Measurement of the W boson mass at LHCb

William Barter – Imperial College London

on behalf of the LHCb collaboration

Lepton-Photon 2022 – 12th January 2022

Introduction

- Will present first measurement of the W boson mass from LHCb.

- LHCb-PAPER-2021-024:
  - Available here, with additional information here.
  - Published (this week): JHEP 01 (2022) 036.

- Paper builds on a rich history of measurements with electroweak bosons at LHCb – more details here.

W mass – status to date

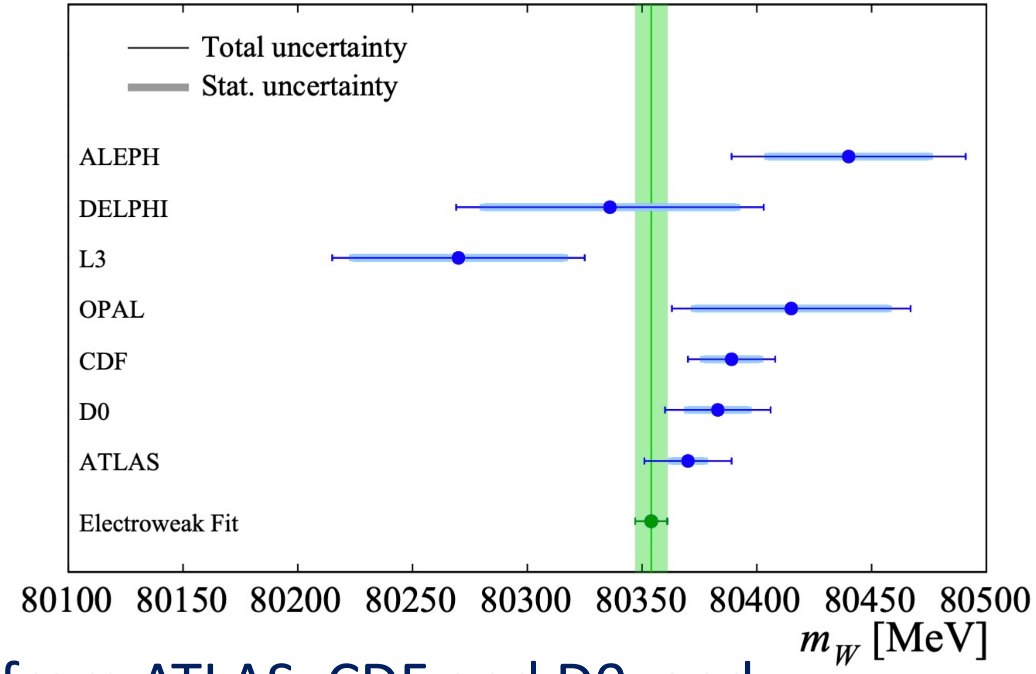
- W mass is at heart of electroweak theory:

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

Where Δ includes higher order effects…

…and potential new physics contributions.

- Global EW fit provides prediction of W mass with 7 MeV precision [EPJC 78 (2018) 675].

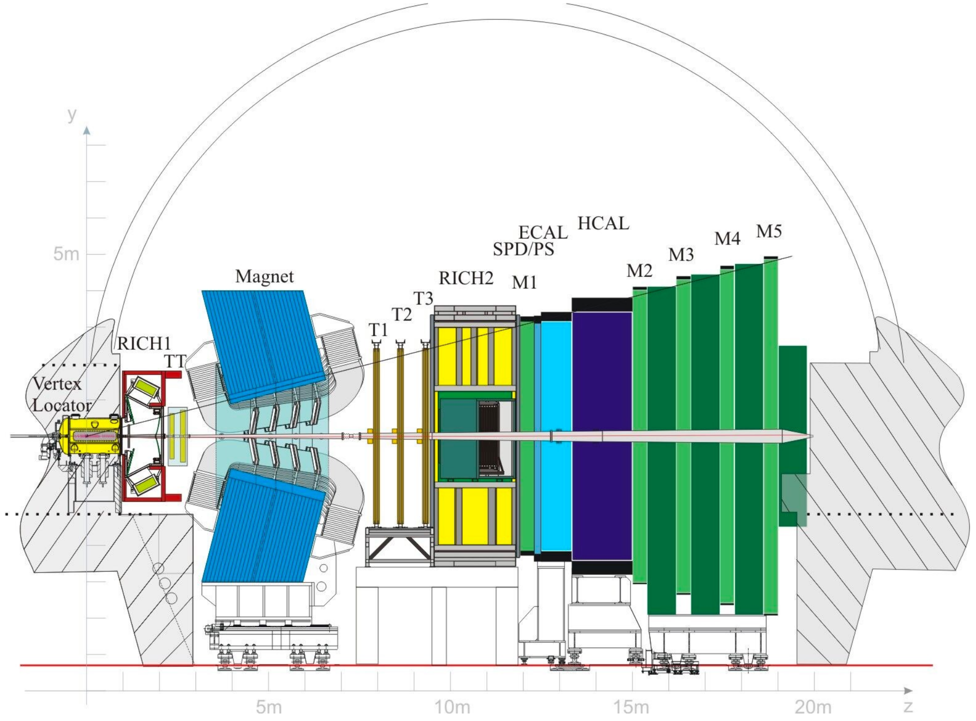


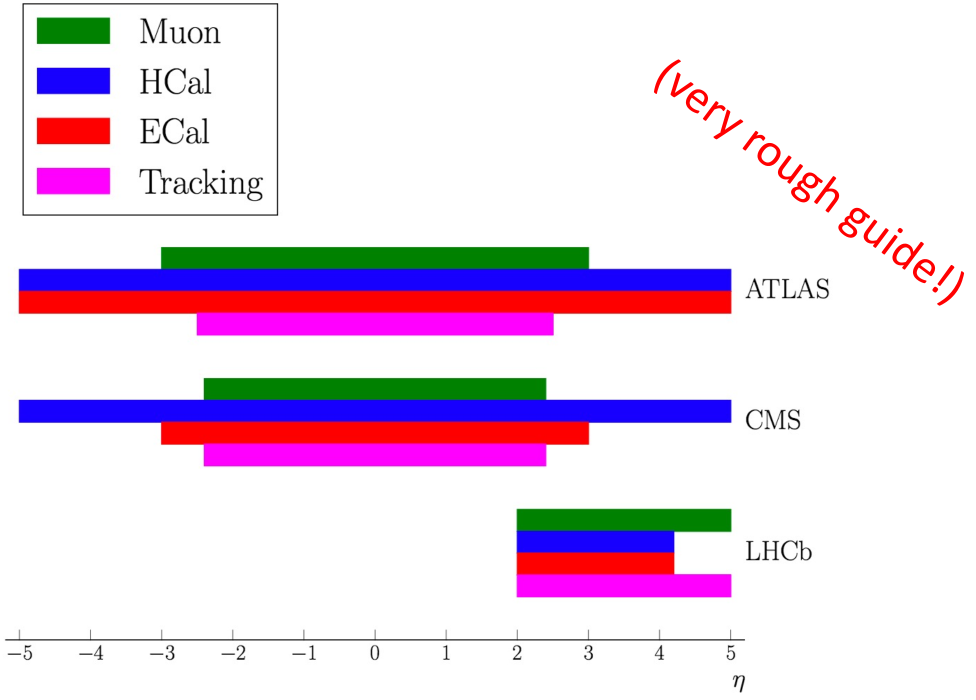
- Hadron Collider measurements already available from ATLAS, CDF and D0, and contribution from CMS expected.
- Precision of direct measurements limits interpretation of global EW fit in terms of new physics.

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

Why LHCb? – the detector

- Single arm spectrometer, fully instrumented in the forward region.





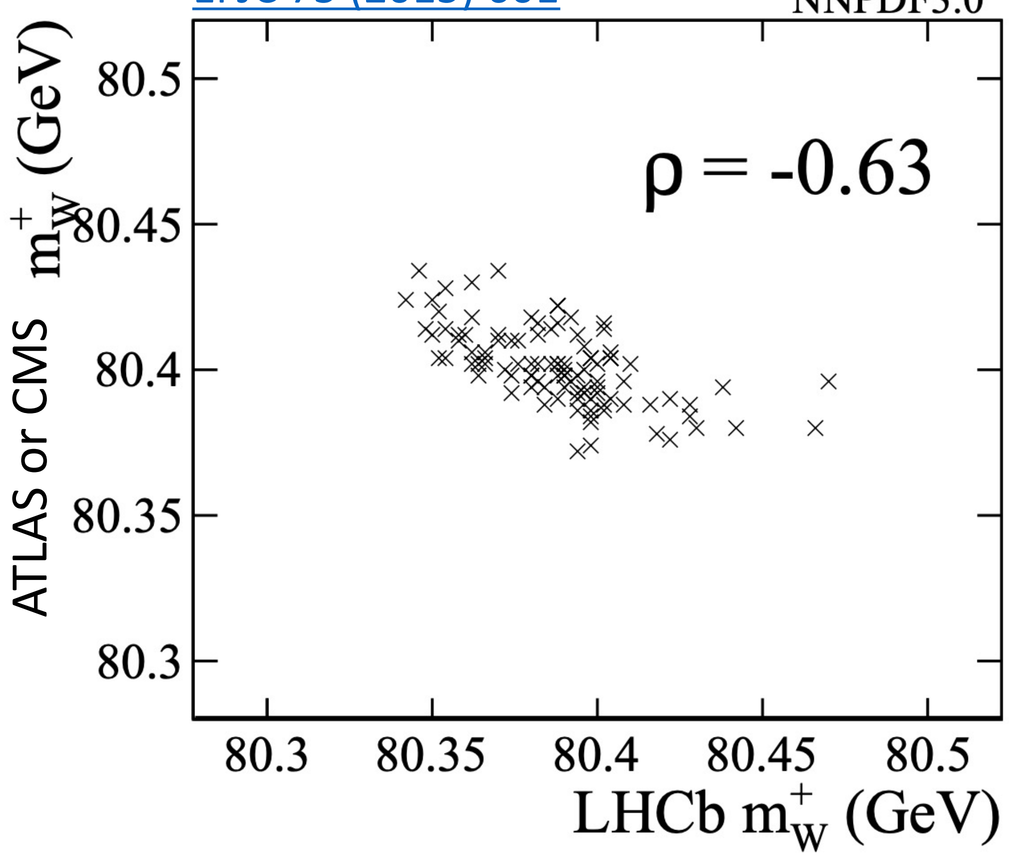
- Designed for flavour physics – but also able to act as general purpose forward detector.
- Overlap with ATLAS/CMS precision coverage in $2.0< \eta<2.5$; unique precision coverage in $2.5<\eta<5$.

Why LHCb? – LHCb acceptance

- The complementary forward coverage at LHCb is a significant advantage.
  - PDF uncertainties are expected to be anti-correlated in any W boson mass measurement between the central and forward regions [EPJC 75 (2015) 601].

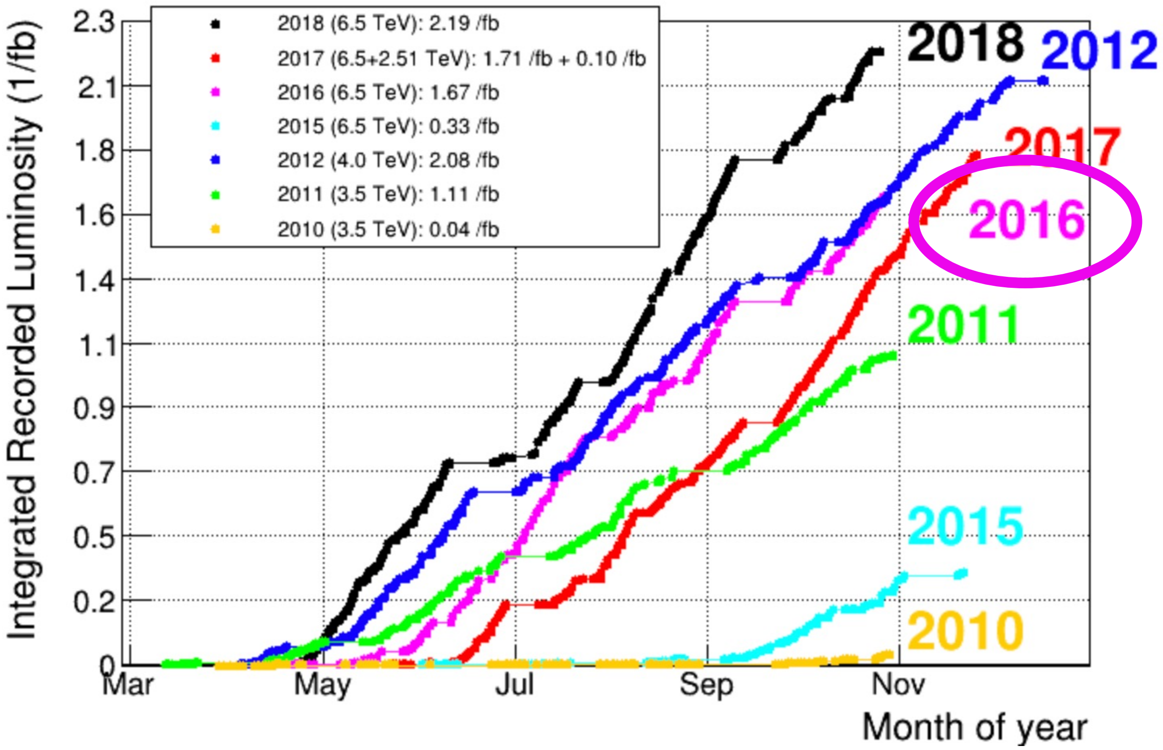
- A measurement from LHCb has the potential to contribute significantly in any LHC-wide average.
  - The overall average is ultimately the quantity that matters.

EPJC 75 (2015) 601



Analysis Strategy – Dataset

- Choose to analyse a fraction of our overall dataset for this first analysis.
- Analyse the dataset collected in 2016.
  - Corresponds to an integrated luminosity of 1.7 fb^{-1}.
- Initial proof of concept measurement, listen to community feedback while we continue to analyse full Run 2 dataset.
  - Measurement presented here uses less than 30% of our Run 2 dataset.



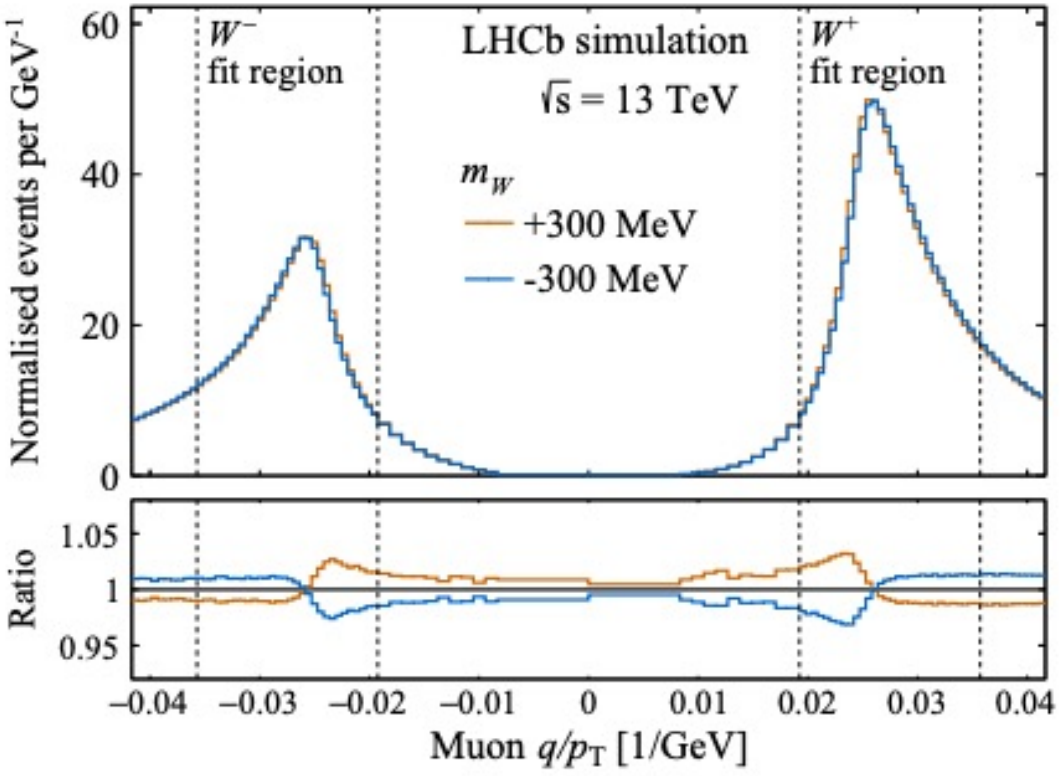
Analysis Strategy – Signal Selection

- Fiducial acceptance ($2.2 < \eta < 4.4$)
- Signal muon candidate, responsible for event selection in trigger.
- Well reconstructed and isolated track associated with primary interaction.
  - Rejects heavy flavour decays and hadronic backgrounds
- No additional high p_T muon measured in LHCb in the event.
  - Reduces background from Z boson decays.
- No use of recoil information – LHCb does not have 4π coverage.

- Select ~2.4M events in the fit window $28 < p_T < 52$ GeV.

Analysis Strategy – Fit

- Seek to measure the W boson mass by fitting the q/p_T spectrum of muons produced in W boson decays.
- Simultaneously fit ϕ^* distribution in Z boson events
  - $\phi^* = \frac{\tan\left(\frac{\pi-\Delta\phi}{2}\right)}{\cosh\left(\frac{\Delta\eta}{2}\right)} \sim \frac{p_T}{M}$
  - Determined solely from final state muon directions – no momentum information needed.
  - Allows additional control of QCD effects.



Modelling Electroweak boson physics

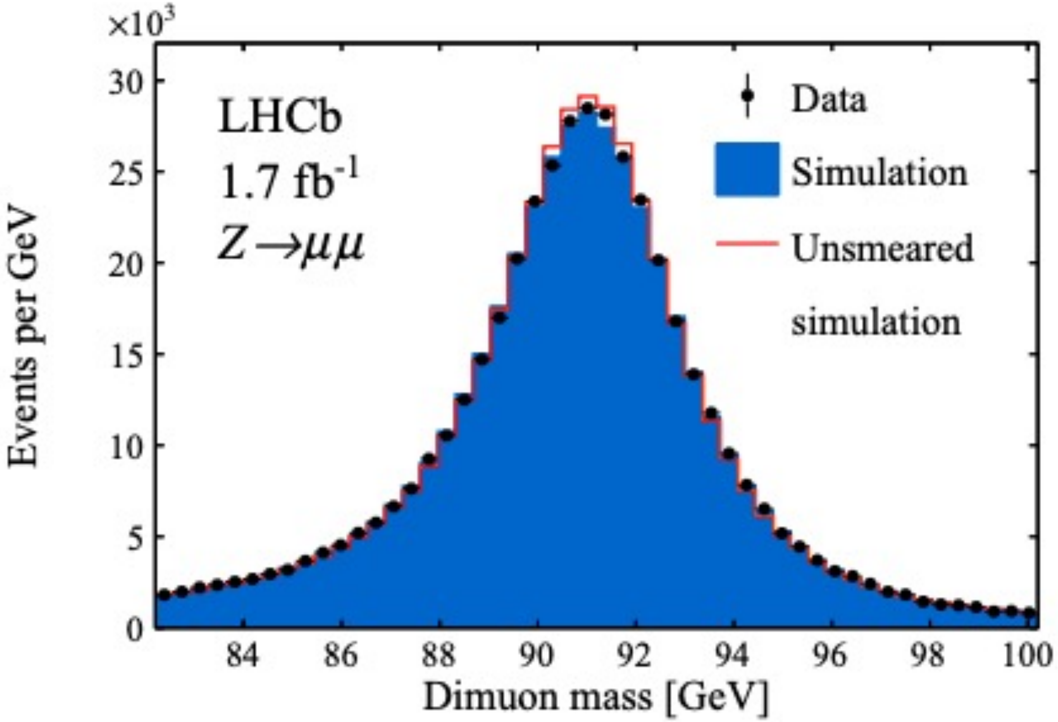
- Electroweak boson physics functional form (at Born level) can be written as:

$$\frac{d\sigma}{dp_T^W\,dy\,dM\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^V\,dy\,dM}$$
$$\{(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+ A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\}$$

- Model boson production using ME+PS simulation (central model used in analysis is POWHEG+Pythia8, as this provides best description of Z boson p_T).
  - Parameters associated with QCD modelling are floated to ensure best description of the QCD physics, following arxiv:1907.09958.
- Model angular structure of boson decay using DYTurbo at $O(\alpha_s^2)$.

Key Experimental Systematics

- Detector alignment and momentum scale calibration – determined using J/ψ, Υ and Z boson data, following EPJC 81 (2021) 251.
- Selection efficiencies – determined using simulation, with corrections applied based on Υ and Z boson data.
- Backgrounds – most significant is the hadronic decay-in-flight, which is determined using a dedicated hadronic data sample.



Key Theoretical Systematics

- Parton Distribution Functions – measurement made independently for 3 global PDF sets. Central result is arithmetic average of these 3, and assumes 100% correlation of them.
- Boson Production Model – measurement repeated using different programs to model W and Z boson production. Envelope of final results sets the systematic uncertainty.
- Boson Decay – angular coefficients varied using uncorrelated scale variation following JHEP 11 (2017) 3. An additional parameter is floated associated with A_3 to compensate for global changes in A_3 associated with scale variation that otherwise decrease the data/model agreement.

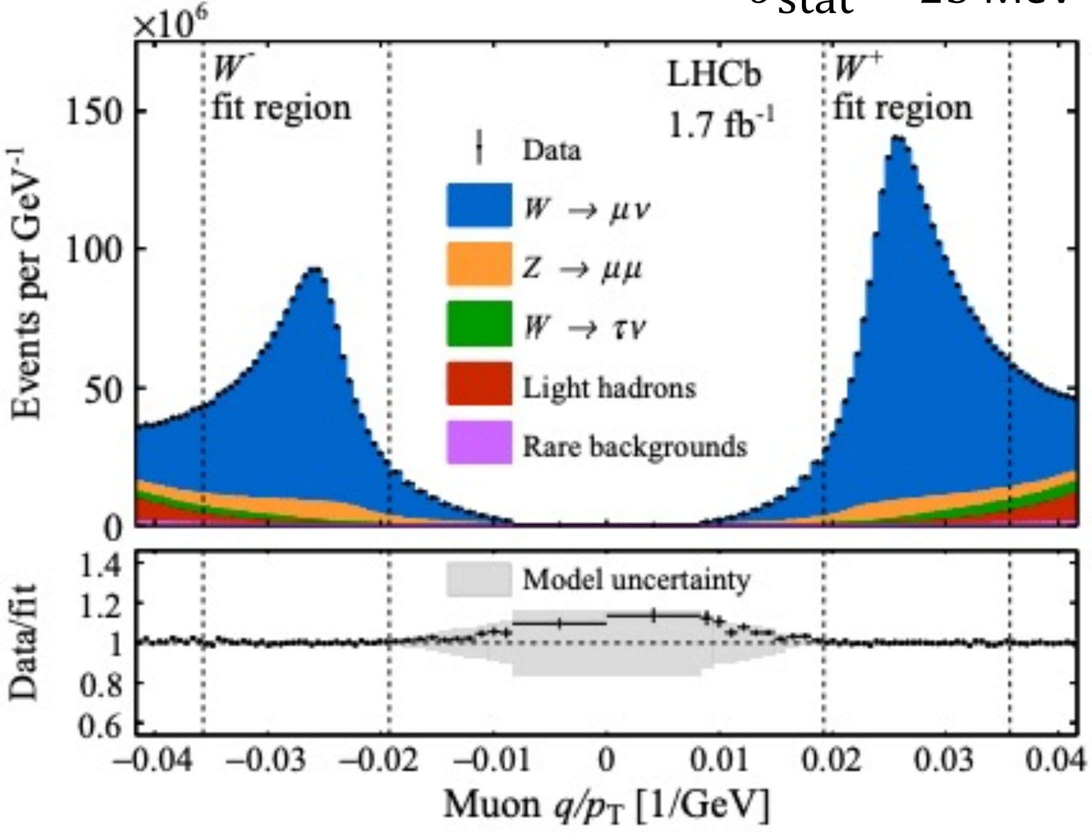
Crosschecks

1. **Fits using pseudodata** demonstrate that the 'QCD parameters' in our default model are sufficient to capture variations between different QCD modelling programs (POWHEG+HERWIG, HERWIG7, DYTURBO…etc) and do not introduce a significant bias in the W boson mass.
2. **50:50 orthogonal splits in the data** (in η region, in azimuthal angle, in magnet polarity, in q $\times$ magnet polarity,…) give consistent W mass results between the two orthogonal splits.
3. **Changes in the fit range** give consistent and stable results.
4. **Changes in the model freedom** give consistent and stable results.
   For example, determining the QCD parameters for the W only using the W boson data (ie not using Z boson data) induces a shift in the W mass below 1 MeV.
5. **A W-like fit of the Z mass** is consistent for the two muon charges, and is consistent with the PDG value.
6. **Floating the W+ and W- mass difference** yields a mass difference consistent with 0.
7. **Additional tests** including use of NNLO PDFs (instead of NLO) impact the W mass at the 1 MeV level.
8. **…**

Fit Result

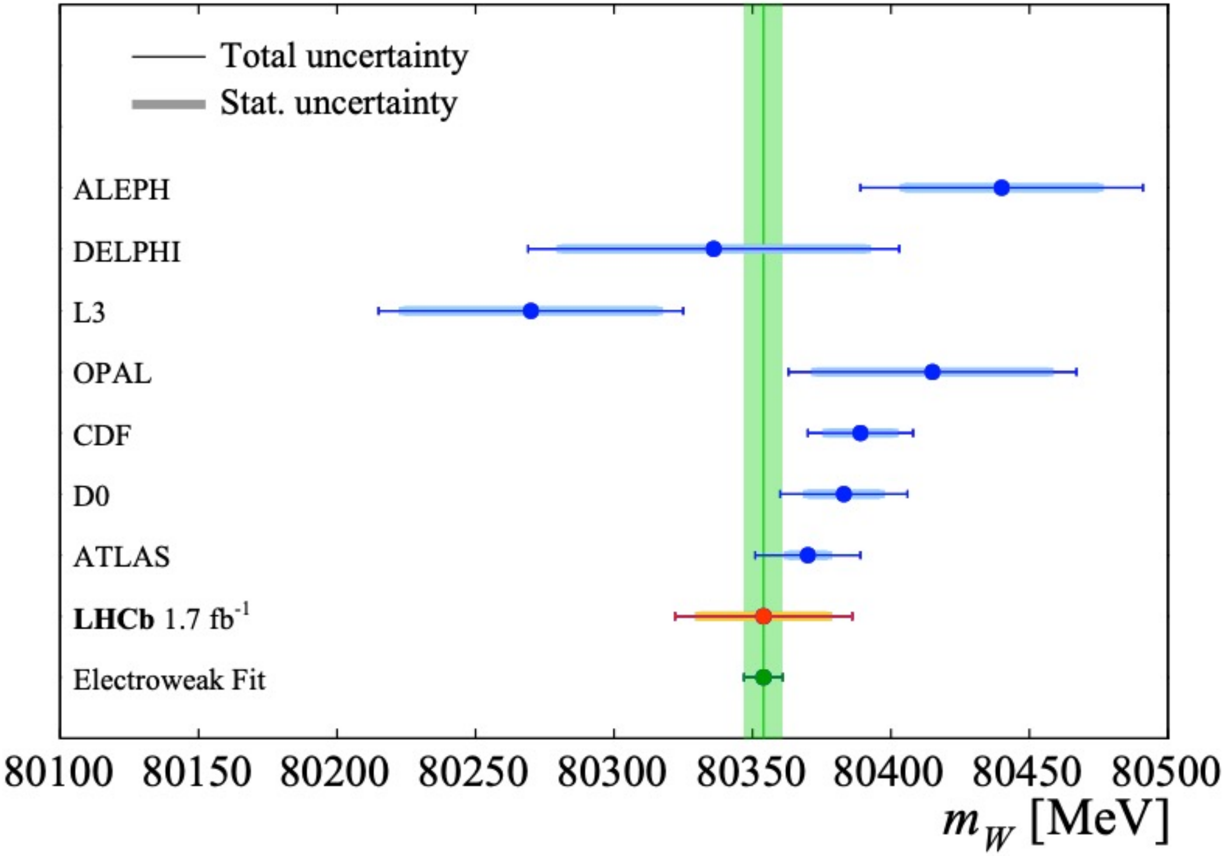
$\chi^2/\text{dof} = 105/102$

$\sigma_{\text{stat}} = 23$ MeV



Source	Size [MeV]
Parton distribution functions	9
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

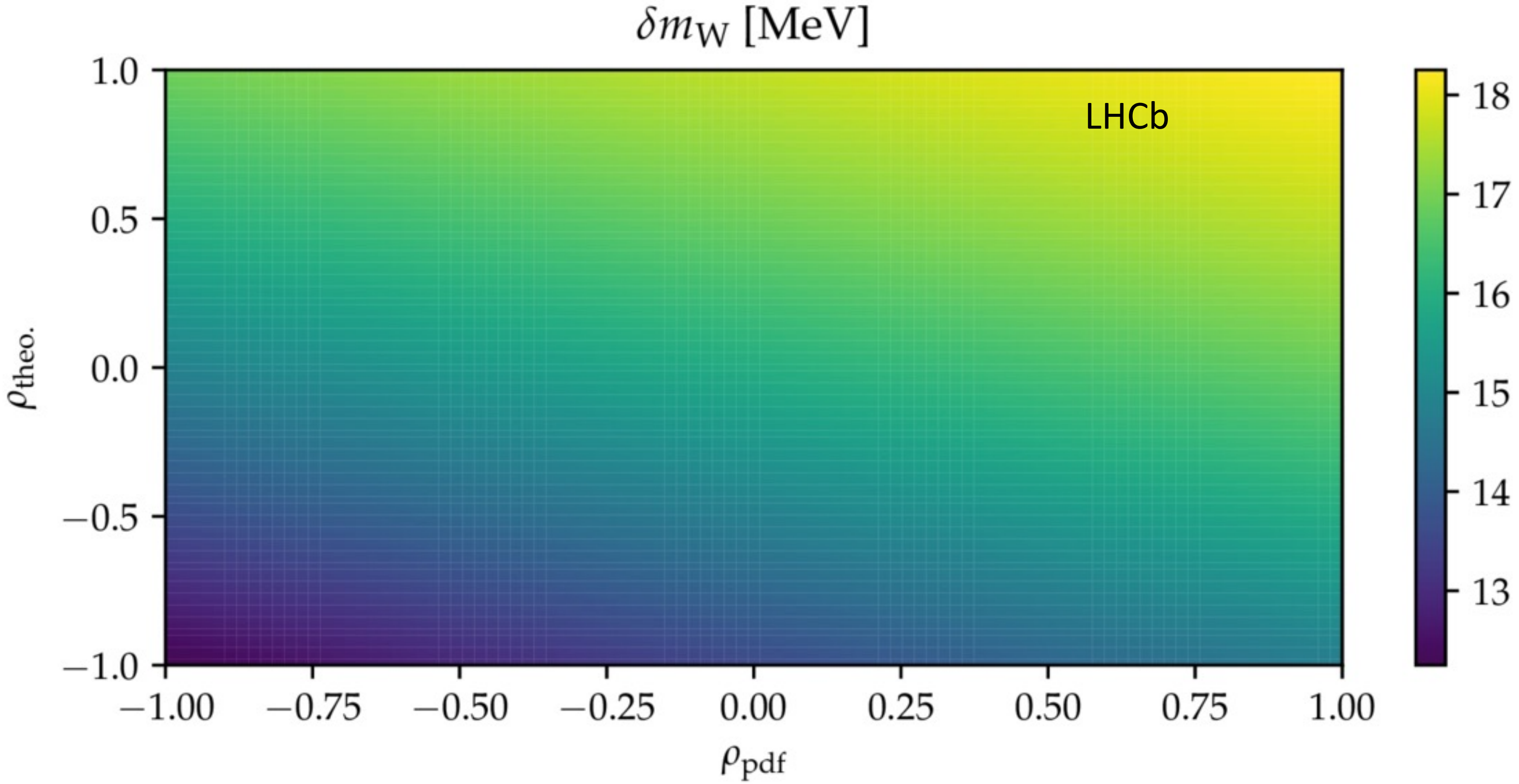
LHCb Result



$$m_W = 80354 \pm 23_{\mathrm{stat}} \pm 10_{\mathrm{exp}} \pm 17_{\mathrm{theory}} \pm 9_{\mathrm{PDF}}\ \mathrm{MeV}$$

(Naïve) LHC average

A full combination may take many years, but can combine with ATLAS measurement using BLUE and simplest approach: experimental uncertainties uncorrelated, and consider different assumptions for the correlation of theoretical and PDF uncertainties.

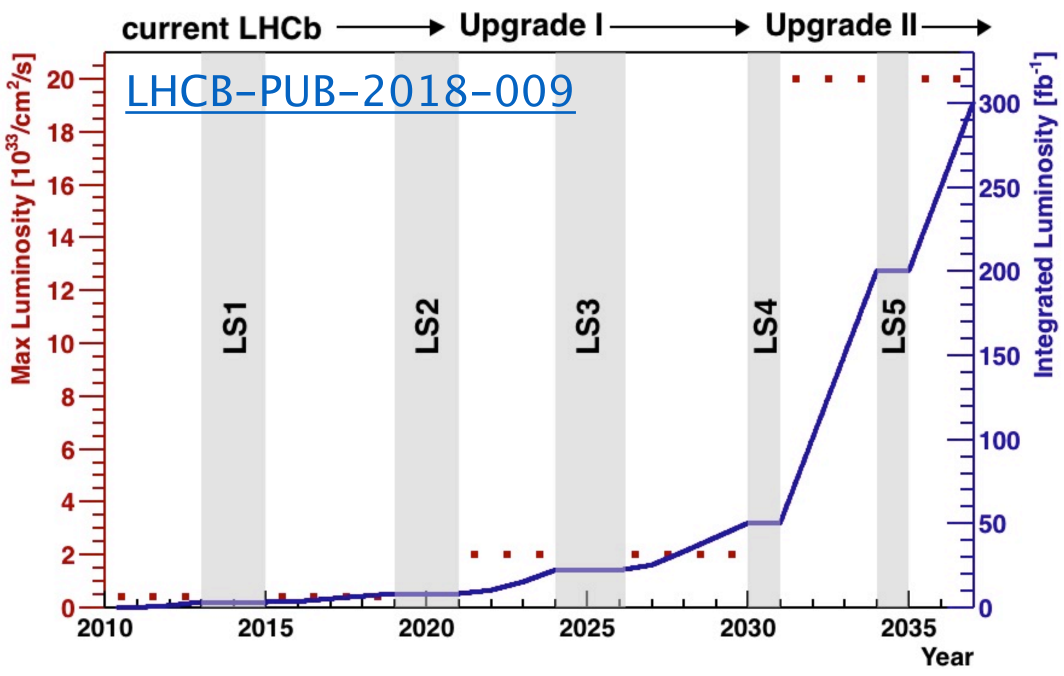


Reminder: we expect a negative PDF correlation between ATLAS and LHCb

EPJC 75 (2015) 601

Future Prospects @ LHCb

- An overall precision $<$ 20 MeV looks achievable with existing LHCb data.
  - Full Run 2 dataset will allow a statistical uncertainty of $\sim$10 MeV.
  - EPJC 79 (2019) 497 encourages a double differential fit in η and q/p_T to further constrain theory systematics.
- Run 3 dataset *could* allow further constraints on systematic effects, and a precision of 10-15 MeV.
  - Major upgrade allows the proton collision rate to be increased by a factor 5.



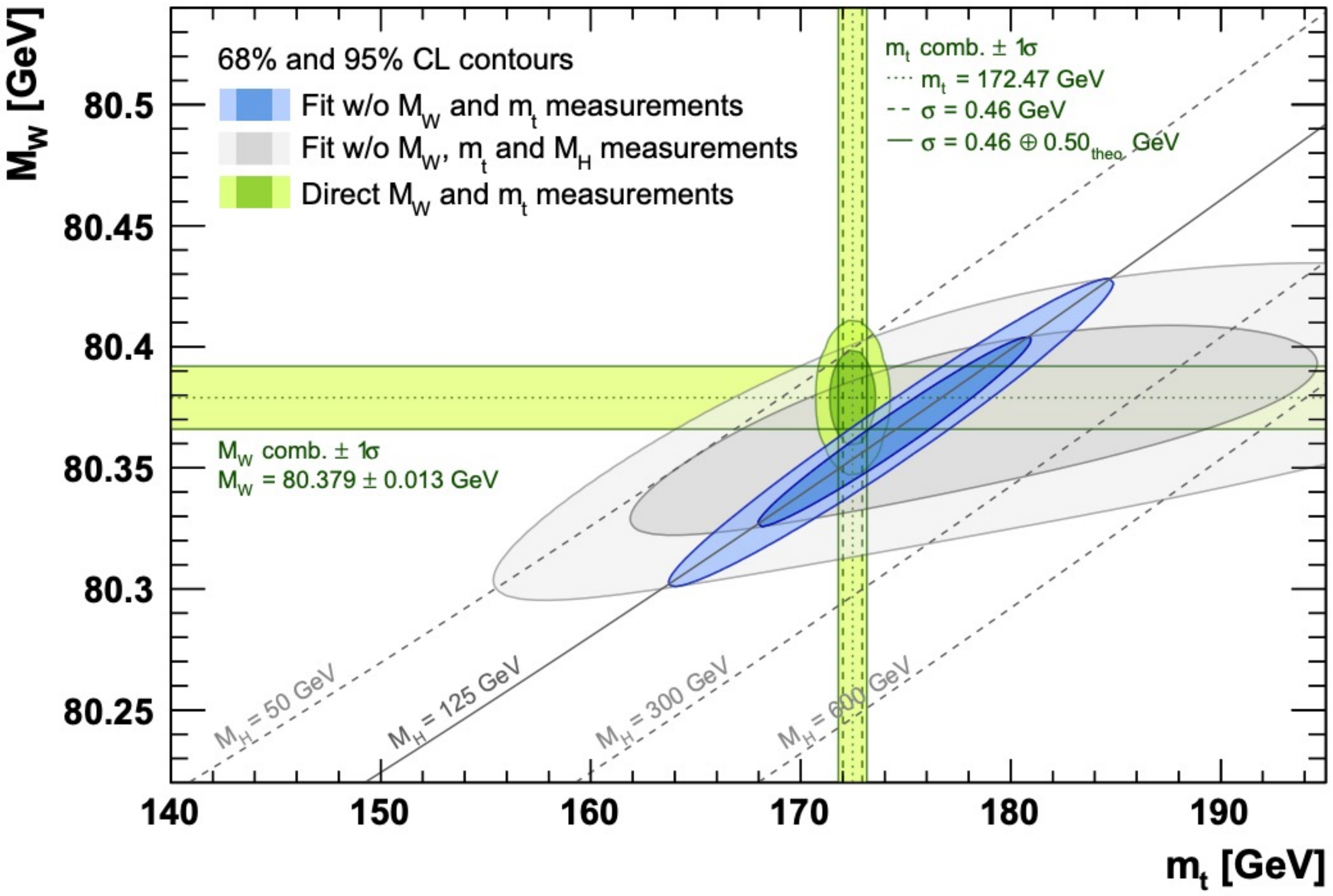
Conclusions

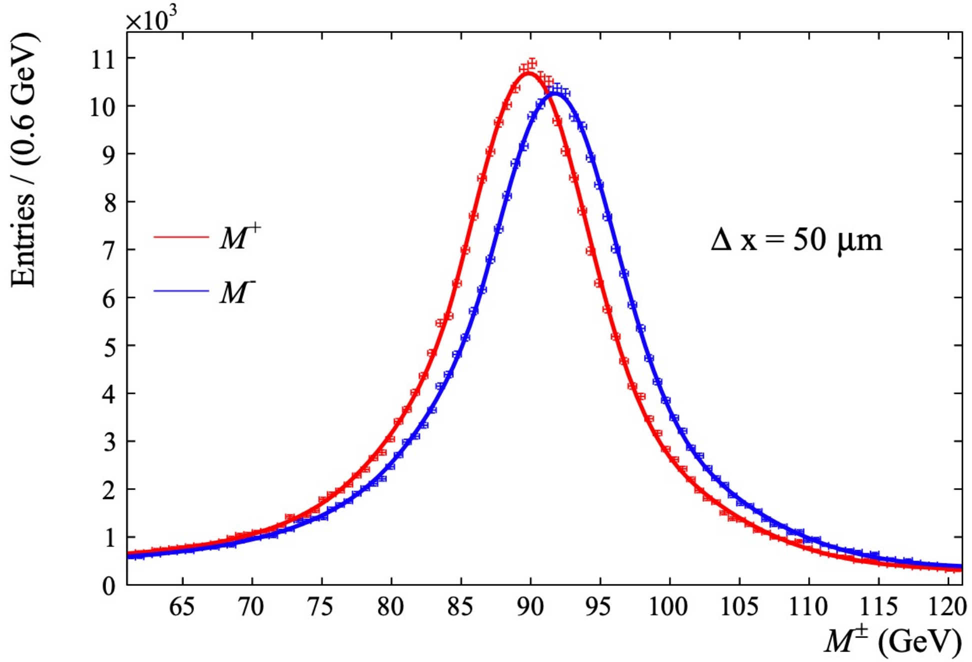
- First measurement of the W boson mass at LHCb.
  - W mass measurements provide information on a fundamental parameter of nature AND provide a key test of the consistency of the Standard Model, indirectly probing new physics.
  - LHCb acceptance complementary to that of ATLAS and CMS – reduced correlation of theoretical uncertainties, so significant impact expected on LHC-wide average.

- The overall precision achieved in the first LHCb measurement is $\sim$32 MeV.
  - Uses LHCb data collected in 2016, corresponding to roughly 1/3 of the LHCb Run 2 dataset.

- Improved modelling and larger datasets will allow < 20 MeV precision.

Backup

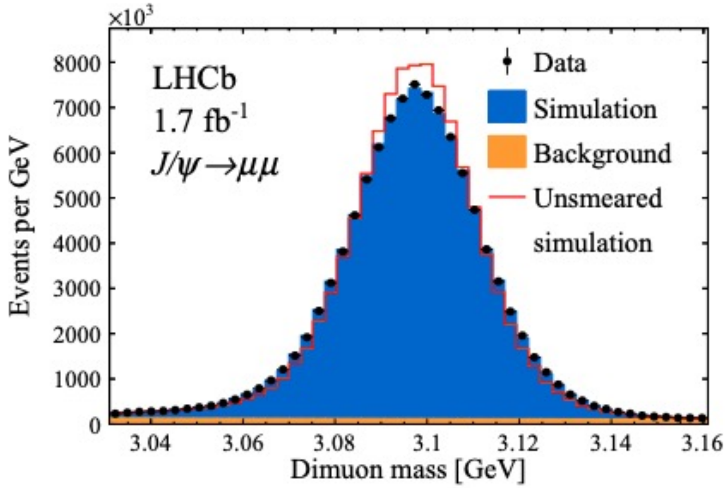

68% and 95% CL contours
Fit w/o M_W and m_t measurements
Fit w/o M_W, m_t and M_H measurements
Direct M_W and m_t measurements
m_t comb. ± 1σ
m_t = 172.47 GeV
σ = 0.46 GeV
σ = 0.46 ⊕ 0.50_theo GeV
M_W comb. ± 1σ
M_W = 80.379 ± 0.013 GeV
M_H = 50 GeV
M_H = 125 GeV
M_H = 300 GeV
M_H = 600 GeV
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190

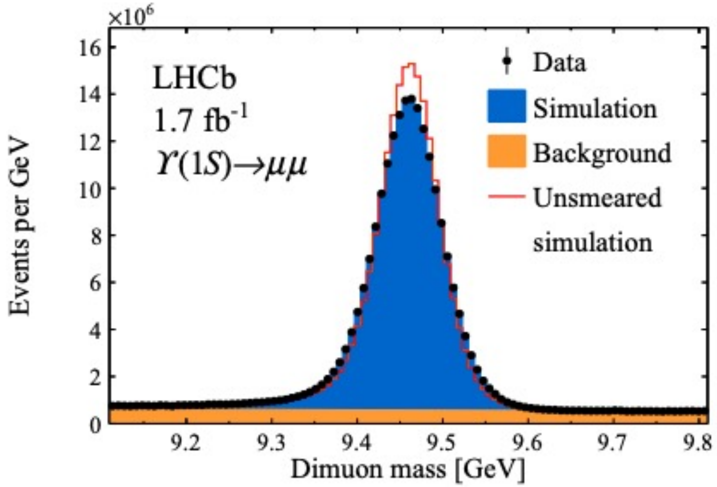


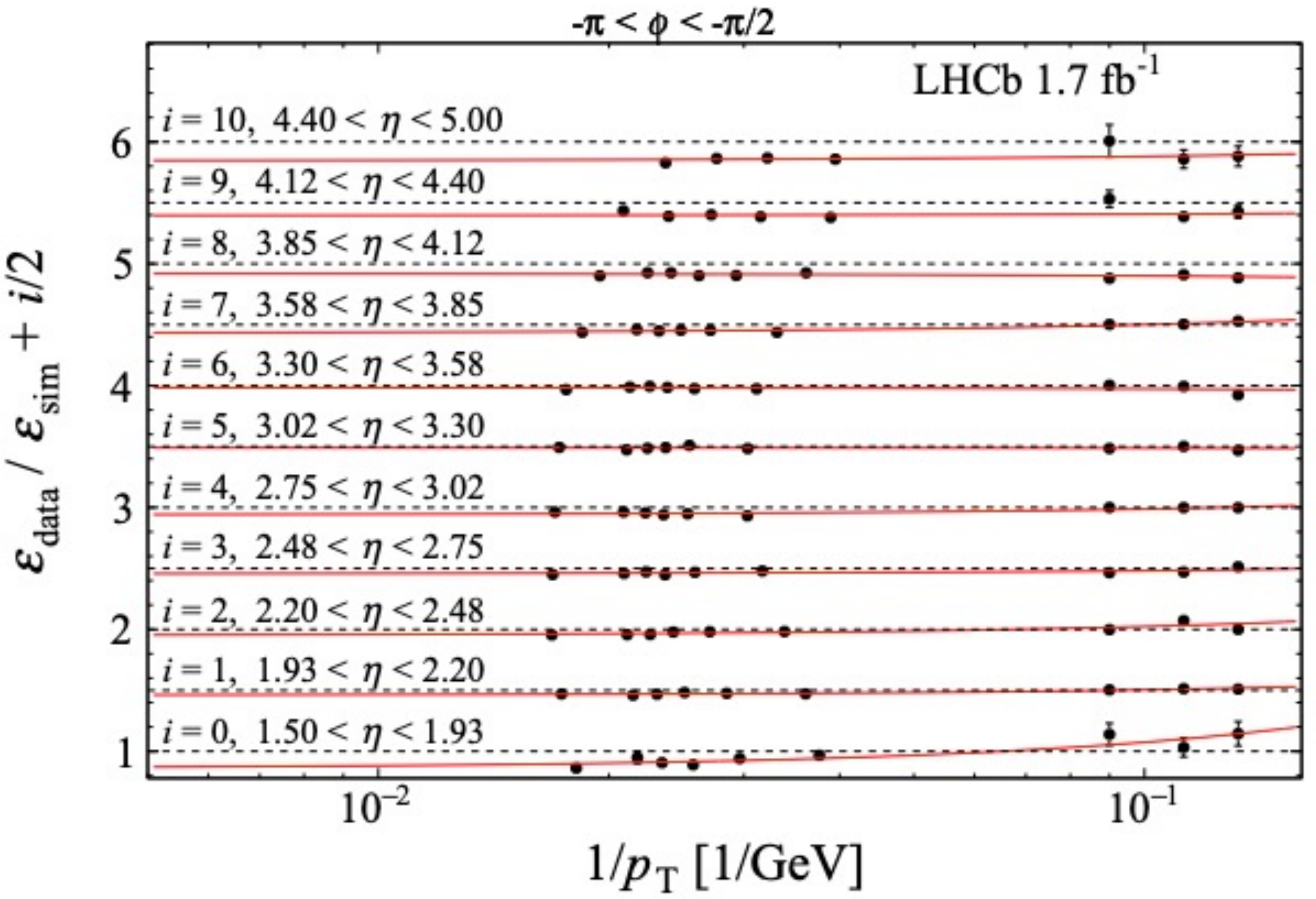
$$m \sim M^{+} = \sqrt{2p^{+}p_{T}^{+}\frac{p^{-}}{p_{T}^{-}}\,(1-\cos\theta)}$$

$$m \sim M^{-} = \sqrt{2p^{-}p_{T}^{-}\frac{p^{+}}{p_{T}^{+}}\,(1-\cos\theta)}$$

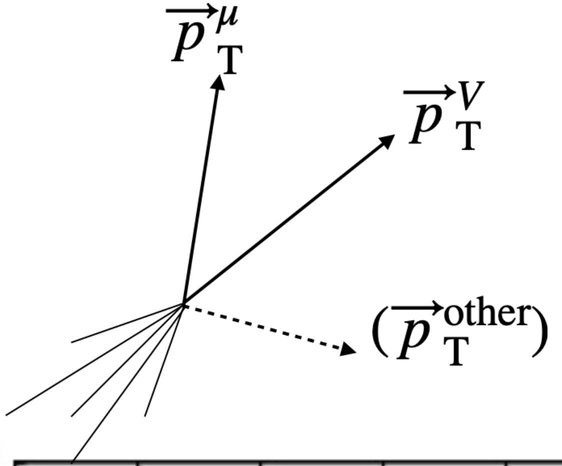
$$\frac{q}{p} \rightarrow \frac{q}{p\cdot\mathcal{N}(1+\alpha,\sigma_{\rm MS})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh\eta}\right)$$



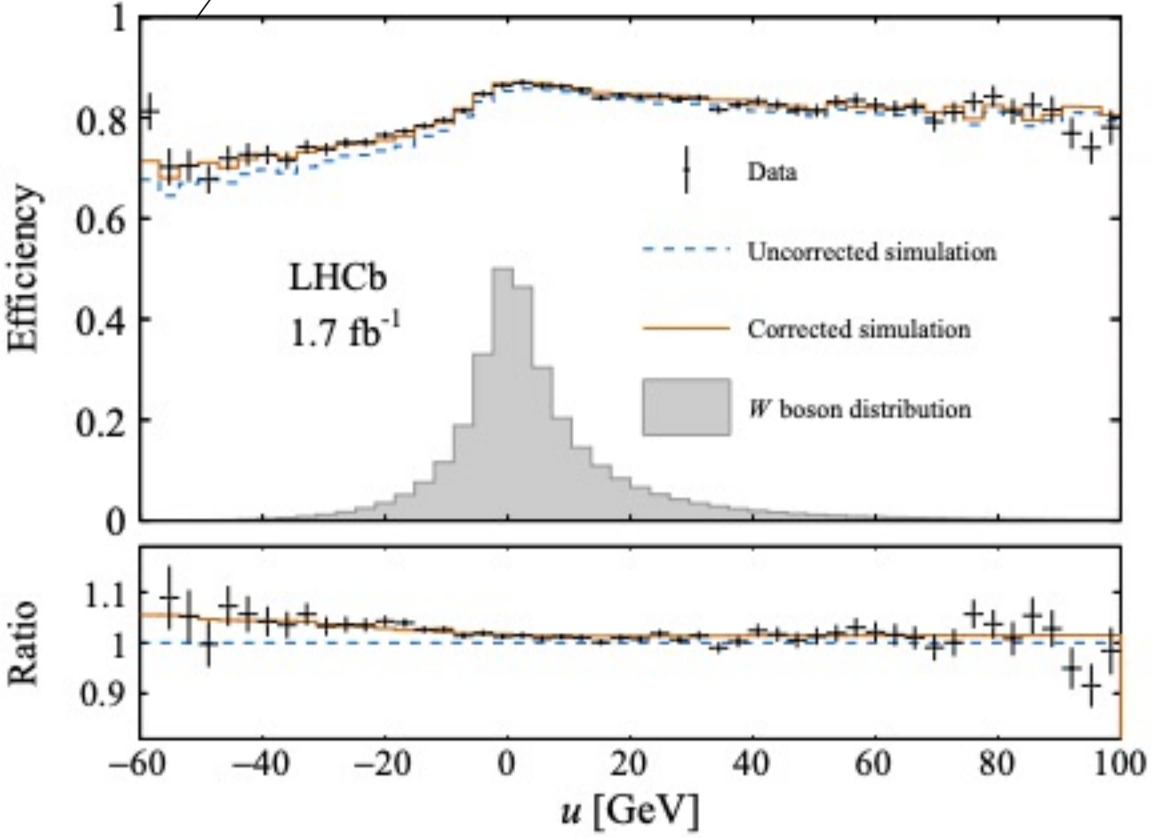


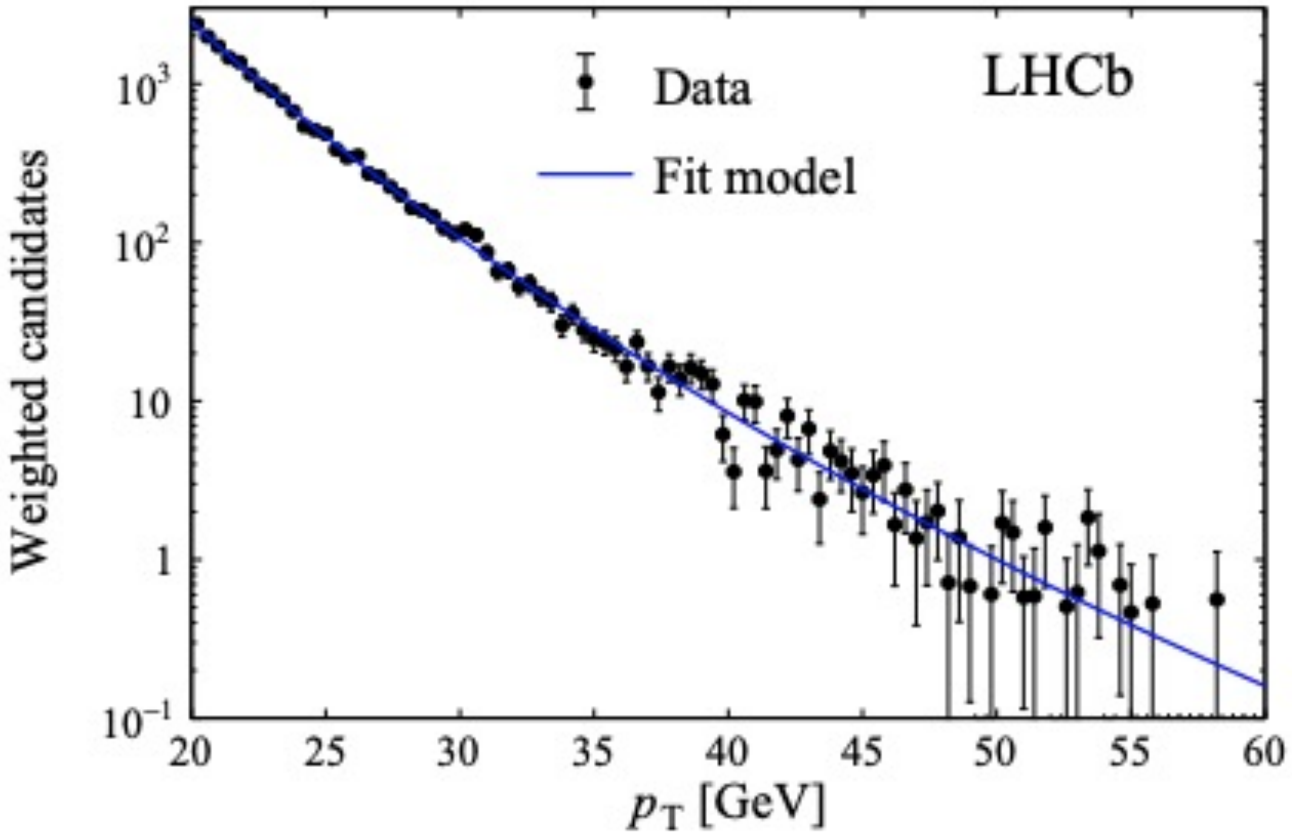


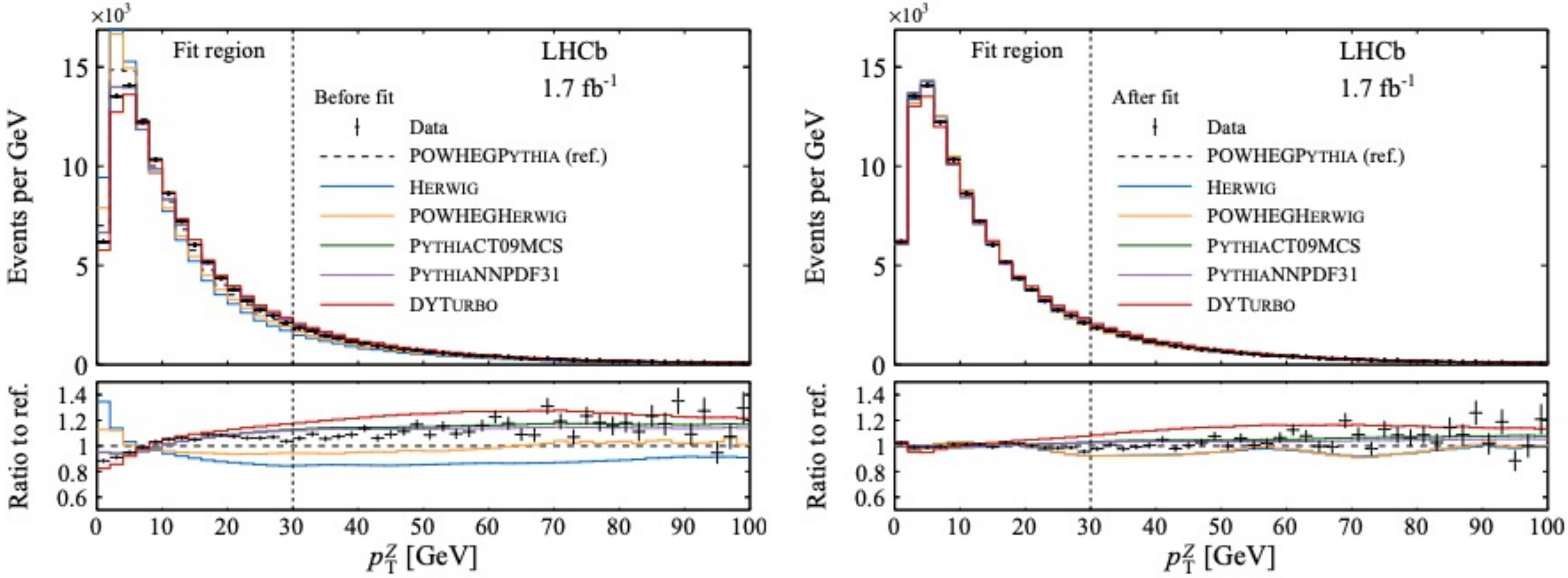
-π < φ < -π/2
LHCb 1.7 fb^-1
i = 10, 4.40 < η < 5.00
i = 9, 4.12 < η < 4.40
i = 8, 3.85 < η < 4.12
i = 7, 3.58 < η < 3.85
i = 6, 3.30 < η < 3.58
i = 5, 3.02 < η < 3.30
i = 4, 2.75 < η < 3.02
i = 3, 2.48 < η < 2.75
i = 2, 2.20 < η < 2.48
i = 1, 1.93 < η < 2.20
i = 0, 1.50 < η < 1.93
ε_data / ε_sim + i/2
1/p_T [1/GeV]

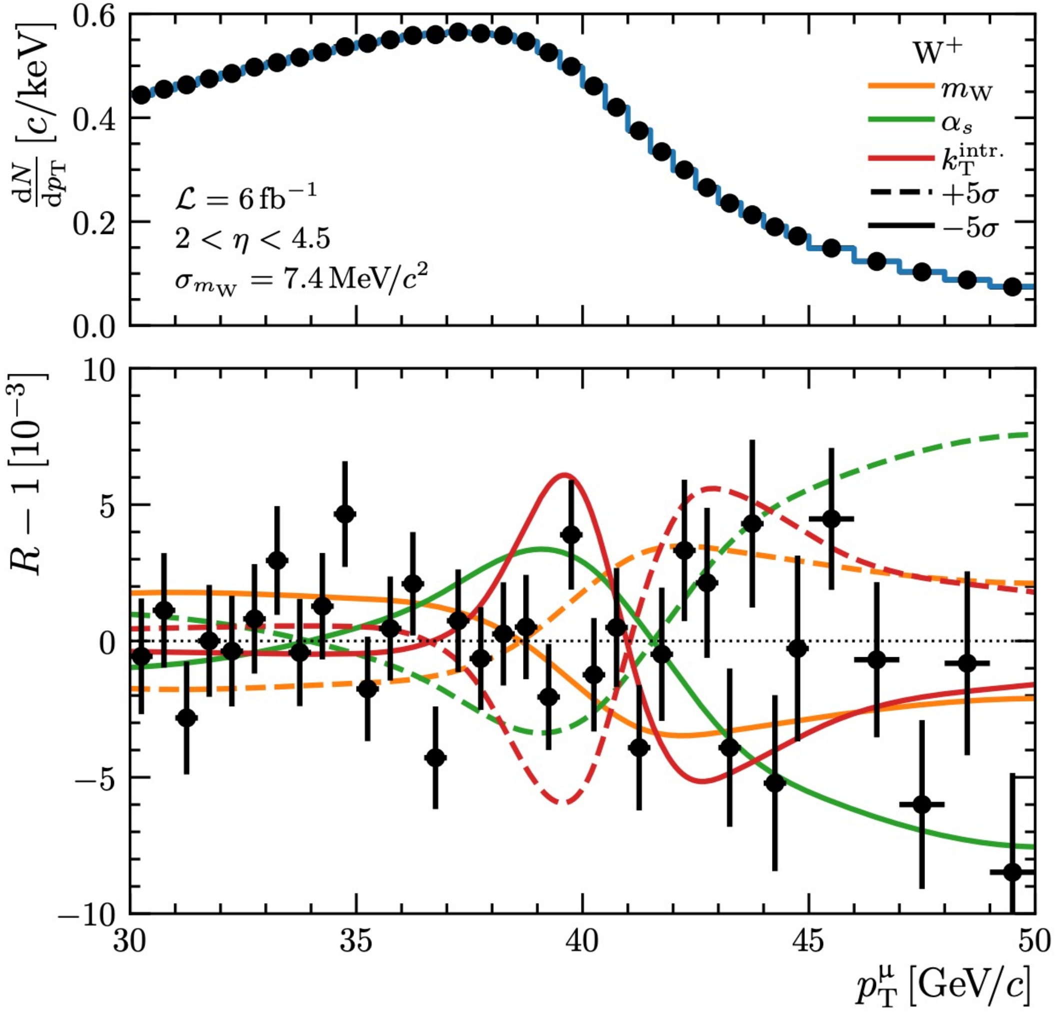


$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$




LHCb
Data
Fit model
Weighted candidates
10^{3}
10^{2}
10
1
10^{-1}
20
25
30
35
40
45
50
55
60
p_{T} [GeV]


×10³
Fit region
LHCb
1.7 fb⁻¹
Before fit
Data
POWHEGPYTHIA (ref.)
HERWIG
POWHEGHERWIG
PYTHIACT09MCS
PYTHIANNPDF31
DYTURBO
Events per GeV
Ratio to ref.
p_T^Z [GeV]
After fit



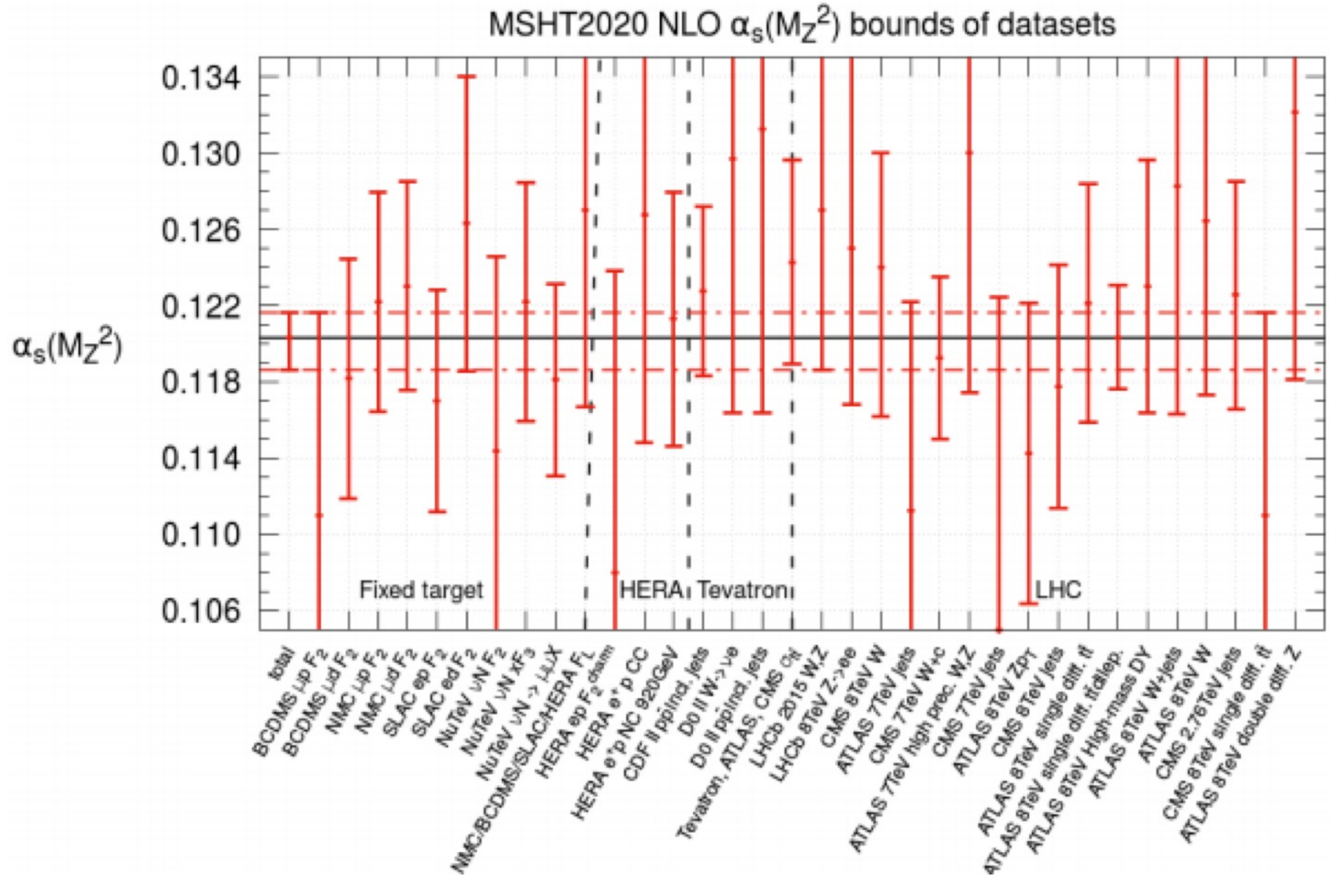
$\frac{dN}{dp_T}$ [c/keV]
W+
m_W
α_s
$k_T^{intr.}$
+5σ
−5σ
$\mathcal{L} = 6\,\mathrm{fb}^{-1}$
$2 < \eta < 4.5$
$\sigma_{m_W} = 7.4\,\mathrm{MeV}/c^2$
$R - 1\,[10^{-3}]$
p_T^μ [GeV/c]

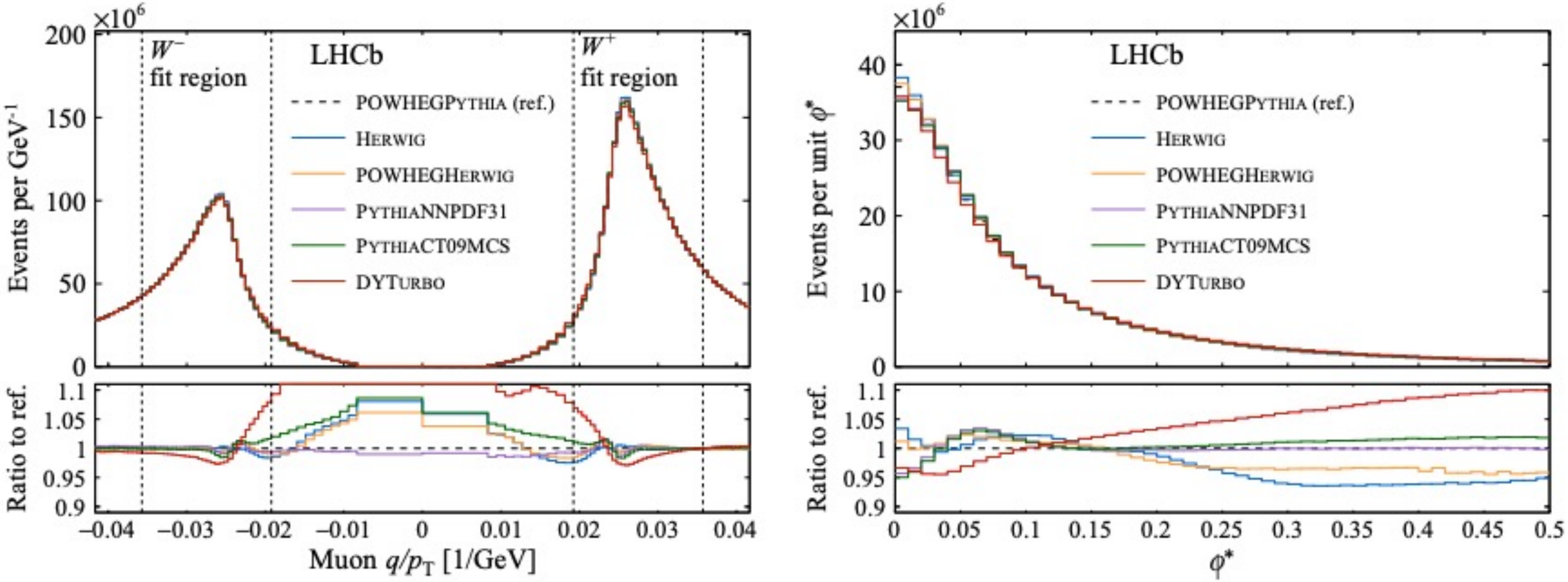
[Submitted on 18 Jun 2021]

An investigation of the α_S and heavy quark mass dependence in the MSHT20 global PDF analysis

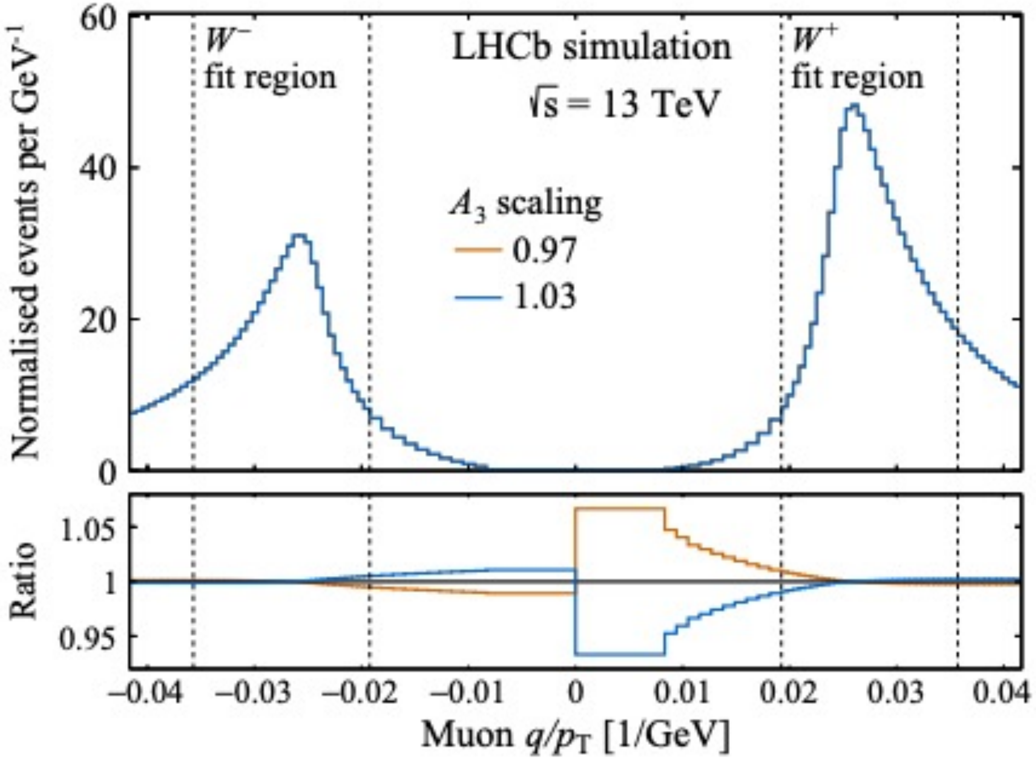
T. Cridge, L.A. Harland-Lang, A.D. Martin, R.S. Thorne

We investigate the MSHT20 global PDF sets, demonstrating the effects of varying the strong coupling $\alpha_S(M_Z^2)$ and the masses of the charm and bottom quarks. We determine the preferred value, and accompanying uncertainties, when we allow $\alpha_S(M_Z^2)$ to be a free parameter in the MSHT20 global analyses of deep-inelastic and related hard scattering data, at both NLO and NNLO in QCD perturbation theory. We also study the constraints on $\alpha_S(M_Z^2)$ which come from the individual data sets in the global fit by repeating the NNLO and NLO global analyses at various fixed values of $\alpha_S(M_Z^2)$, spanning the range $\alpha_S(M_Z^2) = 0.108$ to 0.130 in units of 0.001. We make all resulting PDFs sets available. We find that the best fit values are $\alpha_S(M_Z^2) = 0.1203 \pm 0.0015$ and 0.1174 ± 0.0013 at NLO and NNLO respectively. We investigate the relationship between the variations in $\alpha_S(M_Z^2)$ and the uncertainties on the PDFs, and illustrate this by calculating the cross sections for key processes at the LHC. We also perform fits where we allow the heavy quark masses m_c and m_b to vary away from their default values and make PDF sets available in steps of $\Delta m_c = 0.05$ GeV and $\Delta m_b = 0.25$ GeV, using the pole mass definition of the quark masses. As for varying $\alpha_S(M_Z^2)$ values, we present the variation in the PDFs and in the predictions. We examine the comparison to data, particularly the HERA data on charm and bottom cross sections and note that our default values are very largely compatible with best fits to data. We provide PDF sets with 3 and 4 active quark flavours, as well as the standard value of 5 flavours.





Data config.	χ^2_W	χ^2_Z	δm_W [MeV]	α_s^Z	α_s^W	A_3 scaling
POWHEGPYTHIA	64.8	34.2	–	0.1246 ± 0.0002	0.1245 ± 0.0003	0.979 ± 0.029
HERWIG	71.9	600.4	1.6	0.1206 ± 0.0002	0.1218 ± 0.0003	1.001 ± 0.029
POWHEGHERWIG	64.0	118.6	2.7	0.1206 ± 0.0002	0.1226 ± 0.0003	0.991 ± 0.029
PYTHIA, CT09MCS	71.0	215.8	−2.4	0.1239 ± 0.0002	0.1243 ± 0.0003	0.983 ± 0.029
PYTHIA, NNPDF31	66.9	156.2	−10.4	0.1225 ± 0.0002	0.1223 ± 0.0003	0.967 ± 0.029
DYTURBO	83.0	428.5	4.3	0.1305 ± 0.0001	0.1321 ± 0.0003	0.982 ± 0.028



$$\frac{d\sigma}{dp_T^W\,dy\,dM\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^V\,dy\,dM}$$
$$\Big\{(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+ A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}$$

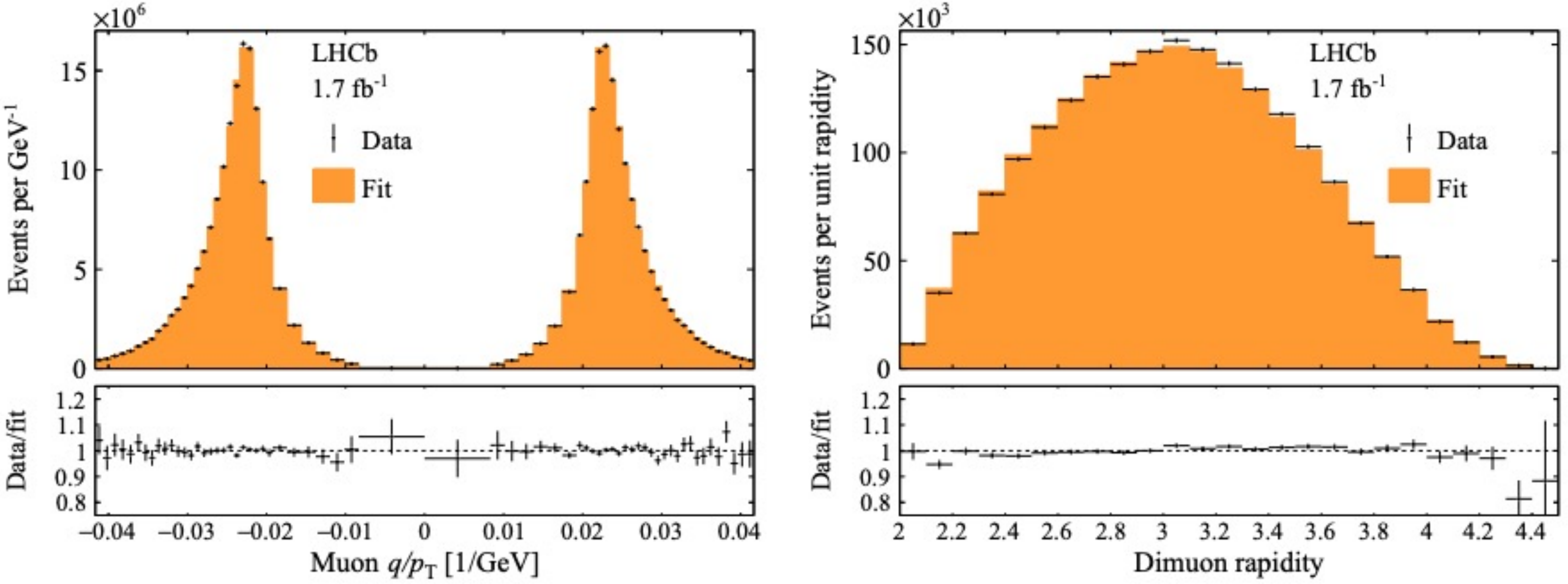
$$A_3(p_T, y, M) \rightarrow f_{A3} \times A_3(p_T, y, M)$$

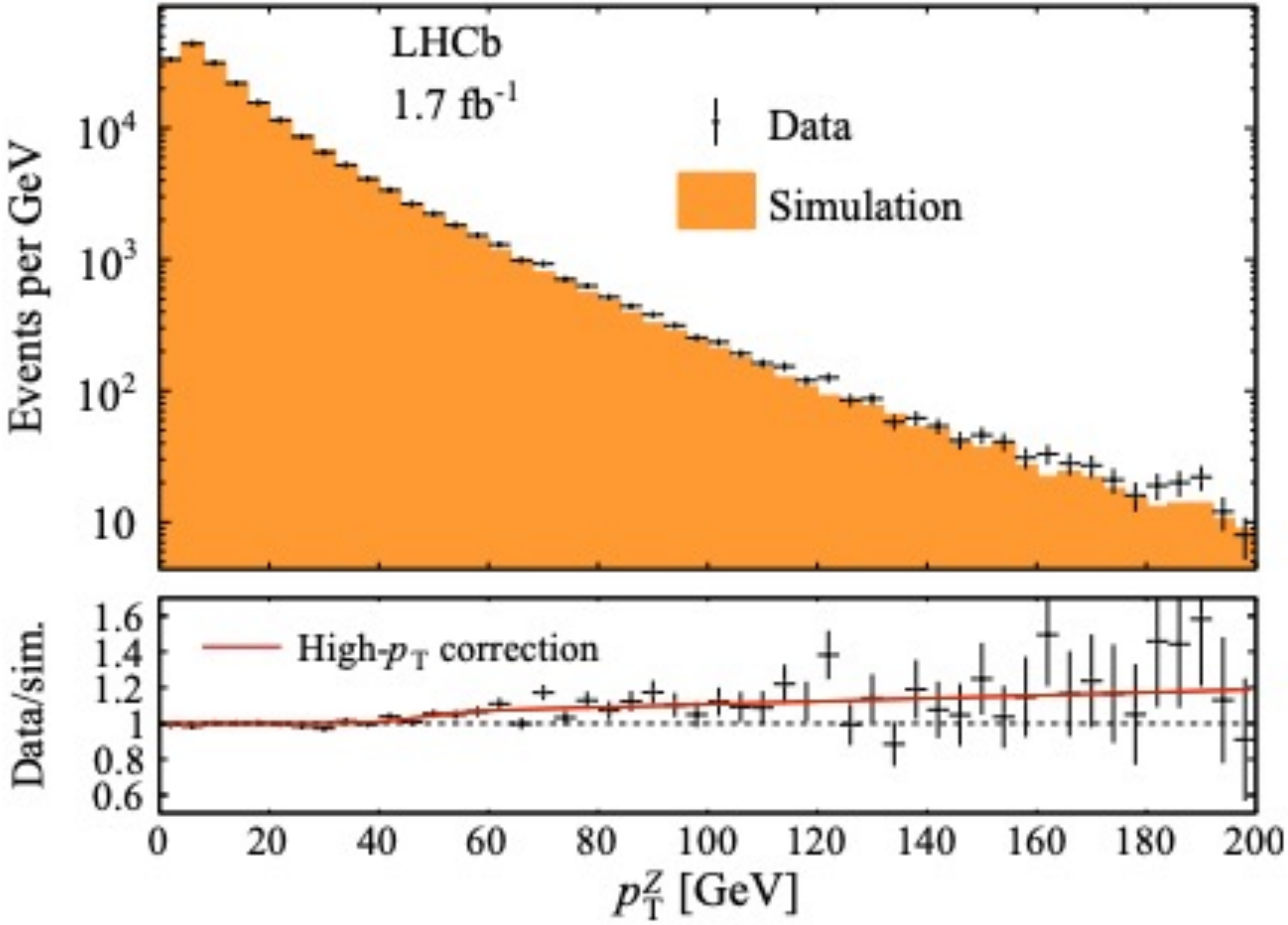
Orthogonal datasets:

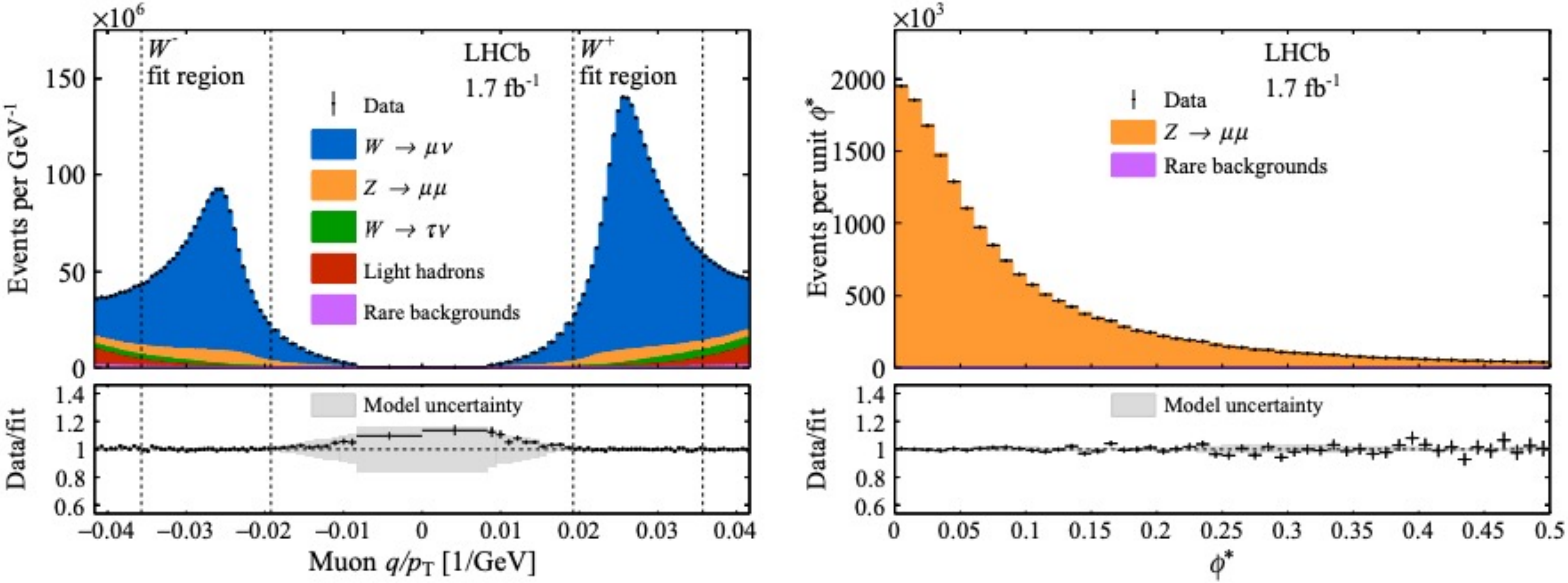
Subset	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]
Polarity $= -1$	$92.5/102$	–
Polarity $= +1$	$97.3/102$	-57.5 ± 45.4
$\eta > 3.3$	$115.4/102$	–
$\eta < 3.3$	$85.9/102$	$+56.9 \pm 45.5$
Polarity $\times\ q = +1$	$95.9/102$	–
Polarity $\times\ q = -1$	$98.2/102$	$+16.1 \pm 45.4$
$\lvert\phi\rvert > \pi/2$	$98.8/102$	–
$\lvert\phi\rvert < \pi/2$	$115.0/102$	$+66.7 \pm 45.5$
$\phi < 0$	$91.8/102$	–
$\phi > 0$	$103.0/102$	-100.5 ± 45.3

Fit model freedom:

Configuration change	χ^2_{tot}/ndf	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$2 \to 3$ α_s parameters	103.4/101	−6.0	±23.1
$2 \to 1$ α_s and $1 \to 2$ $k_{\text{T}}^{\text{intr}}$ parameters	116.1/102	+13.9	±22.4
$1 \to 2$ $k_{\text{T}}^{\text{intr}}$ parameters	104.0/101	+0.4	±22.7
$1 \to 3$ $k_{\text{T}}^{\text{intr}}$ parameters	102.8/100	−2.7	±22.9
No A_3 scaling	106.0/103	+4.4	±22.2
Varying QCD background asymmetry	103.8/101	−0.7	±22.7


×10^6
LHCb
1.7 fb^-1
Data
Fit
Events per GeV^-1
Data/fit
Muon q/p_T [1/GeV]
×10^3
LHCb
1.7 fb^-1
Data
Fit
Events per unit rapidity
Data/fit
Dimuon rapidity

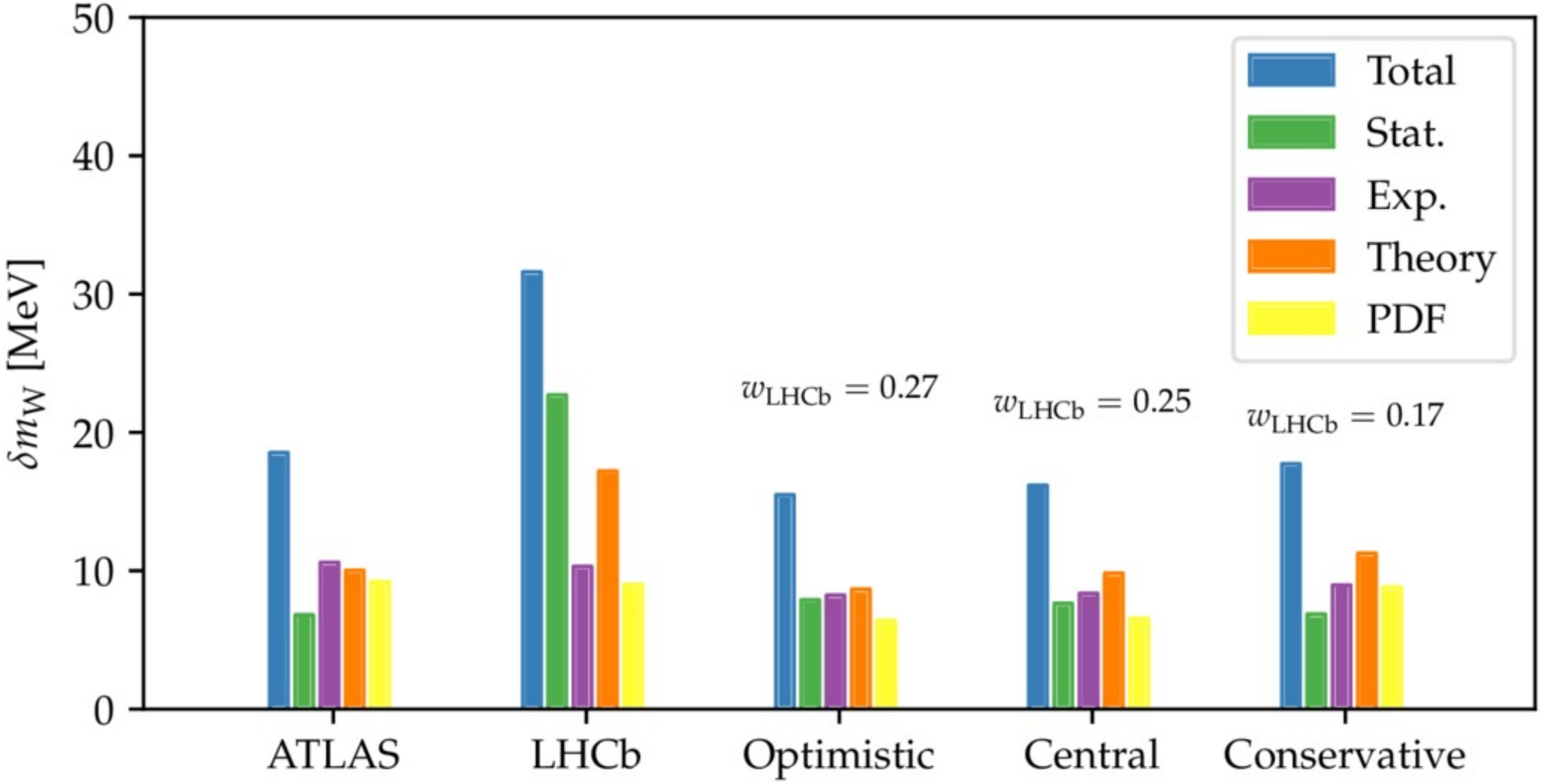

LHCb
1.7 fb^{-1}
Data
Simulation
Events per GeV
10^4
10^3
10^2
10
Data/sim.
High-p_T correction
1.6
1.4
1.2
1
0.8
0.6
0
20
40
60
80
100
120
140
160
180
200
p_T^Z [GeV]


×10^6
W⁻ fit region
LHCb 1.7 fb⁻¹
W⁺ fit region
Data
W → μν
Z → μμ
W → τν
Light hadrons
Rare backgrounds
Events per GeV⁻¹
Model uncertainty
Data/fit
Muon q/pT [1/GeV]
×10^3
LHCb 1.7 fb⁻¹
Data
Z → μμ
Rare backgrounds
Events per unit φ*
Model uncertainty
Data/fit
φ*

ATLAS:

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\,\text{MeV} = 80370 \pm 19\,\text{MeV}$$

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27


50
40
30
20
10
0
δm_W [MeV]
Total
Stat.
Exp.
Theory
PDF
$w_{\mathrm{LHCb}} = 0.27$
$w_{\mathrm{LHCb}} = 0.25$
$w_{\mathrm{LHCb}} = 0.17$
ATLAS
LHCb
Optimistic
Central
Conservative

B. C. Allenach *et al.*, EPJC 81 (2021) 721

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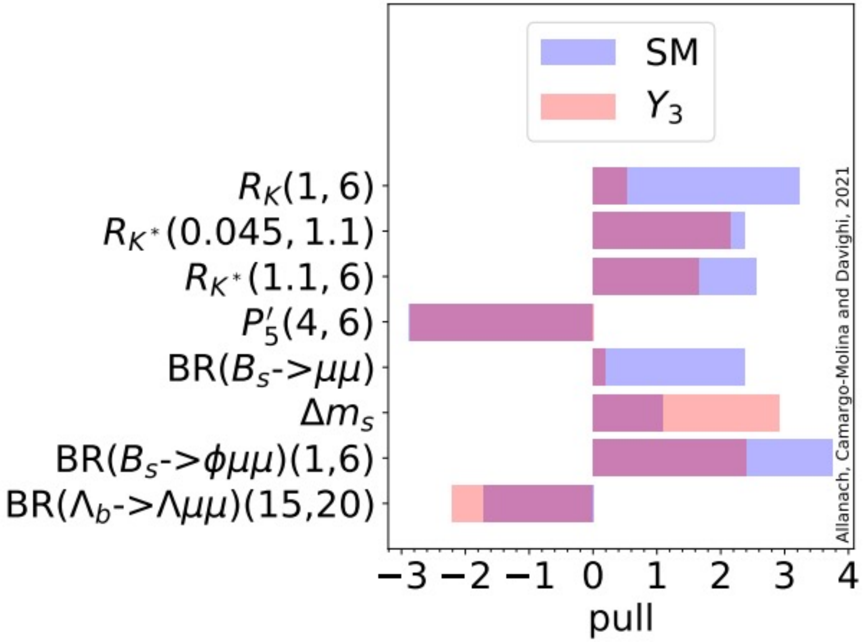

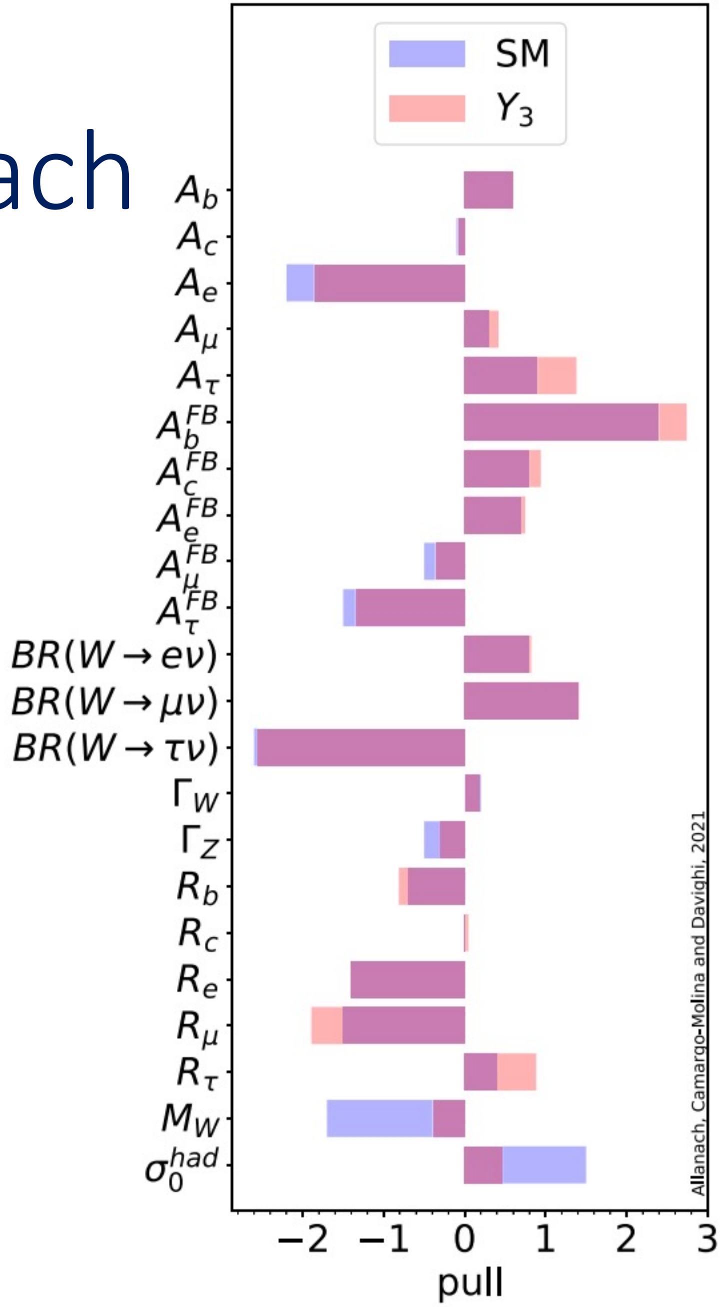

$$\sqrt{\Delta\chi^2(\mathrm{SM}, Y_3)} = 6.5$$