W mass measurement at LHCb

hep-ex:2109.01113 **LHCb-PAPER-2021-024**

Jahrestreffen der deutschen LHCb-Gruppen (Theorie und Experiment)
8 October 2021

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WARWICK

UKRI Science and Technology Facilities Council

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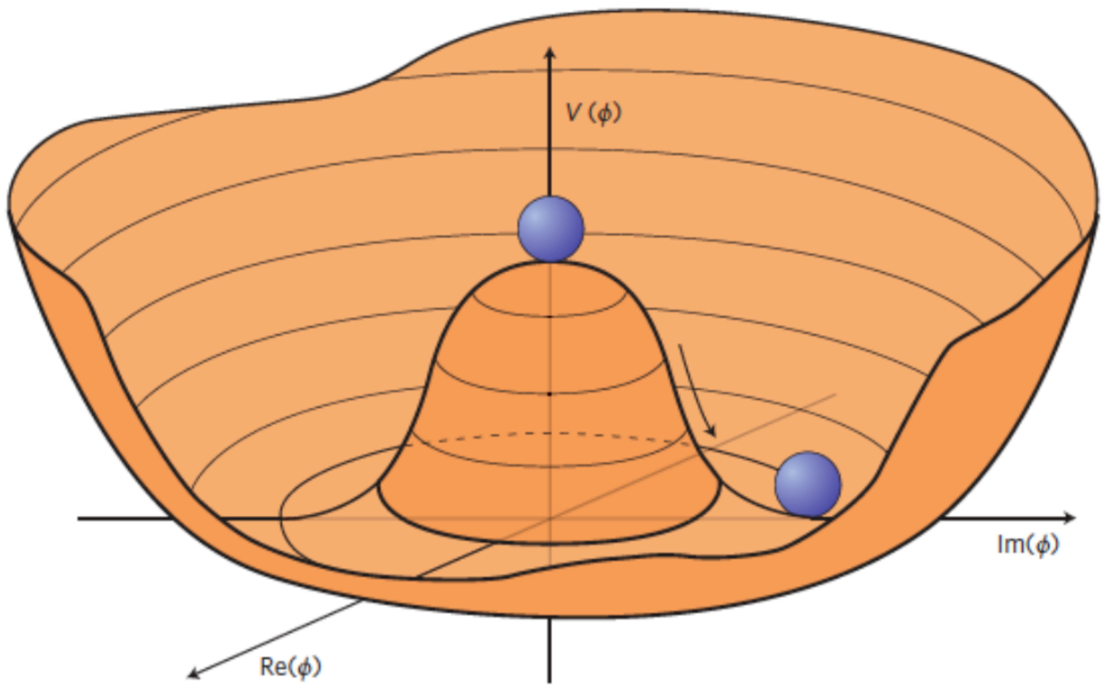
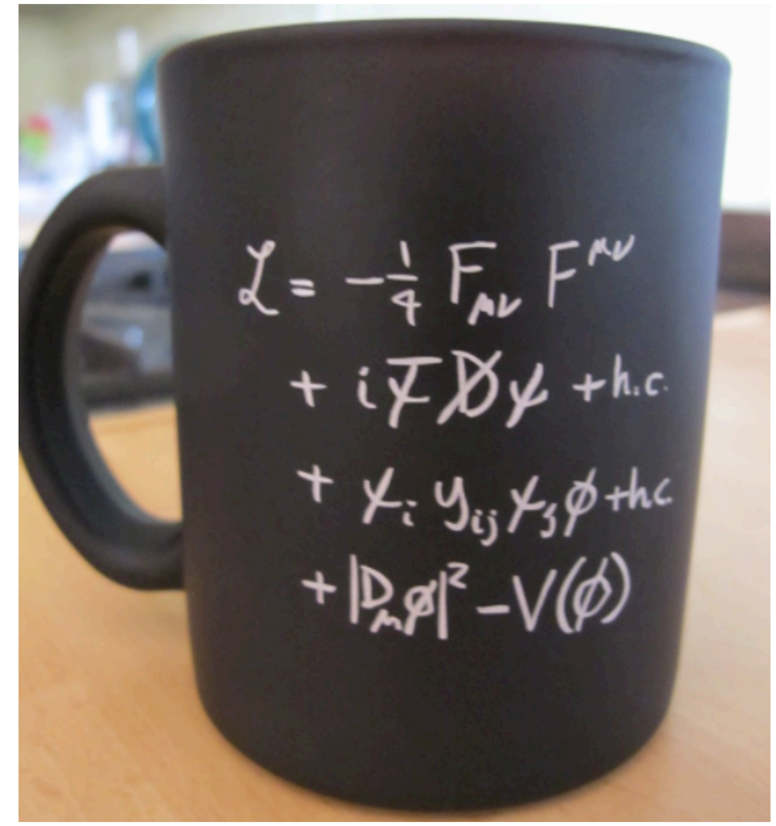
LHCb

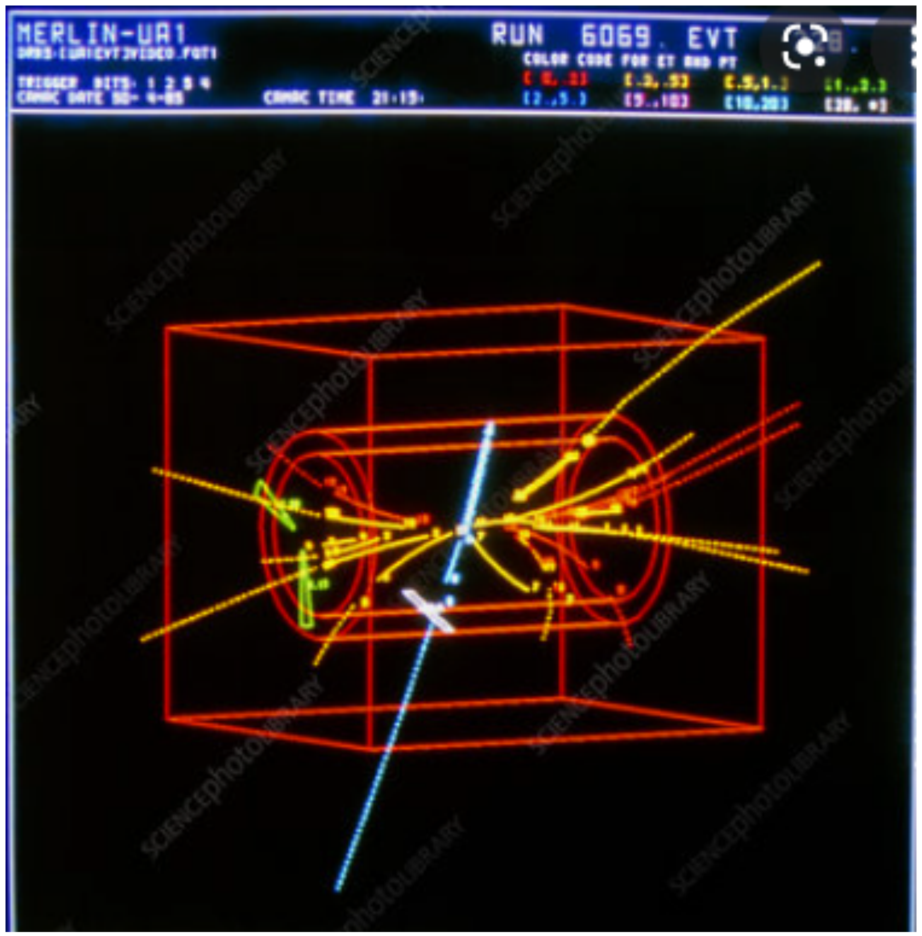


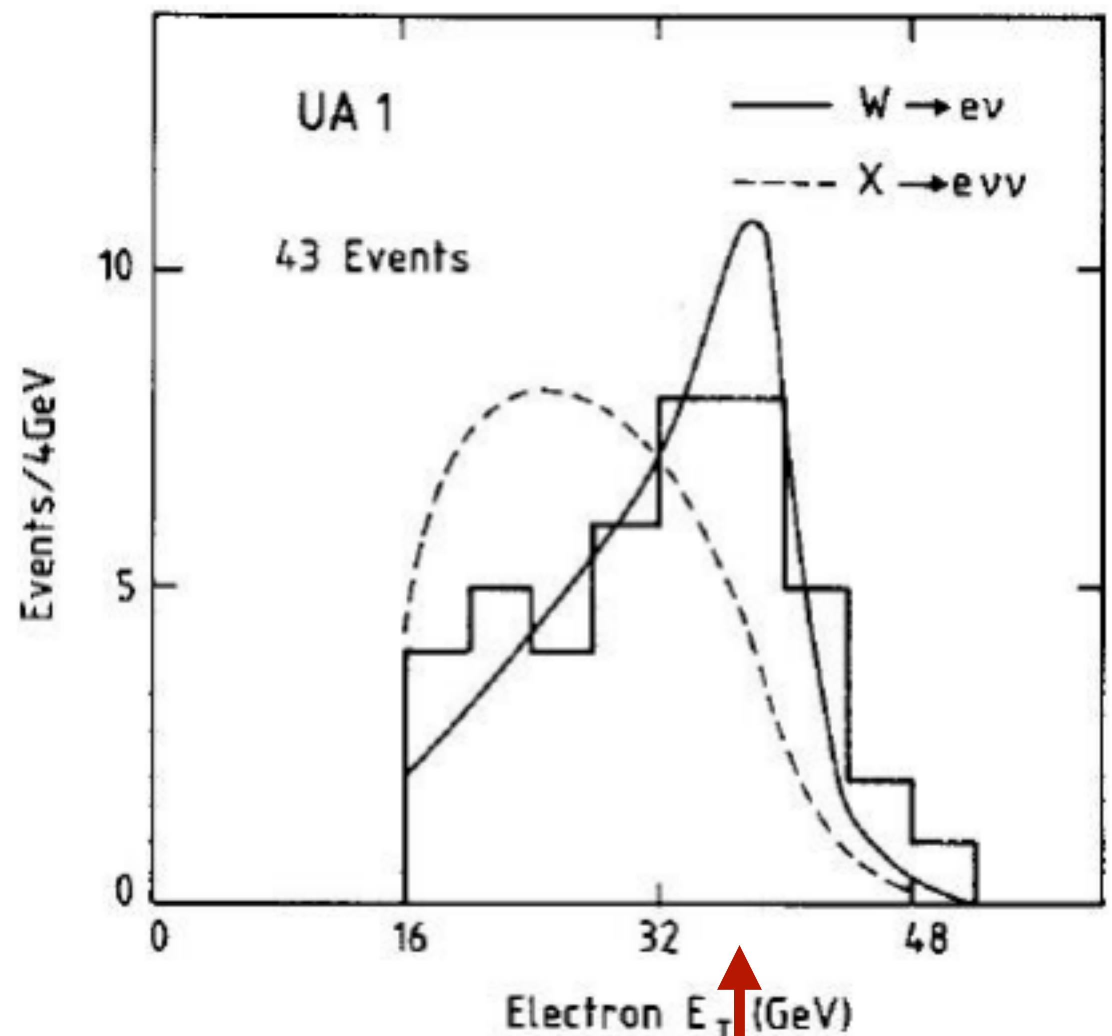


$$m_W = \frac{gv}{2} \sim 80 \text{ GeV}$$

UA1 Collaboration, PLB 122 (**1983**) p103

Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at √s = 540 GeV





$$p_T \approx \frac{m_W}{2}$$

Later combination with UA2 experiment:

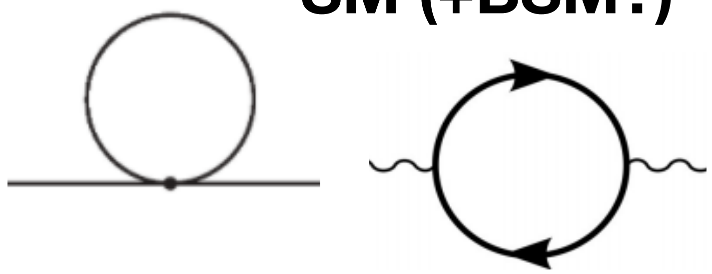
$$m_W = 82.1 \pm 1.7 \text{ GeV}$$

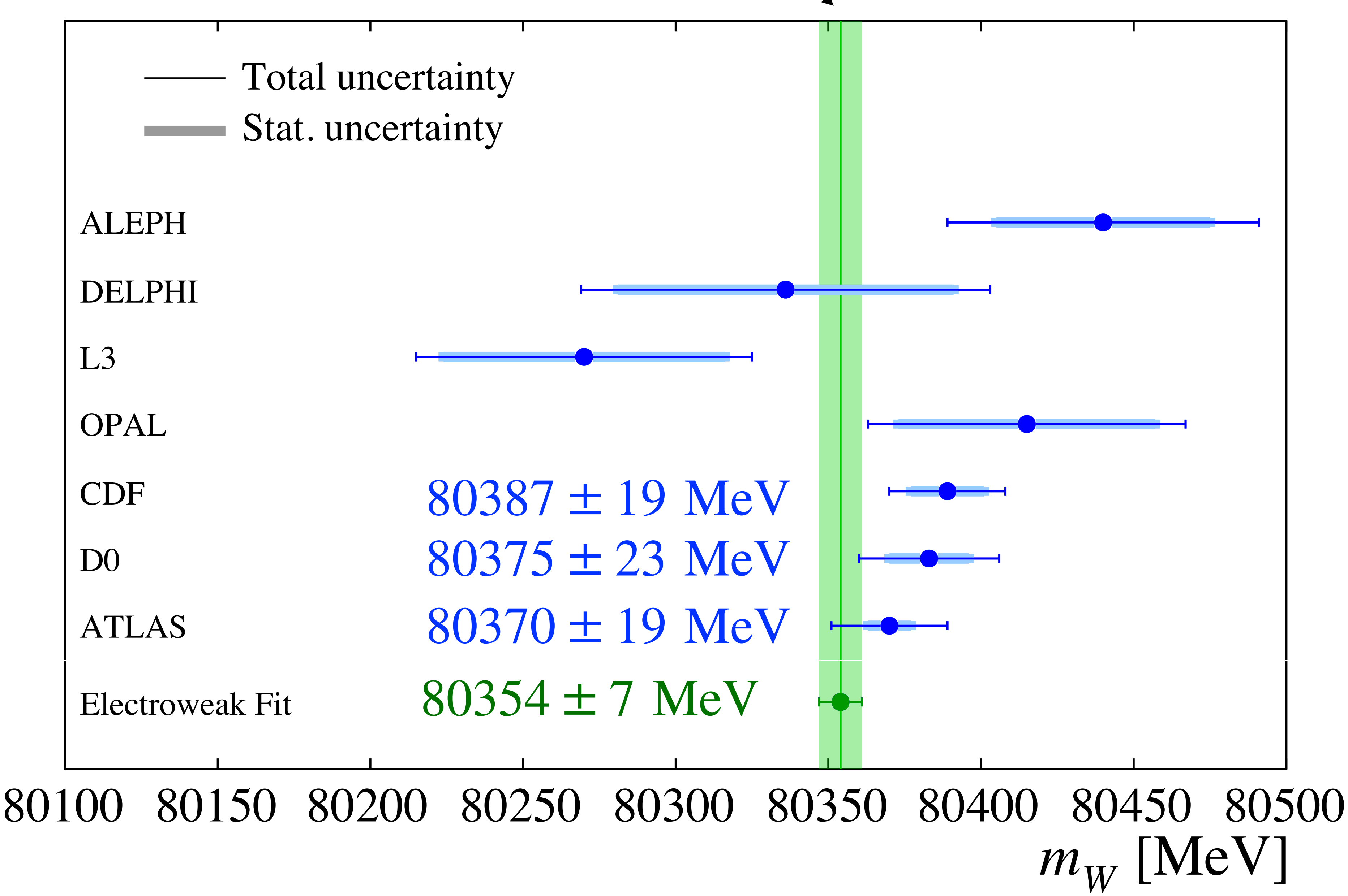
SM prediction (in 1983):

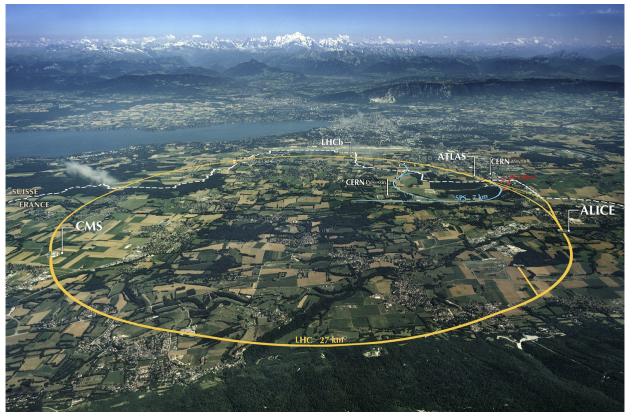
$$m_W = 83 \pm 3 \text{ GeV}$$

SM (+BSM?)

$\alpha, G_F, m_Z, \ldots$

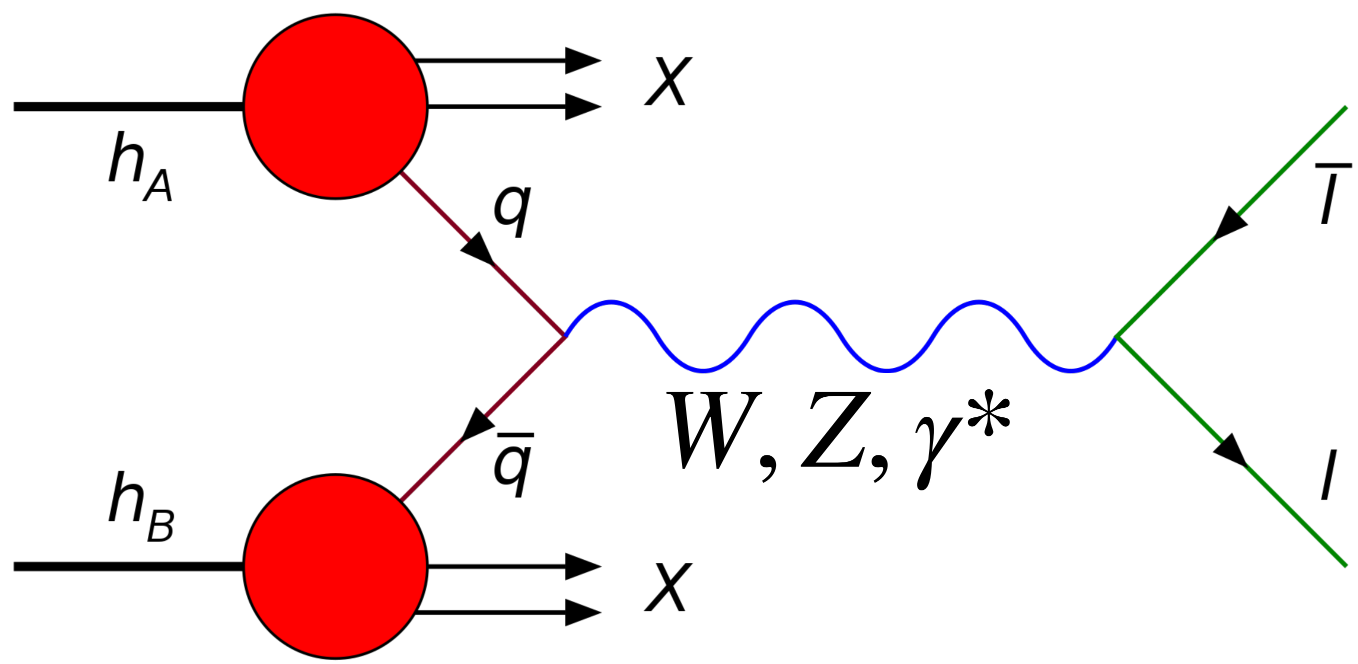


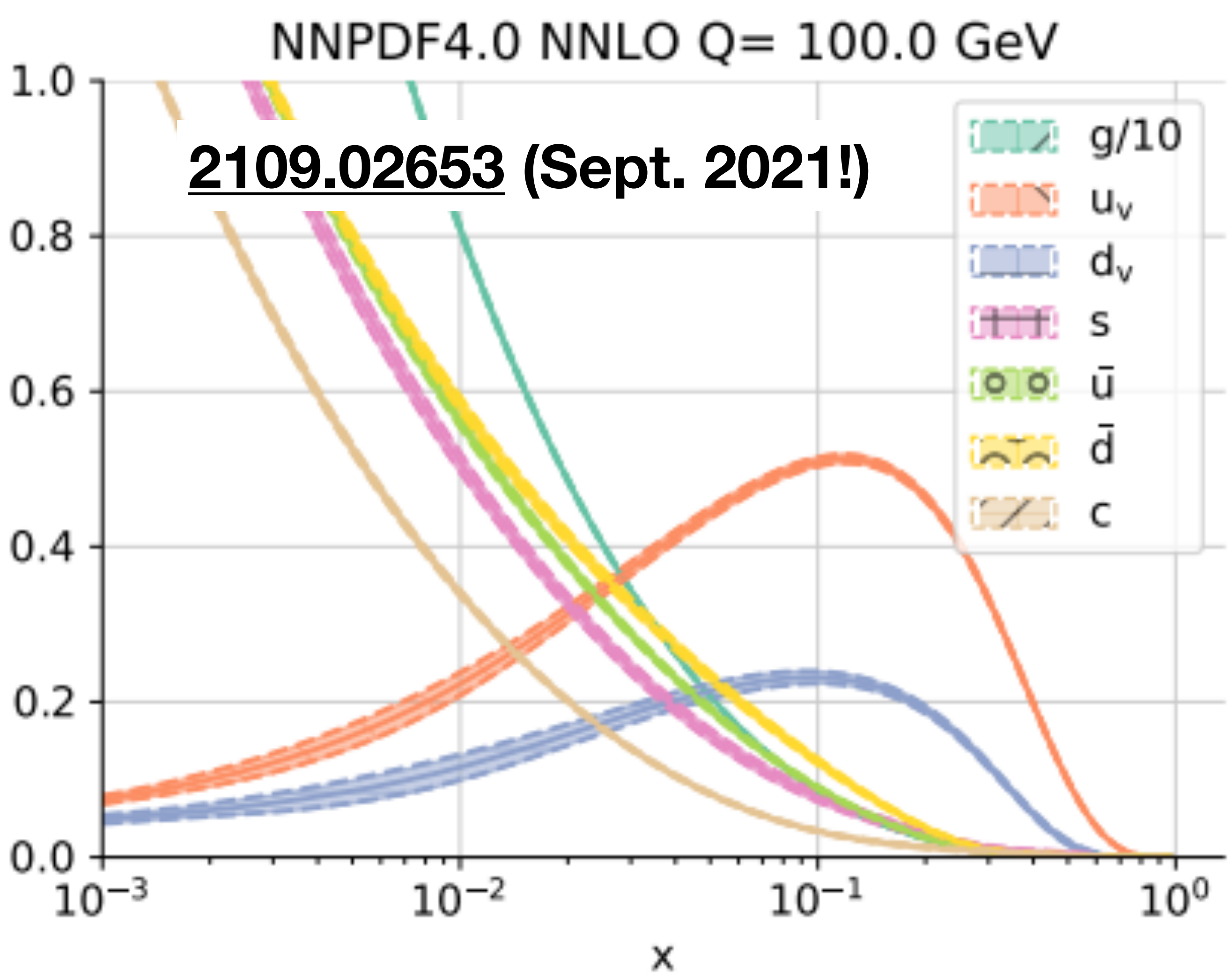




Need to measure m_W more precisely but …

The Drell-Yan process and Parton Distribution Functions



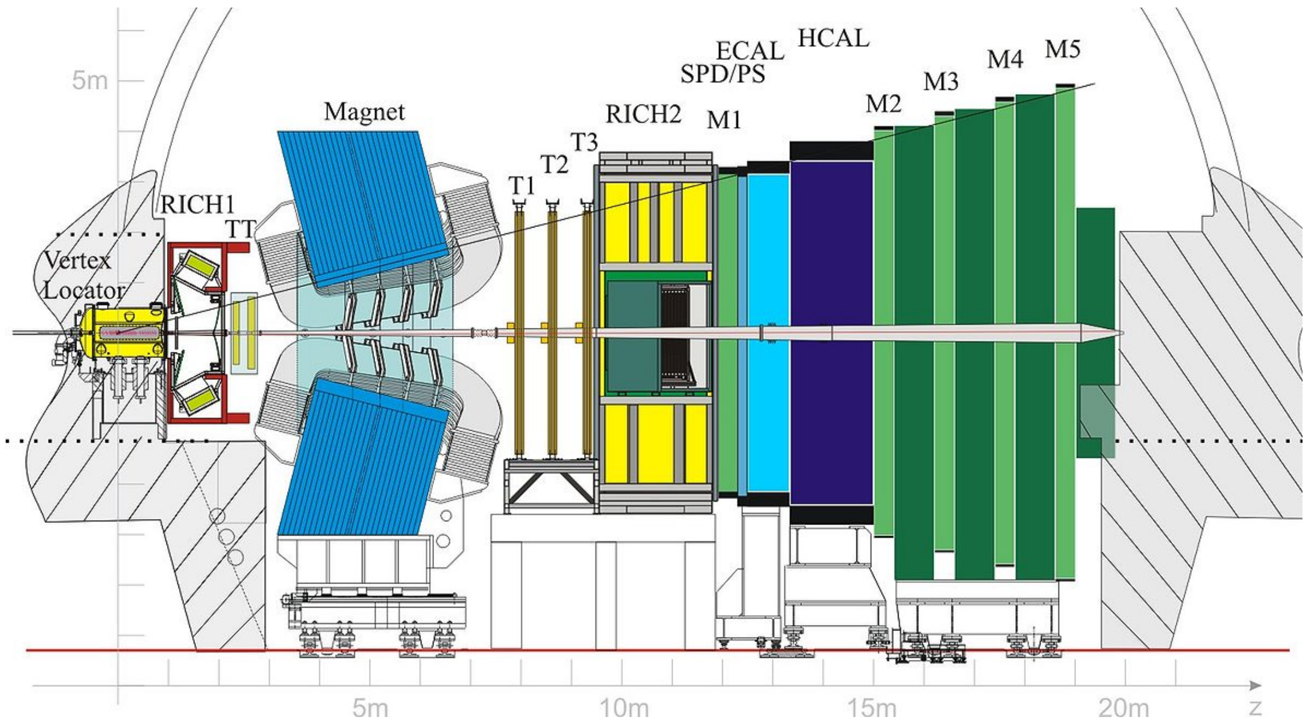


PDF uncertainties may dominate measurements of m_W.

Typical size: σ_{PDF} ~ 10 MeV

LHCb can help in *two* ways…

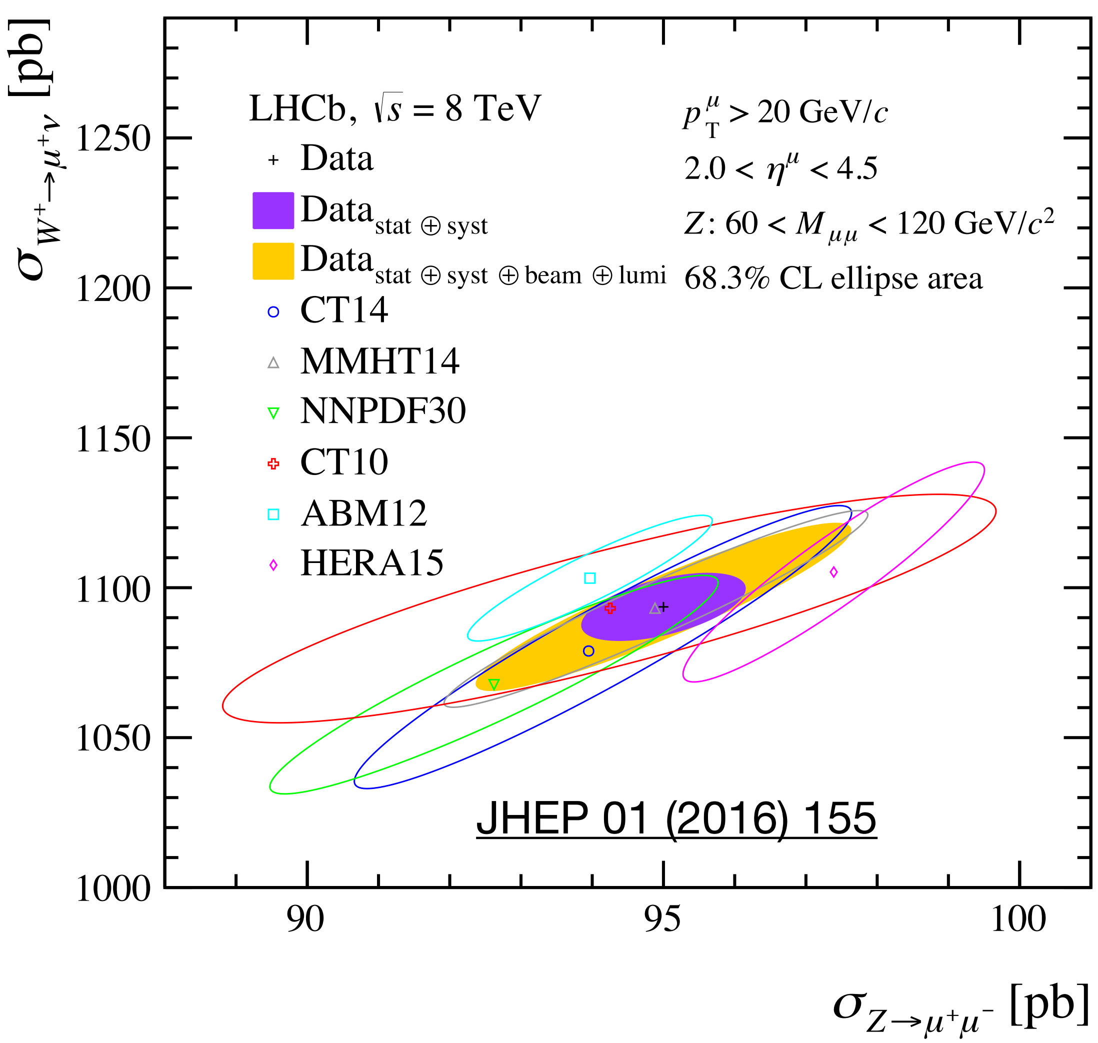
1) Cross-section measurements

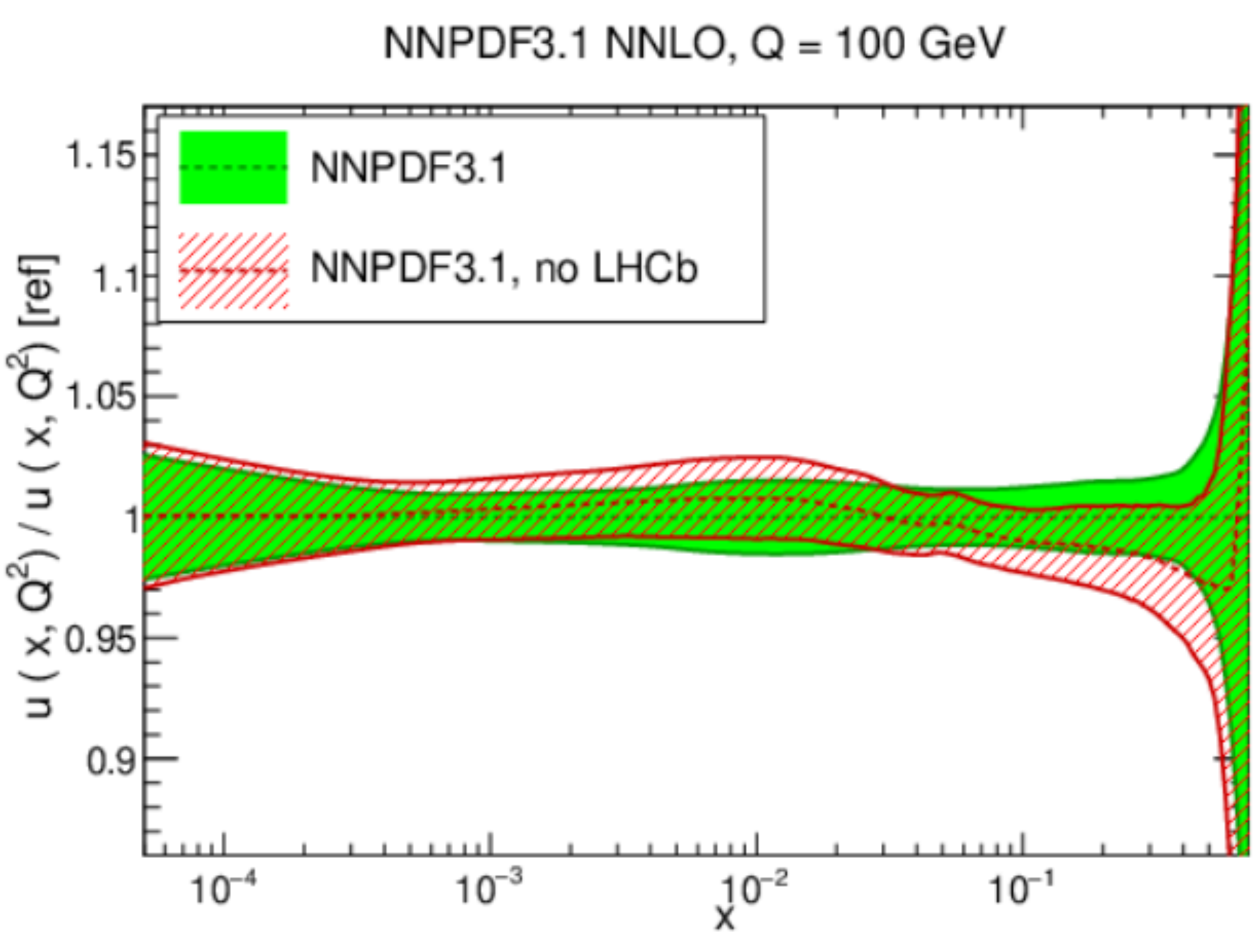


$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

LHCb uniquely covers 2 < y < 5

Constrains PDFs at low and high x

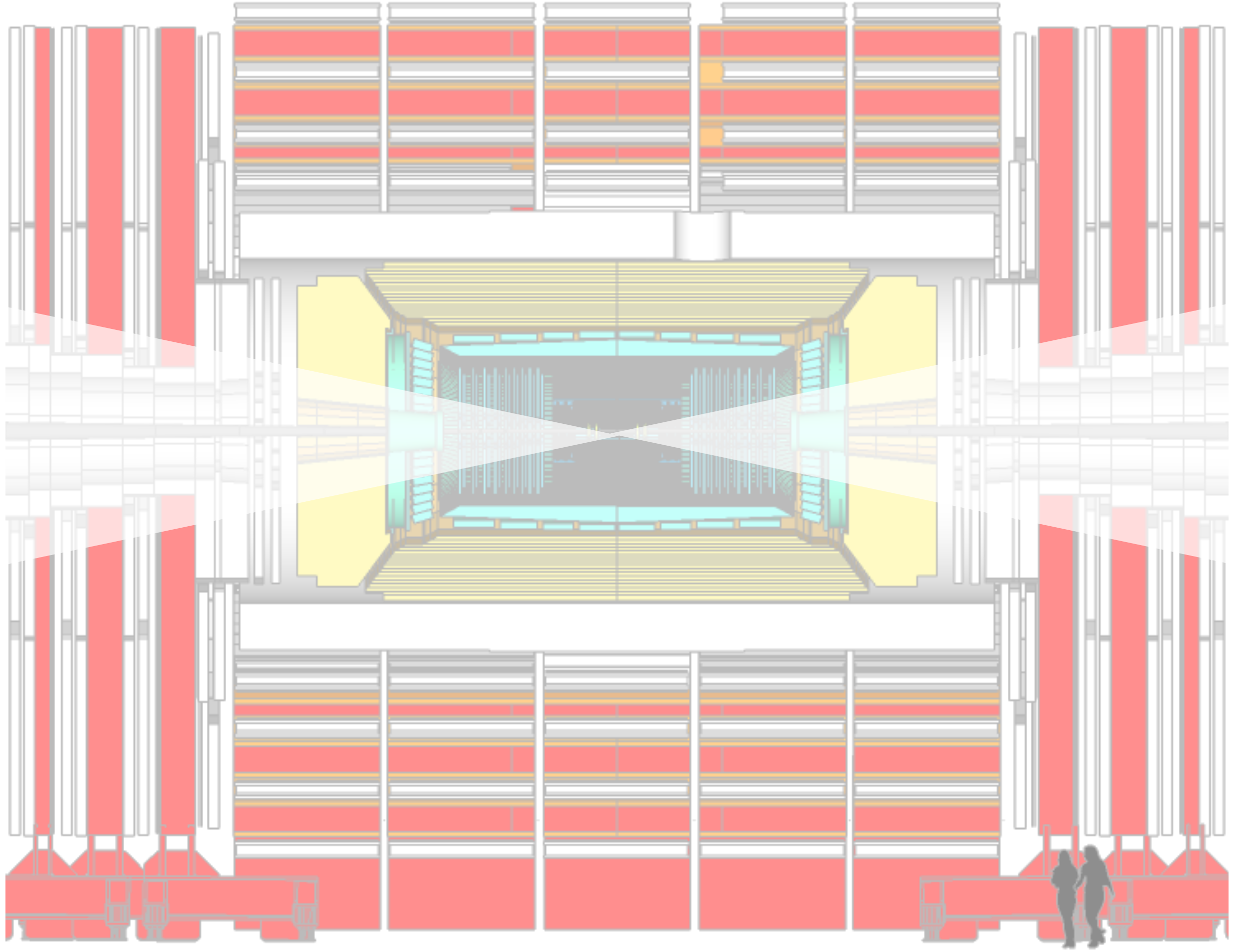




2) Measuring the W mass ourselves!

EPJC 75 (2015) 12, 601

The PDF uncertainty is related to the detector acceptance



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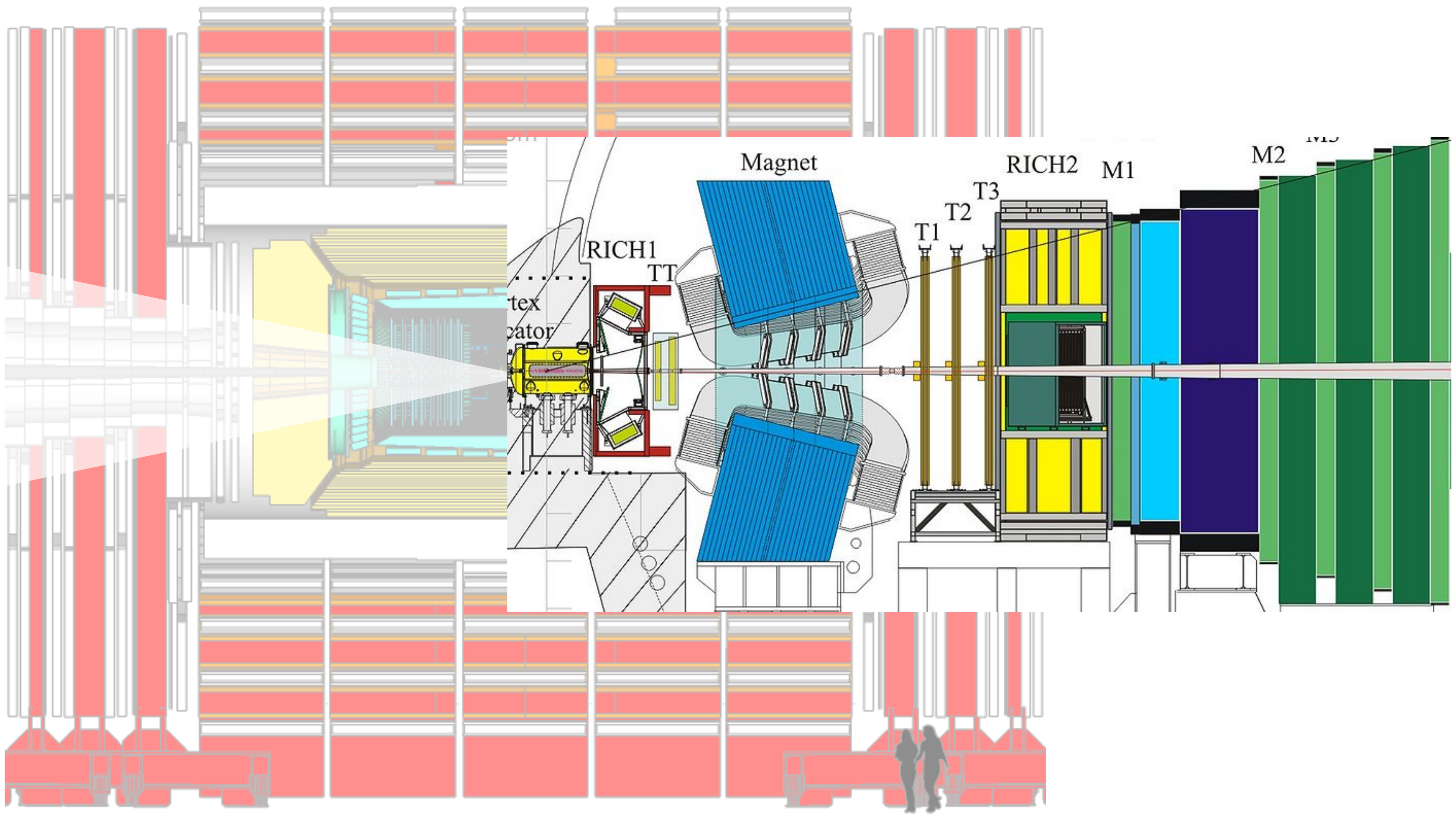

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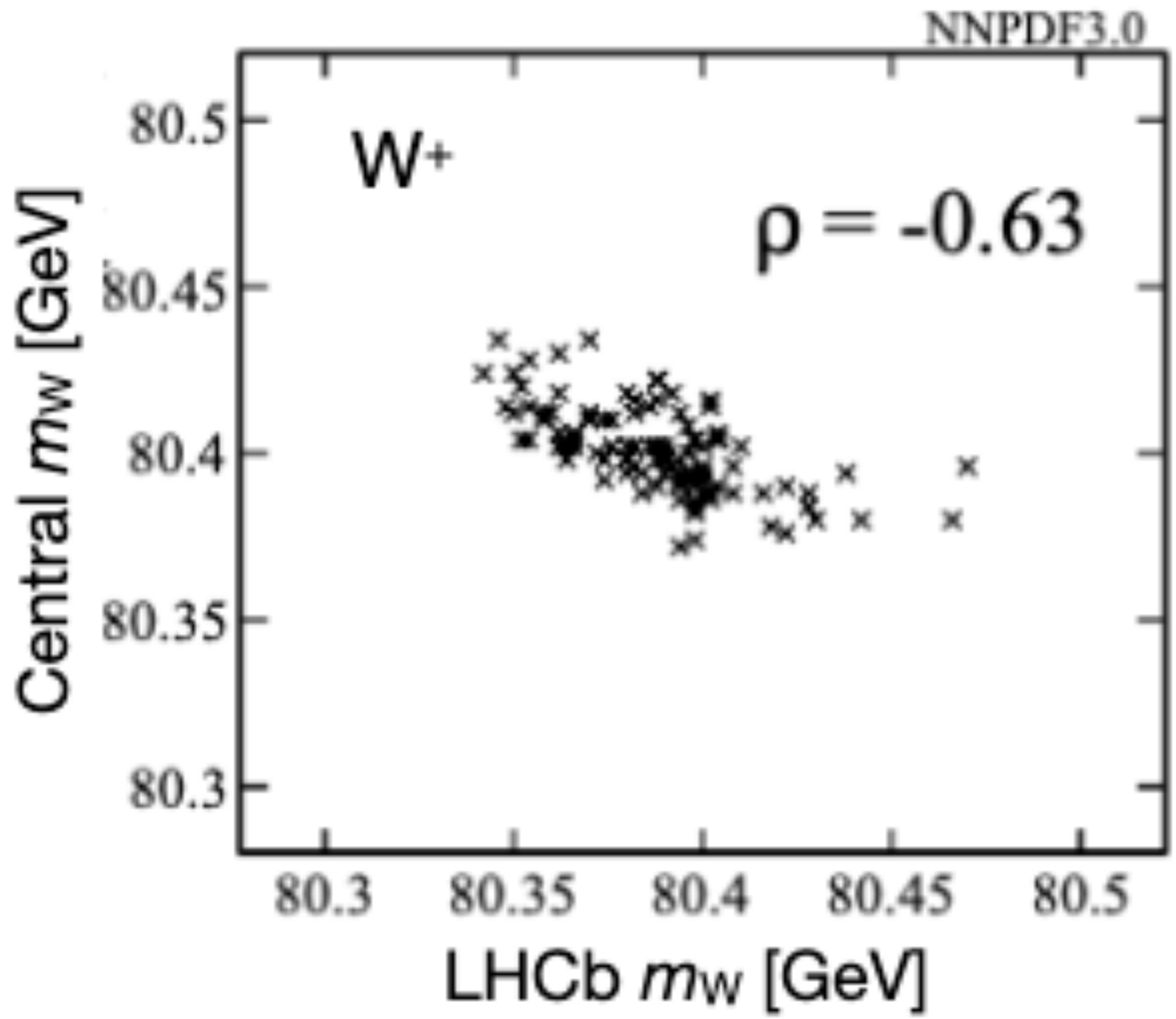
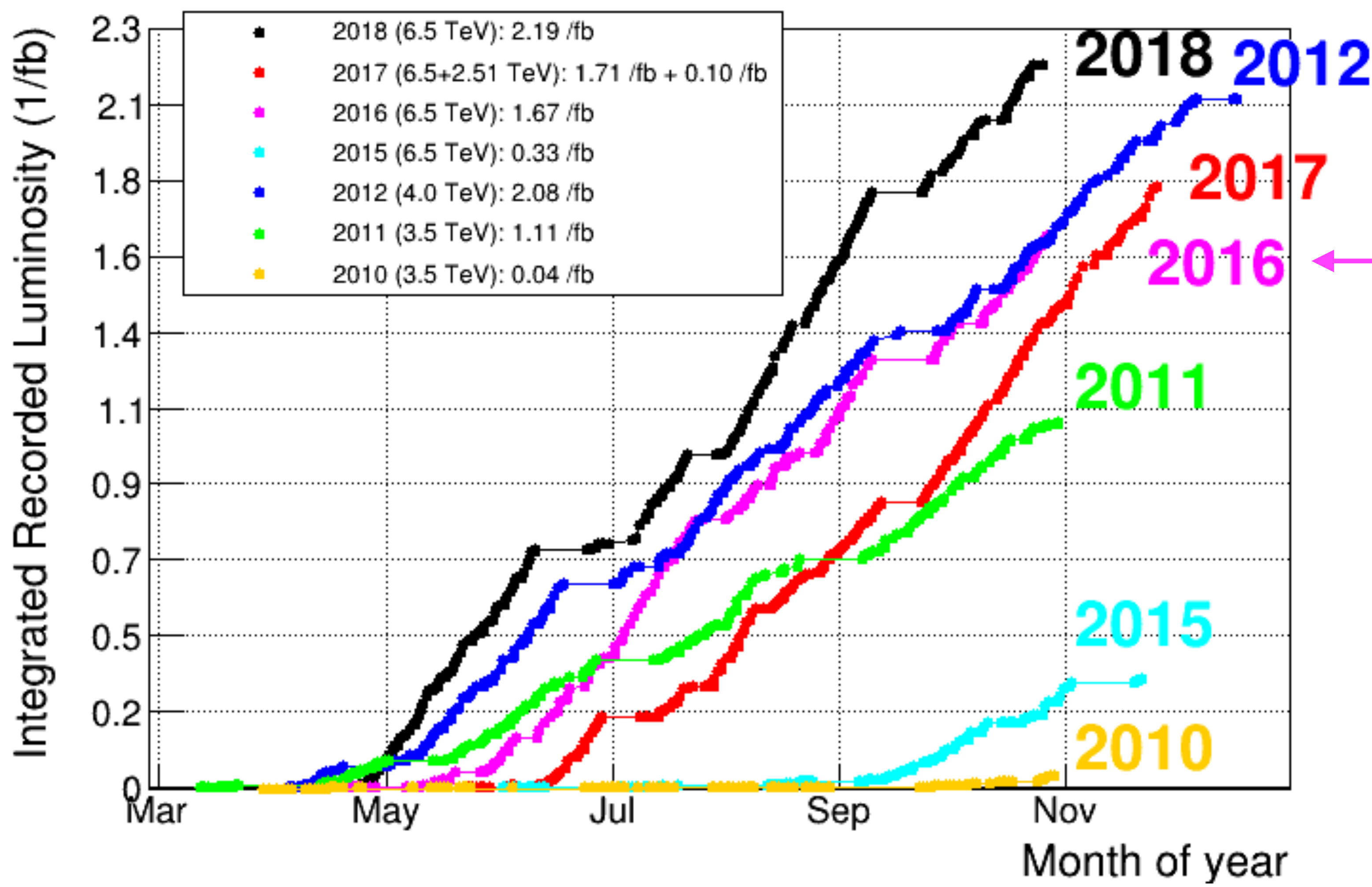
EPJC 75 (2015) 12, 601



Partial anticorrelation of the PDF uncertainty

Building a proof-of-principle measurement of m_W



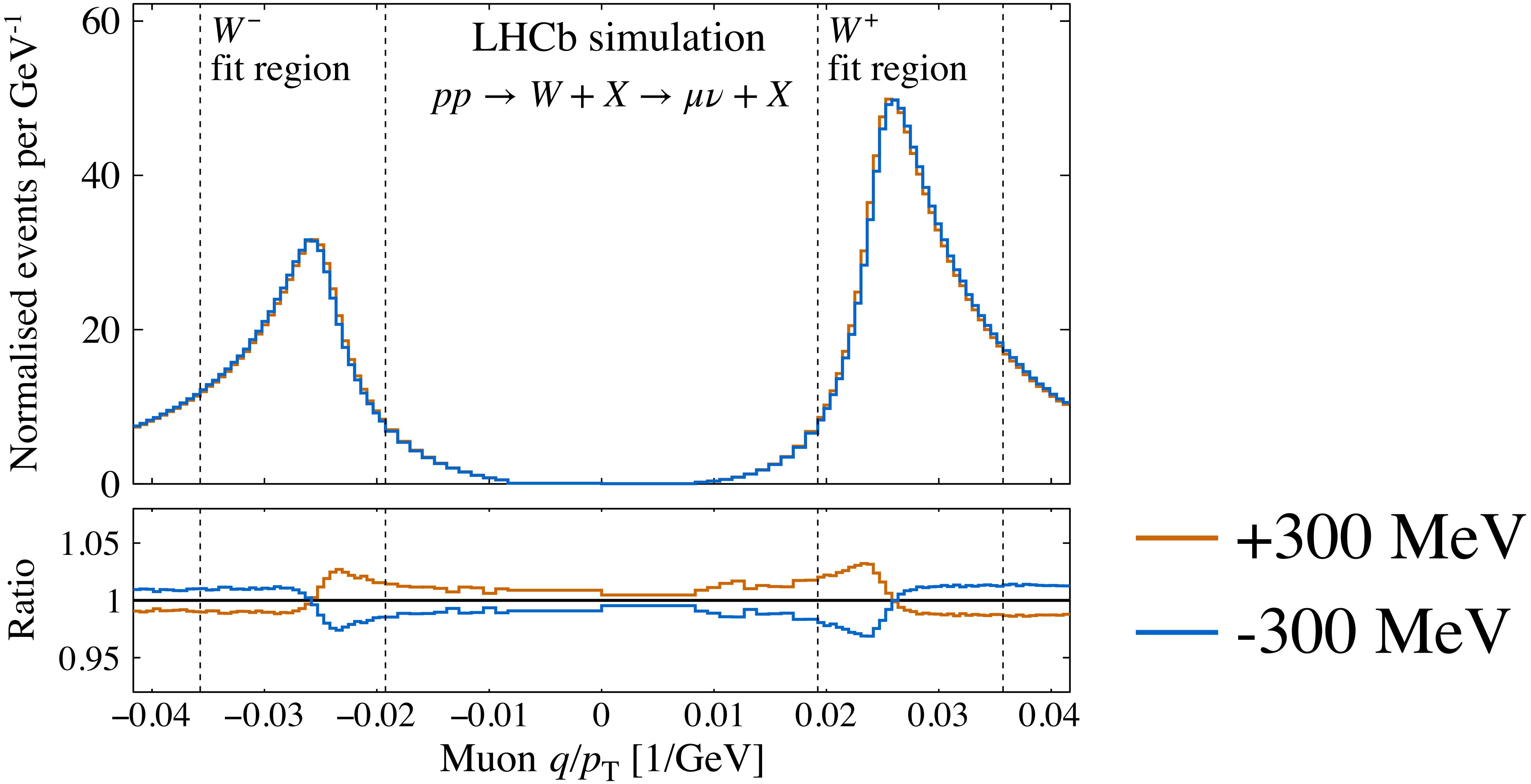
This analysis (1.7 fb^{-1})

≈2.4 million $W \to \mu\nu$ candidates* → $\boldsymbol{\sigma_{stat}(m_W) \sim 20}$ **MeV**

≈0.2 million $Z \to \mu\mu$ events.

*In $28 < p_T < 52$ GeV and $2.2 < \eta < 4.4$ region used for m_W fit

Building the m_W fit model



Start from W, Z, other backgrounds… events simulated with Pythia and will full GEANT-based detector simulation

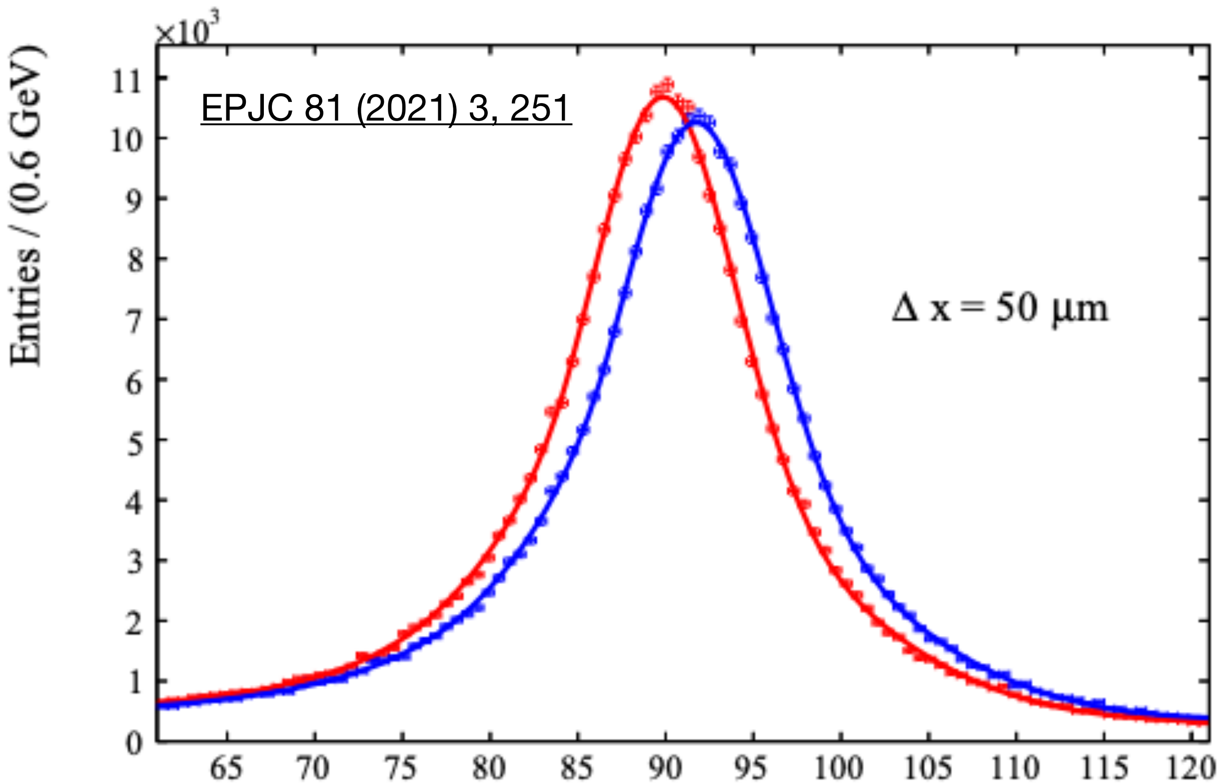
⚠️ Pythia is only leading order: reweighting to higher orders…

⚠️ Detector simulation is also approximate…

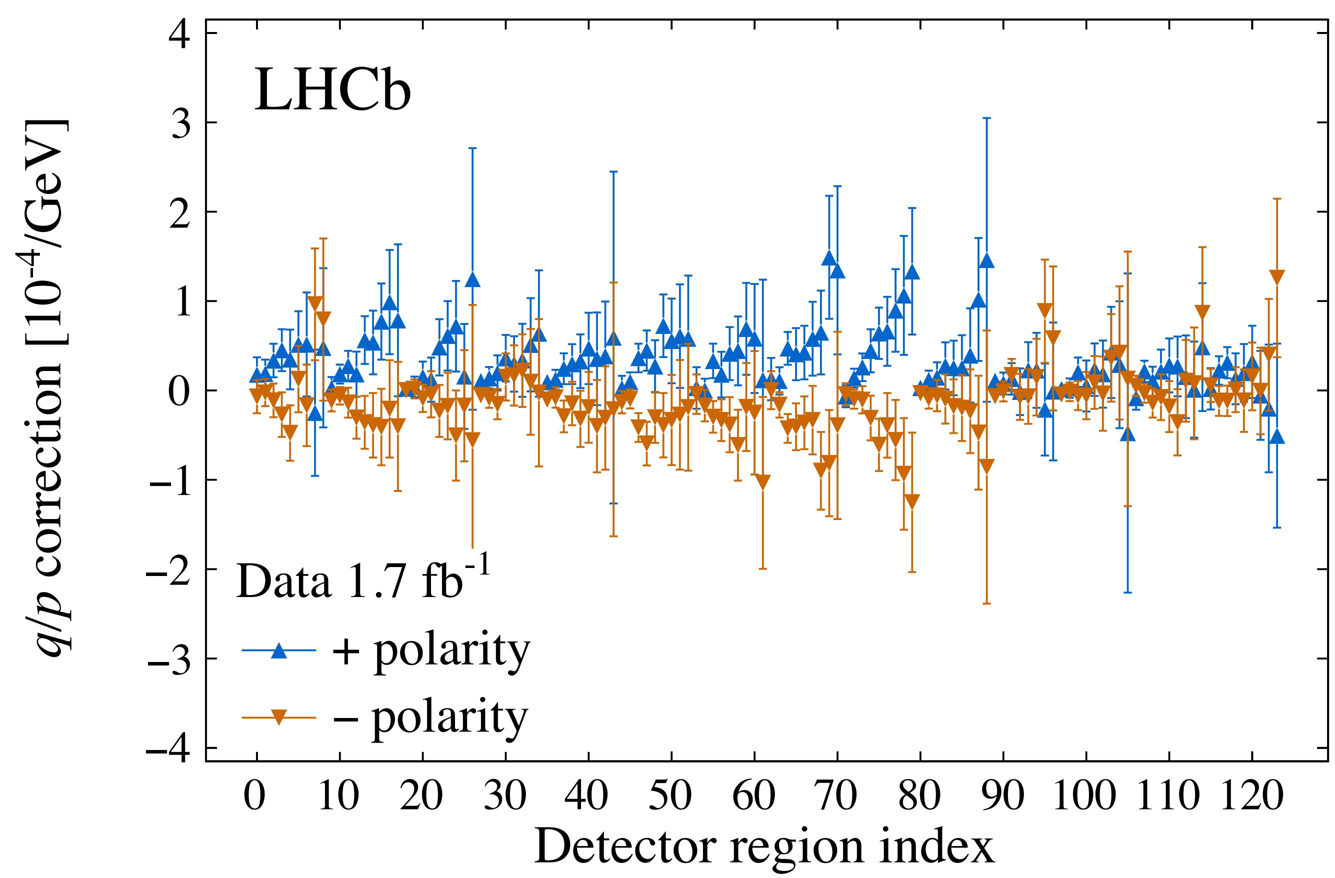
Making the data easier to model

1) Custom alignment of the tracking system for high p_T physics
LHCb-FIGURE-2020-009

2) The pseudomass method ⟶ **Curvature corrections**



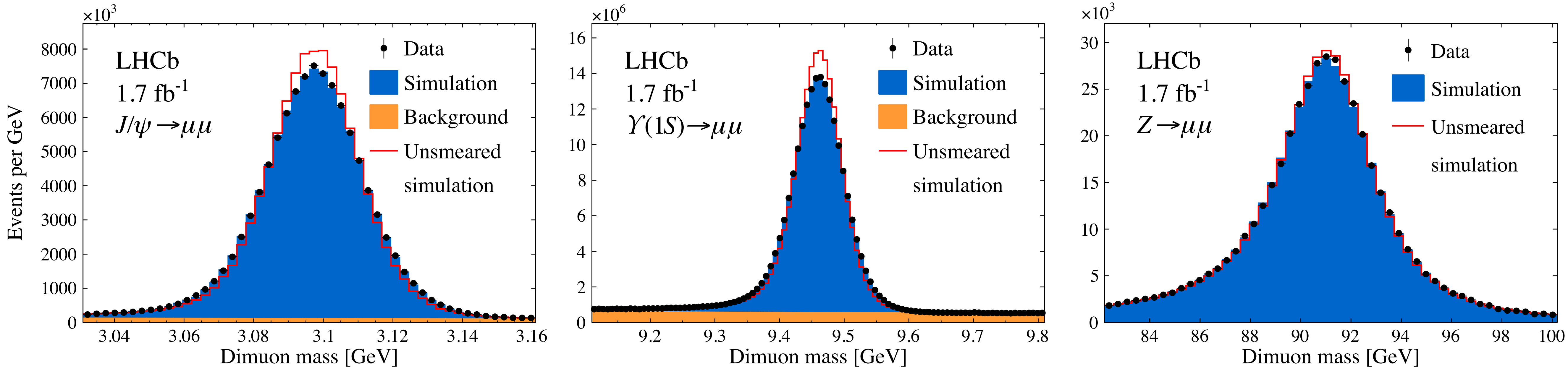
$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)},$$



Muon momentum smearing

$\chi^2_{\text{total}}/\text{ndf} = 1862/2082$

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



Simultaneous fit of Z, Υ(1S) and J/Ψ data (and simulation) in many categories[1]

Contribution to uncertainty on m_W → 7 MeV

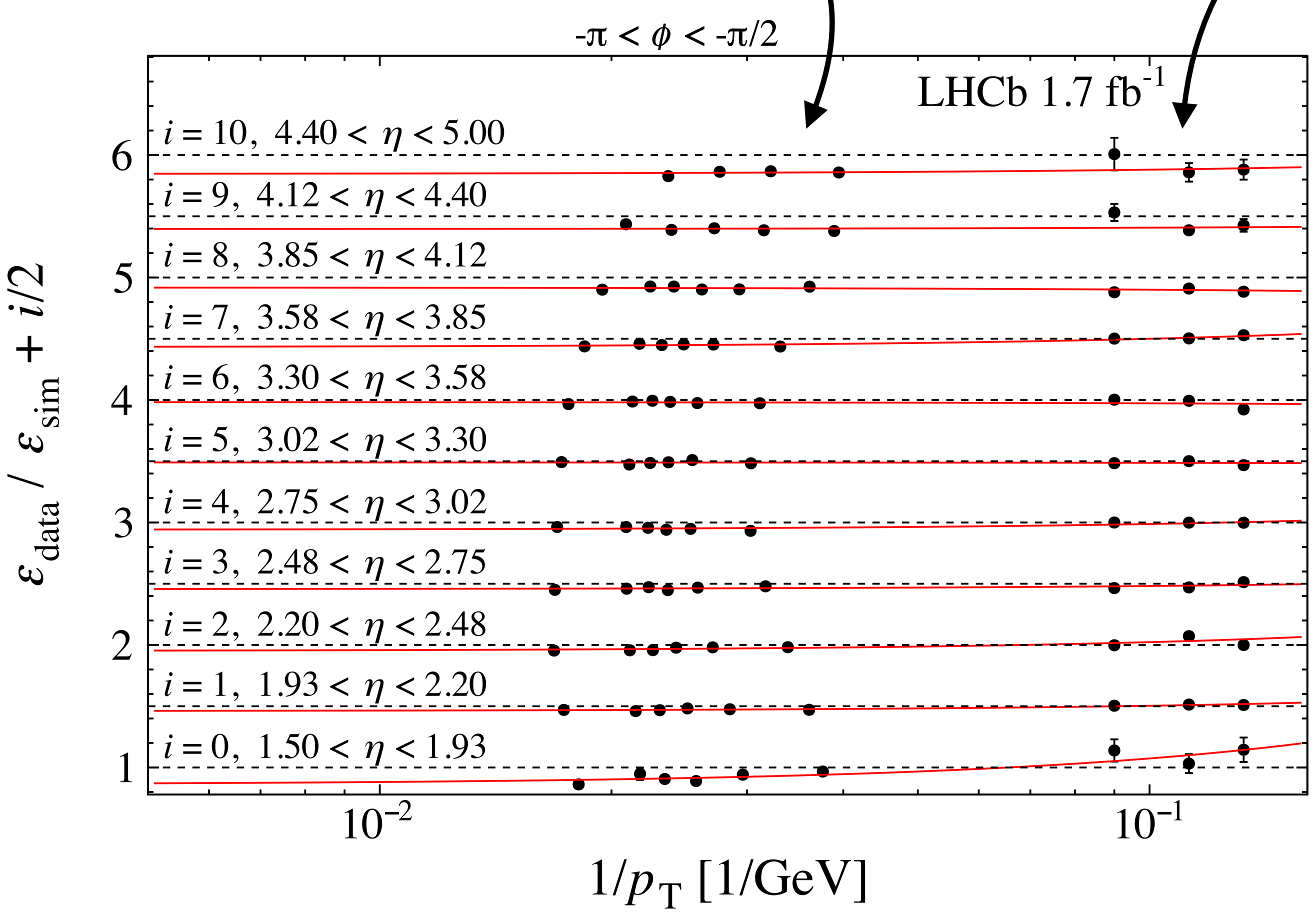
[1] 36 fit categories (based on species, magnet polarity, η of the two muons).
[2] Includes statistics, variations in the PDG resonance masses, detector material budget, final state radiation and the form of the smearing function.

Muon (trigger, tracking, ID) efficiency modelling

Sufficient sub detector redundancy to measure the efficiencies.

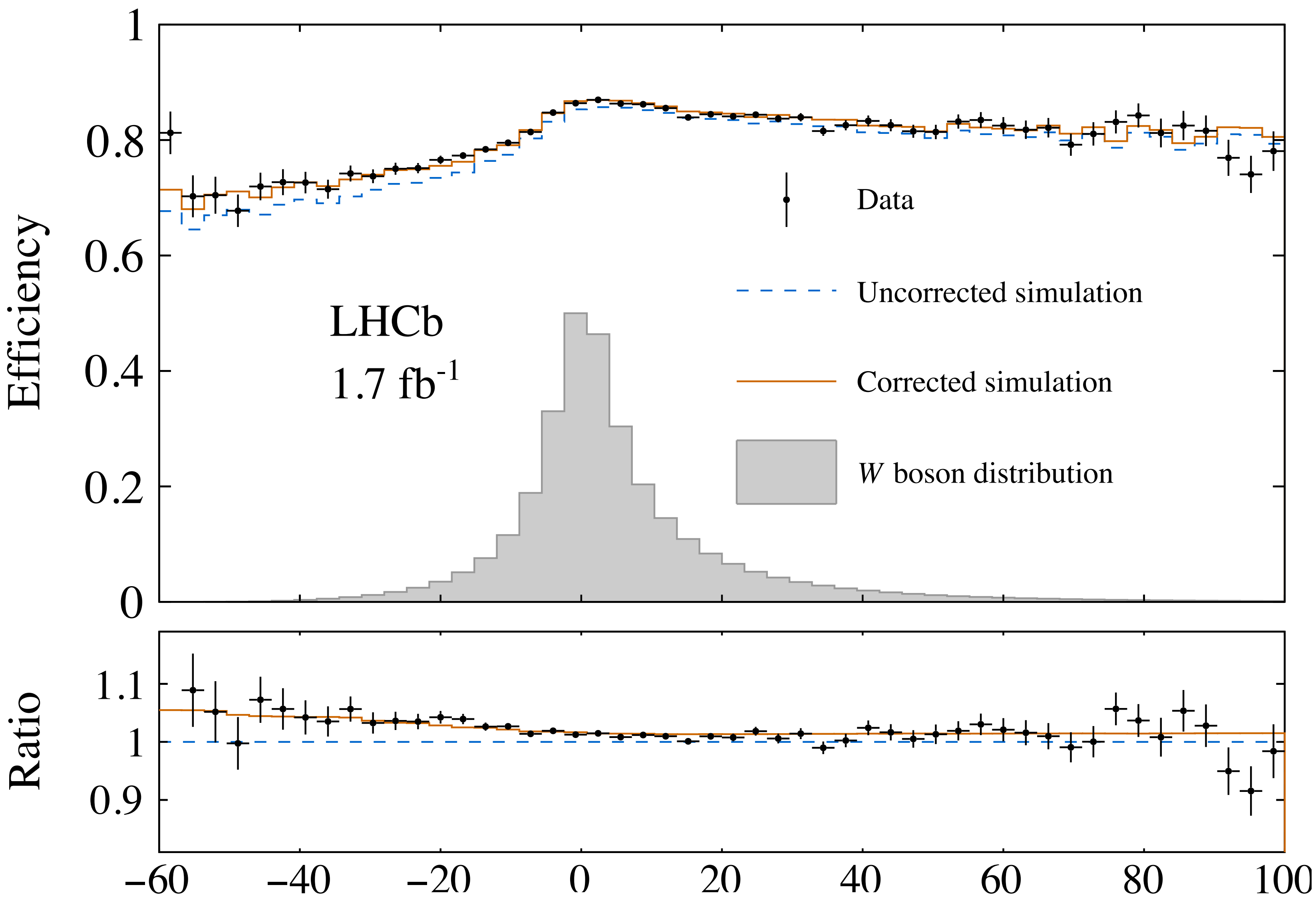
$Z \to \mu\mu$ $\Upsilon(1S) \to \mu\mu$

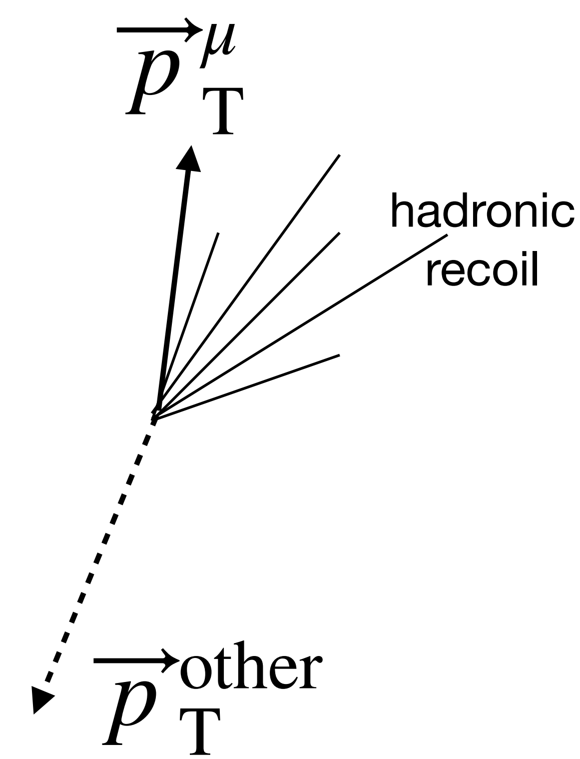
E.g. Trigger efficiency corrections



Contribution to uncertainty on m_W → 6 MeV

Isolation efficiency modelling



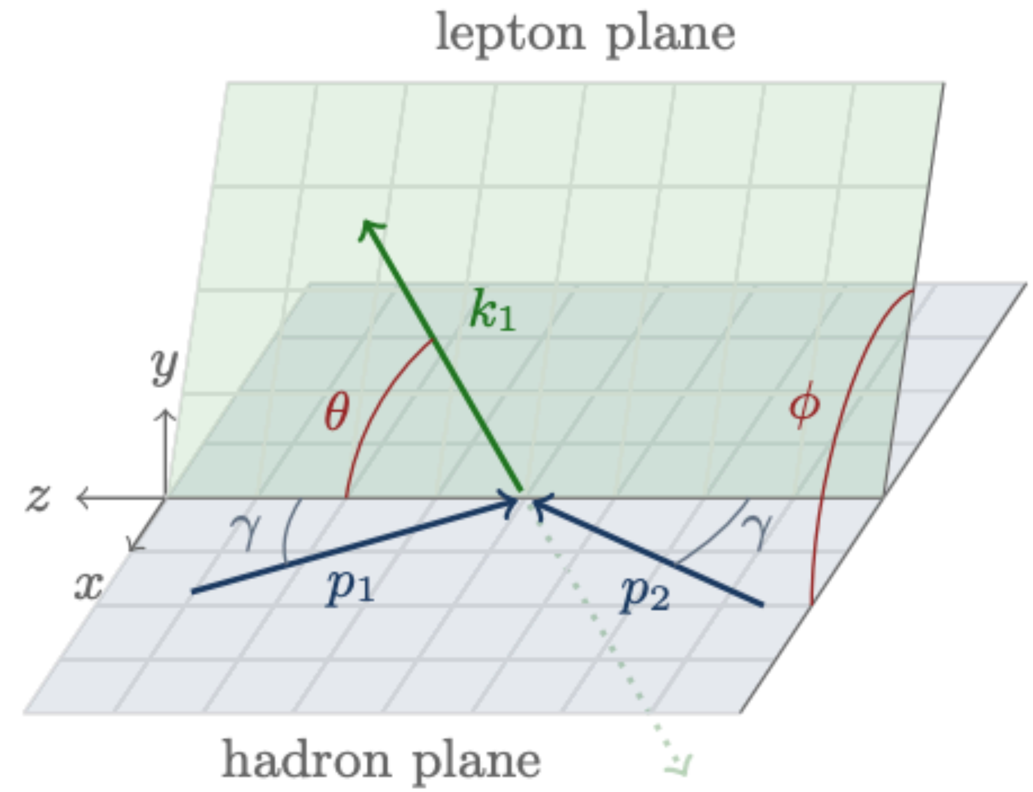


$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$ [GeV]

Contribution to uncertainty on m_W → 4 MeV

Vector boson production model

θ and ϕ in the Collins-Soper frame



Electroweak part:
QED FSR →**7 MeV uncertainty**
Missing EW corrections → **5 MeV uncertainty**

General **QCD** form of kinematics:

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

$$\Big\{(1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$

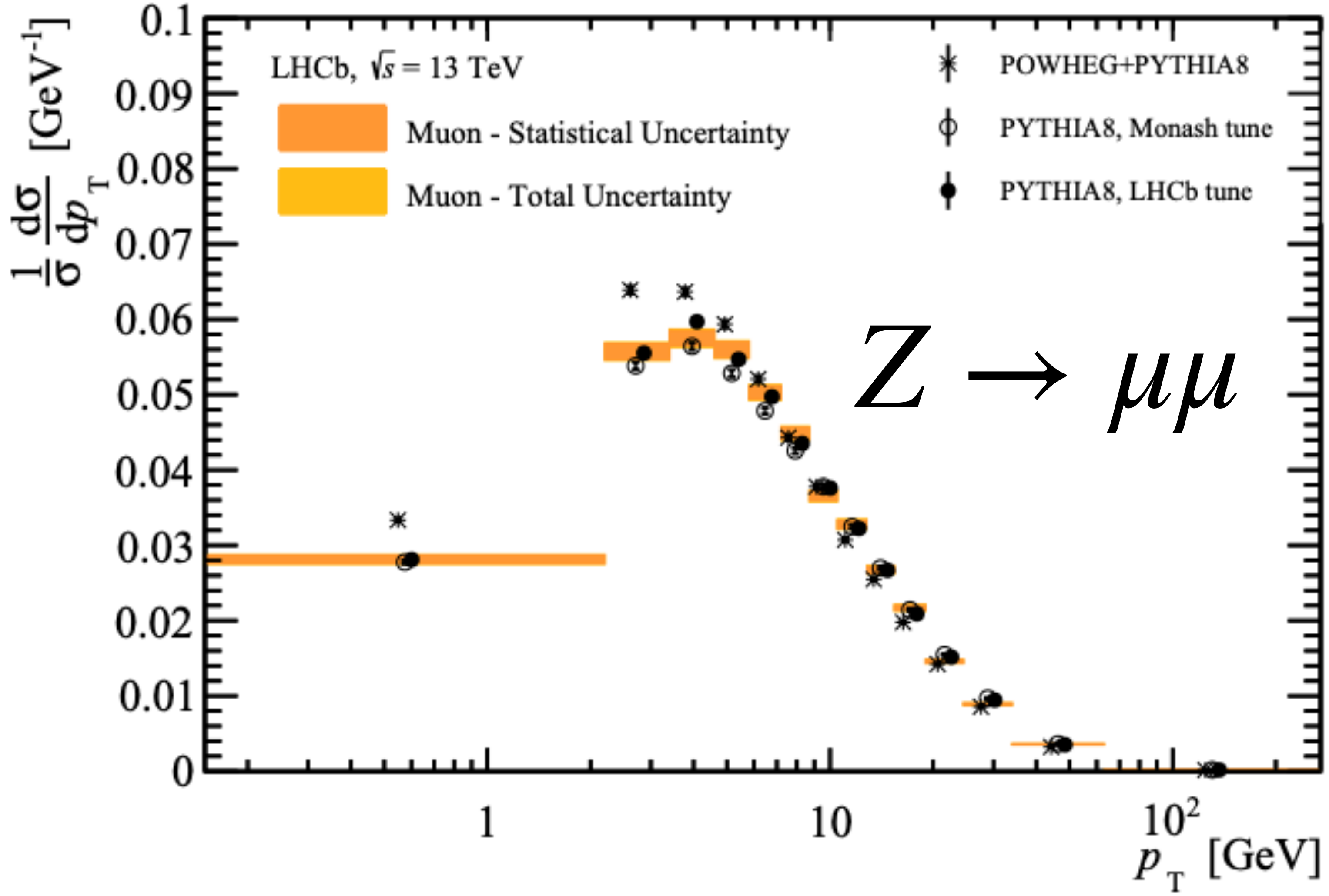
$$+ A_2 \frac{1}{2} \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\},$$

The p_T dependence of the cross section is particularly important…

1708.00008 acknowledged for the figure.

Boson p_T distribution

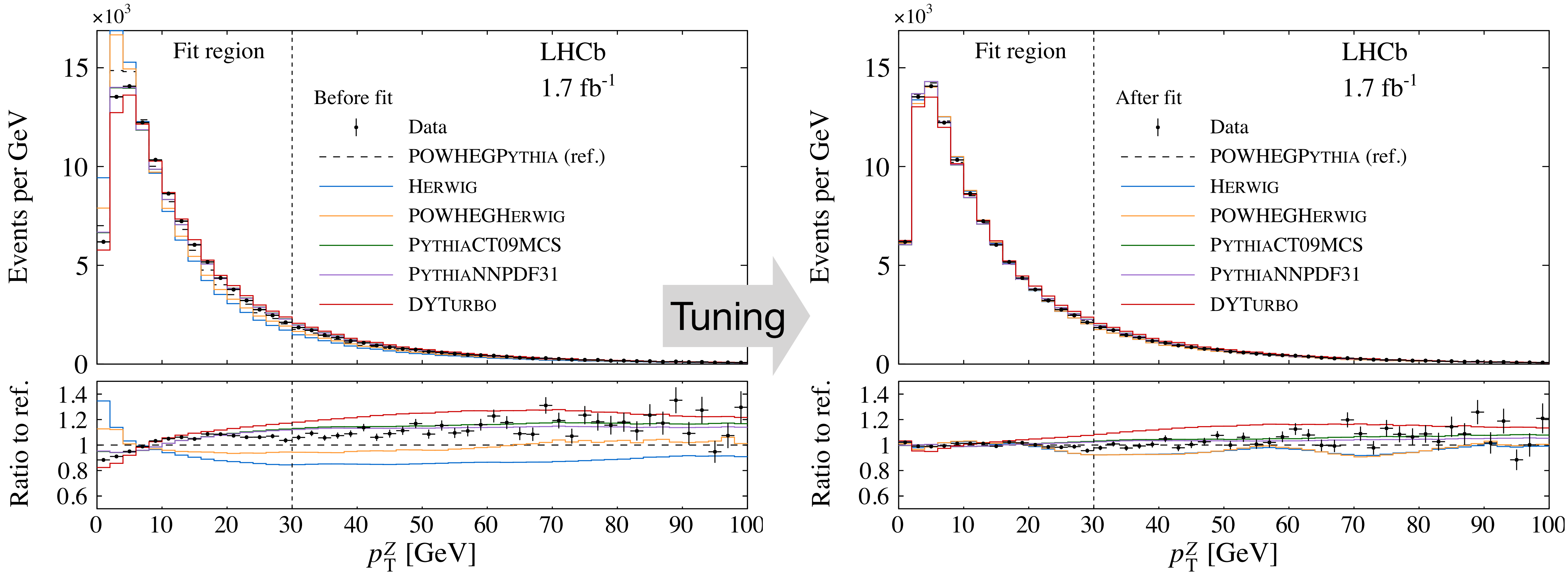


Predictions with various perturbative accuracies.

Showed in 1907.09958 (2019) that we can simultaneously measure m_W and tune event generator parameters (α_s and intrinsic k_T) that control the p_T shape.

Which programs could we use?

Tuning and validation with Z p_T data

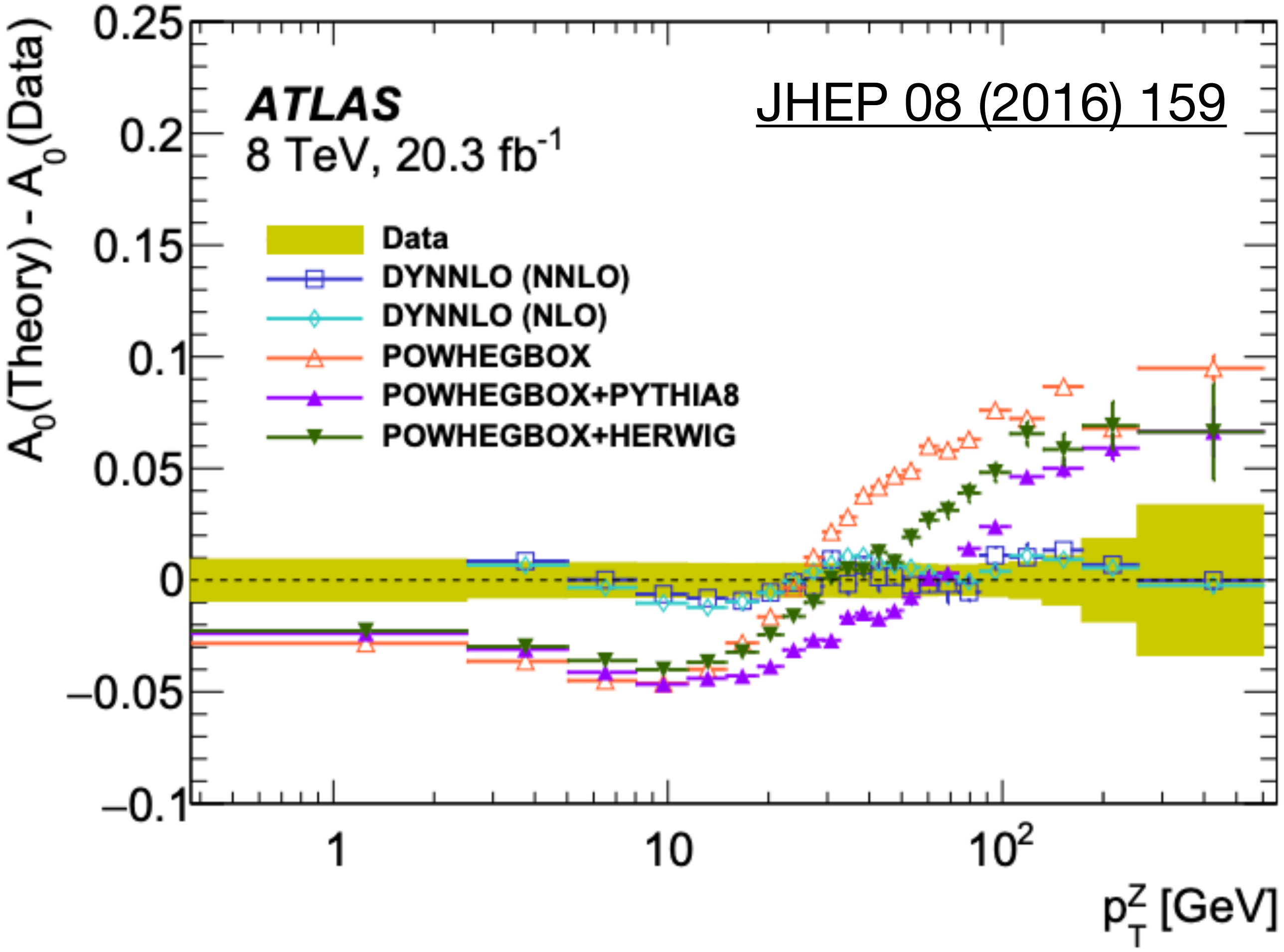


Best description from POWHEG+Pythia.

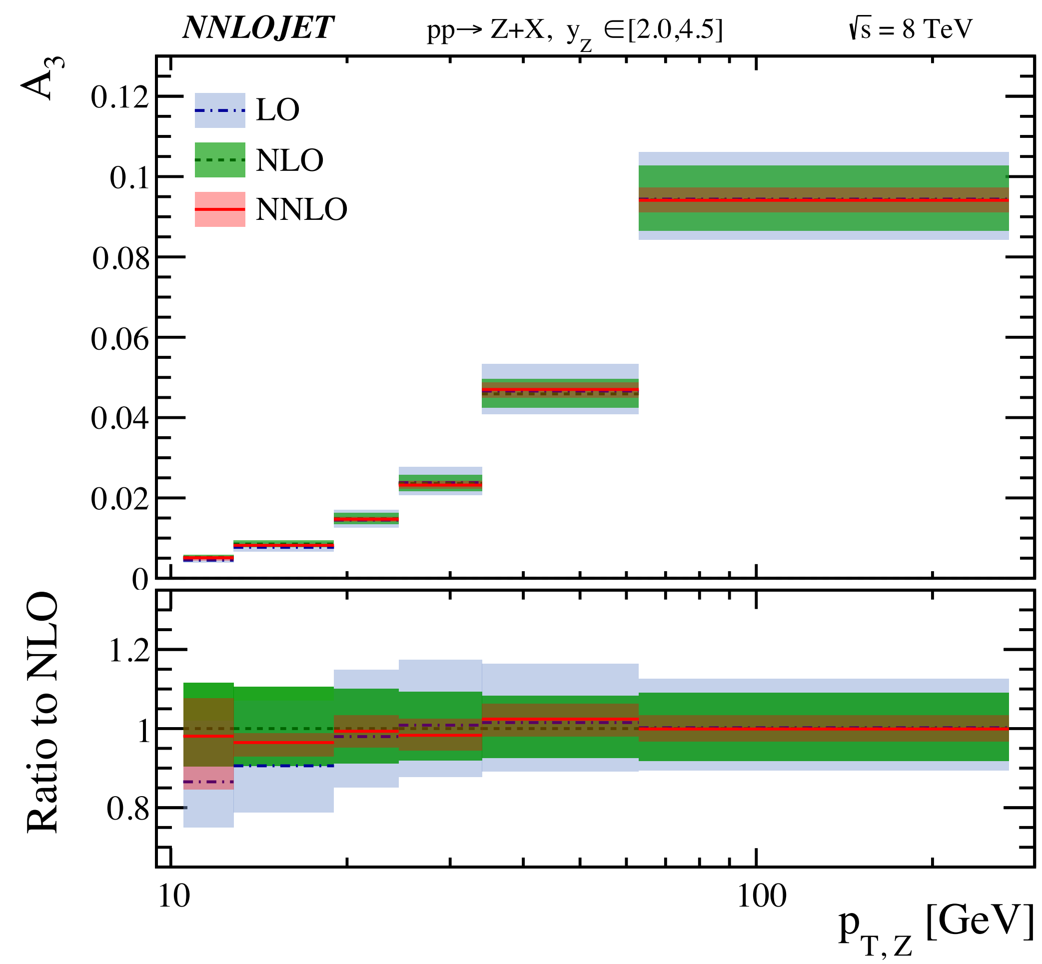
Uncertainty from envelope of m_W fits based on 5 models.

Contribution to m_W uncertainty → 11 MeV

Angular coefficients



JHEP 11 (2017) 003

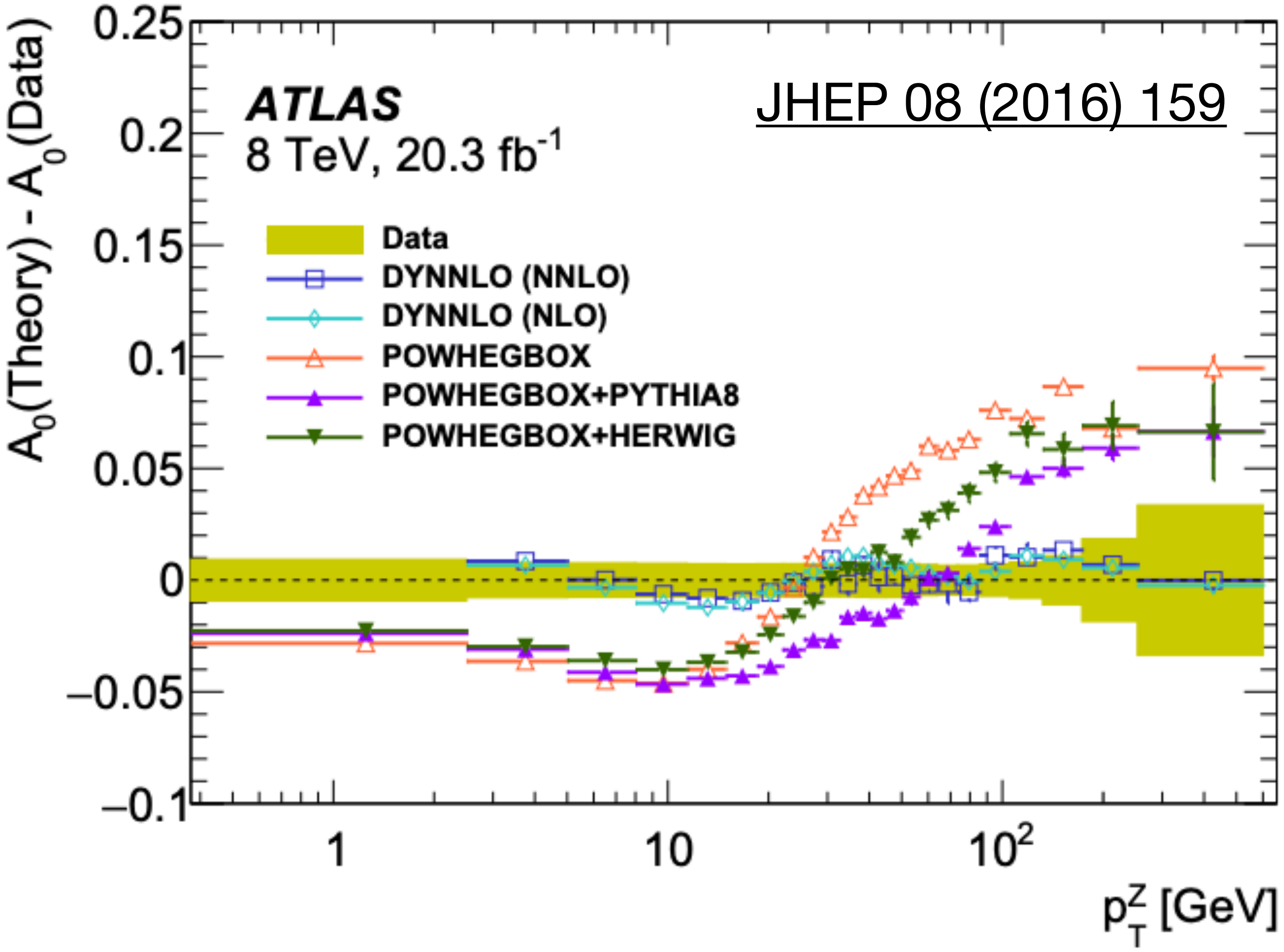


❌ Event generators (e.g. POWHEG)

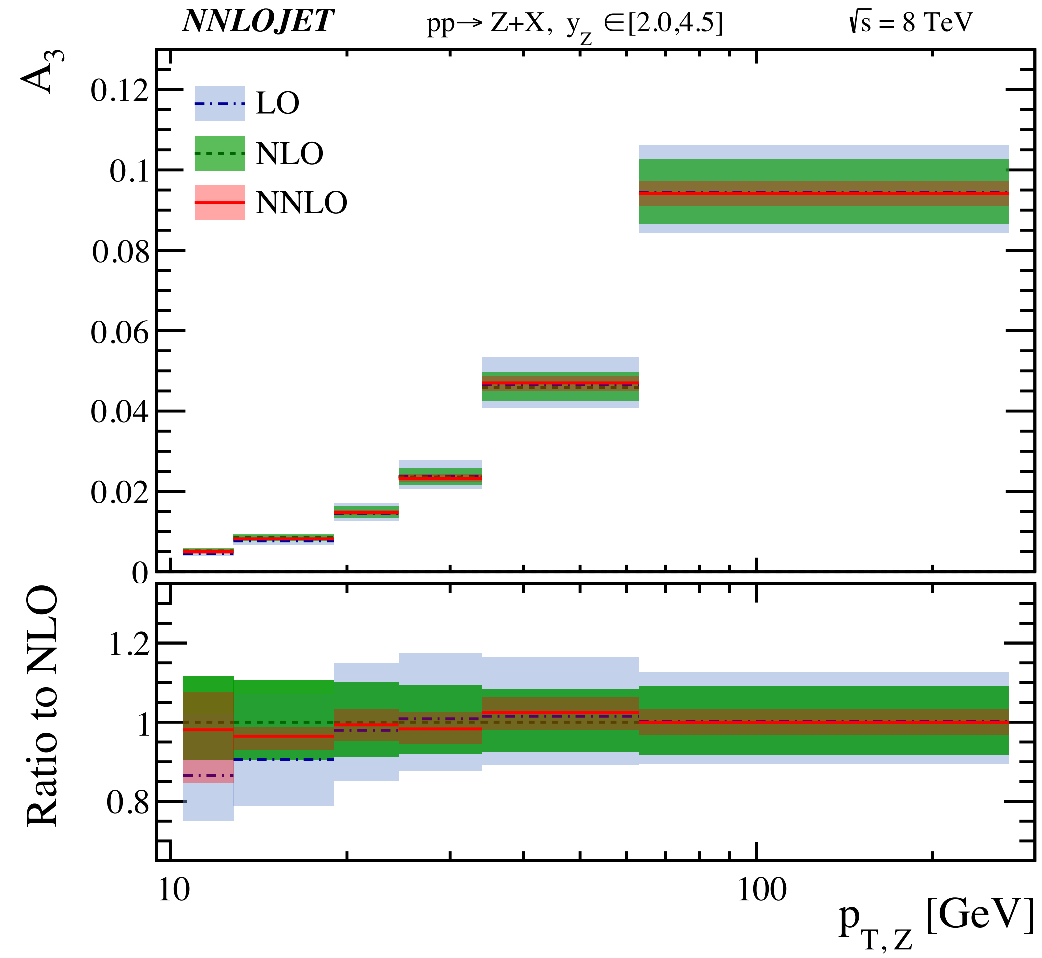
✅ Fixed order QCD

For the renormalisation and factorisation scale uncertainties we use the *uncorrelated* (31-point) scheme.

Angular coefficients



JHEP 11 (2017) 003



Using α_s^2 fixed order predictions from DYTurbo

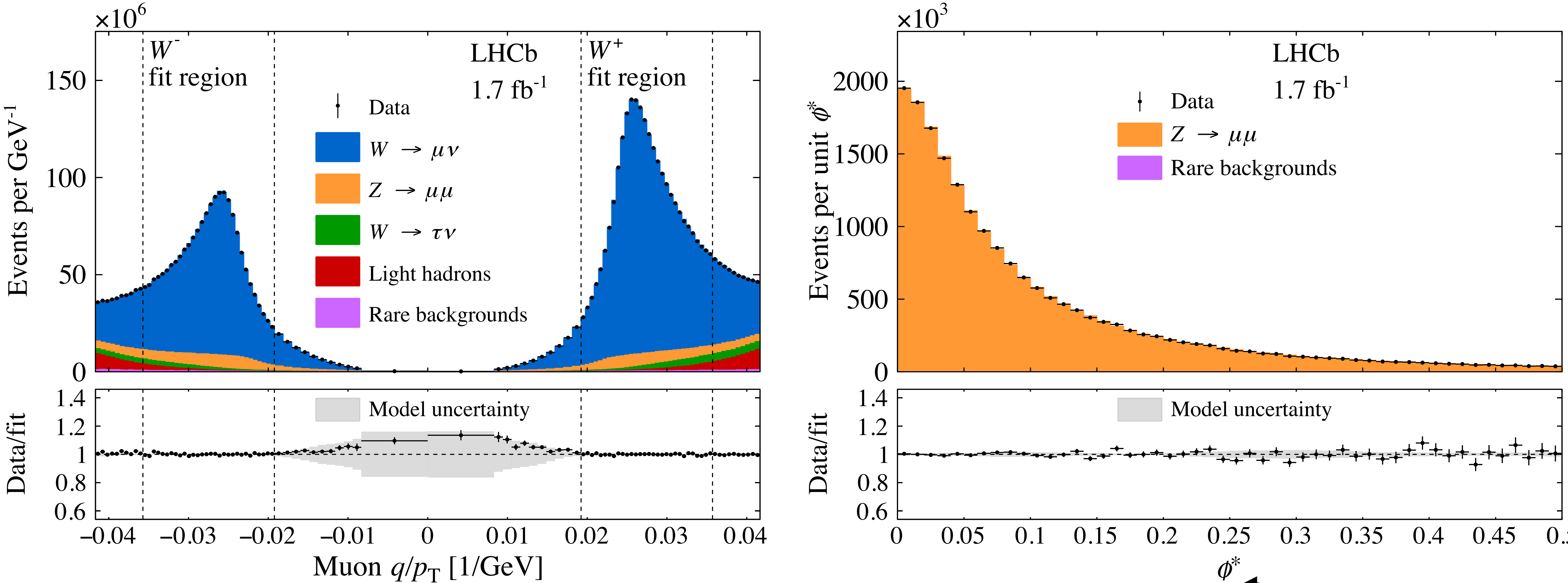
31-point scale variations → 20-30 MeV uncertainty on m_W.

Mitigate by introducing a floating A_3 scale factor in the m_W fit.

Contribution to uncertainty on m_W → 9 MeV

The simultaneous fit to W and Z data

$\chi^2/\mathrm{ndf} = 105/102$

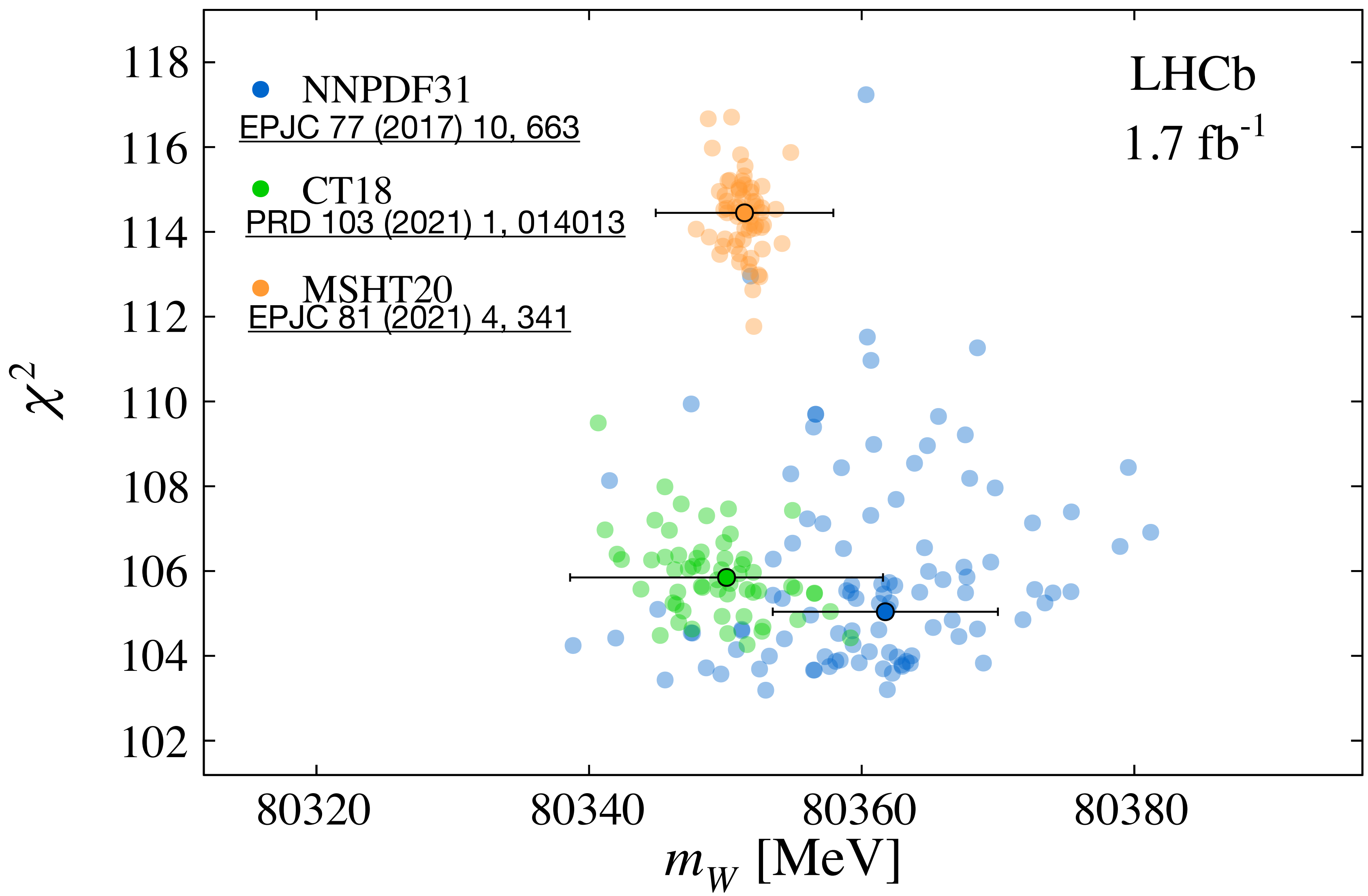


EPJ C71 1600 (2011)

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
m_W	80362 ± 23 MeV

With NNPDF31 PDFs, but there are alternatives…

Democratic PDF average and uncertainty



Three separate results are reported in the paper.

Central result is a simple average of the three (**9 MeV PDF uncertainty**)

Measurement uncertainty summary

Source	Size [MeV]	
Parton distribution functions	9	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	17	
Transverse momentum model	11	Envelope from five different models
Angular coefficients	10	“Uncorrelated” 31 point scale variation
QED FSR model	7	Envelope of Pythia, Photos and Herwig
Additional electroweak corrections	5	Test with POWHEGew
Experimental total	10	
Momentum scale and resolution modelling	7	Includes simple statistical contributions, dependence on external inputs and details of the methods.
Muon ID, trigger and tracking efficiency	6	
Isolation efficiency	4	
QCD background	2	
Statistical	23	
Total	32	

[Pre-unblinding] 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…)

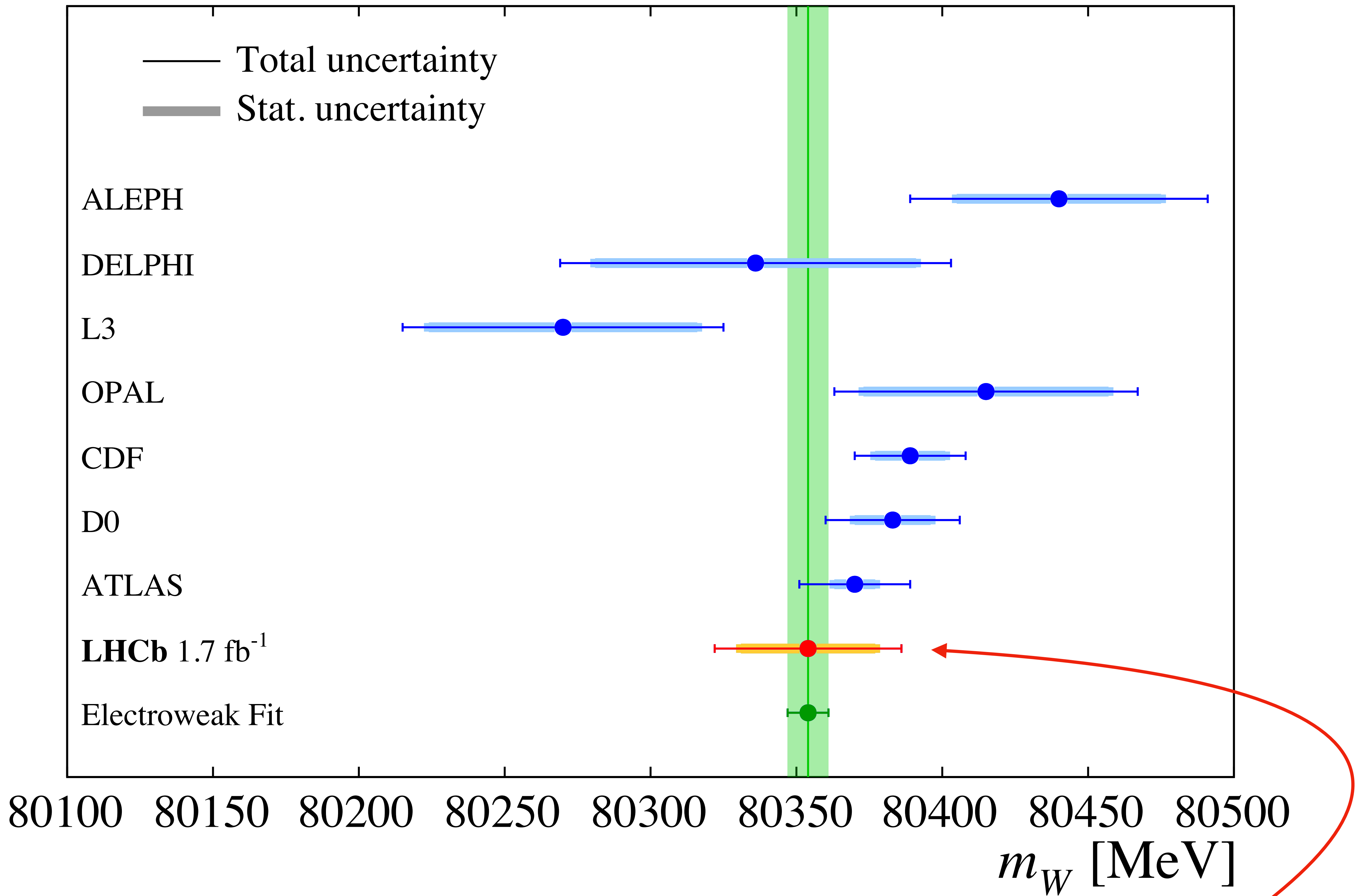
4. **W-like fit of the Z mass:** Measurements with μ^+ and μ^- agree to better than 1σ and their average agrees with the PDG value to better than 1σ.

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.

7. **Pseudodata challenges:** fitting the default POWHEG+Pythia model to pseudo data with DYTurbo, Herwig, etc… based models of the boson p_T. Results are commensurate with our 11 MeV uncertainty.

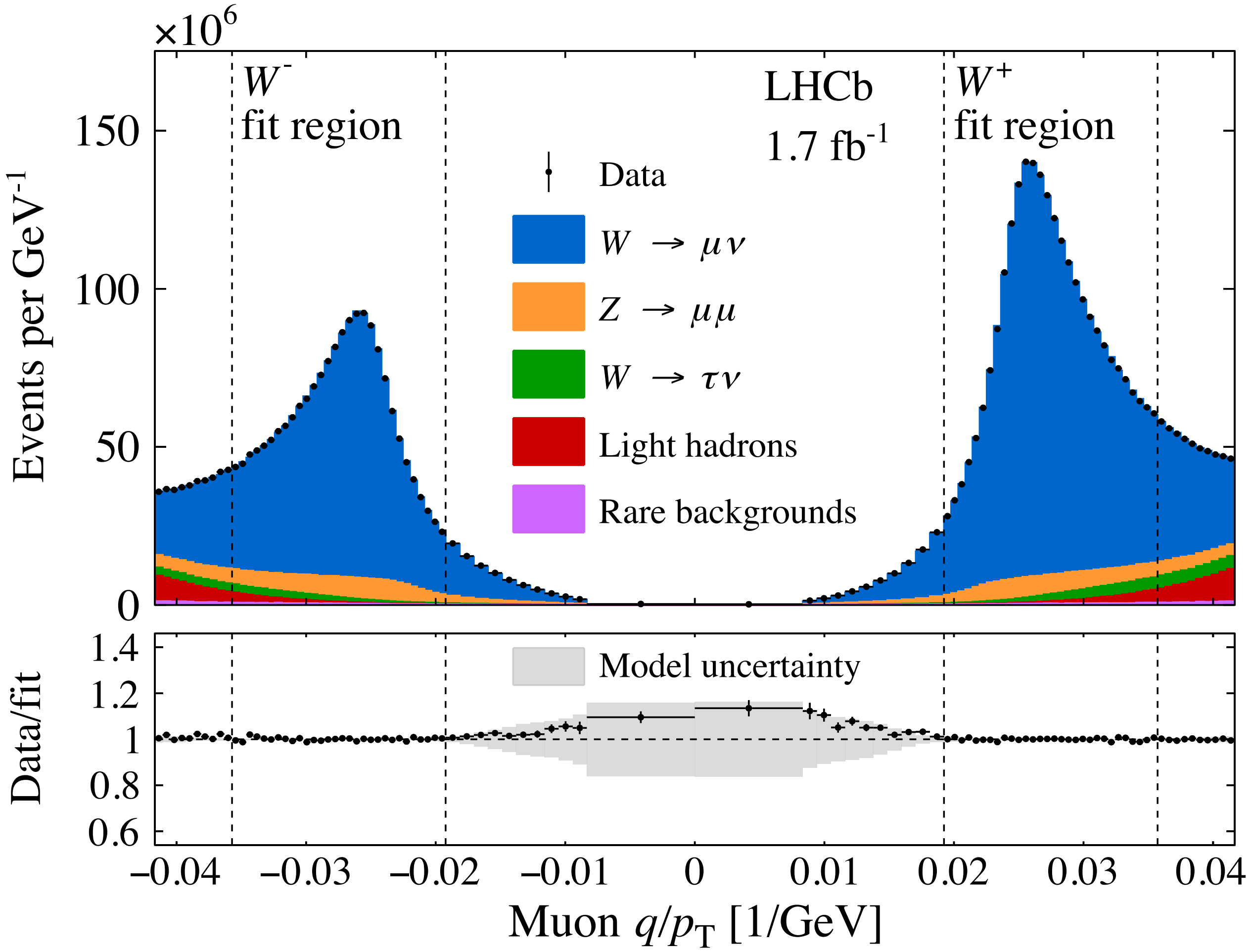
8. ….

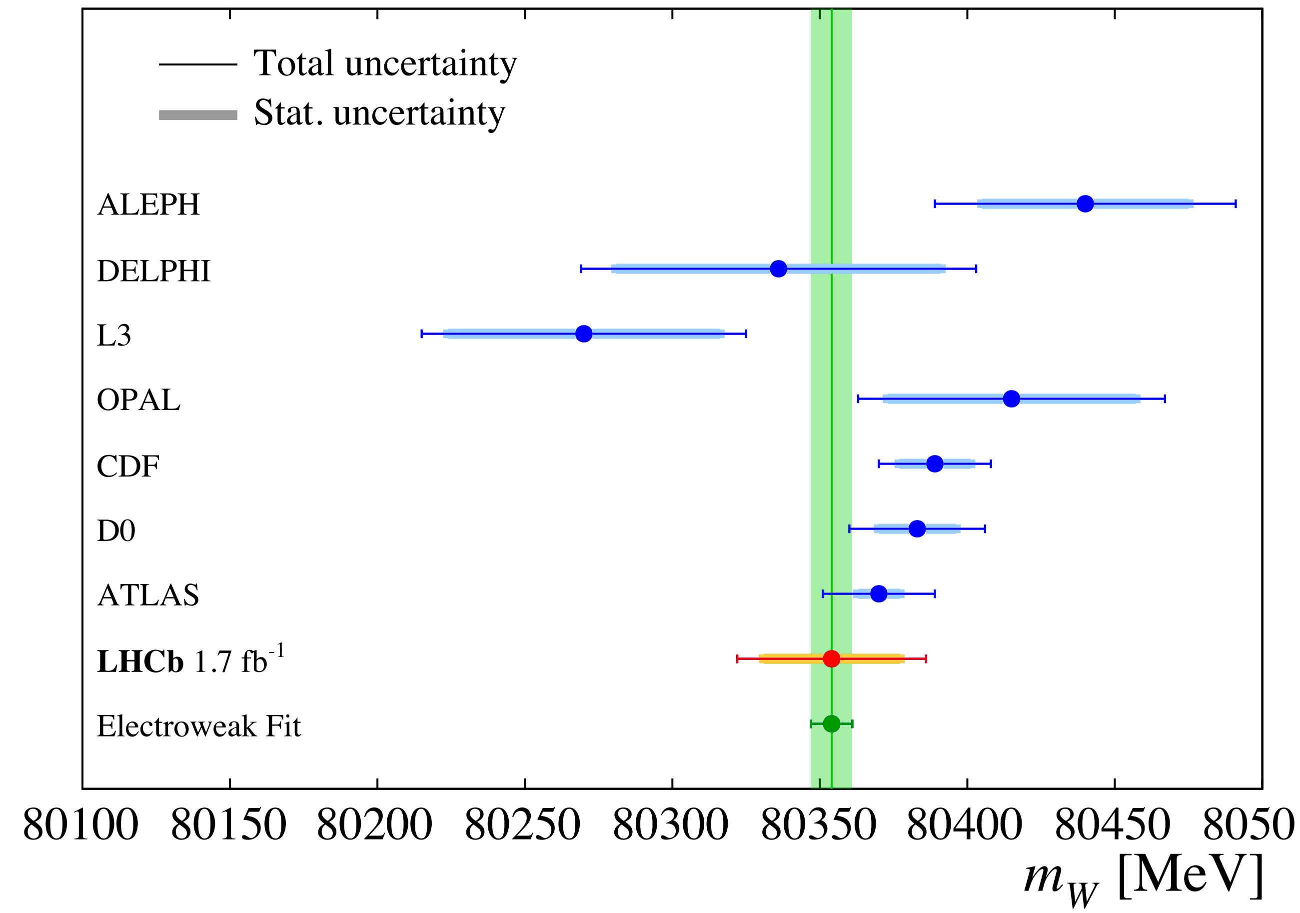


$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Conclusions and outlook

hep-ex:2109.01113 LHCb-PAPER-2021-024





First measurement of m_W from LHCb with 32 MeV uncertainty is consistent with previous measurements and with the prediction.

A total uncertainty of ≲ 20 MeV looks achievable with existing LHCb data.

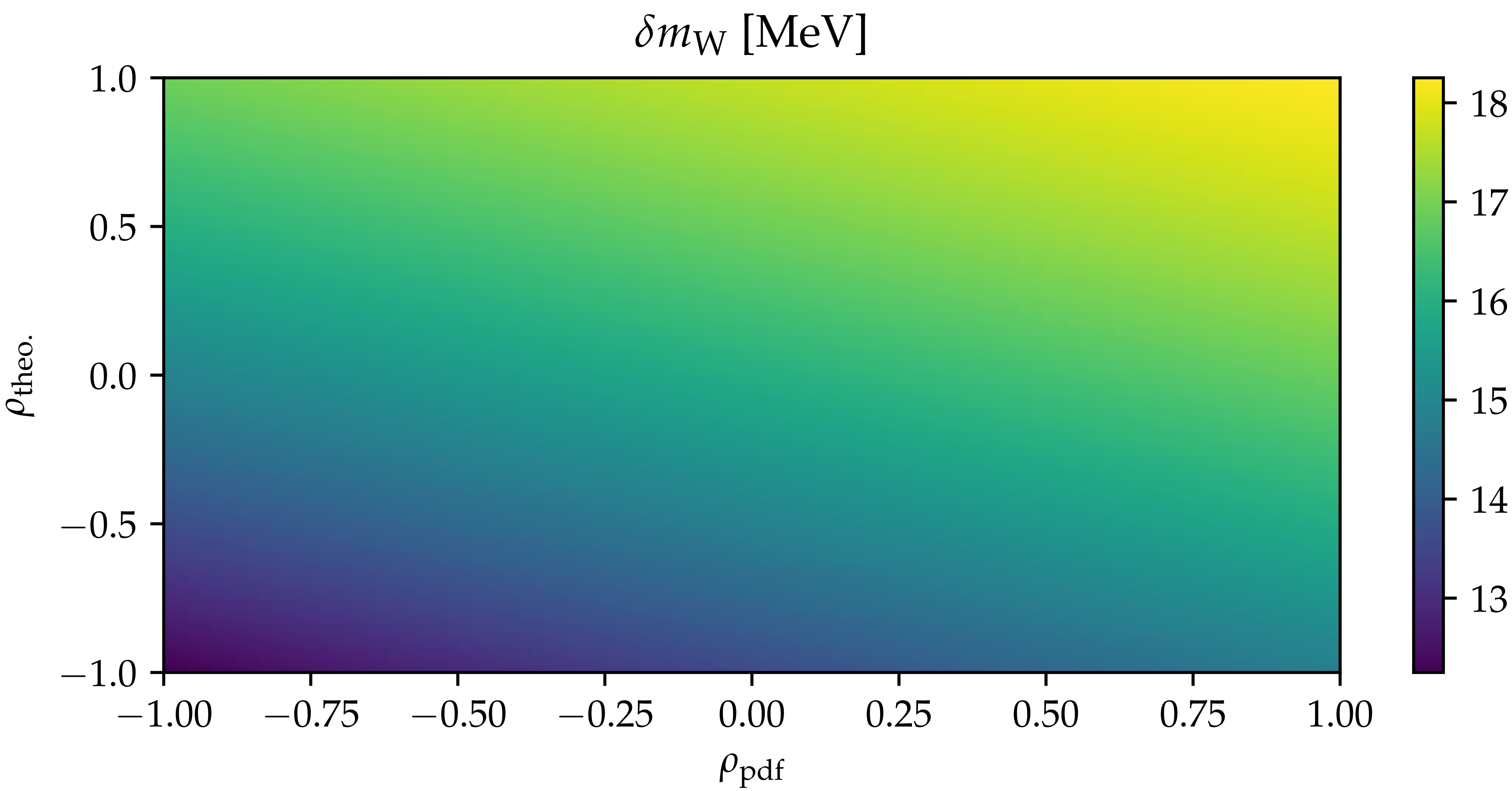
EPJC 79 (2019) 6 encourages us to upgrade to a double-differential fit.

We look forward to working with the other LHC experiments, and the theory community, to fully exploit LHCb's unique/complementary rapidity coverage to achieve the ultimate precision on m_W.

Backup slides

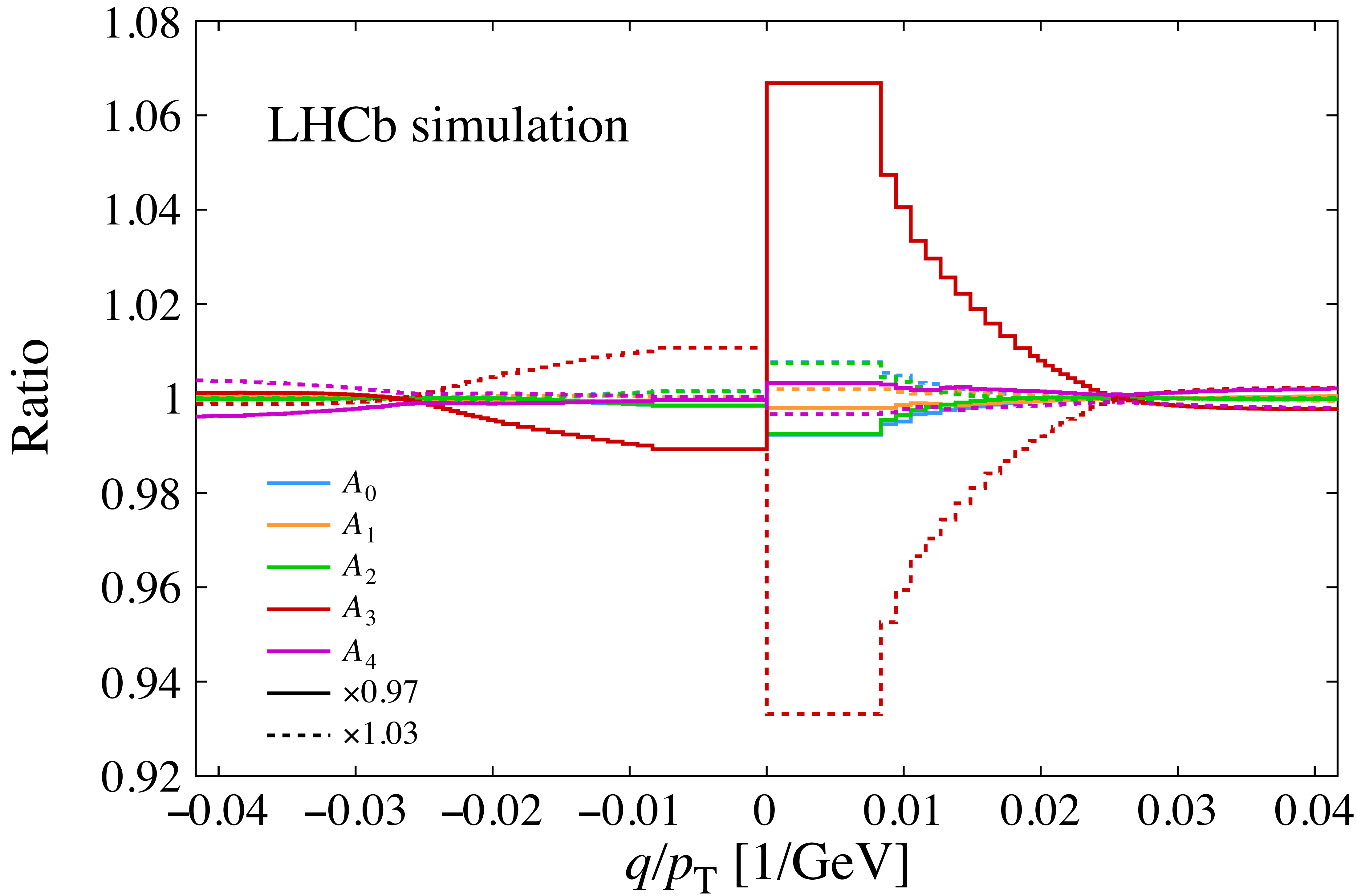
Prospects for LHC average

ATLAS+LHCb average under the simplest assumptions:

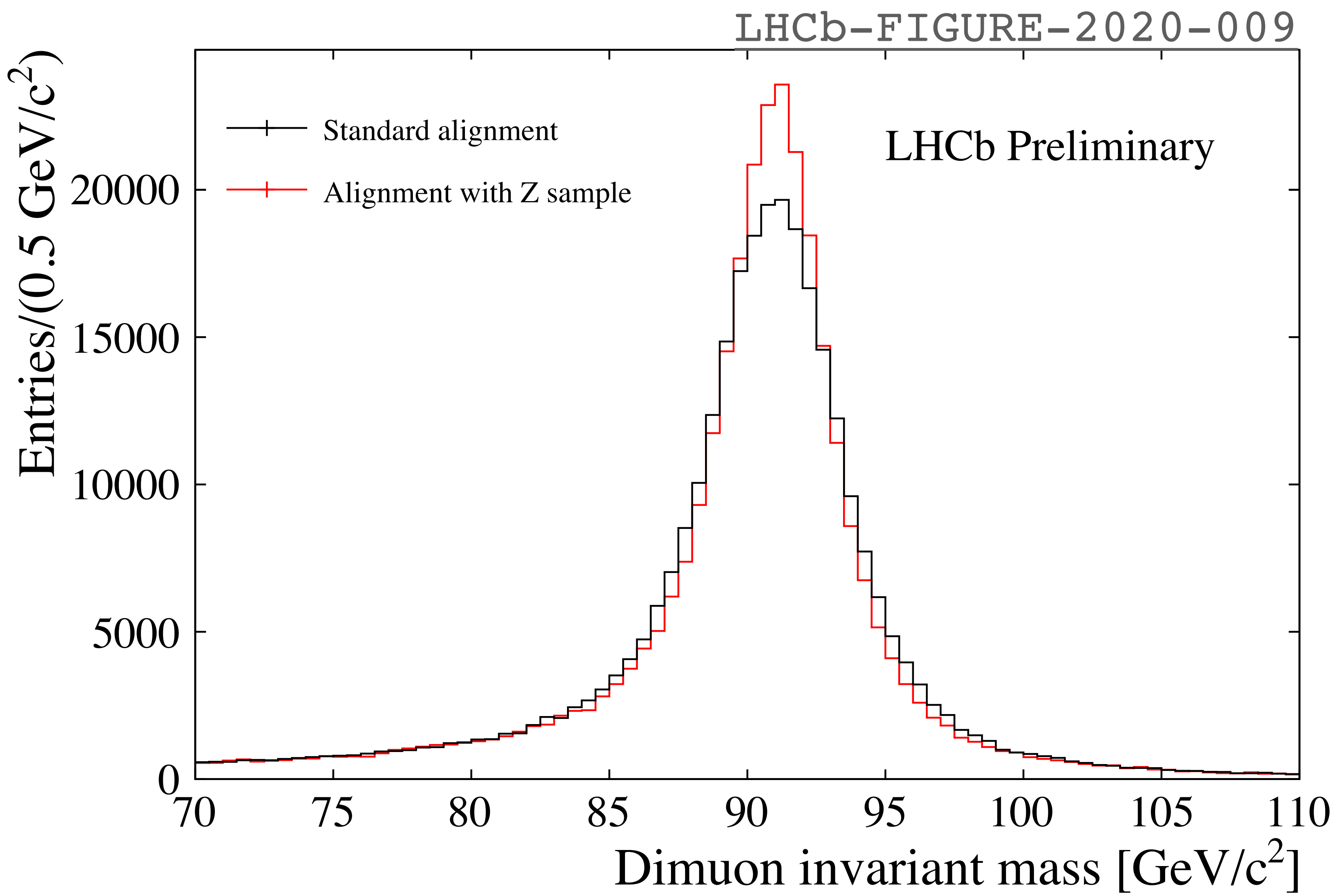


A detailed ATLAS+LHCb collaborative effort will be required to precisely determine these two correlation coefficients but it seems likely that ρ_{PDF} will be negative 1508.06954 while the (non-PDF) theory uncertainty will have a positive coefficient.

Sensitivity to other angular coefficients



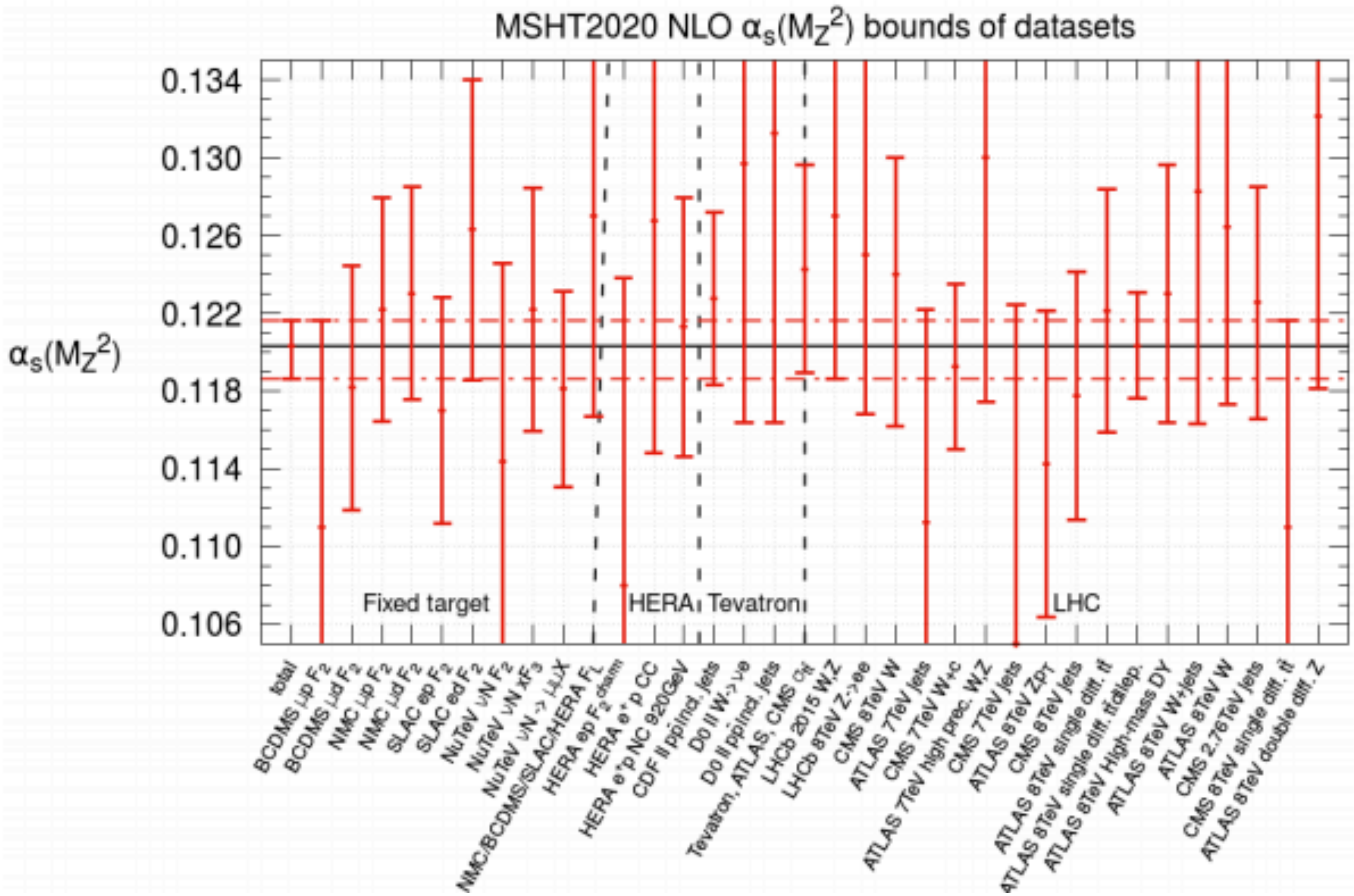
Custom alignment for high p_T analyses



LHCb's successful real-time alignment and calibration was commissioned in Run-2 JINST 14 (2019) P04013

For the very high (up to ~1 TeV) momentum muons in EW processes the resolution could be improved with a custom alignment including mass-constrained Z candidates.

Recent study on α_s 2106.10289



[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.

Momentum smearing fit parameter values

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

Parameter	Fit value
α ($\eta < 2.2$)	$(0.58 \pm 0.10) \times 10^{-3}$
α ($2.2 < \eta < 4.4$)	$(-0.0054 \pm 0.0025) \times 10^{-3}$
δ	$(-0.48 \pm 0.37) \times 10^{-6}$ GeV^{-1}
σ_δ ($\eta < 2.2$)	(17.7 ± 1.2) keV^{-1}
σ_δ ($2.2 < \eta < 4.4$)	(14.9 ± 0.9) keV^{-1}
σ_{MS}	$(2.015 \pm 0.019) \times 10^{-3}$

Our tunes to the Z p_T data

Program	χ^2/ndf	α_s	
DYTurbo	208.1/13	0.1180	$g = 0.523 \pm 0.047\,\mathrm{GeV}^2$
POWHEGPythia	30.3/12	0.1248 ± 0.0004	$k_\mathrm{T}^\mathrm{intr} = 1.470 \pm 0.130\,\mathrm{GeV}$
POWHEGHerwig	55.6/12	0.1361 ± 0.0001	$k_\mathrm{T}^\mathrm{intr} = 0.802 \pm 0.053\,\mathrm{GeV}$
Herwig	41.8/12	0.1352 ± 0.0002	$k_\mathrm{T}^\mathrm{intr} = 0.753 \pm 0.052\,\mathrm{GeV}$
Pythia, CT09MCS	69.0/12	0.1287 ± 0.0004	$k_\mathrm{T}^\mathrm{intr} = 2.113 \pm 0.032\,\mathrm{GeV}$
Pythia, NNPDF31	62.1/12	0.1289 ± 0.0004	$k_\mathrm{T}^\mathrm{intr} = 2.109 \pm 0.032\,\mathrm{GeV}$

Data challenge exercise

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

Consistency between orthogonal subsets of data

Subset	$\chi^2_{\mathrm{tot}}/\mathrm{ndf}$	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

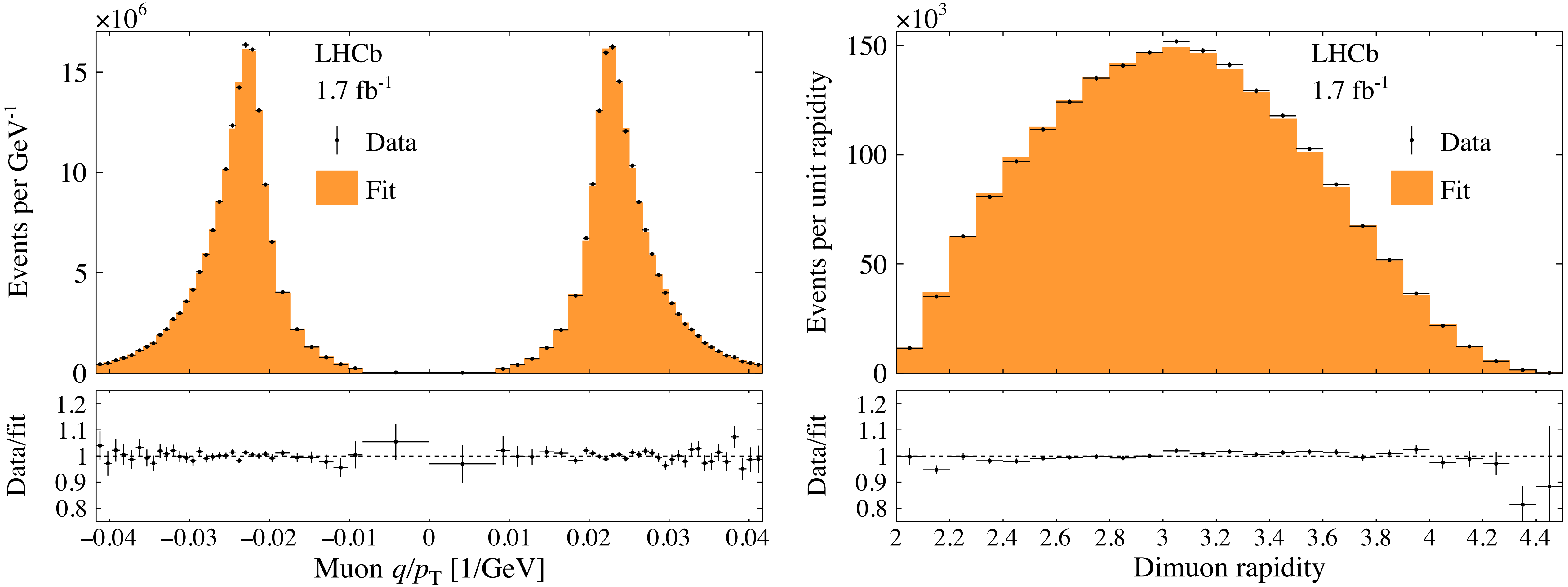
Varying the freedom of the fit model

Configuration change	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$2 \rightarrow 3$ α_s parameters	103.4/101	−6.0	±23.1
$2 \rightarrow 1$ α_s and $1 \rightarrow 2$ $k_{\text{T}}^{\text{intr}}$ parameters	116.1/102	+13.9	±22.4
$1 \rightarrow 2$ $k_{\text{T}}^{\text{intr}}$ parameters	104.0/101	+0.4	±22.7
$1 \rightarrow 3$ $k_{\text{T}}^{\text{intr}}$ 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

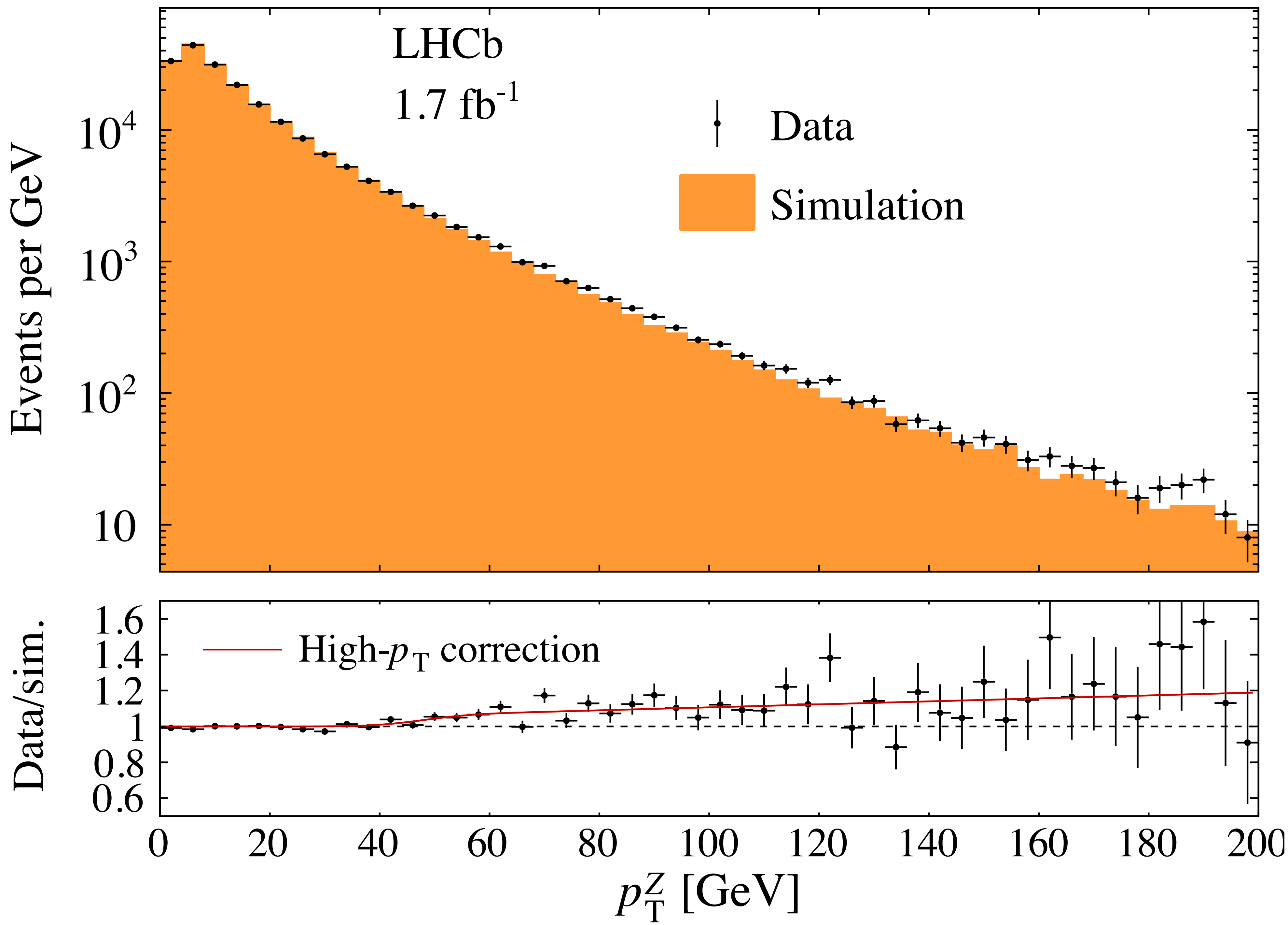
Stability w.r.t. varying the [q/p_T] fit range

Change to fit range	$\chi^2_{\mathrm{tot}}/\mathrm{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$p_{\mathrm{T}}^{\mathrm{min}} = 24$ GeV	96.5/102	+6.8	19.7
$p_{\mathrm{T}}^{\mathrm{min}} = 26$ GeV	97.7/102	+9.6	20.9
$p_{\mathrm{T}}^{\mathrm{min}} = 30$ GeV	102.7/102	+3.0	25.7
$p_{\mathrm{T}}^{\mathrm{min}} = 32$ GeV	84.9/102	−21.6	30.8
$p_{\mathrm{T}}^{\mathrm{max}} = 48$ GeV	105.3/102	−3.8	23.2
$p_{\mathrm{T}}^{\mathrm{max}} = 50$ GeV	103.0/102	−2.1	23.0
$p_{\mathrm{T}}^{\mathrm{max}} = 54$ GeV	96.3/102	−8.6	22.6
$p_{\mathrm{T}}^{\mathrm{max}} = 56$ GeV	103.7/102	−14.3	22.4

Example postfit projections



Parametric correction at high boson p_T

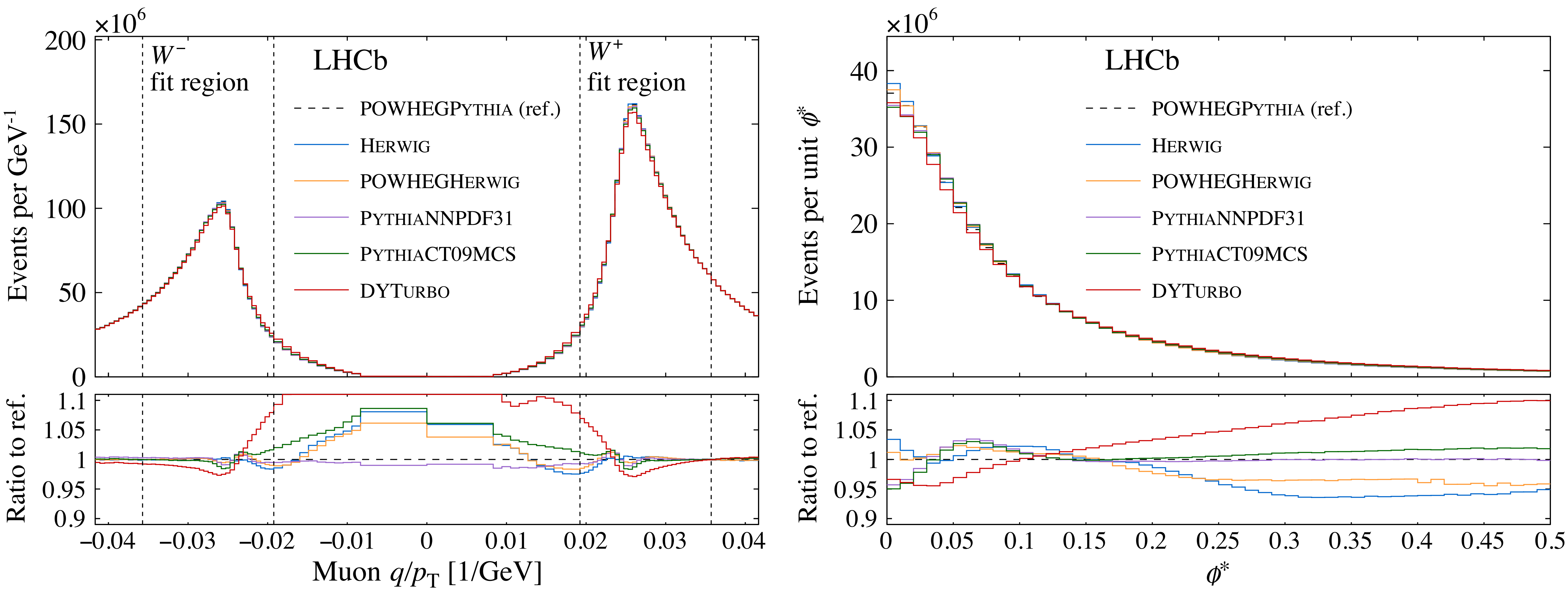


Also applied to the model of W production but with 100% uncertainty => ~1 MeV on m_W.

The ϕ* variable EPJC 71:1600 (2011)

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

[Pseudo]data challenges



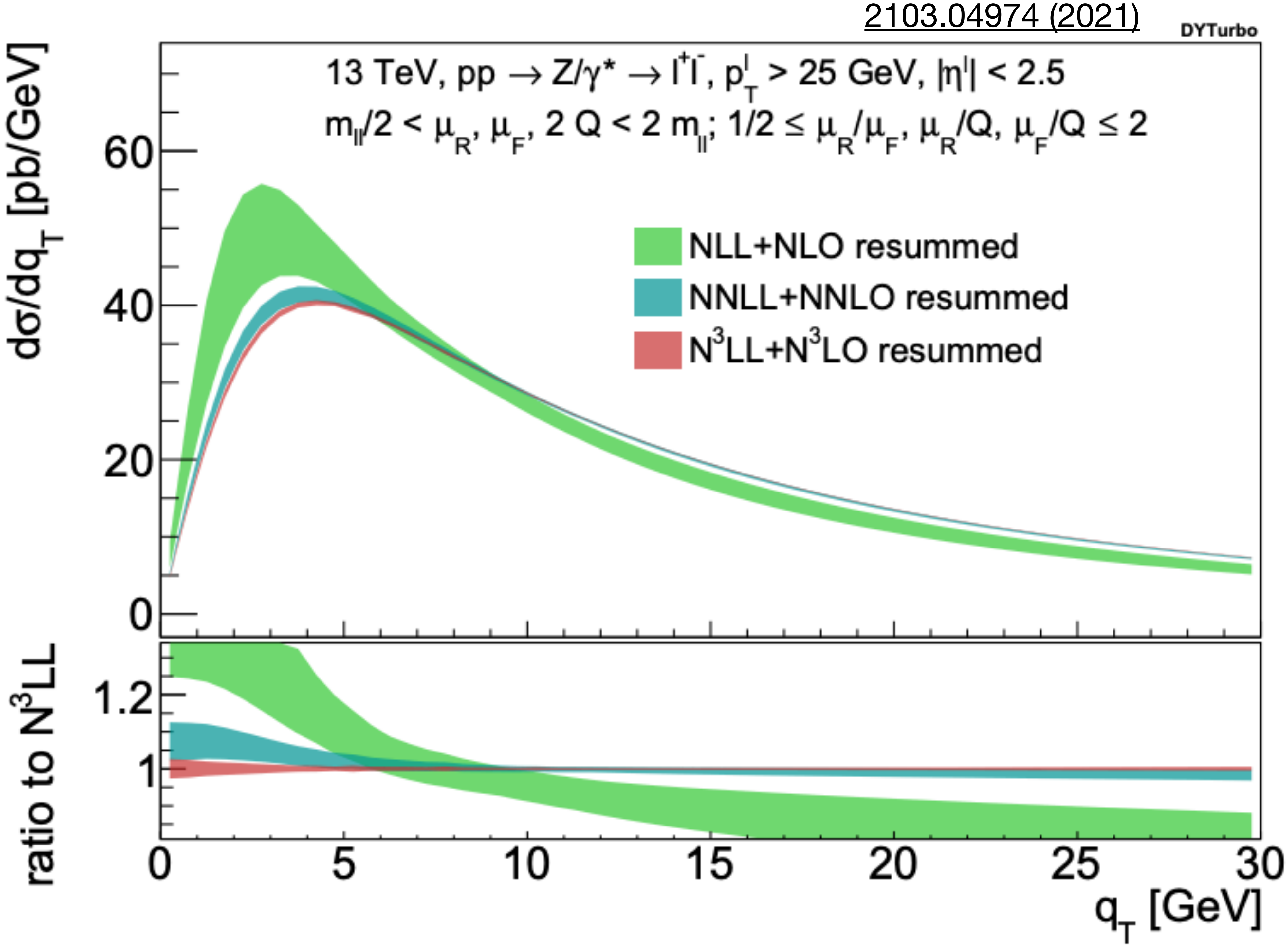
Can our [POWHEG+Pythia] model adapt itself to pseudo data corresponding to *other* models of the W/Z p_T distributions?

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

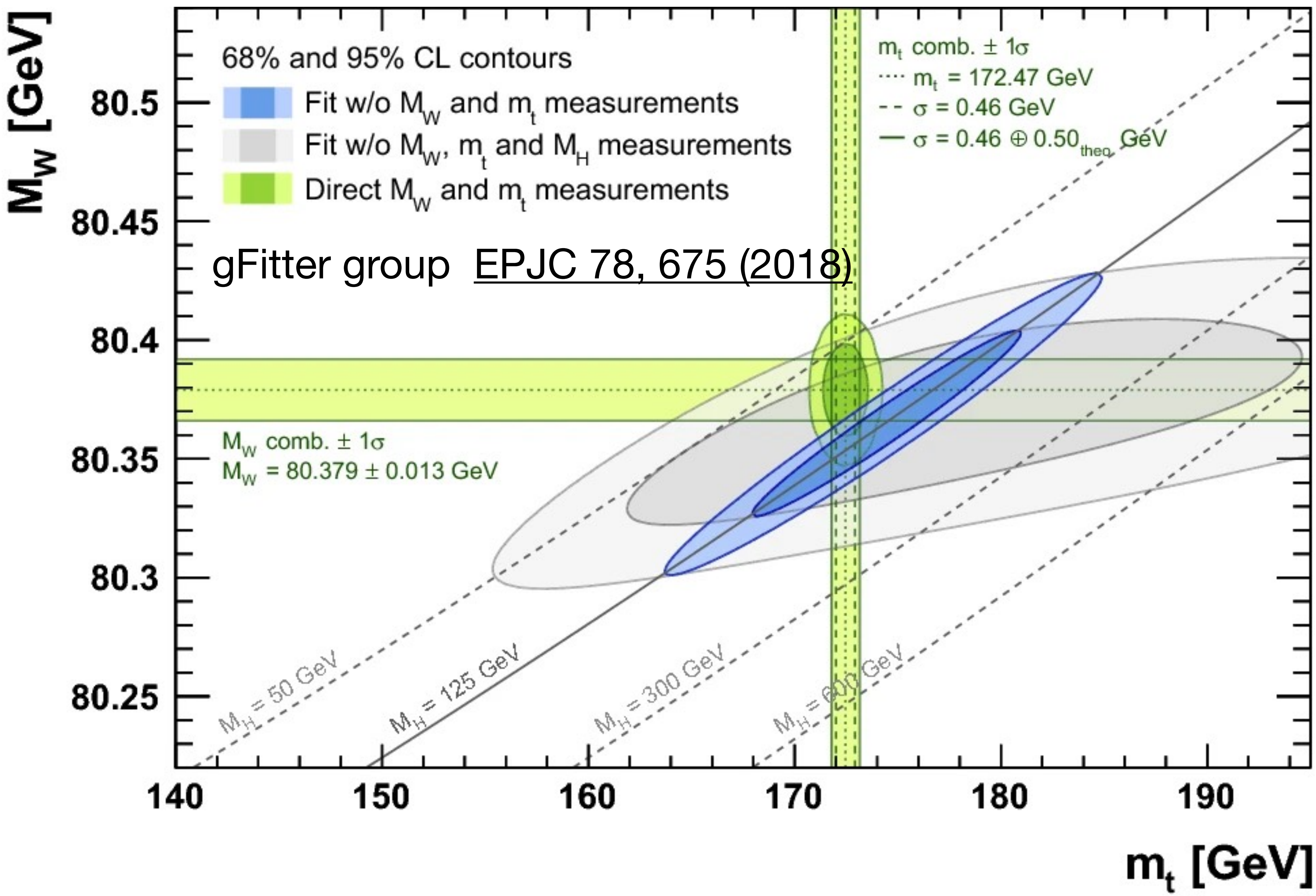
✅ No more than 10 MeV bias on m_W!

Boson p_T state-of-the-art (example, of many groups)

2103.04974 (2021)

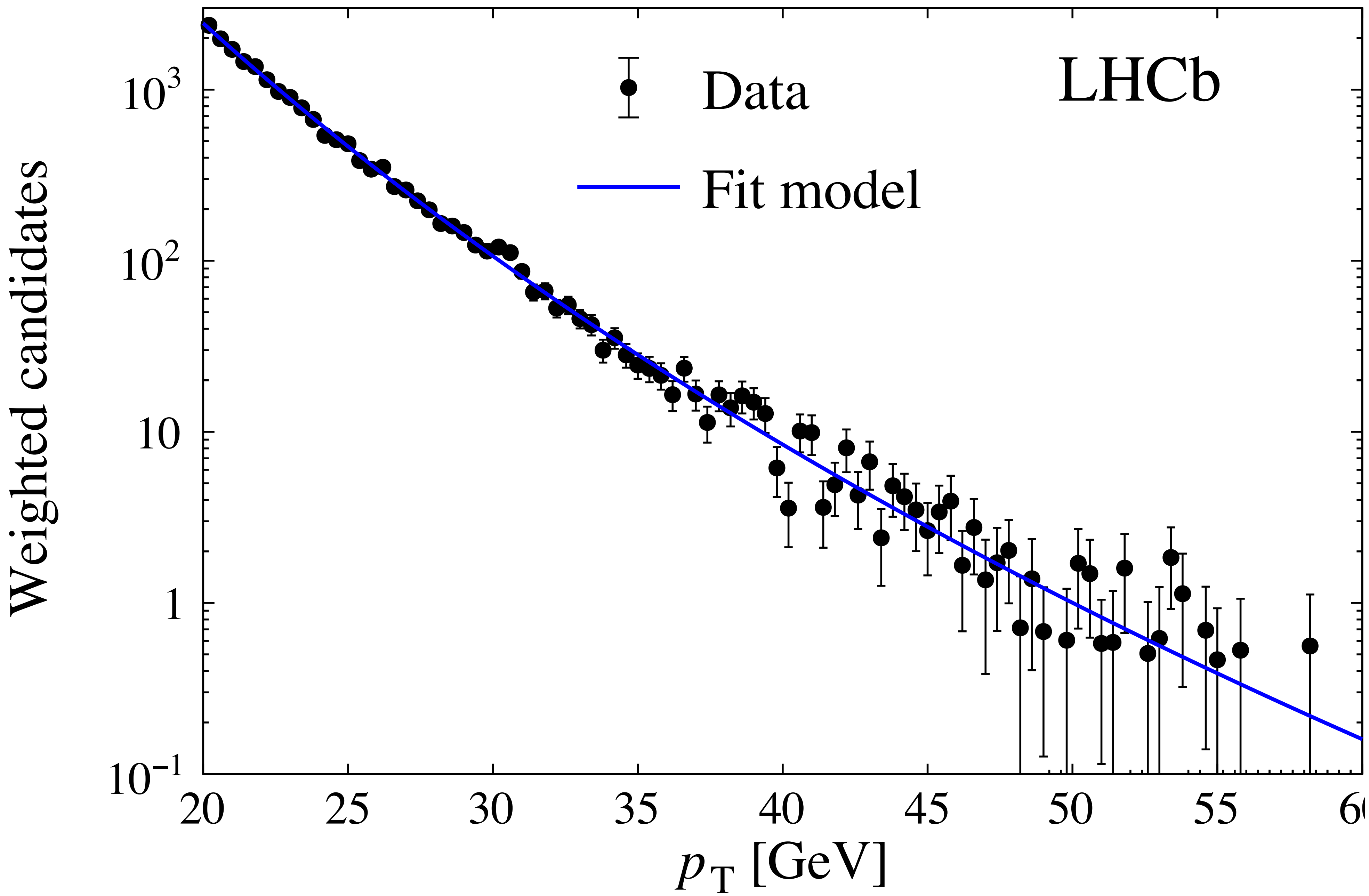


Global EW fit in m_W versus m_t plane



gFitter group EPJC 78, 675 (2018)

Hadronic background model



Effect of α_s and intrinsic k_T tuning

1907.09958 (2019)