Recent WZ precision measurements in LHCb

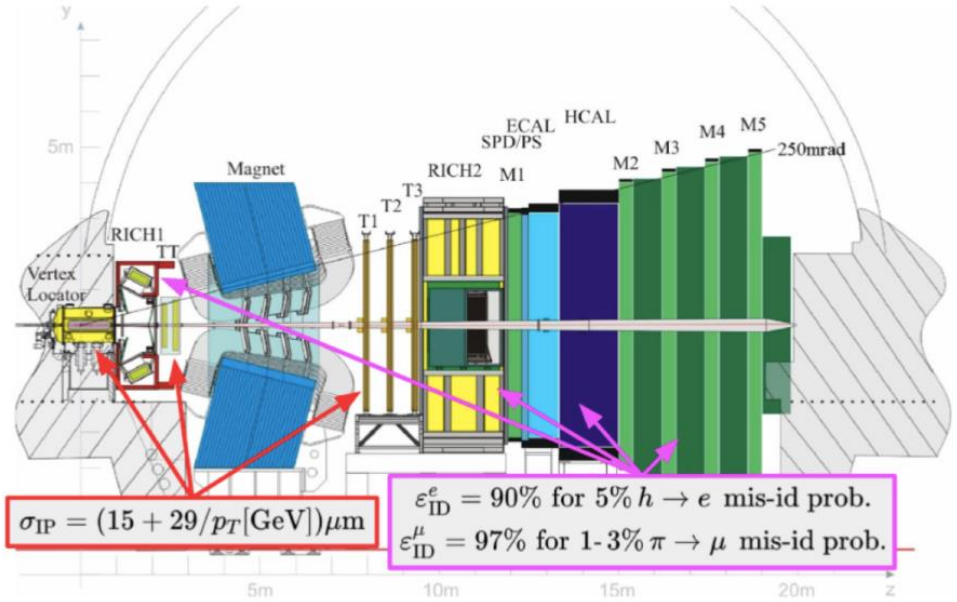
Jianqiao Deng

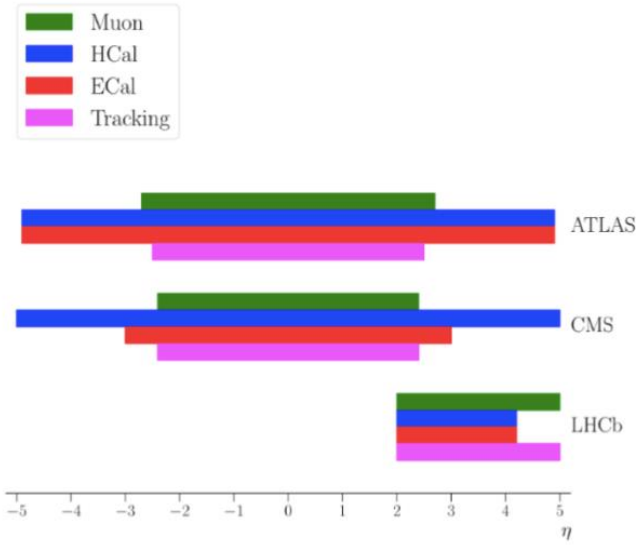
On behalf of the LHCb Collaboration

LHCP 2023.05.26

LHCb detector

- Single-arm forward spectrometer
  - Designed for the heavy flavor physics with $2 < \eta < 5$
  - Coverage is complementary to ATLAS and CMS
  - Extended to EW measurements: excellent performance of tracking and muon detector

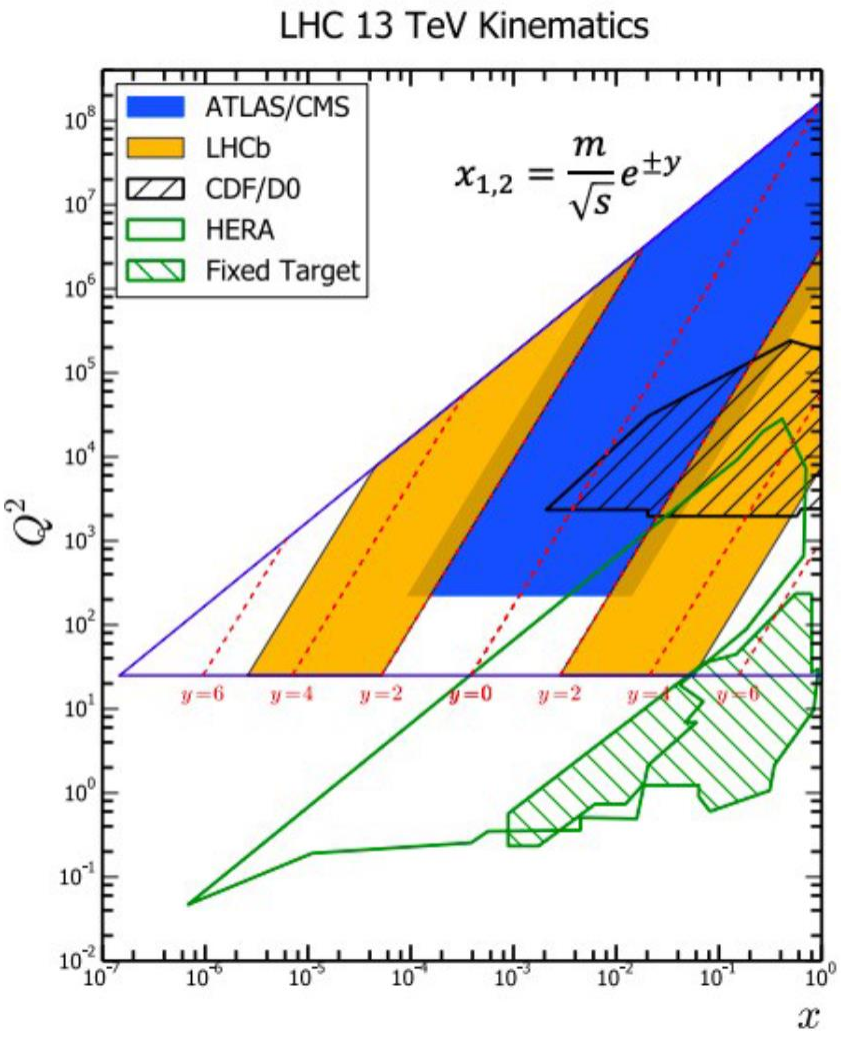




JIST 3 (2008) S08005
Int. J. Mod. Phys. A 30. 1530022 (2015)

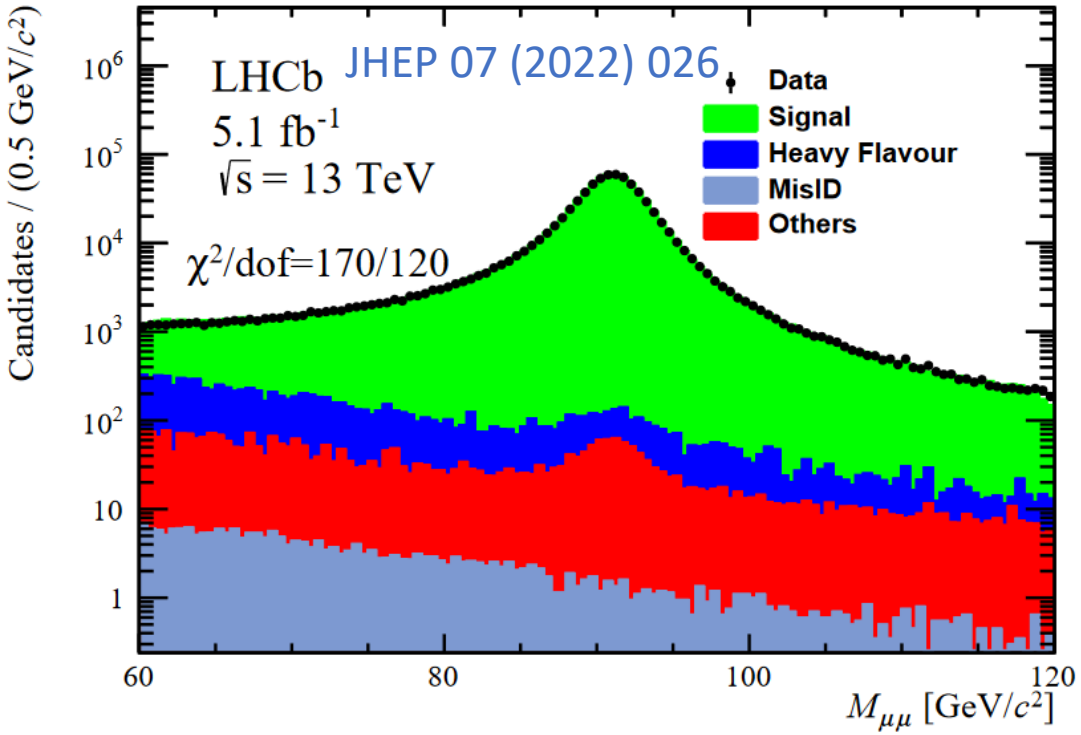
WZ physics at LHCb

- LHCb has already delivered a strong program of physics with W and Z boson mainly probing QCD
- LHCb detector provides access to PDFs
  - High Bjorken-x region
  - Low Bjorken-x region: has not been probed directly at electroweak energy scales before



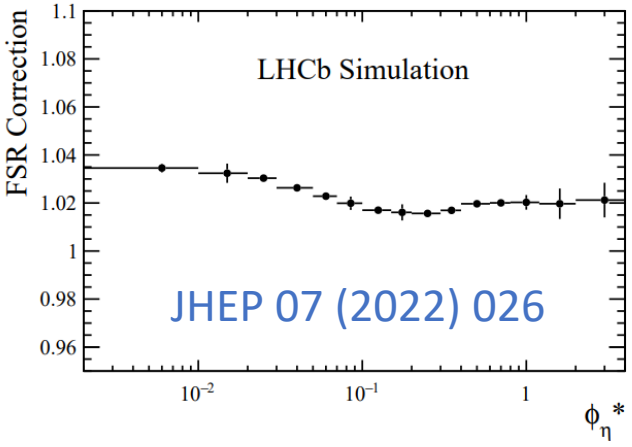
Z cross section 13 TeV - Strategy

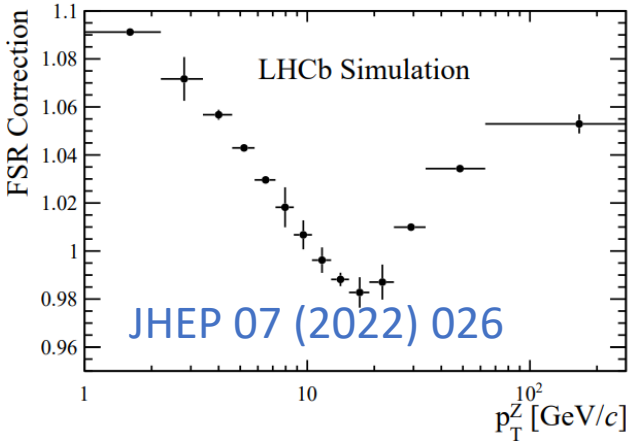
- Datasets:2016, 2017 and 2018 data: $5.1 \pm 0.1 fb^{-1}$
- Very high purity, $\frac{N_{bkg}}{N_{sig}} \sim 1.5\%$
- Fiducial region: Muon $P_T > 20$ GeV, $2 < \eta_\mu < 4.5$, $60 < M_{\mu^+\mu^-} < 120$ GeV

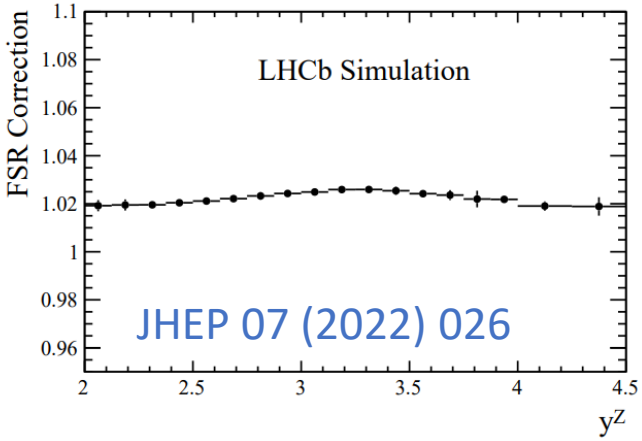


Z cross section 13 TeV – Final state radiation

- In order to compare with theoretical predictions, the measured cross-section must be corrected to Born level (evaluated with ResBos + Photos) Resbos: https://resbos.hepforge.org/

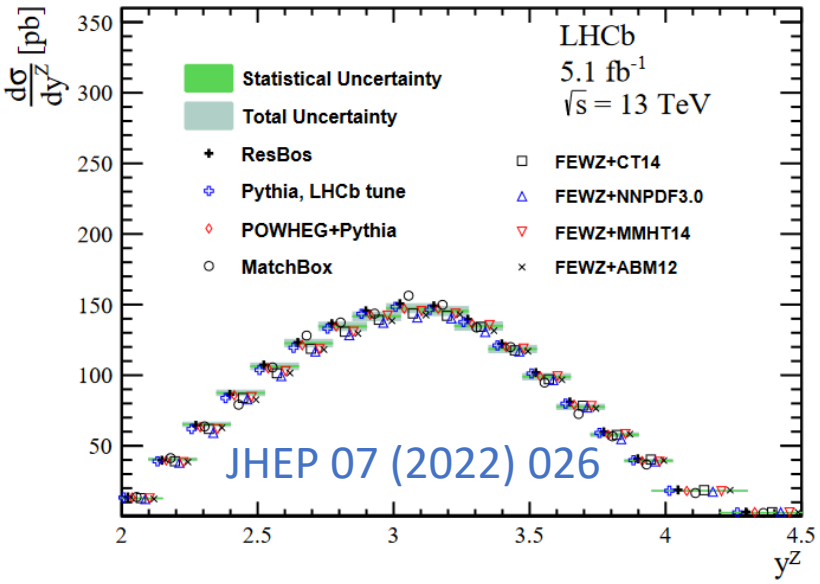


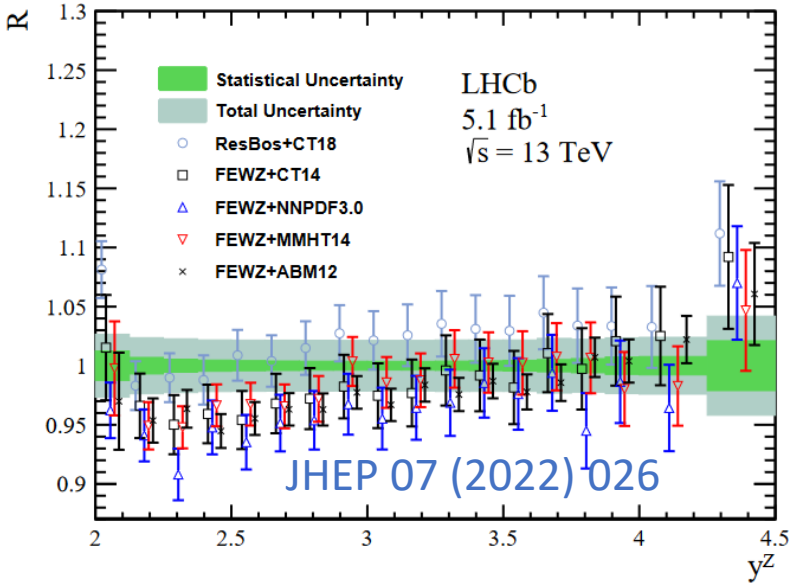




Z cross section 13 TeV – Z-y

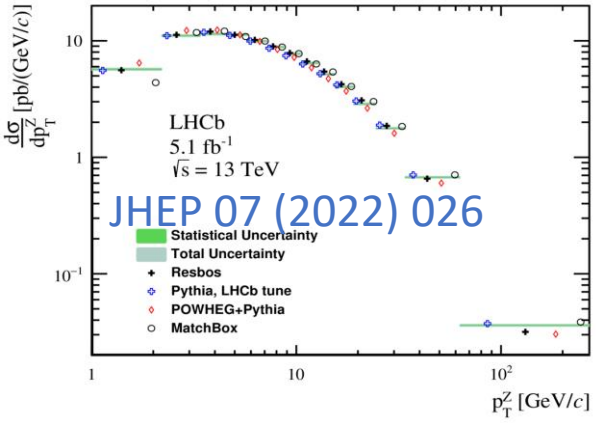
- Reasonable agreement between data and predictions, ratio(R)~1
- FEWZ predictions are systematically smaller than the measured results in the lower rapidity region

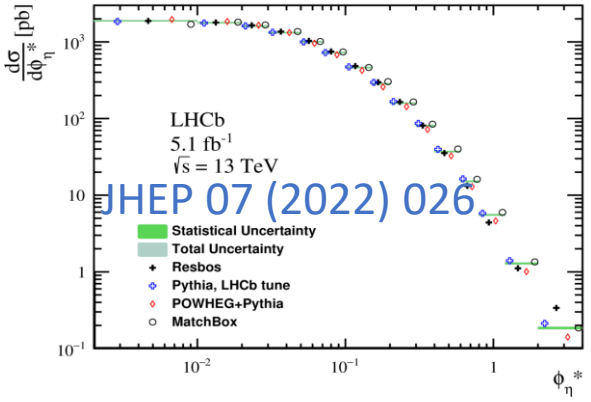


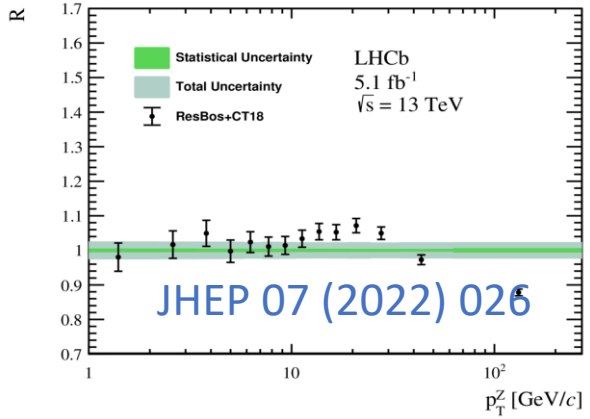


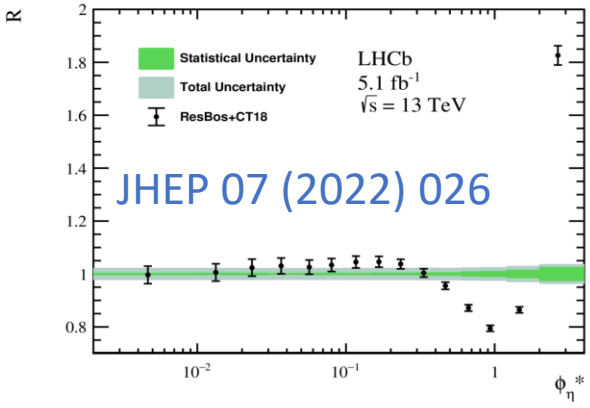
Z cross section 13 TeV – Z-p_T and ϕ^*

- ϕ^*: the scattering angle of the muons with respect to the proton beam direction in the rest frame of the dimuon system
- At high p_T (ϕ^*) region, tension between data and prediction mainly due to ResBos does not include NNLO calculation in the higher p_T (ϕ^*) region



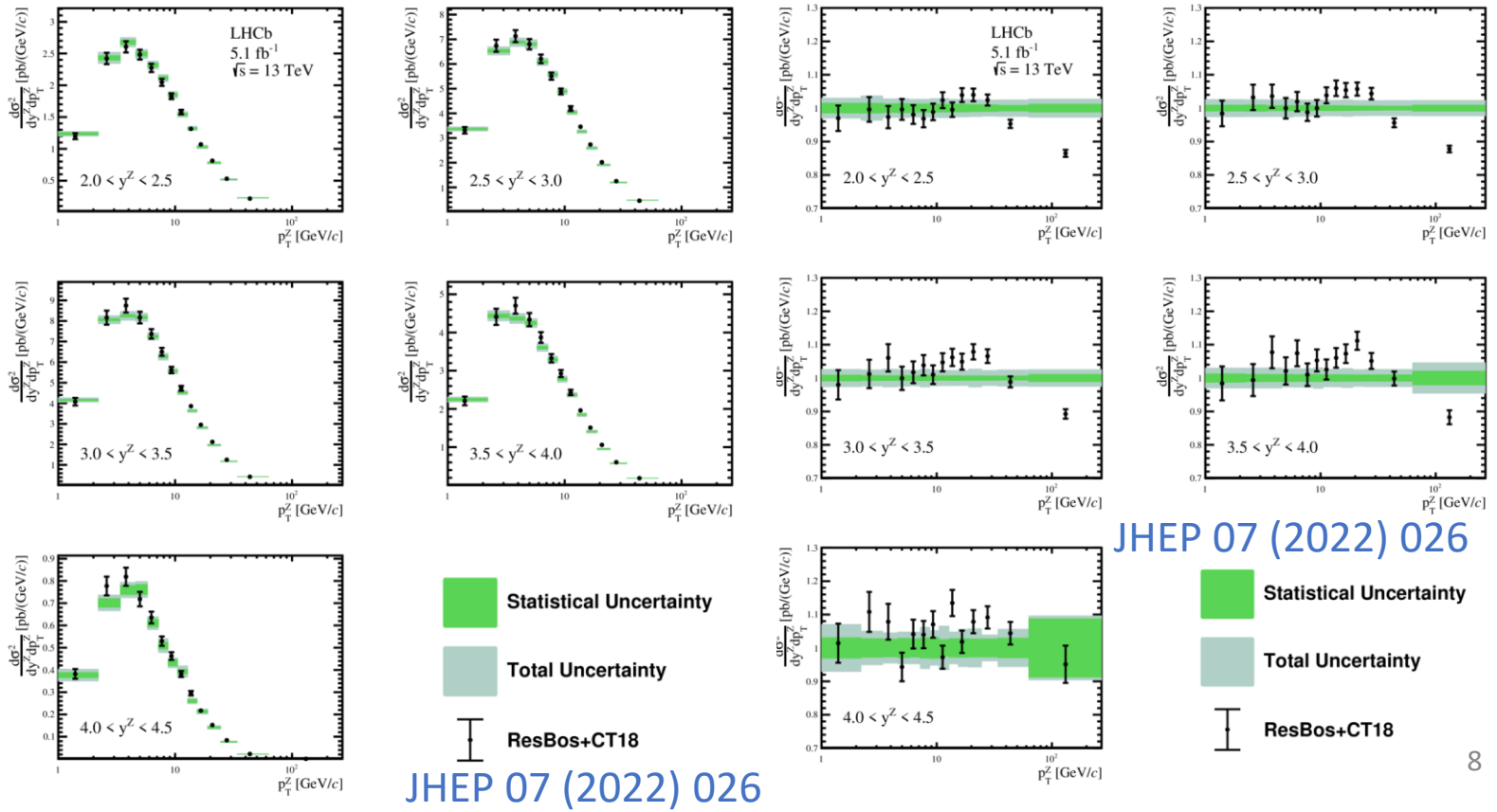






Z cross section 13 TeV – Z-p_T and y

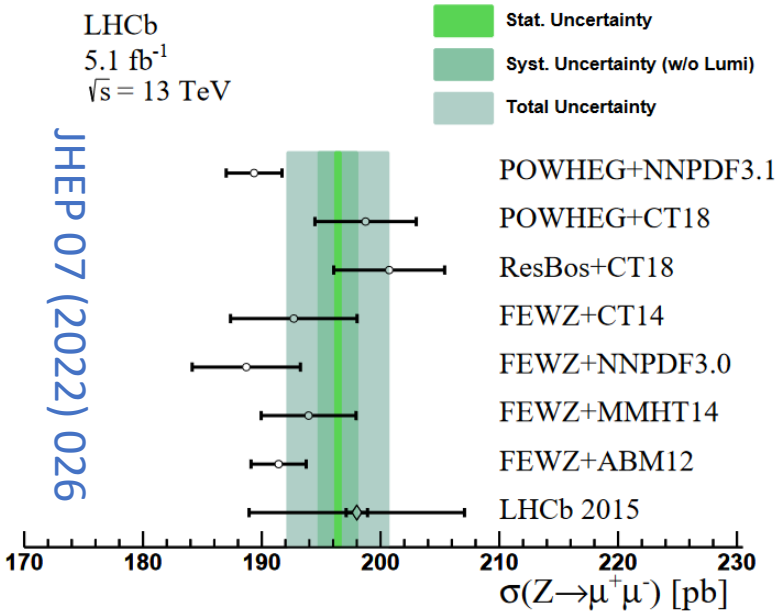
- The first double differential cross-section measurement in the forward region
- Tensions between measured results with ResBos predictions in the high p_T region



Z Integrated cross section

- The most precise measurement in the forward region @ 13 TeV

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



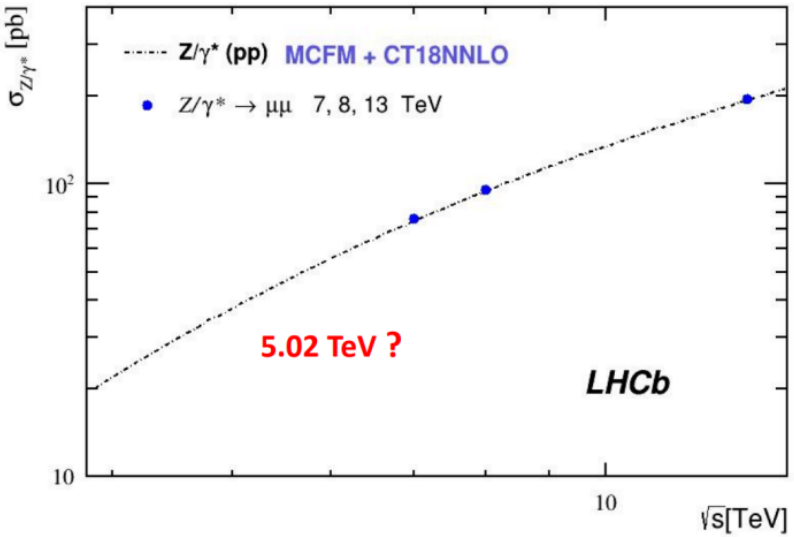
Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.06
Alignment & calibration	-
Efficiency	0.77
Closure	0.23
FSR	0.15
Total Systematic (excl. lumi.)	0.82
Luminosity	2.00
Total	2.16

JHEP 07 (2022) 026

Z cross section 5 TeV-Introduction

- Provide important tests of the QCD and the EW sectors of SM at LHC energies
- Constrain the uncertainty of PDF @ 5.02TeV

- Data: 2017, $99.86pb^{-1}$
- Selection requirements: Muon $P_T > 20$ GeV, $2 < \eta_\mu < 4.5$, $\frac{\sigma_P^\mu}{P} < 0.1$, $60 < M_{\mu^+\mu^-} < 120$ GeV

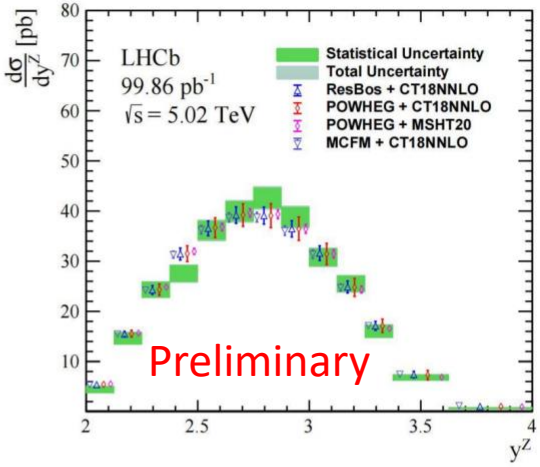


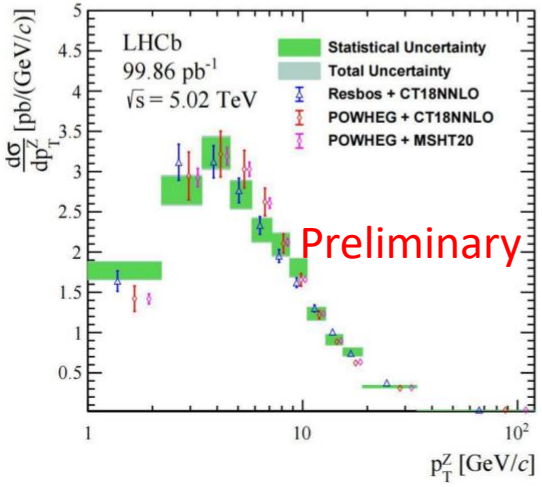
Z cross section 5 TeV-Differential cross

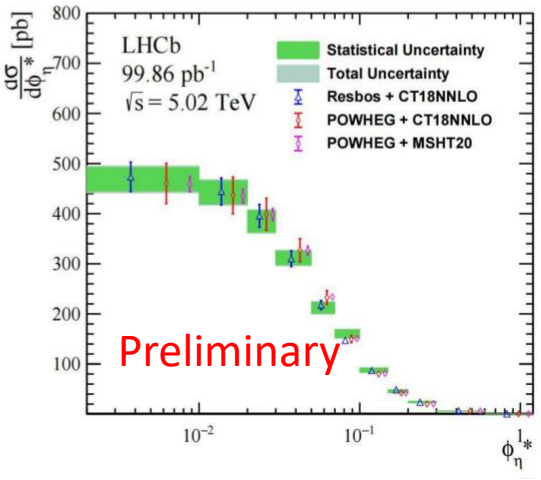
- Reasonable agreements between data and predictions
- The uncertainty is dominated by statistical uncertainty

Source	$\Delta\sigma/\sigma$ [%]
Statistical	1.77
Background	0.48
Momentum scale/smear	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
Total	3.02

Preliminary



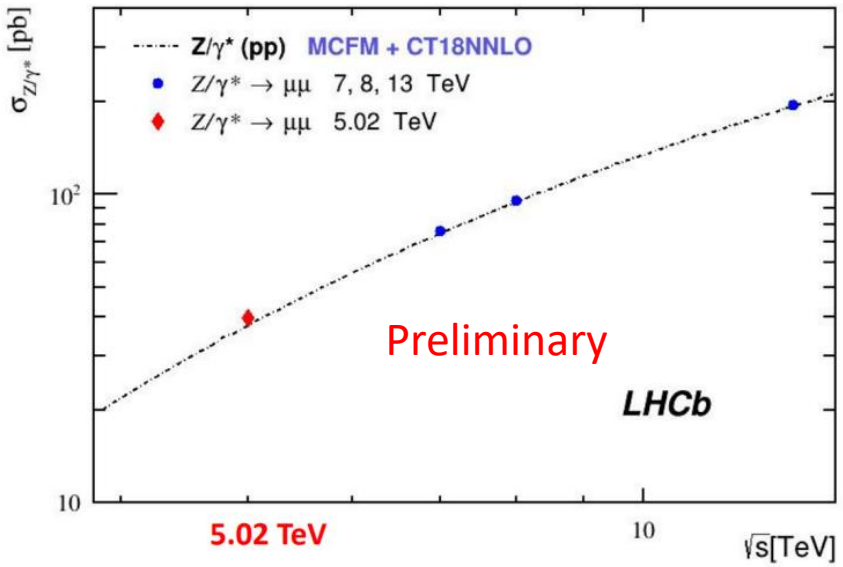


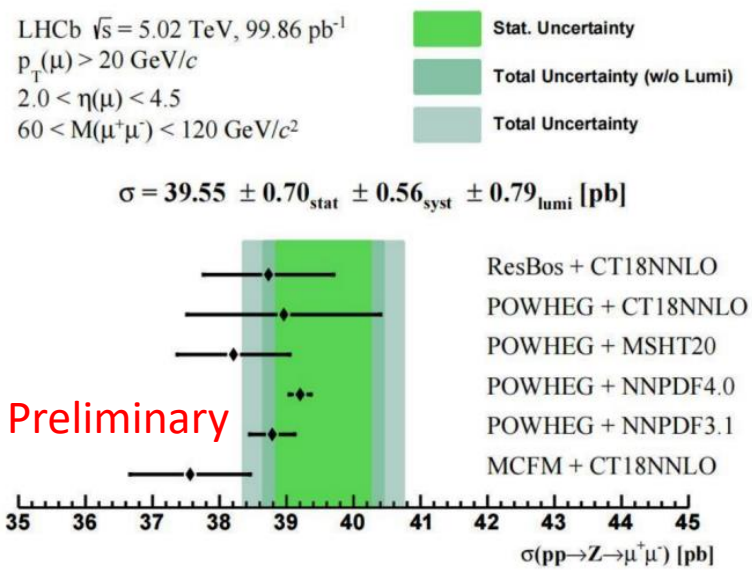


LHCB-PAPER-2023-010 in preparation

Z cross section 5 TeV-Preliminary result

- For total cross section, there are also reasonable agreements between data and predictions

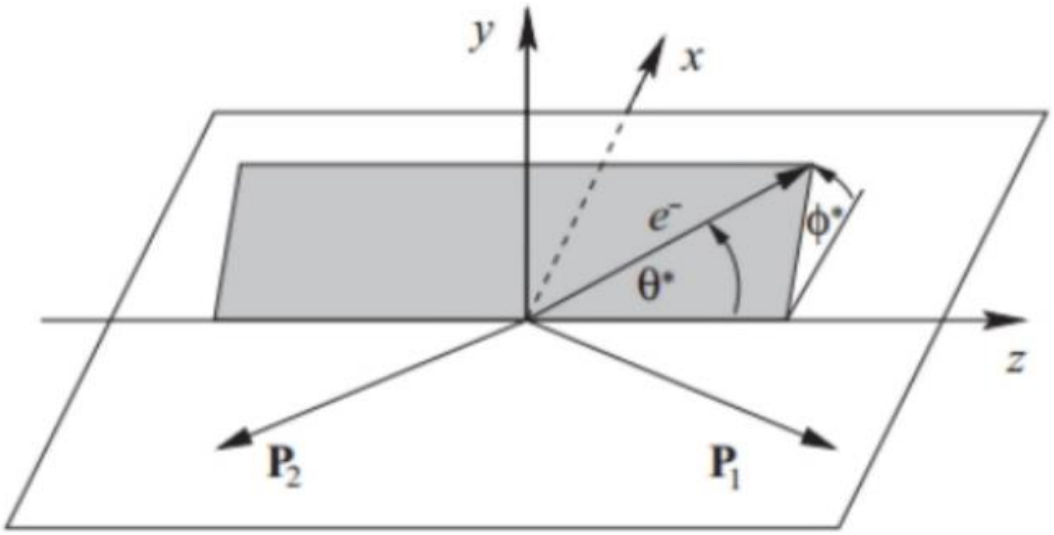




LHCB-PAPER-2023-010 in preparation

Z angular coefficient-introduction

- The kinematic distribution of the final-state leptons provides a direct probe of the polarization of the intermediate gauge boson
- Differential cross section of the lepton decay angle $(cos\theta, \phi)$ in Collins-Soper frame



Z angular coefficient-introduction

- A_0 A_1 A_2 A_3 ΔA_4 and A_0 - A_2 are measured

$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$

(1 + cos²θ) → LO term

½A₀(1 − 3cos²θ) → cos²θ : higher order term

A₁ sin 2θ cos φ + ½A₂ sin² θ cos 2φ + A₃ sin θ cos φ → (θ, φ) terms

A₄ cos θ → LO term : determine A_{fb}

A₅ sin² θ sin 2φ + A₆ sin 2θ sin φ + A₇ sin θ sin φ → very small terms

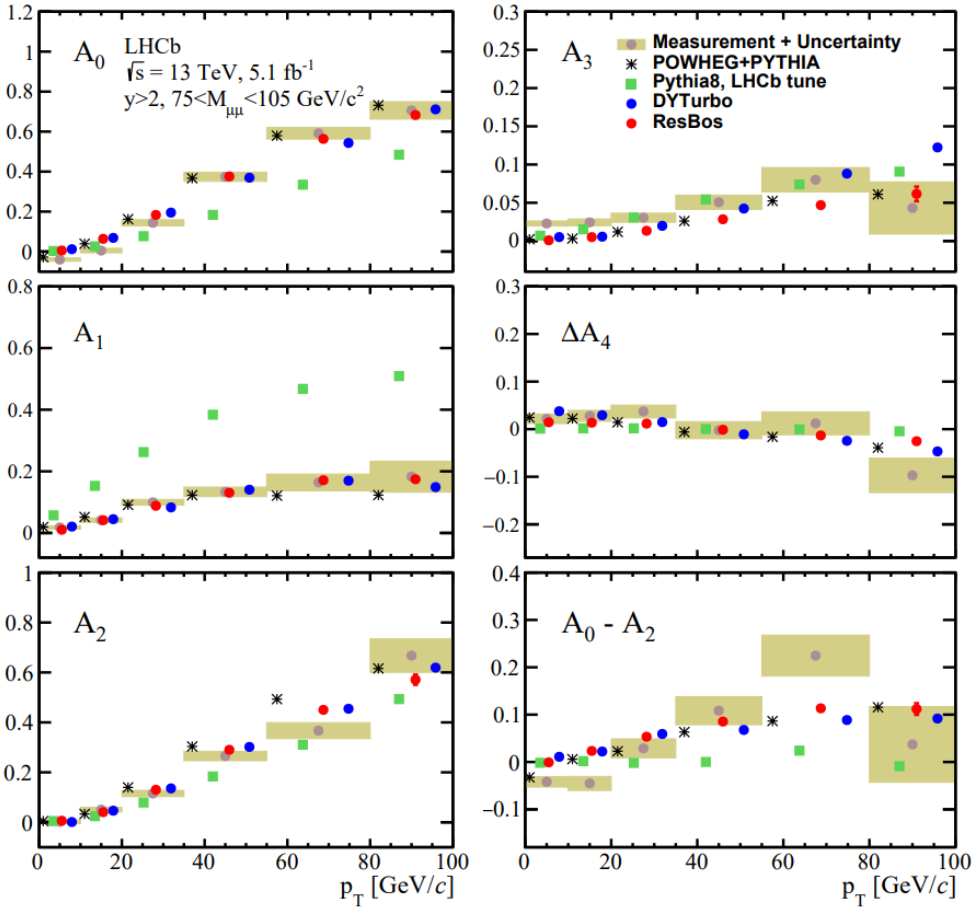
- Dateset: 2016 2017 2018

- Selection requirements:

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	$\frac{p_T^{\mu}}{p_T^{\mu} + p_T^{\mu-cone}} > 0.85$

Z angular coefficient- p_T dependent results

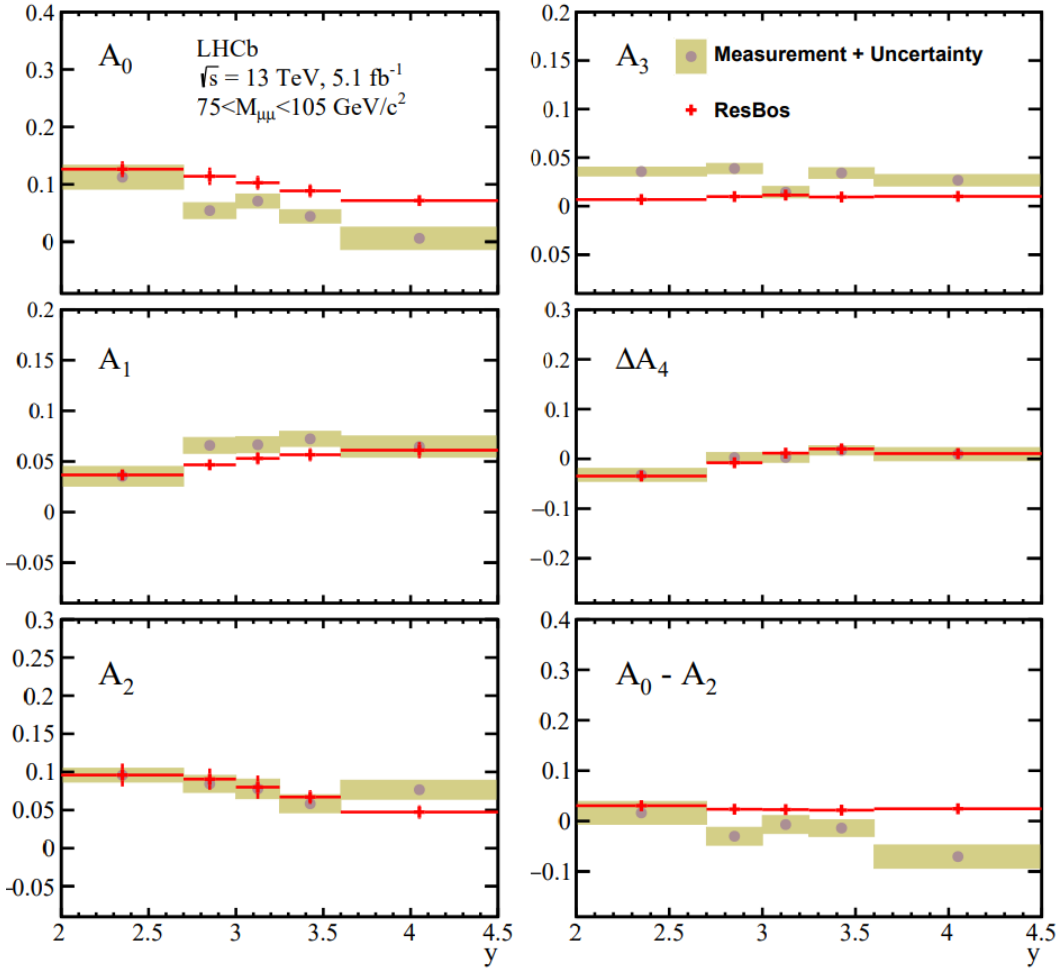
- The uncertainty is dominated by statistical uncertainty, Measurements are at Born level
- In order to investigate its variation across the kinematic range, ΔA_4 is measured
- $\Delta A_4$is the difference between this bin value and 5 bins average value



PRL 129 (2022) 091801

Z angular coefficient- y dependent results

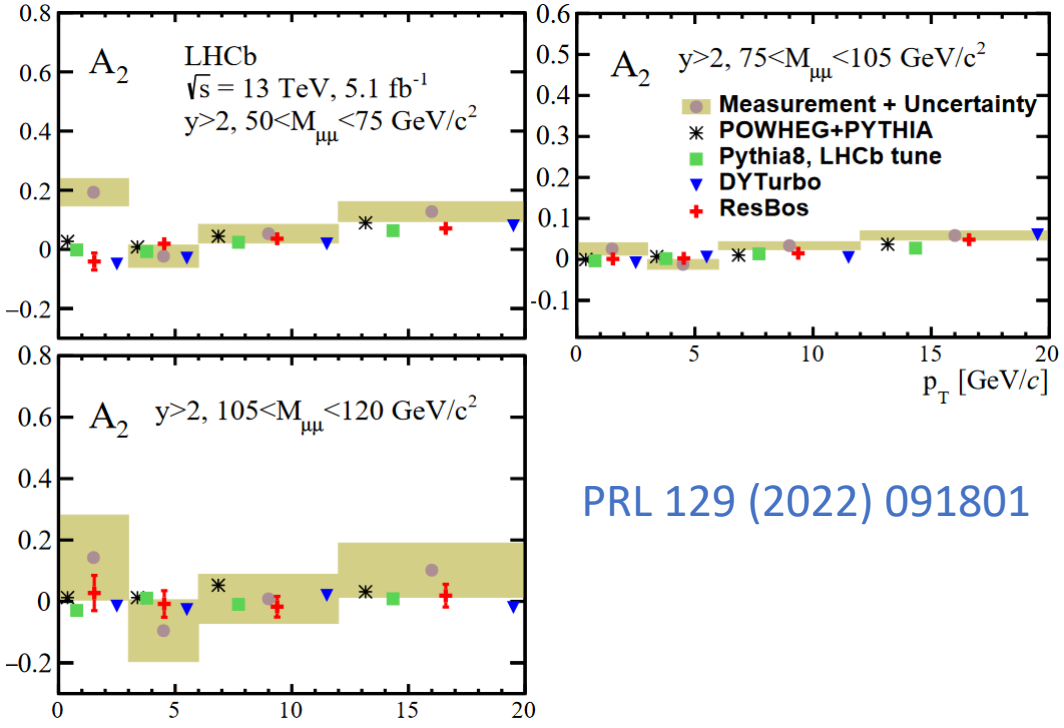
- $A_0 - A_2$: differences between measurements and predictions, especially in the highest y region
- A y dependence in the QCD resummation or high-order effects



PRL 129 (2022) 091801

Z angular coefficient-Boer-Mulders TMD

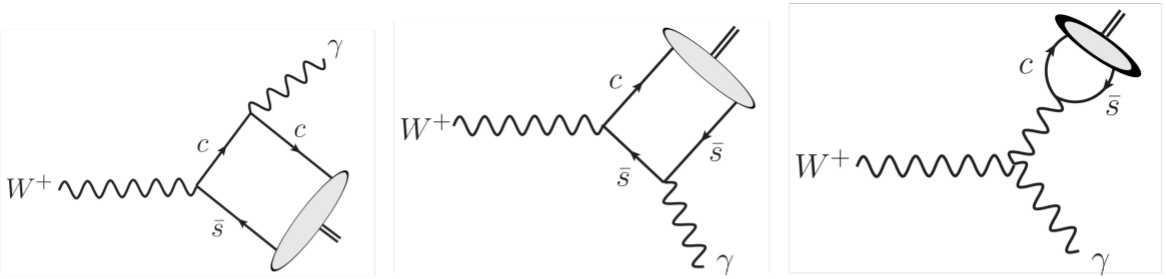
- A_2 is sensitive to the Boer-Mulders transverse momentum dependent PDFs
- The measured A_2 values deviate significantly from all predictions in the lowest p_T region for the low-mass region
- None of the predictions include nonperturbative spin-momentum correlations



PRL 129 (2022) 091801

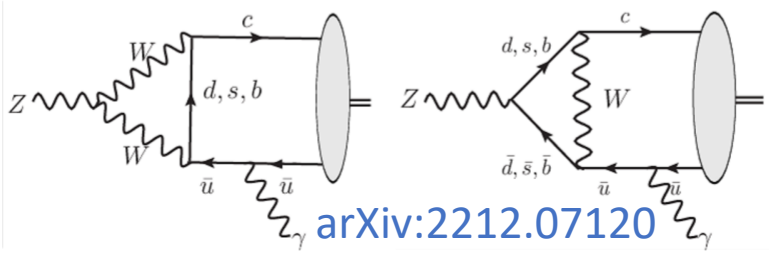
WZ Rare Decay-introduction

- Limited knowledge on W/Z boson rare decay
- The upper limit on the relative branching fraction of $W^{\pm} \to D_s^{\pm}\gamma$ is determin to 1.2×10^{-2} (CDF, PRD 58 (1998) 091101)



arXiv:2212.07120

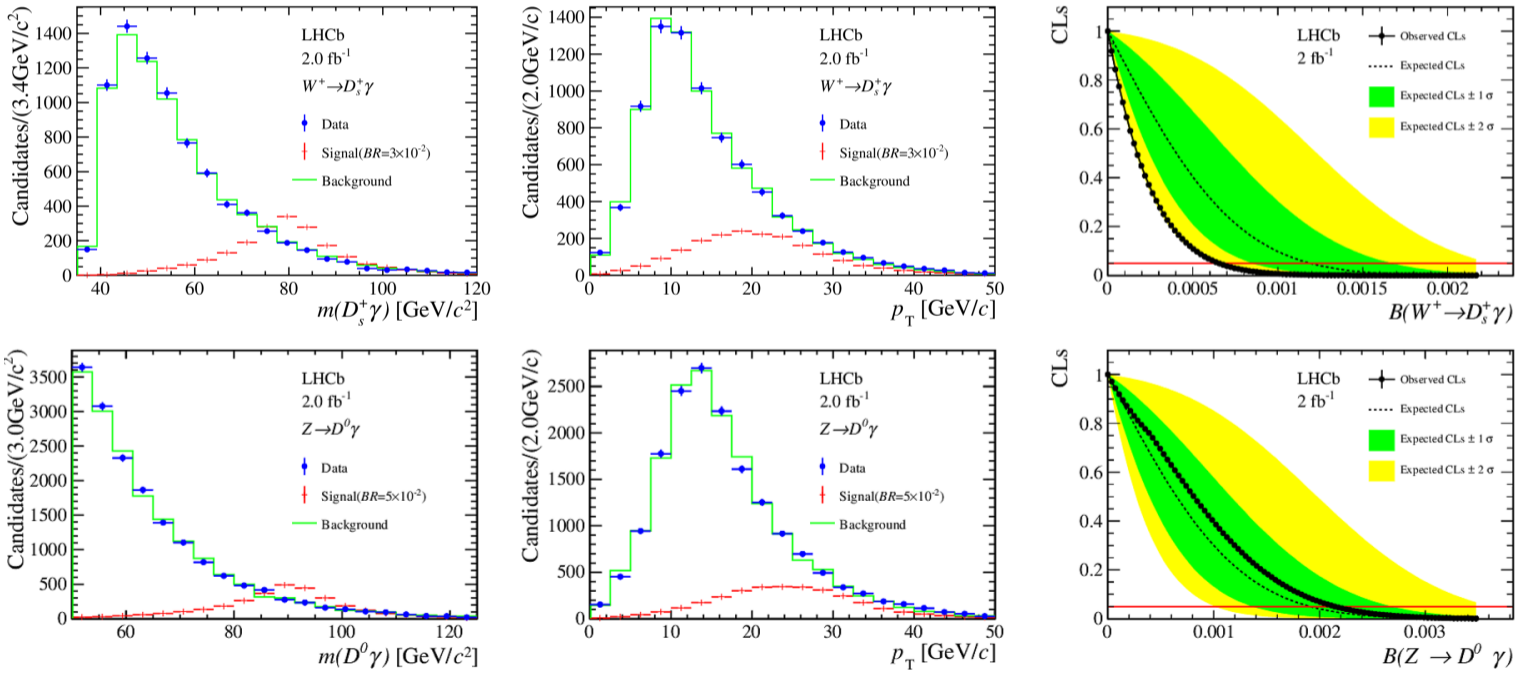
- $Z \to D^0\gamma$ has not been searched, theory prediction branching fraction $\left[10^{-12} - 10^{-6}\right]$



arXiv:2212.07120

WZ Rare Decay-CLs method

- We use LHCb 2018 data and there is no visible signal
- The CLs method is used to set upper limit for these rare decay searches
- X axis variable for left column plots is pseudo mass

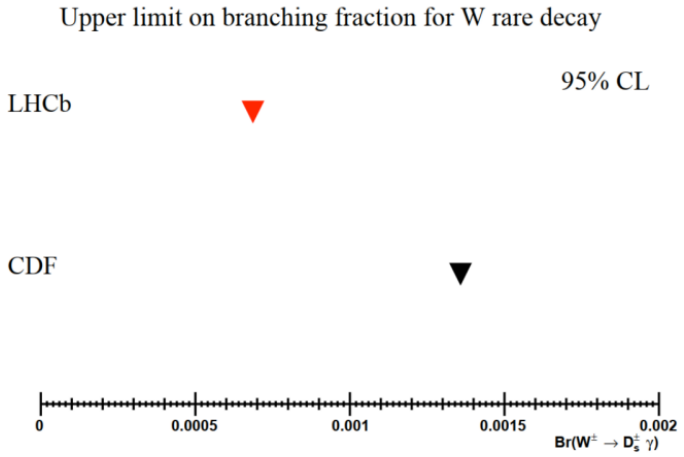


arXiv:2212.07120

WZ Rare Decay-Result

- The upper limit of $W^{\pm} \to D_s^{\pm}\gamma$ is set at 6.5 $\times 10^{-4}$ and for $Z \to D^0\gamma$ is 2.1 $\times 10^{-3}$

Source	$Z \to D^0\gamma$ (%)	$W^+ \to D_s^+\gamma$ (%)
Meson BF	0.76	1.86
Normalization	0.96	3.08
Dalitz	-	0.24
MC sample size	0.11	0.09
PID	0.09	0.17
Photon ID	2.32	0.95
Calorimeter saturation	3.00	3.10
Background	0.36	0.08
Acceptance	0.18	0.21
PV association	0.57	0.29
Resolution	0.20	0.09
Total	4.04	4.86



arXiv:2212.07120

- World best limit on $W^{\pm} \to D_s^{\pm}\gamma$ Decay
- First upper limit on the exclusive $Z \to D^0\gamma$ Decay

The paper is accepted by CPC

Summary

- The LHCb detector has proved its capability to do high-precision measurements of EW observables
- The most precise measurement to date of the Z boson production cross-section in the forward region
- The first measurement of the angular coefficients of Drell-Yan $\mu^+\mu^-$ pairs in the forward region of pp collisions at 13 TeV
- The World best limit on $W^{\pm} \to D_s^{\pm}\gamma$ and $Z \to D^0\gamma$

End

Thank you for your listening!

Backup

Uncertainties of Z angular coefficient:

	$y^Z \in [2, 2.7]$						$y^Z \in [2.7, 3]$					
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