Status and plans for m_W with LHCb

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MWAPP meeting
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Mika Vesterinen,
University of Warwick

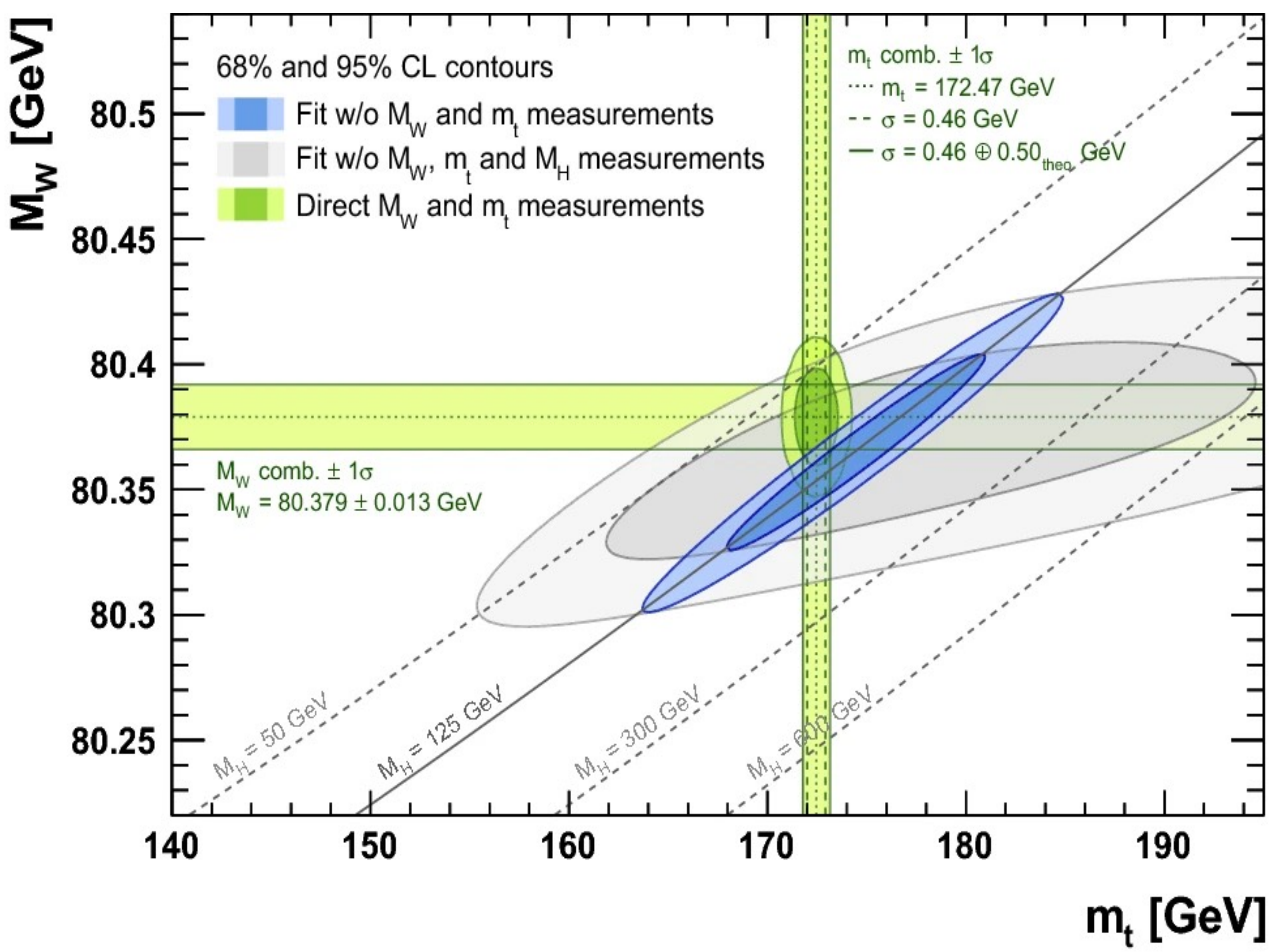
With R. Hunter, M. Ramos Pernas, A. Abdelmotteleb, M. Xu, E. Muhammed and MPhys students (R. Preston, G. Epsinal-Lugo, L. Duran Fervenza)

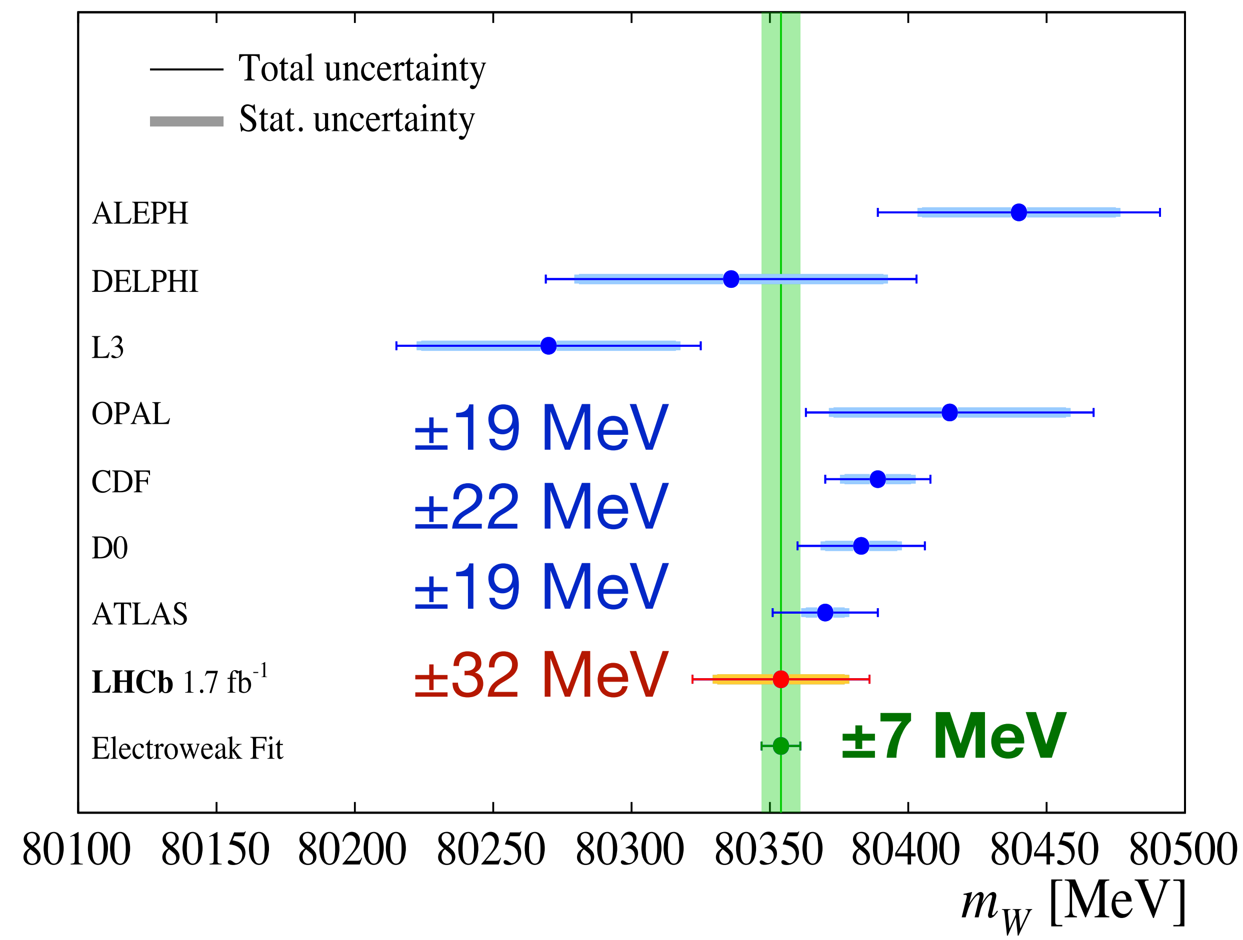
WARWICK

UKRI Science and Technology Facilities Council

erc European Research Council

LHCb





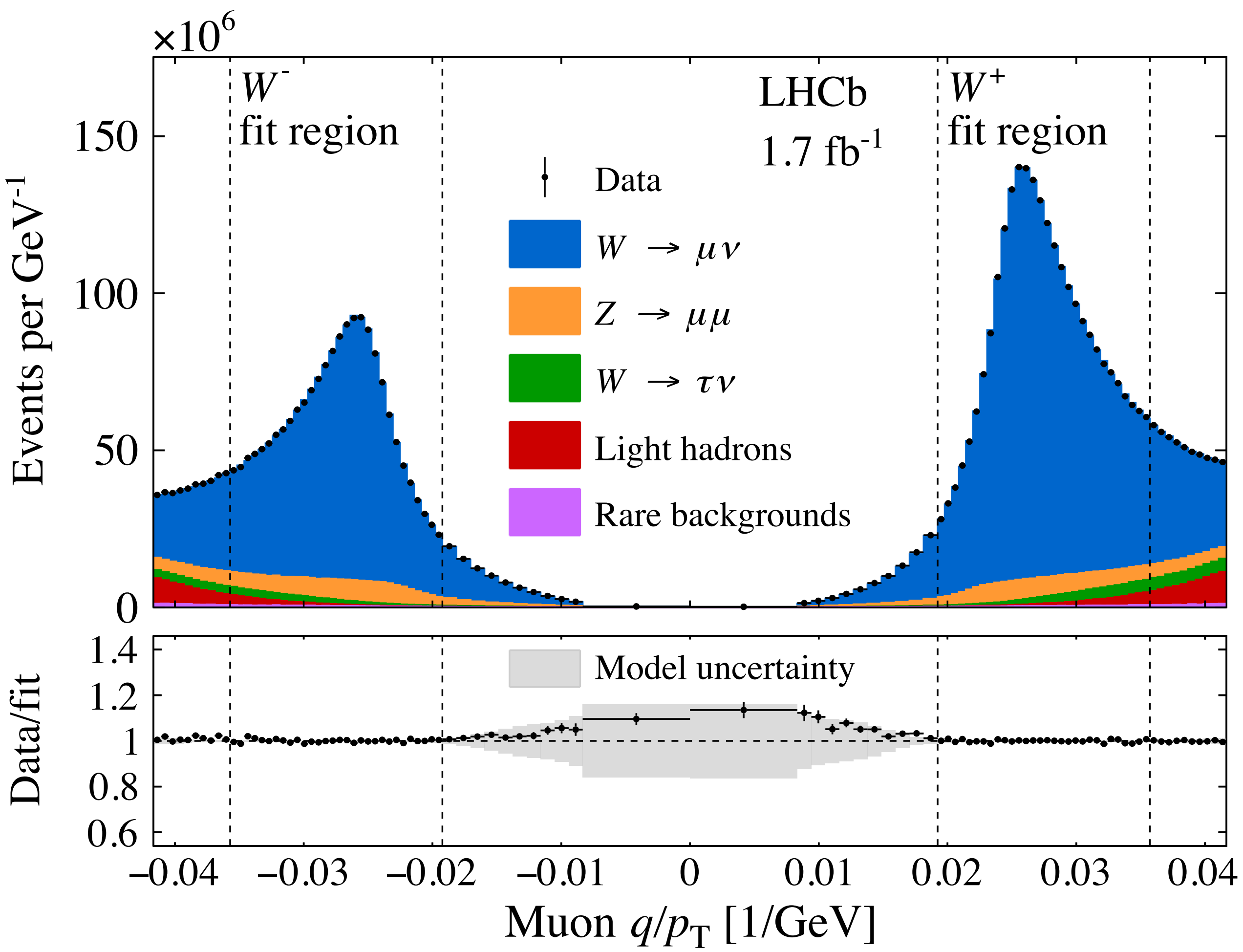
Global EW fit is sensitive to BSM corrections to propagators and vertices of electroweak boson fields.

Precision of direct m_W measurements is the sensitivity bottleneck.

LHCb's measurement with 2016 data

Fit model based on W, Z, .. events from Pythia with full (GEANT) detector simulation.

Most of the analysis effort is on making small corrections (weights, smearing,…) and evaluating the associated systematics.



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

What next? We have 3x more data on tape so we should reduce all systematics by at least a factor of two.

The Drell-Yan process at Born-level

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

The Drell-Yan process at Born-level

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

Problems: limited perturbative accuracy, PDF uncertainties, other “hacks” in the theory predictions.

“Solution” for 2016 analysis, developed by O. Lupton 1907.09958, is to use leading-log event generators but tune α_s and (less important) k_T. Base model is POWHEG+Pythia. 11 MeV uncertainty from envelope over [POWHEG+Pythia,Herwig+Pythia,Herwig,Pythia]. For the PDF uncertainty (10 MeV) we don’t do anything clever.

For full dataset: WIP (M. Xu): use DYTurbo (up to N3LL accuracy), but *in situ* “tune” still required. Considering dependence on perturbative order, scale, scheme, (and PDFs of course) in uncertainty….

The Drell-Yan process at Born-level

$$\frac{d\sigma}{dp_T^W \, dy \, dM \, d\cos\theta \, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{\text{unpol.}}}{dp_T^V \, dy \, dM}$$
$$\Big\{(1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
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Event generators appear to be unreliable w.r.t. the **angular coefficients**

The 2016 analysis used exact $O(\alpha_s^2)$ predictions from DYTurbo. Main uncertainty from 31-point scale variation. Reduced from 30 MeV to 10 MeV by introducing a floating "form factor" for the A_3 term…

For the full dataset: the 31-pt. scale variation was probably too conservative so we have a reduction for free. If we need further control, the obvious upgrade would be to introduce some binning in η.

Electroweak corrections

Formula on the previous slide assumes a 2 body final state and a factorisation into production and decay.

Broken by QED FSR and higher-order EW corrections, respectively!

The QCD reweighting is based on “dressed” muons kinematics

Proxy for kinematics before QED FSR, but this is a hack of course…

7 MeV uncertainty attributed to QED FSR model, via reweighting in $\log_{10}(E_{dressed} - E_{bare})$. Central value (uncertainty) from average (envelope) of Pythia, Herwig and Photos.

Current MPhys project looking at possibility of measurement with FSR recovery…

5 MeV uncertainty attributed to fits with pseudo data reweighted to POWHEGew with/without EW corrections (beyond QED FSR).

Detector modelling corrections

Muon momentum measurement

- Scale, resolution, charged-dependent biases,…

Muon selection efficiencies (R. Hunter, E. Muhammed)

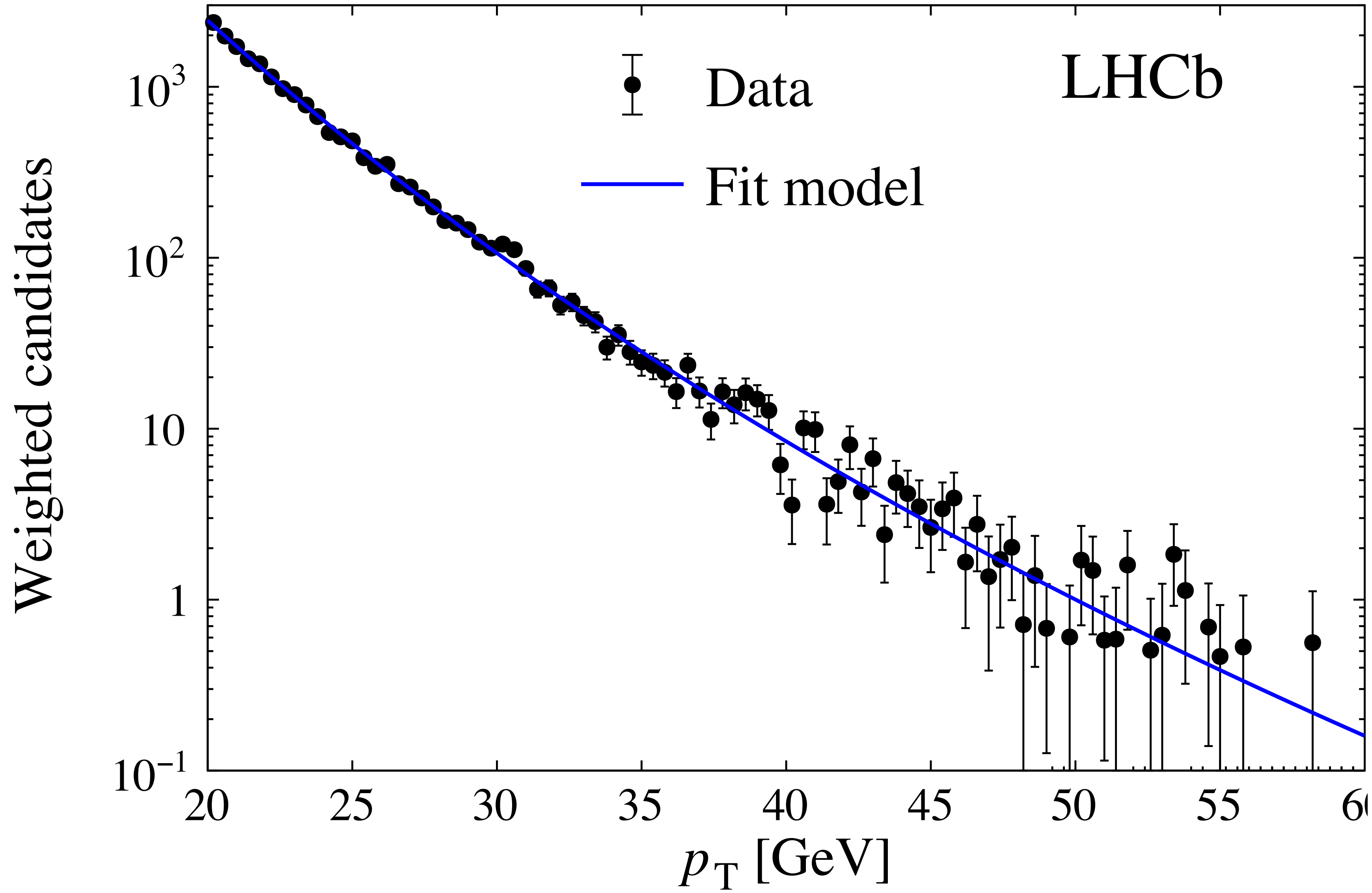
- Detector related: trigger, tracking, muon ID
- Physics related: isolation cut

Hadronic background (M. Ramos Pernas)

Electroweak backgrounds

Hadronic background model (M. Ramos Pernas)

Inclusive charged hadron data



Basic idea is to parametrise the p_T distribution of charged hadrons in real data and use weights to correct for the π,K→μX decay length acceptance.

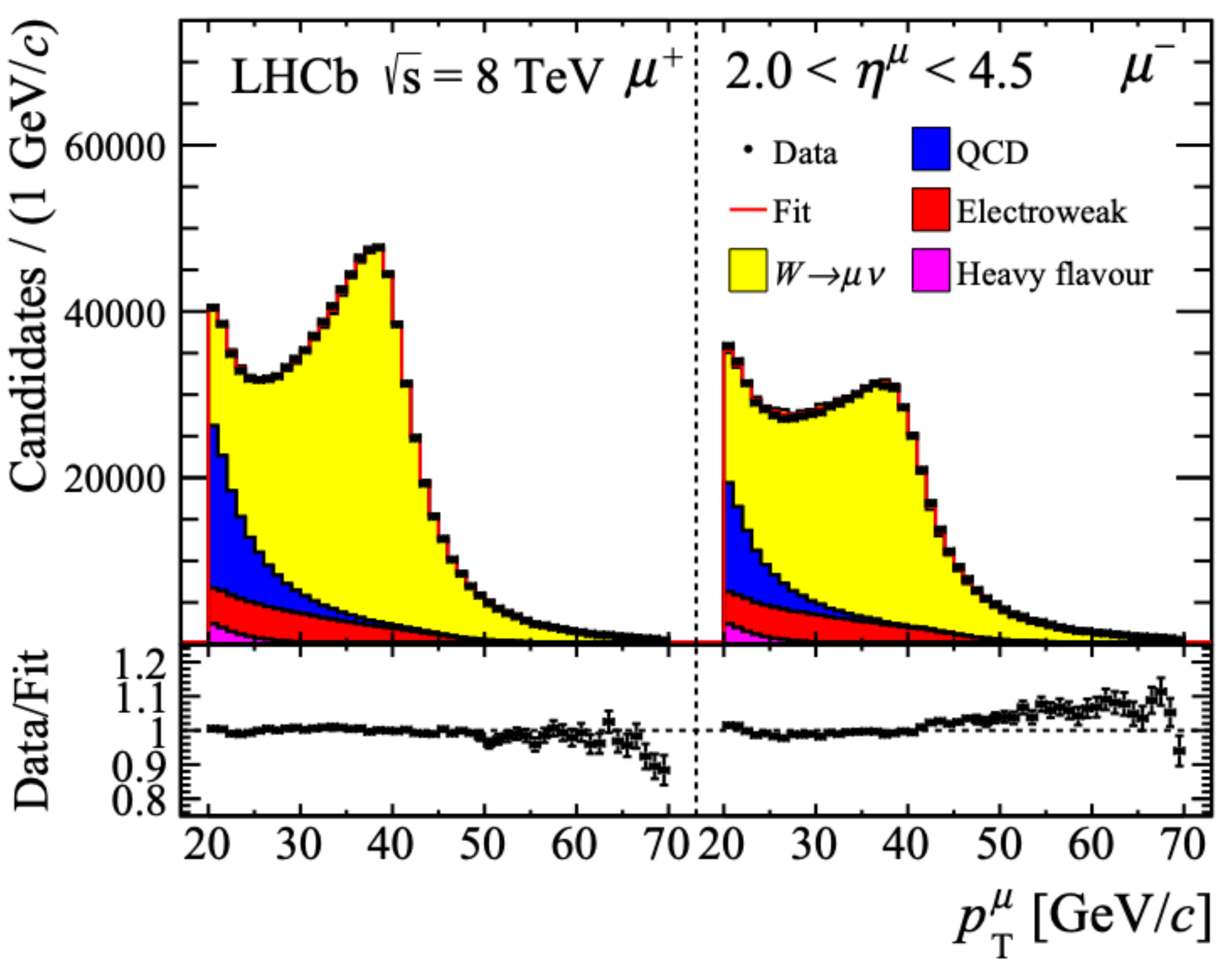
- We see a charge asymmetry of ~20% with a strong dependence on p_T and η. How interesting to measure this? Data seemed to be qualitatively consistent with Pythia.
- Investigating using simulation for the hadronic background, with small shape corrections from data, but still emulating the muonic decay with weights.

m_W determination from unfolded $d\sigma/dp_T$

Measurements of m_W have always been at “reco level” but there are obvious long term scientific advantages of measuring $d\sigma/dp_T$ and fitting m_W with a “truth level” model?

Usual problems of unfolding, but less obvious: subtracting the hadronic background without any assumption about $d\sigma/dp_T$!

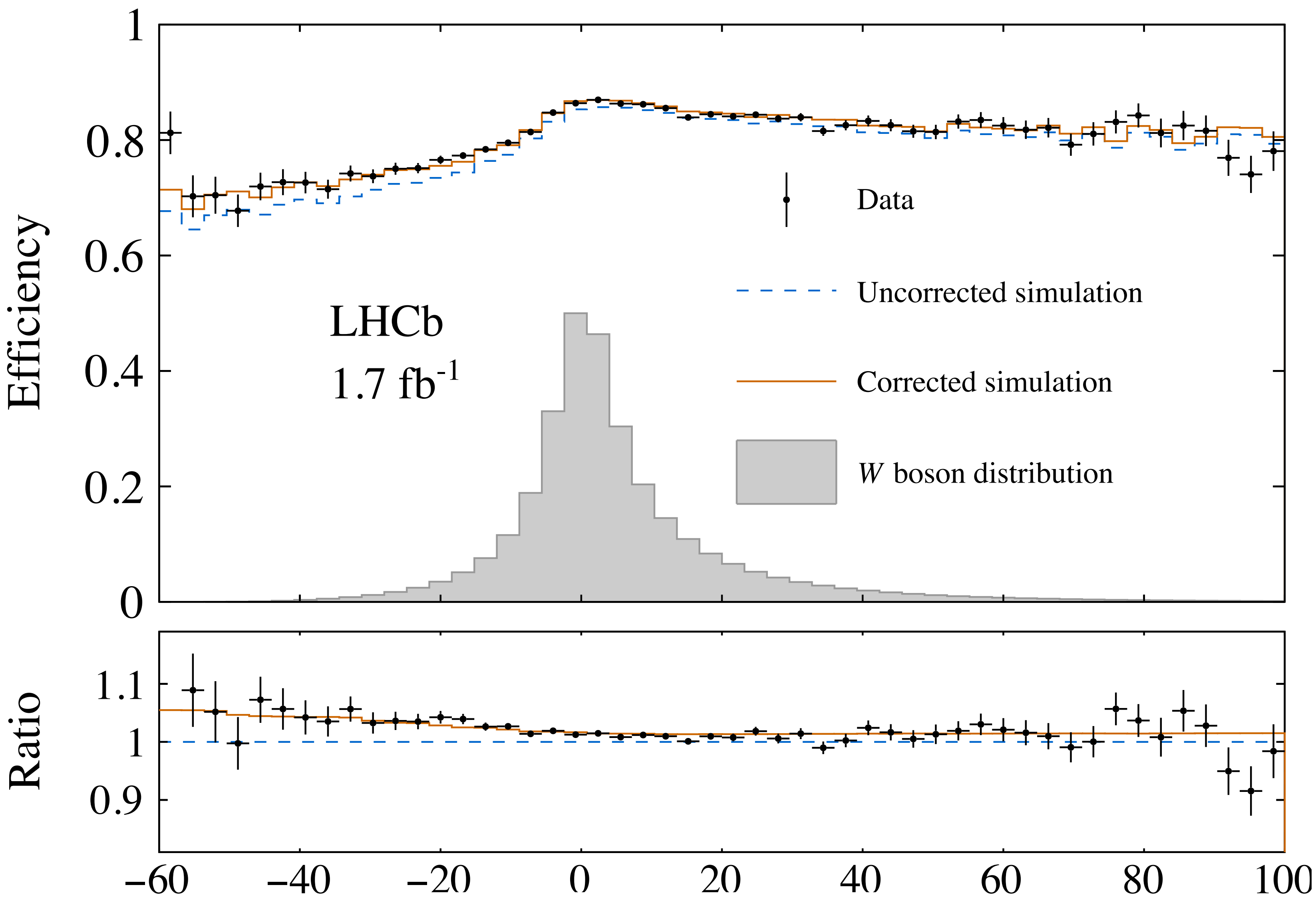
Ahmed+Miguel have developed an isolation based fitter to solve this problem. Considering a proof-of-principle measurement on ~100/pb of 5 TeV data.

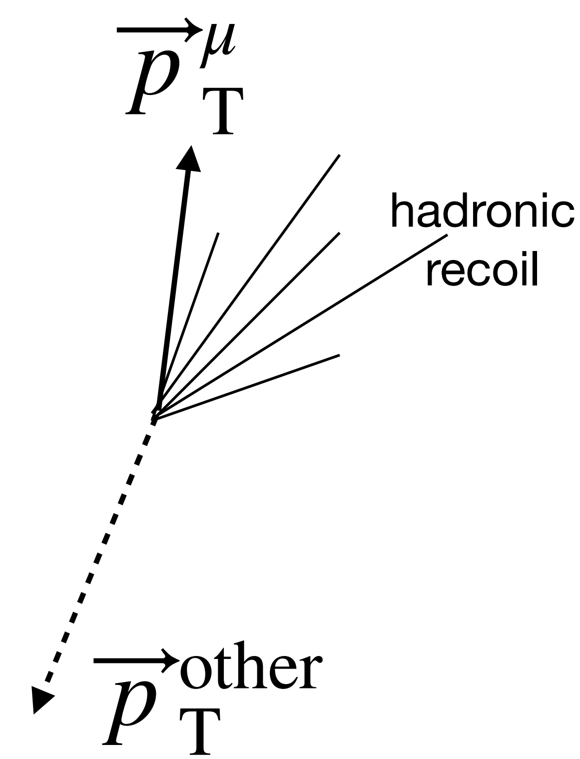


From LHCb’s last measurement of the W cross section

Backup slides

Isolation efficiency modelling

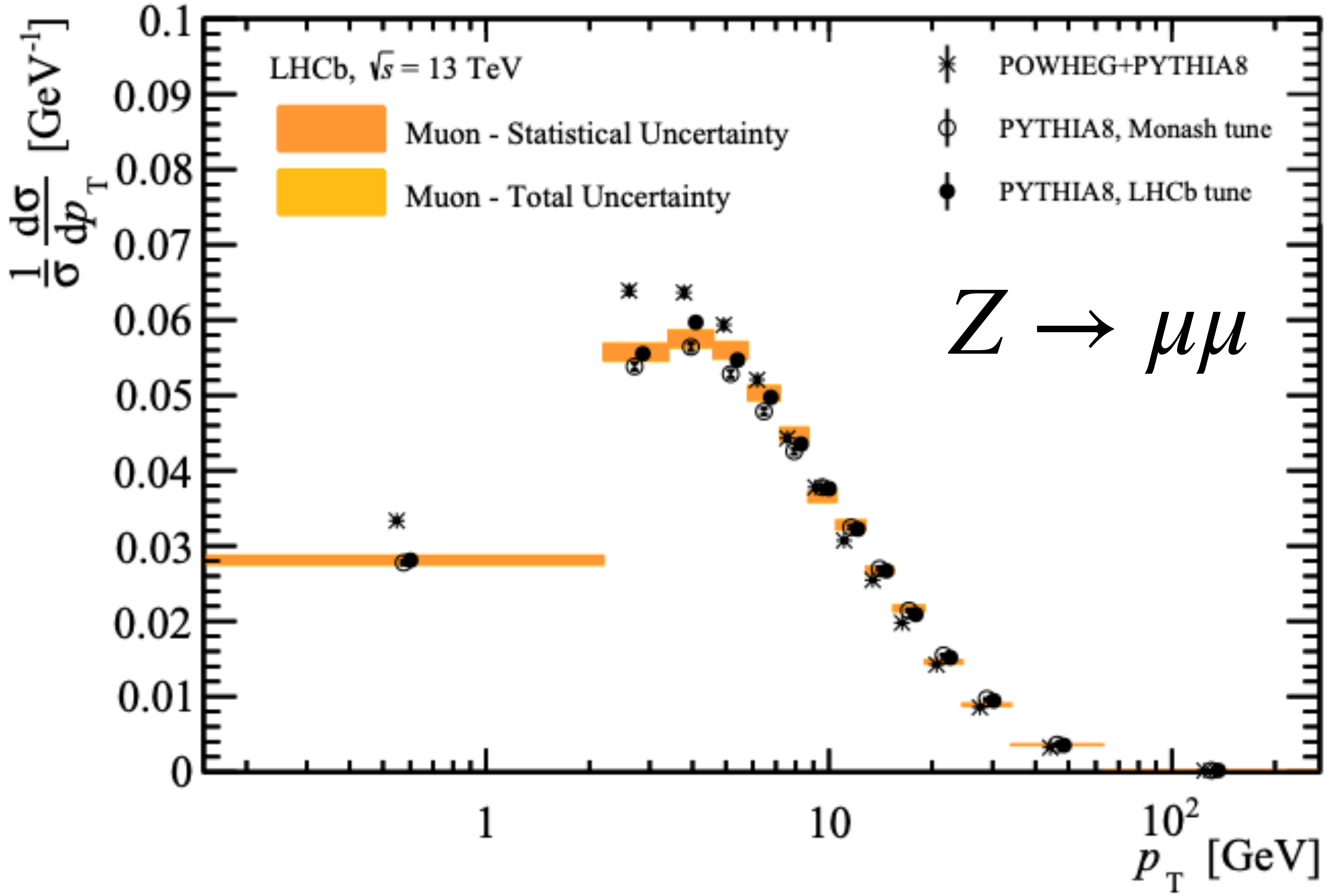




$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}} \quad \text{[GeV]}$$

Contributes **4 MeV** uncertainty on m_W

Boson p_T distribution



Related observable with better experimental resolution:

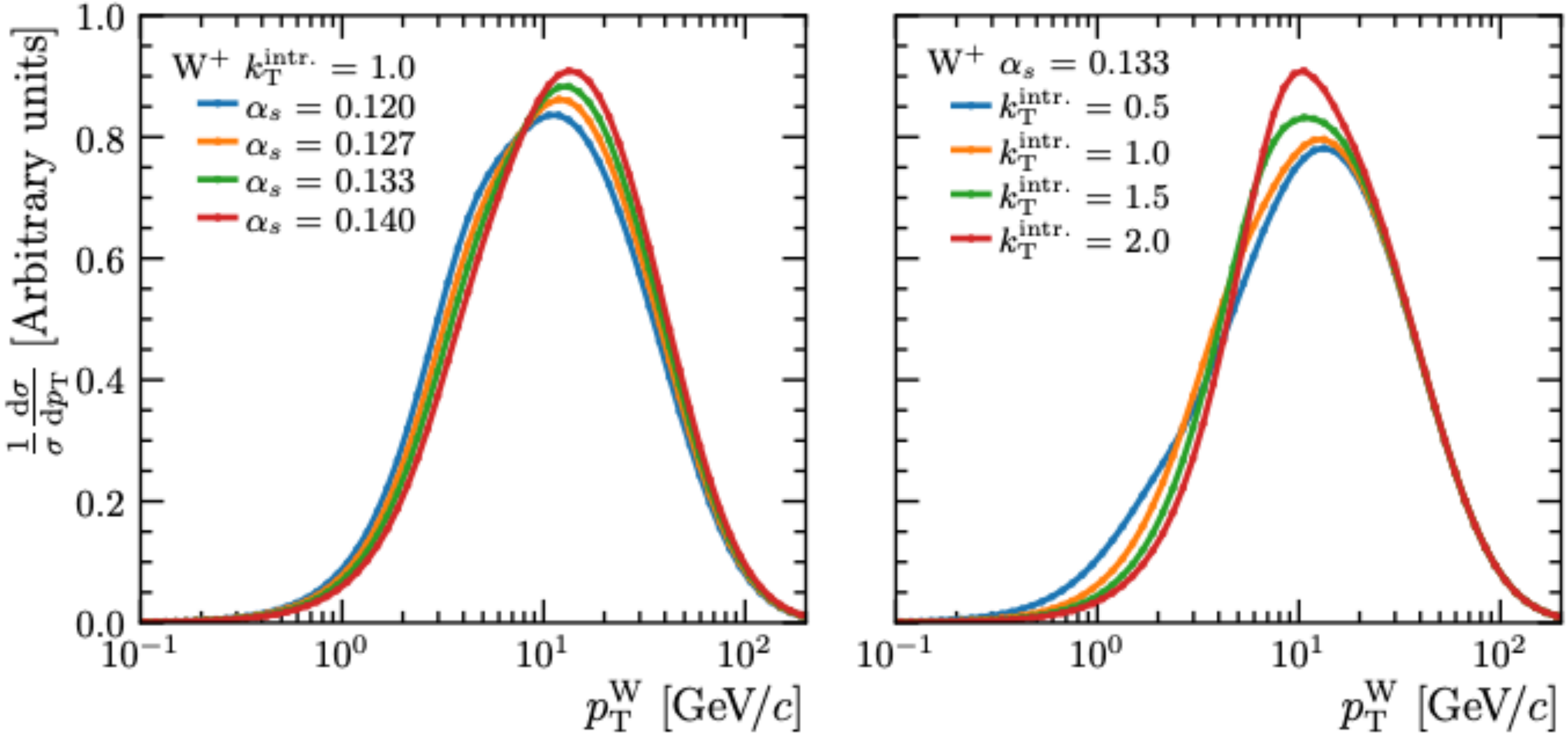
$$\phi^* \equiv \tan\left(\frac{\pi - \Delta\phi}{2}\right)/\cosh\left(\frac{\Delta\eta}{2}\right) \sim \frac{p_T}{M}$$ EPJC 71:1600 (2011)

The large logs

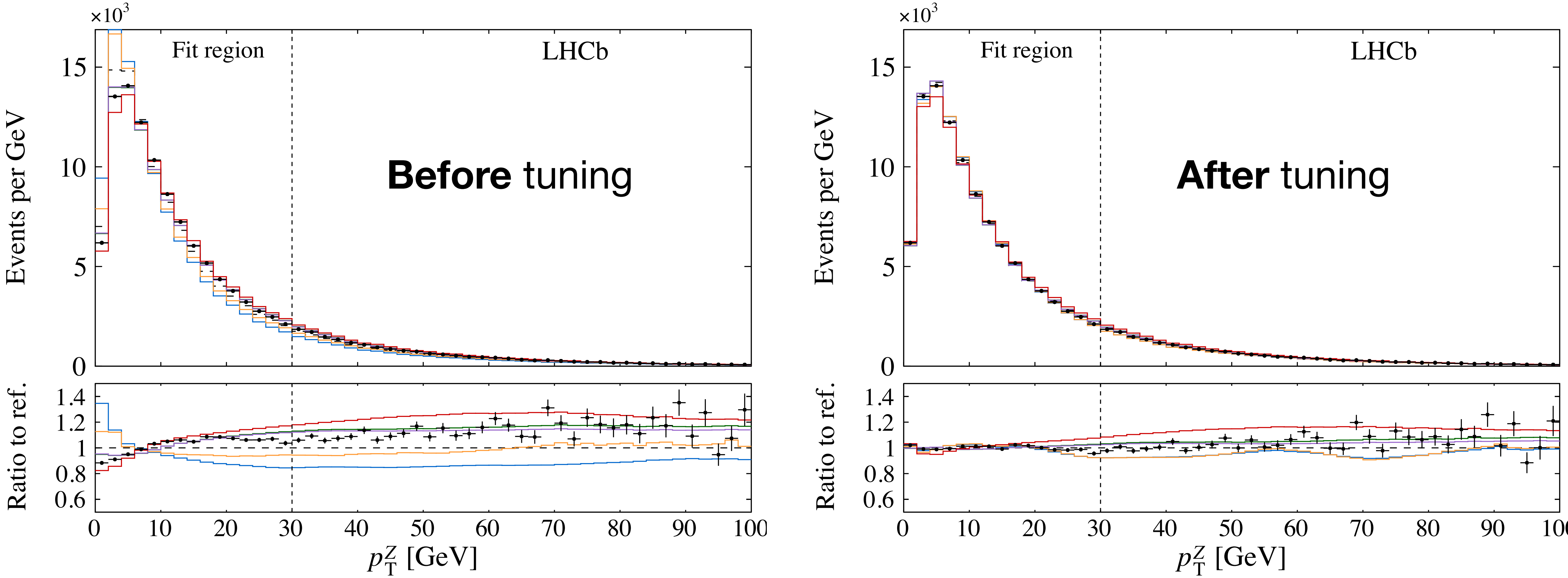
$$\frac{\alpha_s^n}{p_{\mathrm{T}}} \sum_m^{2n-1} \ln^m \frac{M}{p_{\mathrm{T}}}$$

Effect of α_s and intrinsic k_T variation [in Pythia] 1907.09958 (2019)

Varying α_s or intrinsic k_T



Tuning and validation with Z p_T data



Note that the W boson model gets an independent tune in the m_W fit 1907.09958 (2019)

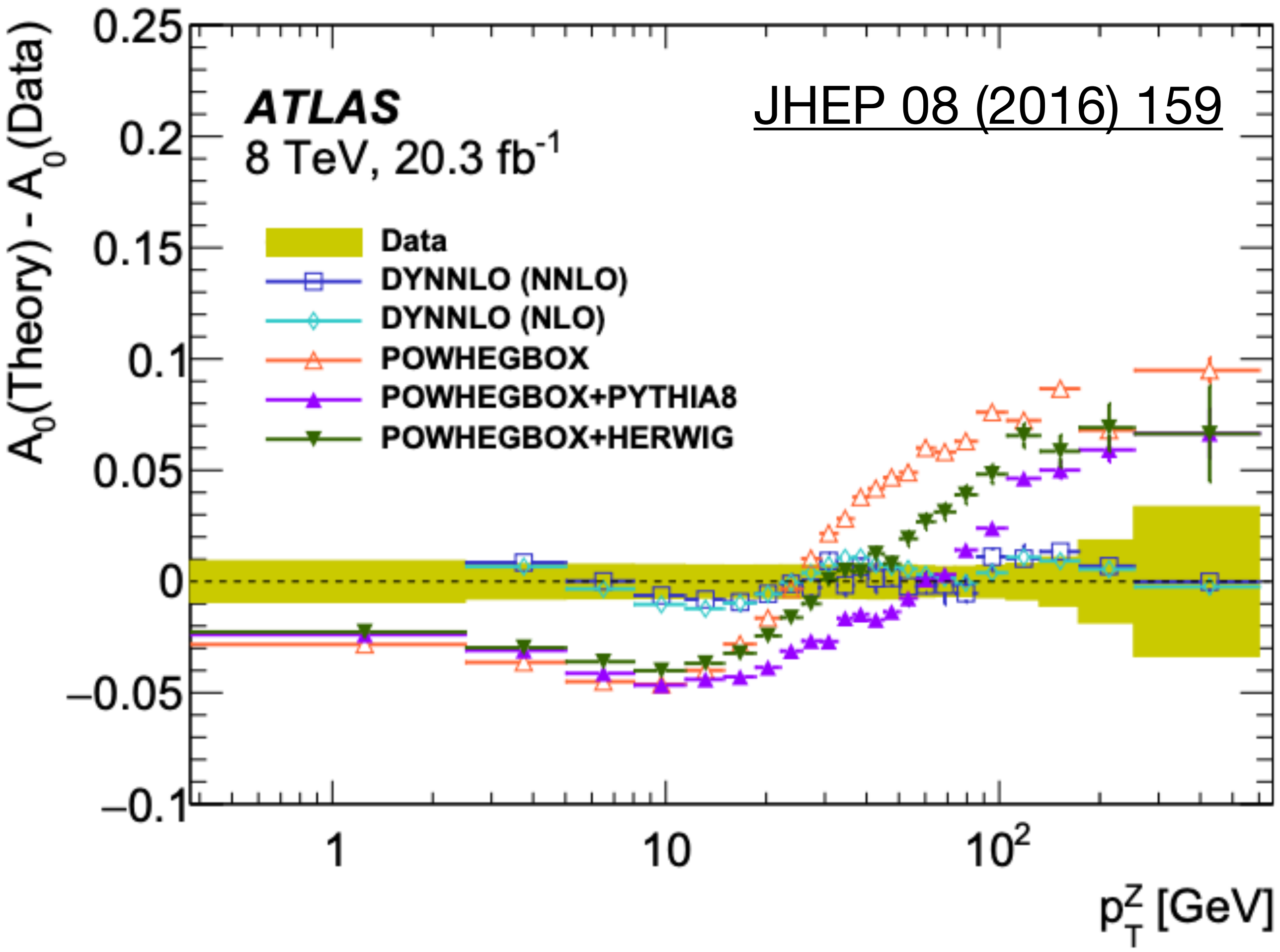
Best description from POWHEG+Pythia with $\alpha_s \approx 0.125$

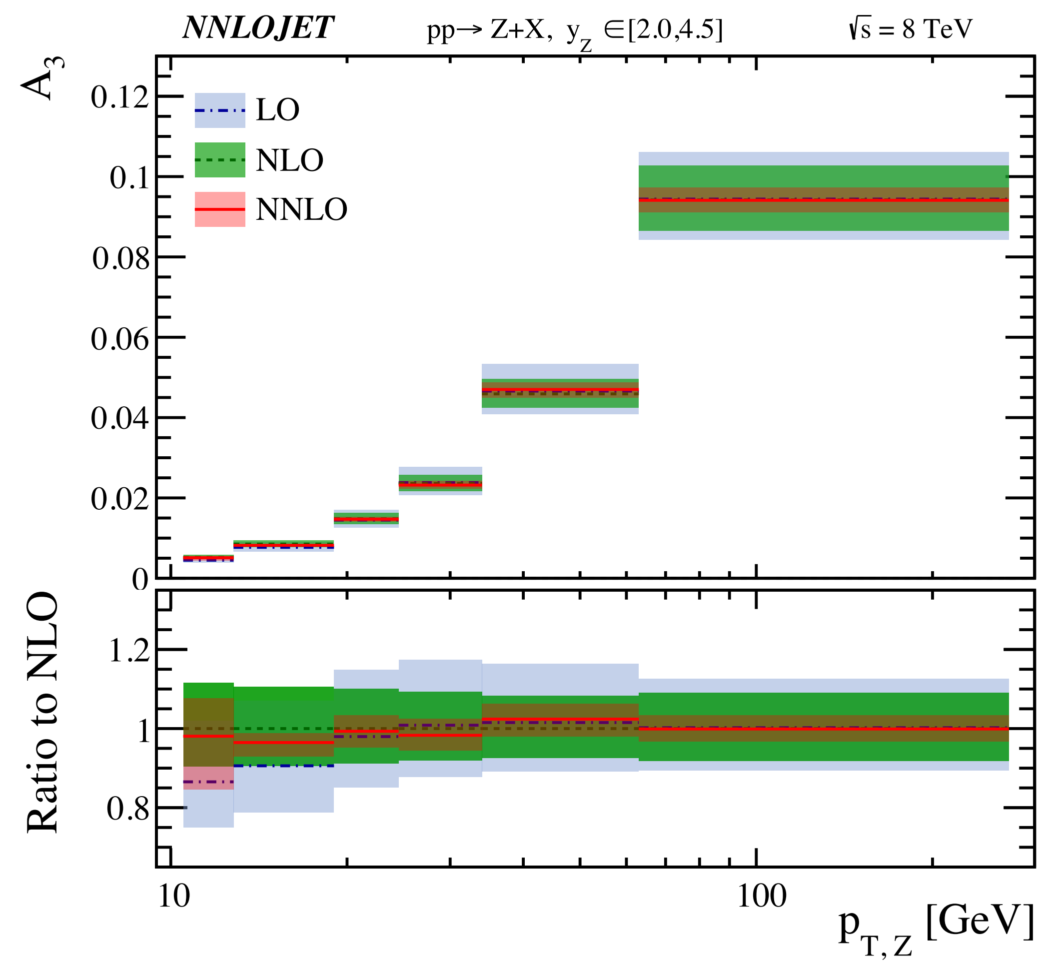
Uncertainty from envelope of m_W fits based on 5 models.

Contributes **11 MeV** uncertainty on m_W

Angular coefficients

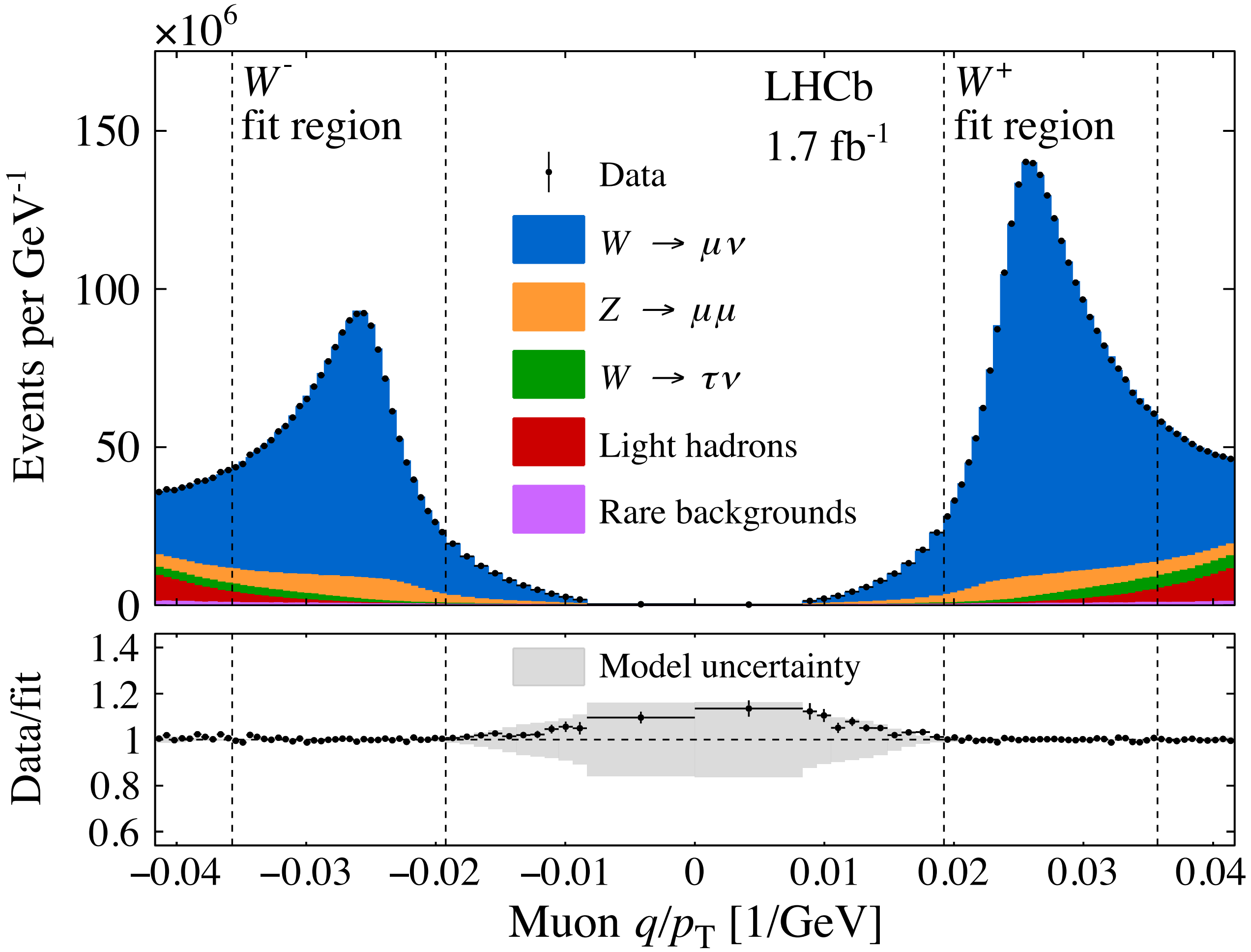
JHEP 11 (2017) 003

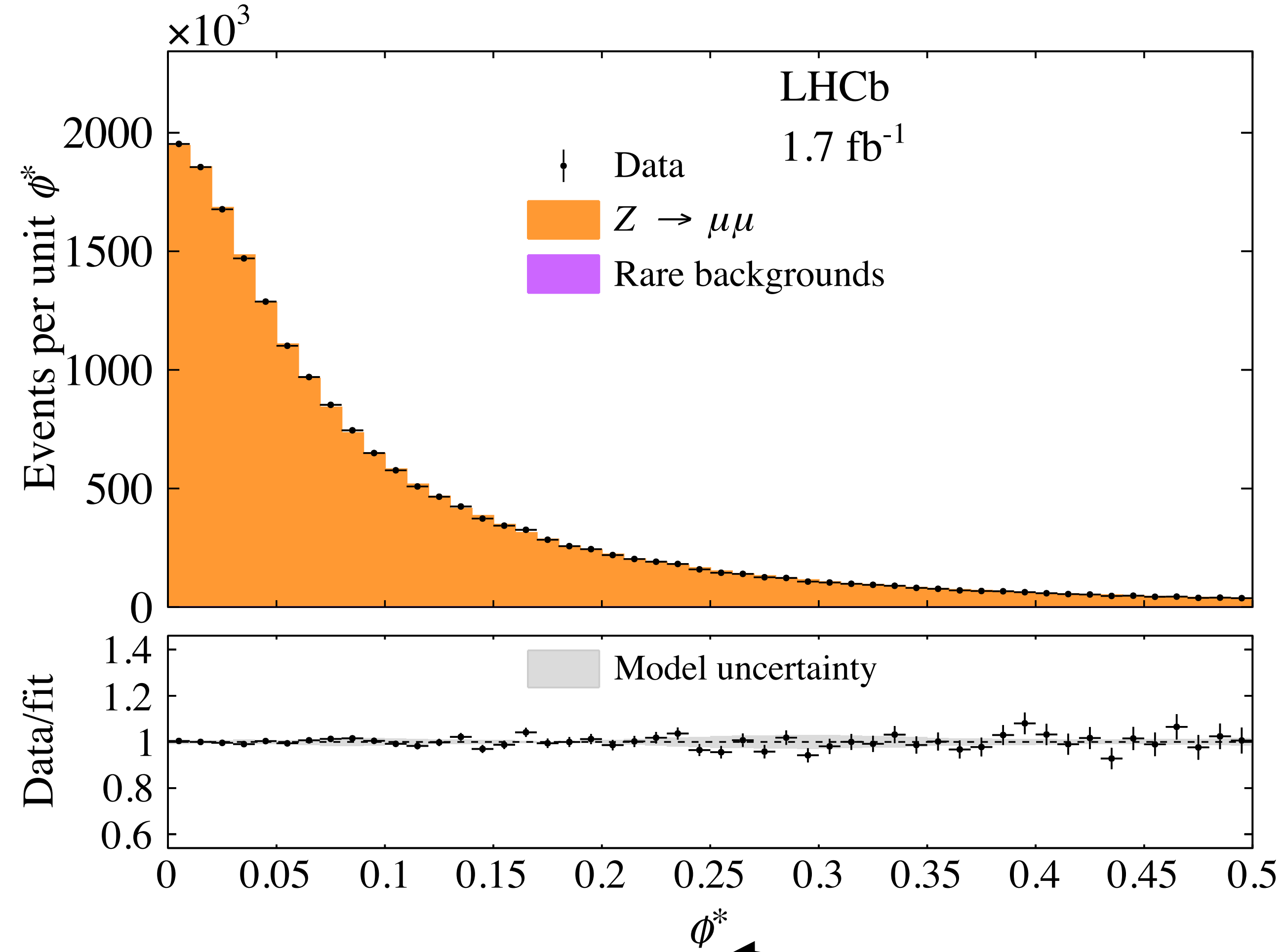




The simultaneous fit to W and Z data

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



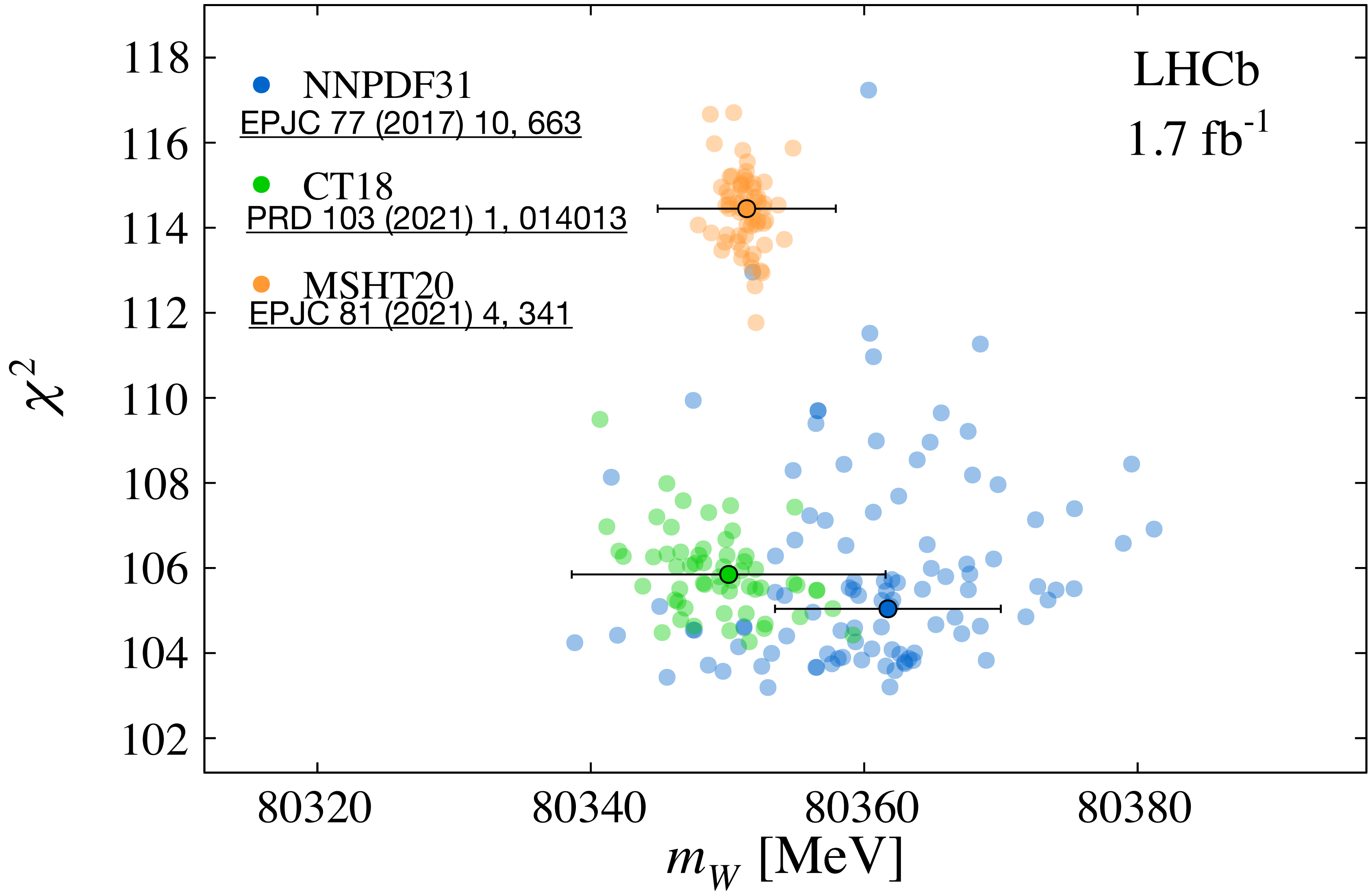


EPJ C71 1600 (2011)

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_T^{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

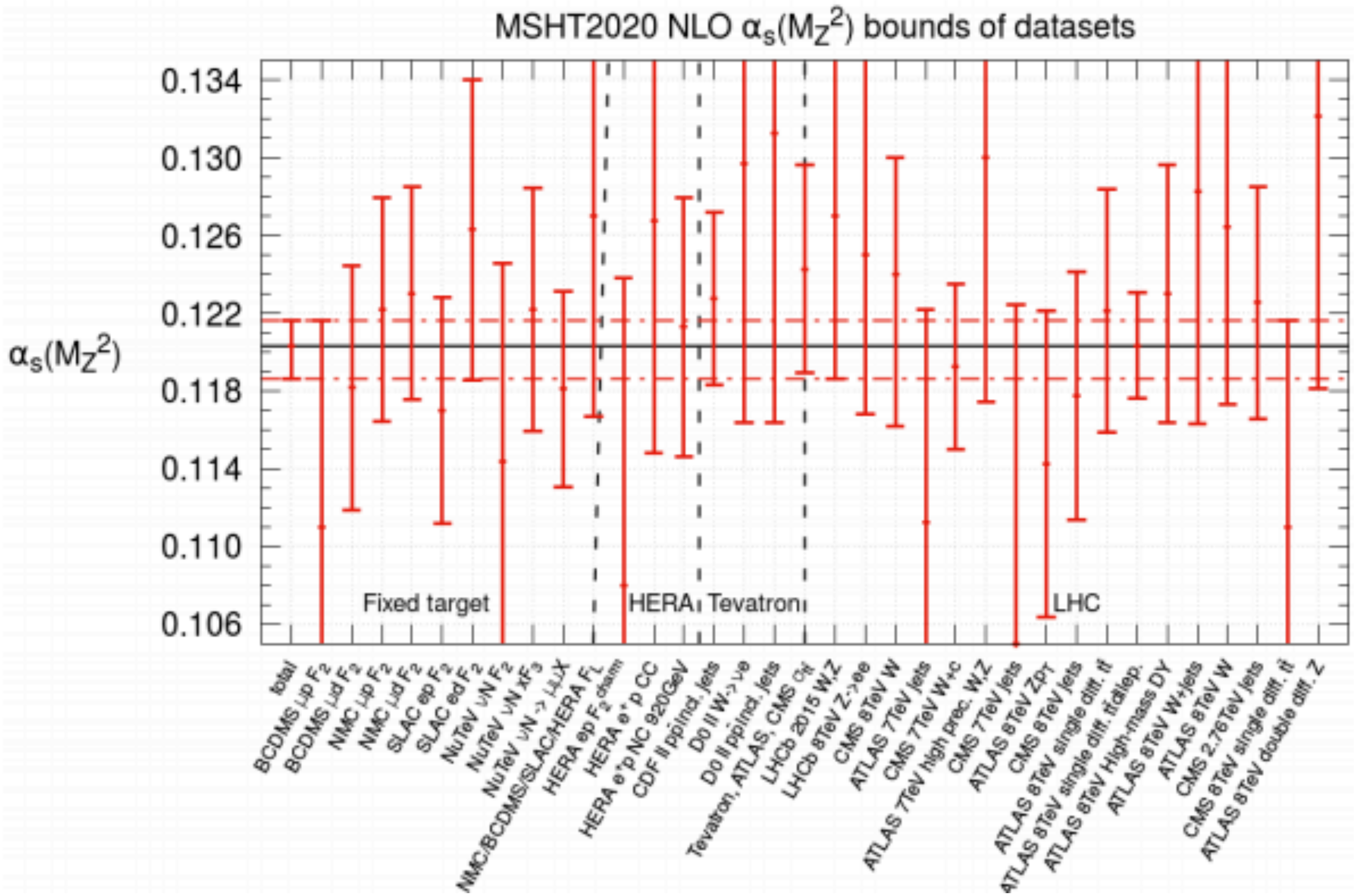


Three separate results are reported in the paper.

Central result is a simple average of the three.

Contributes **9 MeV** uncertainty on m_W

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.