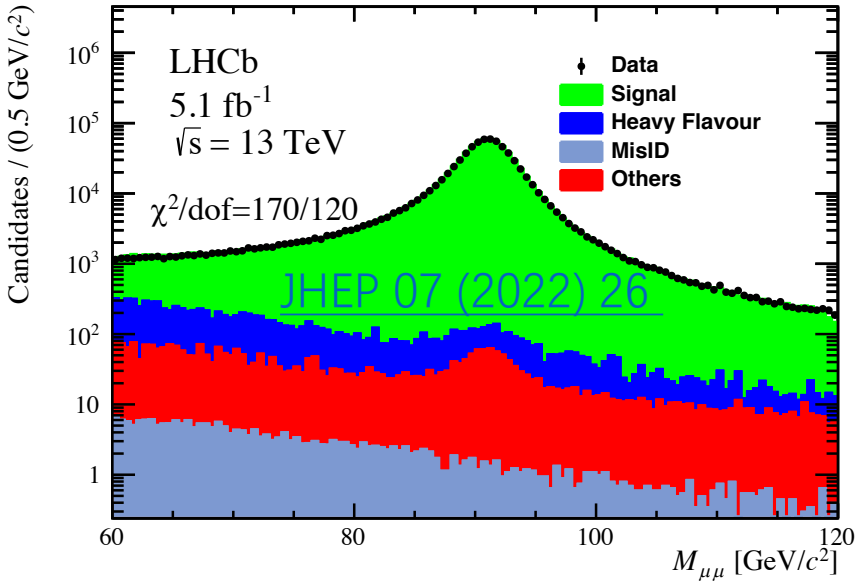
➢ Differential cross-section of y^Z:

Signal yield after background subtraction

FSR correction factor

$$\frac{d\sigma_{Z\to\mu^+\mu^-}}{dy}(i) = \frac{N_Z(i)\cdot f^Z_{FSR}(i)}{\mathcal{L}\cdot \varepsilon^Z_{REC}(i)\cdot \Delta y(i)},$$

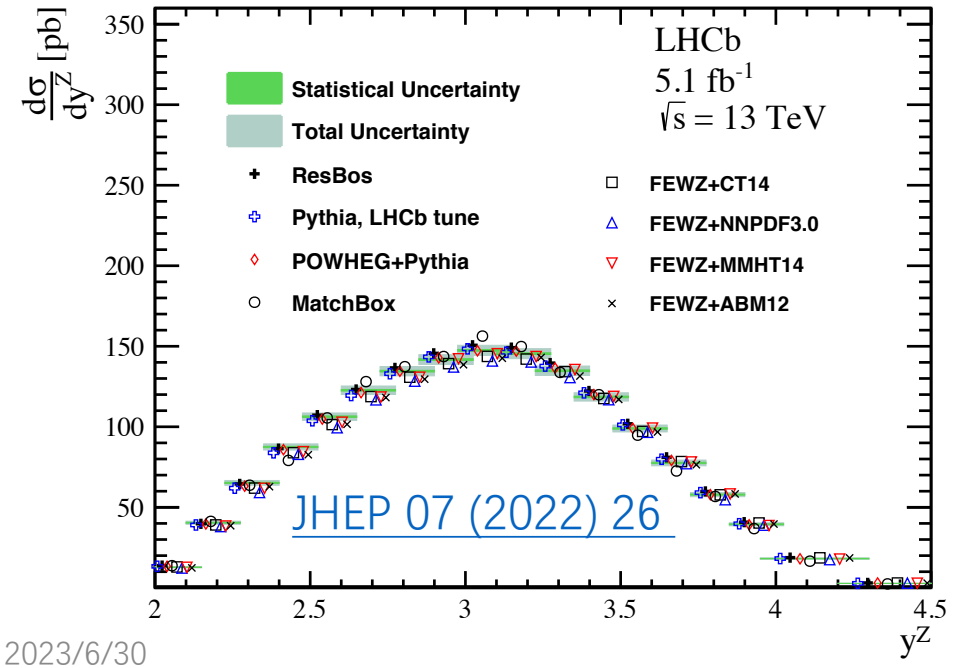
Reconstructed efficiency of Z

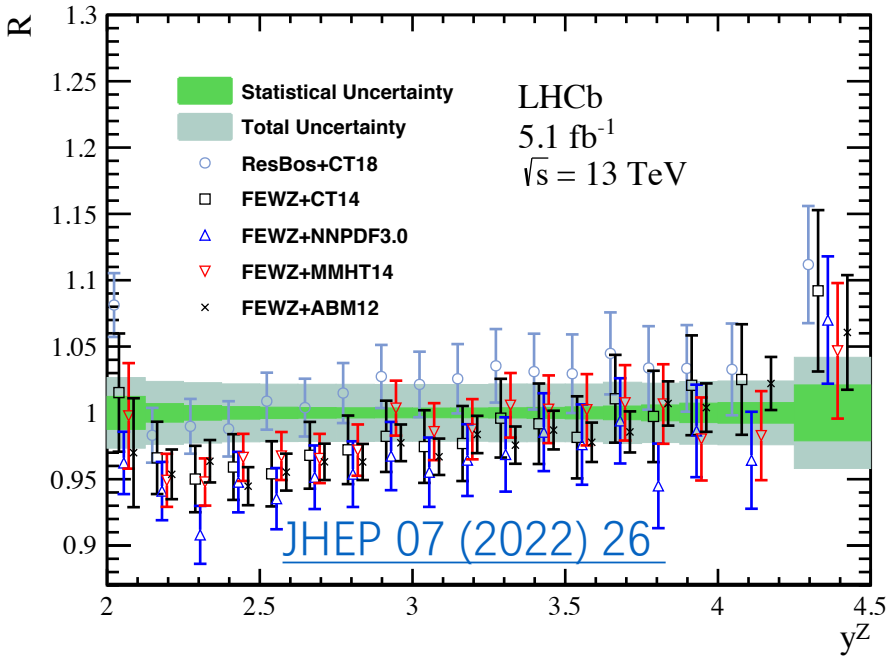


Very high purity: $\frac{N_{bkg}}{N_{sig}} \sim 1.5\%$

Differential Cross-Section – y^Z

- Different theoretical predictions are compared with the measurements
- Calculated the ratio of theoretical predictions to measured values
  - Good agreement between data and predictions
  - In the lower y^Z region, the FEWZ predictions are systematically smaller than the measured results





Differential Cross-Section – Z-p_T and ϕ_η^*

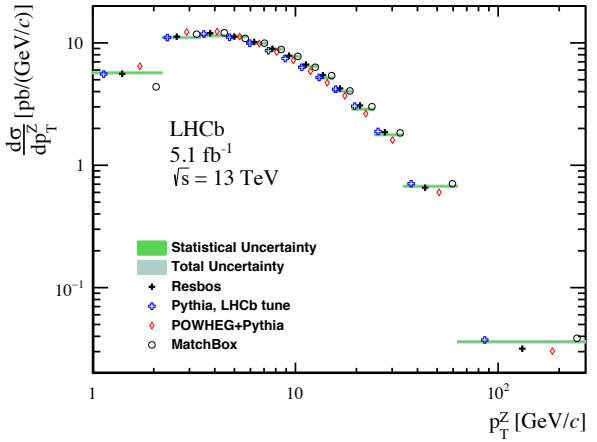
- ϕ_η^*: An angular observable which has better resolution than p_T^Z

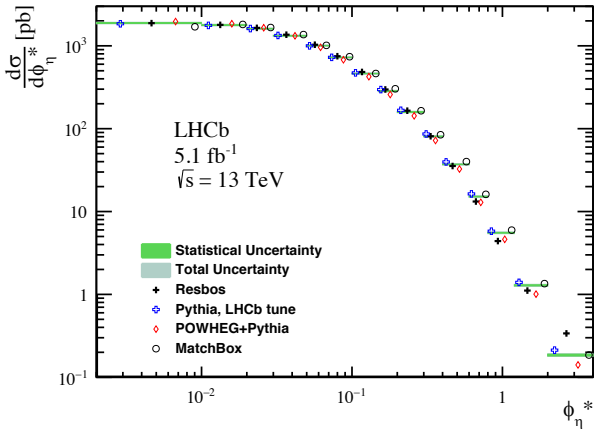
The complementary angle between the two muon

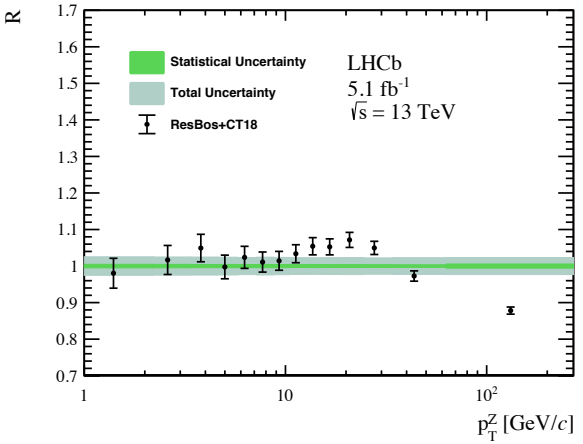
$$\Phi_\eta^* = \frac{\tan(\phi_{acop}/2)}{\cosh(\Delta\eta/2)} \approx \frac{p_T}{M}$$

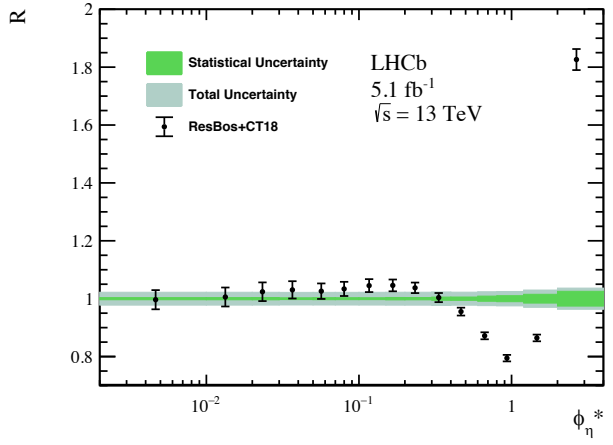
The difference in pseudorapidity between the two muons.

- In the large $p_T^Z(\phi_\eta^*)$ region, RESBOS predictions are in disagreement with data
  - Mainly because the RESBOS only calculate the NLO fixed-order at larger $p_T^Z(\phi_\eta^*)$ region









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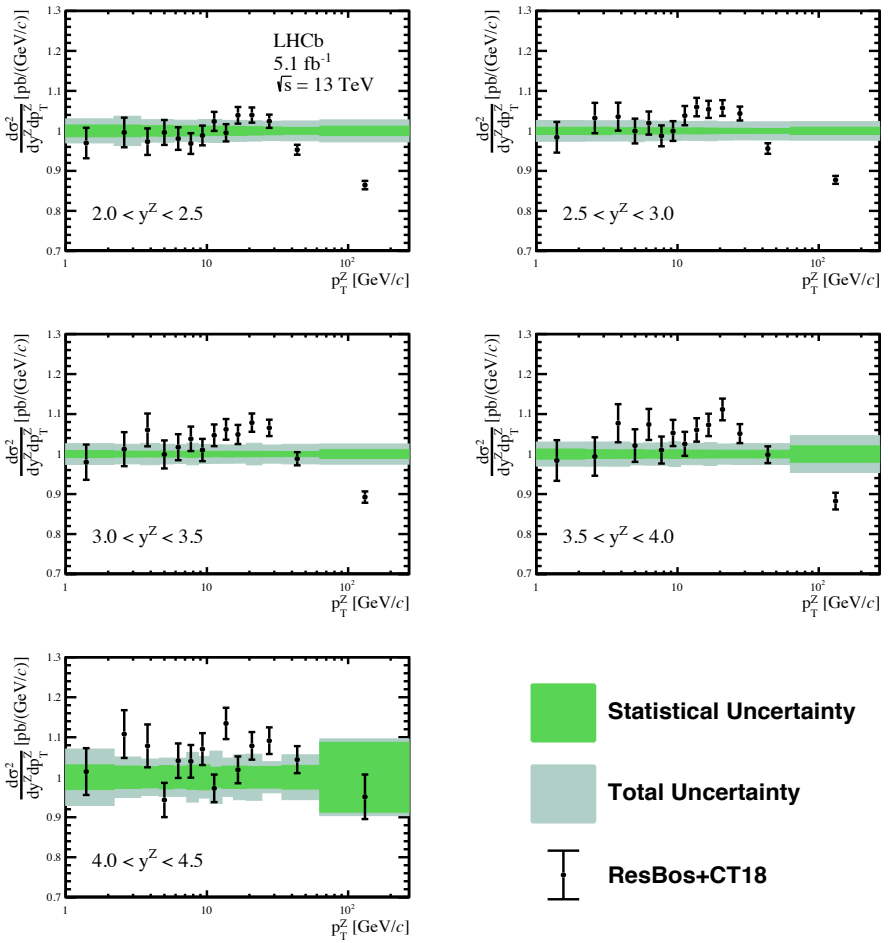
Double Differential Cross-Section – Z-p_T and y^Z

- Double Differential Cross-Section compared with the RESBOS predictions
  - Tensions are seen at larger $p_T^Z(\phi_\eta^*)$ region



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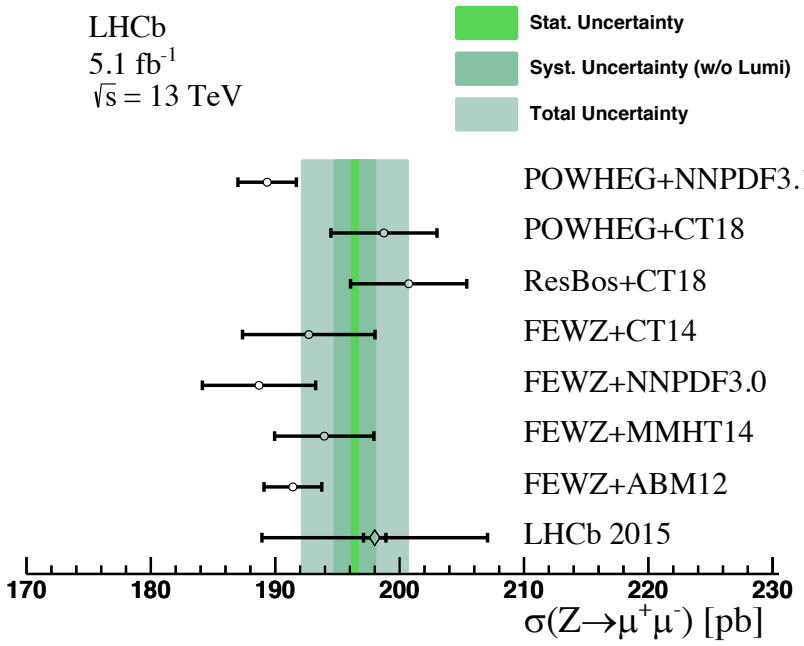
Integrated Cross-Section

- In the forward region, the most precise measurement at 13 TeV:

$$\sigma(Z \to \mu^+\mu^-) = 196.4 \pm 0.2(stat.) \pm 1.6(sys.) \pm 3.9(lumi.)\, pb$$



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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

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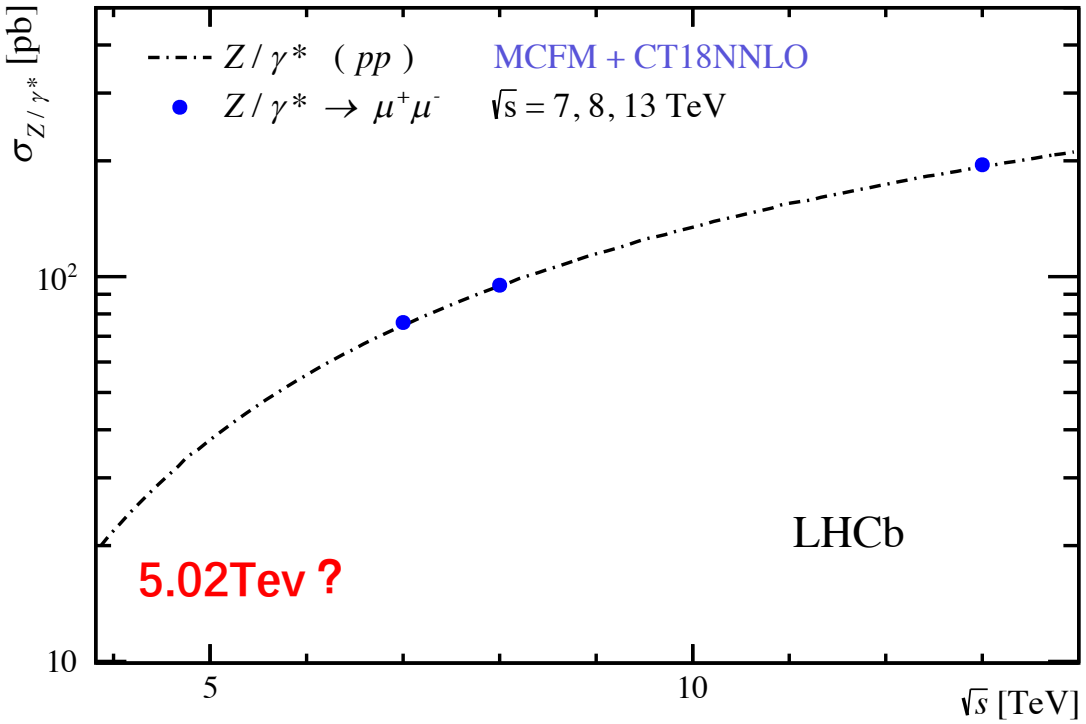
Motivation and Strategy

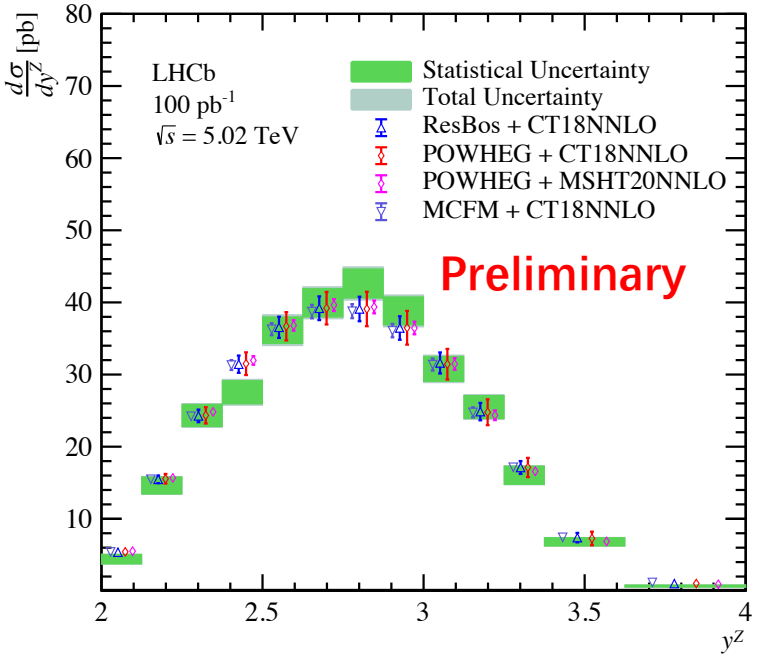
- A following up analysis at $\sqrt{s}$ =5.02 TeV
- Dataset: LHCb 2017 pp collider data: 99.86 pb^{-1}
- Fiducial region: Same as 13 TeV

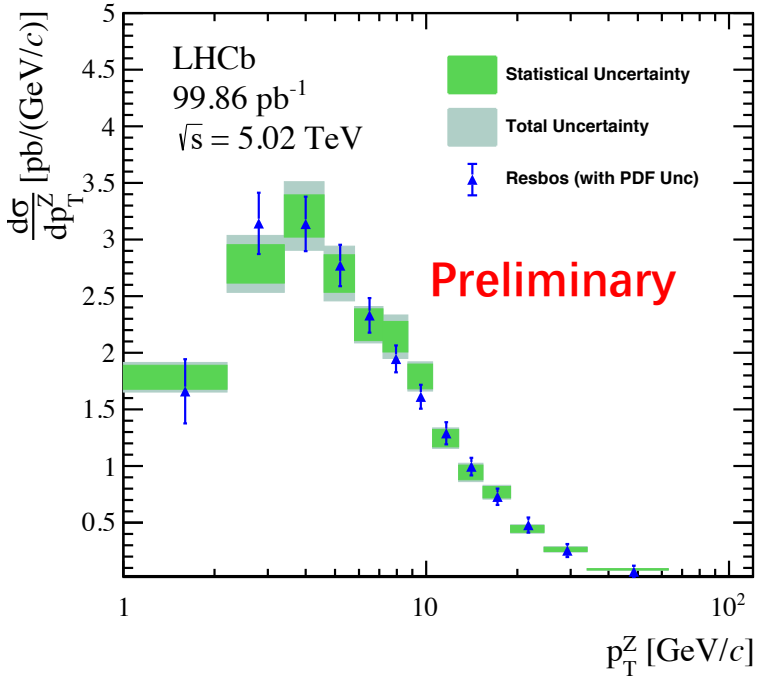


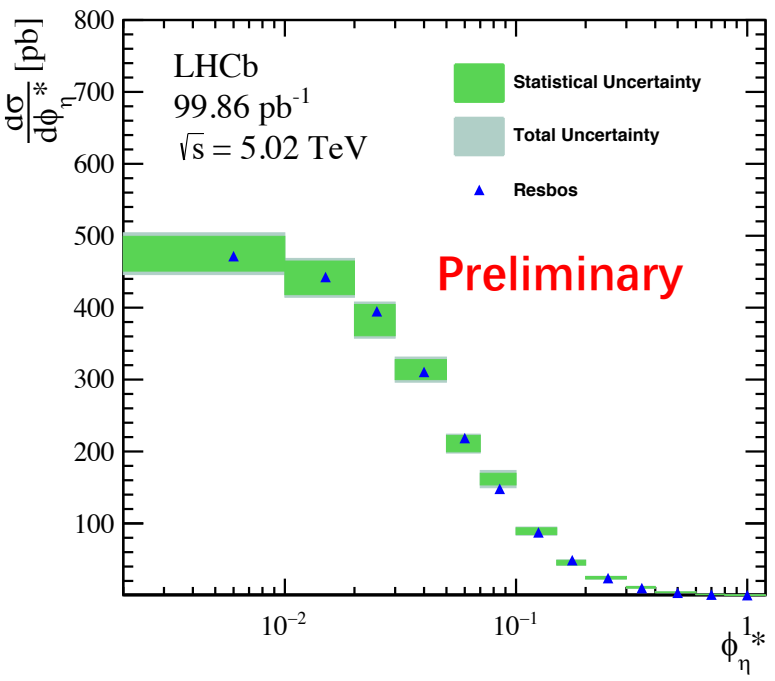
$Z \to \mu\mu$ Cross-Section at 5.02 TeV

Differential Cross-Section – y^Z, Z-p_T and ϕ^*_η

- Reasonable agreement with the different theoretical predictions







LHCB-PAPER-2023-010 in preparation

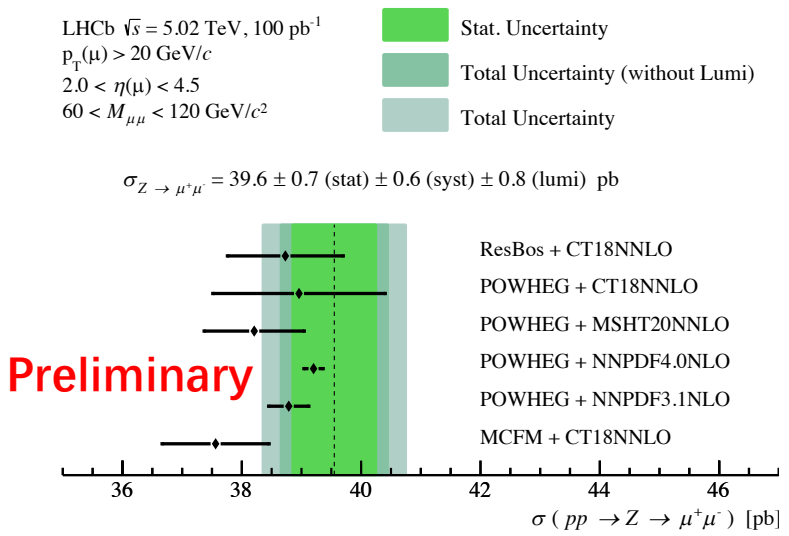
Integrated Cross-Section

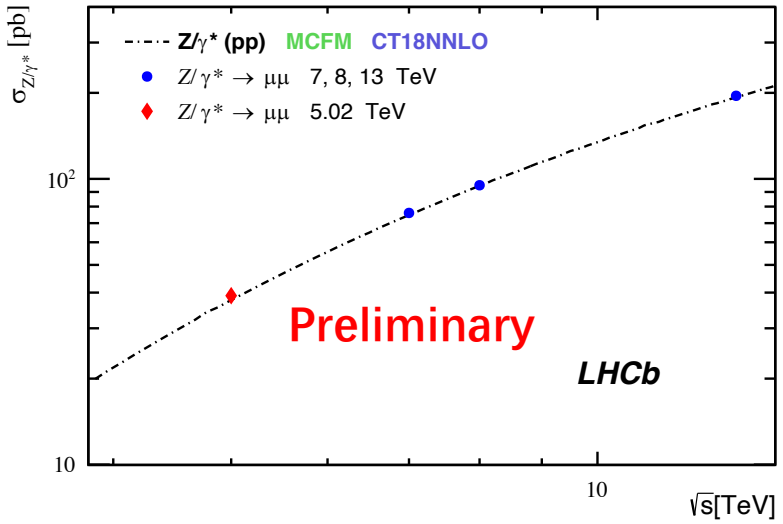
- In fiducial region, using 2017 pp collision data at 5.02 TeV:

$$\sigma(Z \to \mu^+\mu^-) = 39.6 \pm 0.7(stat.) \pm 0.6(sys.) \pm 0.8(lumi.)\, pb$$

Source	$\Delta\sigma/\sigma$ [%]
Statistical	1.77
Background	0.48
Calibration	0.01
Tracking	1.01
Identification	0.25
Trigger	0.54
Efficiency Closure	0.61
FSR	0.18
Total Systematic (excl. lumi.)	1.42
Luminosity	2.00

Preliminary



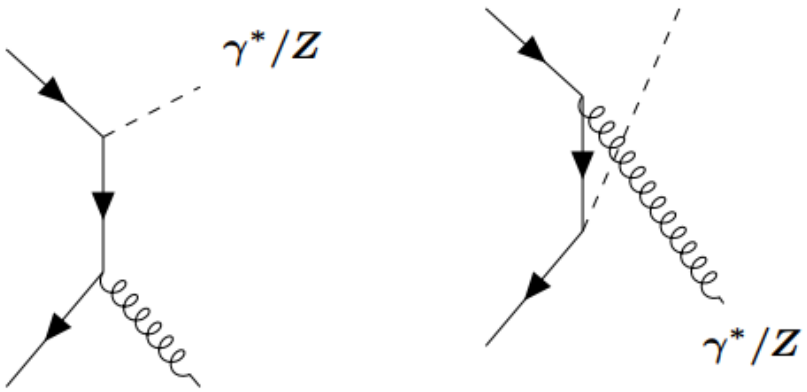


LHCB-PAPER-2023-010 in preparation

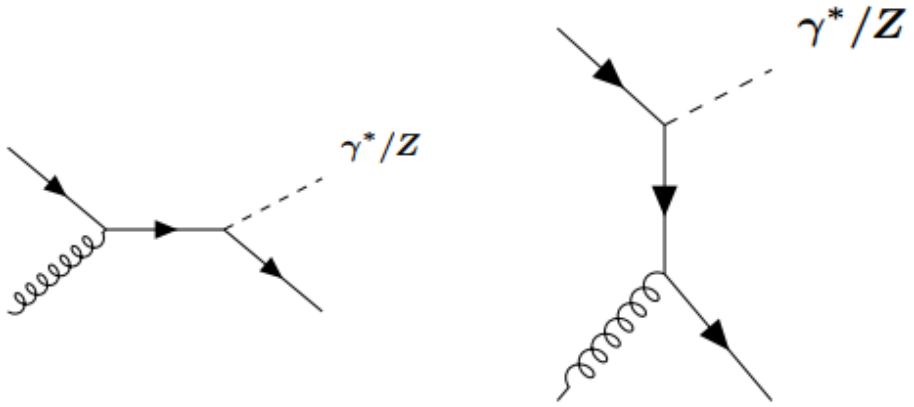
Z angular coefficient

Motivation

- Provide important information for the tests EW parameters, proton structure and QCD production
- Provide a direct probe of the polarization of the intermediate gauge boson, which is in turn sensitive to the underlying QCD production mechanisms.



Annihilation diagram

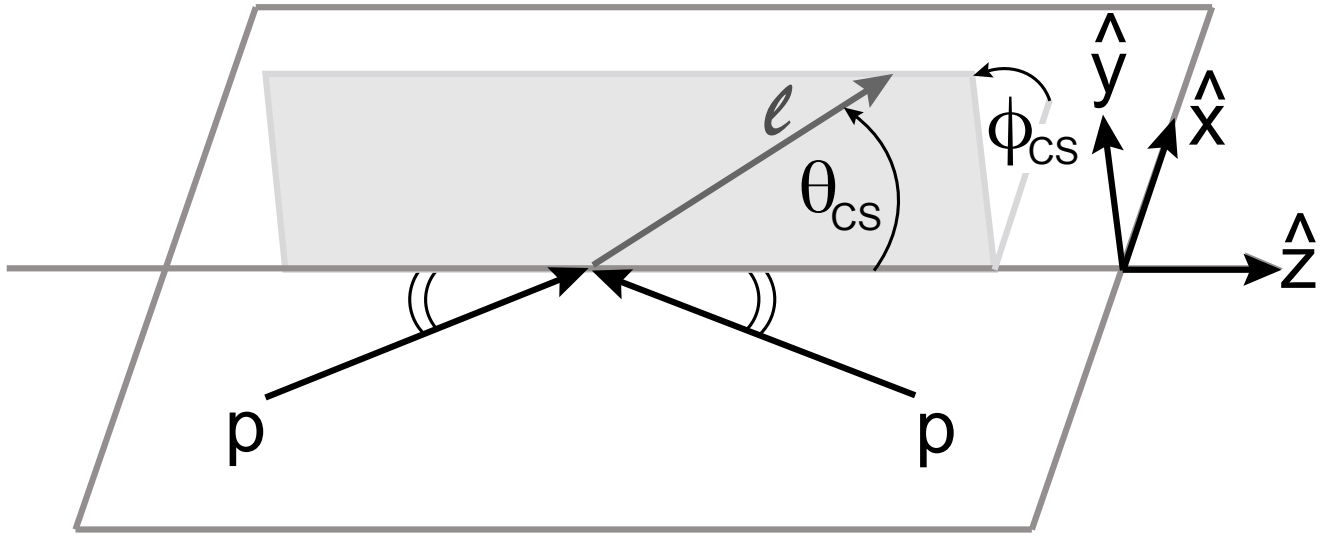


Compton diagram

Z angular coefficient

Introduction

- Collins-Soper frame: the center of dimuon mass frame
  - Z-axis: The bisector of angle between the two particles p direction
  - θ_{CS}: The angle between final state lepton ℓ and Z-axis
  - ϕ_{CS}: The angle between the lepton plane (grey) and incident hardon (white)



Z angular coefficient

Introduction

- The differential cross-section of angle θ_{CS} and ϕ_{CS} in CS frame
  - A_1: The difference in the probability of emission of gluons by low and high x parton
  - A_2: Sensitive to the Boer-Mulders transverse momentum dependent (TMD) PDFs
  - A_4: Related to the parity violation in the weak interaction ~ A_{fb}
  - $A_5 - A_7$: Expected to be zero
  - Lam-Tung relation: $A_0 = A_2$

$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta) \rightarrow \text{LO term}$$

$$+ \frac{1}{2}A_0(1-3\cos^2\theta) \rightarrow \cos^2\theta : \text{higher order term}$$

$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi \rightarrow (\theta, \phi) \text{ terms}$$

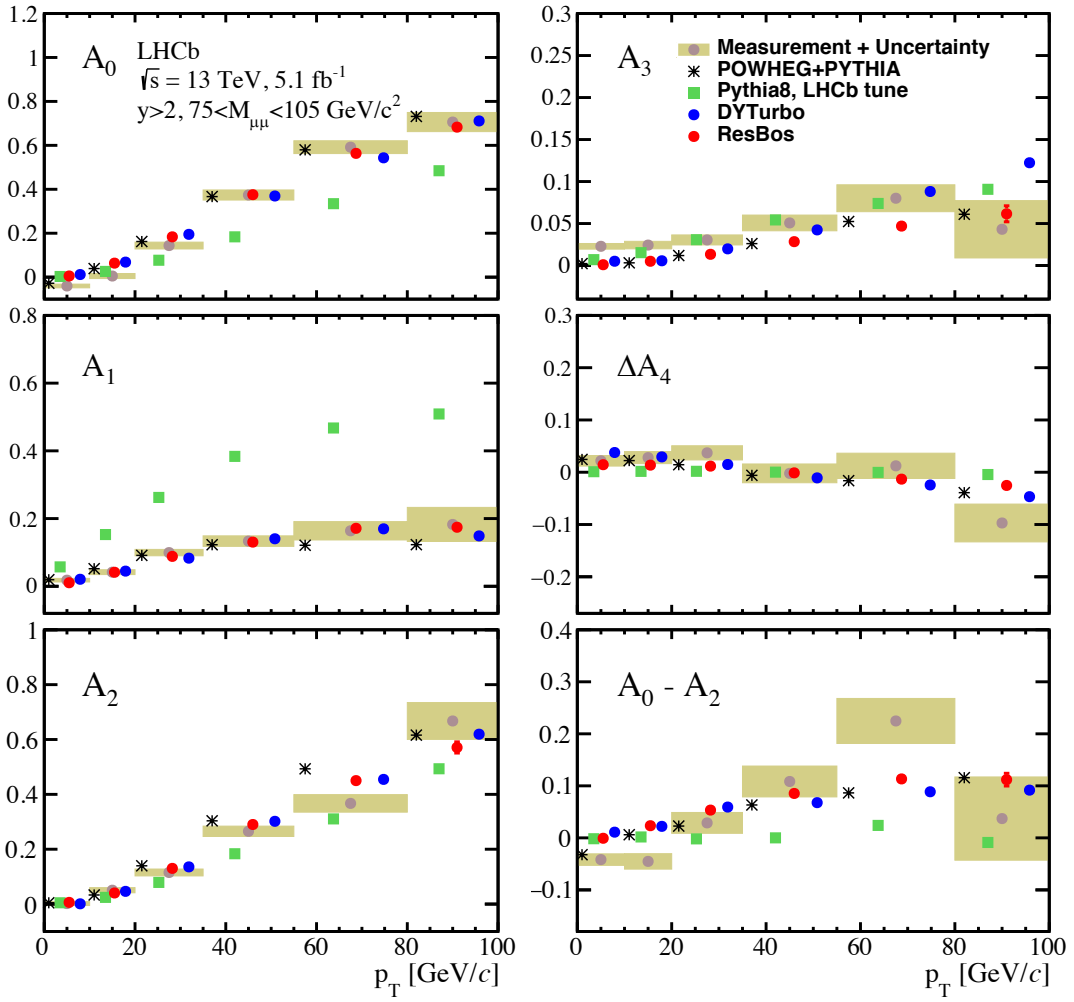
$$+ A_4 \cos\theta \rightarrow \text{LO term : determine } A_{fb}$$

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \rightarrow \text{very small terms}$$

Z angular coefficient

p_T dependent results

- Measured A_i coefficients are corrected to the Born level
  - A_0, A_1
    - Disagreement with PYTHIA 8 predictions(Show similar increasing trends)
  - ΔA_4: The difference with respect to its mean value
    - Good agreement with other predictions
  - A_0-A_2: Investigate the violation of the Lam-Tung relations
    - Not compatible with zero in all p_T region except the last bin



PRL 129 (2022) 091801

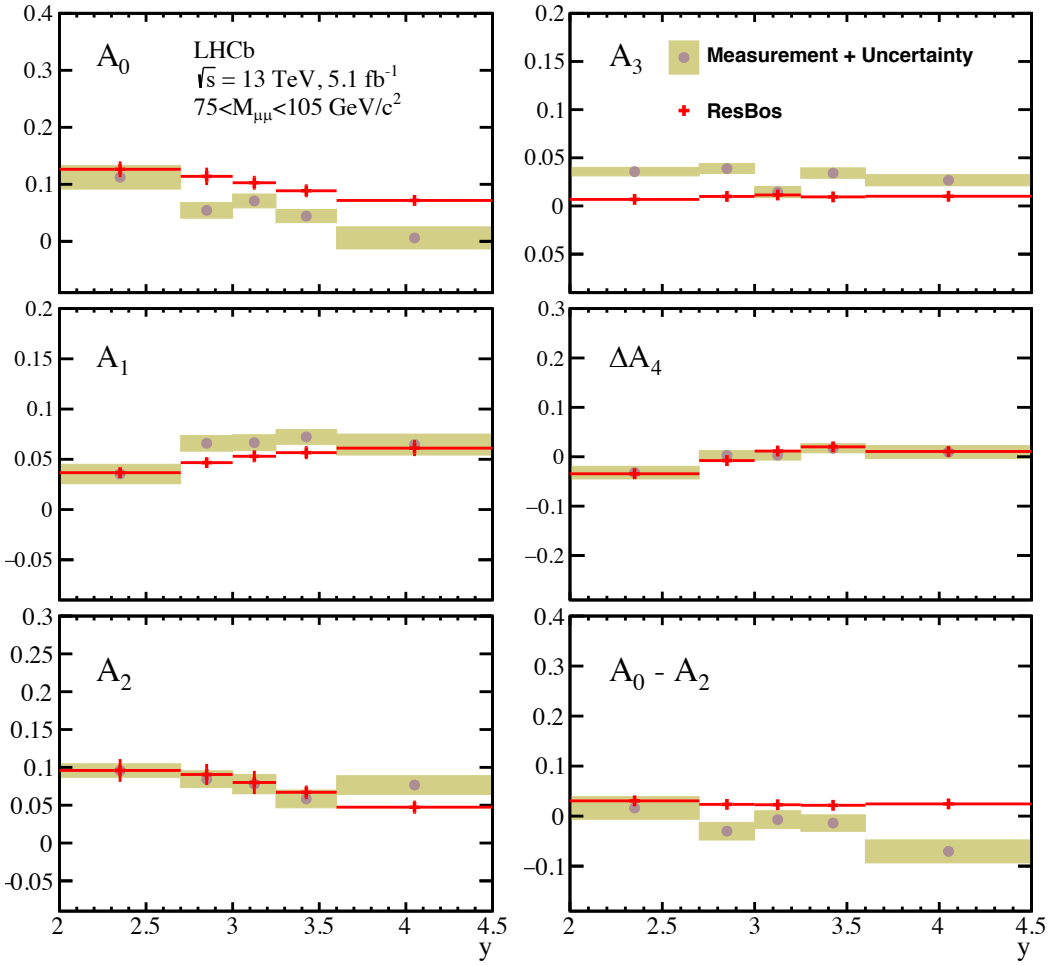
Z angular coefficient

y dependent results

- Provide important information for the resummation
  - The QCD effects in the Z boson P_T have been integrated

- The measured result do not have significant dependences as a function of y^Z except A_0
  - A_0, A_0-A_2
    - Tensions are seen especially in high rapidity region

  - ΔA_4: The difference with respect to its mean value
    - Good agreement with other predictions

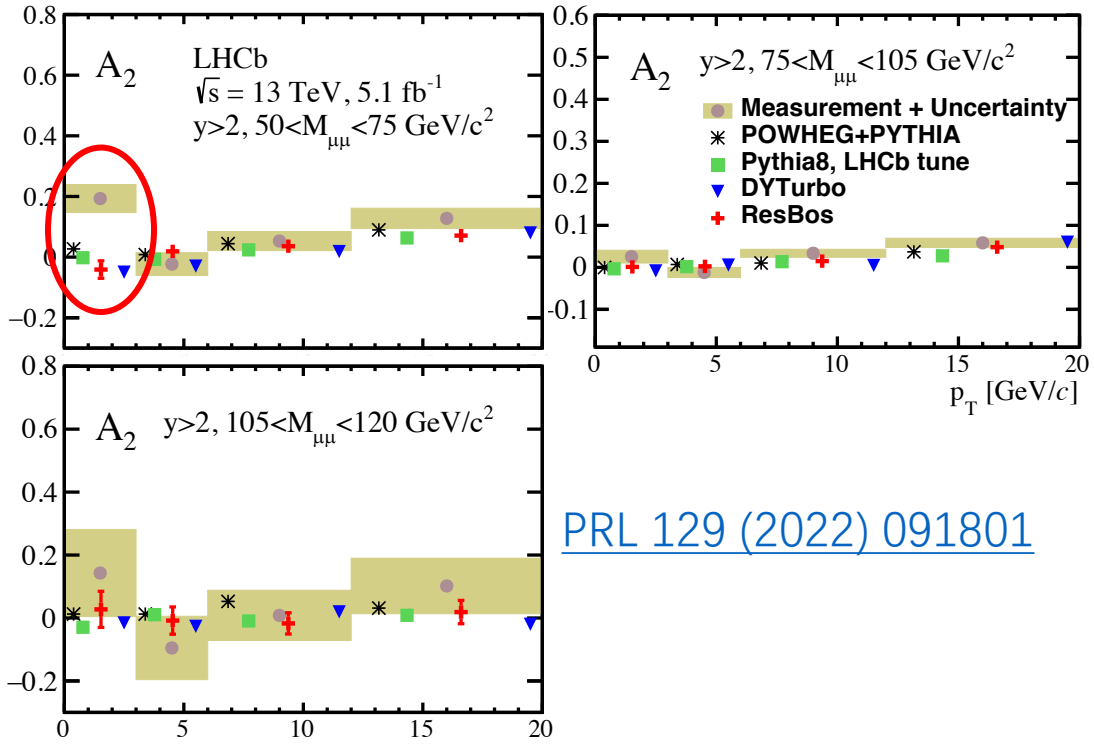


PRL 129 (2022) 091801

Z angular coefficient

A_2 in low p_T region

- In the low p_T region, the nonperturbative TMD PDFs can be probed though A_2
- Deviation has seen in low mass and low p_T (p_T <3GeV/c) region
- None of the prediction include nonperturbative spin-momentum correlations

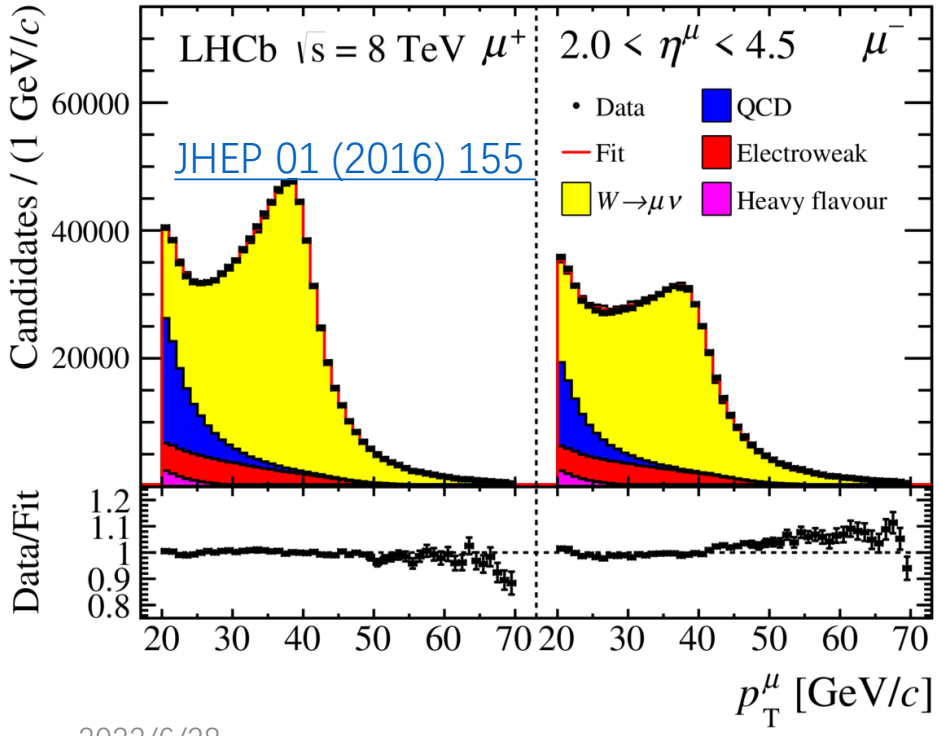


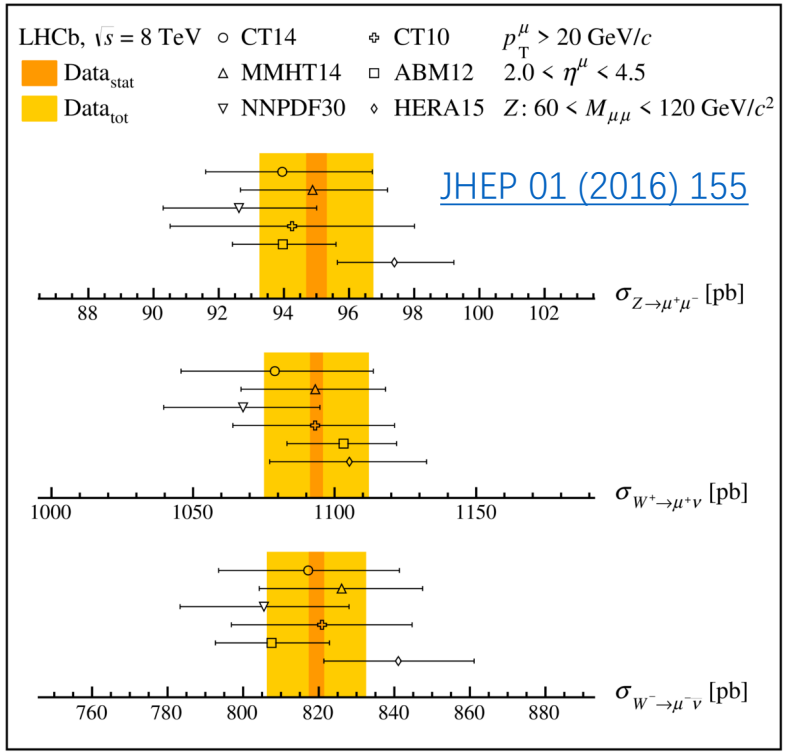
PRL 129 (2022) 091801

W and Z Cross-Section at 8 TeV

- In fiducial region, the inclusive W and Z cross-section at 8 TeV:

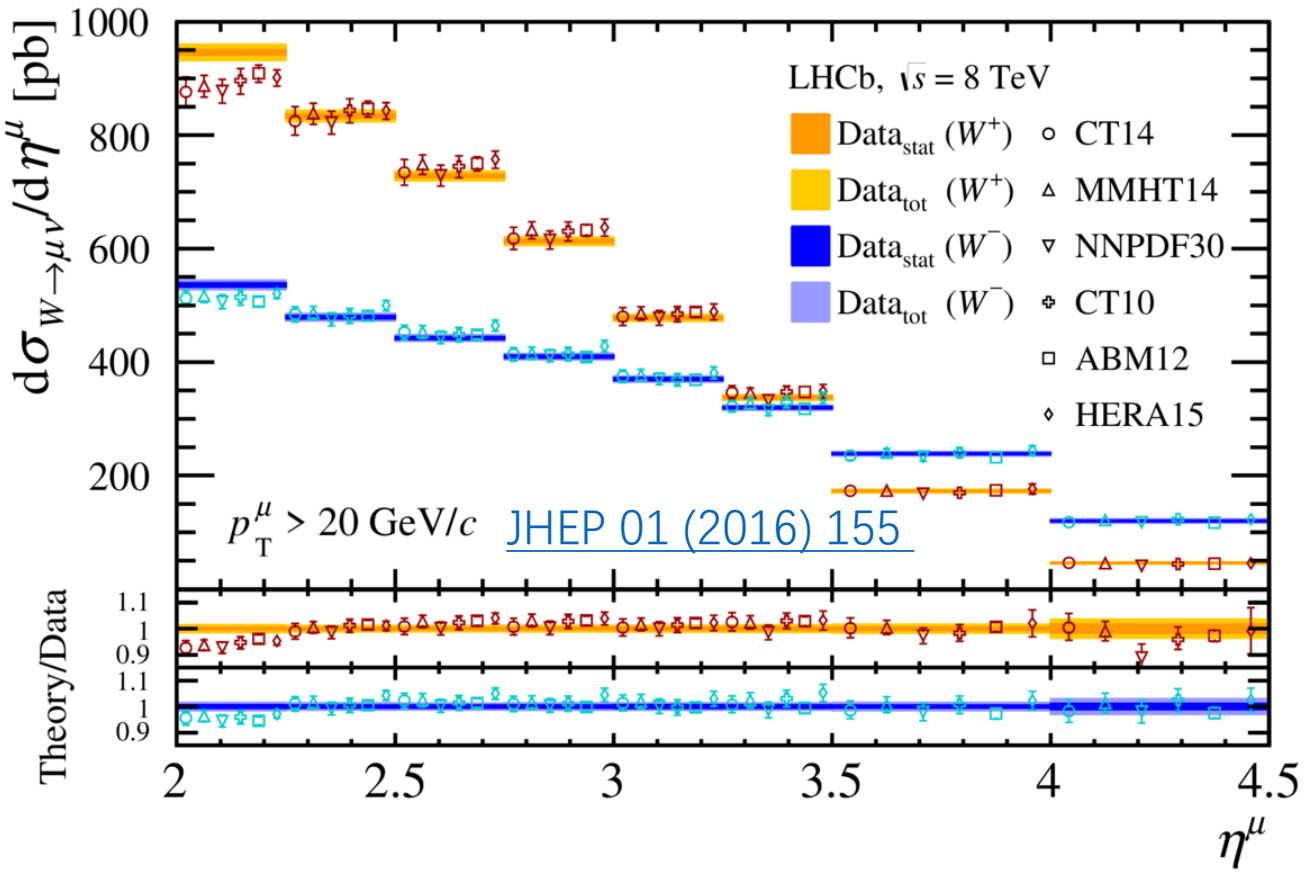
$$\sigma(W^+ \to \mu^+\nu) = 1093.6 \pm 2.1(stat.) \pm 7.2(sys.) \pm 10.9(beam) \pm 12.7(lumi.)\ pb$$
$$\sigma(W^- \to \mu^-\nu) = 818.4 \pm 1.9(stat.) \pm 5.0(sys.) \pm 7.0(beam) \pm 9.5(lumi.)\ pb$$
$$\sigma(Z \to \mu^+\mu^-) = 95.0 \pm 0.3(stat.) \pm 0.7(sys.) \pm 1.1(beam) \pm 3.9(lumi.)\ pb$$





W and Z Cross-Section at 8 TeV

- W^+ and W^- cross-sections compare with NNLO predictions in bins of η^μ
  - In agreement with NNLO calculations



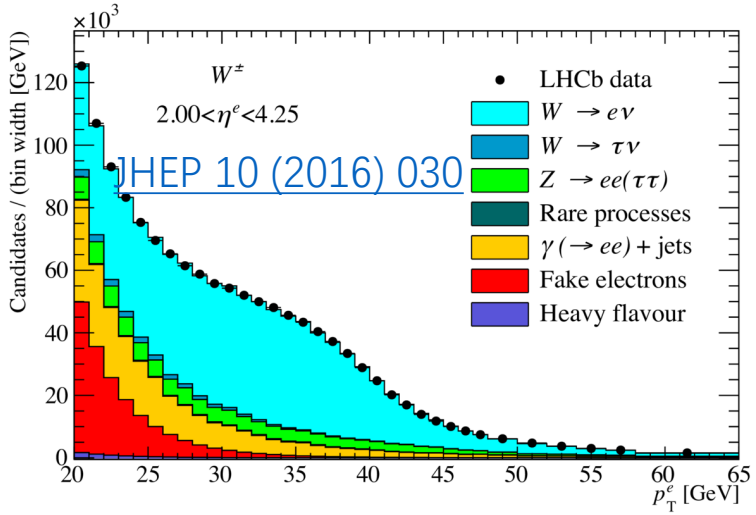
Progress in W Cross-Section

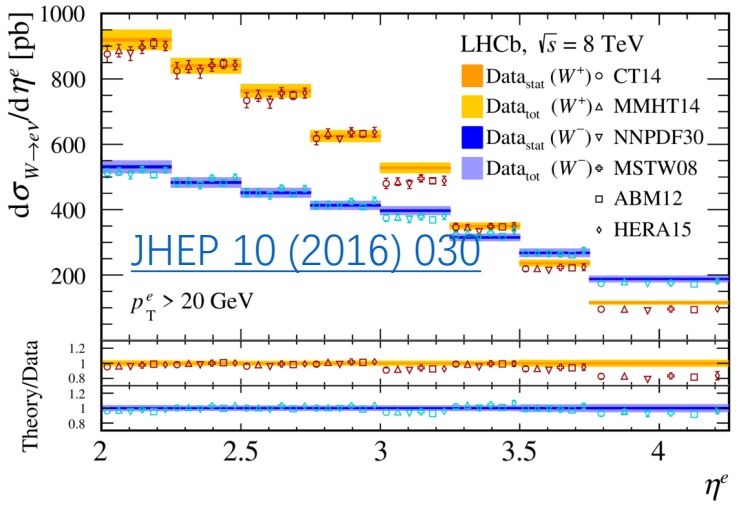
W → eν Cross-Section at 8 TeV

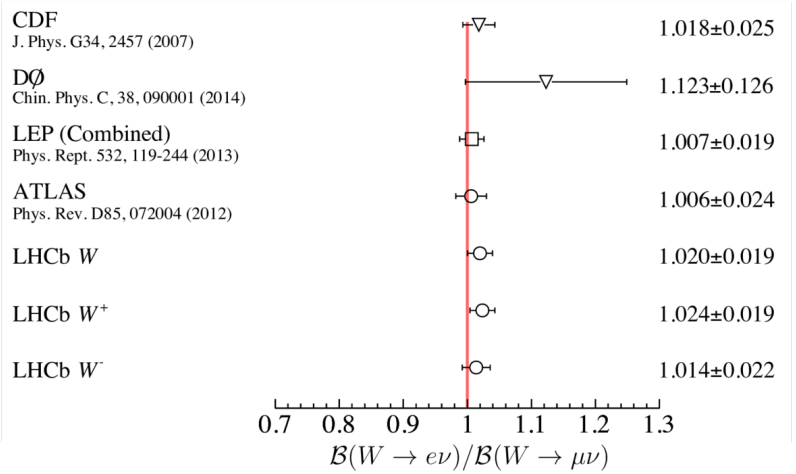
- Template fits to the p_T distribution are performed in the range $20 < p_T^e < 65$ GeV
- The first measurement of **W → eν** production in forward region :

$$\sigma(W^+ \to e^+\nu_e) = 1124.4 \pm 2.1(stat.) \pm 21.5(sys.) \pm 11.2(beam) \pm 13.0(lumi.)\, pb$$
$$\sigma(W^- \to e^-\nu_e) = 809.0 \pm 1.9(stat.) \pm 18.1(sys.) \pm 7.0(beam) \pm 9.4(lumi.)\, pb$$

- The ratio of branching fractions is compared to hadron collider, LEP and theory (red line)







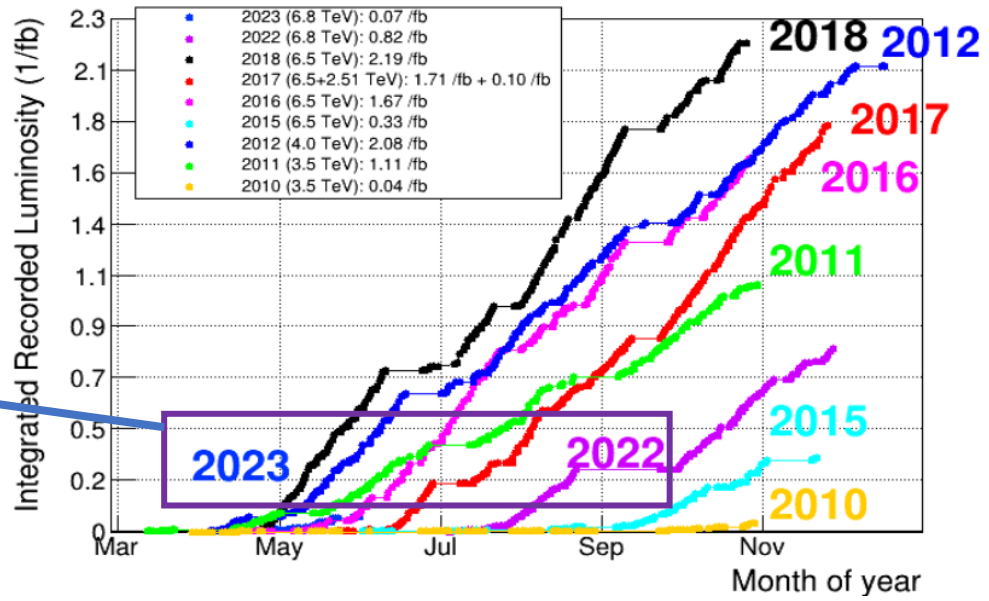
The following 13 TeV is ongoing now

JHEP 10 (2016) 030

Summary and outlook

- LHCb has an extensive program for EW precision measurements
- Latest W and Z production cross-section measurements are reported
  - Most precise measurement of Z production in forward region
  - The first measurement of $Z \to \mu^+\mu^-$ angular coefficients in forward region
  - The measurement of W production at 8 TeV
- In the future, with huge luminosity at Run 3 data, LHCb will perform more analyses on W and Z productions

Run 3 data taking

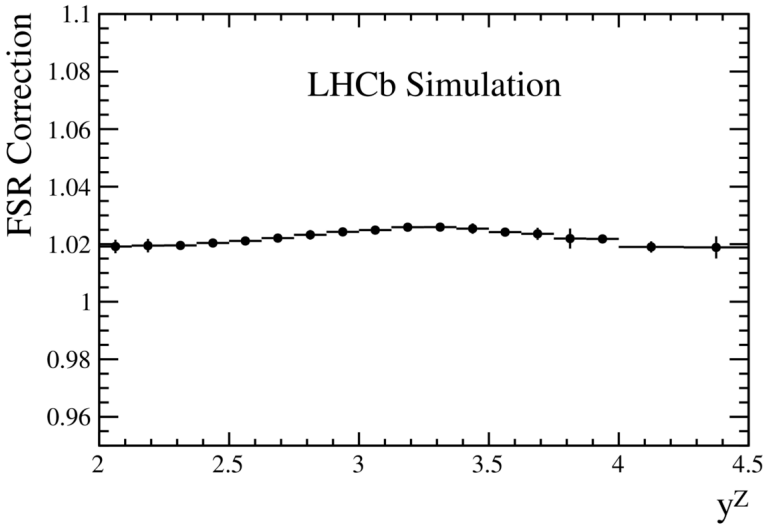


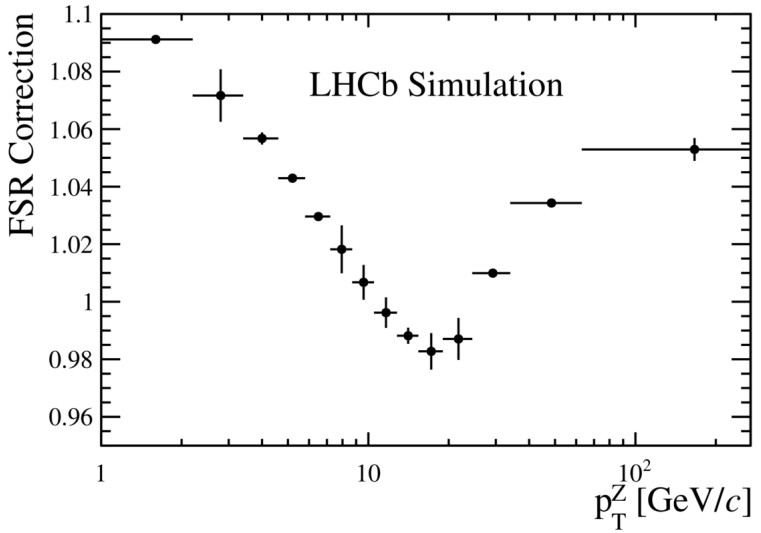
Thank you for attention !

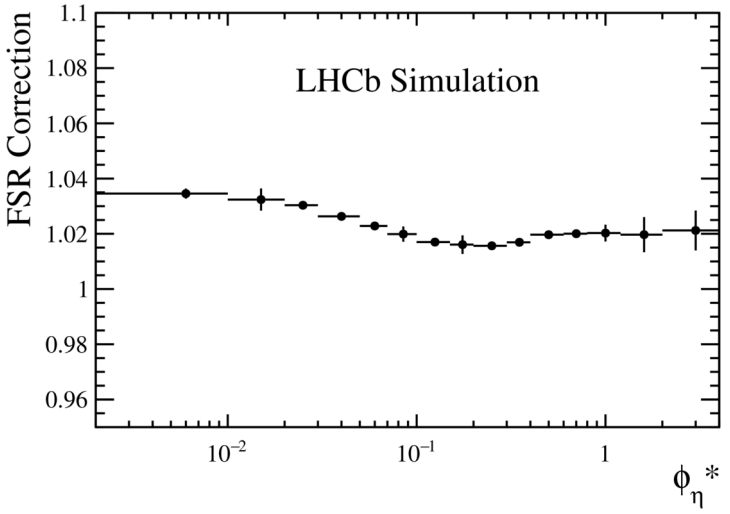
Back up

Z Cross-section -FSR

- In order to compare with theoretical predictions, the measured cross- section must be corrected to Born level (evaluated with ResBos┼Photos)







Z Angular coefficient -Uncertainty

	$y^Z \in [2, 2.7]$						$y^Z \in [2.7, 3]$					
Coefficient	A_0	A_1	A_2	A_3	ΔA_4	$A_0 - A2$	A_0	A_1	A_2	A_3	ΔA_4	$A_0 - A2$
Total	0.1124	0.0354	0.0958	0.0357	-0.0321	0.0162	0.0543	0.0659	0.0843	0.0388	0.0026	-0.0302
Stat	0.0180	0.0085	0.0078	0.0039	0.0103	0.0197	0.0119	0.0067	0.0096	0.0046	0.0077	0.0153
Syst	0.0102	0.0046	0.0044	0.0022	0.0062	0.0112	0.0068	0.0038	0.0055	0.0024	0.0041	0.0088
MC Stat	0.0102	0.0044	0.0043	0.0022	0.0062	0.0111	0.0067	0.0035	0.0054	0.0024	0.0041	0.0086
FSR	0.0006	0.0013	0.0004	0.0001	0.0001	0.0007	0.0006	0.0013	0.0005	0.0002	-	0.0008
Eff	0.0005	0.0002	0.0001	-	-	0.0005	0.0002	-	-	-	-	0.0002
Bkg	0.0003	-	0.0001	-	-	0.0003	0.0001	-	-	-	-	0.0001
Smear	-	-	-	-	-	-	-	-	-	-	-	-
PDF	0.0001	0.0003	0.0004	0.0001	0.0004	0.0004	0.0007	0.0010	0.0011	0.0003	0.0004	0.0017
Extraction	0.0011	0.0002	0.0004	-	0.0004	0.0012	0.0006	0.0001	0.0003	0.0001	0.0003	0.0007
	$y^Z \in [3, 3.25]$						$y^Z \in [3.25, 3.6]$					
Coefficient	A_0	A_1	A_2	A_3	ΔA_4	$A_0 - A2$	A_0	A_1	A_2	A_3	ΔA_4	$A_0 - A2$
Total	0.0708	0.0665	0.0778	0.0144	0.0029	-0.0070	0.0443	0.0723	0.0583	0.0341	0.0171	-0.0139
Stat	0.0107	0.0068	0.0110	0.0051	0.0075	0.0154	0.0102	0.0065	0.0102	0.0047	0.0072	0.0145
Syst	0.0058	0.0039	0.0064	0.0028	0.0040	0.0087	0.0053	0.0036	0.0059	0.0026	0.0037	0.0078
MC Stat	0.0057	0.0036	0.0063	0.0027	0.0040	0.0085	0.0052	0.0031	0.0057	0.0026	0.0037	0.0077
FSR	0.0009	0.0015	0.0007	0.0003	-	0.0012	0.0007	0.0015	0.0006	0.0002	-	0.0010
Eff	0.0001	-	0.0001	-	-	0.0002	0.0001	-	-	-	-	0.0002
Bkg	-	-	0.0001	-	-	0.0002	-	-	-	-	-	-
Smear	-	-	-	-	-	-	-	-	-	-	-	-
PDF	0.0005	0.0004	0.0006	0.0006	0.0004	0.0009	0.0006	0.0008	0.0008	0.0004	0.0003	0.0005
Extraction	0.0002	0.0001	0.0007	-	0.0002	0.0007	0.0004	0.0001	0.0006	0.0001	0.0002	0.0007

Z Angular coefficient -Strategy

- Dataset: 2016,2017 and 2018 data
- Selection requirement:

Particle	Selections
Z	50<Mass<150GeV
Z	χ^2_{vtx}/ndf<9
All tracks	$2.0 < \eta < 4.5$
All tracks	$P_T > 20$GeV
All tracks	$\frac{\sigma_p}{p} < 0.1$
All tracks	$\frac{p_T^{\mu}}{p_T^{\mu} + p_T^{\mu-cone}} > 0.85$

W and Z Cross-Section at 8 TeV-Uncertainty

Source	Uncertainty [%]		
	$\sigma_{W^+\to\mu^+\nu}$	$\sigma_{W^-\to\mu^-\bar{\nu}}$	$\sigma_{Z\to\mu^+\mu^-}$
Statistical	0.19	0.23	0.27
Purity	0.28	0.21	0.21
Tracking	0.26	0.24	0.48
Identification	0.11	0.11	0.21
Trigger	0.14	0.13	0.05
GEC	0.40	0.41	0.34
Selection	0.24	0.24	—
Acceptance and FSR	0.16	0.14	0.13
Systematic	0.65	0.61	0.67
Beam energy	1.00	0.86	1.15
Luminosity	1.16	1.16	1.16
Total	1.67	1.59	1.79

W → eν Cross-Section -Uncertainty

Source	Uncertainty [%]		
	$\sigma_{W^+\to e^+\nu_e}$	$\sigma_{W^-\to e^-\overline{\nu}_e}$	$R_{W^\pm}$
Statistical†	0.19	0.24	0.30
Yield (statistical)†	0.28	0.40	0.48
Yield (systematic)	1.42	1.79	0.51
Efficiency (statistical)†	0.55	0.55	0.21
Efficiency (systematic)	1.11	1.14	0.54
FSR corrections†	0.05	0.07	0.09
Acceptance corrections (statistical)†	0.00	0.01	0.01
Acceptance corrections (systematic)	0.15	0.15	0.00
Charge mis-identification†	—	—	0.02
Systematic	1.91	2.23	0.91
Beam energy	1.00	0.86	0.14
Luminosity	1.16	1.16	—
Total	2.46	2.67	0.97