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Electroweak Physics at LHCb

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on behalf of the LHCb collaboration

Les Rencontres de Physique de la Vallée d'Aoste

6th -11th March 2023

LHCb

European Research Council
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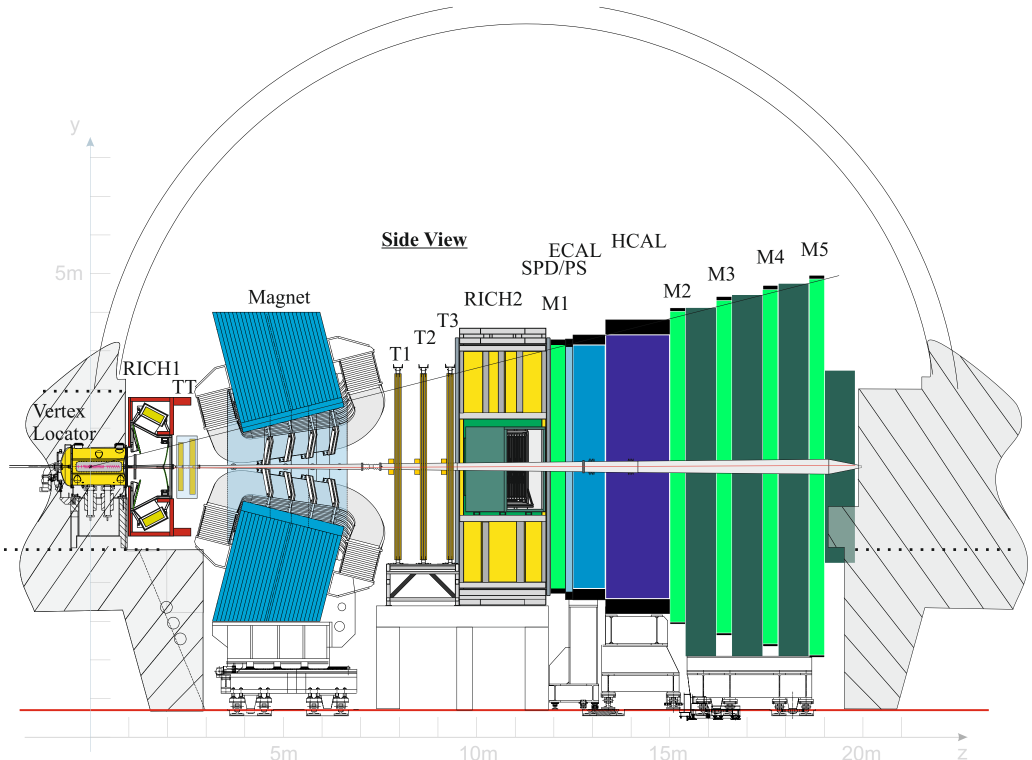
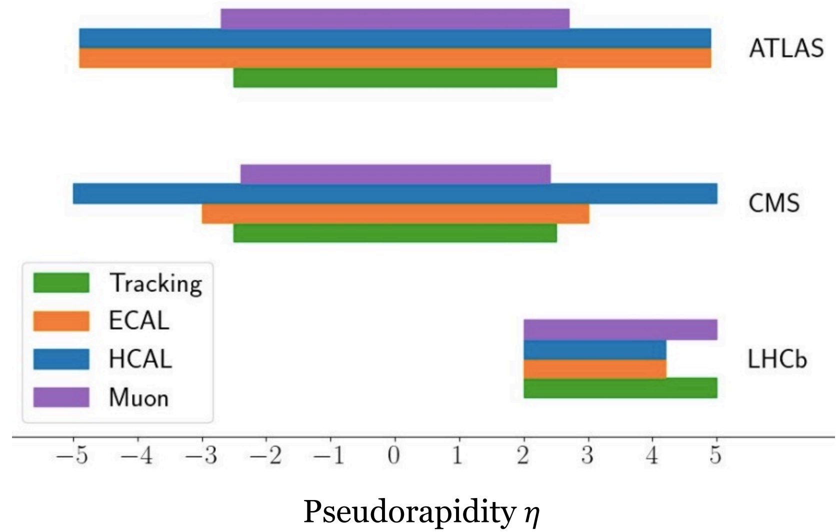
Contents

- Measurement of the W boson mass with 2016 data,
- Future prospects for m_W measurements from LHCb,
- Update with full Run-2 (2016-2018) dataset of the $Z \rightarrow \mu\mu$ differential cross section,
- First measurement of the $Z \rightarrow \mu\mu$ angular coefficients at forward pseudorapidities of pp collisions,
- Search for the rare radiative decays $W^{\pm} \rightarrow D_s^{\pm}\gamma$ and $Z \rightarrow D^0\gamma$,
- Measurements coming in the near future…

The LHCb Experiment in Run 2

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



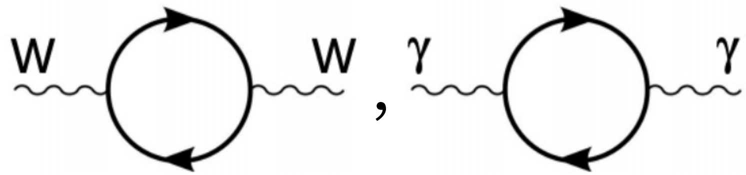


- LHCb is a single-arm, forward spectrometer covering $2 < \eta < 5$, designed for heavy flavour physics,
- Excellent tracking performance allows for high-precision EW tests [Results].

W boson mass measurements

m_W: context

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$



, … NP? …

- Comparing indirect SM predictions with direct m_W measurements constrains new physics.

- 2021 EW fit prediction: arXiv:2122.07274

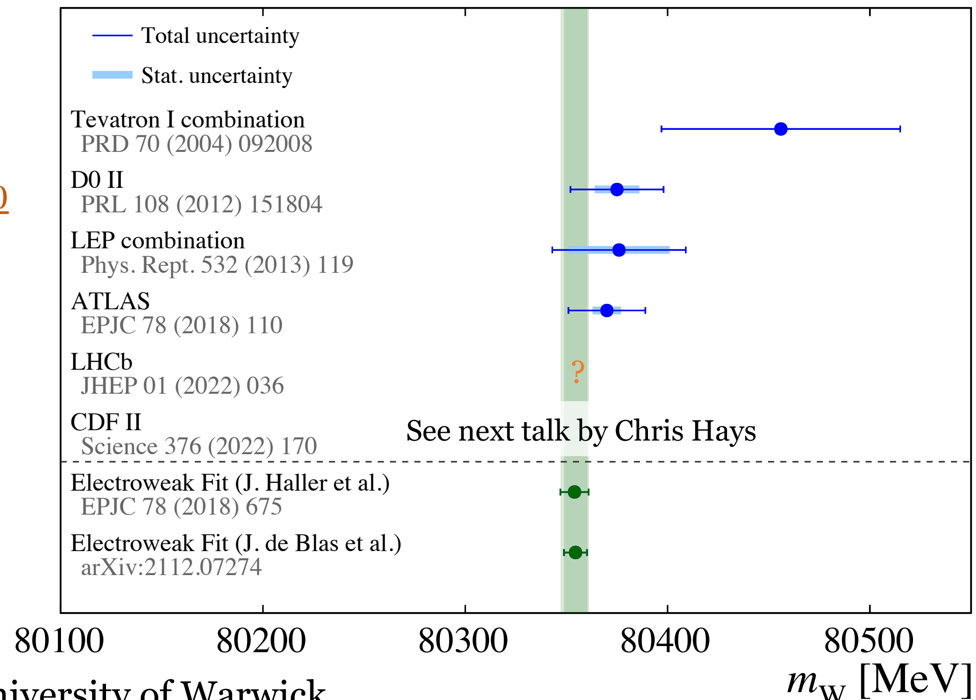
$$\Delta m_W = 6 \text{ MeV},$$

- Only other LHC measurement: EPJC 78 (2018) 110

$$\Delta m_W^{ATLAS} = 19 \text{ MeV}.$$

- Historically-limiting PDF uncertainties expected to anti-correlate in a ATLAS/CMS-LHCb average. EPJC 75 (2015) 601

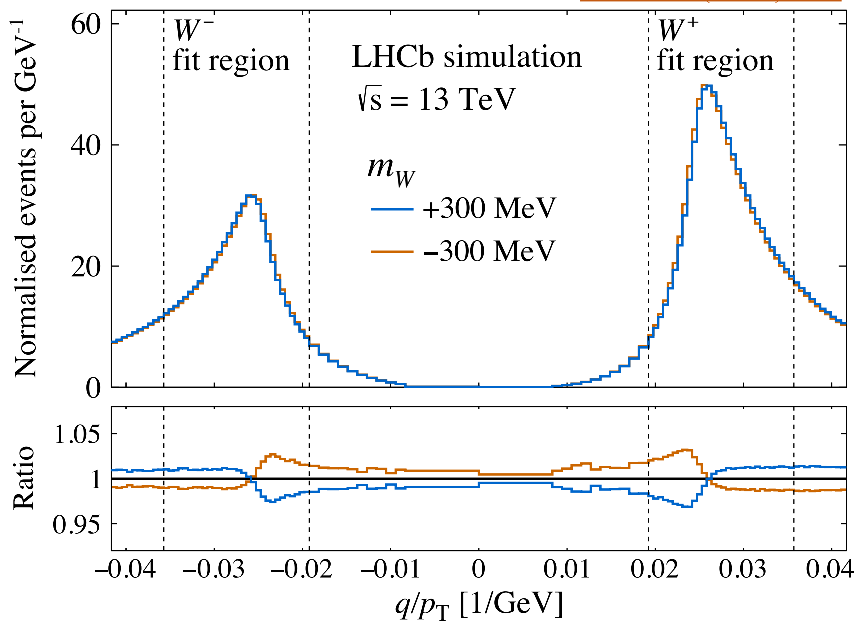
LHCb-FIGURE-2022-003



m_W: strategy

- $W \to \mu\nu$ gives a single, high-p_T, isolated muon
  - (LHCb doesn't reconstruct missing energy).
- p_T^μ peaks at $\sim m_W/2$, $\to$ extract m_W in a template fit to the q/p_T^μ distribution.
- O(10 MeV) determination $\leftrightarrow$ O(0.1%) knowledge of p_T^μ shape.

JHEP 01 (2022) 036

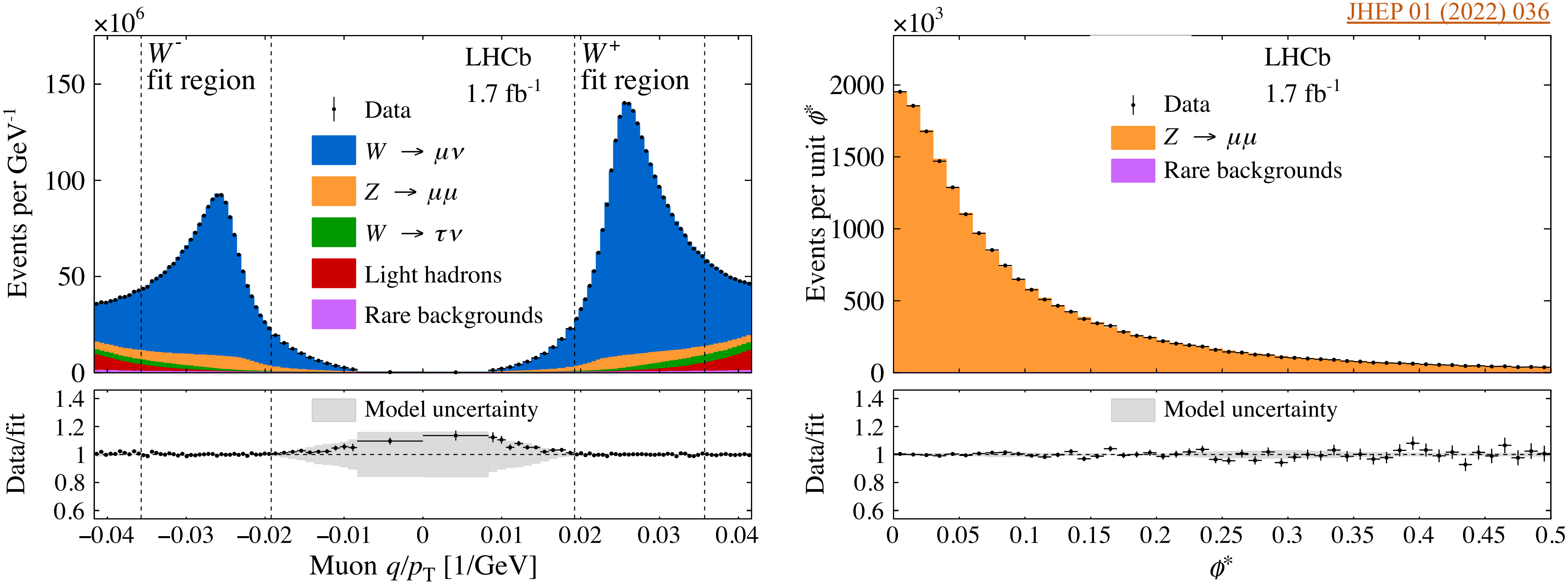


- Any mismodelling of detector response (e.g. misalignments, momentum resolution) or underlying physics (simulated p_T^W, QED FSR) can bias m_W at this scale.
- Given challenging theoretical uncertainties:

1) A proof-of-principle measurement with the 2016 data,
2) A full-Run-2 measurement targeting $\Delta m_W \approx 20$ MeV (approx. as precise as ATLAS).

m_W: central fit result

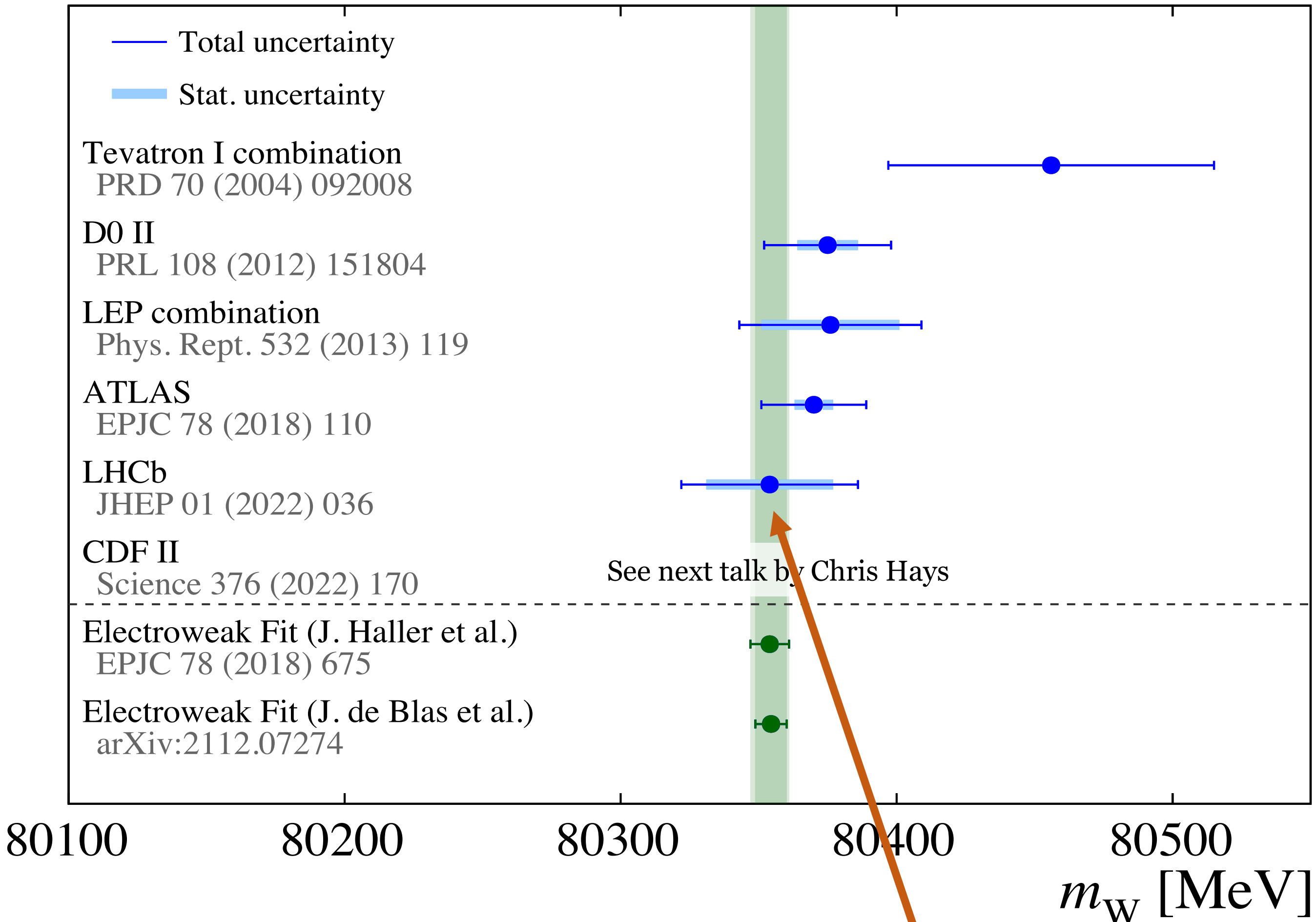
JHEP 01 (2022) 036



- Simultaneous fit to $W\ q/p_T^\mu$ and $Z\ \phi^*$: Δm_W (stat) = 23 MeV.
- Leading systematic uncertainties from theoretical sources: PDFs (9 MeV), p_T^W model (11), A_i predictions (10), QED FSR (7),
- Central result is average from NNPDF31, CT18 and MSHT20 PDF sets.

$$\phi^* \equiv \tan\left(\frac{\pi - \Delta\phi}{2}\right) / \cosh\left(\frac{\Delta\eta}{2}\right) \sim \frac{p_T}{M}$$

m_W result in context



LHCb-FIGURE-2022-003

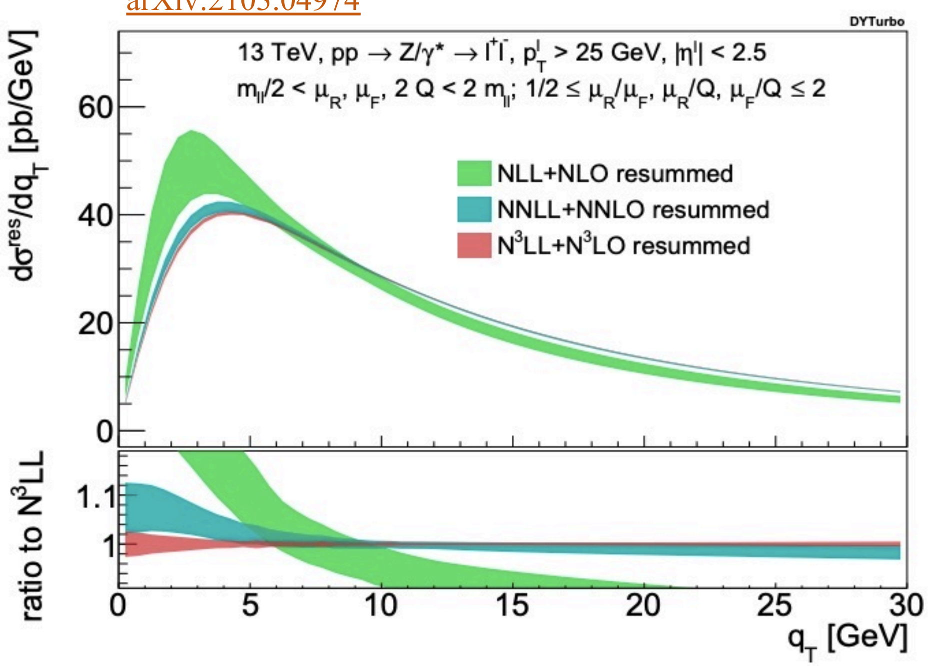
$$m_W = 80354 \pm 23_{stat} \pm 10_{exp} \pm 17_{theory} \pm 9_{PDF}\ \text{MeV} = 80354 \pm 32\ \text{MeV}$$

Prospects for m_W measurements from LHCb

1) A proof-of-principle measurement with the 2016 data, [Published: JHEP 01 (2022) 036]
2) A full-Run-2 measurement targeting $\Delta m_W \approx 20$ MeV (approx. as precise as ATLAS).

- 2016 analysis had 1.7 fb^{-1}. Further ~4 fb^{-1} of Run-2 data to add → $\Delta m_W\ (stat) \approx 14$ MeV.
- Experimental systematics will reduce with more study and data.
- QCD predictions with higher perturbative accuracy are available e.g. from DYTurbo:

arXiv:2103.04974



Measurement of $Z \to \mu\mu$ differential cross section

(JHEP 07 (2022) 026; full Run-2 update on JHEP 09 (2016) 136)

$Z \to \mu\mu$ cross section

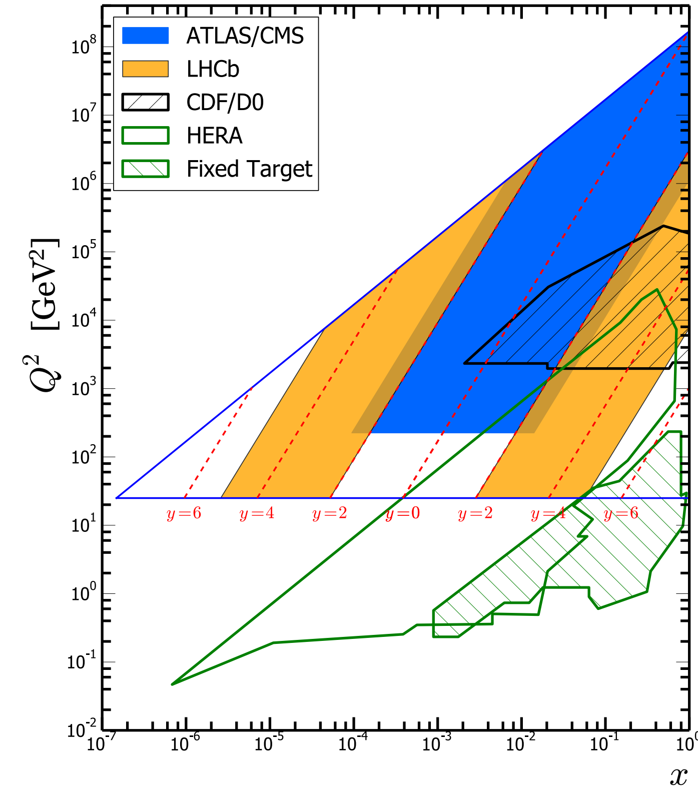
- High-precision test of QCD-EW predictions,
  - (at same level as experimental precision)

- Z decays in LHCb are highly boosted → access PDFs in region (high/low x) complementary to ATLAS/CMS,

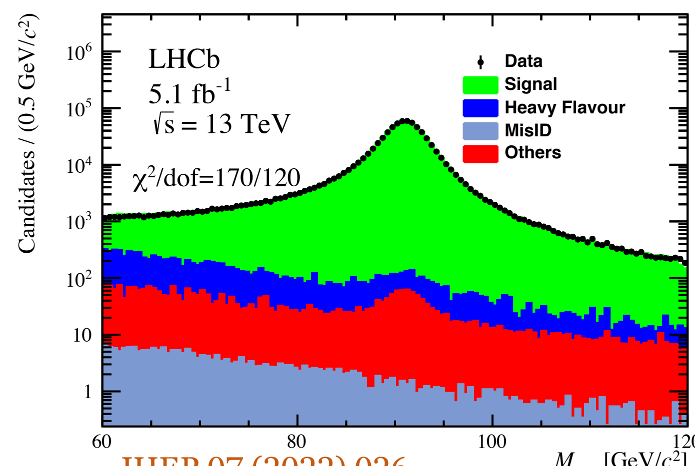
- Full Run 2 data: $L = 5.1 \pm 0.1$ fb^{-1},

- High-purity sample: $N_{bkg}/N_{sig} \sim 1.5\%$,

$$\frac{d\sigma(Z \to \mu\mu)}{dy}_i = \frac{N(Z)_i \cdot f_i^Z(FSR)}{L \cdot \varepsilon_i\,(rec) \cdot \Delta y_i}$$



Inspired by arXiv:0808.1847 & PRD 93 (2016) 074008



JHEP 07 (2022) 026

Single-differential cross sections: y_Z

- Single-differential cross section extracted in p_T^Z, y^Z and ϕ^*,

- Predictions from RESBOS (NLO in QCD + resummation) and FEWZ (NNLO in QCD) agree on overall scale, but are shifted to slightly lower (higher) rapidities than the data.

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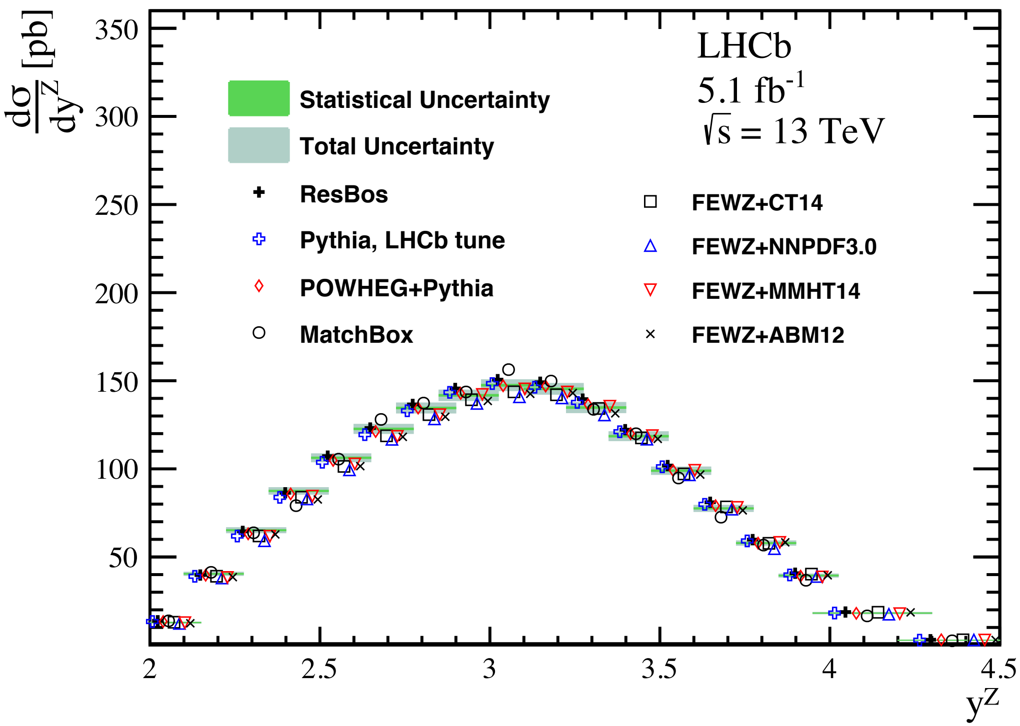

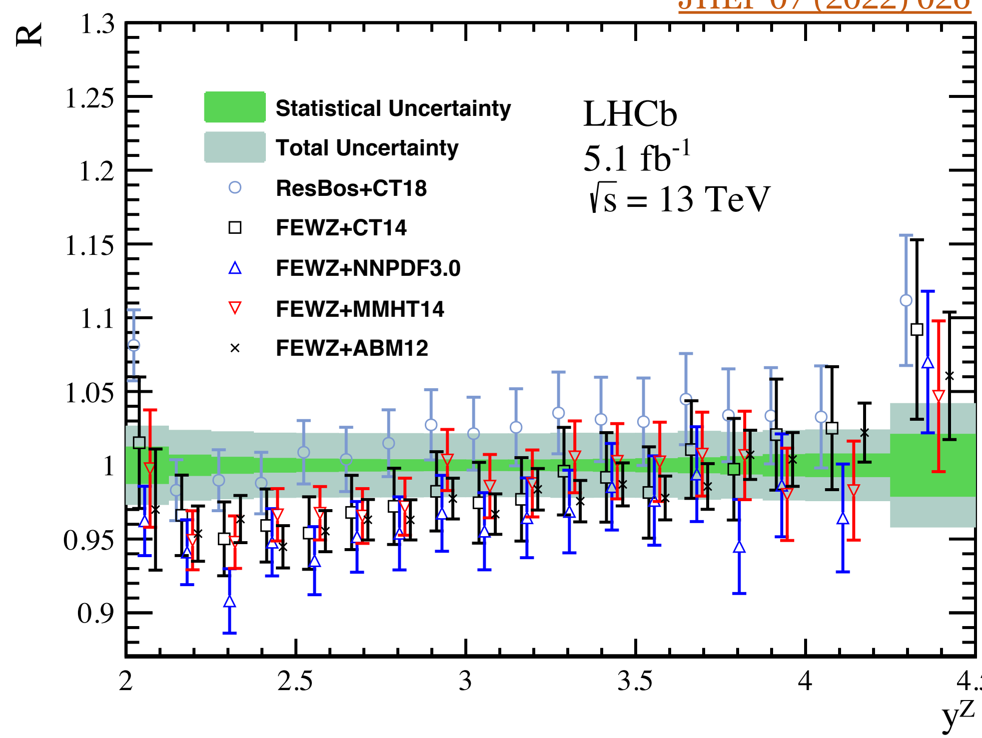

N.B.: $\phi^* \equiv \tan\left(\frac{\pi - \Delta\phi}{2}\right) / \cosh\left(\frac{\Delta\eta}{2}\right) \sim \frac{p_T}{M}$

Single-differential cross sections: p_T^Z

- $d\sigma/dp_T^Z$ at low p_T^Z a stringent test of QCD due to presence of large logs ($\sim \log(p_T^Z/m_Z)$),
- Reasonable agreement of data with predictions, with RESBOS preferring a slightly harder p_T^Z distribution:

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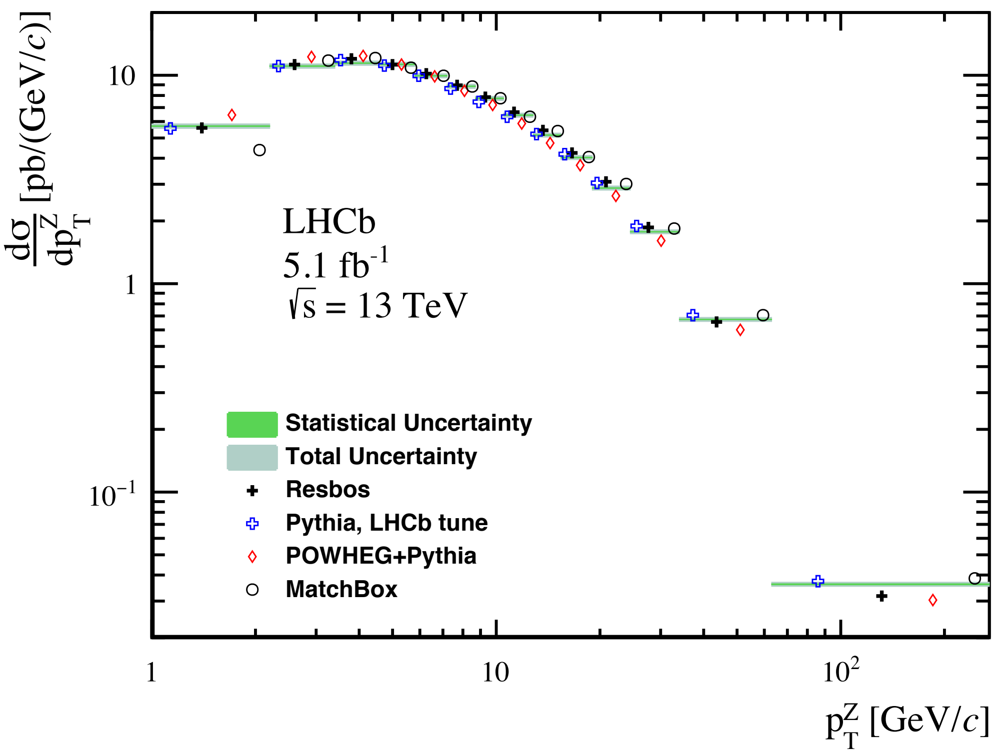

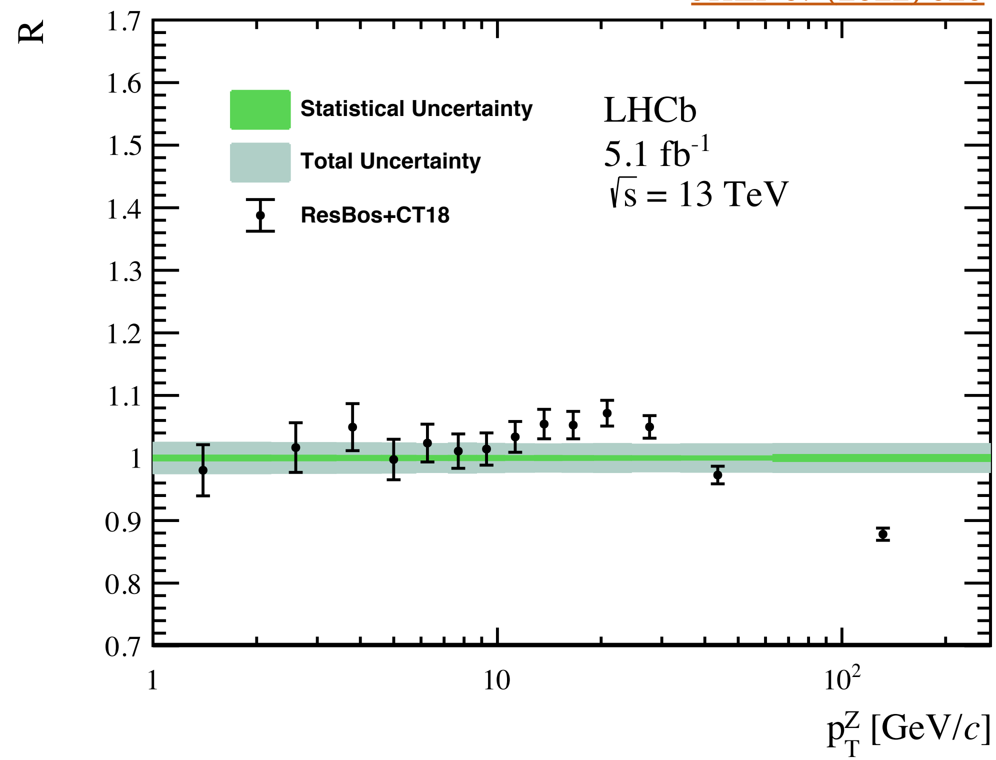

$Z \rightarrow \mu\mu$ inclusive cross section

$$\sigma(Z \rightarrow \mu\mu) = 196.4 \pm 0.2\,(stat) \pm 1.6\,(syst) \pm 3.9\,(lumi)\text{ pb} = 196.4 \pm 4.2\text{ pb}$$

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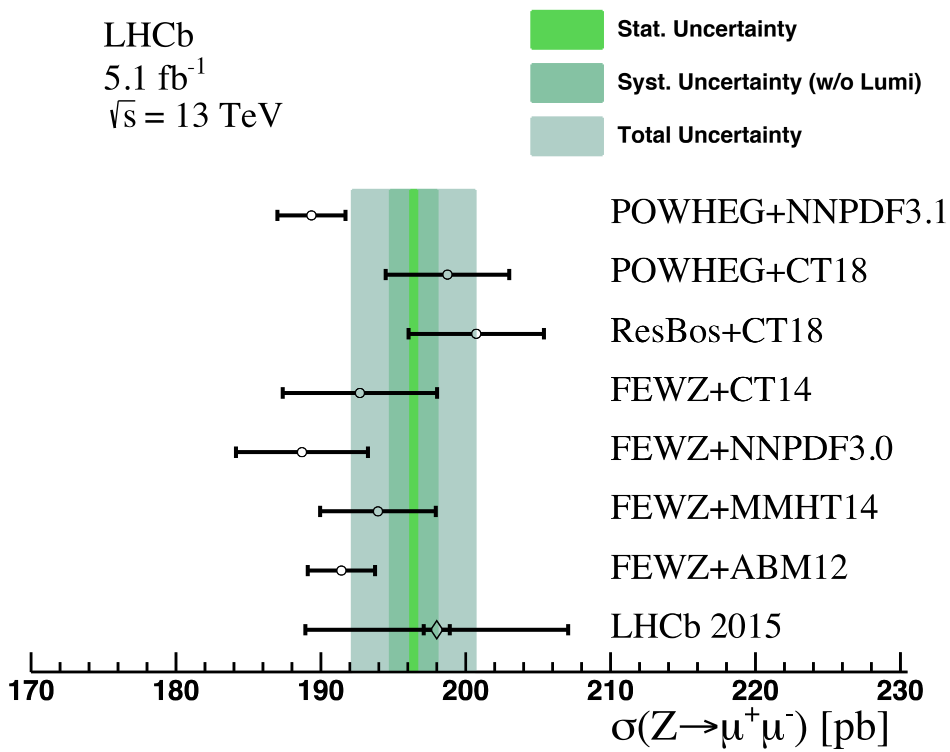


- Uncertainty dominated by uncertainty in luminosity measurement,
- In good agreement with previous measurement and theoretical predictions.

Measurement of $Z \to \mu\mu$ angular coefficients

Phys. Rev. Lett. 129 (2022) 091801

Measurement of the $Z \to \mu\mu$ angular coefficients

- Dimuon angular distribution in $Z \to \mu\mu$ expressed (at Born level) in 8 coefficients A_i:

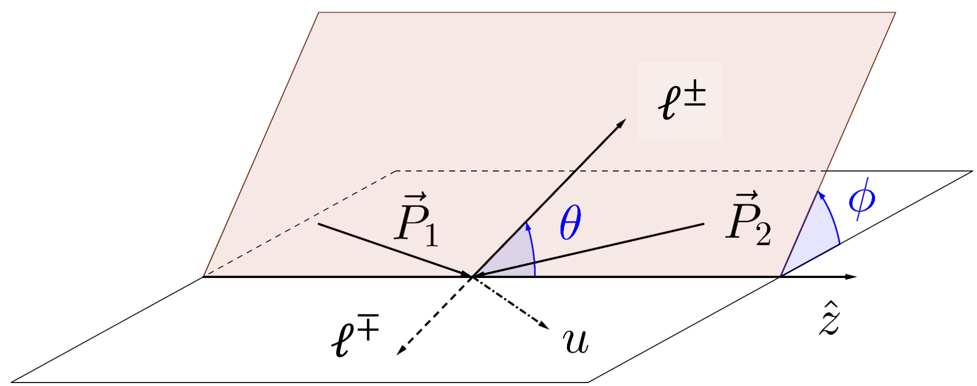
$$\frac{d\sigma}{dcos\theta\, d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$

- Direct probe of the Z-boson polarisation in pp → important test of QCD at EW scales.

- First measurement of $A_i (i = 0 - 4)$ in the forward region of pp collisions at 13 TeV,

- A_i extracted with unbinned maximum likelihood fit to muon cosθ and ϕ.

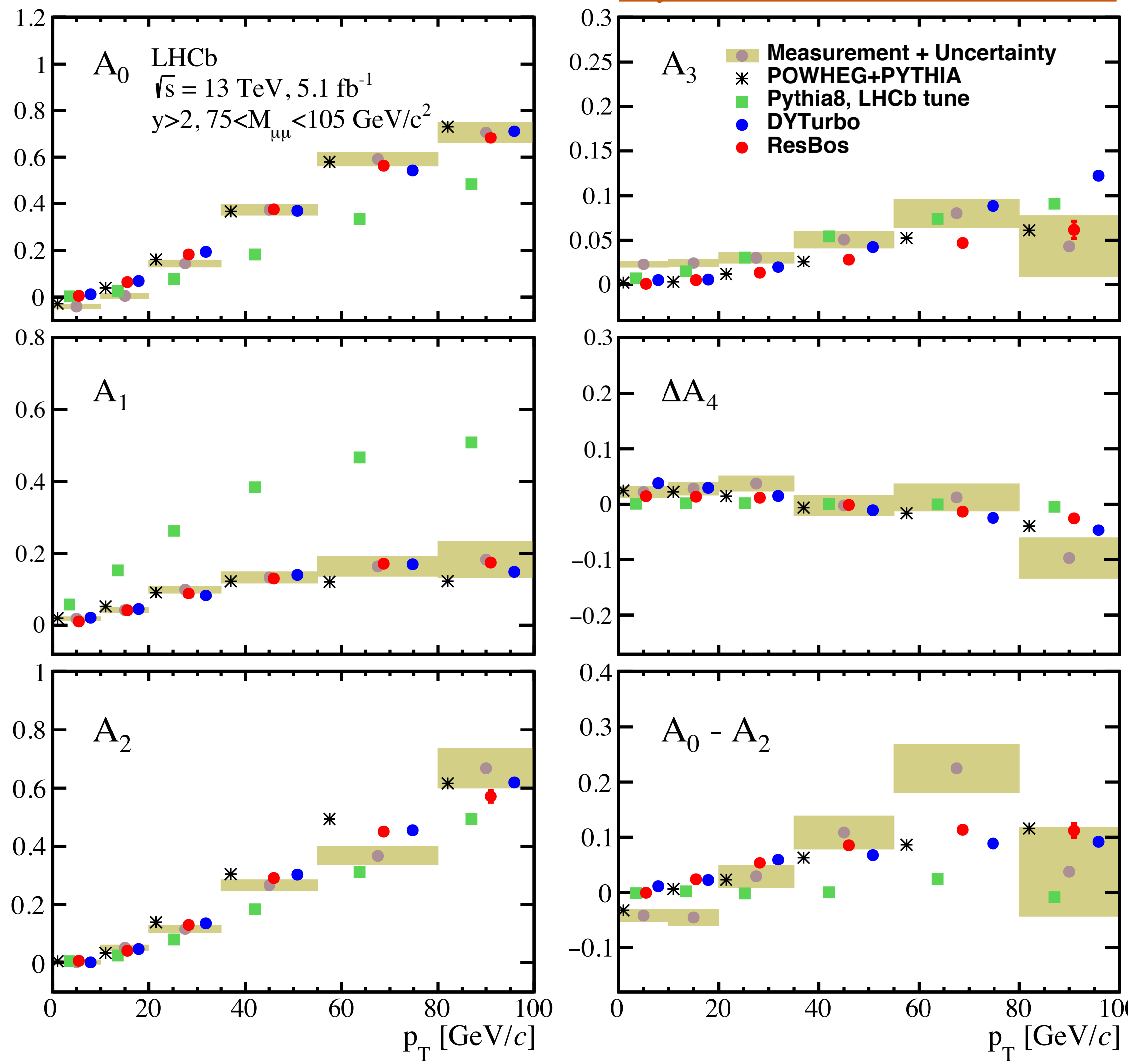
Collins-Soper frame



Measurement of the $Z \to \mu\mu$ angular coefficients

- Results, unfolded to Born level, as function of p_T^Z:
- $\Delta A_4 = A_4 - mean(A_4)$ decouples measurement from the value of the weak mixing angle.
- Statistically-dominated.
- Compared with 4 sets of theoretical predictions,
  - (both fixed-order in QCD and incl. analytic resummation)
- Good general agreement is found, although PYTHIA (LO) descr. is poor in some regions.

Phys. Rev. Lett. 129 (2022) 091801



Constraining non-perturbative QCD with A_2

- Non-perturbative QCD spin-momentum correlations between $q\bar{q}$ in $q\bar{q} \rightarrow Z$ are described by p_T-dependent (TMD) Boer-Mulders PDFs.

- $A_2 \propto$ convolution of TMD PDFs → this measurement can improve constraints on this non-perturbative QCD phenomenon.

- Broad agreement seen with generator predictions, except at low p_T^Z in low $m_{\mu\mu}$.

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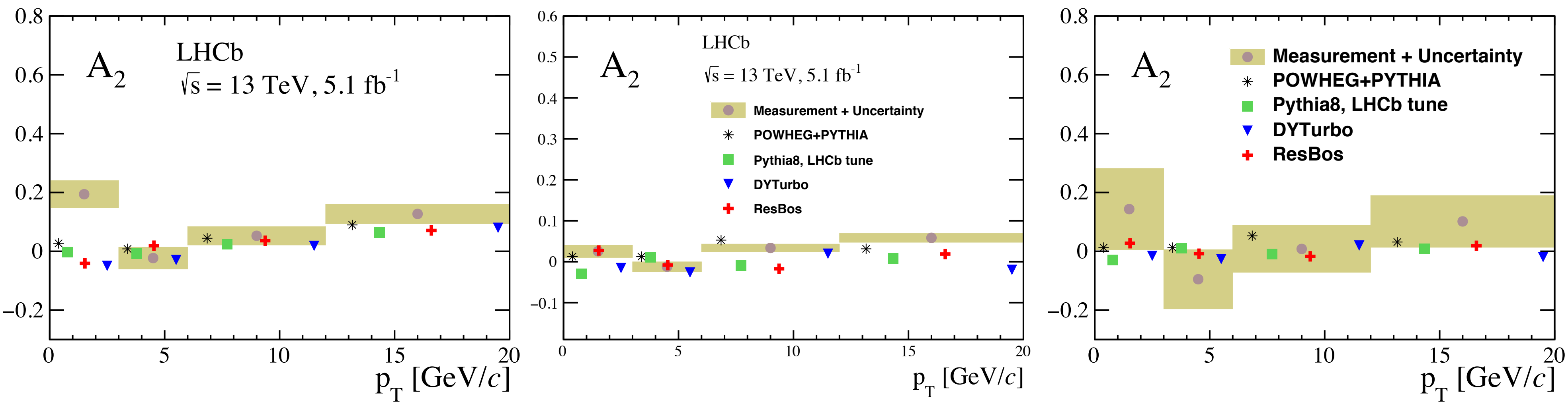
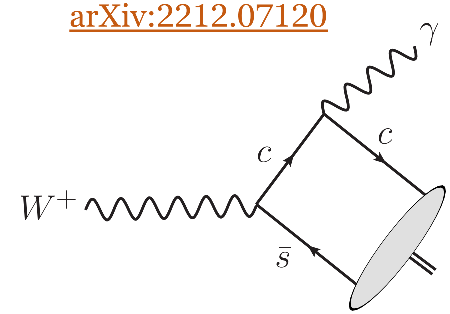
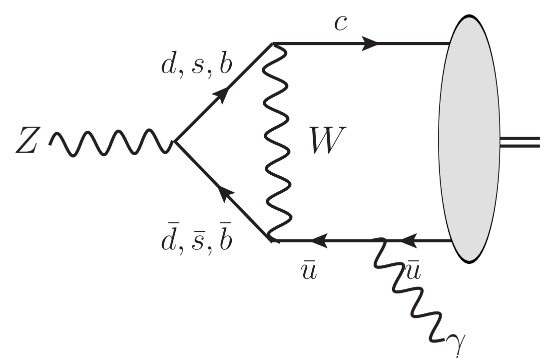
$50 < m_{\mu\mu} < 75$ GeV | $75 < m_{\mu\mu} < 105$ GeV | $105 < m_{\mu\mu} < 120$ GeV



Search for the rare decays $W^{\pm} \to D_s^{\pm}\gamma$ and $Z \to D^0\gamma$

arXiv:2212.07120





- Rare radiative decays of W/Z unobserved,
- SM $B(W/Z \to h\gamma) \sim 10^{-6} - 10^{-15}$; enhanced in some NP models,
- LHCb ideally suited for hadronic final states → use $h = D_s^+ \to K^+K^-\pi^+$ and $h = D^0 \to K^+\pi^-$.
- ECAL saturation means inv. mass is poorly modelled; instead identify signal with the *pseudomass*:

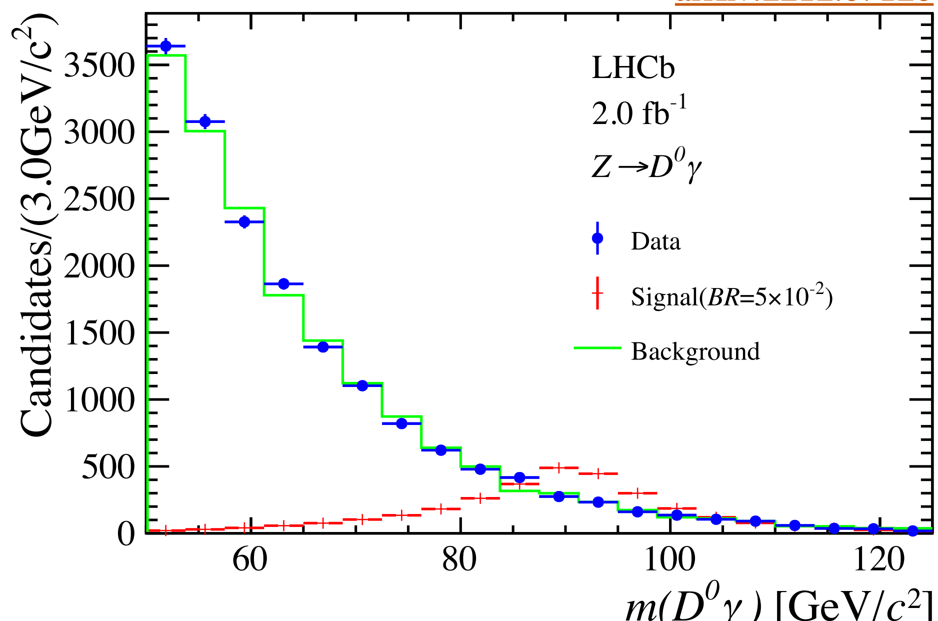
$$m(M\gamma) = \sqrt{2p^M p_T^M \frac{p^\gamma}{p_T^\gamma}(1-\cos\theta)},$$

EPJC 81 (2021) 3, 251

- No signal observed - set world's best limit on both decays:

$$B(W^{\pm} \to D_s^{\pm}\gamma) < 6.5\times10^{-4},$$
$$B(Z \to D^0\gamma) < 2.1\times10^{-3}$$

arXiv:2212.07120



Coming soon to a conference near you...

In the near future:

- $Z \to \mu\mu$ differential cross section at $\sqrt{s} = 5.02$ TeV
- Test of LFU with $R_{\tau\mu} = B(W \to \tau\nu)/B(W \to \mu\nu)$,
- Measurement of the weak mixing angle via A_{FB} in $Z \to \mu\mu$

A little further ahead...

- Measurement of the W boson mass with the full Run 2 dataset
- $W \to \mu\nu$ differential cross section at $\sqrt{s} = 5.02, 13$ TeV
- Measurement of the Z boson mass.

Summary and outlook

- LHCb continues to deliver a strong programme of high-precision electroweak measurements:
    - Proof-of-principle measurement of m_W with $\Delta m_W = 32$ MeV; large expected impact in LHC-wide combination,
    - First measurement of the $Z \to \mu\mu$ angular coefficients in the forward region of pp collisions,
    - Measurement of the $Z \to \mu\mu$ cross section with the full Run 2 dataset.

- World's-best limits on rare decays $W^{\pm} \to D_s^{\pm}\gamma$ and $Z \to D^0\gamma$ outline LHCb's potential as a discovery experiment,

- In the near future: high-precision LFU tests in W decays, $Z \to \mu\mu$ cross section at 5 TeV & a measurement of the weak mixing angle,

- Looking (slightly) further ahead: m_W measurement that rivals ATLAS for the most precise at the LHC so far.

Thank you for your attention.
Any questions?

Backup

m_W: tuning QCD predictions on-the-fly

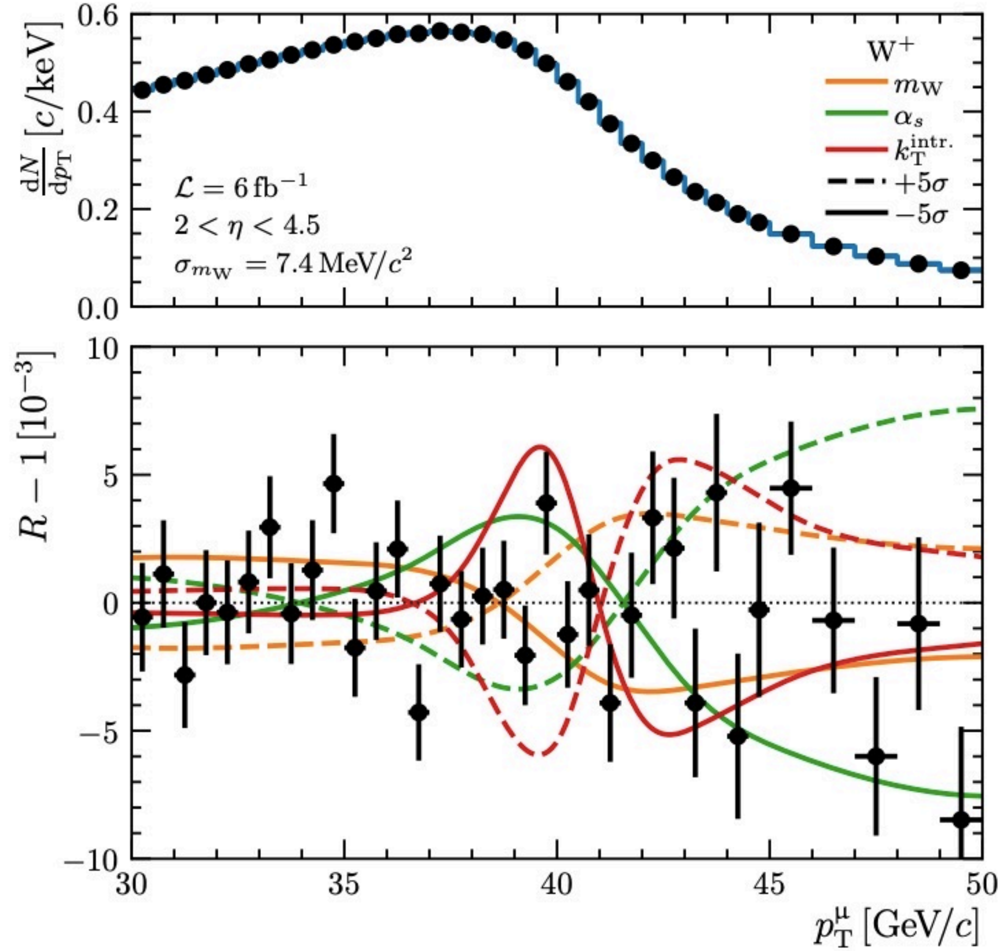
- At the Born level (before QED FSR):

$$\frac{d\sigma}{dp_T^W\,dy\,dM\,dcos\theta\,d\phi} \propto \frac{d\sigma^{unpol}}{dp_T^W\,dy\,dM} \times f(\theta,\phi,A_i)$$

- Predictions of angular coefficients A_i taken from DYTurbo at O(α_S^2).
- Floated a scale factor in the fit to absorb the (dominating) uncertainty on the A_3 prediction.
- POWHEG+Pythia8 provided $\frac{d\sigma^{unpol}}{dp_T^W\,dy\,dM}$,
- Previous m_W measurements rely on tuning to p_T^Z. Does this tune hold for p_T^W?
- Variations in α_S and k_T^{intr} affect p_T^{μ} differently to variations in m_W.

$\Rightarrow$ Floated these QCD parameters in a simultaneous fit to $W\ q/p_T^{\mu}$ and $Z\ \phi^*$.

arXiv:1907.09958



m_W: novel *pseudomass* alignment

- Biases in p_T^μ can originate from detector misalignments. Fix with:
  1) Custom alignment for high-p_T muons,
  2) Finer, analysis-level curvature (q/p) corrections from the "pseudomass" method on $Z \to \mu\mu$.

- Differences in M^+ and M^- allow for mapped curvature bias corrections across the detector.

- Simulation is then smeared to account for mismodelled momentum scale and resolution.

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

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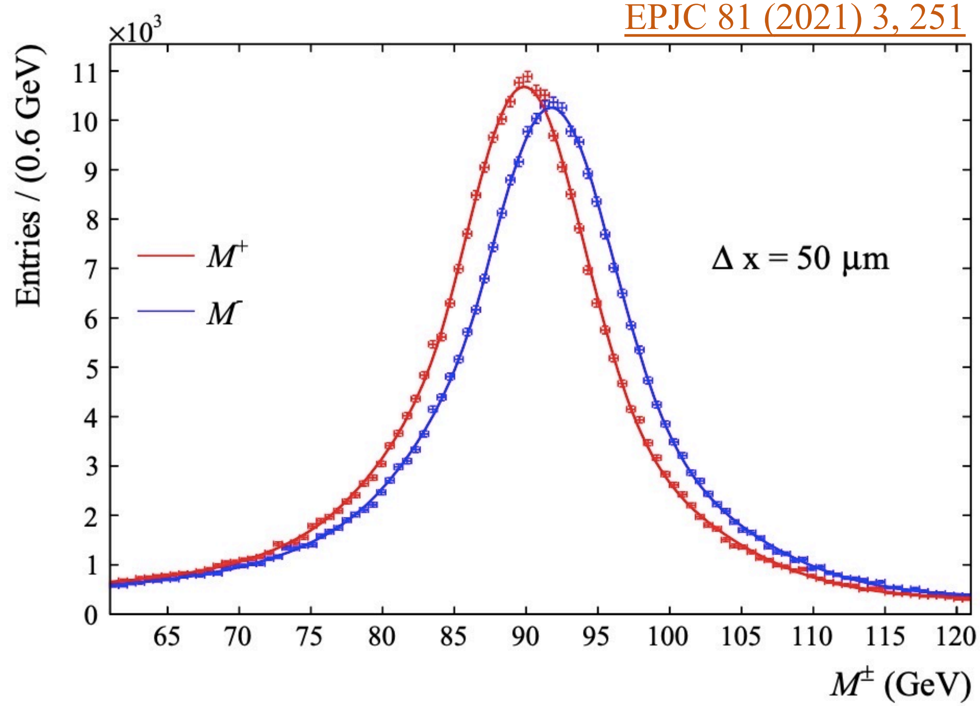


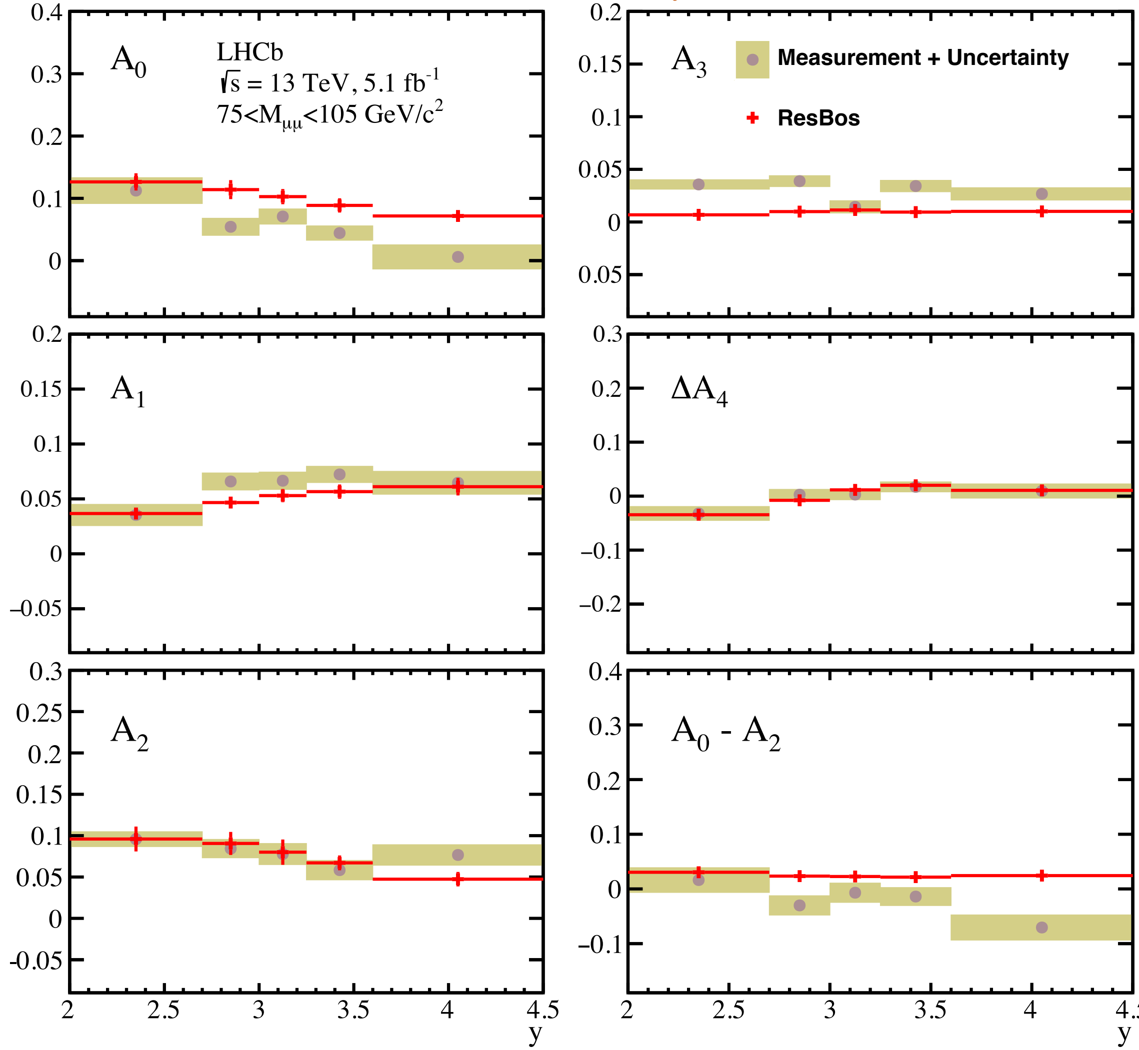
Inspired by PRD 91, 072002 (2015)

m_W: uncertainty breakdown

Source	Size [MeV]	
Parton distribution functions	**9.0**	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) Total	**17**	
Transverse momentum model	11	Envelope from five different models
Angular Coefficients	10	Uncorrelated scale variation
QED FSR model	7	Envelope of Pythia8, Photos and Herwig7
Additional electroweak corrections	5	Tested with POWHEGew
Experimental Total	**10**	
Momentum scale and resolution modelling	7	Includes statistical uncertainties, details of the methods (e.g. binning, smoothing) and dependence on external inputs.
Muon ID, trigger and tracking efficiency	6	
Isolation efficiency	4	
QCD background	2	
Statistical	**23**	
Total	**32**	

Z angular coefficients as function of y

Phys. Rev. Lett. 129 (2022) 091801



Double-differential $Z \to \mu\mu$ cross section

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