(HL-)LHC W mass measurements and prospects

EF04 Topical Group Community Meeting
13 August 2021

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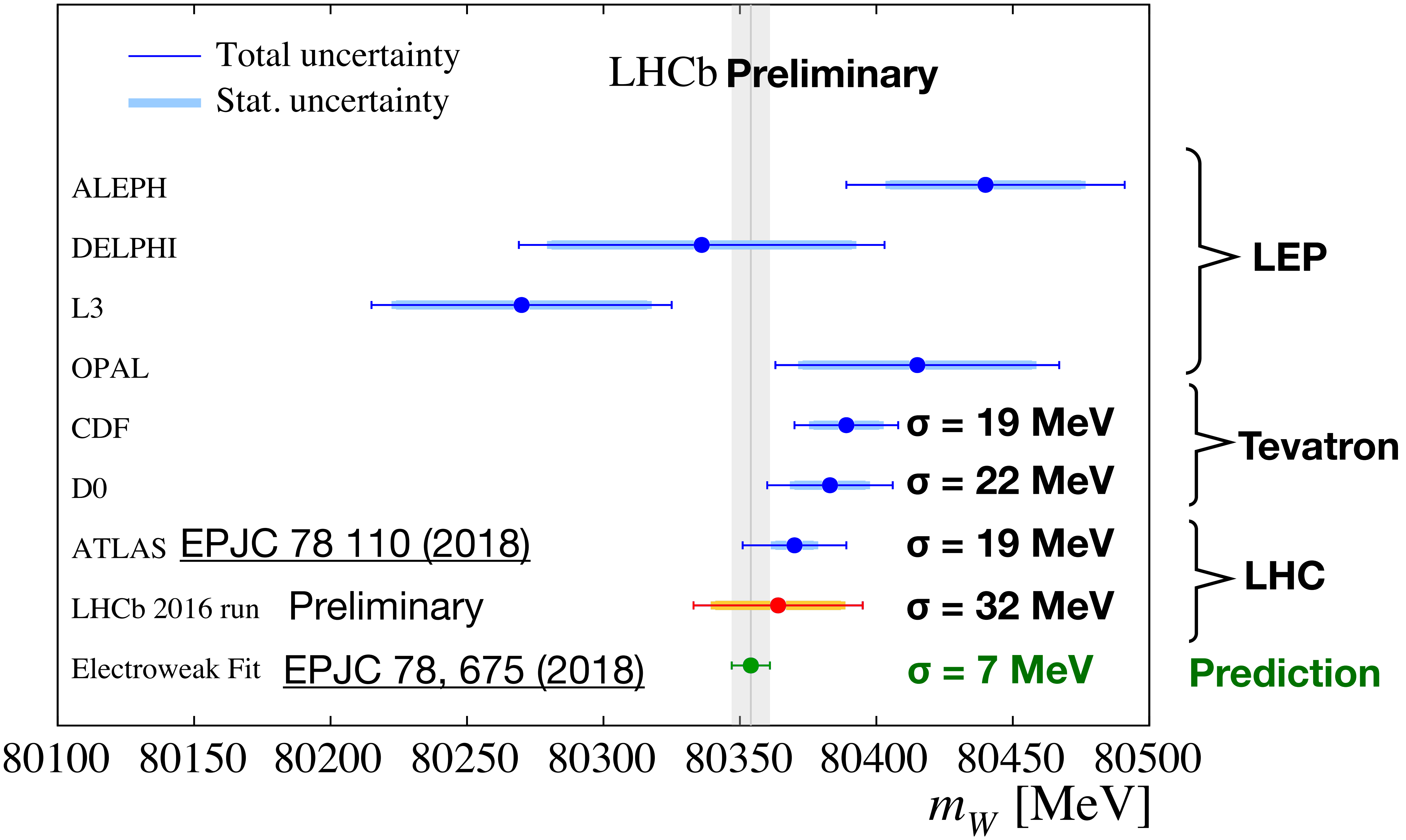
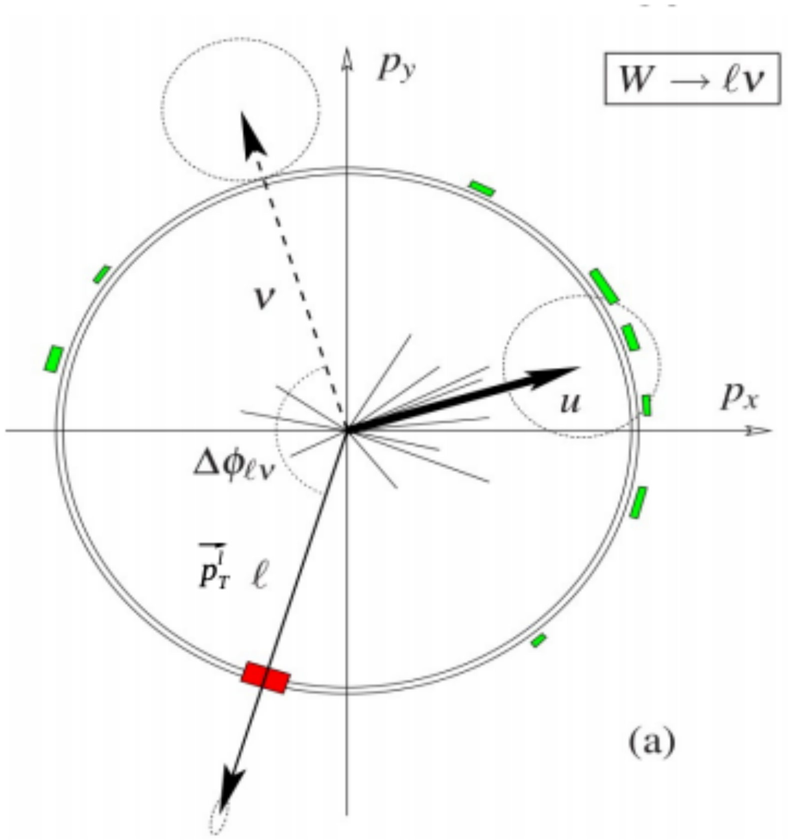
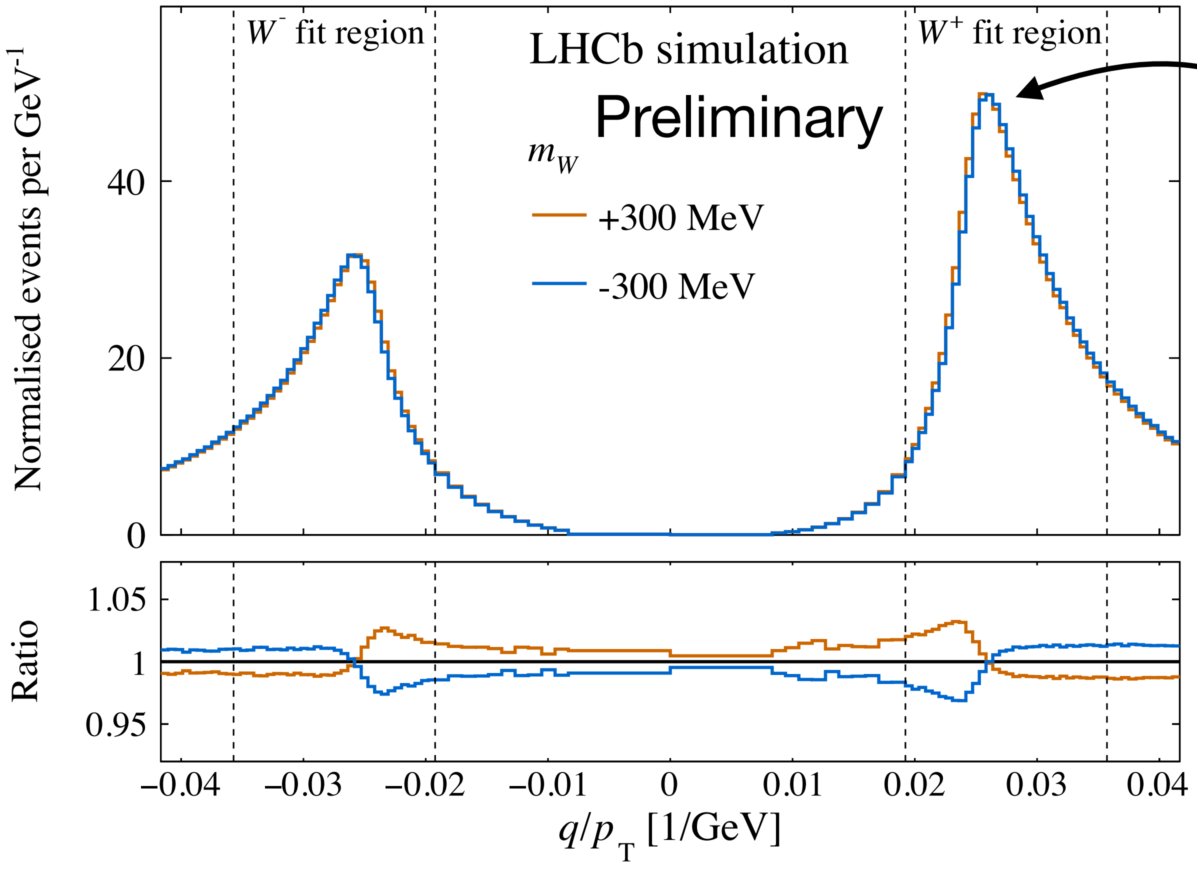
Current state of the art

LHCb-PAPER-2021-024 *in preparation*



Hadron collider m_W-sensitive observables



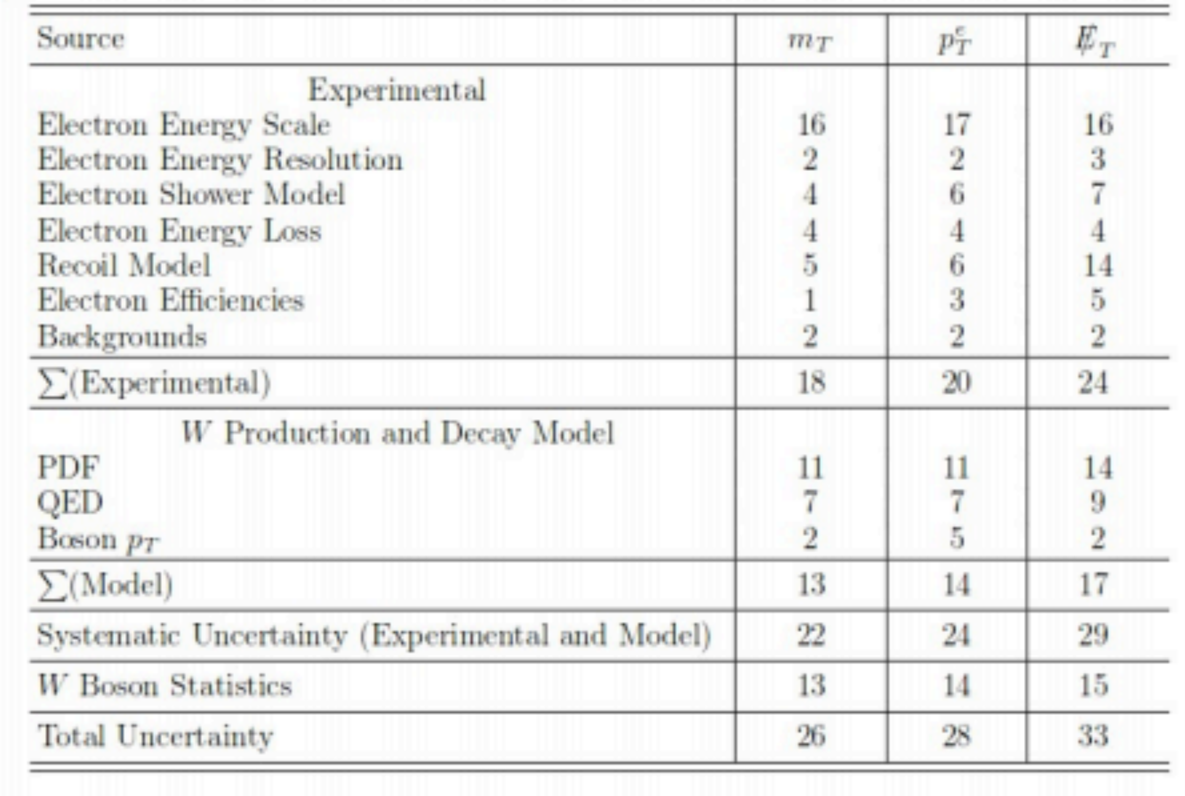


$$q/p_T \approx \frac{2}{m_W}$$

1) Charged lepton p_T	👍👍Good experimental resolution	👎Strongly influenced by boson p_T	Main workhorse at LHC in high pileup data.
2) Transverse mass	👎Limited resolution, which degrades with pileup	👍👍Limited influence from boson p_T	Main variable at the Tevatron. Special low pileup runs at LHC.
3) Missing p_T	👎Poor resolution	👎Strong influence of boson p_T	Less promising for m_W determinations at the LHC

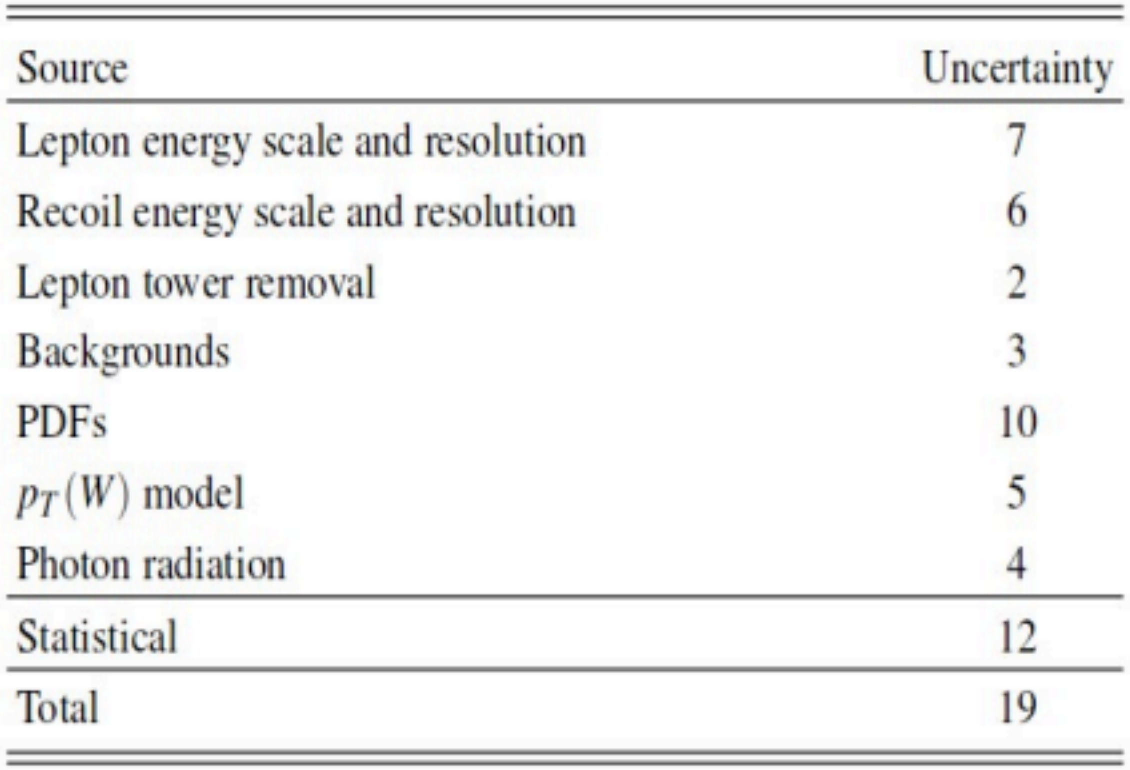
The Tevatron legacy

D0, PRL 108 (2012) 151804



Source	m_T	p_T^e	$\not{E}_T$
Experimental			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Shower Model	4	6	7
Electron Energy Loss	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
$\sum$(Experimental)	18	20	24
W Production and Decay Model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
$\sum$(Model)	13	14	17
Systematic Uncertainty (Experimental and Model)	22	24	29
W Boson Statistics	13	14	15
Total Uncertainty	26	28	33

CDF, 10.1103/PhysRevLett.108.151803



Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

D0	5.3 fb^{-1}	1.7 x 10^6 W →eν	80375 ± 11_{stat} ± 20_{syst} MeV
CDF	2.2 fb^{-1}	1.1 x 10^6 W →[μ,e]ν	80387 ± 12_{stat} ± 15_{syst} MeV

$$\sigma_{stat} \approx \sigma_{calib} \gtrsim \sigma_{theory}$$

From Tevatron to LHC

$\sigma_{\text{stat}} \approx \sigma_{\text{calib}} \gtrsim \sigma_{\text{theory}}$

$\sigma_{\text{theory}} \gg \sigma_{\text{stat}} \approx \sigma_{\text{calib}}$

Billions of W events already recorded by ATLAS/CMS and 10 million recorded by LHCb!

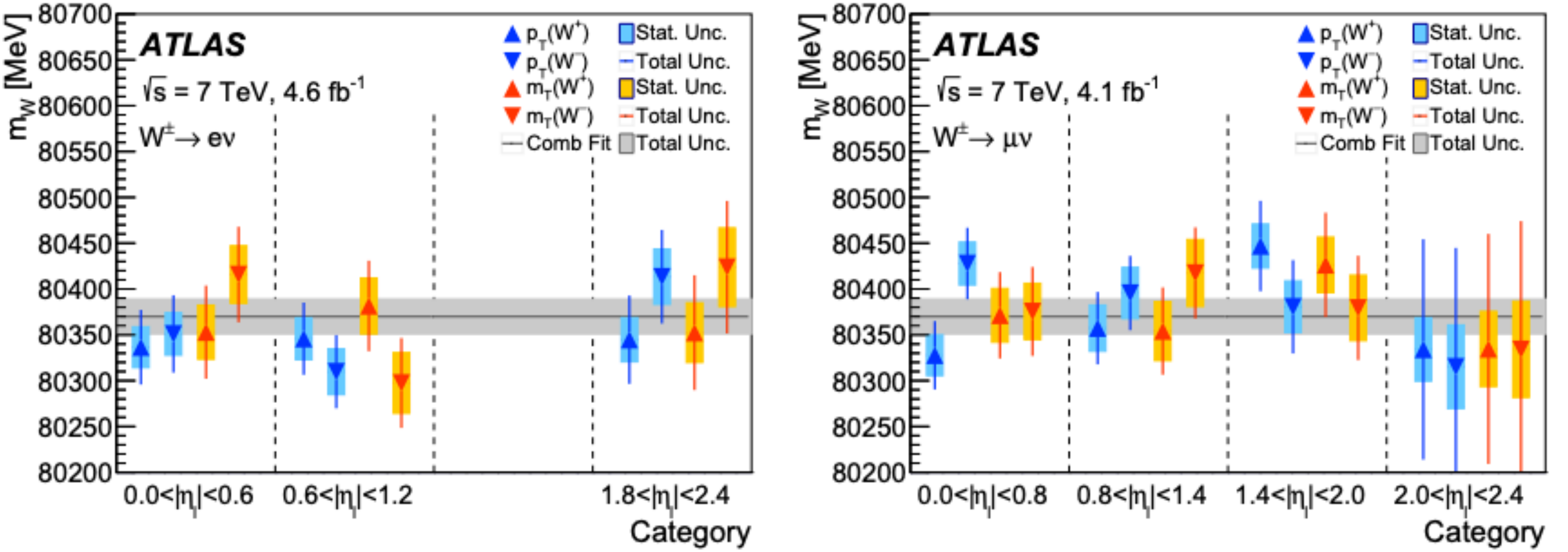
Commensurate samples of Z, quarkonia etc… for calibrations, higher resolution detectors and improvements in the accuracy of full detector simulations.

W production uncertainties are larger because production dominated by valence quark plus sea-quark/gluon subprocesses.

Challenges known for some time. E.g. ATL-PHYS-PUB-2014-015

ATLAS measurement of m_W with 2011 (7 TeV) data

EPJC 78 (2018) 110



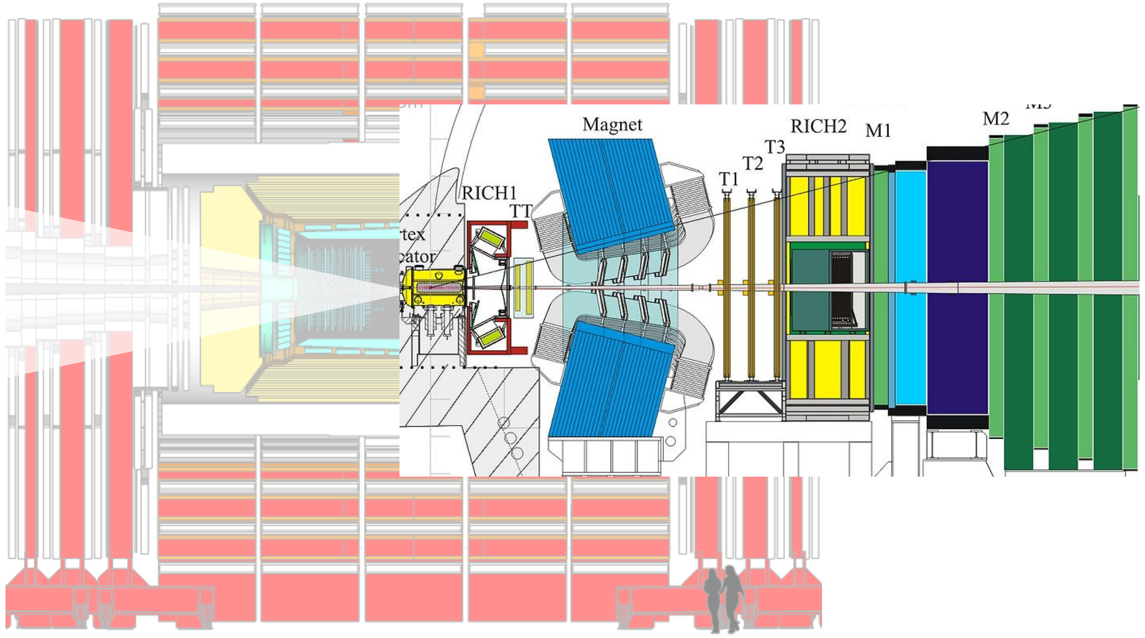
$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}$$

Base simulation with POWHEG+Pythia, reweighted in 5D to hybrid of Pythia (boson p_T) and fixed-order (α_s^2) (angular coefficients and y distribution).

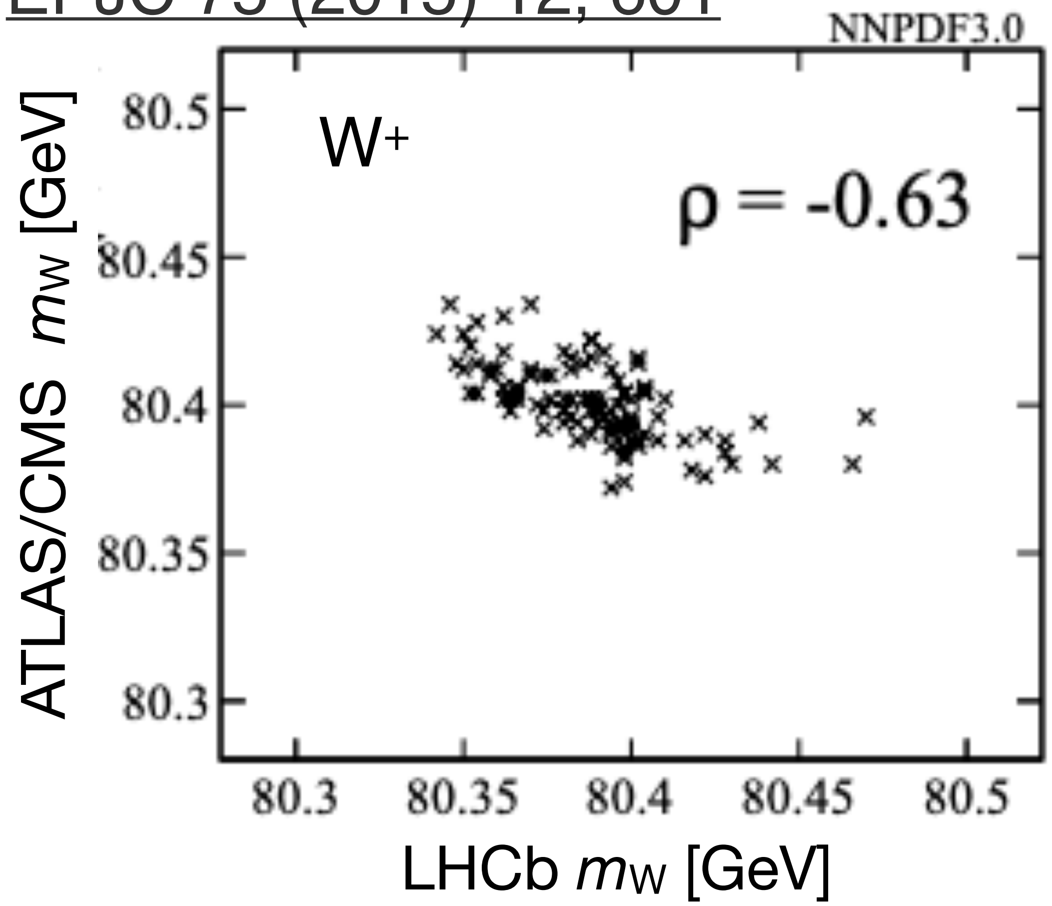
Dominant uncertainties: (i) fixed order PDF and (ii) transport of Z p_T model to the W.

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

LHCb



EPJC 75 (2015) 12, 601



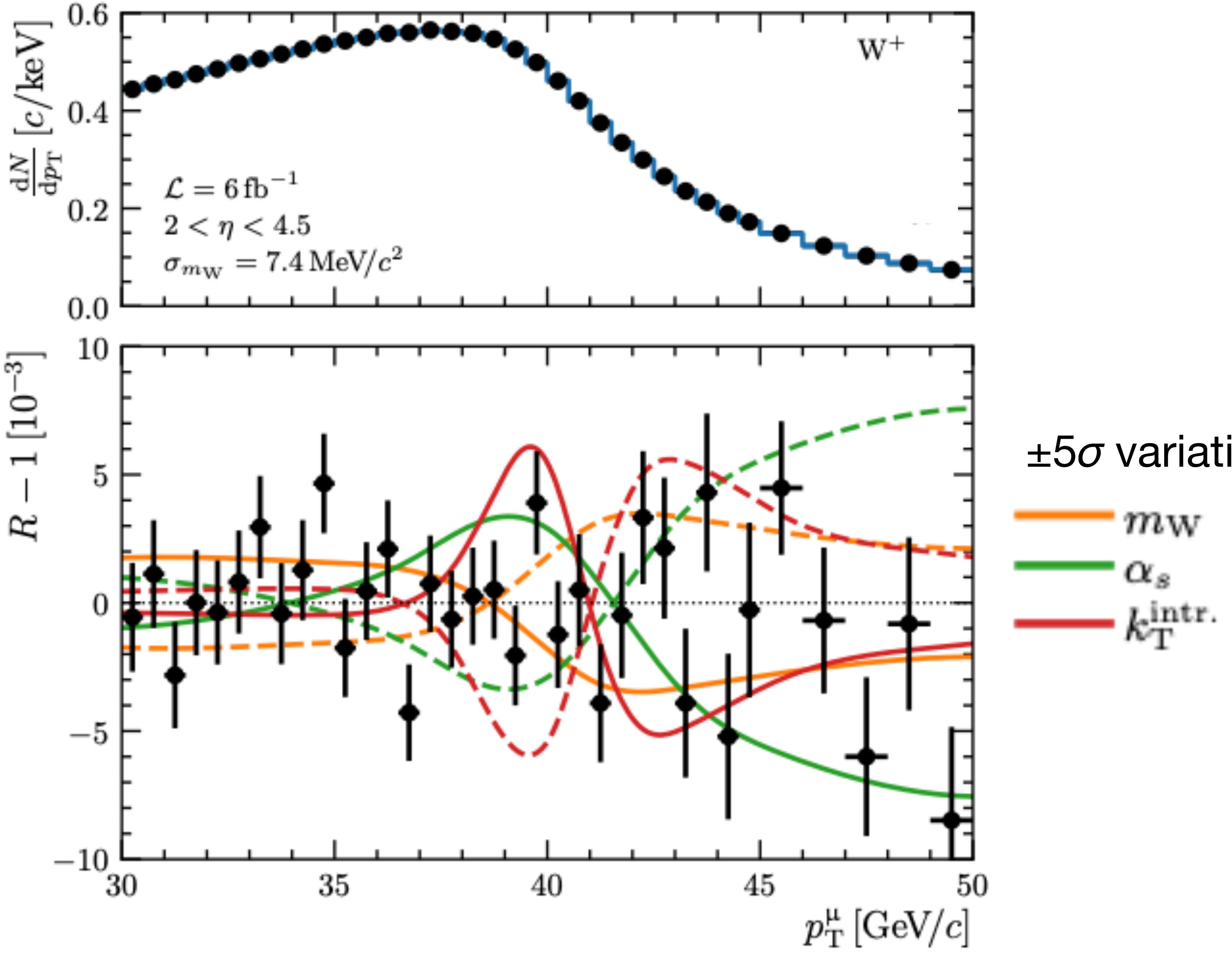
Measurement based on muon p_T in W→μν with Run-II (2015-2018) dataset with statistical uncertainty of ~10 MeV.

Partial anti correlation of PDF uncertainty w.r.t. measurements by ATLAS and CMS.

The key challenge is the W p_T modelling. The ultimate solution must be the use of calculations with the highest logarithmic accuracy but full event-generators (including matching to NLO) can be tuned to describe Z p_T data. How to transport the tunes to W production?

Simultaneous fit of m_W and W-specific tune

1907.09958 (2019)

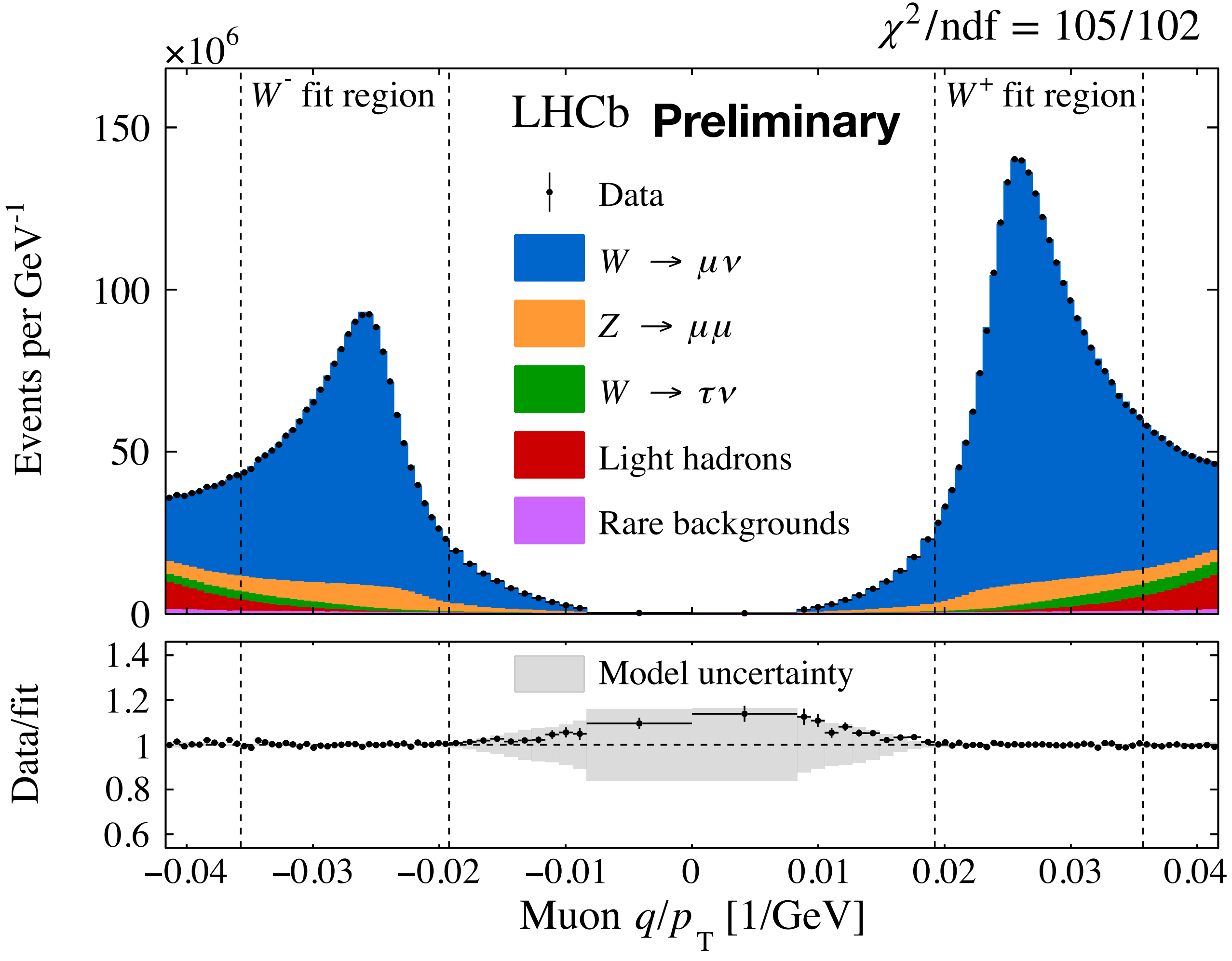


±5σ variations

Pythia parameters

Preliminary LHCb measurement

LHCb-PAPER-2021-024 *in preparation*



$$m_W = 80364 \pm 23_{\text{stat}} \pm 11_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Floating parameter	Postfit value
Fraction of $W^+ \to \mu^+\nu$	0.5293 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3510 ± 0.0005
Fraction of hadron background	0.0151 ± 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	0.979 ± 0.026

Source	Size [MeV]
Parton distribution functions	**9.0**
Theory (excl. PDFs) total	**17.4**
Transverse momentum model	12.0
Angular coefficients	9.0
QED FSR model	7.2
Additional electroweak corrections	5.0
Experimental total	**10.6**
Momentum scale and resolution modelling	7.5
Muon ID, trigger and tracking efficiency	6.0
Isolation efficiency	3.9
QCD background	2.3
Statistical	**22.7**
Total	**31.7**

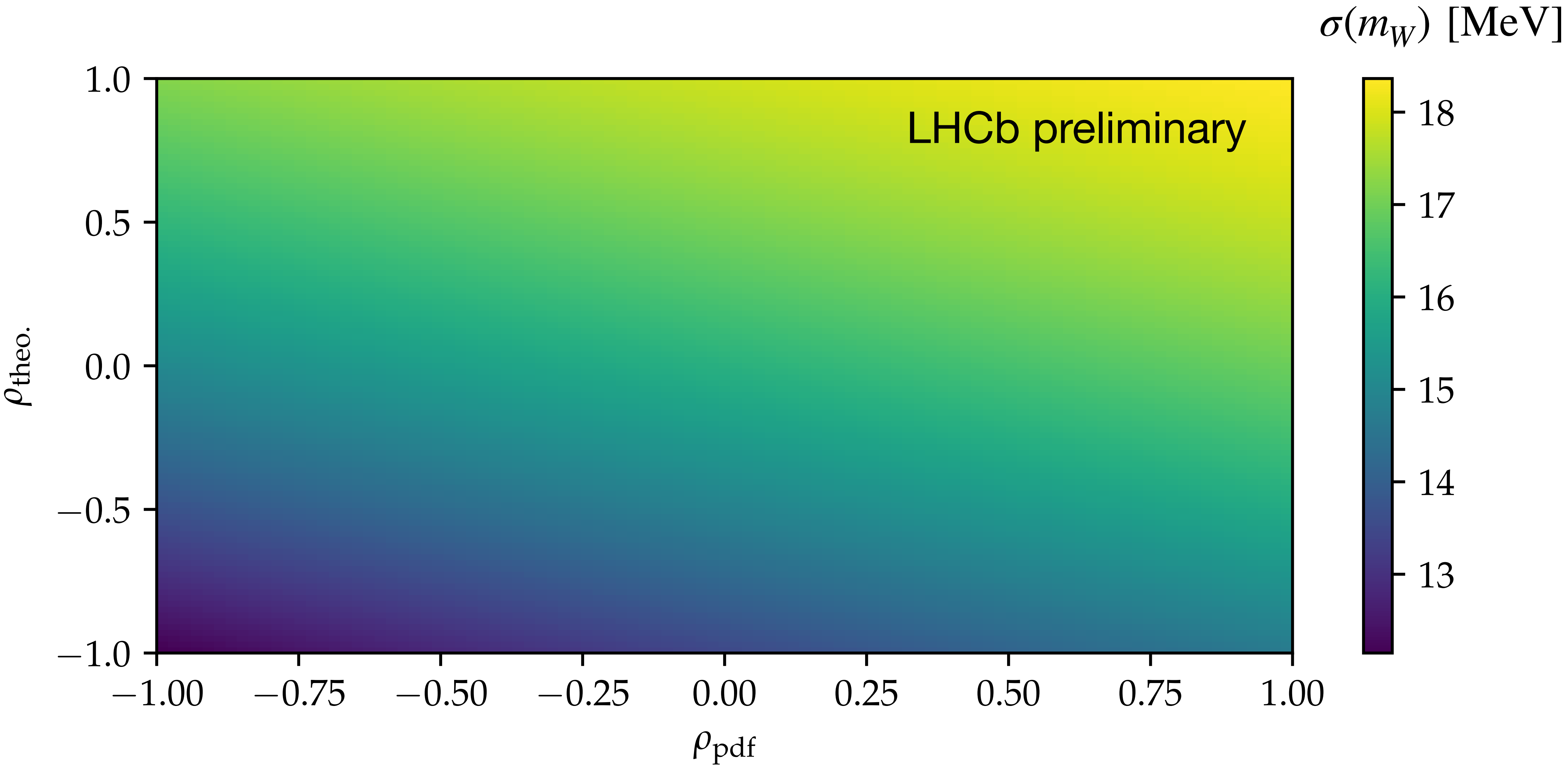
Simultaneous fit of the q/p$_T$ (W events) and ϕ* (Z events)

Base simulation with Pythia+GEANT, with 5D reweighting to POWHEG+Pythia (unpolarised cross-section) and DYTurbo (angular coefficients).

Final result is simple average from fits with NNPDF31, CT18, MSHT20.

Prospects for average of current LHCb+ATLAS results

Under the simplest assumptions:

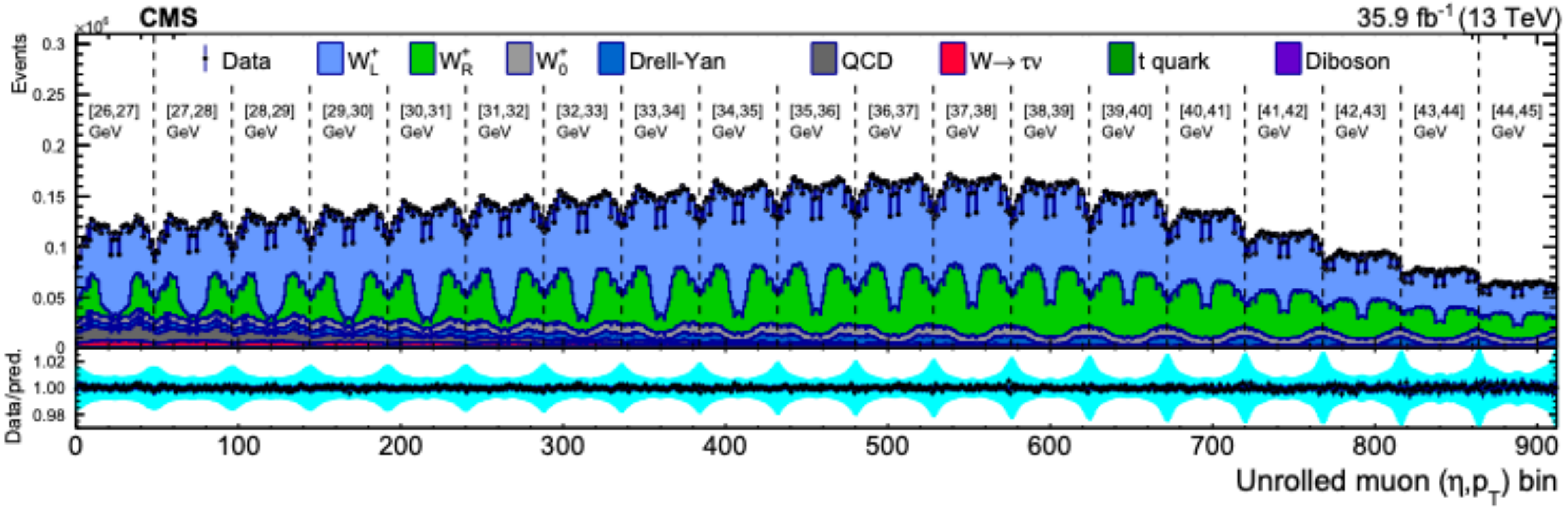


A detailed ATLAS+LHCb collaborative effort will be required to precisely determine these two correlation coefficients but it seems likely that ρ_{PDF} will be negative 1508.06954 while the (non-PDF) theory uncertainty will have a positive coefficient.

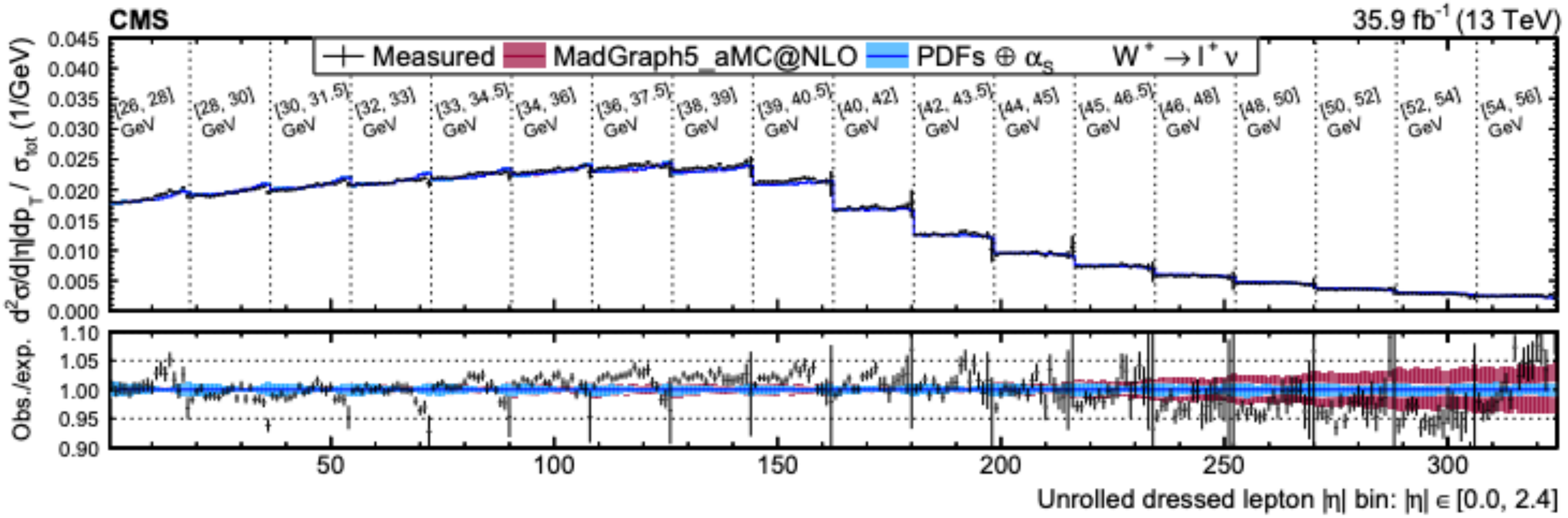
CMS double-differential $W \to l\nu$ with 2016 (13 TeV) data

Disentangling the W_L and W_R cross-sections:

PRD 102 (2020) 092012



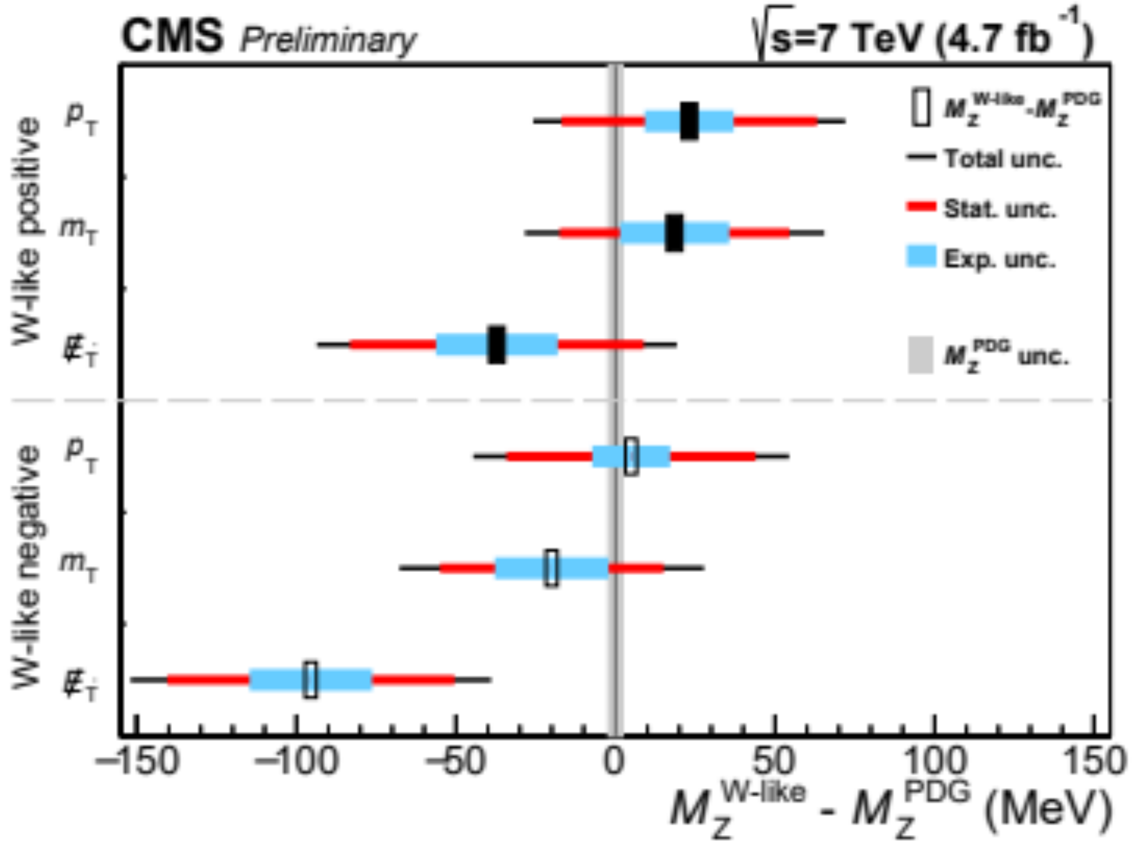
Double differential cross-section

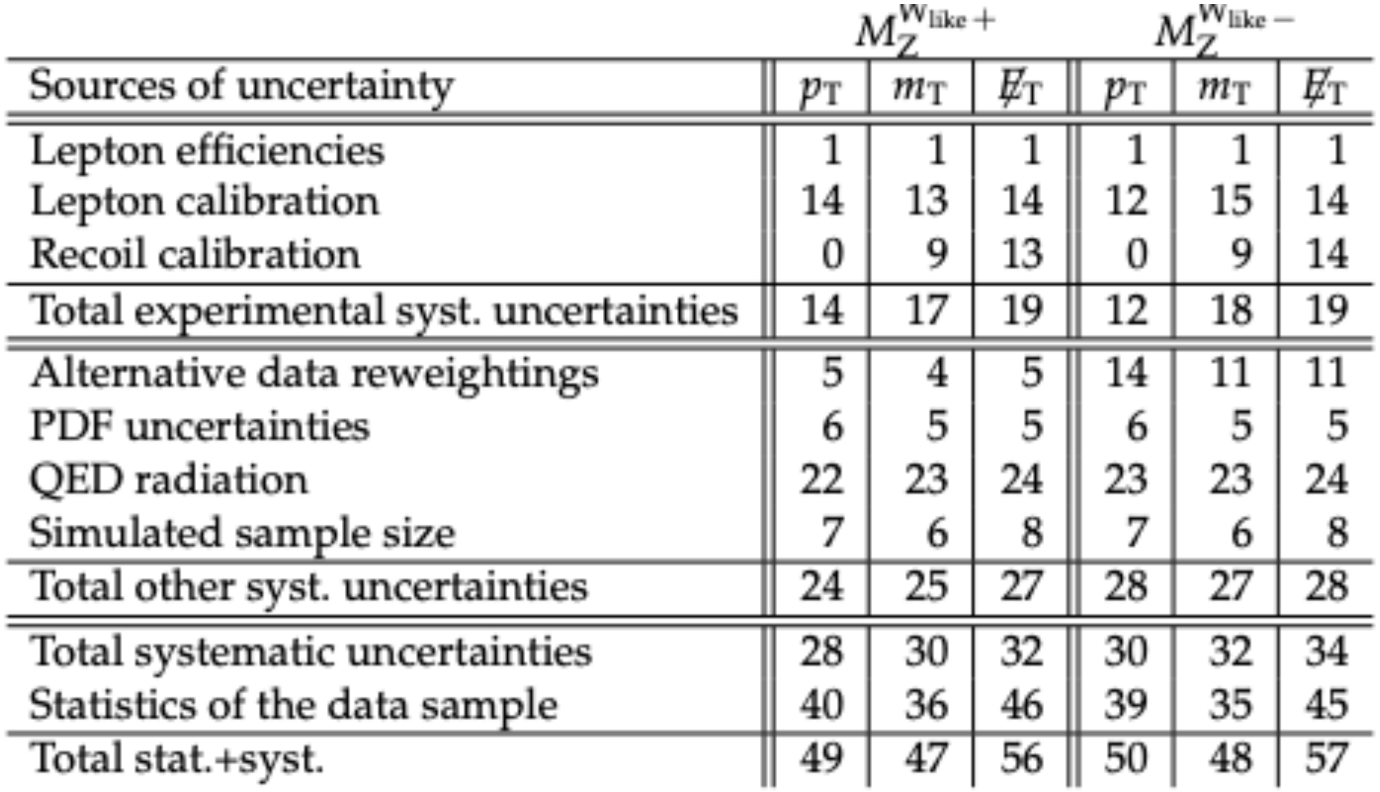


Potential for a very precise m_W measurement with these data, once the W production model is under control.

CMS' W-like measurement of m_Z

CMS-PAS-SMP-14-007





	$M_Z^{W\text{like}+}$			$M_Z^{W\text{like}-}$		
Sources of uncertainty	p_T	m_T	$\not{E}_T$	p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

Demonstrates control over the experimental modelling aspects *for all three* m_W-sensitive observables.

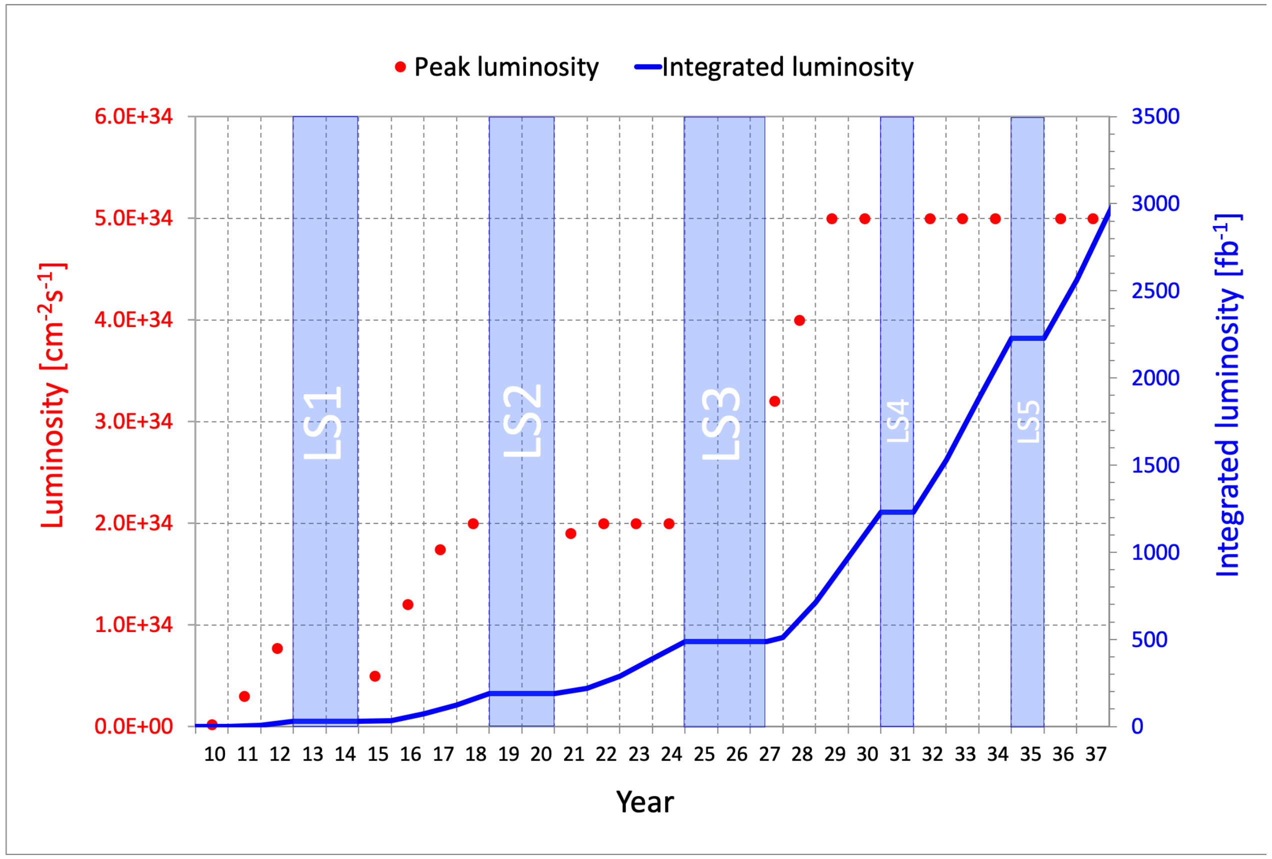
Interesting to see how the missing E_T and M_T-based approaches scale to even higher pileup data.

The W-specific physics modelling is the obvious remaining challenge.

ERC project ASYMOW (L. Bianchini) during 2021—2026 with goal of σm_W < 10 MeV, with reduced dependence on theory modelling.

HL-LHC prospects

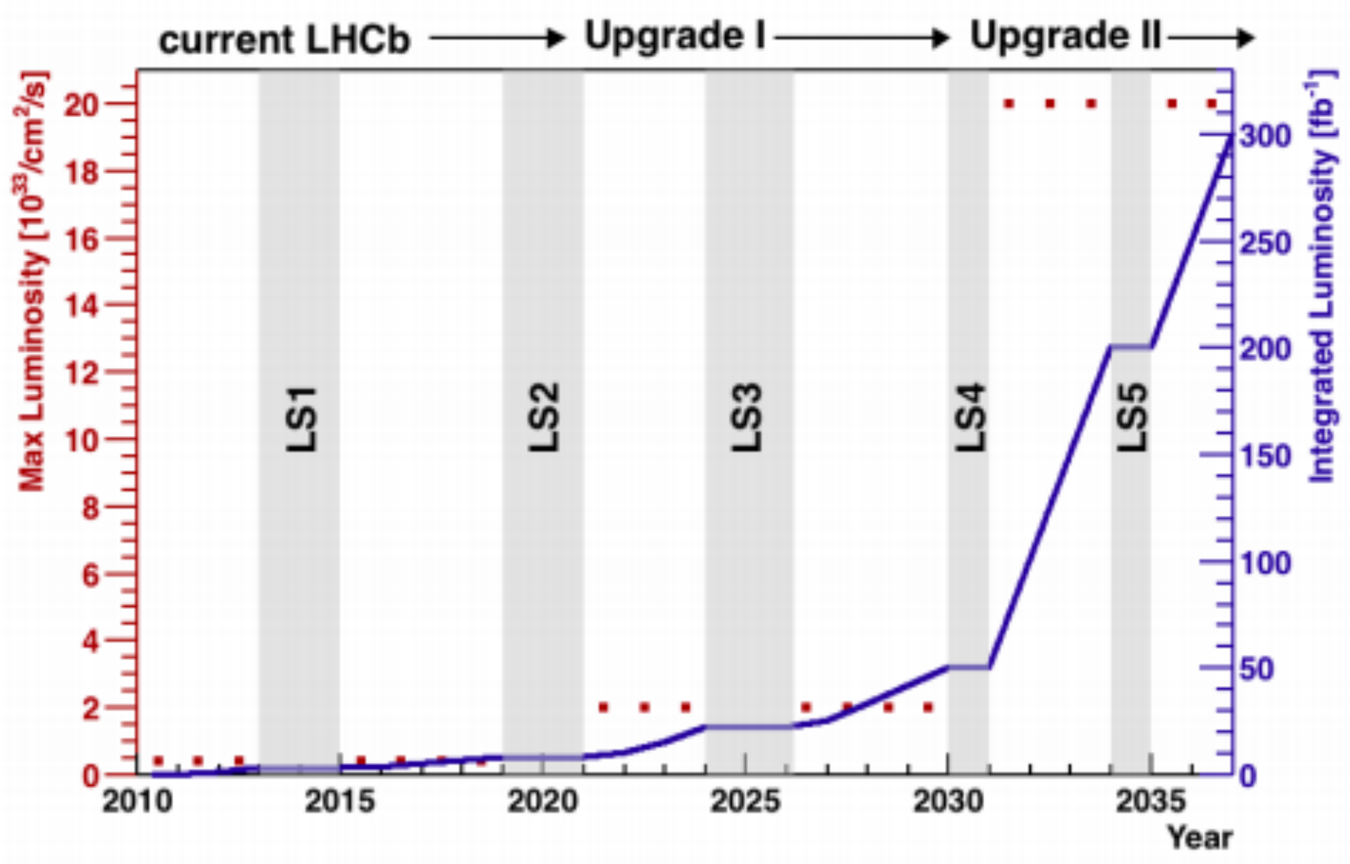
ATLAS and CMS



Extended lepton η coverage.

Case for special low pileup runs for W mass, width and p_T measurements.

LHCb

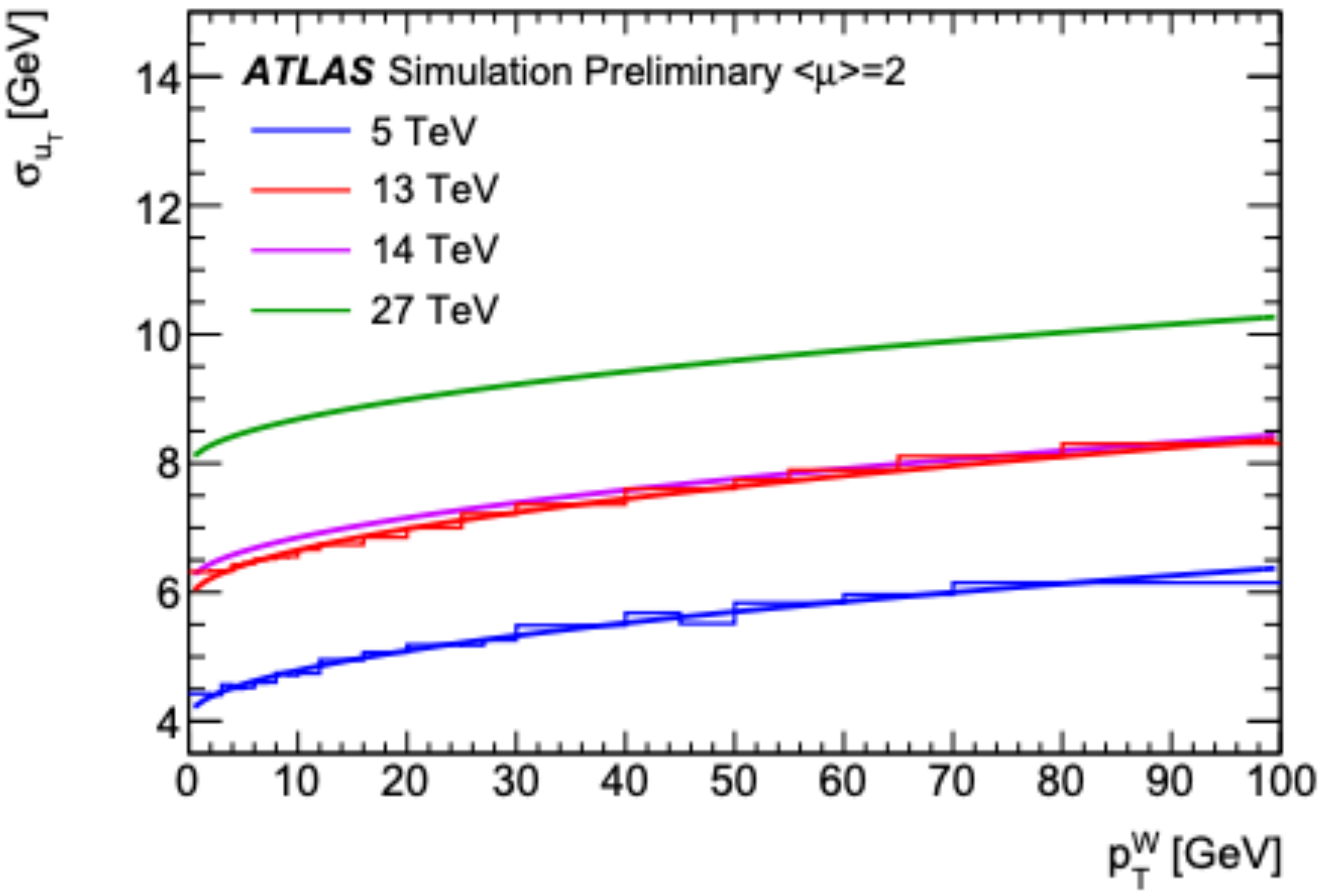


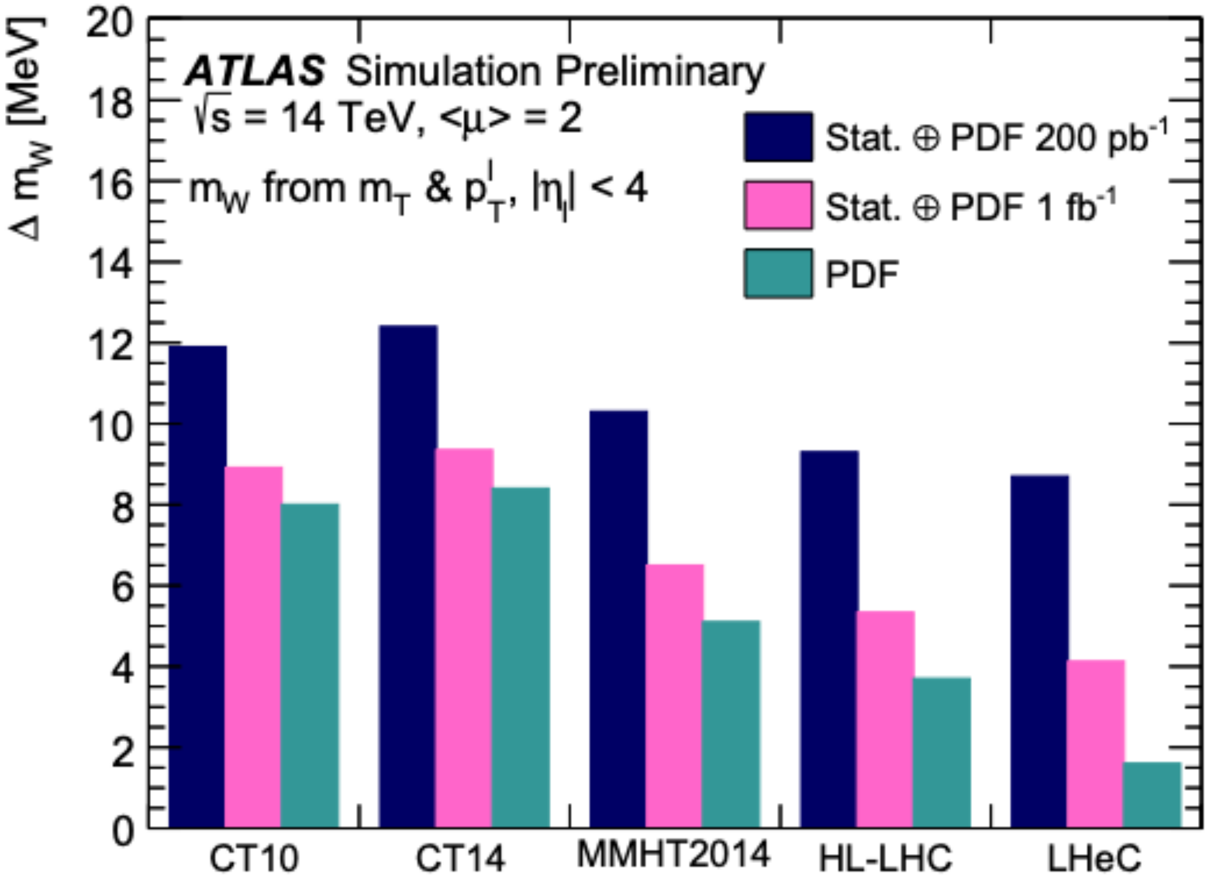
~500M W→μν events

Upgraded ECAL permits similarly precise measurement with electrons.

ATLAS study

ATL-PHYS-PUB-2018-026





ITK extends coverage for electrons (with tracking) from |η| < 2.5 to |η| < 4.

Dedicated low luminosity run at 14TeV for measurement including transverse mass. Requires 1 fb^{-1} to get to 4 MeV statistical precision.

PDF uncertainty reduced to the ~1-2 MeV level with scenario including the LHeC.

The ultimate precision on m_W with the HL-LHC?

What would it take to achieve, *e.g.*, a 5 MeV combination of ATLAS, CMS and LHCb?

Hypothetical/simplified case with just the charged lepton observables, where the extrapolation from existing ATLAS/LHCb measurements is more straightforward.

Source	Today ATLAS(LHCb) [MeV]	Goal per experiment [MeV]	Goal LHC average [MeV]	Comment
Stats	7(22)	3	1	Uncorrelated
PDFs	8(10)	4	2	Partial anticorrelation
QCD	10(12)	6	4	Mostly correlated
EW	5(5)	2	2	Mostly correlated
Calib+bgds	10(10)	3	2	Partially correlated
Total	**19(32)**	**9**	**5**	

LHCb upgrade-II allows ~20x reduction in statistical uncertainty w.r.t. preliminary result on 2016 data (1.7 fb^{-1}).

Assumptions about ATLAS and CMS are more complicated, and depend on the weight given to low/high pileup running, different observables etc…

Now let’s look at some of the challenges…

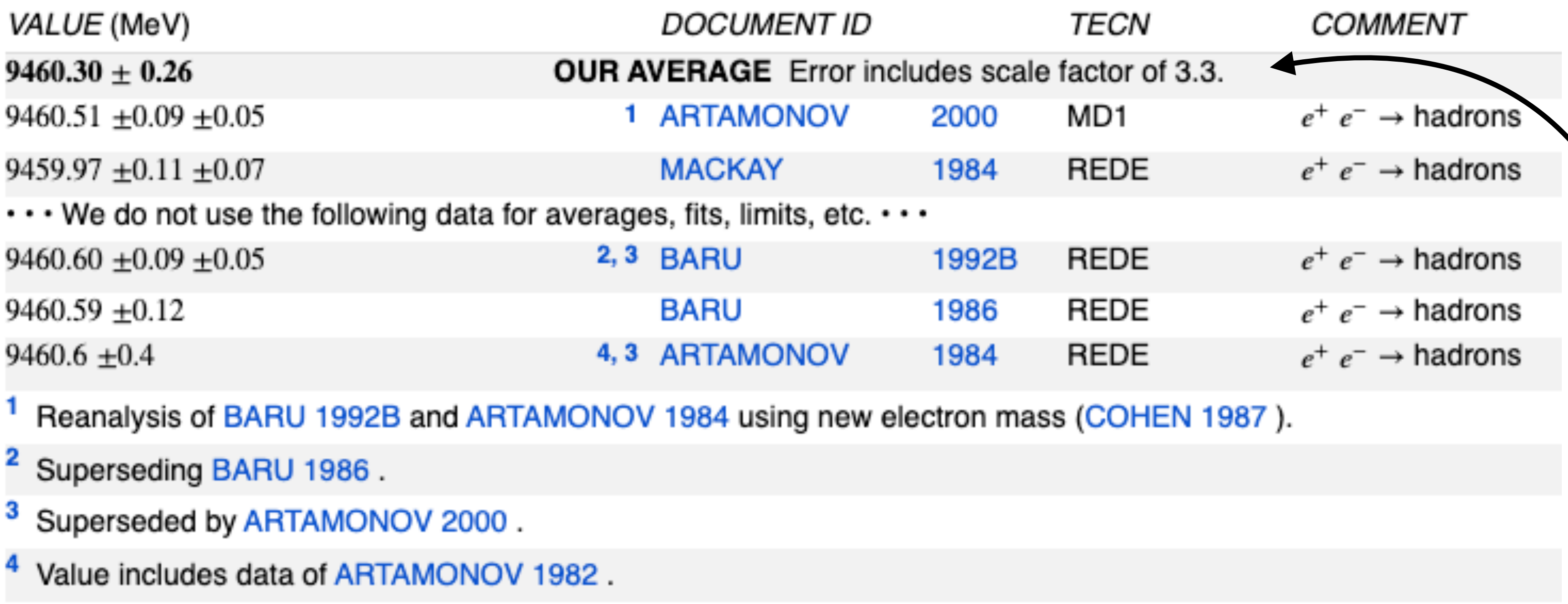
MeV-level momentum scale calibration

Hadron collider experiments require calibration to resonances.

Resonance	σ_m/m	Concerns
Z	2×10^{-5}	Interpretation in EW fit once total m_W uncertainty approaches the 5 MeV level.
Υ(1S)	3×10^{-5}	Precision and $>3\sigma$ tension between the two measurements in PDG average.
J/Ψ	2×10^{-6}	Extrapolation to momenta of leptons from W/Z. Trigger/ selection biases.

Experiment-specific challenges on curvature-biases, material budget etc…

Some unique challenges related to the electron energy scale…



VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
9460.30 ± 0.26	**OUR AVERAGE** Error includes scale factor of 3.3.			
$9460.51 \pm 0.09 \pm 0.05$	[1] ARTAMONOV	2000	MD1	$e^+ e^- \to$ hadrons
$9459.97 \pm 0.11 \pm 0.07$	MACKAY	1984	REDE	$e^+ e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$9460.60 \pm 0.09 \pm 0.05$	[2, 3] BARU	1992B	REDE	$e^+ e^- \to$ hadrons
9460.59 ± 0.12	BARU	1986	REDE	$e^+ e^- \to$ hadrons
9460.6 ± 0.4	[4, 3] ARTAMONOV	1984	REDE	$e^+ e^- \to$ hadrons

[1] Reanalysis of BARU 1992B and ARTAMONOV 1984 using new electron mass (COHEN 1987).

[2] Superseding BARU 1986 .

[3] Superseded by ARTAMONOV 2000 .

[4] Value includes data of ARTAMONOV 1982 .

Do we know the Υ(1S) mass well enough?

MeV-level theory uncertainty

ATLAS and LHCb measurements of m_W are based on full event simulation with 5D reweighting.

Simulation of full events must be required at some level.

Must make use of highest accuracy dedicated cross-section calculations… (N^3LO and N^3LL….)

The key question: how to evaluate the scale uncertainties?

1) range of variation?

2) degree of correlation (between kinematic bins and between numerators and denominators)?

EW and mixed QCD-EW corrections

Not clear how best to fit into reweighting of full event simulation. E.g., ATLAS, LHCb and CMS (W-like m_Z study) have used parametric weighting to vary the m_W hypothesis. The 5D "Born" basis of a 3D cross section and 8 angular coefficients becomes invalid….

Recent theory work on the mixed QCD-EW corrections in 1912.10951

MeV-level PDF uncertainty

Proper treatment of theory uncertainties required.

Better control over the degree of correlation between the uncertainties on the different group's sets.

Deeper validation of *in situ* profiling/weighting to reduce the PDF uncertainties (e.g. EPJC (2019) 79: 497).

Clear benefit of scenario with LHeC.

Some encouraging prospects discussed in Bagnaschi & Vicini, PRL 126, 041801 (2021)

Conclusions and outlook

Realistically it is hard to say what is the ultimate precision that can be achieved with the HL-LHC.

The program is only just getting started with the first measurements from the experiments.

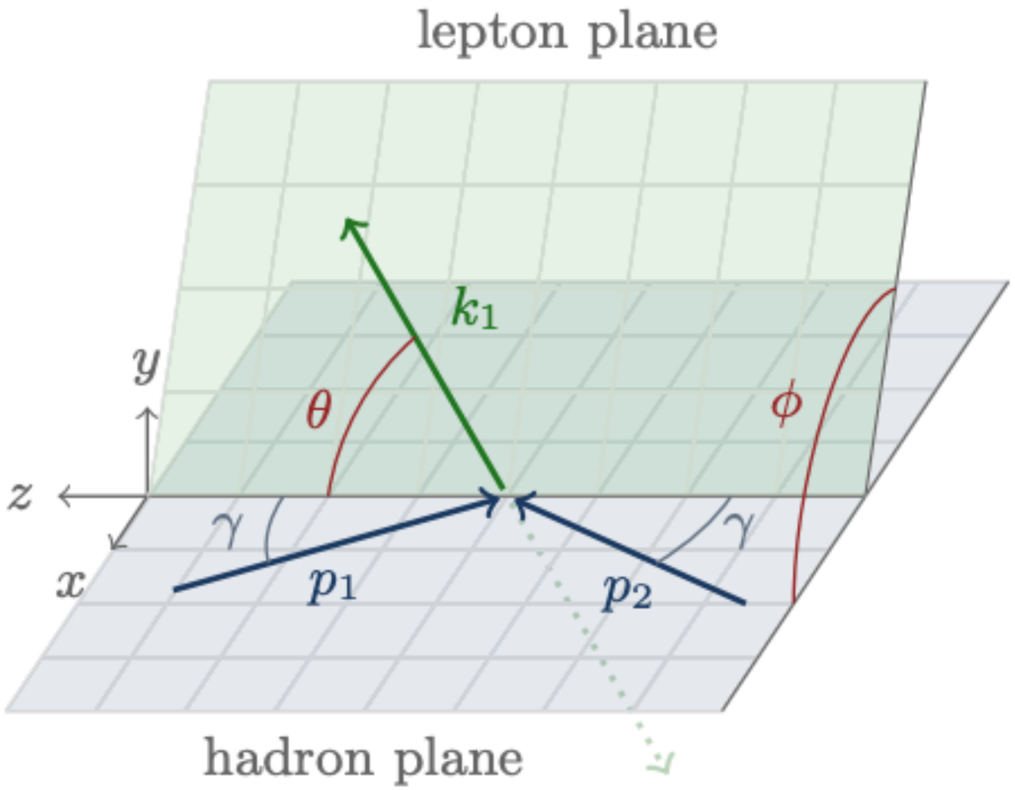
Some current bottlenecks (e.g. prescriptions for scale uncertainties, PDF uncertainties etc…) are already identified.

It will be really fun to try to collaborate closely between the three experiments and the theory community to see how low we can push the m_W uncertainty!

Backup slides

Vector boson production model

θ and ϕ in the Collins-Soper frame



Born-level form of W→μν kinematics:

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

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

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

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

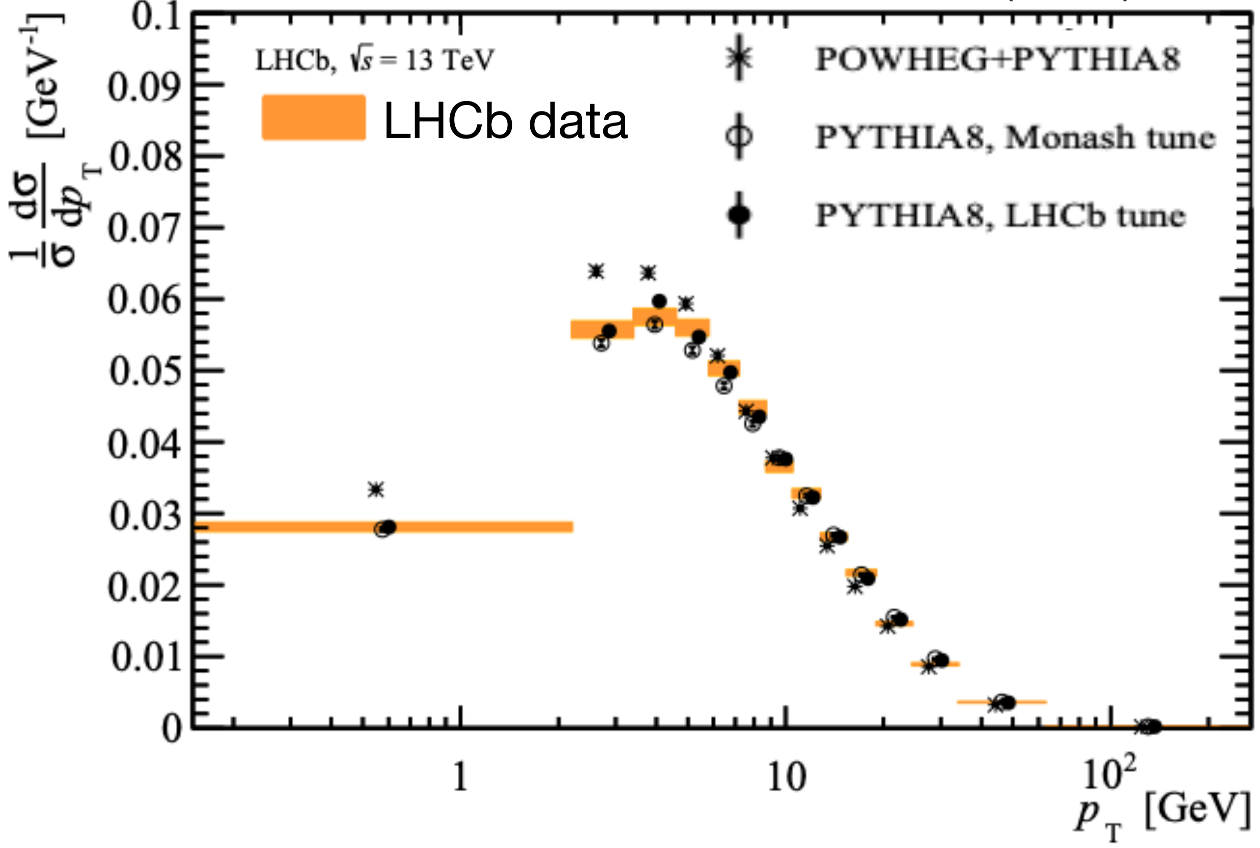
Electroweak corrections must also be considered.

1708.00008 acknowledged for the figure.

The W boson p_T distribution

Complete **event generation** with parton-showers matched to NLO matrix elements

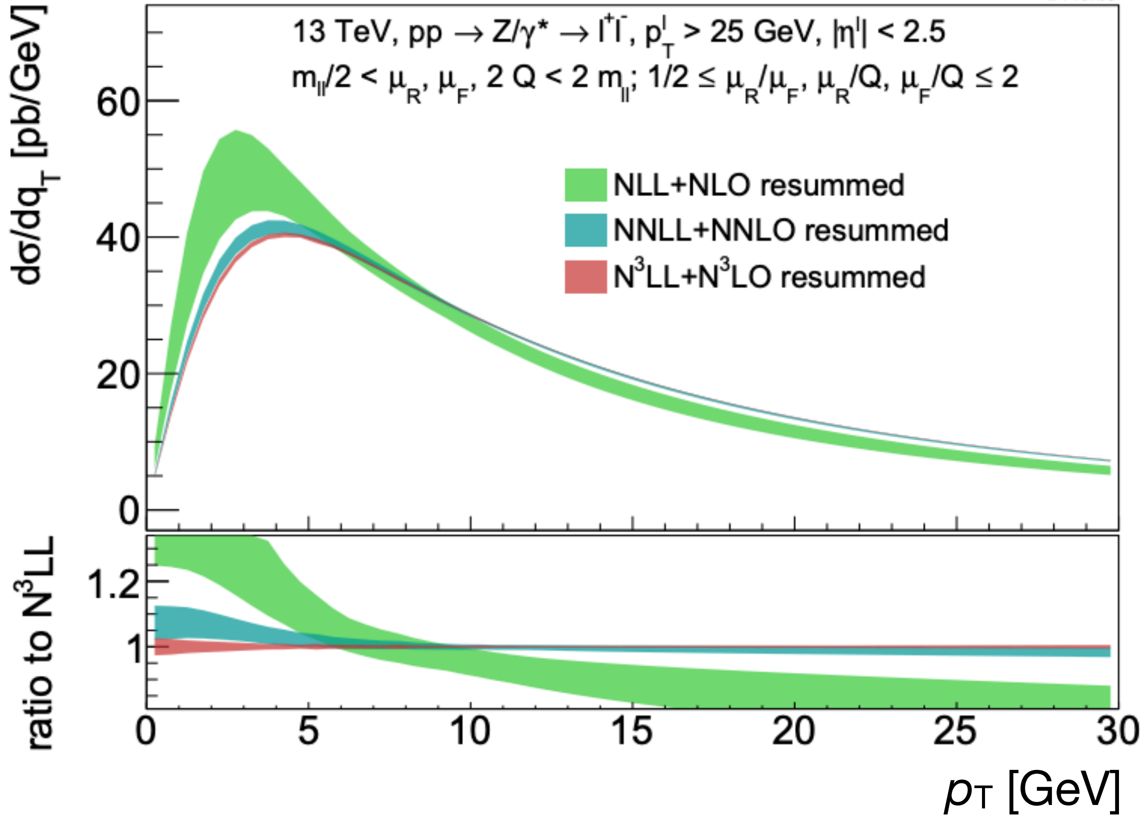
JHEP 09 (2016) 136



Tuning required to compensate for limited perturbative accuracy.

Cross-section calculation at up to N^{3}LL (logarithmic) accuracy, e.g. DYTurbo*:

2103.04974 (2021)



Ultimate perturbative accuracy but debated flexibility to fit the data.

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*As one example out of the work of *many* groups working in this area! Similarly for the event-generator codes.

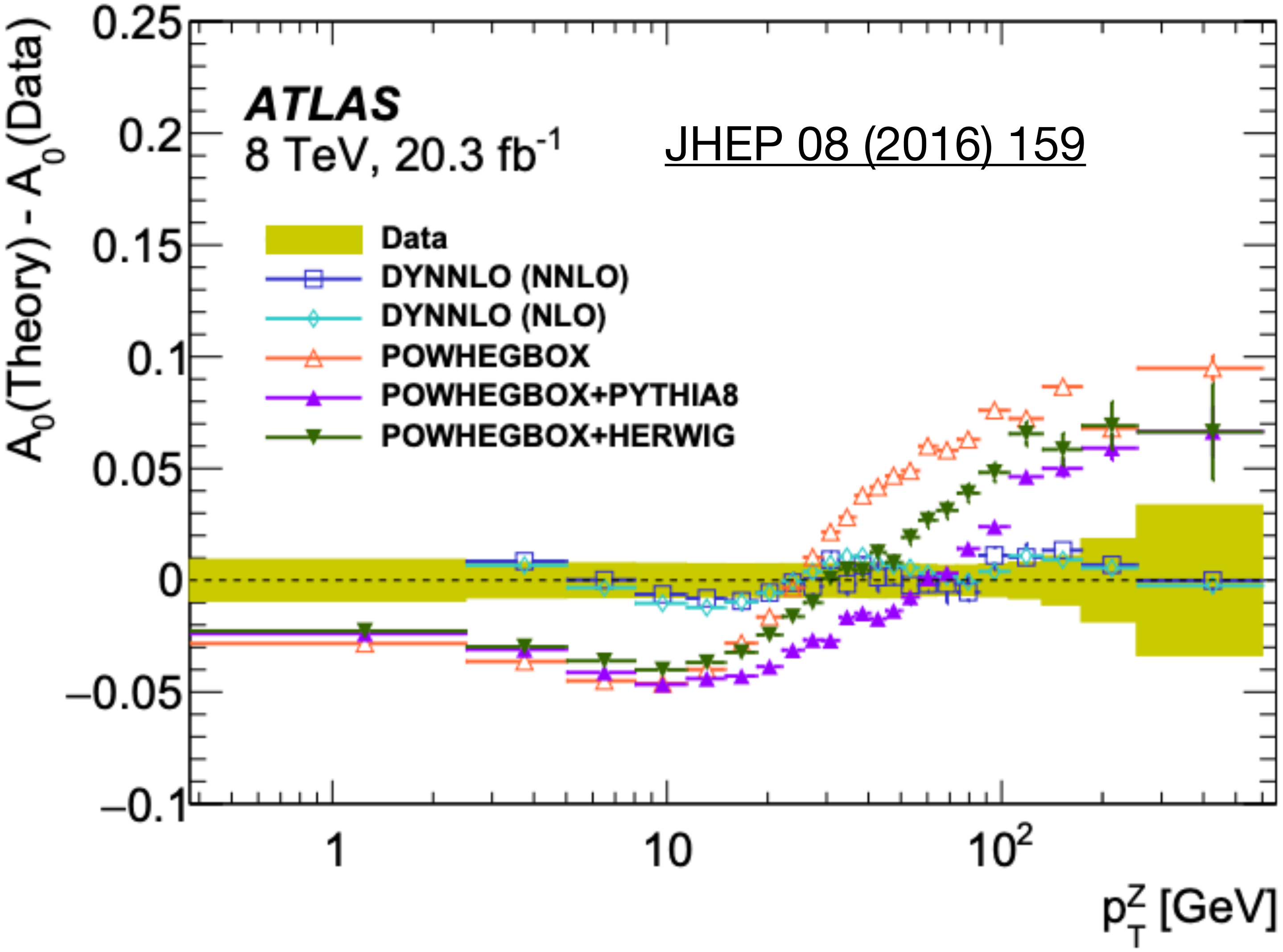
Angular coefficients

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

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

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

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



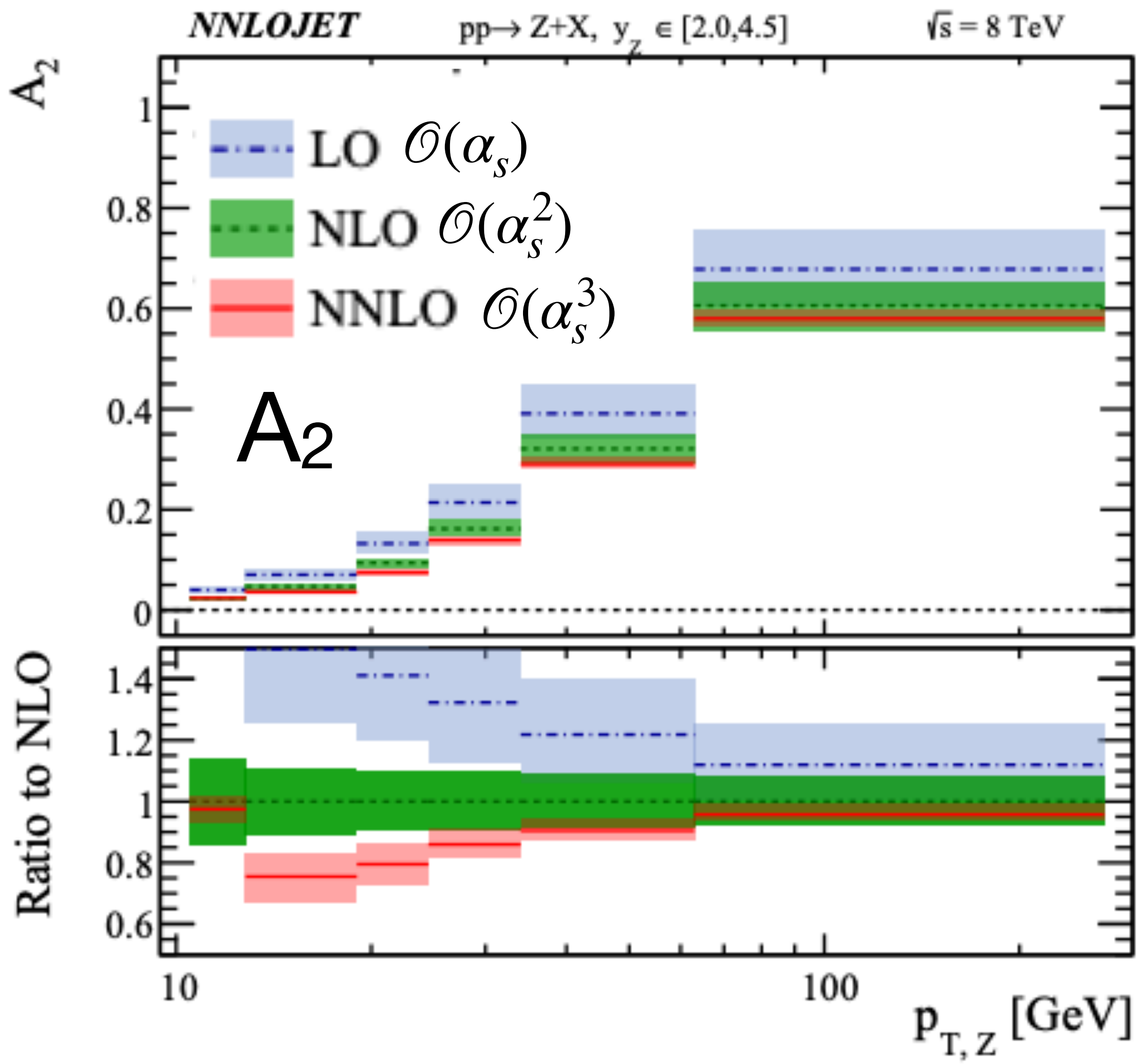
Event generators (e.g. POWHEG) have various difficulties.

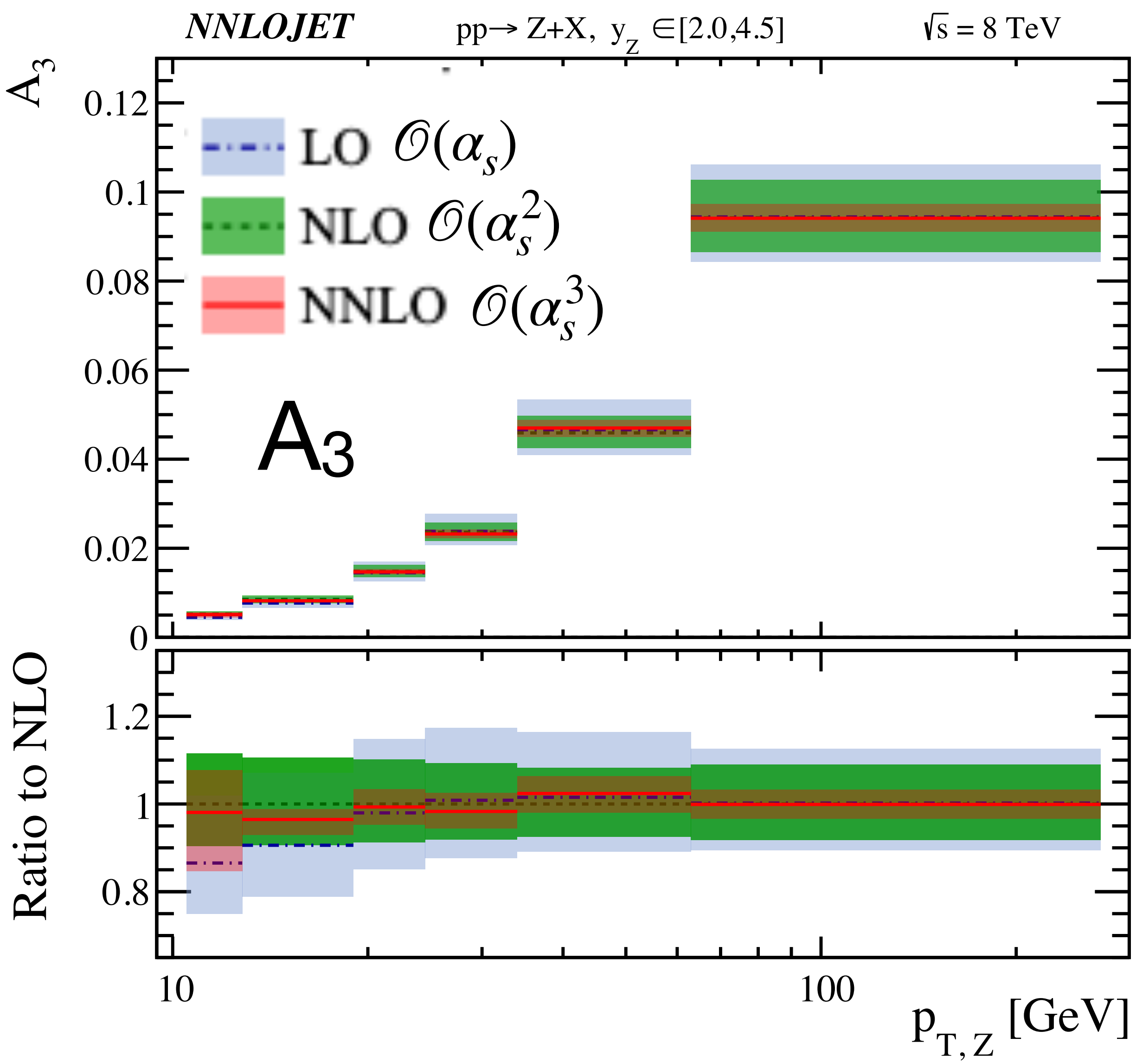
Choose to use predictions at O(α_s^2) from DYTurbo.

The angular coefficients are essentially [helicity] cross-section *ratios*: do we correlate the scale variations?

Angular coefficients in LHCb m_W analysis

We follow the preference of JHEP 11 (2017) 003: *uncorrelated* prescription with 31 point scale variation.

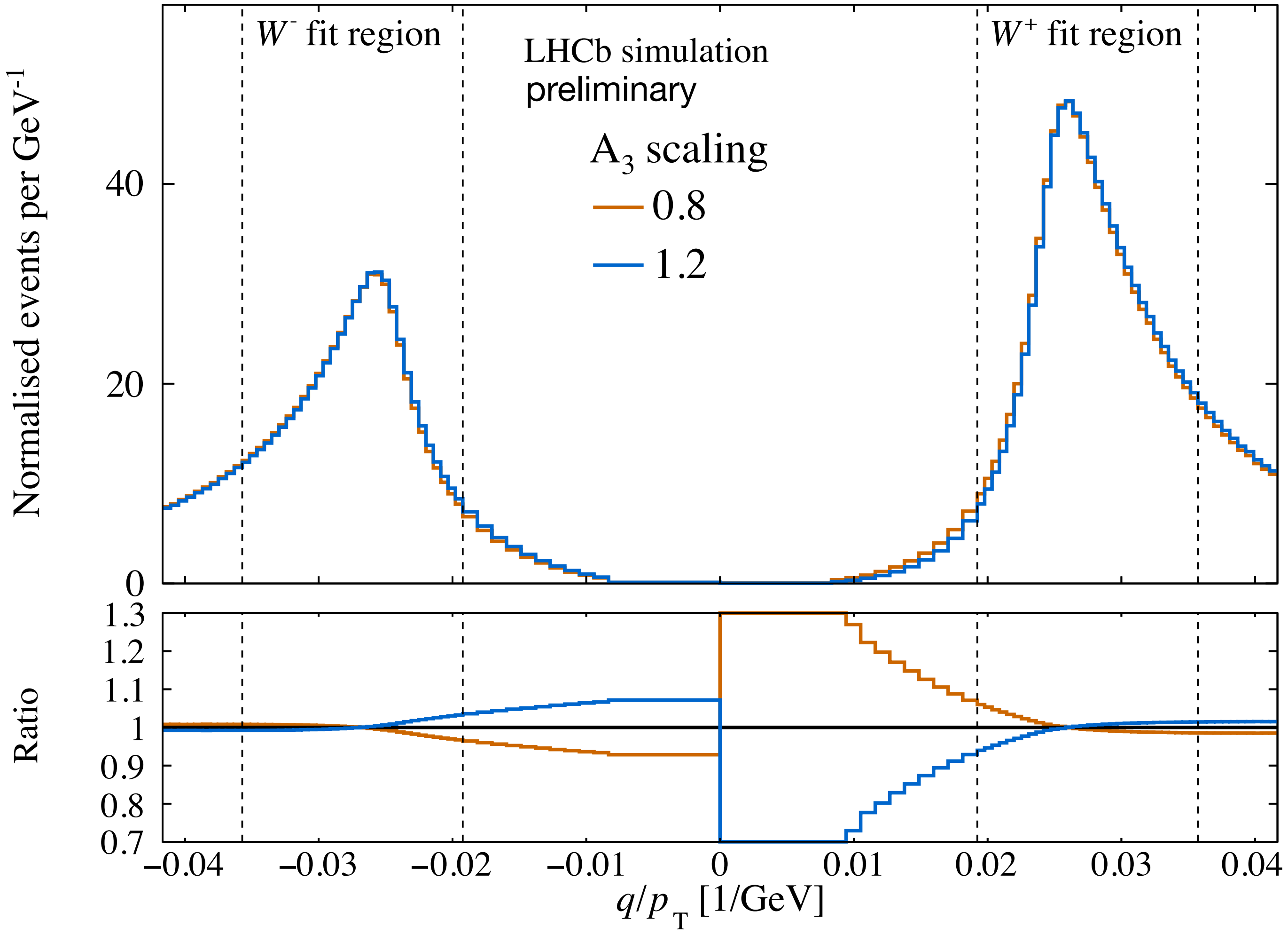




As an aside we look forward to discussing with the [NNLOJet] code authors on the possible usage in future measurement of m_W.
We also thank Rhorry Gauld for sharing the A_3 figure for the LHCb acceptance, which was't in the original publication.

Treatment of A_3 in LHCb measurement of m_W

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



The resulting uncertainty on m_W would be around 20-30 MeV.

Dominant sensitivity traced to the A_3 parameter.

Our solution is to float a single A_3 scale factor, which reduces the uncertainty to below 10 MeV.