Measurement of the W boson mass with the LHCb detector

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on behalf of the LHCb Collaboration

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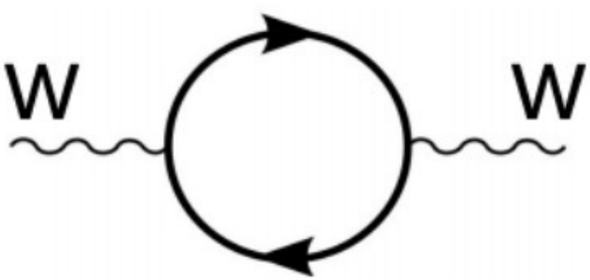
Scientific Context

- Three degrees of freedom in electroweak theory.
- m_W indirectly predictable given well-known m_Z, α, G_F:

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



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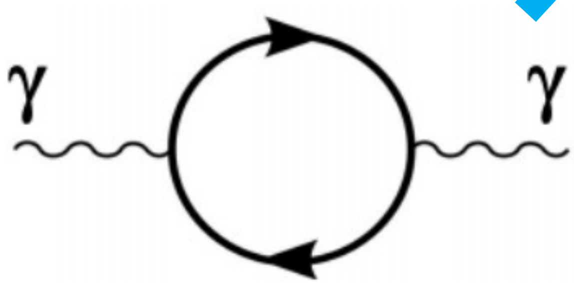


, ... NP? ...

Status of the field

- Combination of global fits to EW sector (indirect) and direct m_W measurements place constraints on new physics.

- $m_W^{EWfit} = 80354 \pm 7$ MeV,
  $m_W^{ATLAS} = 80370 \pm 19$ MeV
  (EPJC 78, 110 (2018)),

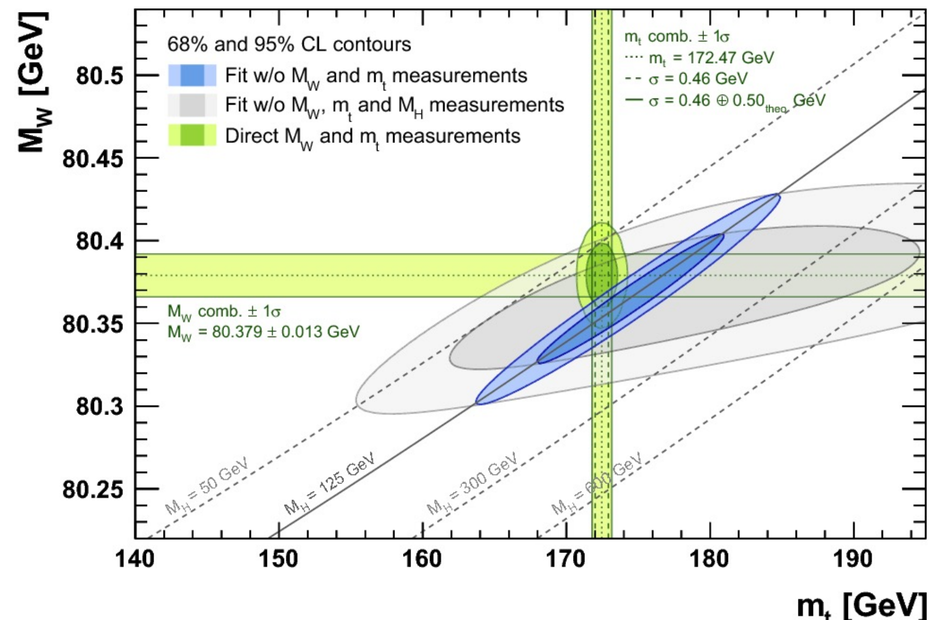
- LHCb full Run-2 data: O(10) MeV statistical uncertainty on m_W,

- Historically-limiting PDF uncertainties expected to anti-correlate in a GPD-LHCb combination…

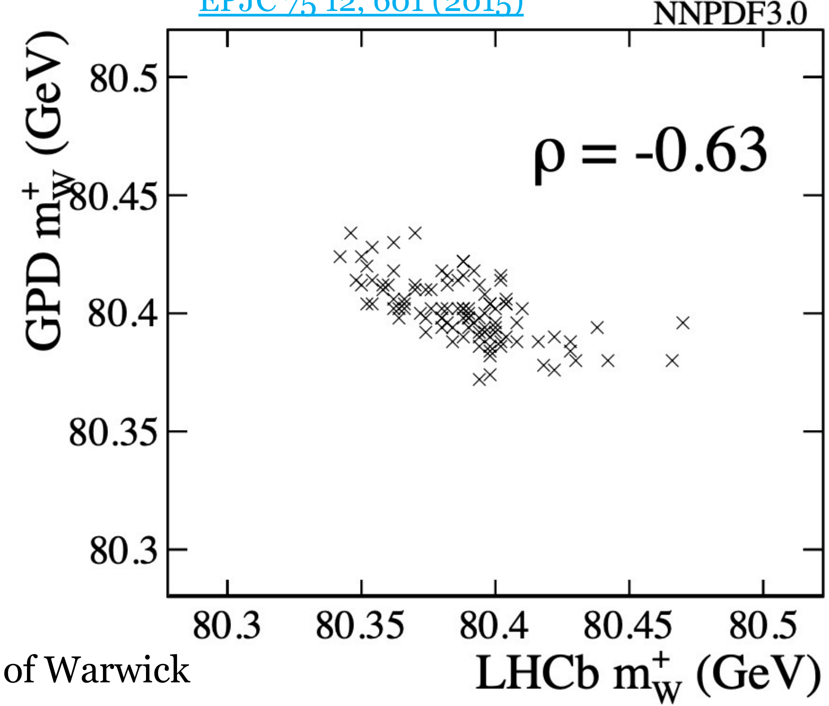
- **…but** limited by theory systematics.

⇒ Today: a proof-of-principle measurement with the 2016 data (1/3 of Run 2).

EPJC 78, 675 (2018)

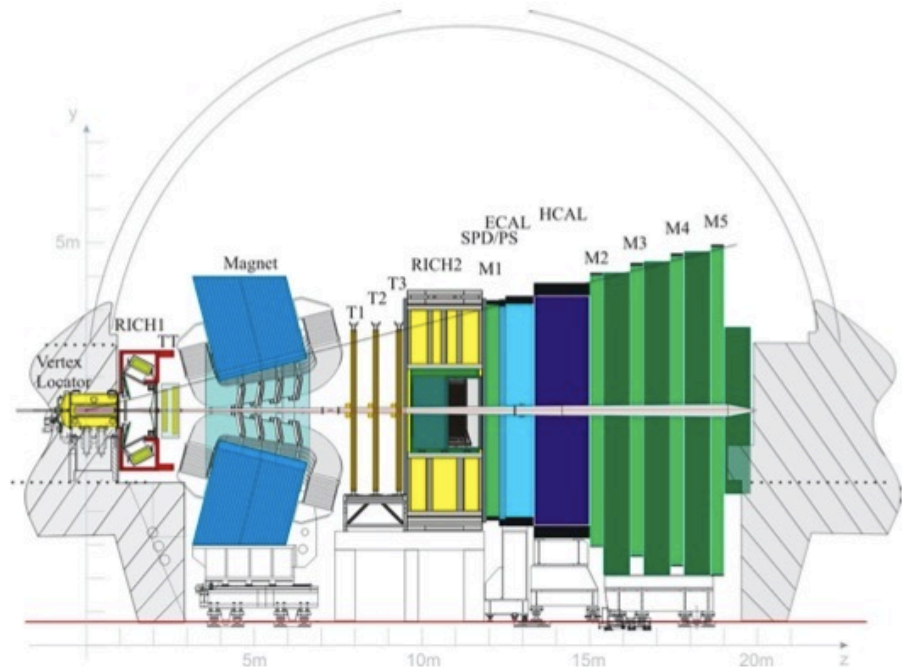


EPJC 75 12, 601 (2015)



LHCb

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



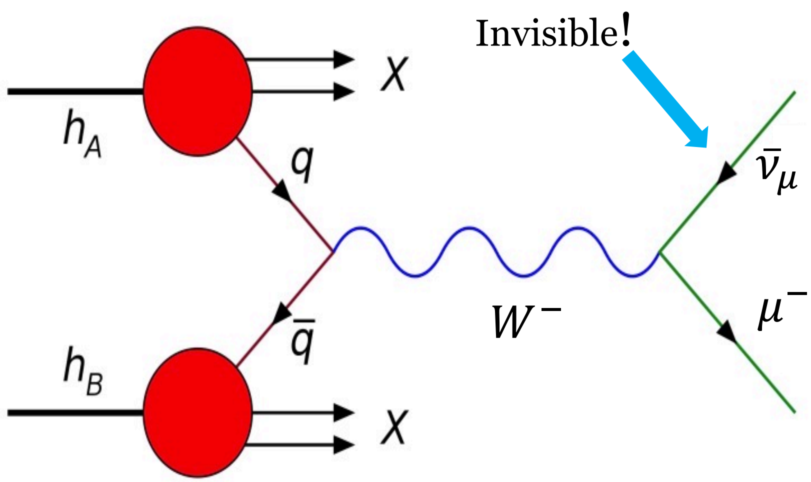
- Single arm spectrometer, fully instrumented in the forward region.
- Mostly designed for flavour physics, but with a strong programme of probing vector boson production*.

*Full list of LHCb EW papers here

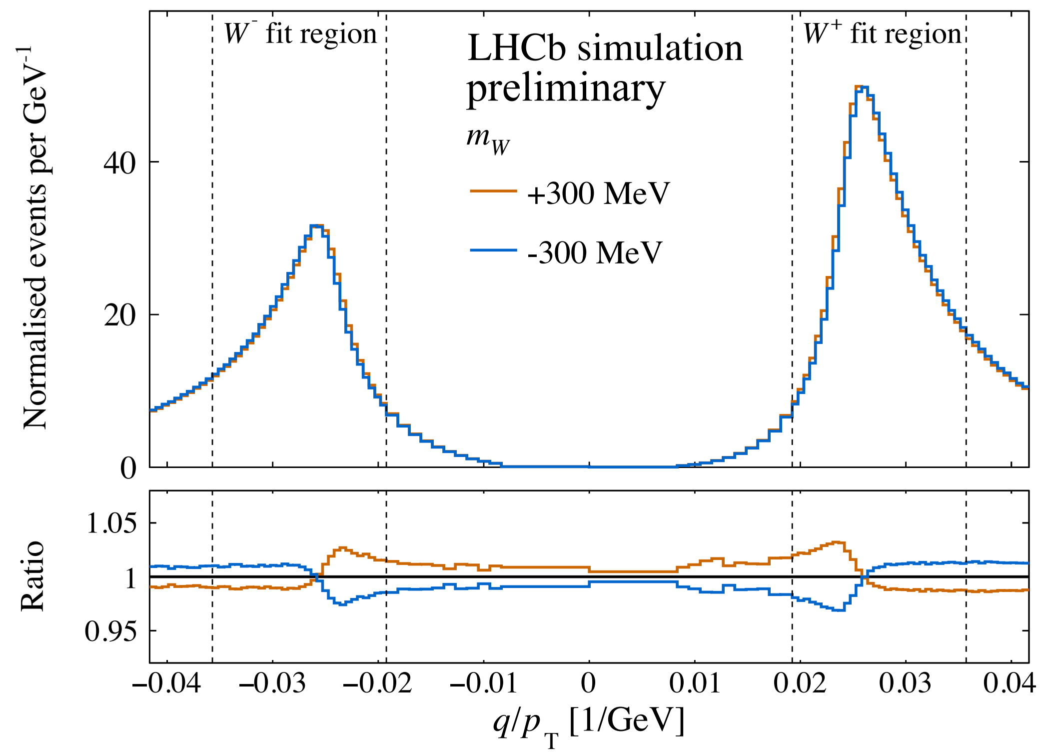
How we measure m_W

- $W \rightarrow \mu\nu$ gives a single, high-p_T, isolated muon. m_W sensitivity from p_T^{μ}, which peaks at $\sim m_W/2$.

$\Rightarrow$Extract m_W in a template fit to the muon q/p_T distribution.



LHCb-PAPER-2021-024 in prep.



Angular coefficients

Before final-state radiation: $$\frac{d\sigma}{dp_T^W\,dy\,dM\,d\cos\theta\,d\phi} = \underbrace{\frac{3}{16\pi}\frac{d\sigma^{\text{unpol}}}{dp_T^V\,dy\,dM}}_{\text{Unpolarised cross-section}}$$

Angular terms (A_i = angular coefficients)

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

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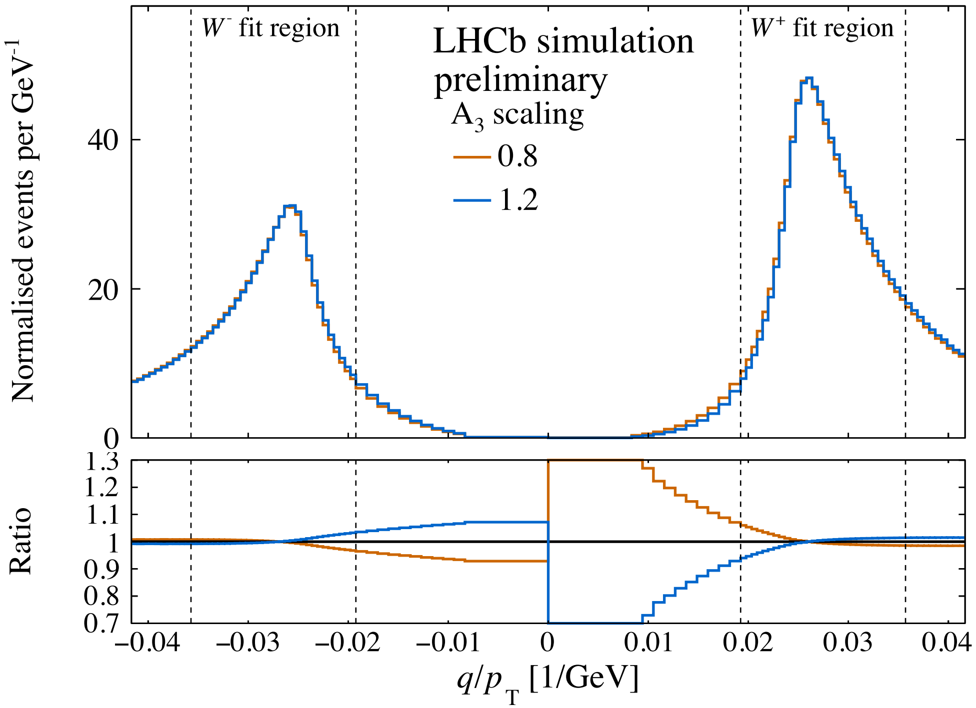
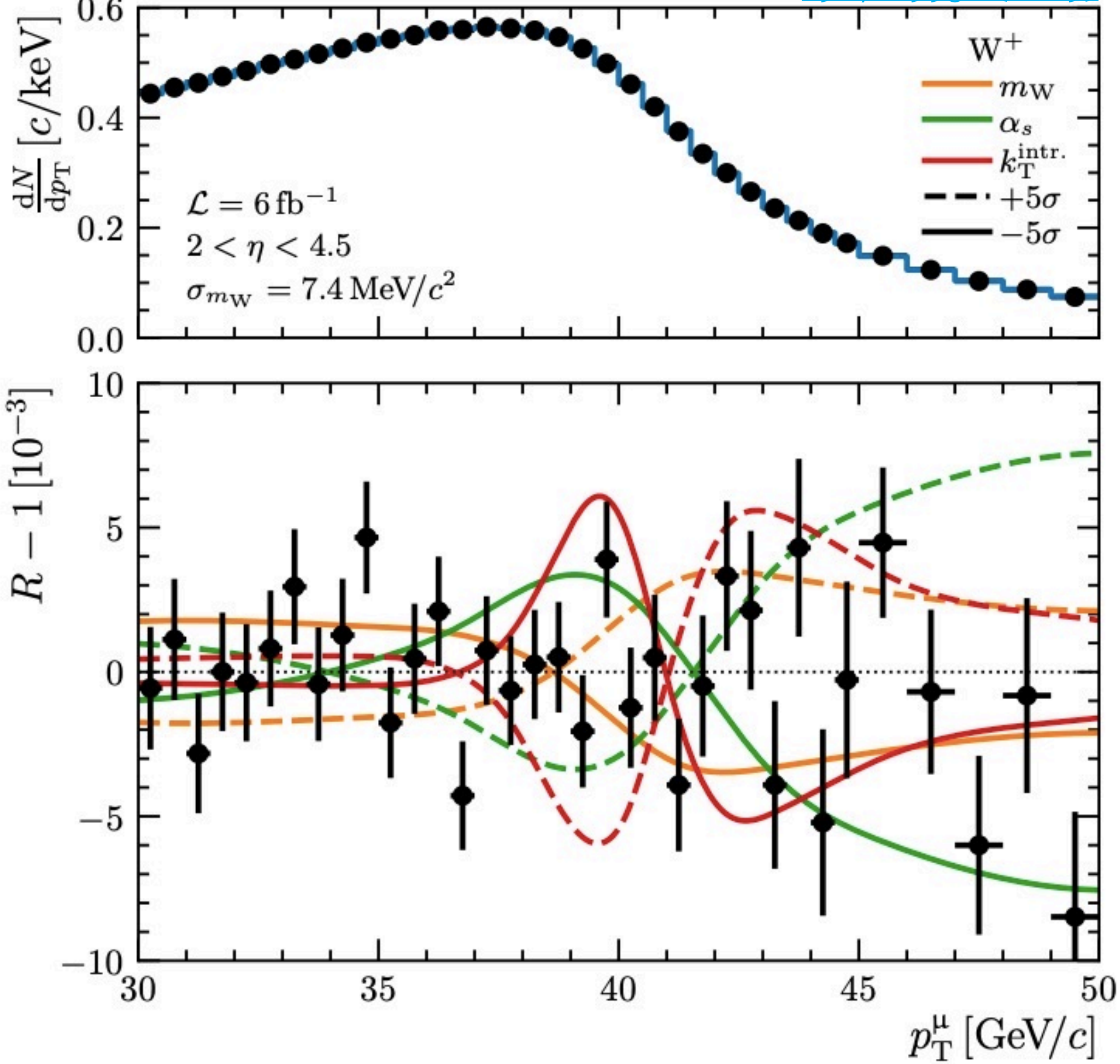


- A_i predictions from DYTurbo at $O(\alpha_S^2)$.
- Problem: too sensitive to uncertainty on prediction of A_3.
- Solution: float a single A_3 scale factor in the fit to absorb this uncertainty.

In-situ MC generator tuning

[1907.09958 (2019)](https://arxiv.org/abs/1907.09958)



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

- POWHEG-Box + Pythia8 is our central model.
- Previous m_W measurements rely on tuning to p_T^Z. Does this tune hold for p_T^W?
- 1907.09958 (2019): variations in α_S and k_T^{intr} affect p_T^μ differently to variations in m_W.

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

[Pseudo]data challenges

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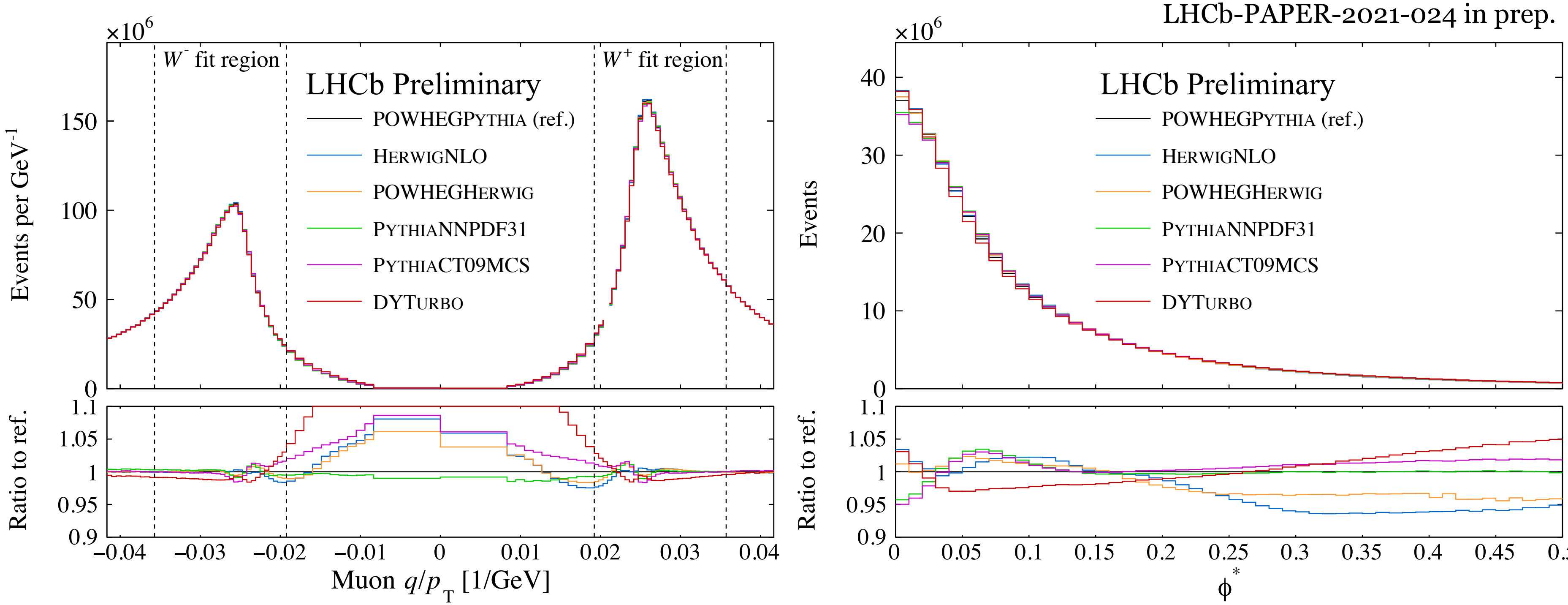


- Using our central model to fit pseudodata generated from different models (e.g. HerwigNLO) gives a similar spread as using those different models to fit the real data.

Data config.	χ^2_W	χ^2_Z	δm_W [MeV]
POWHEGPYTHIA	64.8	34.2	–
HERWIGNLO	71.9	600.4	1.6
POWHEGHERWIG	64.0	118.6	2.7
PYTHIA 8, CT09MCS	71.0	215.8	-2.4
PYTHIA 8, NNPDF31	66.9	156.2	-10.4
DYTURBO	81.5	334.3	-0.8

Detector alignment & calibration

To measure m_W accurately we need to eliminate biases in p_T^μ due to detector misalignment effects.

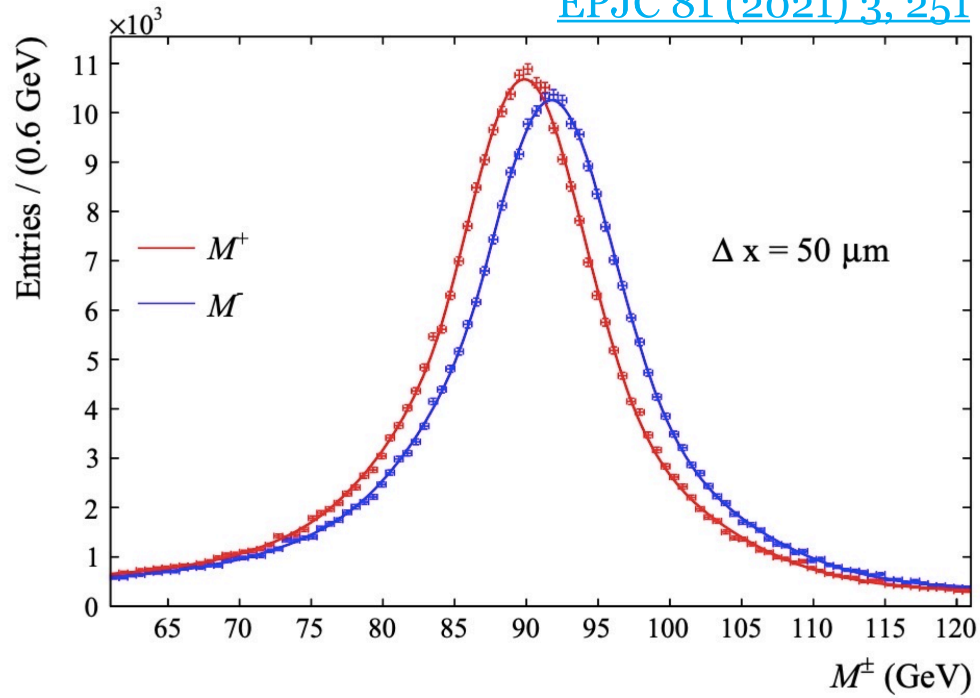
$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)},$$

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 corrections across the detector.

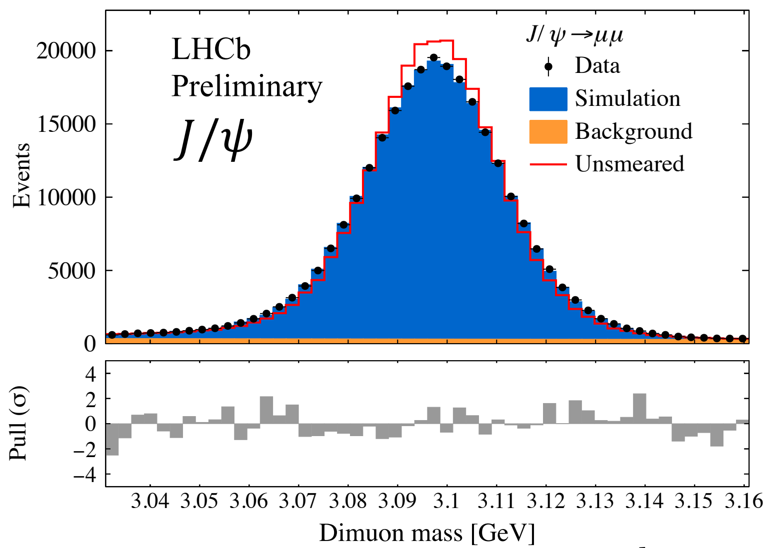
EPJC 81 (2021) 3, 251

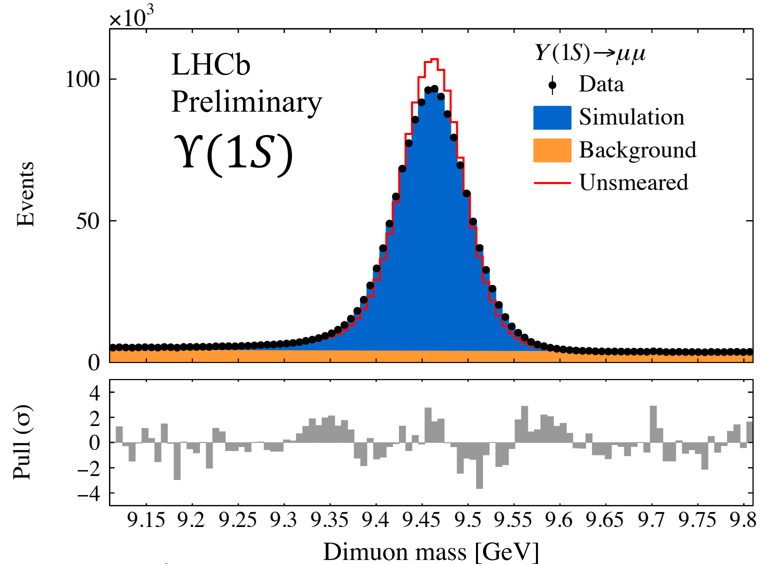


Inspired by PRD 91, 072002 (2015)

Detector alignment & calibration

3. Additional smearing of the simulation:





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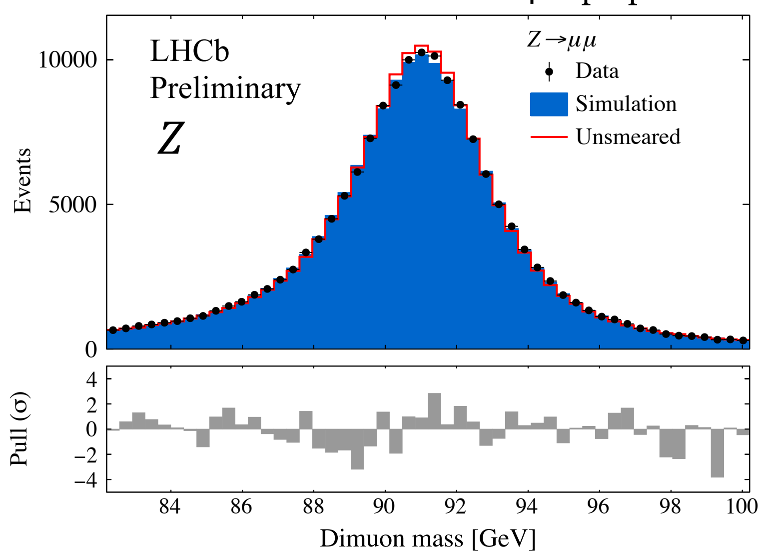

- Fit to the $J/\psi, \Upsilon(1S)$ and Z dimuon invariant mass peaks enable determination of 6 smearing parameters.

- 36 fit categories (species, magnet polarity, η)
- $\chi^2_{total} = 1862/2082$

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 backgrounds.

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

Treatment of backgrounds

- 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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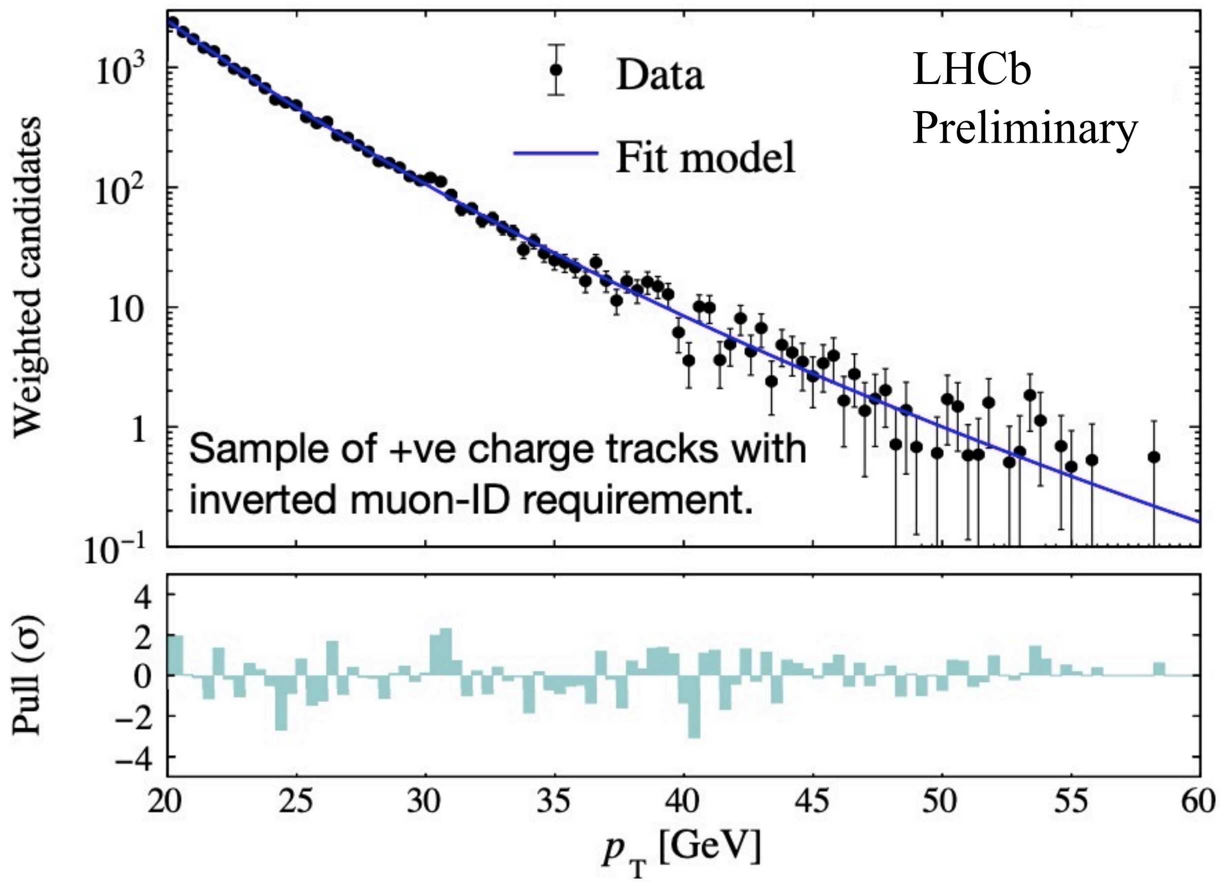
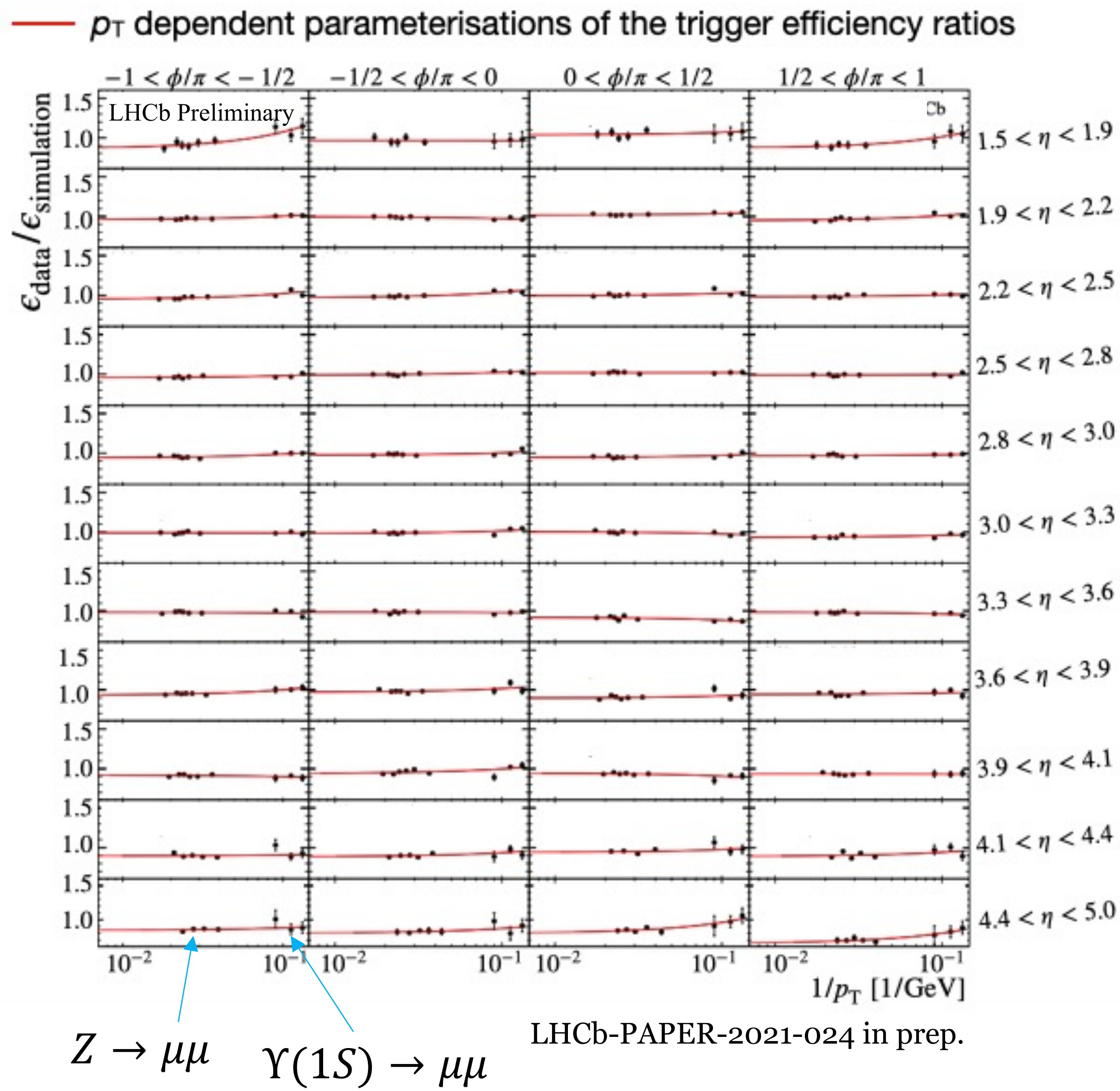


Muon reconstruction efficiencies

- **Simulated events corrected for data/simulation differences using event-by-event weights.**

- Efficiencies from tag-and-probe method with $Z \to \mu\mu$ and $\Upsilon(1S) \to \mu\mu$.

- Muon reconstruction weights from fit to efficiency ratio as function of p_T^{μ}, binned in η and ϕ.



LHCb-PAPER-2021-024 in prep.

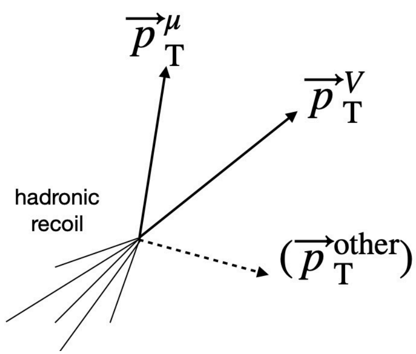
Isolation efficiency

- **Simulated events corrected for data/simulation differences using event-by-event weights.**

- Efficiencies from tag-and-probe method with $Z \rightarrow \mu\mu$.

- Isolation 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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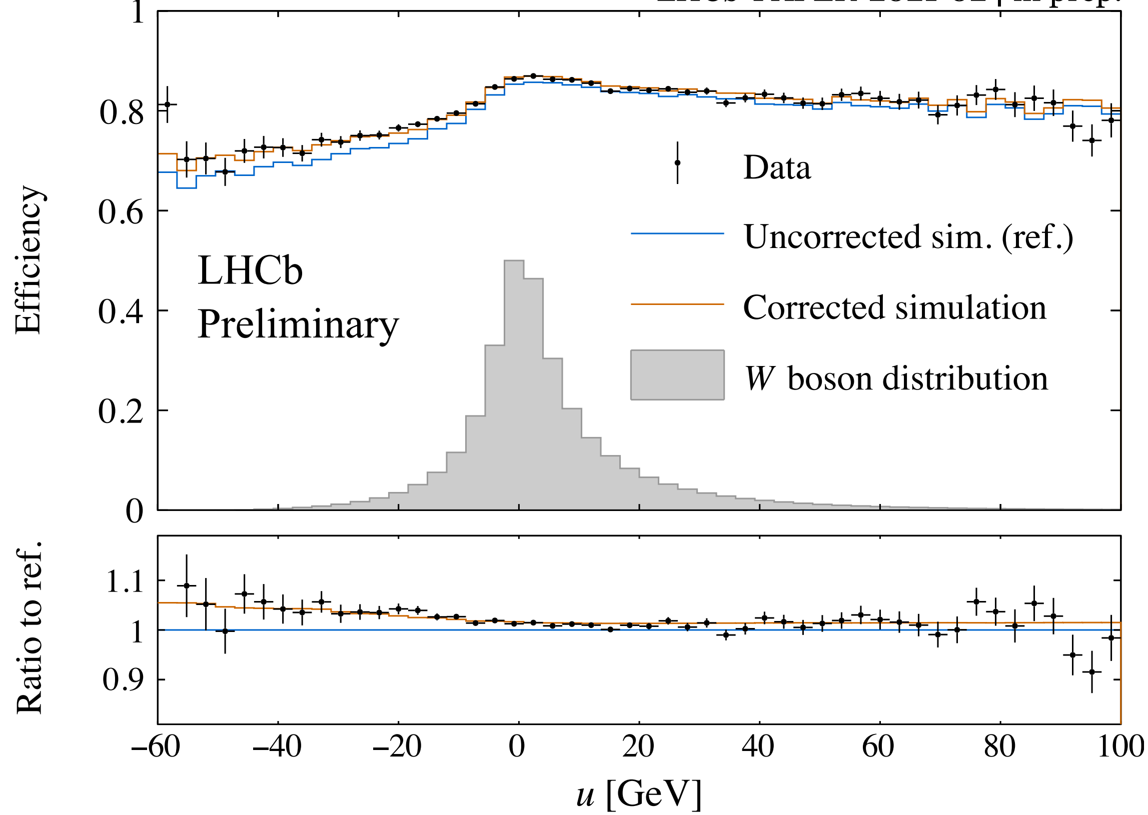

The fit result

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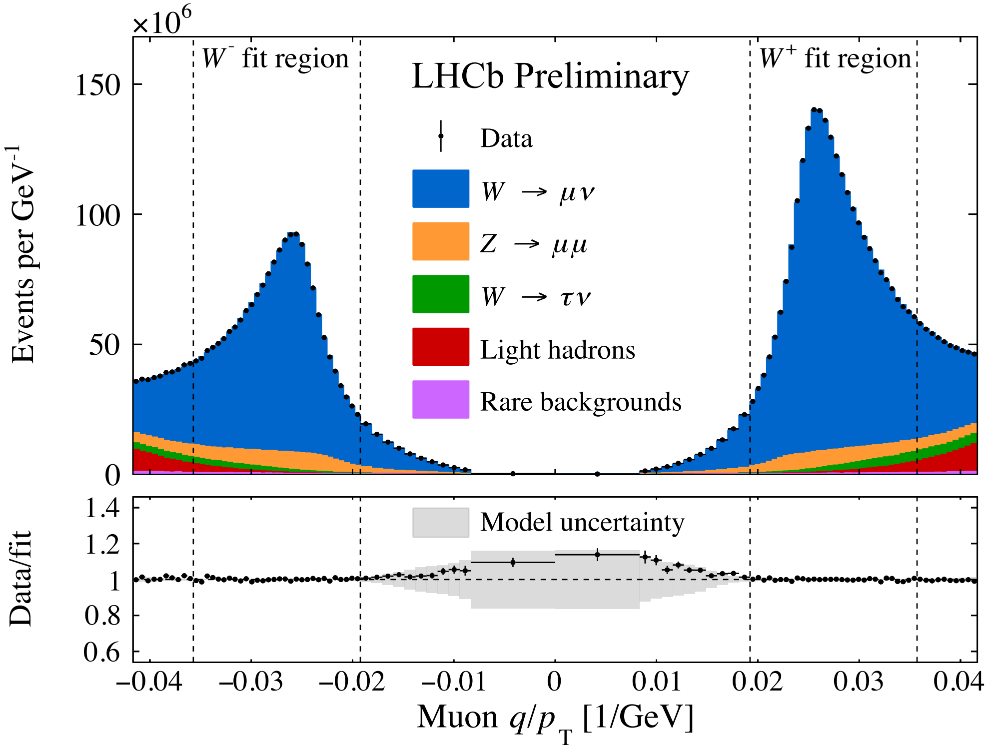
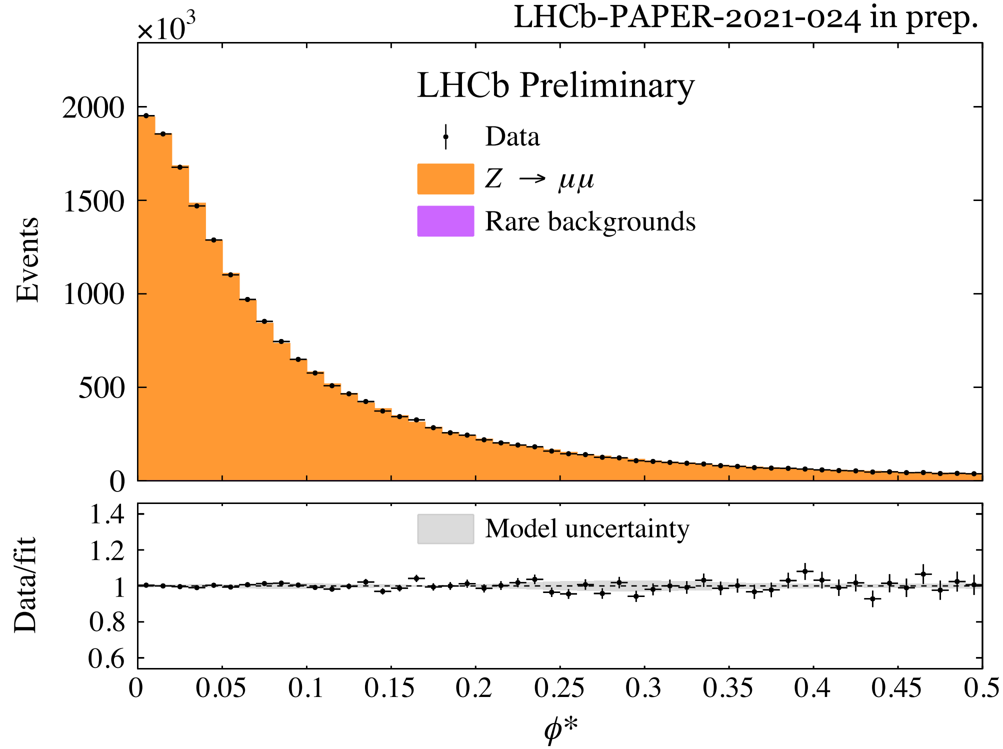




Floating parameter	Postfit value
Fraction of $W^+ \to \mu^+\nu$	0.5293 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3510 ± 0.0005
Fraction of hadron background	0.0151 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
k_T^{intr}	1.57 ± 0.14 GeV
A_3 scaling	0.979 ± 0.026

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

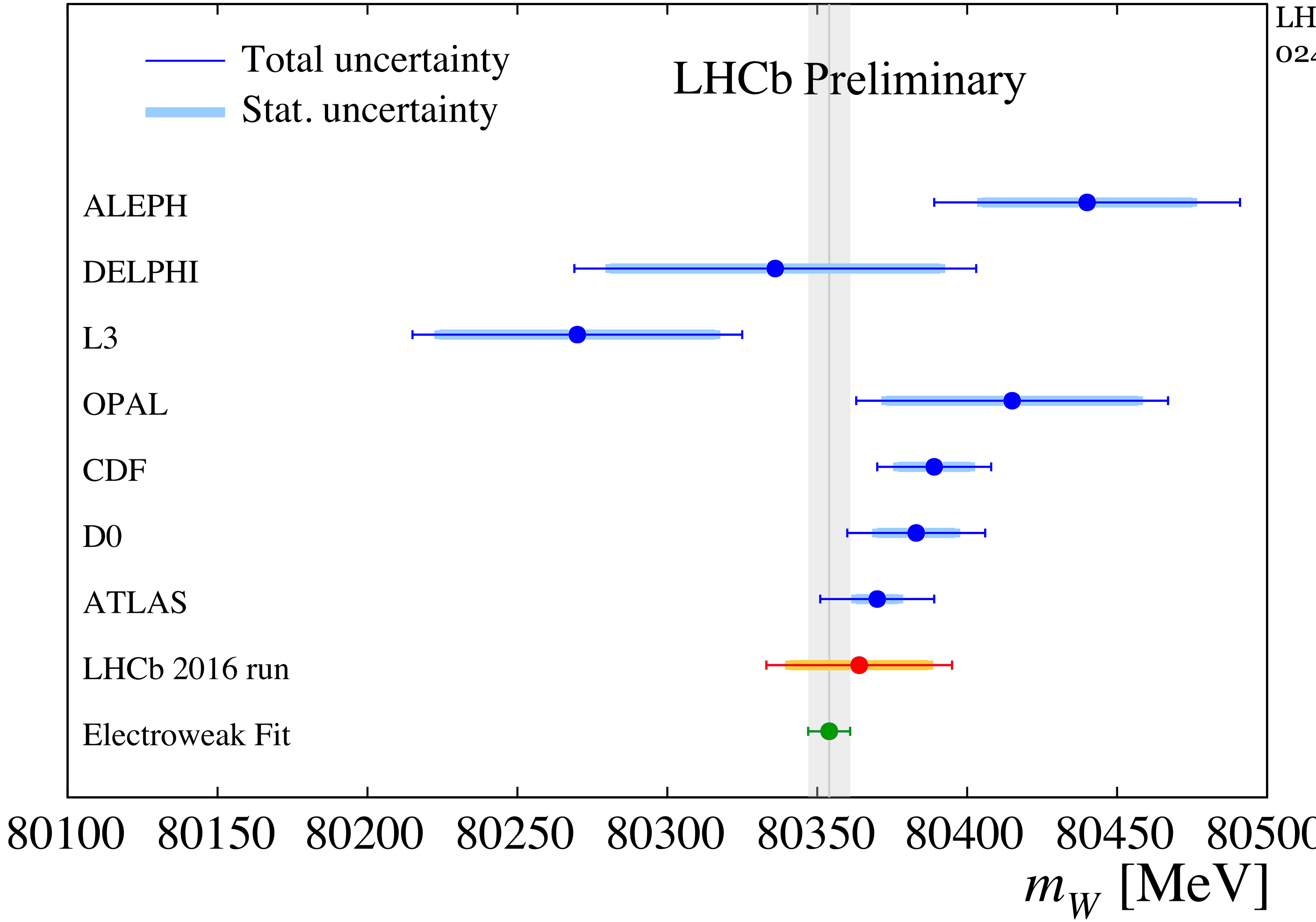
$\sigma_{stat} = 23$ MeV

Uncertainty breakdown

Source	Size [MeV]	
Parton distribution functions	**9.0**	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) Total	**17.4**	
Transverse momentum model	12.0	Envelope from five different models
Angular Coefficients	9.0	Uncorrelated scale variation
QED FSR model	7.2	Envelope of Pythia8, Photos and Herwig7
Additional electroweak corrections	5.0	Tested with POWHEGew
Experimental Total	**10.6**	
Momentum scale and resolution modelling	7.5	Includes statistical uncertainties, details of the methods (e.g. binning, smoothing) and dependence on external inputs.
Muon ID, trigger and tracking efficiency	6.0	
Isolation efficiency	3.9	
QCD background	2.3	
Statistical	**22.7**	
Total	**31.7**	

The result

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



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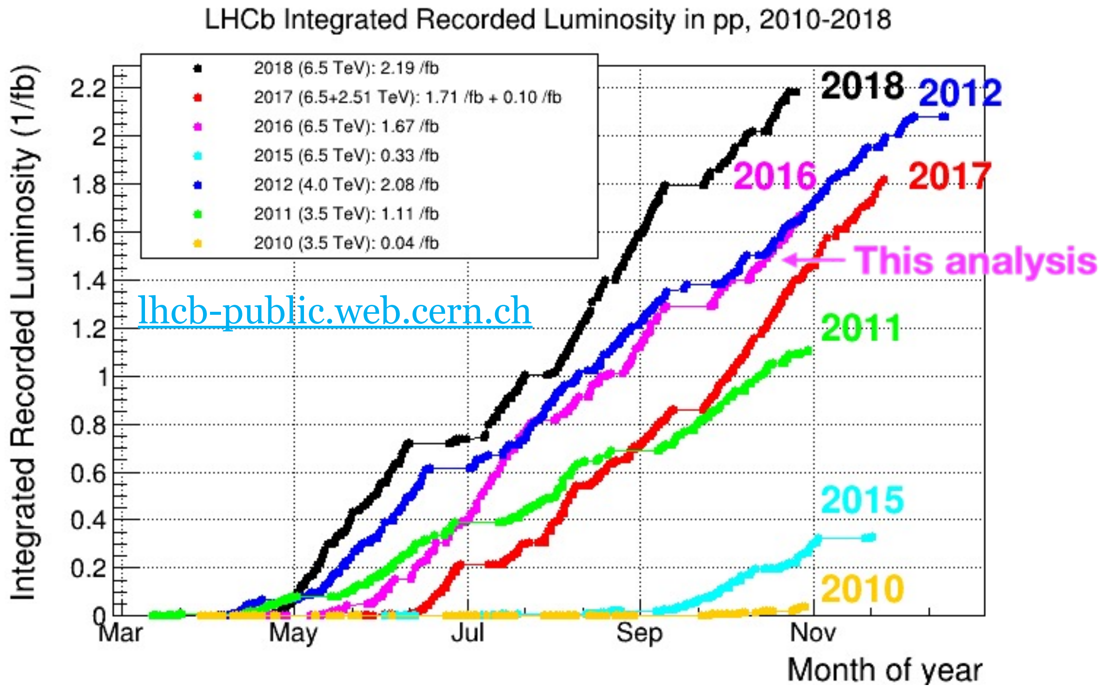
$$\boldsymbol{m_w = 80364 \pm 23_{stat} \pm 11_{exp} \pm 17_{theory} \pm 9_{PDF}\ \mathrm{MeV}}$$

Conclusions and outlook



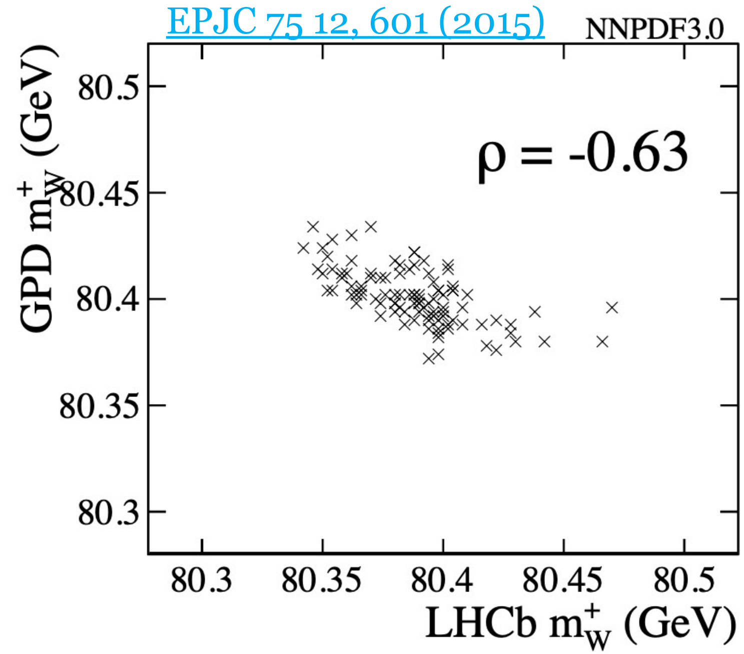
- First measurement of the W boson mass at LHCb achieves a precision of ~32 MeV, using roughly 1/3 of the Run 2 dataset.
- An overall precision < 20 MeV looks achievable with existing LHCb data.
- Measurement expected to provide significant impact on a LHC-wide average due to potential anti-correlation of PDF uncertainties.
- LHCb-PAPER-2021-024 *in preparation*

Thank you for your attention.
Any questions?

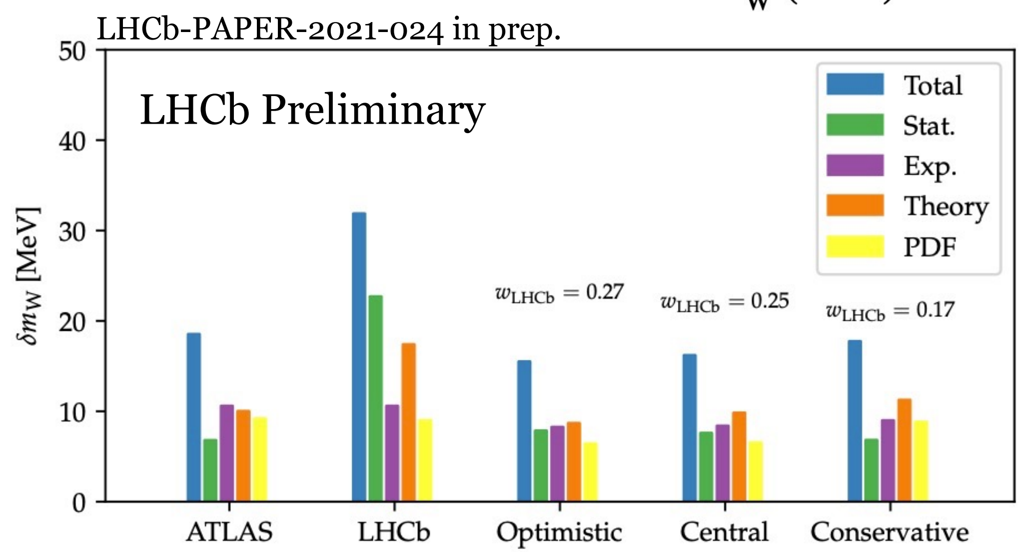
Backup

PDF uncertainty and prospects for combination

- Large PDF uncertainty expected to anti-correlate with PDF uncertainty on a ATLAS or CMS m_W measurement.



- Under some simple assumptions:



Cross-checks

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 $\lesssim$ 1 MeV level.

Limitations of previous m_W measurements

TABLE II: Systematic uncertainties of the M_W measurement.

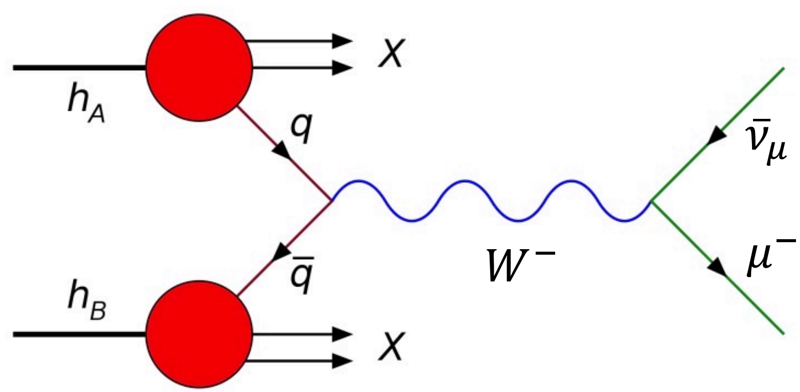
Source	ΔM_W (MeV) m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

D0: PRL 108 (2012) 151804

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

CDF: PRL 108 (2012) 151803

- Expected to be a bigger problem for pp collisions rather than $\bar{p}p$:

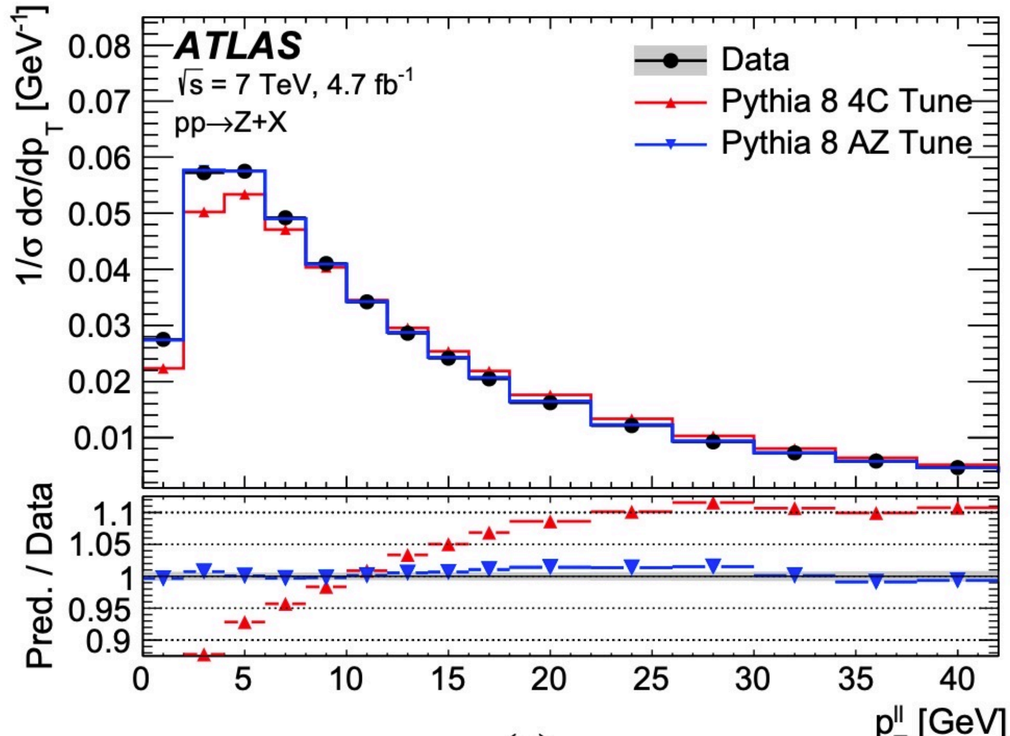


Fitting the Z ϕ^* distribution

EPJC 78, 110 (2018)

- We could fit p_T^Z:

- But v. sensitive to all detector modelling effects!



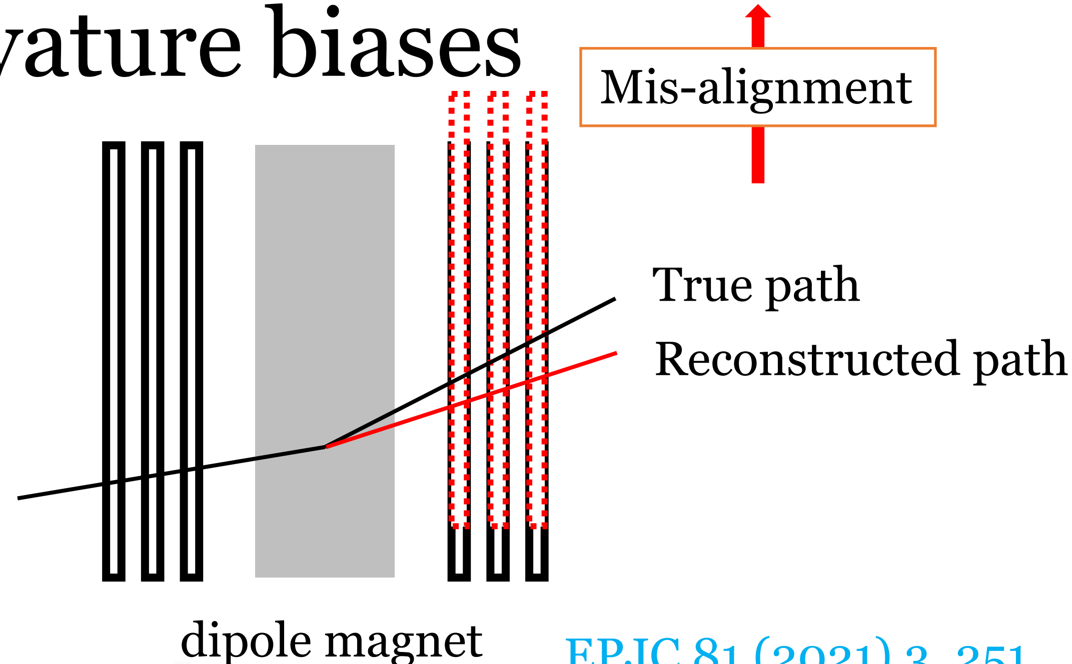
(a)

- Instead fit/bin the Z in ϕ^*:
  - (tuning parameters of fit coming later…)

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

EPJC 71, 1600 (2011)

Charge-dependent curvature biases



- Misalignments like this…

- …are caught by the "pseudomass":

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

- Differences in fitted $M^{\pm} \rightarrow$ curvature bias corrections.

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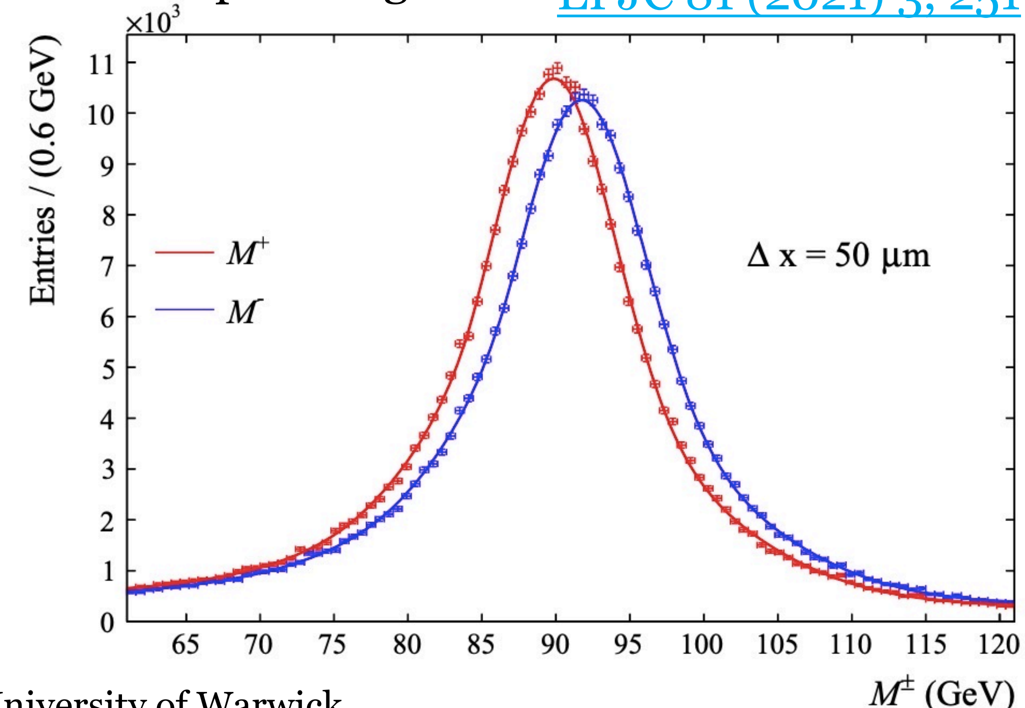

Inspired by PRD 91, 072002 (2015)

Charge-dependent curvature biases

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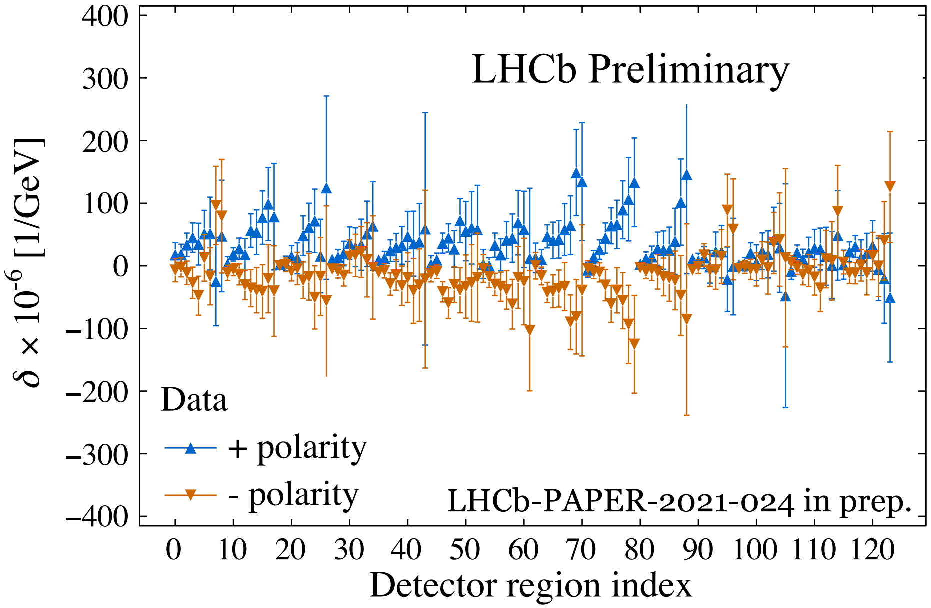

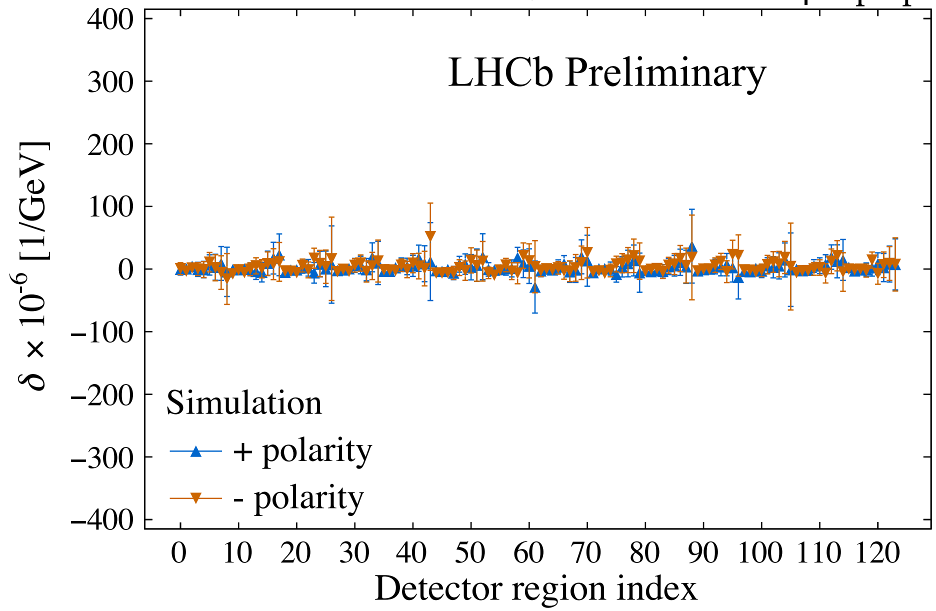

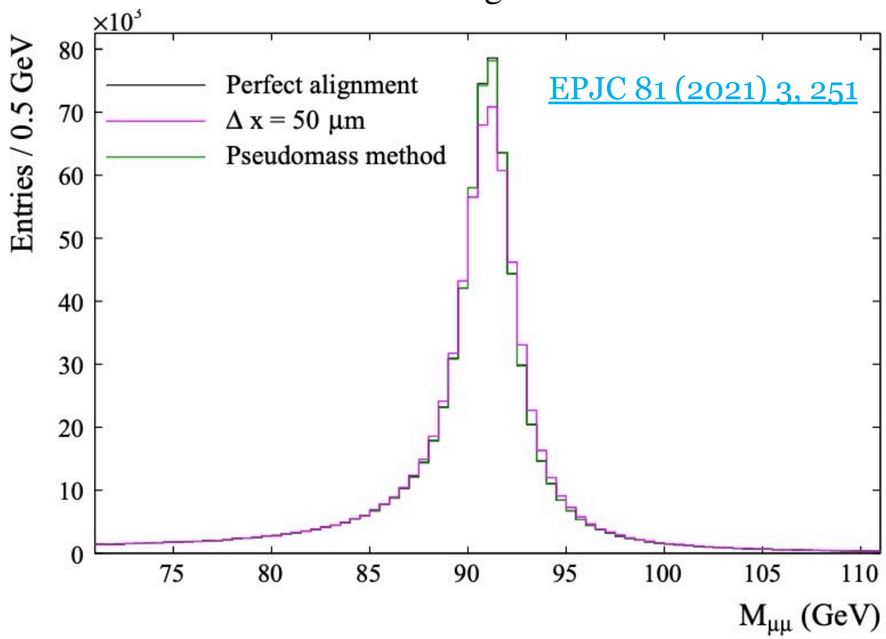

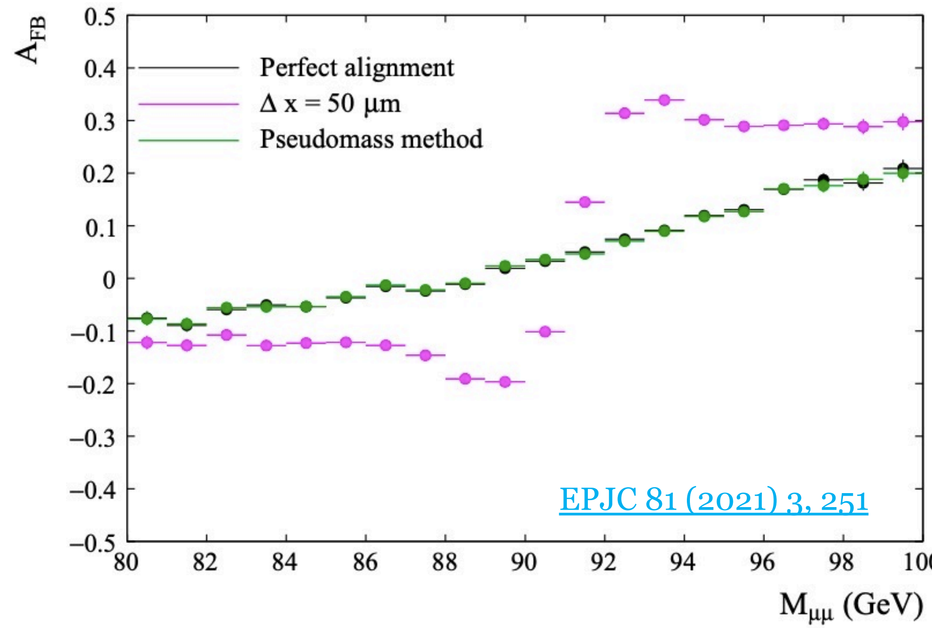

Momentum smearing function

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

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

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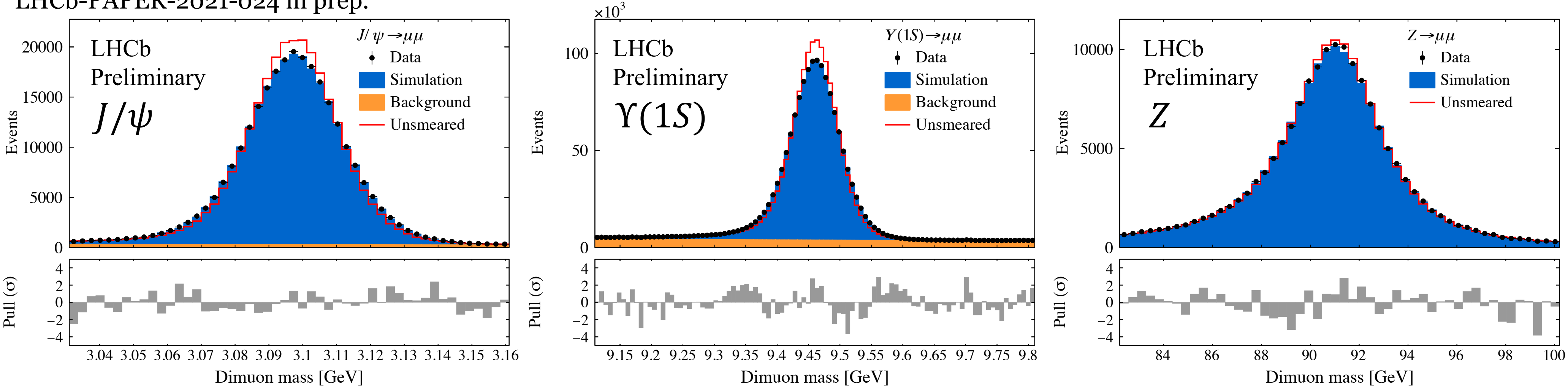

Effects modelled are curvature bias (δ), momentum *scale* ($1+\alpha$), momentum-independent (σ_{MS}) and momentum-dependent (σ_δ) smearing.

POWHEG+Pythia as central model

Tuning of α_s and k_T^{intr}

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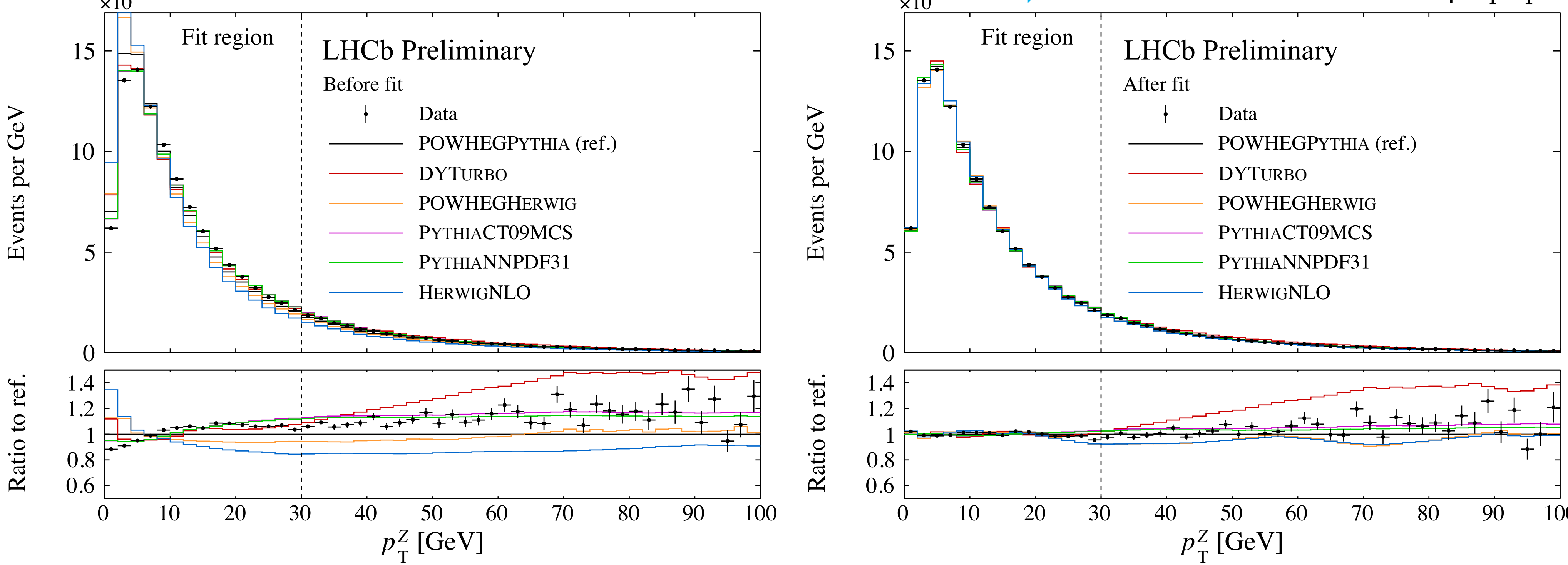
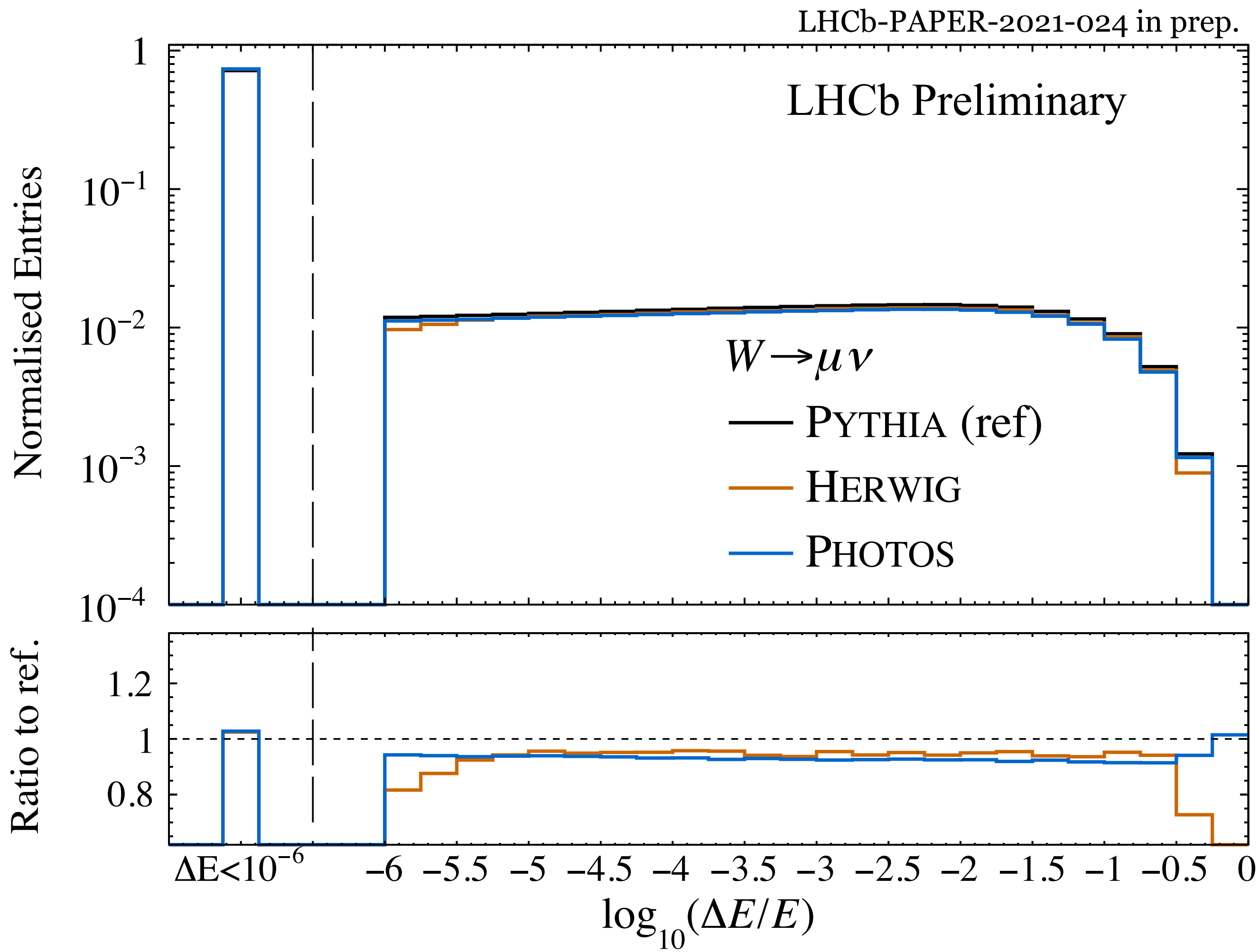


- POWHEG-Box + Pythia8 = best description of p_T^Z -> our central model.
- Other models (POWHEG-HERWIG, PYTHIACT09MCS, PYTHIANNPDF31 and HERWIG NLO) are used to evaluate systematic uncertainty (12 MeV).

Electroweak Corrections



Central result based on the average of these 3 QED FSR models (simulation reweighted according to the relative energy loss).