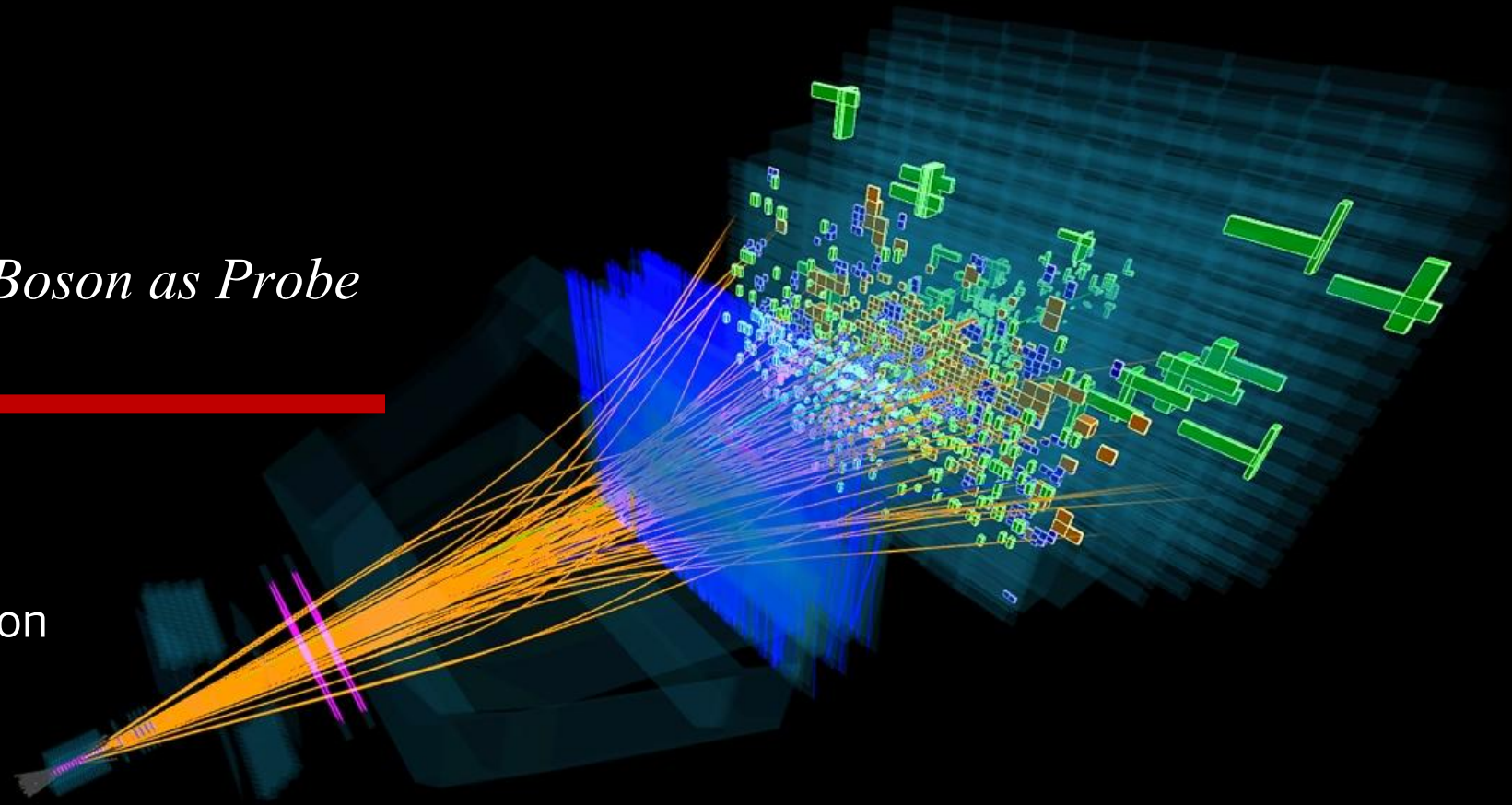
北京大学
PEKING UNIVERSITY

News from LHCb :

Measurement Results with Z Boson as Probe



Yuhao Wang

on behalf on the LHCb collaboration

| CERN | PDF4LHC meeting

17 November 2023

Overview

Only concentrate on the most recent results from LHCb since the last PDF4LHC meeting :

- **Measurement of Z boson angular coefficient @ 13 TeV**
  Phys. Rev. Lett. 129 (2022) 091801
- **Measurement of Z boson production cross-section @ 5.02 TeV**
  arXiv:2308.12940 (submitted to JHEP)

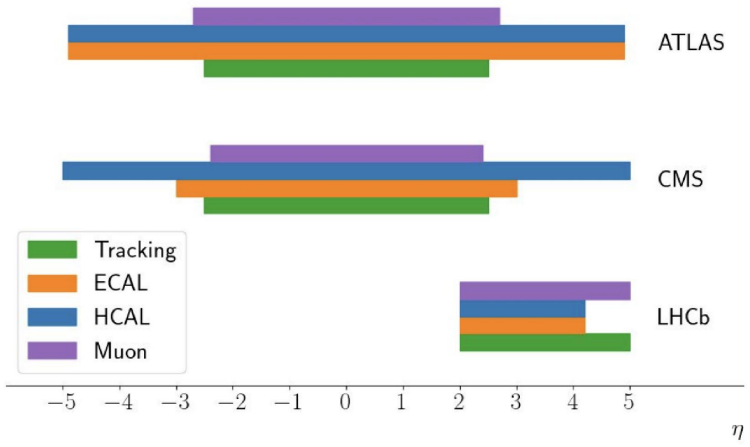
The summary of completed cross-section measurements for W/Z (+jets) production in pp collisions :

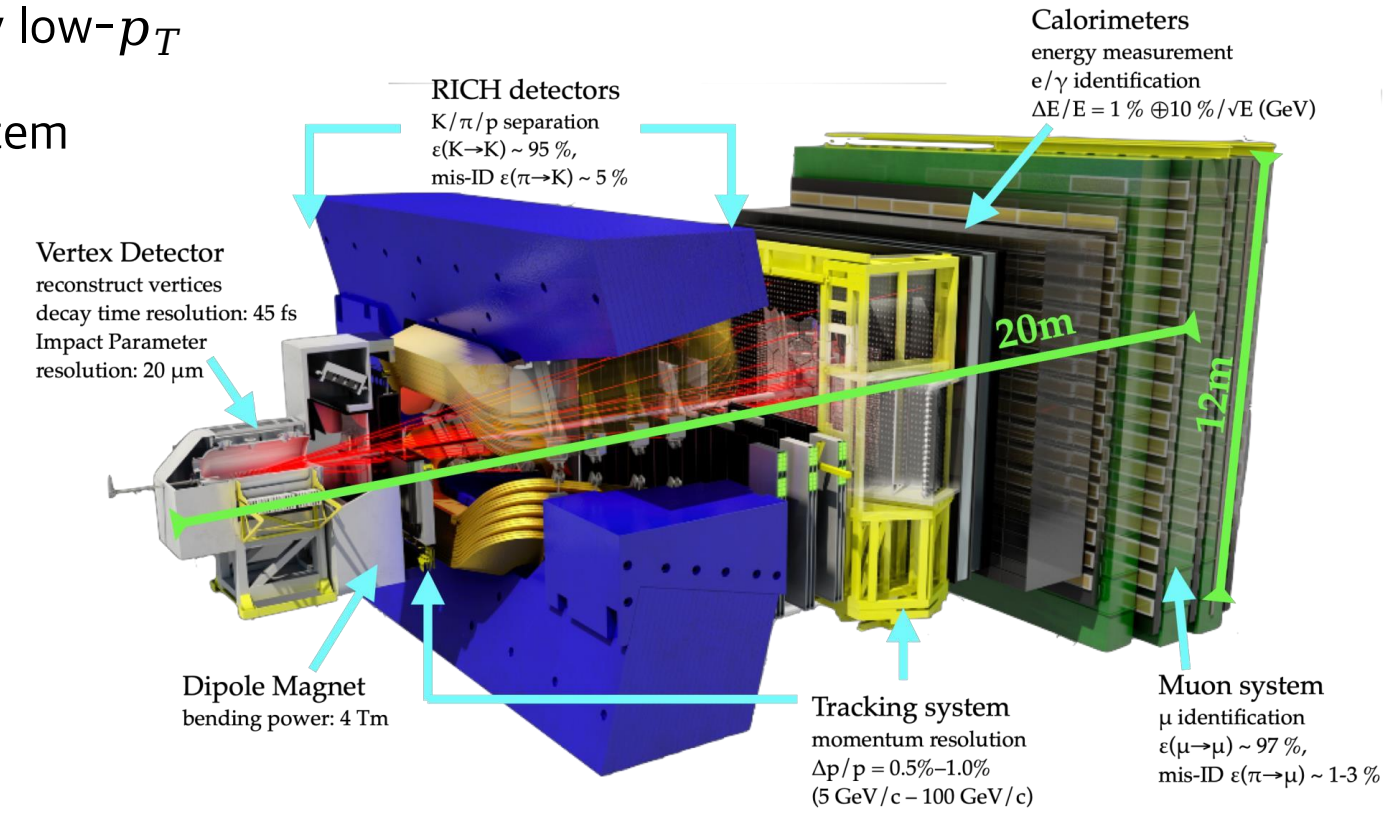
$Z + jets$ @ 7 TeV	JHEP 01 (2014) 33
$Z + b - jets$ @ 7 TeV	JHEP 01 (2015) 064
$W + b/c - jets$ @ 7 TeV	PRD92 (2015) 052001
$W + jets\ and\ Z + jets$ @ 8 TeV	JHEP 05 (2016) 131
$Z+c-jets$ @ 13 TeV	PRL 128 (2022) 082001
$W\ and\ Z$ @ 7 TeV (partial dataset)	JHEP 06 (2012) 58
$W\ and\ Z$ @ 8 TeV	JHEP 01 (2016) 155
W @ 7 TeV (full dataset)	JHEP 12 (2014) 079
$W \to e\nu$ @ 8 TeV	JHEP 10 (2016) 030
$Z \to \mu\mu$ @ 7 TeV (full dataset)	JHEP 08 (2015) 039
$Z \to ee$ @ 7 TeV	JHEP 02 (2013) 106
$Z \to ee$ @ 8 TeV	JHEP 05 (2015) 109
$Z \to \tau\tau$ @ 7 TeV	JHEP 01 (2013) 111
$Z \to \tau\tau$ @ 8 TeV	JHEP 09 (2018) 159
Z @ 13 TeV (partial dataset)	JHEP 09 (2016) 136
$Z \to \mu\mu$ @ 13 TeV (full dataset)	JHEP 07 (2022) 26

Working in progress at 13 TeV !

LHCb detector

- A single-arm forward spectrometer down to very low-p_T
- Excellent performance of tracking and muon system
- Excellent particle ID and vertex reconstruction
- Complementary η range to ATLAS and CMS
  - Overlap for cross check : $2.0 < \eta < 2.5$
  - Unique to LHCb : $2.5 < \eta < 5.0$



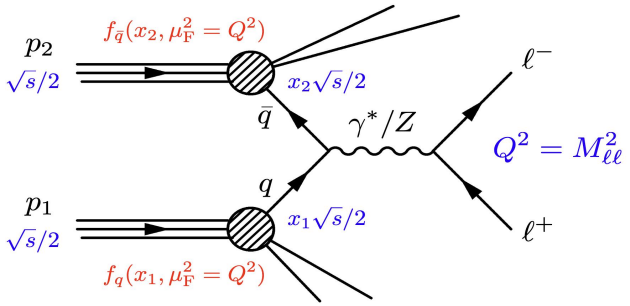


JINST 3 (2008) S08005

Int. J. Mod. Phys. A 30 (2015) 1530022

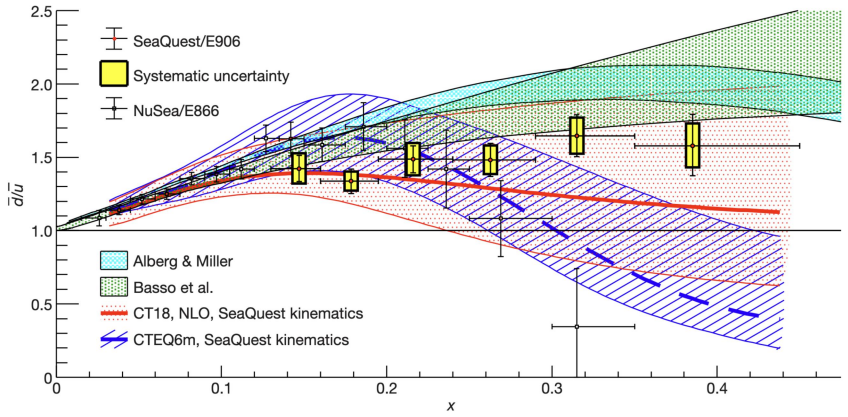
Z boson probe and PDF Measurement

- Ideal probe of the initial and final states:
  - clean final states, unaffected by hadronic activities
  - contributes to the measurement of proton PDFs, nuclear modifications, etc

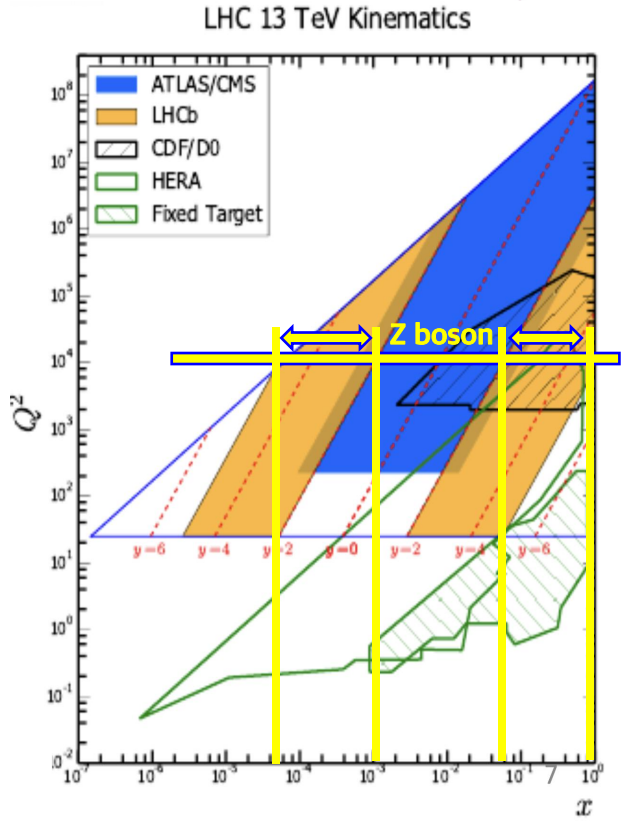


- LHCb can provide important information in unique Bjorken-x regions with $Q^2 \sim m_Z^2 \sim 10^4$ (GeV^2) :
  - Bjorken-x : $x_{min} \sim 5 \times 10^{-5}$, $x_{max} \sim 0.8$
  - the only clean data to clarify the inconsistency in SeaQuest and NuSea results

Nature volume 590, pages 561–565 (2021)



tension exists

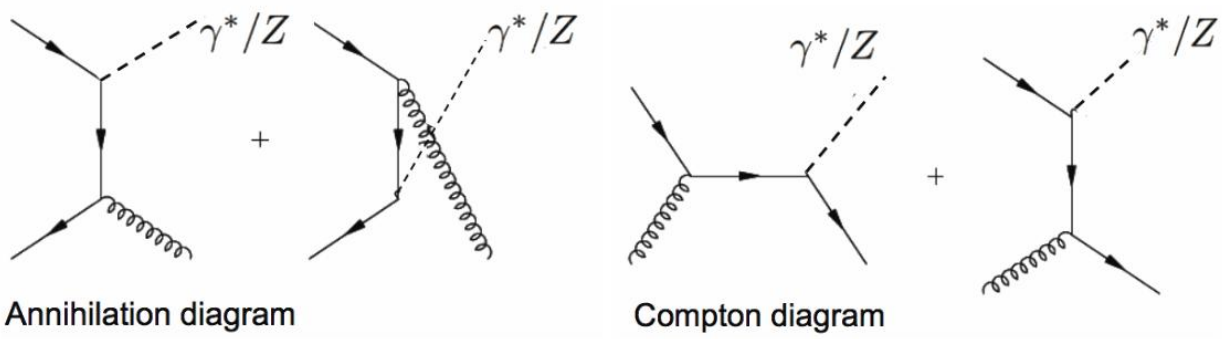


Z Angular Coefficients Measurement

- LHCb pp data @ 13 TeV (2016-2018), $L = 5.1 \pm 0.1\ \text{fb}^{-1}$
  - High signal purity : $N_{bkg}/N_{sig} \sim 0.2\%$
- The QCD process of $pp \longrightarrow \gamma^*/Z + X \longrightarrow \ell\ell + X$ can be described by a set of angular coefficients $A_i (i = 0 \ldots 7)$:

  $\Longrightarrow$ more complex variables, providing precise validation of QCD production mechanisms
- Kinematic distribution : a direct probe of the polarization of the intermediate gauge boson

  $\Longrightarrow$ sensitive to the underlying QCD production mechanisms



Tree-level digrams for Z-boson with finite p_T

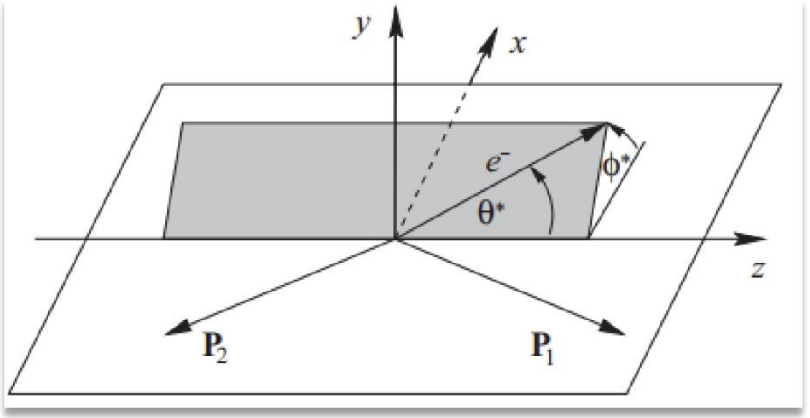
$$\begin{aligned}\frac{d\sigma}{d\cos\theta d\phi} &\propto (1+\cos^2\theta) \\ &+ \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \\ &+ \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi \\ &+ A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi \\ &+ A_6 \sin 2\theta \sin\phi + A_7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

General expression for angular distribution

Z Angular Coefficients Measurement

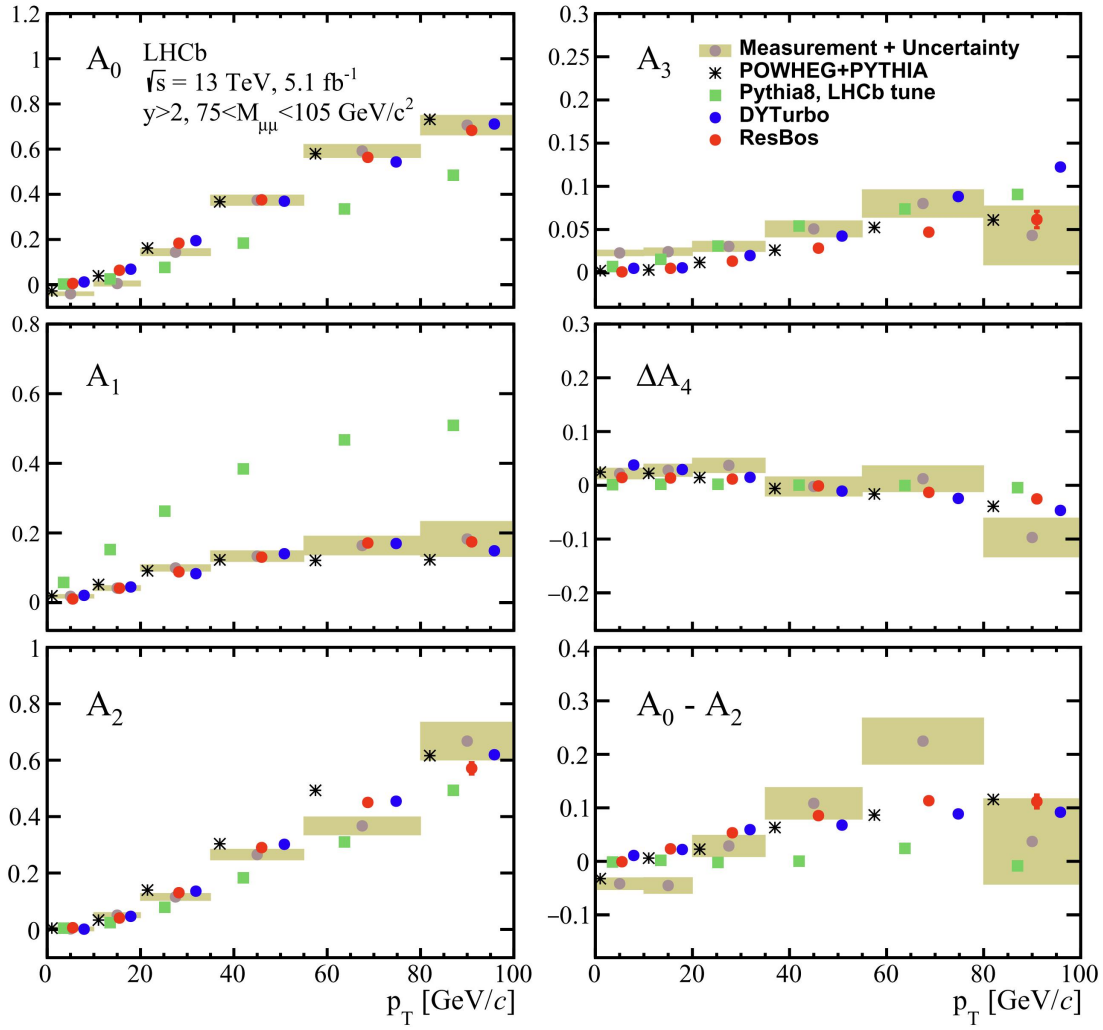
- Differential cross-section of lepton decay angle (θ, ϕ) in CS frame is parametrized by angular coefficients:

$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta) \rightarrow \textit{LO term}$$
$$+ \frac{1}{2}A_0(1-3\cos^2\theta) \rightarrow \textit{cos}^2\theta\textit{ : higher order term}$$
$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi \rightarrow \textit{(}\theta\textit{, }\phi\textit{) terms}$$
$$+ A_4 \cos\theta \rightarrow \textit{LO term : determine } A_{fb}$$
$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \rightarrow \textit{very small terms}$$



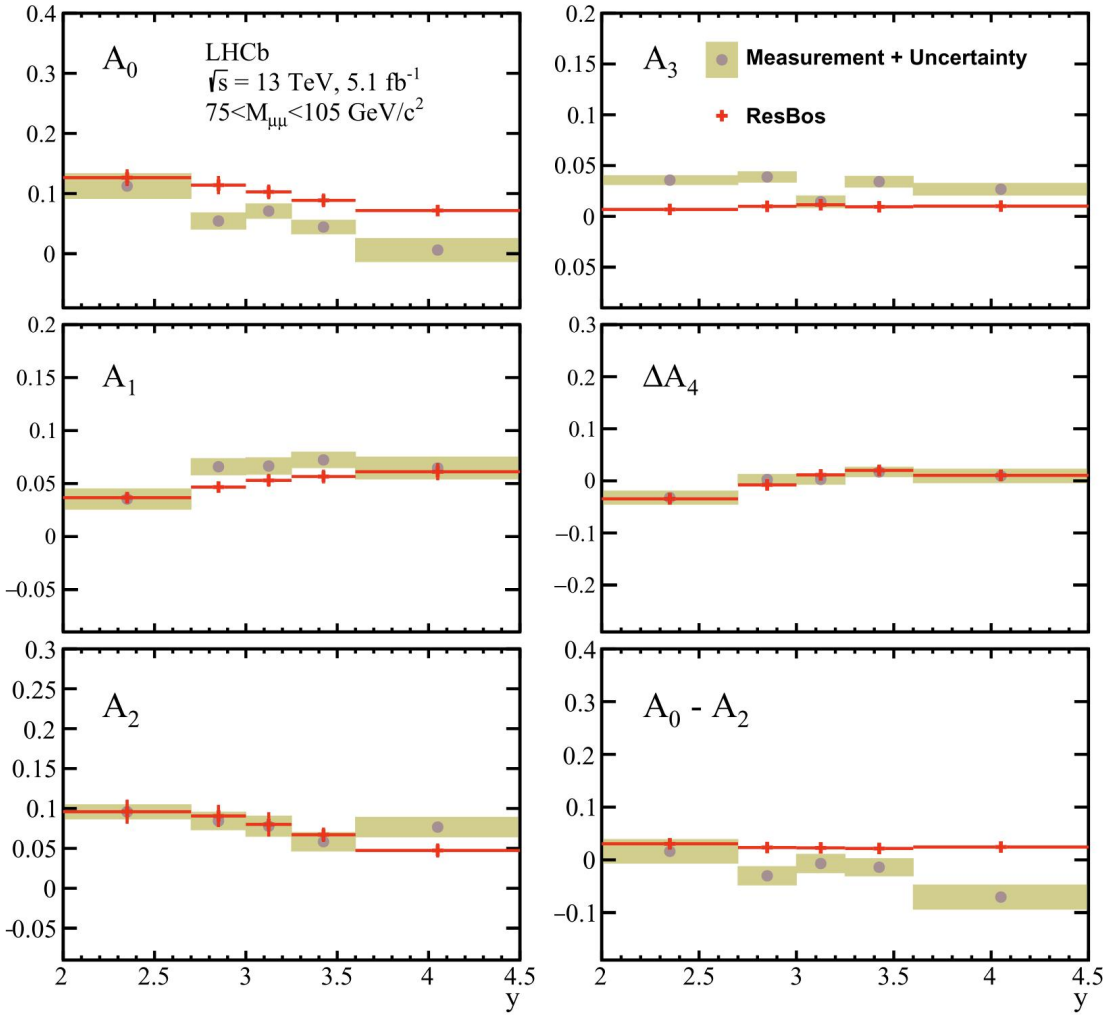
- A_i, the ratio of helicity dependent cross-section over the unpolarized cross-section
  - A_1: the difference in the probability of emission of gluons by low x and high x patrons
  - Lam-Tung relation : $A_0 = A_2$
  - A_2: sensitive to the Boer-Mulders transverse momentum dependent PDFs
  - A_3: is expected to be small
  - A_4: sensitive to the weak mixing angle (investigate its variation ΔA_4)

A_i at LHCb - p_T Dependent



- The first measurements of the angular coefficients of Drell-Yan $\mu^+\mu^-$ pairs in the forward rapidity region of pp collisions at 13TeV
- Measurement are corrected to the Born level
- The uncertainty is dominated by statistical uncertainty

A_i at LHCb - y Dependent



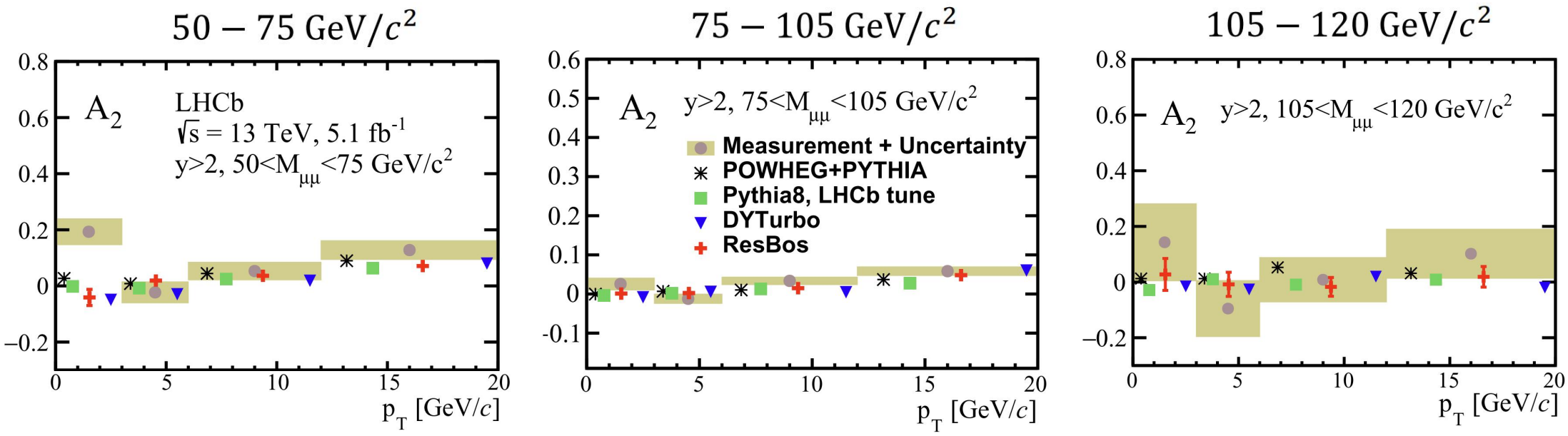
- Reasonable agreement between the measurements and ResBos calculations for A_0 to ΔA_4

- The $A_0 - A_2$ (Lam-Tung relation) has noticeable differences in the highest y region

  $\Longrightarrow$ indicate a y dependence in the QCD resummation or higher-order effects

A_i at LHCb - Boer-Mulders TMD

- A_2 is sensitive to the TMD
- The measured A_2 deviates significantly from all predictions in the lowest p_T region for the low-mass region
- None of the predictions include nonperturbative spin-momentum correlations
- The total uncertainty (shown in the figure) is dominated by the statistical component.



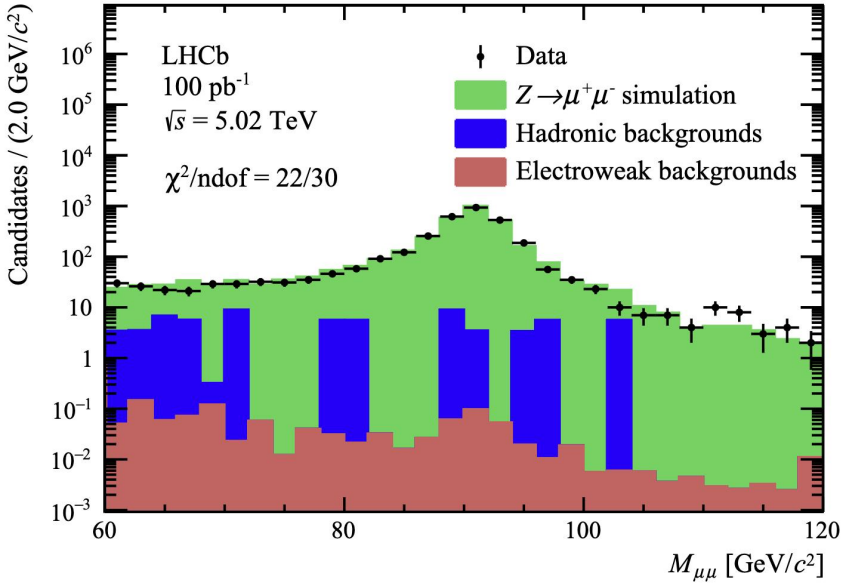
Z Production Cross-section Measurement

- LHCb pp data @ 5.02 TeV (2017), $L = 100 \pm 2\ pb^{-1}$
  - High signal purity : $N_{bkg}/N_{sig} \sim 2\%$
  - Fiducial region :

$\mu^{\pm}$	di-muon
$p_T > 20\,\mathrm{GeV}/c$ $2 < \eta < 4.5$	$60 < M_{\mu^+\mu^-} < 120\,\mathrm{GeV}/c^2$

- Provide important tests of the QCD and the EW sectors
- Constrain the uncertainties of PDFs and nuclear modification factors
- Differential cross-section in bins of $a = y^Z,\ p_T^Z,\ \phi_\eta^*$:

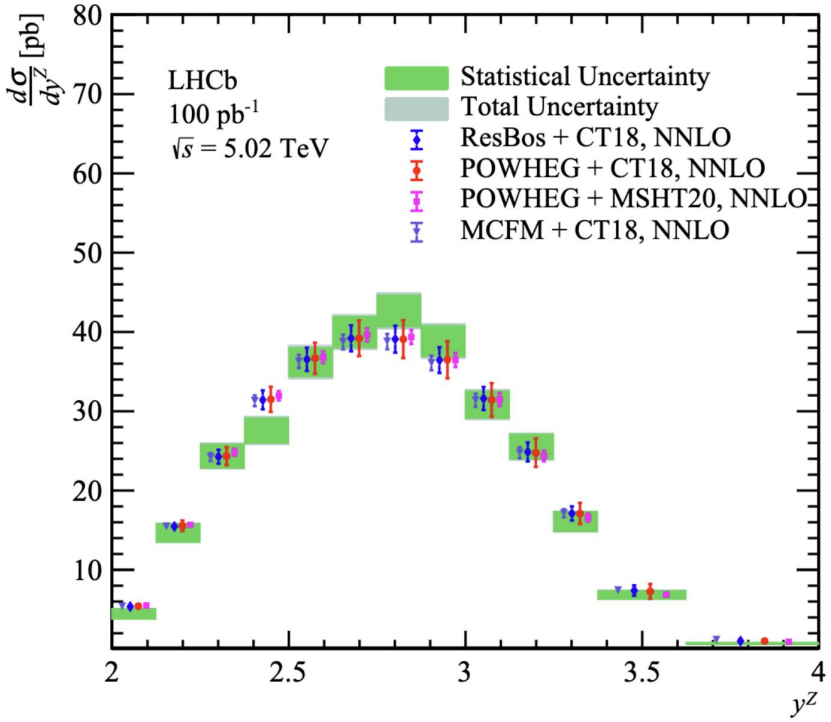
$$\frac{d\sigma_{Z\to\mu^+\mu^-}}{da}(i) = \frac{N_Z(i)\cdot f_{FSR}^Z(i)}{\mathcal{L}\cdot\varepsilon^Z(i)\cdot\Delta a(i)},$$

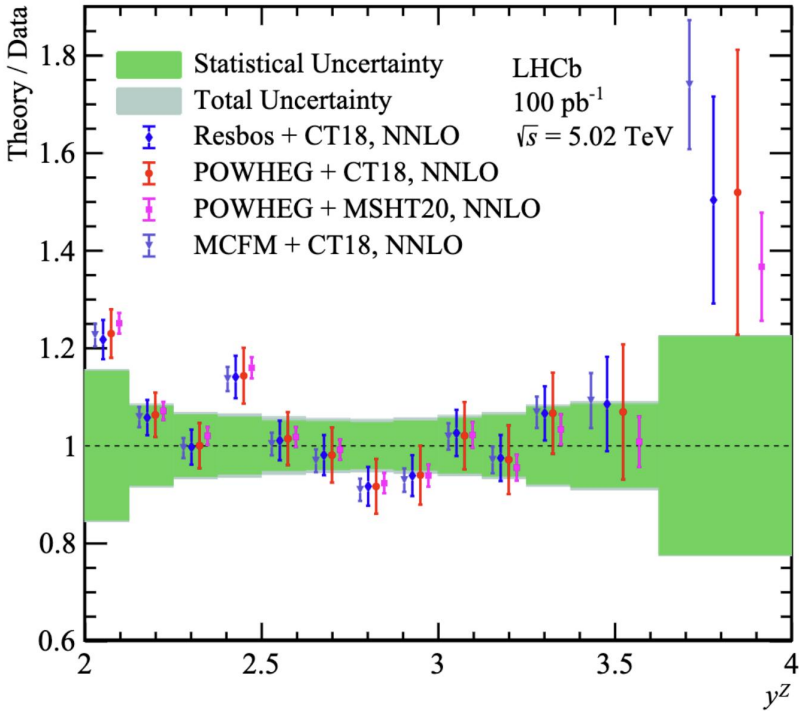


Source	$\Delta\sigma$ [pb]	$\Delta\sigma/\sigma$ [%]
Luminosity	0.79	2.00
Statistical	0.70	1.77
Tracking	0.40	1.01
Efficiency Closure	0.24	0.61
Trigger	0.21	0.54
Background	0.19	0.48
Identification	0.10	0.25
FSR	0.07	0.18
Calibration	$< 4.0 \times 10^{-3}$	< 0.01
Total Systematic (excl. lumi.)	0.56	1.42

Z Production Cross-section Measurement

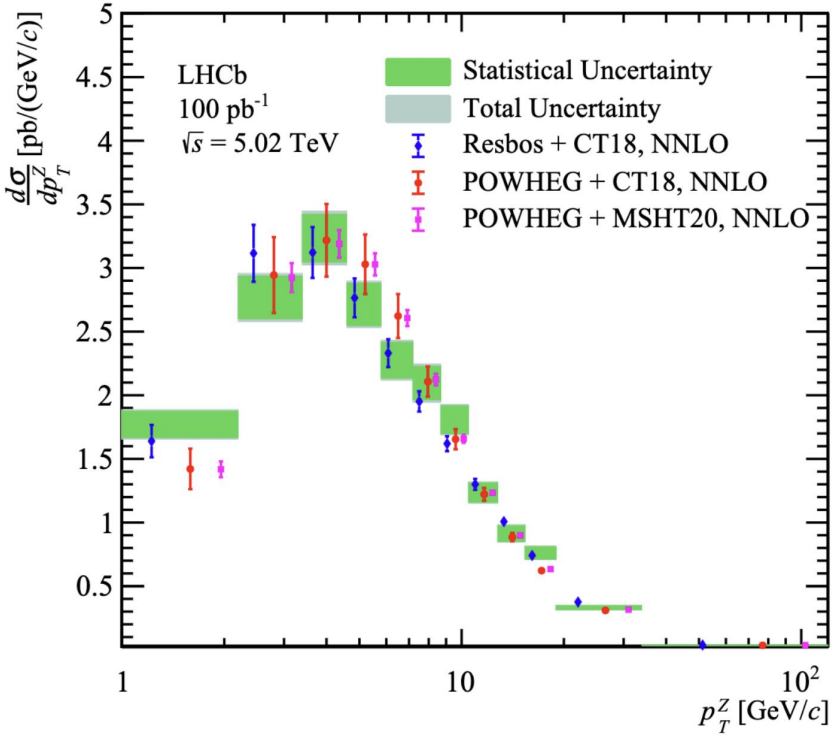
- Single differential cross-section – Z boson rapidity y^Z :
  - Consistent with theoretical predictions.
  - Difference observed at lowest and highest rapidity bins due to the statistical fluctuations

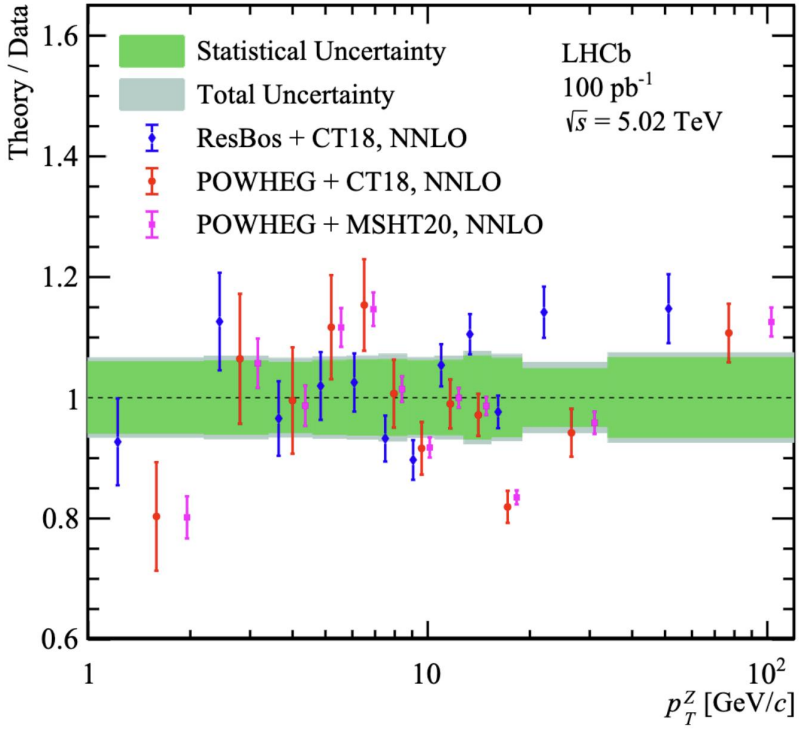




Z Production Cross-section Measurement

- Single differential cross-section – Z boson transverse momentum p_T^Z
  - Consistent with theoretical predictions.
  - Difference observed at low p_T^Z region



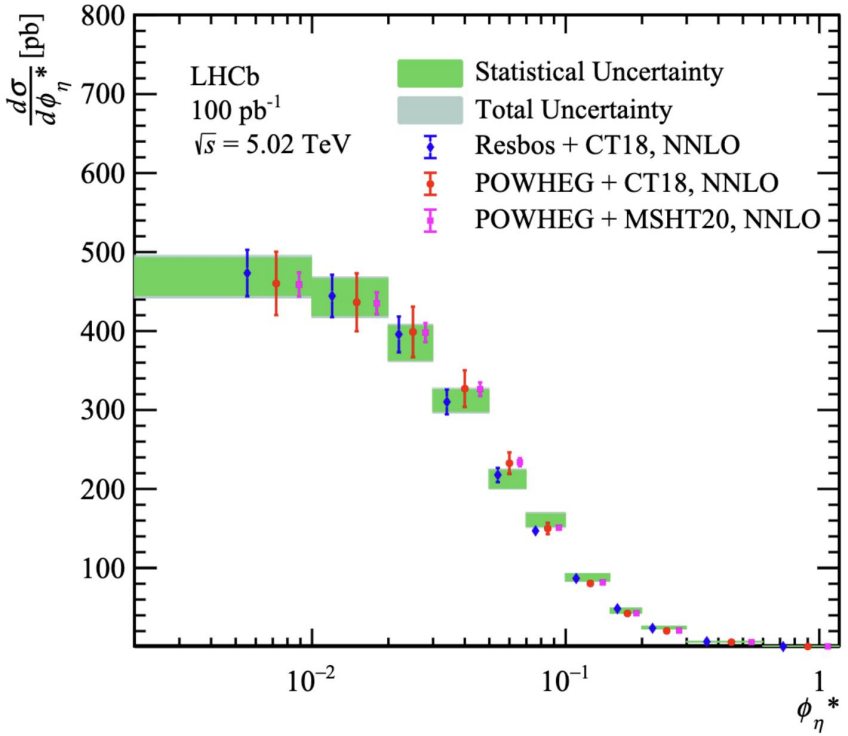


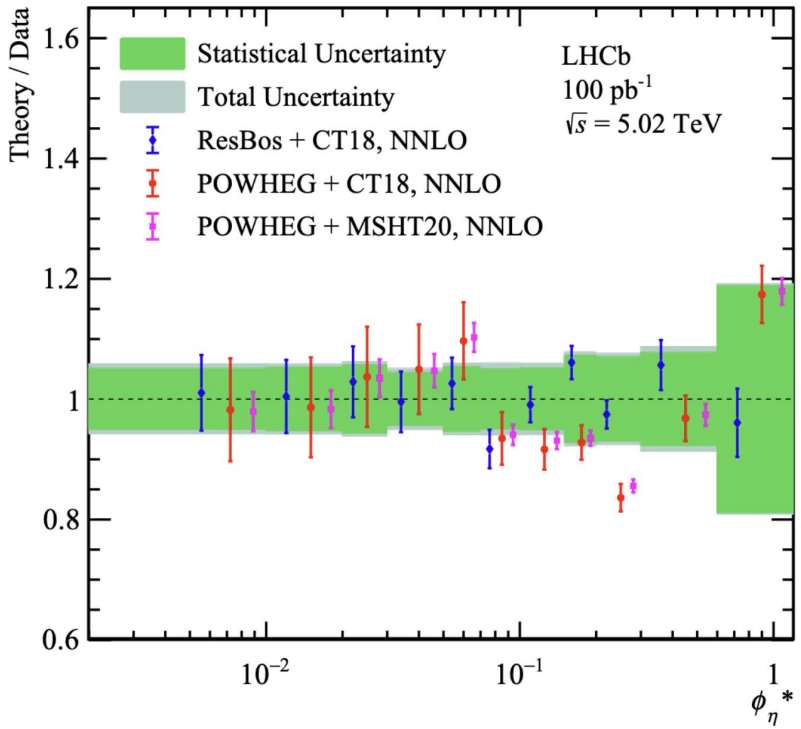
Z Production Cross-section Measurement

- Single differential cross-section - ϕ_η^*:
  - Consistent with theoretical predictions.
  - ϕ_η^* is equivalent to p_T^Z, but less impacted by detector resolution effects

$$\phi_\eta^* = tan[(\pi - \Delta\phi^{ll})/2]/cosh(\Delta\eta^{ll}/2)$$

Eur.Phys.J.C71,1600(2011)



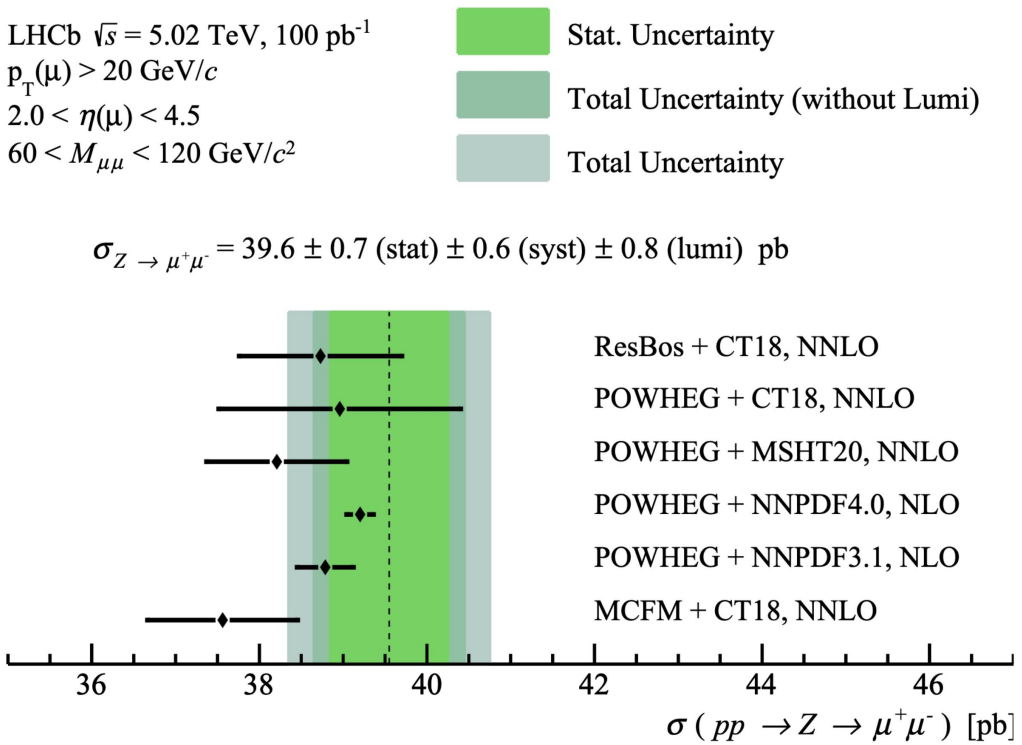


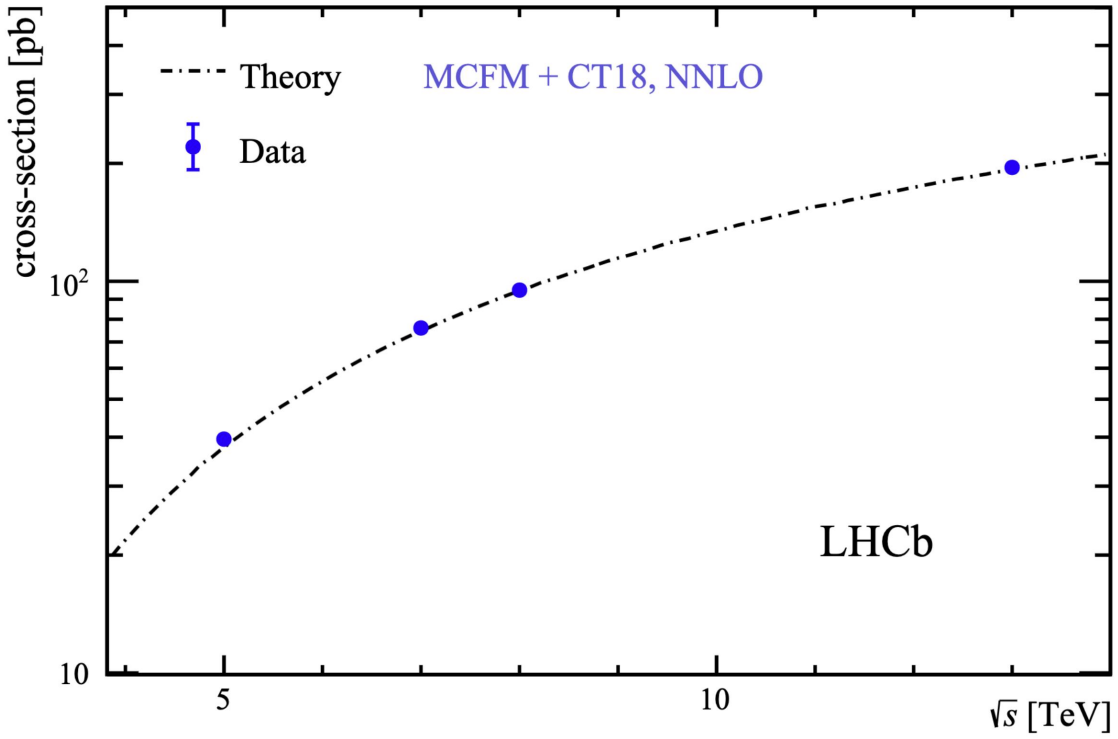
Z Production Cross-section Measurement

- Integrated cross-section at 5.02 TeV in the forward region:

$$\sigma_{Z\to\mu^+\mu^-} = 39.6 \pm 0.7\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.8\,(\text{lumi})\ \text{pb}$$

  - The MCFM predictions are consistent with current measurements of the Z boson at different energies





Z Production Cross-section Measurement

- Update of nuclear modification factors at 5.02 TeV
  - The first Z boson production measurement in pPb collisions : JHEP 09(2014)030

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

$$\sigma_{Z\to\mu^+\mu^-}(\text{bwd}) = 10.7^{+8.4}_{-5.1}(\text{stat.}) \pm 1.0(\text{syst.})\ \text{nb}$$

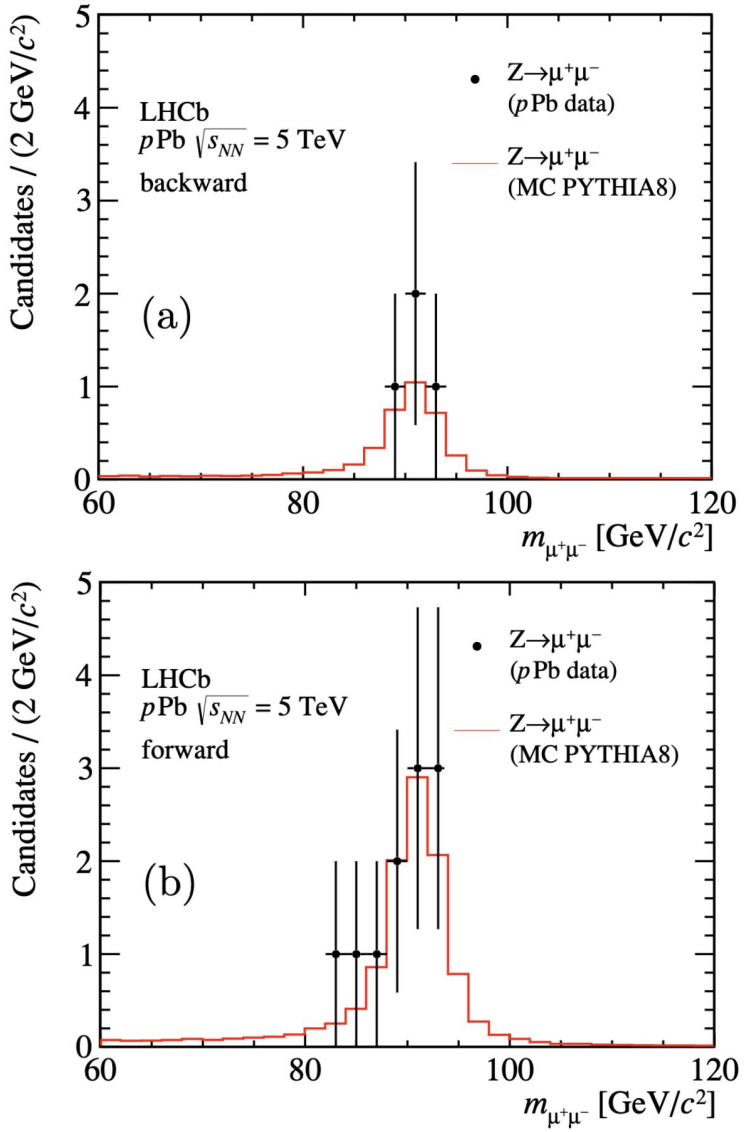
  - With latest results in pp collisions, the NMF in the forward $(1.53 < y^*_\mu < 4.03)$ and backward $(-4.97 < y^*_\mu < -2.47)$ region are first measured as :

$$R^{\text{F}}_{pPb} = 1.2^{+0.5}_{-0.3}\,(\text{stat}) \pm 0.1\,(\text{syst}) \qquad R^{\text{B}}_{pPb} = 3.6^{+1.6}_{-0.9}\,(\text{stat}) \pm 0.2\,(\text{syst})$$

  - The theoretical predictions are :

$$R^{\text{F, theo.}}_{p\text{Pb}} = 0.906^{+0.002}_{-0.007} \qquad R^{\text{B, theo.}}_{pPb} = 0.929^{+0.011}_{-0.028}$$

  $\Longrightarrow$ about 2.3 sigma difference mainly due the low statistics



Summary

- Highlights of last year's LHCb measurements using Z boson as probe:
  - ✓ The first study of the angular coefficients of Drell-Yan $\mu\mu$ pairs in pp collisions at 13 TeV in the forward region
  - ✓ The first measurement of Z boson production cross-section in pp collisions at 5.02 TeV in the forward region
  - ✓ The first measurement of nuclear modification factor in pPb collisions at 5.02 TeV in the forward region

- **A lot of anlayses are working in progress for new exciting measurements ！**
  - W cross-section @ 13 TeV
  - Zee cross-section @ 13.6 TeV
  - Z + jets cross-section @ 13.6 TeV
  - …

Many thanks for your attention !