Electroweak Physics (*W* and *Z*) at LHCb

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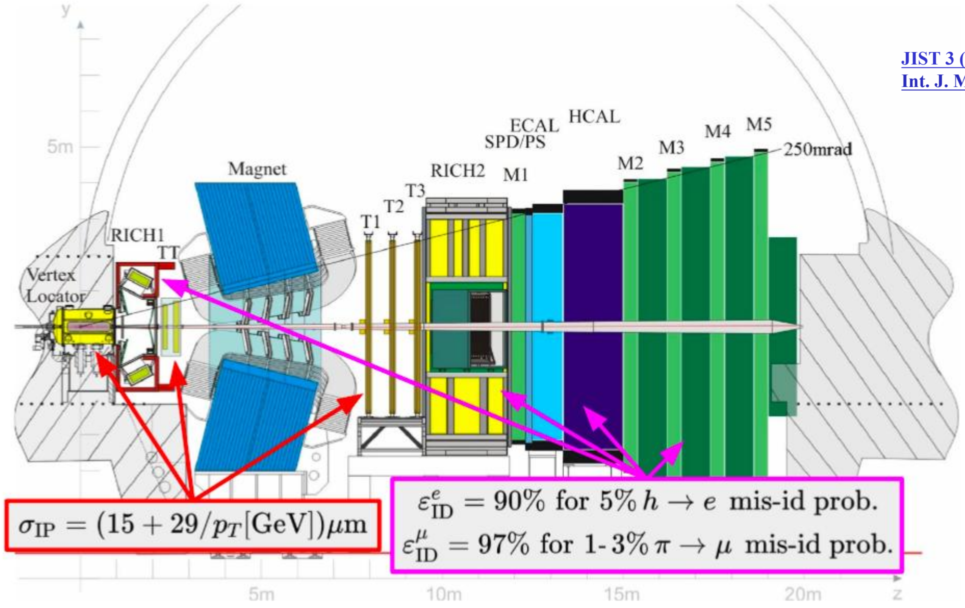
on behalf of the LHCb collaboration
Moriond EW 2023, 23.03

LHCb Detector

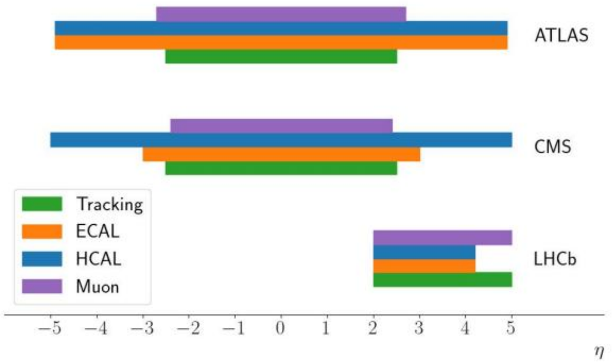
- Single-arm **forward** spectrometer
- Designed for the heavy flavour physics with $\mathbf{2 < \eta < 5}$
- Extended to **EW** measurements: excellent performance of tracking and muon detector



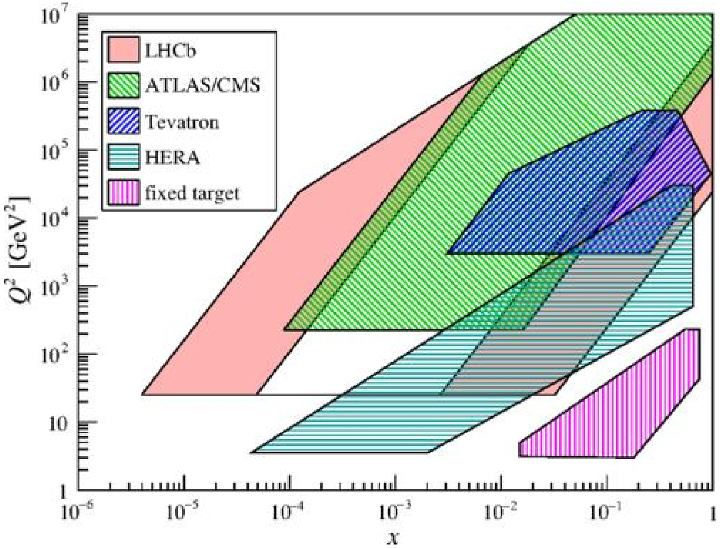
JIST 3 (2008) S08005
Int. J. Mod. Phys. A30(2015) 1530022

Forward Region

- Low pile-up environment
- Forward region: **high/low-x** partons involved



Phys. Rev. D 93, 074008 (2016)



x: parton longitudinal momentum fraction
Q^2: momentum transfer

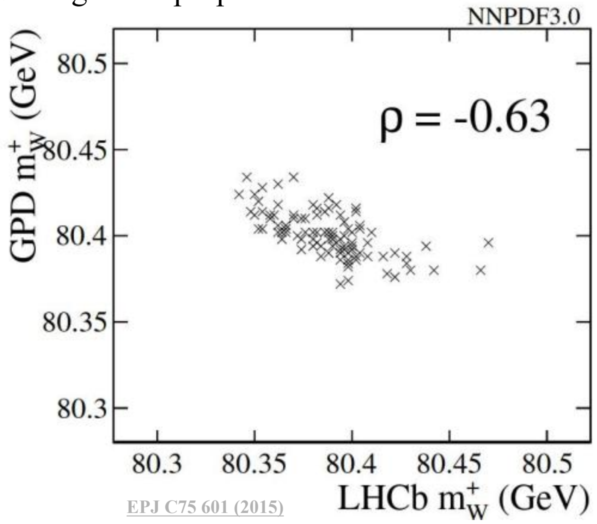
m_W Measurement

- m_W is directly related to electroweak symmetry breaking in the standard model

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F(1 - m_W^2/m_Z^2)(1 - \Delta r)}$$

Δr: loop corrections

GPD: general purpose detector

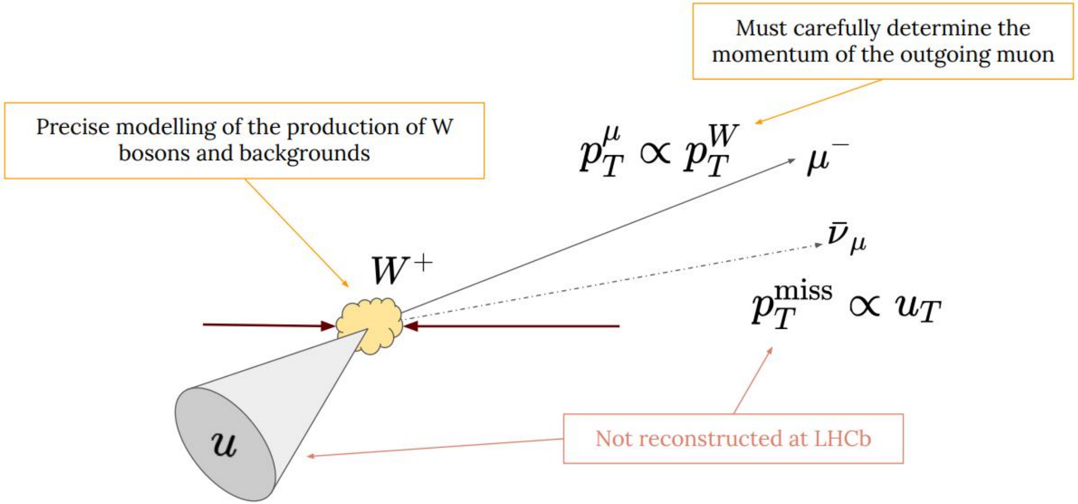


EPJ C75 601 (2015)

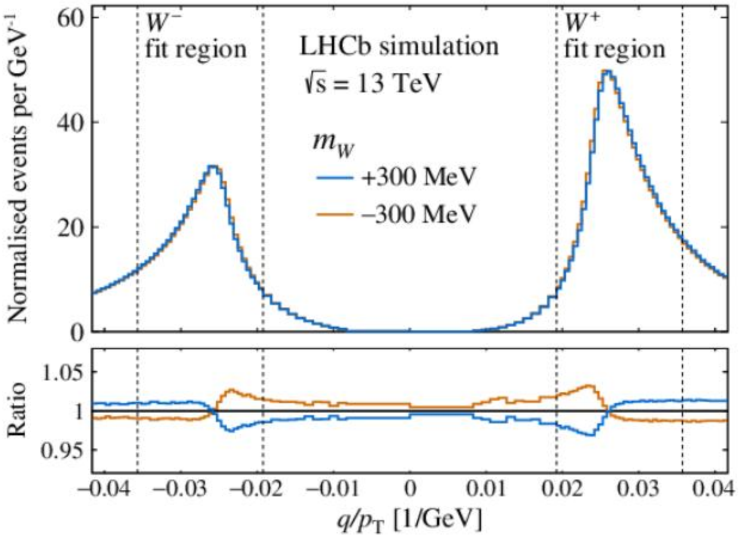
- Uncertainty from PDFs at LHCb is **anticorrelated** to that of ATLAS/CMS ⇒ LHC experiments can achieve a sensitivity closer to the global EW fit (~7 MeV)

m_W: Physics & Detector Modelling

- Measurements based on charged lepton p_T
- m_W determination is highly sensitive to misalignments and miscalibrations of the detector



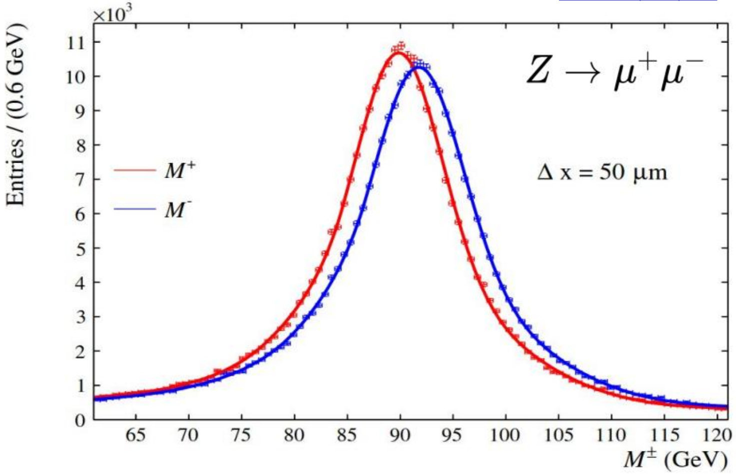
JHEP 01 (2022) 036



m_W at LHCb

- p_T^μ peaks at $\sim m_W/2$, extract m_W in a template fit to the q/p_T^μ distribution

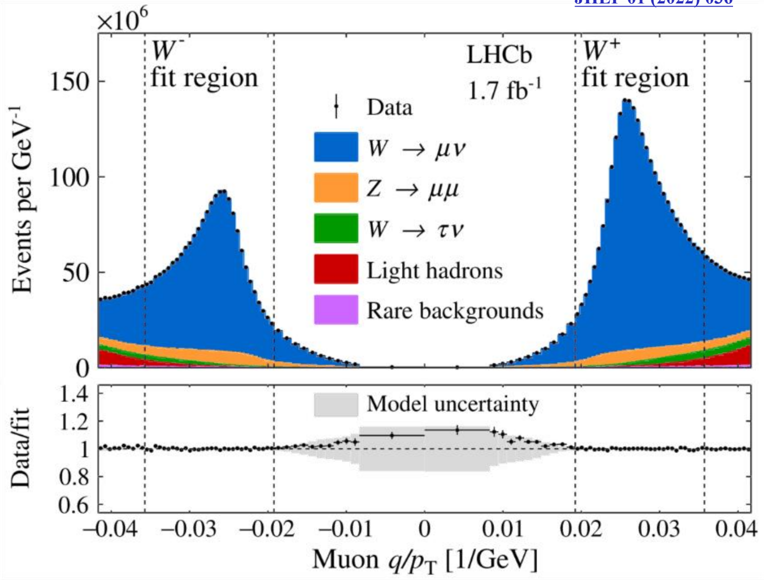
JHEP 01 (2022) 036



$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

Phys. Rev. D 91, 072002

JHEP 01 (2022) 036



m_W: Uncertainties

JHEP 01 (2022) 036

Source	Size (MeV)
Parton distribution functions	**9**
Total theoretical syst. uncertainty (excluding PDFs)	**17**
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Total experimental syst. uncertainty	**10**
Momentum scale and resolution modelling	7
Muon ID, tracking and trigger efficiencies	6
Isolation efficiency	4
QCD background	2
Statistical	**23**
Total uncertainty	**32**

→ average of NNPDF31, CT18 and MSHT20

→ from five different models

→ scale variation

→ envelope of the QED FSR from PYTHIA8 Photos and Herweig

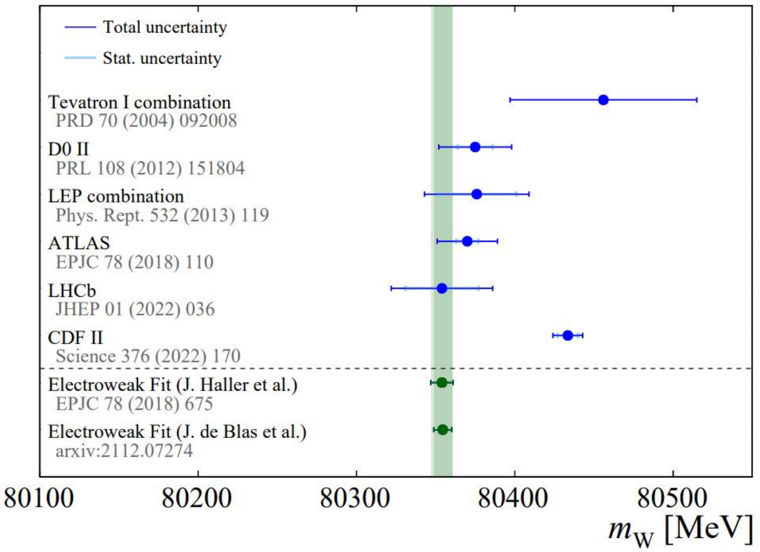
→ statistical uncertainties, details of method (e.g. binning, smoothing)

m_W: Result

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

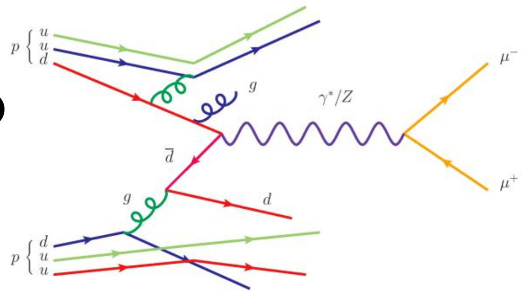
- LHCb achieves a precision of ~ 32 MeV using roughly 1/3 of the Run-II dataset
- Further ~4 fb^{-1} of Run-II data to add → statistical uncertainties ≈ 14 MeV
- Effort now on improving the modelling and reducing the systematic uncertainties
- An overall precision ~ **20** MeV is achievable with all existing LHCb data

LHCB-FIGURE-2022-003



Forward Z Production Cross-Section

- Single gauge boson production
  - Precision tests of the perturbative QCD predictions at NNLO with similar precision experiment/theory $O(1\%)$
  - Measurements at LHCb are particularly important for **constraining u/d quark PDFs at high x region**

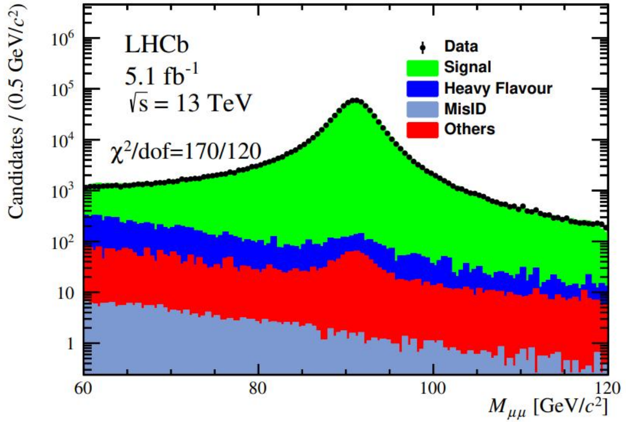


- Z boson production @13TeV at LHCb
  - Datasets: 2016, 2017 and 2018 data, 5.1 ± 0.1 fb^{-1}
  - **Very high purity**, $N_{bkg}/N_{sig} \sim 1.5\%$

fiducial region

μ	Z
$p_T > 20\,GeV/c$	$60 < M_{\mu^+\mu^-} < 120\,GeV/c^2$
$2 < \eta < 4.5$	
$\sigma_P/P < 10\%$	

JHEP 07 (2022) 26



Forward *Z* Differential Cross-Section

- Corrected to the **Born** level in QED

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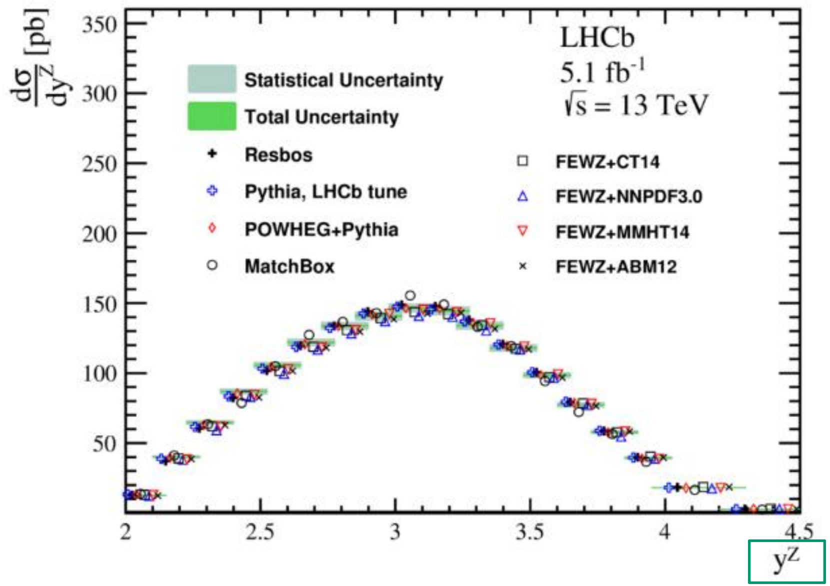

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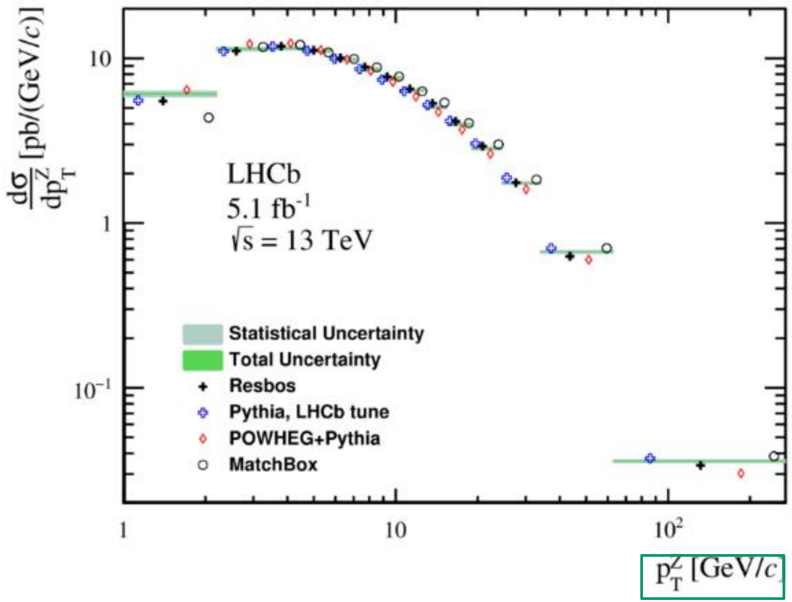

Forward Z Integrated Cross-Section

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

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

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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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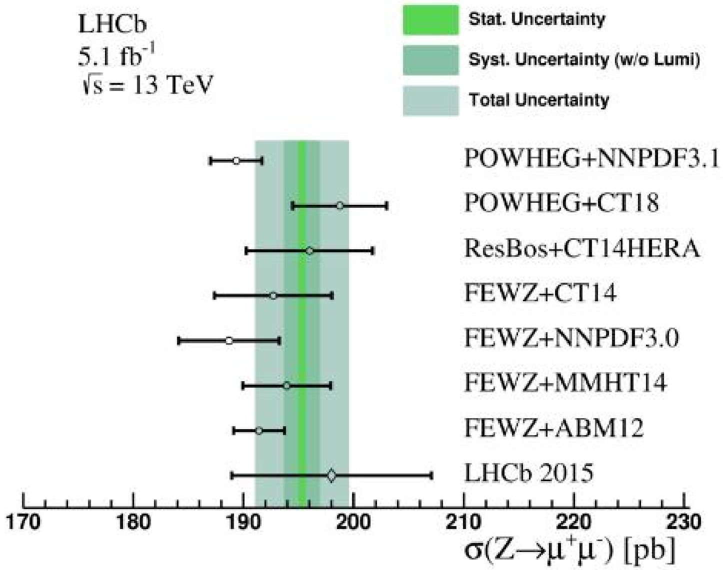


Z Angular Coefficient Measurement

Phys. Lett. B259 (1991) 151
Nucl. Phys. B Proc. Suppl. 23 (1991) 9

- The kinematic distribution of the final-state leptons provides a direct probe of the **polarization** of the intermediate gauge boson
- Study done using LHCb data from 2016, 2017 and 2018

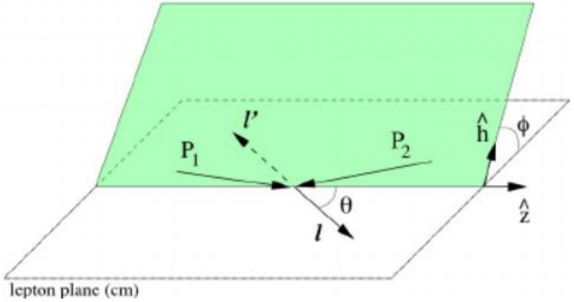
$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta)$$ → *LO term*

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

$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi$$ → *(θ, ϕ) terms*

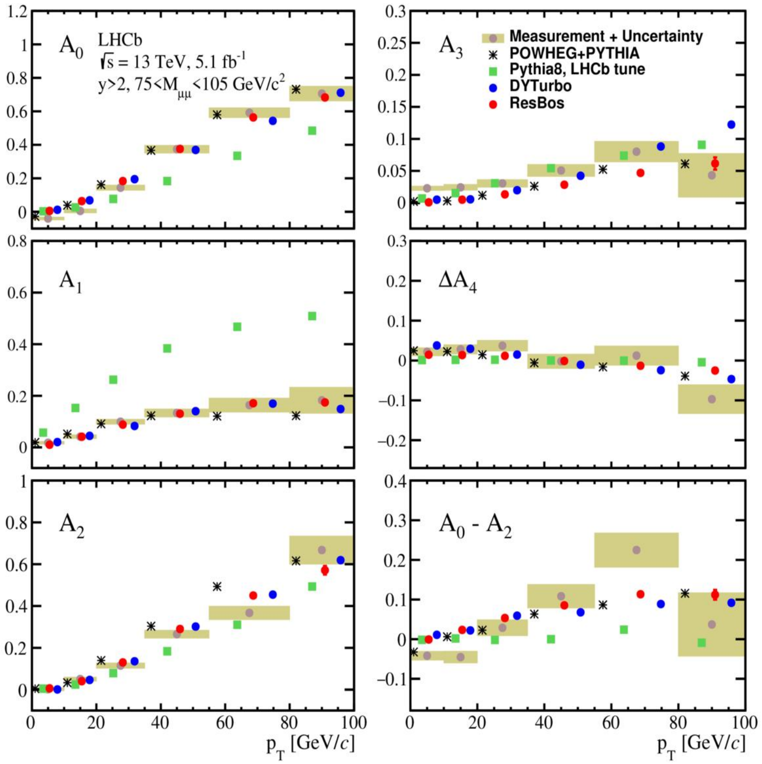
$$+ A_4 \cos\theta$$ → *LO term : determine A_{fb}*

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$ → *very small terms*



A_i - p_T Dependent

Phys. Rev. Lett. 129 (2022) 091801

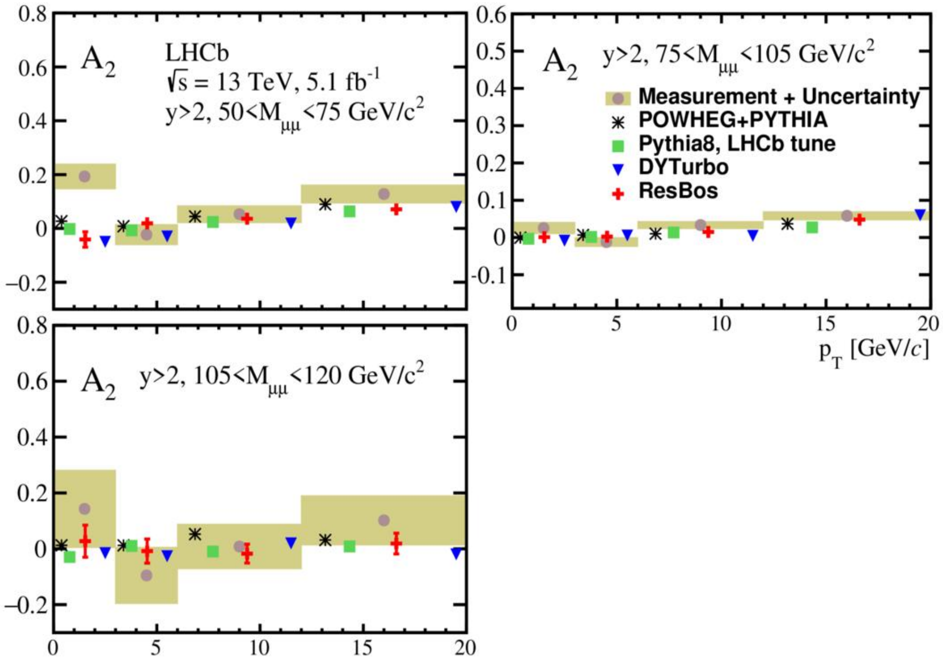


- Measurements are at **Born level**
- The uncertainty is **dominated by statistical uncertainty**
- Interesting violation Lam-Tung relation, $A_0 = A_2$, in agreement with ATLAS [JHEP08(2016)159] and CMS [Phys. Lett. B 750 (2015) 154] results

A_2 - Boer-Mulders TMD

TMD: transvers momentum dependent

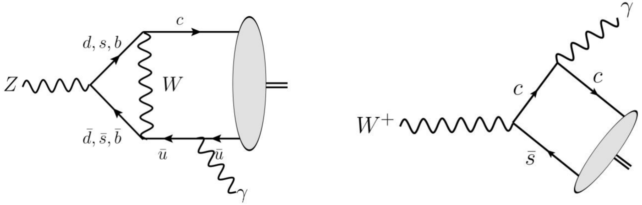
Phys. Rev. Lett. 129 (2022) 091801



- A_2 is sensitive to the TMD PDF, with measurements in multiple mass regions adding sensitivity to the evolution of the TMD PDF with the hard scale
- No phenomenological calculations are available

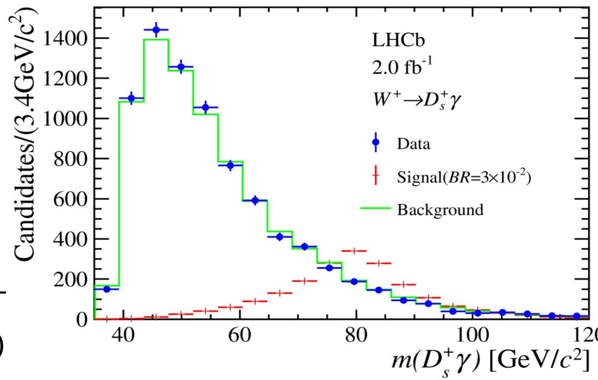
W and Z Rare Decays

- Provide stringent tests of the QCD factorization formalism
- Until now, no hadronic-radiative decay has been observed, the current best limit is $\mathcal{B}(Z \to \phi\gamma) < 9 \times 10^{-7}$



- Search $W^+ \to D_s^+(\to K^+K^-\pi^+)\,\gamma$ and $Z \to D^0(\to K^-\pi^+)\,\gamma$ at LHCb
  - Excellent tracking performance and good particle identification
  - With better resolution of photon angle compared to the energy measurement, pseudomass has better performance than invariant mass

arXiv:2212.07120

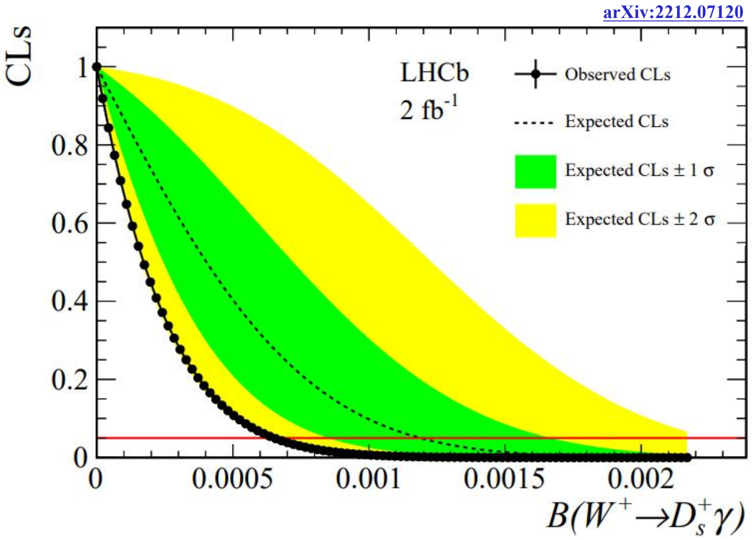


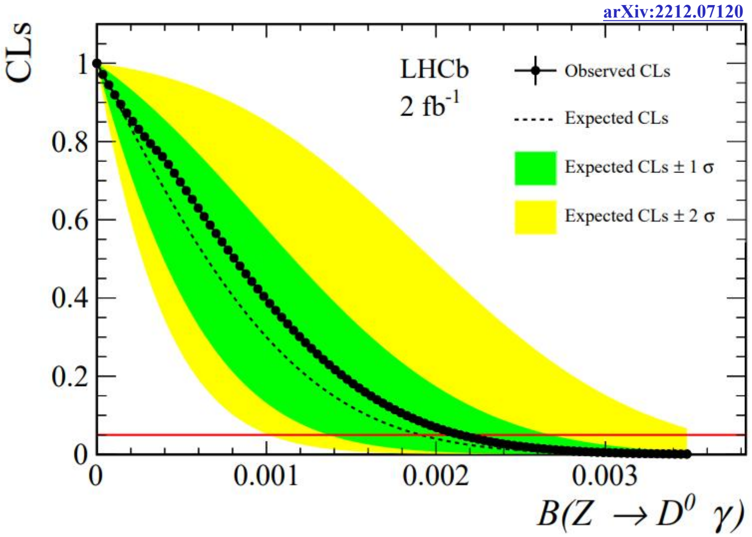
Eur.Phys.J.C 81 (2021) 3, 251

$$M(M\gamma) = \sqrt{2p^M p_T^\gamma \frac{p^\gamma}{p_T^\gamma}(1 - \cos\theta)}$$

W and Z Rare Decays - Results

- No significant signal is observed above background
- $\mathcal{B}(W^+ \to D_s^+\gamma) < 6.5 \times 10^{-4}$ at 95% C.L., the **best limit** to date
- $\mathcal{B}(Z \to D^0\gamma) < 2.1 \times 10^{-3}$ at 95% C.L., the **first** search





Summary

- LHCb has an extensive program on EW precision measurement, only a list of the most recent results are shown here, the whole list can be seen at this link

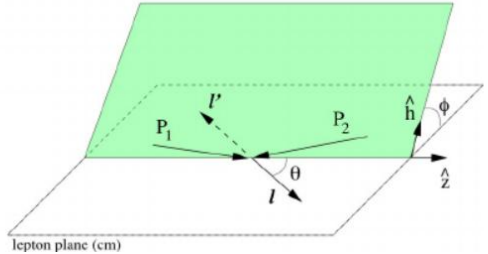
- LHCb can provide very useful data to further tune the generators, understand QCD and EW effects and provide important and unique information to the PDFs global fitting

- What can be expected (soon?)
    - Weak mixing angle with full Run-II dataset
    - W boson mass with full Run-II dataset
    - Test of lepton universality with $\frac{B(W\to\tau\nu_\tau)}{B(W\to\mu\nu_\mu)}$

Back Up

Bore-Mulders TMD PDF

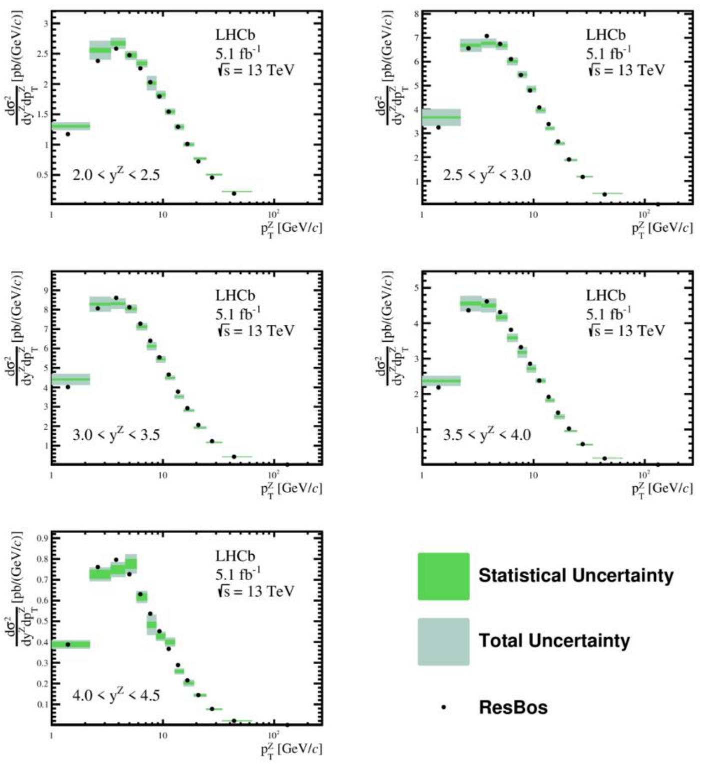
- Bore-Mulders function Phys. Rev. D 57 (1998), 5780
  - Describes a correlation between a transversely polarized quark (antiquark) in an unpolarized proton and the quarks' own nonperturbative momentum with the proton
    - Lead to an azimuthal **$\cos(2\theta)$** dependence in Drell-Yan



- Transvers Momentum Dependent PDFs: TMD
  - The general PDFs describes the parton inside a proton
  - Admit a finite quark transverse momentum k_T
  - **Correlation between parton momentum and hadron spin**

Z Double Differential Cross-Section

JHEP 07 (2022) 26



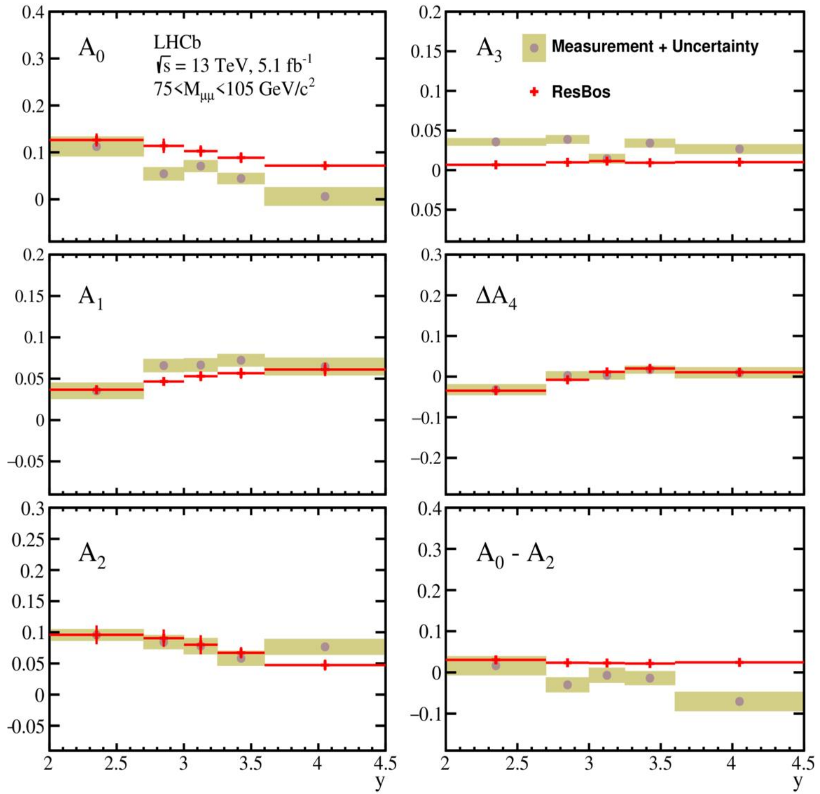
- The first double differential cross-section measurement in the forward region
- No significant deviations are seen between measurements and the theoretical predictions

A_i at LHCb - y Dependent

- Reasonable agreement between the measurements and ResBos calculations for A_0 to Δ A_4

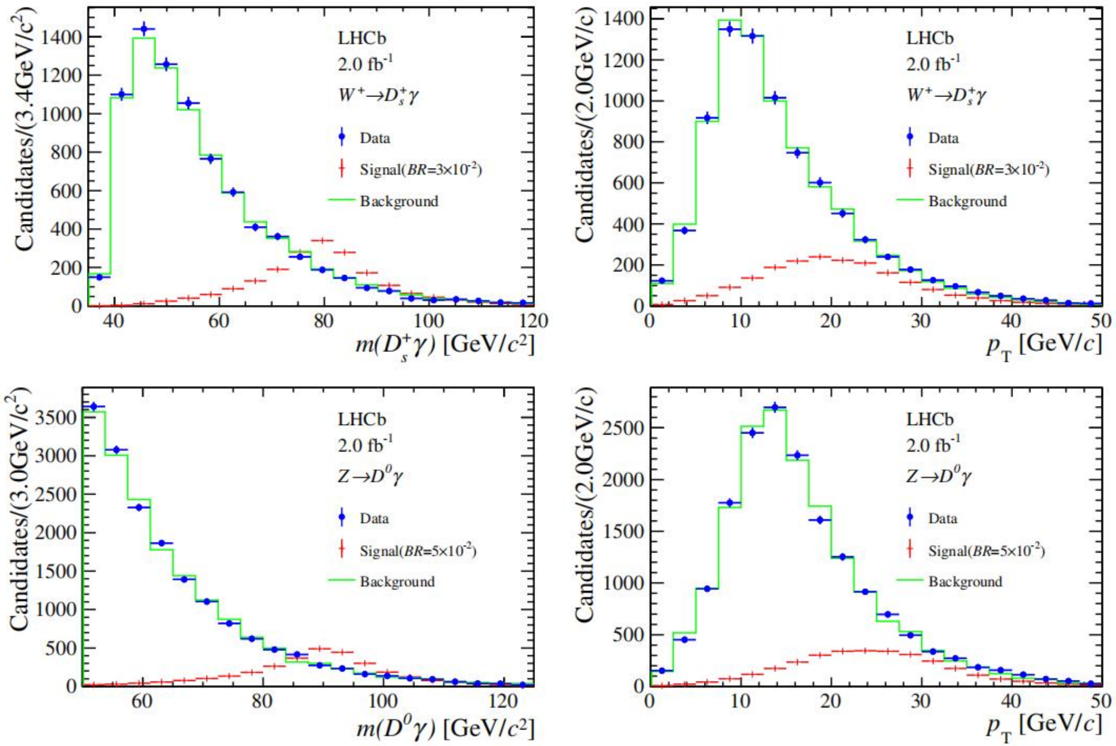
- $A_0 - A_2$: differences between measurements and predictions, especially in the highest y region
  - Indicate a y dependence in the **QCD resummation or higher-order effects**

Phys. Rev. Lett. 129 (2022) 091801



W and Z Rare Decays - Fitting

arXiv:2212.07120



W and Z Rare Decays - Uncertainties

arXiv:2212.07120

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	0.08	0.36
Acceptance	0.57	0.82
PV association	0.57	0.29
Resolution	0.20	0.09
Total	4.04	4.88

$$\mathcal{R}(Z) < 6.4 \times 10^{-2} \text{ at 95\% C.L.,}$$
$$\mathcal{R}(W) < 6.1 \times 10^{-3} \text{ at 95\% C.L.}$$

$$\mathcal{B}(Z \to D^0\gamma) < 2.1 \times 10^{-3} \text{ at 95\% C.L.,}$$
$$\mathcal{B}(W^+ \to D_s^+\gamma) < 6.5 \times 10^{-4} \text{ at 95\% C.L.,}$$

- Prediction:
  - $\mathcal{B}(W^+ \to D_s^+\gamma) < 3.7 \times 10^{-8}$
  - $\mathcal{B}(Z \to D^0\gamma) \sim O(10^{-5})$