Measurement of the W boson mass and LFU in W decays

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LHCb-UK Annual Meeting 2022

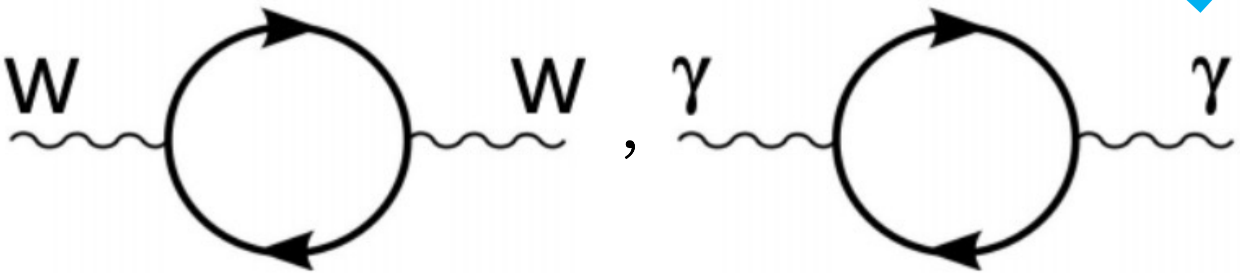
Measurement of the W boson mass

(Public, accepted to JHEP)

Scientific Context

- Three degrees of freedom in electroweak theory.
- Can indirectly measure m_W given measurements of rest of the SM parameters:

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



, … NP? …

Status of the field

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

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

Why LHCb?

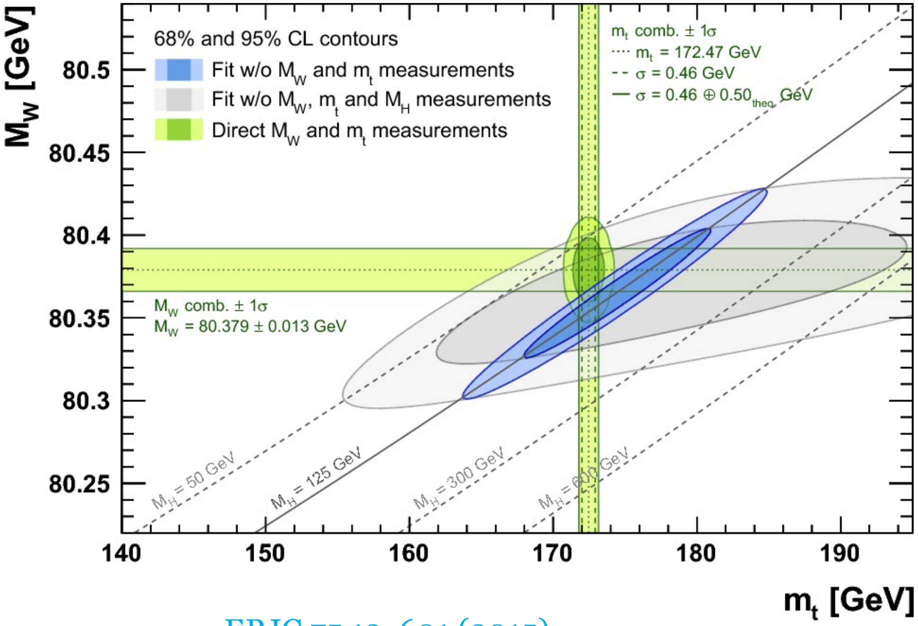
- LHCb full Run-2 data: O(10) MeV statistical uncertainty on m_W,

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

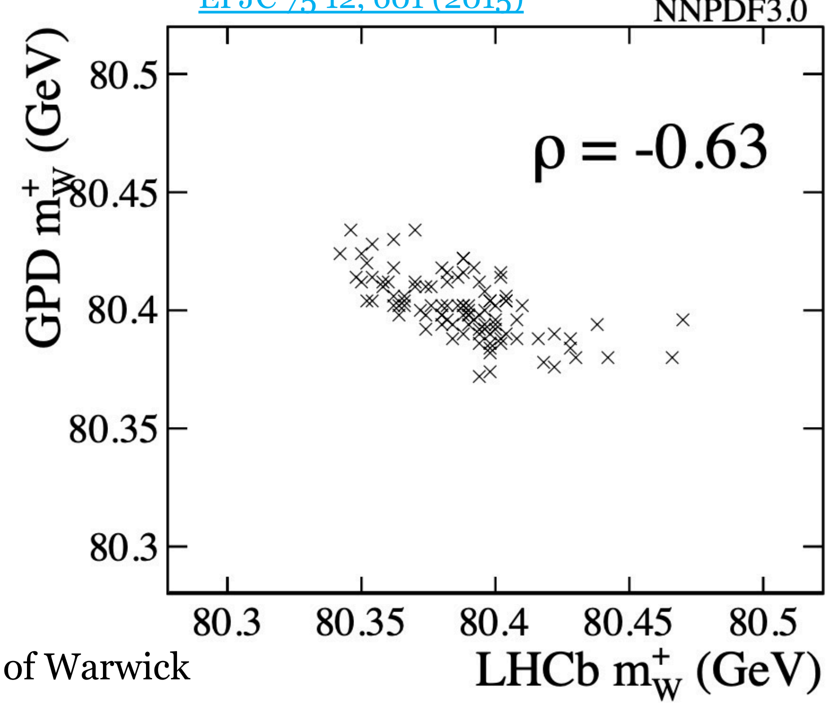
- **…but** limited by theory systematics.

⇒ Today: a proof-of-principle measurement with the 2016 data.

EPJC 78, 675 (2018)



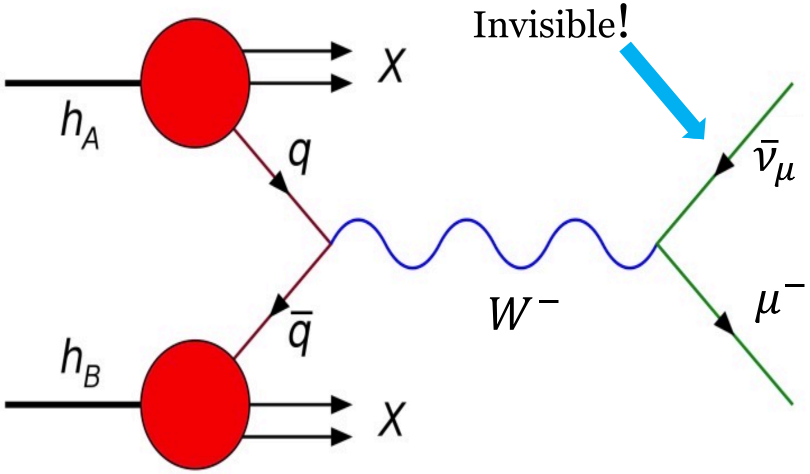
EPJC 75 12, 601 (2015)



How we measure m_W

- $W \to \mu\nu$ 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.



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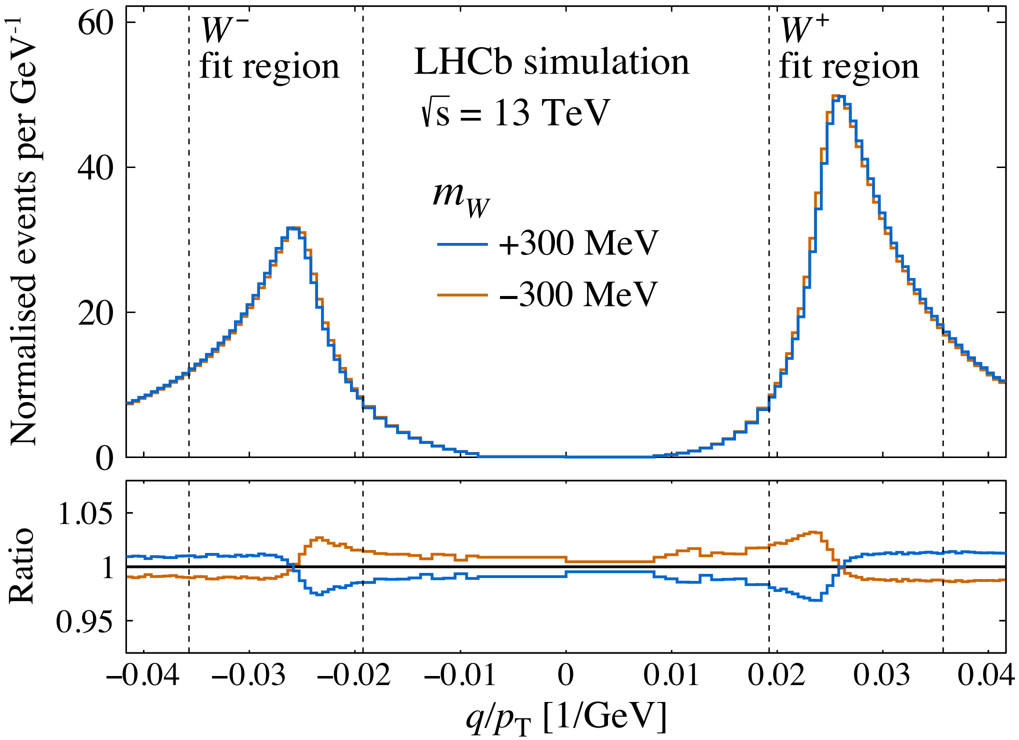

Angular coefficients

Before final-state radiation:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{W}\,\mathrm{d}y\,\mathrm{d}M\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{\mathrm{unpol}}}{\mathrm{d}p_{\mathrm{T}}^{V}\,\mathrm{d}y\,\mathrm{d}M}$$

Unpolarised cross-section

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

Angular terms
(A_i = angular
coefficients)

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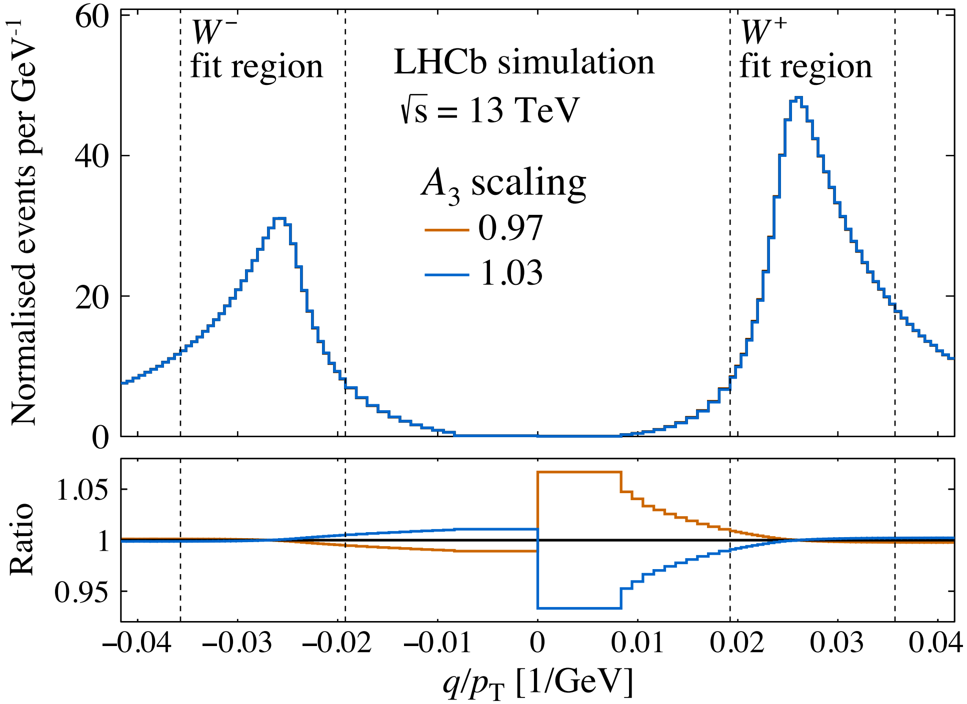
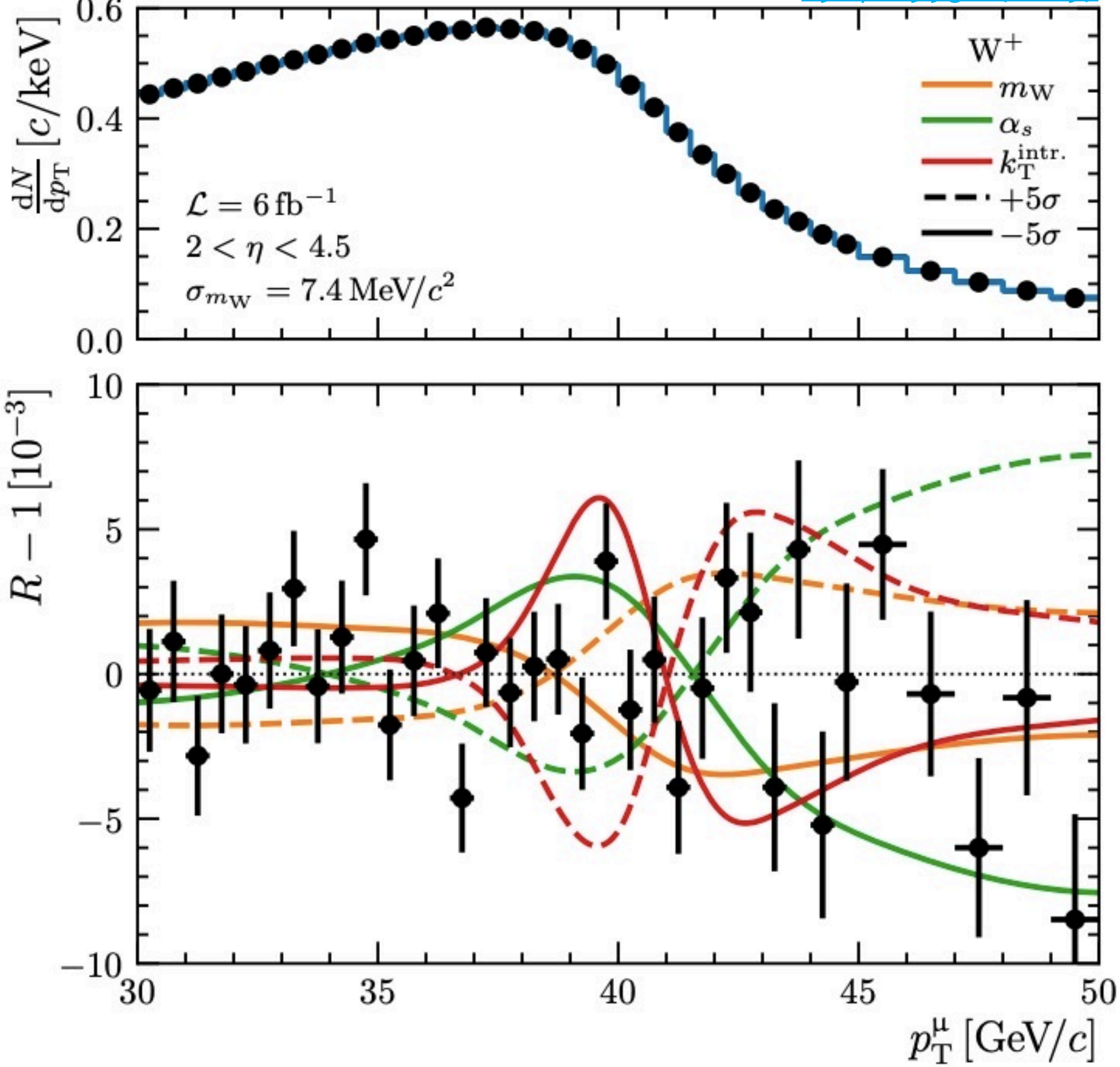


- A_i predictions from DYTurbo at O(α_S^2).
- Problem: too sensitive to uncertainty on prediction of A_3.
- Solution: float a single A_3 scale factor in the fit to absorb this uncertainty.

In-situ MC generator tuning



1907.09958 (2019)

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

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

[Pseudo]data challenges

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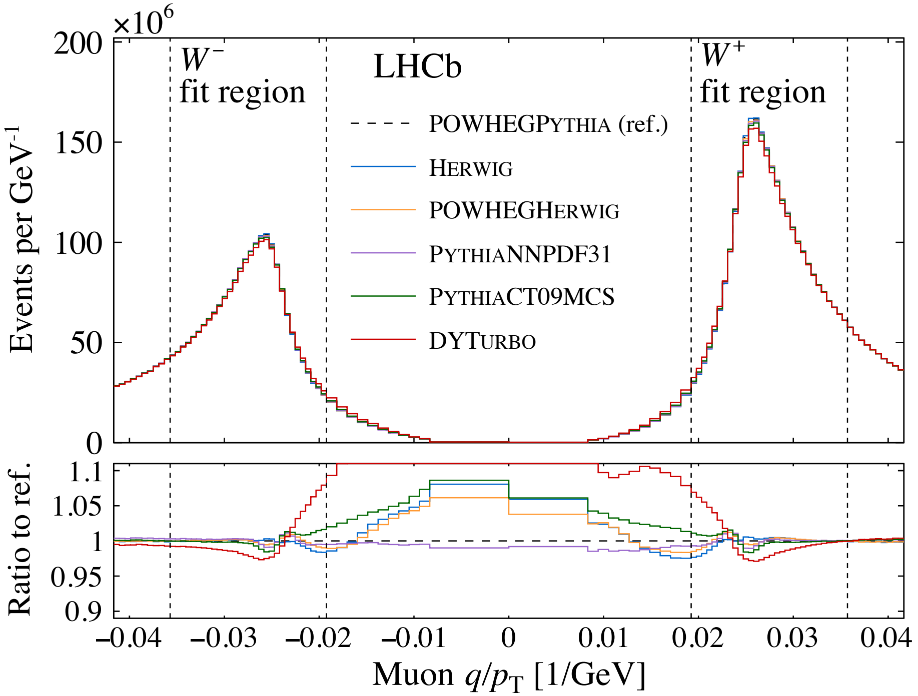
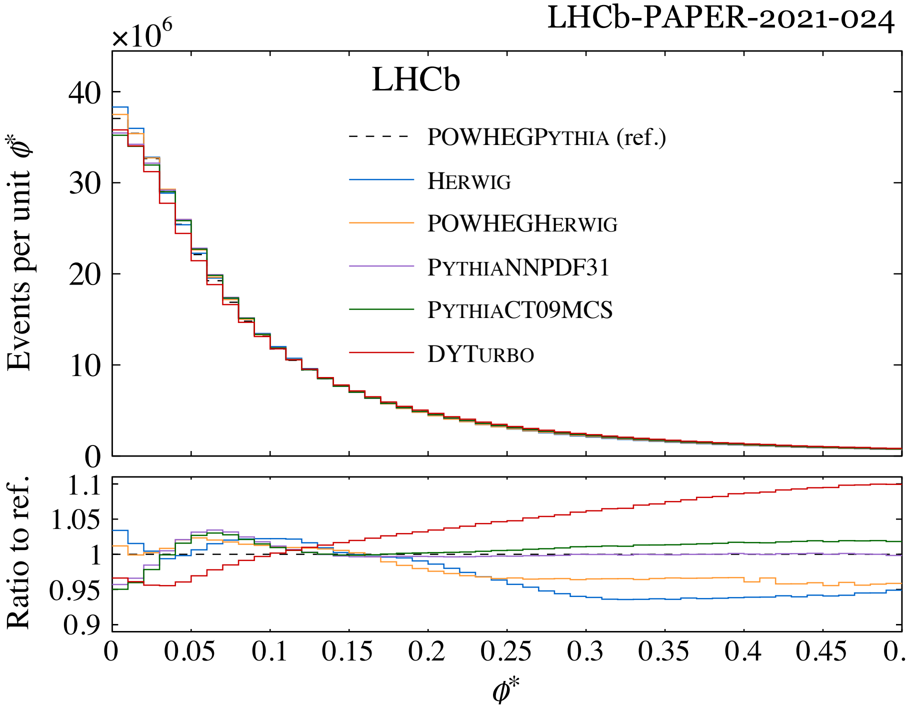




- Using our central model to fit pseudodata generated from different models (e.g. HerwigNLO) gives a similar spread as using those different models to fit the real data.

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

Detector alignment & calibration

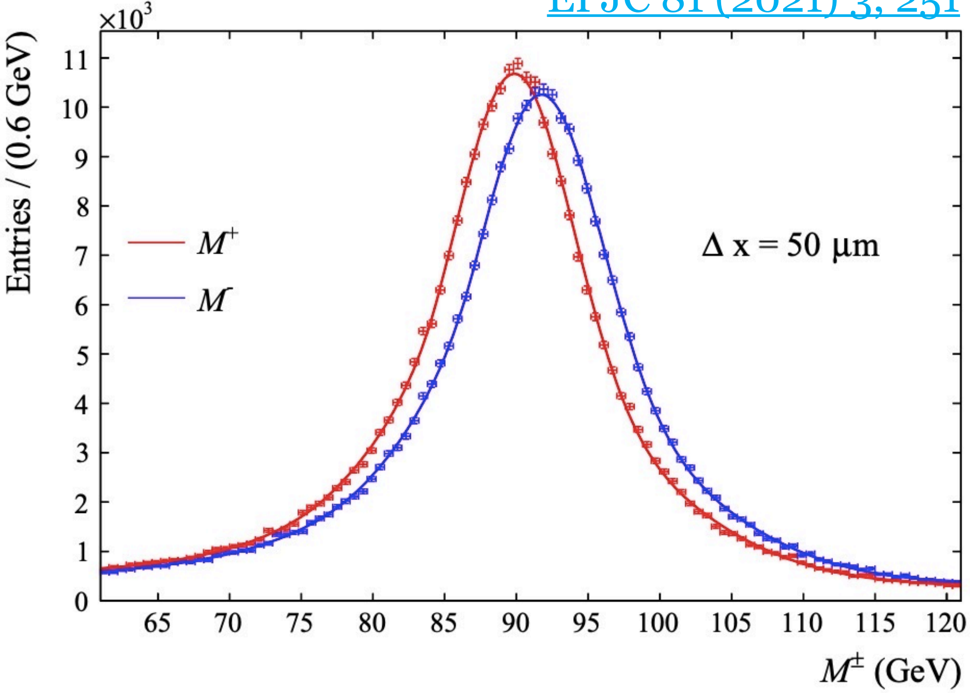
To measure m_W accurately we need to eliminate biases in p_T^μ due to detector misalignment effects.

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

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.

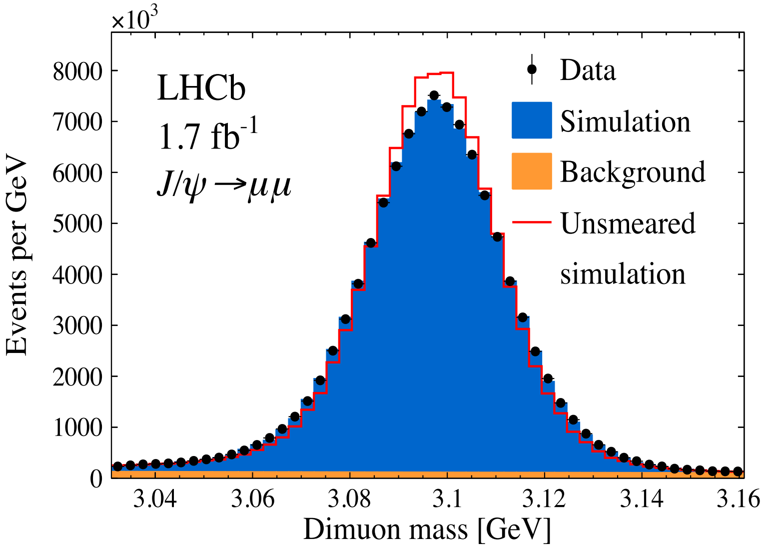
EPJC 81 (2021) 3, 251

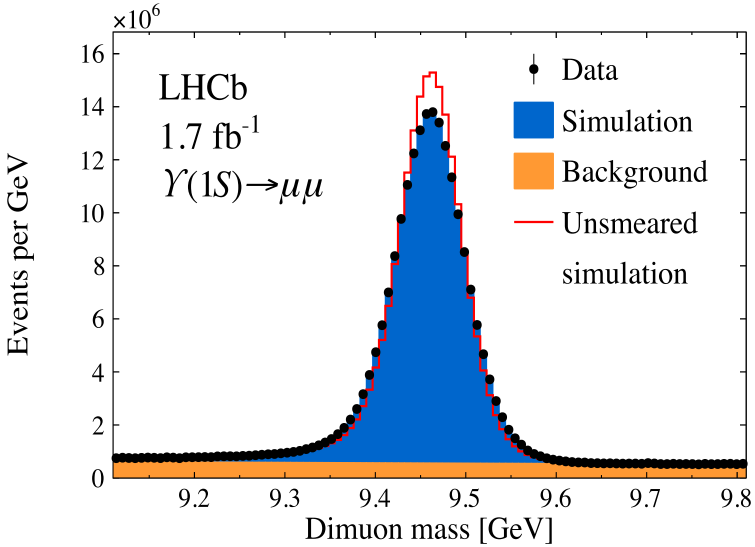


Inspired by PRD 91, 072002 (2015)

Detector alignment & calibration

3. Additional smearing of the simulation:





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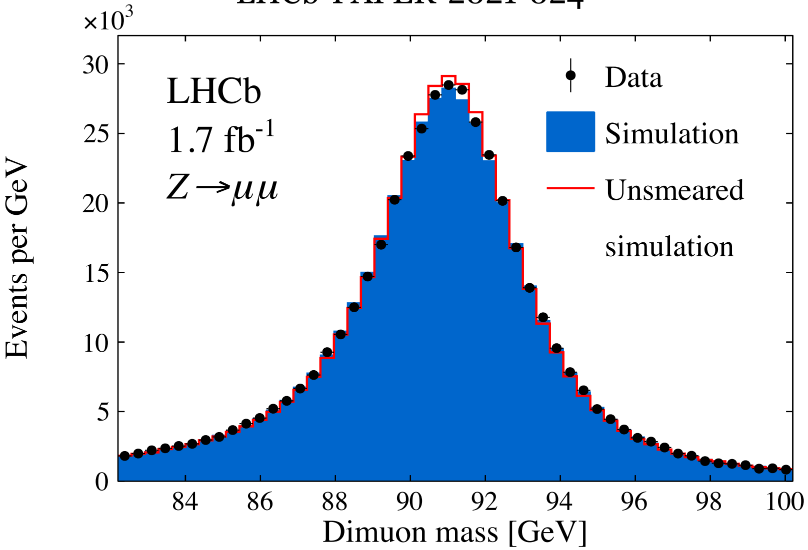

- Fit to the $J/\psi, \Upsilon(1S)$ and Z dimuon invariant mass peaks enable determination of 6 smearing parameters.

- 36 fit categories (species, magnet polarity, η)
- χ^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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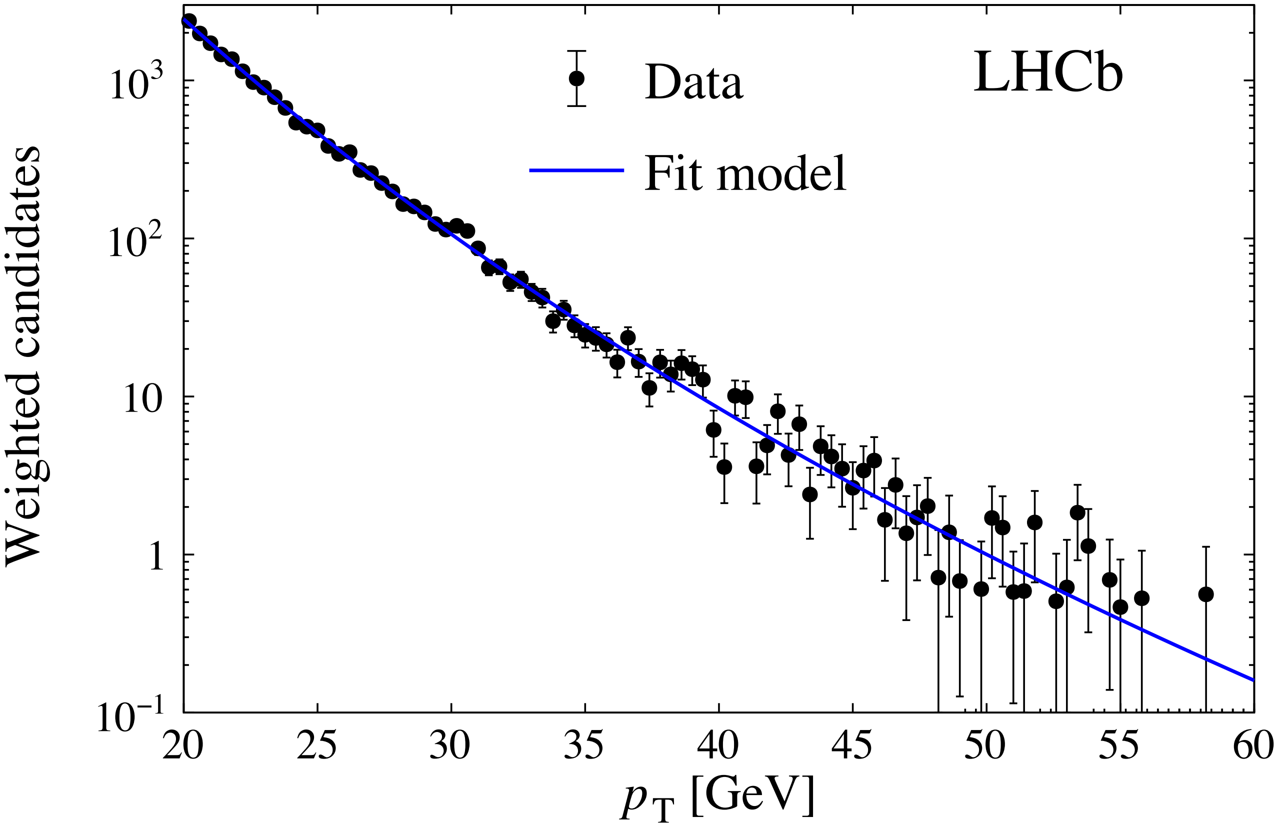

Muon reconstruction efficiencies

- **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.

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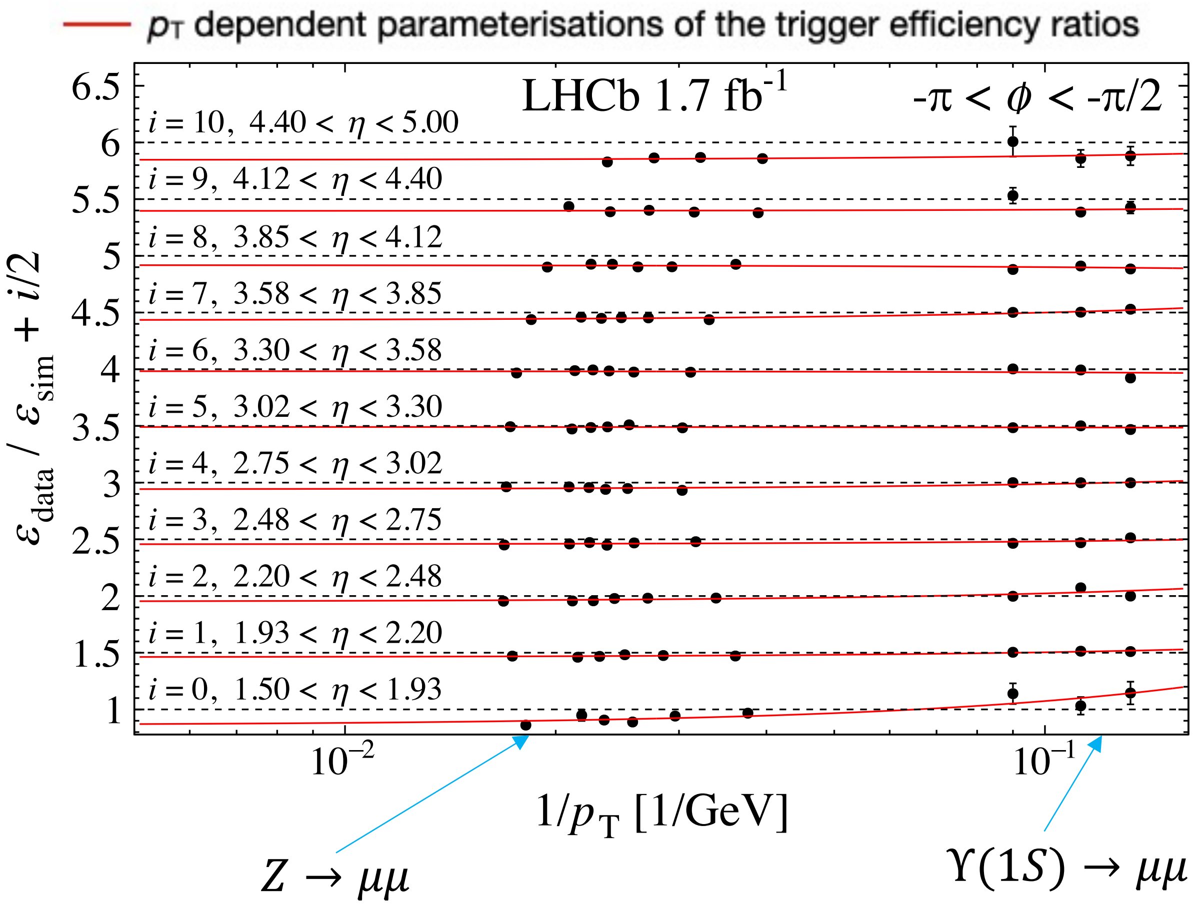


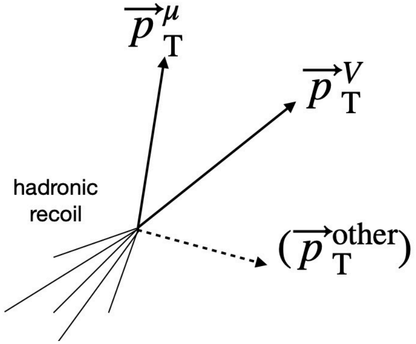
$Z \to \mu\mu$

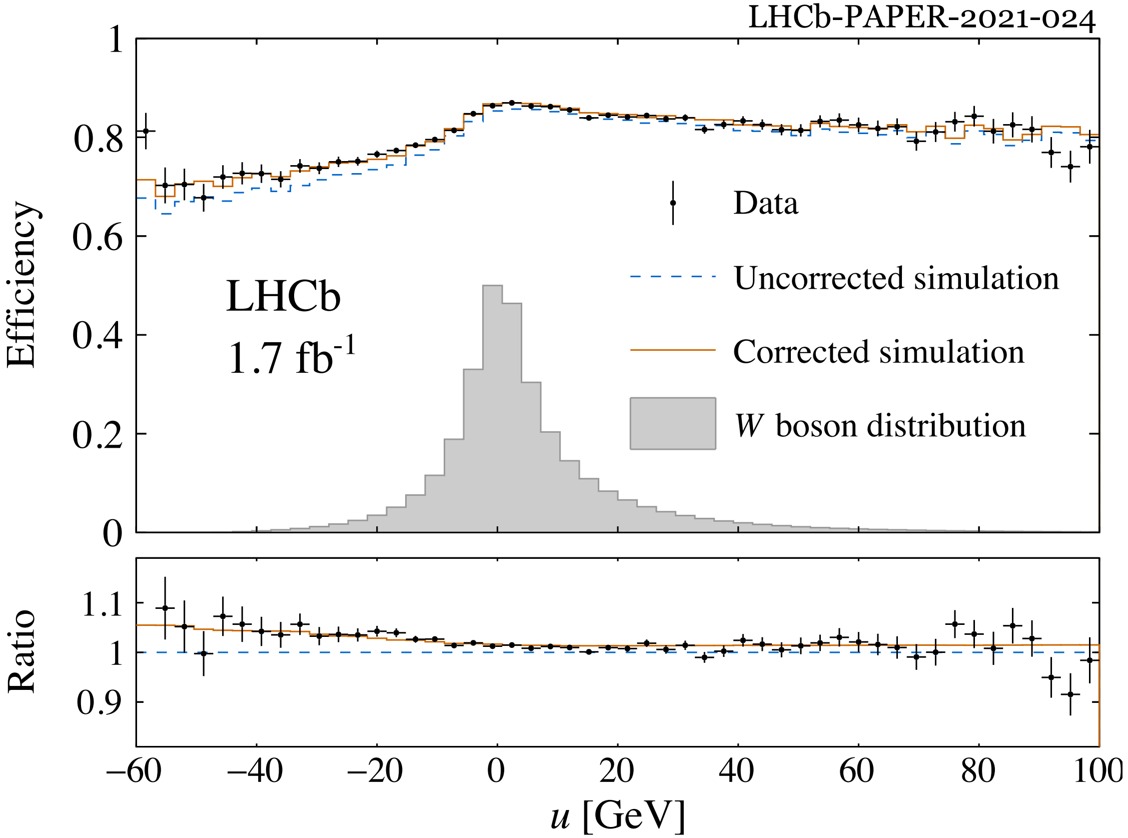
$\Upsilon(1S) \to \mu\mu$

Isolation efficiency

- **Simulated events corrected for data/simulation differences using event-by-event weights.**
- Efficiencies from tag-and-probe method with $Z \to \mu\mu$.
- 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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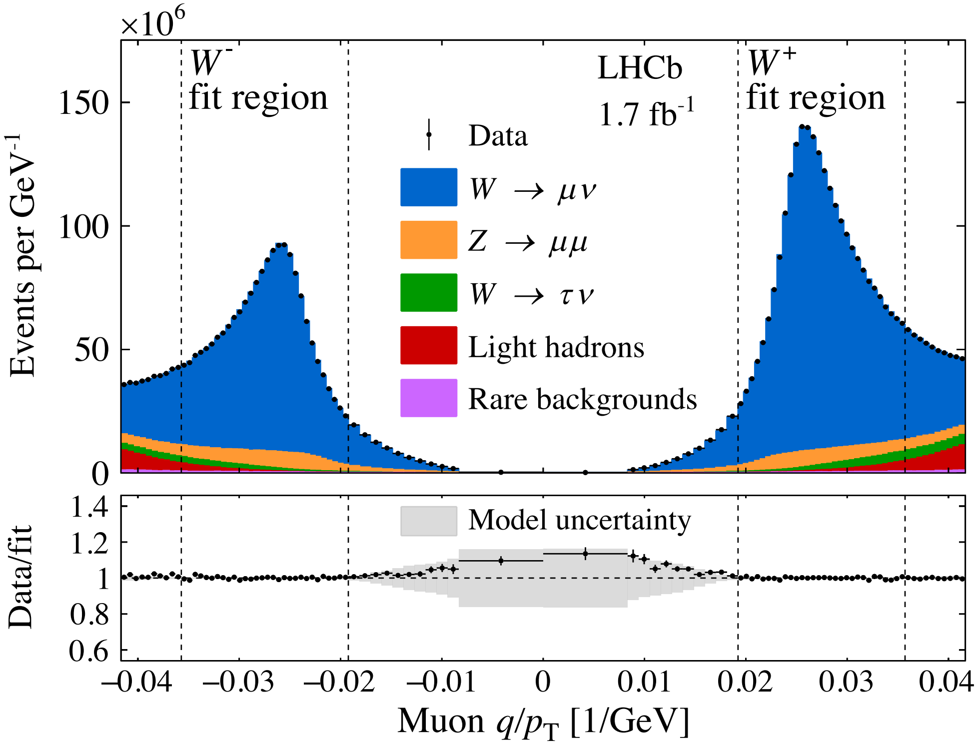
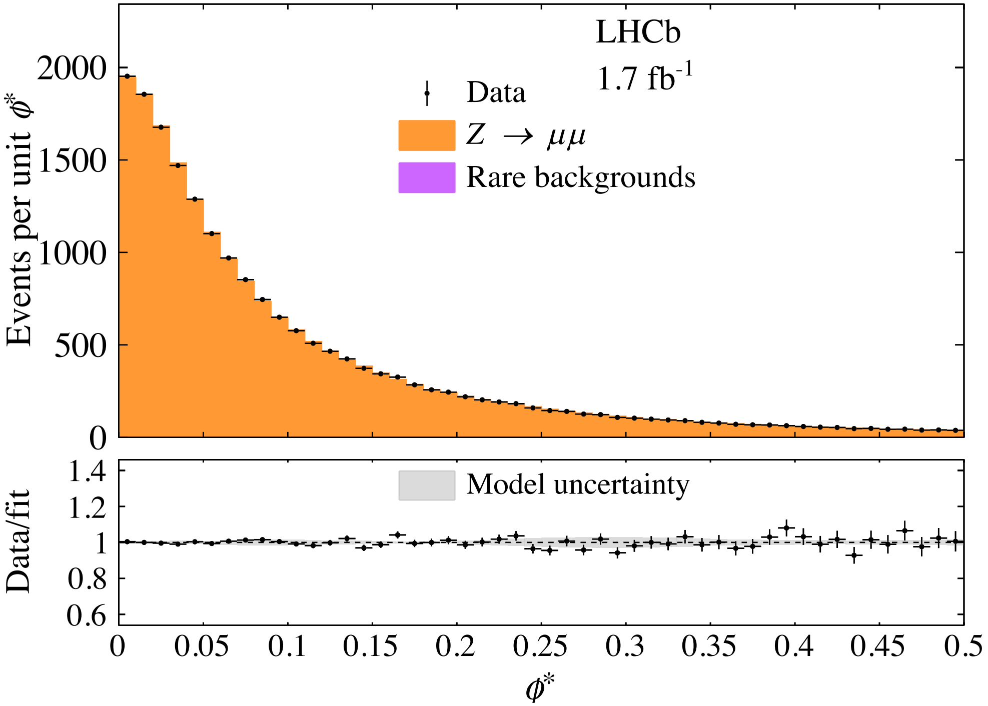
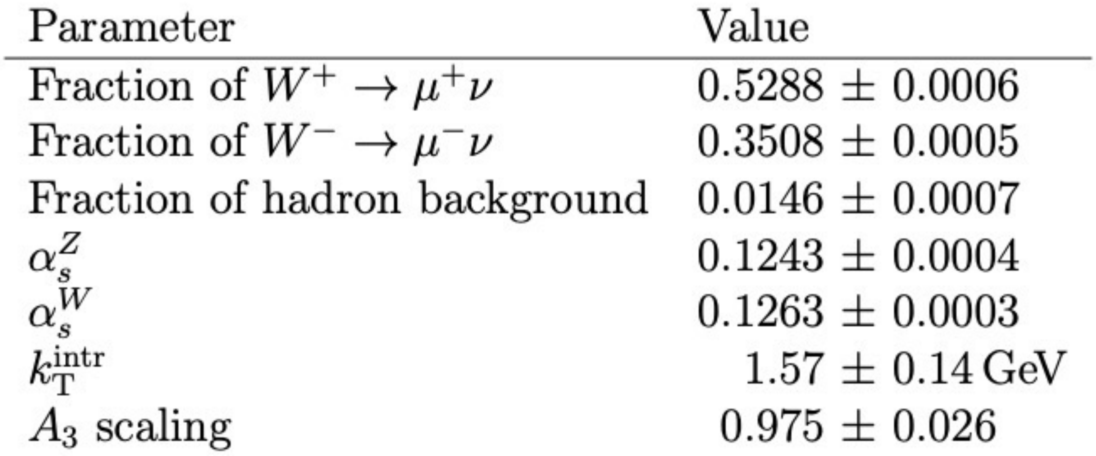






Parameter	Value
Fraction of $W^+ \to \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3508 ± 0.0005
Fraction of hadron background	0.0146 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
$k_{\mathrm{T}}^{\mathrm{intr}}$	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026

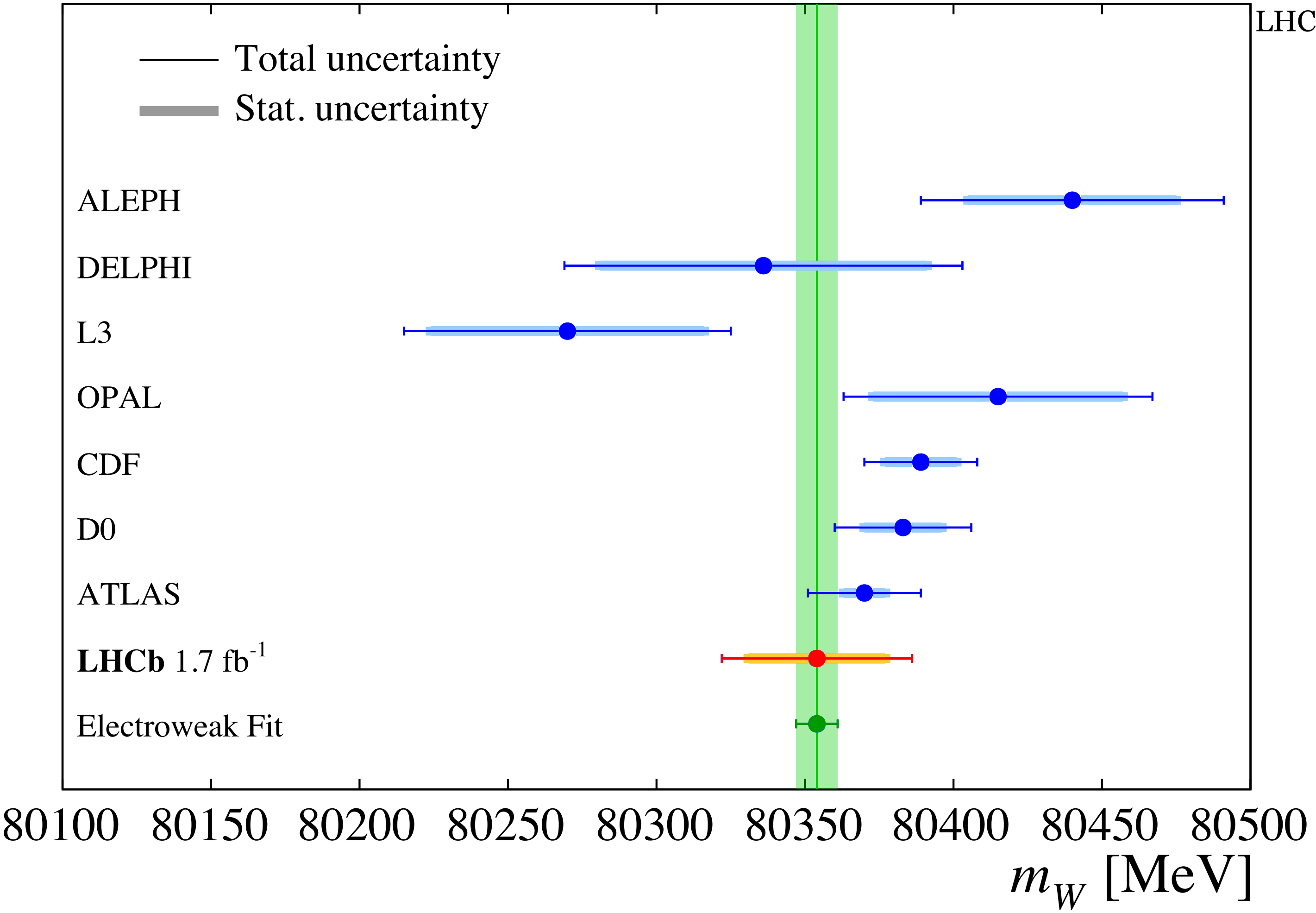
$$\chi^2/ndf = 105/102$$
$$\sigma_{stat} = 23\ \mathrm{MeV}$$

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 POWHEG-EW
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 result

Our central result is the arithmetic average of results with NNPDF31, CT18 and MSHT20:



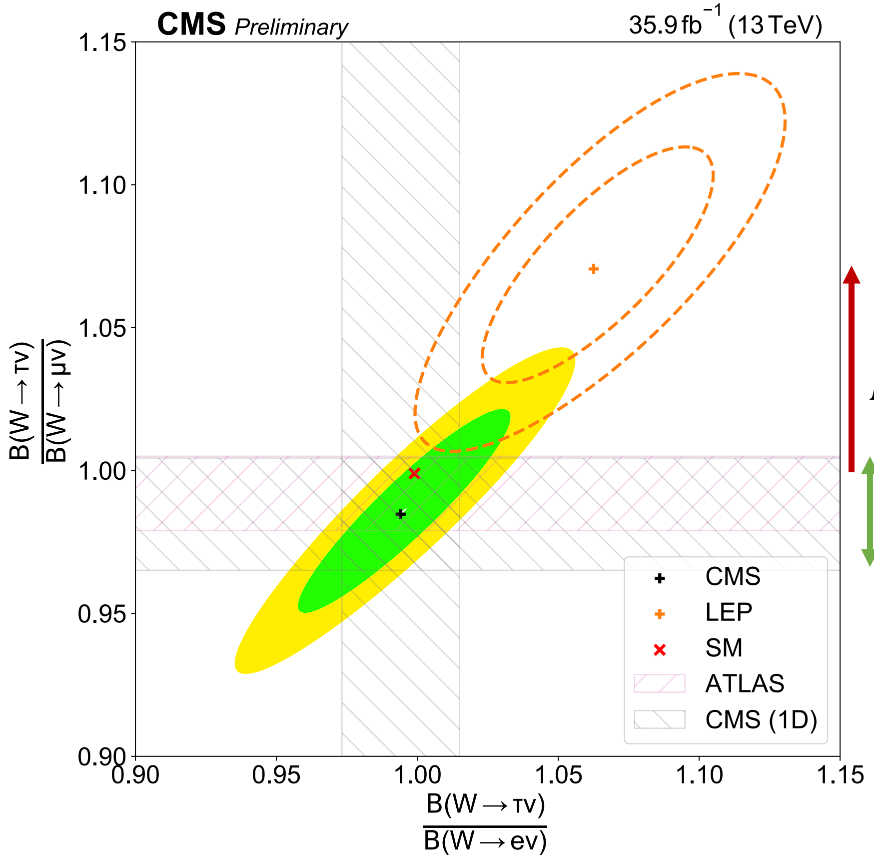
$$\boxed{m_w = 80354 \pm 23_{stat} \pm 10_{exp} \pm 17_{theory} \pm 9_{PDF}\ \text{MeV}}$$

Measurement of $R_{\tau\mu} = B(W \to \tau\nu)/B(W \to \mu\nu)$

(Entering the final stages, unofficial)

Motivation

CMS-PAP-SMP-18-011



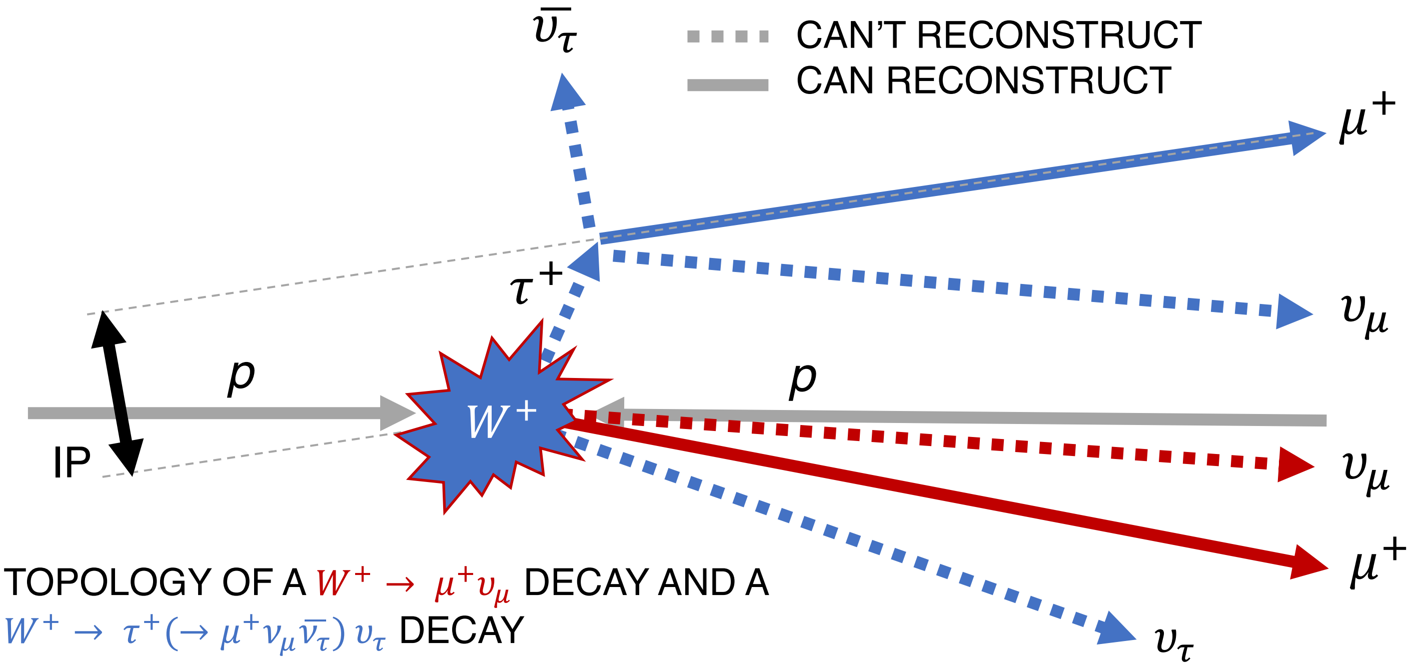
$R_{\tau\mu}^{LEP} - R_{\tau\mu}^{SM\ LFU} = 2.7\sigma$

ATLAS $\Delta R_{\tau\mu} = 1.6\%$

CMS $\Delta R_{\tau\mu} = 2.0\%$

- LEP combination was 2.7σ from the SM expectation (≈ 1).
- Recent ATLAS and CMS $t\bar{t}$ results appear to rule out non-SM behaviour.
- Aim to verify this at similar precision, in a complementary channel.

Similarities/differences with m_W

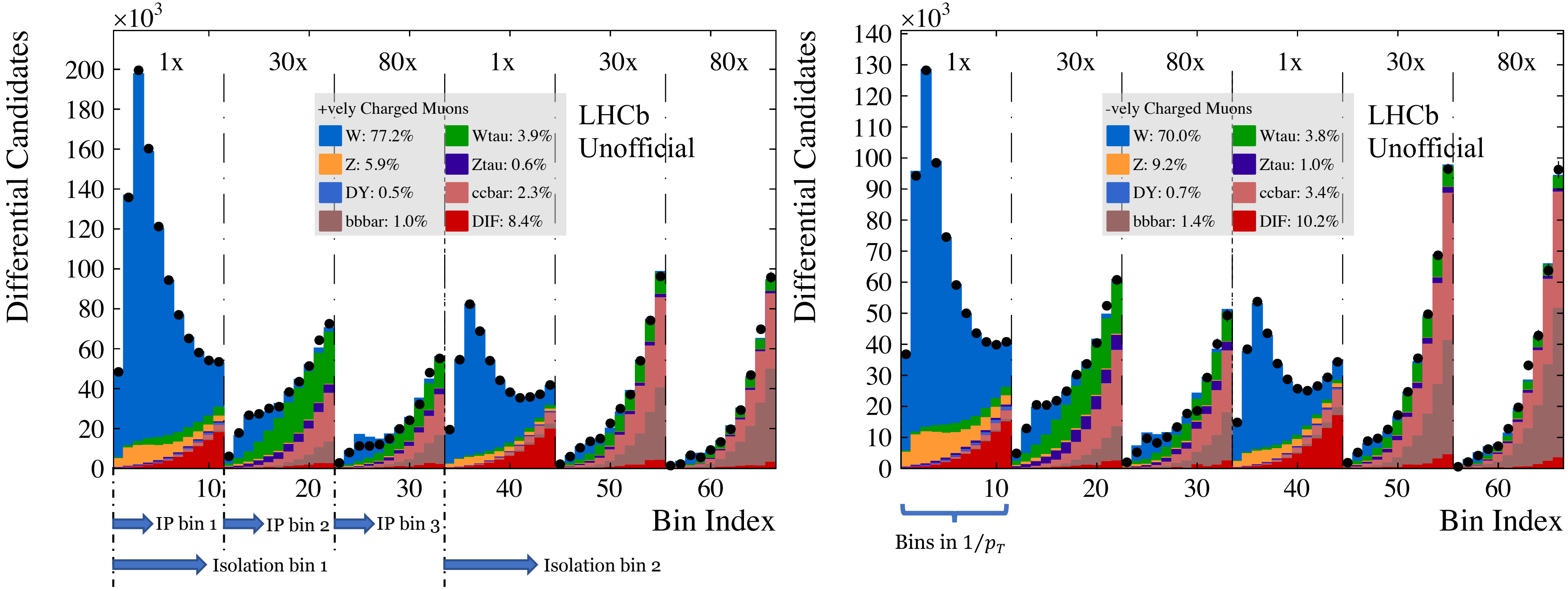


TOPOLOGY OF A $W^+ \to \mu^+\upsilon_\mu$ DECAY AND A
$W^+ \to \tau^+(\to \mu^+\nu_\mu\overline{\nu_\tau})\,\upsilon_\tau$ DECAY

- Both $W \to \mu\nu$ and $W \to (\tau \to \mu\nu\nu)\nu$ give a single high-pT, isolated muon.
  - ✓Also just the 2016 data.
  - ✓Same physics model.
  - ✓Same efficiencies, alignment & calibration.
- Muons from taus are displaced and lower in p_T.
  - Heavy flavour and hadronic decay-in-flight backgrounds are more problematic!

Fit for $R_{\tau\mu}$

To control these important backgrounds we (template) fit the single muon data in 3D: muon $1/p_T$, impact parameter and isolation. Flattened to 1D:

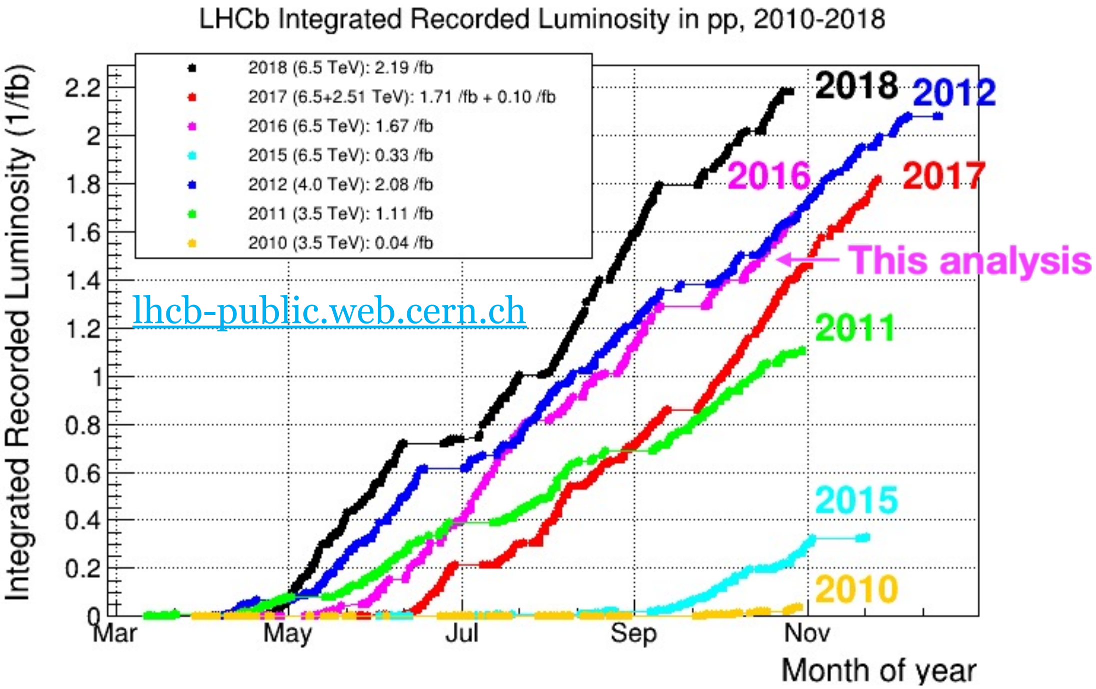


- At the final stages of tweaking and assessing systematics.

Conclusions and outlook

- 2016 measurement of the W boson mass at LHCb achieves a precision of ~32 MeV. 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.



This analysis

lhcb-public.web.cern.ch

- $R_{\tau\mu}$ measurement with the same dataset is nearing completion, and aims to test LFU at a similar precision to recent ATLAS/CMS results, in a complementary channel.

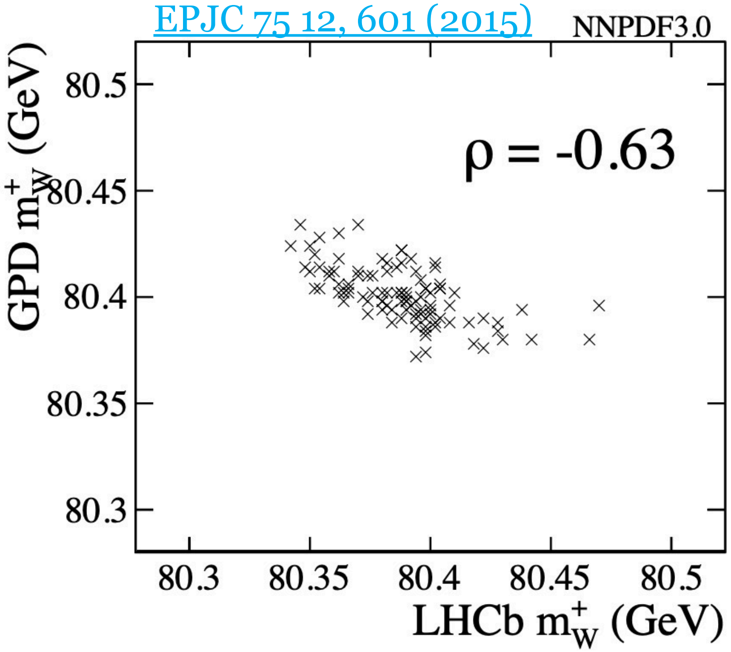
- W mass paper accepted by JHEP, will be published shortly. We're working hard on the full Run 2 measurement!

Thank you for your attention.
Any questions?

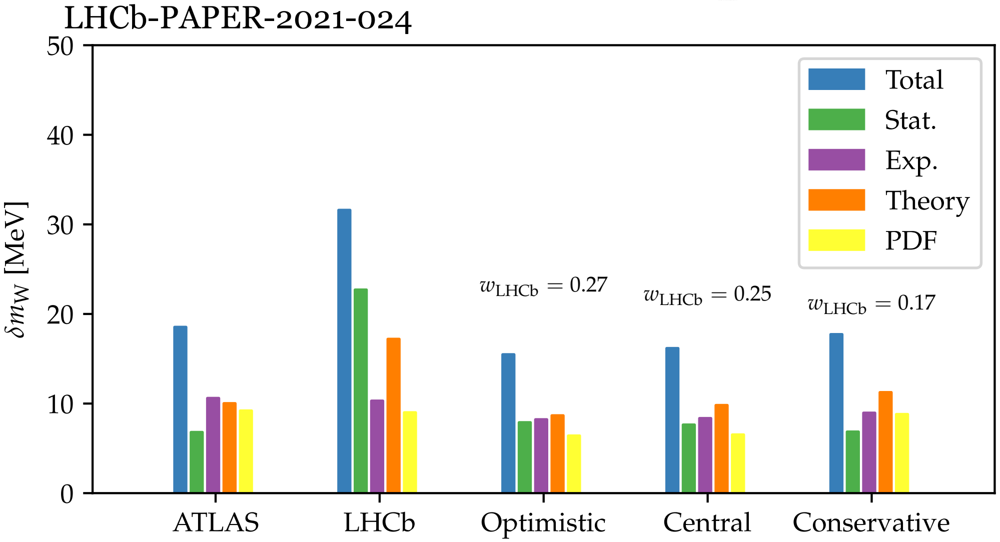
Backup

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

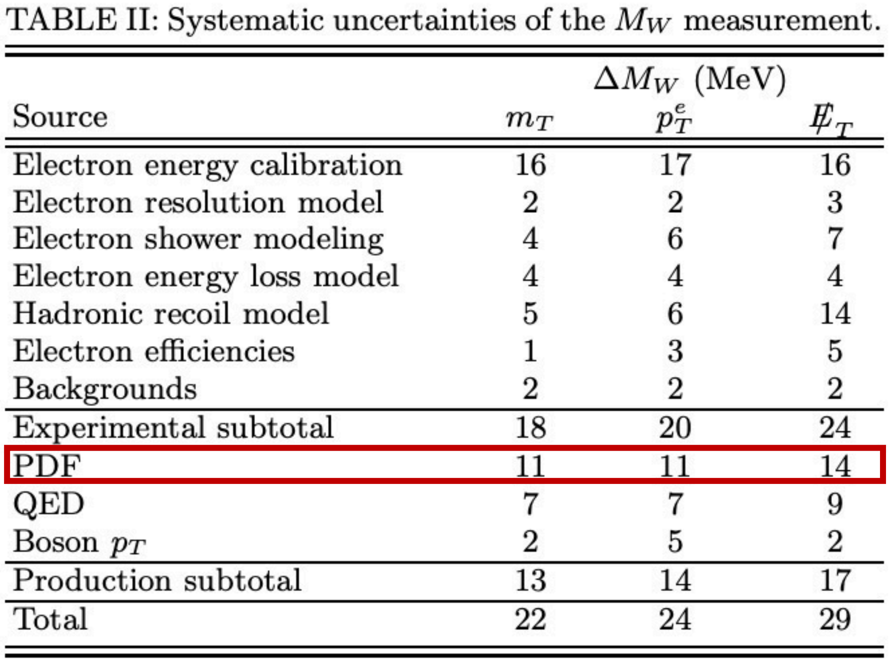
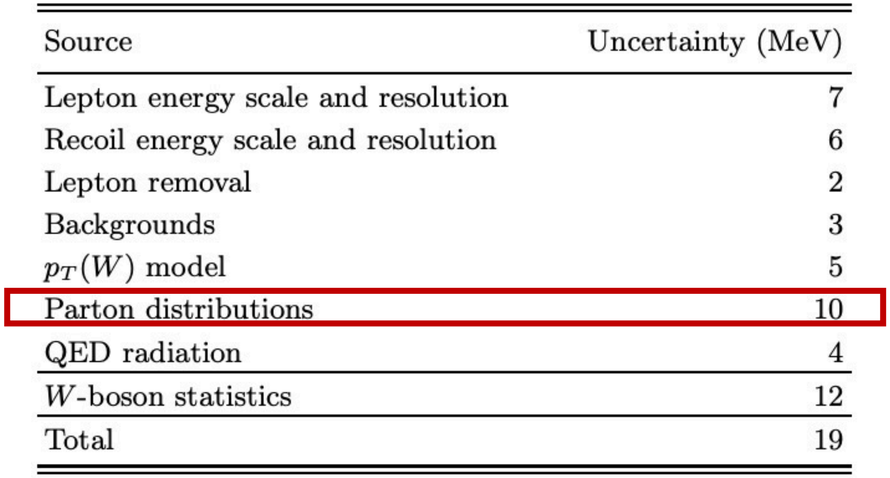


TABLE II: Systematic uncertainties of the M_W measurement.

	ΔM_W (MeV)		
Source	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

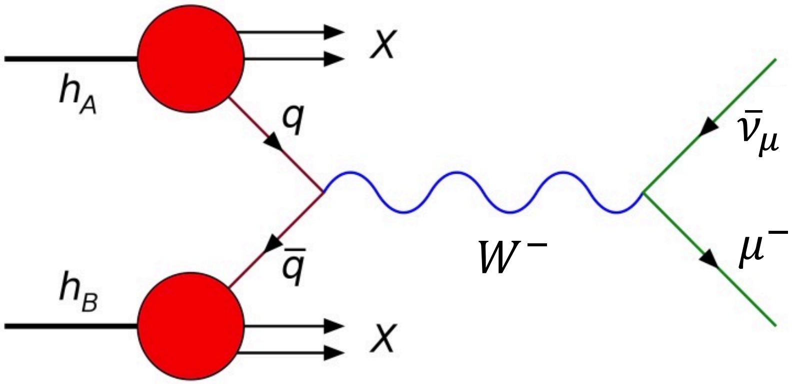
D0: PRL 108 (2012) 151804



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

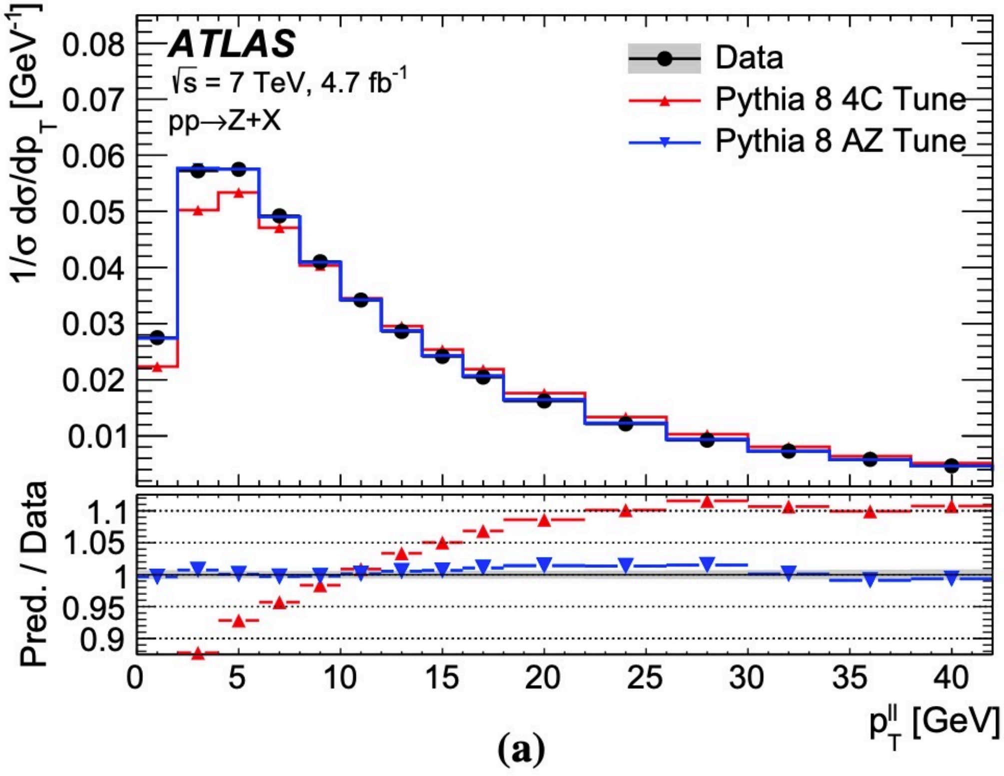
- Expected to be a bigger problem for pp collisions rather than $\bar{p}p$:



Fitting the Z ϕ^* distribution

EPJC 78, 110 (2018)

- We could fit p_T^Z:
- But v. sensitive to all detector modelling effects!



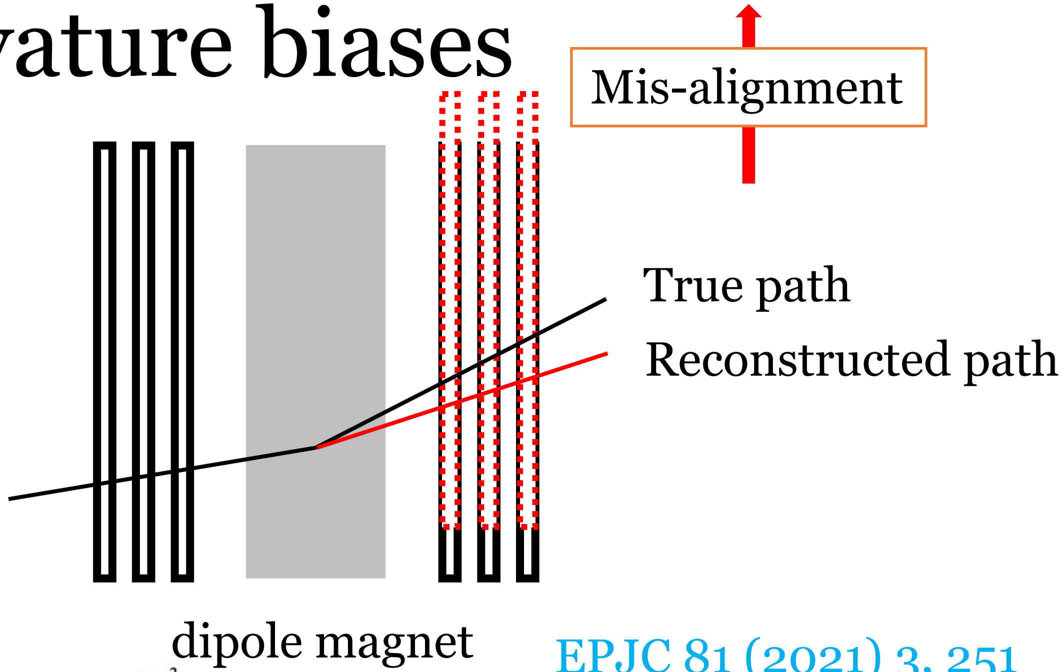
(a)

- 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 $M^{\pm}$ → curvature bias corrections.

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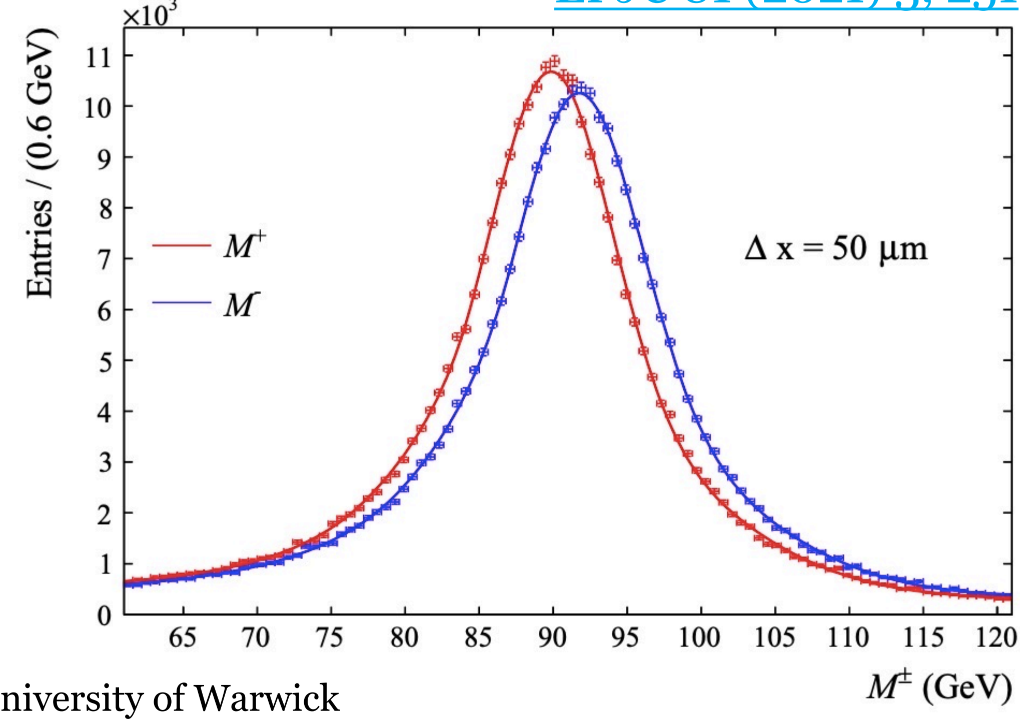

Inspired by PRD 91, 072002 (2015)

Charge-dependent curvature biases

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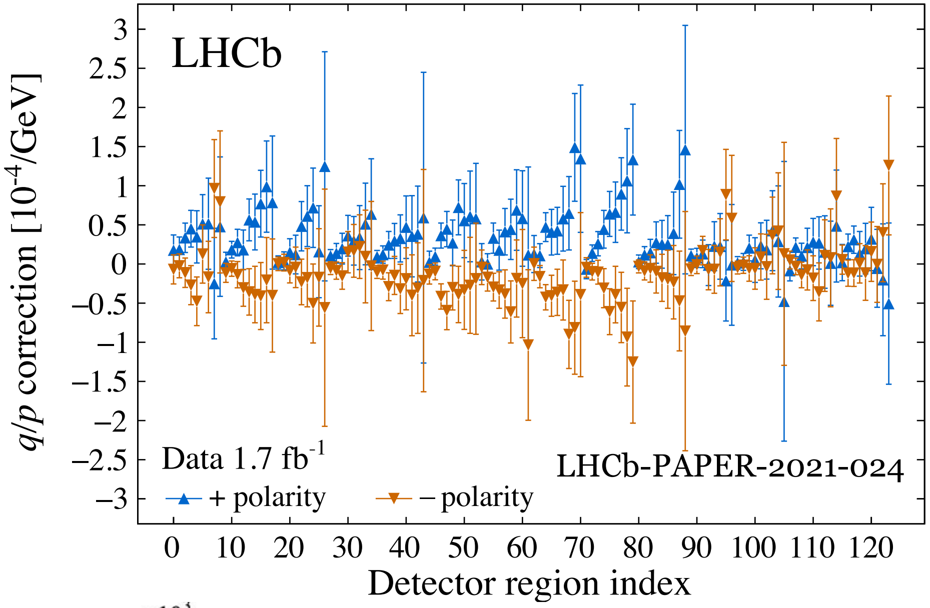

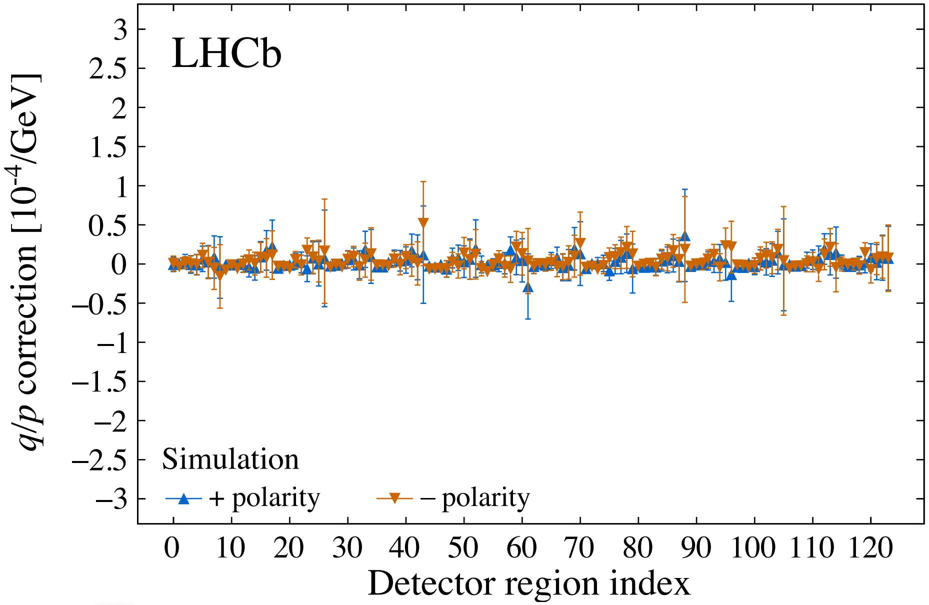

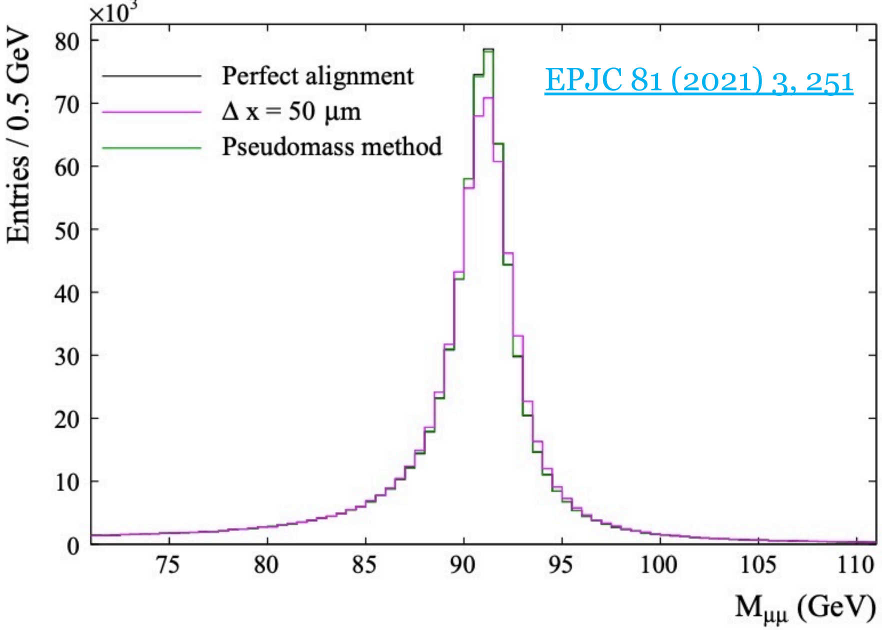

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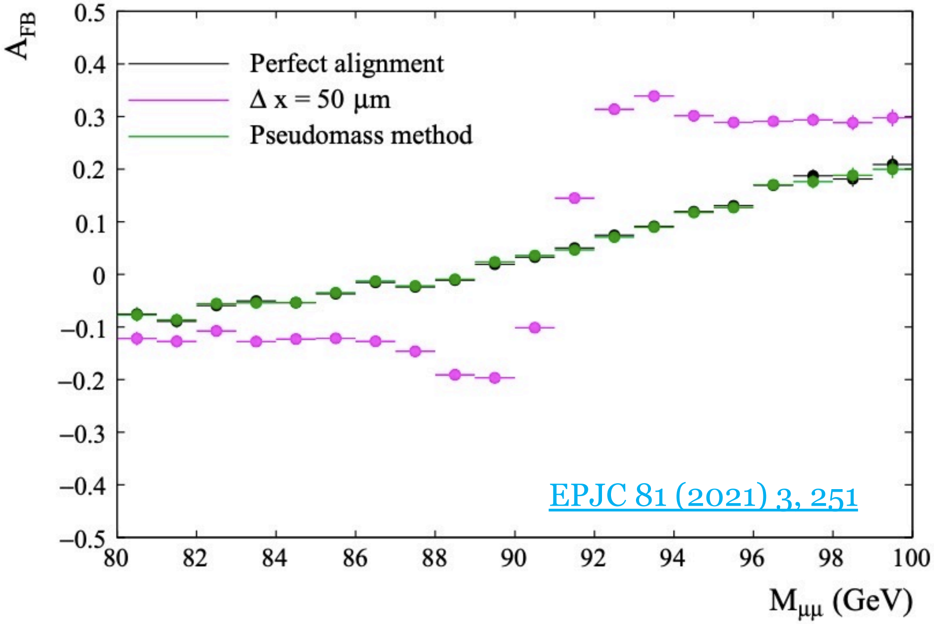

EPJC 81 (2021) 3, 251

Momentum smearing function

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

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

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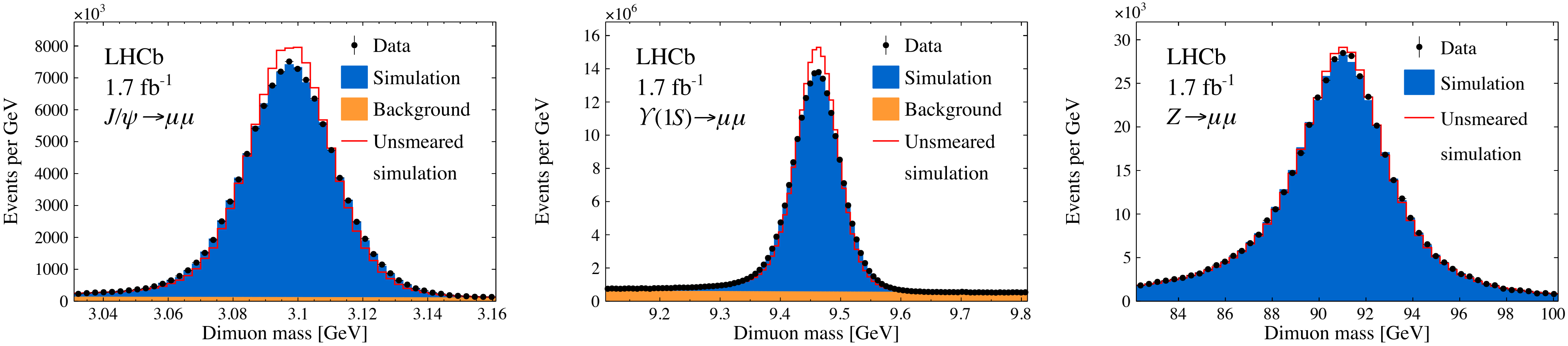
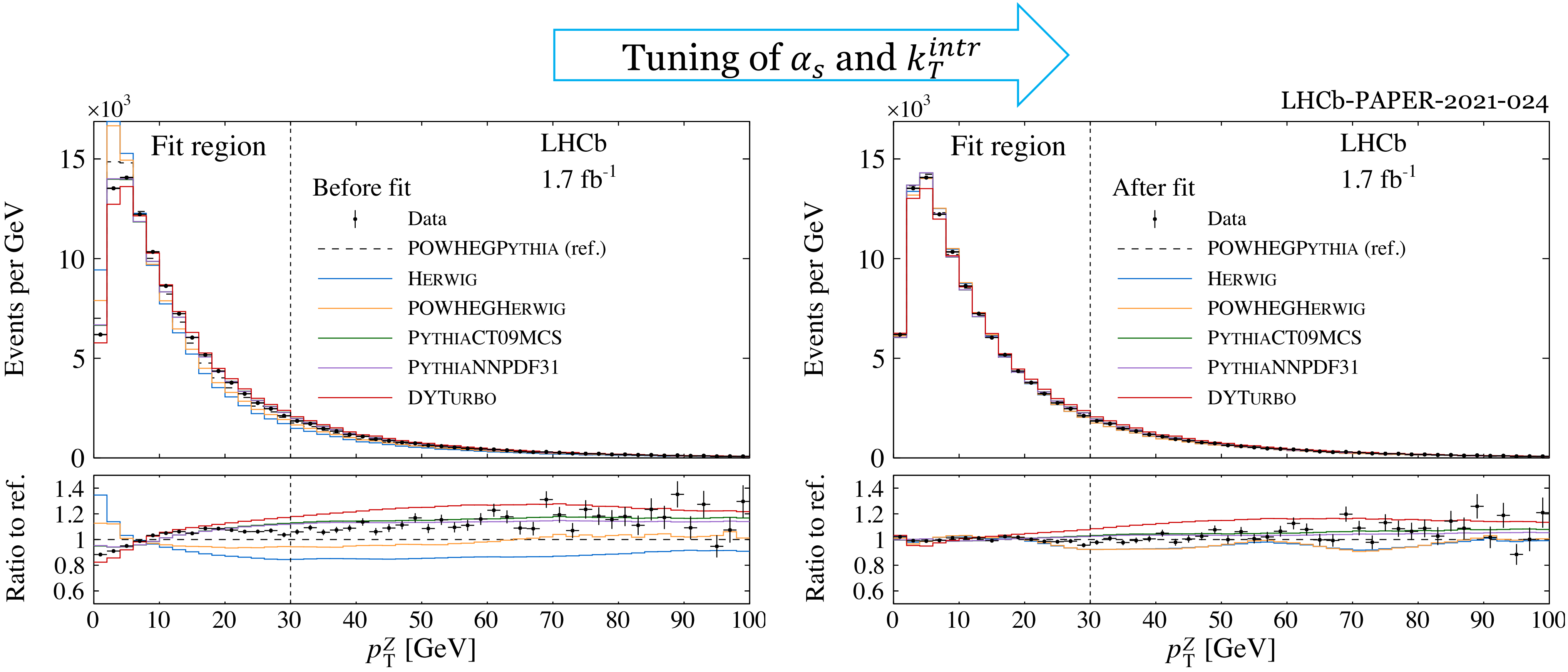


Effects modelled are curvature bias (δ), momentum *scale* ($1+\alpha$), momentum-independent (σ_{MS}) and momentum-dependent (σ_δ) smearing.

POWHEG+Pythia as central model



Tuning of α_s and k_T^{intr}

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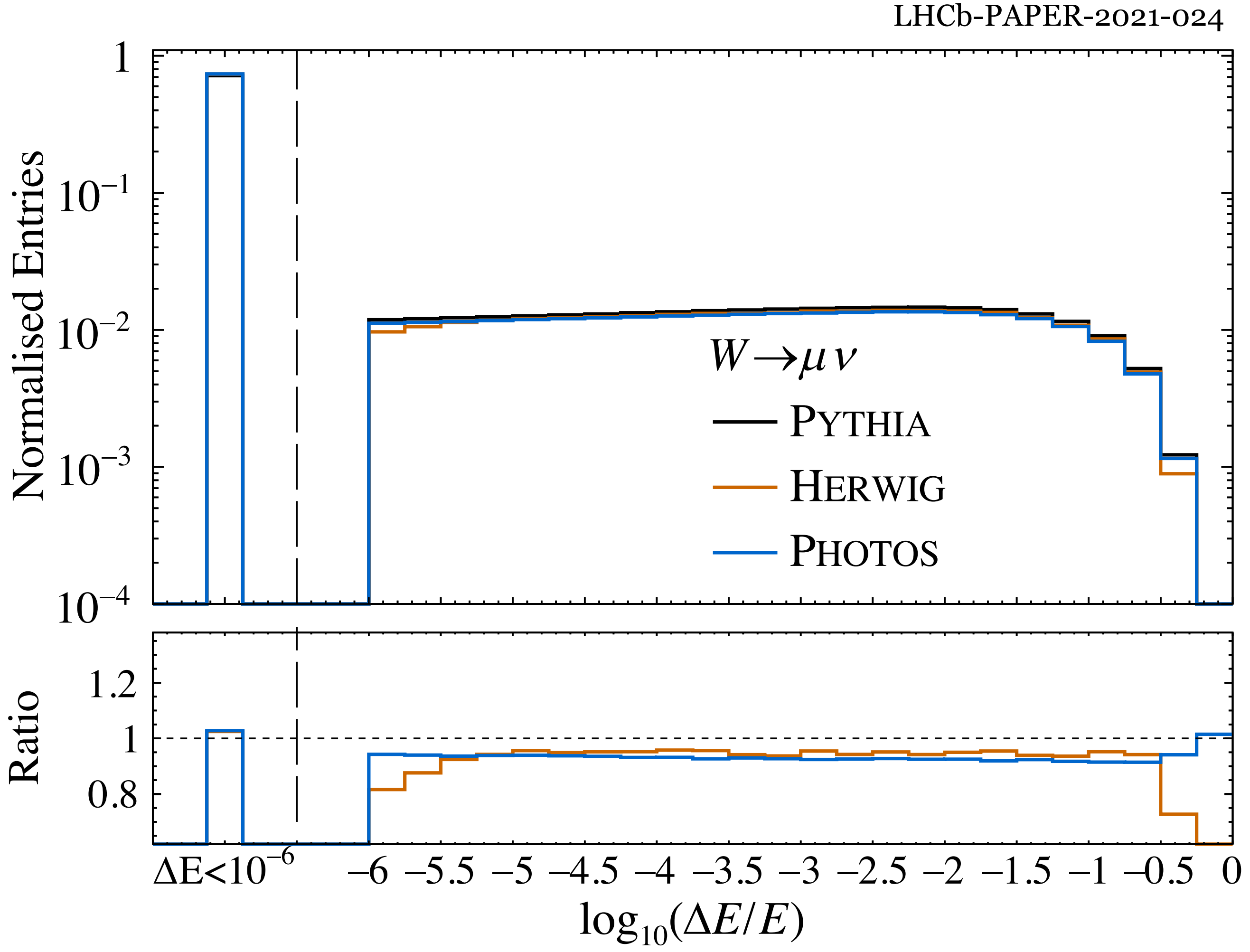
- POWHEG-Box + Pythia8 = best description of p_T^Z -> our central model.
- Other models (POWHEG-HERWIG, PYTHIACT09MCS, PYTHIANNPDF31 and HERWIG NLO) are used to evaluate systematic uncertainty (12 MeV).

Electroweak Corrections



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