News on the Measurements of the W Boson Mass

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Electroweak Precision Physics

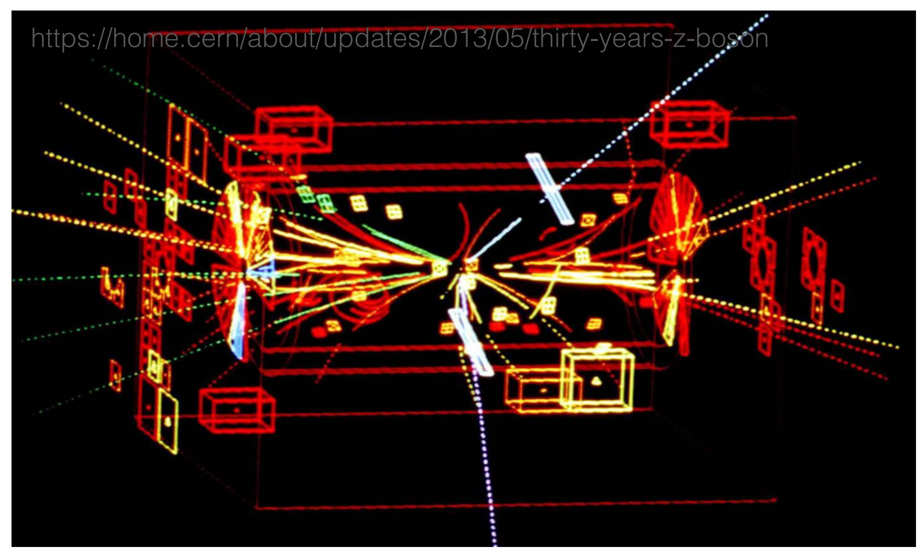
Summary of the Electroweak Sector

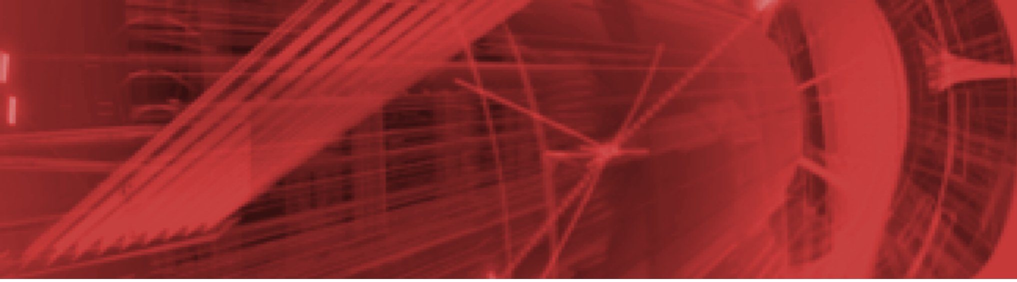
- The electroweak sector of the Standard Model has five parameters
  - α_{em}, G_F, m_W, m_Z, $\sin^2\theta_W$
  - (+ m_H for the scalar sector)

- However, they are not independent, but related by theory

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

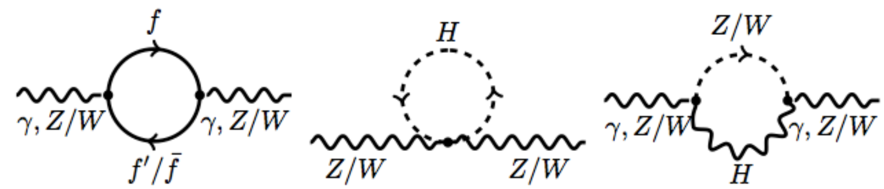
$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$





Radiative Corrections

- Tree-level not sufficient
  - The impact of corrections stored in **EW form factors**



- The relation between SM parameters appear with **quadratic dependence on m_{top}, logarithmic dependence on M_H**

$$\sin^2\theta^f_{\text{eff}} = \kappa^f_Z \sin^2\theta_W$$

$$g_{V,f} = \sqrt{\rho^f_Z}(I^f_3 - 2Q^f \sin^2\theta^f_{\text{eff}})$$

$$g_{A,f} = \sqrt{\rho^f_Z} I^f_3$$

$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

- Idea of electroweak fits
  - Measure many different observables
  - Calculate the relations between all observables
  - **Probe the consistency of the SM / Predict observables**

$$M_W\left(\ln(M_H), m_t^2, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M_Z^2), \alpha_s(M_Z^2)\right)$$

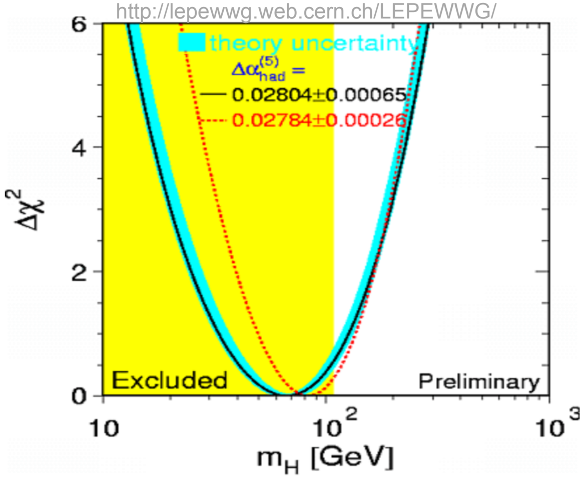
$$\sin^2\theta^f_{\text{eff}}\left(\ln(M_H), M_H, m_t^2, M_Z, \Delta\alpha^{(5)}_{\text{had}}(M_Z^2), \alpha_s(M_Z^2)\right)$$

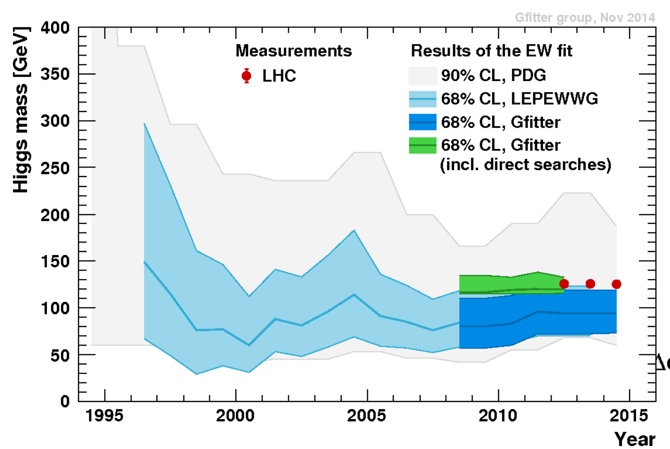
Input and Outcome to the Electroweak Fit

- Input for the gobal electroweak fit mostly from
  - LEP: Z boson observables
  - Tevatron: W boson, top quark mass
  - LHC: **Higgs Boson, top quark mass**

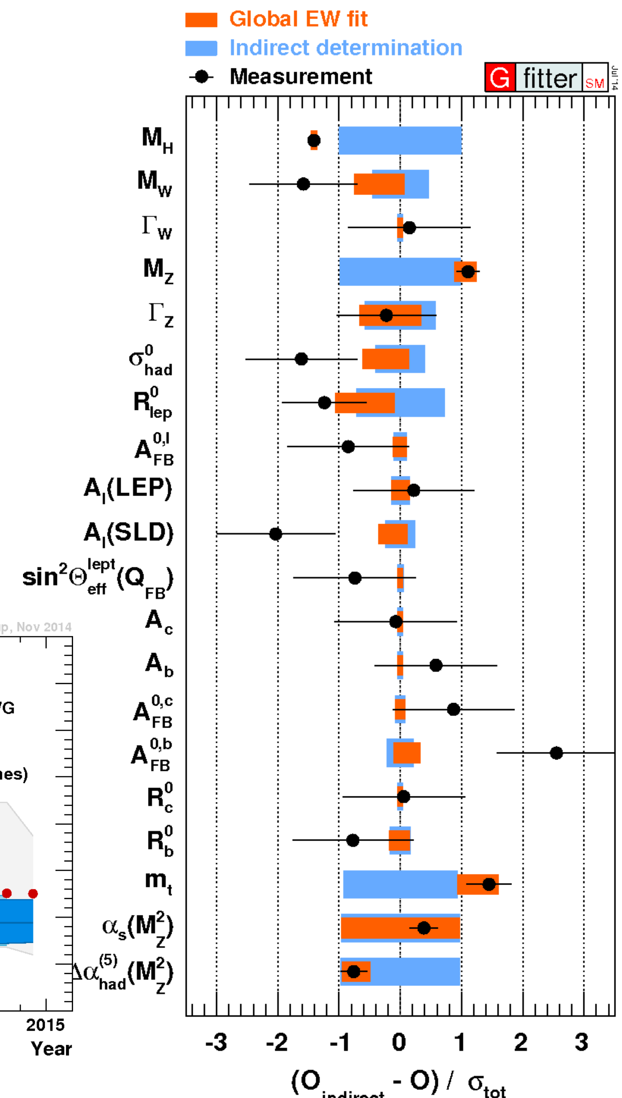
- Result: **Amazing predictions!**
  - Top-Quark mass before its discovery
  - Higgs-Boson mass before its discovery and the funding argument for the LHC

http://lepewwg.web.cern.ch/LEPEWWG/



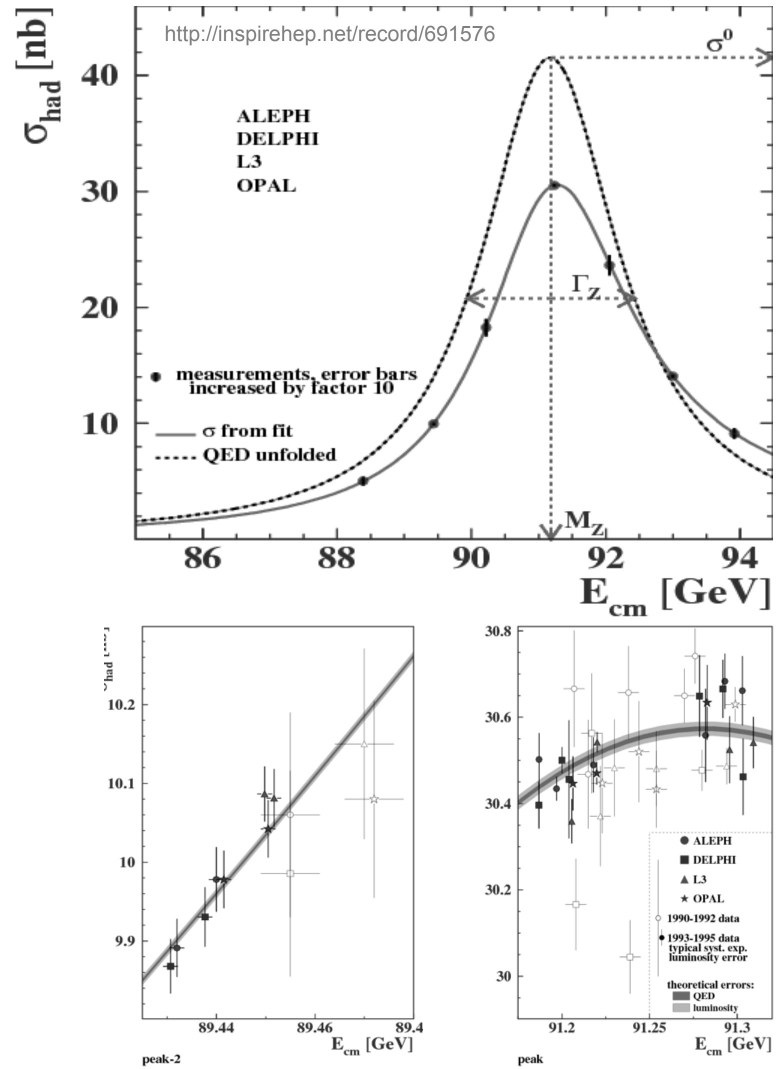


http://project-gfitter.web.cern.ch/project-gfitter/



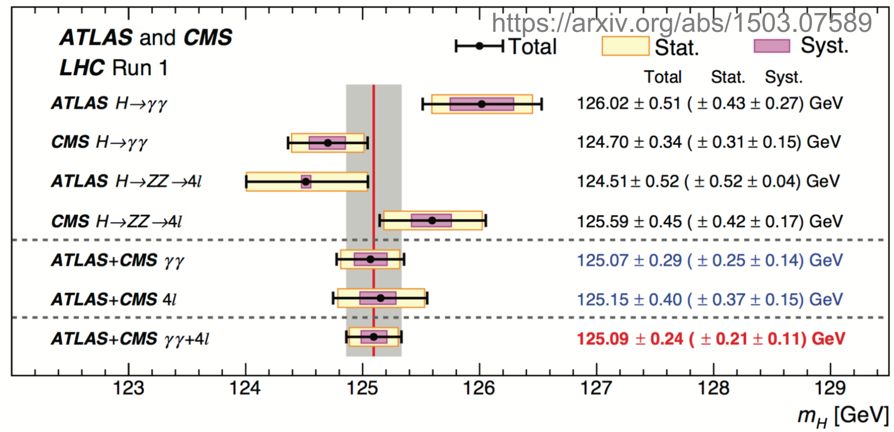
Z Boson Measurements at LEP

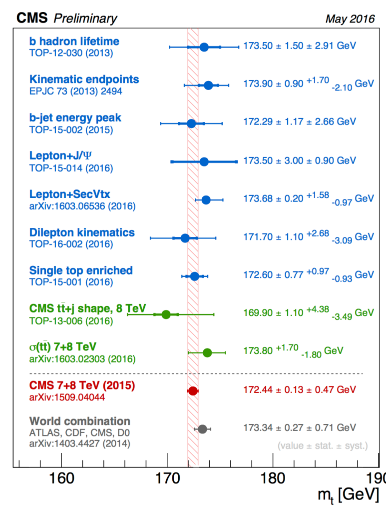
- Z bosons can be produced directly in e^+e^- collisions, i.e. we can scan the Breit-Wigner lineshape
- We do **not need to reconstruct energy** of the decay particles
  - Mass measurement is reduced to a **pure counting experiment**
- Reach enormous precision
  - **Mass known to 2 MeV!**
- Not only crucial input for the electroweak fit, but also for the LHC detector calibration!



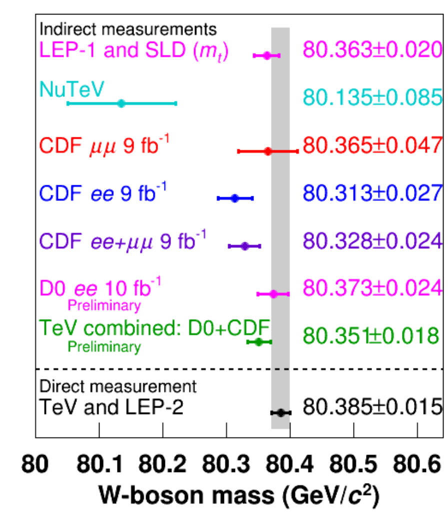
Where do we stand and what do we need?

- Z boson observables: **LEP was great**; we can't do better (now)
- Top-quark mass: huge progress; **new approaches** to overcome theoretical unc. on m_{top}
  - (SM prediction ±2.5 GeV, measurement unc. <0.7 GeV)
- Higgs mass: Only **logarithmic dependence**, hence not important for the fit
- **W mass:** SM prediction at 5 MeV precision, known only to 19 MeV!
  - **Here we can gain a lot!**





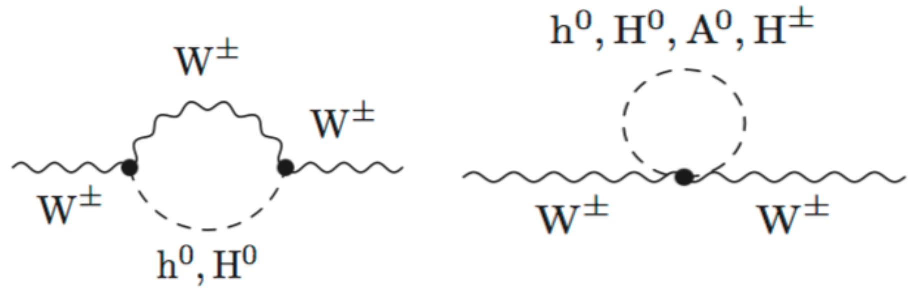
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures



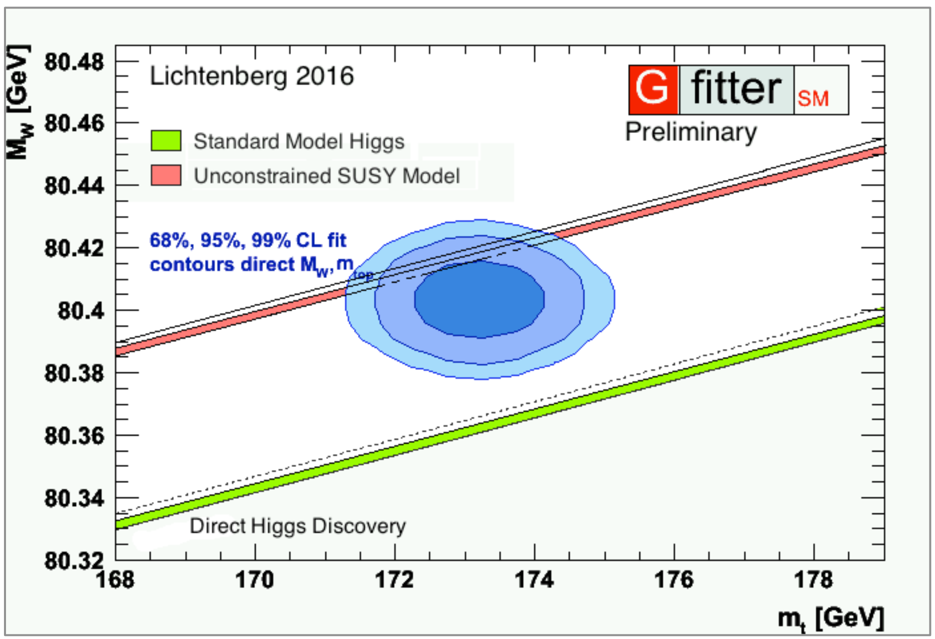
http://pdg.lbl.gov/2014/reviews/rpp2014-rev-w-mass.pdf

Why do we need that?

- So far a "simple" thing: test consistency of the SM
  - Current **p-value = 0.22**
- But electroweak precision measurements are **sensitive to several new physics scenarios**, e.g. SUSY
  - Radiative correction depends on mass splitting (Δm^2) between squarks in SU(2) doublet
  - Precision on m_W could significantly limit the allowed MSSM space



Inspired by [S. Heinemeyer et. al. arXiv:1311.1663]



Measurement Strategy

Mass Sensitive Variables

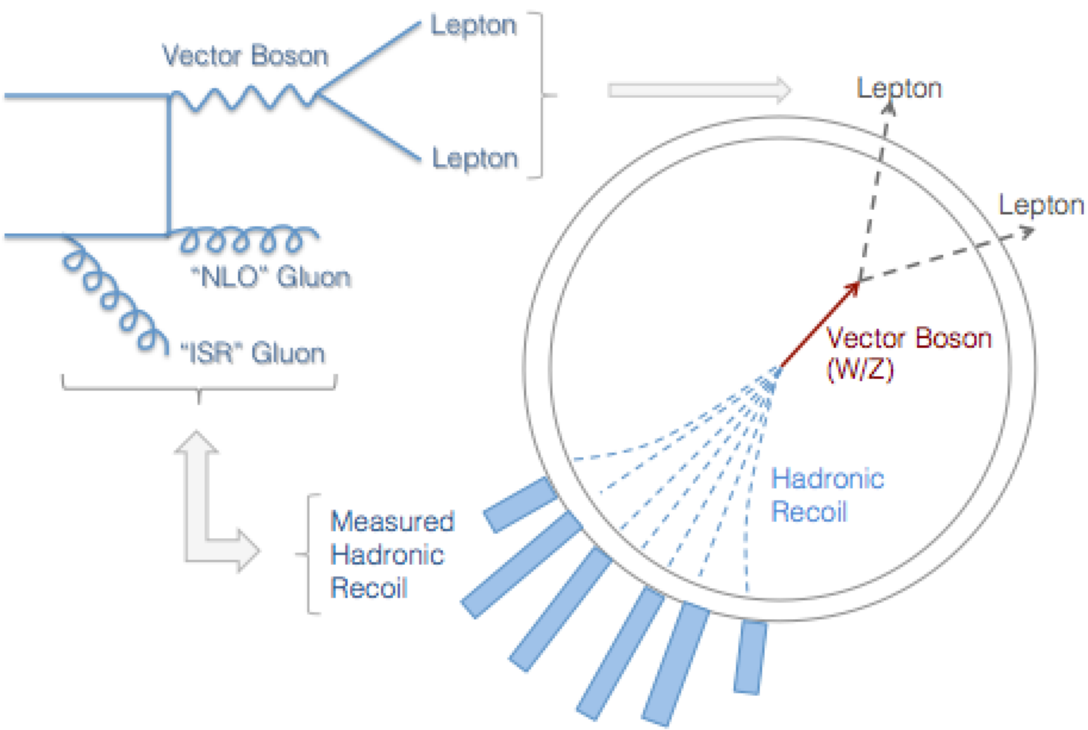
- **Main signature**: final state lepton (electron or muon): p_T(lepton)

- **Recoil:** sum of "everything else" reconstructed in the calorimeters
  - a measure of $p_T(W,Z)$
  - gives us also missing transverse energy

$$\vec{u}_T = \sum_i \vec{E}_{T,i}$$

$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,l} + \vec{u}_T\right)$$

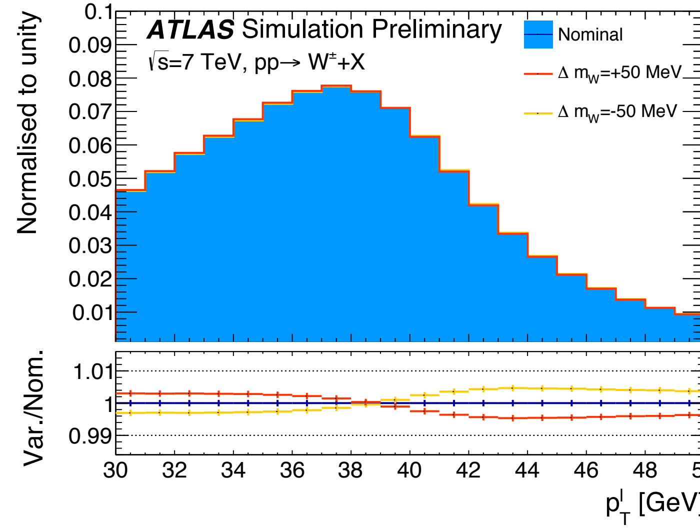
$$m_T = \sqrt{2 p_T^l p_T^{miss}(1 - \cos\Delta\phi)}$$

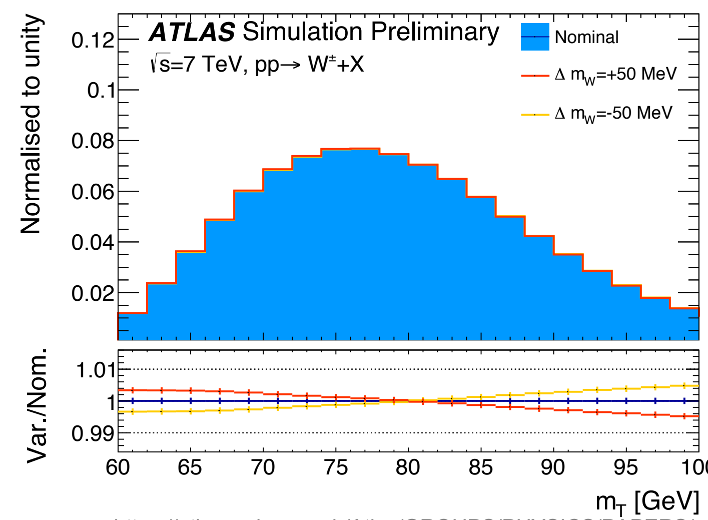


Mass Sensitive Variables

- Sensitive final state distributions:
  - Lepton transverse momentum $p_T(l)$
  - Transverse mass: m_T
  - Missing transverse energy ("neutrino p_T"): p_T^{miss}

- Template-Fit approach
  - Assume various W boson mass values in MC event generator and predict the $p_T(l)$, m_T , p_T^{miss} distributions
  - Compare to data
  - Mass determination by χ^2 minimization





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-18/

Why is this measurement complicated?

W Boson Mass

We want to achieve a relative precision of 0.01%

Experimental Aspects

To which precision do we know what the detector measures?

Physics Modelling

The W boson is not at rest, so with which kinematics is the W boson produced?

Muons	Electrons	PDFs	$p_T(W)$
Had. Recoil	Backgrounds	EW Cor.	Angular Coeff.

Focus during the first years of the project

Focus during the last years of the project

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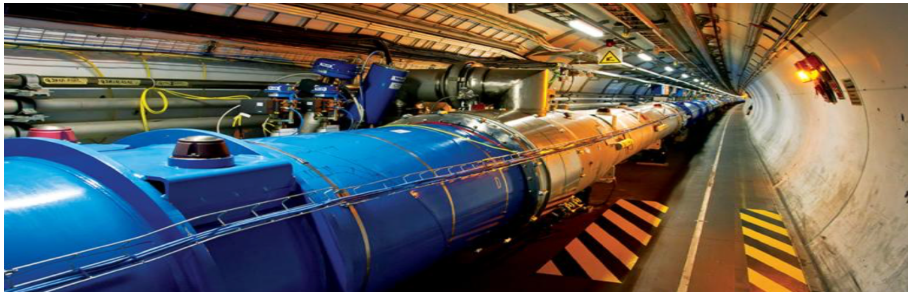
Simple Life in the USA

Measurement Strategy at LHC and Tevatron



- **Parameterized** (not full) **simulation** that includes all corrections
- Low pile-up

- CDF-Experiment: e/mu channel
  - Only 20% of data-set used
  - Calibration: J/Psi, Upsilon, Z

- D0-Experiment: e-channel
  - Acceptance up to $\eta<1.0$
  - Calibration: Z boson only

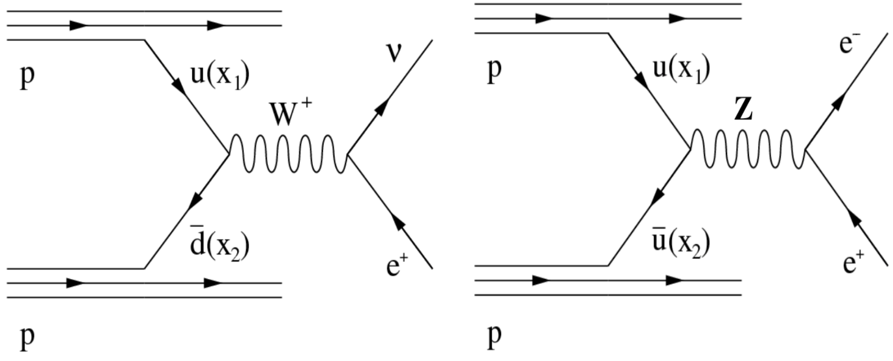
- Analysis based on **full simulation**
  - PowhegPythia (NLO QCD+PS);
  - QED FSR using PHOTOS
  - **Reweighting to correct for physics and detector modelling**

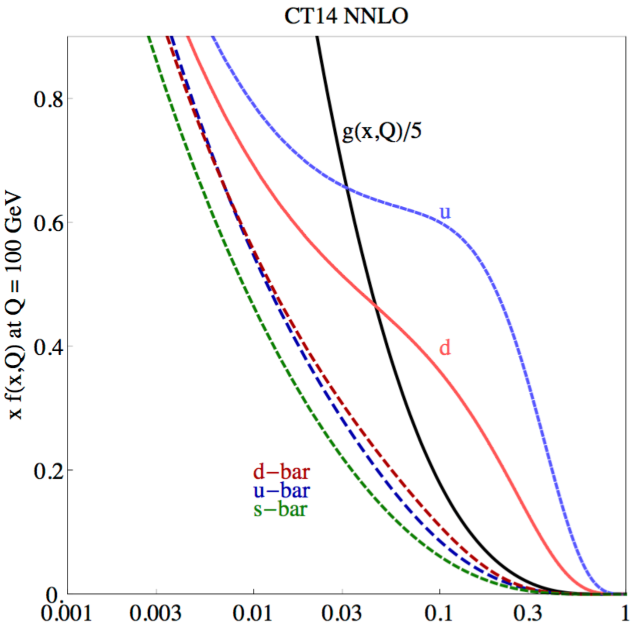
- Data-Set: Run 1 (2011)
  - 7 TeV, 4.6 fb^{-1} (e), 4.1 fb^{-1} (μ)
  - Mature, well understood data; moderate (but still significant) pile-up

Production of W Bosons at the LHC and Tevatron

- **Tevatron:** Proton / anti-protons
  - Main production involves up and down quarks
  - small impact of heavy quarks
  - No differences between W+/W-
  - Similar production of Z bosons

- **LHC:** Proton-proton collisions
  - Heavy quarks become important in the production
  - Different production modes of W+ and W-
  - Z Boson production still dominated by light quarks





http://hep.pa.msu.edu/cteq/public/

Measurements at the Tevatron

- Do not worry about tables
  - These tables have been my life for 5 years!
- Experimental uncertainties
  - CDF: 10 MeV (Lepton Scale, Hadronic Recoil)
  - D0: 18 MeV (Lepton Scale)
- Physics modelling dominated by PDFs: **10-11 MeV for both**
- Precision after >10 years
  - **CDF: 19 MeV**
  - **D0: 26 MeV**

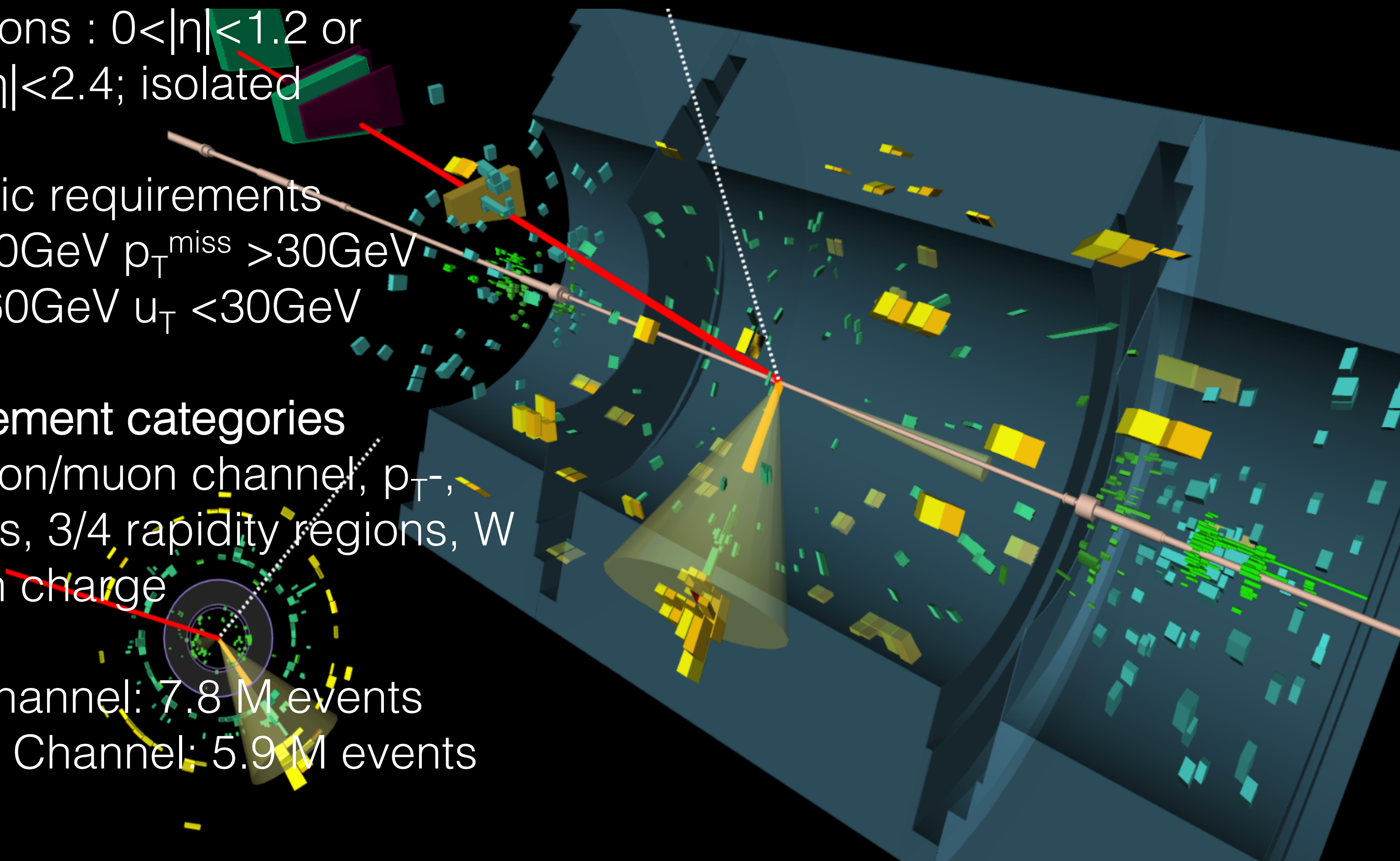
[Phys Rev. D88 (2013)]

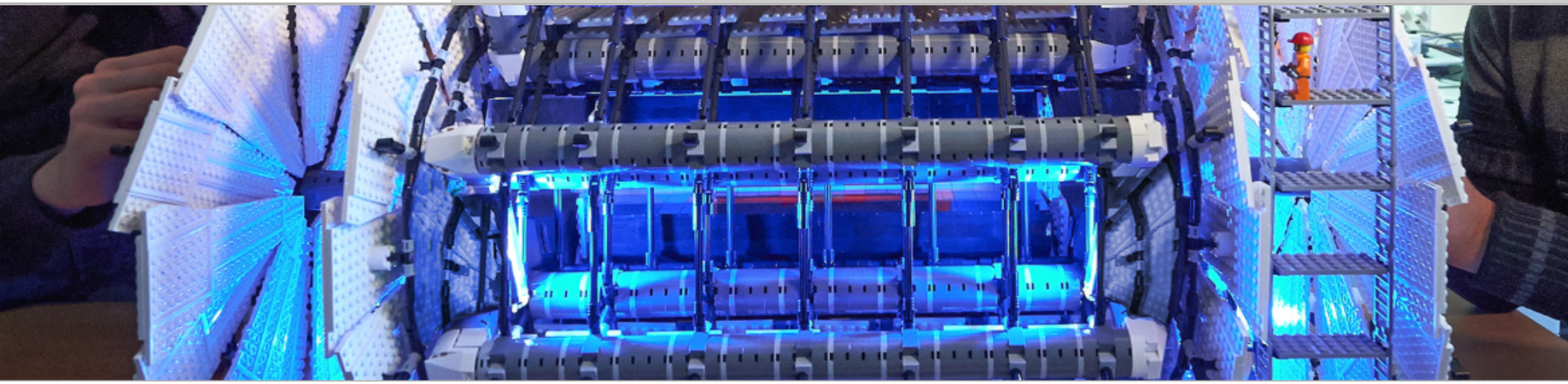
Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal from recoil	2
Backgrounds	3
Experimental subtotal	10
Parton distribution functions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson event yield	12
Total uncertainty	19

Source	Uncertainty (MeV)
Electron energy calibration	16
Electron resolution model	2
Electron shower modeling	4
Electron energy loss model	4
Recoil energy scale and resolution	5
Electron efficiencies	2
Backgrounds	2
Experimental subtotal	18
Parton distribution functions	11
QED radiation	7
$p_T(W)$ model	2
Production subtotal	13
Total systematic uncertainty	22
W-boson event yield	13
Total uncertainty	26

Signal Selection and Measurement Regions

- Lepton selections
  - Muons : $|\eta| < 2.4$; isolated
  - Electrons : $0<|\eta|<1.2$ or $1.8<|\eta|<2.4$; isolated
- Kinematic requirements
  - $p_T > 30$GeV $p_T^{miss} > 30$GeV
  - $m_T > 60$GeV $u_T < 30$GeV
- **Measurement categories**
  - Electron/muon channel, p_T-, m_T-Fits, 3/4 rapidity regions, W boson charge
- Muon Channel: 7.8 M events
- Electron Channel: 5.9 M events

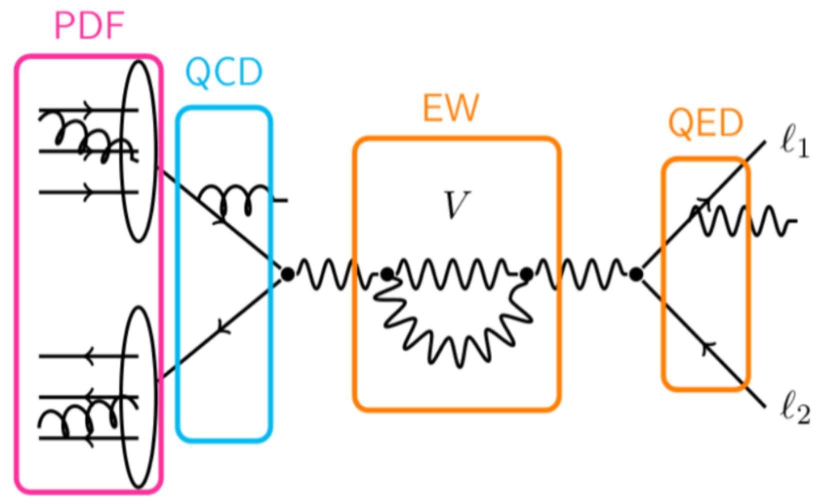




Physics Modelling

Physics Modelling

- No available generator can describe all observed features: $p_T(Z)/p_T(W)$, A_i, …
  - Variation of $d\sigma/dm$ modeled with a Breit-Wigner + EW cor.
  - $d\sigma/dp_T$ is modeled with PS MC
  - $d\sigma/dy$ modeled at NNLO
  - $A_i(y,pt)$ modeled at NNLO



- QCD aspects
  - Rapidity, p_T distributions; angular distributions

$$\frac{d\sigma}{dp_1 dp_2} = \left(\frac{d\sigma}{dm}\right)\left(\frac{d\sigma}{dy}\right)\left(\frac{d\sigma(p_t,y)}{dpt}\frac{1}{\sigma(y)}\right)\cdot$$

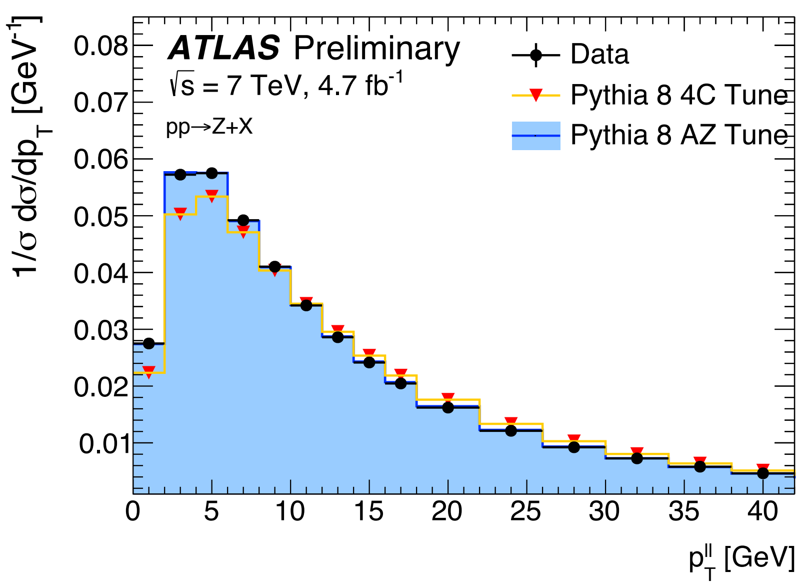
$$\cdot\left(\sum_i A_i(y,p_t)P_i(\cos\theta,\phi)\right)$$

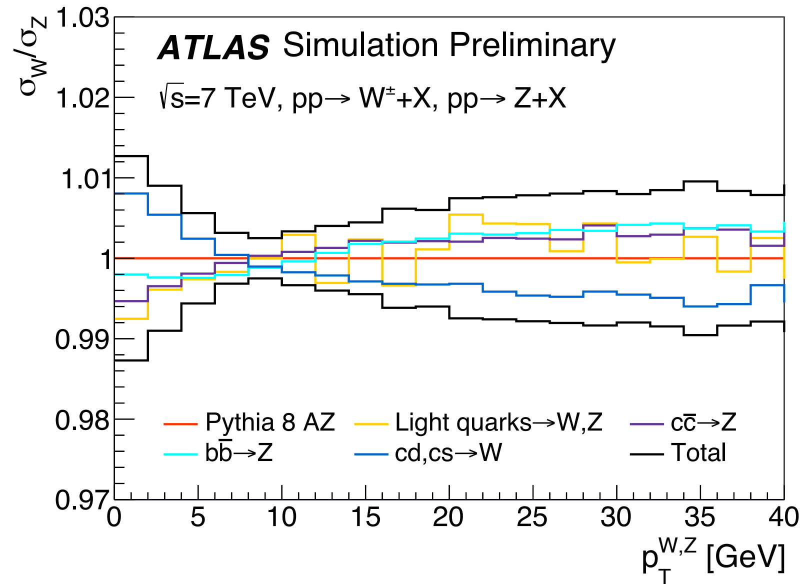
- EW aspects
  - ISR and FSR QED corrections
    Missing higher-order effects

Transverse Momentum (A several years effort)

- **Traditional approach:** fit predictions to Z data, apply to W
  - primordial k_T; α_S^{ISR}; ISR cut-off
  - Tested with Powheg+Pythia8, and **Pythia8 standalone**

- **Associated Uncertainties:** Z Boson Data, Parton Show Variations and
  - Z→W extrapolation : factorization scale variations (separately for light- and heavy-quark induced production), heavy quark masses

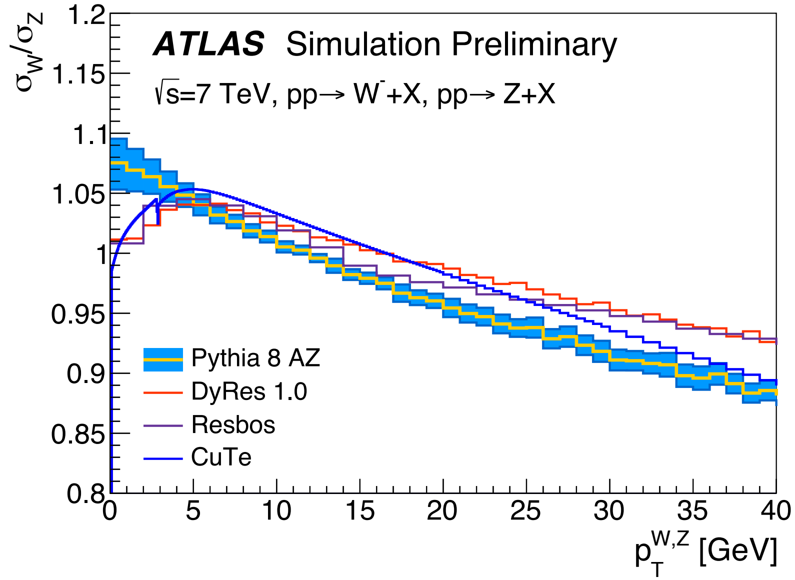


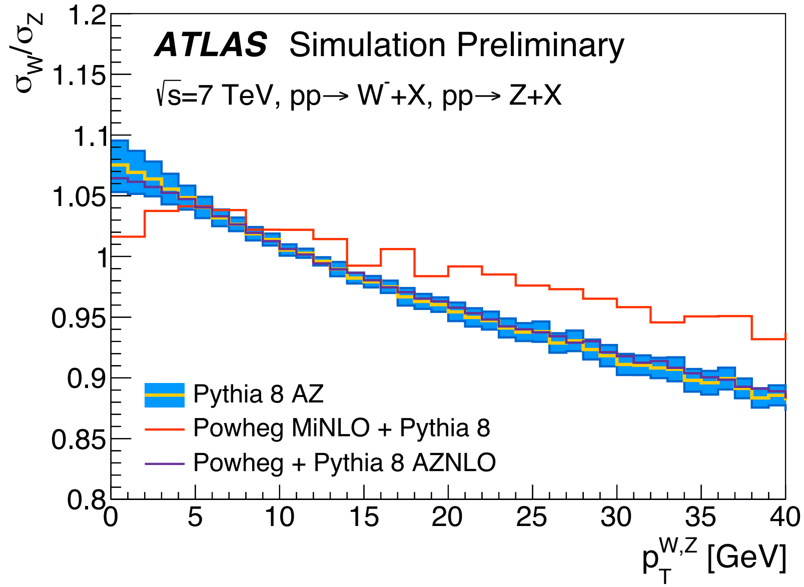


Transverse Momentum (A several years effort)

- Theoretically more advanced calculations were also attempted
  - DYRES (and other resummation codes : ResBos, CuTe)
  - Powheg MiNLO + Pythia8

- All predict a **harder $p_T(W)$ spectrum for given $p_T(Z)$** distribution
  - Behaviour is **disfavoured by data** (see later)





Overview of QCD Uncertainties

- CT10nnlo uncertainties (synchronized in DYNNLO and Pythia) + envelope comparing CT10 to CT14 and MMHT.
  - Strong **anti-correlation of uncertainties for W_+ and W^-!**
- AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
- **A_i uncertainties from Z data**; envelope for A_2 discrepancy

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

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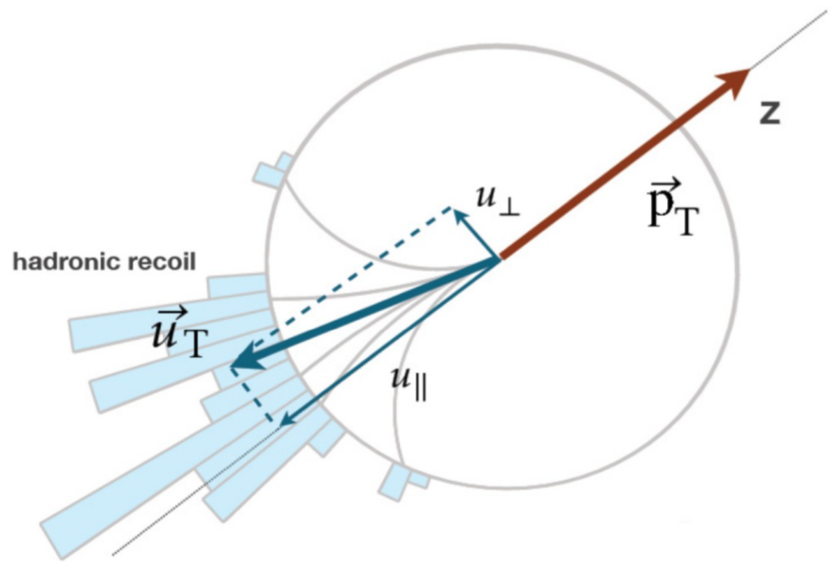
Detector Calibration

Mass Sensitive Variables

- Lepton calibration
  - momentum calibration using the Z peak
  - efficiency corrections (reconstruction, identification, trigger) rederived via tag- and probe-method in 3 dimensions

- Recoil calibration
  - Event activity corrections
  - Recoil response calibration using expected p_T balance between lepton pairs and u_T in Z events

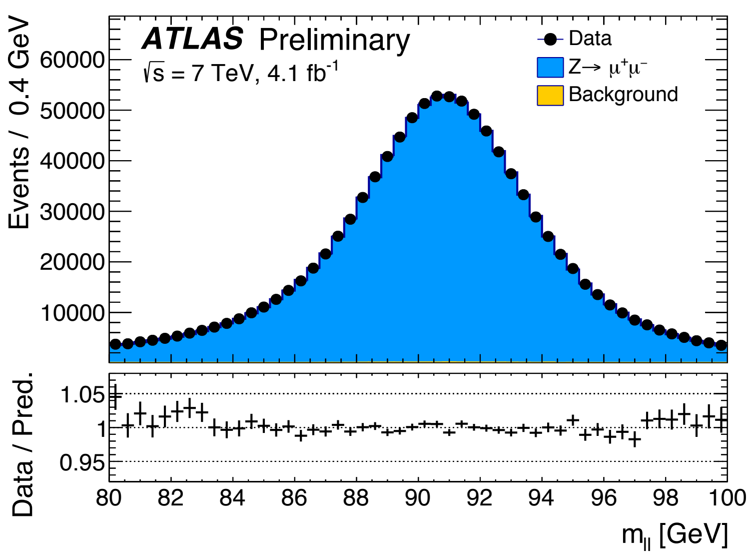


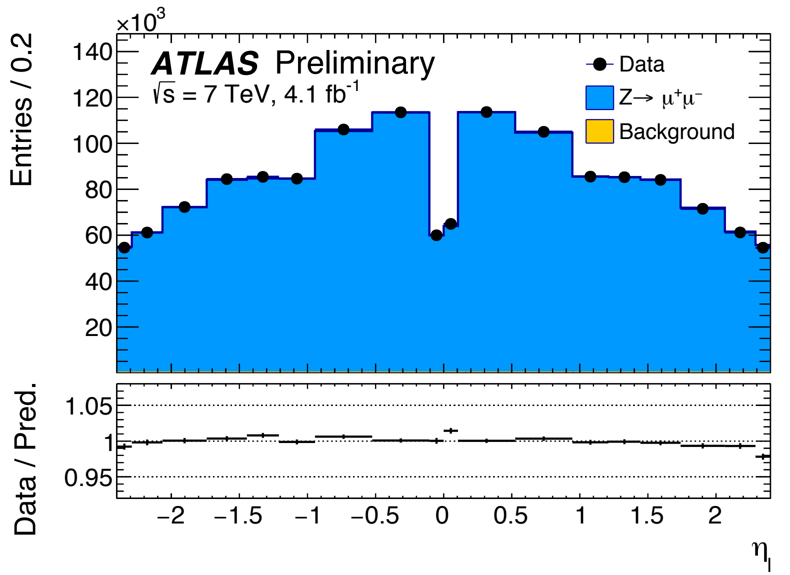
Muon Momentum and Efficiency Calibration

- Parameterization of momentum corrections:

$$p_T^{MC,corr} = p_T^{MC} \times \left[1 + \alpha(\eta.\phi)\right] \times \left|1 + \beta_{curv}(\eta) \cdot G(0,1) \cdot p_T^{MC}\right|$$

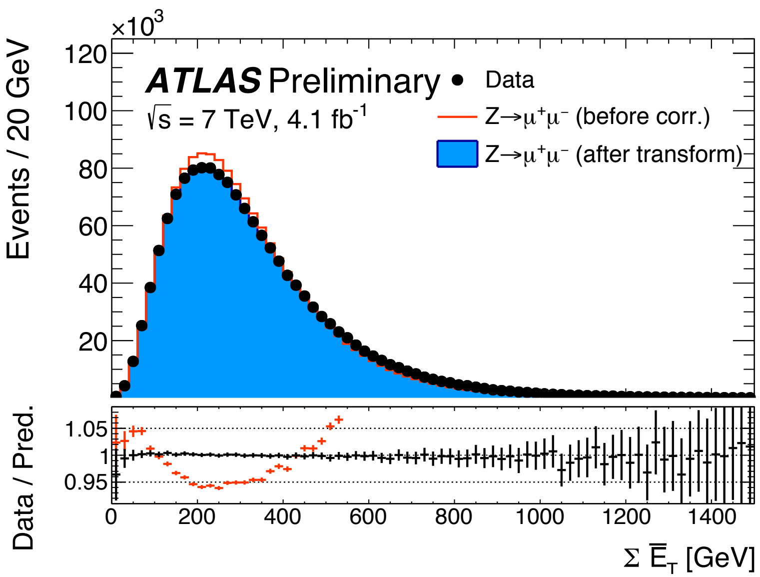
- Momentum scale and resolution corrections probed using Z→μμ events
- Also to correct: **Track sagitta** bias from rotational detector deformations
  - Using W→μν events for overall effect and Z→μμ for eta-calibration

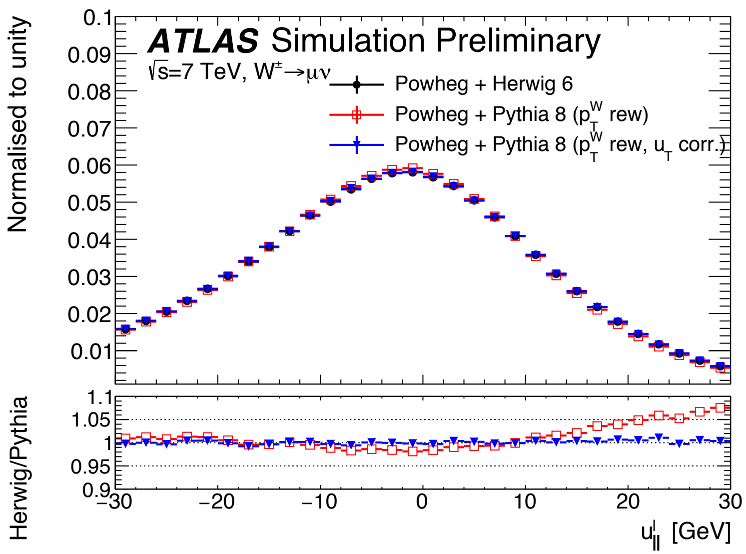




Hadronic Recoil Calibration

- Recoil correction steps
  - Step 1: Equalize pile-up multiplicity distribution in data and MC
  - Step 2: Correct for residual differences in the ΣE_T distribution
    - removes u_T resolution discrepancy due to imperfect event activity mis-modeling
  - Can be done directly in W events – no extrapolation systematics
- MC based closure test!

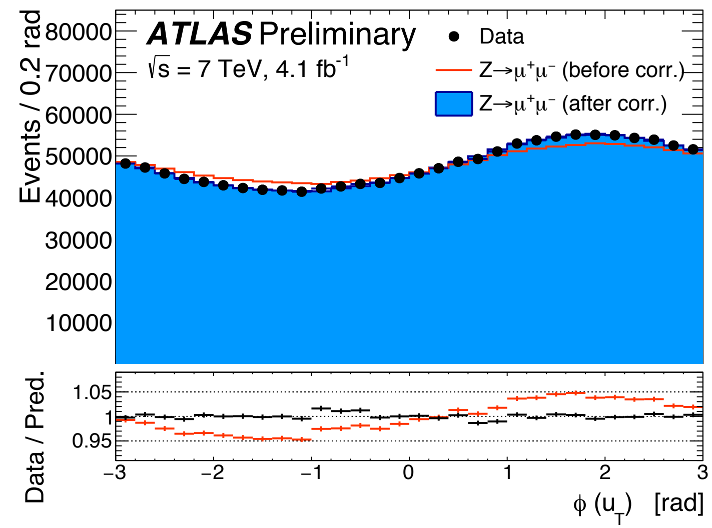


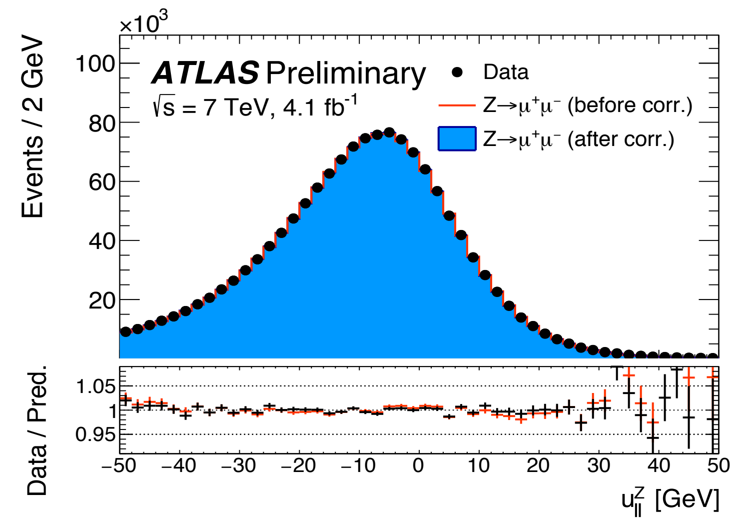


A distribution which took us months

- Typically one expects a Φ symmetry of the detector response (and the physics)

- We observed significant differences to MC
  - **offset of the interaction point** with respect to the detector center in the transverse plane
  - **Non-zero crossing angle** between the proton beams
  - **ϕ-dependent response of the calorimeters**





3 tables after 3 years of work

- Experimental uncertainty due to muon detector calibration on the 10 MeV level
  - In terms of average accuracy on the position resolution, this means μm-precision!
- Not even discussed here: **How to estimate backgrounds**
  - We control the background contributions on **a rel. 5% level!**
  - Final background related uncertainties
    - p_T-fit: 3-5 MeV
    - m_T-fit: 8-9 MeV (elec.)
    - m_T-fit: 3-5 MeV (muon)

$\|\eta_\ell\|$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

$\|\eta_\ell\|$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mis-measurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

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]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

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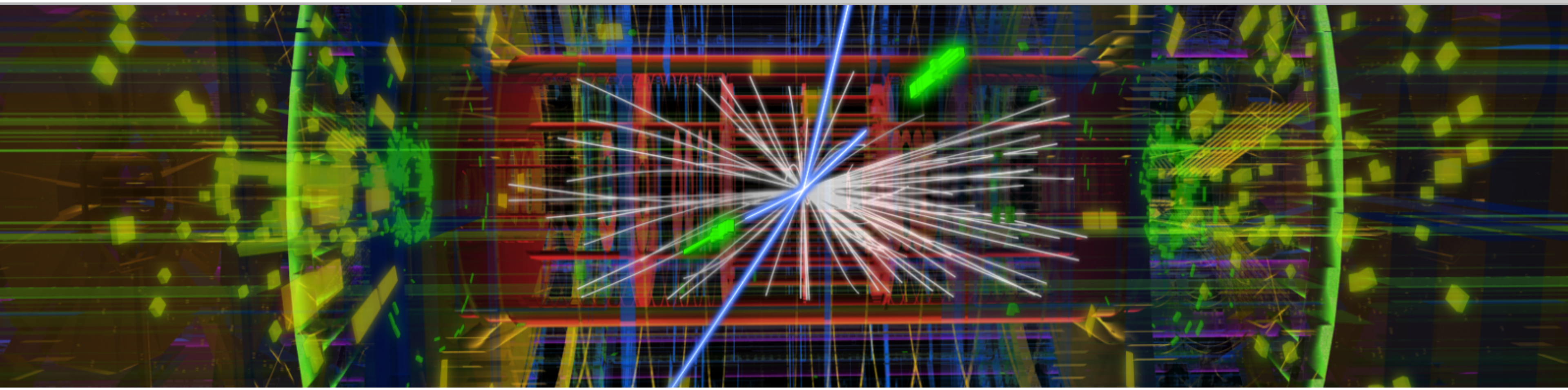
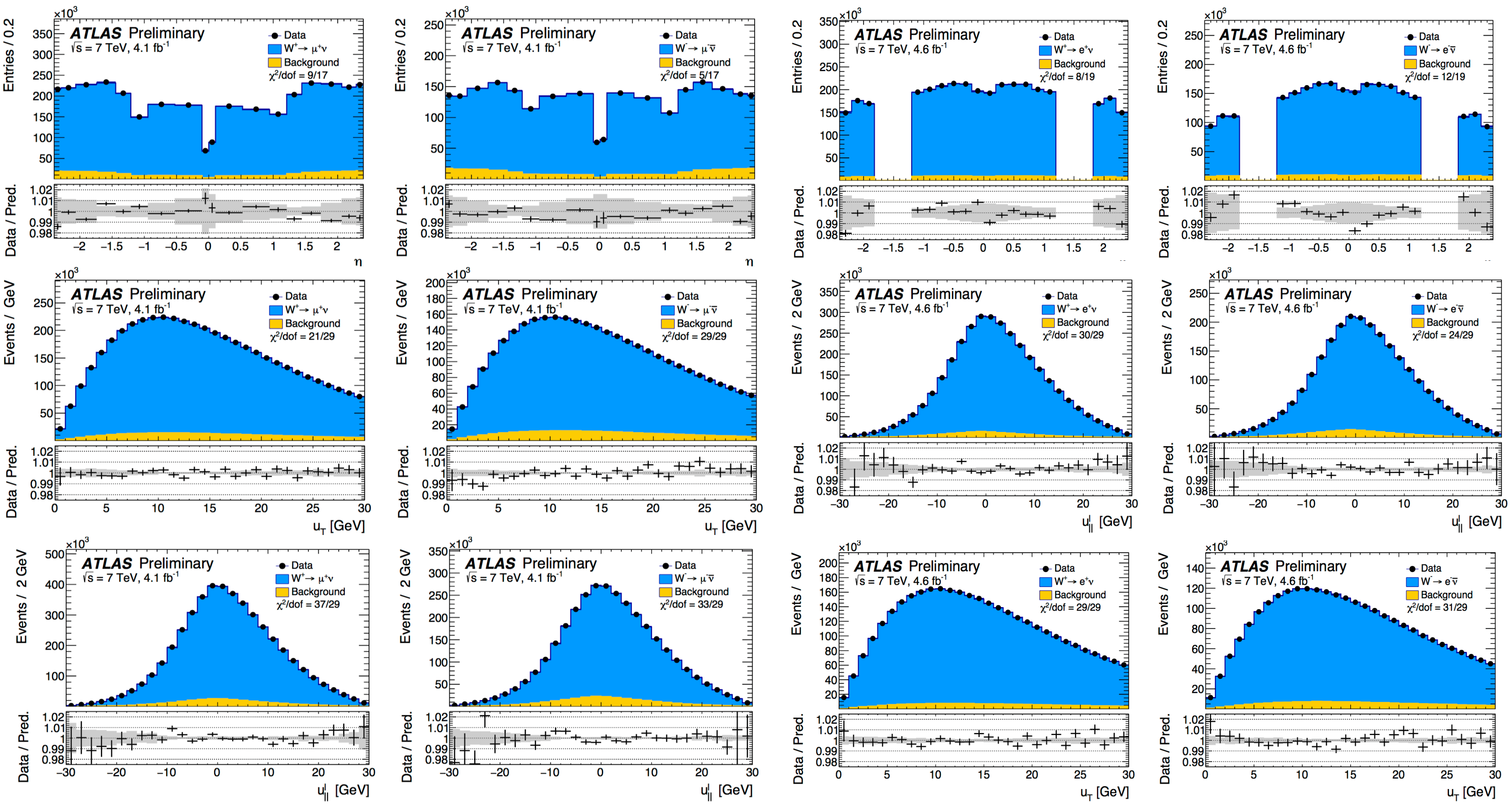


W Boson Analysis

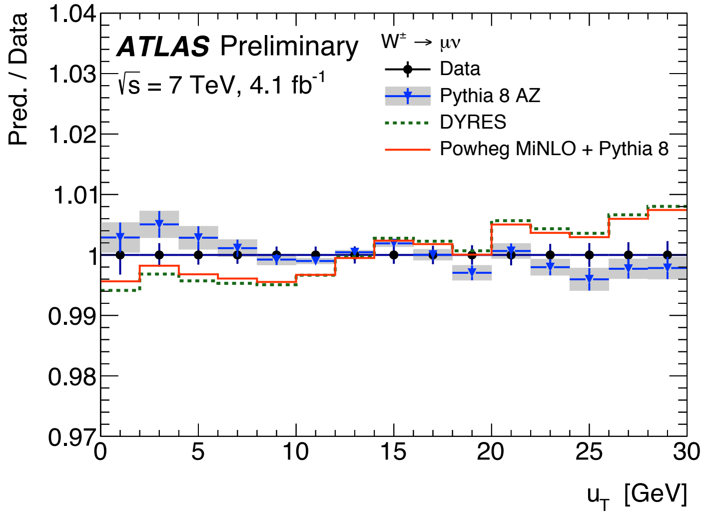
Control Distributions (non m_W sensitive)

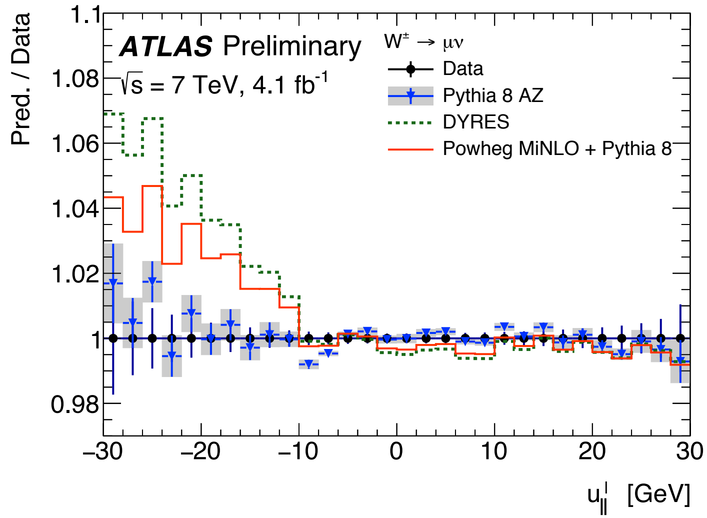


Crucial Test of $p_T(W)$ modelling

- **Remember the problem with the $p_T(W)$ description?**
  - How do we know, which MC generator to trust?
  - How do we know, that our assigned uncertainty makes sense?

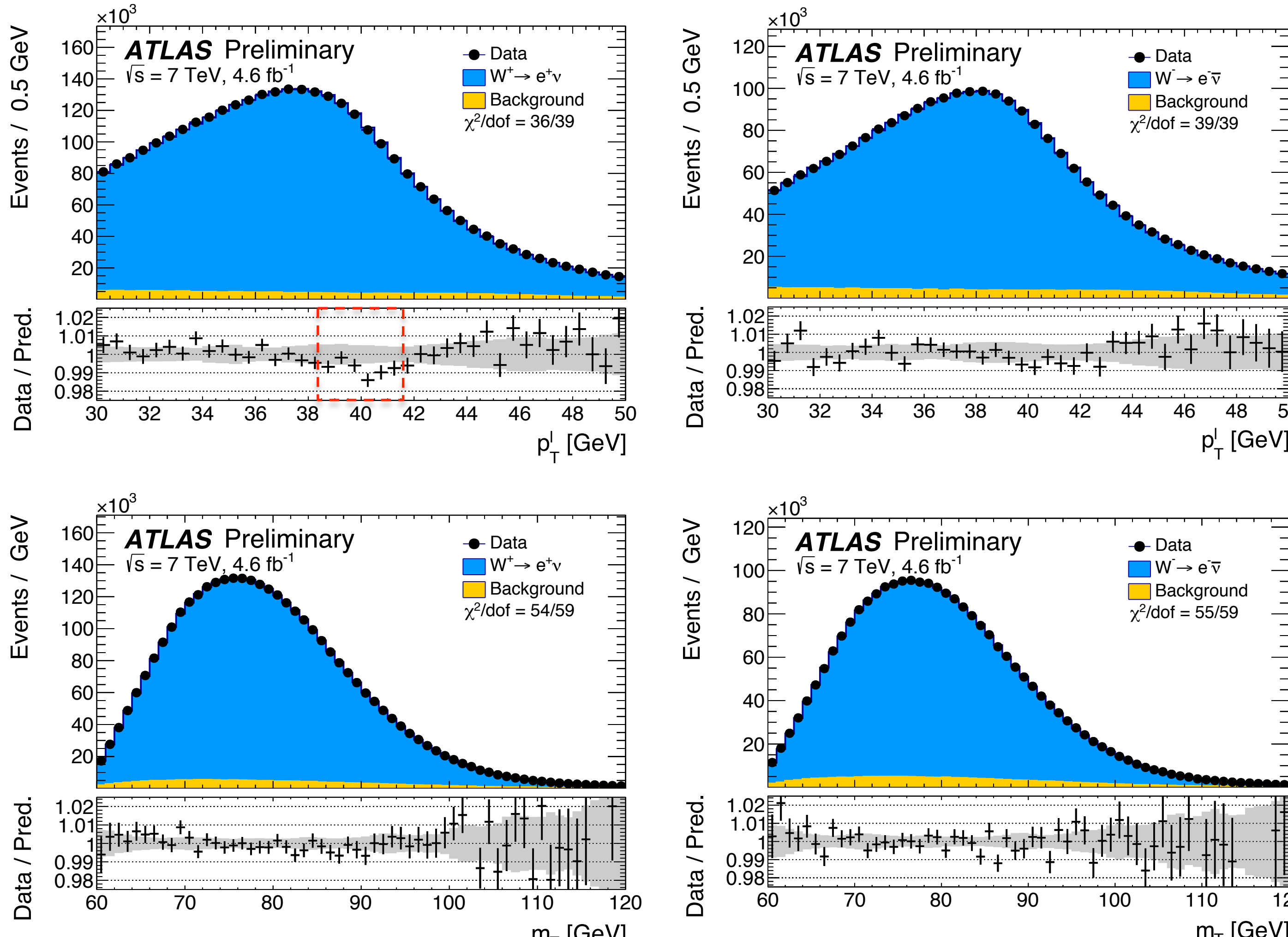
- The **$u_{||}(l)$ distribution is very sensitive** to the underlying $p_T(W)$ distribution
  - Can exploit this feature to verify the accuracy of our baseline model, and compare to alternative calculations





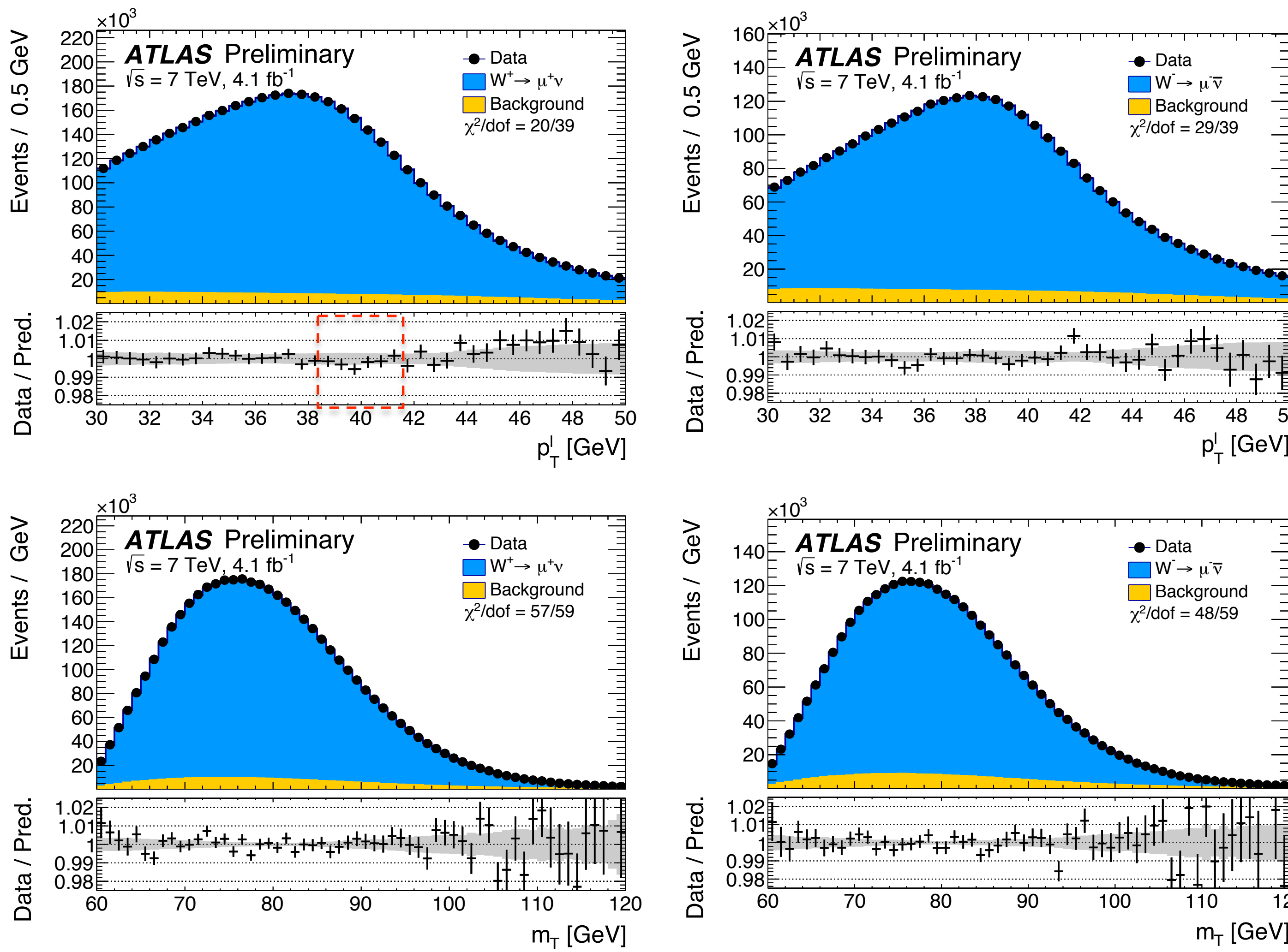
W-Mass Distributions: Electrons

- Predictions set to final combined m_W value
- Dip at 40GeV was studied thoroughly
  - No striking effects: stays at 2σ
  - Only mild impact on final m_W



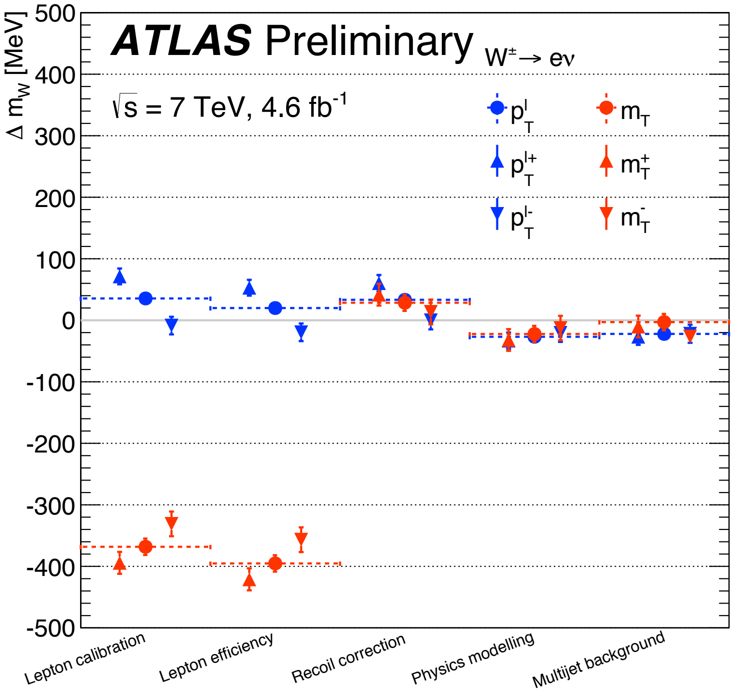
W-Mass Distributions: Muons

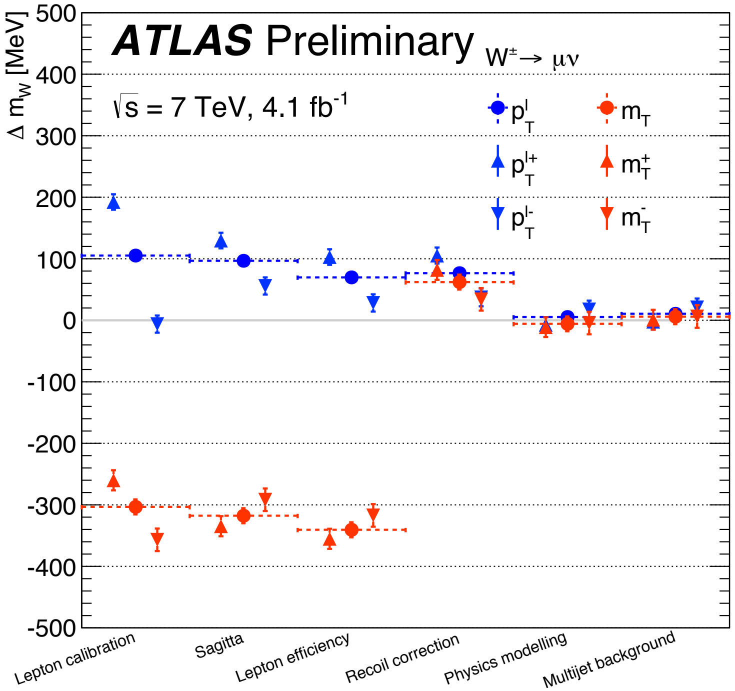
- Very good agreement for muons
- Overall: χ^2/n_{dof} probability distribution from 84 data/ prediction comparison
  - <P>= 0.54



A Little Bit of History

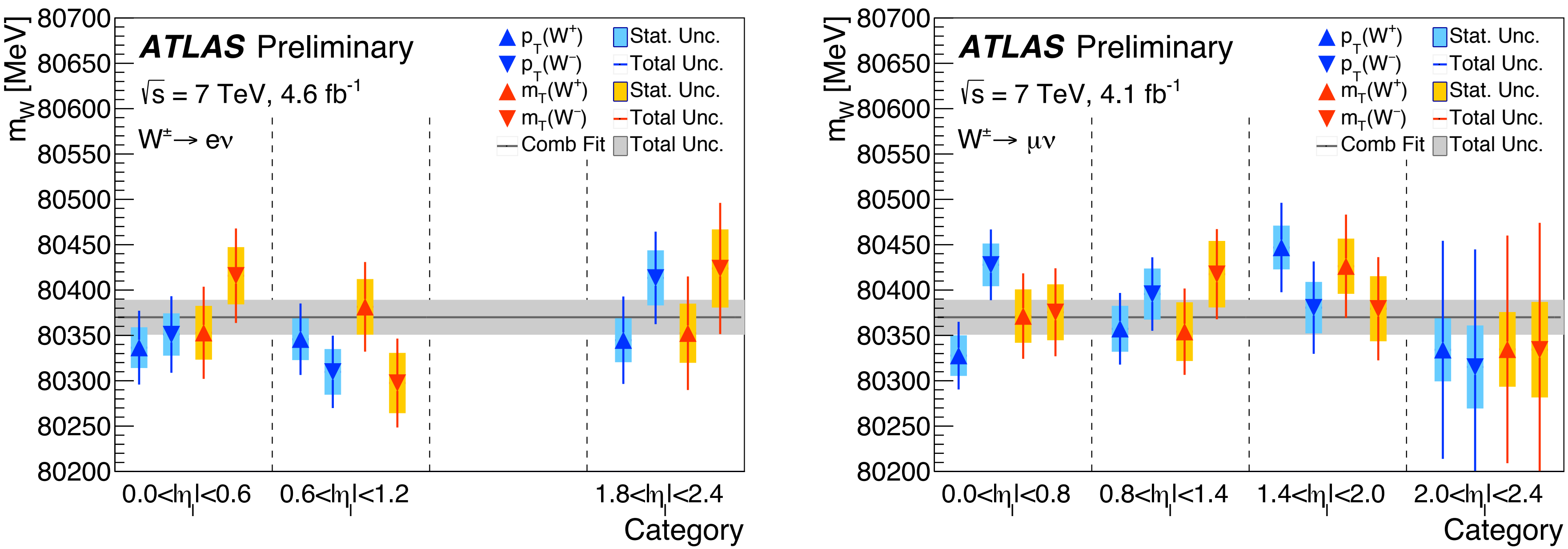
- Over many years we investigated differences in blinded m_W mass-fits in different channels, templates, categories
  - Only after all corrections applied (and all bugs where found), we achieved consistent results





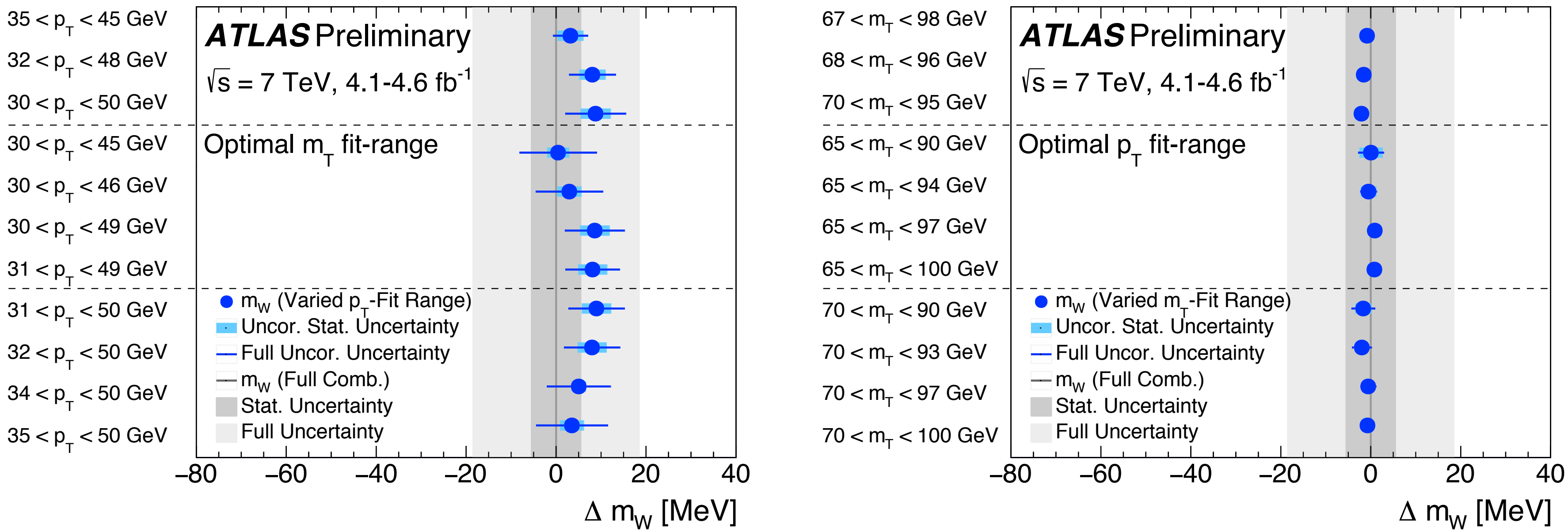
Final Measurement

m_W Fit Results in Various Categories



- Illustration of fit-results in all measurement categories based on p_T and m_T templates for W^+ and W^- in the electron and muon channel
- Compatibility tests **performed before unblinding:** χ^2/n_{dof} **= 29 / 27**

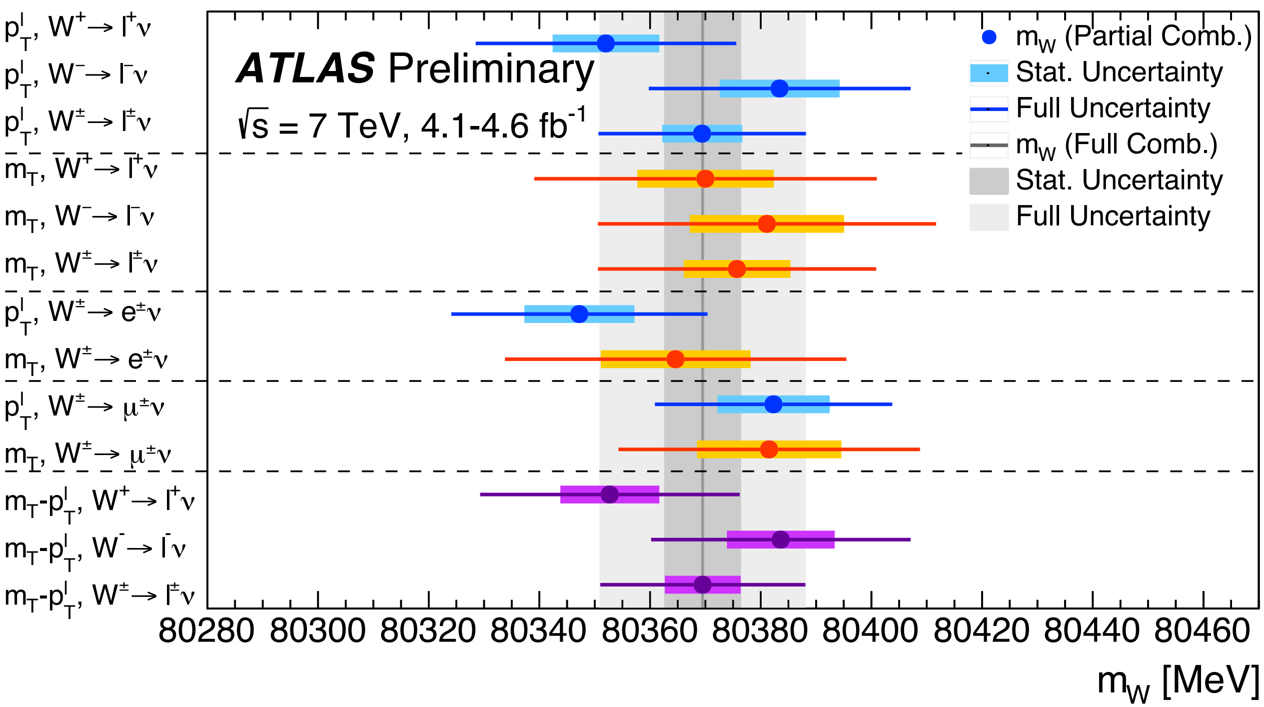
Testing stability for different Fit-Ranges



- The fitting ranges have been optimized on MC predictions for reducing overall systematic uncertainty

- **Stability of fit-results was studied**, taking into account (de-)correlations

m_W Fit Results in Various Combinations



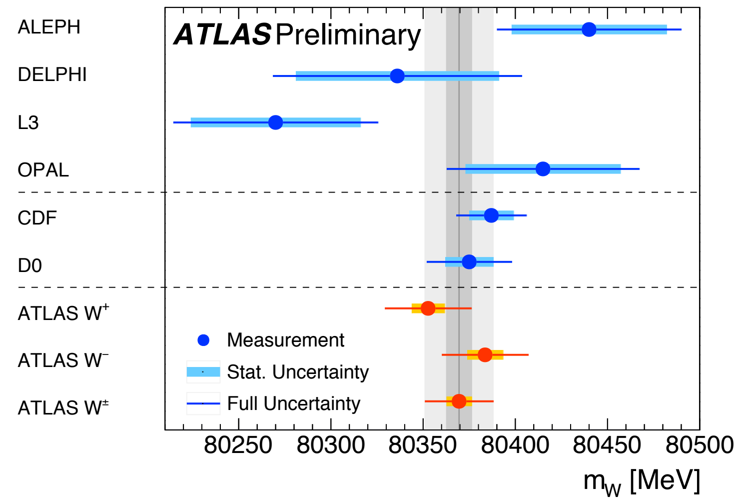
Combination	Weight
Electrons	0.427
Muons	0.573
m_{T}	0.144
p_{T}^{ℓ}	0.856
W^+	0.519
W^-	0.481

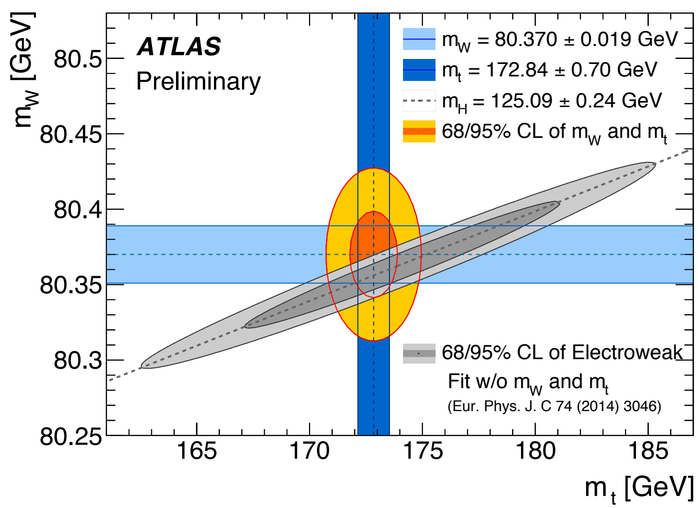
Nobody cares about your method. People remember only your last number!

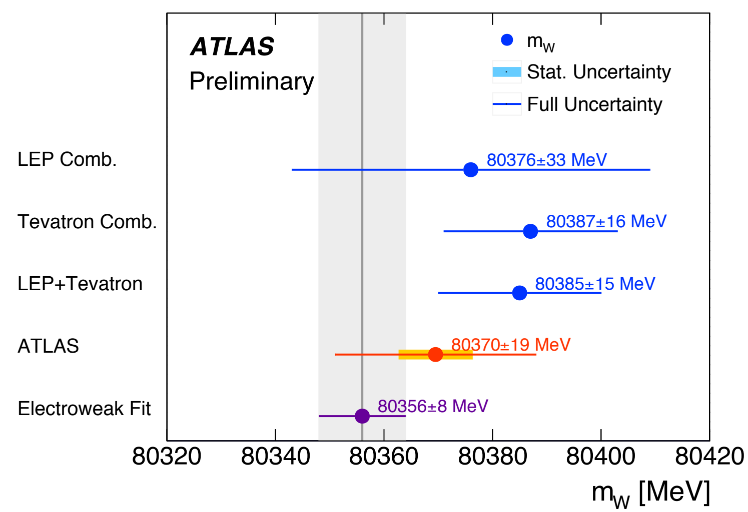
Final measured mass of the W boson
= 80.370±0.007(stat.)±0.011(exp.)±0.014 (mod) GeV
= **80.370±0.019 GeV**

Comparison to previous measurements and the Global Electroweak Fit

- **Good news:** New measurement reaches precision of CDF and is now the world leading measurement
- Bad news: **We are even more Standard Model …**

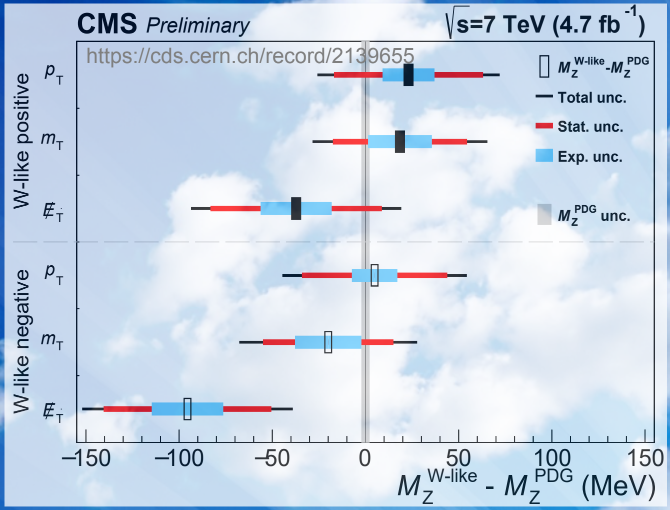




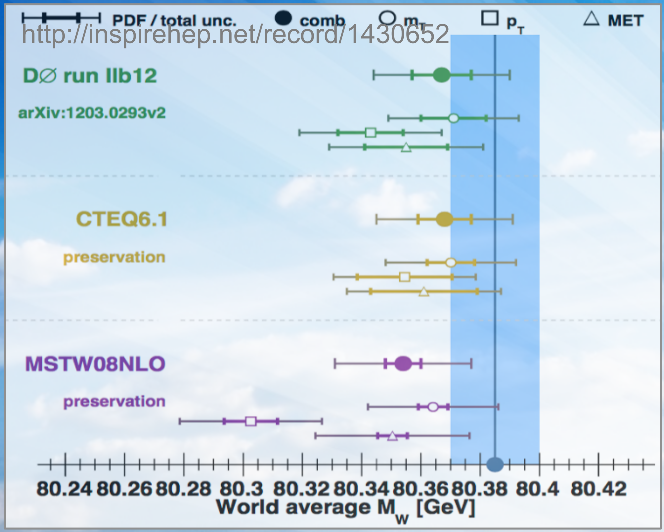


Outlook

- LHC
  - CMS will hopefully also publish soon a m_W measurement
  - ATLAS still has data-sets of 2012/2015/2016
  - **Room for improvements** on the theory and calibration
    - **IMHO: <10 MeV is feasible**



- Tevatron
  - x2-5 more statistics available (+ **forward detectors**)
  - **Use improved PDFs based on** LHC measurements



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Summary

- Five years effort from a large team and the full collaboration comes to an end
  - Many important discussions with colleagues from Theory and CMS
- First W mass measurement at the LHC unfortunately shows no signs of BSM
- Need some “break-through” in the MC event generator developments
  - We have quite some ideas to improve the achieved precision significantly!