LHCb m_W measurement with 2016 data

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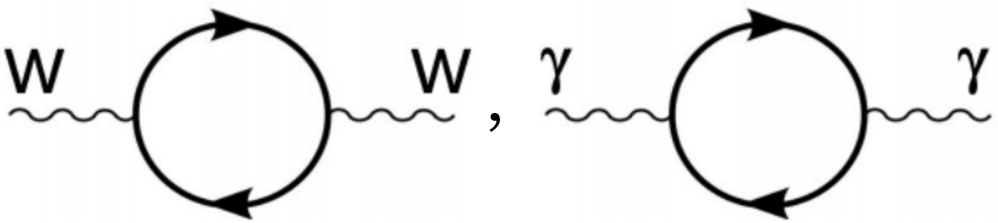
on behalf of the LHCb Collaboration

W mass workshop, Paris, 23/02/23 - 24/02/23

Scientific Context

In the Standard Model:

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



, … NP? …

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

- Comparing with direct m_W measurements constrains new physics.

Status of the field

- 2021 global EW fit:

$$\Delta m_W^{EW fit} = 6 \text{ MeV},$$

- Recent direct measurements:

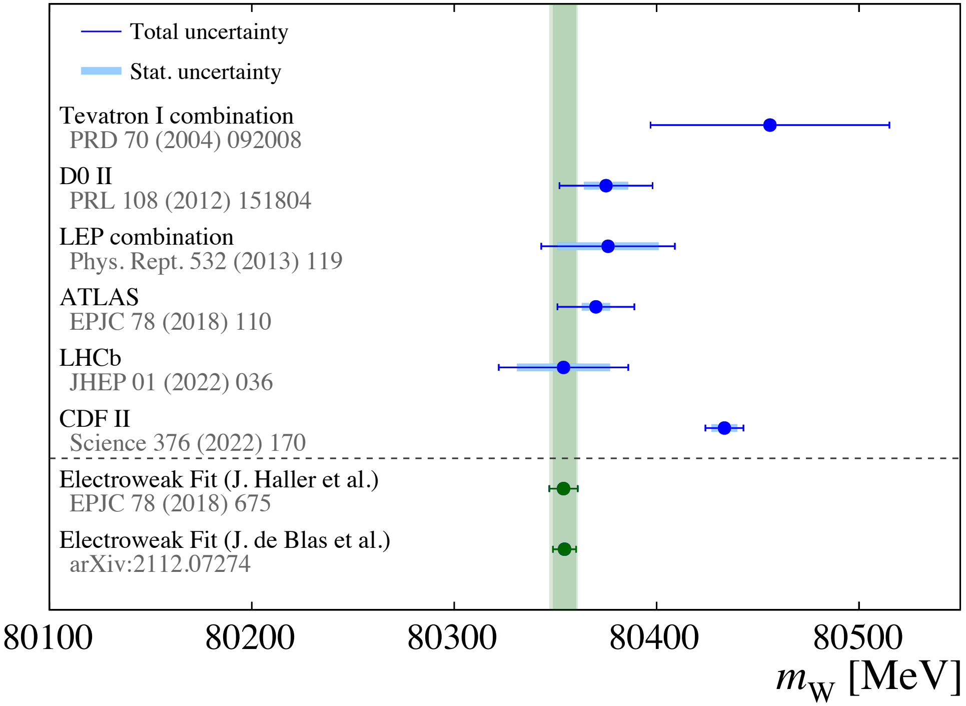
$$\Delta m_W^{ATLAS} = 19 \text{ MeV},$$

$$\Delta m_W^{CDF\ II} = 9 \text{ MeV},$$

$$m_W^{CDF\ II} - m_W^{EW\ fit} \approx 7\sigma,$$

$$m_W^{CDF\ II} - m_W \text{ (LEP, D0 + LHC)} \approx 4\sigma.$$

LHCb-FIGURE-2022-003



More m_W measurements from the LHC are necessary!

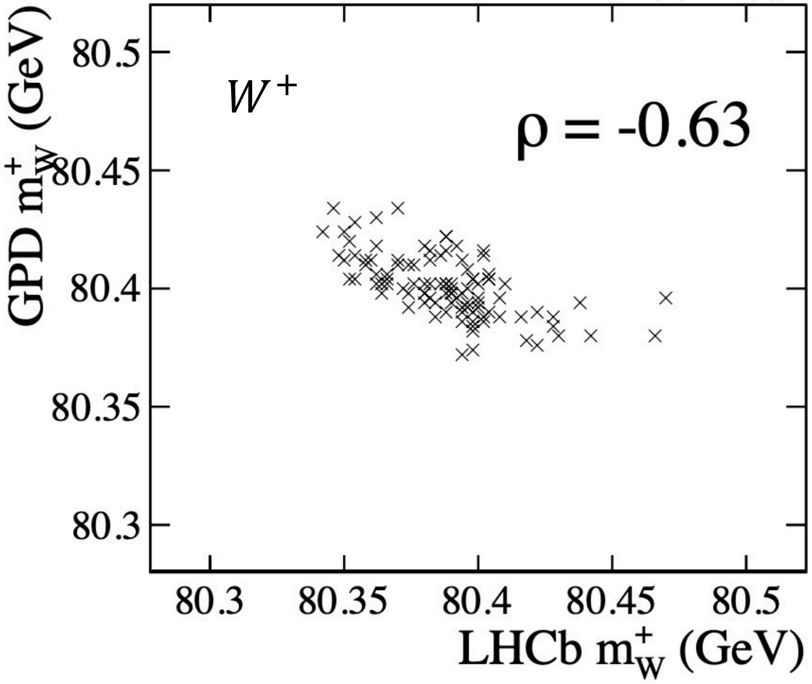
Why LHCb?

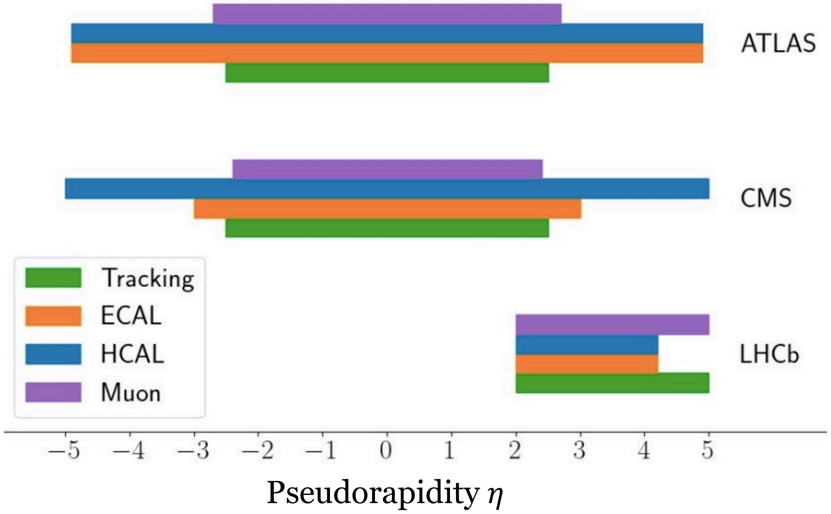
- LHCb Run-2 data: $O(10)$ MeV statistical uncertainty on m_W ($O(10^7)$ $W \to \mu\nu$ candidates),

- 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)





How we measure 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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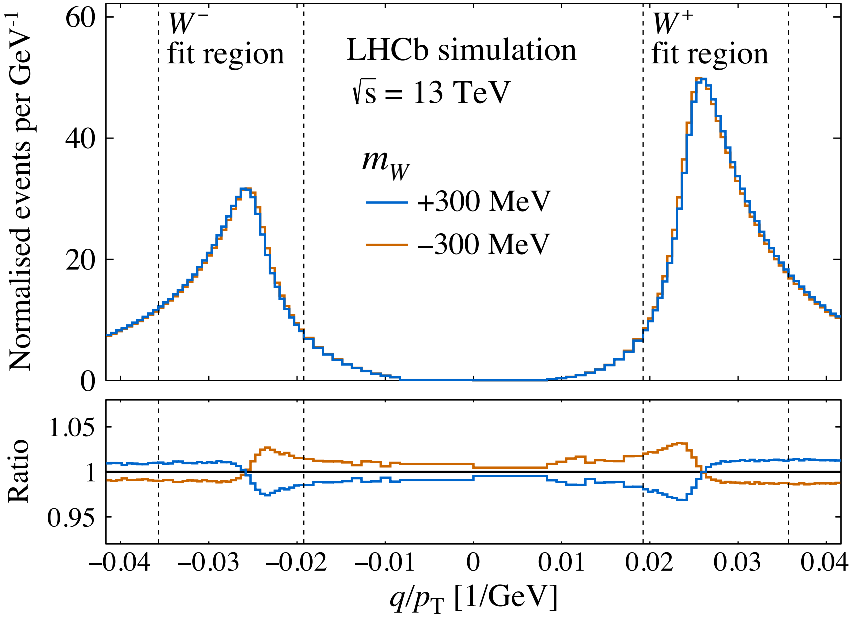

“Experimental” modelling

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.

Experimental modelling

Detector alignment corrections

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

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

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

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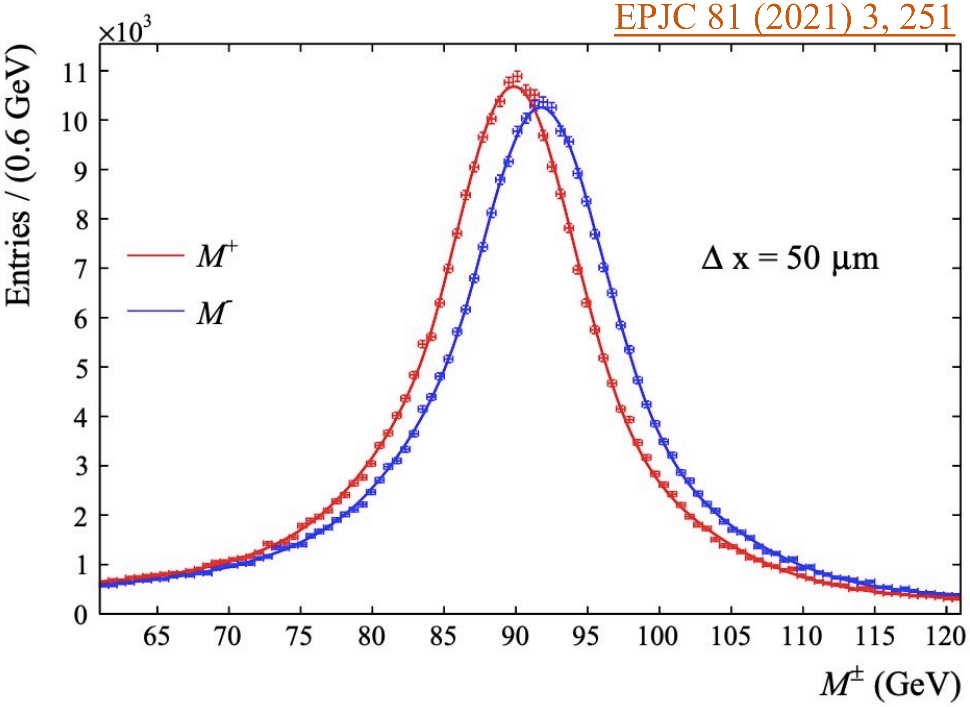
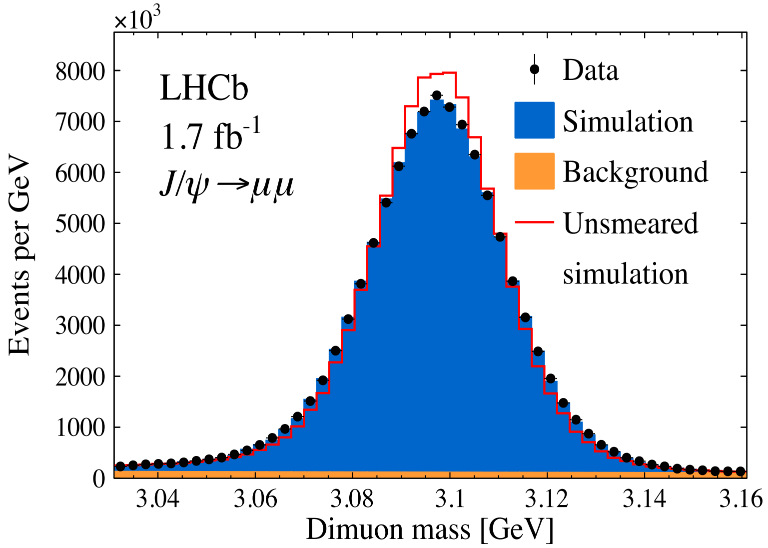
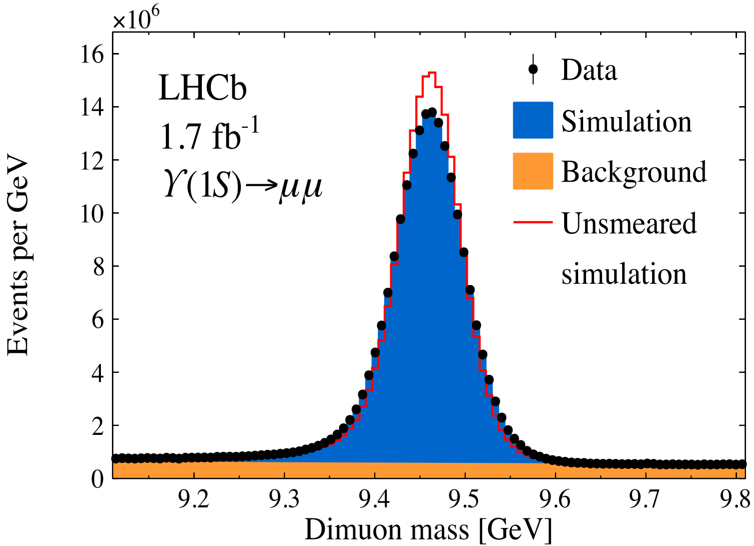


Inspired by PRD 91, 072002 (2015)

Momentum scale calibration

Further smearing of the simulation is then needed:





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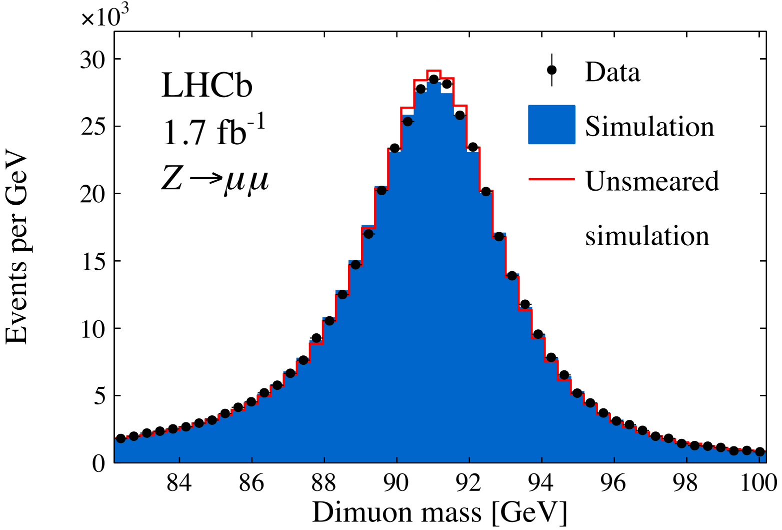

Simultaneous fit to the $J/\psi, \Upsilon(1S)$ and Z $m_{\mu\mu}$

(binned in different detector regions, polarities…)

Smearing model applied to all templates.

Signal selection

- Veto events with second high-p_T^{μ} muon in acceptance ($p_T^{\mu} > 25$ GeV); rejects $Z \rightarrow \mu\mu$,
- 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, $2.2 < \eta < 4.4$.

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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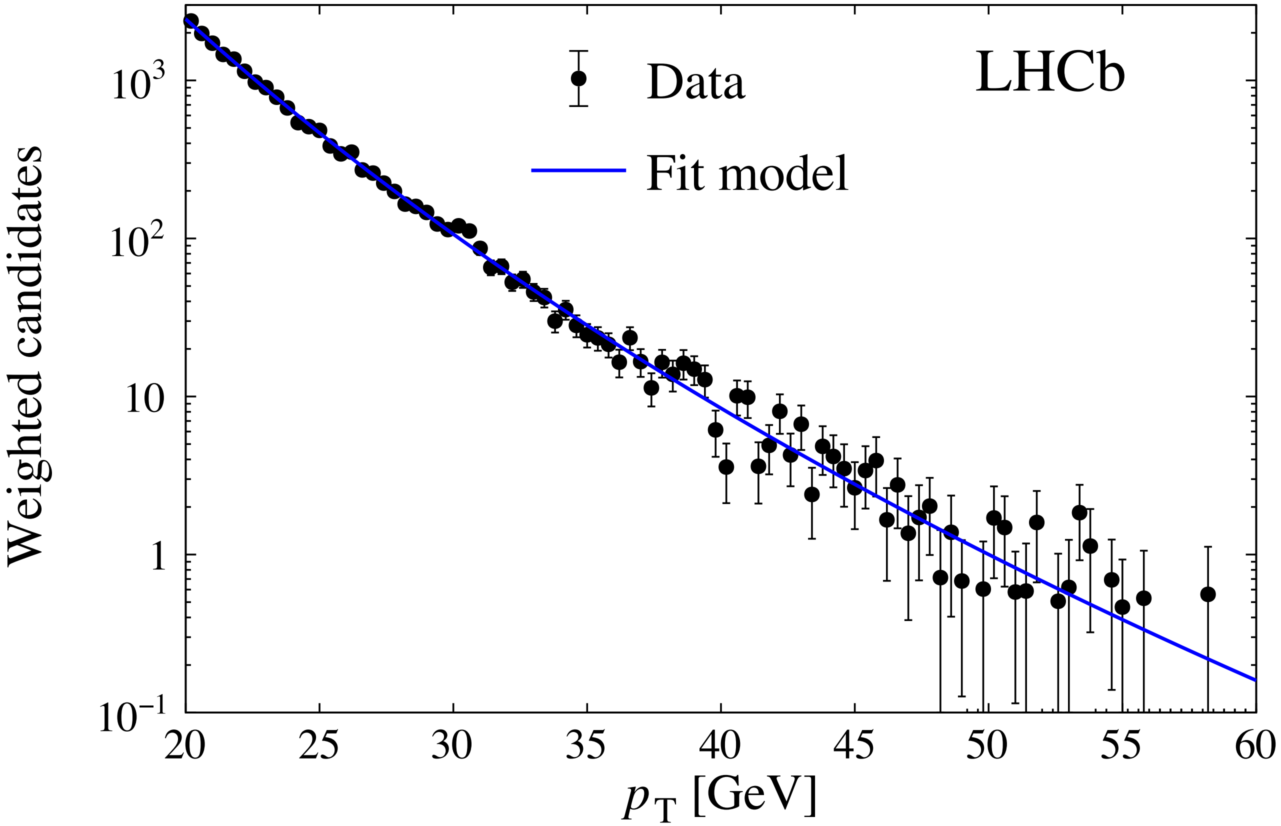

Theoretical modelling

Angular coefficients

At the Born level (before QED FSR):

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

$$\underbrace{\left\{(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + \boxed{A_3\sin\theta\cos\phi} + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\right\}}_{\text{Angular terms } (A_i = \text{angular coefficients})}$$

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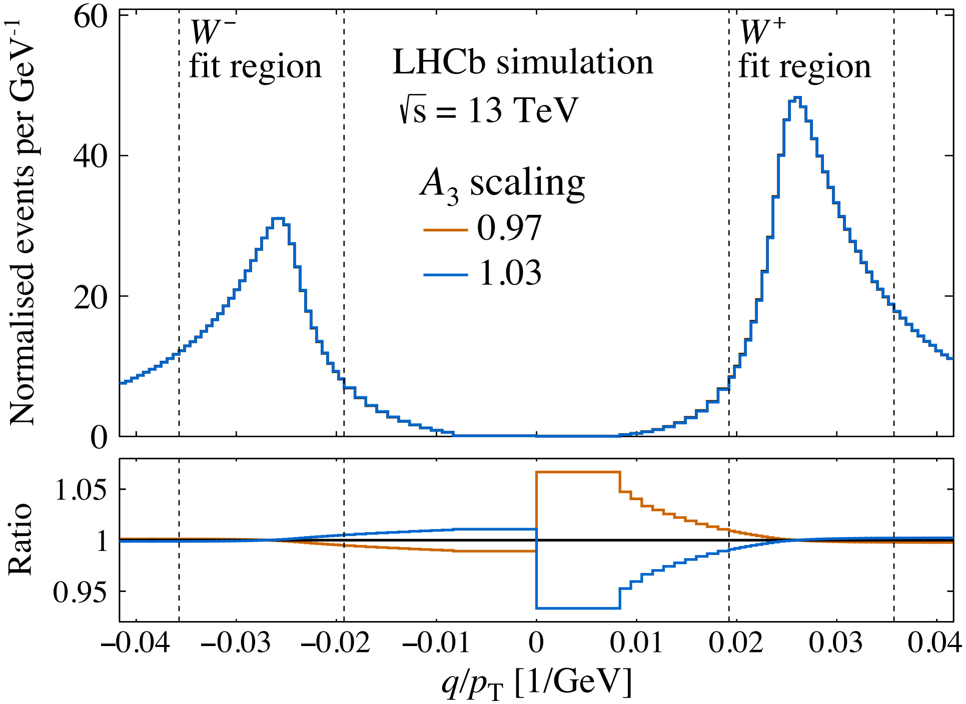
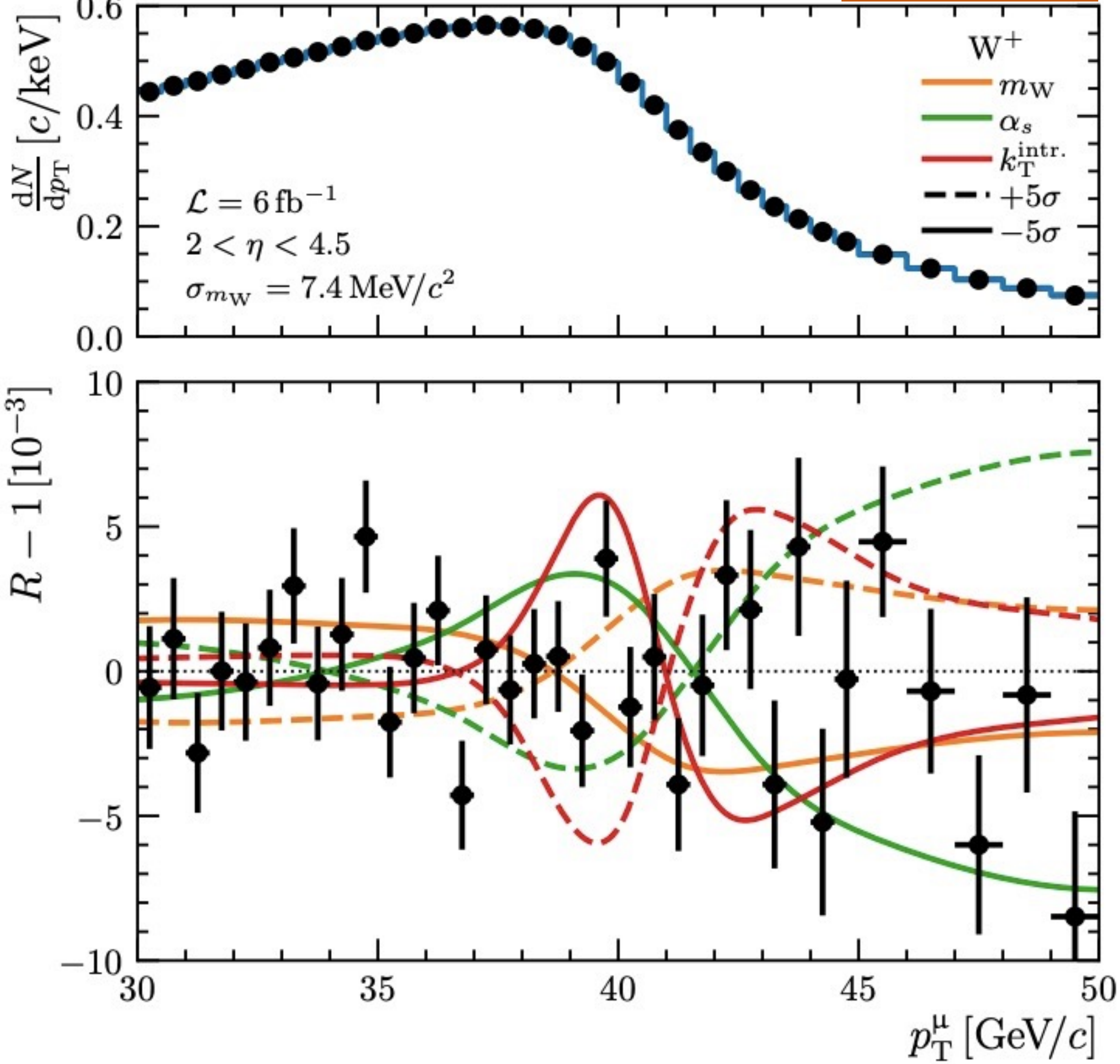


2016 measurement strategy:

- A_i predictions from DYTurbo at $O(\alpha_S^2)$.
- 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

$$\left.\frac{d\sigma^{unpol}}{dp_T^V\,dy\,dM}\right\}$$

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 $Z\ \phi^*$.

QED Final State Radiation

- Different FSR predictions mimicked by reweighting in ΔE/E,

- No preference between predictions from Pythia, Herwig and Photos,

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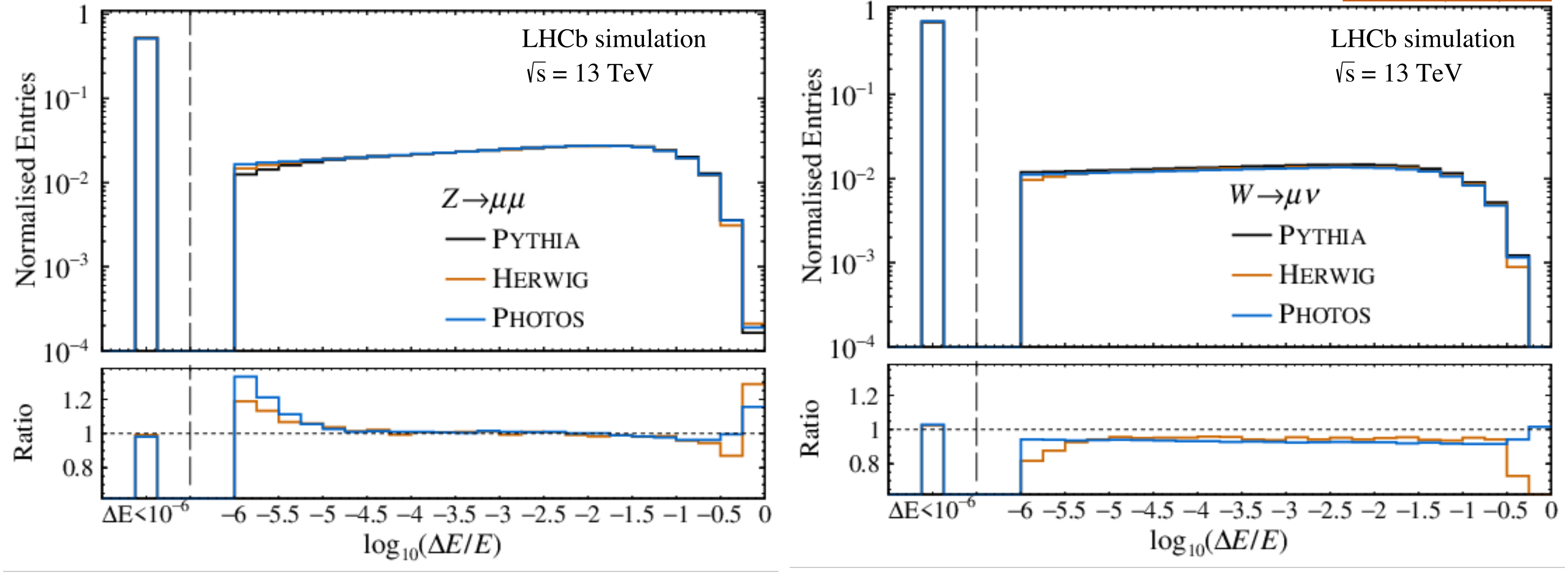


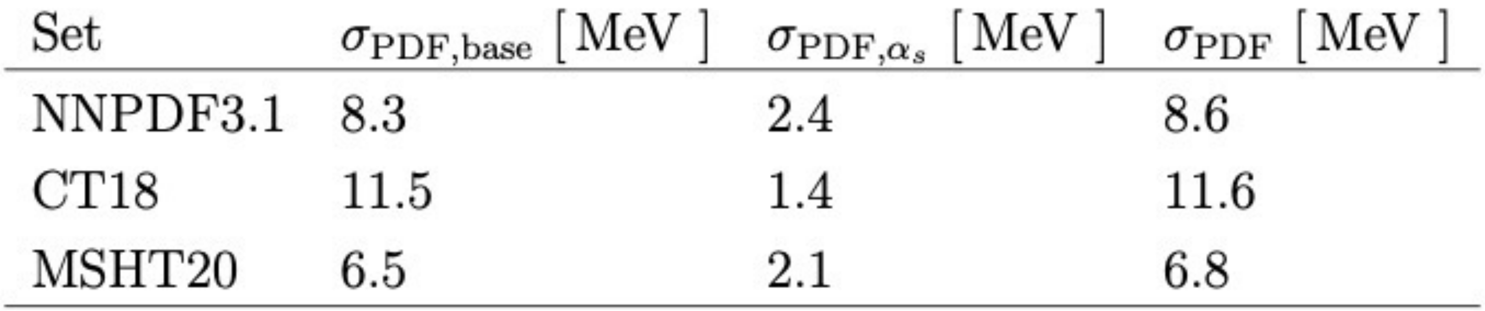
- Uncertainty from the envelope of fits with each.

PDFs and their uncertainties

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

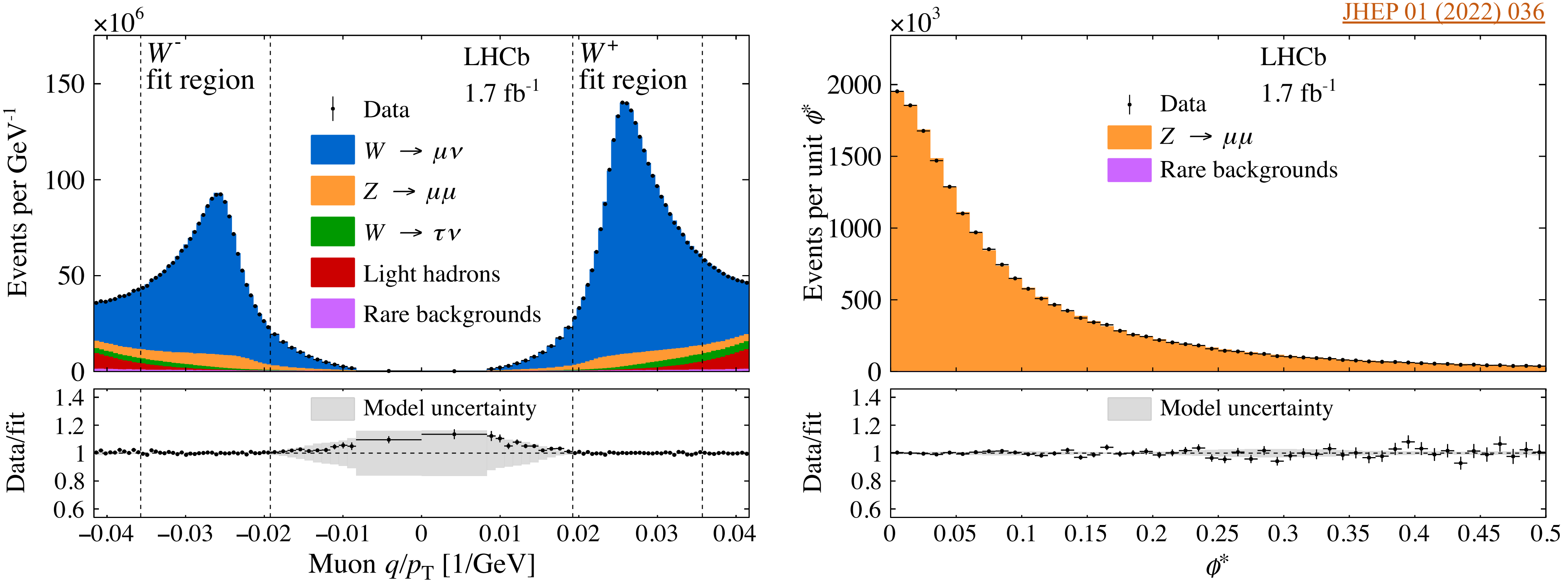
$$m_W = \frac{1}{3}[m_W(\text{NNPDF}) + m_W(\text{CTEQ}) + m_W\,(\text{MSHT})],$$

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



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

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
$k_\mathrm{T}^\mathrm{intr}$	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026

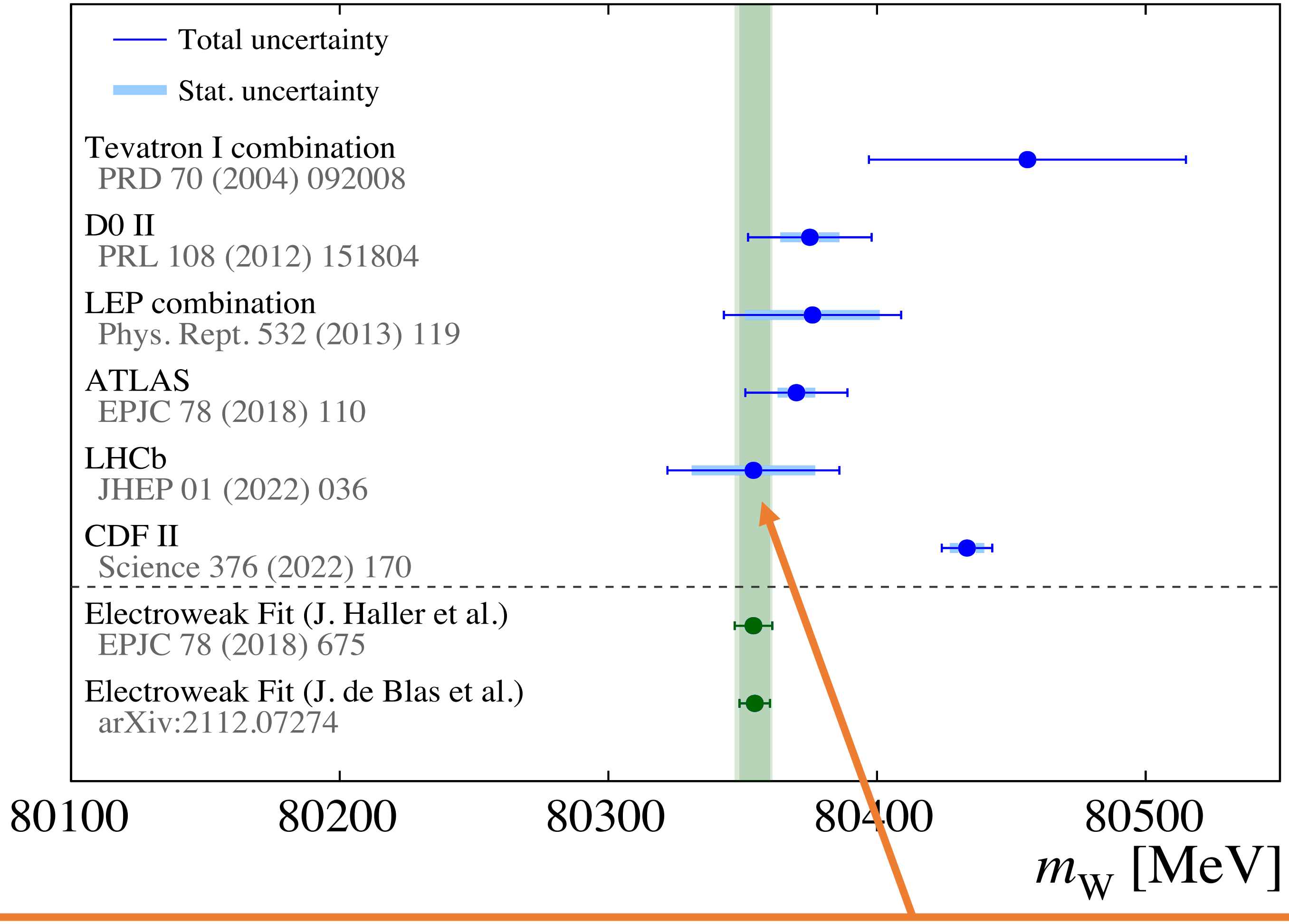
$$\chi^2/ndf = 105/102$$
$$\sigma_{stat} = 23\ \mathrm{MeV}$$

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**	

The 2016 result

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



LHCb-FIGURE-2022-003

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

Conclusions and outlook

- First measurement of the W boson mass at LHCb achieved a precision of ~32 MeV, using roughly 1/3 of the Run 2 dataset,
- Result was published at beginning of 2022 as JHEP 01 (2022) 036,
- Largest uncertainties were theoretical (angular coefficients, PDFs and boson p_T model),
- Future prospects from LHCb → talk on Friday by Miguel Ramos Pernas,
- LHCb measurement(s) expected to provide significant impact on a LHC-wide average due to potential anti-correlation of PDF uncertainties → next talk by Maarten Bonnekamp.

Thank you for your attention.
Any questions?

Backup

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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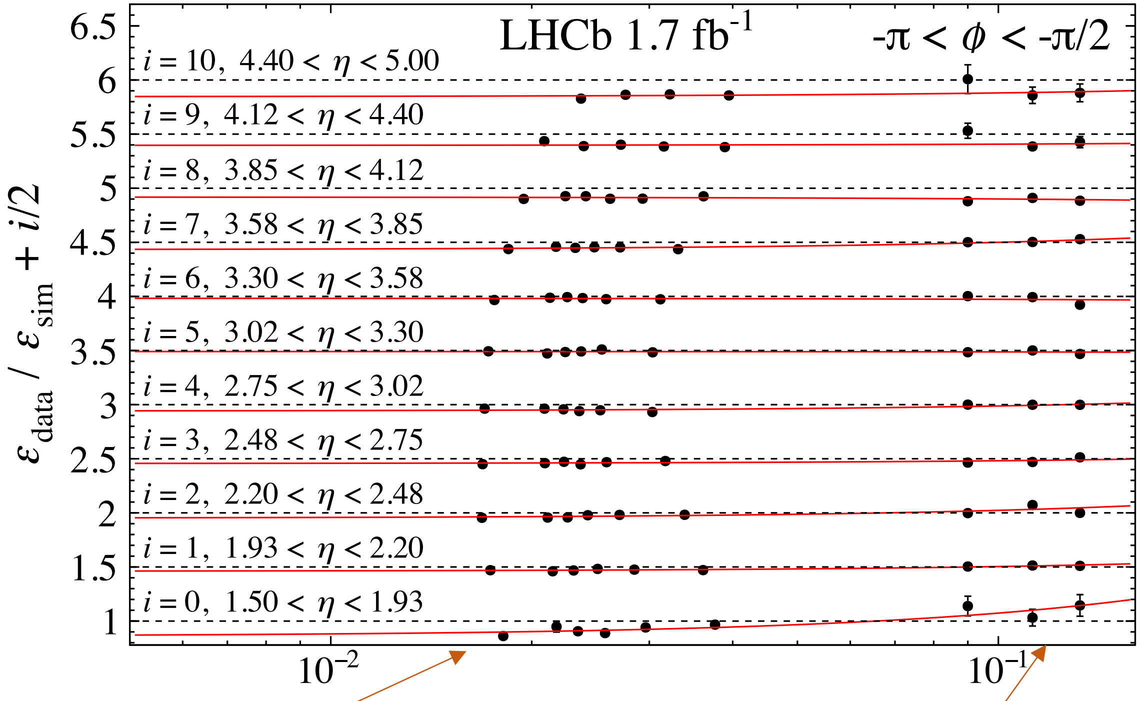


$Z \to \mu\mu$

$\Upsilon(1S) \to \mu\mu$

Reconstruction & selection efficiencies

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

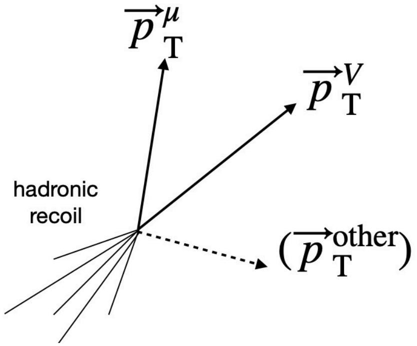
$$\varepsilon_{sim}\,(p_T,\eta,\phi,\ldots) = \varepsilon_{data}(p_T,\eta,\phi,\ldots)\ ?$$

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 $Z \rightarrow \mu\mu$ 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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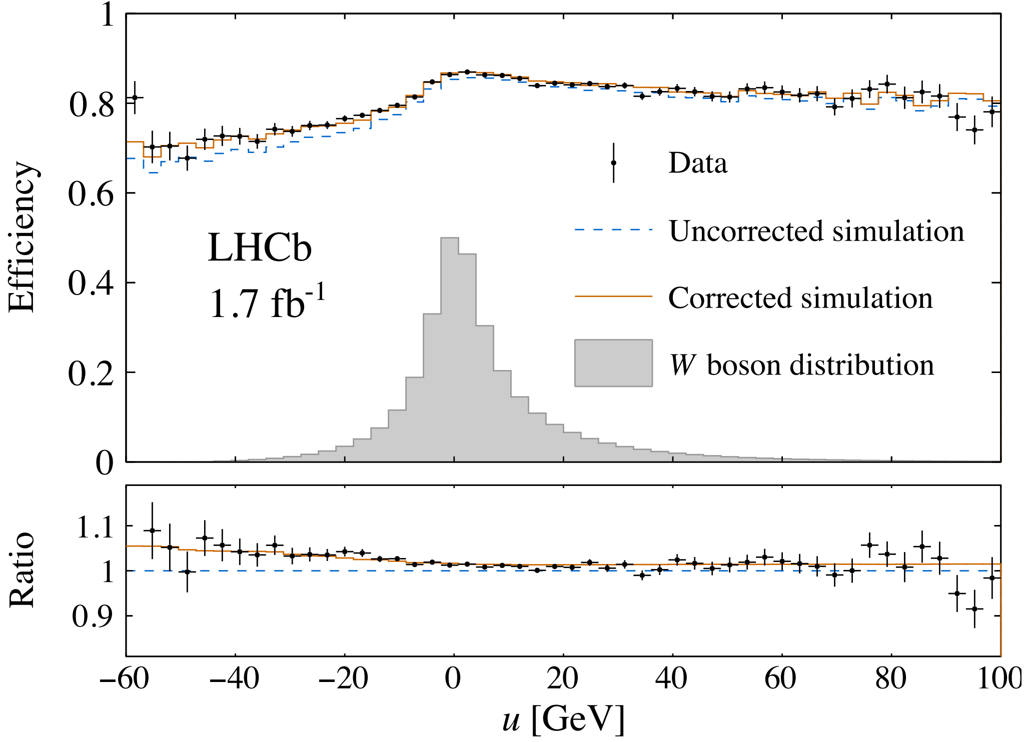
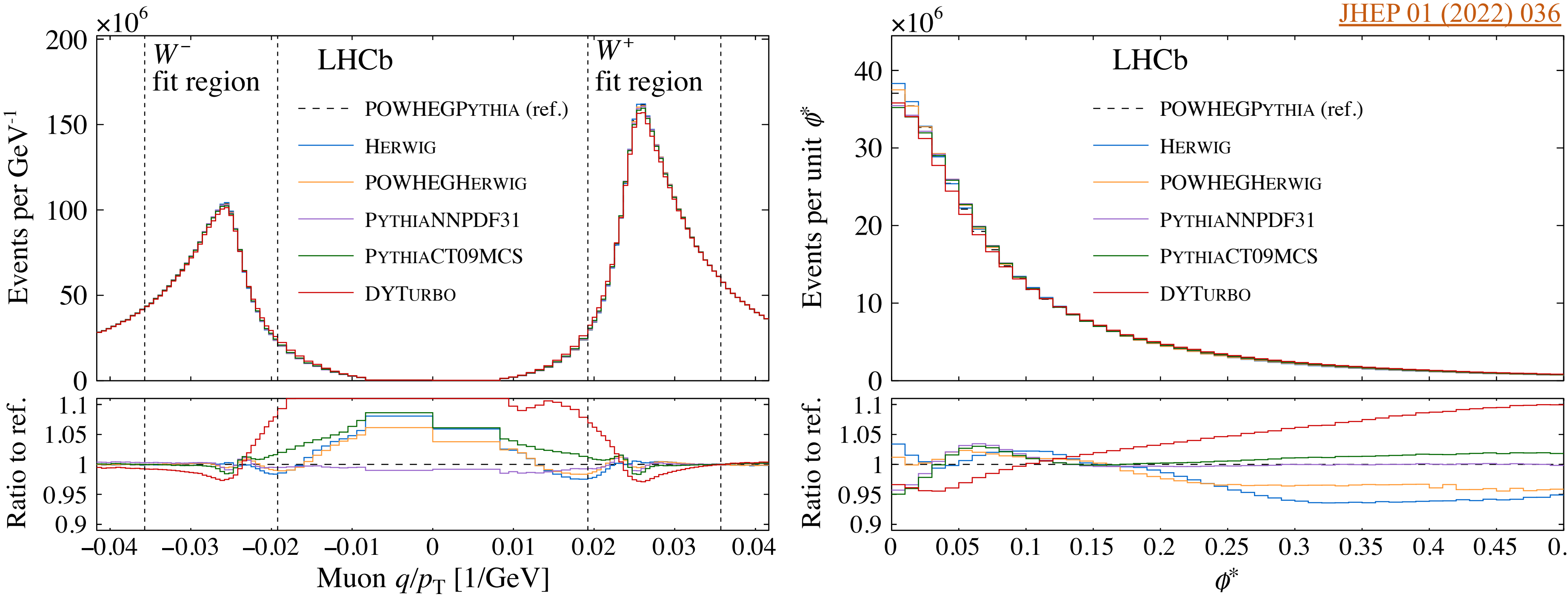


Cross-checks

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.

Model validation: [Pseudo]data challenges



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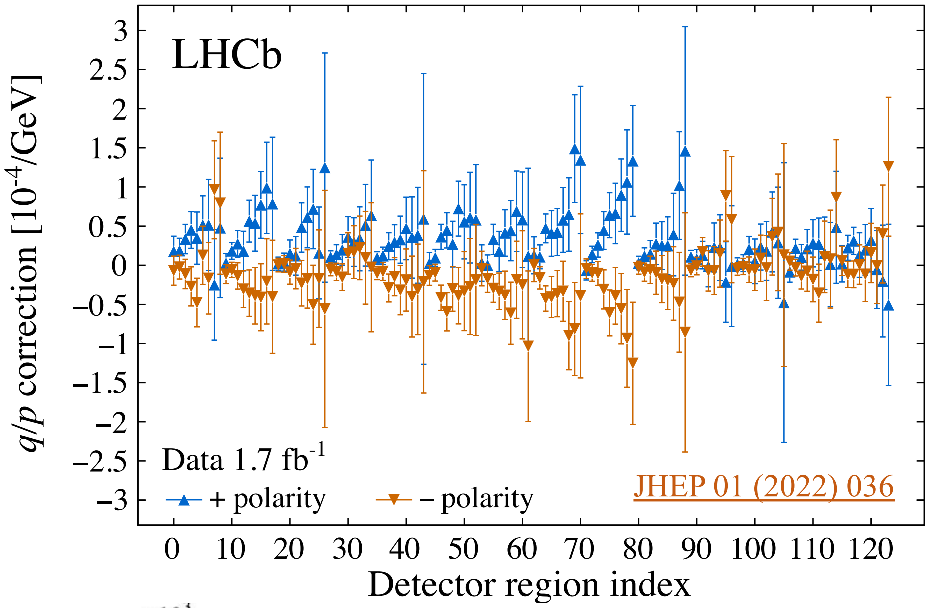
- Using our central model to fit pseudodata generated from different models (e.g. HerwigNLO) gives a similar spread as using those different models to fit the real data.

Data config.	χ^2_W	χ^2_Z	δm_W [MeV]
POWHEGPYTHIA	64.8	34.2	–
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



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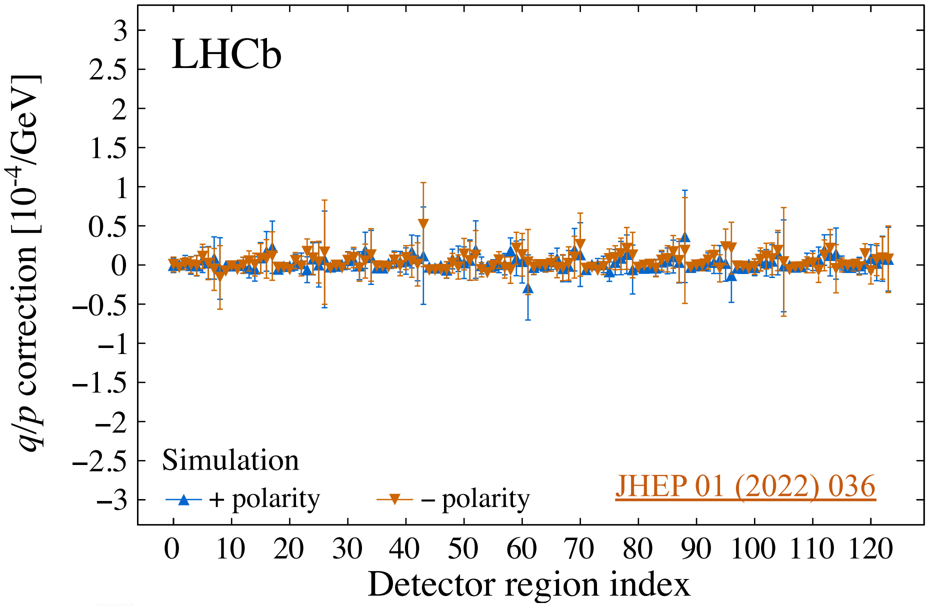

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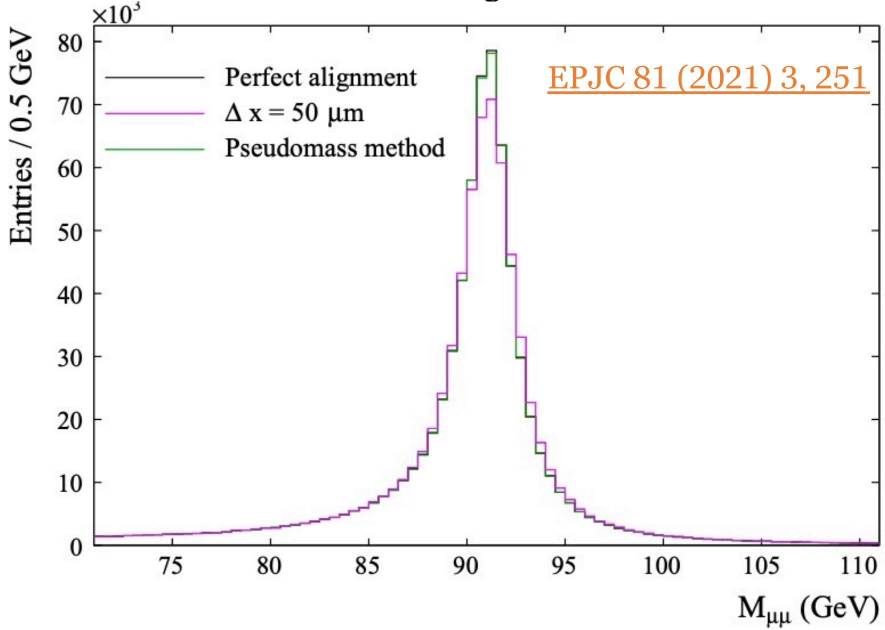

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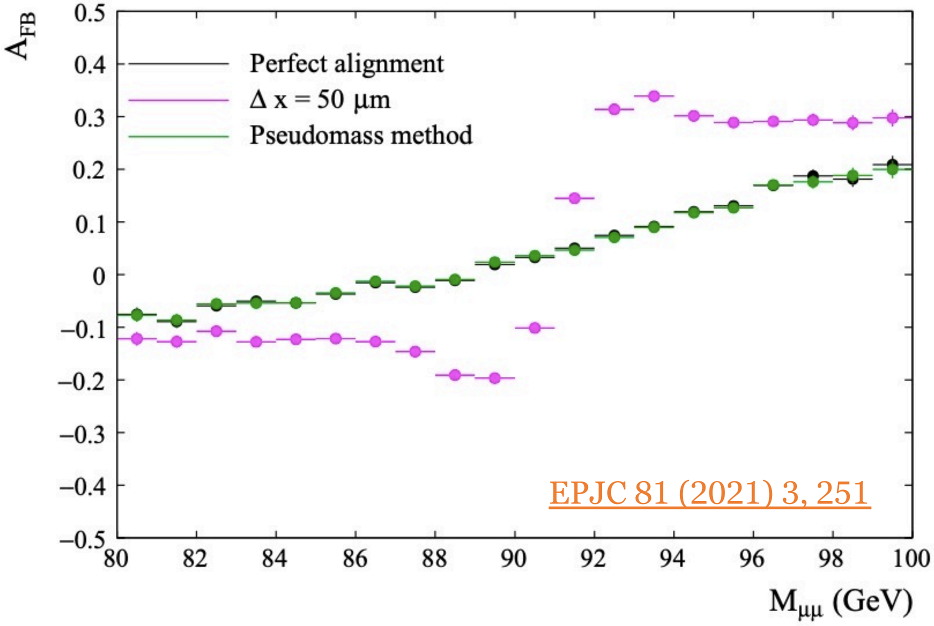

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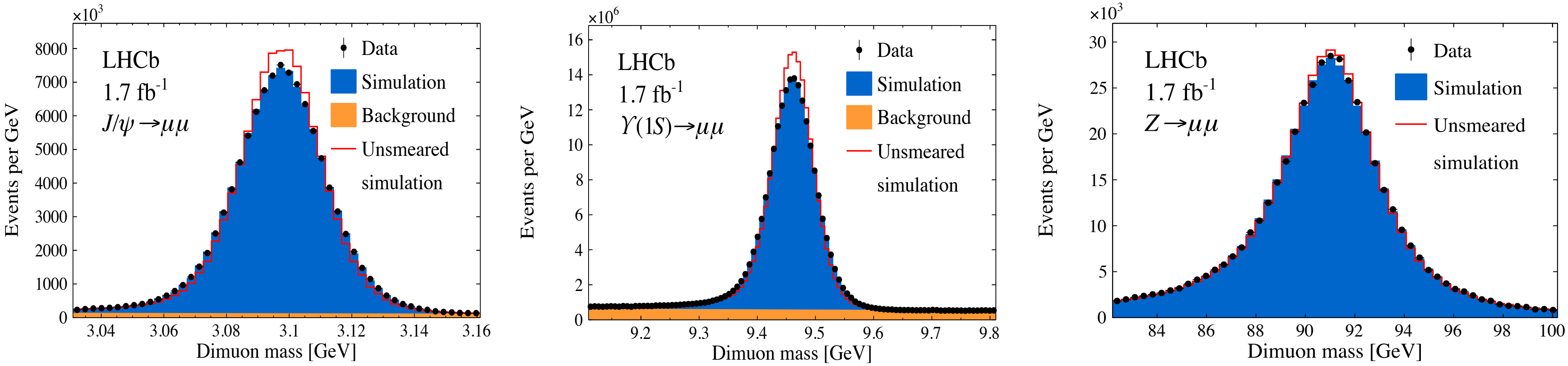
Momentum smearing function

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.

POWHEG+Pythia as central model

Tuning of α_s and k_T^{intr}

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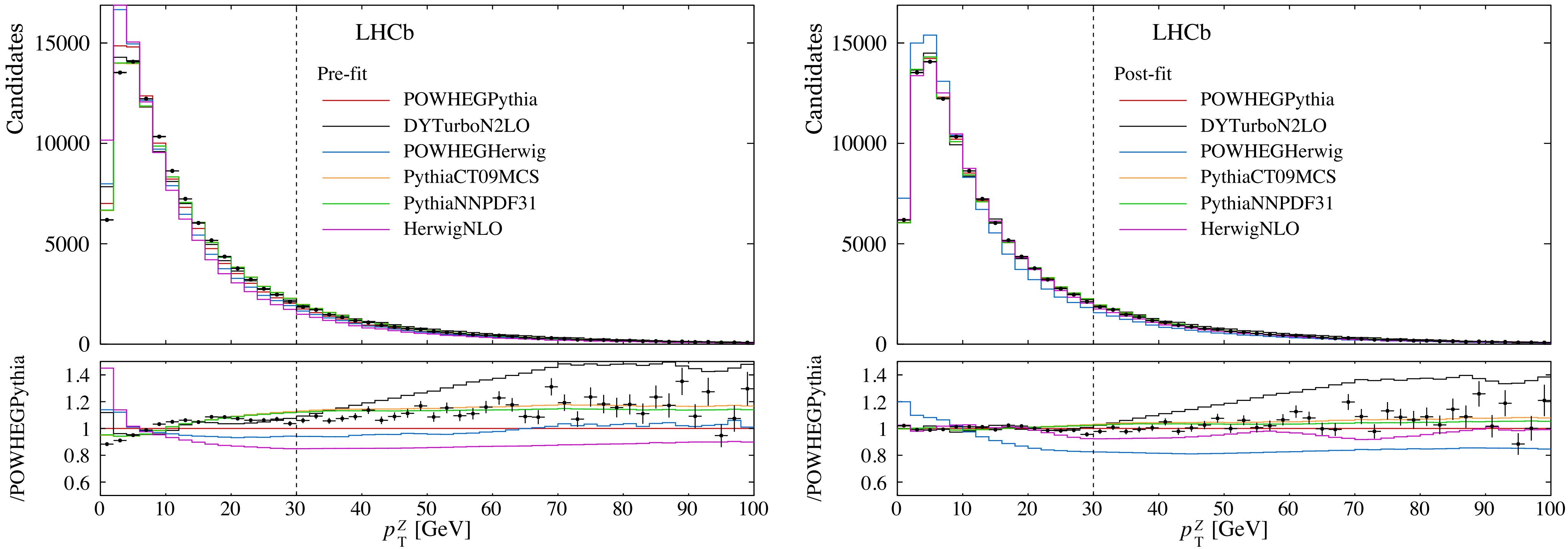

- POWHEG-Box + Pythia8 = best description of p_T^Z -> our central model.
- Other models (POWHEG-HERWIG, PYTHIACT09MCS, PYTHIANNPDF31 and HERWIG NLO) are used to evaluate systematic uncertainty (12 MeV).