Measurement of the W boson mass at LHCb

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QMUL PPRC Seminar: 16/12/21

What we mean by "precision"

A precision of 1 part in…		is equivalent to measuring	to an accuracy of	or roughly the relative precision to which we know or have confirmed
10	10^1	The height of a person	one hand length	various Higgs boson signal strengths;
100	10^2	The height of the tallest tree	the height of a car	lepton universality in rare B meson decays; lepton universality in W boson decays; the strong coupling constant; the W boson width
1,000	10^3	The height of Mount Everest	the height of a London double decker bus	the Higgs boson mass; the Z boson width
10,000	10^4	The height of a basketball hoop	the width of a grain of sand	the W boson mass; the free neutron lifetime ← TODAY
100,000	10^5	The width of a football goal	the thickness of a piece of A4 paper	the Z boson mass; Newton's gravitational constant (G)
1,000,000	10^6	The distance from the Earth to the International Space Station	the length of a cat	the muon lifetime; the pion mass
10,000,000	10^7	The height a plane cruises at	the width of a grain of sand	the experimental value of muon $(g-2)/2$
10,000,000,000	10^{10}	The width of the sun	one hand length	the fine structure constant; the proton mass (*but not in atomic mass units*); the electron mass

Today's Seminar

- The rewards of measuring the W boson mass
- How we can measure m_W at the LHC
- LHCb: the detector, and why we want to use it to measure m_W
- The first LHCb analysis (arxiv:2109.01113):
    - Analysis strategy
    - Discussion of different systematic effects (experimental, theoretical)
    - Our result and potential impact
- Where this programme goes next

All the technical detail!

W mass – status to date

- W mass is at heart of electroweak theory:

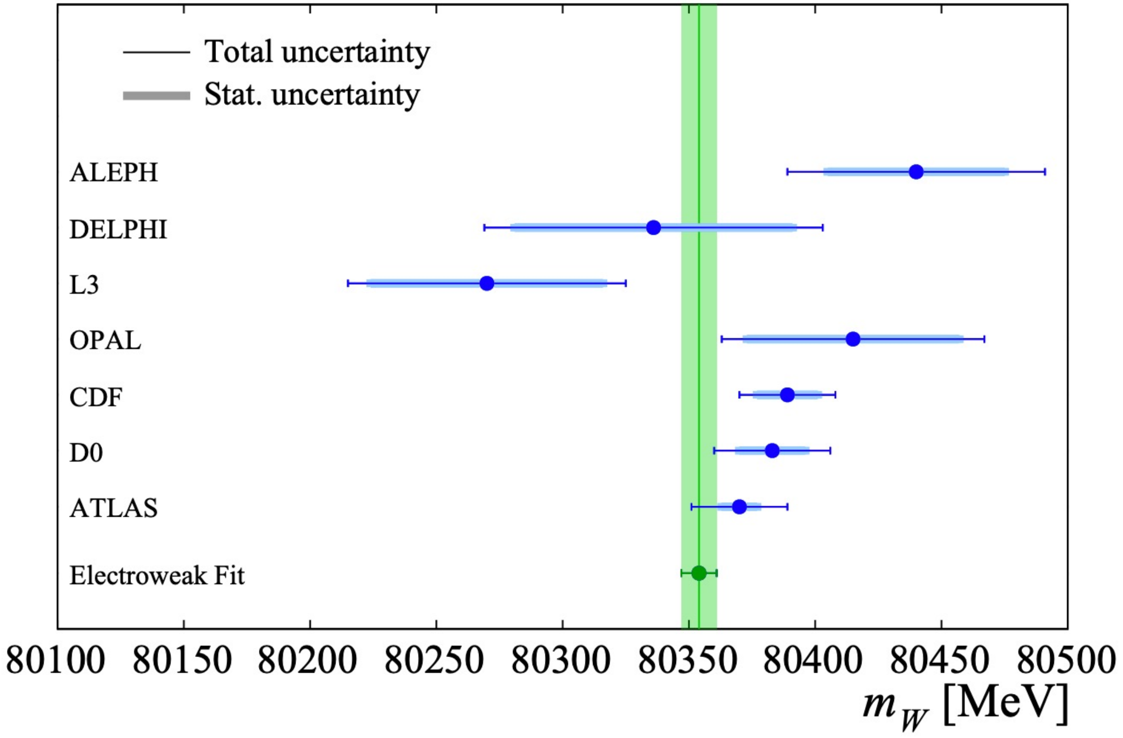
$$m_W^2\left(1 - {m_W^2}/{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

  Where Δ includes higher order effects…

  …and potential new physics contributions.

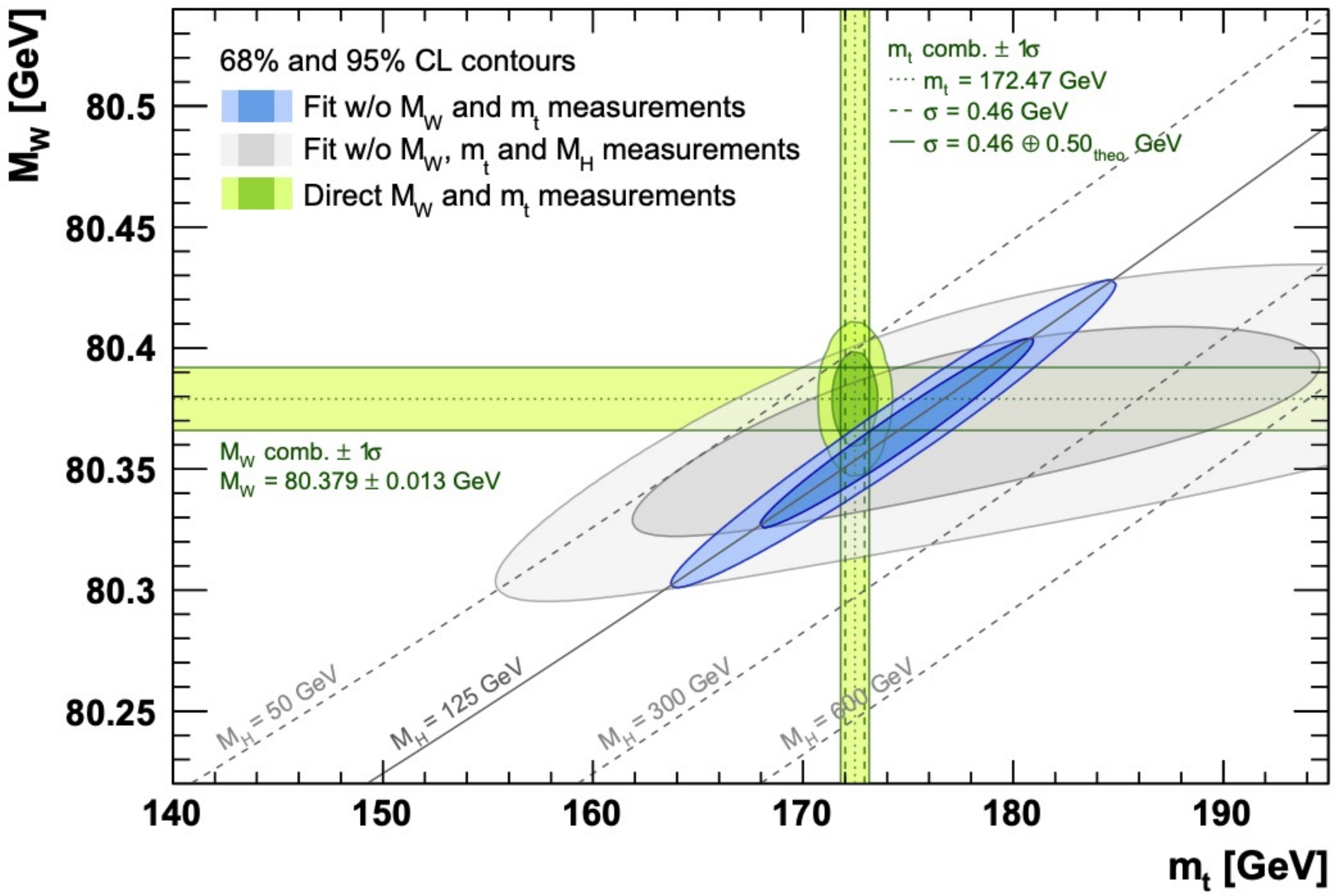
- Global EW fit provides prediction of W mass with 7 MeV precision.

- Hadron Collider measurements already available from ATLAS, CDF and D0, and contribution from CMS expected.
  - Most precise measurements to date (ATLAS, CDF) achieve 19 MeV precision.



W mass – status to date

- Precision of direct measurements limits interpretation of electroweak fit in terms of new physics.
- Improving our knowledge of the W boson mass is a major physics goal of the different LHC experiments.



How to measure m_W at the LHC

- Two main methods exploited at hadron colliders, considering $W \to l\upsilon$ events.

1. Measure lepton p_T distribution
   - W boson mass sets location of the peak
   - LHCb measurement makes use of this method, using muons.
   - Main method at ATLAS – receives weight of 86% in overall ATLAS analysis.

2. Measure W boson m_T distribution
   - Different uncertainties dominate with this method.
   - Not possible at LHCb – not a hermetic detector.

Muon p_T distribution

- At leading order (no W p_T) simple peak in muon p_T distribution set by the W mass.
  - We can fit the muon p_T distribution with different W mass hypotheses, and determine the best fit to find the W boson mass.

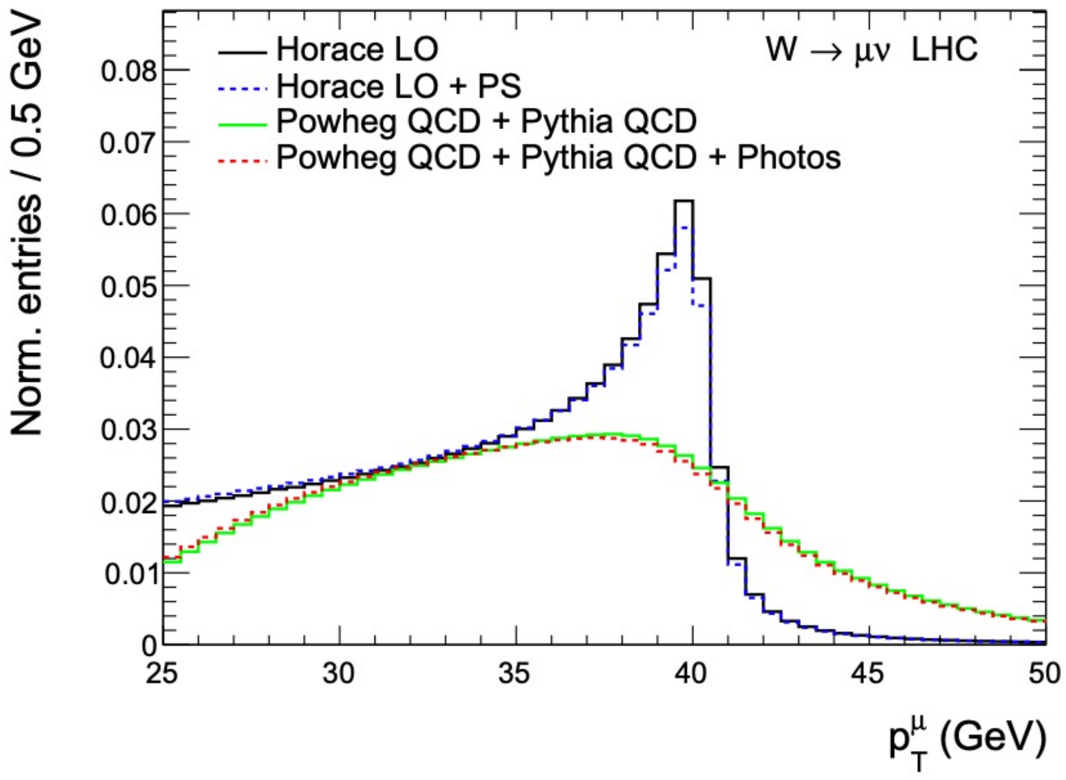
- However, accurately measuring the W mass from the distribution requires careful understanding of higher order theoretical effects and the experimental environment.
  - Have to account for small theoretical and systematic effects, and quantify uncertainties.

- (Most of the) rest of this talk: setting these effects out in ever more detail!

Plot From Phys. Rev. D 96, 093005 (2017)

Muon p_T distribution: theoretical ingredients

- Muon p_T distribution:
  - Depends on the W boson production model: how much p_T does the W boson transfer to the final state particles?
  - Depends on the angular distributions of W boson decays: what direction relative to the W boson does the muon travel in?
  - Need to understand the partonic environment – parton distribution functions.



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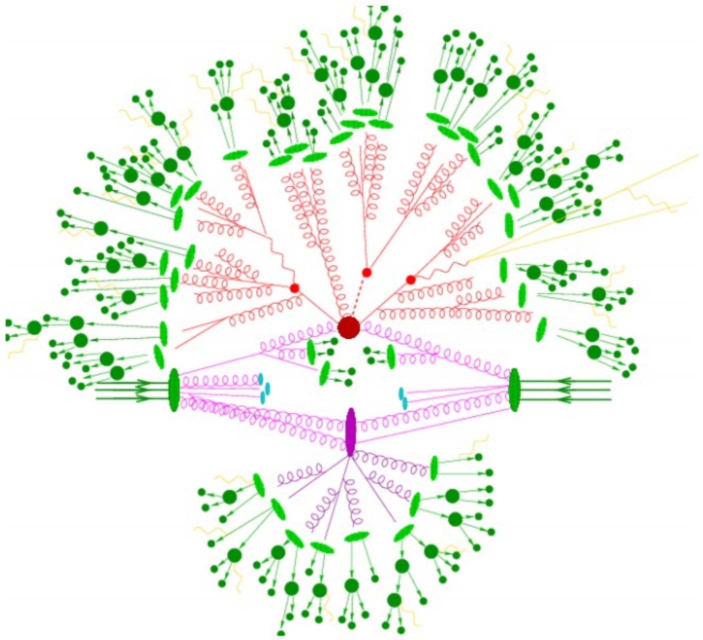
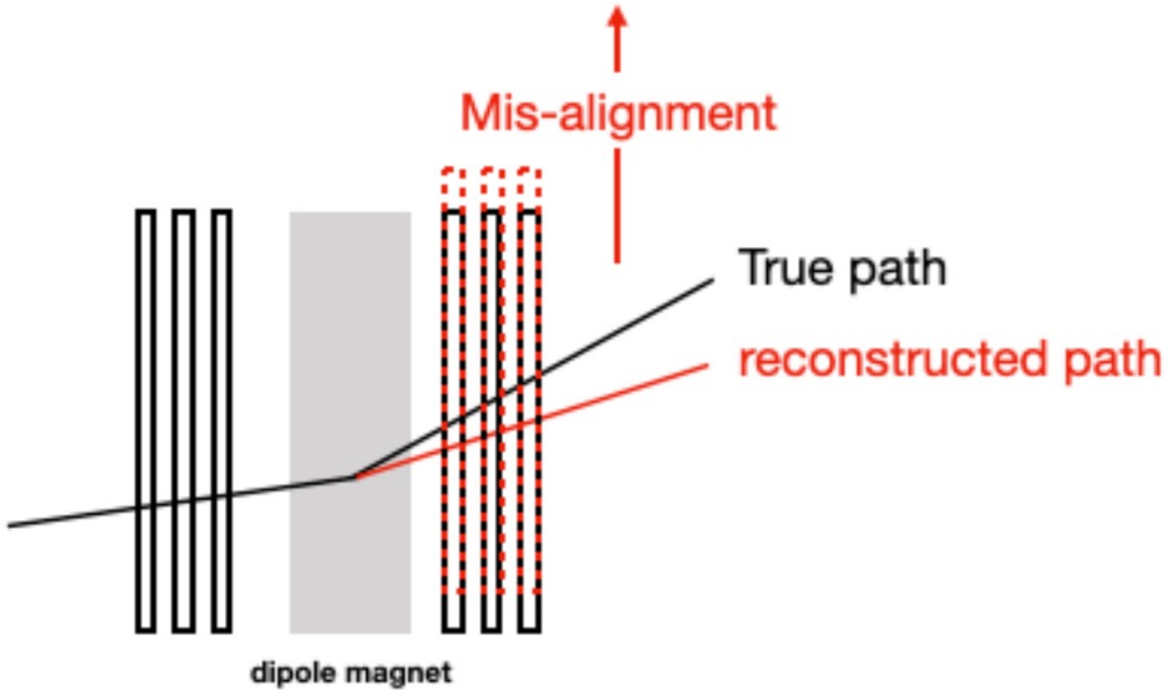


Muon p_T distribution: experimental ingredients

- Crucial to understand the detector environment to a high degree of precision.

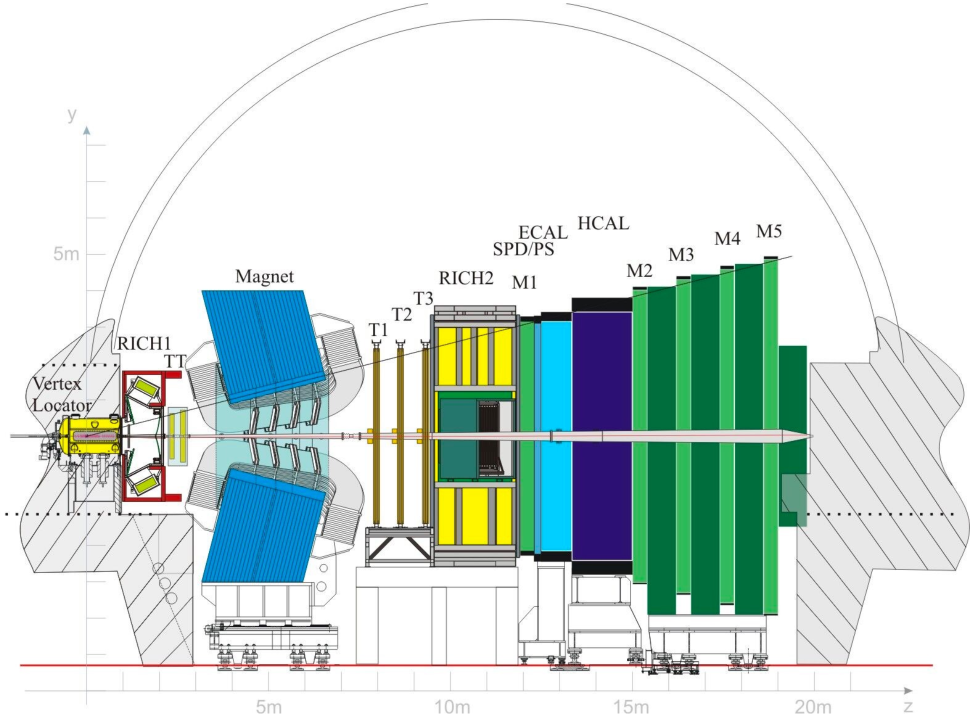


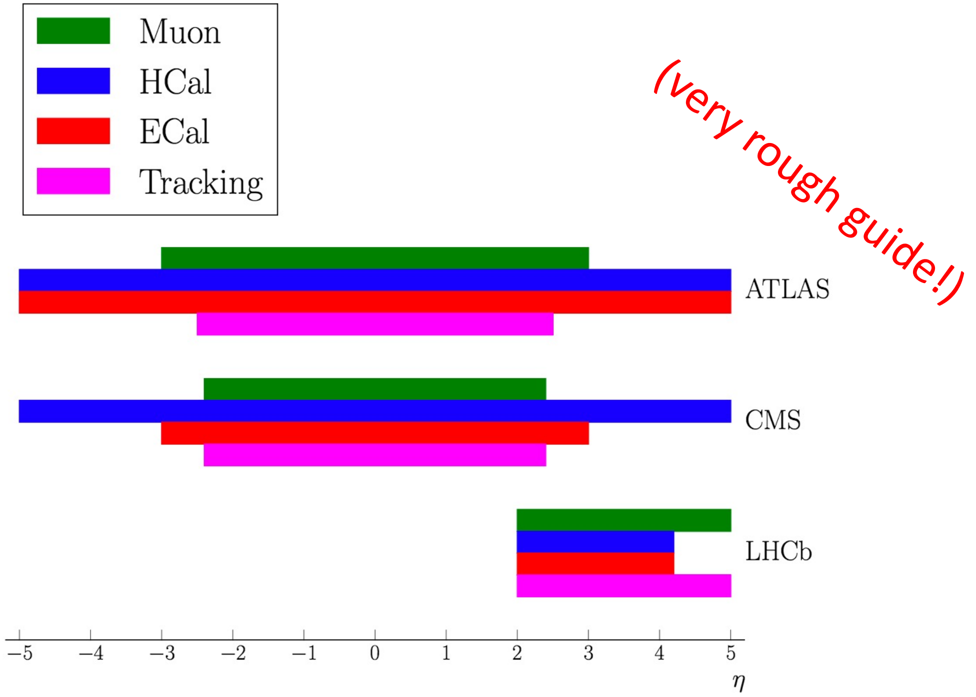
- Alignment effects particularly critical, since misalignments could shift the muon p_T peak.
  - At LHCb, a 5 micron misalignment could cause a 50 MeV bias in the W boson mass measurement.

- Other effects also important – e.g. p_T dependent efficiency would sculpt the distribution

LHCb

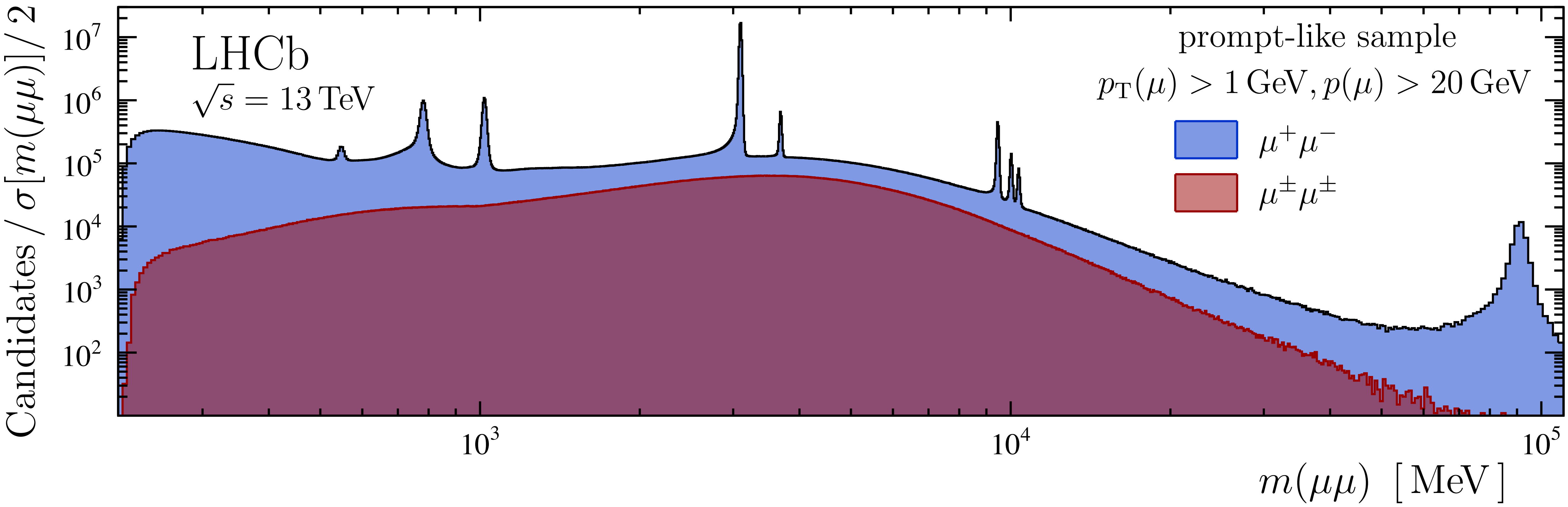
- Single arm spectrometer, fully instrumented in the forward region.





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

LHCb Detector Output



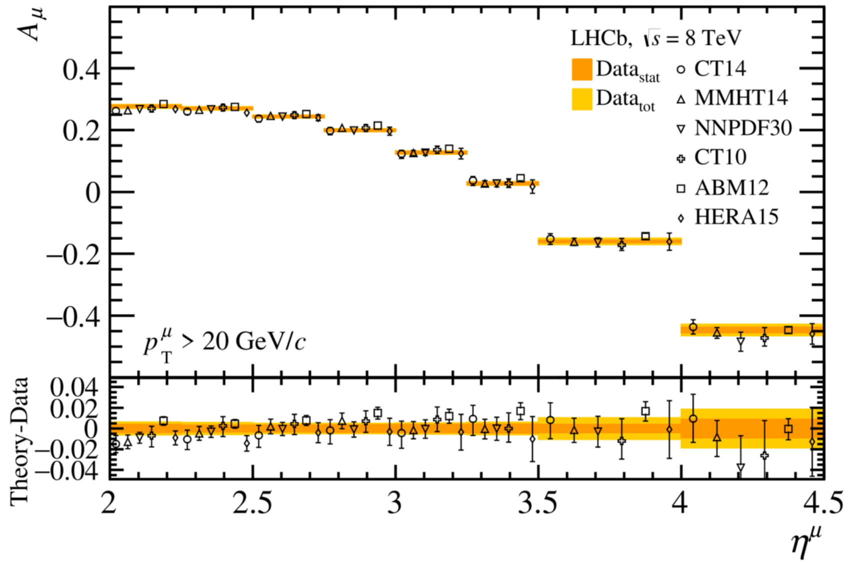
Excellent performance across a wide range of momenta!

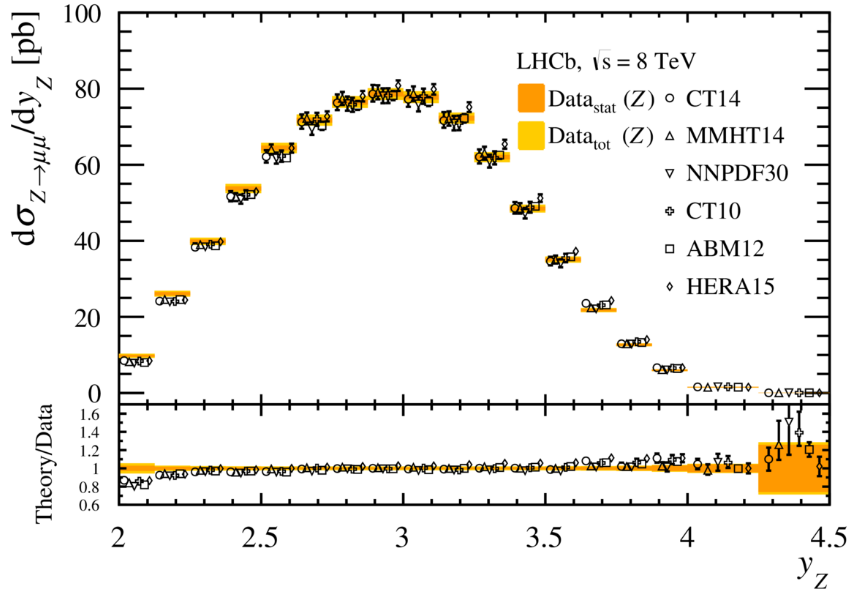
Full list of EW papers to date here

Why LHCb?

- LHCb has already delivered a strong programme of physics with W and Z bosons, mainly probing QCD.

- LHCb's precision coverage of the forward region enables complementary studies to those possible at ATLAS and CMS.
    - Though we are excited to see expanded use of forward coverage at ATLAS and CMS.





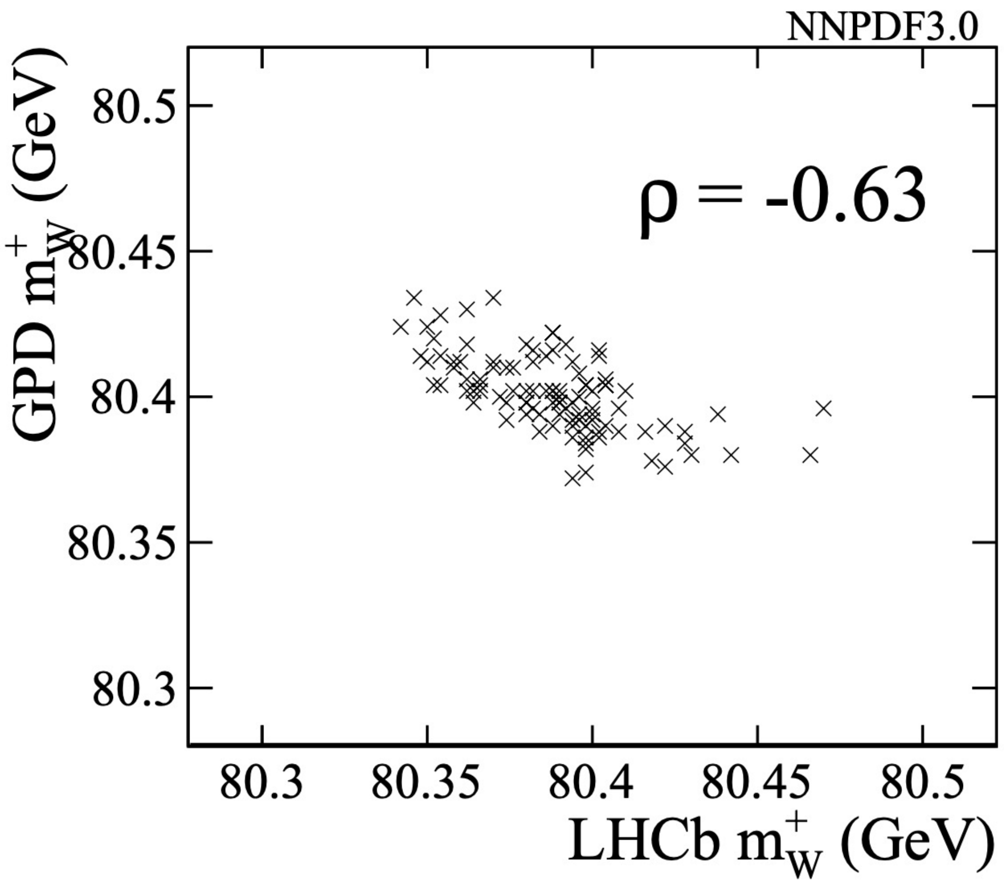
Aside – impact of these QCD studies

- LHCb provides unique information on the structure of the proton:
  - Strong constraints on the most energetic quarks in the proton (at high x) – improving our knowledge by a factor of 2.
  - Key constraints on the charm quark content of the proton – place bound that 'intrinsic' charm component of proton's momentum is < 0.7%.
  - New: tentative evidence for small intrinsic charm content of proton – seen in study of Z+c-jets.

See EPJC 75 (2015) 601

m_W: Why LHCb?

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

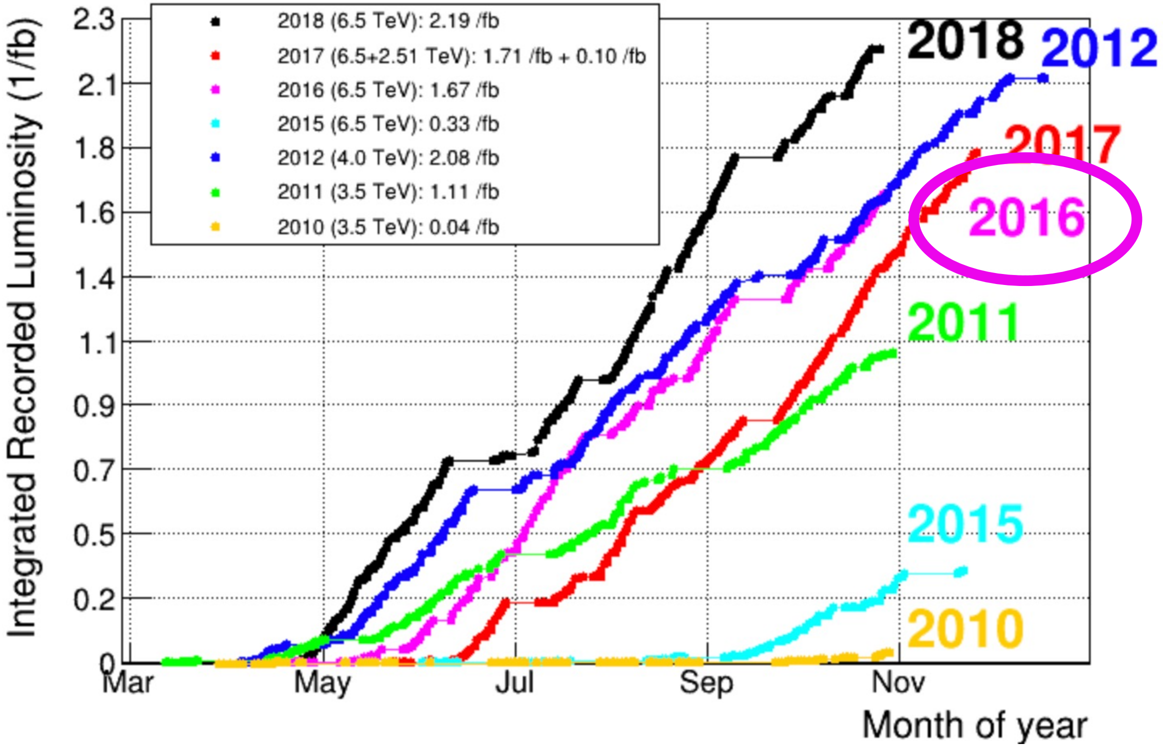


Analysis Strategy - Dataset

- 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.



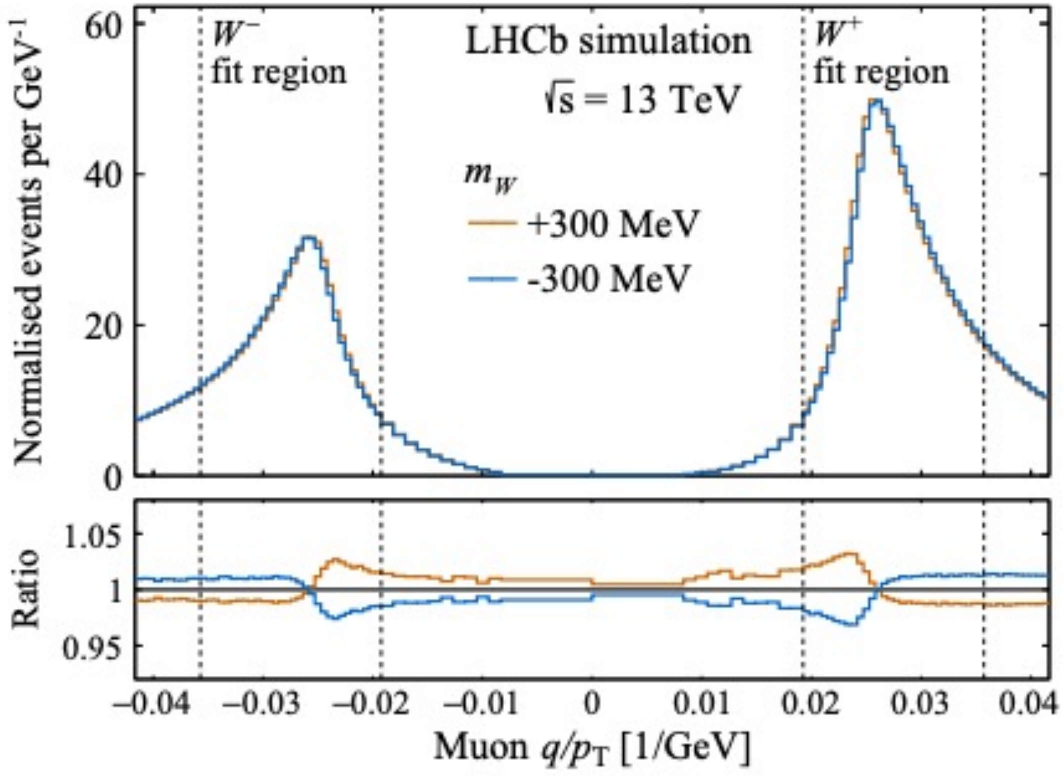
Analysis Strategy – Signal Selection

- Fiducial acceptance ($2.2 < \eta < 4.4$)
- Signal muon responsible for event selection in trigger.
- Well reconstructed track associated with primary interaction.
  - Rejects HF decays
- Isolated muon candidate
  - Rejects HF 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.

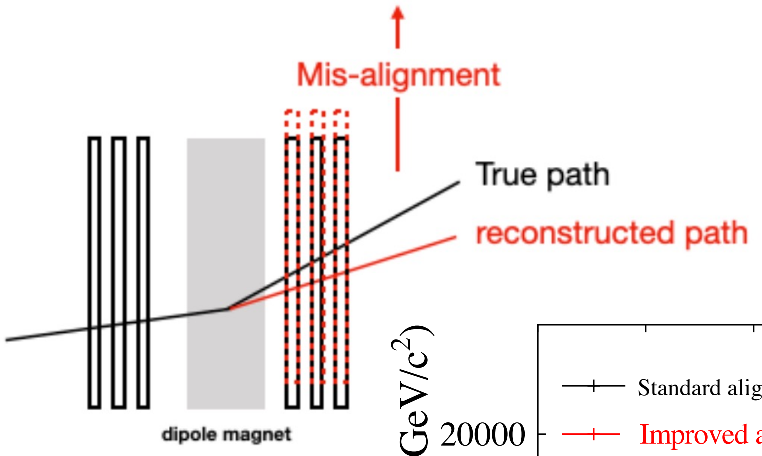
Analysis Strategy – Fit

- 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.



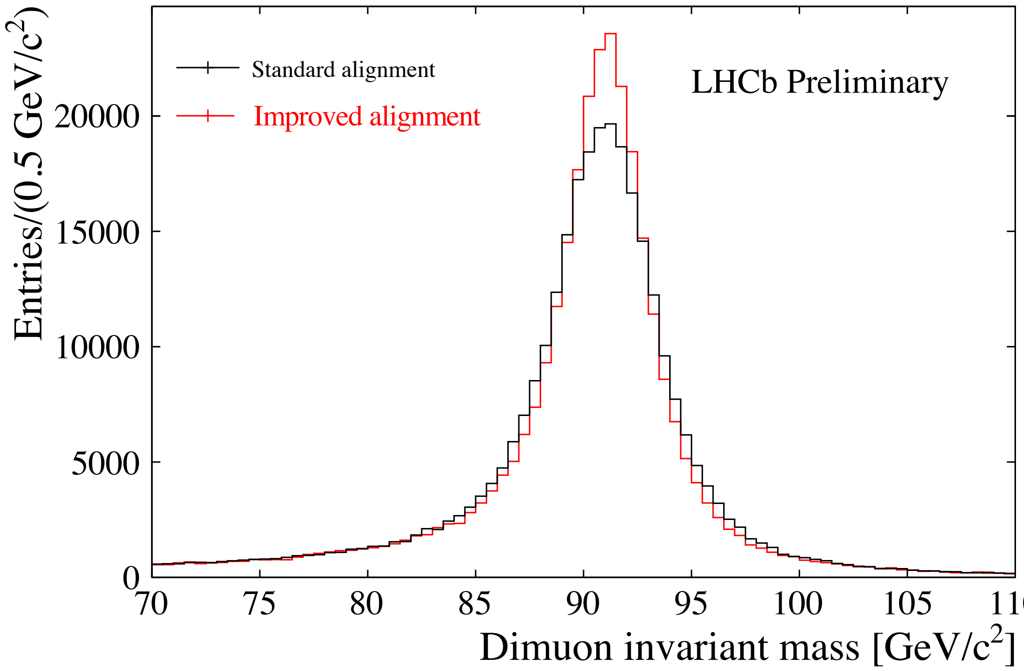
Understanding the experimental environment

- Knowledge of detector alignment is crucial for providing accurate and precise measurements of particle momenta.



- Use $Z \rightarrow \mu\mu$ events to study detector alignment directly.

- Able to improve dimuon invariant mass resolution by $\sim 35\%$.



Understanding the experimental environment

- We know that Z bosons are predominantly produced with little p_T.
- Conservation of momentum

  $\Longrightarrow$ muons in $Z \to \mu^+\mu^-$ events should have similar p_T to each other.
- Can construct a proxy for the dimuon invariant mass using the momentum information of only one muon.
- Differences between M^+ and M^- constrain charge dependent curvature biases and allow corrections to be mapped across the detector.

$$\frac{p_T^+}{p_T^-} \sim 1$$

$$m \approx \sqrt{2p^+p^-(1-\cos\theta)}$$

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

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

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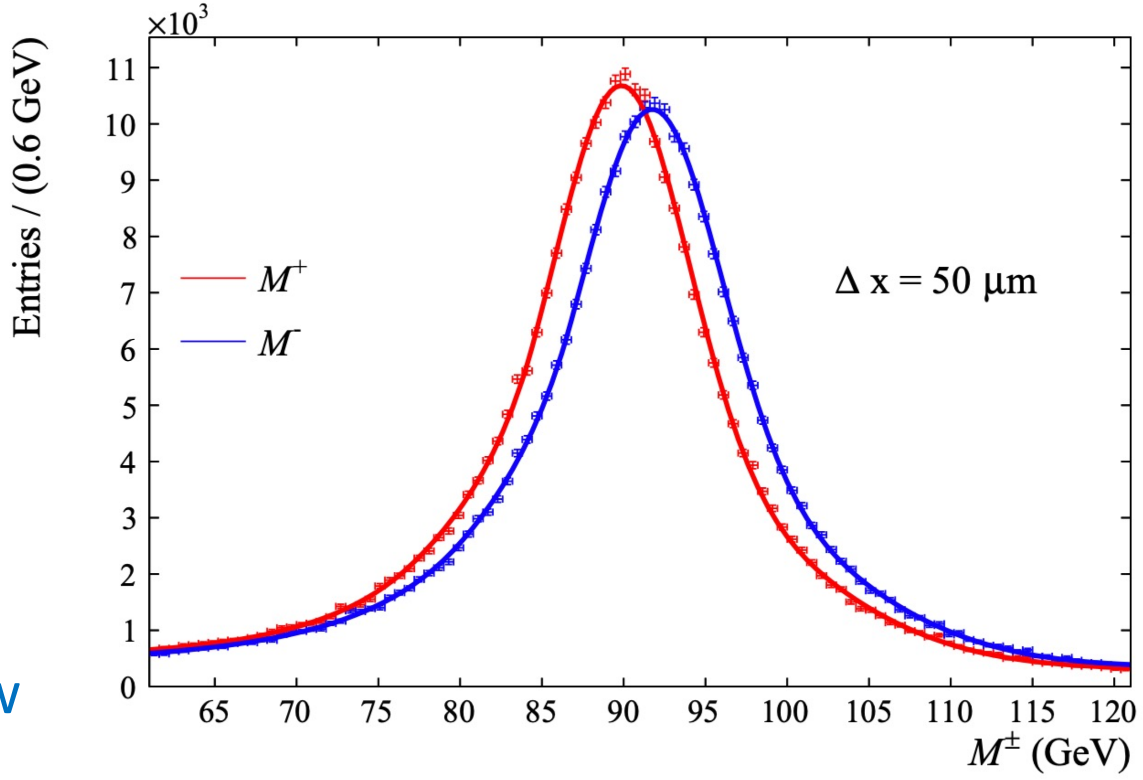
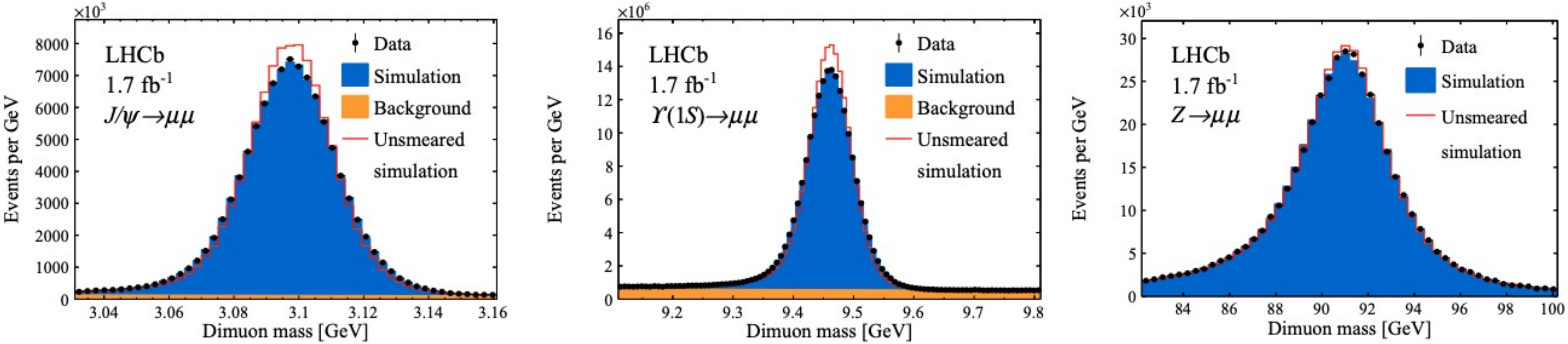


Additional Muon Momentum Calibration

- Additional smearing of simulation to better model the J/ψ, $\Upsilon(1S)$ and Z

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



Additional Muon Momentum Calibration

- Uncertainties propagated through to m_W measurement include:
  - statistical uncertainties on the smearing parameters,
  - knowledge of resonance masses,
  - detector material budget,
  - modelling of FSR,
  - reasonable variations of the smearing function.

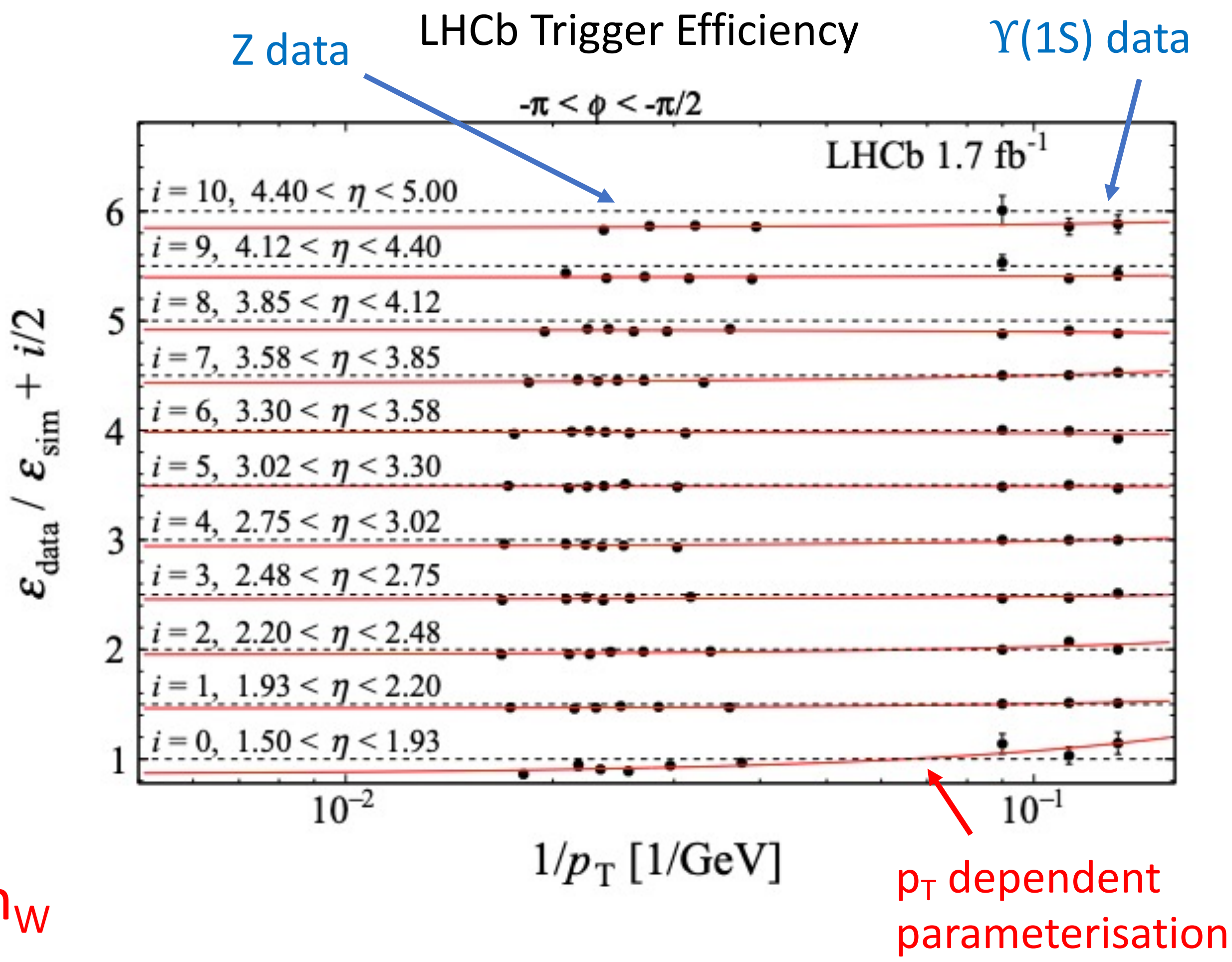
  - Contributes 7 MeV uncertainty on m_W

Modelling the Selection

- Consider two main components of selection inefficiencies:
  1. Muon reconstruction and detection requirements

     Simulated events corrected for data/simulation differences using event-by-event weights.

     Uncertainties propagated include statistical uncertainty on parameterisation, variations in binning, selection, and form of parameterisation.
     Contributes 6 MeV uncertainty on m_W



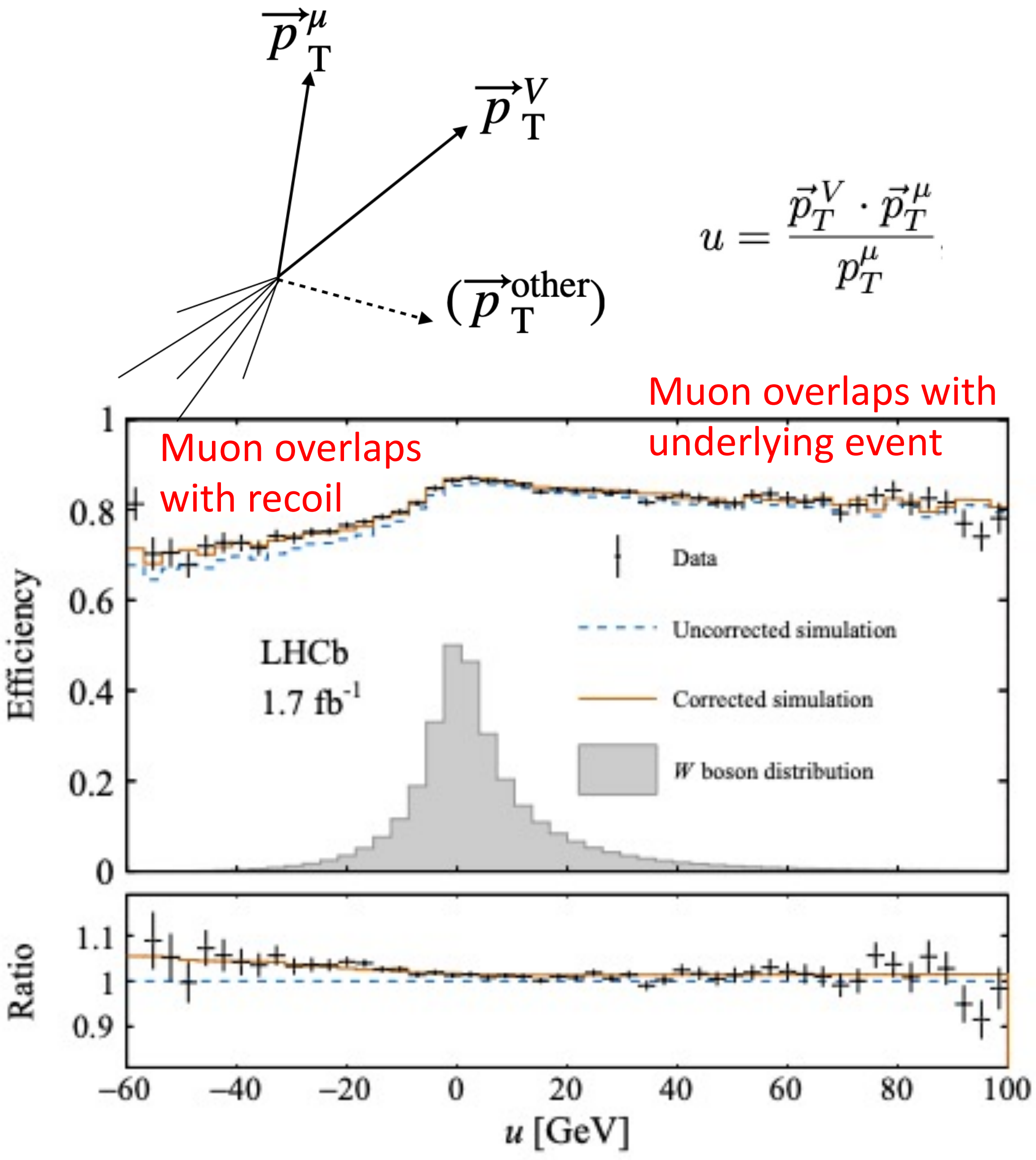
Modelling the Selection

- Consider two main components of selection inefficiencies:
   2. <u>Isolation efficiency modelling</u>

      Efficiency strongly dependent on muon direction. Determine corrections to modelling using Z boson simulation.

      Uncertainties include: Statistical uncertainty on corrections, binning scheme used for corrections, additional method details.
      Contributes 4 MeV uncertainty on m_W

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



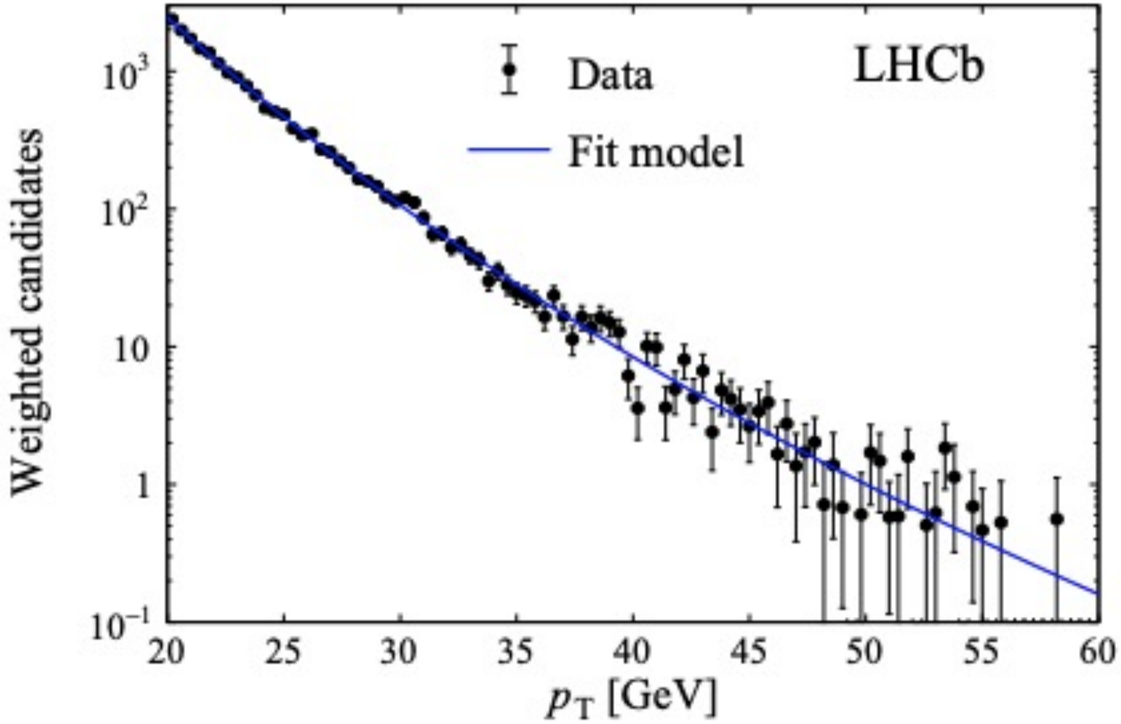
Modelling Backgrounds

- Different backgrounds considered:
  - Hadronic decay-in-flight

    Parametric model fit to hadron sample in LHCb data, and then weighted for decay probability.

    p_T shape and charge asymmetry are fixed using data, but background fraction left free in W mass fit.

    Contributes 2 MeV uncertainty on m_W



Modelling Backgrounds

- Different backgrounds considered:
  - Z boson decays (with only one muon identified); $W \to \tau\nu$ decays
    Modelled using the same simulation as is used for the W boson signal.
    Rates normalised to $Z \to \mu\mu$ events (both muons identified) and W $\to \mu\nu$ events respectively.
  - Heavy Flavour decays and other rare backgrounds
    HF contribution factor 10 lower in rate than the hadronic background.
    Modelled using dedicated simulation.
- Systematic variations considered include rate of these backgrounds relative to the $Z \to \mu\mu$ process, and knowledge of branching fractions. Impact on the W boson mass from these variations is 1 MeV and smaller.

Modelling Boson Production and Decay

- Vector boson production and decay can be modelled (at Born level) as:

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

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

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

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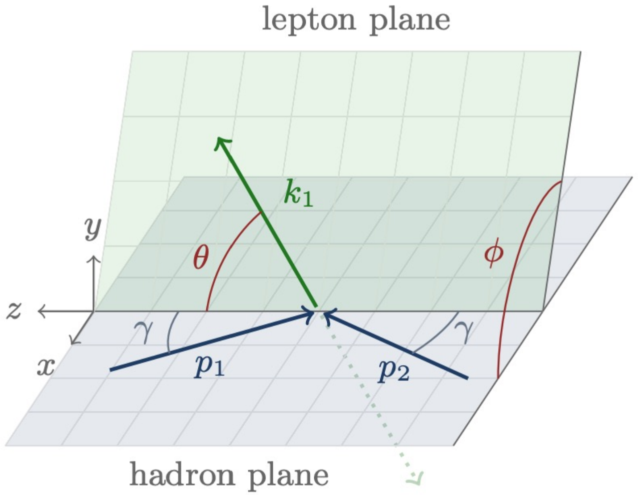
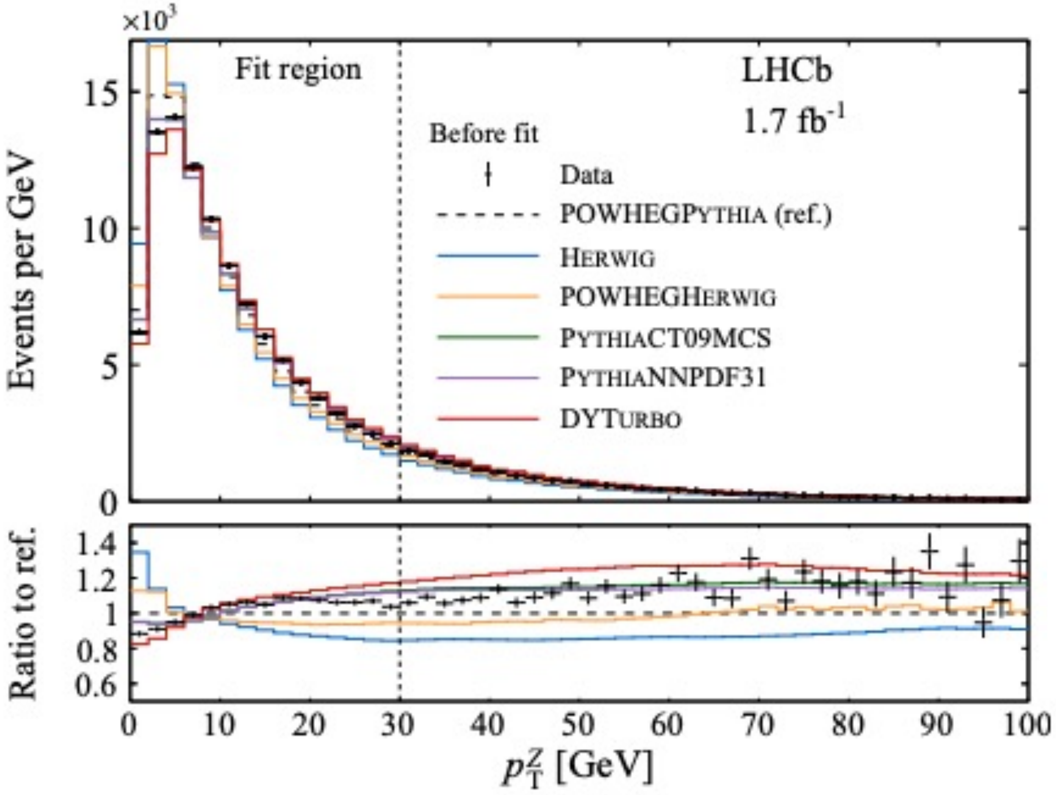


- Accurate modelling of the W boson p_T and the angular coefficients both crucial to the W mass measurement.

Modelling Boson p_T

- Tuning and validation of different approaches using Z p_T data



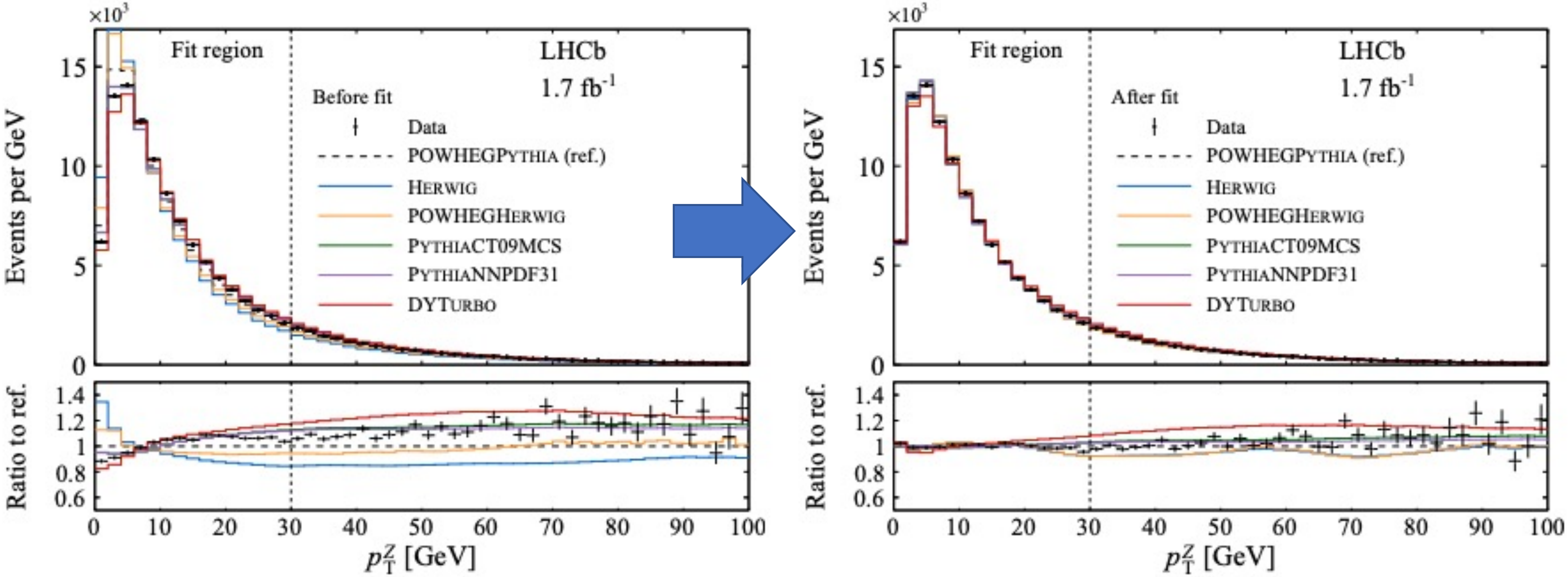
Various different programs compared to LHCb data (using default settings).

Best description at low p_T comes from DYTurbo.

What happens if we tune the value of α_s used along with non perturbative parameters (eg intrinsic k_T carried by initial state partons)?

Modelling Boson p_T

- Tuning and validation of different approaches using Z p_T data



Best description of Z boson p_T following tuning is from POWHEG-BOX interfaced with Pythia8 – this is our central model for the analysis.

Modelling Boson p_T

- Variations in intrinsic k_T and α_s already demonstrated to have a different impact on the muon p_T distribution to variations in the W mass.

- For the W boson mass fit, we float these QCD parameters.

  - Can view these as 'nuisance parameters' that we float to absorb QCD effects.

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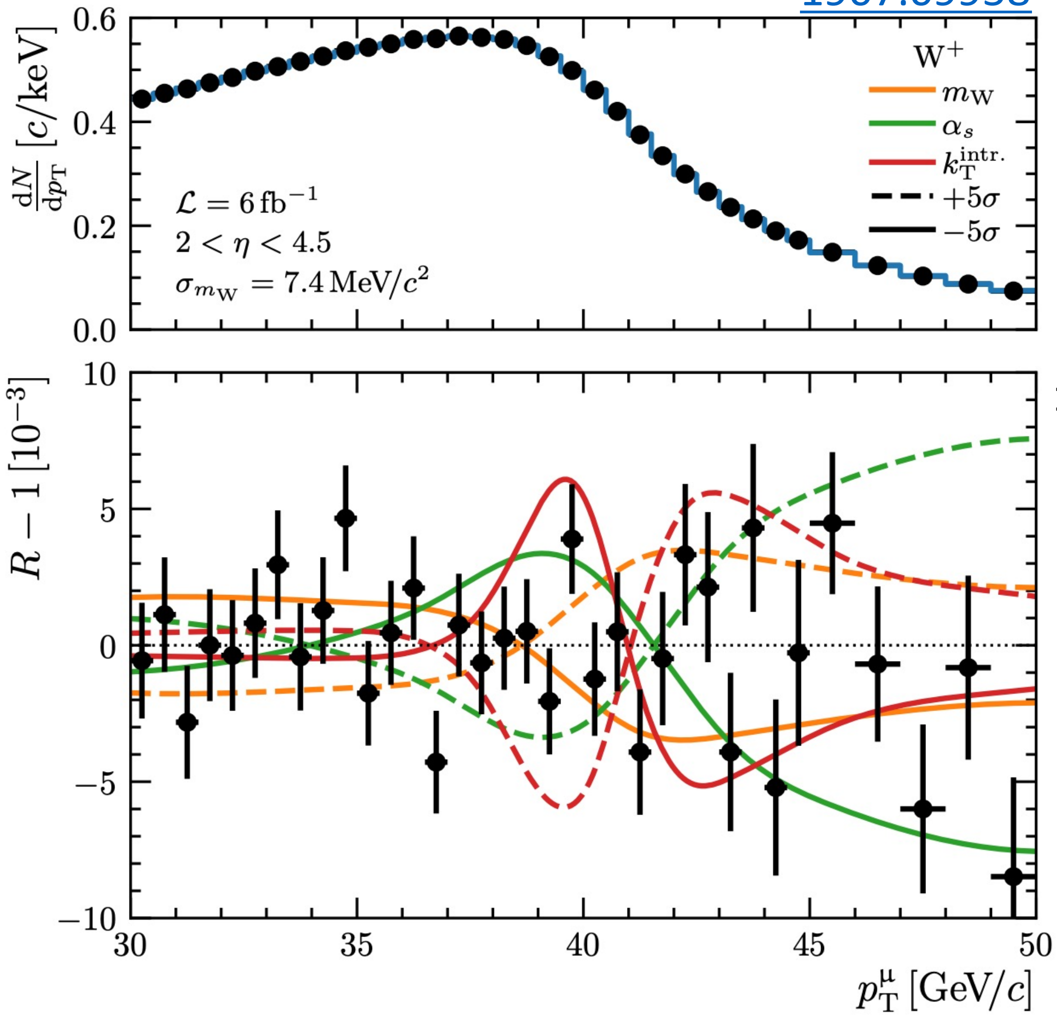
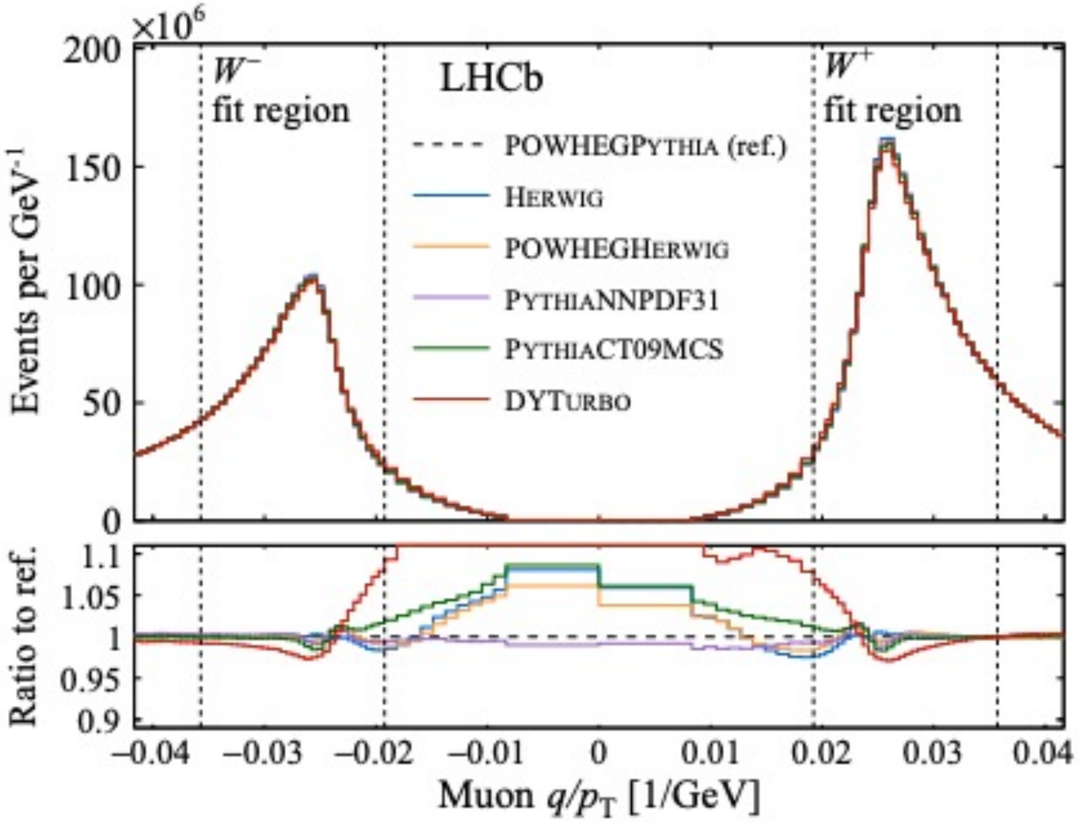
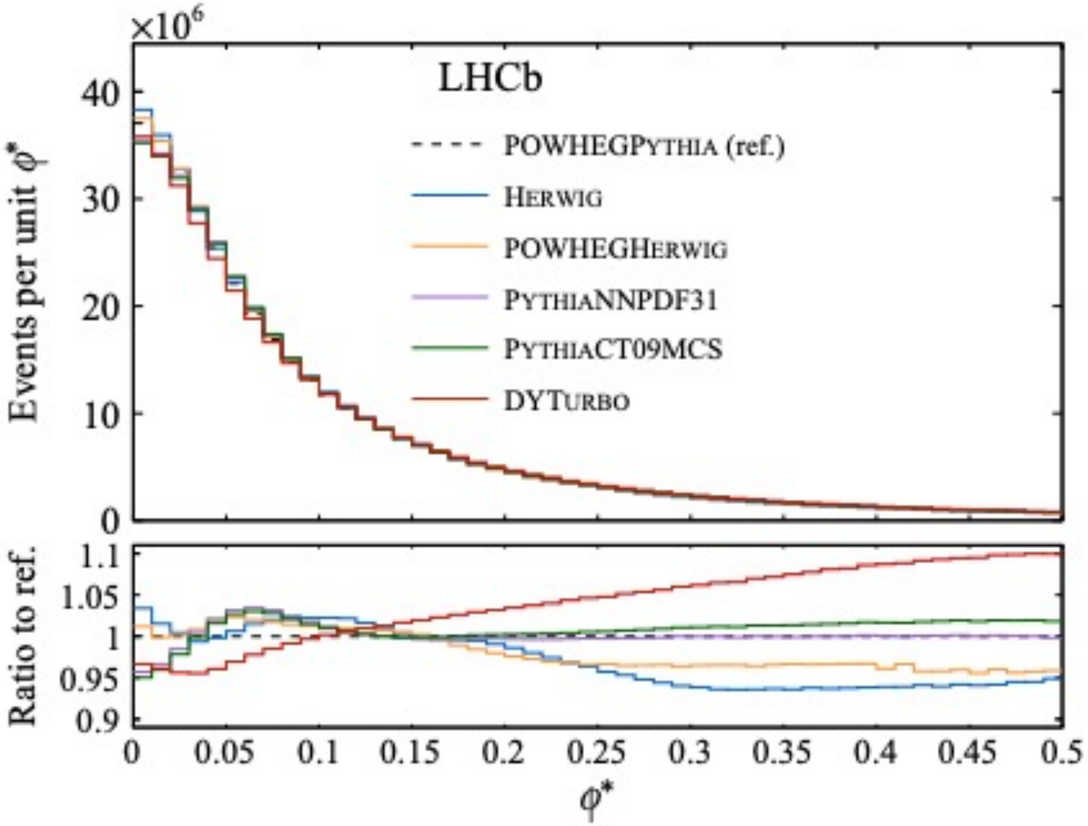


$\pm5\sigma$ variations
m_W
α_s
$k_T^{intr.}$

Modelling Boson p_T – Data Challenges

- We test how well our default model performs by fitting pseudodata generated using other models.





Modelling Boson p_T – Data Challenges

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

Maximum bias seen in m_W is about 10 MeV – rest of the differences in the QCD modelling are absorbed into the floating parameters in our model.

Modelling Boson p_T

- We consider different programs for modelling W boson production:
  - POWHEG+Pythia (NLO+PS) – default model
  - POWHEG+Herwig (NLO+PS)
  - Pythia (LO+PS)
  - Herwig7 (NLO+PS)
  - DYTurbo (NNLO+Resummation)

- Spread in final result from the different models of W production sets the uncertainty from the p_T model.

Modelling the Angular Coefficients

- Angular coefficients also crucial – set the relative amount of W p_T carried by the muon.

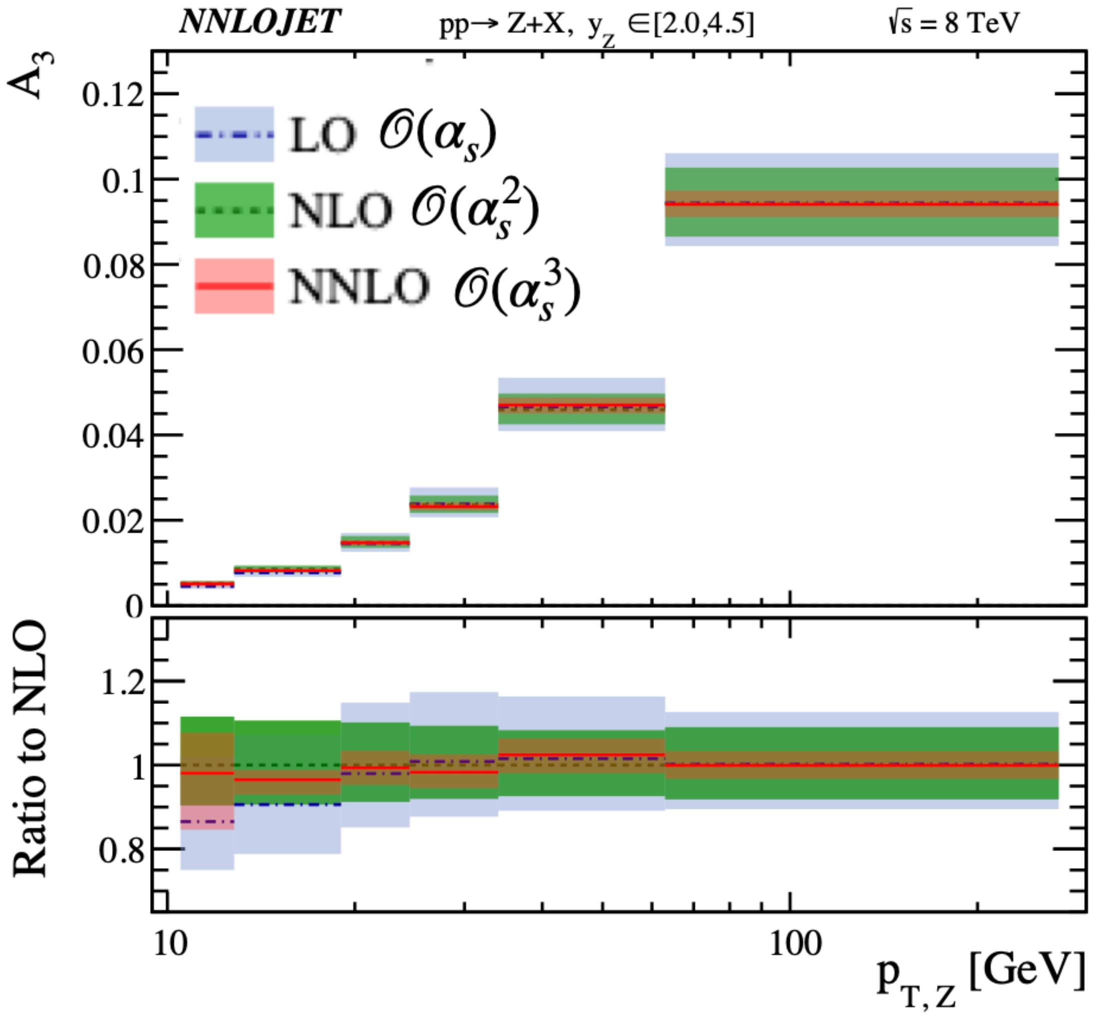
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^W \mathrm{d}y \mathrm{d}M \mathrm{d}\cos\theta \mathrm{d}\phi} = \frac{3}{16\pi} \frac{\mathrm{d}\sigma^{\text{unpol.}}}{\mathrm{d}p_T^V \mathrm{d}y \mathrm{d}M}$$
$$\{(1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
$$+ A_2 \frac{1}{2}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

- Angular coefficients set by various expectation values, e.g. $A_3 = 4\, \langle \sin\theta\ \cos\phi \rangle$

- Our default model uses DYTurbo calculation of these coefficients at $O(\alpha_s^2)$.

Modelling the Angular Coefficients

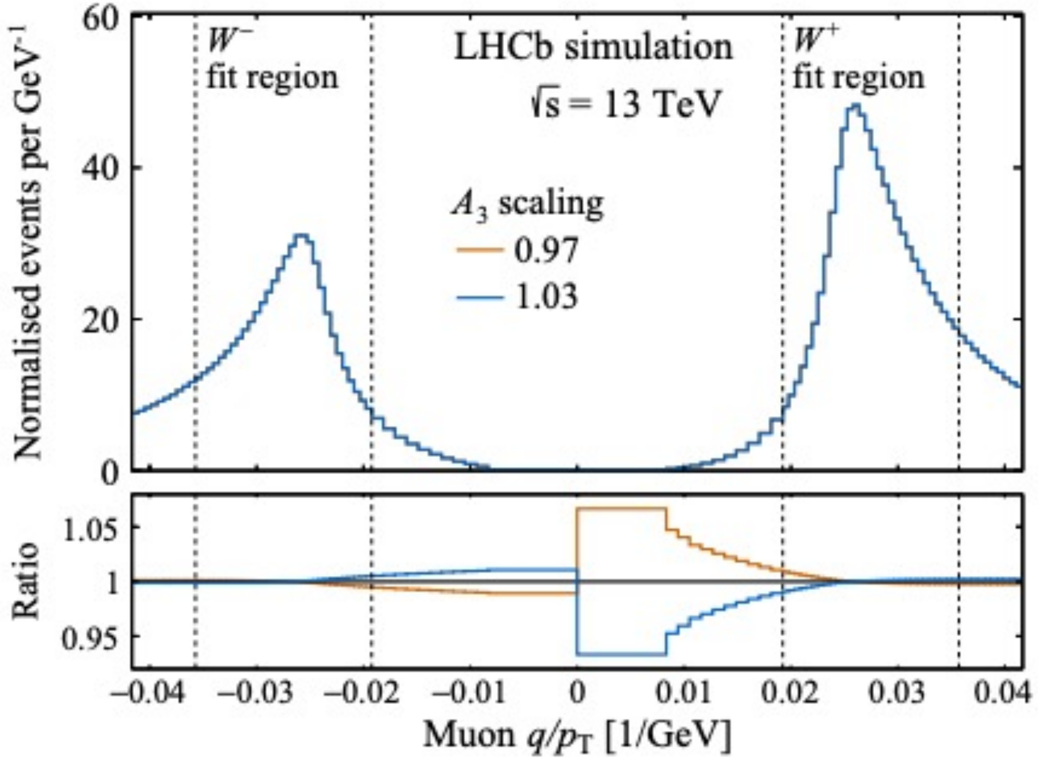
- Angular coefficients determined at fixed order in QCD.
- There is an uncertainty associated with higher order effects and degree to which perturbative calculation has converged by making the calculation at fixed order.
- Evaluate impact of these effects by varying factorisation and renormalisation scales.



Modelling the Angular Coefficients

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

- The angular coefficient A_3 has particular, significant impact on muon p_T in LHCb acceptance.
- Would contribute ~30 MeV uncertainty on W mass (using a conservative approach to scale variation following JHEP 11 (2017) 3).



Modelling the Angular Coefficients

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

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

- For the A_3 coefficient, we therefore float an additional scale factor f_{A3} in our fit for the W boson mass:
  - Scale factor independent of p_T, y, M.
  - We use the data to constrain effects associated with the value of A_3.
  - The scale factor compensates for global changes in A_3 associated with scale variation that otherwise decrease the data/model agreement.

Uncertainty on the W mass from knowledge of angular coefficients is about 10 MeV.

Modelling the Production

- Consider three different global PDF sets
  - NNPDF3.1, CT18, MSHT20
  - None of these PDFs considered LHCb Run 2 data in the fits.

- PDF uncertainties for each set evaluated following prescription of different groups

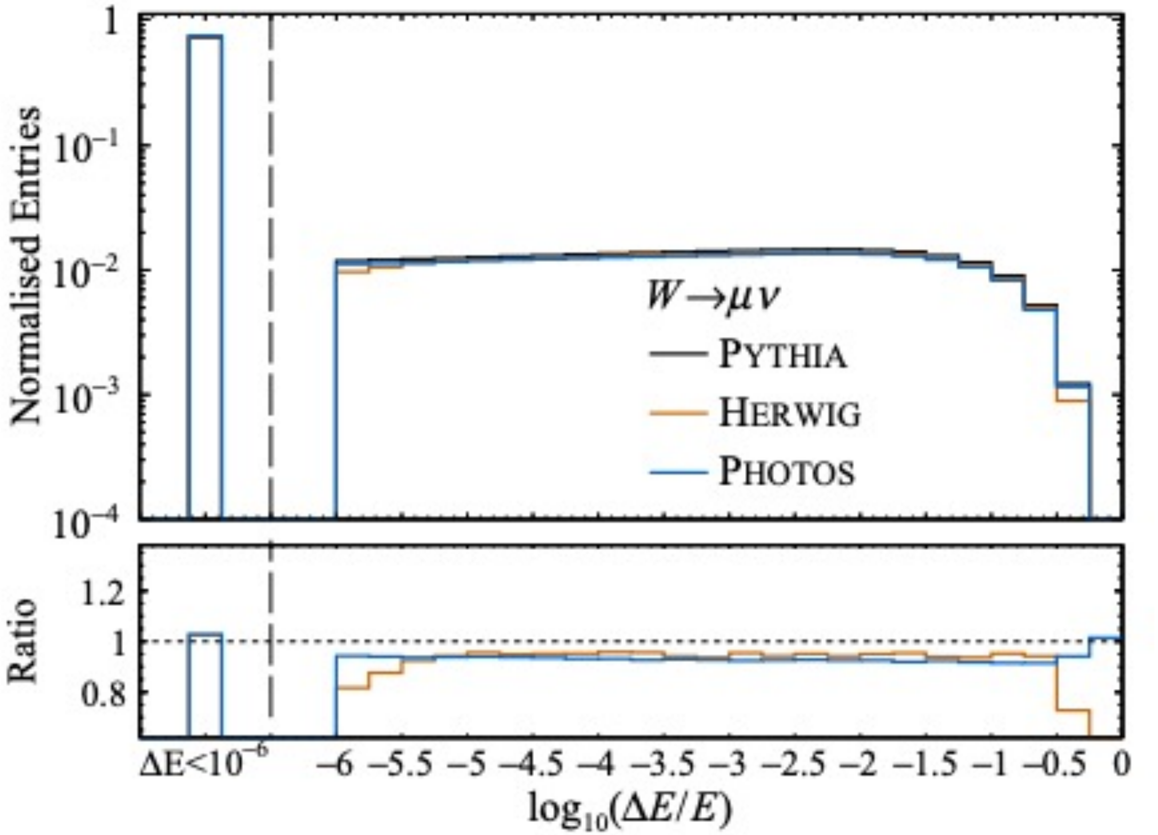
- Central result determined from arithmetic mean of the three different PDFs, uncertainty calculated assuming 100% correlation of the different global sets.

Set	$\sigma_{\mathrm{PDF,base}}$ [MeV]	$\sigma_{\mathrm{PDF},\alpha_s}$ [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

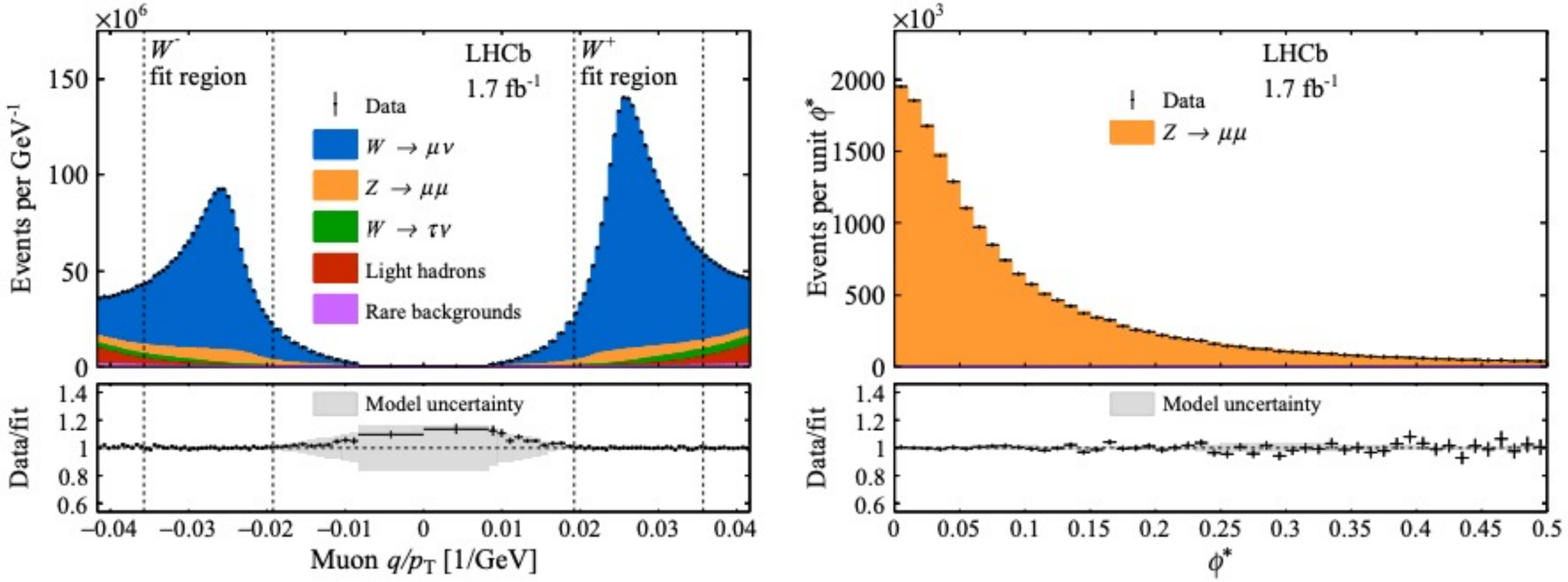
11 MeV envelope of central values from the different PDF sets.

Additional EW Effects

- Final State Radiation modelled using Photos, Pythia8 and Herwig7.
- Data exhibit little preference for one approach; take arithmetic mean of the three as central value, and envelope as uncertainty.
  Contributes 7 MeV to uncertainty on m_W
- Additional EW corrections studied using POWHEG EW – includes additional EW effects in the Hard Process Calculation.
  - no significant difference observed with these corrections turned on/off: 5 MeV uncertainty assigned.



Fit Result



Statistical uncertainties only

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}	$1.57 \pm 0.14\,\text{GeV}$
A_3 scaling	0.975 ± 0.026

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

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

Systematic Uncertainties

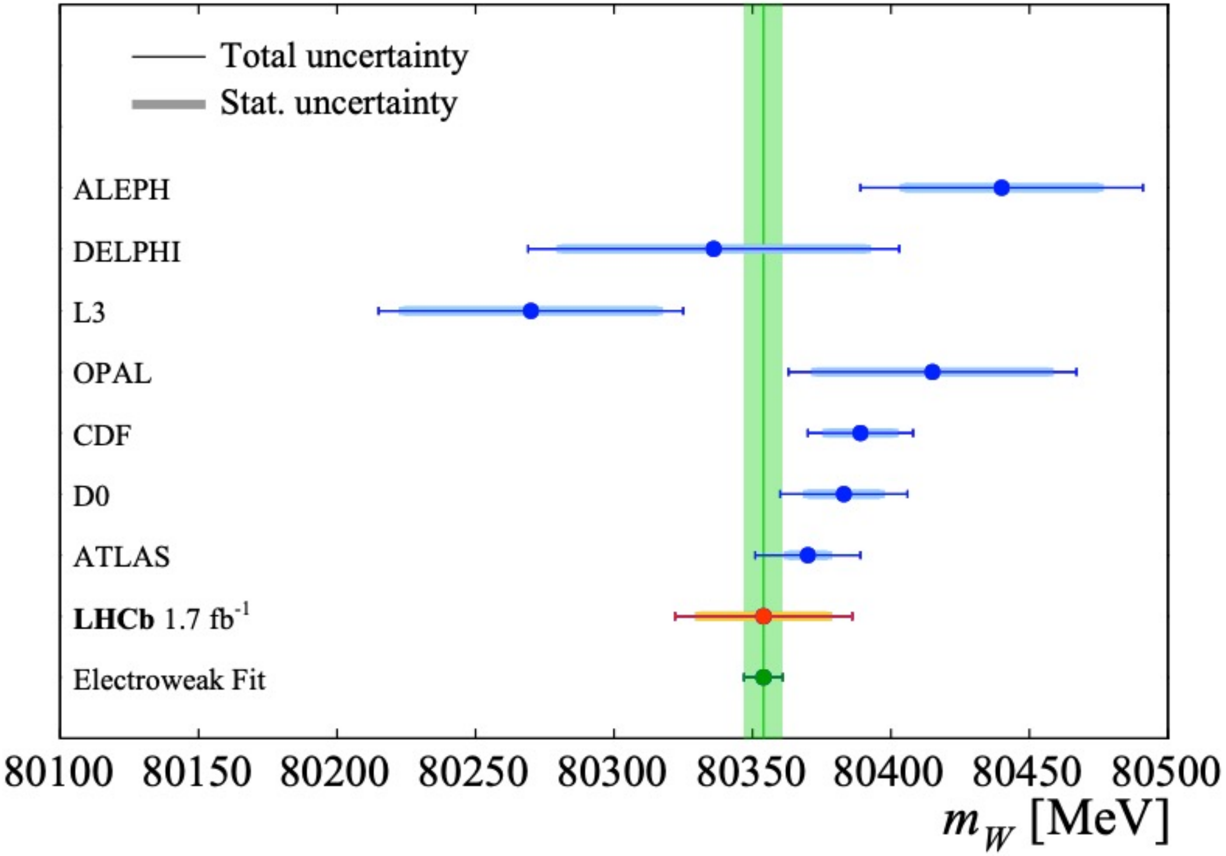
Source	Size [MeV]	
Parton distribution functions	9	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	17	
Transverse momentum model	11	Envelope of 5 different models*
Angular coefficients	10	Uncorrelated scale variation
QED FSR model	7	Envelope of Photos, Pythia8, Herwig7
Additional electroweak corrections	5	Tested with POWHEG ew
Experimental total	10	
Momentum scale and resolution modelling	7	Determined from statistical variations, modelling details, and dependence on external inputs
Muon ID, trigger and tracking efficiency	6	
Isolation efficiency	4	
QCD background	2	
Statistical	23	
Total	32	

*This 11 MeV envelope is consistent with the 10 MeV spread observed in the data challenges.

Crosschecks

1. **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.
2. **Changes in the fit range** give consistent and stable results.
3. **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 induces a shift in the W mass below 1 MeV.
4. **A W-like fit of the Z mass** is consistent for the two muon charges, and is consistent with the PDG value.
5. **Floating the W+ and W- mass difference** yields a mass difference consistent with 0.
6. **Additional tests** including use of NNLO PDFs (instead of NLO) impact the W mass at the 1 MeV level.
7. …

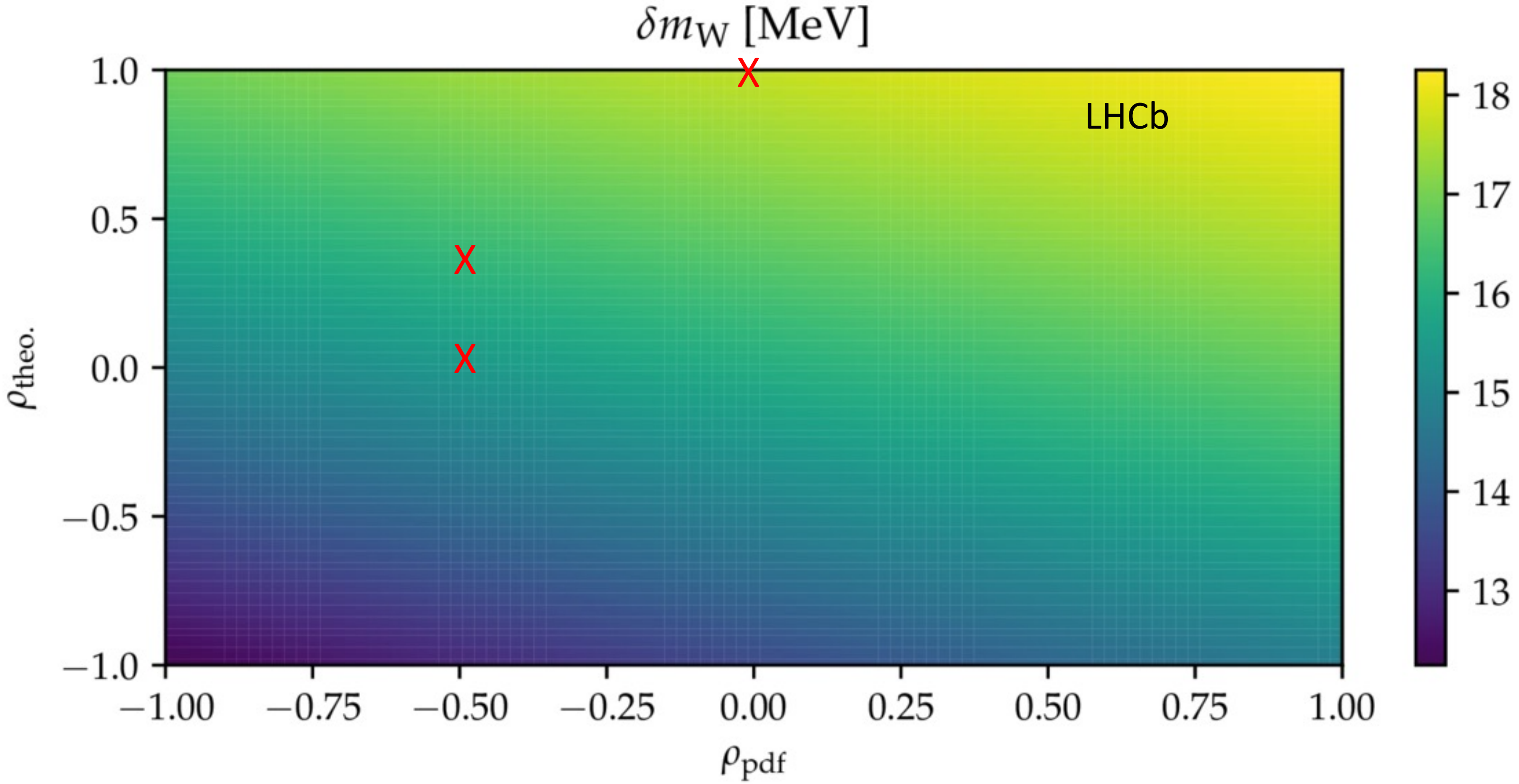
LHCb Result



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

Future Prospects – (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.

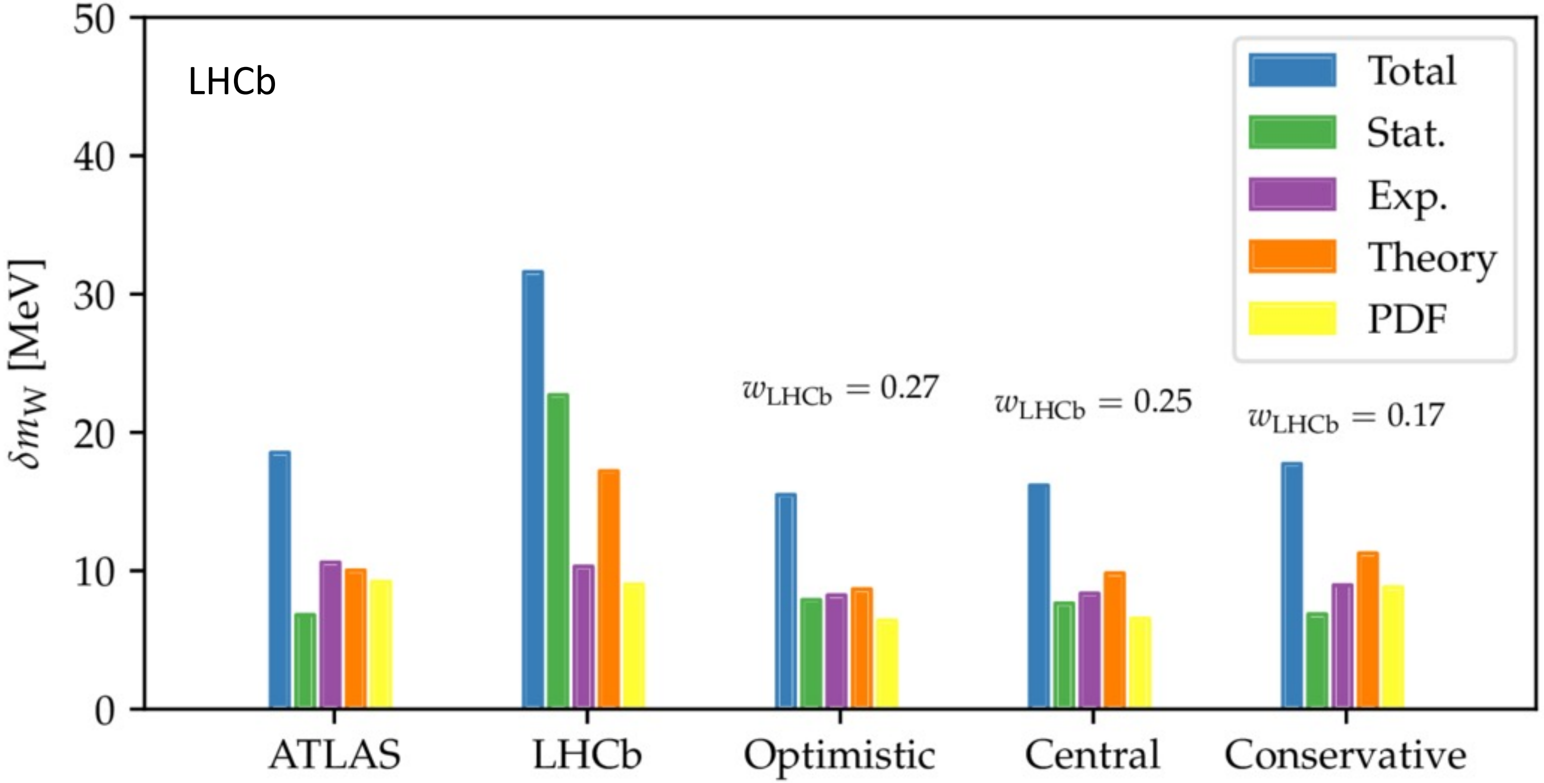


Reminder: we expect a negative PDF correlation between ATLAS and LHCb

EPJC 75 (2015) 601

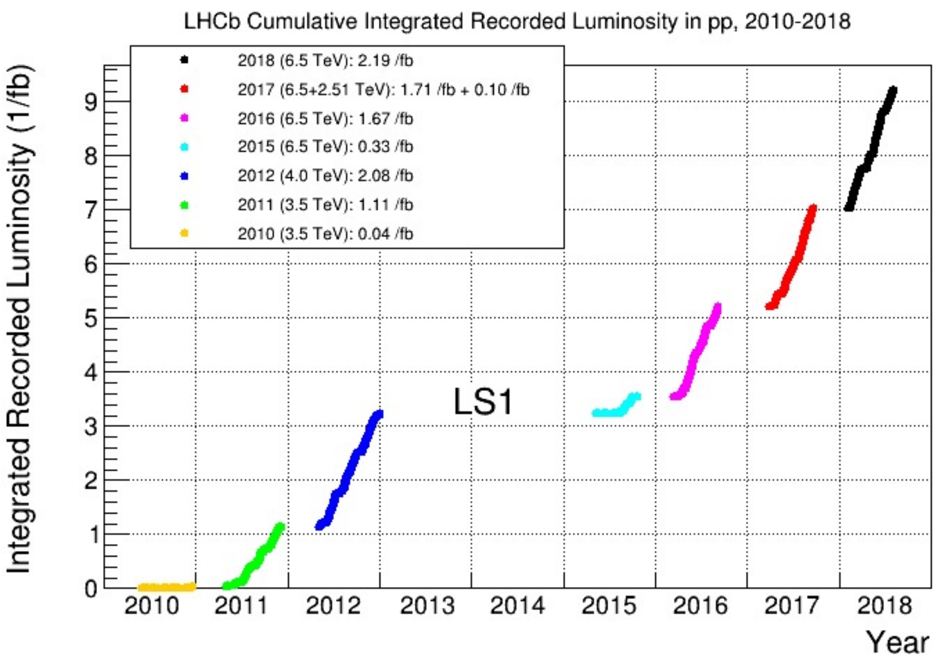
Future Prospects – (Naïve) LHC average

A full combination will 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.



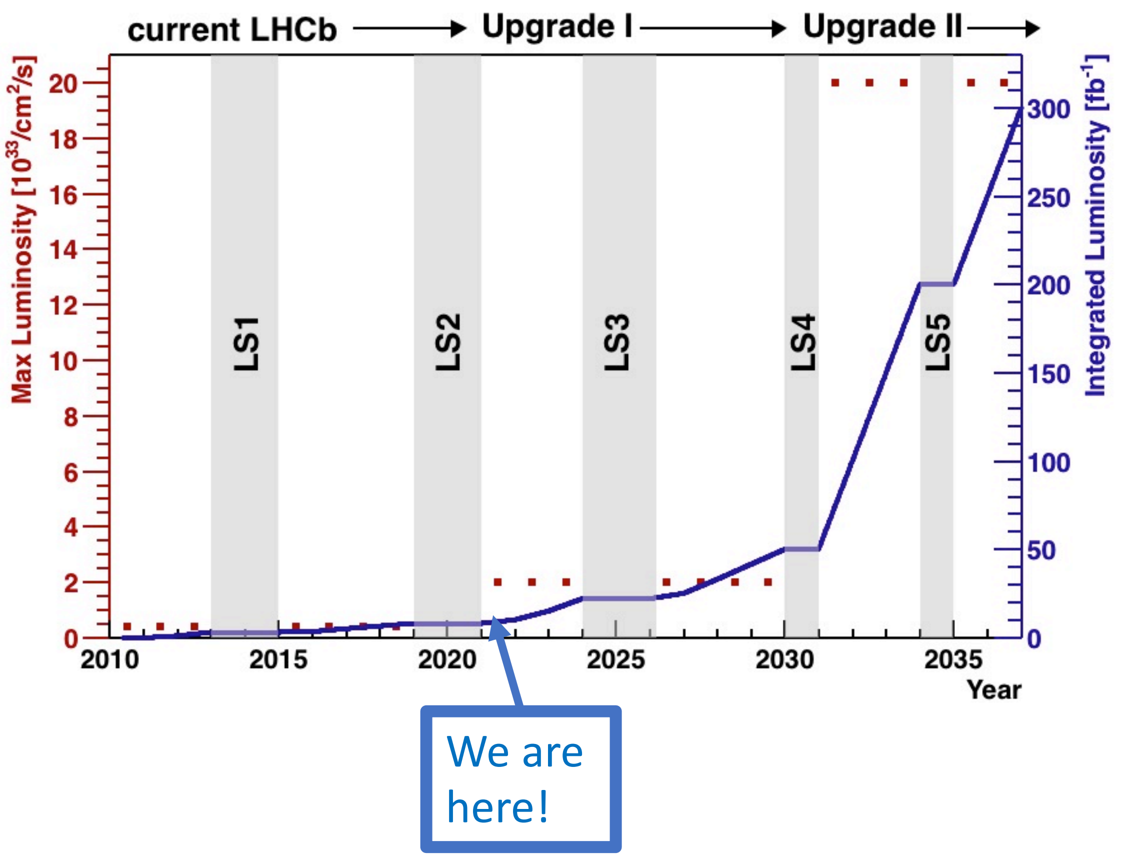
Future Prospects – LHCb

- The overall precision achieved is $\sim$32 MeV.
  - Uses LHCb data collected in 2016, corresponding to roughly 1/3 of the LHCb Run 2 dataset.
- An overall precision $<$ 20 MeV looks achievable with existing LHCb data.
  - Analysis of the full Run 2 dataset is beginning, and 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.



Future Prospects – LHCb

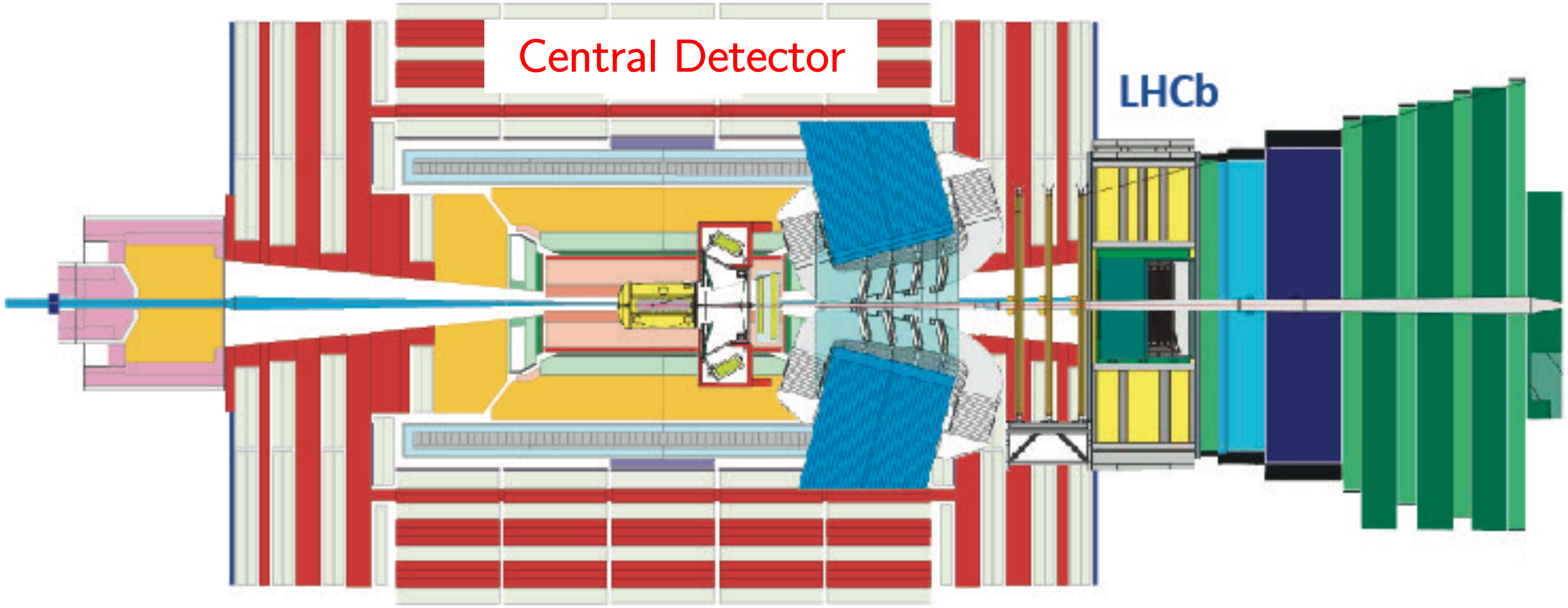
- Far more data to be collected in the future.
- LHC is roughly 10 years into a decades-long programme.
- LHCb first upgrade will allow about 50 fb^{-1} of data, still at (relatively) low pileup, with 300 fb^{-1} available following the proposed second upgrade.
  - In near future – using Run 3 data – we will target 10 - 15 MeV precision.
  - Plenty of data to constrain experimental and theoretical systematics!



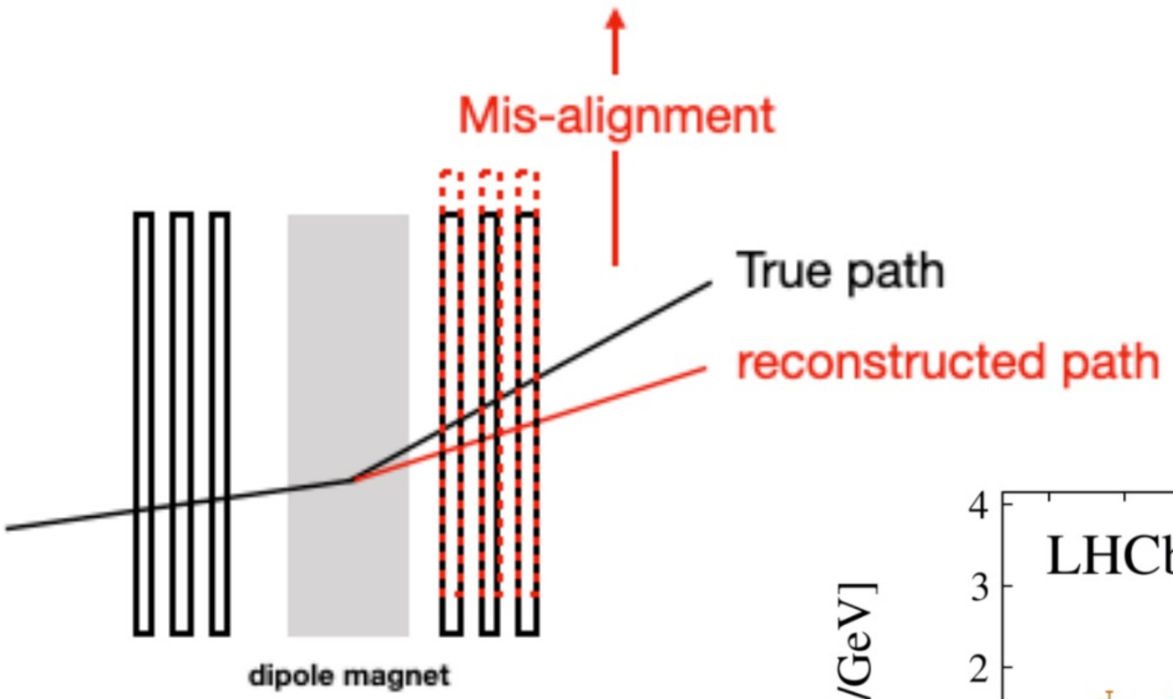
Summary

- W mass measurement one of the most challenging and rewarding high precision measurements in the field.
- First measurement of the W boson mass at LHCb achieves a precision of ~32 MeV, using roughly 1/3 of the Run 2 dataset.
- An overall precision of ~20 MeV looks achievable with existing LHCb data from Run 2, and plan to target 10 - 15 MeV precision using Run 3 data.
- Measurement expected to provide significant impact on a LHC-wide average due to potential anti-correlation of PDF uncertainties, and reduced correlation of other theory uncertainties.
- Full paper available at arxiv:2109.01113 and submitted to JHEP.

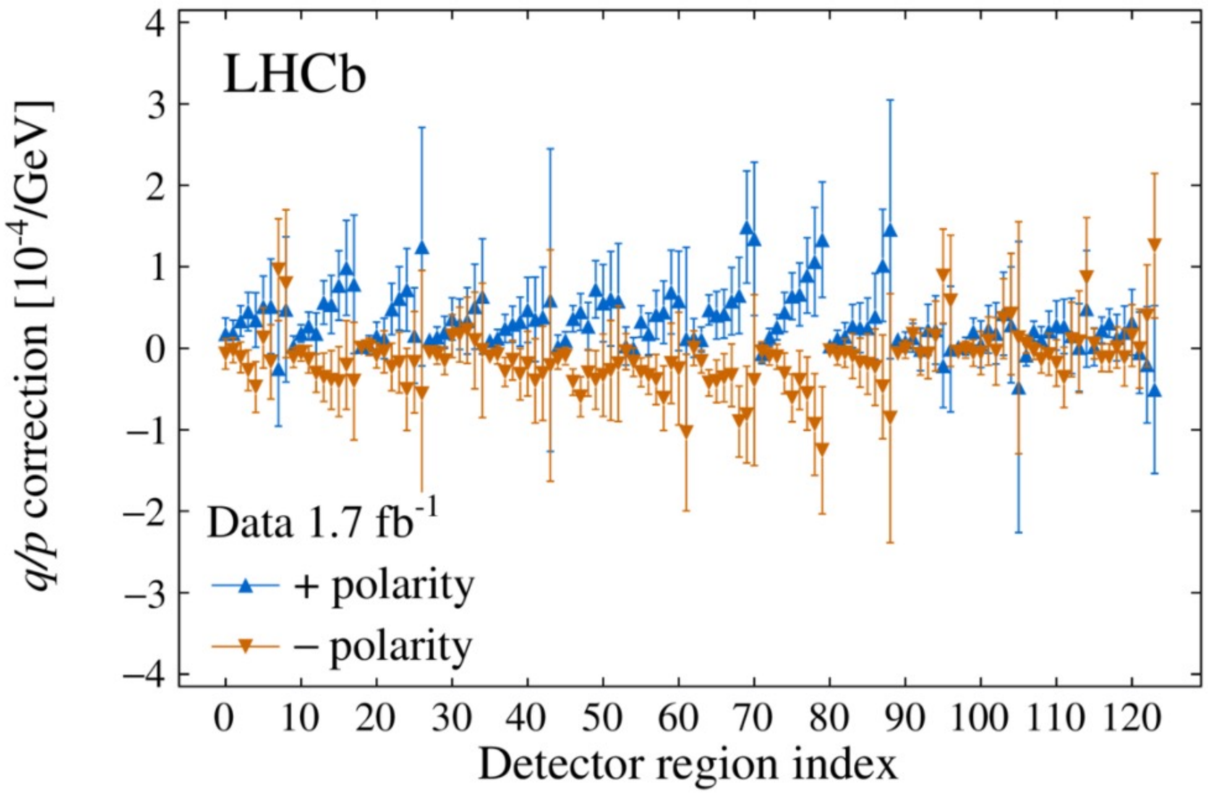
Backup Slides



Precision instrumentation of forward region by LHCb means experiment also operates as a "General Purpose Forward Detector" in addition to performing key flavour physics studies.



Pseudomass corrections

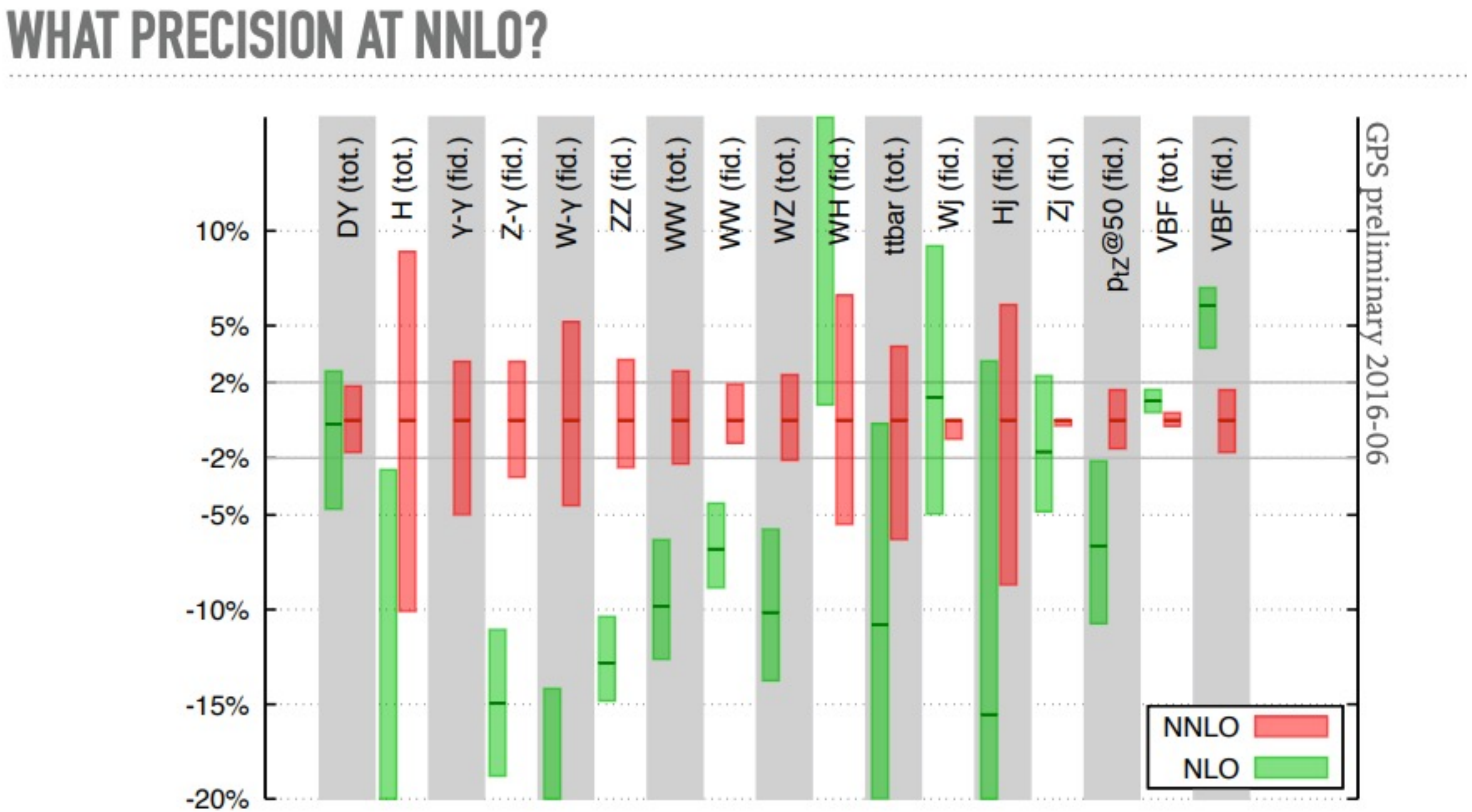


Smearing Model:

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

Parameter	Postfit value
$\alpha\ (\eta < 2.2)$	$(0.58 \pm 0.10) \times 10^{-3}$
$\alpha\ (2.2 < \eta < 4.4)$	$(-0.0054 \pm 0.0025) \times 10^{-3}$
δ	$(-0.48 \pm 0.37) \times 10^{-6}\ \mathrm{GeV}^{-1}$
$\sigma_\delta\ (\eta < 2.2)$	$(17.7 \pm 1.2)\,\mathrm{keV}^{-1}$
$\sigma_\delta\ (2.2 < \eta < 4.4)$	$(14.9 \pm 0.9)\,\mathrm{keV}^{-1}$
σ_{MS}	$(2.015 \pm 0.019) \times 10^{-3}$

Aside: perturbative convergence & scale variation



For many processes NNLO scale band is ~±2%

Though only in 3/17 cases is NNLO (central) within NLO scale band…

Tuning on the Z boson p_T

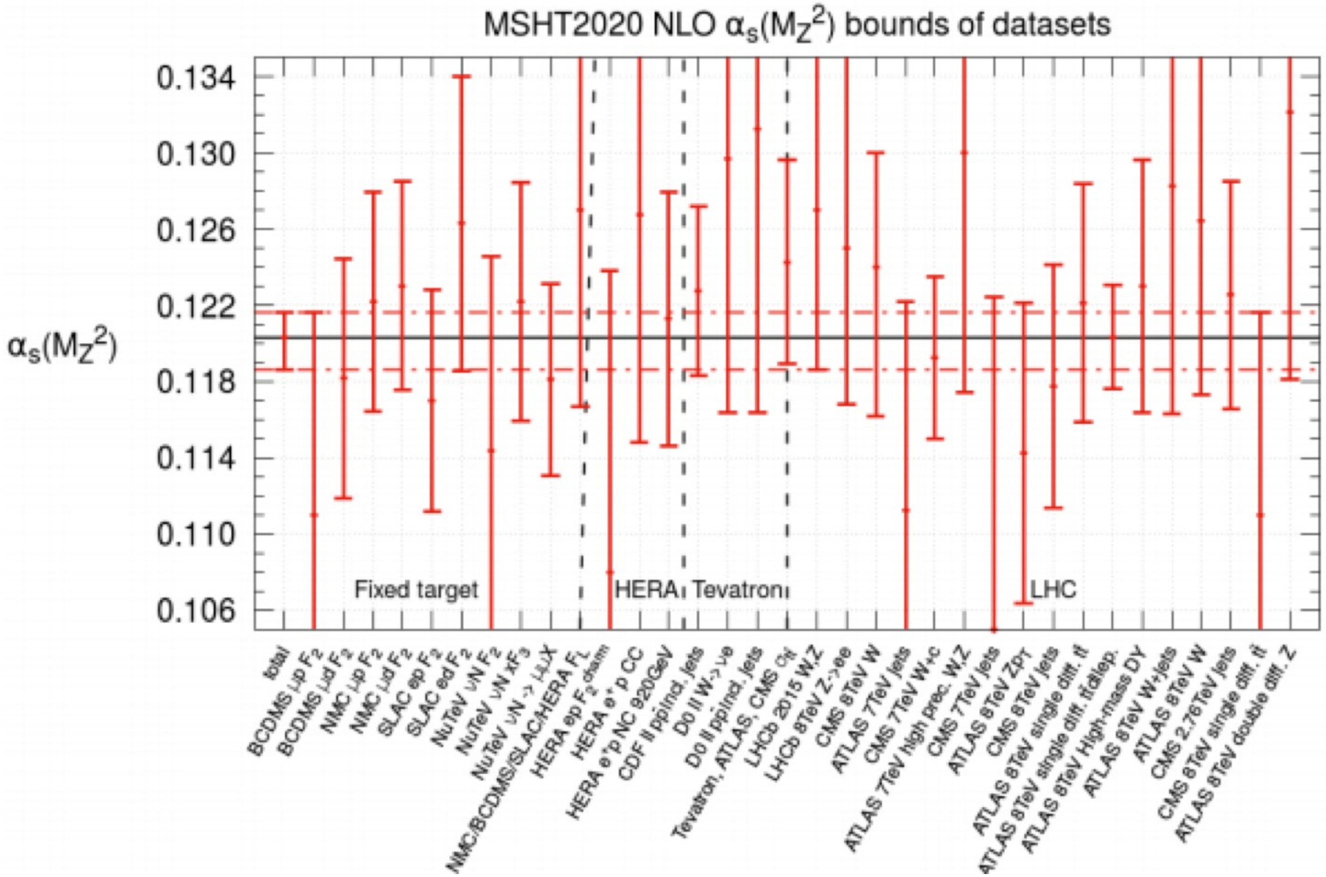
Program	χ^2/ndf	α_s	Non-perturbative parameter
DYTurbo	79.5/13	0.11800	$2.330 \pm 0.028\,\text{GeV}^2$
POWHEGPythia	30.3/12	0.12476 ± 0.00043	1.470 ± 0.130 GeV
POWHEGHerwig	55.6/12	0.13613 ± 0.00007	0.802 ± 0.053 GeV
HerwigNLO	41.8/12	0.13520 ± 0.00019	0.753 ± 0.052 GeV
Pythia 8, CT09MCS	69.0/12	0.12870 ± 0.00044	2.113 ± 0.032 GeV
Pythia 8, NNPDF31	62.1/12	0.12893 ± 0.00044	2.109 ± 0.032 GeV

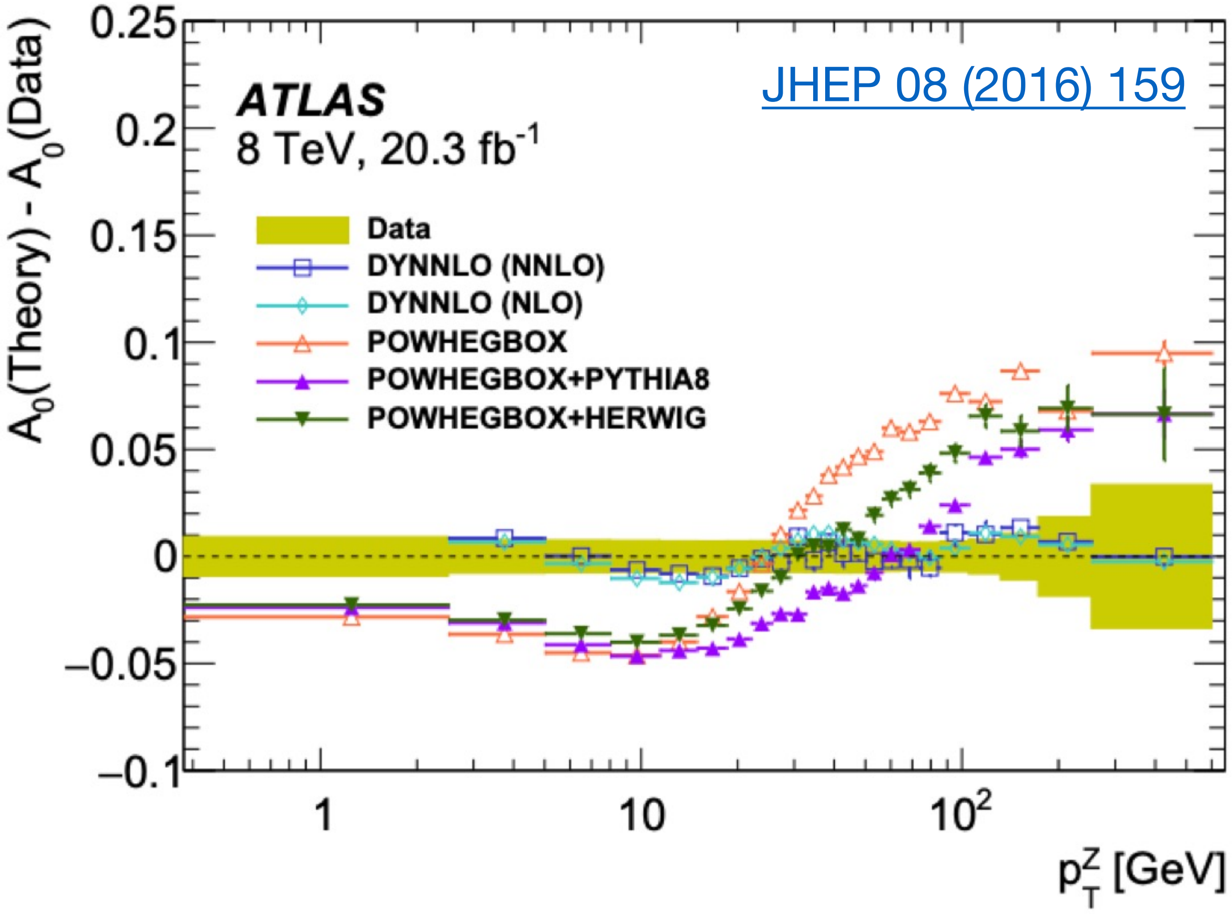
[Submitted on 18 Jun 2021]

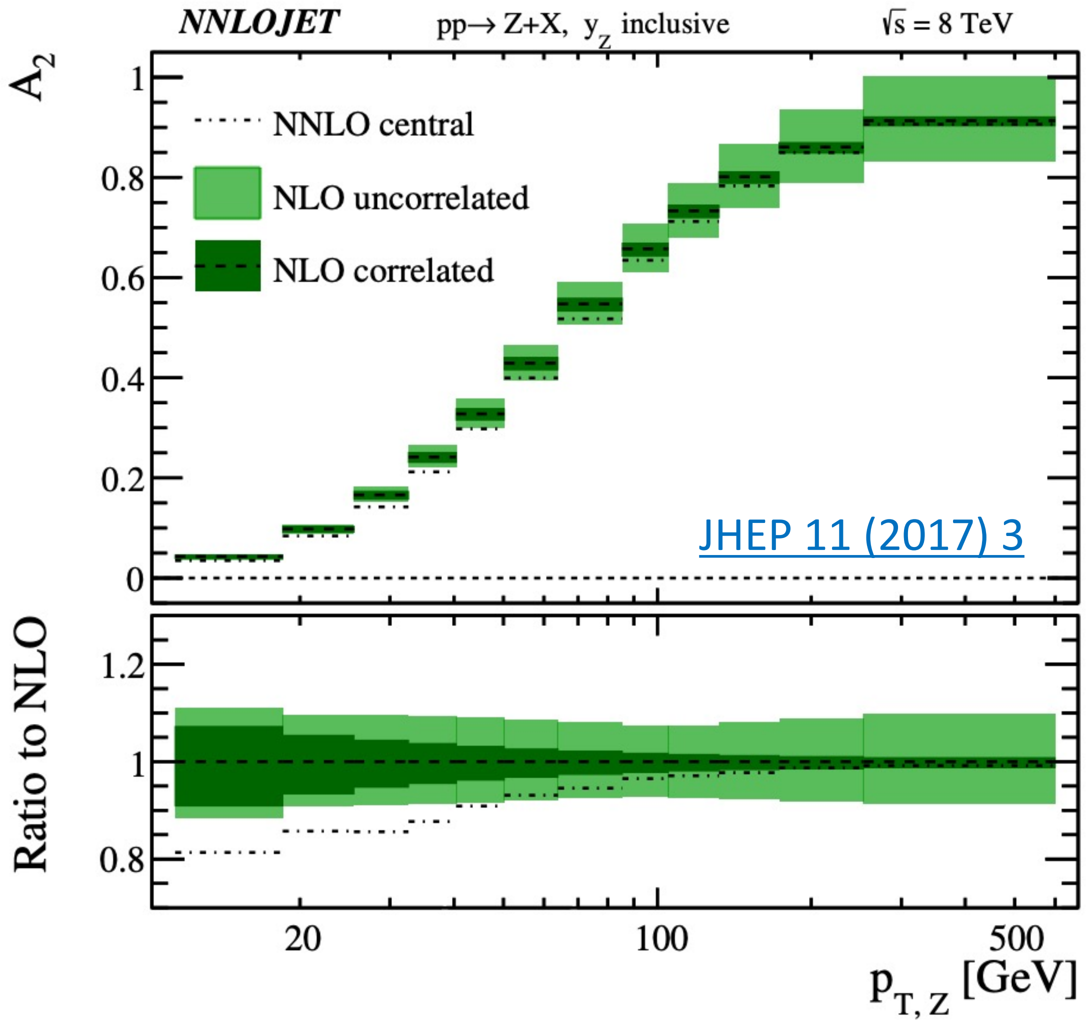
An investigation of the α_S and heavy quark mass dependence in the MSHT20 global PDF analysis

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.




ATLAS
8 TeV, 20.3 fb^{-1}
JHEP 08 (2016) 159
Data
DYNNLO (NNLO)
DYNNLO (NLO)
POWHEGBOX
POWHEGBOX+PYTHIA8
POWHEGBOX+HERWIG
A_0(Theory) - A_0(Data)
p_T^Z [GeV]

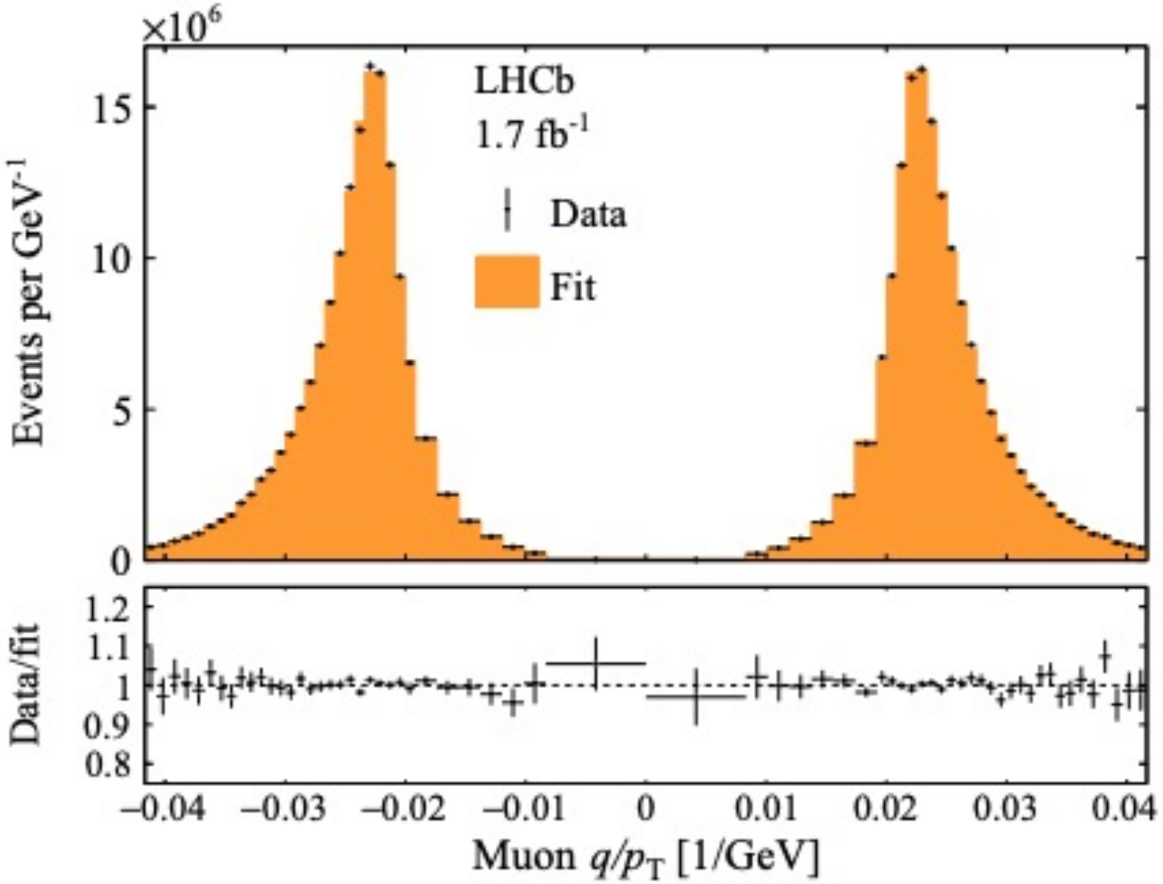

NNLOJET
pp→ Z+X, y_Z inclusive
$\sqrt{s}$ = 8 TeV
A_2
NNLO central
NLO uncorrelated
NLO correlated
JHEP 11 (2017) 3
Ratio to NLO
$p_{T,Z}$ [GeV]

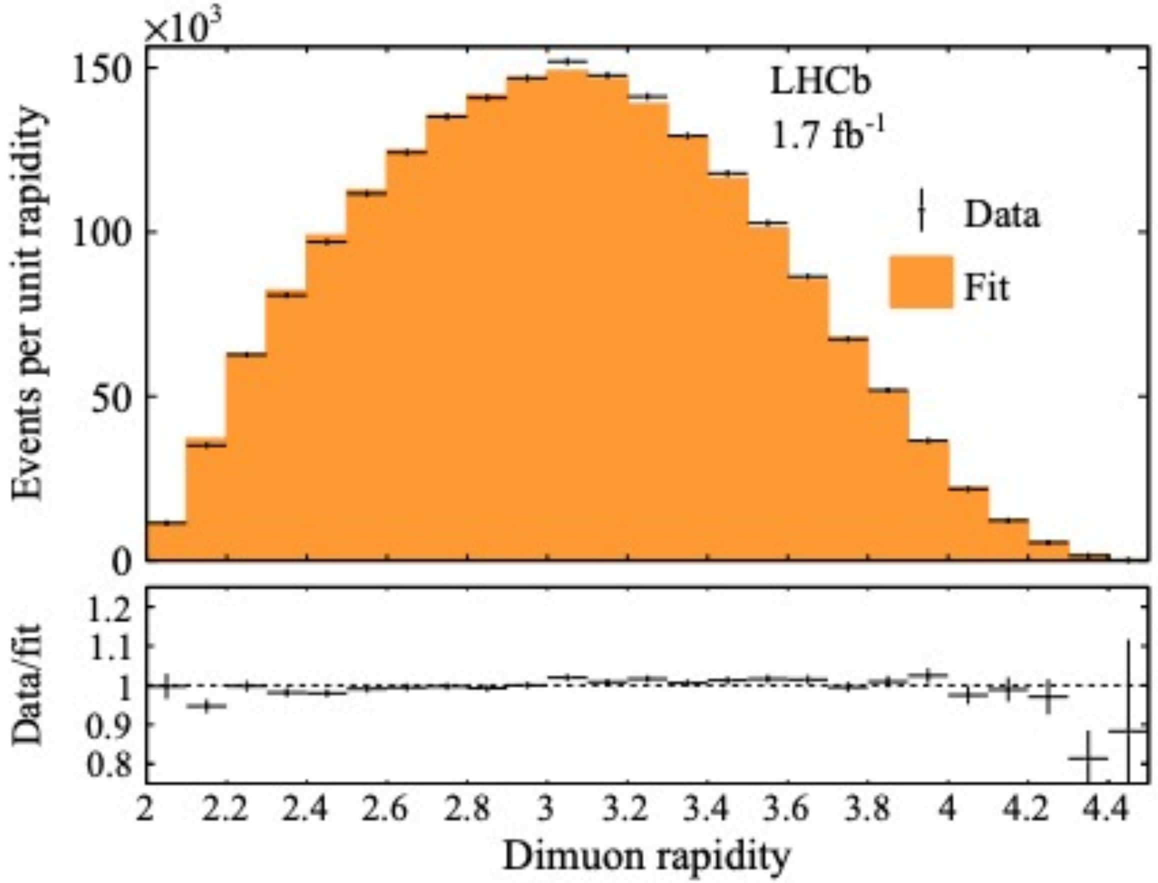
Orthogonal datasets:

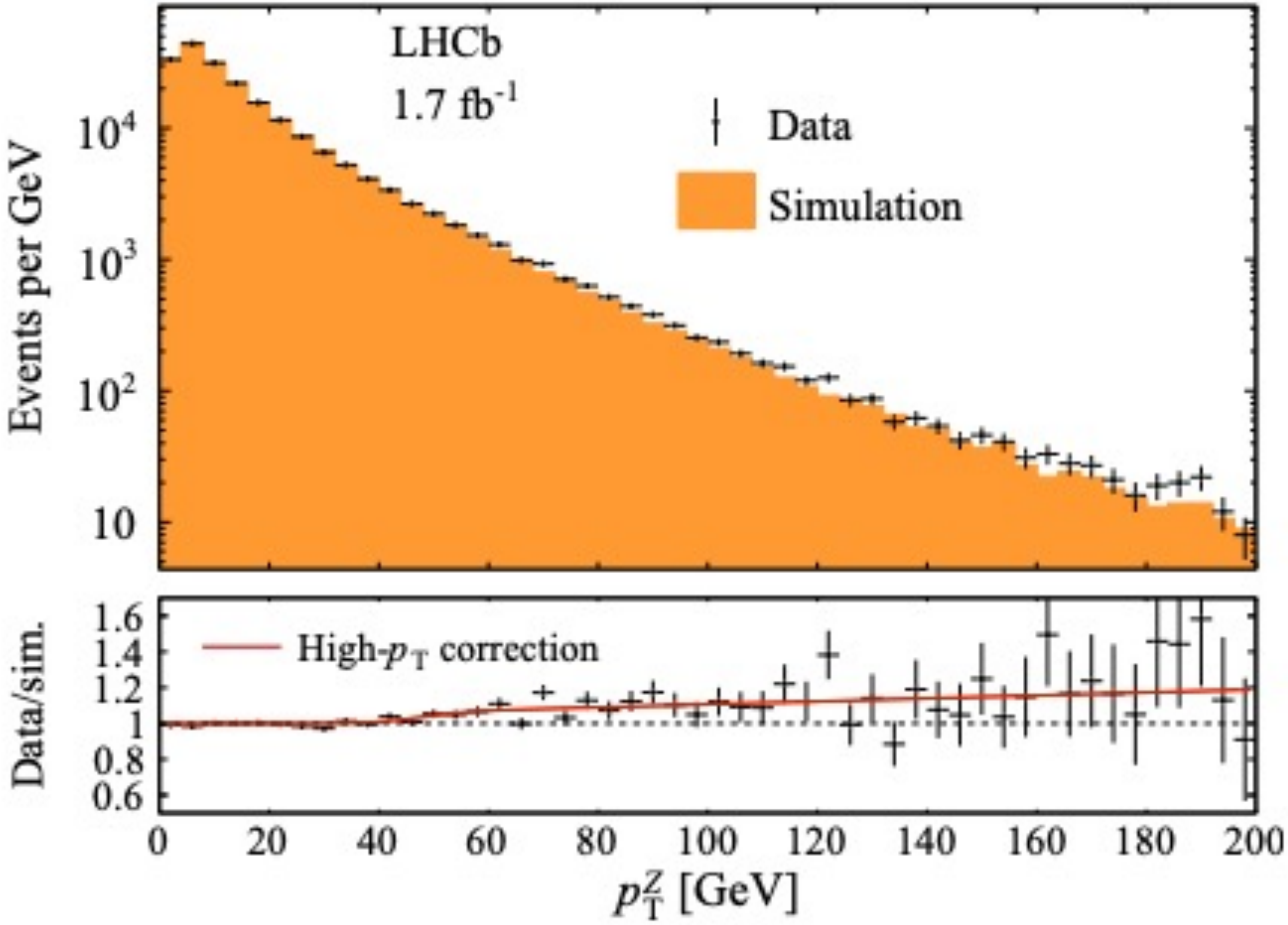
Subset	$\chi^2_{\mathrm{tot}}/\mathrm{ndf}$	δm_W [MeV]
Polarity $= -1$	$92.5/102$	–
Polarity $= +1$	$97.3/102$	-57.5 ± 45.4
$\eta > 3.3$	$115.4/102$	–
$\eta < 3.3$	$85.9/102$	$+56.9 \pm 45.5$
Polarity $\times\, q = +1$	$95.9/102$	–
Polarity $\times\, q = -1$	$98.2/102$	$+16.1 \pm 45.4$
$\lvert\phi\rvert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

Fit model freedom:

Configuration change	$\chi^2_{\mathrm{tot}}/\mathrm{ndf}$	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 $1 \to 2$ $k_{\mathrm{T}}^{\mathrm{intr}}$ parameters	116.1/102	$+13.9$	± 22.4
$1 \to 2$ $k_{\mathrm{T}}^{\mathrm{intr}}$ parameters	104.0/101	$+0.4$	± 22.7
$1 \to 3$ $k_{\mathrm{T}}^{\mathrm{intr}}$ 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



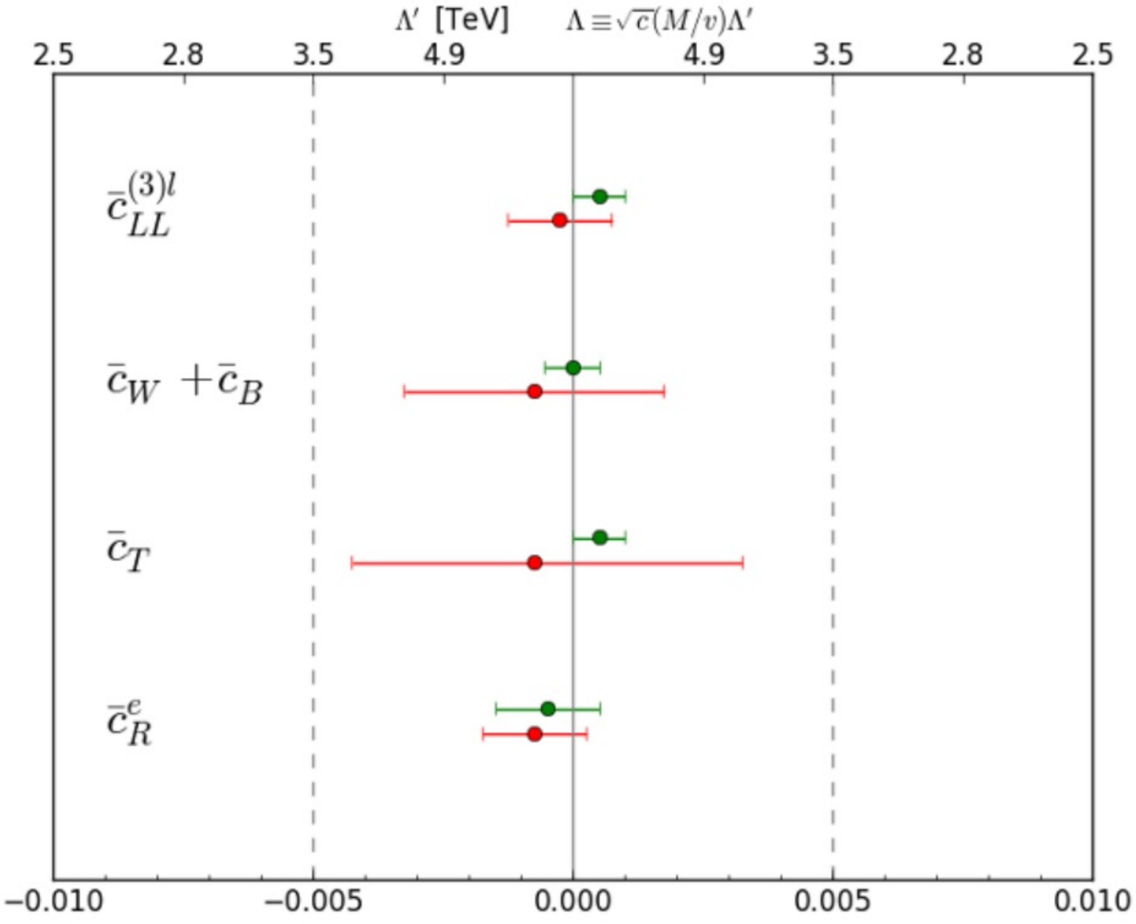
LHCb
1.7 fb-1
Data
Simulation
Events per GeV
High-p_T correction
Data/sim.
p_T^Z [GeV]

ATLAS:

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

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

New Physics Reach



95% CL ranges
For individual coefficients
and for multi-coefficient fits