Measuring the W boson mass at LHCb

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With thanks to the other LHCb team members (EW analyses team)

13 November 2025

Warwick Seminar

Topics

- Motivation
- Analysis strategy
- Dataset
- Calibrations and corrections
- Background subtraction and "unfolding" fit
- Differential and integrated cross-section
- m_W fit
- Future plans for m_W at LHCb?
- Summary

A brief dive into history

The problem before unification

- Weak and electromagnetic forces described by very different formalisms
- Weak interaction (β decay) modelled by a contact Fermi theory
  → non-renormalisable, valid only at low energies
- QED (electromagnetism) was a successful renormalisable gauge theory
- Both act on the **same fermions** (electrons, quarks, neutrinos)
  - ❖ weak force only couples to **left-handed** ones
- Physicists wanted a renormalisable theory for weak interactions, similar in spirit to QED

The electroweak theory

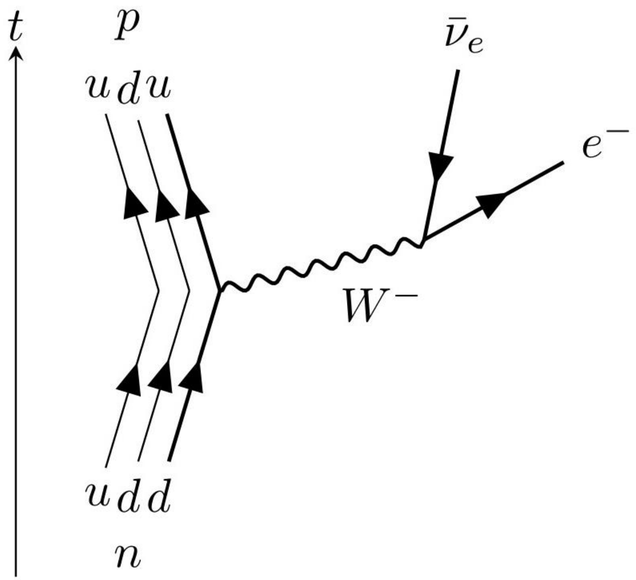
- Developed by Glashow, Weinberg, and Abdus Salam (1960s)
- Gauge symmetry: $SU(2)_L \times U(1)_Y$
- Predicted 4 gauge bosons: W^+, W^-, Z^0, and the photon γ
- After spontaneous symmetry breaking:
  - ❖ $W^{\pm}, Z^0$ acquire mass
  - ❖ γ remains massless
- Weak charged current interactions mediated by $W^{\pm}$
- Achieved a **unified, renormalisable theory** of weak and electromagnetic forces!
- Nobel prize in Physics 1979

At tree level:

$$m_W = \frac{gv}{2}$$

$$m_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$$

$$cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} = \frac{m_W}{m_Z}$$

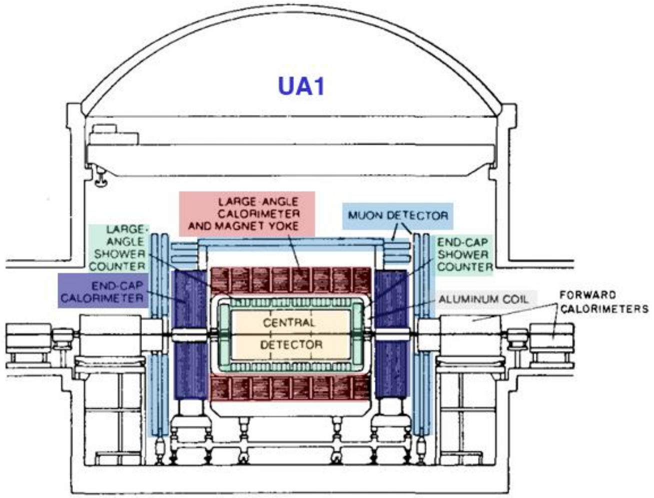


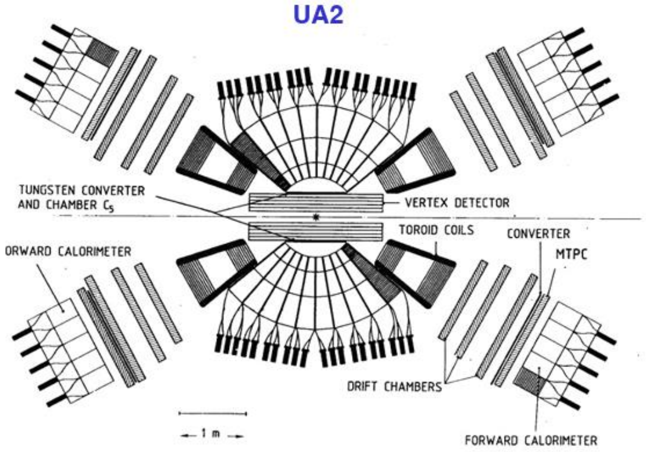
The discovery of the W boson

- The W boson decays predominantly (~70%) to $q\bar{q}$ pairs
  - ❖ difficult to measure this way

- UA1 and UA2 experiments chose to identify the W via its leptonic decays
  - ❖ UA1: $W^{\pm} \rightarrow e^{\pm}\nu_e(\bar{\nu}_e)$ and $W^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$
  - ❖ UA2: $W^{\pm} \rightarrow e^{\pm}\nu_e(\bar{\nu}_e)$ only

- Main features:
  - High transverse momentum (p_T) isolated lepton
  - A peak in the lepton p_T distribution at $\sim\frac{m_W}{2}$ ("Jacobian" peak)
  - High missing transverse momentum from undetected neutrino



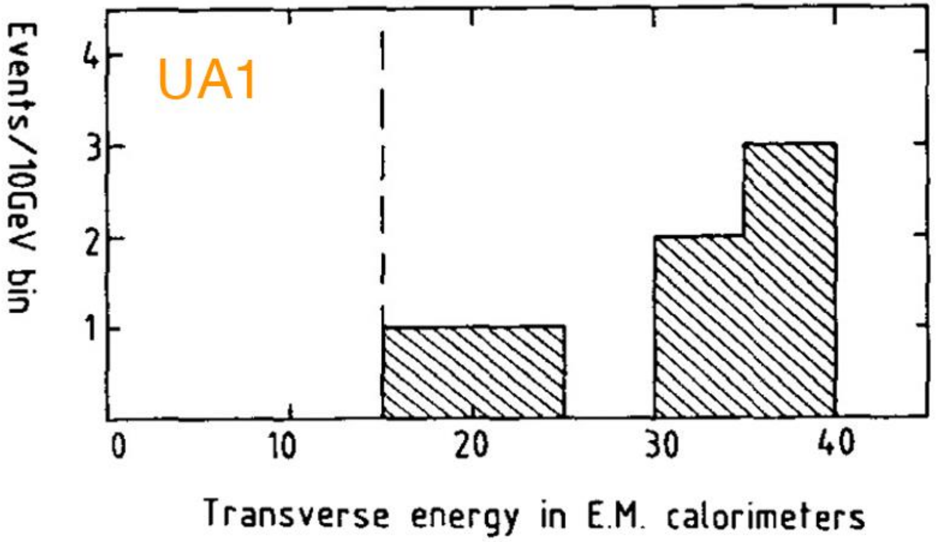


[arXiv:2307.02921]

The discovery of the W boson - continued

January 1983
42 years ago!

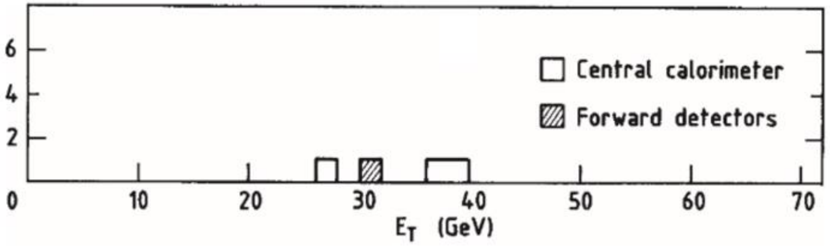
UA1



UA1: $M_W = 81 \pm 5$ GeV

[Phys. Lett. B 122, 103 (1983)]

UA2

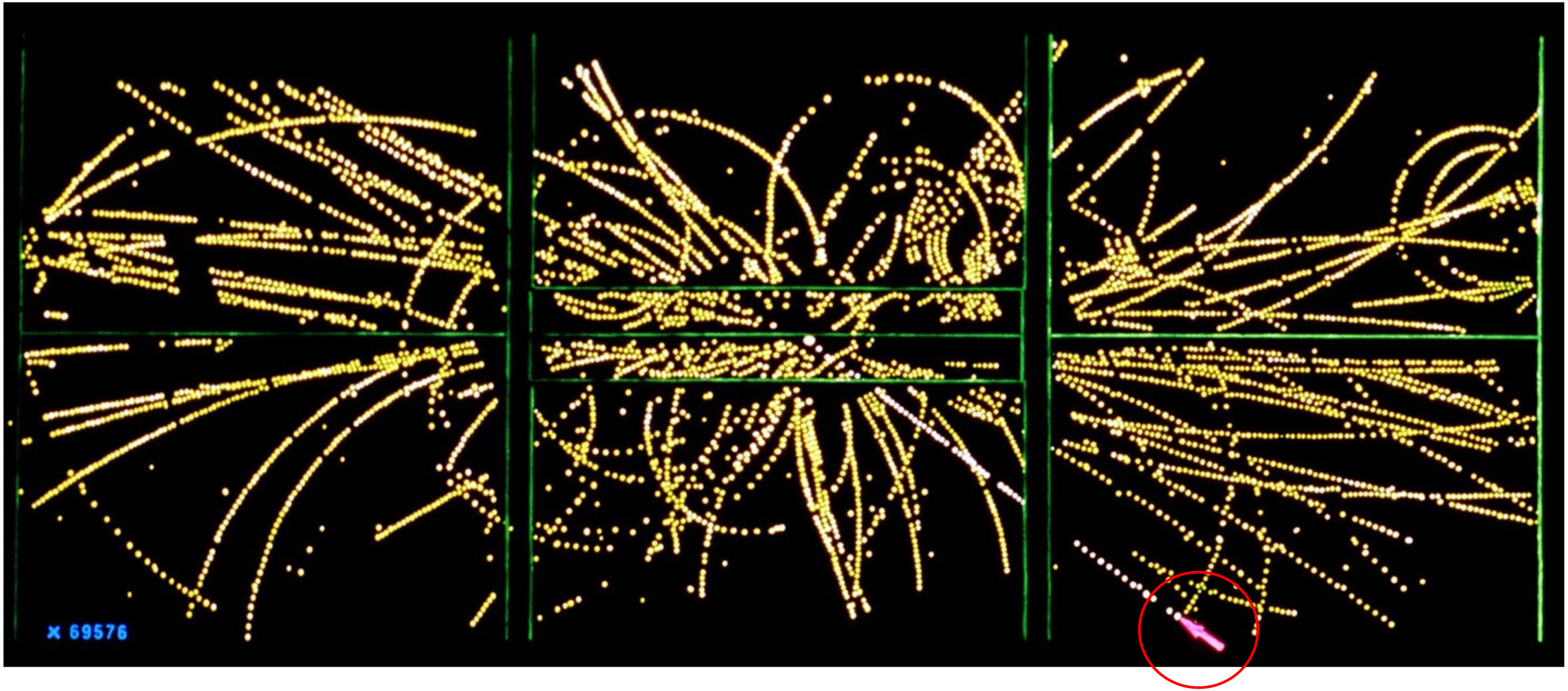


UA2: $M_W = 80 + 10 - 6$ GeV

[Phys.Lett.B 122 (1983) 476-485]

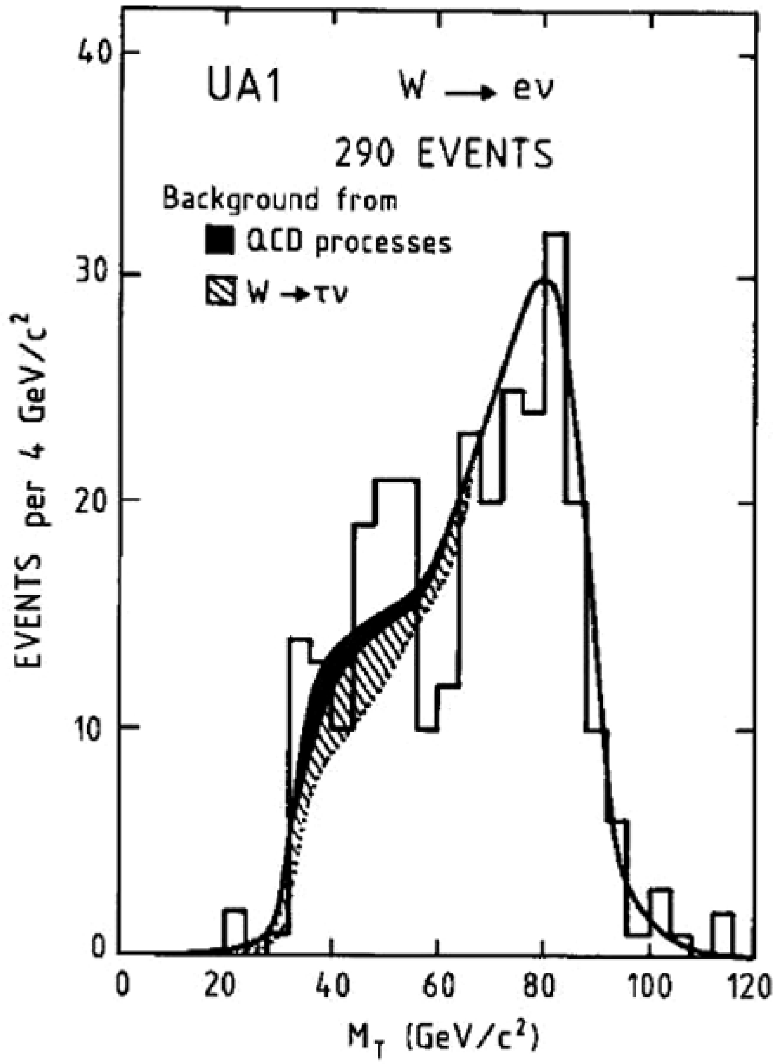
- Z boson was discovered later that same year
- Nobel prize in Physics 1984 (Carlo Rubbia and Simon van der Meer)

Display of a $W \rightarrow e\nu$ event at UA1



Transverse mass plot

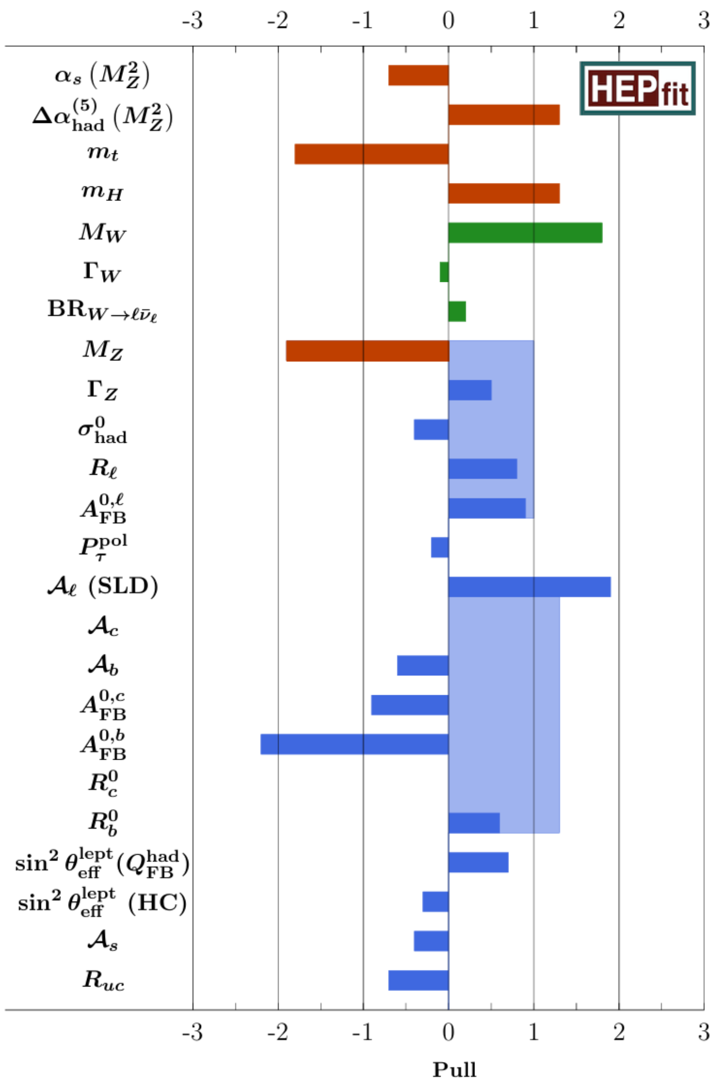
- All $W \rightarrow e\nu$ events recorded by UA1 between 1982 and 1985
- Amounted to less than 300 events



Back to more recent times

Electroweak precision measurements

- At tree level, all electroweak (EW) observables can be predicted from just 3 input parameters (e.g. G_μ, m_Z, m_W)
- Radiative corrections connect EW observables to heavy particles like the top quark and Higgs boson
- The EW scale (~100 GeV) is the highest fundamental energy scale we know of that we can access at colliders
- High-precision measurements of EW observables provide stringent constraints to the SM and indirect sensitivity to new physics



[Phys. Rev. D 106, 033003]

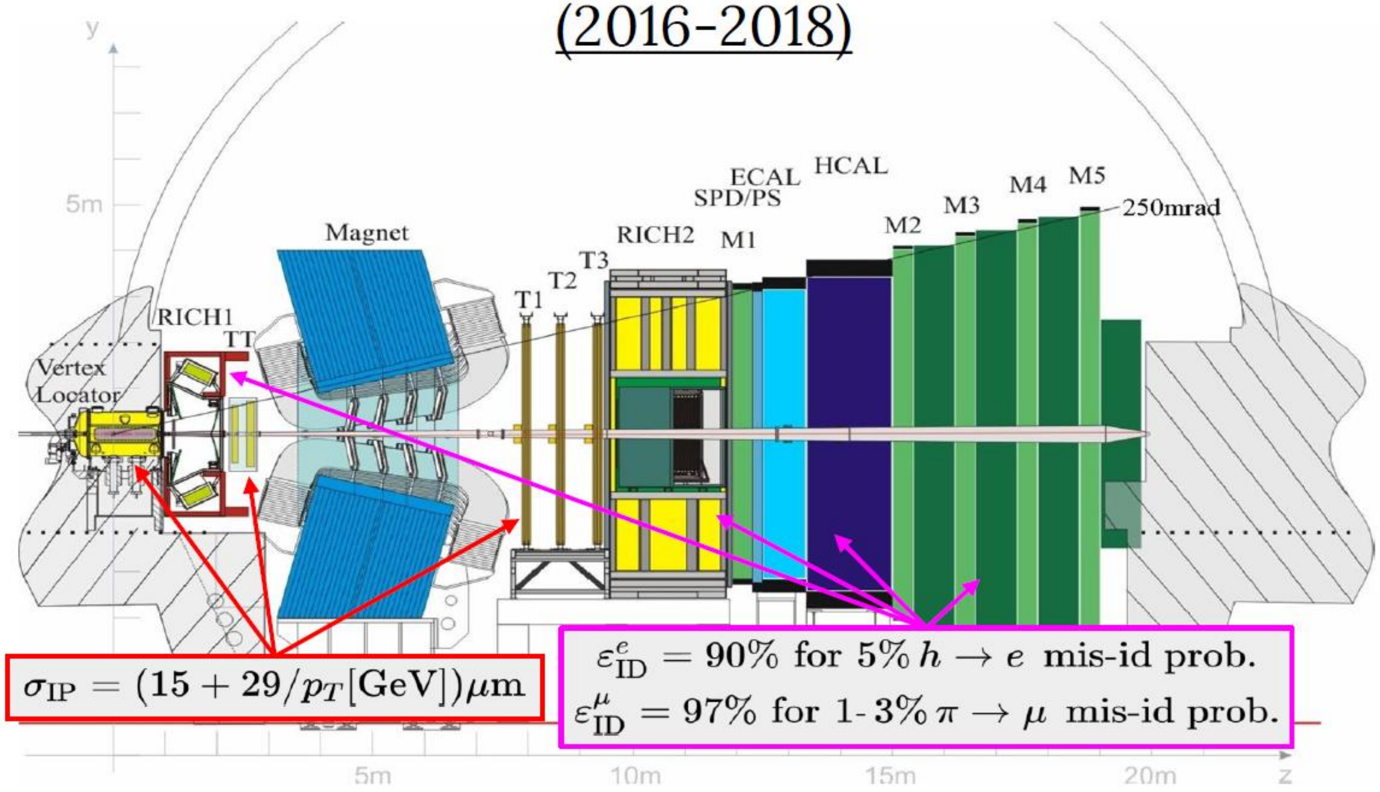
The LHCb detector (Run 2)

- Single-arm forward spectrometer
- Designed for heavy flavour physics (b and c hadrons)

Key features:

- Forward geometry (covering pseudorapidity range $2 < \eta < 5$)
- Excellent vertex resolution and particle identification
- High-precision momentum measurement
- Great mass resolution: e.g. 15 MeV for J/ψ

Detector used in Run-II (2016-2018)

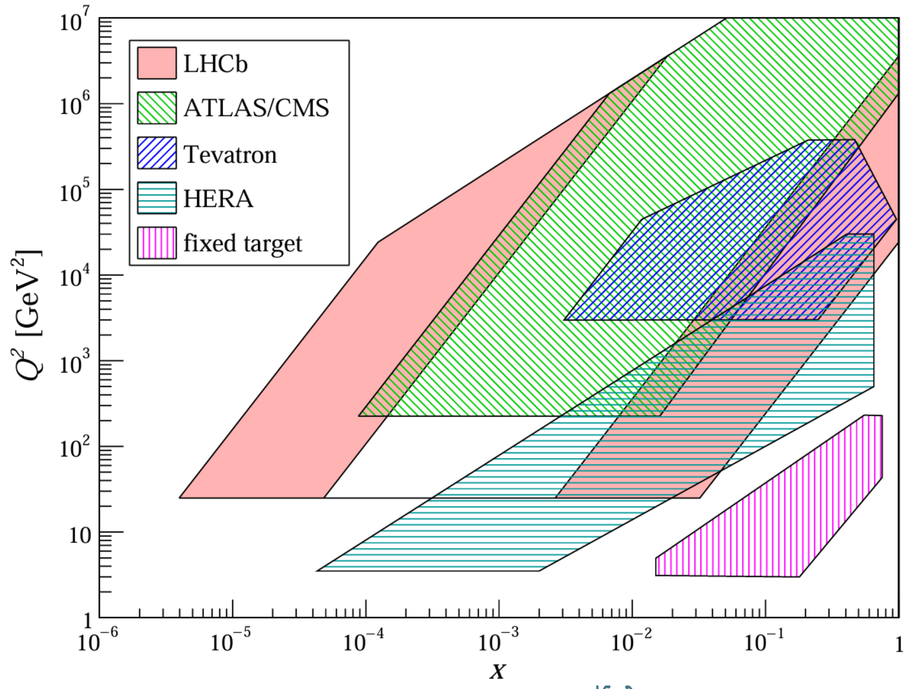


[JINST 3 (2008) S08005]

Electroweak physics at LHCb

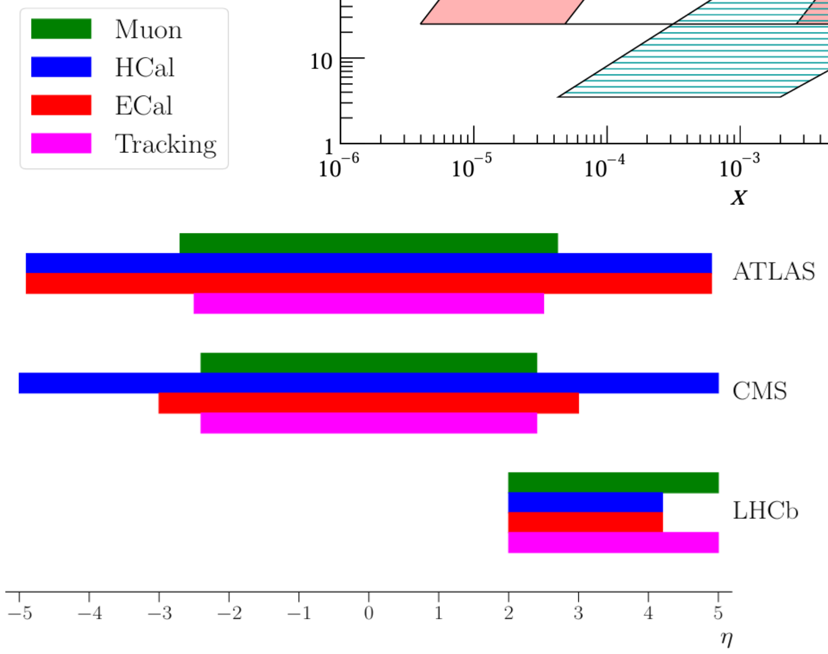
- Cannot measure missing energy
- Low luminosity with respect to ATLAS and CMS

+ Low pile-up environment
+ Low momentum triggers
+ Complementary coverage to ATLAS and CMS (with some overlapping at low pseudorapidity)
+ Focuses on **muons** with excellent tracking and detection



[arXiv: 1512.06666]

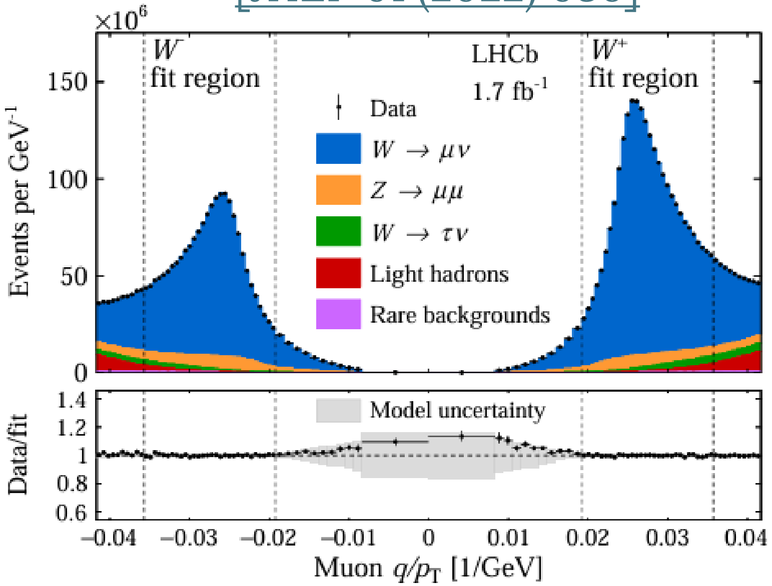
- ➢ Boson Production and asymmetries (e.g. W and Z cross-sections, charge asymmetry)
- ➢ Electroweak parameters (e.g. $m_W, m_Z, \sin^2\theta_{eff}^{lept}$)
- ➢ Having 3 experiments with complementary coverage has big implications on modelling – especially with **PDFs**



[Int. J. Mod. Phys. A 30, 1530022 (2015)]

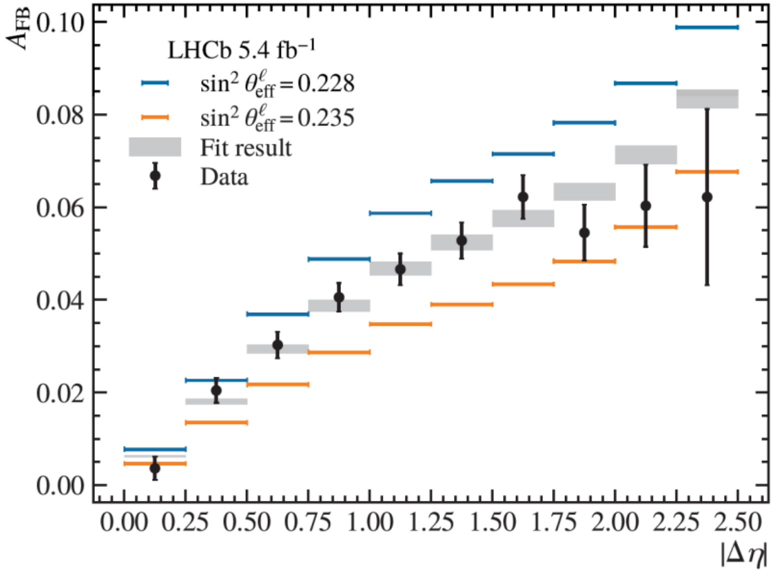
Electroweak physics at LHCb

[JHEP 01 (2022) 036]



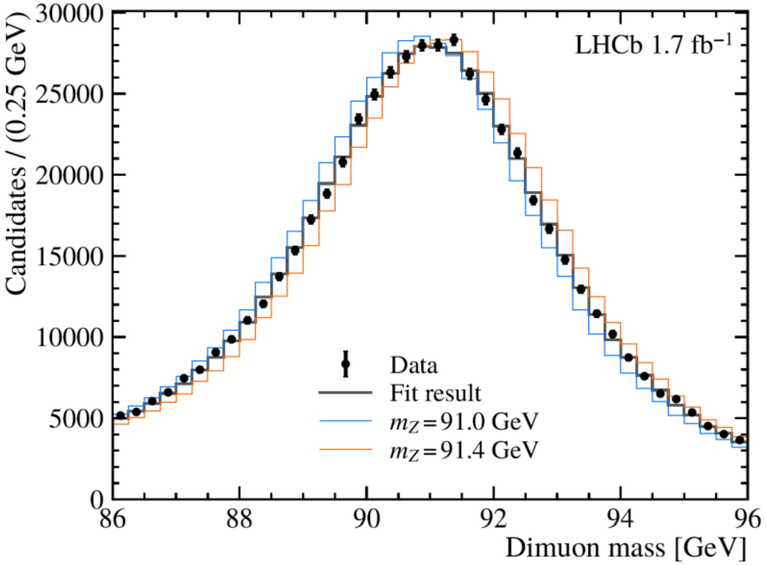
m_W [2021]

[JHEP12(2024)026]



$\sin^2\theta_{eff}^{lept}$ [2024]

[Phys. Rev. Lett. 135, 161802(2025)]



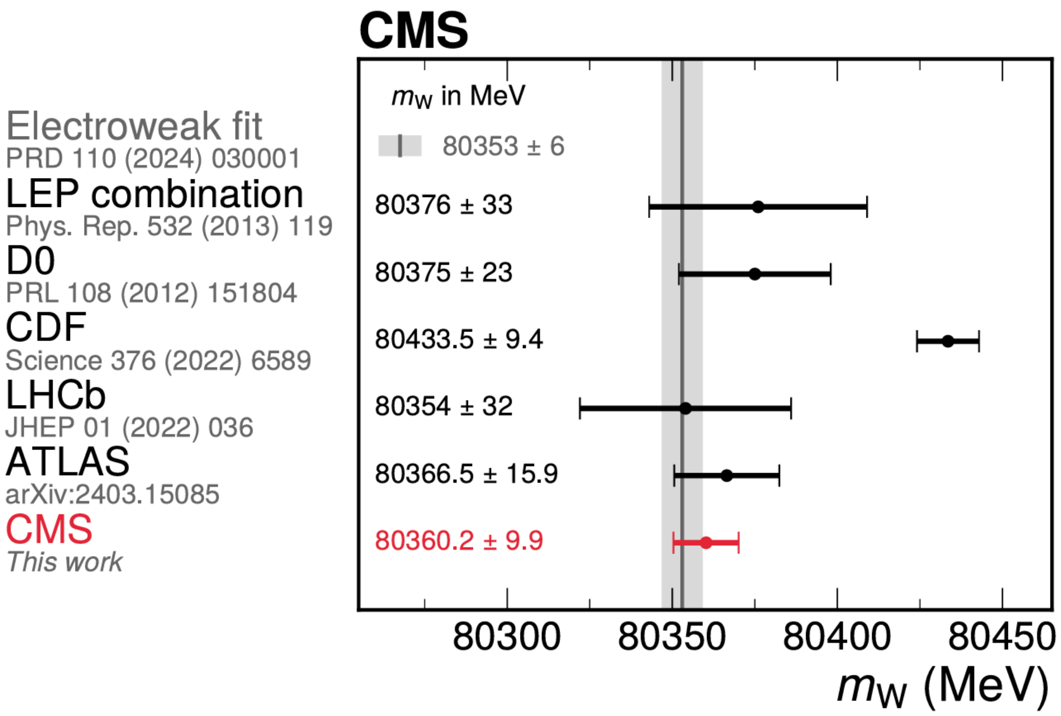
m_Z[2025]

- Measured m_W, m_Z and $\sin^2\theta_{eff}^{lept}$ at LHCb
- **First LHC experiment to do so!**
- Want to measure m_W and m_Z with full Run 2 data (instead of limited datasets)
- Target **world's best measurement** of $\sin^2\theta_{eff}^{lept}$ with Run 3!
- m_Z, $\sin^2\theta_{eff}^{lept}$ and m_W presented at CERN seminars here, here and here

Motivation for more precise m_W measurements

- Z mass directly measured to **2 MeV**; W mass less precise due to the challenges posed by the undetectable neutrino in the final state
- SM global EW fit predicts **6 MeV** uncertainty for m_W. Matching this would test the SM
- LHCb (2021) m_W measurement uses only 2016 data – want to use full Run 2 data (2016-2018)
- CDF (2022) m_W measurement astonishing precision, hints at new physics?
- CMS (2024) m_W measurement opposes CDF, also impressive precision

[arXiv:2412.13872]

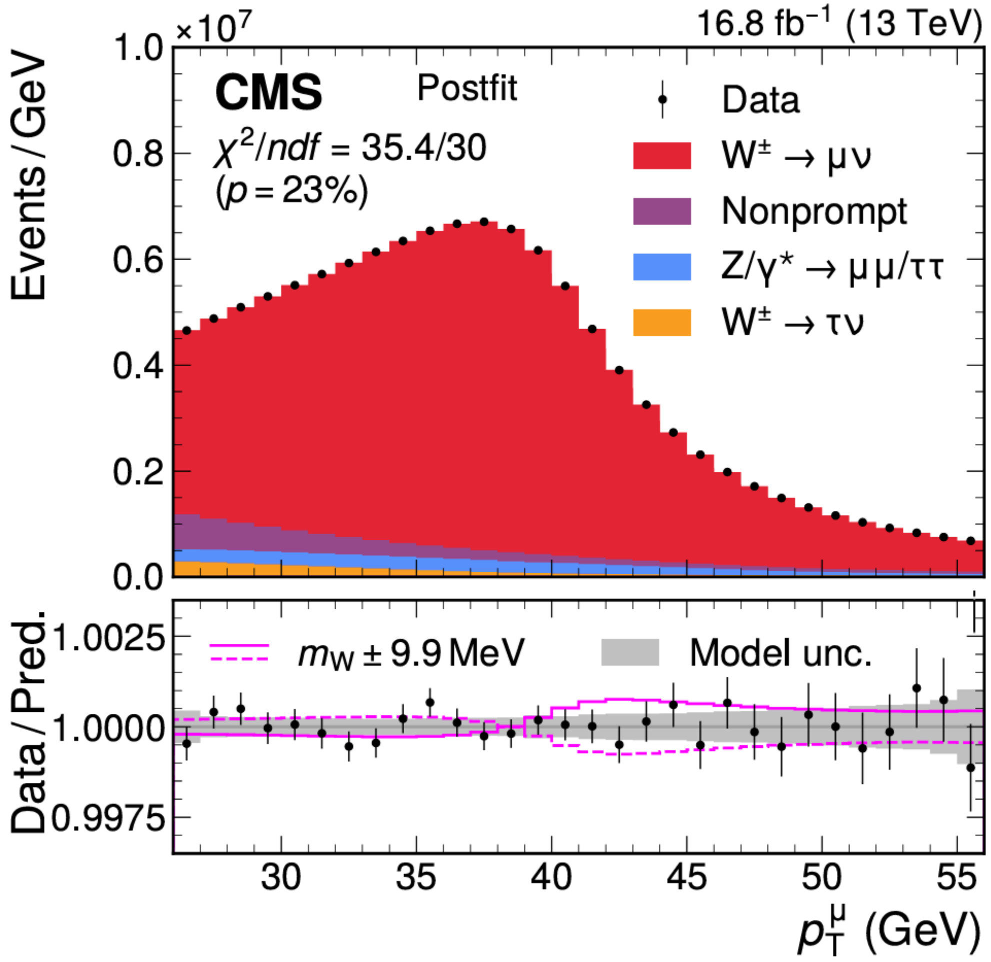


Limitations of older m_W measurements

- W boson mass can be measured with fits to the charged-lepton transverse momentum (or transverse mass)
- Traditional approach of fitting m_W in one step, with a model including backgrounds and the detector response
- Theoretical assumptions deeply baked into the experimental analysis

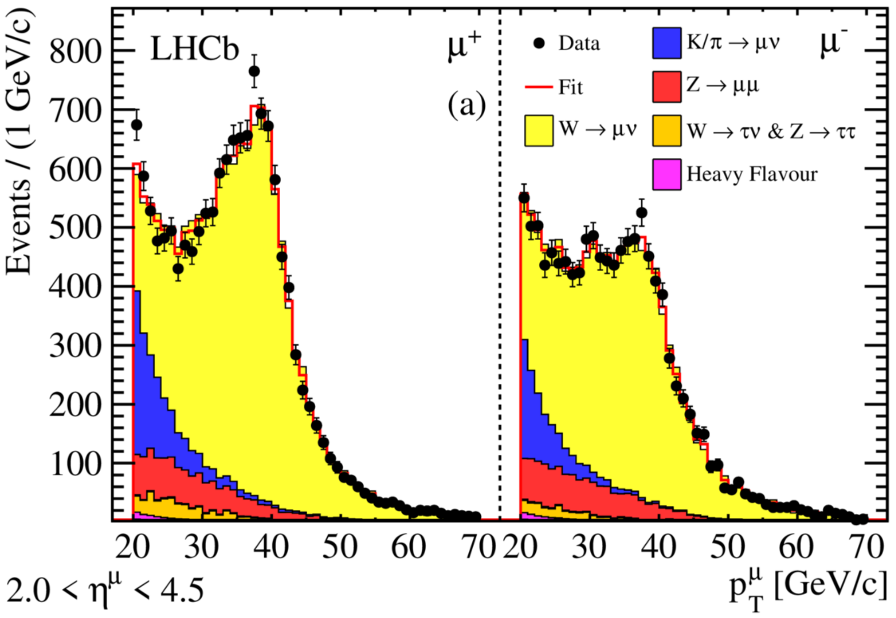
→ Extremely difficult to reinterpret and analyse later with different models ☹

[arXiv:2412.13872v1]

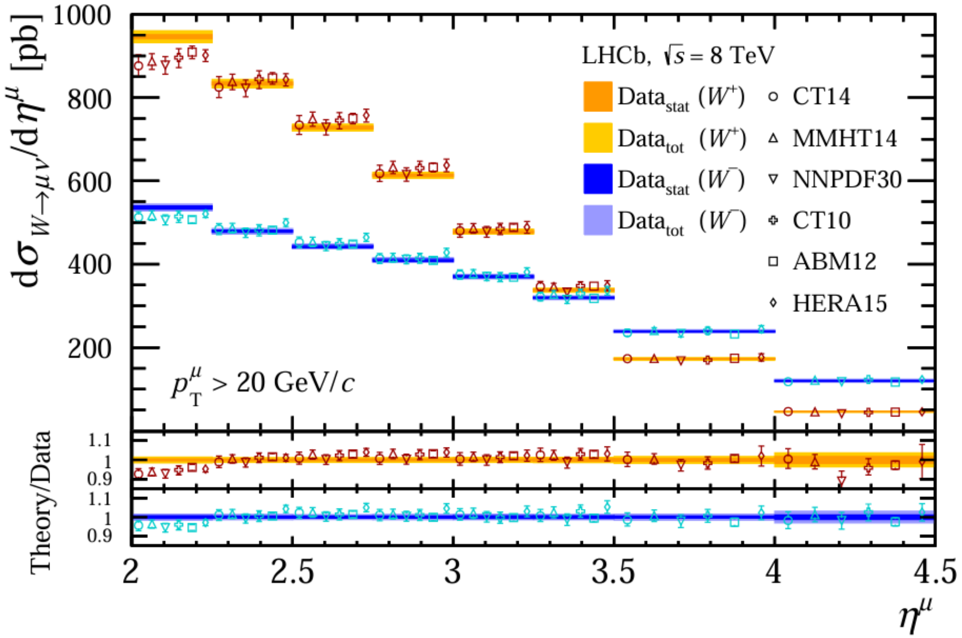


Our goal is to perform the first determination of the W boson mass in 2 steps at a hadron collider - using the measured $d\sigma/dp_T$ distribution for W production

Limitations of older W cross-section measurements



[JHEP 12 (2014) 079]



[JHEP 01 (2016) 155]

- $W^+$and W^- differential cross-sections were previously measured in bins of muon pseudorapidity
- At LHCb, measurements of the W cross-section could not be split in bins of p_T because the shape of the p_T distribution was used to subtract the background

A new perspective

Proposed methodology

- Extract the differential cross-section of W boson decays as a function of the muon p_T ($\frac{d\sigma}{dp_T}$)
  - ➢ Correcting for migration/efficiencies ("unfolding")

- Can later fit the W boson mass (**model-independent way**)

- Ensures long-term reusability of the cross-section measurement for evolving models

- More power to the community (particularly theorists) ☺

- LHCb m_W measurement can be a significant contribution towards an **LHC-wide average,** also, this method facilitates combinations with other experiments

- Proof-of-principle analysis
  - ➢ Starting with the smaller $\sqrt{s} = 5.02$ TeV dataset (2017) → 100 pb^{-1} (limited precision)
  - ➢ Plan to extend this to full Run 2 data at $\sqrt{s} = 13$ TeV → 5.4 fb^{-1} ($> 50 \times$ larger!) – **analysis in preparation phase**

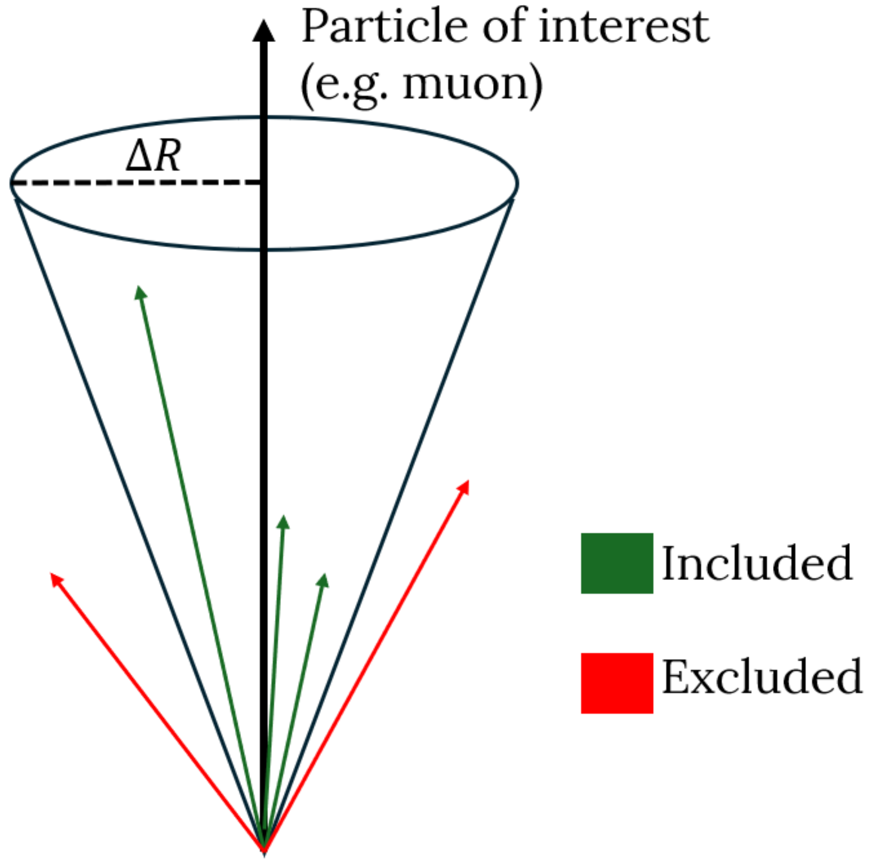
New variable of interest

- Unlike previous LHCb analyses of W production, we cannot assume a signal p_T^μ shape for the **background subtraction** (template fit)

  → add the dimension of the **muon isolation***

- Fit the 2D distribution of p_T^μ and isolation to extract the number of muon decays coming from the W boson in each bin of p_T^μ

- W signal fiducial region:
  - ❖ $2.2 < \eta_\mu < 4.4$
  - ❖ $28 < p_T^\mu < 52$ GeV/c
  - ❖ Isolation < 8 GeV/c



* sum of p_T of neutral and charged particles within a cone of $\sqrt{(\Delta\eta)^2 + (\phi)^2} < 0.4$ around the signal (muon) [$\Delta R < 0.4$]

Analysis steps (in a nutshell)

1. Get data and MC tuples (corrected for momentum smearing, alignment, etc.)

2. Fit the p_T, isolation distribution to determine $d\sigma/dp_T$, correcting for backgrounds, migration and resolution (using response matrix)

3. Compare the integrated cross-section results to predictions with different PDFs

Bonus!

4. Fit $d\sigma/dp_T$ against theoretical models/predictions with m_W as a free (floating) parameter*

***Last step could be replicated by any other person aiming at doing any meta-analysis**

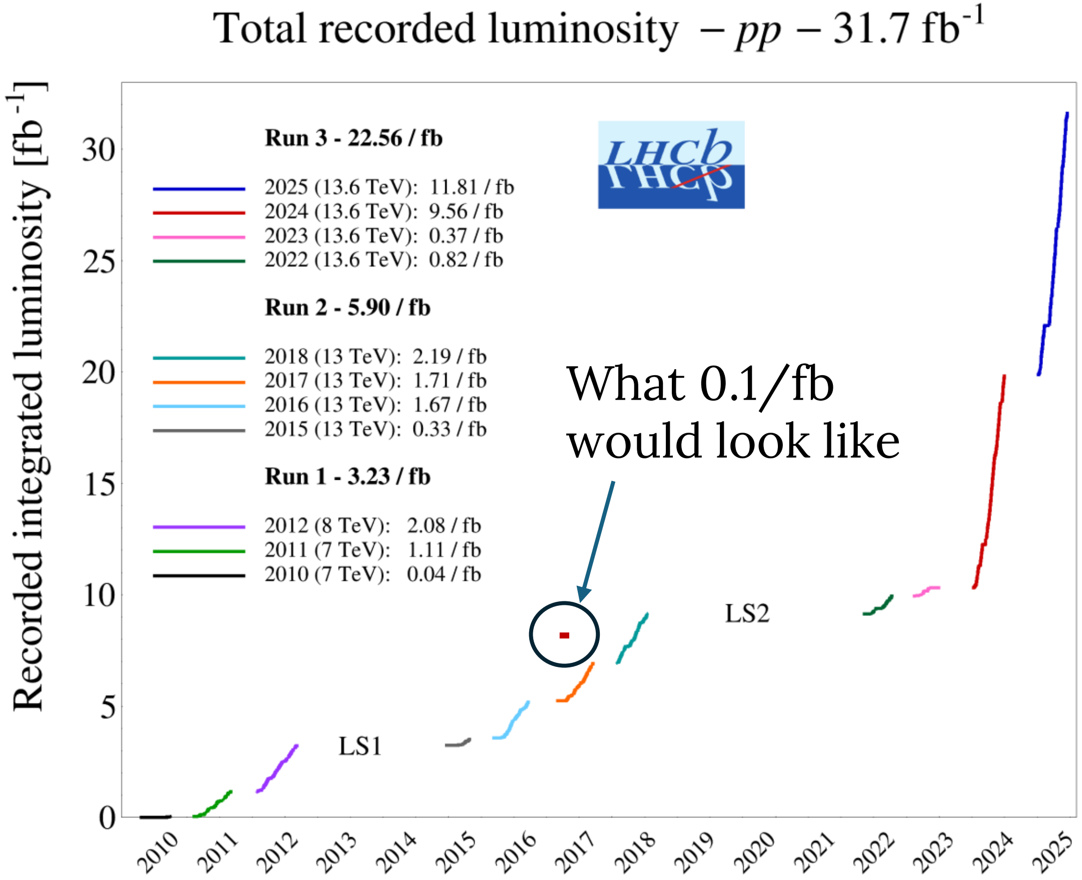
Dataset

- Only 2017 data available at $\sqrt{s} = 5.02$ TeV

- $\#W^+$ candidates: 27,586
- $\#W^-$ candidates: 21,678
- $\#Z$ candidates: 3,495

- Data is filtered after applying luminosity calibration to retain events from “good runs”

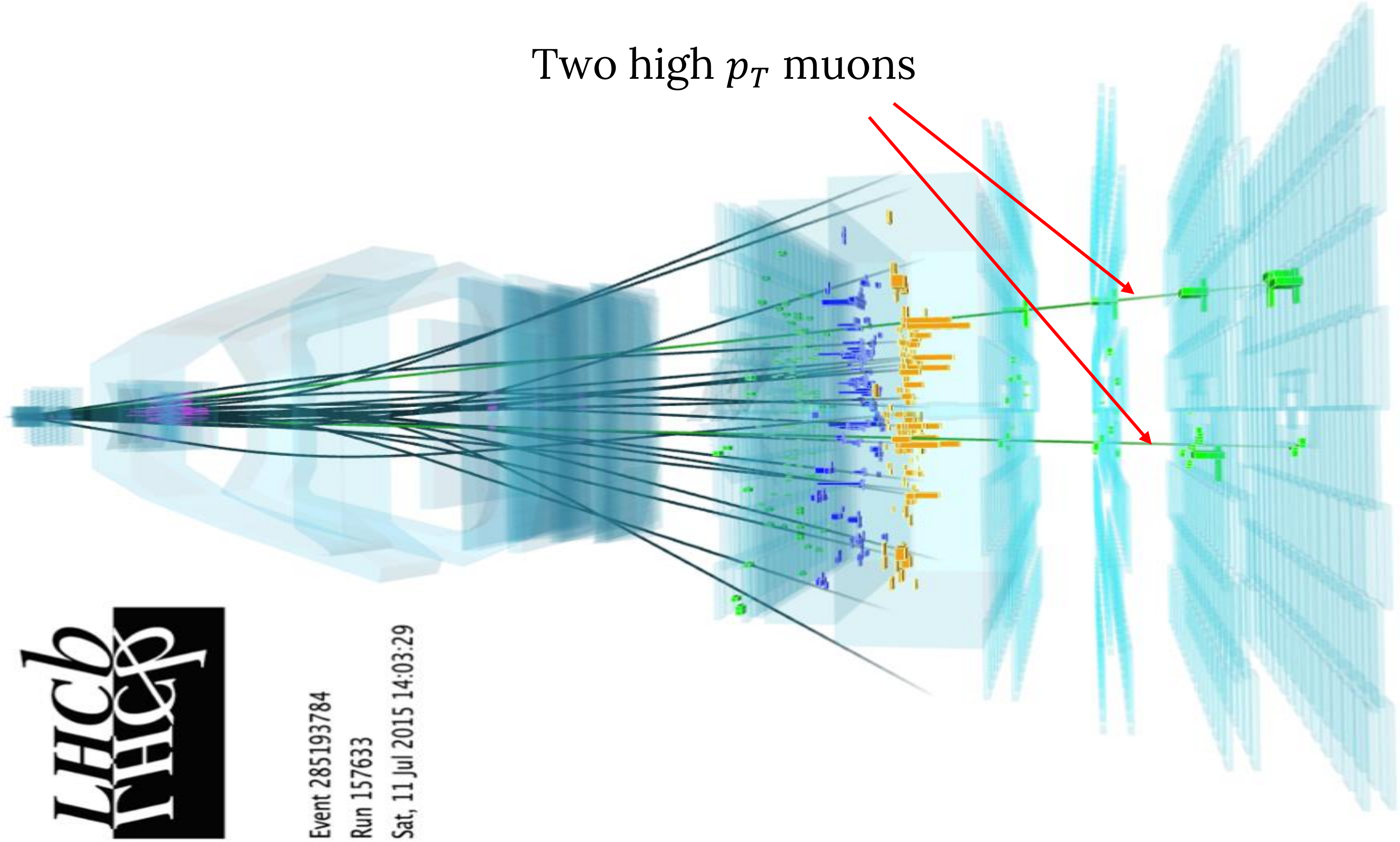
$\rightarrow \mathcal{L}_{int} = 99.86 \pm 2.00\ pb^{-1}$
$(\sim 0.1 \pm 0.002\ fb^{-1})$



Backgrounds:

hadronic (QCD), $\boldsymbol{Z \rightarrow \mu\mu}$, $W \rightarrow \tau\nu_\tau$, $Z \rightarrow \tau\tau$, DY, $(t\bar{t})_q$, $(t\bar{t})_g$, single-top, $c\bar{c}$, $b\bar{b}$

Z event display at LHCb



Simulation Samples

- Generated with Pythia 8
- Includes LHCb detector simulation handled by GEANT4

Process	Purpose
$W \to \mu\nu_\mu$	Signal
Inclusive hadrons, $p_T > 18$ GeV	Background
$Z \to \mu^+\mu^-$, $M > 40$ GeV	Background and calibrations
$W \to \tau\nu_\mu$	Background
$Z \to \tau^+\tau^-$	Background
$\gamma^* \to \mu^+\mu^-$, $20 < M < 40$ GeV	Background
$q\bar{q} \to t\bar{t}$	Background
$gg \to t\bar{t}$	Background
Single top quark	Background
$c\bar{c} \to \mu X$	Background
$b\bar{b} \to \mu X$	Background

Calibrations and corrections

Calibrations and corrections

Corrections to data:

- Charge-dependent curvature bias (“pseudomass” correction)

Corrections to Simulation:

- Momentum smearing
- Isolation calibration (signal and hadronic background)
- Efficiency corrections (trigger/muid/trk)

Corrections to the data

Charge-dependent curvature bias [JINST 19 (2024) P03010]

- High momentum charged particles are susceptible to charge-dependent curvature bias
  - ➢ Comes from residual misalignments of the tracking detectors

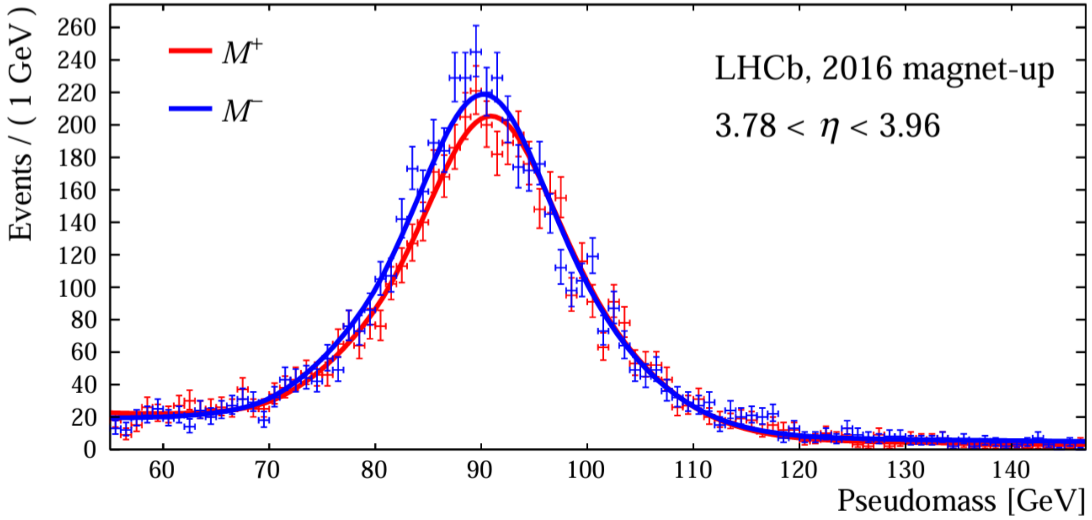
$$\frac{q}{p} \rightarrow \frac{q}{p} + \delta$$

- **Pseudomass;** $M^{\pm}$ with $Z \rightarrow \mu\mu$:

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

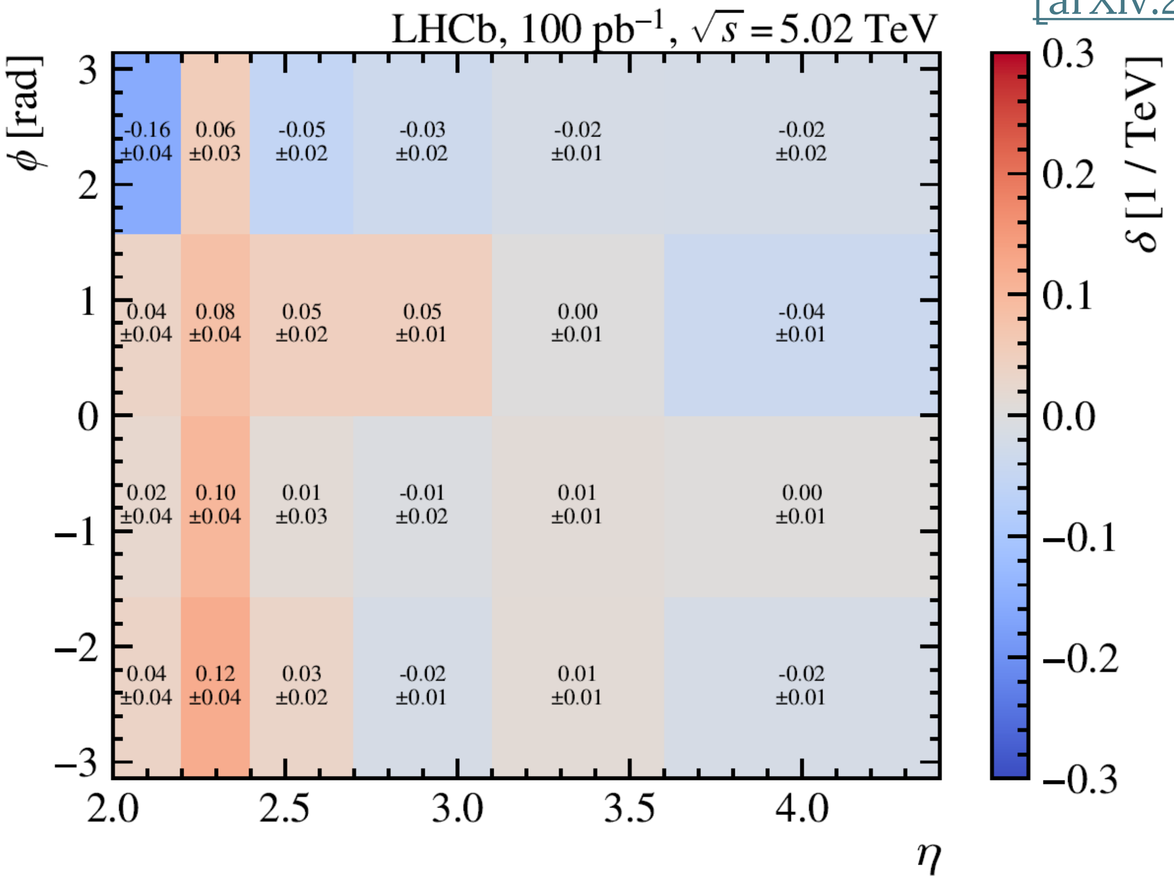
where
- M is the invariant mass of the dimuon system
- θ is the opening angle between the two muons

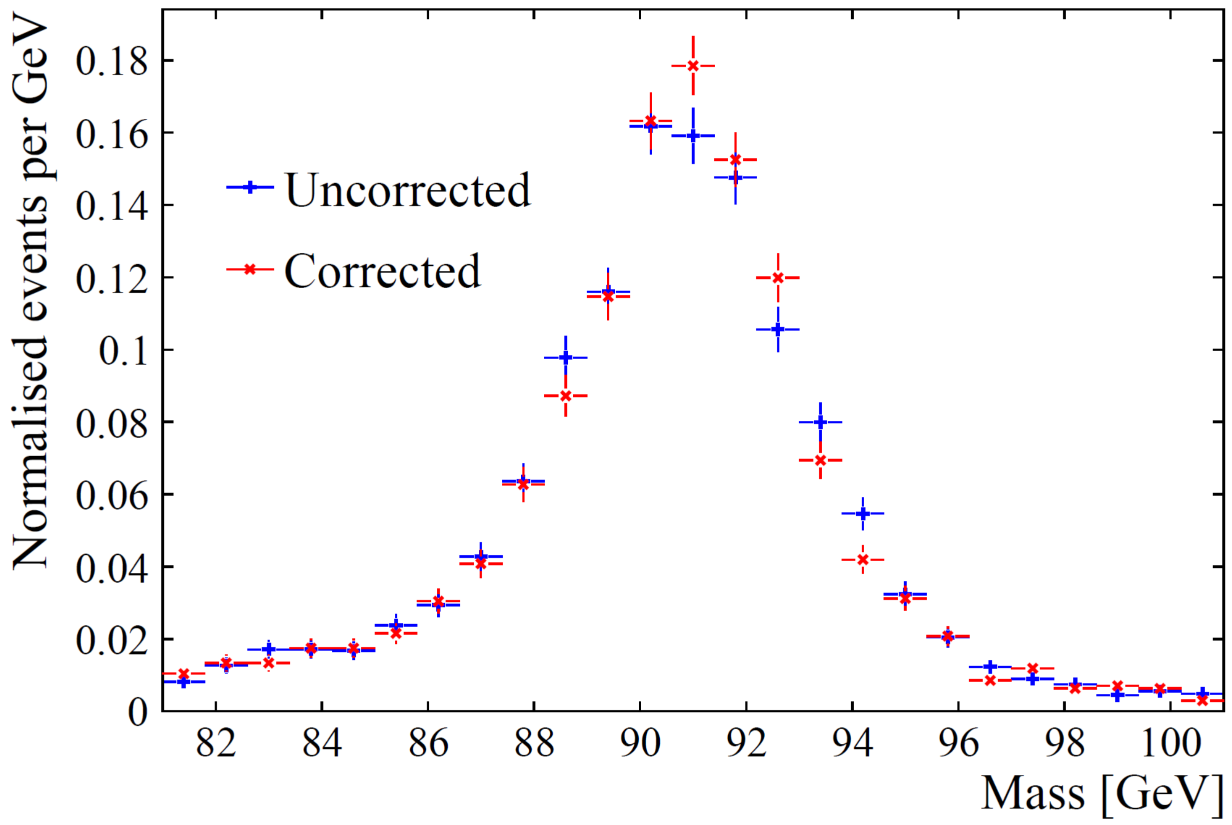
- Corrections applied to muon momenta in bins of η and ϕ



Charge-dependent curvature bias

[arXiv:2509.18817]





- Coarse binning in η and ϕ needed due to limited $Z \rightarrow \mu^+\mu^-$ candidates→ large uncertainties
- Resolution of $Z \rightarrow \mu^+\mu^-$ peak is improved by $O(10\%)$

Corrections to the simulation

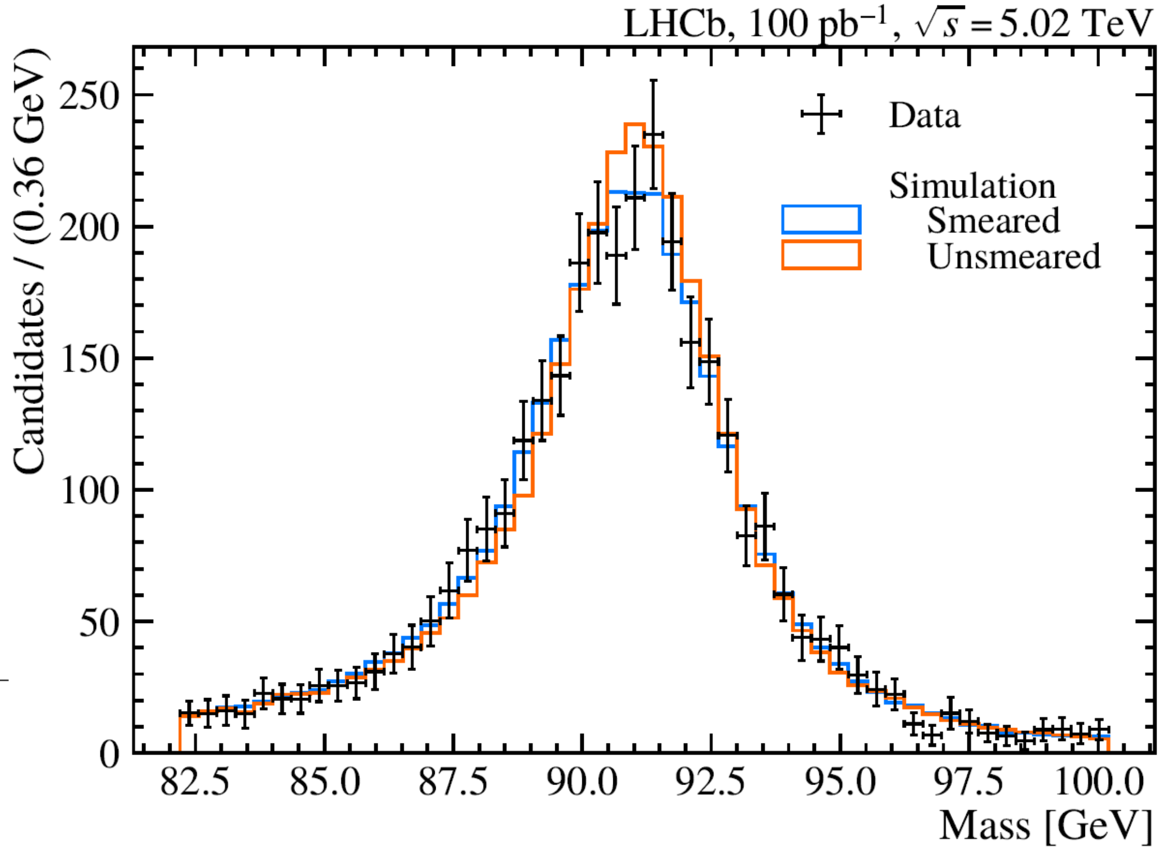
Momentum smearing

[arXiv:2509.18817]

$$p \rightarrow p' = (1+\alpha)(1+f_1(\eta)R_1\sigma_1)(1+pf_2(\eta)R_2\sigma_2)$$

- R_i are independent random numbers sampled from a Gaussian,
- α is the momentum scale offset,
- σ_1 is the momentum smearing parameter (fixed to 2.0),
- σ_2 is the curvature smearing parameter,
- $f_1(\eta) = 1$ (1.5) for η values below (above) 3.3,
- $f_2(\eta) = 1/\cosh(\eta)$

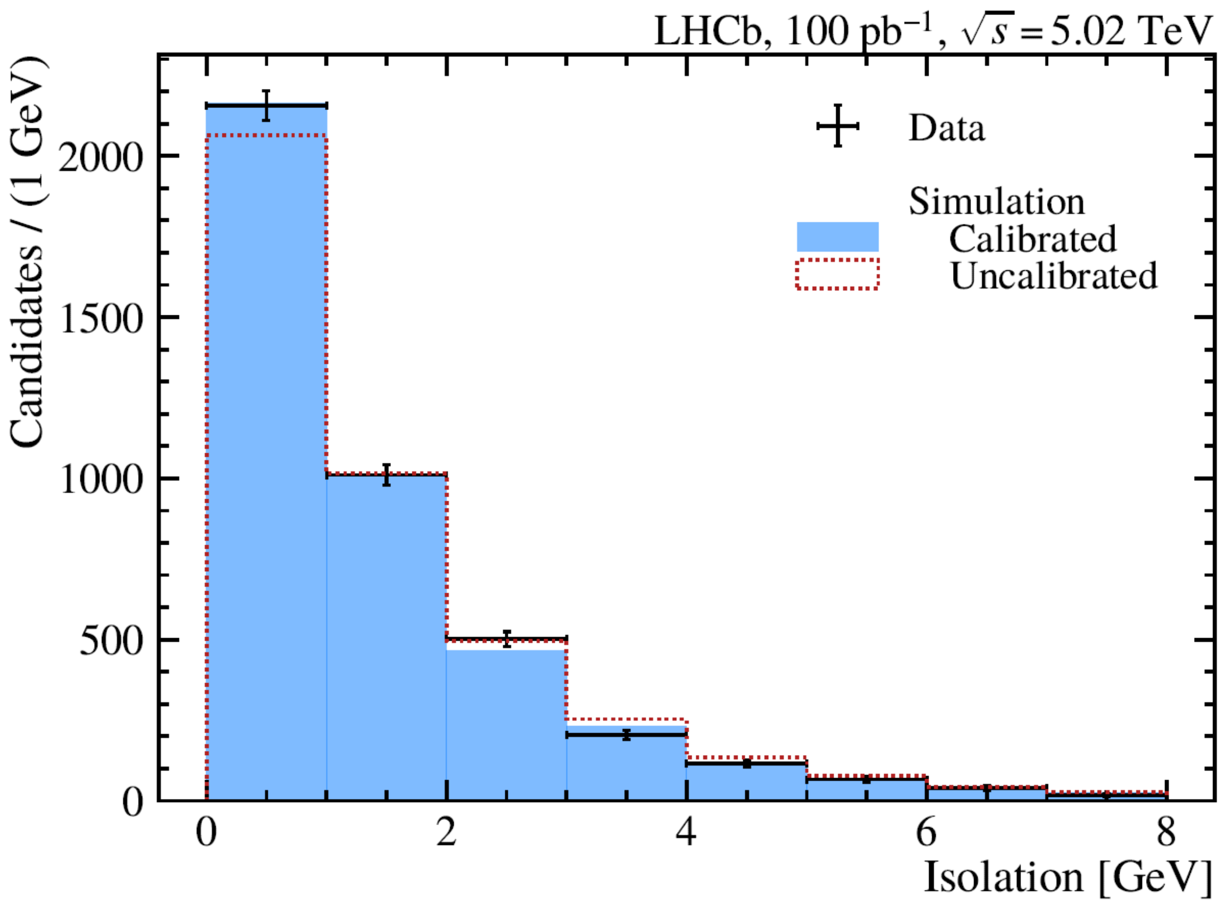
Parameter	η range	Fit result
α	$\eta < 2.2$	$(0.2 \pm 0.9) \times 10^{-3}$
	$2.2 < \eta < 4.4$	$(-1.2 \pm 0.6) \times 10^{-3}$
σ_2	$\eta < 2.2$	$(15.4 \pm 3.1) \times 10^{-5}$ GeV^{-1}
	$2.2 < \eta < 4.4$	$(24.7 \pm 2.8) \times 10^{-5}$ GeV^{-1}



Signal isolation calibration

[arXiv:2509.18817]

- $Z \to \mu^+\mu^-$ represents our signal
- Fit both muon charges simultaneously
- Calibration factor applied to Z MC isolation distribution to match Z data
- Fit gives a $\chi^2 = 16.3/13$
- Best fit calibration factor is 0.926 ± 0.018



Hadronic background modelling

- A major background arises from light hadrons (e.g. pions, kaons) misidentified as muons, either via decay-in-flight or punchthrough

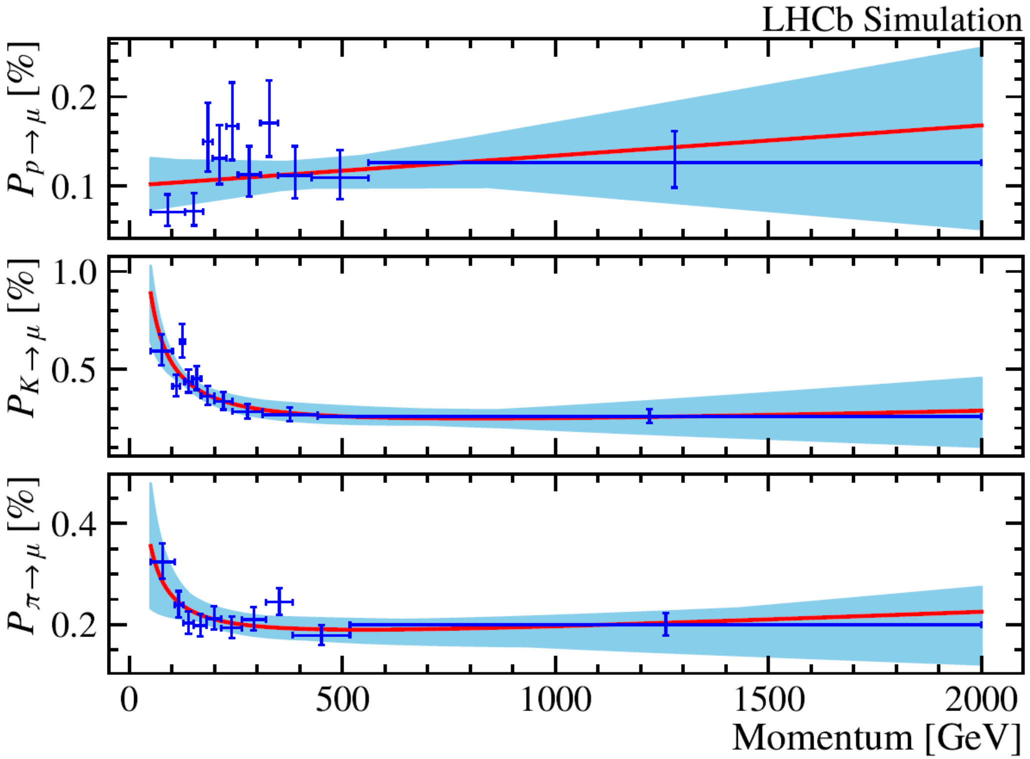
- Due to the lack of a dedicated hadron trigger during in 5.02 TeV data taking, data-driven corrections couldn't be applied (what was done in previous LHCb m_W measurement)

- Instead, we apply corrections on simulation

- Hadronic background normalisation is also floated in the differential cross-section fit, allowing freedom in the p_T shape

[arXiv:2509.18817]

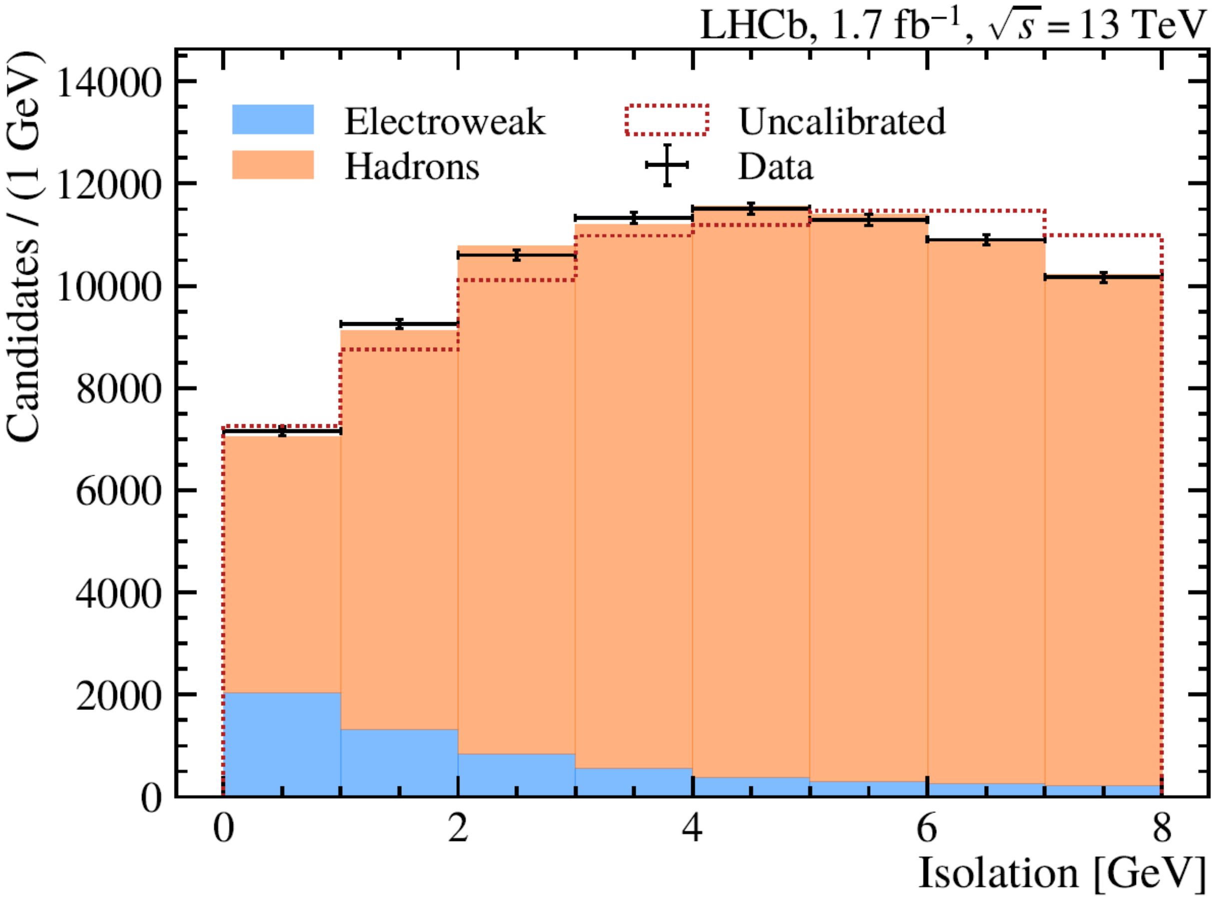
Mis-ID probabilities



Hadronic background isolation calibration

- Don't have hadronic background proxy **data** for 5.02 TeV (NoMuID)
  →Use 13 TeV hadronic background proxy **data** for calibration
- We use the $Z \to \tau^+\tau^-$ **MC** as a constraint for the EW contribution at low isolation
- Compare uncalibrated hadronic MC (including $Z \to \tau^+\tau^-$) against hadronic data
- Fit gives a $\chi^2 = 6.12/10$
- Best fit params:
  - $C' = 0.83 \pm 0.013$
  - $\delta = 0.048 \pm 0.013$

$$C = C' + q\delta$$



[arXiv:2509.18817]

$$d\sigma/dp_T$$

Differential cross-section fit

- We aim to measure the **true** differential cross-section, $\boldsymbol{d\sigma/dp_T}$, across n intervals of **true** transverse momentum (p_T), accounting for:
  - Background contamination (f_{bgd})
  - Reconstruction efficiency (ϵ_{ijk})
  - p_T resolution
  - Integrated luminosity($\boldsymbol{\mathcal{L}}_{int}$)

- We define a **negative log-likelihood (NLL)** function (Beeston-Barlow Lite), with the fit parameters being the **differential** cross-sections ($\sigma_1, \ldots, \sigma_n$) over n p_T bins

- In short, the likelihood relates the $\boldsymbol{d\sigma/dp_T}$ values to the observed counts in **reconstructed** p_T – isolation space, accounting for efficiency and resolution

Signal model

Truth-level

Reco-level

$$\lambda_i^{\mathrm{s}}(\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}) = \mathcal{L}_{\mathrm{int}} \sum_j R_{ij} \mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}_j} \Delta p_{\mathrm{T}},$$

- $d\sigma/dp_T$ denotes the (true) differential cross-section values (**fit parameters**)
- $\Delta \mathrm{p_T}$ denotes p_T bin widths → uniform; 2 GeV
- R, the response matrix, encodes the detector effects and maps the true (generator-level) distribution to the reconstructed (detector-level) distribution

$$p_{\mathrm{T},i}^{\mathrm{reco.}} = \sum_j R_{ij} p_{\mathrm{T},j}^{\mathrm{true}}$$

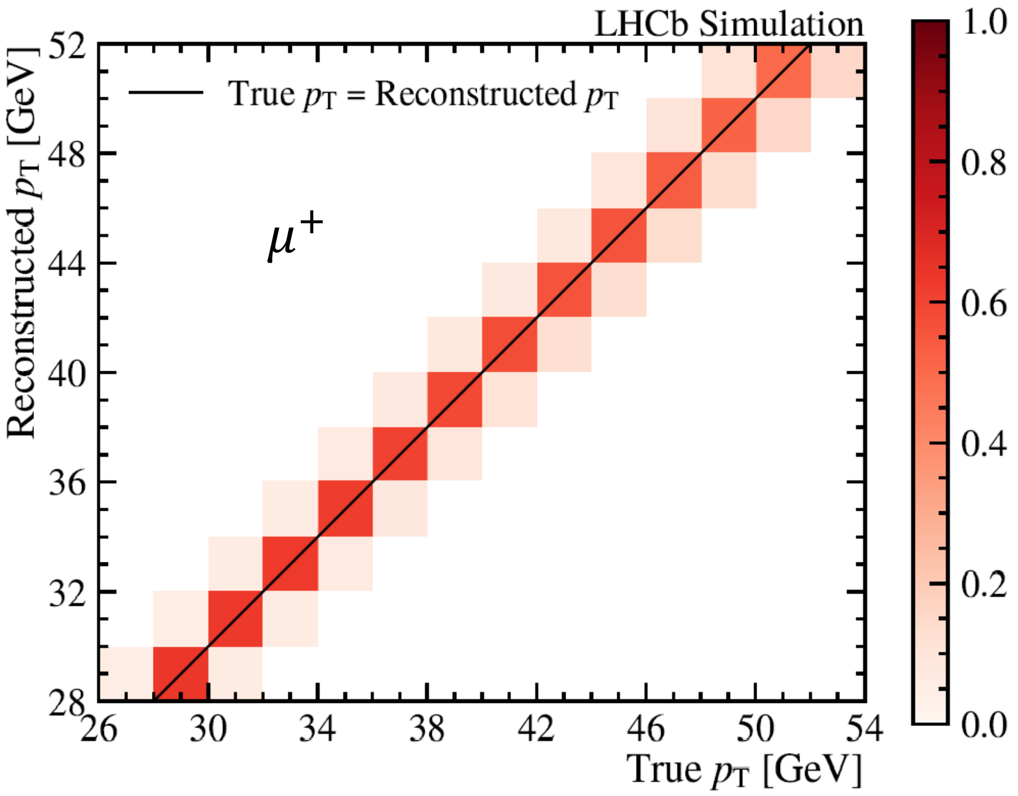
Response matrix

- Isolation dimension is integrated over in this plot

- Minimal migration

- The efficiency in each true p_T bin is obtained by summing the elements of all the rows

- The response matrix for the other charge is qualitatively similar



[arXiv:2509.18817]

Fit function minimisation

- The negative log-likelihood is as setup as follows:

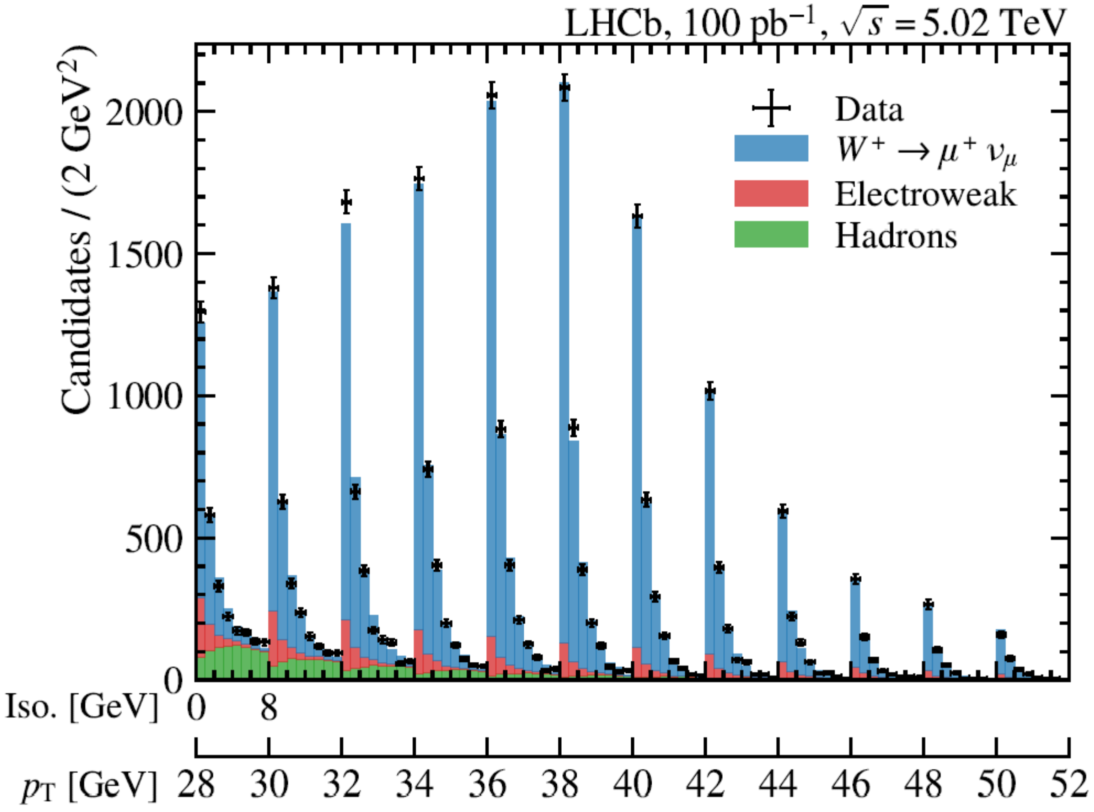
$$-\ln \mathcal{L} = \sum_{i}^{n} \left[-k_i \ln \beta_i \lambda_i + \beta_i \lambda_i\right] + \frac{1}{2} \sum_{i,k}^{n} (\beta_i - 1) \left(\frac{C_{i,k}}{\lambda_i \lambda_k}\right)^{-1} (\beta_k - 1),$$

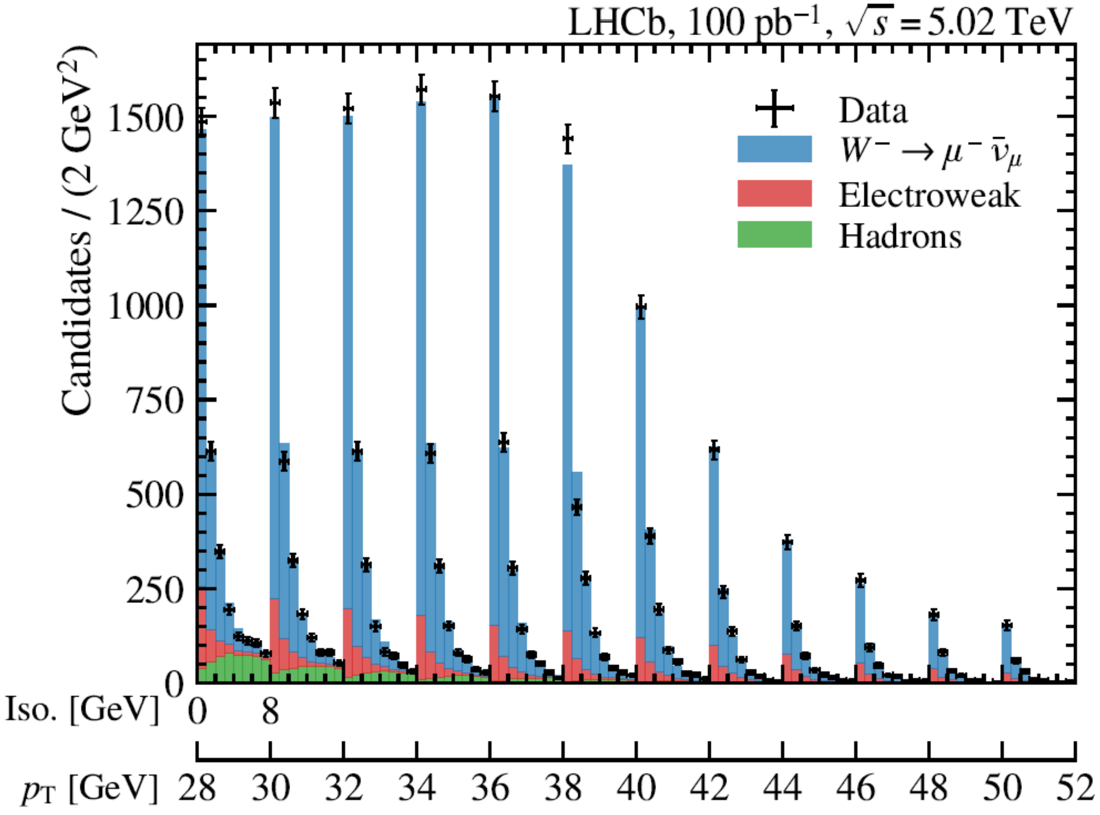
where
- k_i is the data
- λ_i are the model predictions (based on simulation),
- β_i are nuisance parameters accounting for the finite sizes of MC samples,
- C is the total (statistical) covariance matrix of the prediction

- Log-likelihood fit between the **observed data** and the **signal + background model (at reco level)** to get best values of $d\sigma/dp_T$ (at truth-level)

Fit results

- 8 bins of isolation, 12 bins of p_T (fit of 2D distribution)
- (true) $d\sigma/dp_T$ are the fit parameters
- What you see here is the best fitting model (λ_i; at reco − level) to the data





[arXiv:2509.18817]

Systematic uncertainties

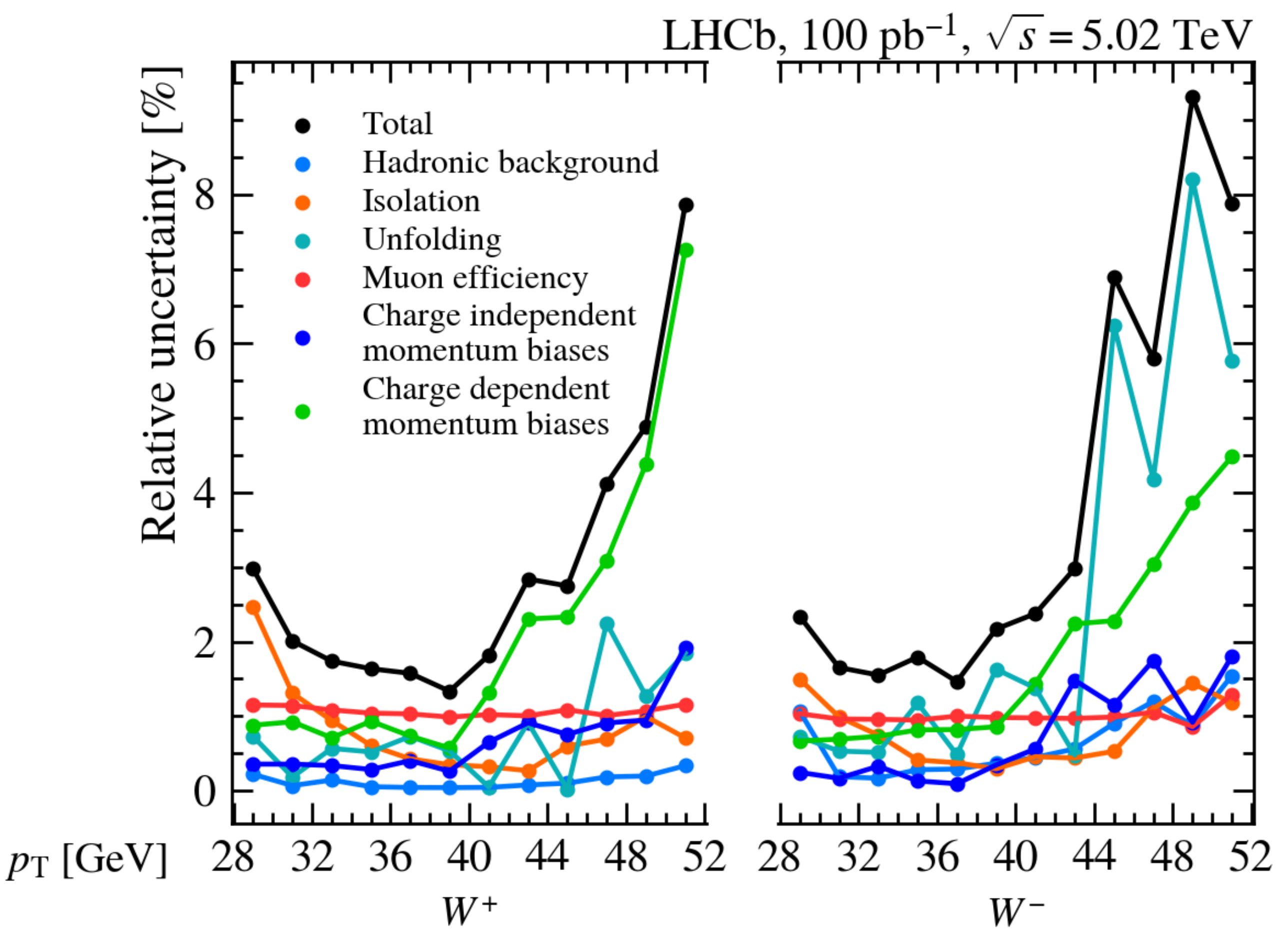
- Experimental systematic uncertainties come from the detector response and calibration
- Systematic uncertainties are estimated by varying analysis settings and observing the effect on the differential cross-section
- Compute covariance matrices for each uncertainty source and propagate them to the m_W measurement
- Covariances quantify correlations between W^+ and W^- and their effect on the final m_W measurement
- Helps identify the largest uncertainty sources and focus on reducing them in future analyses

Systematic uncertainties examples

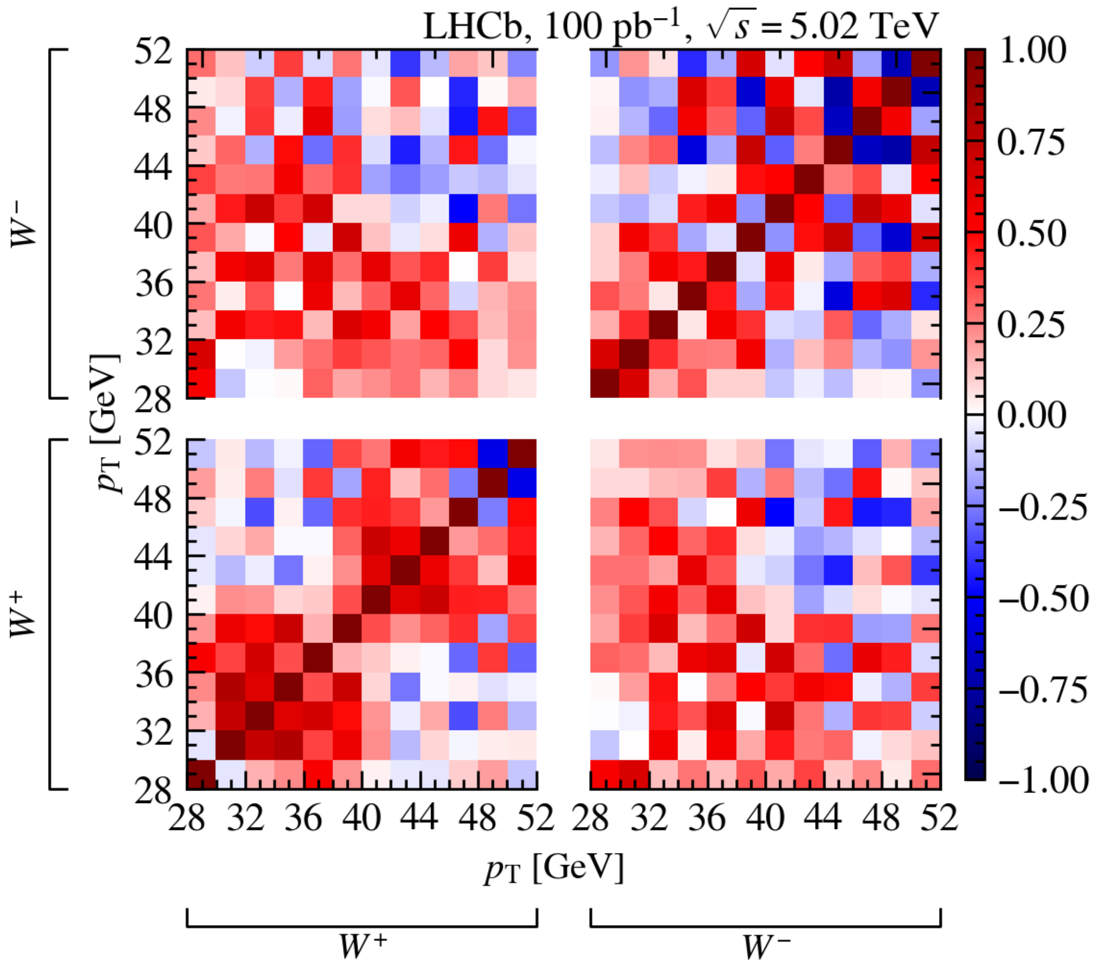
- Trigger, Tracking, Muon ID Efficiency
- Momentum smearing (charge independent)
- Pseudomass (charge dependent)
- Number of muon isolation bins
- Hadronic bkg/signal isolation calibration
- Hadronic bkg misid rate model
- Hadronic bkg proportions of pions, kaons and protons
- Number of reco p_T bins

Systematic uncertainties

Relative systematic uncertainty (grouped)



Total systematic correlation matrix



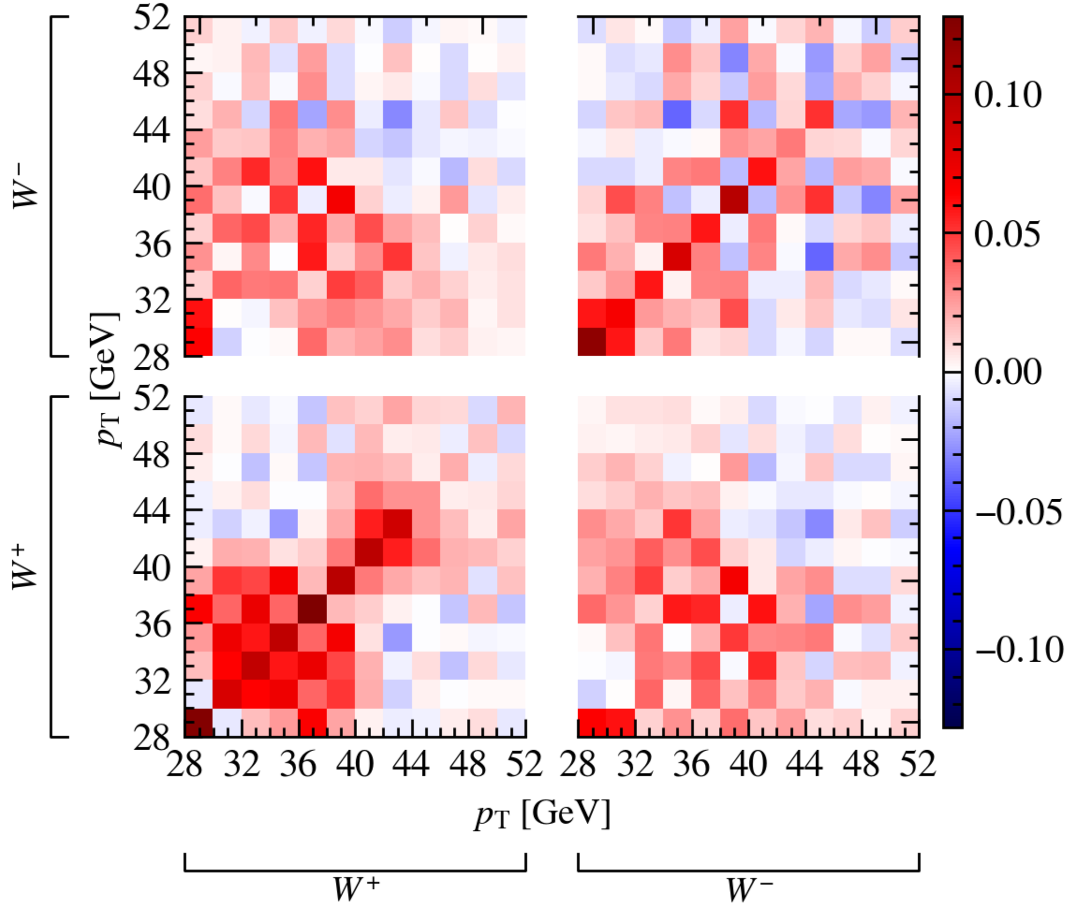
[arXiv:2509.18817]

Results – $d\sigma/dp_T$ and covariance matrix

All a theorist needs to fit m_W with a model of choice

- HEPData Record

Interval in p_T [GeV]	$\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}$ [pb/GeV] $W^+ \to \mu^+\nu_\mu$	$\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}$ [pb/GeV] $W^- \to \mu^-\overline{\nu}_\mu$
28–30	$11.93 \pm 0.44 \pm 0.36$	$14.81 \pm 0.47 \pm 0.35$
30–32	$14.36 \pm 0.46 \pm 0.29$	$15.70 \pm 0.48 \pm 0.26$
32–34	$17.66 \pm 0.48 \pm 0.31$	$15.59 \pm 0.48 \pm 0.24$
34–36	$18.87 \pm 0.51 \pm 0.31$	$16.09 \pm 0.48 \pm 0.29$
36–38	$22.73 \pm 0.56 \pm 0.36$	$16.53 \pm 0.49 \pm 0.24$
38–40	$23.50 \pm 0.58 \pm 0.31$	$14.57 \pm 0.48 \pm 0.32$
40–42	$17.16 \pm 0.53 \pm 0.31$	$10.26 \pm 0.42 \pm 0.24$
42–44	$10.45 \pm 0.43 \pm 0.30$	$6.13 \pm 0.35 \pm 0.18$
44–46	$6.01 \pm 0.35 \pm 0.17$	$3.28 \pm 0.28 \pm 0.23$
46–48	$3.46 \pm 0.30 \pm 0.14$	$2.41 \pm 0.24 \pm 0.14$
48–50	$2.59 \pm 0.26 \pm 0.13$	$1.65 \pm 0.22 \pm 0.15$
50–52	$1.75 \pm 0.21 \pm 0.14$	$1.42 \pm 0.18 \pm 0.11$

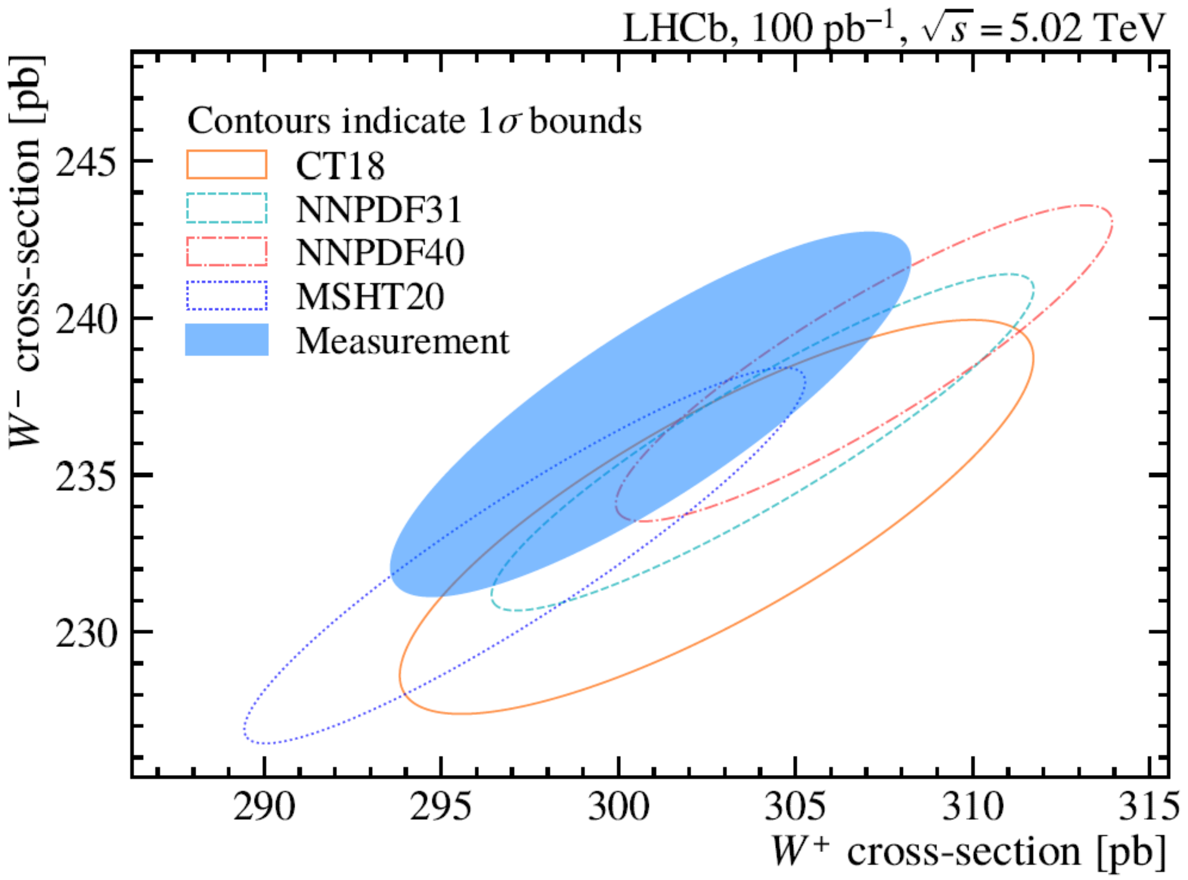


Results – integrated cross-section

Predictions using MCFM at $\mathcal{O}(\alpha_s^2)$

- $\sigma_{W^+\to\mu^+\nu_\mu} = 300.9 \pm 2.4\,(stat) \pm 3.8\,(syst) \pm 6.0\,(lumi)$ pb

- $\sigma_{W^-\to\mu^-\nu_\mu} = 236.9 \pm 2.1\,(stat) \pm 2.7\,(syst) \pm 4.7\,(lumi)$ pb



[arXiv:2509.18817]

- ❖ Integrated over the region $28 < p_T < 52$ GeV and $2.2 < \eta < 4.4$
- ❖ We apply QED corrections to the MCFM predictions (determined with Pythia)
- ❖ Predictions have uncertainties on varying PDF members and scale variations

m_W

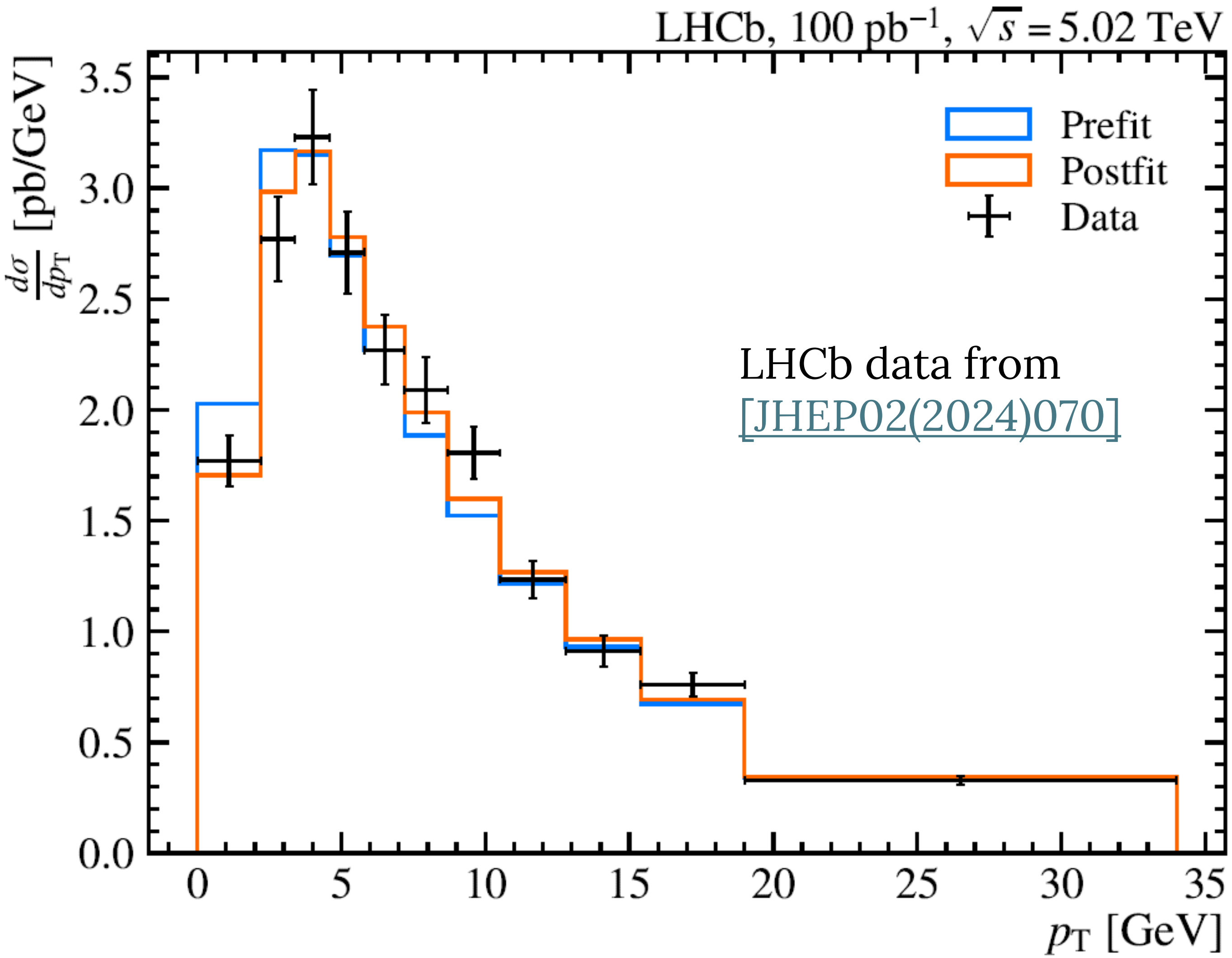
Methodology

- The template $pp \to W \to \mu\nu$ events are generated using **Pythia8** with the same version and tune as the samples with full detector simulation
- Use **DYTurbo** to reweight templates for enhanced accuracy (unpolarised and angular components) – Similar to the 2021 LHCb m_W analysis
- Implement a 5D weighting procedure to fit the model (predictions) to measured corrected data ($d\sigma/dp_T$ results)
- We also default to fitting the Z boson cross-section to constrain QCD modelling (α_s and g parameters)
  - Use the published Z cross-section at 5.02 TeV
- m_W results were **blinded** throughout all analysis stages

Z fit results

- This fit gives us results for α_s and g factor values that we can later utilise for the W boson mass fit
- We choose to **float g** and **fix α_s** using the Z fit results by default when performing the W fit (recommended by theorists)

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

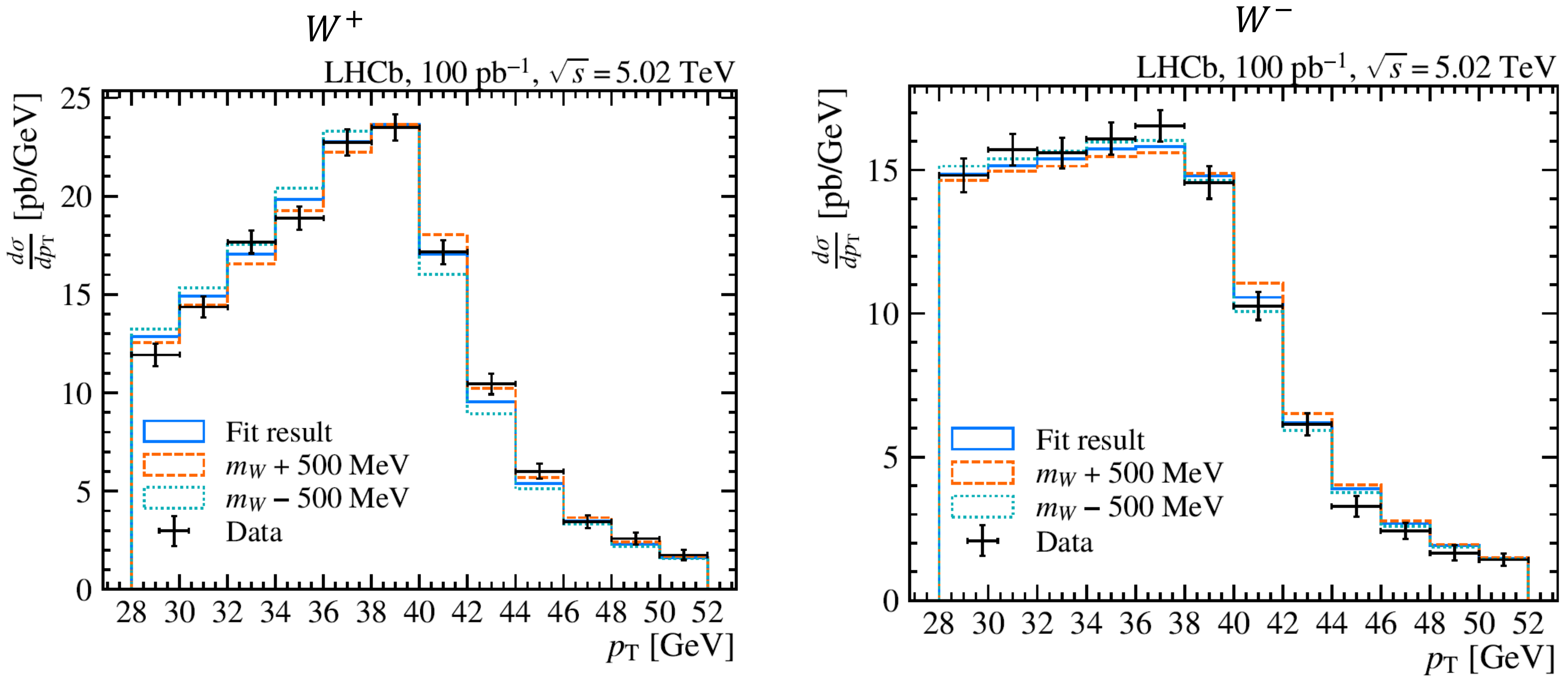


LHCb data from [JHEP02(2024)070]

[arXiv:2509.18817]

W fit results

[arXiv:2509.18817]

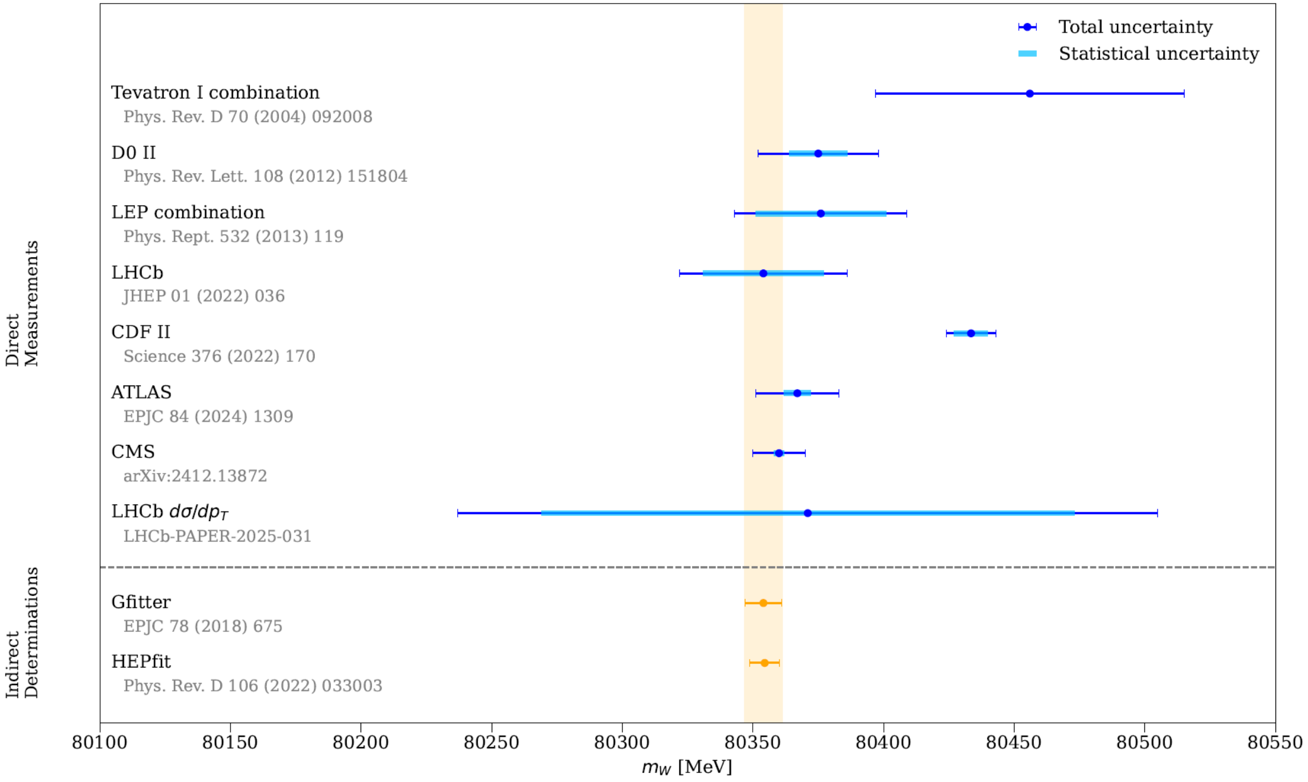


W mass results

The final m_W result is a simple average of the results from using the 3 PDF sets:

PDF set	χ^2/ndf	m_W	σ_{theory}	σ_{PDF}
NNPDF3.1	25.6/21	80366 ± 130 MeV	25 MeV	28 MeV
MSHT20	27.2/21	80380 ± 129 MeV	25 MeV	15 MeV
CT18	23.9/21	80362 ± 130 MeV	25 MeV	23 MeV

$$m_W = 80371 \pm 130_{stat+syst} \pm 32_{theo*}$$
(~100 MeV stat)



- **Submitted to JHEP**
- **Now onto full Run 2 analysis!**
  (at $\sqrt{s}$ = 13 TeV)

*The theory uncertainty is the combination of the PDF members uncertainty and other variations (namely, varying α_s+ QED FSR radiation + the 7-point variation of the DYTurbo QCD scale factors)

Cross-checks

Differential cross-section fit variations:

- Changing applied recalibrations of data concerning W cross-section model (unpolarized, angular, m_W value)
- Fit with a simple χ^2 instead of Beeston-Barlow Lite method

DYTurbo variations:

- Trying a different PDF set
- Using higher order calculations for the unpolarised component
- Changing QCD scale scheme
- Changing the blim cut-off value

***m_W* fit variations**

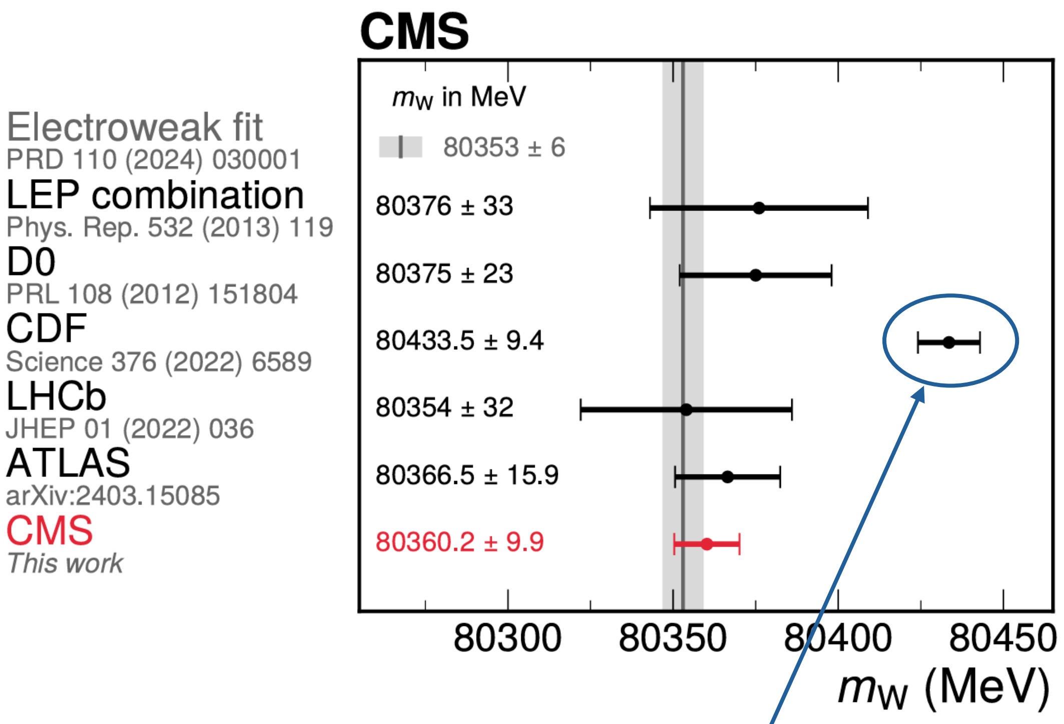
- Changing the Z/W fit strategies

All results are compatible.

Analysis preservation

Importance of analysis preservation

- Theories are validated through experiments
- Similar experiments studying the same phenomena should yield compatible results
- Ideally, a researcher from the future should be able to repeat an analysis and get compatible results
- Very difficult to explain everything in a paper
- Data tuples need to be preserved somewhere
- Data analysis results depend on software versions, operating systems, and computing environments

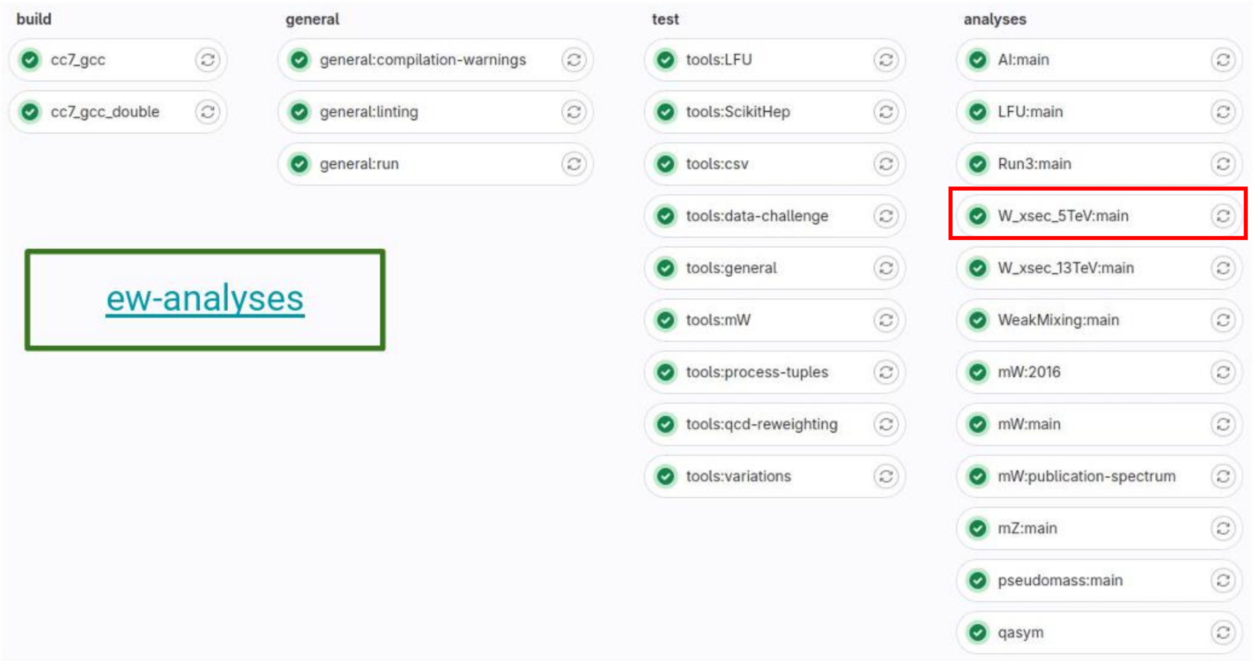


Impossible or extremely difficult to re-run all parts of the analysis

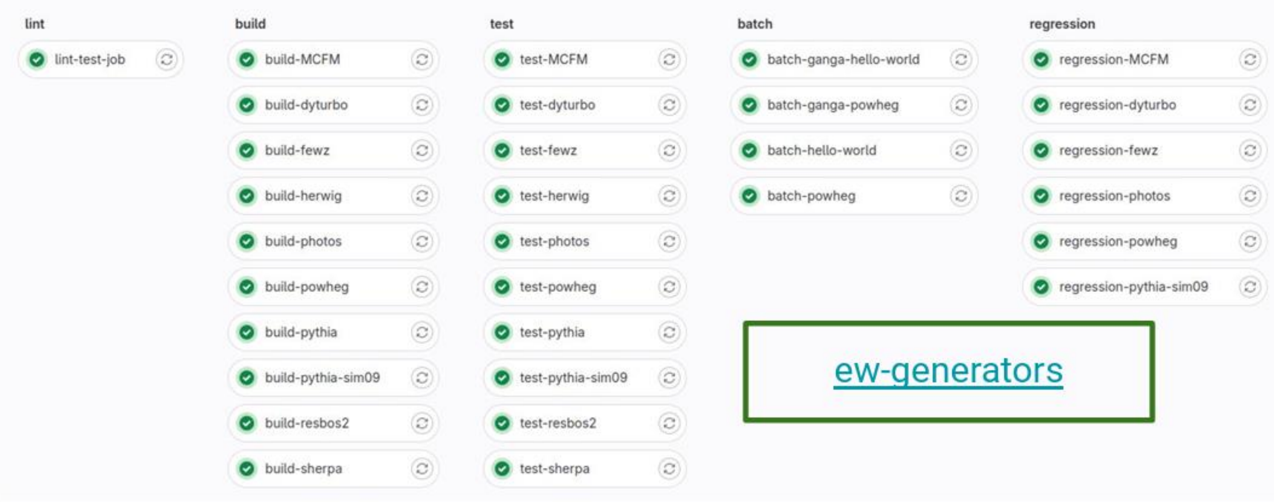
ew-analyses (Gitlab)

- Leverage 'lb-conda' (LHCb's conda-based environment) to standardise the software stack and ensure compatibility across analyses
- Use containers for operating system environments
- Common Gitlab repository for EW analyses (cross-sections, masses, weak mixing, LFU, etc.)
- Analysis methodology is similar – lots of shared tools
- Sharing knowledge is easier
- Contributions are subject to constant review

Regular testing

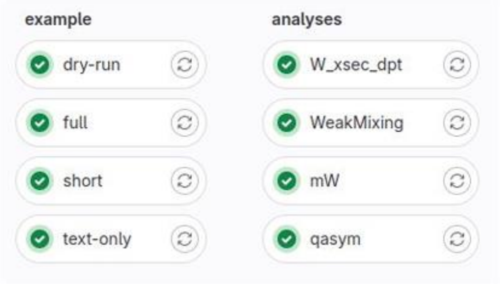


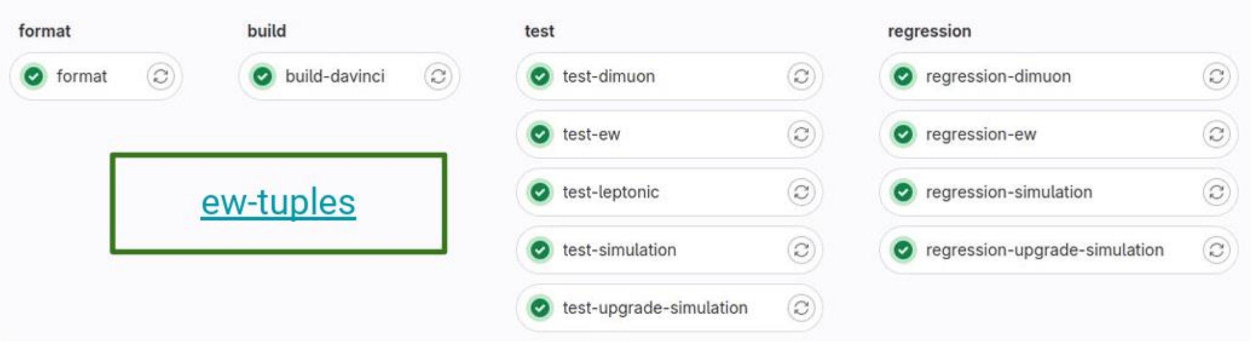
ew-analyses



ew-generators

ew-docs





ew-tuples

Tags and protected branches

- Scheduled pipelines to ensure reproducibility
- Once an analysis is finished, define an associated tag and make a dedicated directory for the tuples on CERN storage (EOS) (read-only)
- Isolated publication branches

pseudomass-run2-publication protected
2aa56d33 · Merge branch 'mvesteri-cc7-to-el9-in-ci-pseudomass-run2' into 'publication/pseudomass-run2' · 2 months ago

```
State of the publication/pseudomass-run2 branch that reproduces the
results in LHCb-DP-2023-001
```

Create release

W-xsec-dpt-5TeV-2017-unblinding protected
099b2a21 · Merge branch 'ahabdelm-unblind' into 'master' · 5 months ago

```
State of the software corresponding to the unblinding of the W mass
measurement using 5 TeV data collected in 2017
```

Create release

mZ-2016-unblinding protected
1d4e7d2e · Update tracked results · 8 months ago

```
Project at the unblinding of mZ 2016 analysis (18 March 2025, CERN
Seminar day)
```

Create release

WeakMixing-run-2-unblinding protected
12dc96f0 · Merge branch 'mvesteri-weak-mixing-unblind' into 'master' · 25 Jun 2024

```
Project at the unblinding of the WeakMixing analysis (24th July 2024)
```

Create release

mW-2016-unblinding protected
e48b2066 · Merge branch 'mpili_mW_summary_plot' into 'master' · 9 Jun 2021

```
Version of the code for the unblinding of the W mass measurement using
2016 data on 08/06/2021
```

Create release

publication/W-xsec-dpt-5TeV protected
1a2427af · Merge branch 'ahabdelm-hep-data-recast' into 'publication/W-xsec-dpt-5TeV' · 2 weeks ago

226 | 14

What’s next?

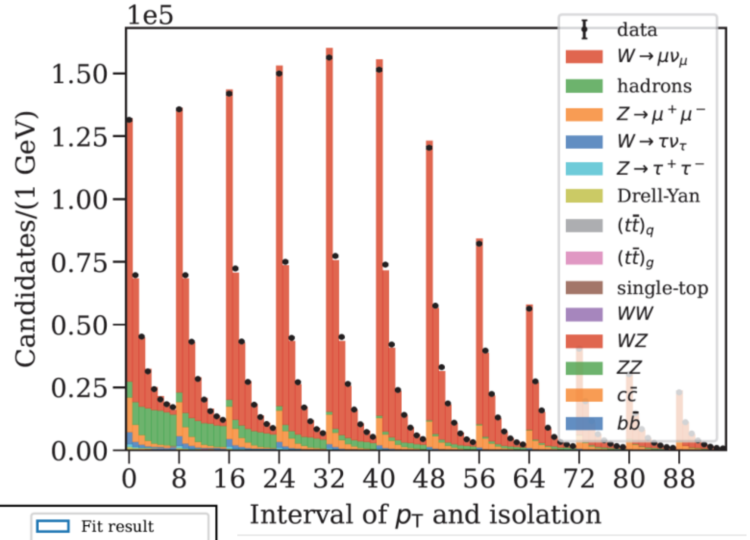
Future m_W measurement at LHCb

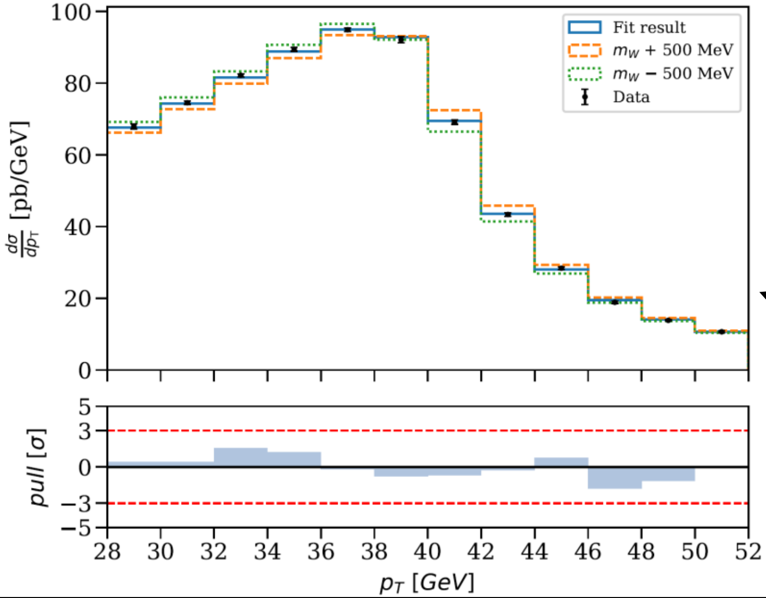
- Use same analysis techniques to measure m_W with full Run 2 dataset (2016-2018) at $\sqrt{s} = 13$ TeV

- Expect to produce and rely on a double-differential cross-section measurement for the W ($\frac{d^2\sigma}{dp_T d\eta}$)

- Currently, using the 2017+2018 data at $\sqrt{s} = 13$ TeV is currently giving a **14 MeV** statistical uncertainty

- Expect a measurement with close to **20 MeV** total uncertainty





blinded

Summary

- First W boson mass measurement using corrected $d\sigma/dp_T$ (2-step analysis)

- Corrected production then used it to measure m_W (model-independent way)

- Proof-of-principle → used $\sqrt{s} = 5.02$ TeV sample
  - ❖ Statistically limited

- Aim to repeat the analysis using the full Run 2 dataset (> 50 × larger than the 5.02 TeV sample)
  - ❖ Currently in preparation

Stay tuned!

Backup Slides

Selections W/Z

Requirement	$W \to \mu\nu$	$Z \to \mu\mu$
Muon:		
η	$2.2 < \eta < 4.4$	$1.7 < \eta < 4.4$
p_T	$28 < p_T < 52$ GeV	> 20 GeV
IP χ^2	< 9	< 100
HCAL E_T	< 5 GeV	–
σ_p/p	$< 6\%$	$< 6\%$
track fit χ^2/ndof	< 1.8	< 1.8
isolation	< 8 GeV	< 10 GeV
momentum	< 2 TeV	< 2 TeV
Candidate:		
mass	–	$77 < M < 105$ GeV
trigger	TOS	TOS
`nCandidate`	$= 0$	$= 0$

Handling the signal

- Start with a prediction of the **true signal** differential cross-section ($\frac{d\sigma}{dp_T^{bare}}$)

  →(floating fit params, including 2 **fixed** overflow bins – nuisance params)

- Convert to a true signal yields model (array of counts) (p_T^{bare})

$$p_T^{true} = \frac{d\sigma}{dp_T^{true}} \times \Delta p_T^{true} \times \mathcal{L}_{int},$$

  where Δp_T^{bare} is the bin width of the p_T^{bare} distribution

- Multiply by the normalised response matrix (R_{ij}) to get a **reco signal model** (p_T^{reco})

Hadronic background modelling

Unstable hadrons (pions and kaons) are parametrised using two components. For the first one, accounting for decays-in-flight, we make use of the formula

$$f(p) = \alpha \left(1 - e^{-\frac{md}{pc\tau}}\right), \qquad (6)$$

where p is the momentum of the particle, α is a multiplicative factor corresponding to the amount of decays-in-flight that are produced with respect to other processes, d is the decay-length of the particles in the detector, m is the invariant mass of the particle, c is the speed of light in vacuum and τ is the lifetime of the particle. The decay-length of the particles is fixed to 15 m in the fits, corresponding to decays happening right before the muon stations[5], which are more likely to satisfy the selection requirements and still have the track aligned with hits in the muon chambers. A systematic uncertainty is later assigned by varying this quantity, described in Section 5.3. The second component corresponds to punch-through processes, which grow increasingly with the energy of the particles. This process is expected to exhibit a linear behavior at high energies, and is parametrised with a straight line. For stable particles (essentially protons), the overall parametrization takes into account only punch-through processes.

Handling the hadronic background

- As mentioned and seen earlier, our simulation of the hadronic bkg is not ideal

- Need to scale the p_T^{reco} distribution:

$$\lambda_i^{had} = n^{obs} f_{had} \mathrm{t}_{had,i}^{rec}$$

where

- ❖ n^{obs} is the observed number of signal candidates (normalisation)
- ❖ f_{had} is a freely-varying (floating) fit fraction
- ❖ $\mathrm{t}_{had,i}^{rec}$ is the simulated, normalized hadronic distribution/template (with misID probability weights applied)
- ❖ This template represents the expected shape of the background across bins, with $\sum_i \mathrm{t}_{had,i}^{rec} = 1$

Handling other backgrounds

- The remaining backgrounds,
  ($Z \to \mu\mu$, $W \to \tau\nu_\tau$, $Z \to \tau\tau$, DY, $(t\bar{t})_q$, $(t\bar{t})_g$, single-top, $c\bar{c}$, $b\bar{b}$),

are determined from simulation and scaled to the Z distribution using the known theory cross-sections

$$\lambda_i^b = \left(\frac{n_Z^{\text{obs}}}{\sigma_Z \varepsilon_Z}\right)\left(\frac{n_{b,i}^{\text{rec}}}{n_b^{\text{gen}}}\right)\sigma_b,$$

Background process cross-section

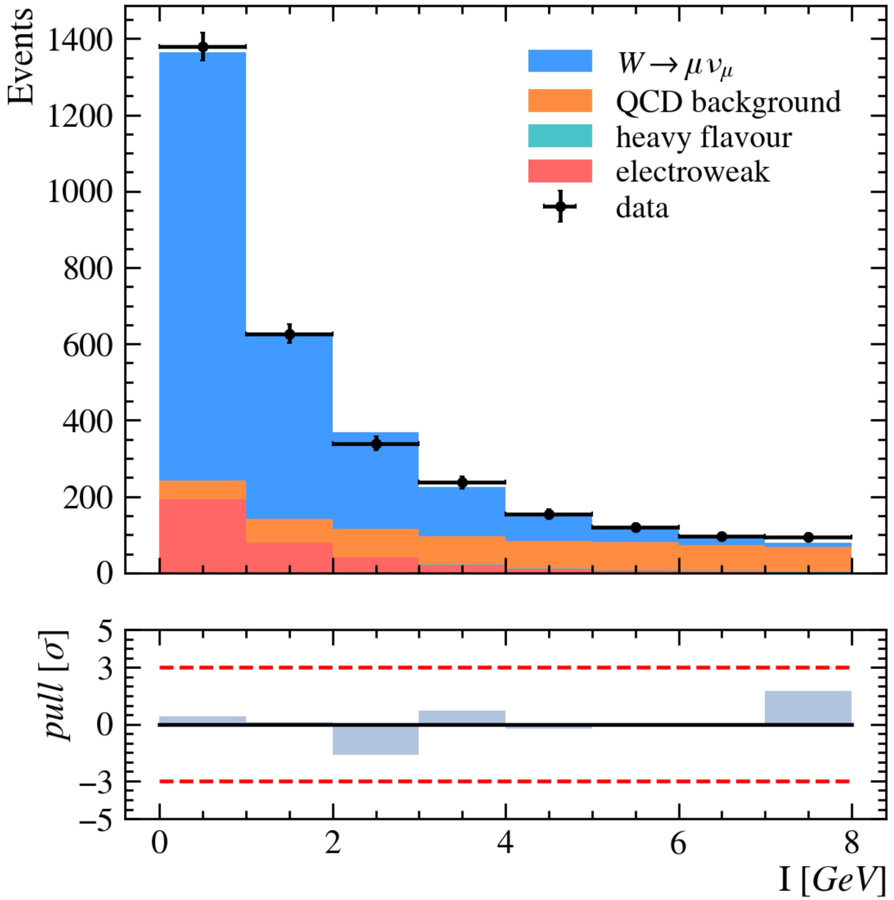
- The first factor is an estimate of the integrated luminosity based on the observed number of $Z \to \mu^+\mu^-$ events, n_Z^{obs}, the corresponding cross-section, σ_Z, and the simulated efficiency, ϵ_Z

- These are now **fixed** components of the fit

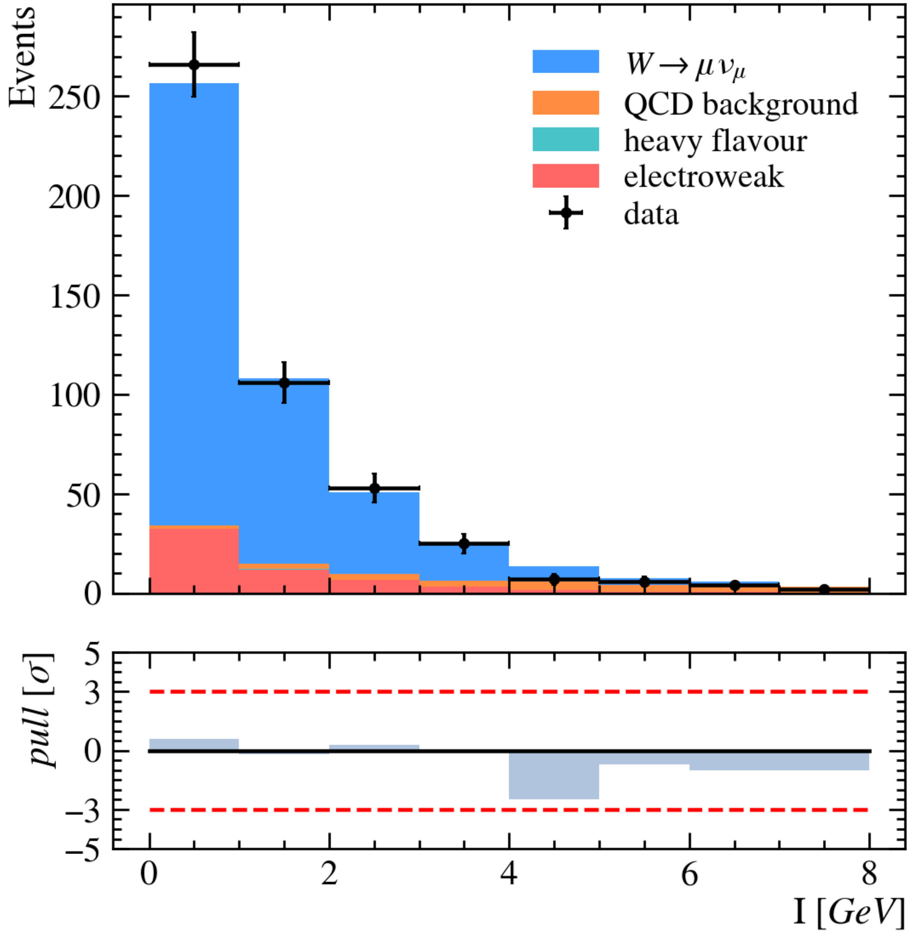
- They are also normalised to the data

Results – example low vs high p_T bin

$W^+, p_T \in [30, 32]$ GeV, $\eta \in [2.2, 4.4]$, p_T bin index 1

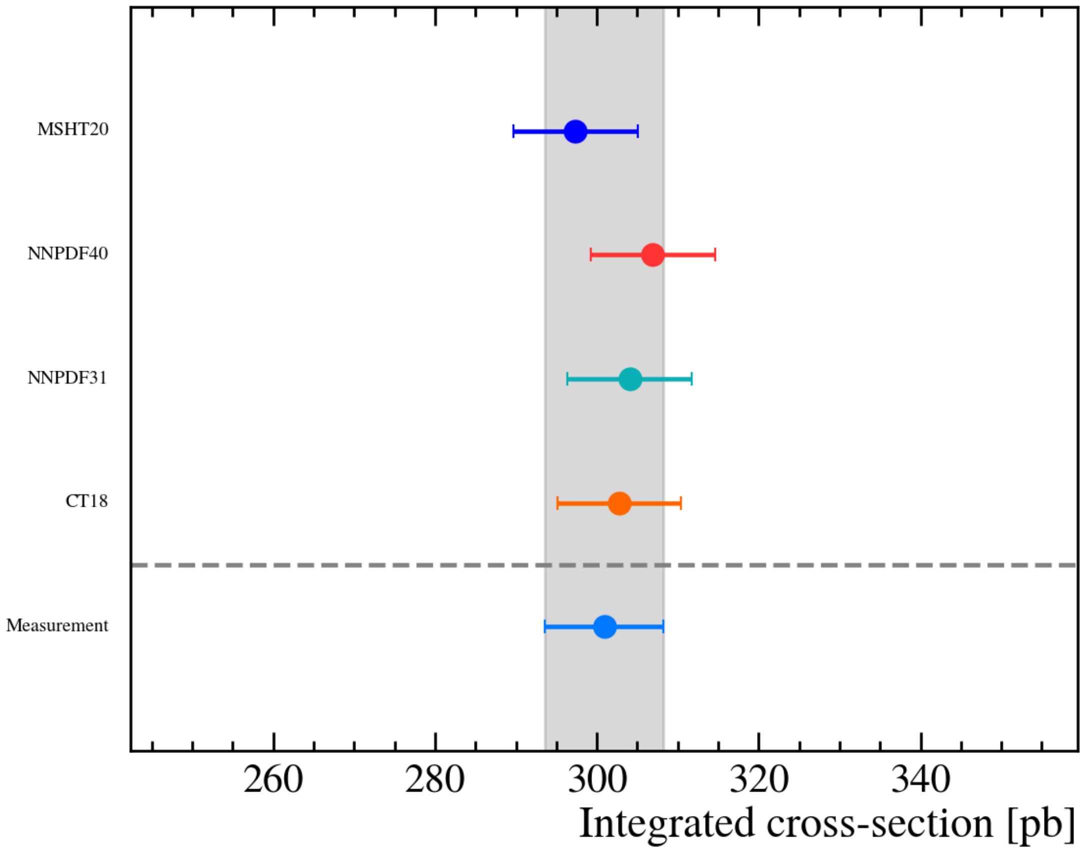


$W^+, p_T \in [48, 50]$ GeV, $\eta \in [2.2, 4.4]$, p_T bin index 10

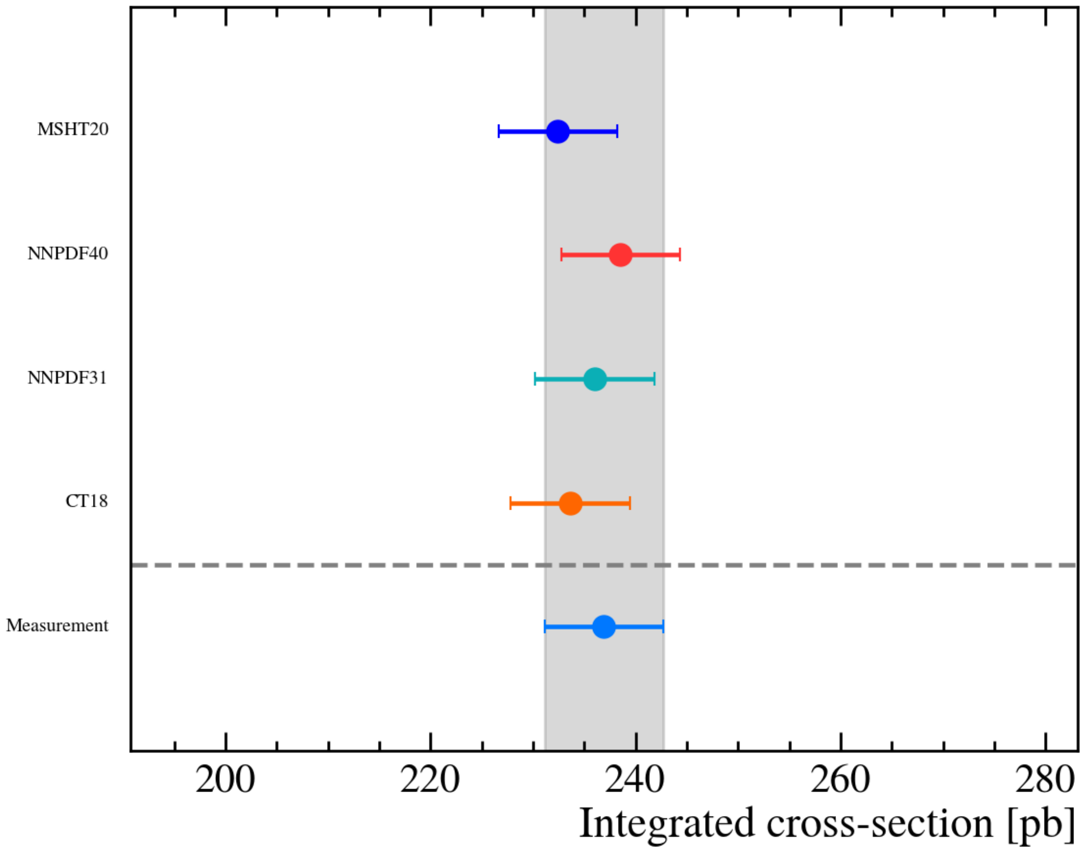


Results – Integrated cross-section 1D

W^+

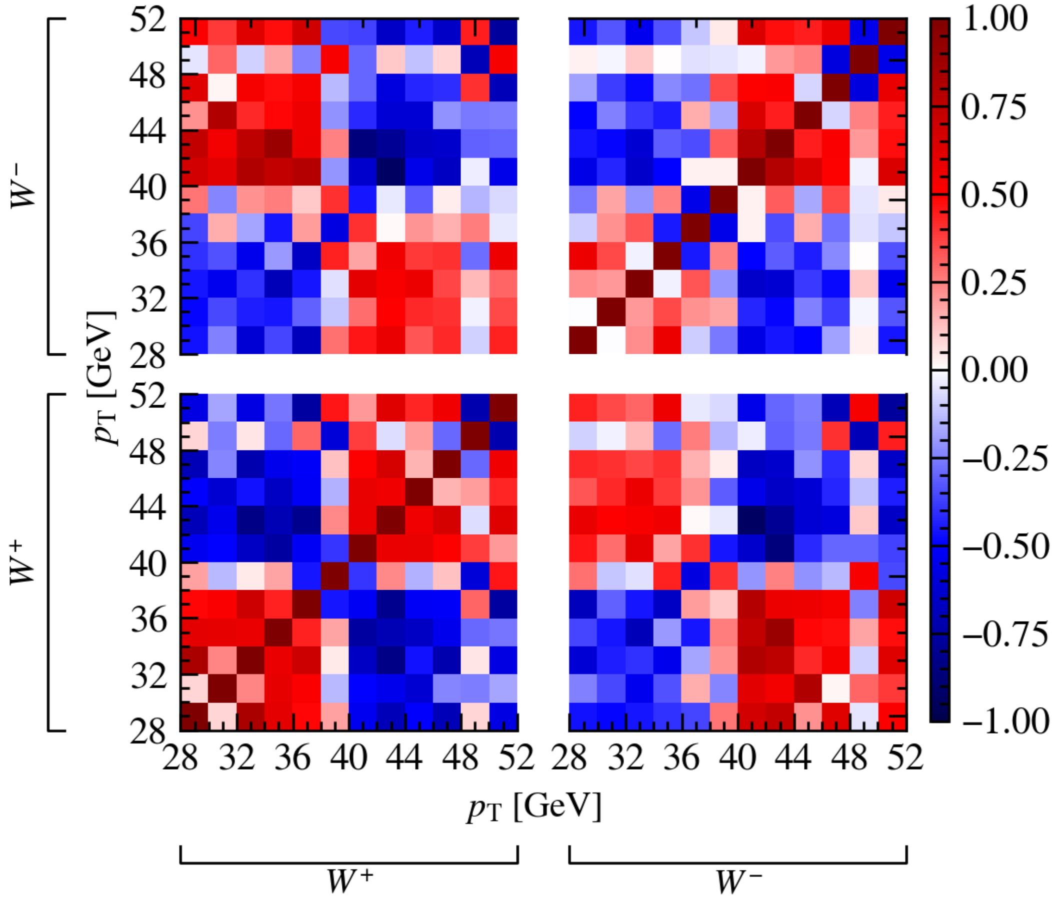


W^-

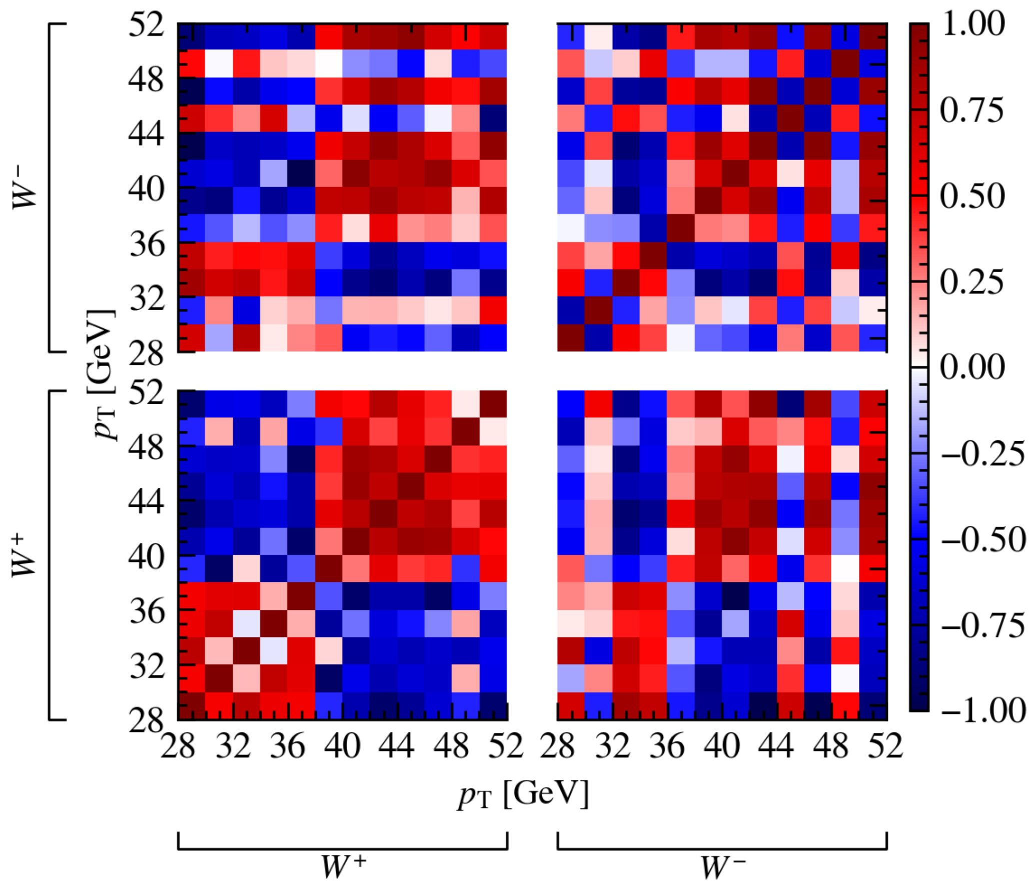


Results – Systematics correlation matrix

Pseudomass

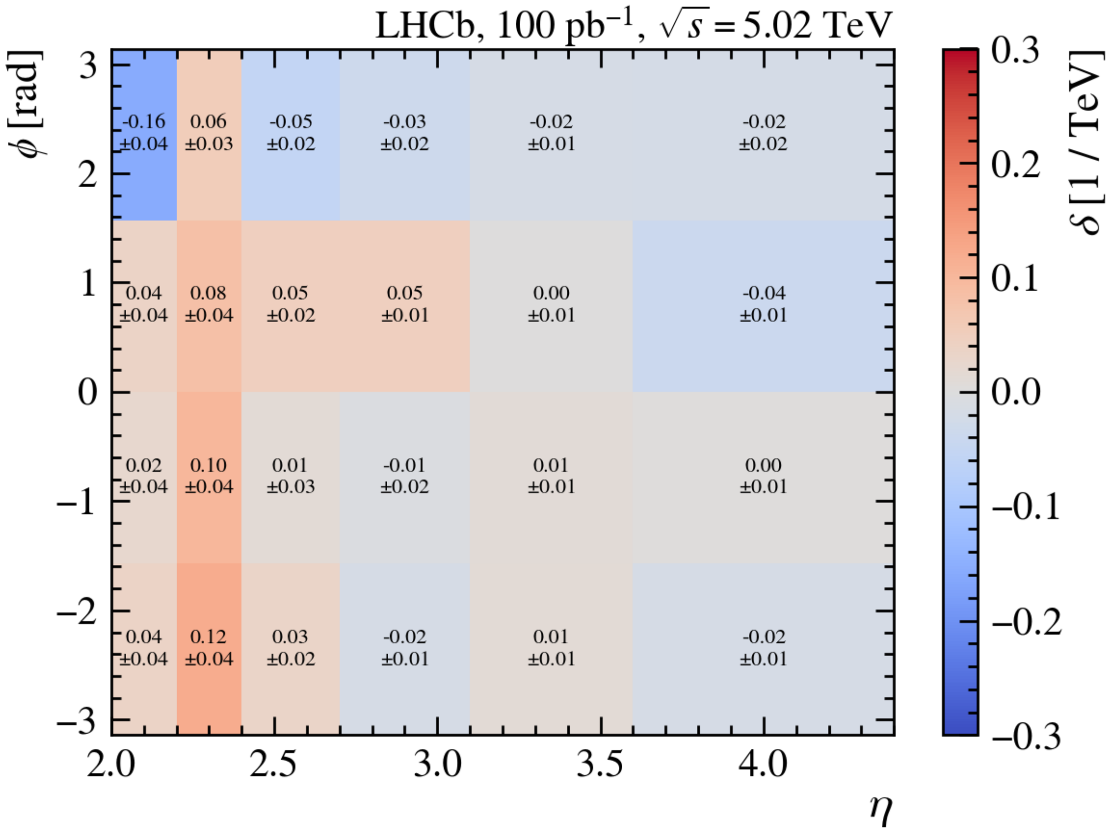


Momentum Smearing

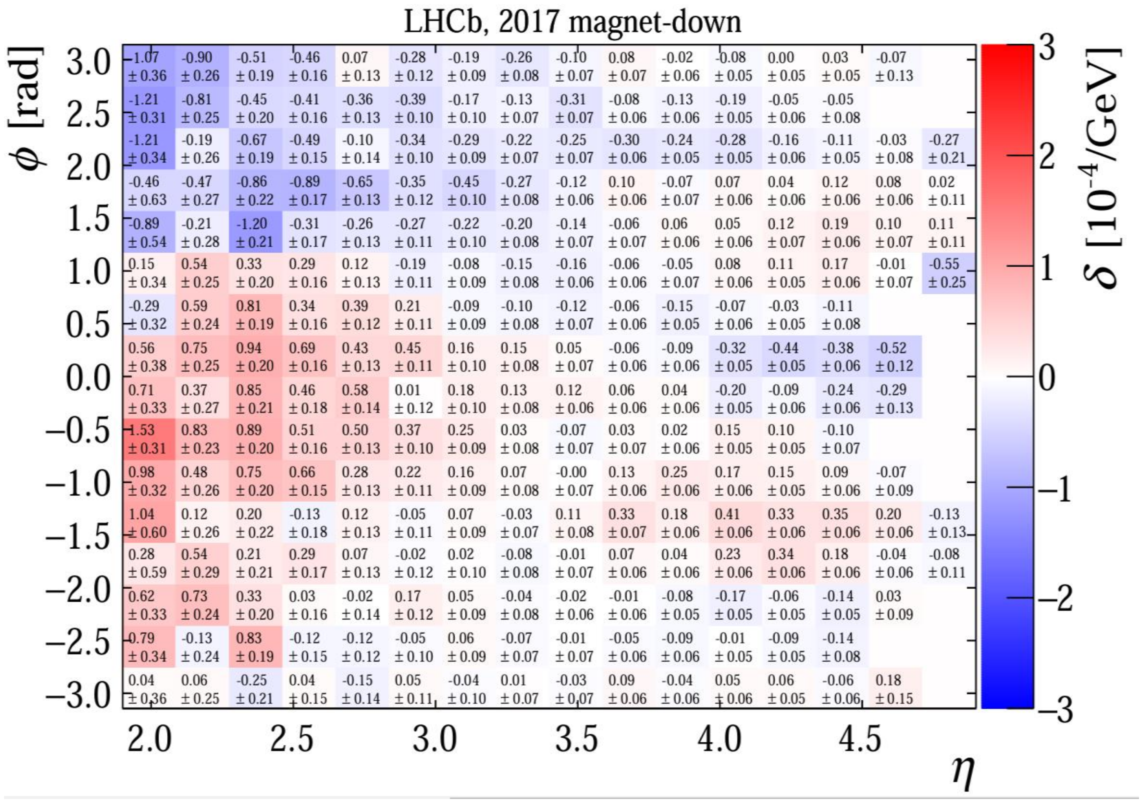


Pseudomass comparison

5.02 TeV

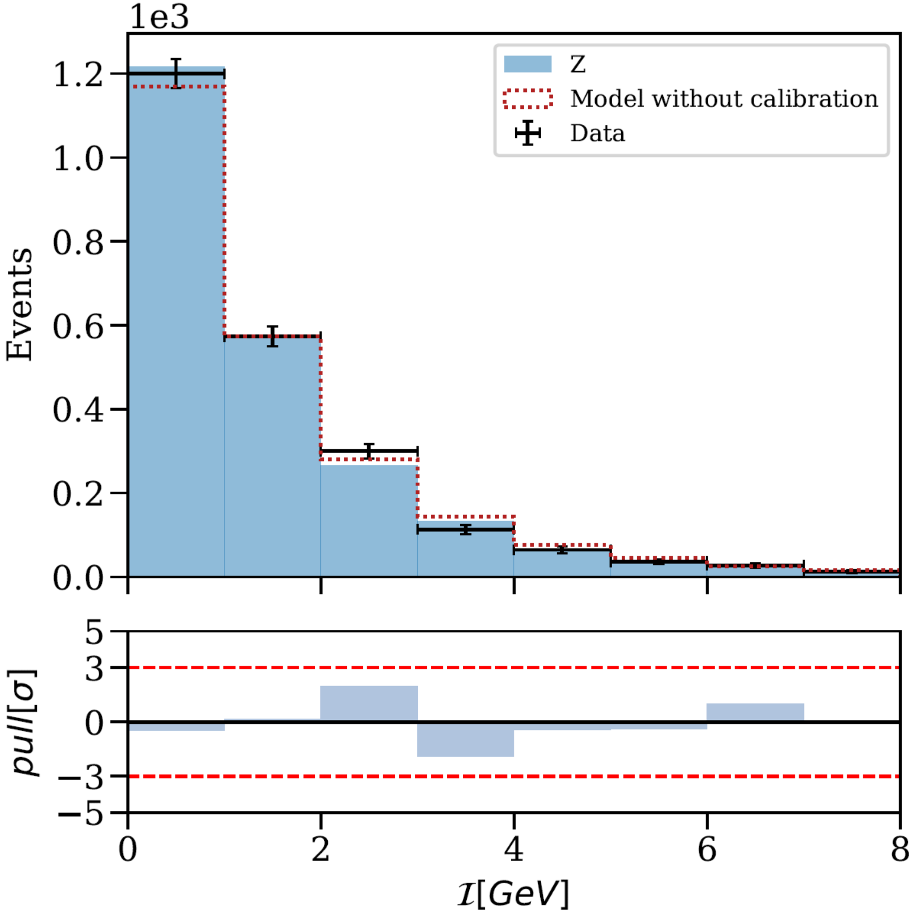


13 TeV [JINST 19 (2024) P03010]



Signal Isolation Calibration 13 TeV comp

Ad hoc (one-off) cross-check



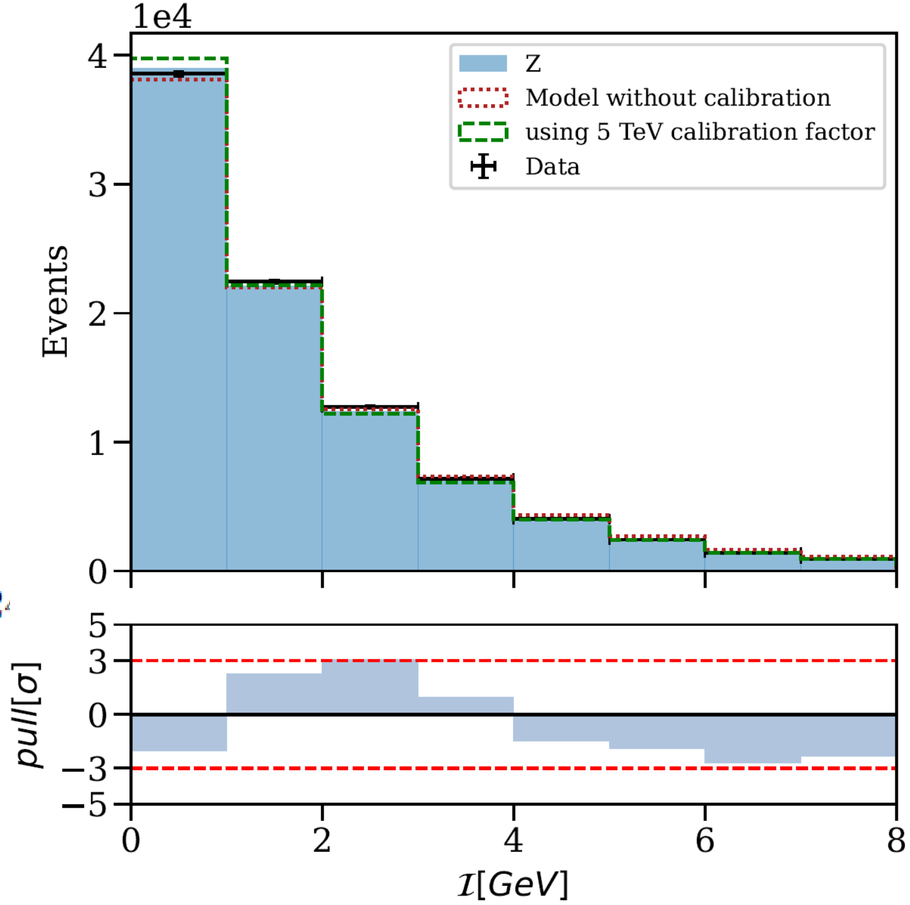
$$C = C' + q\delta$$

name	value	error
Z calib factor	0.938	0.01653
χ^2	15.207	-
ndf	13	-

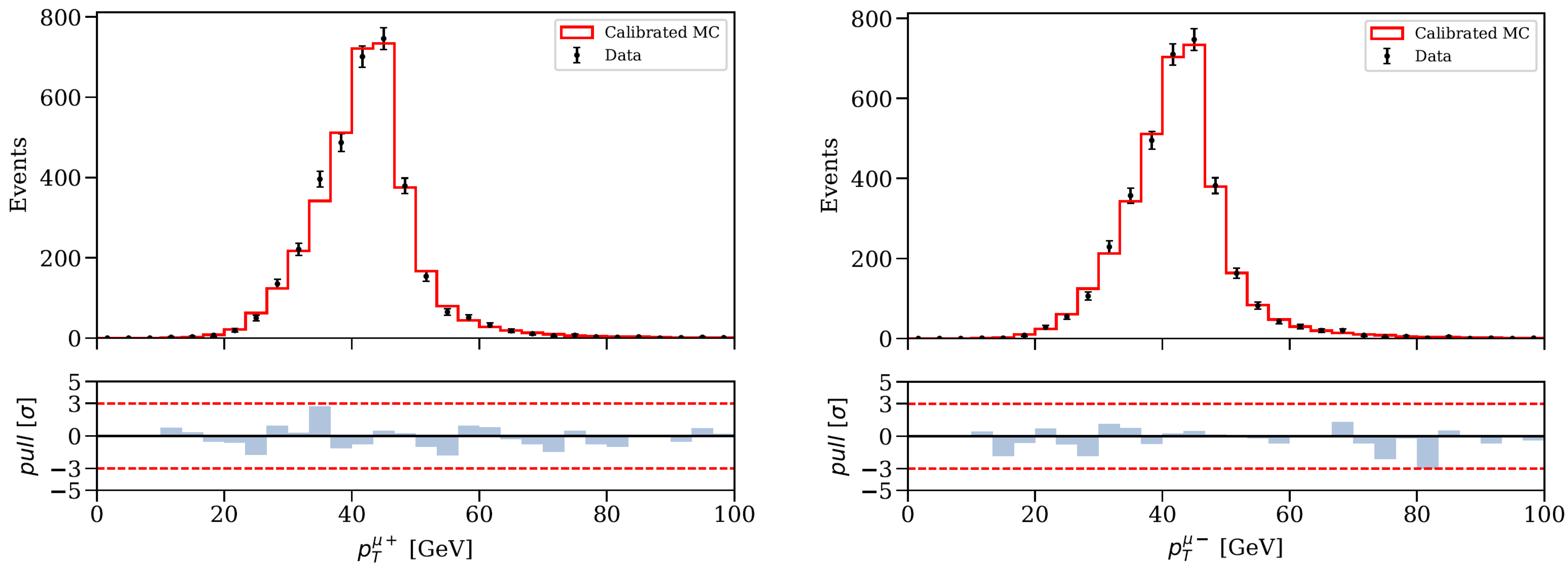
13 TeV

name	value	error
Z calib factor	0.967	0.00432
χ^2	48.458	-
ndf	13	-

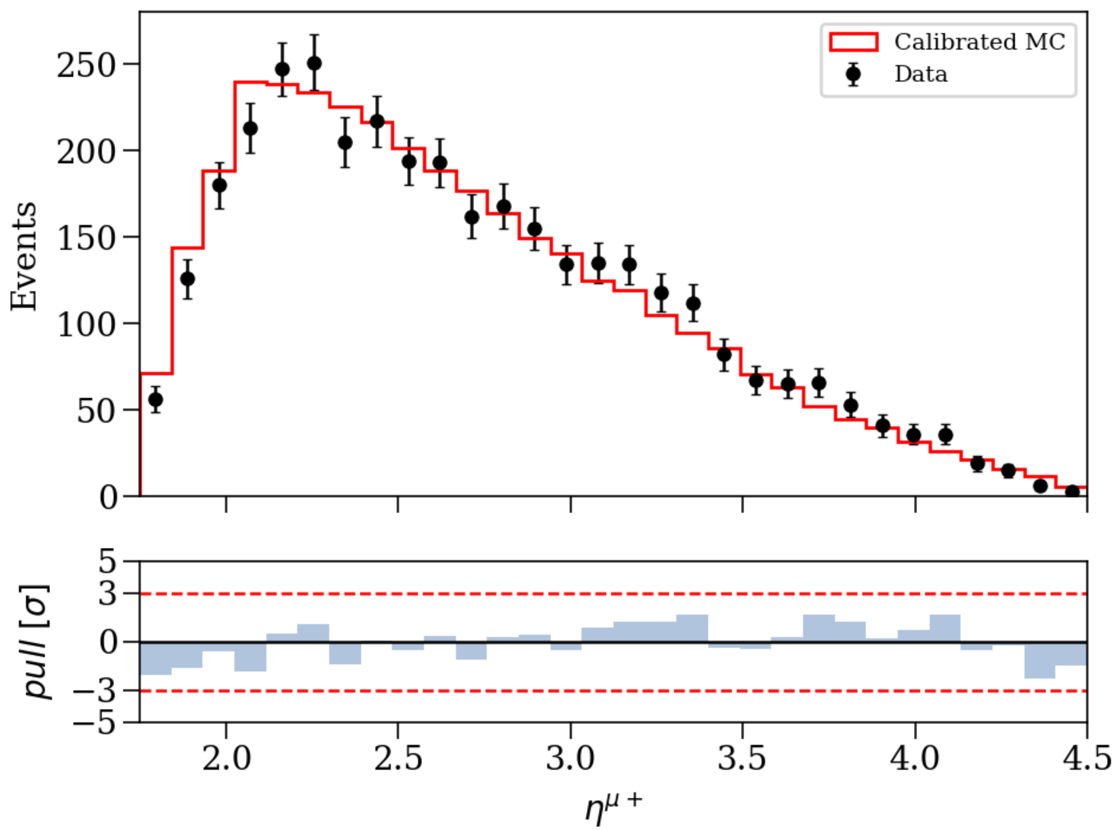
- Within 1.5 σ

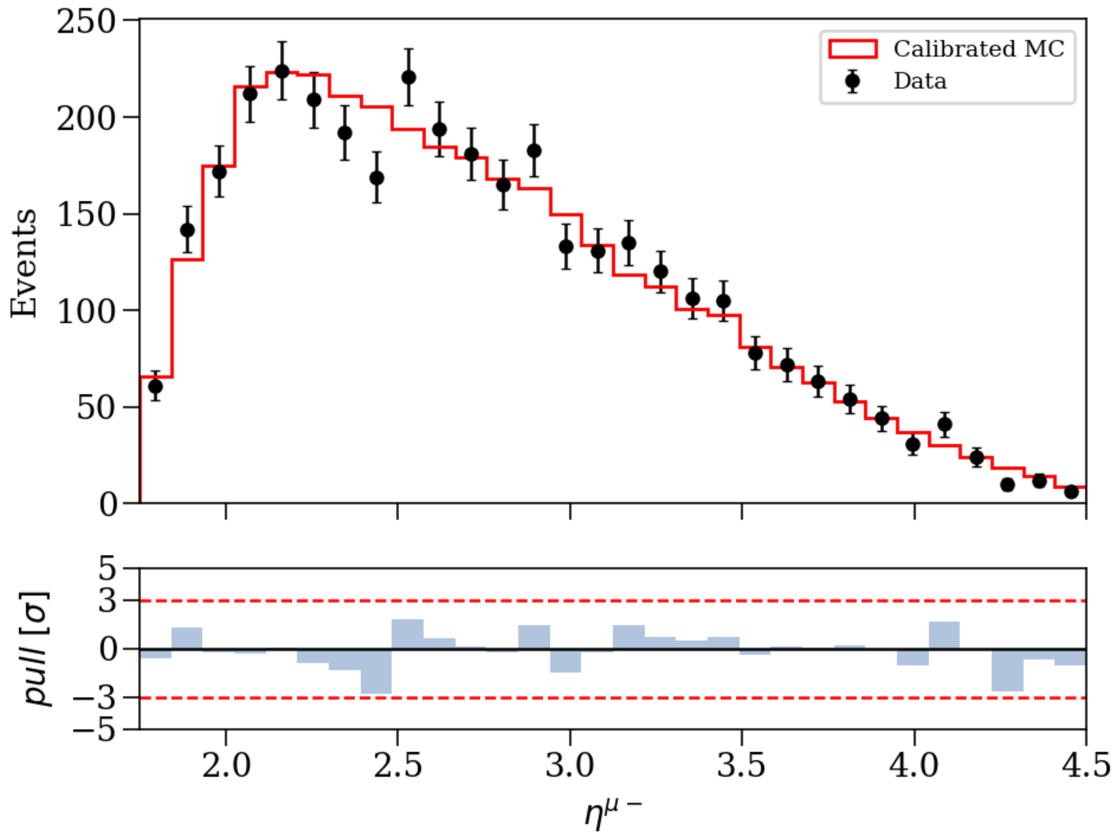


Validation of corrected simulation

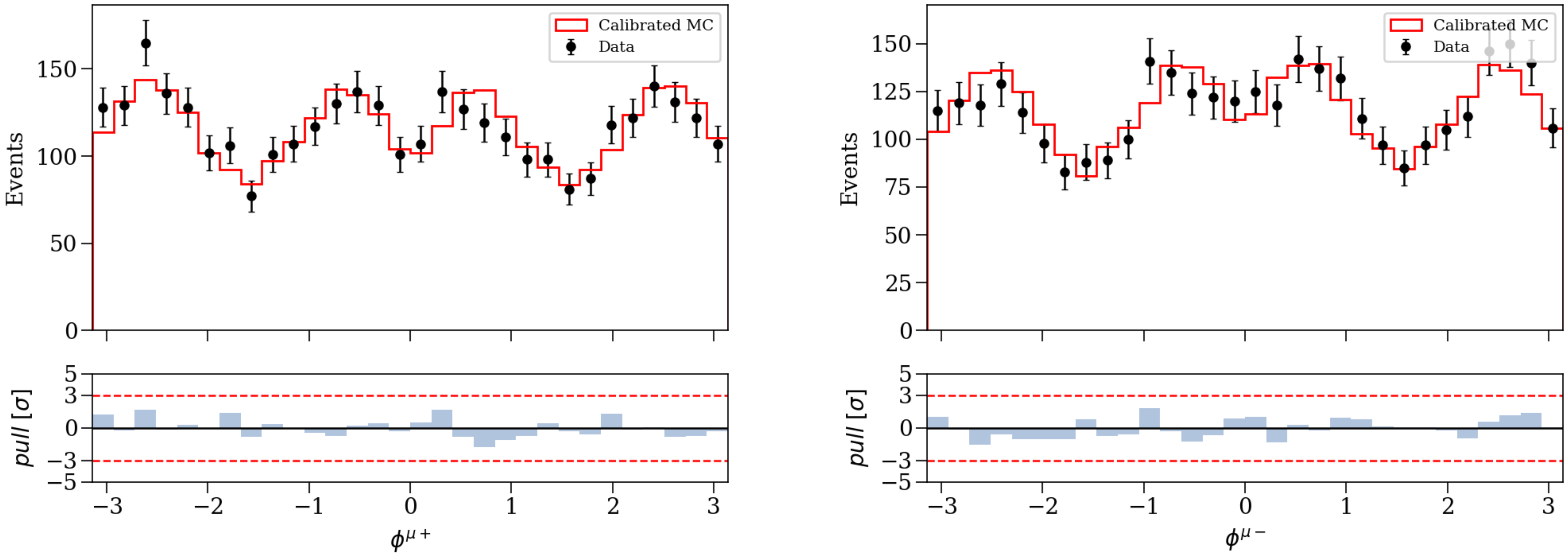


Validation of corrected simulation

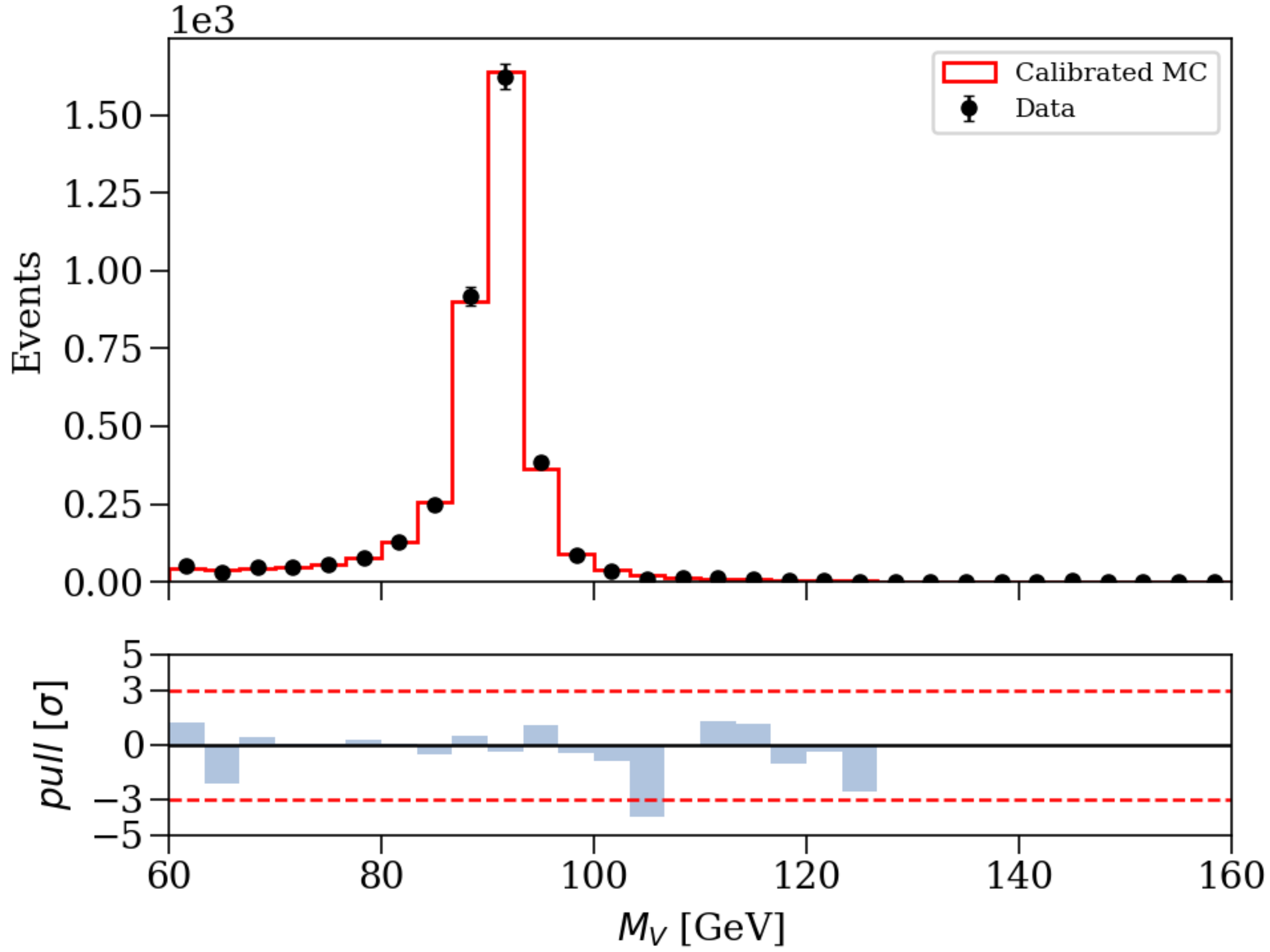




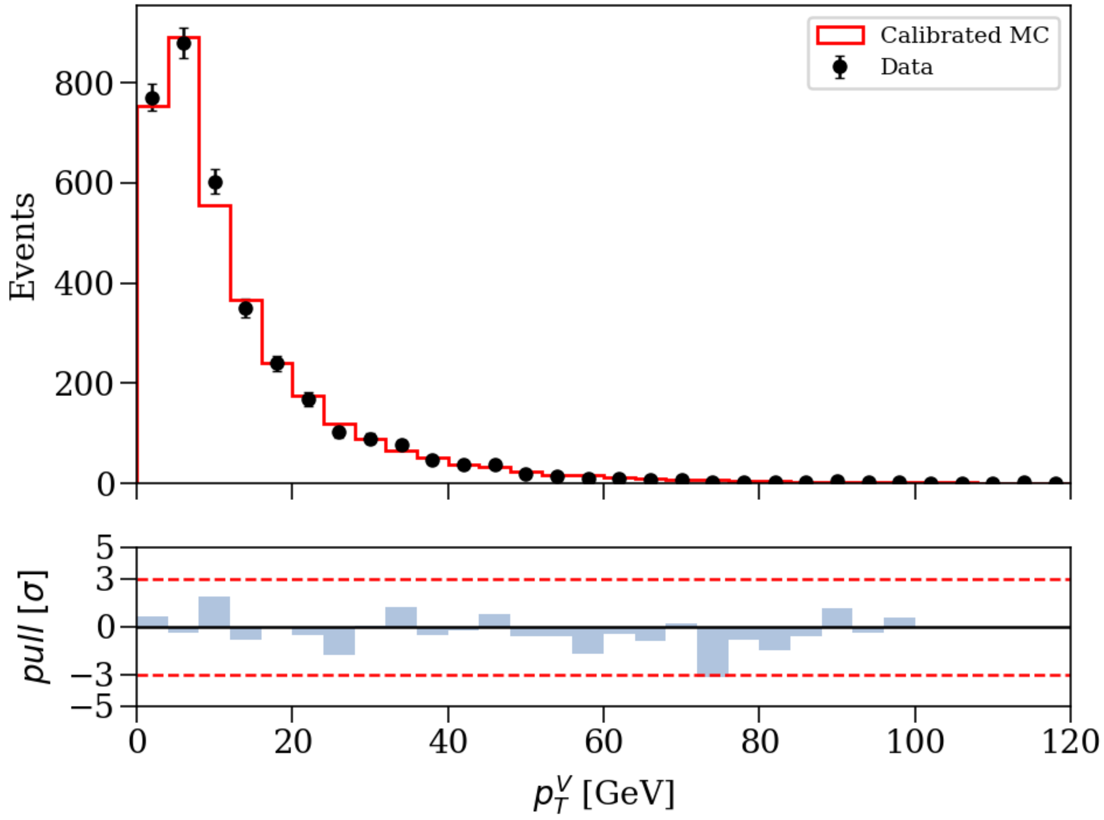
Validation of corrected simulation

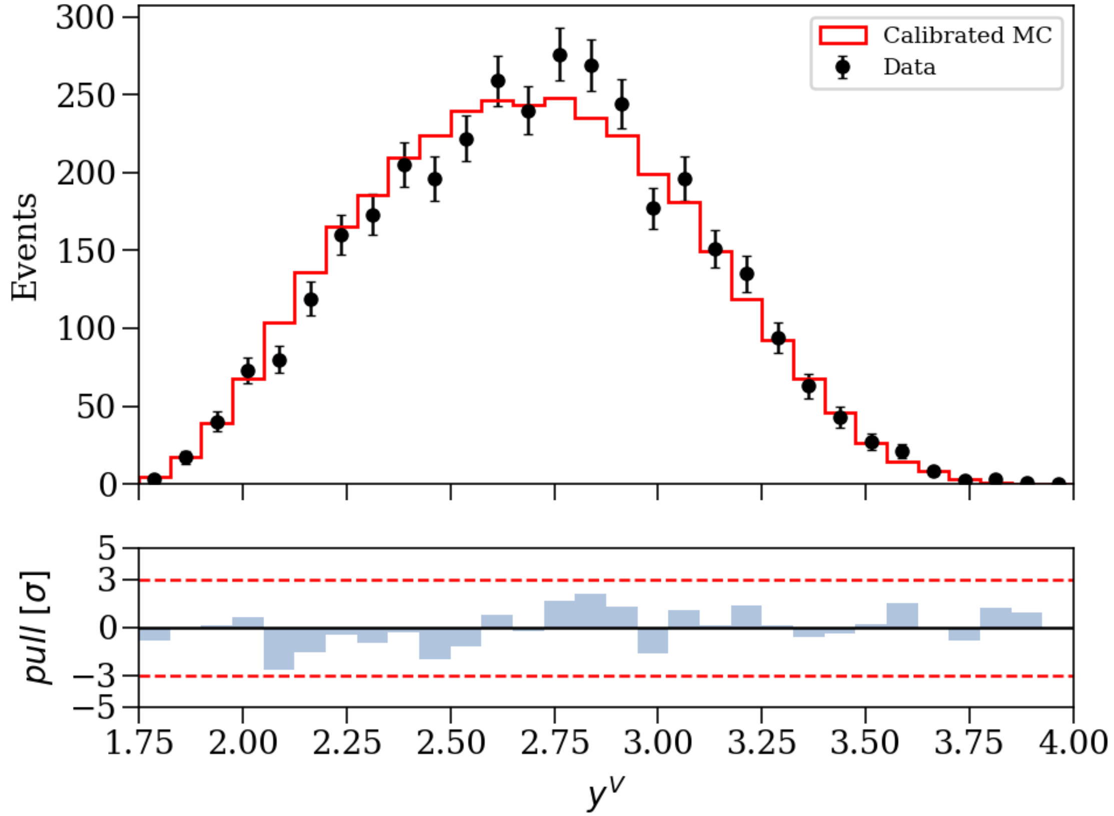


Validation of corrected simulation



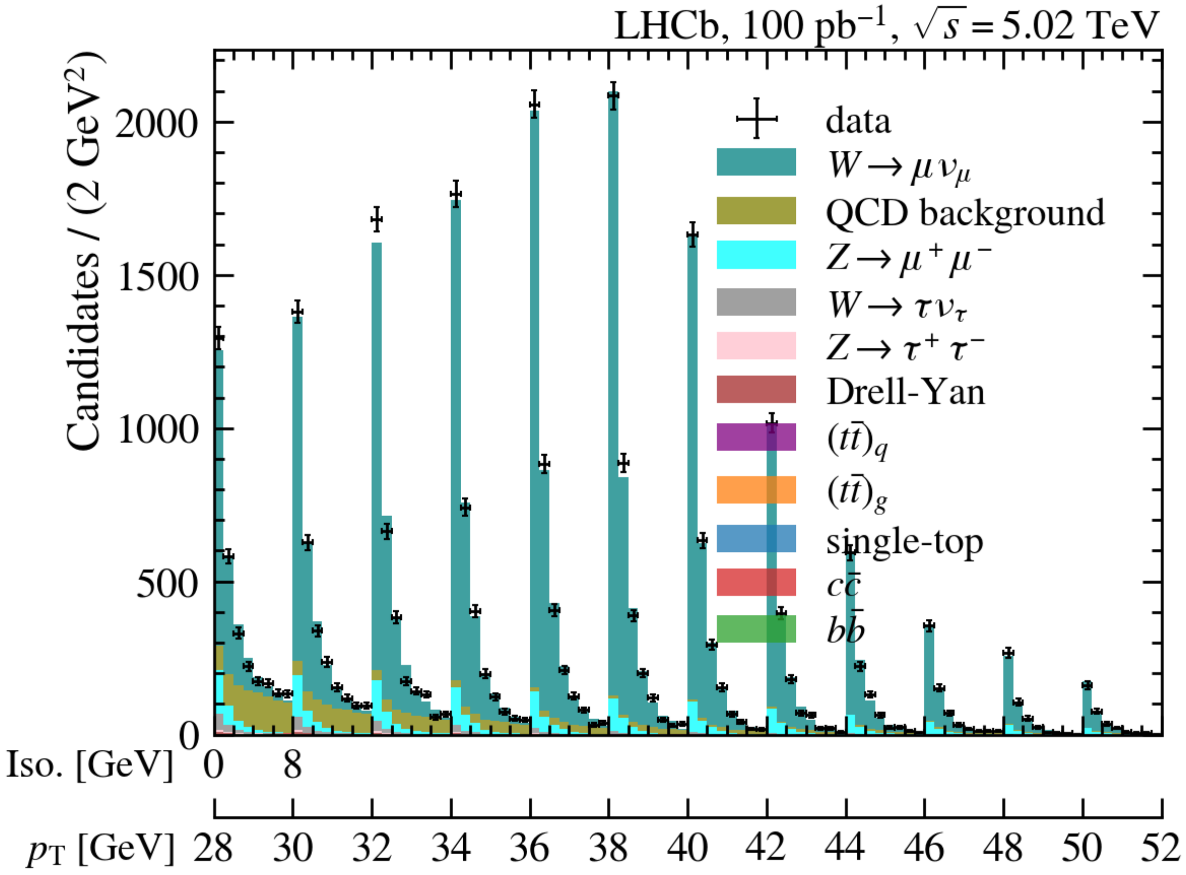
Validation of corrected simulation



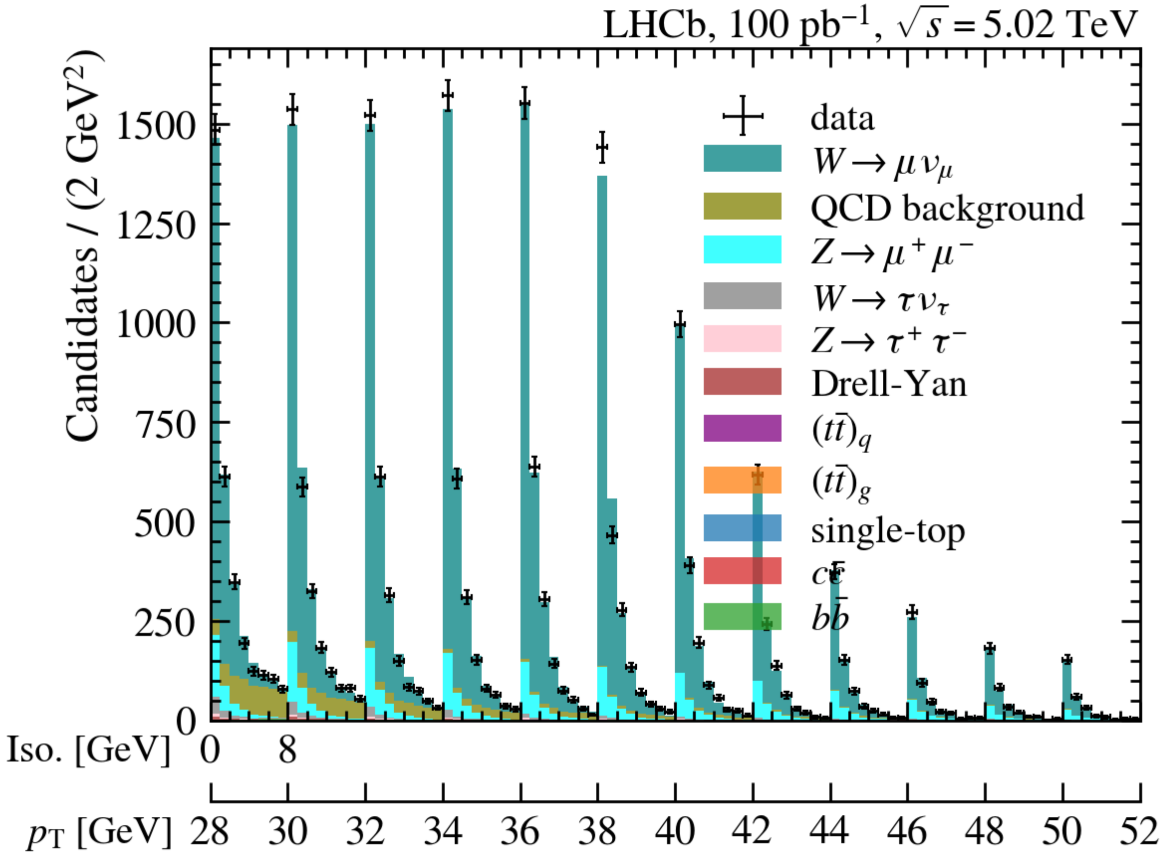


Results – reco yields/counts (stacked)

W^+

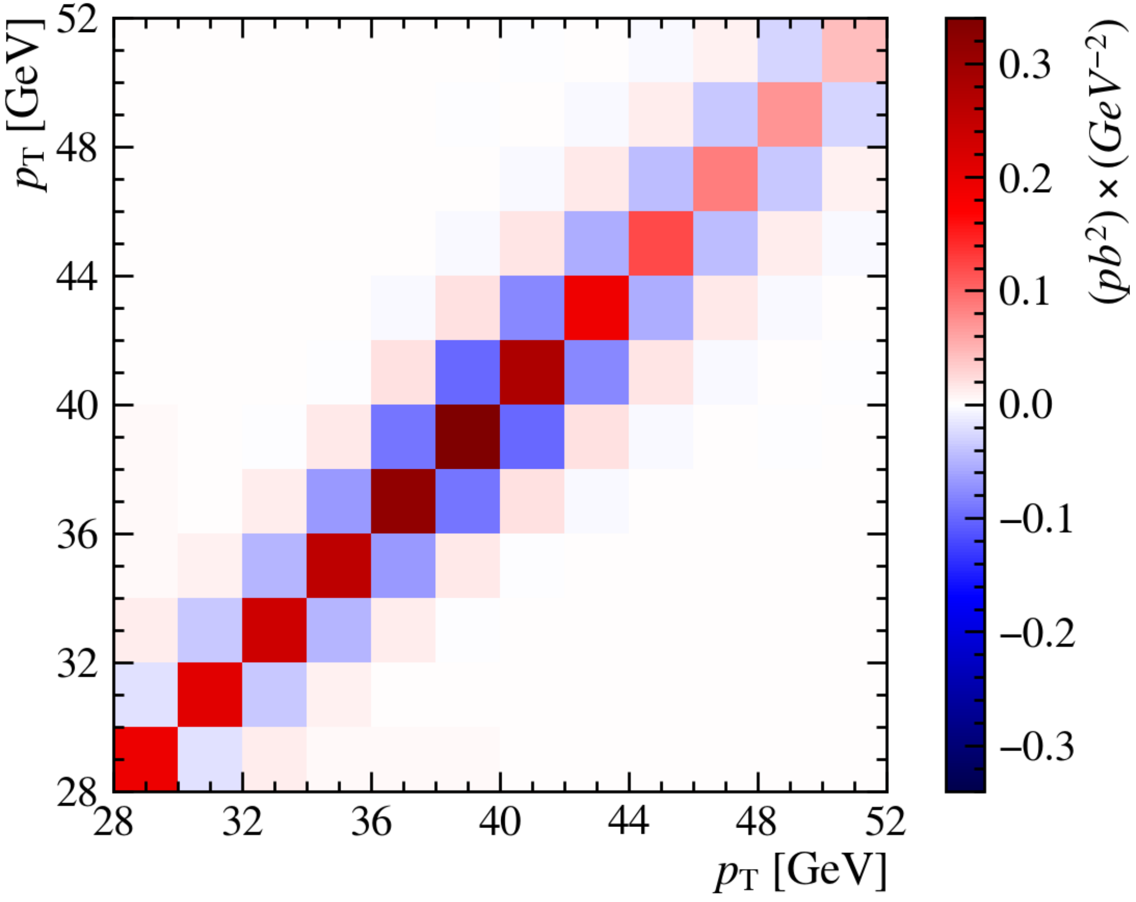


W^-

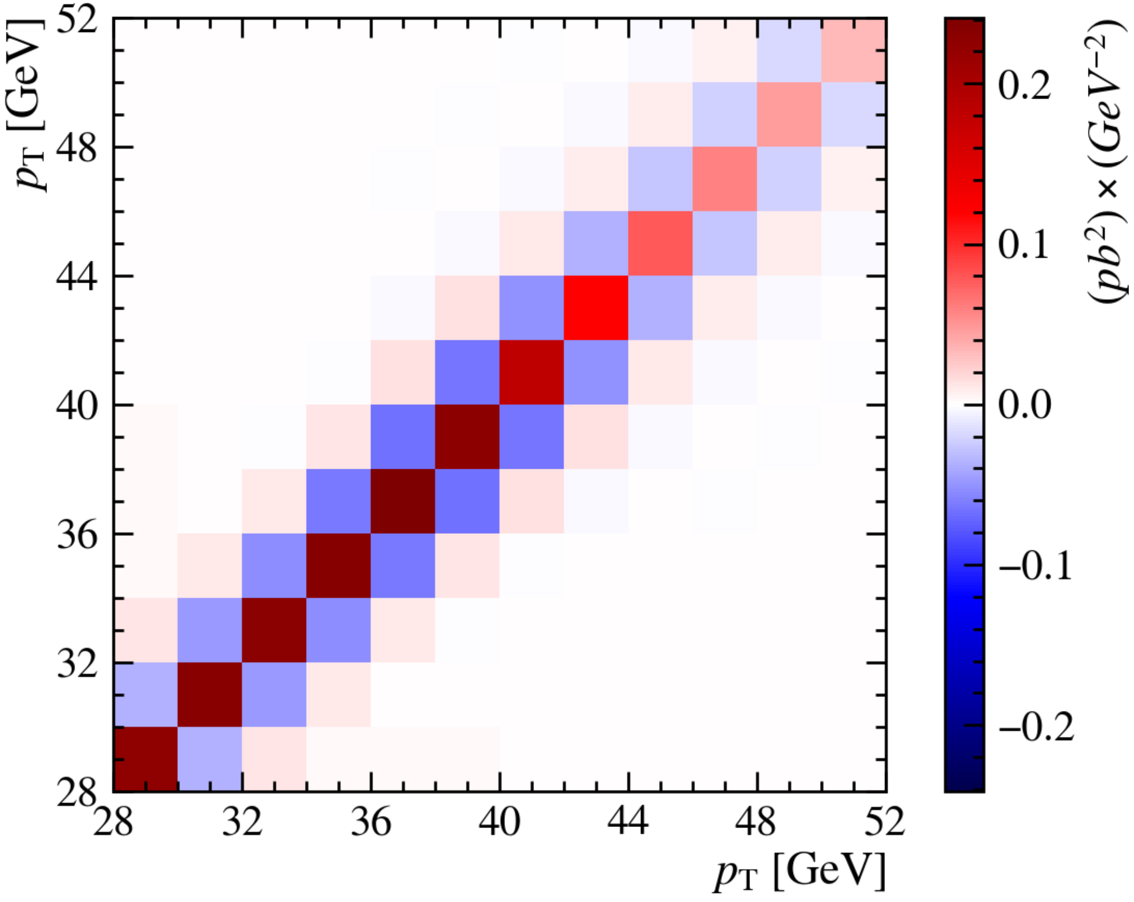


Results – statistical covariance matrix

W^+



W^-



Systematics

- **Hadronic Background**: Includes variations in the QCD background misidentification rate model (20 randomized models) and adjustments to the hadron species abundance, where each hadron fraction is varied by factors of 0.8, 1.0, or 1.2. It also includes an uncertainty on the hadronic background p_{T} modelling, which is described in as

$$\text{Hadronic background model} = f \cdot N \cdot T \cdot \left(1 + w\frac{p_T - p_{T,\text{mid}}}{N_{\text{bins}}}\right), \qquad (16)$$

where f is the background fraction, N normalizes the template to data, T is the hadronic background template, w controls the p_{T} shape modification, p_{T} is the bin centers of the muon transverse momentum, and $p_{T,\text{mid}}$ is the median p_{T} value (40 GeV). Setting $w = 0$ retains the default method for the hadronic background model which uses only one fit parameter (fraction) for fitting the hadronic background.

Systematics

- **Muon Efficiencies**: Includes variations in the seed values for trigger efficiency and muon identification (tested with values from 1 to 10). It also includes changes to specific efficiency models: using a flat model instead of a linear model for trigger efficiency, using a flat model instead of a linear model for muon identification, and a flat model instead of a linear model for track efficiency.

- **Charge-independent momentum biases**: Includes variations in the seed values for momentum smearing, tested with values from 1 to 9.

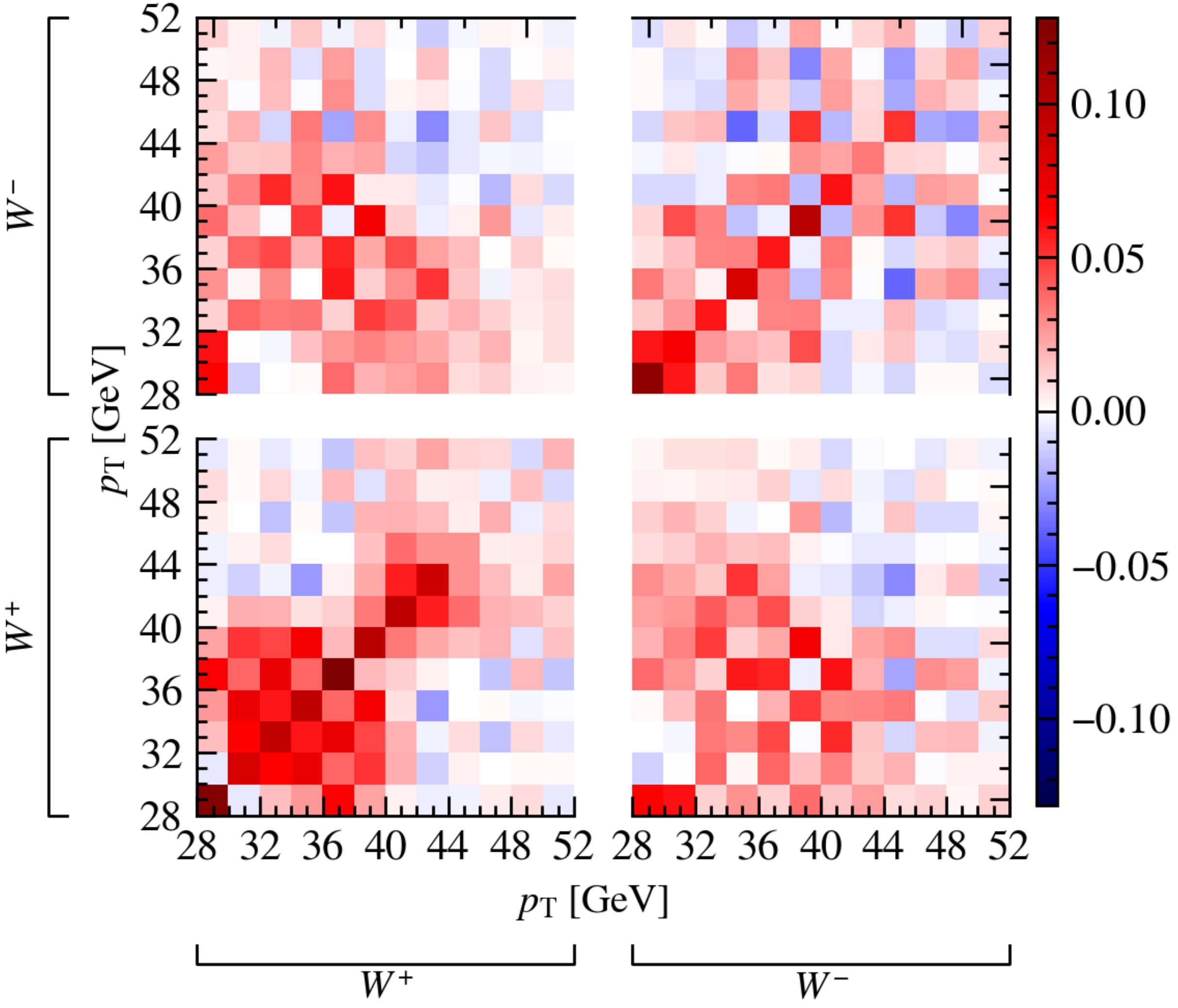
- **Charge-dependent momentum biases**: 16 dsigma/dpT measurements are made in which the psuedomass corrections are randomly varied within the bin-by-bin uncertainties assuming Gaussian statistics. A different starting seed is used for each of these 16 measurements.

- **Isolation**: Includes variations in the number of bins for muon isolation, tested with ± 2 bins compared to the default value of 8 bins. It also includes variations in the signal isolation calibration offset, tested with shifts of $+10\%$ (up) and -10% (down), as well as the QCD background isolation calibration offset, similarly tested with $+10\%$ (up) and -10% (down) shifts.

Systematics

- **Unfolding:** In the background-subtraction fit, the true-level differential cross-section values corresponding to the underflow and overflow bins[6] are fixed to the predictions from simulation. This is done to avoid fit instabilities arising in `MIGRAD` due to the handling of parameters that are multiplied by very small values, corresponding to the low efficiency of events that migrate into the fiducial region. In order to evaluate the impact of this assumption, we recompute the differential cross-sections varying the predictions from simulation up and/or down for the underflow and overflow bins. Additionally, we double the number of reconstructed p_T bins (12 to 24) while keeping the number of truth bins fixed (12 + 2 overflows), to test the stability of the unfolding without redefining the measurement. This probes sensitivity to binning without introducing regularisation, which our method avoids by requiring small bin migrations. As each truth bin now spans multiple reconstructed bins, the method becomes slightly more sensitive to the assumed detector response shape, mildly reducing model independence.

Results – total systematic covariance matrix



W mass fit - Systematics impact

Table 4: Impact of each source of experimental systematic uncertainty on the m_W uncertainty. The impact is defined as the square root of the difference in quadrature between the statistical uncertainty and the uncertainty including a single systematic source. The changes in the fit χ^2 and best-fit m_W values are also shown. The shift in the W-boson mass, denoted Δm_W, is defined as the value after the change minus the value before. Impacts or changes in the χ^2 of less than one unit are indicated with a dash.

Source	Impact [MeV]	$\Delta\chi^2$	Δm_W [MeV]
Charge-independent momentum biases	58	–	−8
Charge-dependent momentum biases	41	−19	−150
Hadronic background	7	−2	+13
Muon efficiency	15	−1	+8
Isolation	15	–	−3
Unfolding	–	−1	+7
Quadrature sum	75		

W mass fit results – no systematics

$$m_W = 80522 \pm 103(stat) \text{ [unblinded]}$$

Cross-checks

Table 17: Fit results with alternative PDF sets.

Name	Value	Stat. unc.	χ^2	Variation
NNPDF 3.1 nnlo	80366	130	26	0
MSHT20nnlo	80380	129	27	15
CT18NNLO	80362	130	24	-4
NNPDF 4.0 nnlo	80361	130	26	-5

Cross-checks

7.2 Changing the scheme

The functional form of QCD scales are parameters in the DYTurbo calculation that can be varied to study its impact on the results. We vary the Functional form of the renormalisation scale and the factorisation scale (fmuren and fmufac respectively). The default scheme is 2, and we have used the other scheme 1 as a cross-check. As a reference, these are the available schemes:

- #0: $\mu^2 = mV^2$
- #1: $\mu^2 = m_{ll}^2$
- #2: $\mu^2 = m_{ll}^2 + p_T^2$
- #3: $\mu^2 = m_{ll}^2 + p_T^2 + m_{jj}^2$
- #4: $\mu^2 = (p_T + \sqrt{m_{ll}^2 + p_T^2})^2$

We do not vary the resummation scale, as using the schemes 2, 3 are all equivalent to the default scheme 1.

Table 18: Fit results with alternative QCD scheme choices.

Name	Value	Stat. unc.	χ^2	Variation
2	80366	130	26	0
1	80364	130	26	-2

Cross-checks

11.4 Changing the blim value

Since we are dealing with the inverse Bessel transform, we need to provide a cutoff value for the inverse Bessel transform to avoid the Landau pole. This value is called the blim value, and it can be varied to study its impact on the results. The default value is 3.0 GeV. We have used 1.0 and 2.0 GeV as cross-checks.

Table 19: Fit results with alternative choices of the b_{lim}value.

Name	Value	Stat. unc.	χ^2	Variation
3.0	80366	130	26	0
1.0	80368	130	26	2
2.0	80363	130	26	-3

Cross-checks

7.4 Changing the order of the unpolarised component

By default, the unpolarised component is calculated at order NNLO. We have used the N3LO order as a cross-check. This is only done at the level of the unpolarised component. As for the angular component, we only stick to using the NLO order, as the NNLO order is prohibitively expensive.

Table 20: Baseline fit result compared to the result with N3LO accuracy for the unpolarised component.

Name	Value	Stat. unc.	χ^2	Variation
NNLO	80366	130	26	0
N3LO	80358	131	28	-8

Cross-checks

Table 21: Fit results with alternative fit functions used in the $d\sigma/dp_{\mathrm{T}}$ measurement.

Name	Value	Stat. unc.	χ^2	Variation
BBLite	80366	130	26	0
χ^2	80388	130	26	22

Cross-checks

7.7 Changing the Physics weights

Another cross-check we performed is related to the physics weights. We have three variables that we vary individually:

- The unpolarised component weight.
- The angular component weight.
- The W boson mass.

Table 22: Fit results with additional physics weights included in the $d\sigma/dp_{\mathrm{T}}$ measurement.

Name	Value	Stat. unc.	χ^2	Variation
Unpolarised Weights=False, Angular Weights=False, $m_W = 80.385$ GeV,	80366	130	26	0
Unpolarised Weights=True, Angular Weights=False, $m_W = 80.385$ GeV,	80360	130	25	-6
Unpolarised Weights=False, Angular Weights=True, $m_W = 80.385$ GeV,	80383	130	25	17
Unpolarised Weights=False, Angular Weights=False, $m_W = 80.485$ GeV	80363	130	25	-3

Cross-checks

Table 23: Impact of modifications to the W/Z fit strategy.

Name	Value	Stat. unc.	χ^2	Variation
sequential, Fixed α_s, Floating g,	80366	130	26	0
sequential, Fixed α_s, Fixed g,	80308	125	28	-58
sequential, Floating α_s, Floating g,	80366	130	25	0
sequential, Floating α_s, Fixed g,	80319	125	27	-47
spectating, Fixed α_s, Floating g,	80366	130	25	-0
spectating, Fixed α_s, Fixed g,	80382	123	26	16
spectating, Floating α_s, Floating g,	80365	130	25	-1
spectating, Floating α_s, Fixed g	80379	125	26	13