m_Z and m_W measurements with LHCb

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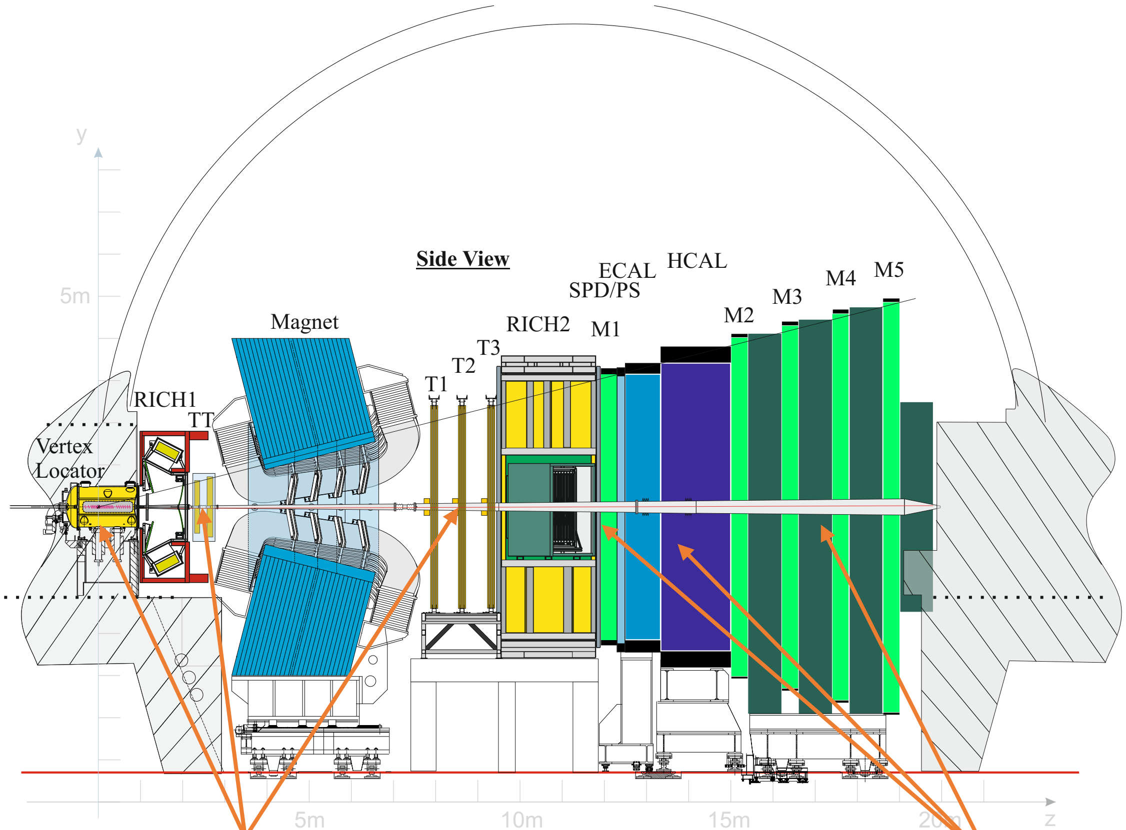
on behalf of the LHCb Collaboration

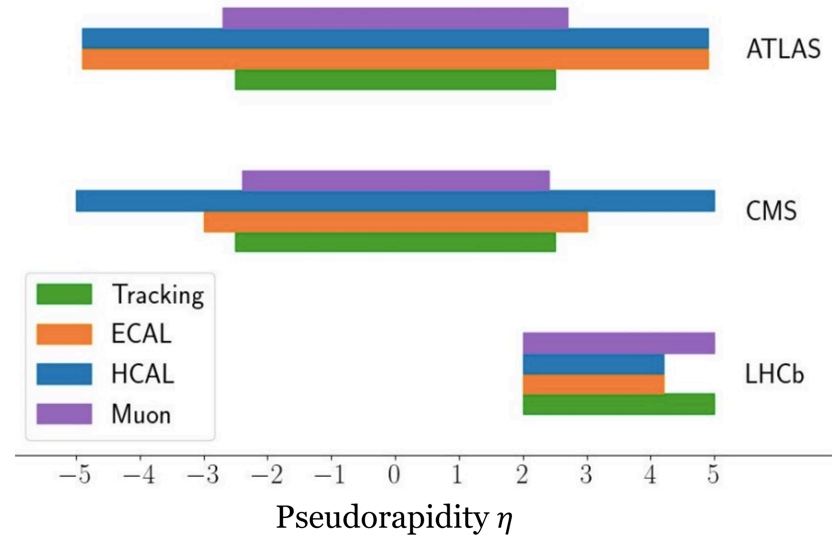
GDR QCD workshop on W mass, 30/06/25

Contents

- Introduction to LHCb and why we do m_W and m_Z,
- Recap of m_W measurement with 2016 data and impact on LHC combination,
- m_Z measurement and what we've learned for m_W,
- Steps and projections towards a full-Run-2 m_W measurement,
- (NEW!) Proof-of-principle m_W measurement from $\frac{d\sigma}{dp_T^\mu}$.

The LHCb Experiment in LHC’s Run 2





$\sigma_m/m \approx 2\%$ at m_Z,
$\sigma_p/p \approx 1\%$ at $p = 300$ GeV

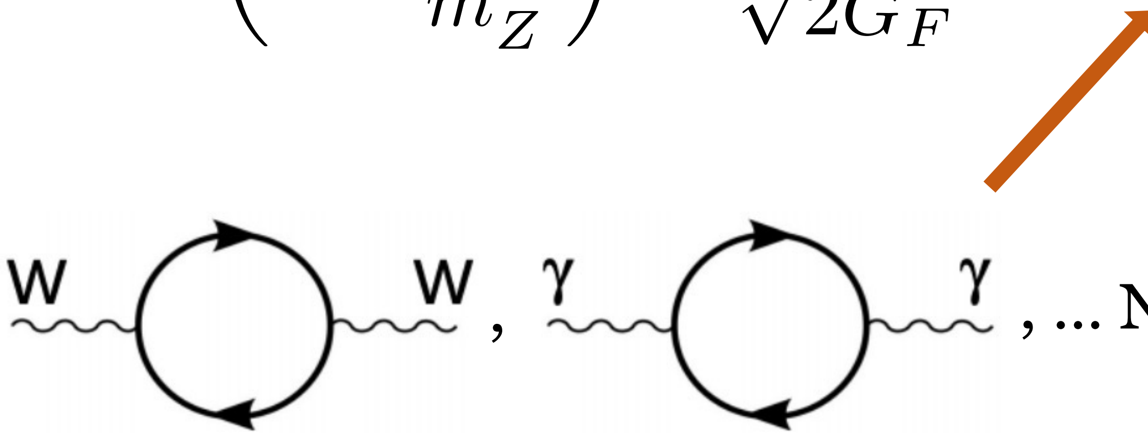
$\varepsilon^{\mu}_{ID} = 97\%$ for ~1% $\pi \to \mu$ mis-ID prob.

- Detector in the forward region with excellent muon ID, momentum & vertex resolutions,
- Complimentary solid-angle coverage to ATLAS and CMS.

Scientific Context

In the Standard Model:

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



, ... NP? ...

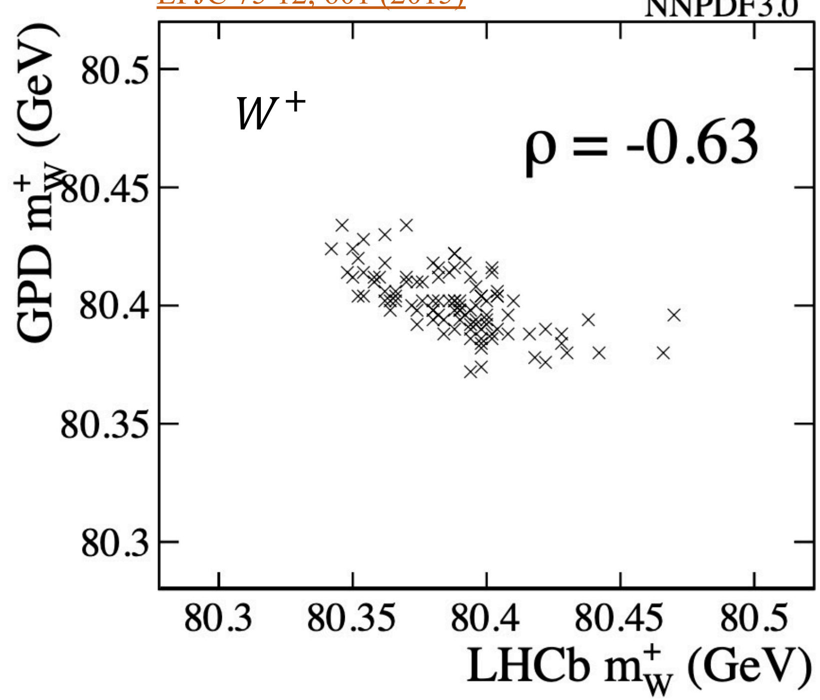
- Can indirectly predict m_W, m_Z in global EW fits with inputs from rest of the SM parameters.

- Comparing with direct m_W, m_Z measurements constrains new physics.

Why LHCb?

- LHCb Run-2 data: $O(10)$ MeV statistical uncertainty on m_W ($O(10^7)$ $W \to \mu\nu$ candidates),
- Historically-limiting PDF uncertainties expected to anti-correlate in a GPD-LHCb combination.
- Mostly designed for flavour physics, but with a strong programme of probing vector boson production.
  - Full list of LHCb EW papers here.

EPJC 75 12, 601 (2015)



m_W measurement with 2016 data

How we measured m_W

- $W \to \mu\nu$ gives a single, high-p_T, isolated muon (LHCb doesn't reconstruct missing energy).
- m_W sensitivity from p_T^μ, which peaks at $\sim m_W/2$, therefore we extract m_W in a template fit to the muon q/p_T distribution.
- Need supreme understanding of important factors that affect the p_T^μ shape.

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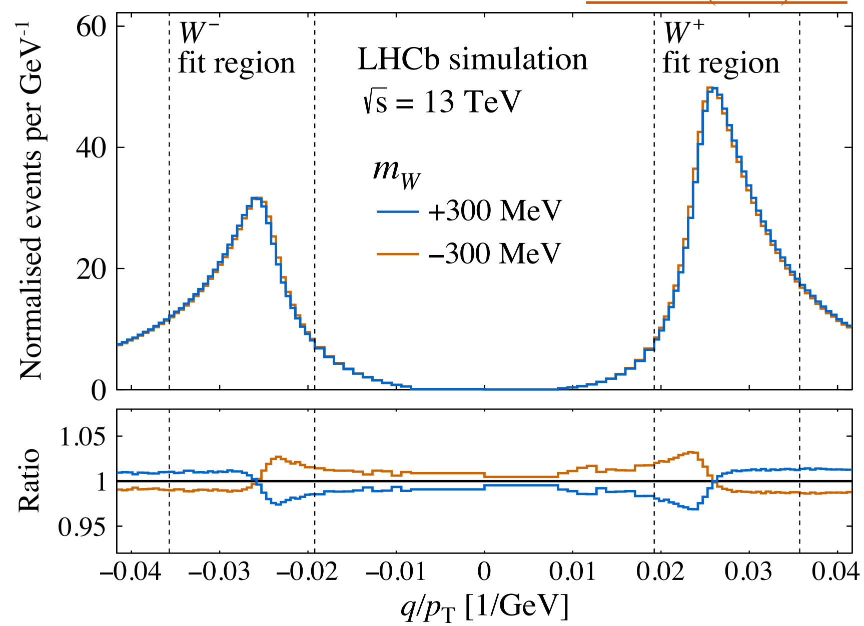

"Experimental" modelling

e.g. muon momentum scale & calibration, detector misalignment, reconstruction & selection efficiencies etc.

"Theoretical" modelling

e.g. W cross-section predictions (unpolarised and angular distribution), QED FSR, PDFs etc.

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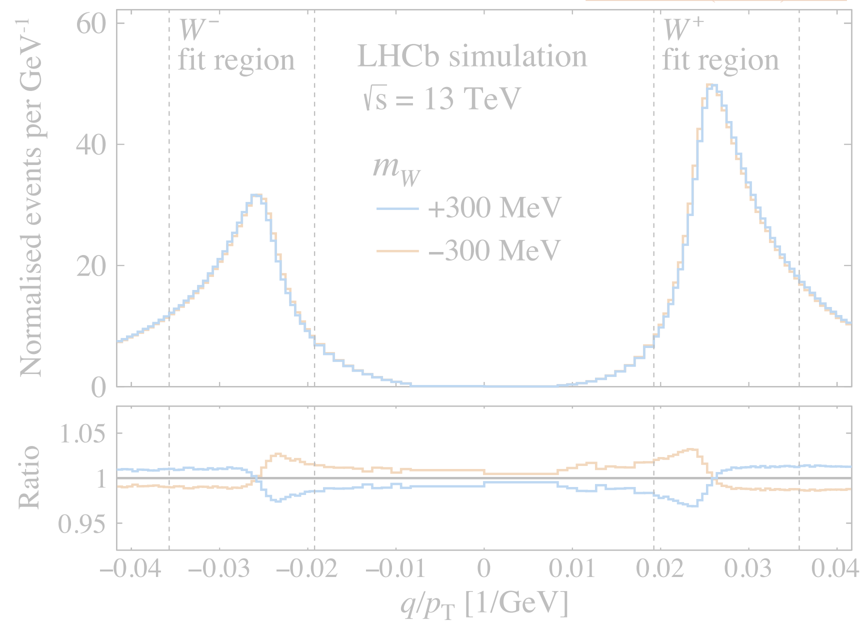


<u>"Experimental" modelling</u>
e.g. muon momentum scale & calibration, detector misalignment, reconstruction & selection efficiencies etc.

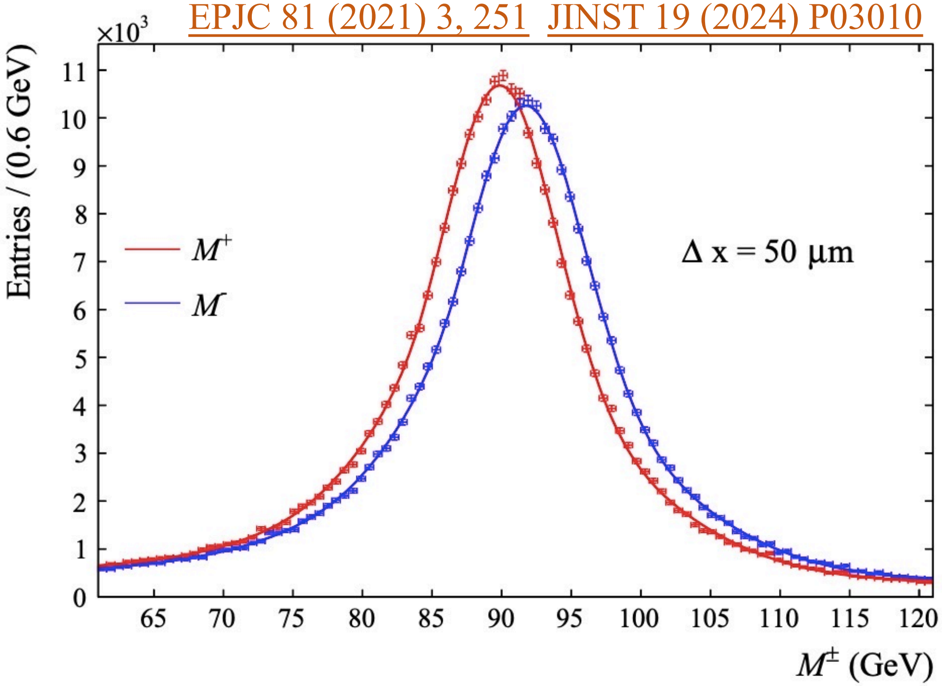
<u>"Theoretical" modelling</u>
e.g. W cross-section predictions (unpolarised and angular distribution), QED FSR, PDFs etc.

Momentum calibration

- Curvature biases (from imperfect tracker alignment) are corrected with $Z \to \mu\mu$ decays using the *pseudomass* method:

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

EPJC 81 (2021) 3, 251 JINST 19 (2024) P03010



Inspired by PRD 91, 072002 (2015)

- Template shapes for the m_W fit are corrected via a stochastic smearing derived by comparing $m_{J/\psi}, m_{\Upsilon(1S)}$ and m_Z in MC to data:

$$\frac{q}{p} \to \frac{q}{p\cdot\mathcal{N}(1+\alpha,\sigma_{\rm MS})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh\eta}\right)$$

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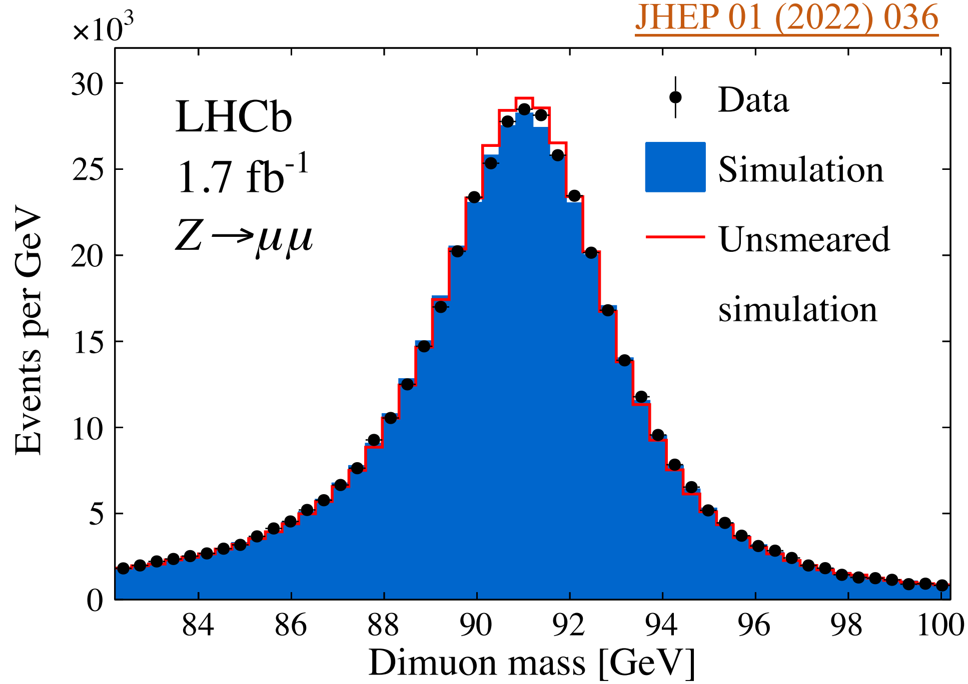

Angular coefficients

At the Born level (before QED FSR):

$$\frac{d\sigma}{dp_T^W\, dy\, dM\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol}}}{dp_T^V\, dy\, dM}$$

Unpolarised cross-section

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

Angular terms (A_i = angular coefficients)

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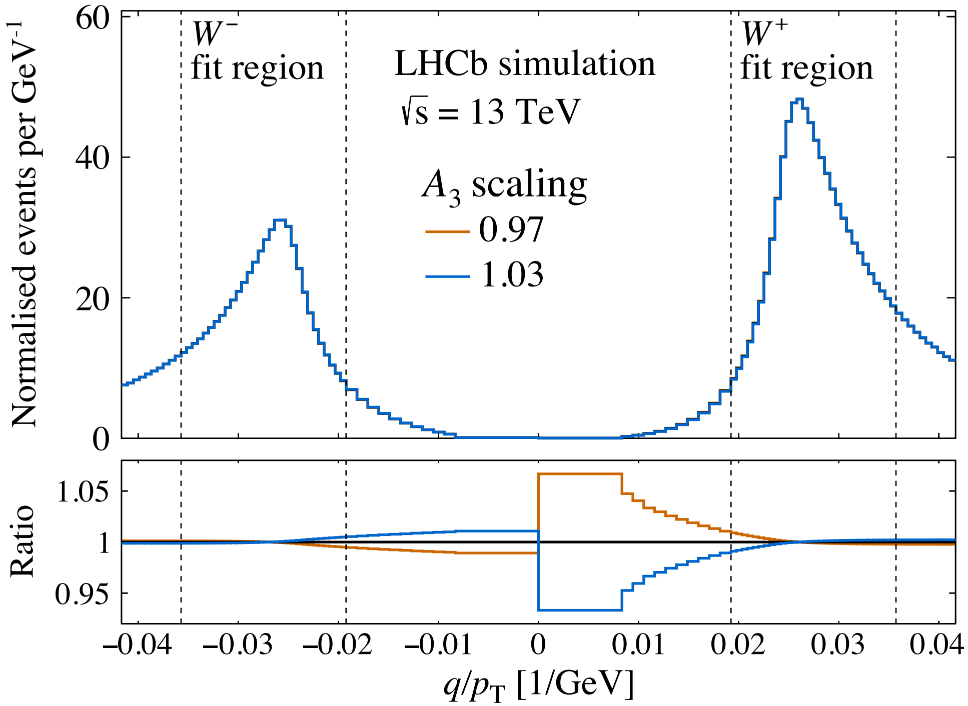
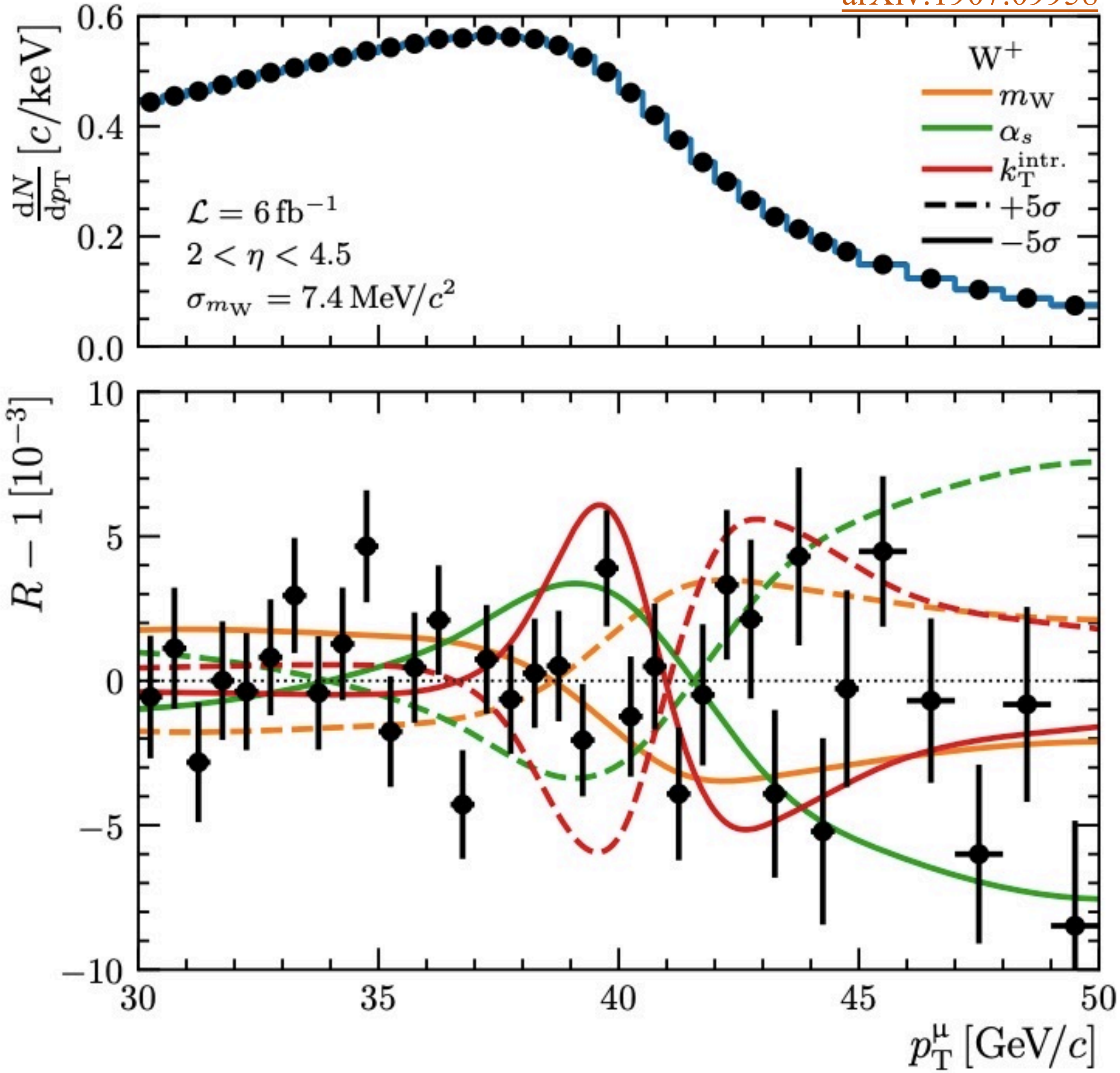


2016 measurement strategy:

- A_i predictions from DYTurbo at O(α_S^2).
- Floated a scale factor in the fit to absorb the (dominating) uncertainty on the A_3 prediction.
- Conservative uncertainty treatment (from JHEP 11(2017) 003) with uncorrelated scale variations → 10 MeV.

Physics modelling: σ^{unpol}

arXiv:1907.09958



$$\frac{d\sigma^{\mathrm{unpol}}}{dp_T^V\,dy\,dM}$$ } Unpolarised cross-section

- POWHEG-Box + Pythia8 was our central model.
- 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.

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

PDFs and QED FSR uncertainties

- Treated PDFs from NNPDF3.1, CT18 and MSHT20 equally, and their uncertainties as fully-correlated:

$$m_W = \frac{1}{3}[m_W(\text{NNPDF}) + m_W(\text{CTEQ}) + m_W(\text{MSHT})],$$
$$\Delta m_W(\text{PDF}) = \frac{1}{3}[\Delta m_W(\text{NNPDF}) + \Delta m_W(\text{CTEQ}) + \Delta m_W(\text{MSHT})].$$

Set	$\sigma_{\text{PDF,base}}$ [MeV]	$\sigma_{\text{PDF},\alpha_s}$ [MeV]	σ_{PDF} [MeV]
NNPDF3.1	8.3	2.4	8.6
CT18	11.5	1.4	11.6
MSHT20	6.5	2.1	6.8

- No preference for FSR between Pythia, Herwig and Photos; used average with a 7 MeV uncertainty envelope,
- Higher-order EW corrections tested with POWHEG-ew → 5 MeV uncertainty.

The 2016 fit result

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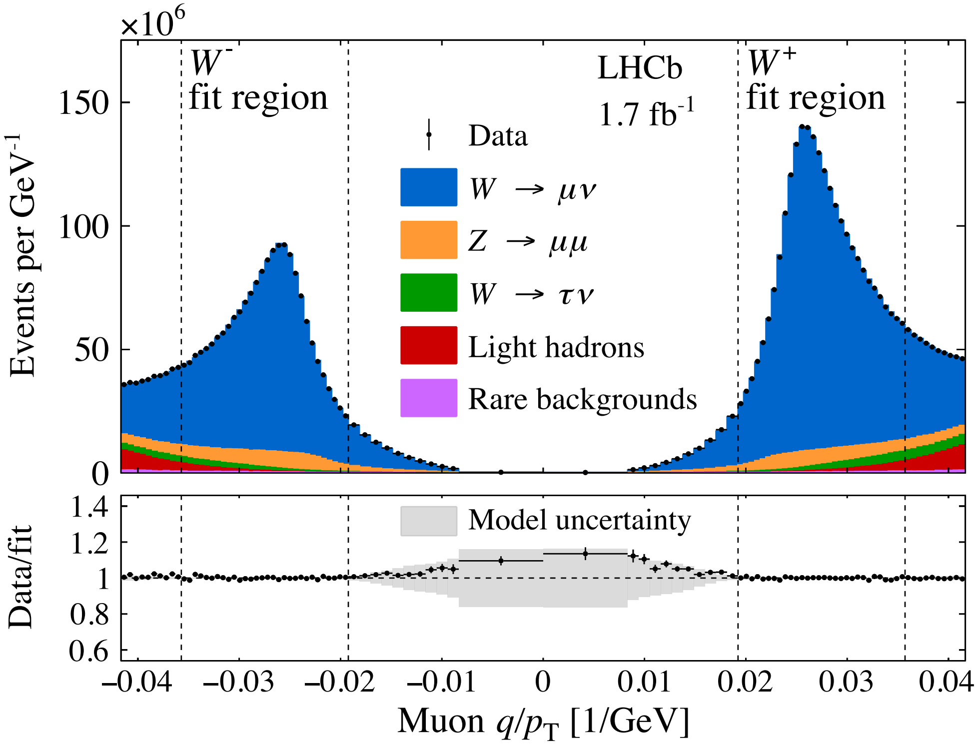
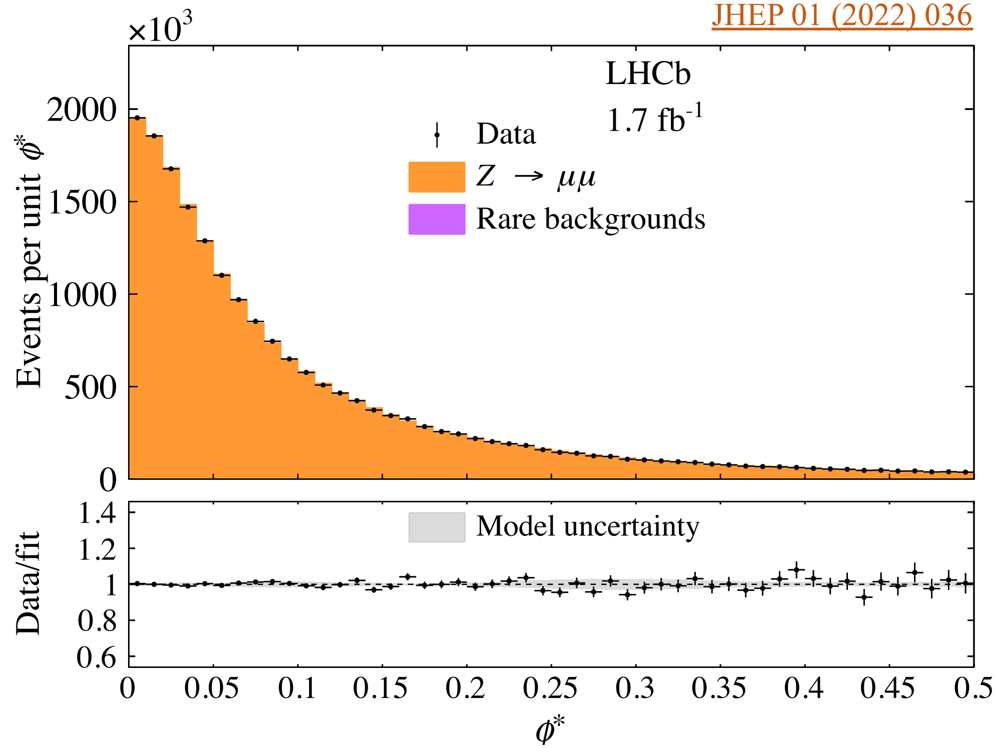




Parameter	Value
Fraction of $W^+ \to \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3508 ± 0.0005
Fraction of hadron background	0.0146 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
k_T^{intr}	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026

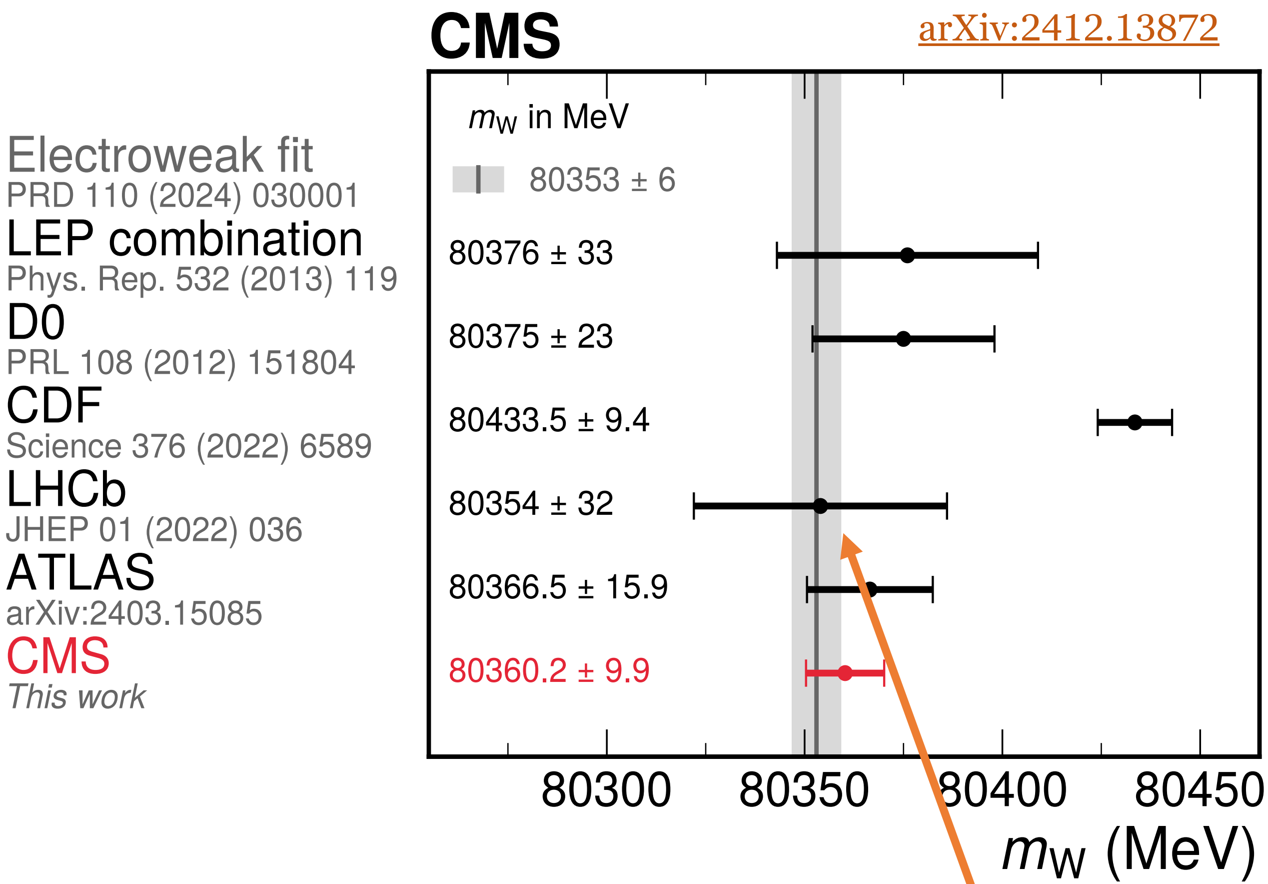
$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$

$\chi^2/ndf = 105/102$

$\sigma_{stat} = 23$ MeV

The 2016 result

- Taking the arithmetic average of results with NNPDF31, CT18 and MSHT20:

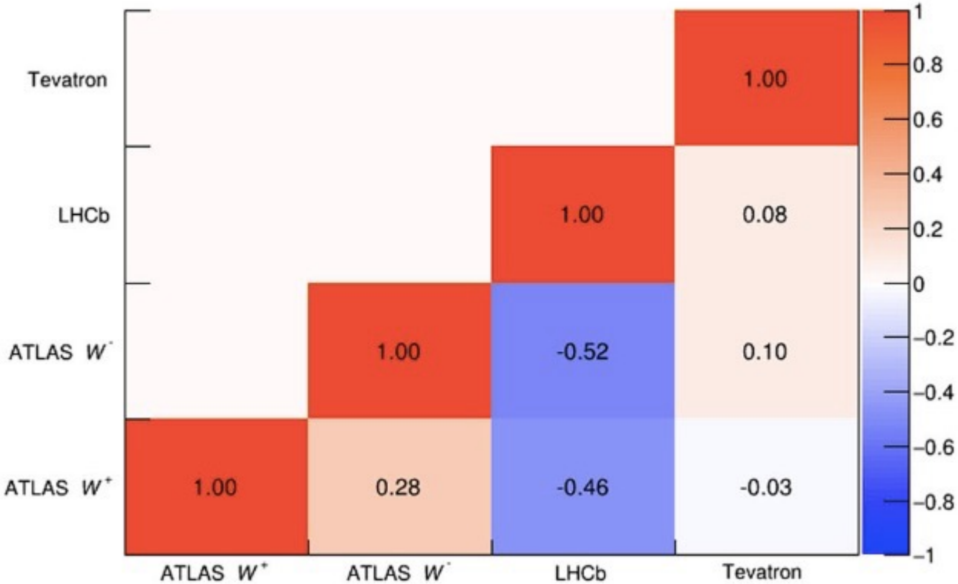


$$m_w = 80354 \pm 23_{stat} \pm 10_{exp} \pm 17_{theory} \pm 9_{PDF}\ \text{MeV} = 80354 \pm 32\ \text{MeV}$$

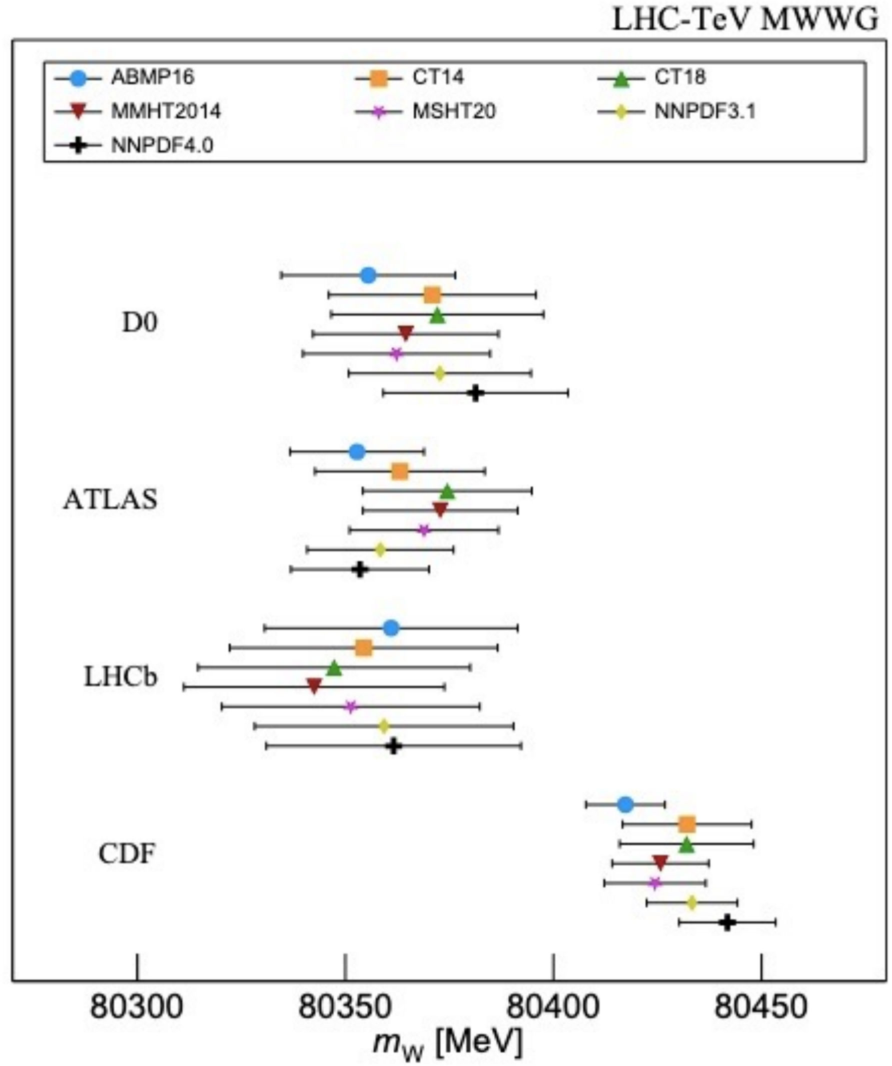
Combination with other results

EPJC 84 451 (2024) (before latest CMS & ATLAS m_W measurements)

- PDF uncertainty anticorrelation present as foreseen:



- But difficult to make a meaningful cross-experiment average of incompatible results.



m_Z measurement with 2016 data

arXiv:2505.15582, submitted to PRL

Status of m_Z measurements

- Like m_W, m_Z can be indirectly determined in a global EW fit:

$$m_Z^{HEPfit} = 91204.7 \pm 8.8 \text{ MeV},$$

- Experimental measurements:

$$m_Z^{LEP} = 91187.6 \pm 2.1 \text{ MeV},$$

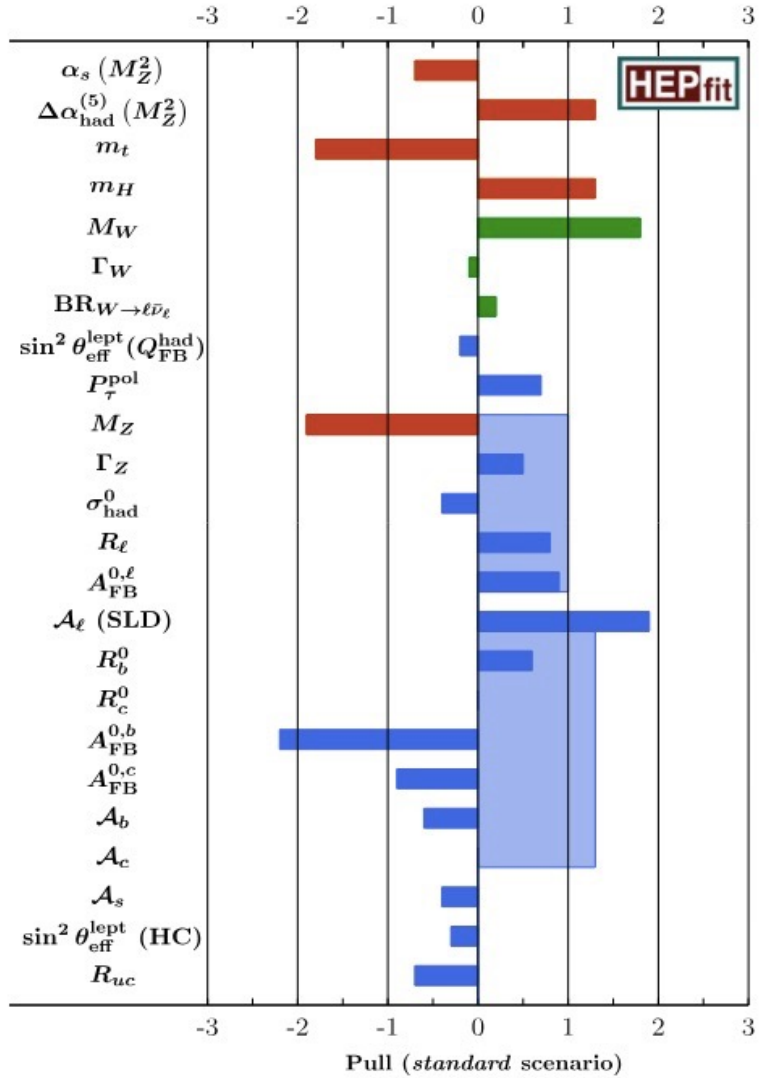
$$m_Z^{CDFII} = 91192.3 \pm 7.1 \text{ MeV},$$

$$m_Z^{CMS} - m_Z^{PDG} = -2.2 \pm 4.8 \text{ MeV}$$

"Since J/ψ vs Z closure was used to tune calibration and enters the uncertainty model, not (yet) a fully independent measurement for inclusion in world average"

- No dedicated LHC measurement of m_Z yet!

PRD 106 (2022) 033003



m_Z in the context of m_W

LHCb m_W measurement relied heavily on calibrating to the Z.

- Do we sufficiently understand the Z?
- Do we sufficiently understand our momentum measurement?
- Experimentally, are muons from Zs sufficiently like muons from Ws?

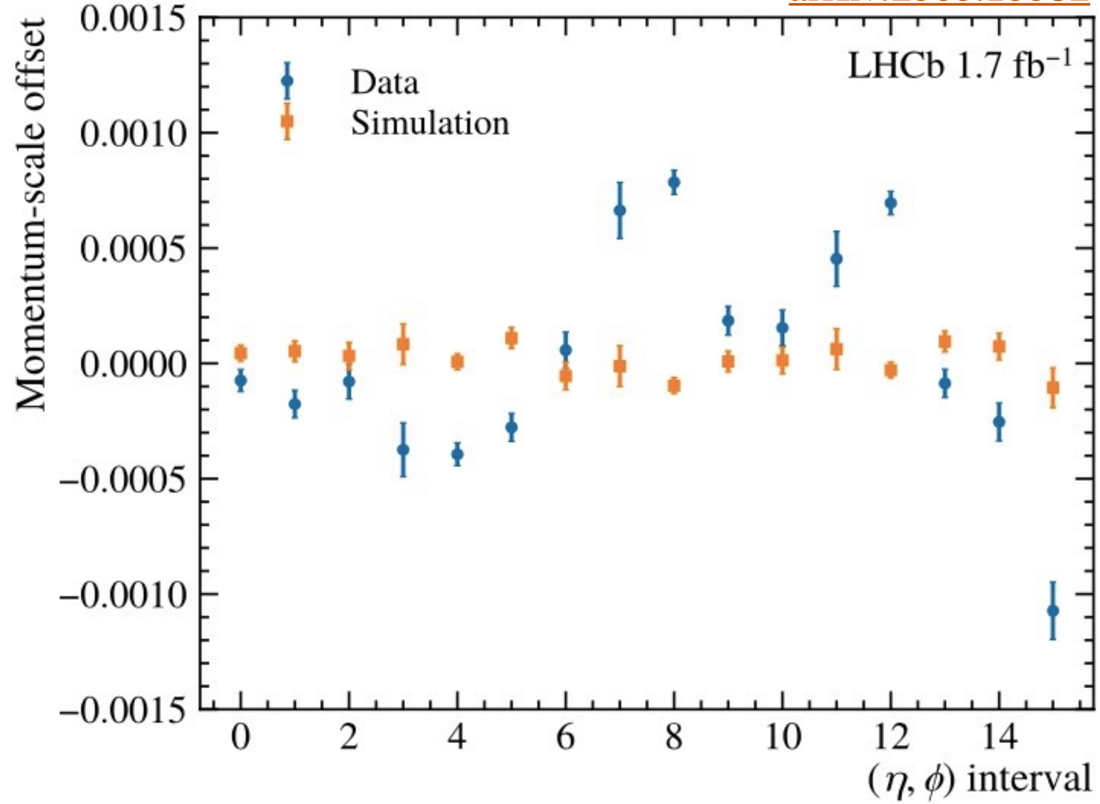
A measurement of m_Z would shed some light on these important questions.

m_Z momentum calibration (1)

Revisited our momentum bias / smearing function:

- Added an energy loss term ($p \to p + \beta$) to momentum bias / smearing function,
- Introduced a direction (η/ϕ)-dependent momentum scale correction:

arXiv:2505.15582



- Extracted from $\Upsilon(1S)$ lineshapes in data / MC in each bin:
- Corrected MC to match data.
- Also corrected time-dependent shifts in $\Upsilon(1S)$ mass from PDG in the data*.

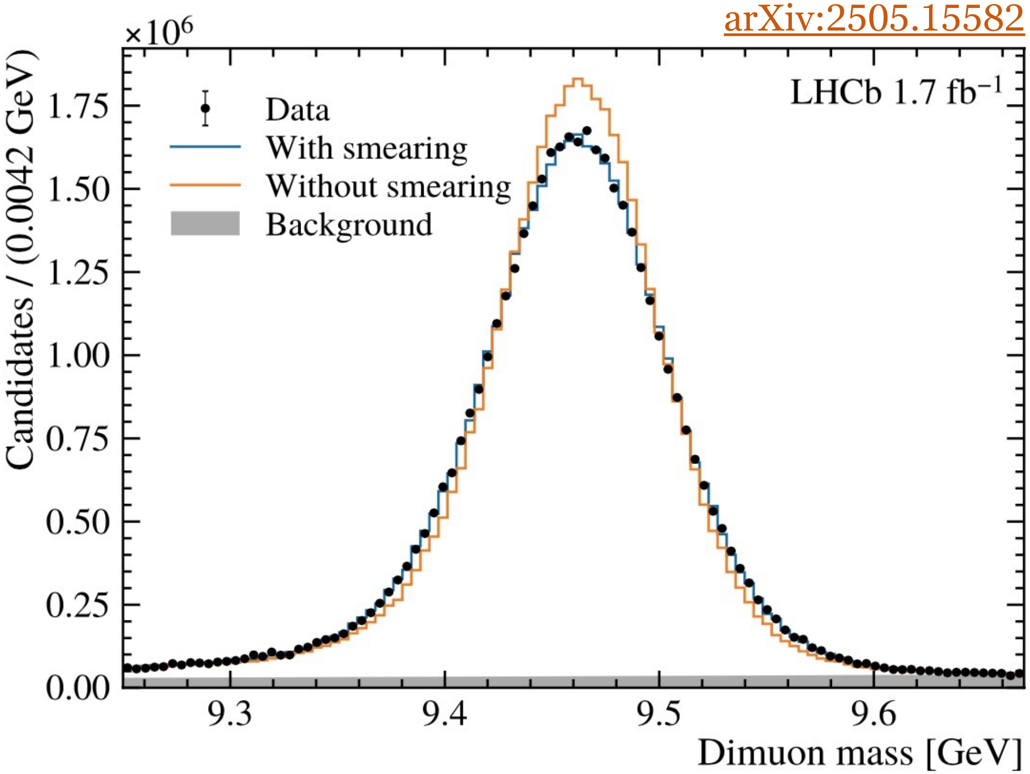
*mW 2016 had this too.

m_Z momentum calibration (2)

- Alignment: still used the *pseudomass* method with $Z \to \mu\mu$;
  - Checked that shifting $\Delta m_Z^{MC} = \pm 100$ MeV → 300 keV bias in m_Z measurement,

- Momentum smearing performed only with $\Upsilon(1S)$:

arXiv:2505.15582

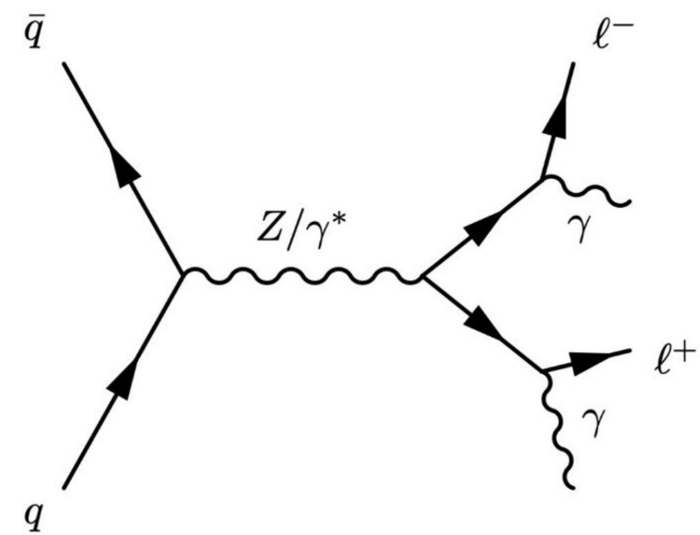


Parameter	Value
Momentum scale	$(-0.65 \pm 0.16) \times 10^{-4}$
Momentum-independent smearing (multiple scattering)	$(1.98 \pm 0.07) \times 10^{-3}$
Momentum-dependent smearing (curvature resolution)	(0.147 ± 0.009) /TeV

Smearing params partially anticorrelated without constraint from Z → have to float a multiplicative factor in m_Z fit.

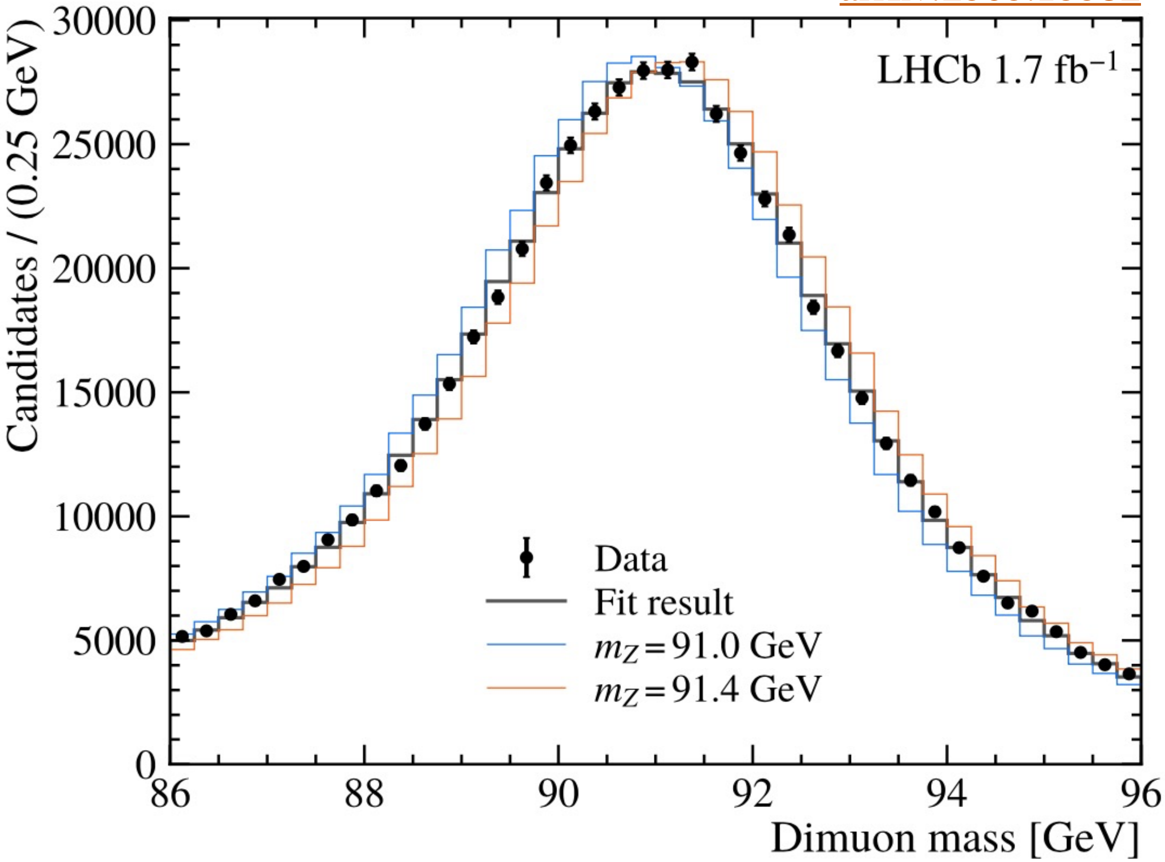
Dimuon mass templates

- Generated $m_{\mu\mu}$ templates with different m_Z hypotheses:
  - Input scheme: (m_Z, m_W, G_F).
- Template model: special version of POWHEG-Box (EPJC 73 (2013) 6).
  - NLO QCD + QED corrections,
  - Exact computation of first photon emission (ISR, FSR and their interference).
- Additional FSR modelled with PHOTOS.
  - Pythia taken as a systematic.
- Used NNPDF3.0 as central PDF set, with envelope including CT18 and MSHT20 as an uncertainty.



Fit for m_Z

arXiv:2505.15582



$\chi^2/ndf = 44/37$,

$\sigma_{stat} = 8.5$ MeV,

$^1/_p$ smearing factor = 1.3 ± 0.1,

$corr(^1/_p$ smearing, m_Z) = 0.015.

Uncertainty breakdown

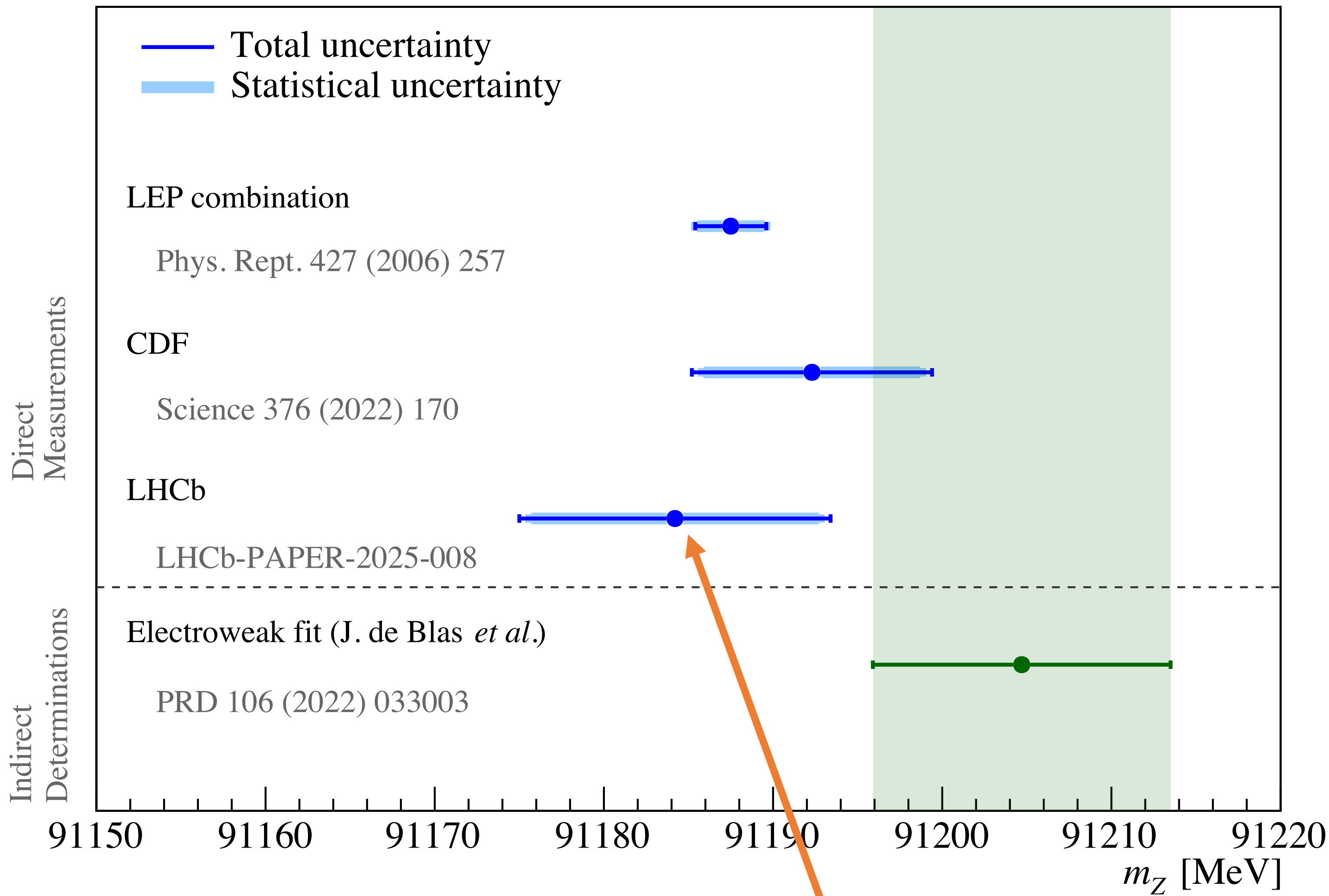
Source	Size [MeV]	
Momentum scale and resolution modelling	3.6	Detector material, stat. unc., external inputs
QED corrections	0.8	Pythia instead of PHOTOS
Parton distribution functions	0.7	Envelope from NNPDF31, CT18, MSHT20
Muon ID, trigger and tracking efficiency	0.1	Statistical uncertainties; method choices
Statistical	**8.5**	
Total	**9.5**	

- Much less sensitive to boson production kinematics than mW,
- Use NNPDF3.1 for central result, consider MSHT20 and CT18 for uncertainty,
- No systematics due to suppressed or modelling significant backgrounds (there are none),
- Statistically limited, with momentum measurement the only significant systematic.

Also made a variety of cross-checks on the consistency of the result (backup).

Result

arXiv:2505.15582



$$m_Z = 91184.2 \pm 8.5_{stat} \pm 3.8_{syst}\ \text{MeV} = 91184.2 \pm 9.3\ \text{MeV}$$

Towards a full-Run-2 m_W measurement

- 2016 -> 2016-18,
- ~3x more data,
- Targeting 20 MeV uncertainty.

Uncertainty breakdown in 2016 measurement

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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**

- $\Delta m_W(syst) < \Delta m_w(stat)$,
- PDF uncertainty was not limiting,
- Good control over experimental sources of uncertainty (all individually $\leq$ 7 MeV),
- Limited by uncertainties related to theoretical inputs.
- How will this evolve in our next measurement?

Experimental uncertainties

ALL PROJECTIONS ARE VERY PRELIMINARY

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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 -> 7**
Momentum scale and resolution modelling	7 -> 5
Muon ID, trigger and tracking efficiency	6 -> 4
Isolation efficiency	4 -> 3
QCD background	2 -> 2
Statistical	**23**
Total	**32**

- Systematic uncertainties originated from
  - Control sample size,
  - Details of the methods (binnings, smoothing, choice of parametrisation etc.),
  - External inputs ($\Upsilon(1S)$ mass).
- Expected to reduce as the data sample grows.
- Work ongoing on gaining deeper understanding and simplifying/consolidating if possible.
  - m_Z enabled improvements in our momentum resolution modelling.
- These should not become limiting uncertainties.

PDF uncertainties

ALL PROJECTIONS ARE
VERY PRELIMINARY

Source	Size [MeV]
Parton distribution functions	**9 -> 9**
Theory (excl. PDFs) Total	**17**
Transverse momentum model	11
Angular Coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental Total	**10 -> 7**
Momentum scale and resolution modelling	7 -> 5
Muon ID, trigger and tracking efficiency	6 -> 4
Isolation efficiency	4 -> 3
QCD background	2 -> 2
Statistical	**23**
Total	**32**

- Not a showstopper to get to $\Delta m_W \approx$ 20MeV,
- Analysis framework set-up to quickly integrate new PDF sets.
- Observed strong anti-correlation in a LHC combination.
- Conservatively project it stays at 9 MeV.

Boson p_T model uncertainty

ALL PROJECTIONS ARE VERY PRELIMINARY

- 2016 uncertainty based on the envelope of fits using p_T^V predictions from:
  - POWHEG (NLO)+Pythia (LL) (default),
  - Herwig (NLO),
  - POWHEG+Herwig,
  - Pythia (LO) with two different PDF sets.

- NNLO + NNLL QCD predictions are available e.g. from DYTurbo. *Tentatively* project a reduction to a ~6 MeV uncertainty from scale variations.

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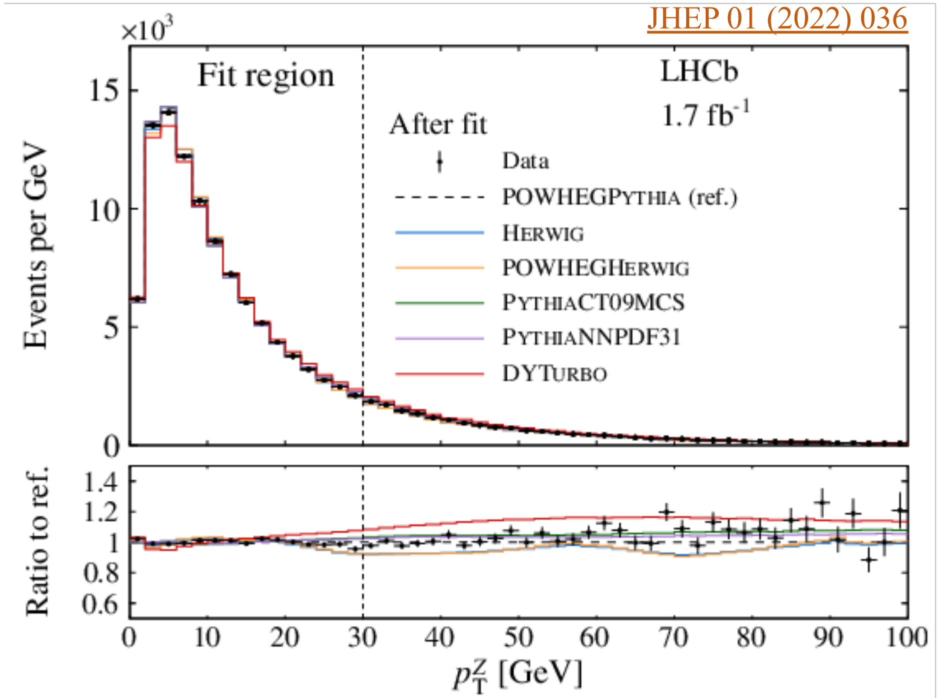
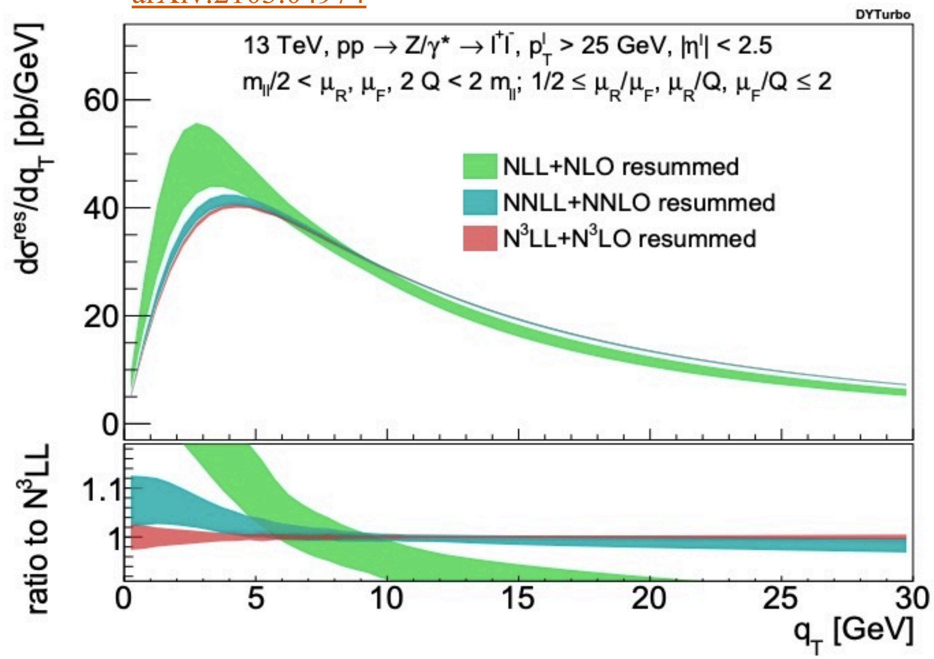


arXiv:2103.04974



A_i & EW uncertainties

ALL PROJECTIONS ARE VERY PRELIMINARY

Source	Size [MeV]
Parton distribution functions	**9 -> 9**
Theory (excl. PDFs) Total	**17 -> 8**
Transverse momentum model	11 -> 6
Angular Coefficients	10 -> 4
QED FSR model	7 -> 4
Additional electroweak corrections	5 -> ~0
Experimental Total	**10 -> 7**
Momentum scale and resolution modelling	7 -> 5
Muon ID, trigger and tracking efficiency	6 -> 4
Isolation efficiency	4 -> 3
QCD background	2 -> 2
Statistical	**23**
Total	**32**

- Conservative 21-point → more realistic 7-point variation in DYTurbo,
- Vary the key scales / details in 1 FSR generator, rather than taking envelope of 3 generators,
- Go from L0 → NLO EW by default.
  - (This syst. was based on LO → NLO)
- Your input on this is very welcome.

Tentative projections

ALL PROJECTIONS ARE VERY PRELIMINARY

Source	2016 Size [MeV]	2016-18 size [MeV]
Parton distribution functions	**9**	**~9**
Theory (excl. PDFs) Total	**17**	**~8**
Transverse momentum model	11	~6
Angular Coefficients	10	~4
QED FSR model	7	~4
Additional EW corrections	5	~0
Experimental Total	**10**	**~7**
Momentum scale and resolution modelling	7	~5
Muon ID, trigger and tracking efficiency	6	~4
Isolation efficiency	4	~3
QCD background	2	~2
Statistical	**23**	**~14**
Total	**32**	**~20**

Tentative projections

ALL PROJECTIONS ARE
VERY PRELIMINARY

Source	2016 Size [MeV]	2016-18 size [MeV]
Parton distribution functions	**9**	**~9**
Theory (excl. PDFs) Total	**17**	**~8**
Transverse momentum model	11	~6
Angular Coefficients	10	~4
QED FSR model	7	~4
Additional EW corrections	5	~0
Experimental Total	**10**	**~7**
Momentum scale and resolution modelling	7	~5
Muon ID, trigger and tracking efficiency	6	~4
Isolation efficiency	4	~3
QCD background	2	~2
Statistical	**23**	**~14**
Total	**32**	**~20**

VERY PRELIMINARY

A different approach: measure $\frac{d\sigma}{dp_T^{\mu}}$?

LHCb-PAPER-2025-031 (in preparation)

Limitations of reco-level m_W measurement

- Previous m_W measurements fit $\frac{d\sigma}{dp_T^\mu}$ at the reco. level.
- Requires fully-calibrated simulation to fit data,
- Theoretical model deeply baked into the analysis,
- Got a new theory model? You have to give it to us and ask to re-run the analysis for you,
- It would be much simpler to measure $\frac{d\sigma}{dp_T^\mu}$ first, then extract m_W separately.

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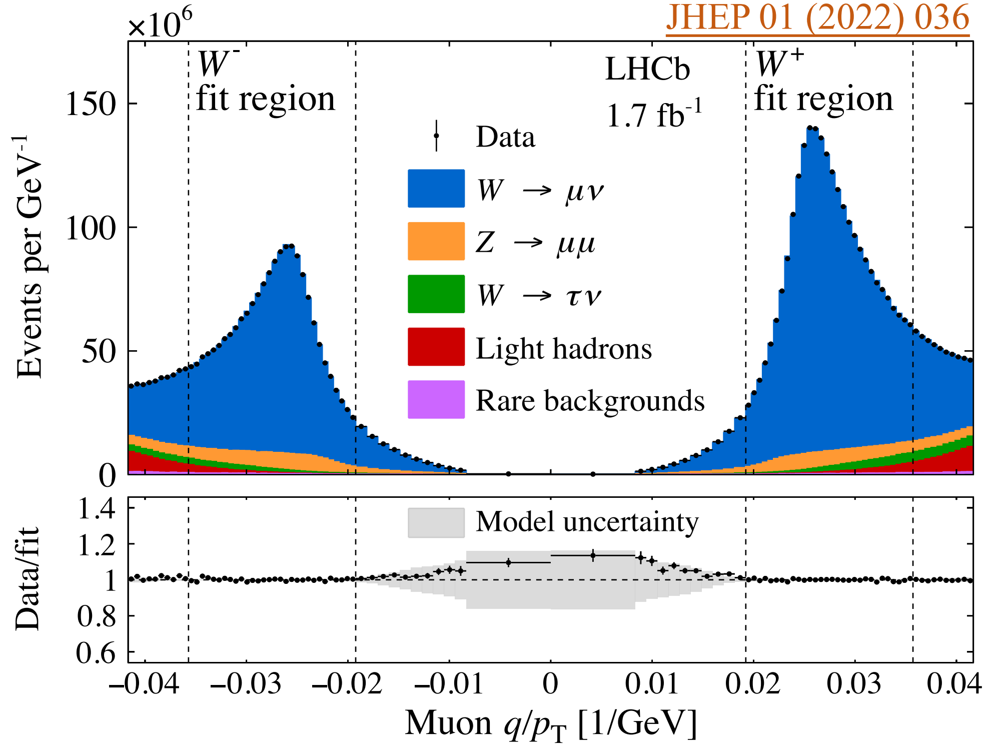
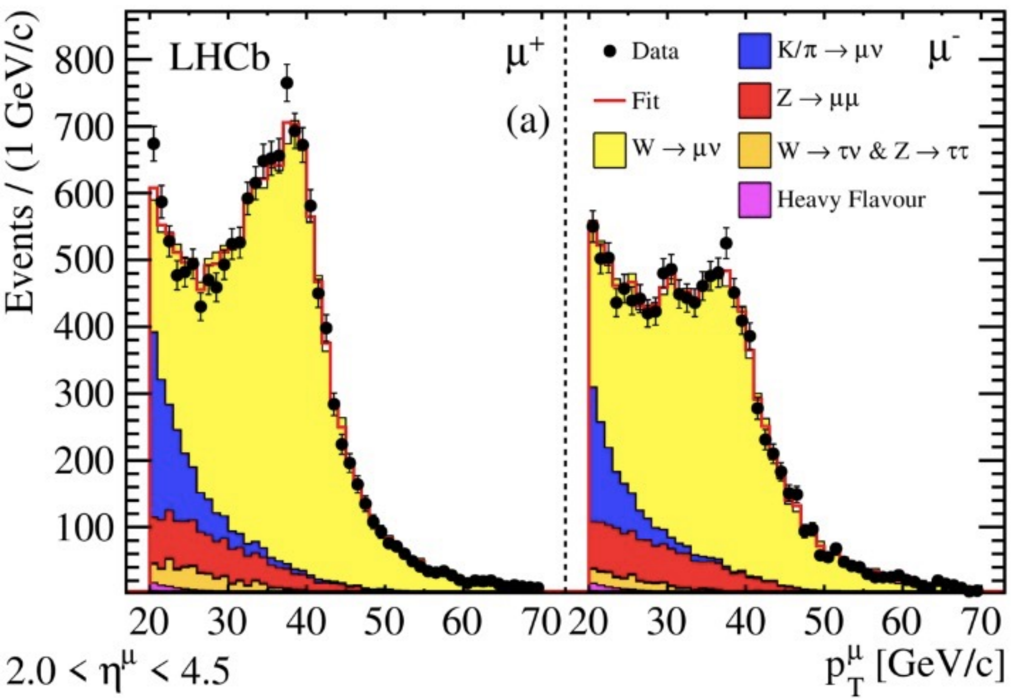


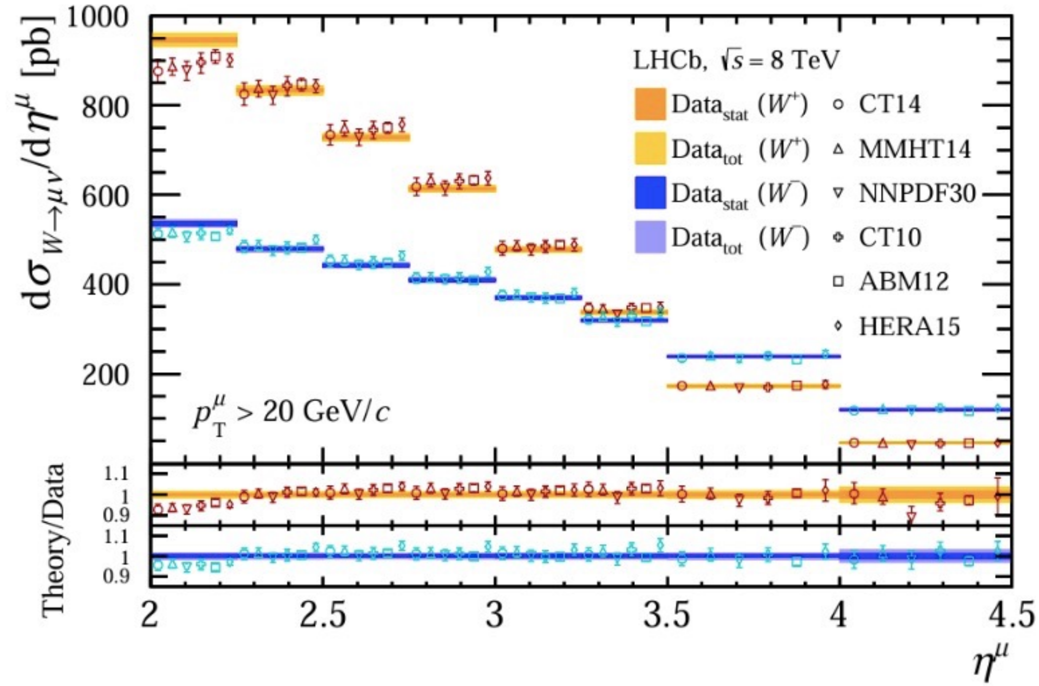
W cross sections at LHCb

- Previous W cross sections have used $\frac{d\sigma}{dp_T}$ and assumed a signal shape to subtract background, and produced e.g. $\frac{d\sigma}{d\eta^\mu}$:

JHEP 12 (2014) 079



JHEP 01 (2016) 155

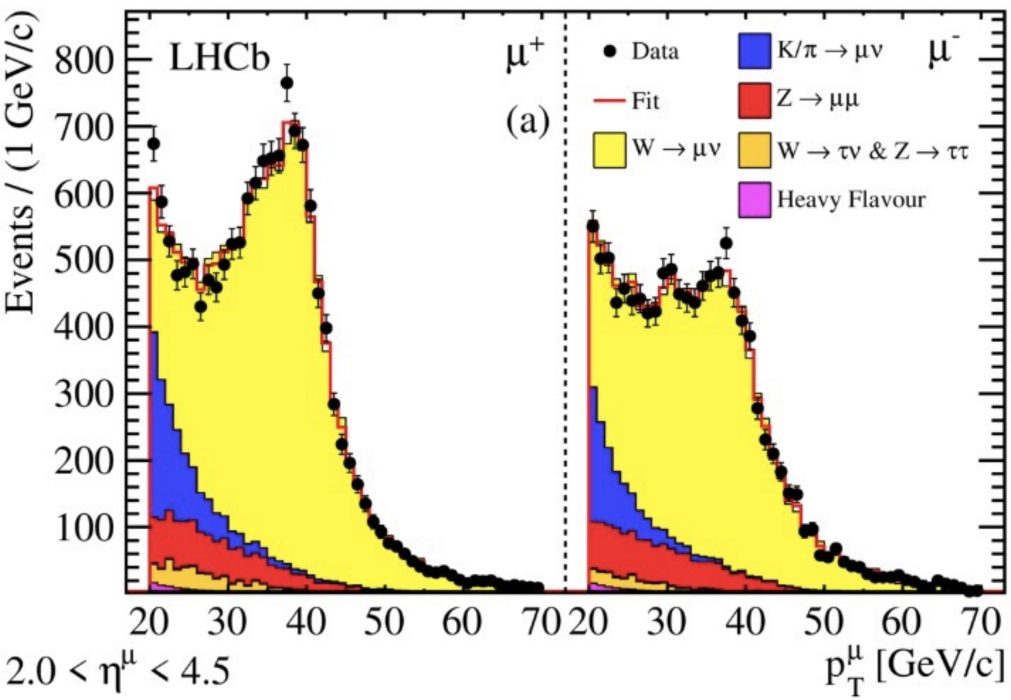


- Can we background-subtract in another dimension that is less theory-dependent?

W cross sections at LHCb

- Previous W cross sections have used $\frac{d\sigma}{dp_T}$ and assumed a signal shape to subtract background, and produced e.g. $\frac{d\sigma}{d\eta^\mu}$:

JHEP 12 (2014) 079



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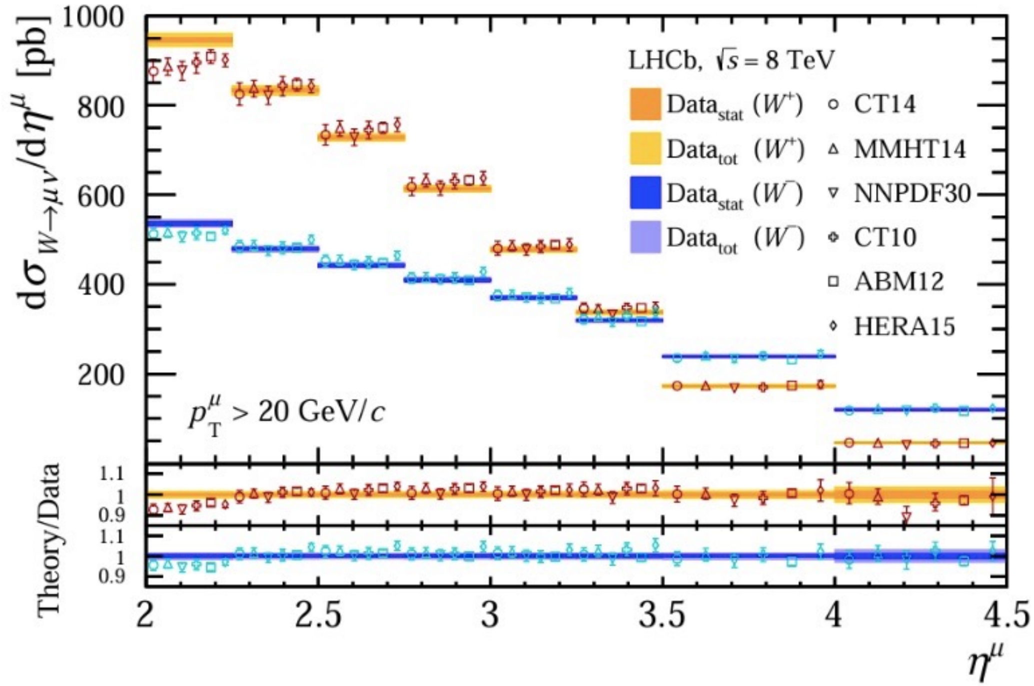


- Can we background-subtract in another dimension that is less theory-dependent?
  → Muon isolation*.

*$\sum p_T^i$ of neutral and charged particles within cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5$ around the signal (muon)

Strategy of $d\sigma/(dp_T^\mu)$ measurement

1. In many bins of p_T^μ, fit isolation I^μ with fully-simulated templates to extract the bare-level, efficiency-corrected $N(W \to \mu\nu)$ (correcting for bin migration and finite template statistics in the fit),

2. Translate to $d\sigma/(dp_T^\mu)$ with bin width & luminosity,

3. Compare integrated cross sections to predictions with different PDFs,

4. Fit $d\sigma/(dp_T^\mu)$ with a semi-arbitrary model to make an m_W measurement,

- Start with our 2017 5TeV dataset (~100pb^{-1}, $\Delta m_W(stat) \approx 100$MeV) to prove the principle.

Strategy of $d\sigma/(dp_T^\mu)$ measurement

1. In many bins of p_T^μ, fit isolation I^μ with fully-simulated templates to extract the bare-level, efficiency-corrected $N(W \to \mu\nu)$ (correcting for bin migration and finite template statistics in the fit),
2. Translate to $d\sigma/(dp_T^\mu)$ with bin width & luminosity,
3. Compare integrated cross sections to predictions with different PDFs,
4. Fit $d\sigma/(dp_T^\mu)$ with a semi-arbitrary model to make an m_W measurement,

- Start with our 2017 5TeV dataset (~100pb^{-1}, $\Delta m_W(stat) \approx 130$MeV) to prove the principle.
- This step could be done by any theorist with a new model once our measurement is published.

Calibrations and corrections

Corrections to data:

- Charge-dependent curvature bias (pseudomass correction).

Corrections to simulation:

- Momentum scaling & smearing,
- Isolation calibration (signal and hadronic background),
- Efficiency corrections.

Calibrations and corrections

Corrections to data:

- Charge-dependent curvature bias (pseudomass correction) - Same method as 2016 m_W

Corrections to simulation:

- Momentum scaling & smearing, - Same method as 2016 m_W, m_Z
- Isolation calibration (signal and hadronic background), - NEW!
- Efficiency corrections - Same method as 2016 m_W, m_Z

Isolation calibration

- $Z \to \mu\mu$ MC compared to data to derive a scaling factor:

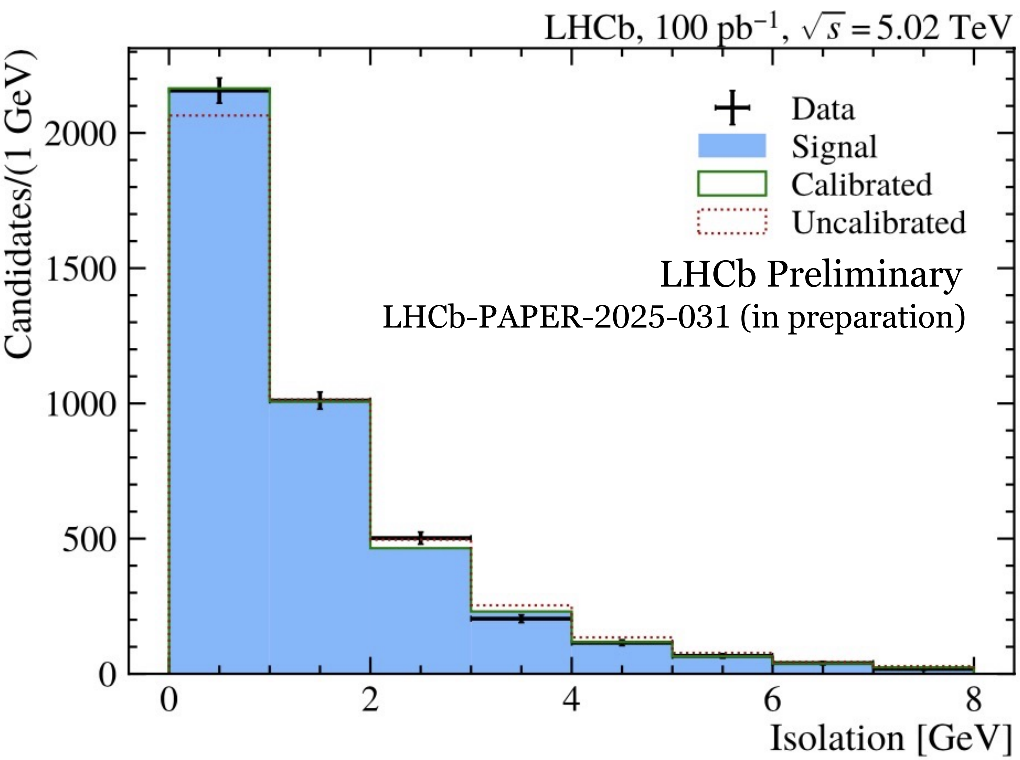
$$I^{\mu} \to kI^{\mu},$$

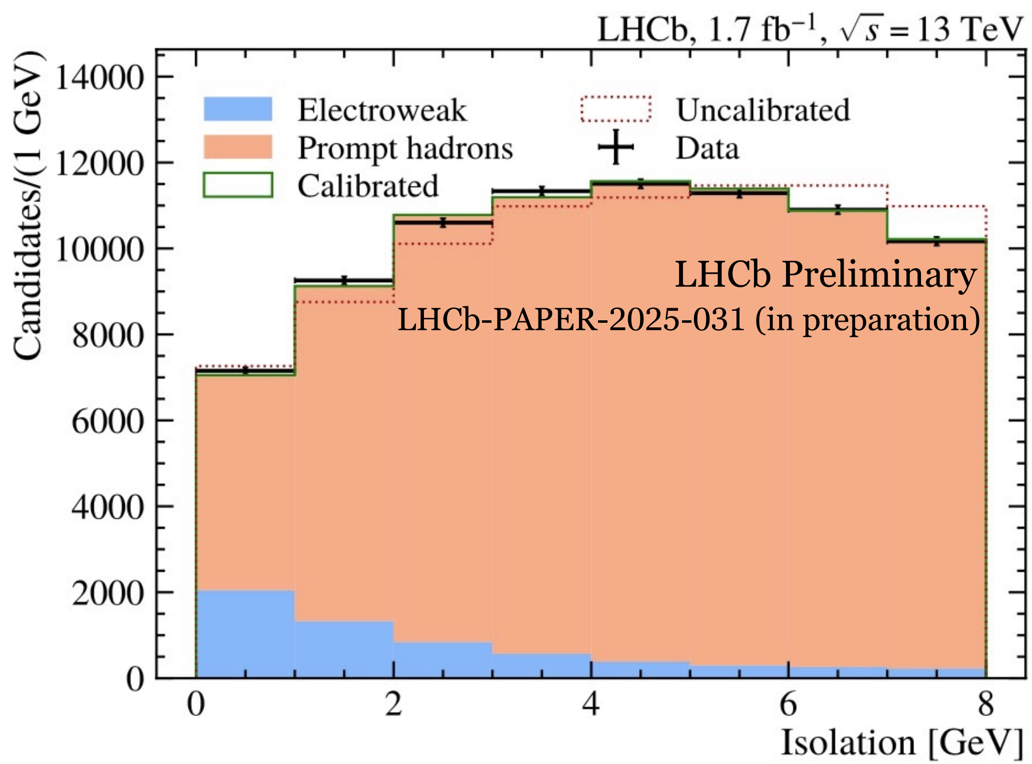
$$\text{with } k = 0.926 \pm 0.018.$$

- Anti-muonID sample* provides control sample of hadronic background.
- Fit MC (+some signal contamination) to data for a charge-dependent scaling factor:

$$I^{\mu} \to (C + q\delta)I^{\mu},$$

$$\text{with } C = 0.83 \pm 0.013, \delta = 0.048 \pm 0.013.$$

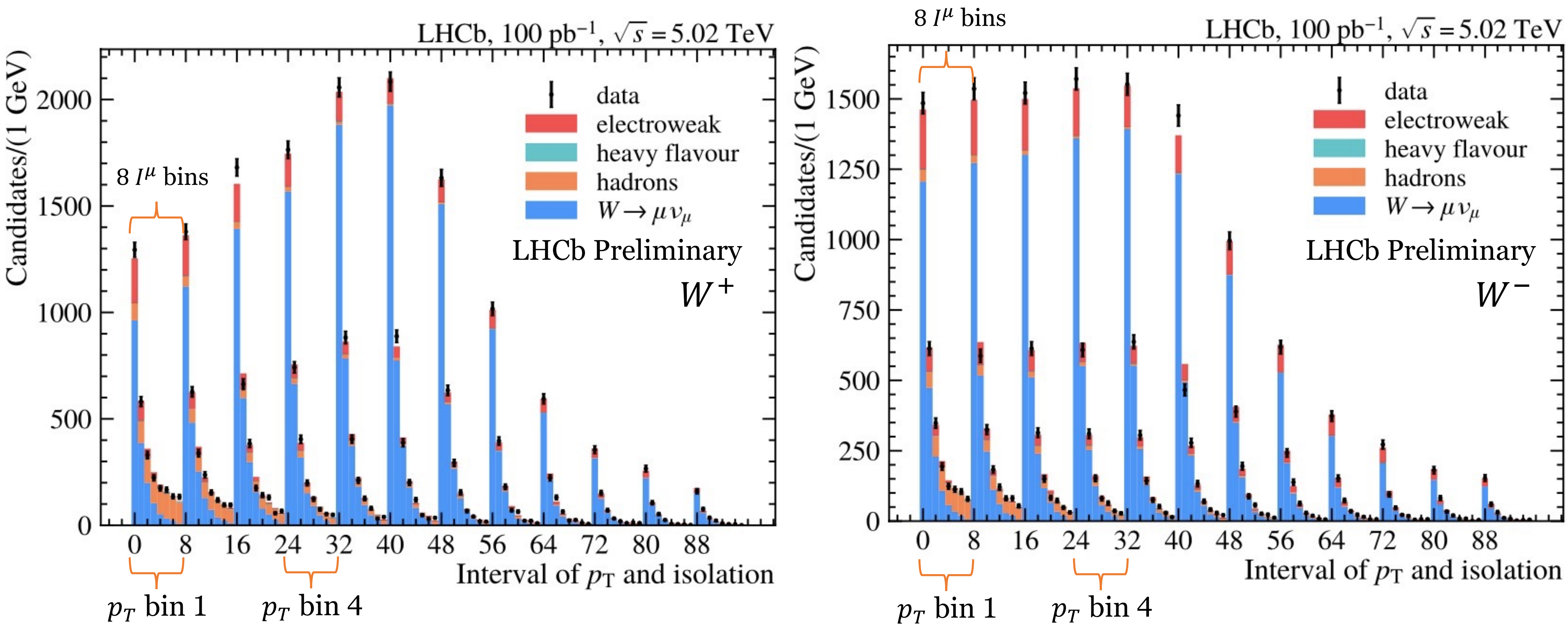




Differential cross section fit

LHCb-PAPER-2025-031 (in preparation)

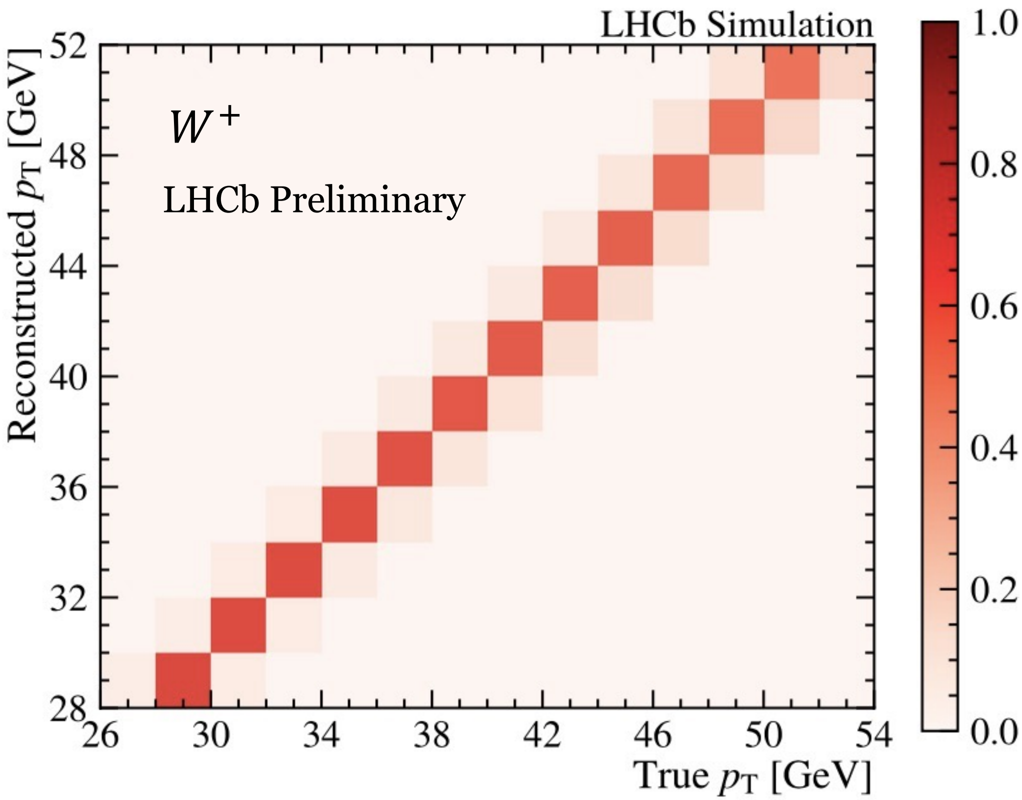
- 12 bins of p_T, 8 bins of isolation in each; $0 < I^\mu < 8$ GeV, $28 < p_T < 52$ GeV,
- $d\sigma/(dp_T^\mu)$ and hadronic background yield floats:



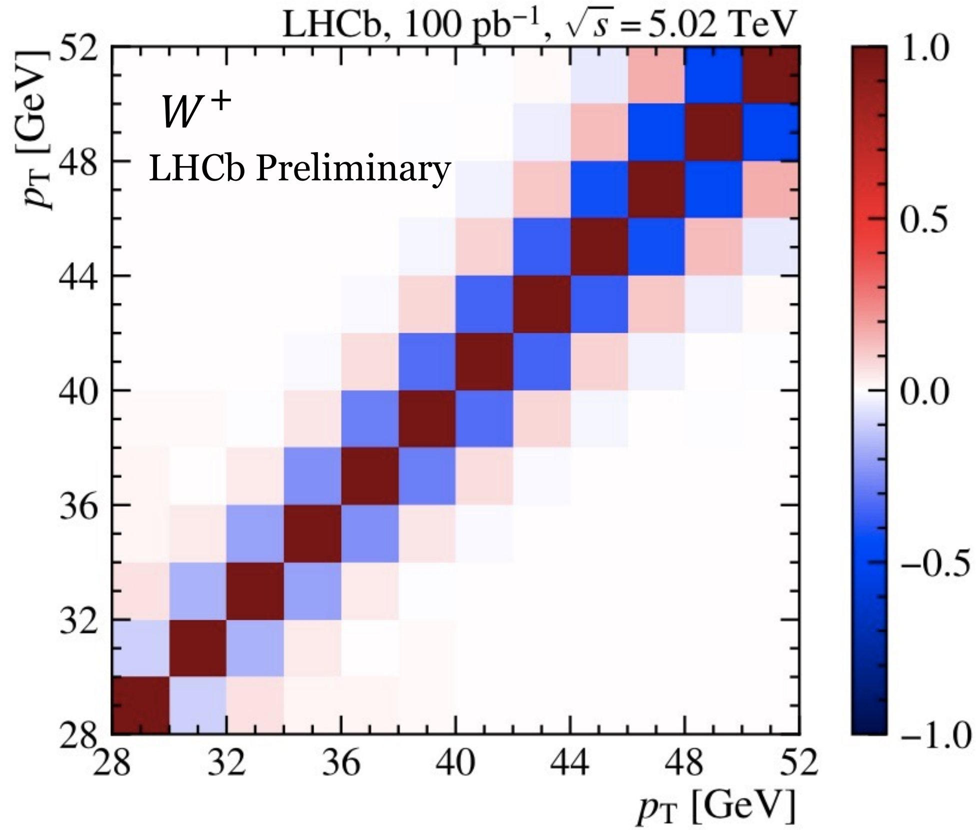
Response matrix & statistical correlation

LHCb-PAPER-2025-031 (in preparation)

- Integrating over isolation. Largely diagonal due to excellent $\vec{p}$ resolution:



- Statistical correlation matrix :



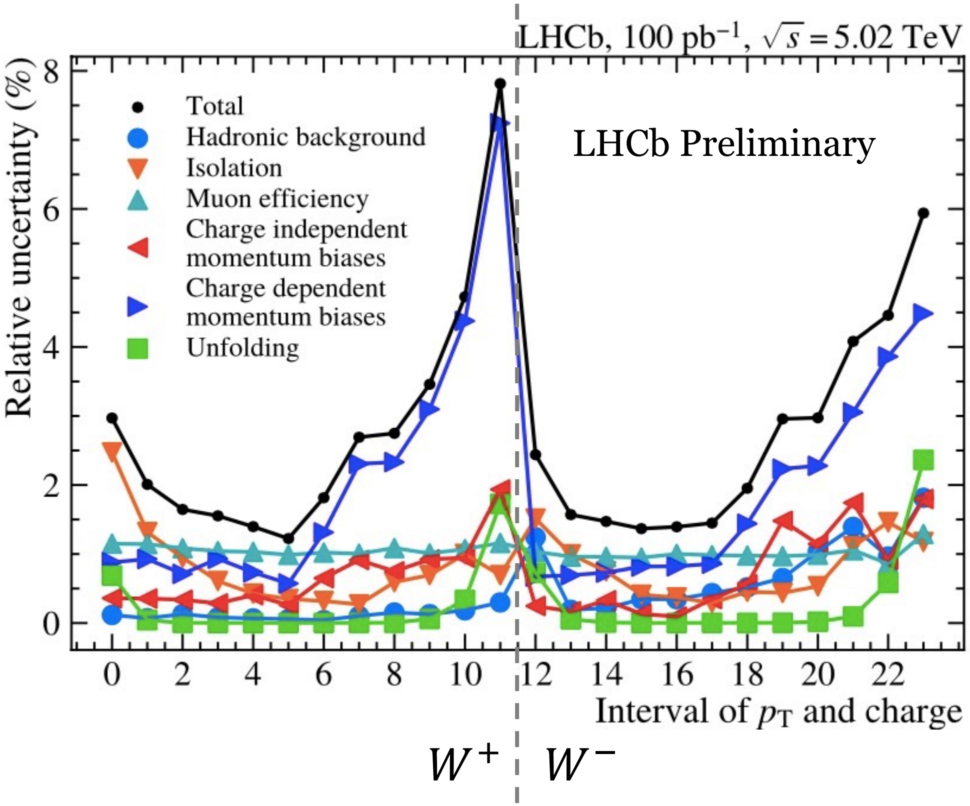
- (N.B. Efficiency in each true p_T bin is the sum of all rows in that column)

Systematic uncertainties

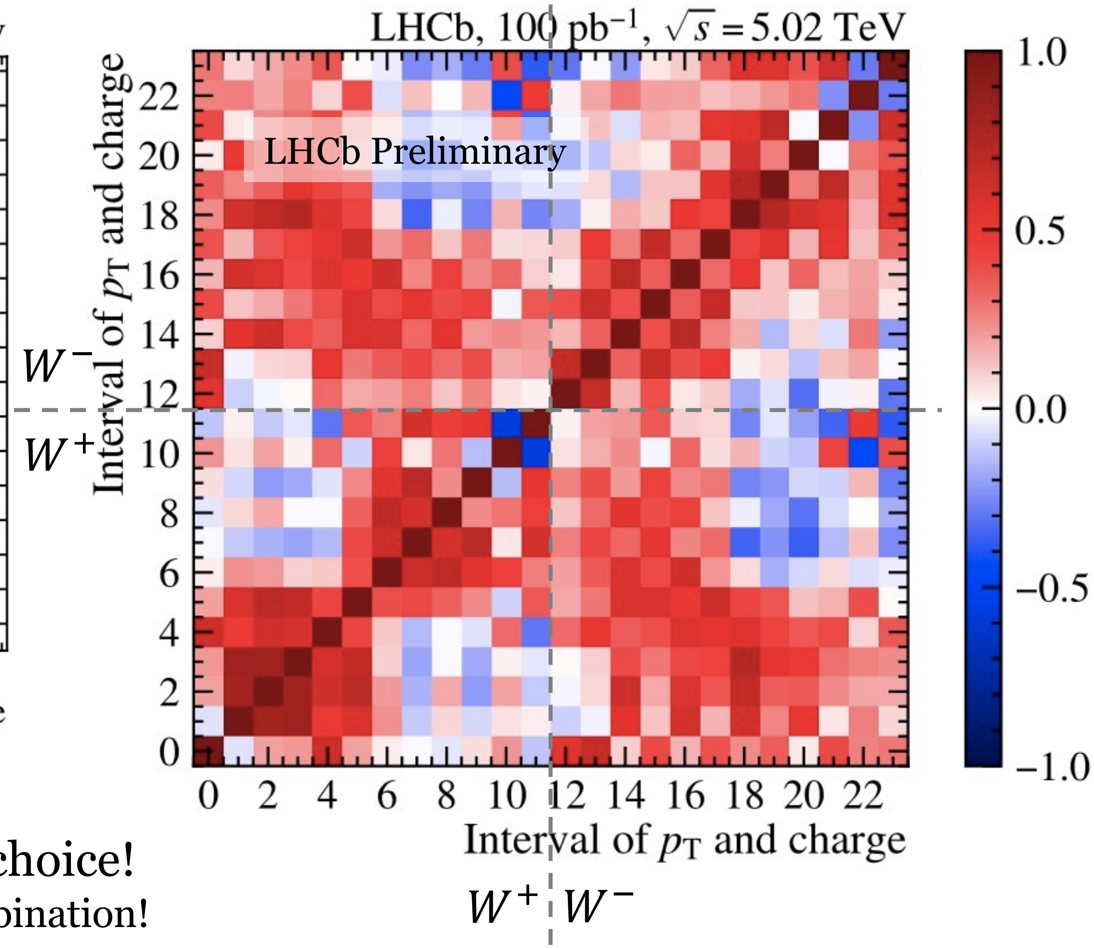
LHCb-PAPER-2025-031 (in preparation)

- Similar sources to m_W 2016 analysis. Larger pseudomass systematic due to smaller control sample size (but anti-correlated between W^+/W^-).
  - (Details of uncertainties in backup/ feel free to ask)

Relative uncertainties (grouped)



Total systematic correlation matrix



- All a theorist needs to fit m_W is a model of choice!
  - Very easy to add this to a cross-experiment combination!

m_W measurement details

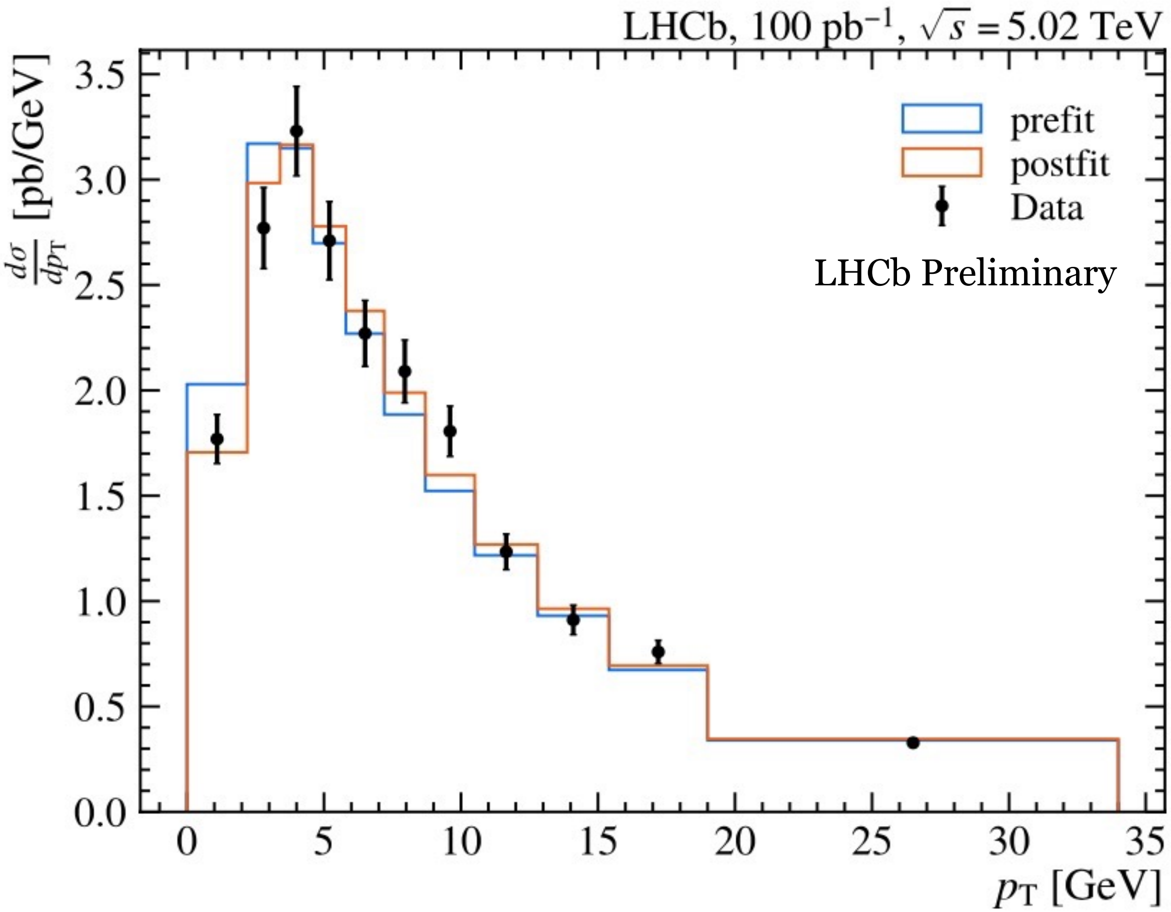
- Now have $(d\sigma^W)/(dp_T^\mu)$ at the truth level -> fit with a model to obtain m_W,

- Input to this fit: just 24 $(d\sigma^W)/(dp_T^\mu)$ values and a 24x24 covariance matrix - super compact,

- Model: L0 Pythia, reweighted to DYTurbo (NNLO + NNLL unpolarised, NLO angular terms), for different m_W hypotheses,
  - (but *now* it could be whatever generator / prediction you want…)

- Like m_W 2016, need to tune model QCD parameters to obtain a good description. Do it in the fit, and from comparison to published 5 TeV $(d\sigma^Z)/(dp_T^\mu)$.

Fit to published $(d\sigma^Z)/(dp_T^\mu)$



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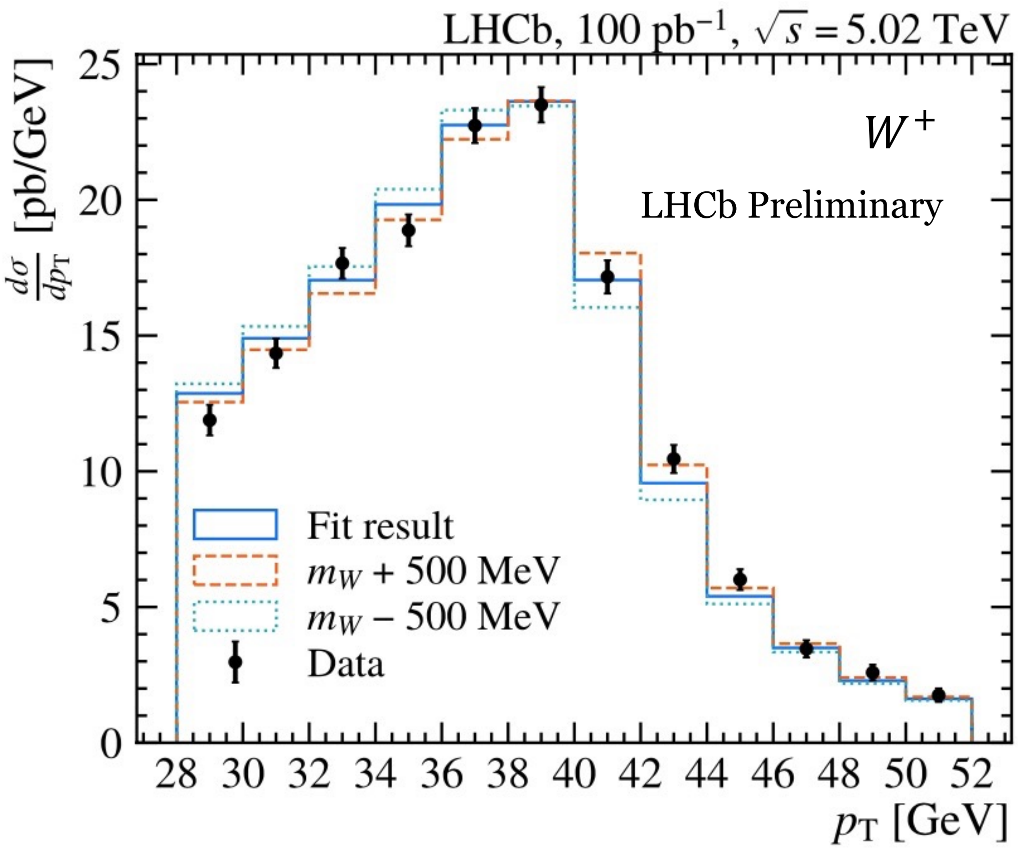
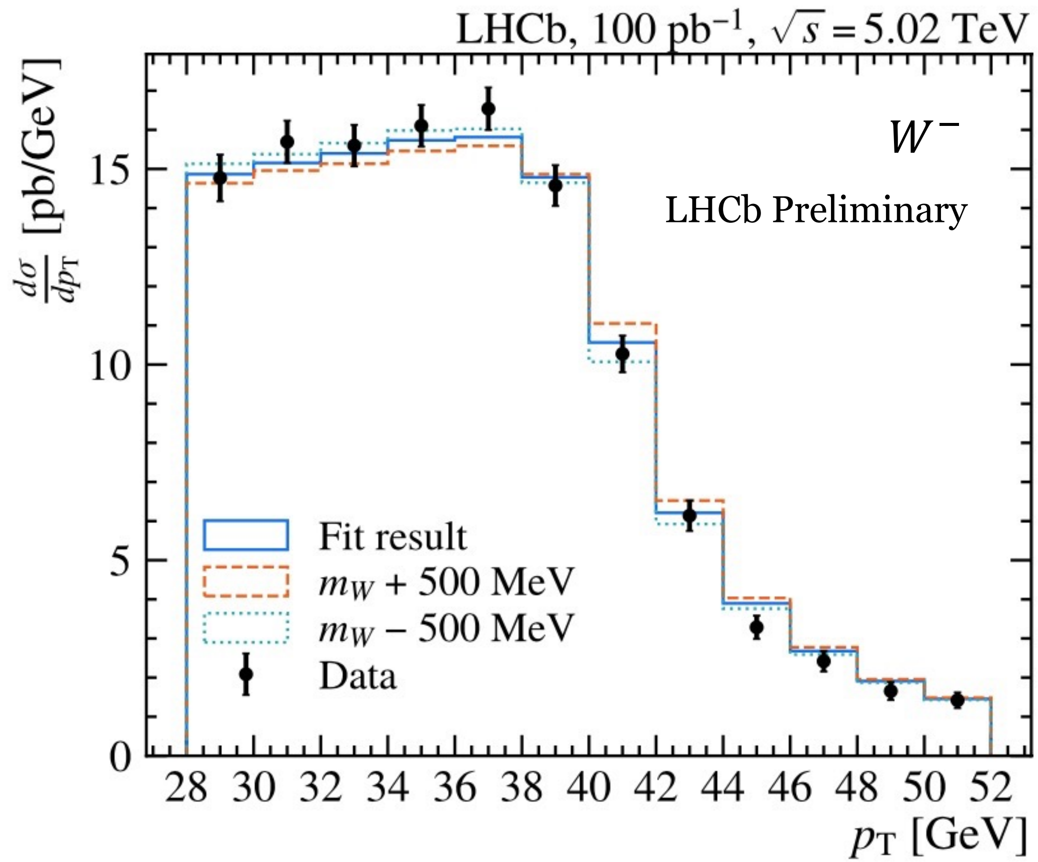
	Z fit
minimum	10.3029
α_s value	0.1120
α_s error	0.0056
g value	1.9517
g error	0.4863

- Following theorist recommendations, use this value of α_s in the fit for m_W.
- Fit g separately in fit for m_W.

Fit to $(d\sigma^W)/(dp_T^\mu)$ for m_W

LHCb-PAPER-2025-031 (in preparation)





- This fit uses NNPDF3.1 (semi-arbitrary), central result is again a simple average of central values from NNPDF3.1, CT18 and MSHT20.

m_W measurement

$$m_w = 80371 \pm 130_{(exp)} \pm 32_{(theory)} \text{ MeV} = 80371 \pm 134 \text{ MeV}$$

- Experimental uncertainty = all uncertainties on $(d\sigma^W)/(dp_T^\mu)$ (included stats.),
- Theory systematics on α_S, 7-point QCD scale variation, FSR model and PDF uncertainties,
- First analysis to measure $(d\sigma^W)/(dp_T^\mu)$ at a hadron collider,
- Proof-of-principle with 5.02 TeV dataset,
- Same method on 2017+18 13TeV data gives a ~12 MeV statistical uncertainty!

Summary and outlook

- Pathfinder: reco-level m_W measurement with 2016 13TeV data,
  - 32 MeV uncertainty, statistically-limited, SM compatible.

- Combination with ATLAS/CMS shows the expected PDF uncertainty cancellation in m_W.

- First dedicated m_Z measurement from LHC (2016 13TeV data).
  - 9 MeV uncertainty, statistically-limited, SM compatible,
  - Gave us a deeper understanding of LHCb's momentum response.

- Full Run-2 13TeV updates are ongoing, targeting 20 MeV uncertainty on m_W.

- (NEW!) m_W measurement from $(d\sigma^W)/\left(dp_T^\mu\right)$ with 2017 5.02TeV data.
  - Proof-of-principle first measurement of its kind,
  - Method being explored for 13TeV datasets.

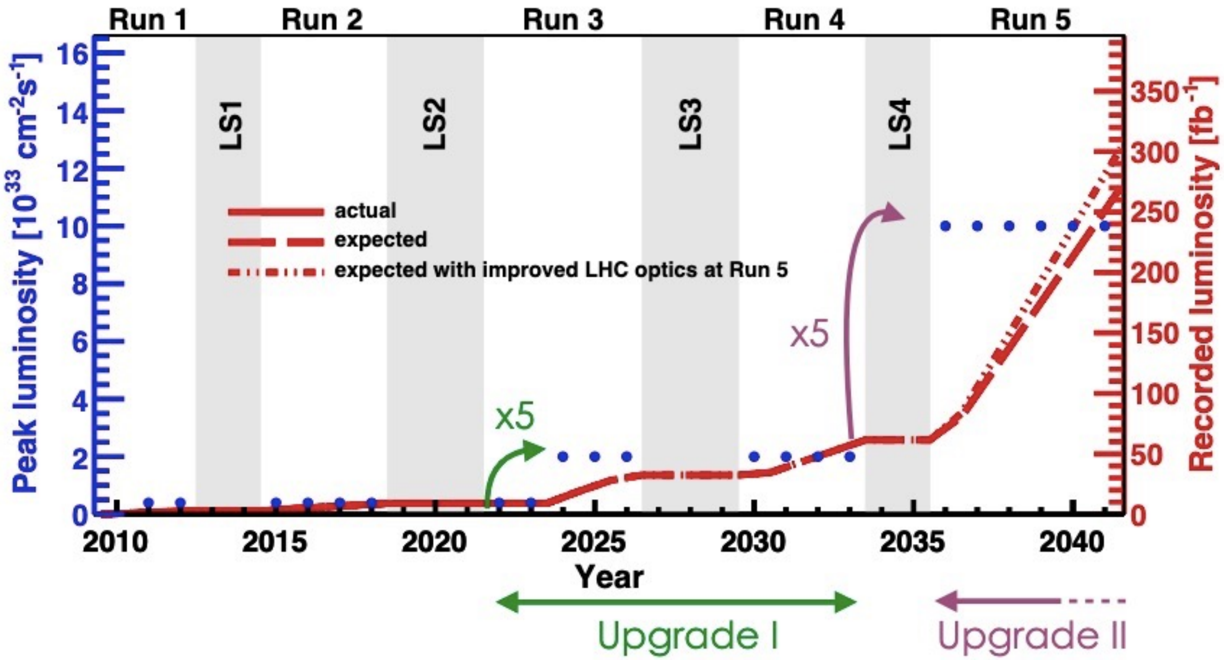
- Run-3 $\sigma(W \to \mu\nu)$ is not far away - lays foundations on our new dataset.

Thank you for your attention.
Any questions?

Backup

Beyond Run 2

- 2016 analysis had 1.7 fb^{-1}. Further approx. 4 fb^{-1} of Run-2 data to add. Runs 3-4 are aiming for ~50 fb^{-1}.



2016 $\Delta m_W\,(stat) = 23\text{MeV}$, $\Delta m_W\,(total) = 32\text{ MeV}$

Run 2 $\Delta m_W\,(stat) \approx 14\text{ MeV}$, $\Delta m_W\,(total) \sim 20\text{ MeV}$

Run 3-4 $\Delta m_W\,(stat) \sim 5\text{ MeV}$, $\Delta m_W\,(total) \lesssim 10\text{ MeV??}$

- Experimental uncertainties will reduce with more understanding, the improved LHCb Upgrade-I detector, and larger control samples.

- 2024 $W \to \mu\nu$ cross section analysis entering final stages.

- Uncertainties from the Drell-Yan physics modelling, PDFs and QED final-state radiation will continue to limit us - collaboration will be needed with the theory community.

mW 2016 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**	

mW 2016 signal selection

- Veto events with second high-p_T^μ muon in acceptance ($p_T^\mu > 25$ GeV); rejects $Z \to \mu\mu$,
- Signal muon is well-reconstructed, muon ID-ed and required to fire high-p_T single muon triggers,
- Muon candidate is isolated; rejects heavy flavour & decay-in-flight backgrounds.

This selects 2.4M events in the fit window $28 < p_T^\mu < 52$ GeV, $2.2 < \eta < 4.4$.

QED Final State Radiation (mW 2016)

- Different FSR predictions mimicked by reweighting in ΔE/E,
- No preference between predictions from Pythia, Herwig and Photos → weights from the average,

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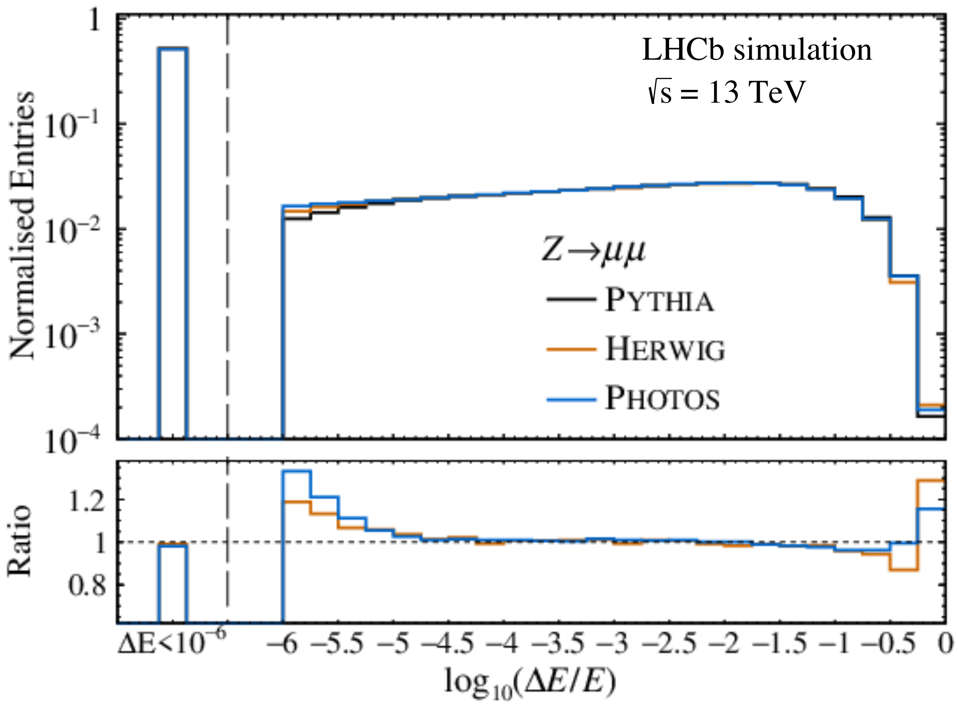

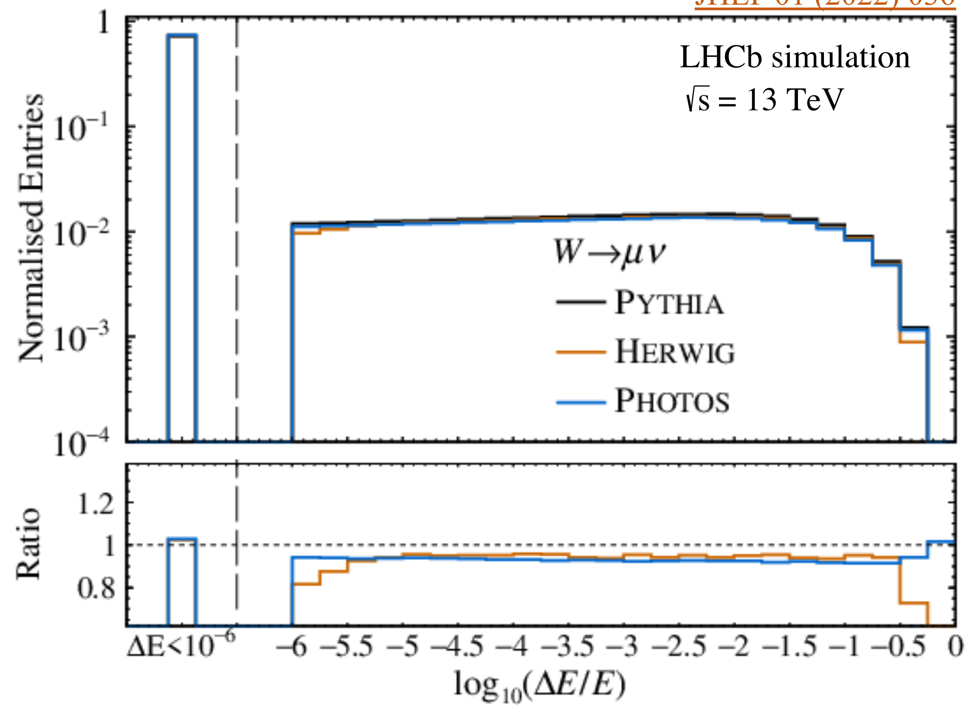

- Uncertainty from the envelope of fits with each → 7 MeV uncertainty.
- Higher-order EW corrections tested with POWHEG-ew → 5 MeV uncertainty.

Treatment of backgrounds (mW 2016)

- Electroweak backgrounds constrained with $Z \to \mu\mu$.

- Remaining decay-in-flight hadronic background (10x heavy flavour) modelled with a parametric shape, trained on a hadron-enriched data sample:

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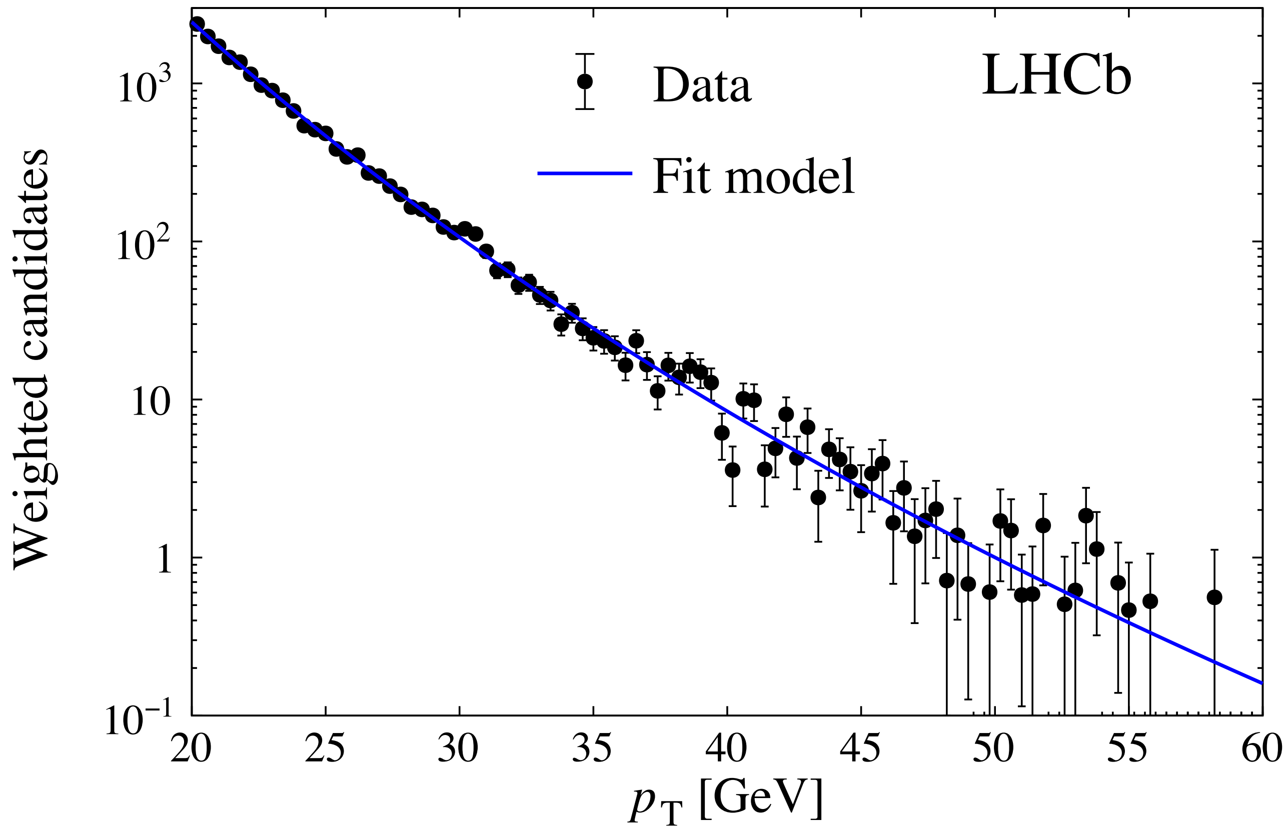

Reconstruction & selection efficiencies

Each muon is well-reconstructed & identified, fires relevant triggers and is isolated.

$$\varepsilon_{sim}\,(p_T, \eta, \phi, \dots) = \varepsilon_{data}(p_T, \eta, \phi, \dots)\ ?$$

Simulation corrected with event weights $w(p_T, \eta, \phi, \dots) = \varepsilon_{data}/\varepsilon_{sim}\,(p_T, \eta, \phi, \dots)$

Reco, ID & trigger efficiencies:

- Tag & probe method with $Z \to \mu\mu$ and $\Upsilon(1S) \to \mu\mu$ gives ε_{sim} & ε_{data}.
- Weights from fit to efficiency ratio as function of p_T^{μ}, binned in η and ϕ.

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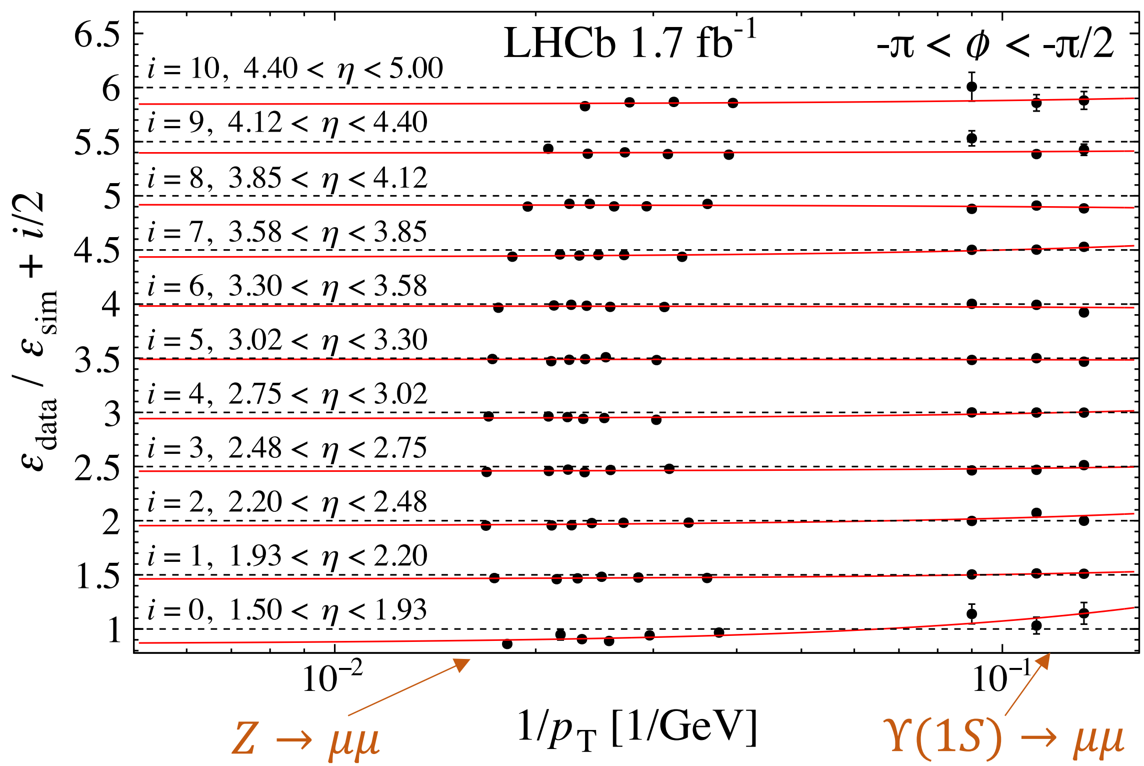


Reconstruction & selection efficiencies

Each muon is well-reconstructed & identified, fires relevant triggers and is isolated.

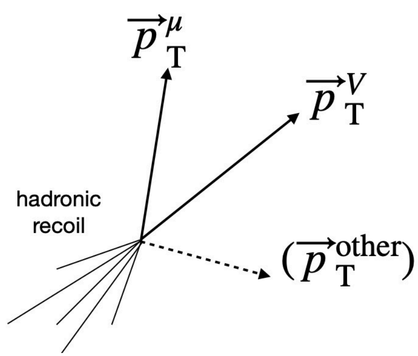
$$\varepsilon_{sim}\,(p_T, \eta, \phi, \ldots) = \varepsilon_{data}(p_T, \eta, \phi, \ldots)\ ?$$

Simulation corrected with event weights $w(p_T, \eta, \phi, \ldots) = \varepsilon_{data}/\varepsilon_{sim}\ (p_T, \eta, \phi, \ldots)$

Isolation efficiencies:

- Tag & probe method with $Z \to \mu\mu$ gives ε_{sim} & ε_{data}.
- Weights from efficiency ratios binned in recoil projection u and η.

$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$



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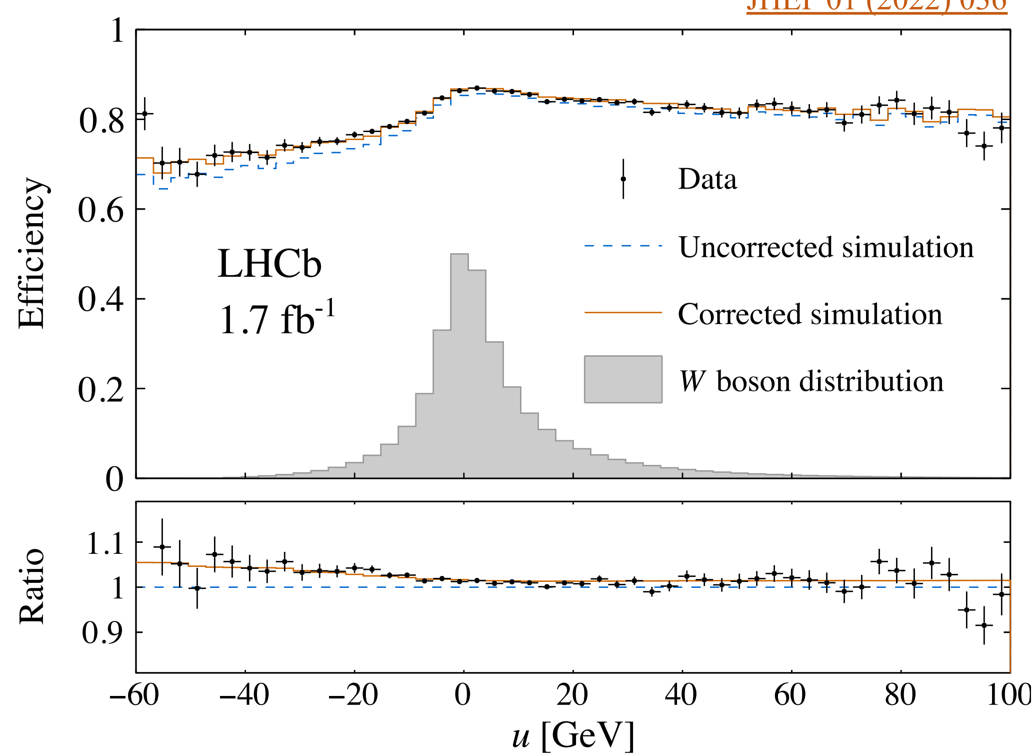


Cross-checks mW 2016

1. **Orthogonal splits:** Five ~50:50 splits of the data (polarity, charge × polarity, etc…) all result in [m_W] differences within 2σ.

2. **Fit range:** The result is stable w.r.t. variations in the upper/lower limits.

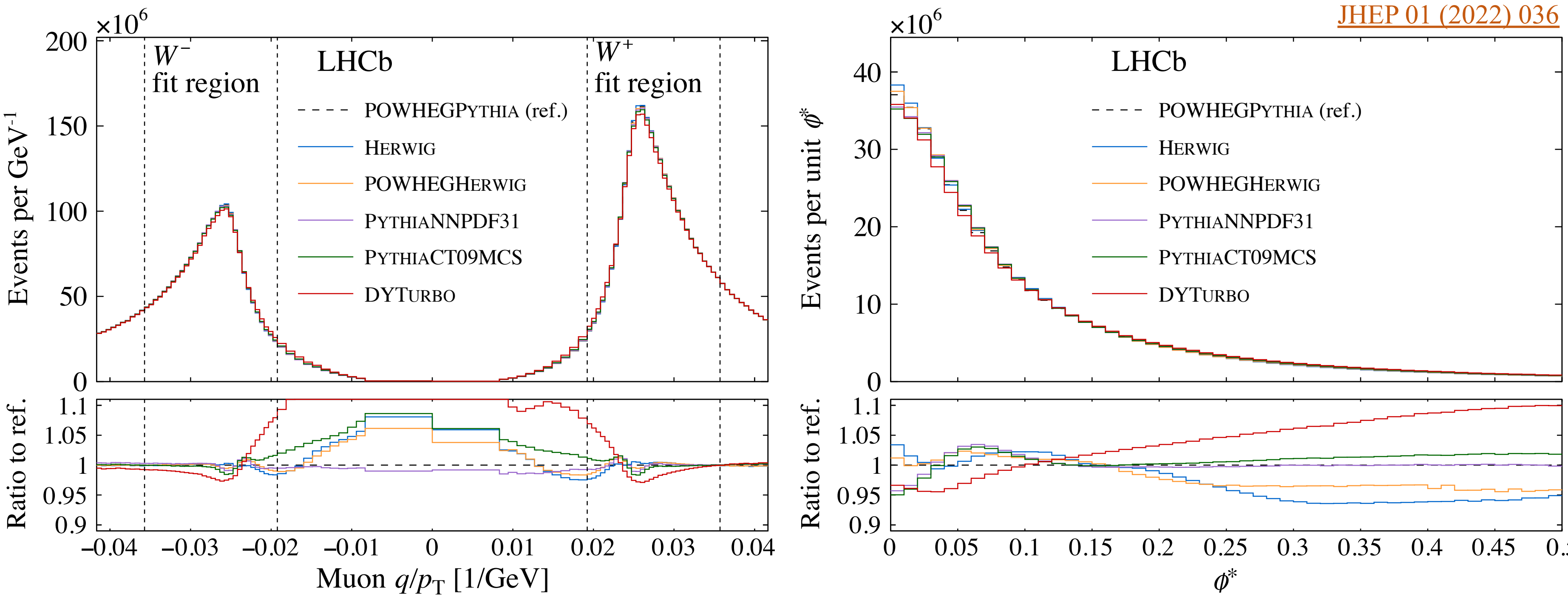
3. **Fit freedom:** The result is stable w.r.t. variations in the model freedom (e.g. 3 independent α_s values instead of 2, etc…)

4. **W-like fit of the Z mass:** Measurements with μ^+ and μ^- agree to better than 1σ and their average agrees with the PDG value to better than 1σ.

5. **δm_W fit:** Alternative fit with the difference between the W^+ and W^- masses as another floating parameter: this parameter is consistent with zero within 1σ.

6. **Additional tests** with NNLO PDFs instead of NLO PDFs, variations in the charm quark mass, etc… affect m_W at the ≲ 1 MeV level.

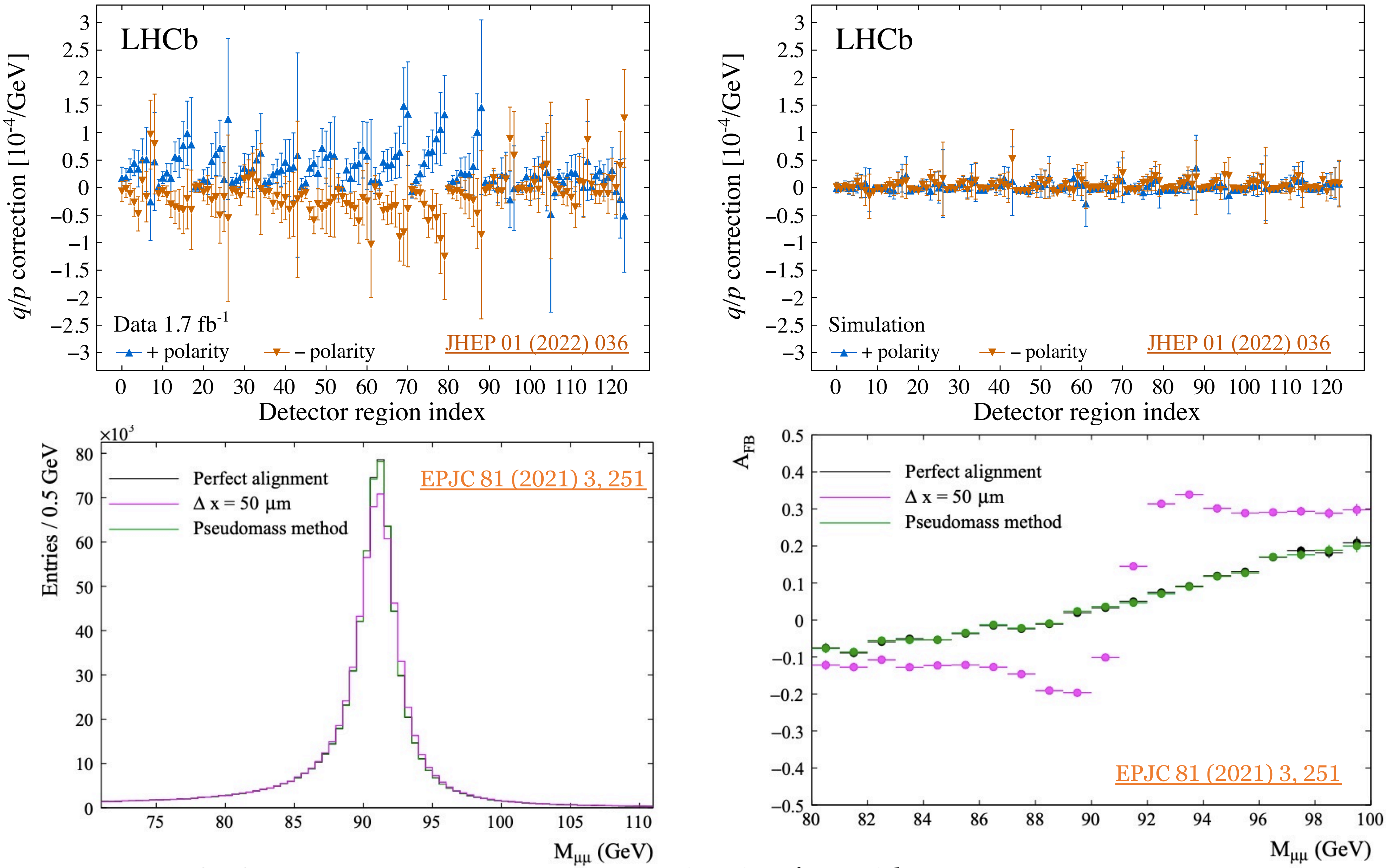
Model validation: [Pseudo]data challenges



- Using our central model to fit pseudodata generated from different models (e.g. HerwigNLO) gives a similar spread as using those different models to fit the real data.

Data config.	χ^2_W	χ^2_Z	δm_W [MeV]
POWHEGPYTHIA	64.8	34.2	–
HERWIG	71.9	600.4	1.6
POWHEGHERWIG	64.0	118.6	2.7
PYTHIA, CT09MCS	71.0	215.8	−2.4
PYTHIA, NNPDF31	66.9	156.2	−10.4
DYTURBO	83.0	428.5	4.3

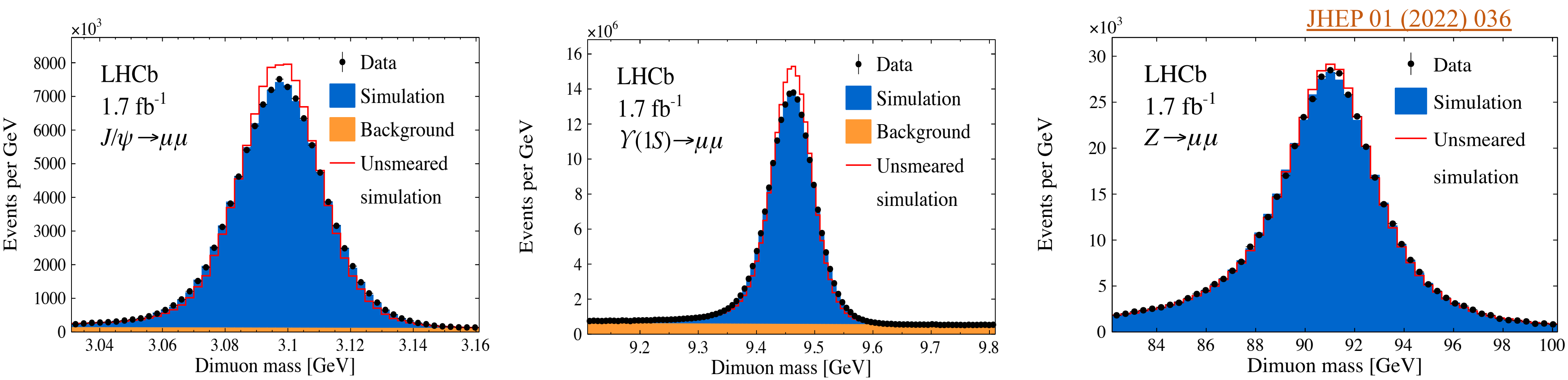
Charge-dependent curvature biases



Momentum smearing function (mW 2016)

3) Additional smearing of the simulation to better model the data:

$$\frac{q}{p} \rightarrow \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{\mathrm{MS}})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh \eta}\right),$$



Effects modelled are curvature bias (δ), momentum *scale* ($1 + \alpha$), momentum-independent (σ_{MS}) and momentum-dependent (σ_δ) smearing.

QED Final State Radiation (mW 2016)

◦ Made no preference between predictions from Pythia, Herwig and Photos,

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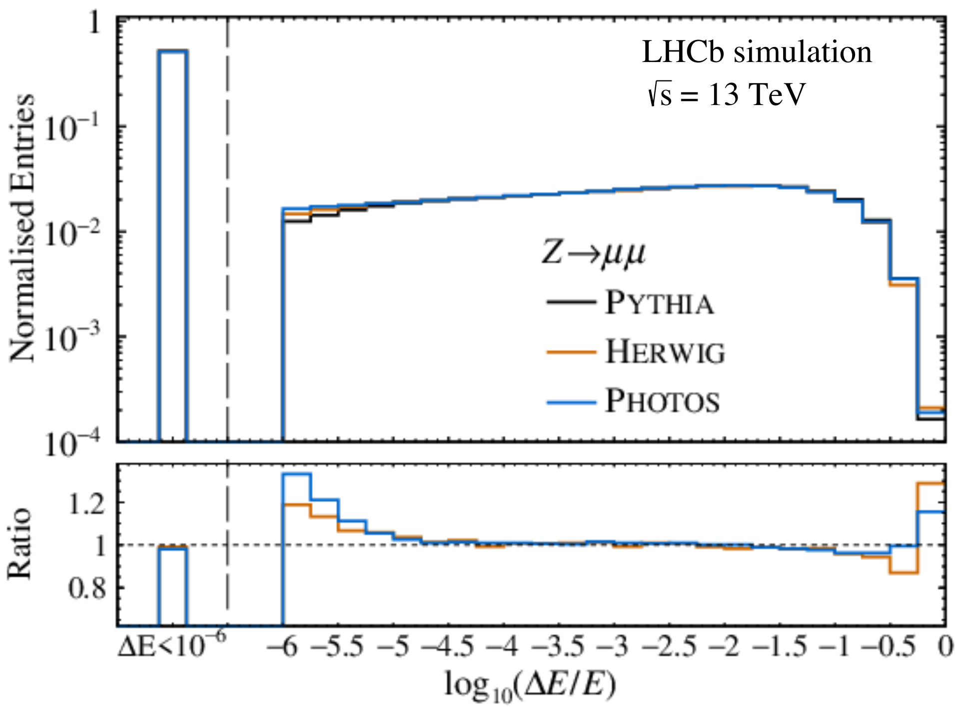
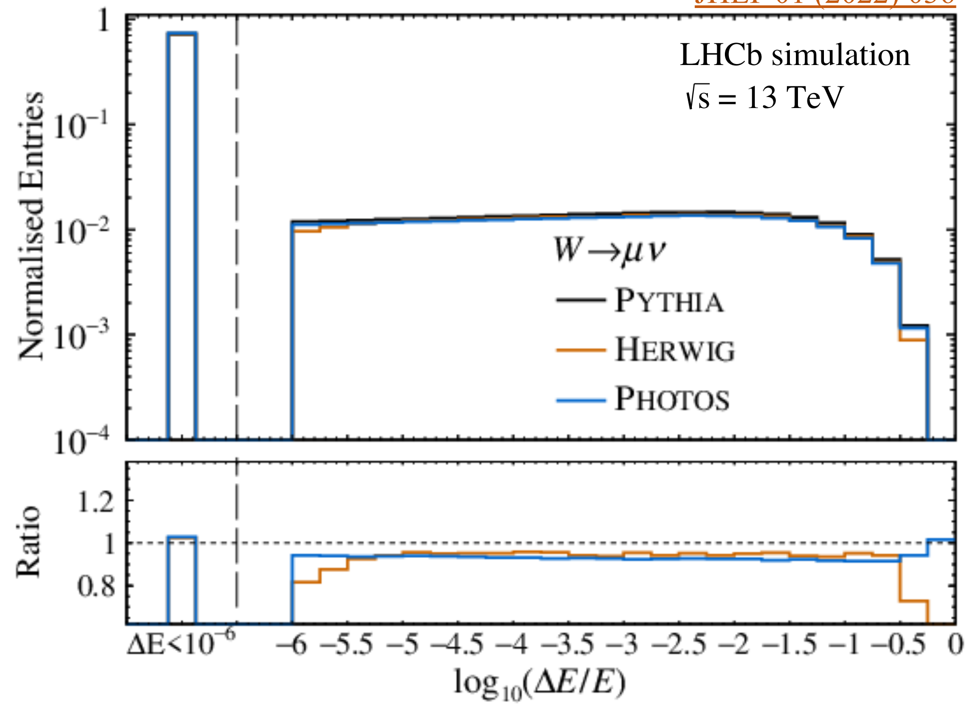
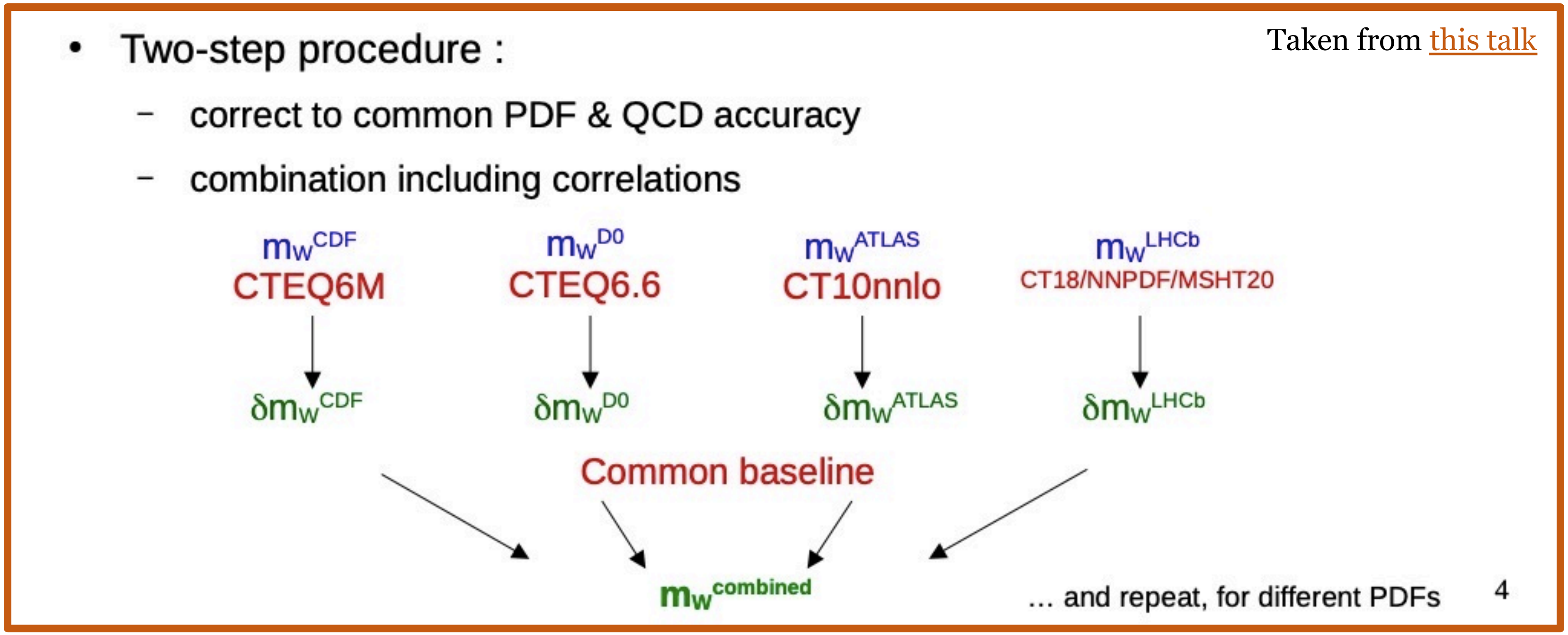




◦ Uncertainty is just the envelope of fits from all three (templates weighted in ΔE/E to the different models),

mW Combination procedure

- Culmination of large effort in the Tevatron-LHC W-boson mass Combination Working Group,
- Need to translate measurements to a common PDF set and a common description of QCD.
  - Easy for LHCb as we can readily re-run our measurement with new PDF set, QCD predictions etc.



Taken from this talk

Momentum calibration uncertainty in m_Z

Source	Size [MeV]
Detector material description	2.6
Smearing fit	1.8
Mass of Y(1S)	1.5
Curvature biases	0.7
FSR corrections for Y(1S)	0.6
Total	**3.8**

arXiv:2505.15582

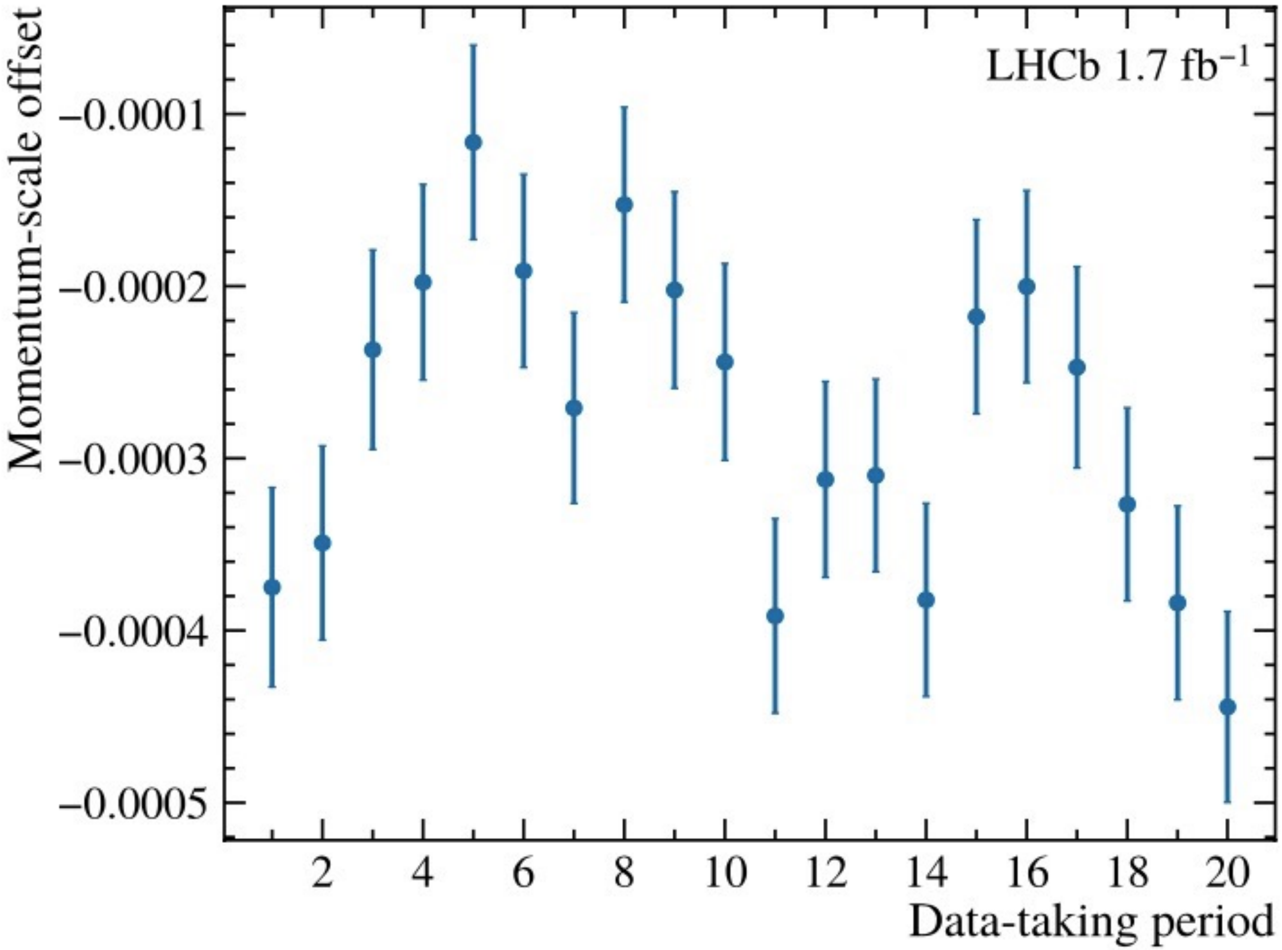
- Material: energy loss term b = 0 by default, emulate 10% uncertainty on material with pm 2 MeV shift; influences alpha,
- Smearing fit: stat. unc. on parameters,
- Y(1S) mass: influences alpha,
- Curvature biases: stat. unc. on parameters,
- QED corrections: Pythia v Photos FSR for Y(1S).

m_Z: Checks

- Splitting dataset in 22 orthogonal directions (e.g. low / high rapidity) - no differences $> 2\sigma$,
- Numbers of bins, fit ranges etc. give < 1 MeV shifts,
- Use J/ψ instead of $\Upsilon(1S)$, or a lower-p_T $\Upsilon(1S)$ sample in momentum smearing: < 2 MeV shift.
- All the fitters involved show good closure.

m_Z : time-dependent momentum scale corrections

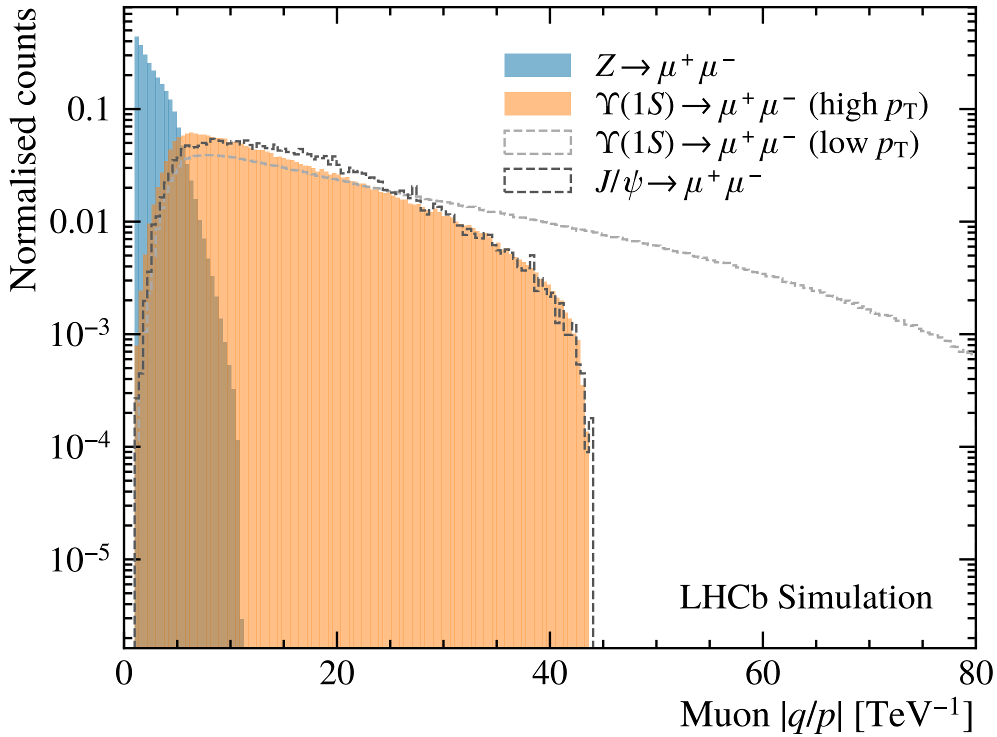
◦ Intervals are non-uniform in time to give equal size of sample:

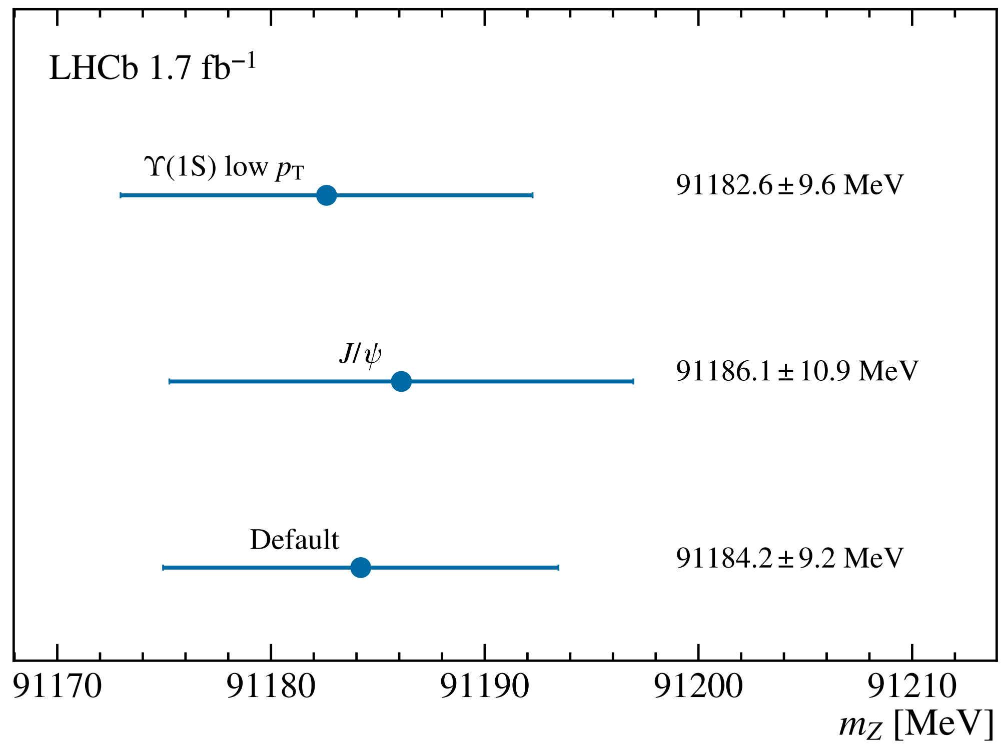


arXiv:2505.15582

m_Z : different momentum calibration samples

arXiv:2505.15582





m_Z : master smearing formula

- From Emir's CERN seminar:

The momentum response

$\mathcal{R} \sim \mathcal{N}(0,1)$

$$p^{\pm} \to \left(1 + \alpha + \frac{\beta}{p^{\pm}} \mp \delta p^{\pm}\right)\left(1 + a\mathcal{R}_1\sigma_1\right)\left(1 + b\mathcal{R}_2\sigma_2 p^{\pm}\right)p^{\pm}$$

Bias terms

Smearing terms

Momentum Scale
(time/direction dependent)

Detector Misalignment

Detector resolution

Energy Loss

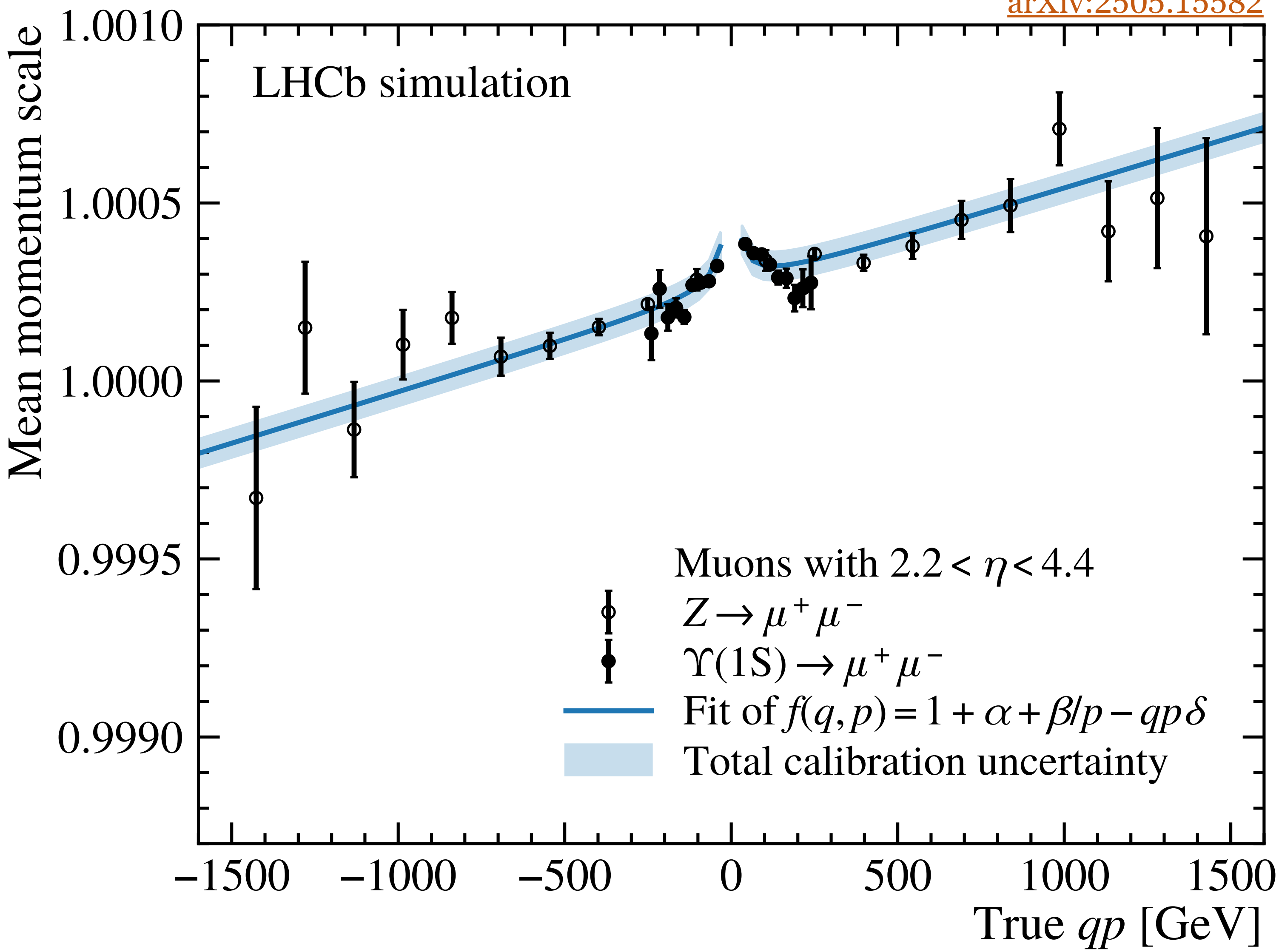
Material scattering

$$a(\eta) = \begin{cases} 1, & \eta < 3.3 \\ 1.5, & \eta \geq 3.3 \end{cases} \qquad b(\eta) = \frac{1}{\cosh \eta}$$

24

m_Z : simulated momentum response

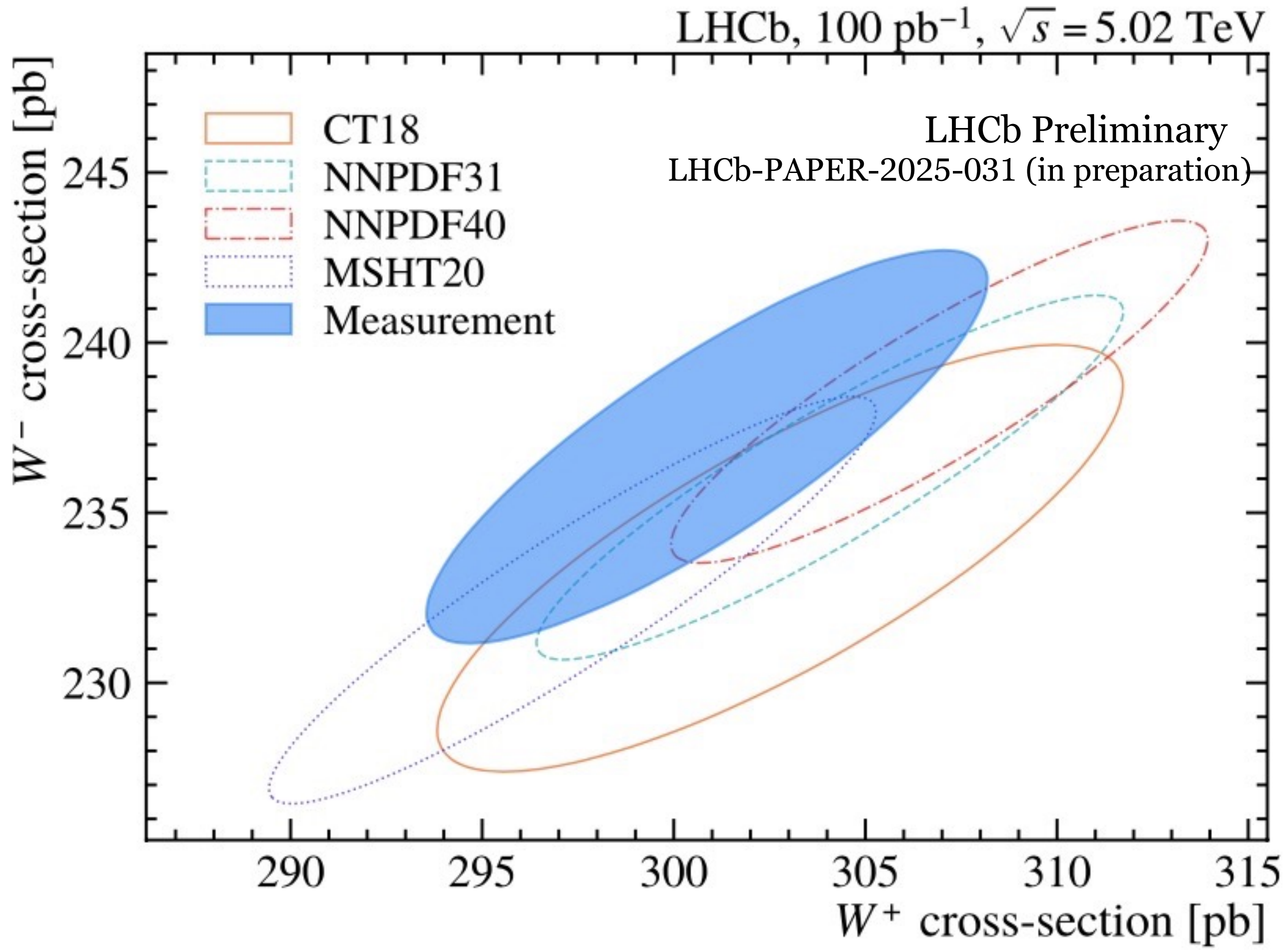
[arXiv:2505.15582]



5TeV: systematics

- Muon efficiencies: propagate statistical uncertainties, and choices in the parametrisation as a function of p_T.
- Isolation calibration: propagate statistical uncertainites; change the number of bins in calibration fits up/down by 2.
- Charge-independent momentum biases: propagate statistical uncertainties on momentum smearing values.
- Charge-dependent momentum biases: statistical uncertainties on pseudomass corrections are propagated as additional curvature biases on the simulation.
- Hadronic background: assumption on fractions of each hadronic species is varied, mis-ID fit uncertainty is propagated, p_T shape is made shallower / steeper.
- Unfolding: for numerical stability have to fix under/over flow bins to prediction. Vary prediction up / down by 10%.

5.02 TeV W cross sections (integrated)



$$\sigma_{W^+\to\mu^+\nu_\mu} = 300.9 \pm 2.4 \pm 3.8 \pm 6.0\,\text{pb},$$
$$\sigma_{W^-\to\mu^-\overline{\nu}_\mu} = 236.9 \pm 2.1 \pm 2.8 \pm 4.7\,\text{pb},$$