Towards the next W mass measurement at LHCb

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(on behalf of the LHCb collaboration)

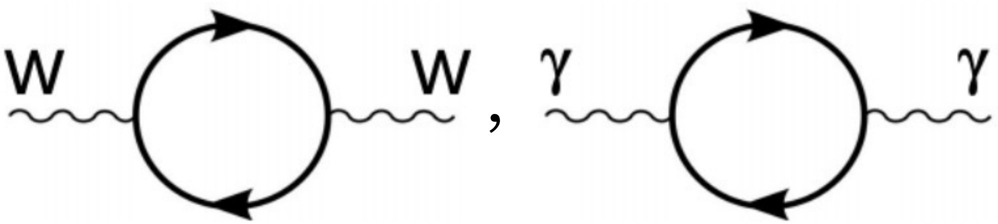
Implications of LHCb measurements and future prospects
19th - 21st October 2022, CERN

European Research Council
Established by the European Commission

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? …

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

Status of the field

- 2021 global EW fit:

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

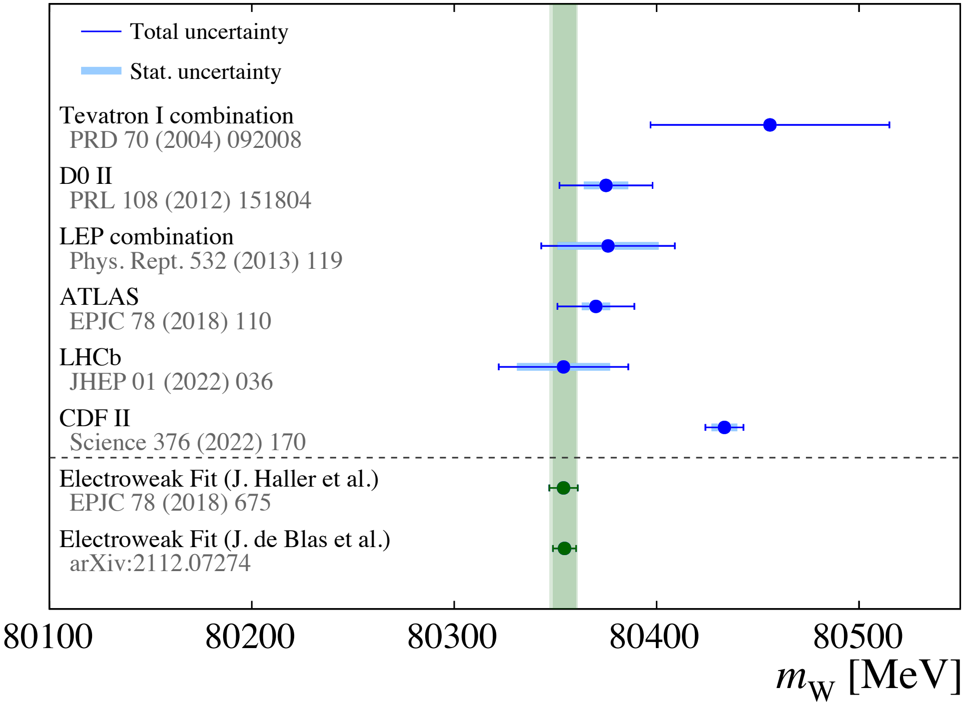
- Recent direct measurements:

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

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

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

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



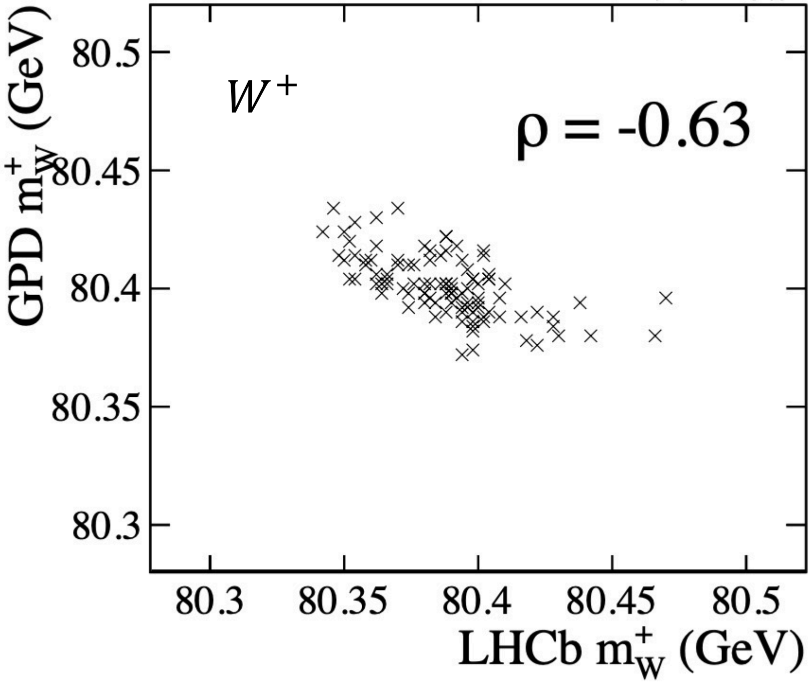
LHCb-FIGURE-2022-003

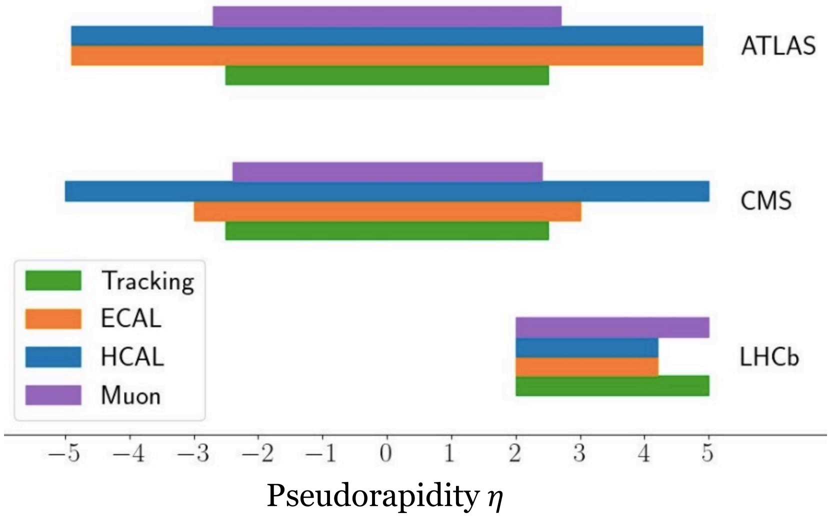
More m_W measurements from the LHC are necessary!

Why LHCb?

- LHCb Run-2 data: $\mathcal{O}(10)$ MeV statistical uncertainty on m_W ($\mathcal{O}(10^7)$ $W \to \mu\nu$ candidates),
- Historically-limiting PDF uncertainties expected to anti-correlate in a GPD-LHCb combination by up to factor of two.
- The challenge is suppressing the experimental & theoretical systematic uncertainties!

EPJC 75 12, 601 (2015)





How we measure m_W

- $W \rightarrow \mu\nu$ 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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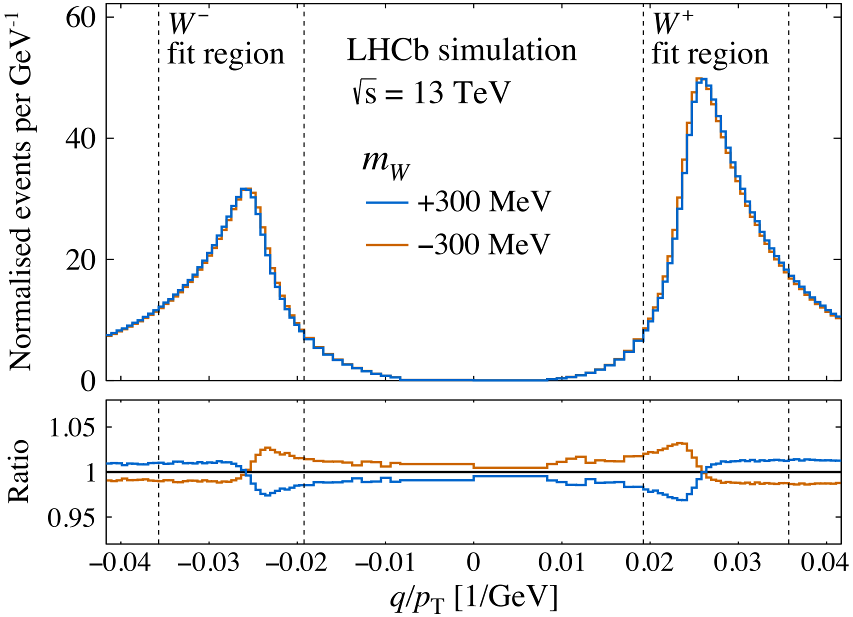
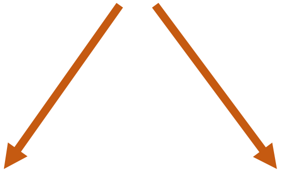




<u>"Detector" modelling</u>

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

- Under our control,
- Uncertainties largely scale with the size of the control samples.

<u>"Physics" modelling</u>

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

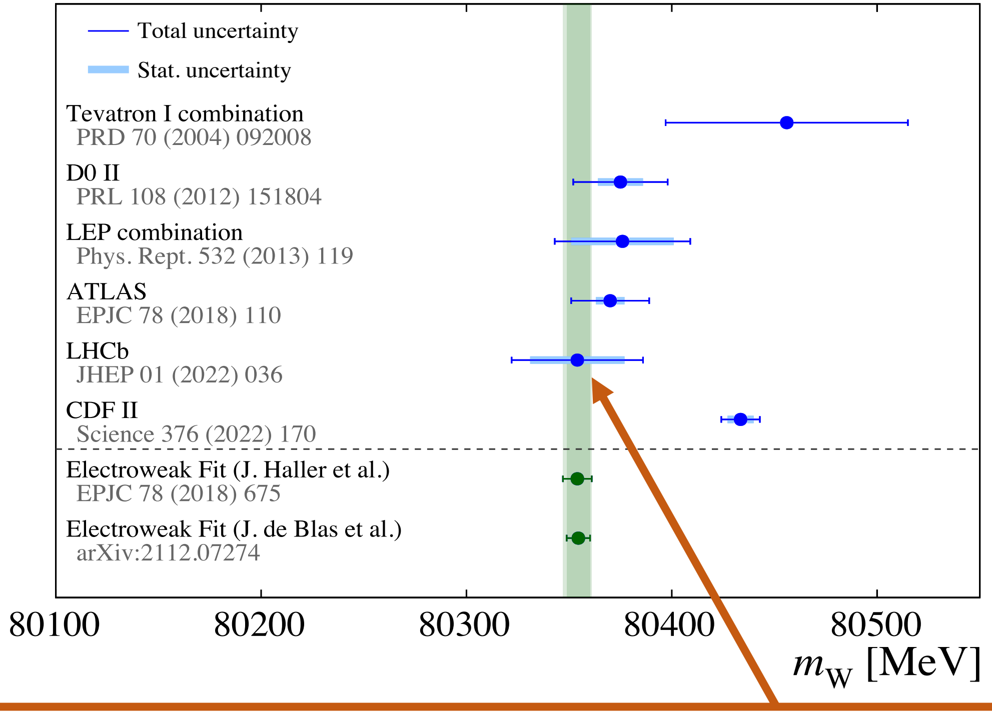
- Mostly external, theory-based inputs,
- Uncertainties inherent in the method/tools.

Our proof-of-principle measurement

- Given the challenging theoretical uncertainties, converged on the strategy:

1) A proof-of-principle measurement with the 2016 data,
2) A full-Run-2 measurement targeting $\Delta m_W \approx 20\text{MeV}$ (approx. as precise as ATLAS).

- The first step is complete. Published in January (JHEP 01 (2022) 036):



LHCb-FIGURE-2022-003

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

Uncertainty breakdown in 2016 measurement

Source	Size [MeV]
Parton distribution functions	**9.0**
Theory (excl. PDFs) Total	**17**
Transverse momentum model	11
Angular Coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental Total	**10**
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	**23**
Total	**32**

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

Experimental uncertainties

Source	Size [MeV]
Parton distribution functions	**9.0**
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- Systematic uncertainties originated from
    - Control sample size,
    - Details of the methods (binnings, smoothing, choice of parametrisation etc.),
    - External inputs ($\Upsilon(1S)$ mass).
- Expected to largely reduce as the data sample grows (by 3x) from 2016 to 2016-18.
- Work ongoing on gaining deeper understanding and simplifying/consolidating if possible.
- These should not become limiting uncertainties.

Theoretical uncertainties

Source	Size [MeV]
Parton distribution functions	**9.0**
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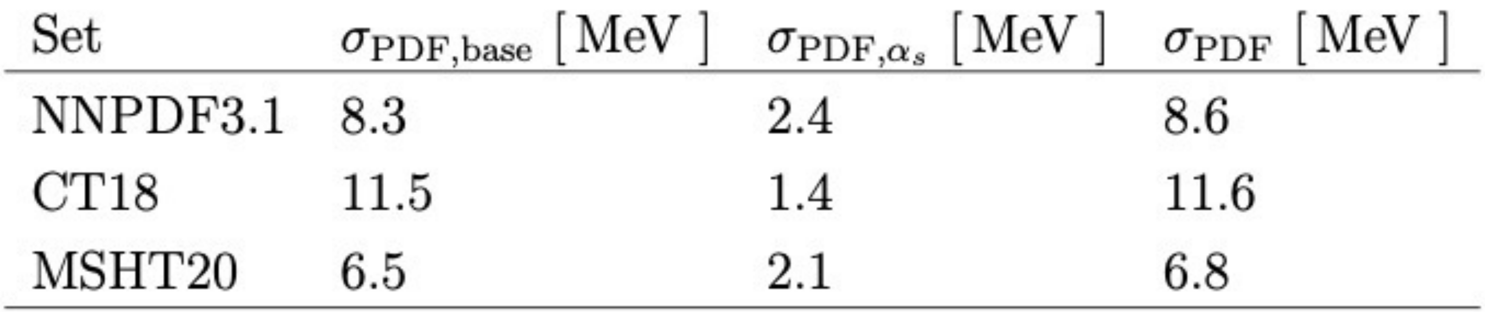
- Largely external inputs,
- Won’t come down with more LHCb data.
- What can we do about these uncertainties?

Parton distribution functions

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

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

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



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

- Analysis framework set-up to quickly integrate new PDF sets (e.g. NNPDF4.0).
- Fortunately only 9 MeV, and should anti-correlate in a GPD-LHCb combination.

Angular coefficients

At the Born level
(before QED FSR):

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

Unpolarised cross-section

Angular terms
(A_i = angular
coefficients)

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

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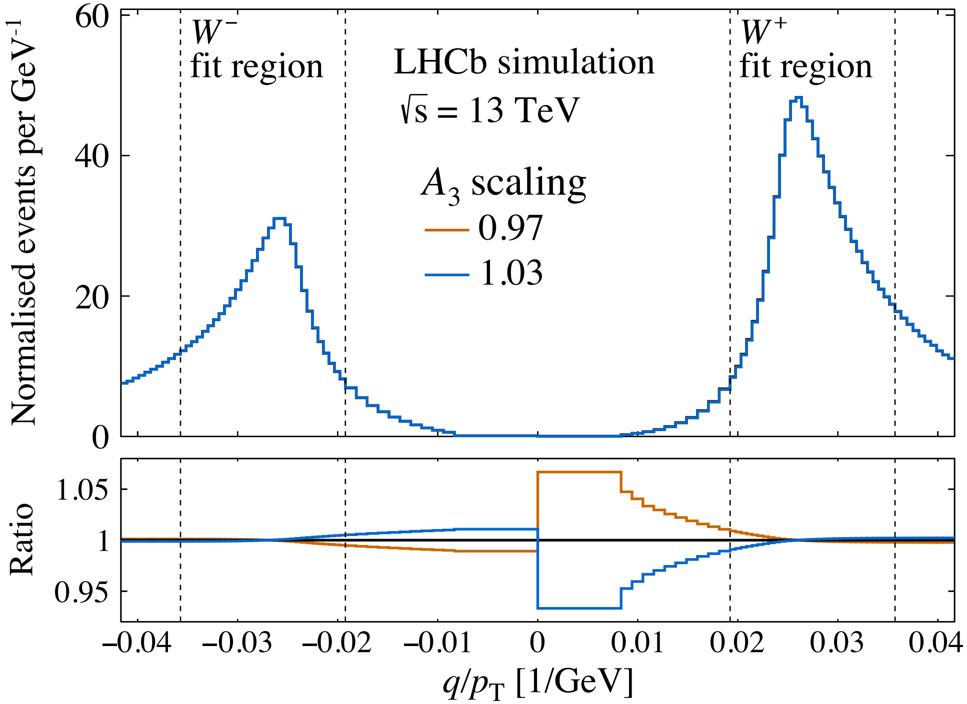
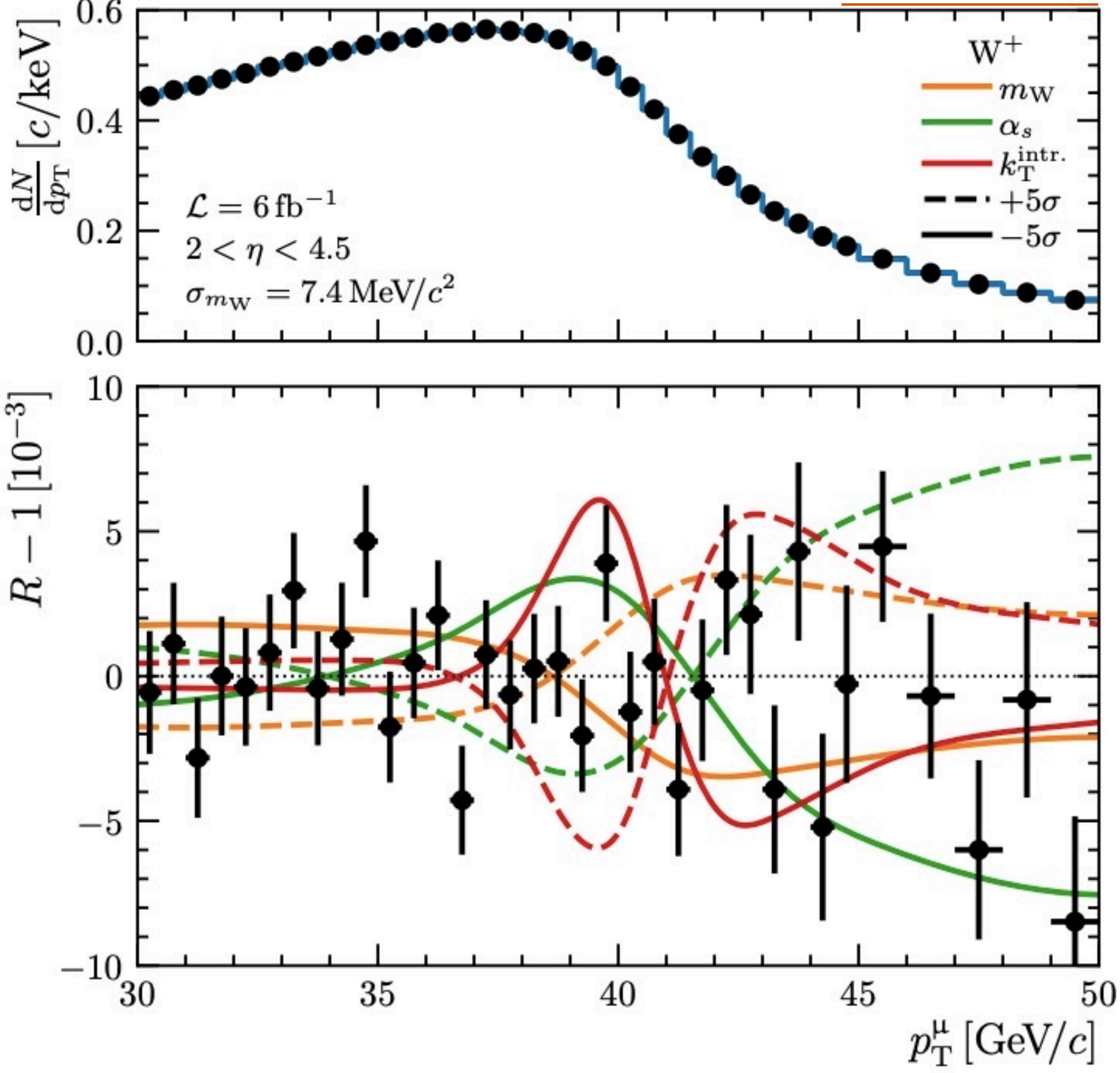


2016 measurement strategy:

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

Physics modelling: σ^{unpol}

arXiv:1907.09958



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

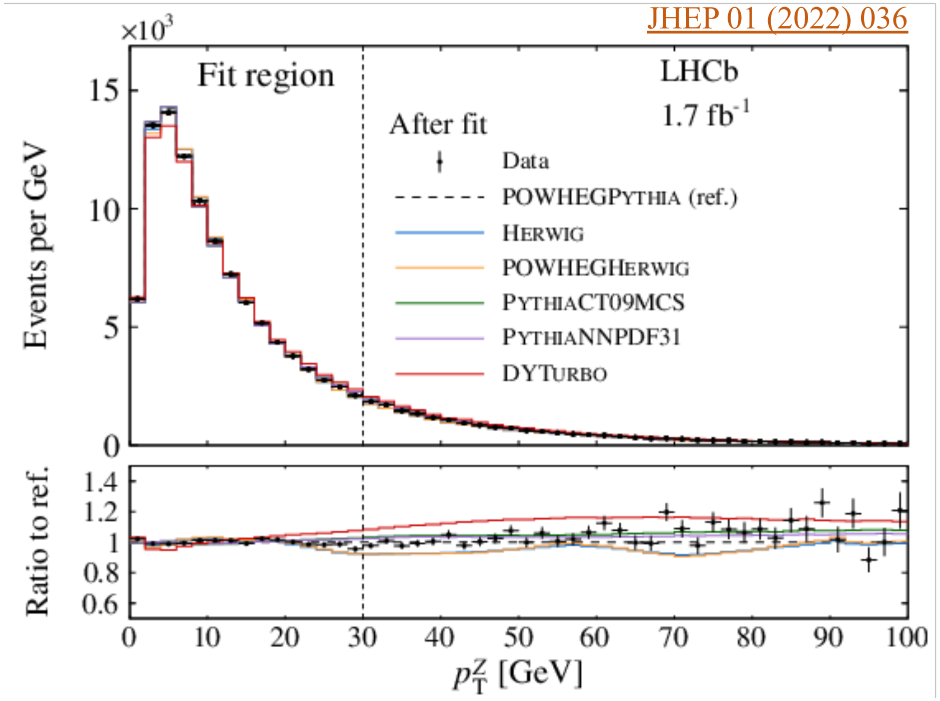
- POWHEG-Box + Pythia8 was our central model.
- Previous m_W measurements rely on tuning to p_T^Z. Does this tune hold for p_T^W?
- Variations in α_S and k_T^{intr} affect p_T^μ differently to variations in m_W.

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

Boson p_T model uncertainty

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

- QCD predictions with higher perturbative accuracy are available e.g. from DYTurbo.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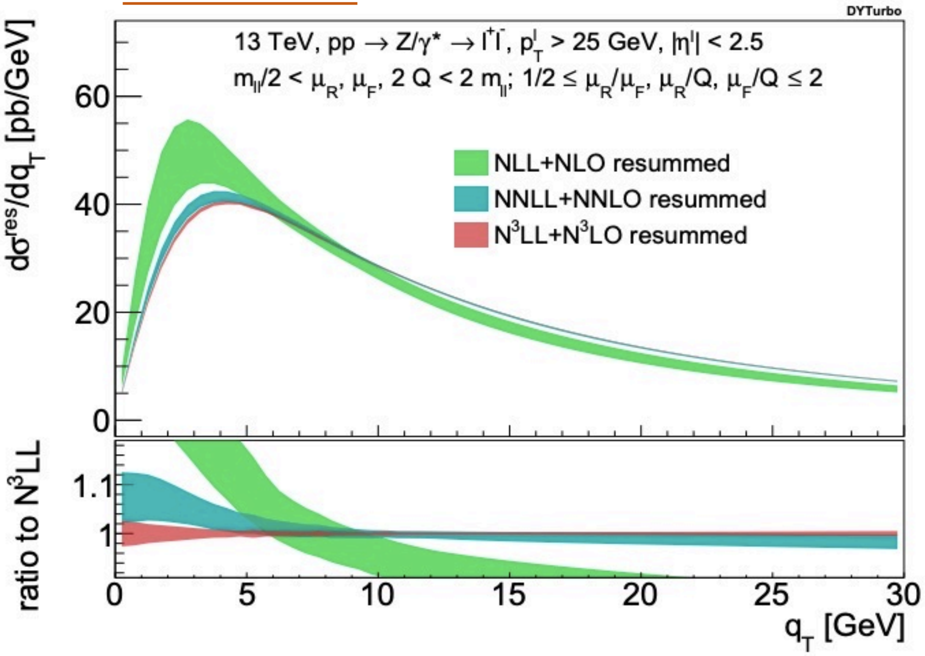
arXiv:2103.04974



QED Final State Radiation

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

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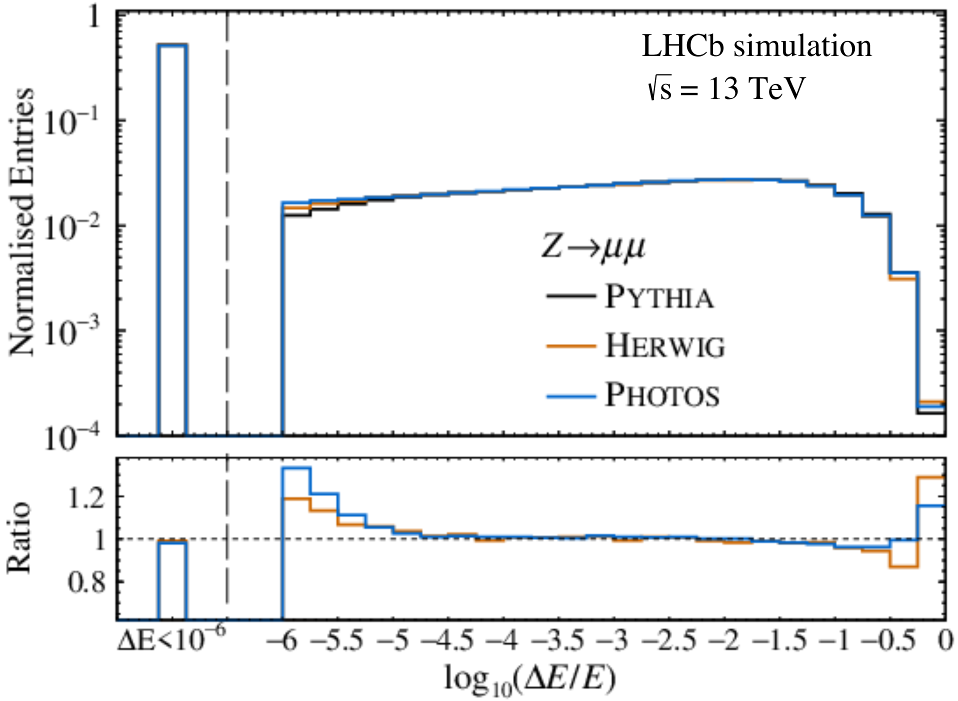

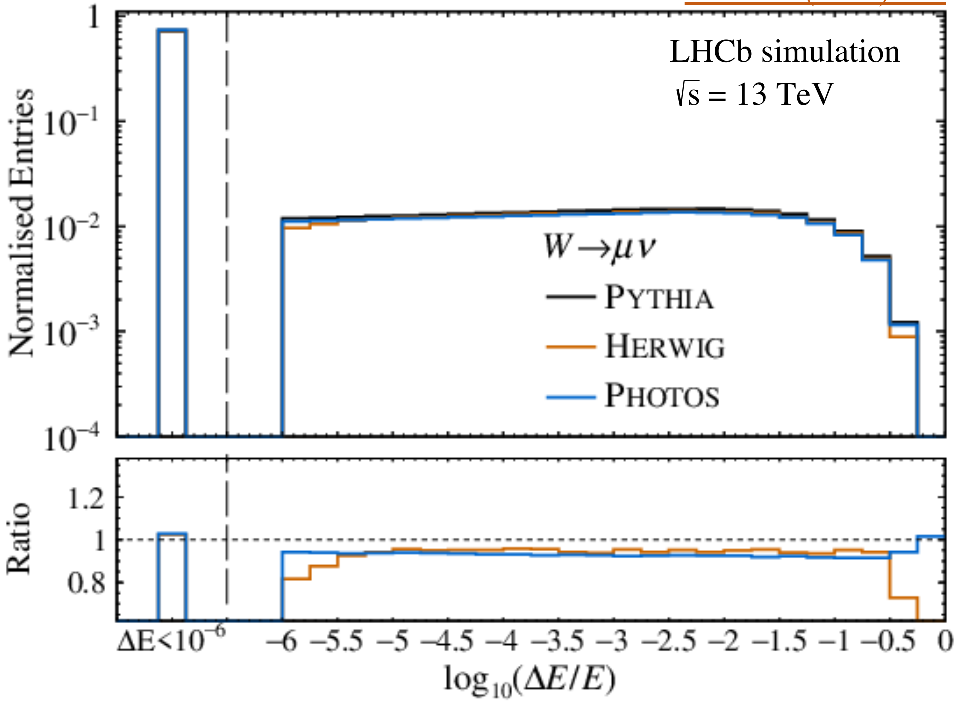

- Uncertainty is just the envelope of fits from all three (templates weighted in ΔE/E to the different models),

- A more systematic treatment of this uncertainty (e.g. varying the key details/scales) can be taken.

Theoretical uncertainties

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- Largely external inputs,
- Won’t come down with more LHCb data.
- What can we do about these uncertainties?
- We can make more controlled/systematic evaluations of the uncertainties, and use higher-accuracy tools.
- The theory community’s input is very welcome.

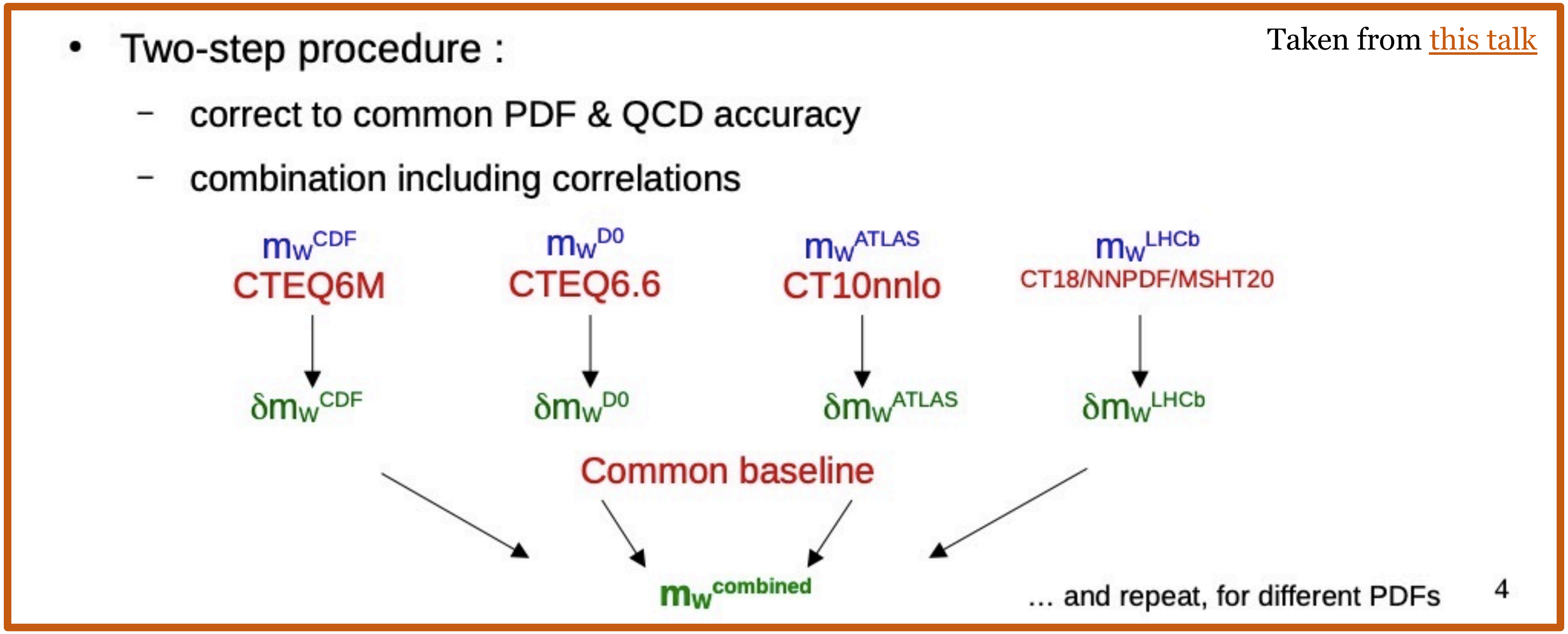
Looking further ahead

m_W combinations & beyond Run 2

m_W cross-experiment combinations

- Large effort ongoing in the Tevatron-LHC W-boson mass Combination Working Group,

- Need to translate measurements to a common PDF set and a common description of QCD.
  - Easy for LHCb as we can readily re-run our measurement with new PDF set, QCD predictions etc.



Taken from this talk

- Two-step procedure :
  - correct to common PDF & QCD accuracy
  - combination including correlations

m_W^{CDF} CTEQ6M → δm_W^{CDF}

m_W^{D0} CTEQ6.6 → δm_W^{D0}

m_W^{ATLAS} CT10nnlo → δm_W^{ATLAS}

m_W^{LHCb} CT18/NNPDF/MSHT20 → δm_W^{LHCb}

Common baseline

$m_W^{combined}$

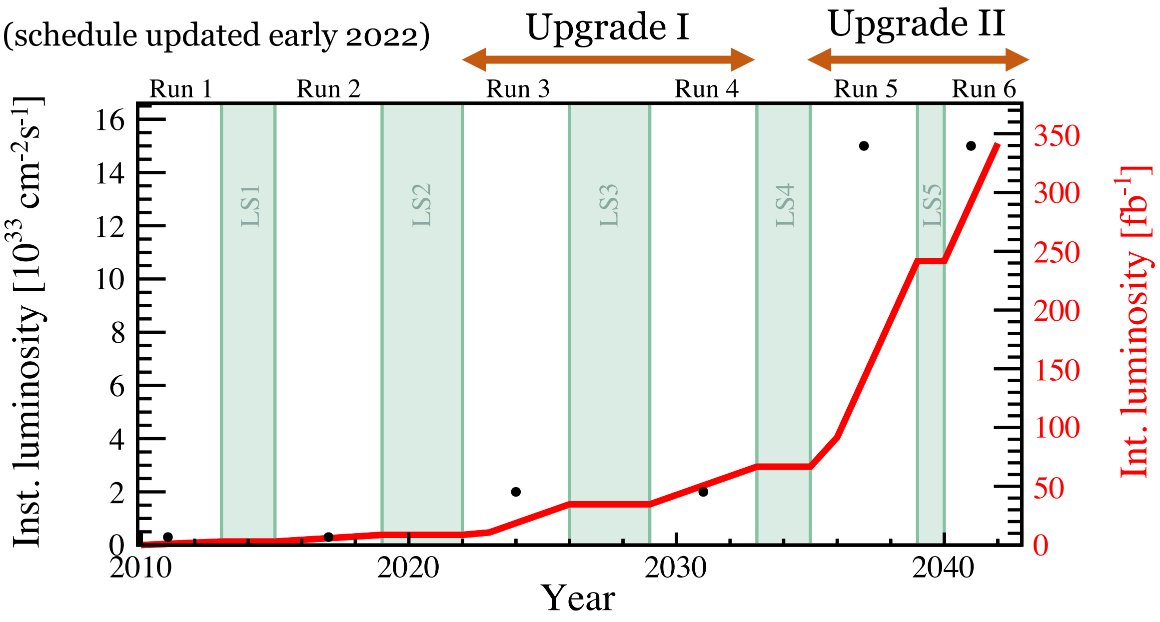
… and repeat, for different PDFs

4

- Recent update confirms a CDF-I, D0, ATLAS + LHCb combination is not far away. Anti-correlation in PDF uncertainties is seen as expected.

Beyond Run 2

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



2016

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

Run 2

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

Run 3-4

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

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

- Upgraded ECAL of the LHCb Upgrade II detector will permit m_W measurement in $W \to e\nu$, with largely orthogonal experimental uncertainties to $W \to \mu\nu$.

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

Summary

- More extractions of m_W are necessary for understanding the tension between recent measurements and probing new physics in the EW sector,

- LHCb has already published a proof-of-principle measurement, with $\Delta m_W = 32$ MeV. Full-Run-2 measurement targets $\Delta m_W \approx 20$ MeV,

- $\Delta m_W(stat)$ will reduce to ≈ 14 MeV; experimental systematics will largely reduce with the larger control samples,

- Strategies are taking shape to reduce our key systematic uncertainties related to theoretical inputs,

- Further input from the theory community is always welcome!

- Run 3 is underway, and we can look forward to even more precise measurements in the future!

Thank you for your attention.
Any questions?

Backup

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 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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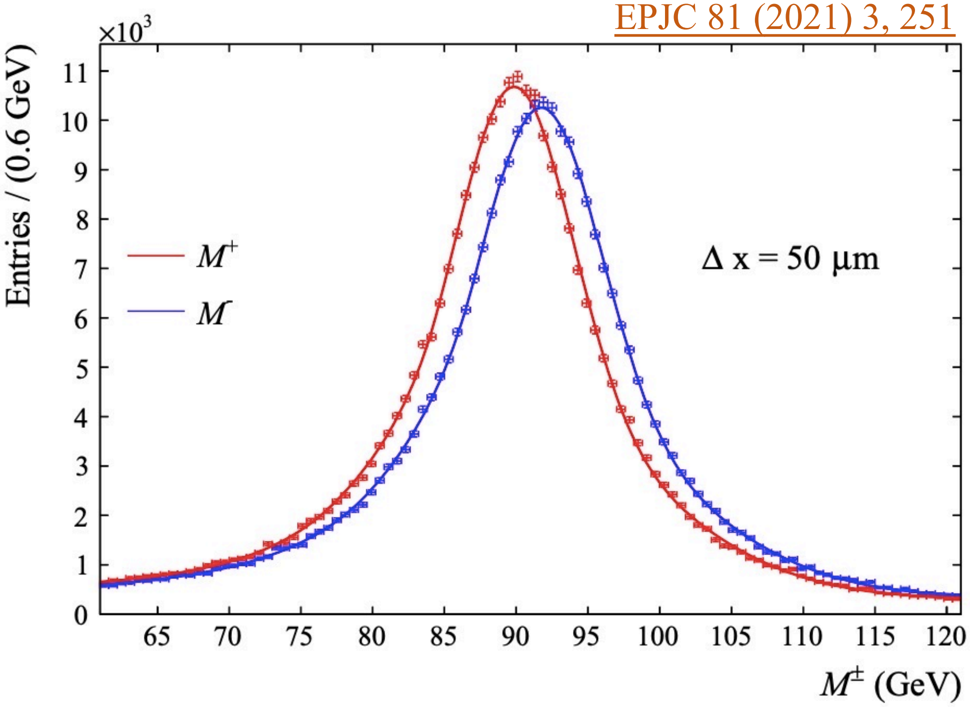
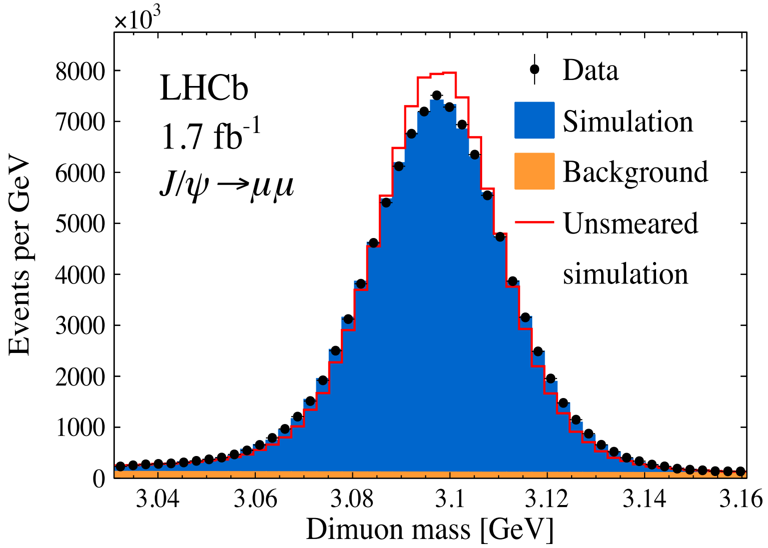
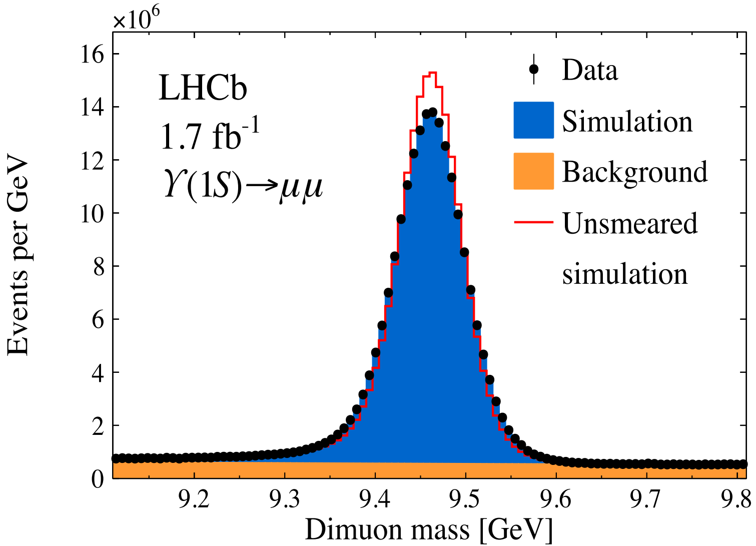


Inspired by PRD 91, 072002 (2015)

Momentum scale calibration

Further smearing of the simulation is then needed:





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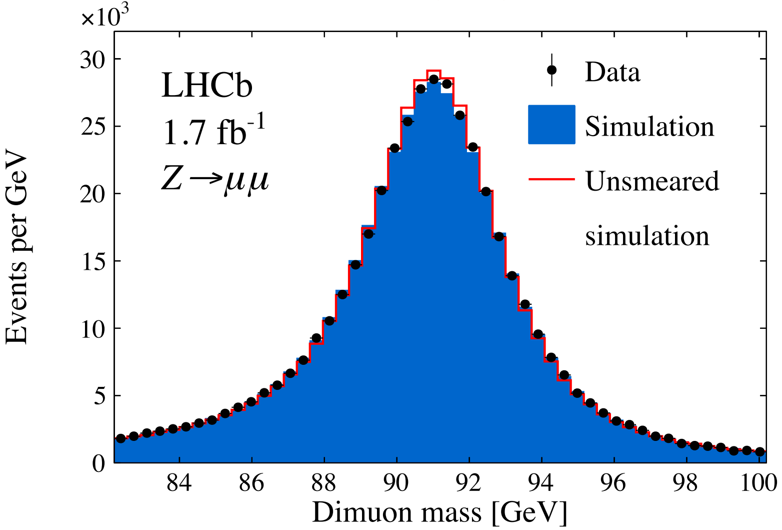

Simultaneous fit to the $J/\psi, \Upsilon(1S)$ and Z invariant mass (in different detector regions, polarities…) determined a smearing model, then applied to all muons.

Reconstruction & selection efficiencies

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

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

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

Reco, ID & trigger efficiencies:

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

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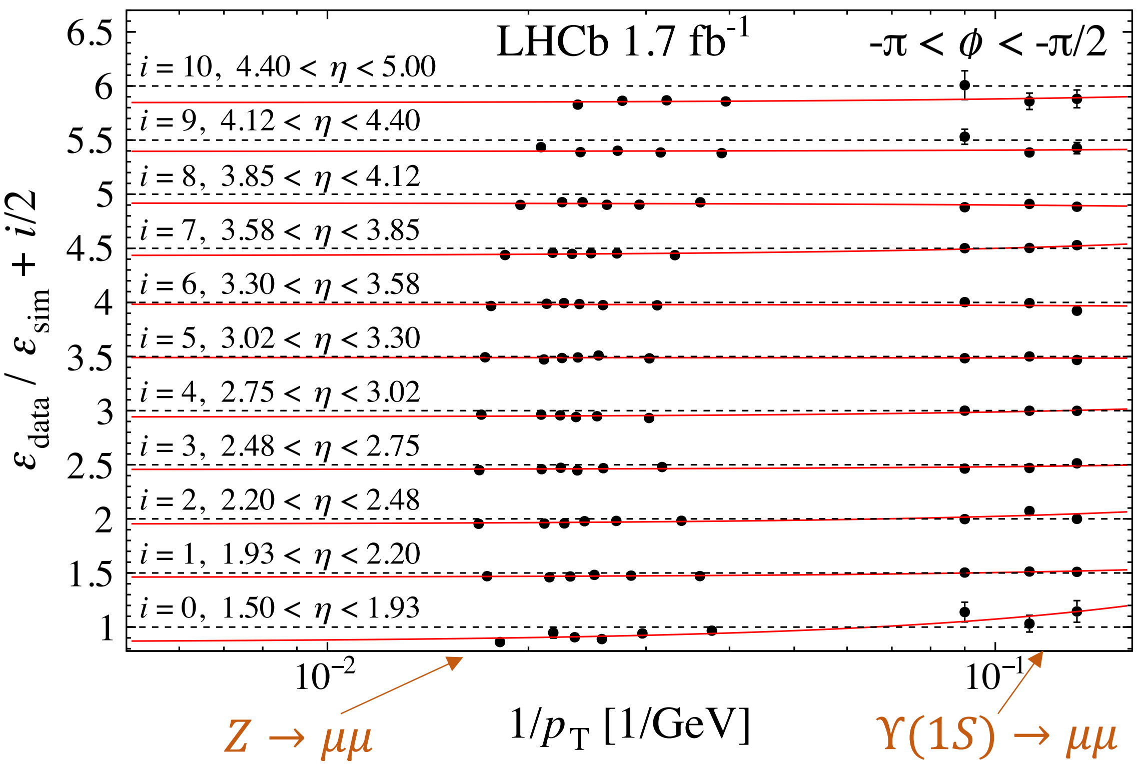


Reconstruction & selection efficiencies

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

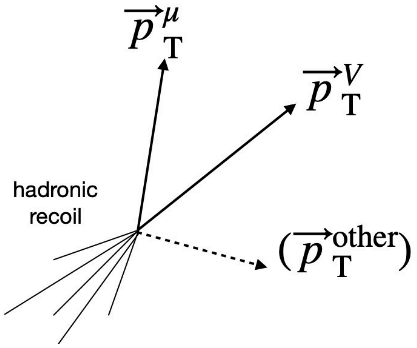
$$\varepsilon_{sim}\,(p_T, \eta, \phi, \ldots) = \varepsilon_{data}(p_T, \eta, \phi, \ldots)\ ?$$

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

Isolation efficiencies:

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

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



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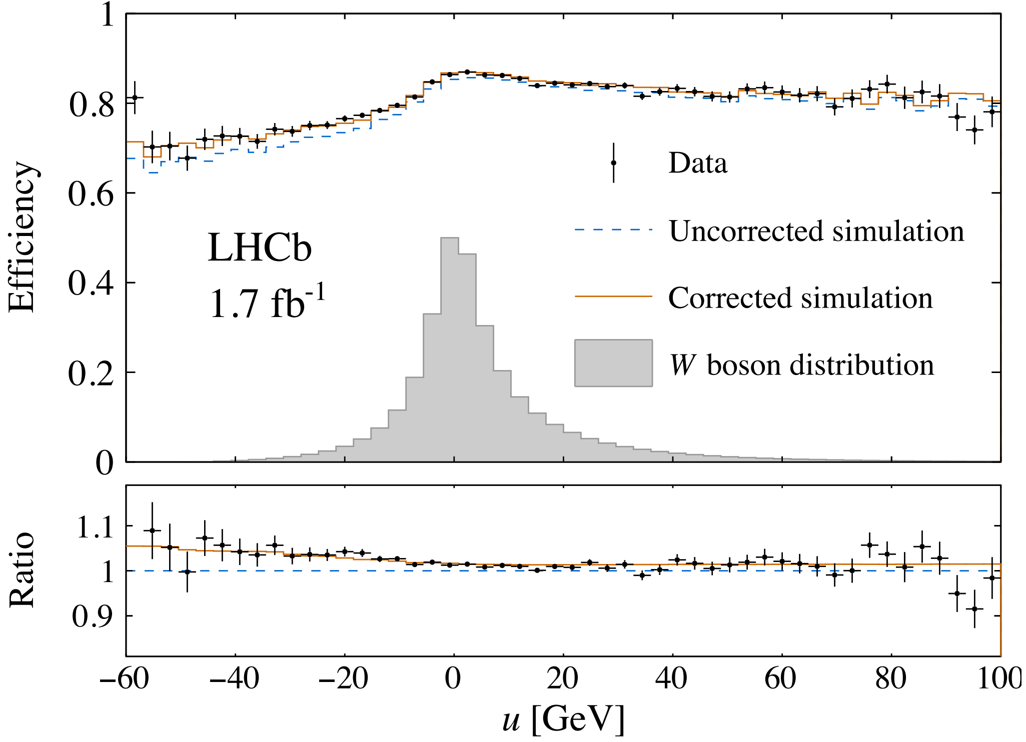

Signal selection

- 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, $2.2 < \eta < 4.4$.

2016 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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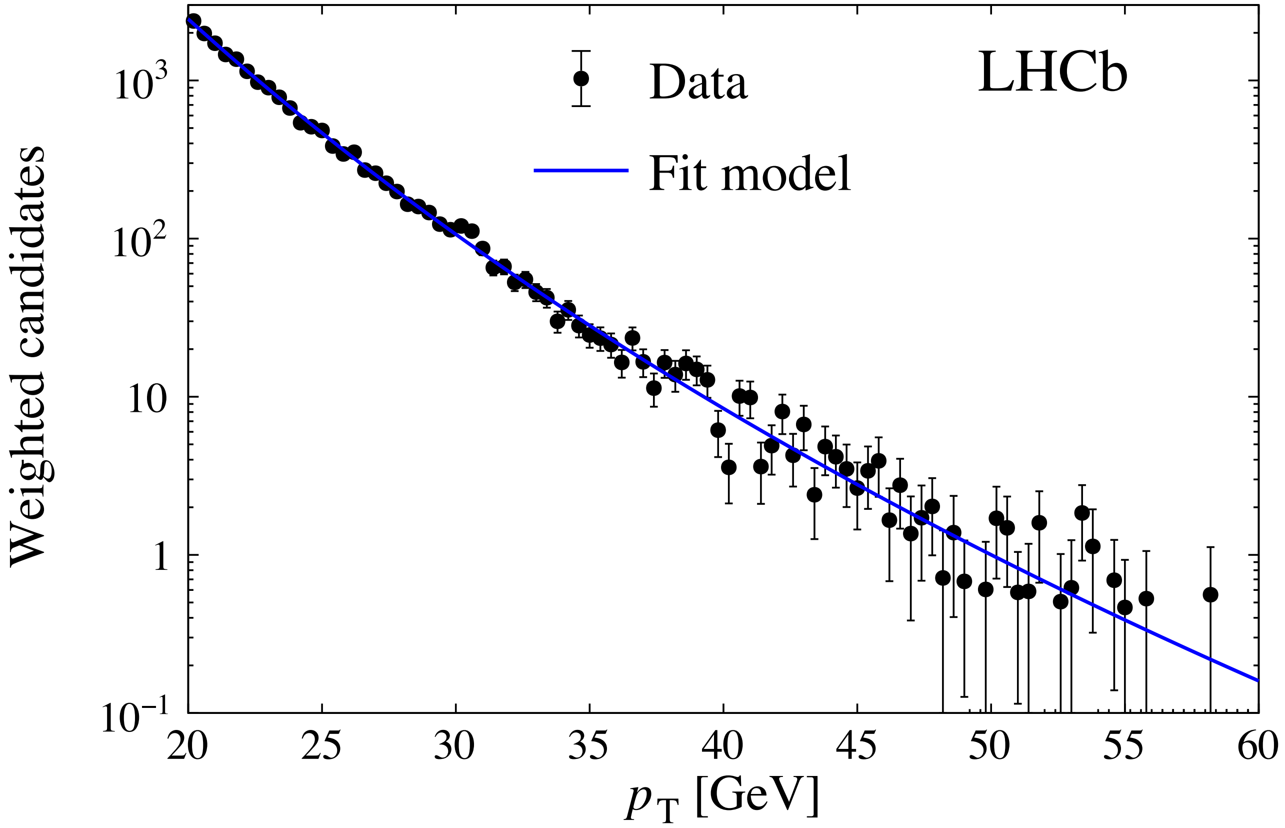
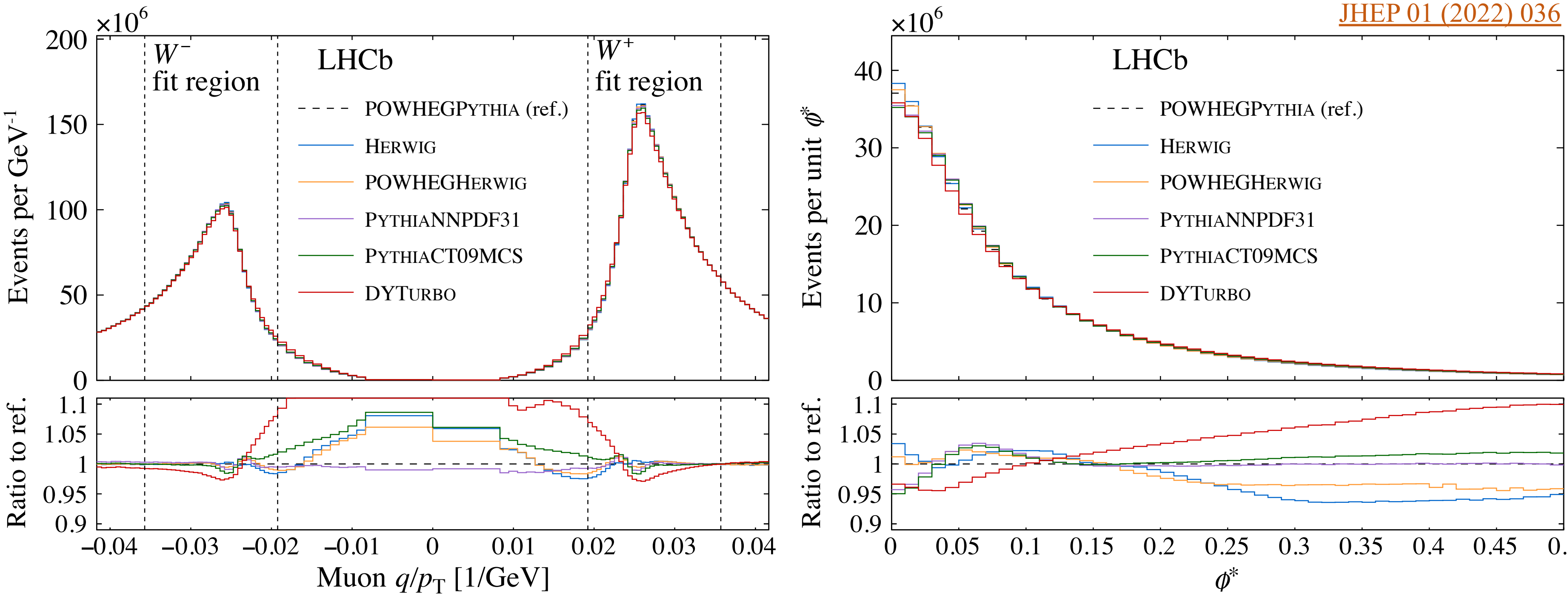


Model validation: [Pseudo]data challenges



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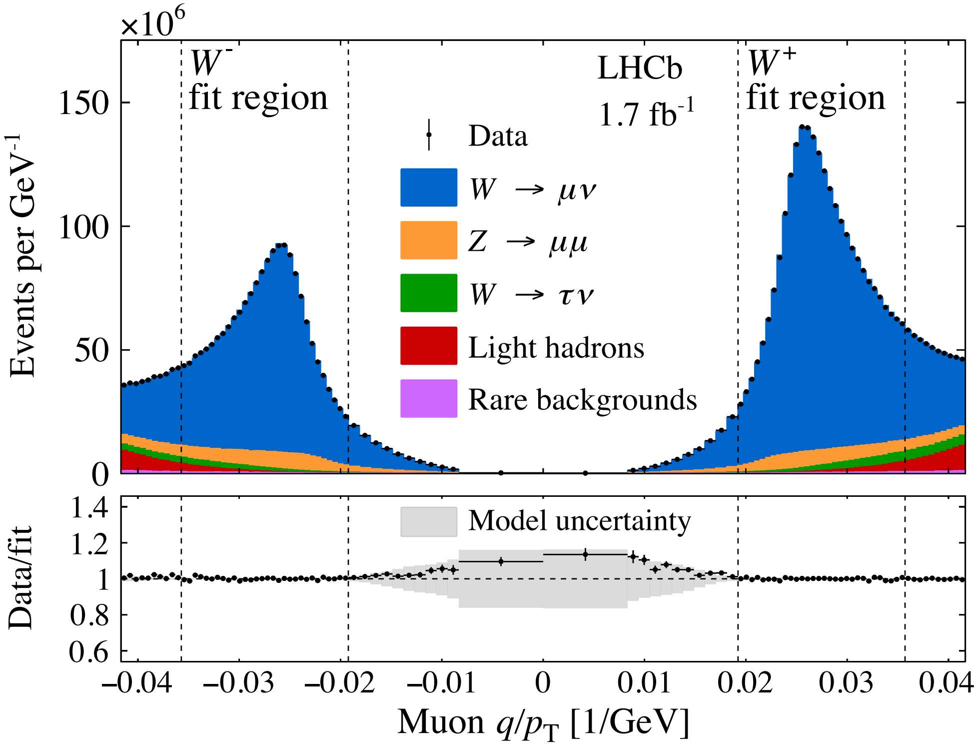
- Using our central model to fit pseudodata generated from different models (e.g. HerwigNLO) gives a similar spread as using those different models to fit the real data.

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

The 2016 fit result



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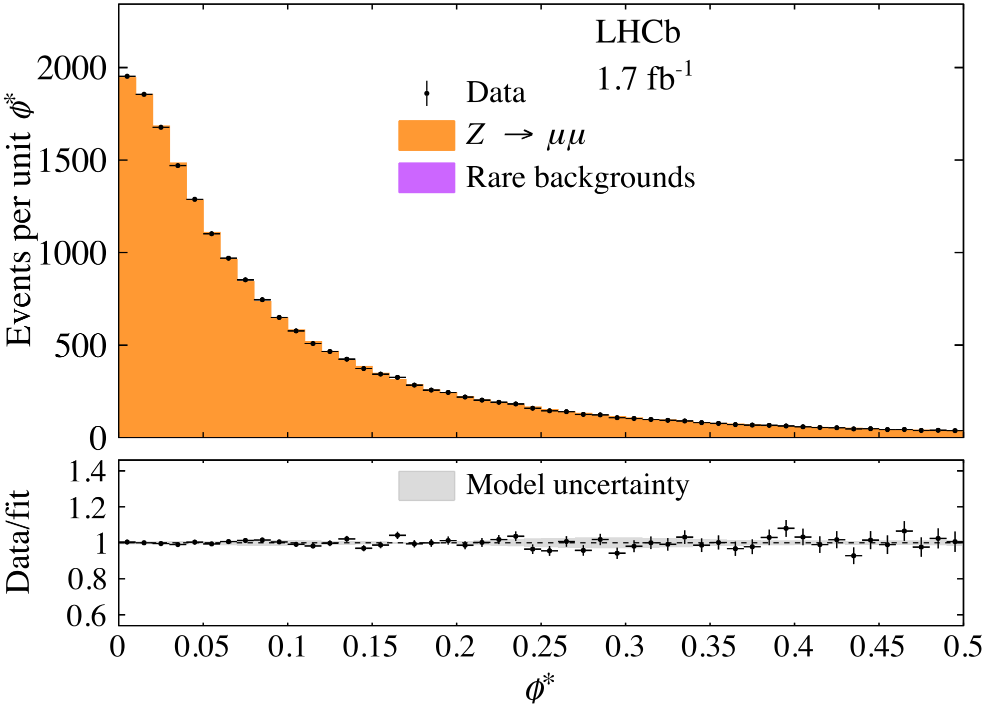

Parameter	Value
Fraction of $W^+ \to \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3508 ± 0.0005
Fraction of hadron background	0.0146 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
k_T^{intr}	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026

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

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.