W-mass and Z-production at LHCb

La Thuile 2022

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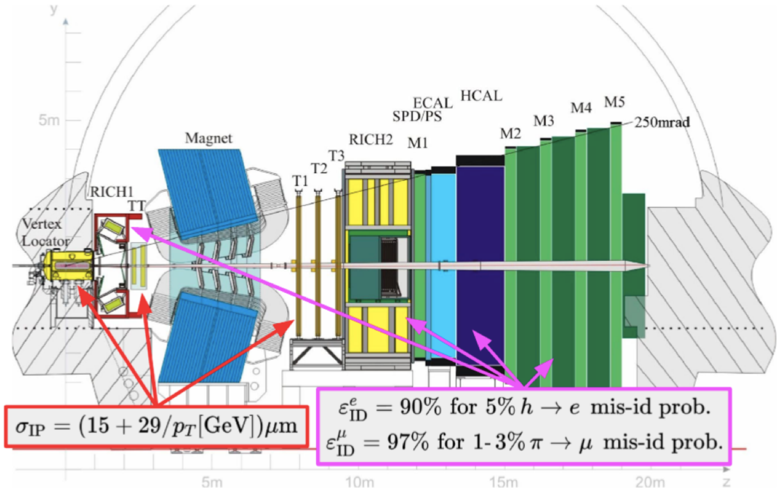
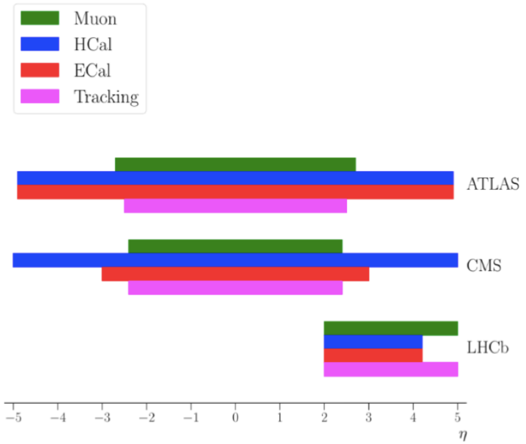
On behalf of the LHCb collaboration

LHCb detector

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

- 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**

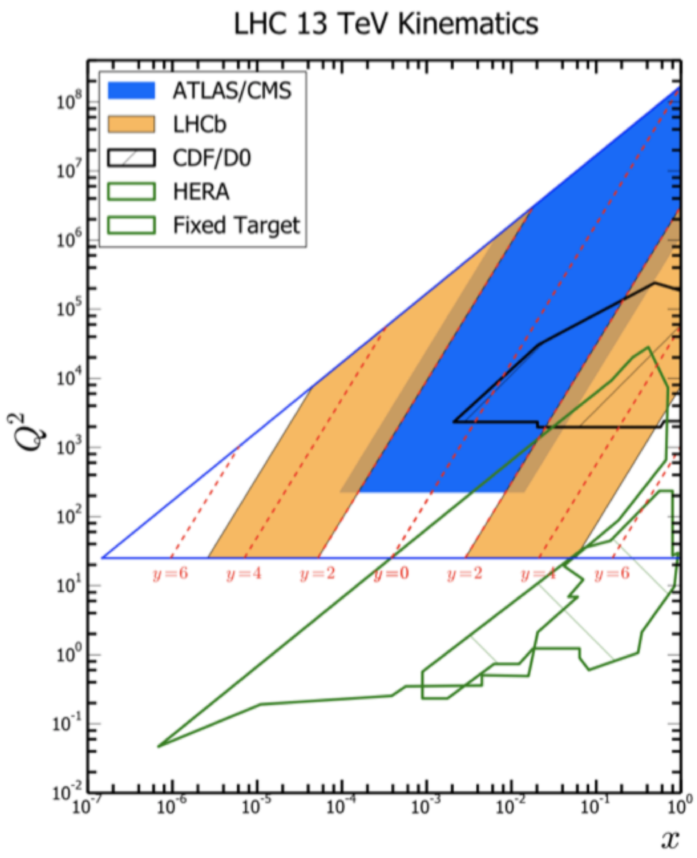




W and *Z* physics at LHCb

- LHCb has already delivered a strong program of physics with W and Z boson mainly probing QCD

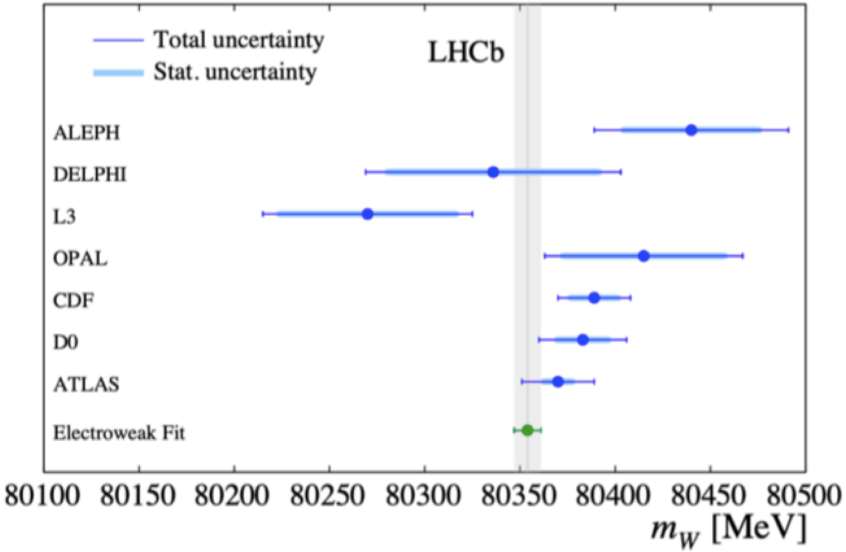
- LHCb detector provides access to PDFs
  - ➢ High Bjorken-x region
  - ➢ Low Bjorken-x region: has not been probed directly at electroweak energy scales before



m_W - Introduction

- Long term goal: close gap in precision between direct and indirect determinations of the m_W
- Global EW fit provides prediction with 7 MeV precision ~ almost half the uncertainty of the PDG average of direct measurement (12 MeV)
- Most precise measurements at LHC to data achieve 19 MeV precision

[JHEP 01 (2022) 036]



m_W - at LHCb

- High precision measurement of m_W is possible at LHCb, PDF systematic uncertainty can be reduced **by a factor 2**
- Sensitivity to the m_W by carefully measuring the muon p_T
- Simulation weighted in 5D

Unpolarized part: POWHEG + Pythia8

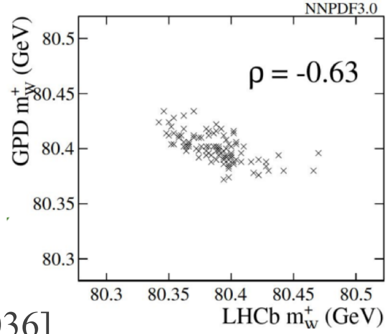
$$\frac{d\sigma}{dp_T^W\, dy\, dM\, d\cos\vartheta\, d\varphi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^W\, dy\, dM}$$

(At order α_s^2)

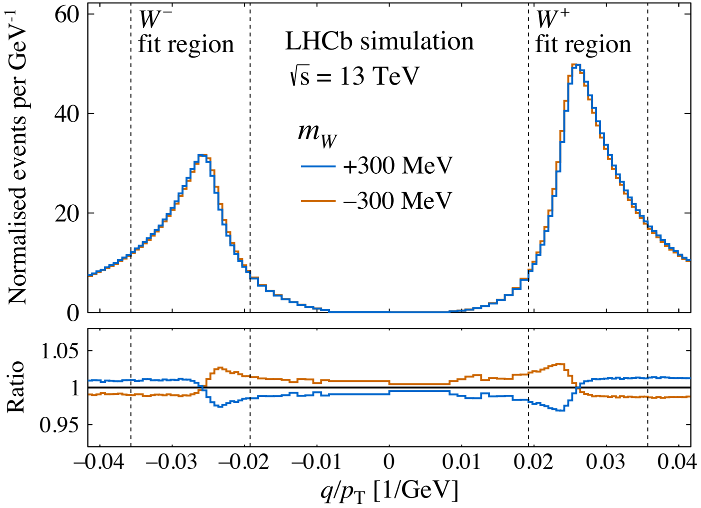
$$\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1 \sin 2\vartheta\cos\varphi + A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta + A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\}$$

Angular part: DYTurbo

[Eur. Phys. J. C 75, 601 (2015)]



[JHEP 01 (2022) 036]



m_W - Uncertainties

[JHEP 01 (2022) 036]

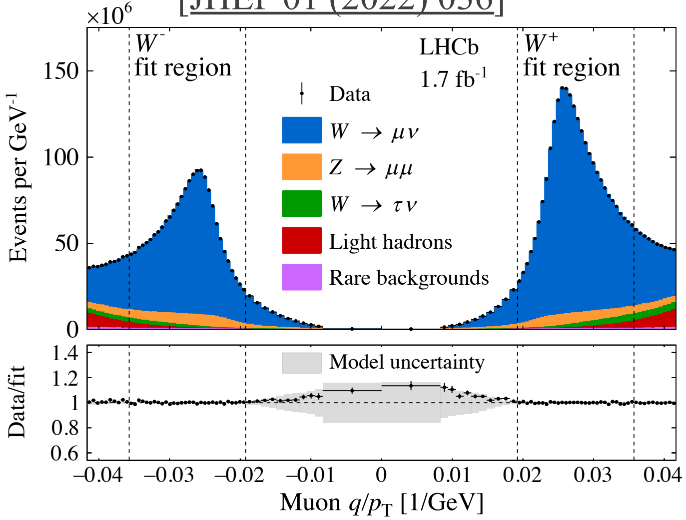
Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

- Parton distribution functions (9) → Average of NNPDF31, CT18, MSHT20
- Transverse momentum model (11) → **Envelope from five different models**
- Angular coefficients (10) → Uncorrelated scale variation
- QED FSR model (7) → **Envelope of the QED FSR from Pythia8, Photos and Herweig7**
- Experimental uncertainties (7, 6, 4, 2) → Includes statistical uncertainties, details of the methods (e.g. binning, smoothing)

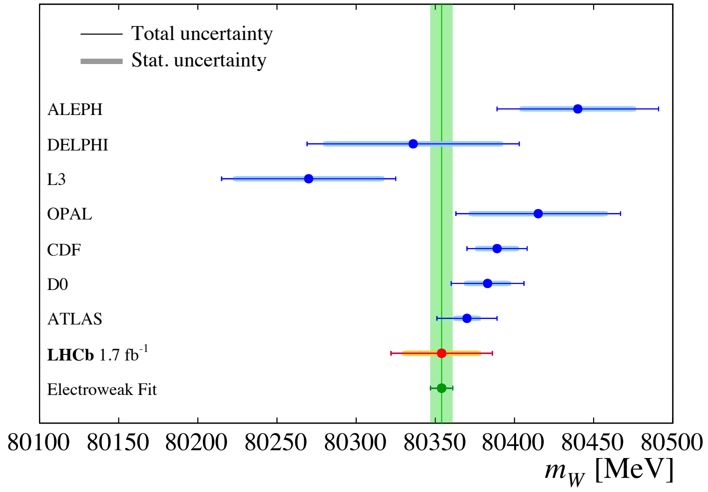
m_W - Results

- LHCb achieves a precision of ~32 MeV using roughly 1/3 of the Run-II dataset
- An overall precision < 20 MeV is achievable with all existing LHCb data

[JHEP 01 (2022) 036]



[JHEP 01 (2022) 036]



$$m_W = 80354 \pm 23_{\text{stat.}} \pm 10_{\text{exp.}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Z production cross-section - Strategy

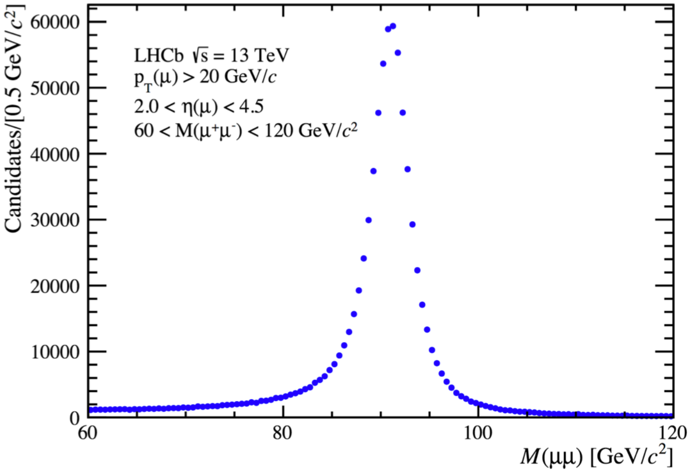
- Datasets: 2016, 2017 and 2018 data: $\mathbf{5.1 \pm 0.1}\ fb^{-1}$
- Very high purity, N_{bkg} / N_{sig} ~2%

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

fiducial region

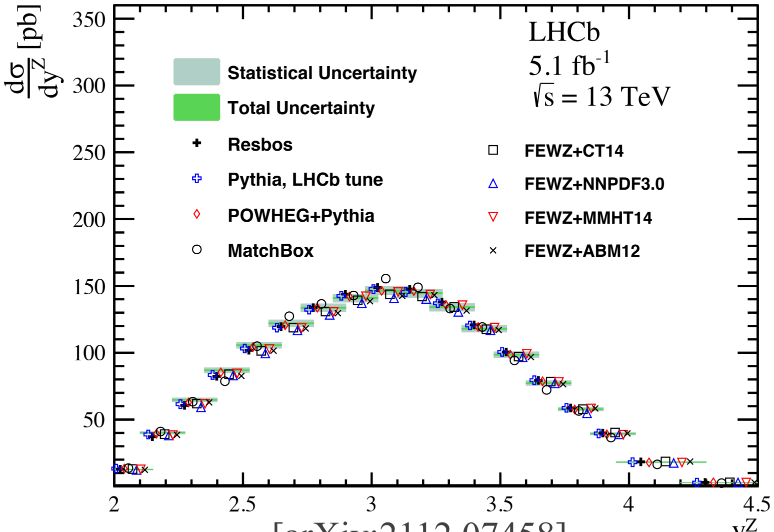
$\mu^\pm$	di-muon
$p_T > 20\ \mathrm{GeV}/c$	
$2 < \eta < 4.5$	$60 < M_{\mu^+\mu^-} < 120\ \mathrm{GeV}/c^2$

[arXiv:2112.07458]

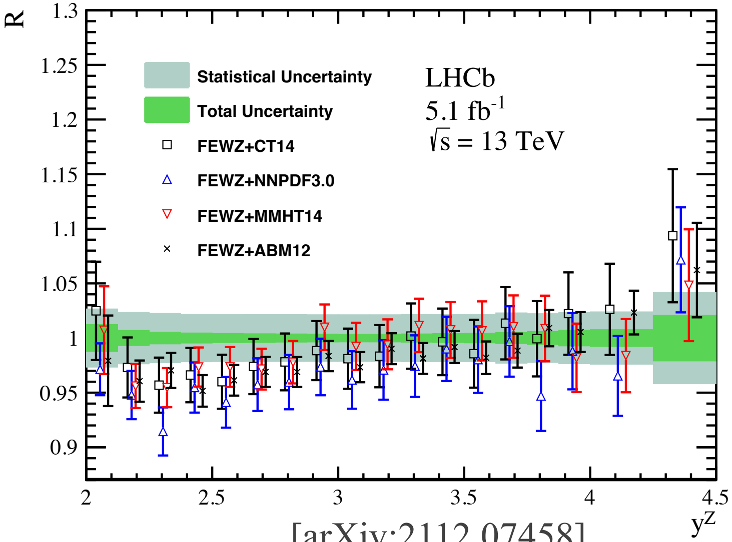


Z differential cross section: *Z* - *y*

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



[arXiv:2112.07458]

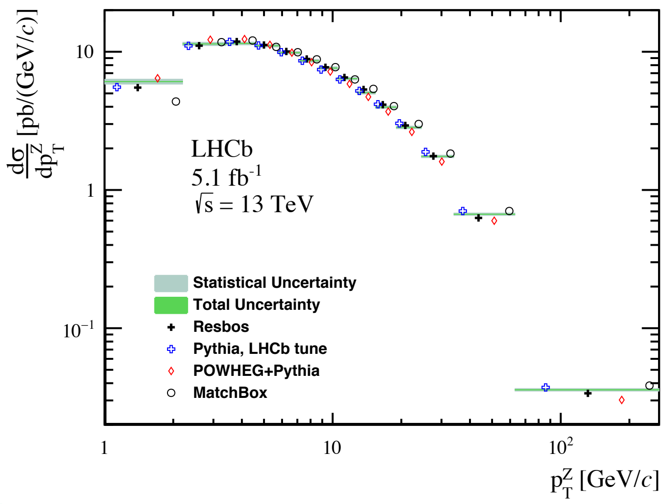


[arXiv:2112.07458]

Z differential cross section: Z- p_T and ϕ_η^*

- ϕ_η^*: the scattering angle of the muons with respect to the proton beam direction in the rest frame of the dimuon system
- Reasonable agreement between data and predictions
- Provide a stringent test on different QCD calculations

[arXiv:2112.07458]



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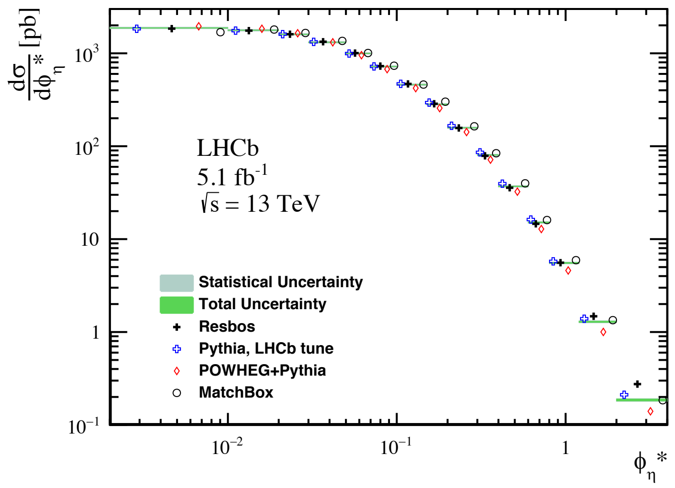
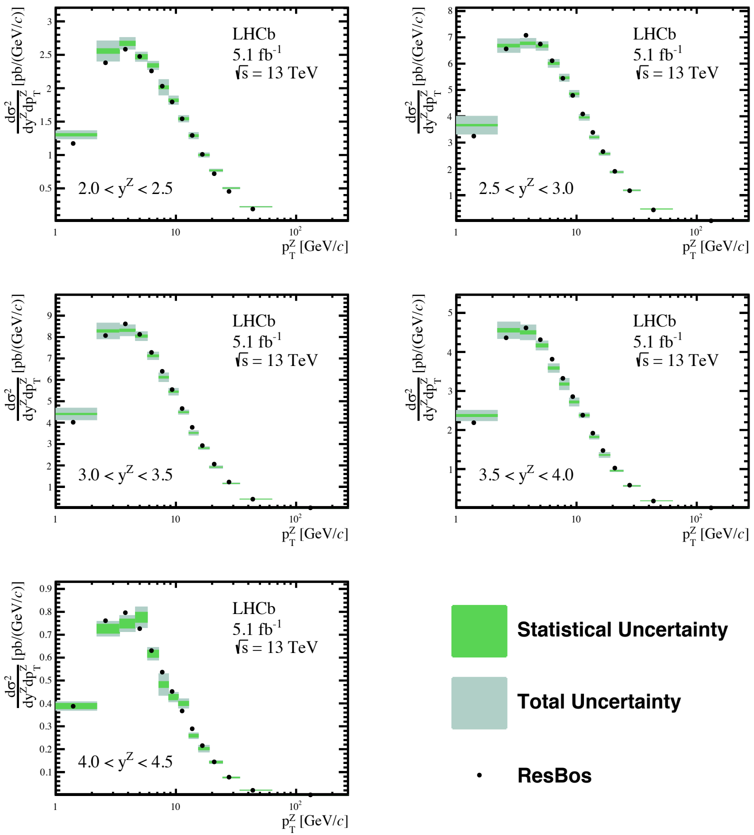


Z double differential cross-section

[arXiv:2112.07458]

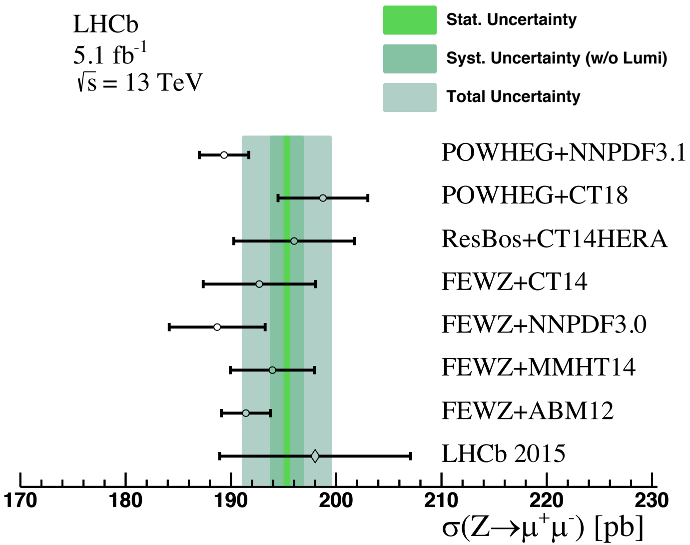
- The first double differential cross-section measurement in the forward region
- No significant deviations are seen between measurements and the theoretical predictions



Z Integrated cross section

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

$$\sigma(Z \to \mu^+\mu^-) = 195.3 \pm 0.23\,(\text{stat.}) \pm 1.5\,(\text{sys.}) \pm 3.9\,(\text{lumi.})\ \text{pb}$$



[arXiv:2112.07458]

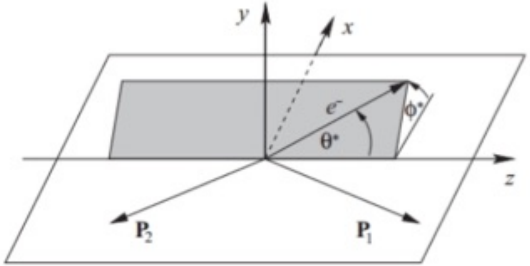
[arXiv:2112.07458]

Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.03
Alignment & calibration	-
Efficiency	0.77
Closure	0.06
FSR	0.04
Total Systematic (excl. lumi.)	0.77
Luminosity	2.00
Total	2.15

Z angular coefficient measurement - 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 lepton decay angle $(cos\theta, \phi)$ in Collins-Soper frame

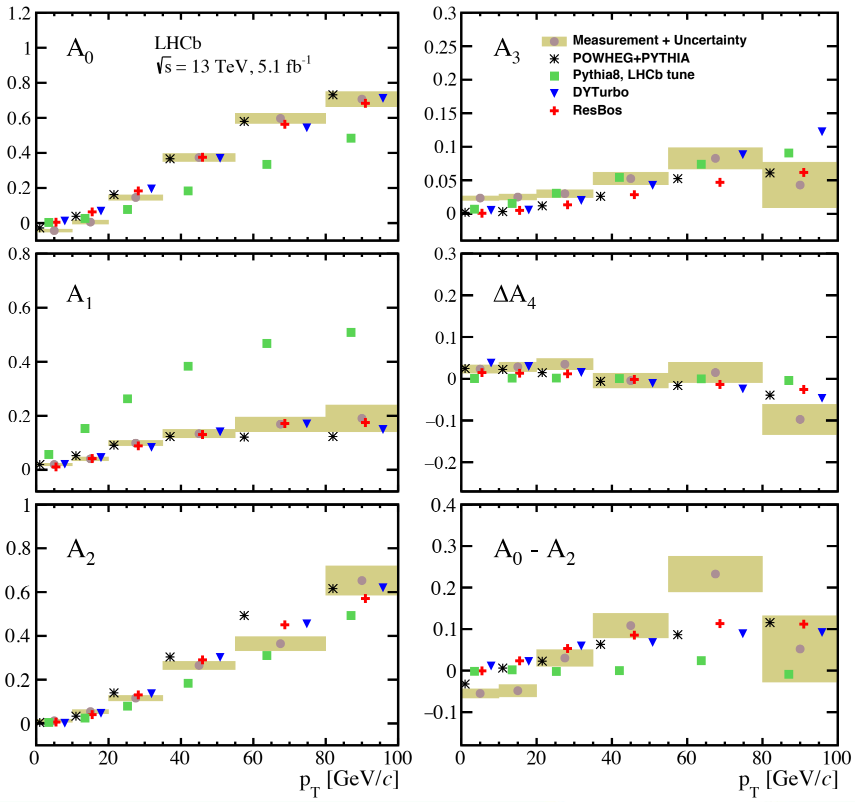
$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta) \longrightarrow \textit{LO term}$$
$$+ \frac{1}{2}A_0(1-3\cos^2\theta) \longrightarrow \cos^2\theta: \textit{higher order term}$$
$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi \longrightarrow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



Z angular coefficient measurement - p_T dependent results

[arXiv:2203.01602]

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

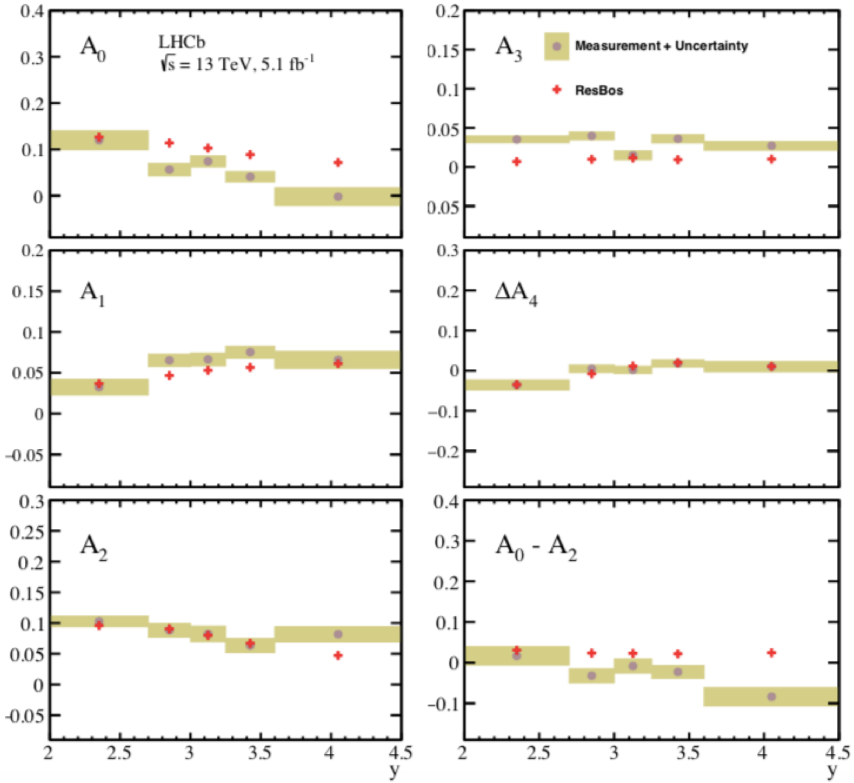


Z angular coefficient measurement - y dependent results

[arXiv:2203.01602]

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

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

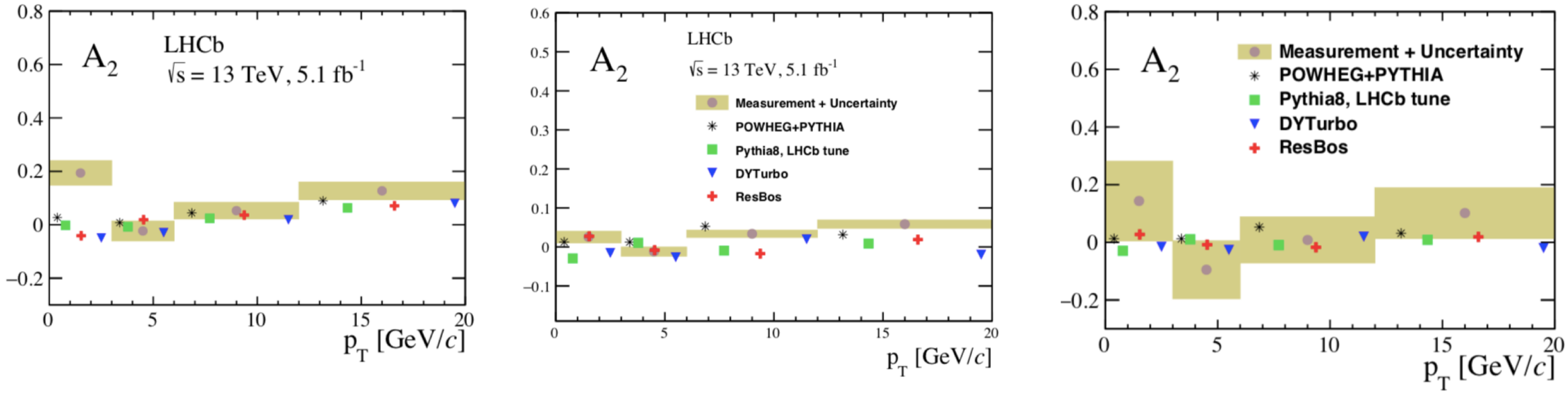


Z angular coefficient measurement - Boer-Mulders TMD

- A_2 is sensitive to the Boer-Mulders transverse momentum dependent PDFs (TMD)
- The measured A_2 values 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

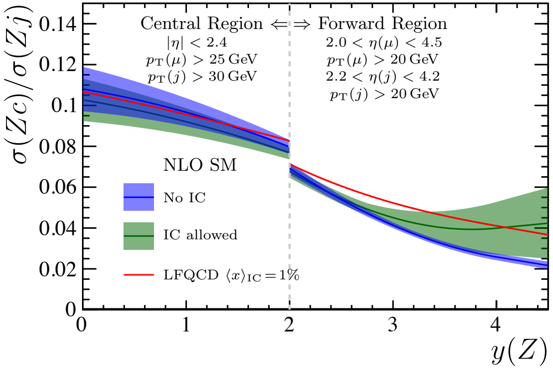
[arXiv:2203.01602]

$50 - 75\ \mathrm{GeV}/c^2$ | $75 - 105\ \mathrm{GeV}/c^2$ | $105 - 120\ \mathrm{GeV}/c^2$



Z boson produced in association with charm - Introduction

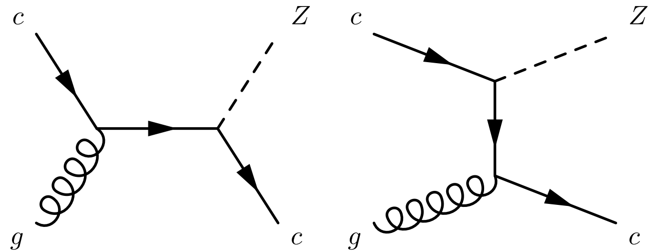
- Extrinsic charm content of the proton arises due to perturbative gluon radiation
- Proton may also have an intrinsic charm (IC) content bound to valance quarks
- Measure $\boldsymbol{\sigma(Z_c)/\sigma(Z_j)}$
  - IC would give significant enhancement over no-IC at high $y(Z)$
  - **IC-allowed model at high $y(Z)$ is largely unconstrained**
  - Many jet-related systematics cancel in the ratio



[arXiv:2109.08084]

$$|\text{proton}\rangle = |uud\rangle + \epsilon|uudc\bar{c}\rangle \text{ ?}$$

$$\epsilon \lesssim \mathcal{O}(\%)$$



Z boson produced in association with charm - Systematics

- Leading systematic uncertainty due to c-tagging calibration

[LHCb-DP-2021-006]

[arXiv:2109.08084]

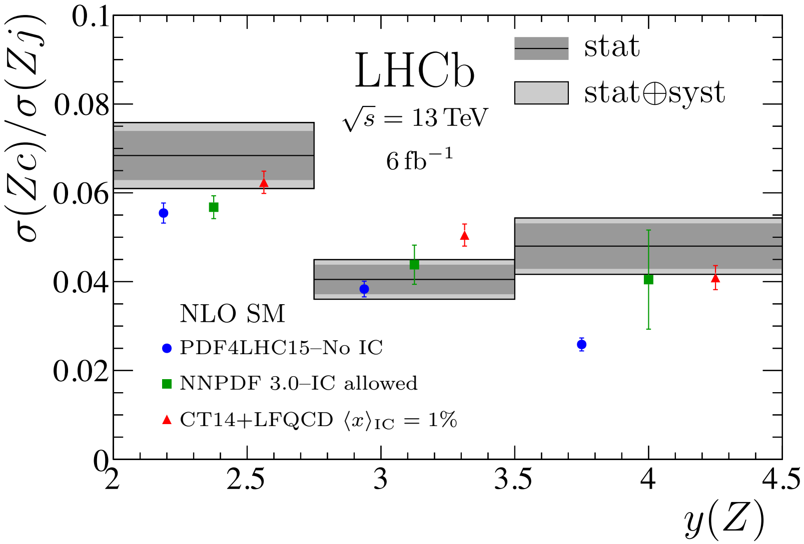
Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_{T} scale & resolution	1%
Total	8%

fiducial region

Z bosons	$p_{\mathrm{T}}(\mu) > 20\,\mathrm{GeV}$, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120\,\mathrm{GeV}$
Jets	$20 < p_{\mathrm{T}}(j) < 100\,\mathrm{GeV}$, $2.2 < \eta(j) < 4.2$
Charm jets	$p_{\mathrm{T}}(c\text{ hadron}) > 5\,\mathrm{GeV}$, $\Delta R(j, c\text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

Z boson produced in association with charm - Results

[arXiv:2109.08084]



- Clear enhancement in highest y bin
- Inconsistent with NO-IC theory at **>3σ**
- More consistent with expected effect form $|uudc\bar{c}\rangle$ component predicted by LFQCD
- Current results are statistically limited, Run-III dataset will allow for finer binning

- PDF4LHC15: purely extrinsic
- NNPDF3.0 IC: allows global fit to include IC where not excluded by existing measurements, uncertainties reflect current experimental limits
- LFQCD: with fixed IC contribution, uncertainties reflect model assumptions

Summary

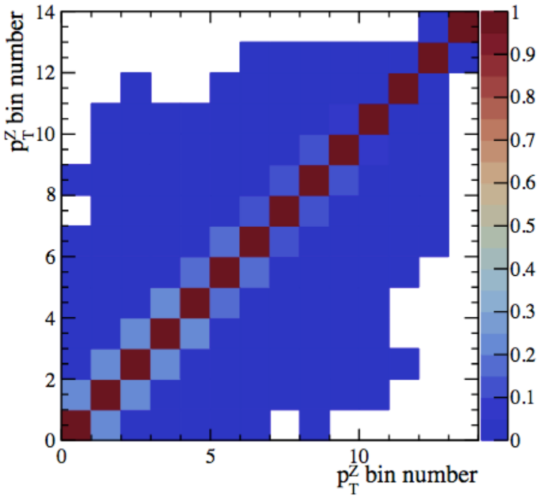
- The LHCb detector has proved its capability to do **high-precision** measurements of EW observables
- Probe perturbative QCD and EW theory in a novel region of phase space as functions of the Bjorken-x of the proton and energy scale of the interaction
- Provide important and unique information to the PDFs global fitting, especially in the **large and small x region**
- Last year, four promising analyses about m_W and Z production have been done at LHCb

Back Up

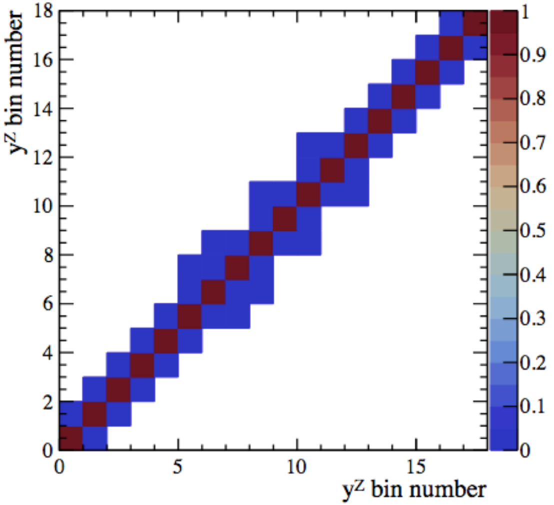
Statistical correlation matrix

- Determined using the simulation events
- Large correlations in low p_T^Z region, small correlations in the high p_T^Z region
- For y_Z and ϕ_η^*, the correlations between different bins are negligible

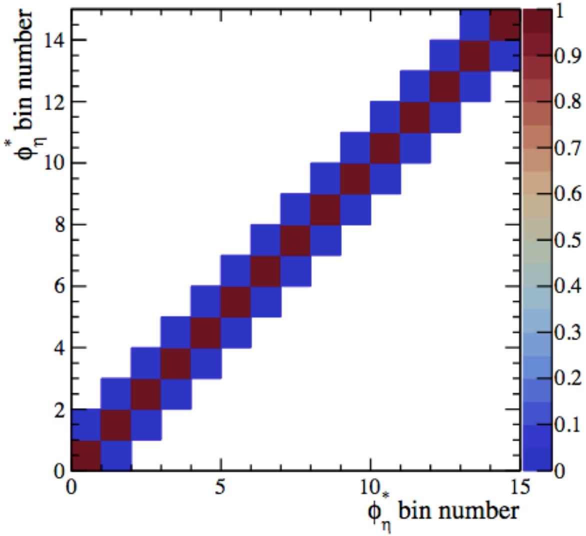
p_T^Z [arXiv:2112.07458]



y_Z



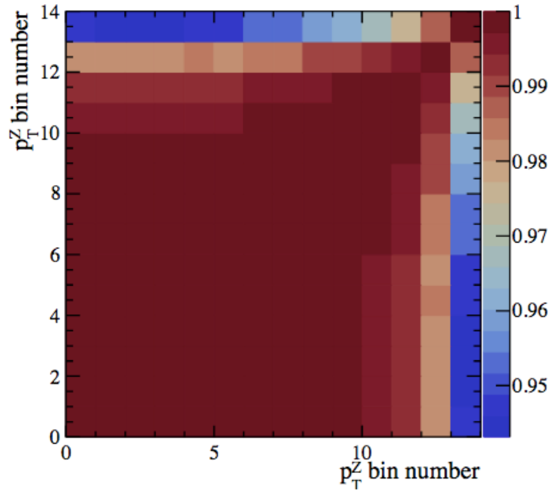
ϕ_η^*



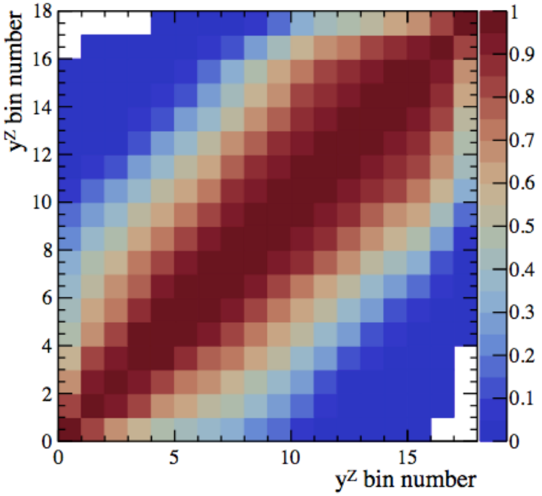
Systematic correlation matrix

- Systematic uncertainties from background, alignment, efficiency closure test, and FSR are considered to be uncorrelated
- Luminosity uncertainties are considered to be 100% correlated [arXiv:2112.07458]

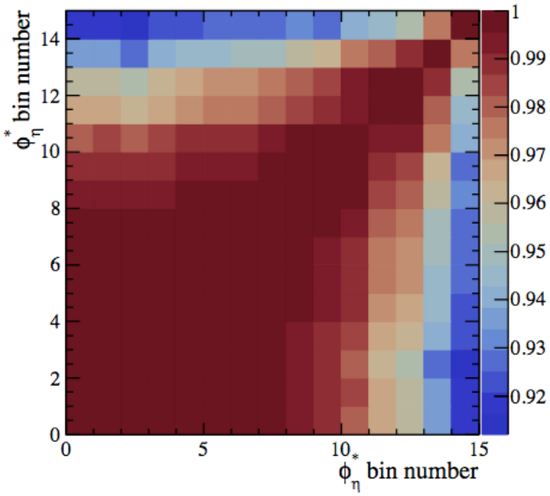
p_T^Z



y_Z



ϕ_η^*



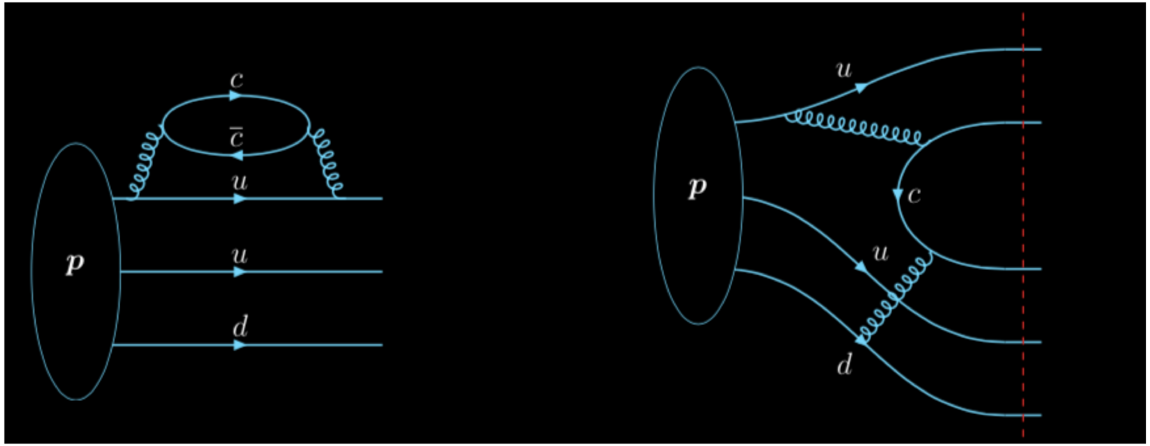
Z boson produced in association with charm – Charm in proton

Extrinsic charm from gluon splitting

- Perturbative
- Short time scales

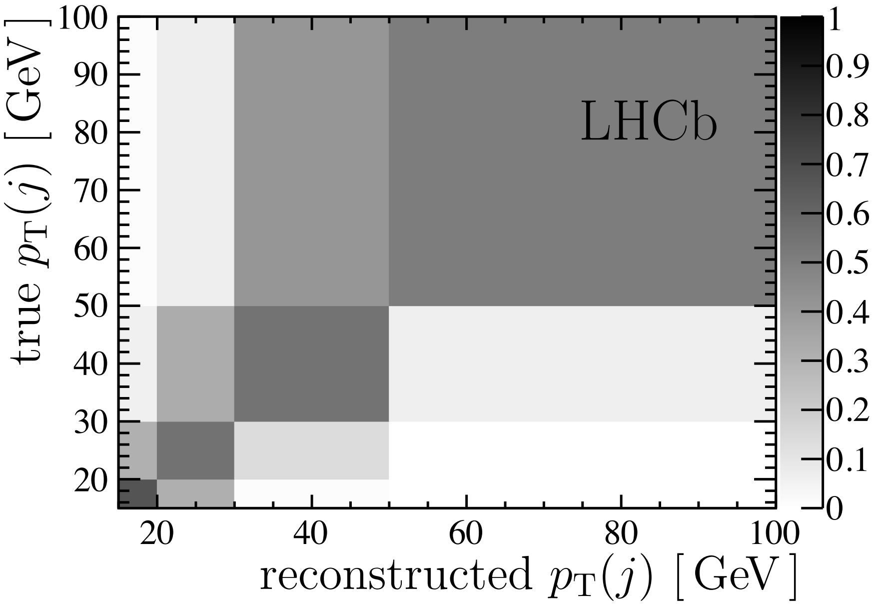
Intrinsic charm

- Bound to multiple valance quarks
- Longer time scales



Z boson produced in association with charm - Detector-response matrix for c-tagged jets

[arXiv:2109.08084]



- The interval-to-interval migration probabilities
- Jets with true (reconstructed) $p_T(j)$ is either <15 GeV/c or >100 GeV/c are included in the unfolding but not shown graphically