W mass measurements at Tevatron and LHC

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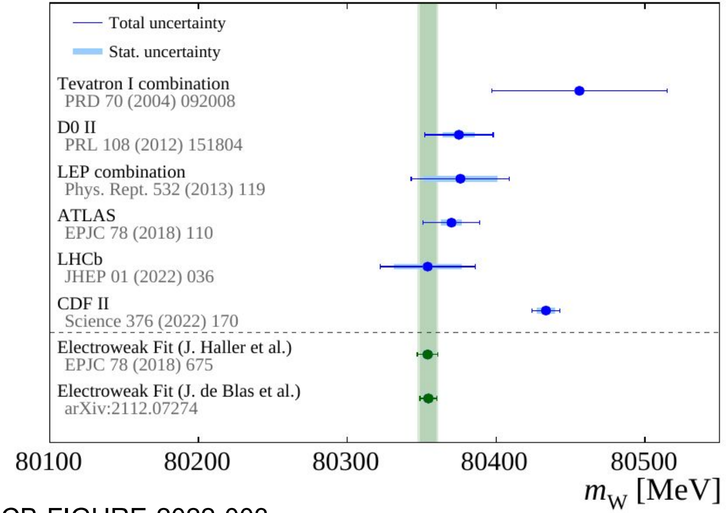
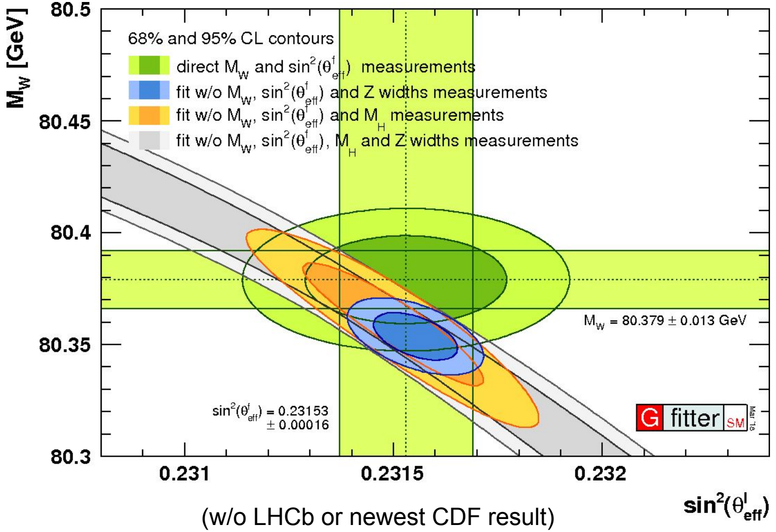
For CDF, D0, ATLAS, CMS, LHCb, LHC-Tevatron mW combination working group
LHC Days in Split
Oct. 6, 2022

m_W as a precision test of the SM



LHCB-FIGURE-2022-003

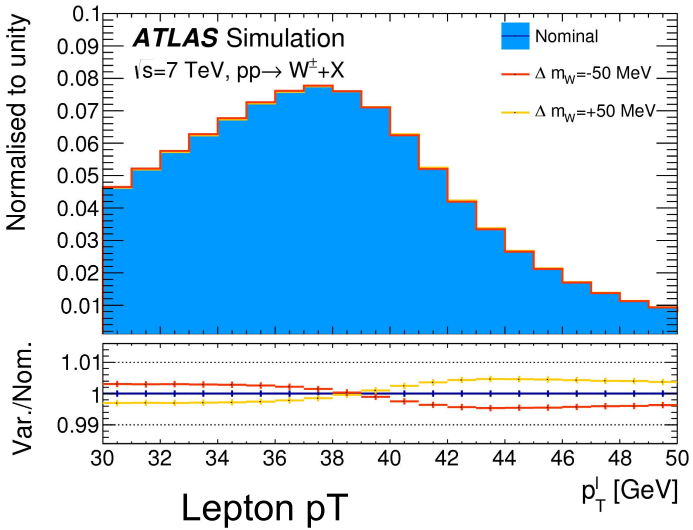


(w/o LHCb or newest CDF result)

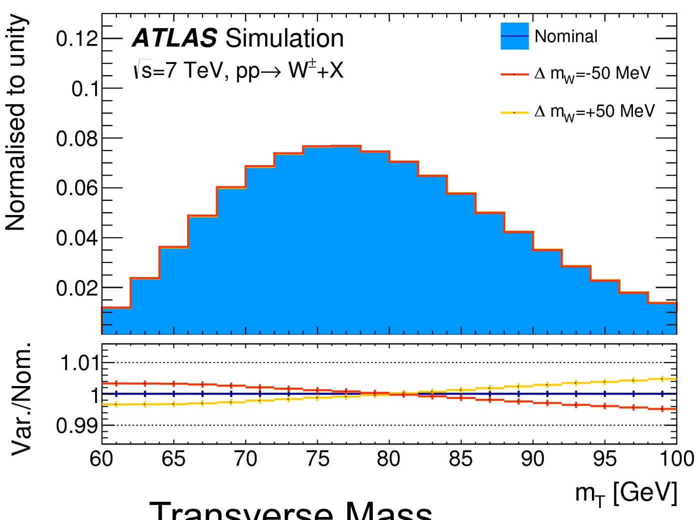
- The discovery of the Higgs and the measurement of its mass allowed (more) precise predictions of $m_W/\sin^2\theta_W/m_t$/etc from the global EW fit
- New CDF measurement in significant tension with SM prediction and previous measurements

mW measurements at hadron colliders

- Hadronic channel not feasible due to huge QCD backgrounds/Jet energy scale
- W cannot be fully reconstructed in leptonic channel due to neutrino
- Mass must be inferred from lepton pT or transverse mass distributions (1D template fits)
- mW is sensitive to 0.1% level variations in templates
  - Extreme control needed over all experimental and theoretical aspects



Lepton pT

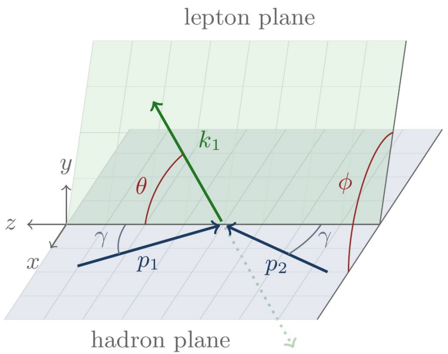


Transverse Mass

Theoretical Considerations

- W (and Z) production at hadron colliders described by PDFs + Perturbative QCD/EWK
  - Small additional non-perturbative effects from “intrinsic kT” (ie beyond-collinear-factorisation QCD effects in the proton)
- Relatively large theoretical uncertainties: usual strategy is to use precise Z->ll pT spectrum from data to tune the theoretical prediction
  - Potential residual uncertainties from Z->W extrapolation

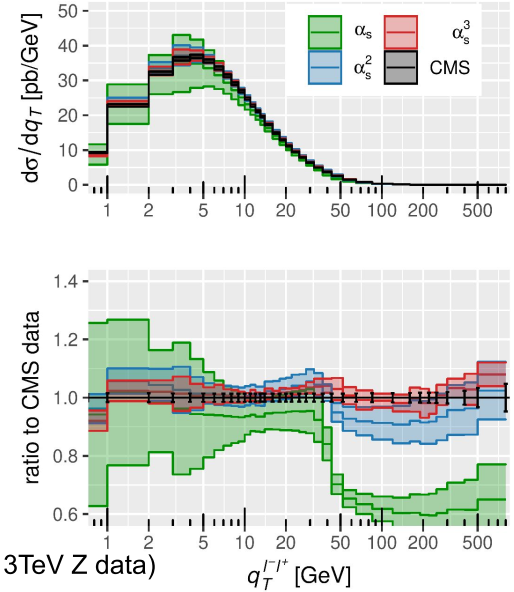
$$
\begin{aligned}
\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm\,dp_T\,dy} \Big[(1+\cos^2\theta) &+ \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \\
&+ \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi \\
&+ A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi \\
&+ A_6 \sin 2\theta \sin\phi + A_7 \sin\theta\sin\phi \Big],
\end{aligned}
$$



JHEP 11 (2017) 003

W/Z production described by differential xsec + angular coefficients driven by polarization

- Low pT region is challenging due to large logarithms
- Need resummed predictions
- State-of-the-art is N4LL+N3LO



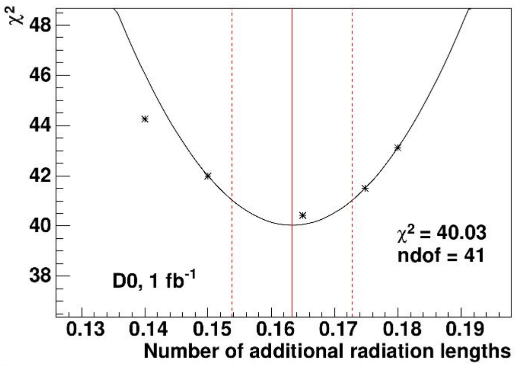
arXiv:2207.07056
(comparison to CMS 13TeV Z data)

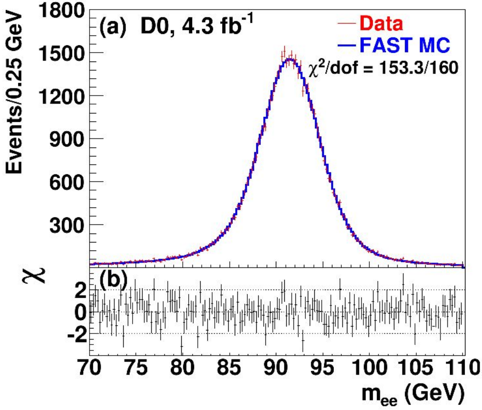
D0

Phys. Rev. D 89, 012005 (2014)

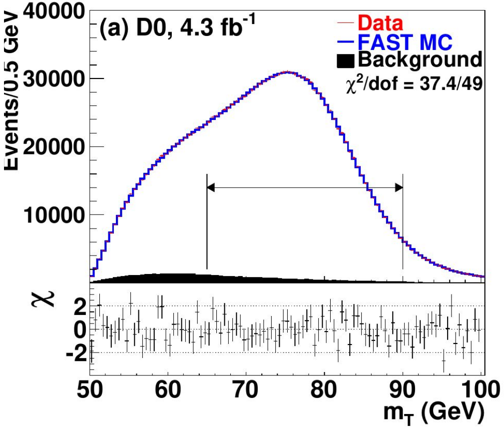
- Measurement with 4.3 +1.0/fb in electron channel
- Electron energy scale, hadronic recoil, theory model calibrated/tuned with Z->ee

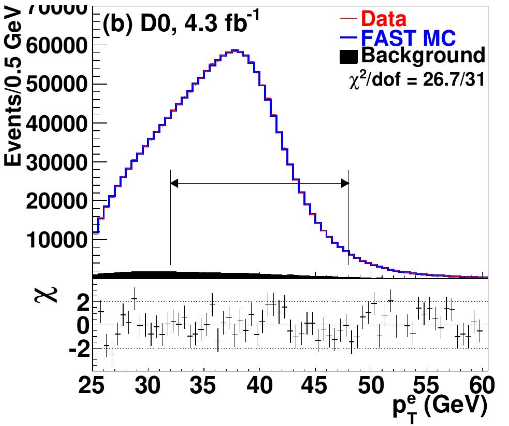
$$M_W = 80.375 \pm 0.023 \text{ GeV}.$$





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



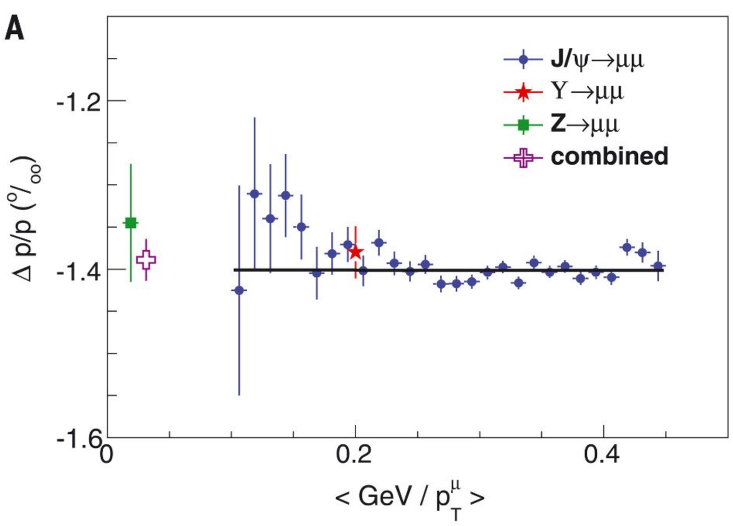


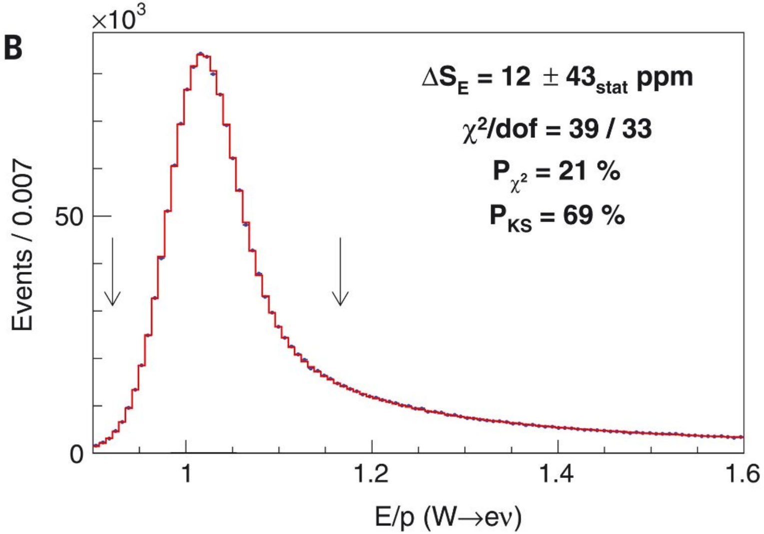
Variable	Fit Range (GeV)	Result (GeV)	χ^2/d.o.f.
m_T	$65 < m_T < 90$	80.371 ± 0.013	37/49
p_T^e	$32 < p_T^e < 48$	80.343 ± 0.014	27/31
$\not{E}_T$	$32 < \not{E}_T < 48$	80.355 ± 0.015	29/31

CDF: Energy/Momentum Scale Calibration

Science 376 (2022) 6589, 170-176

- Recent measurement with 8.8/fb of Tevatron data (1.96 TeV ppbar)
- Both electron and muon channels with high precision energy/momentum calibration



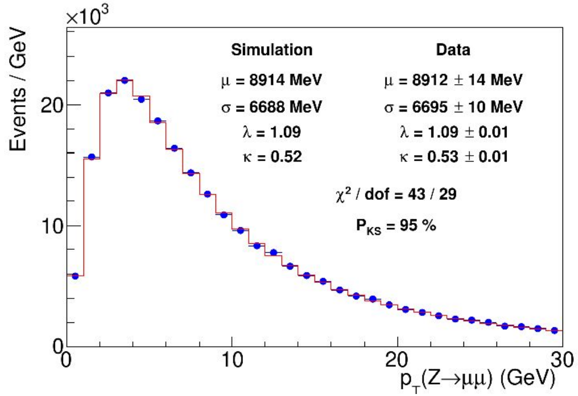


- Ultra-precise calibration of tracking momentum scale from J/psi and Y validated and combined with Z->mu mu
- After corrections for residual misalignment and material, momentum scale determined to relative accuracy of 25ppm

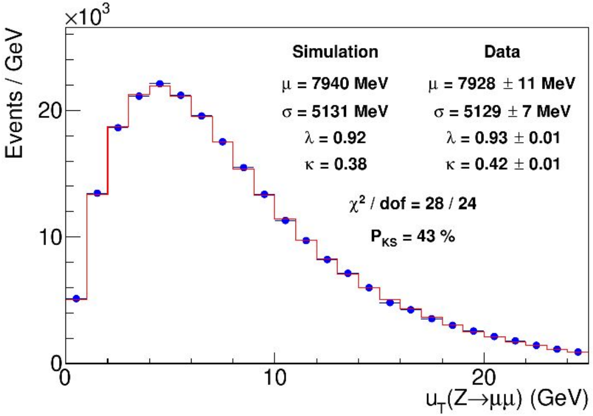
- Tracking momentum scale transported to electron energy scale in calorimeter with E/p
- Residual uncertainties from material model in inner detector (~0.2 radiation lengths) and calorimeter, non-linearity
- Total uncertainty of ~80ppm

Science 376 (2022) 6589, 170-176

CDF: Z->ll Standard Candle

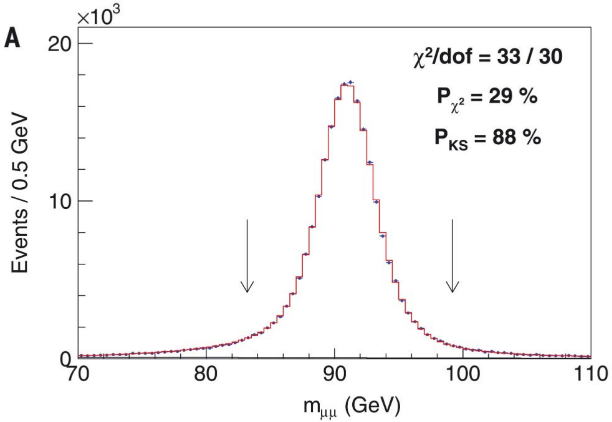


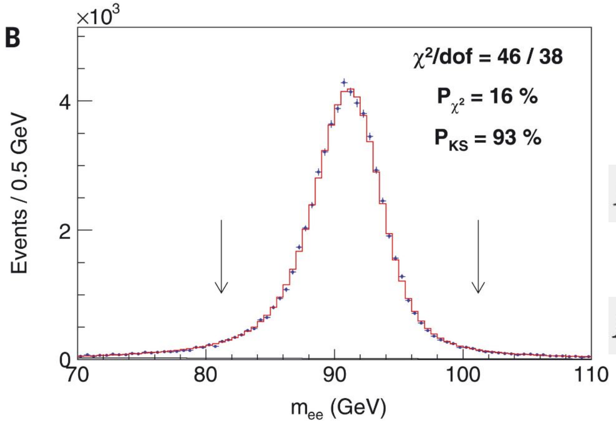
Tuned production model (Resbos)



Calibrated Hadronic Recoil

- Z->ll data used extensively for calibration and validation
  - Theory model tuning
  - Hadronic Recoil Calibration
  - Lepton Efficiencies





Final Z mass measurements consistent with world average:

Muons:

$$M_Z = 91,192.0 \pm 6.4_{\mathrm{stat}} \pm 4.0_{\mathrm{syst}}\ \mathrm{MeV}$$

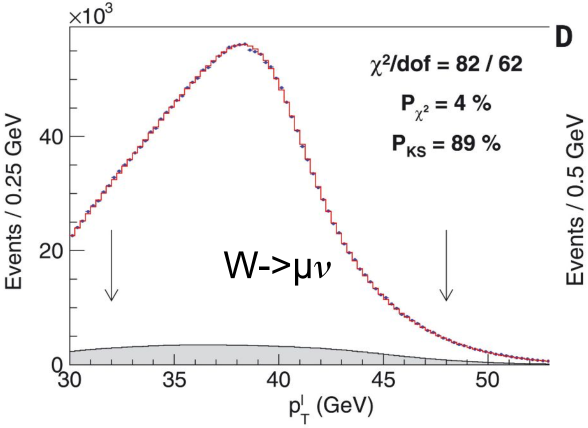
Electrons:

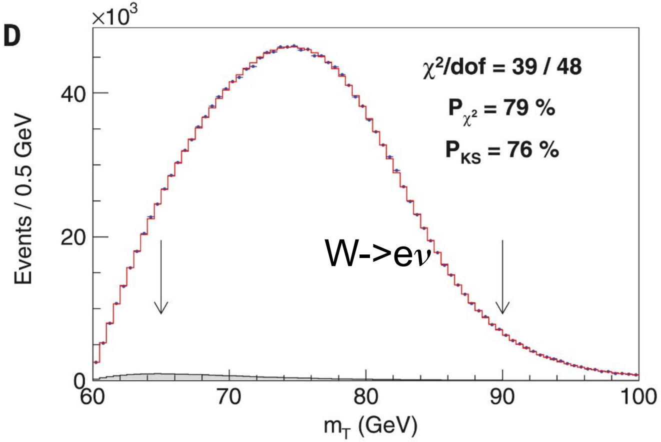
$$M_Z = 91,194.3 \pm 13.8_{\mathrm{stat}} \pm 7.6_{\mathrm{syst}}\ \mathrm{MeV}$$

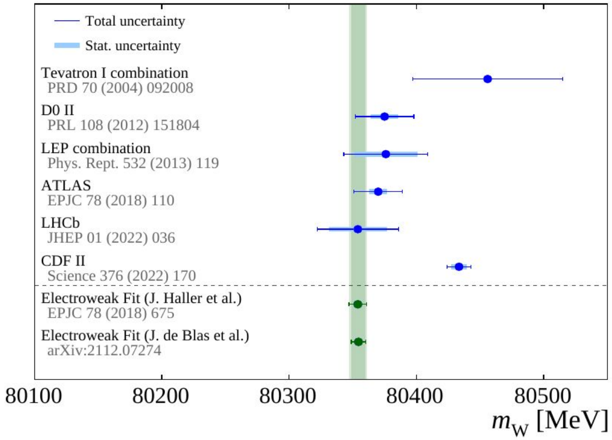
Science 376 (2022) 6589, 170-176

CDF: Results

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4





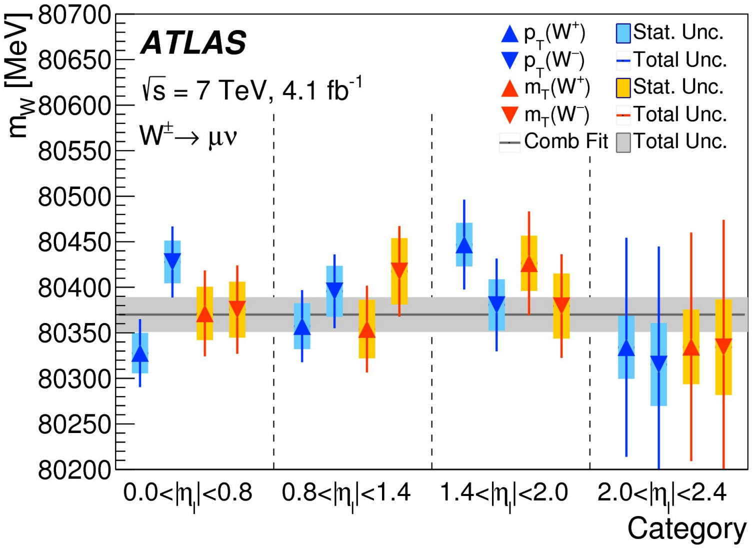


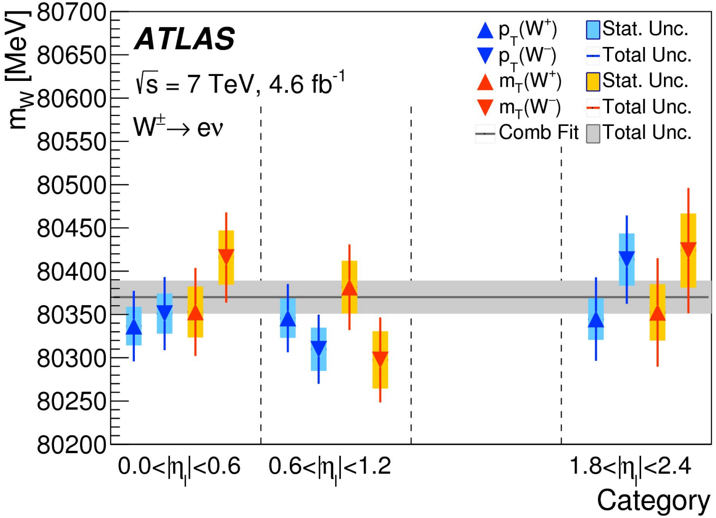
- Most precise measurement
- In significant tension with Standard Model prediction

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4\ \text{MeV}/c^2$$

Eur. Phys. J. C 78 (2018) 110

ATLAS





- W production at LHC charge-asymmetric, much more sensitive to sea quark and gluon PDFs
- Charge and rapidity-dependence partly exploited to reduce PDF uncertainties in combination

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

$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp.}) \pm 8.3(\text{QCD}) \pm 5.5(\text{EWK}) \pm 9.2(\text{PDF})\ \text{MeV}$$

	PDF Uncertainty (MeV)
per $\|\eta\|$-charge cat.	20-34
per-charge	14-15
full combination	9.2

ATLAS: Production Modeling

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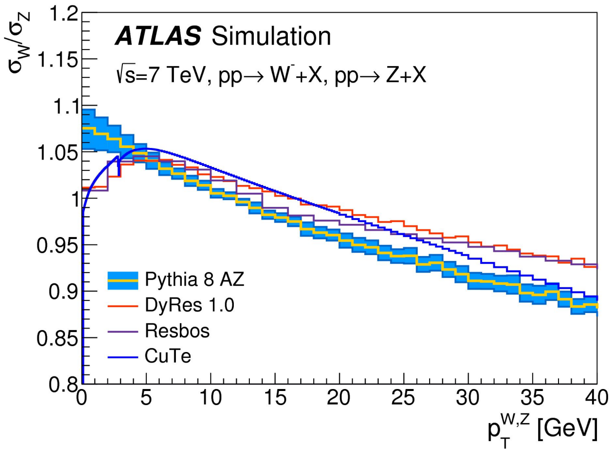

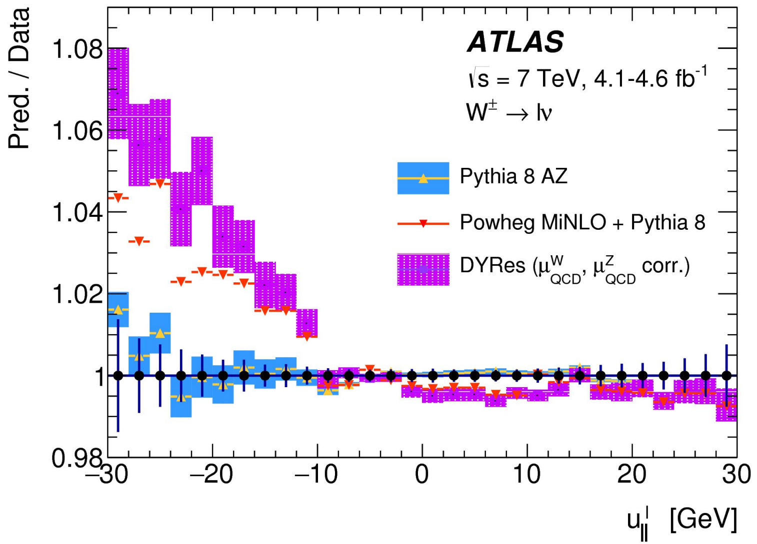

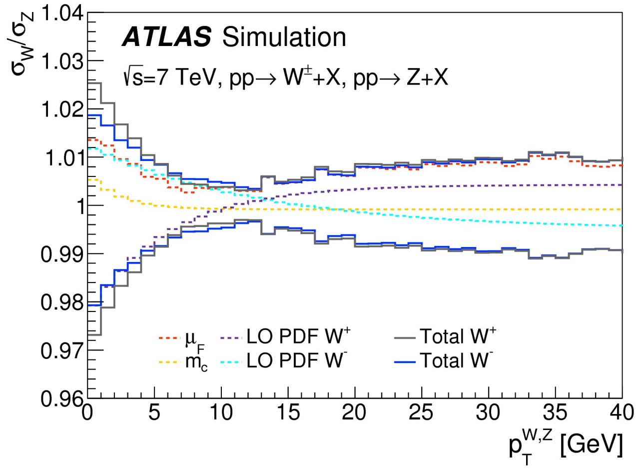

- Measured hadronic recoil distribution has some sensitivity to W pT distribution, appears to disfavour more advanced calculations of W/Z pT ratio
- Measurement relies on Pythia model tuned to Z pT, with residual uncertainties for W->Z extrapolation

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

ATLAS

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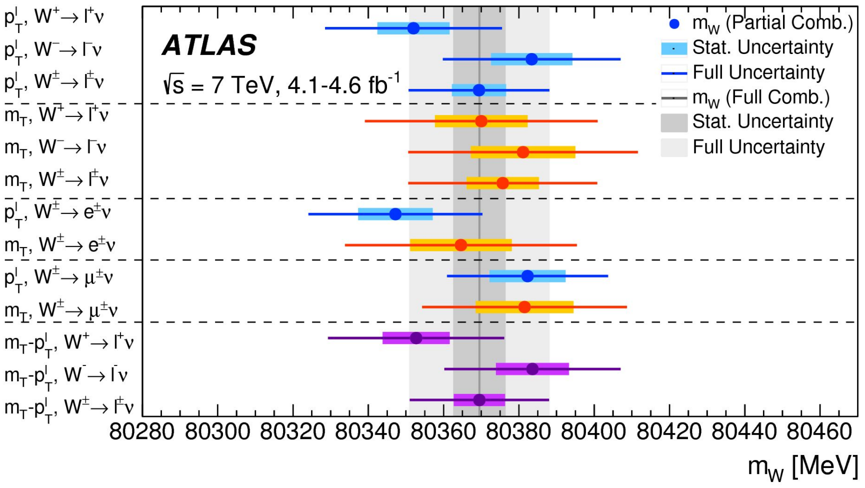
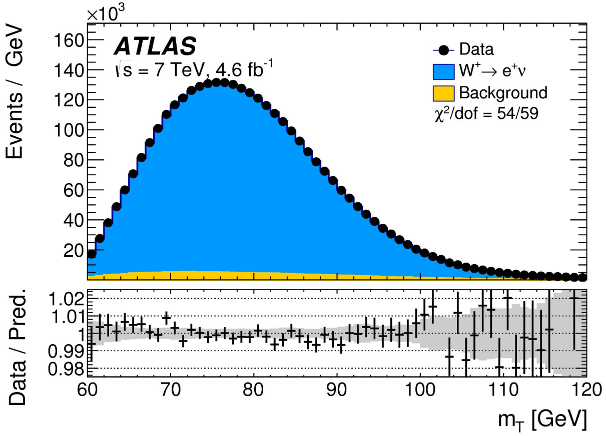
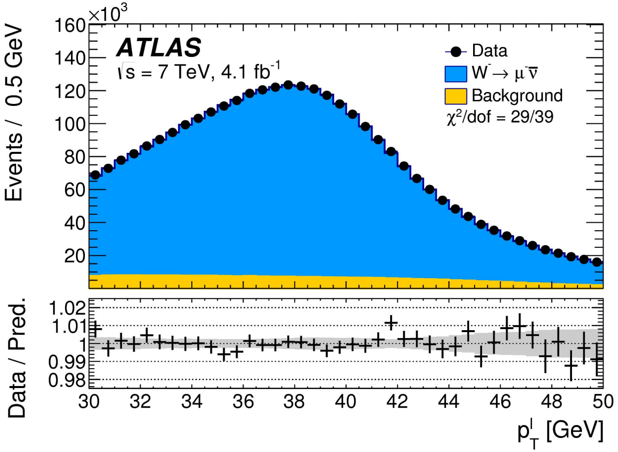




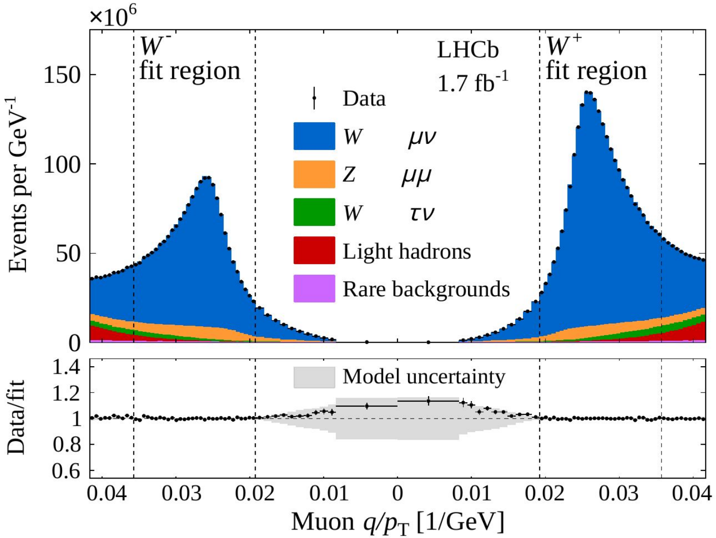


- Lepton pT has the largest contribution in combination (86%) vs transverse mass (14%)
- Electrons and muons both contribute (43%/57%)

$$m_W = 80369.5 \pm 6.8\ \text{MeV(stat.)} \pm 10.6\ \text{MeV(exp. syst.)} \pm 13.6\ \text{MeV(mod. syst.)}$$
$$= 80369.5 \pm 18.5\ \text{MeV},$$

LHCb

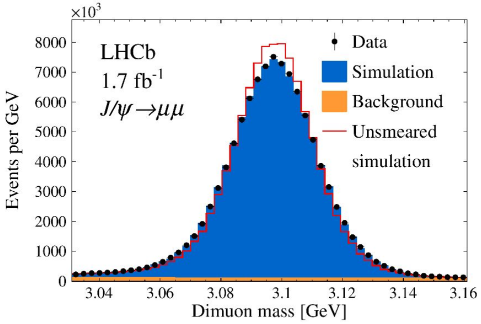
JHEP 01 (2022) 036

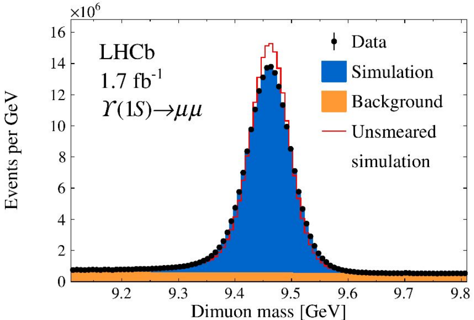


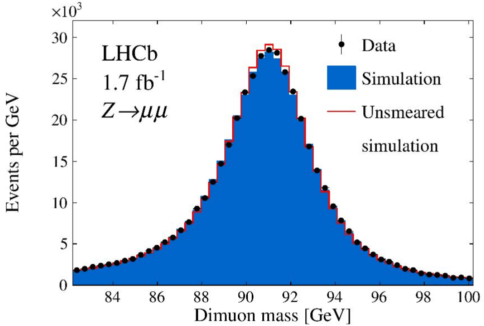
Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

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

- Detector design limits measurement to muon transverse momentum, but excellent calibration possible with quarkonia
- Unique forward phase space







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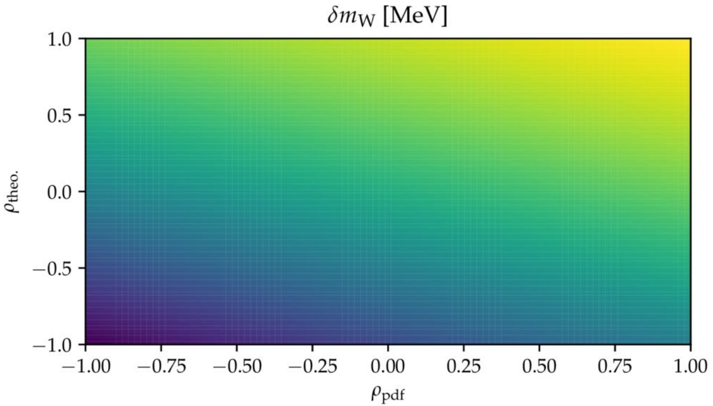
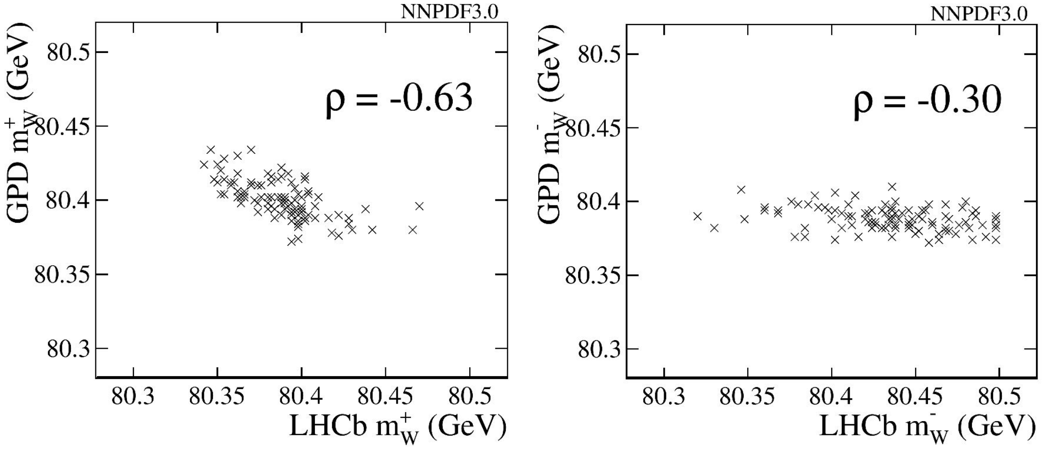
LHCb Combination prospects

- Forward phase space with respect to ATLAS and CMS leads to an anti-correlation of PDF uncertainties
- PDF uncertainties can be further reduced in combination

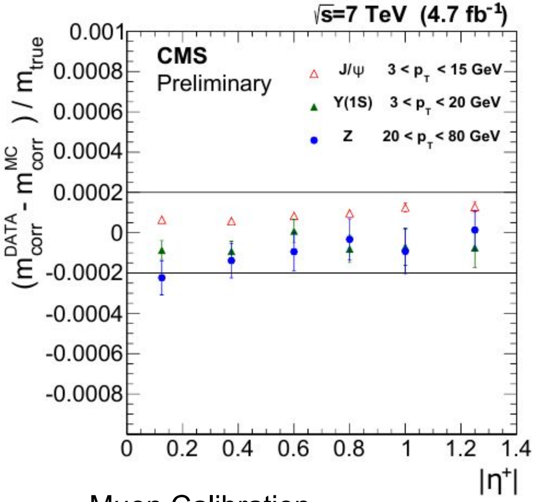




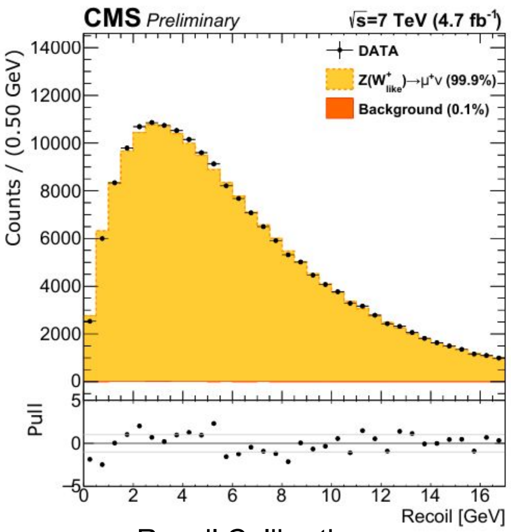
Eur. Phys. J. C **75**, 601 (2015)

CMS: W-like measurement at 7TeV

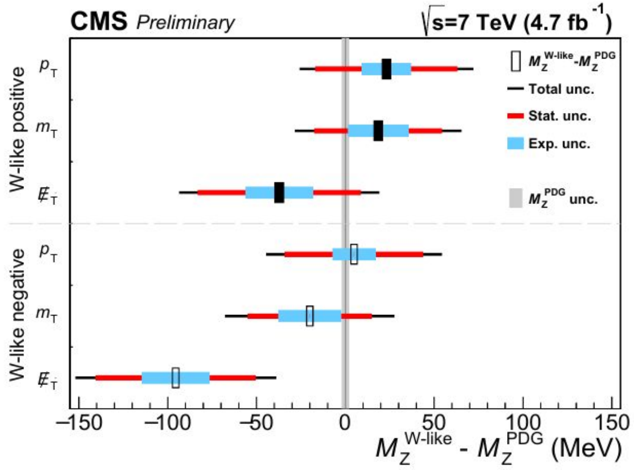
- "W-like" measurement of the Z mass
  - removing one lepton and treating as missing energy
- "Tevatron-like" like p_T^{ℓ}/m_T template fits using 7 TeV data from 2011 (4.7/fb with <μ> ~= 10)
- Central muons only (|η|< 0.9)
- J/Psi-driven momentum scale calibration for alignment, b-field, material residuals
- Commissioning/demonstration of experimental techniques as a step towards an mW measurement



Muon Calibration



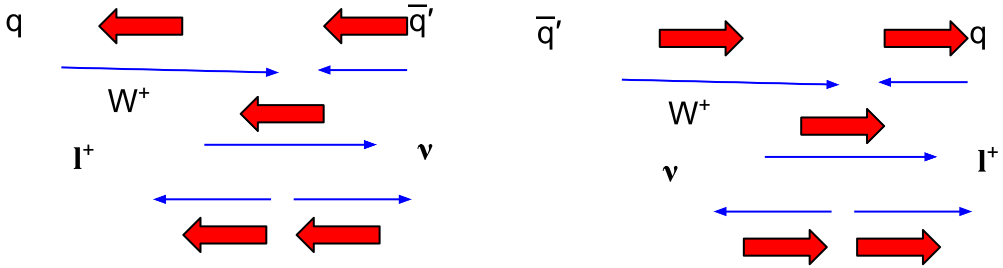
Recoil Calibration

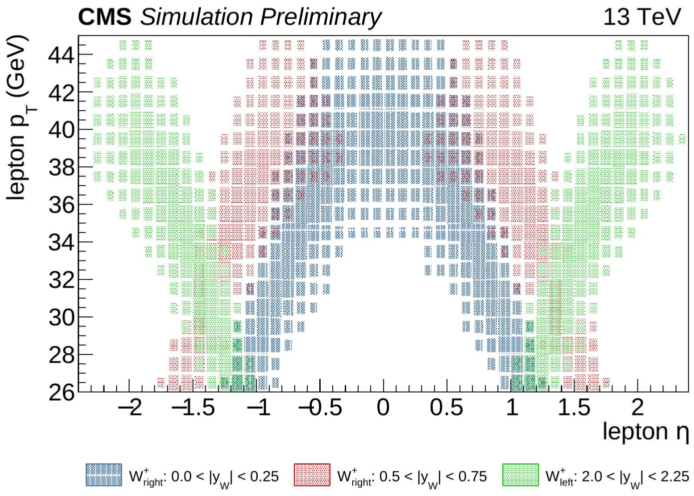


Dominant uncertainty 23 MeV on QED FSR due to issues with NLO EW matching in MC

CMS: Measurement of W helicity/rapidity

- Precision measurements of (polarized) W cross sections vs rapidity with sensitivity to PDFs
- W rapidity and helicity are inferred statistically from lepton pT-eta distribution given pure left handed coupling of the W and resulting strong correlation with lepton direction



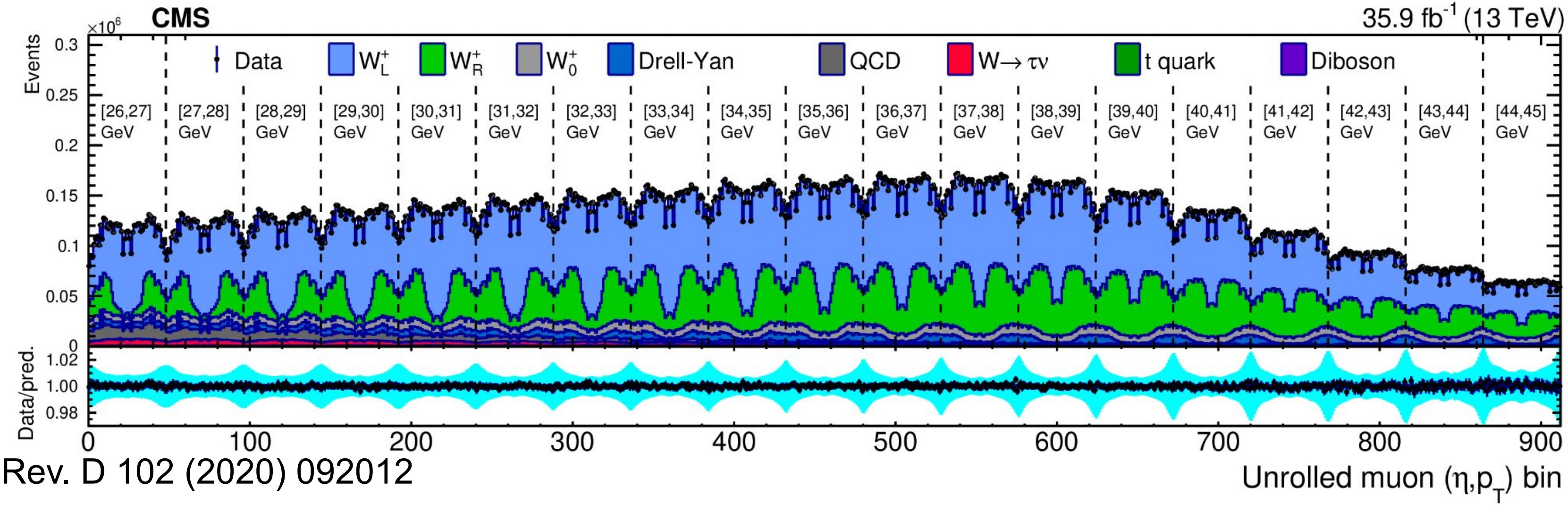


- W helicity strongly correlated with direction of incoming quark vs antiquark

Phys. Rev. D 102 (2020) 092012

CMS: Measurement of W helicity/rapidity

- Develop physics, experimental and technical aspects towards an mW measurement with reduced PDF uncertainties
  - High precision efficiencies building on 13 TeV differential Z cross section publication
  - Less stringent requirements on MC/theory uncertainties/energy/momentum calibration compared to full m_W measurement
  - Complex maximum likelihood fit to lepton pT-η distributions with O(1000) nuisance parameters

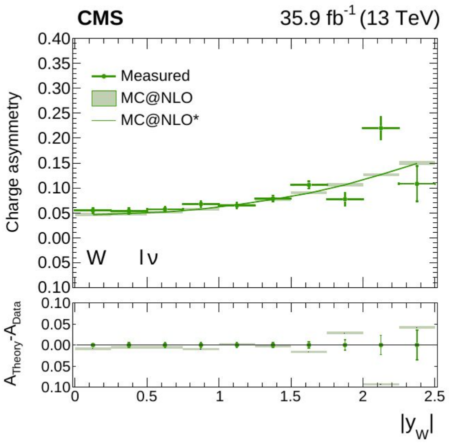


Phys. Rev. D 102 (2020) 092012

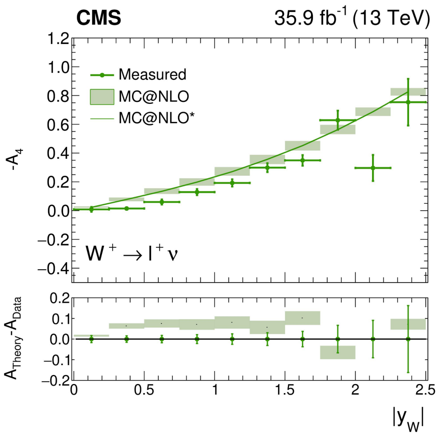
CMS: Measurement of W helicity/rapidity

Phys. Rev. D 102 (2020) 092012

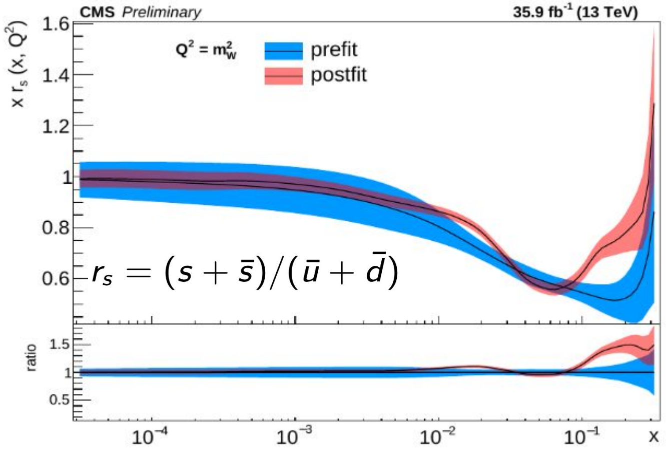
- Helicity-integrated quantities also measured without needing to make assumptions about underlying polarization



Forward-Backward Asymmetry

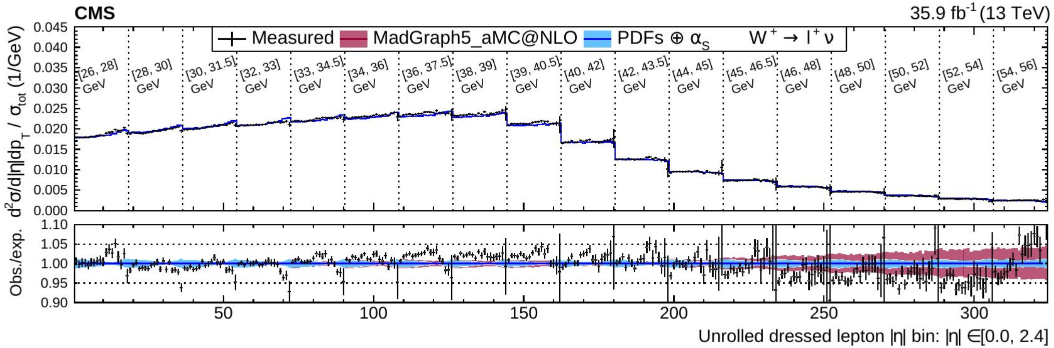


Unfolded W Charge Asymmetry



PDF Constraints

Double differential lepton xsecs



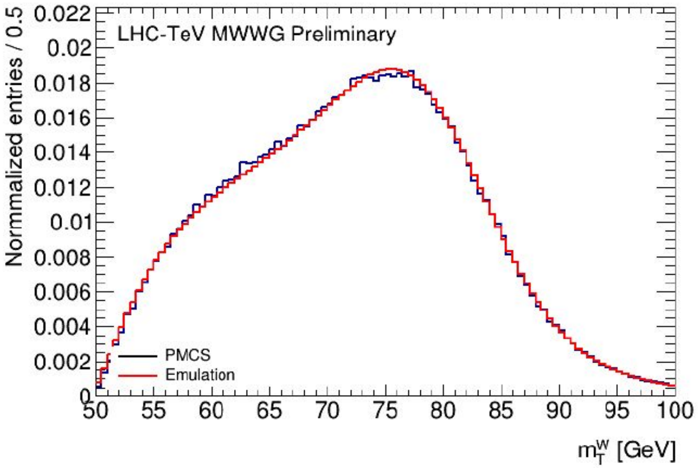
mW combination working group

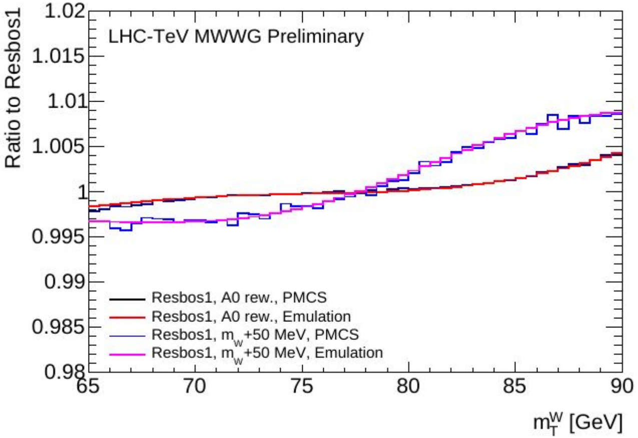
- Formal combination working group created in 2020 by agreement of ATLAS, CMS, CDF, D0 spokespersons
- LHCb started to participate following the release of their result
- **Main goal:** Official combinations of published mW results with proper treatment of correlations of systematic uncertainties
- Prerequisites
  - Discussion (documentation) of statistical methodology
  - Discussion (documentation) of theoretical modeling issues entering the measurements and their uncertainties (in close connection with LHC Electroweak Working group/WG1: Drell-Yan physics and EW precision measurements)

Combination methodology: Detector Emulation

CERN-LPCC-2022-06
FERMILAB-TM-2779-V

- Calculate shifts and/or uncertainties from changes in PDFs or theoretical modeling from a parameterized detector simulation for ATLAS/CDF/D0 (LHCb can rerun the original analysis with reweighting of fully simulated events)





D0 emulation example

- Even if emulation is not perfect, **relative** change in mW/angular coefficients/PDFs/etc can be estimated very accurately
- Systematic uncertainties from emulation at the level of 1-2 MeV

Combination Strategy

- First correct individual measurements so they are on coherent theoretical grounds
  - Common treatment of angular coefficients
  - Common PDF
    - Starting point: CDF: CTEQ6M/NNPDF31, D0: CTEQ66: ATLAS: CT10, LHCb: NNPDF31, CT18, MSHT20 average
  - Changes in (fiducial) pTW distributions from different predictions or theoretical treatment are assumed to be reabsorbed by the tuning to Z data in each experiment
- Then uncertainties are evaluated on top of this starting point and correlations properly evaluated

$$m_W^{\text{updated}} = m_W^{\text{ref}} - \delta m_W^{\text{QCD}} - \delta m_W^{\text{PDF}}$$

- This can be accomplished by reweighting generator-level events and propagating through detector emulation, **but starting point for each measurement needs to be known accurately**

Angular Coefficient Comparison: CDF/D0 vs newer generators

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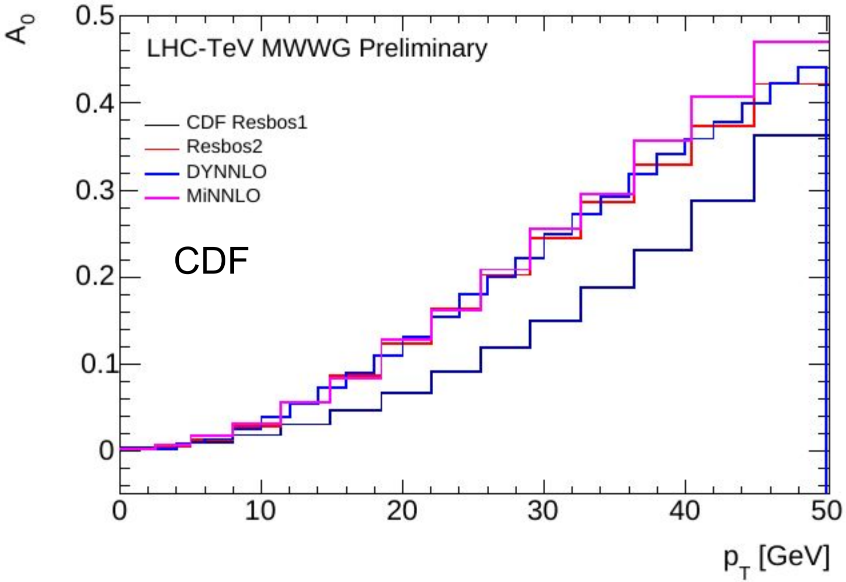

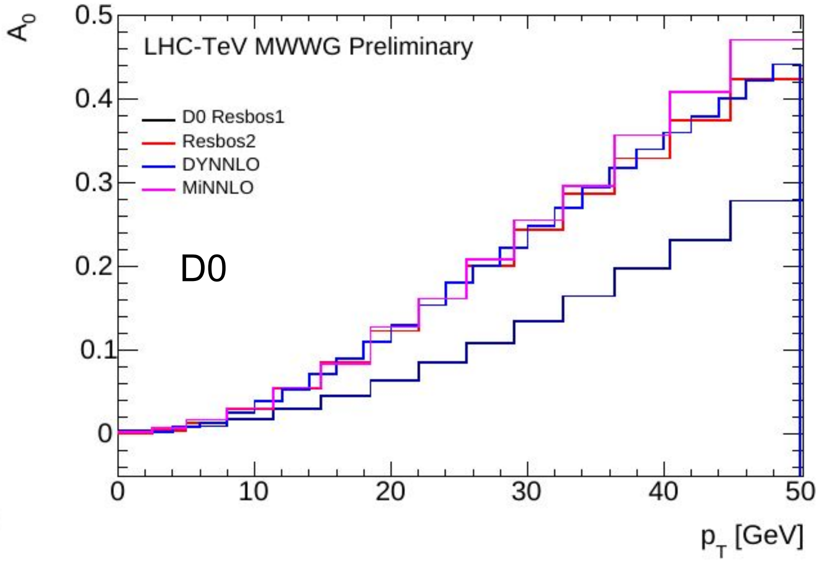

- CDF and D0 both used older (and not identical) versions of “Resbos 1” to predict W production and decay kinematics
- Older Resbos versions predict quite different angular coefficients compared to modern generators due to evolving understanding of interplay between helicity components and resummation
- Difference in fixed order accuracy (NLO vs NNLO QCD) is **NOT** the main effect here

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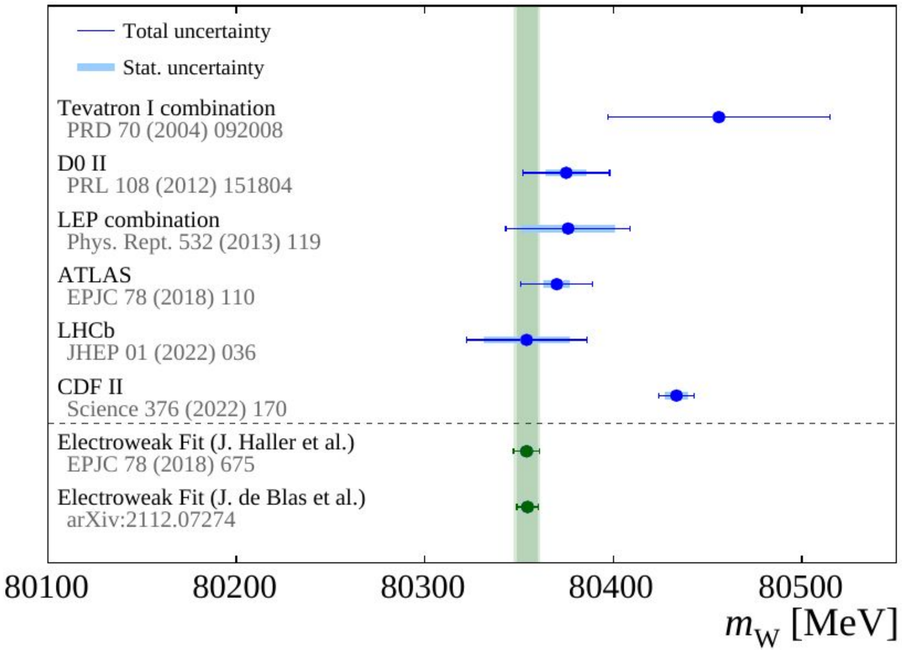
Angular Coeff Effect on mW measurement (D0) and next steps

Correction	δm_W^{QCD} [MeV]					
	p_T^W-constrained			No constraint		
	p_T^ℓ	m_T	p_T^ν	p_T^ℓ	m_T	p_T^ν
Invariant mass	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Rapidity	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
A_0	7.6	10.0	15.8	16.0	12.6	19.5
A_1	-2.4	-1.9	-1.8	-1.2	-1.6	-1.4
A_2	-3.0	-2.6	2.9	-4.2	-3.0	2.3
A_3	2.9	1.6	-0.5	3.5	1.8	-0.2
A_4	2.4	-0.1	-0.5	0.1	-0.7	-1.0
$A_0 - A_4$	7.6	7.0	16.0	14.1	9.1	18.9
Total	7.6	7.0	16.0	14.1	9.1	18.9
ResBos2	7.3±1.1	8.4±1.0	16.6±1.2	13.9±1.1	10.3±1.0	19.8±1.2
Non-closure	-0.3±1.1	1.4±1.0	0.6±1.2	-0.2±1.1	1.2±1.0	0.9±1.2

Table 5: Effect of reweighting the angular coefficients in the D0 ResBos1 events to those of ResBos2, as well as a direct fit of ResBos1 to ResBos2. Good closure is observed.

- 7-14 MeV shift of D0 measurement to **lower** mW values
- Next steps
  - Corresponding numbers being evaluated for CDF
  - Evaluation of PDF shifts to be completed
  - Strategy to be finalized for compatibility between measurements and/or different PDF sets
  - Full combination in progress (including LHCb measurement)

Conclusions

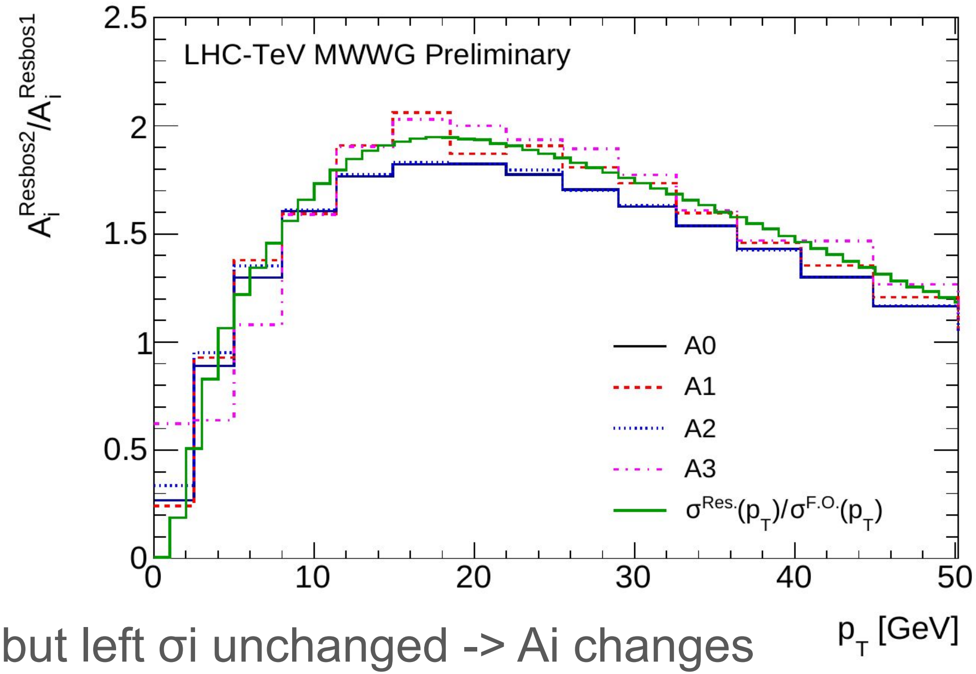


- mW measurements at hadron colliders are an extreme experimental and theoretical challenge
- Measurements of mW so far from CDF, D0, ATLAS, LHCb
- Most recent and precise measurement from CDF in significant tension with the Standard Model and other measurements
- Ongoing effort in LHC-Tevatron mW combination working group including detailed understanding of experimental and theoretical correlations
- Theory community is actively engaged through LHC Electroweak WG and other fora, with rapid progress on precise W/Z predictions
- Further measurements expected from ATLAS, CMS, LHCb
  - More data
  - Exploit different beam energy and pileup conditions
  - More advanced analysis techniques
  - More advanced theoretical inputs

Backup

Why do old Resbos versions predict “different” angular coefficients?

- “Angular coefficient” Ai can be constructed as a ratio of cross sections σi/σUL (where σUL is the unpolarized xsec)
- Unpolarized xsec σUL is divergent as pT->0 at fixed order and must be resummed
- Because Ai=0 at LO (except for A4), the numerator remains finite



- Old resbos versions resummed σUL but left σi unchanged -> Ai changes wrt fixed order prediction
- Newer generators apply the same ratio to numerator and denominator to preserve fixed order Ai
- Theoretical ambiguity to some extent

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