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Determination of the W boson mass at the ATLAS experiment

GRK Seminarvortrag Freiburg 2017

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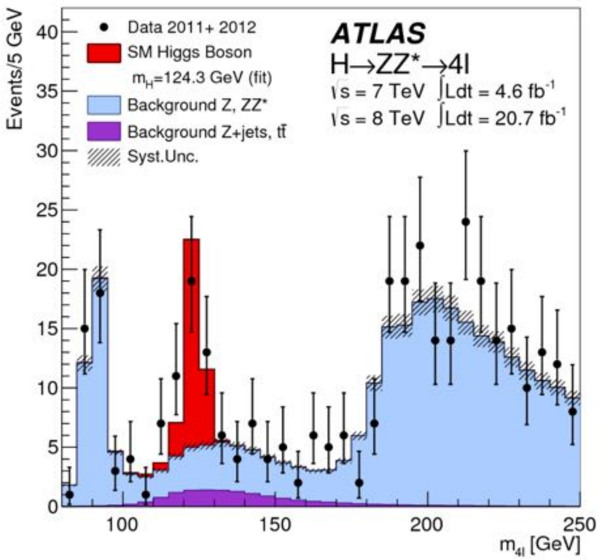
My Top Seven of Open Questions

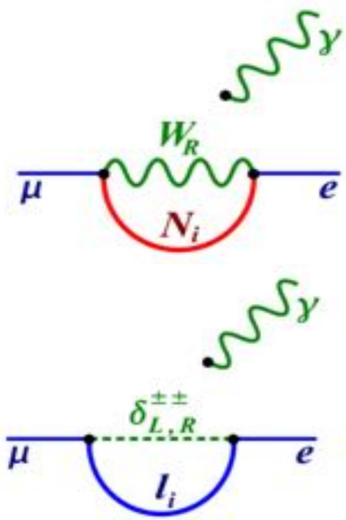
- What is Dark Matter?
- How to explain the matter-antimatter asymmetry?
- Is the Higgs-mass fine-tuned?
- How to solve the strong CP problem?
- What is the physics behind dark energy?
- What is the origin of neutrino masses?

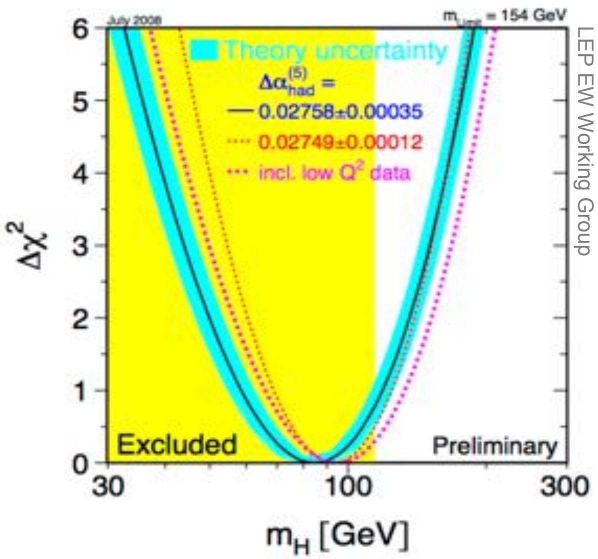
- And number seven as G. Zanderighi puts it: Are these the right questions?
  - Is naturalness a good argument? It seems to fail at the LHC!

http://www.blirk.net/wallpapers/1280x960/universe-wallpaper-9.jpg

How to Answer these Questions?



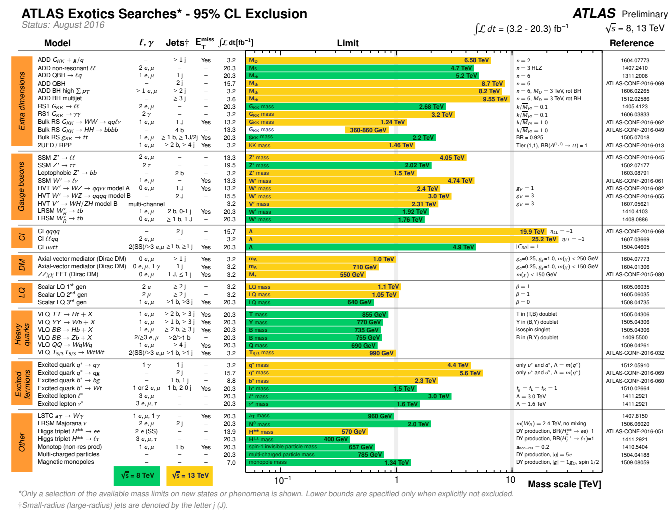


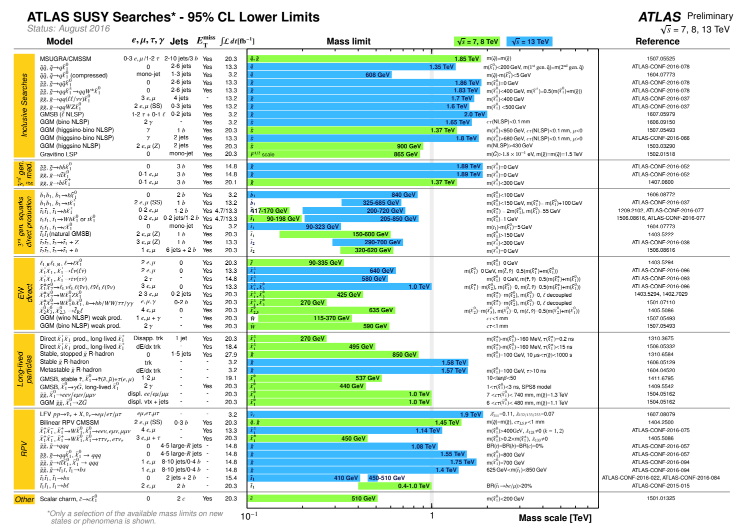


- Direct Searches
  - production of new particles (e.g. LHC)
  - Interaction of particles with detectors (e.g. CRESST)
- Rare processes
  - New Physics can lead to enhanced cross-sections
  - Typically: high-intensity beams, sensitive detectors (e.g. Belle-2)
- Indirect searches
  - look for deviations from SM predictions
  - e.g. due to quantum loop effects of new virtual particles

Direct Searches at the LHC

- As of 2017, we have seen no significant excess in analyses, aiming at SUSY models or more exotic BSM models
  - By now, we are probing the TeV scale!





- Decisive point is coming soon!
  - What is excluded by 2019, will not be discovered in 2030 at the LHC

Indirect Searches and Loops

Let's move to the Electroweak Sector

- The electroweak gauge sector of the Standard Model is constrained by three precisely measured parameters

$$\alpha = 1/137.035999139(31)$$

$$G_F = 1.1663787(6)\times 10^{-5}\,GeV^{-2}$$

$$m_Z = 91.1876(21)\,GeV$$

- At tree level, other EW parameters can be expressed in terms of G_F, m_Z and α
- Higher order corrections modify these relations, and determine sensitivity to other particle masses and couplings

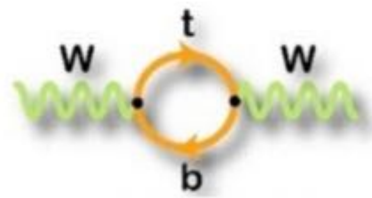
$$m_W^2 = \frac{\alpha\pi}{\sqrt{2}\cdot G_F\cdot(1-m_W^2/m_Z^2)}$$

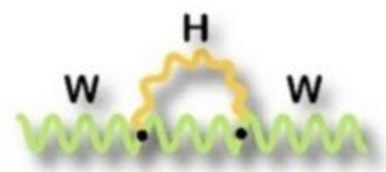
$$\sin^2_{eff}\theta_W = \left(1-\frac{m_W^2}{m_Z^2}\right)$$

$$\Gamma_W = \frac{3G_F m_W^3}{2\sqrt{2}\pi}$$

Radiative Corrections and New Physics

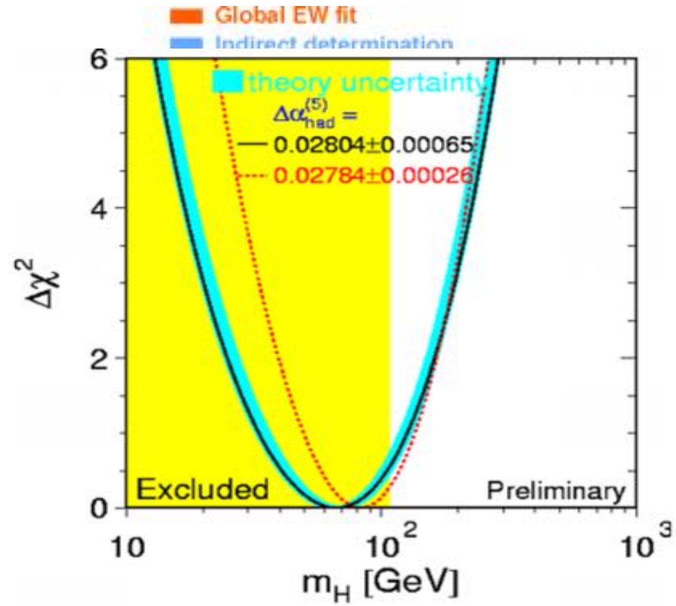
- Radiative corrections Δr to m_W are dominated by top and Higgs loops

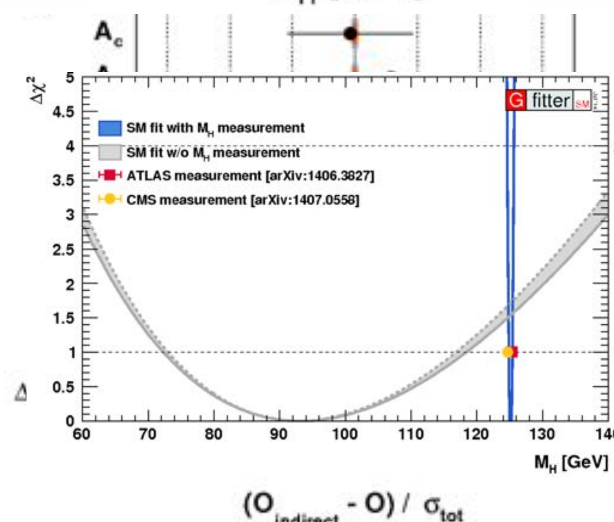




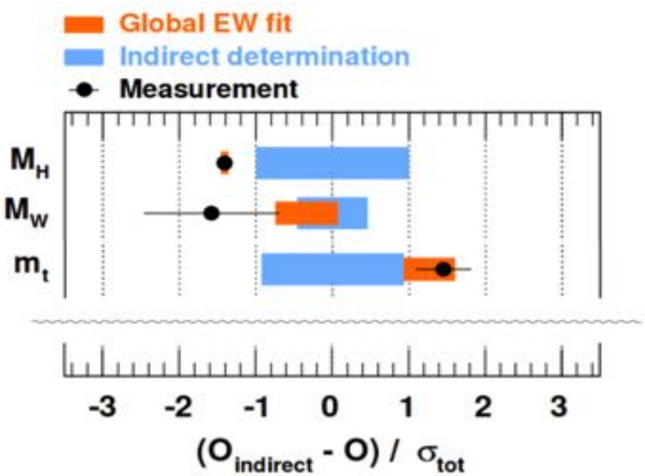
- Idea of the global electroweak fit:
  - Measure many observables and compare to their predicted values

- Prediction of m_{top} and m_H before their discovery (That's why we have the LHC)
  - After measurement of m_H, all the free parameters of the SM are known
  - Relations between electroweak observables predicted at 2-loop level

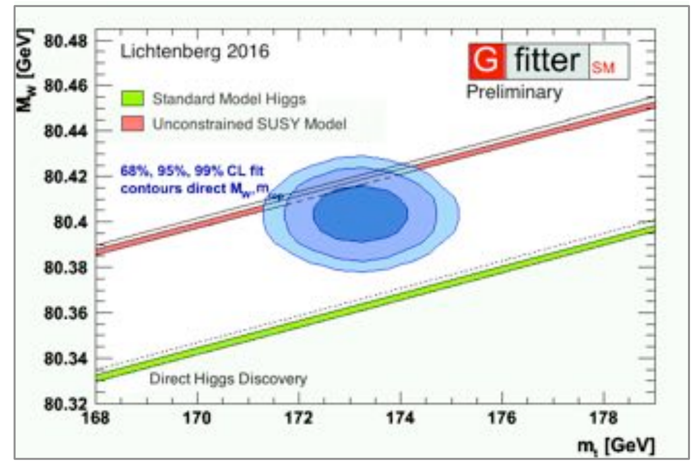




The Global Electroweak Fit



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



- The measurements of m_H and m_{top} are currently more precise than their indirect determination
  - Improving precision will not increase sensitivity to new physics
  - Indirect determination of m_W (±8 MeV) is more precise than the experimental measurement
    - Call for Δm_{exp} < 10 MeV
- Precise measurements of the electroweak parameters
  - allow stringent test of SM self consistency
  - Looking for hints of BSM physics

Electroweak Precision Measurements at the LHC

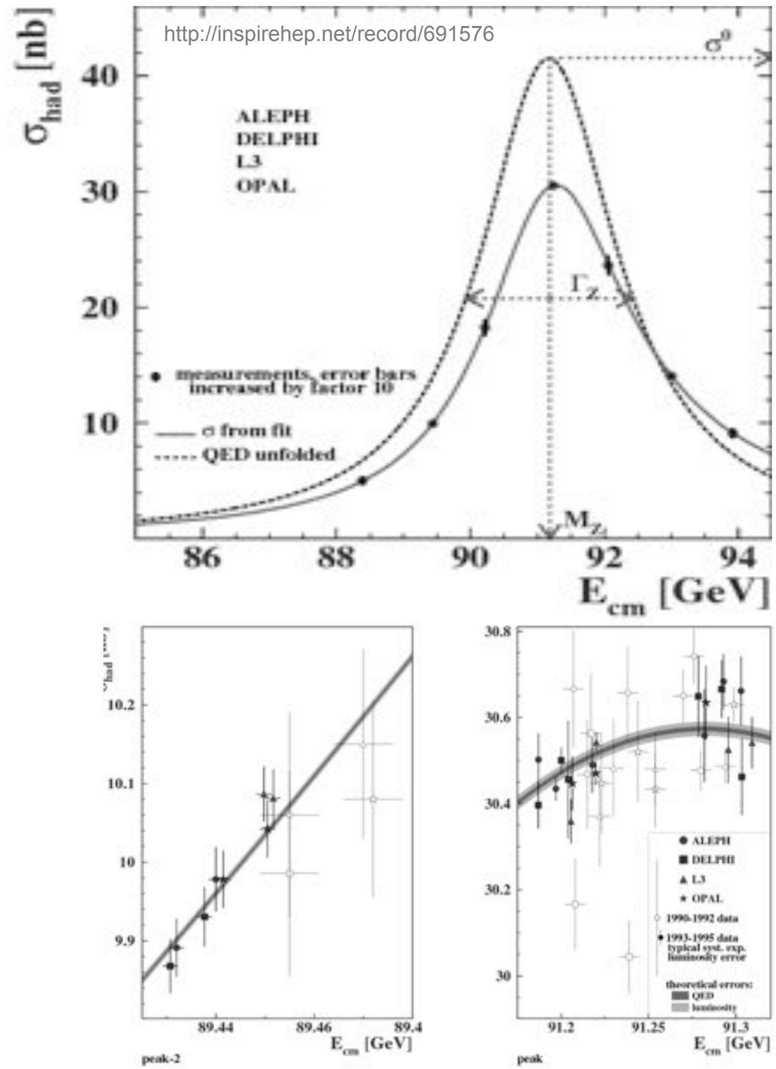
- Various SM parameters can be measured at the LHC with a precision competitive with previous determinations

m_H	125.09 ± 0.24 GeV (ATLAS+CMS) arXiv:1503.07589	Uniquely measured at the LHC (but not important for the fit)
m_T	172.84 ± 0.70 GeV (ATLAS) arXiv:1606.02179 172.44 ± 0.49 GeV (CMS) arXiv:1509.04044	Superseding Tevatron precision (but "unknown" theory unc.)
$\sin^2\theta_W$	0.2308 ± 0.0012 (ATLAS) arXiv:1503.03709 0.2287 ± 0.0032 (CMS) arXiv:1110.2682 0.2314 ± 0.0011 (LHCb) arXiv:1509.07645	Not yet competitive with LEP, SLD and Tevatron
$\alpha_s(m_Z)$	0.1164 ± 0.0052 (CMS jets) arXiv:1609.05331 0.1151 ± 0.0028 (CMS tt) arXiv:1307.1907 0.1173 ± 0.0046 (ATLAS TEEC) arXiv:1508.01579	Currently dominated by large theory uncertainty (PDFs, …) Most precise value from lattice.
m_W	80.XXX ± 0.XXX GeV (ATLAS) arXiv:1701.07240	Competing with Tevatron precision
Γ_W	2144 ± 62 MeV (CMS) arXiv:1107.4789	From W/Z cross section ratio

- Focus of this talk: Measurement of the W boson mass at the LHC

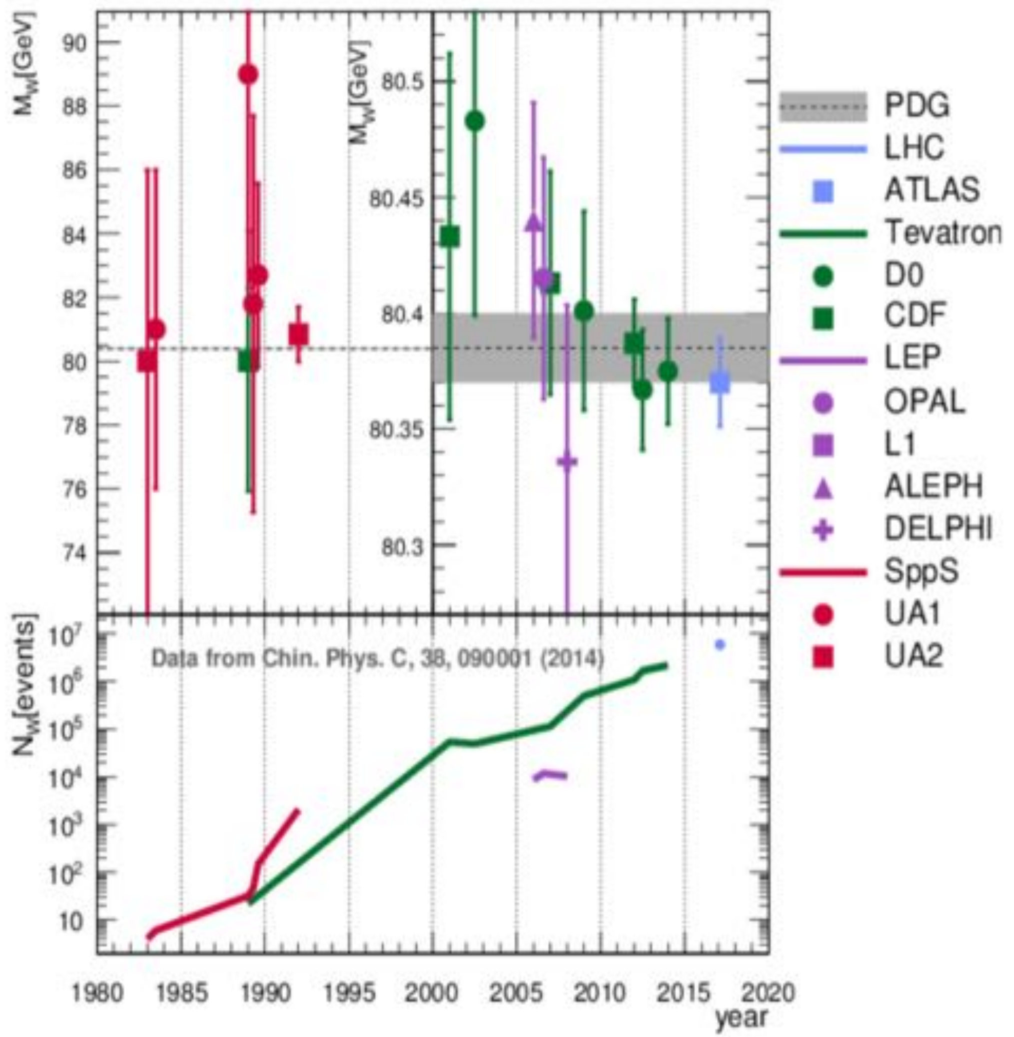
Z Boson Measurements at LEP

- 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!



W Boson Mass History

- 1983 – UA1:
  - m_W =81±5 GeV
- 1992 – UA2 (using Z-mass from LEP)
  - m_W = 80.35 ± 0.37 GeV
- 2013 – LEP (Combined):
  - m_W = 80.376± 0.033 GeV
- 2013 – Tevatron (Combined):
  - m_W = 80.387 ± 0.016 GeV
- Only four m_W measurements in the last seven years
  - Complex measurements which require O(5-7) years



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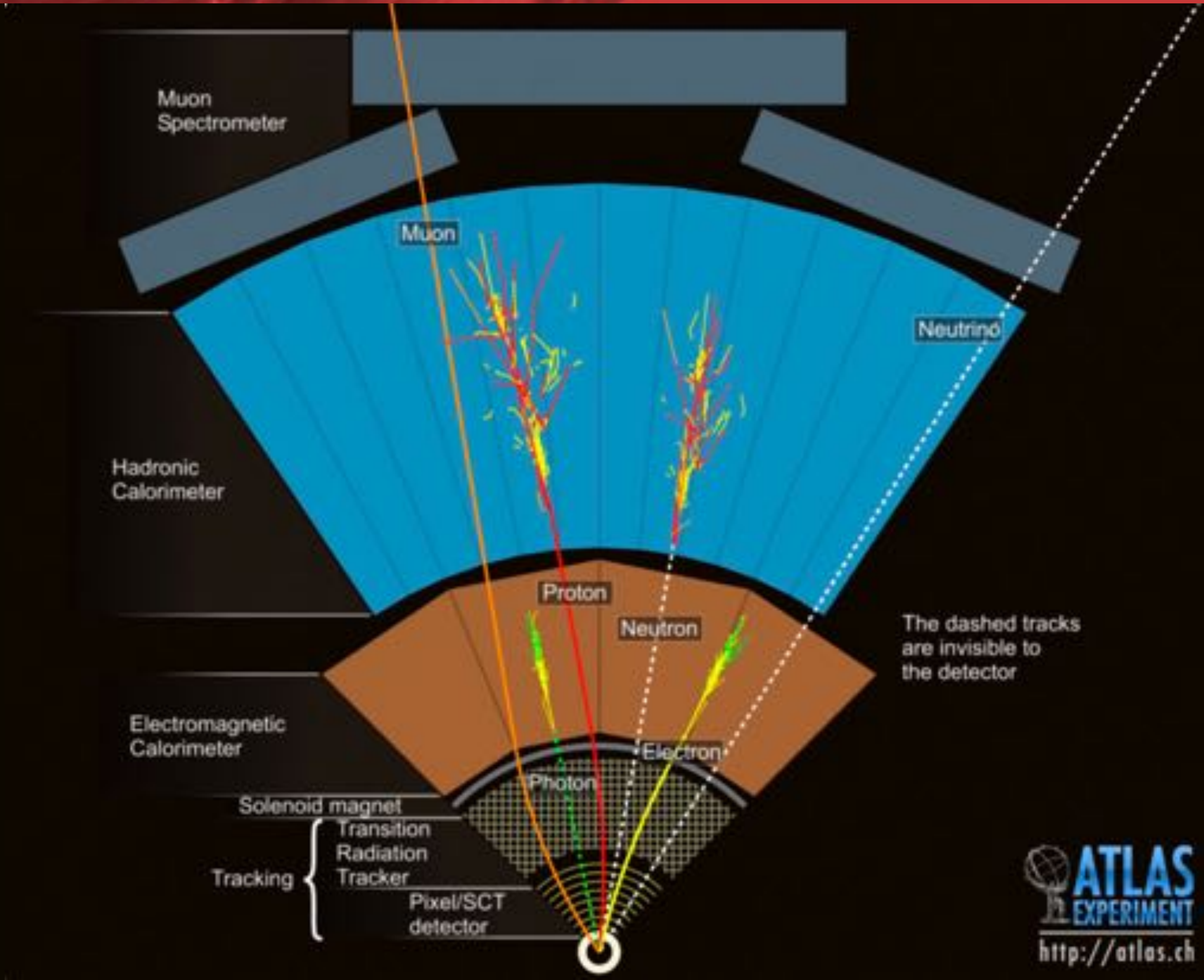
Measurement Strategy

Get an Amazing Particle Detector and many W bosons

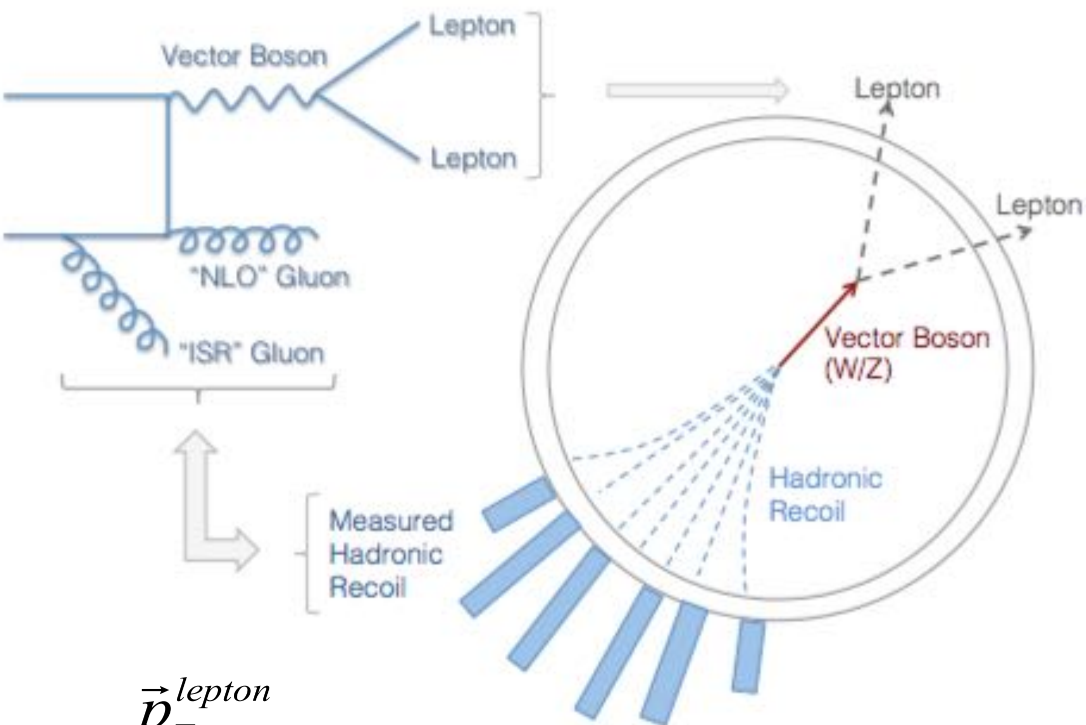


Mass Sensitive Variables

- Main signature: final state lepton (electron or muon):
  - transverse momentum p_T(lepton)
- Recoil u: sum of "everything else" reconstructed in the calorimeters

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

  - a measure of p_T(W,Z)
  - gives us also missing transverse energy (not used for m_W)
- The transverse mass m_T is defined in transverse plane



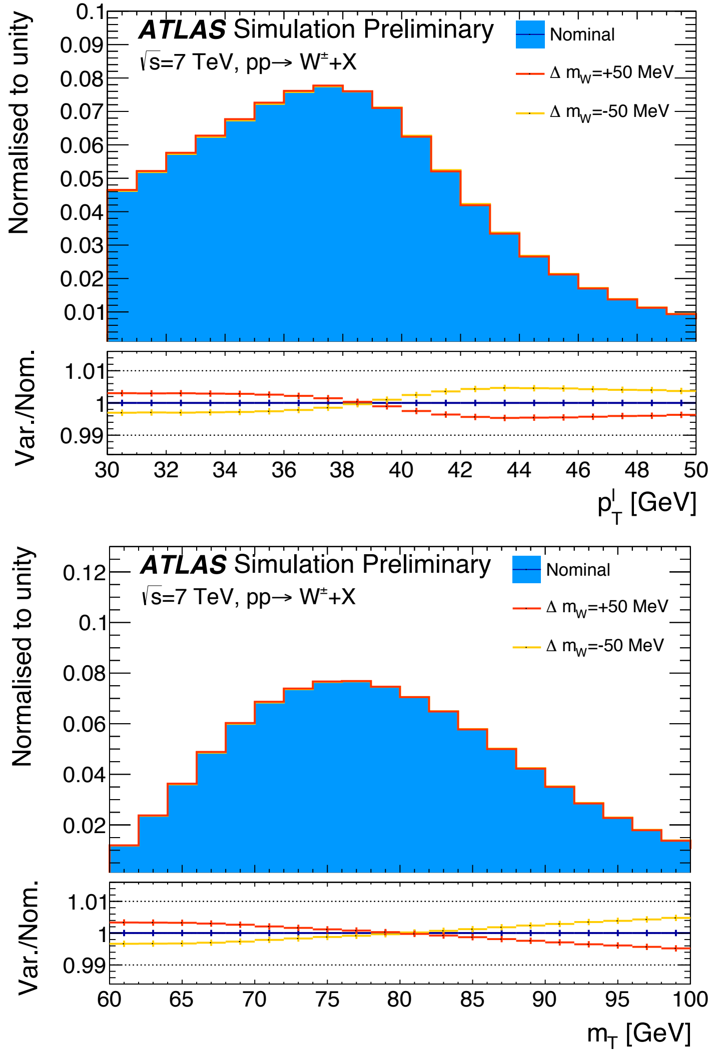
$$\vec{p}_T^{\,lepton}$$

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

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

Mass Sensitive Variables

- Sensitive final state distributions
  - Lepton transverse momentum
    - $p_T(l)$
  - Transverse mass
    - m_T
  - Missing transverse energy, i.e. "neutrino p_T" (not used in m_W)
    - 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



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?

- Muons
- Electrons
- Had. Recoil
- Backgrounds

Focus during the first years of the project

Physics Modelling

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

- PDFs
- $p_T(W)$
- EW Cor.
- Angular Coeff.

Focus during the last years of the project

Measurement Strategy: Categories

- Crucial idea: Perform measurements in different categories
  - validate detector calibration
  - validate physics modelling and improve accuracy

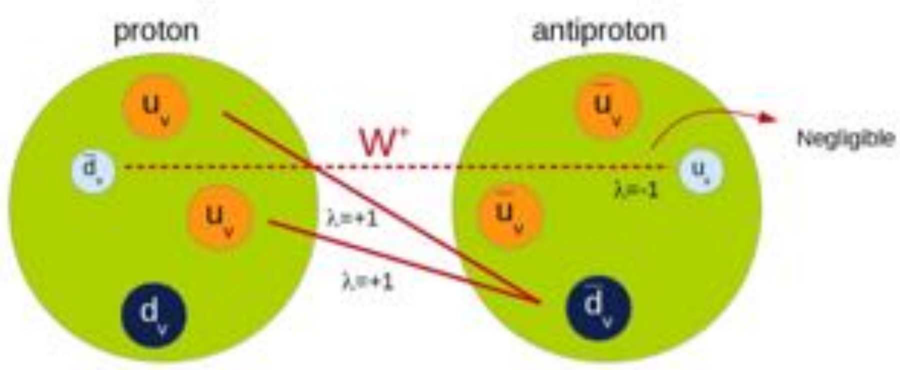
- Categories are sensitive to different experimental and theoretical biases
  - Measurement was considered ready for unblinding only when all the categories yield consistent values of m_W
  - Experimental and theoretical uncertainties have different correlation or anti-correlation patterns, the categorisation allows to constrain them, and increase the sensitivity to m_W

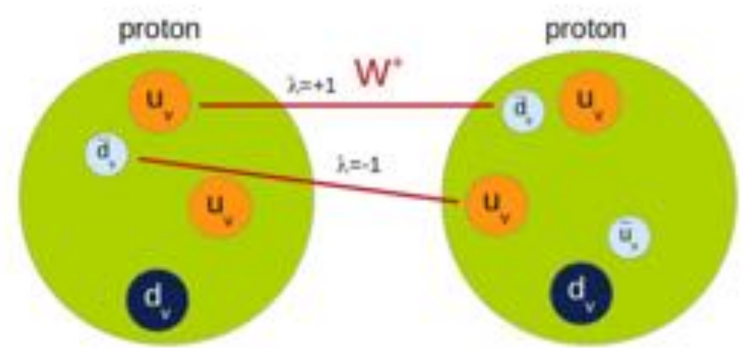
- Categories used for the combination (28 in total):

Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\|\eta_\ell\|$ categories	$[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$	$[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$

Why things are more complicated at the LHC?

- A proton-proton collider is the most challenging environment to measure m_W, worse compared to e^+e^- and proton-antiproton



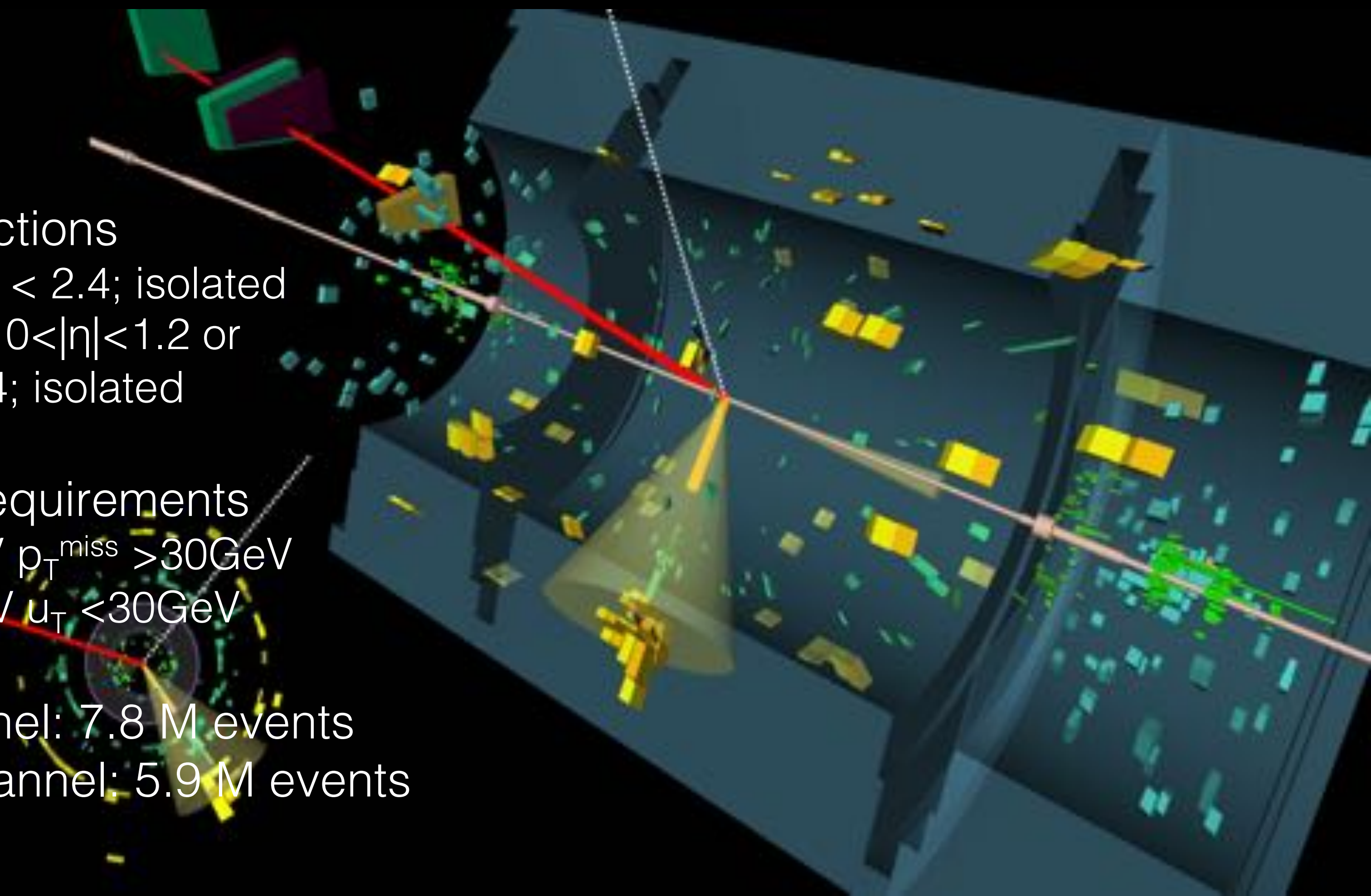


- W bosons are mostly produced in the same helicity state

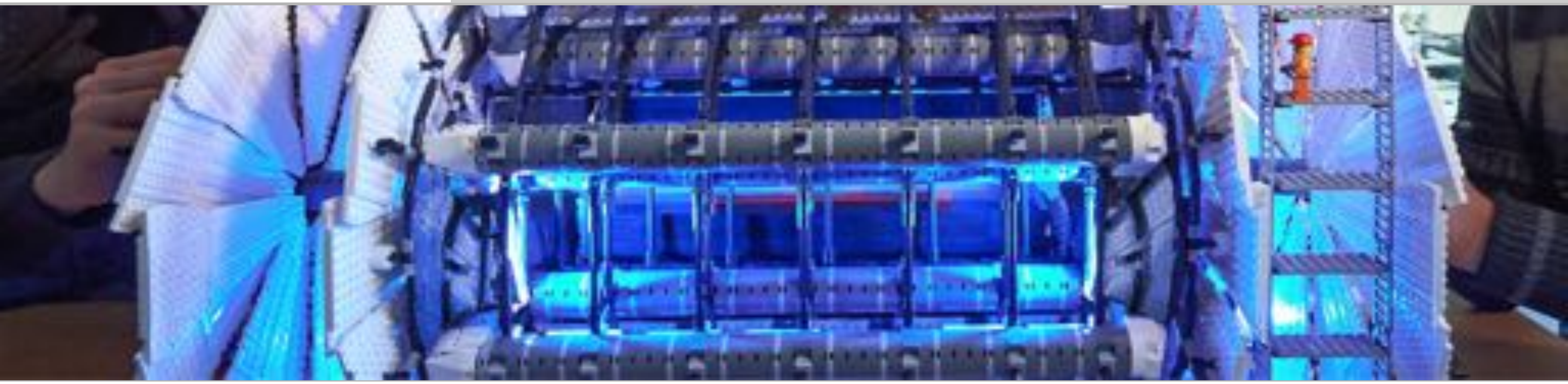
- Further QCD complications at LHC
  - Heavy-flavour-initiated processes
  - W^+, W^- and Z are produced by different light flavour fractions
  - Larger gluon-induced W production

- W bosons are equally distributed between positive and negative helicity states
  - Large PDF-induced W-polarisation uncertainty affecting the p_T lepton distribution

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 >30GeV p_T^{miss} >30GeV
  - m_T >60GeV u_T <30GeV
- Muon Channel: 7.8 M events
- Electron Channel: 5.9 M events



Physics Modelling

Physics Modelling

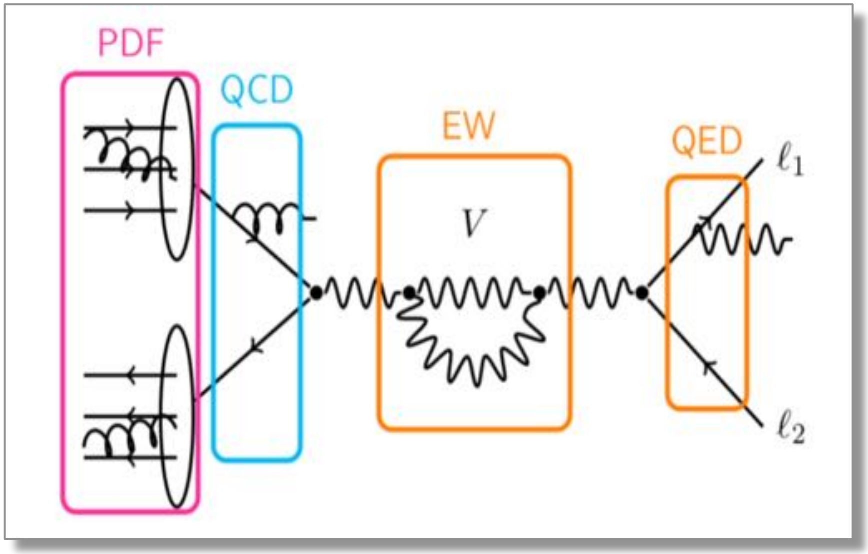
- No available generator can describe all observed features
  - QCD aspects: Rapidity, p_T distributions; angular distributions, …
  - EW aspects: ISR and FSR QED corrections, missing higher-order effects

Breit-Wigner, Parton Shower

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

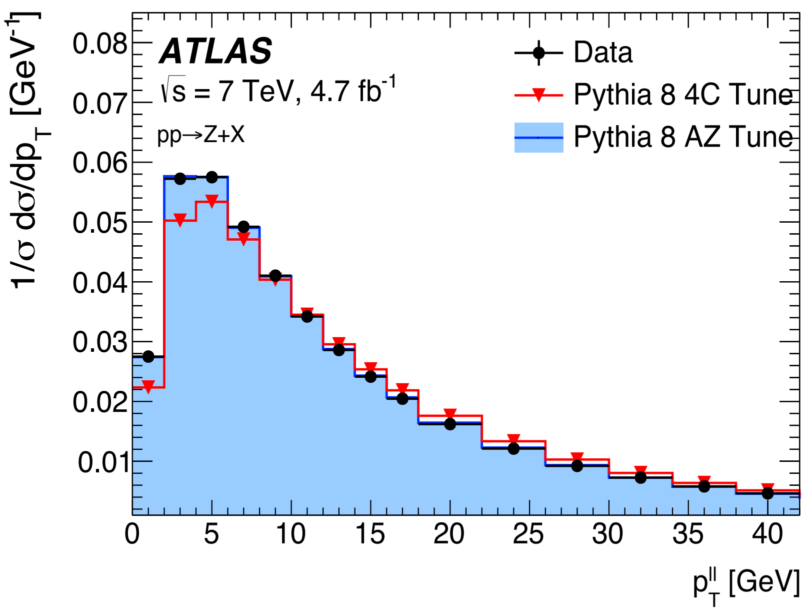
NNLO pQCD

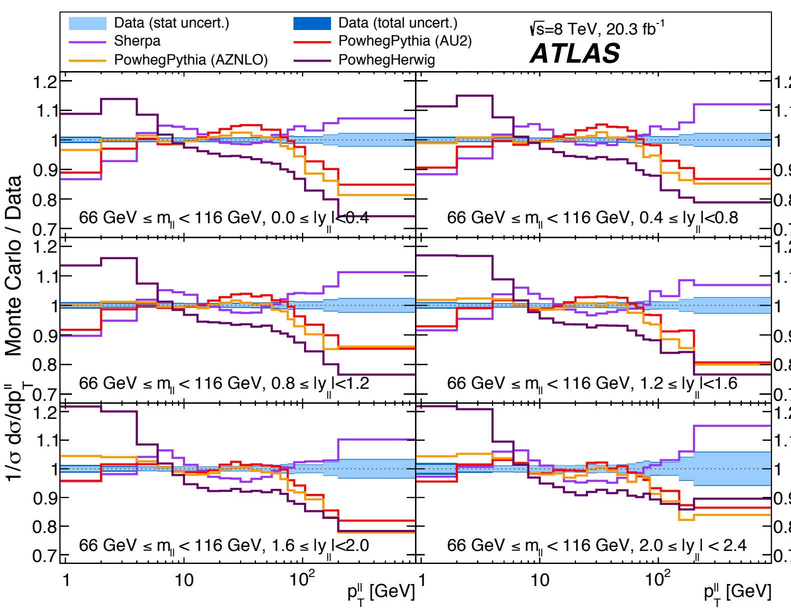
$$\cdot \left(\sum_i A_i(y,p_t)P_i(\cos\theta,\phi)\right)$$



Transverse Momentum (A several years effort)

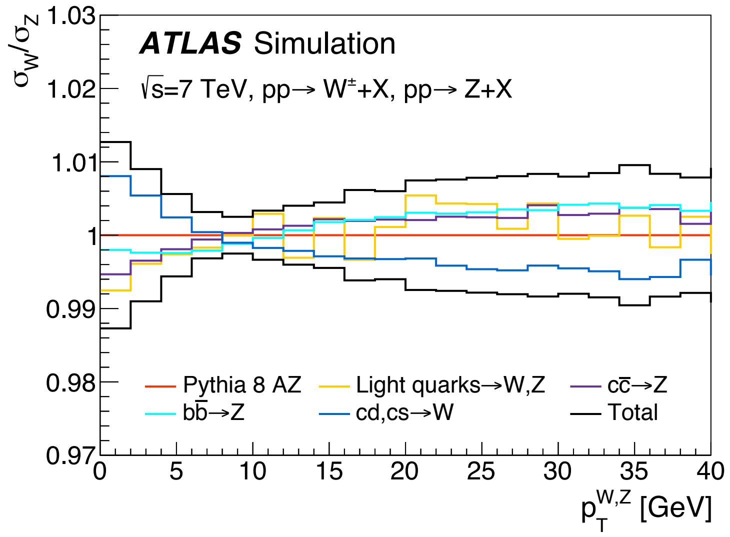
- The Pythia8 p_T-ordered parton shower is used as model for the $p_T(W)$
  - Model-parameters are fit to the $p_T(Z)$ measurement at 7 TeV (AZ tune)
- Pythia8 AZ tune describes $p_T(Z)$
  - data within 2% inclusively and in rapidity bins
  - Pythia8 is used to transfer from the $p_T(Z)$ to the $p_T(W)$ distribution and to evaluate theory uncertainties on the W/Z p_T ratio

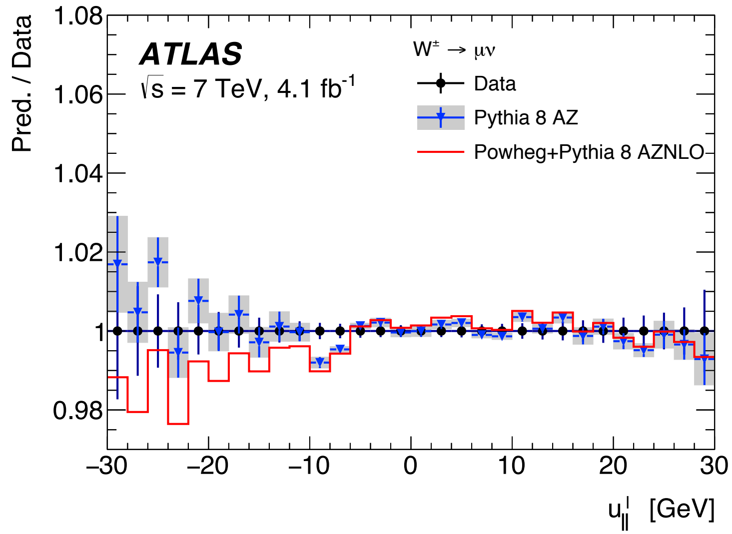




Transverse Momentum - Uncertainties

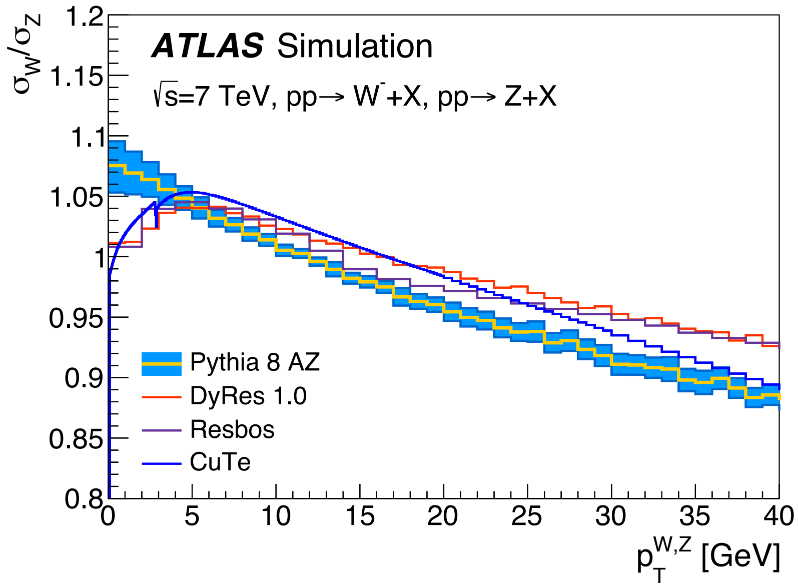
- Uncertainties from exp. $p_T(Z)$ unc. and theory unc. on the W/Z p_T ratio
- Heavy-flavour-initiated (HFI) production introduce decorrelation
  - bb/cc→Z accounts for 3-6%
  - cs→W is ~20% of W production
  - HFI addressed with
    - charm mass variations
    - decorrelating the PS between light and HFI processes
- Central prediction and uncertainty validated with the recoil distribution
  - end up with compatible central value and similar uncertainties compared to "model approach"

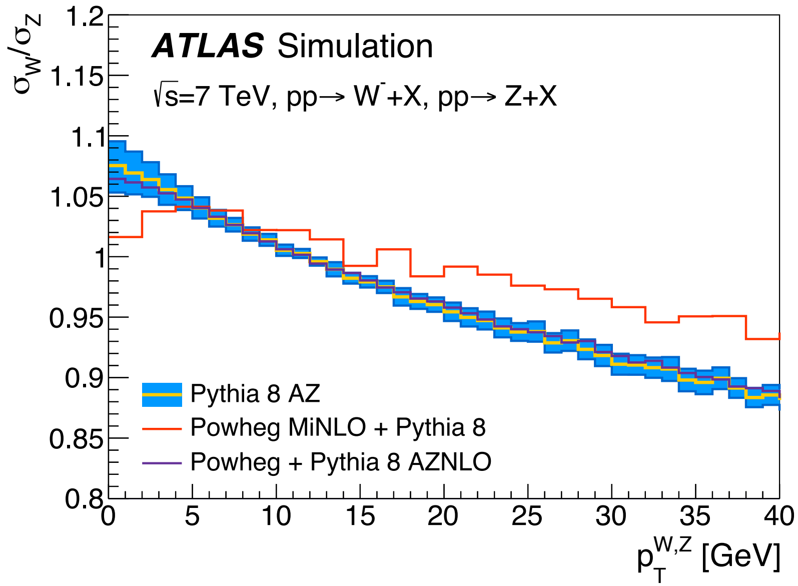




Transverse Momentum - Alternative Models

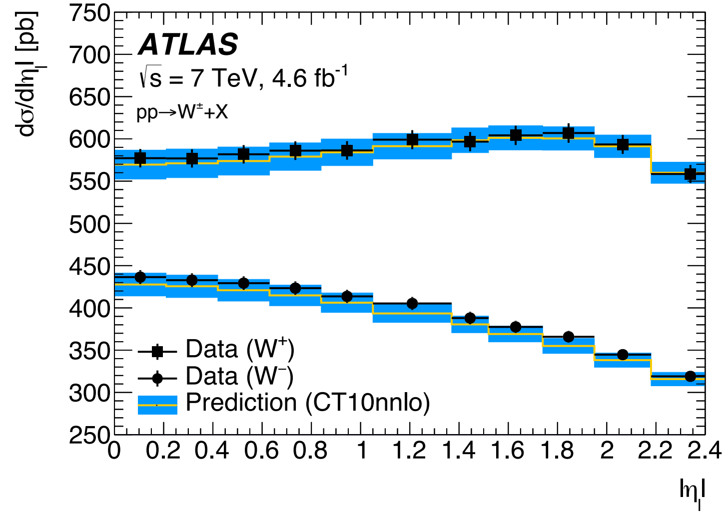
- Theoretically more advanced calculations were also attempted
  - DYRES (and other resummation codes : ResBos, CuTe)
  - Powheg MiNLO + Pythia8
- All predict a harder $p_T(W)$ spectrum for given $p_T(Z)$ distribution
  - Behaviour is disfavoured by data (see later)

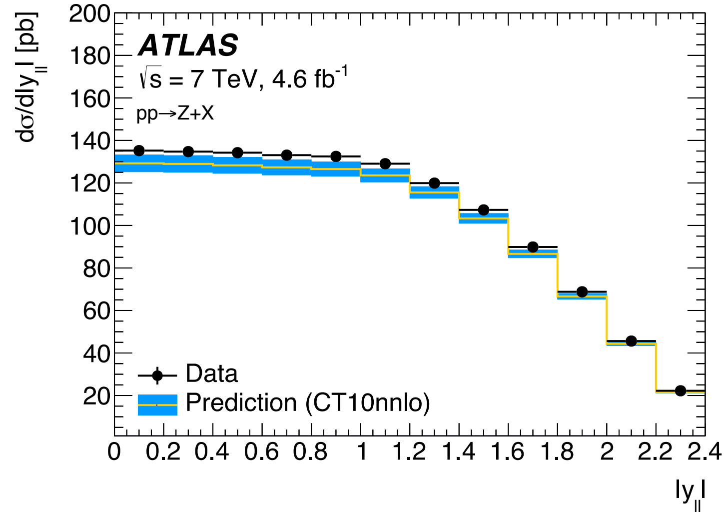




Rapidity Distributions and PDFs

- Rapidity distributions are modelled with NNLO predictions
- Baseline: CT10nnlo PDF set
  - provides good agreement with data thanks to its milder strangeness suppression.
  - CT14 and MMHT considered as uncertainty, other PDF sets excluded by data
- W/Z precision measurements at 7 and 8 TeV
  - Strong indication of unsuppressed strangeness





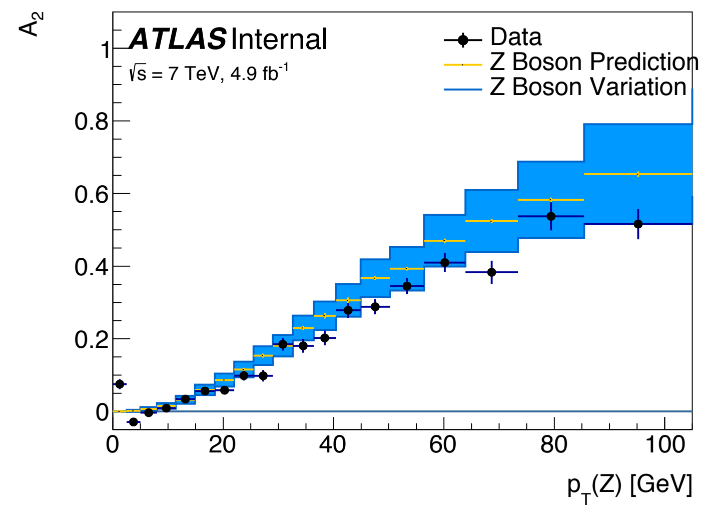
Angular Coefficients and Polarization

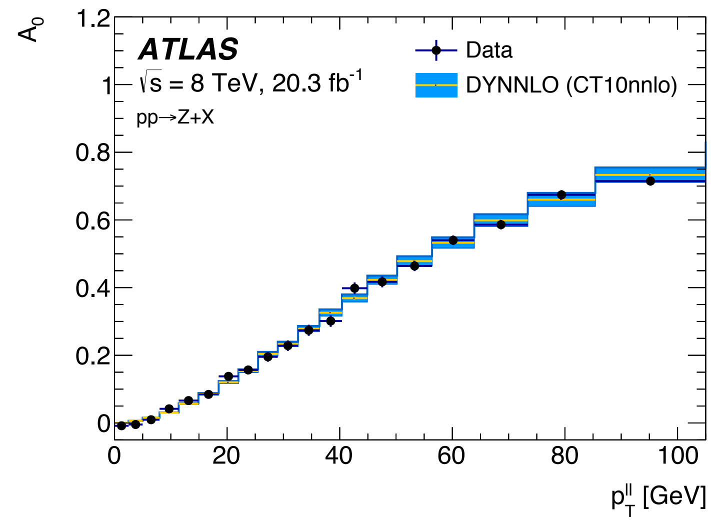
- The DY cross section can be reorganised by factorising the dynamic of boson production, and decay kinematic

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma}{dp_T dydm} \sum_i A(y, p_T, m) P_i(\cos\theta, \phi)$$

  - $P_i(\cos\theta, \phi)$ are 9 spherical harmonics.
  - complete decomposition

- Angular coefficients are modeled with pQCD at NNLO
  - validated by Z's at 8 TeV
  - Uncertainty: difference between prediction and measurement





Overview of QCD Uncertainties

- CT10nnlo uncertainties (synchronized in DYNNLO and Pythia) + envelope comparing CT10 to CT14 and MMHT.
  - Dominant uncertainty
  - Strong anti-correlation of uncertainties for W^+ and W^-!

- Second largest model uncertainty: $p_T(W)$ modeling
  - similar for m_W extracted from p_T lepton and from m_T

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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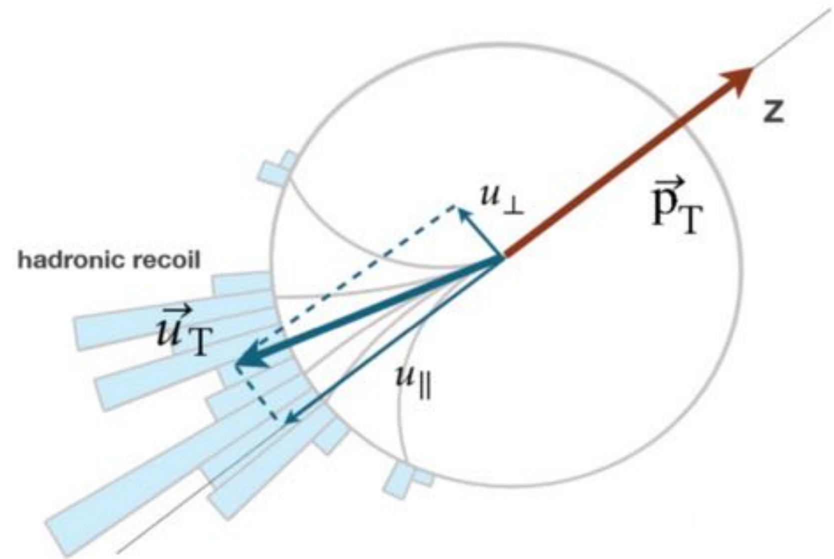
Detector Calibration

Need to Understand the Detector Response

- 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

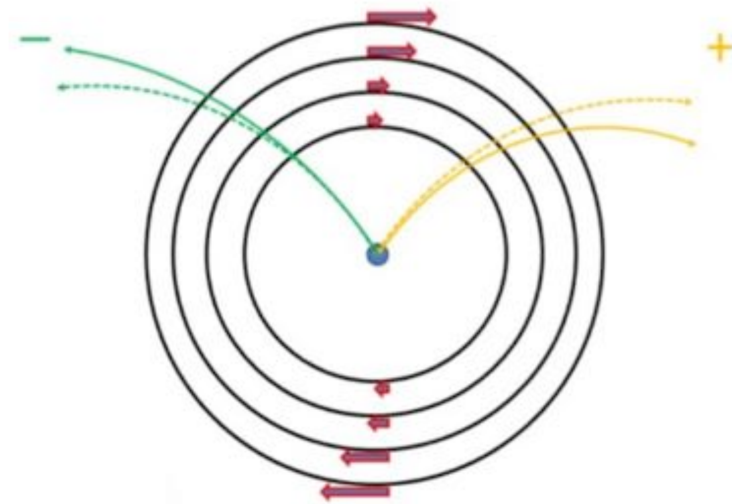
- Muon momentum only from inner detector: simplifies calibration

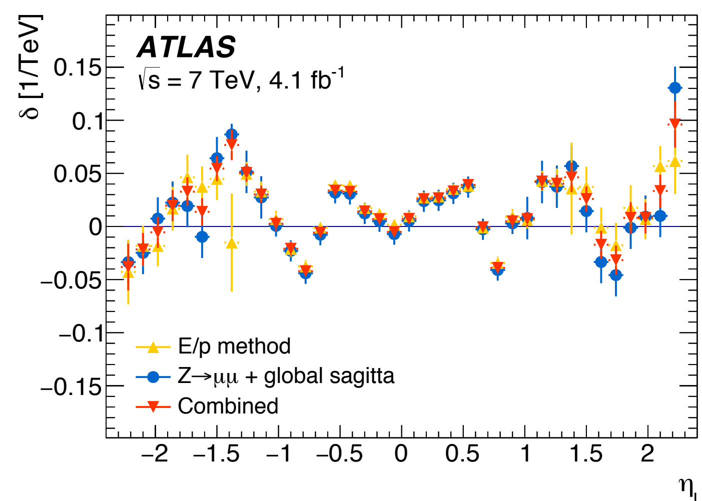
- Parameterization of corrections:

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

  - α: radial bias (scale)
  - δ: sagitta bias
  - β: resolution correction

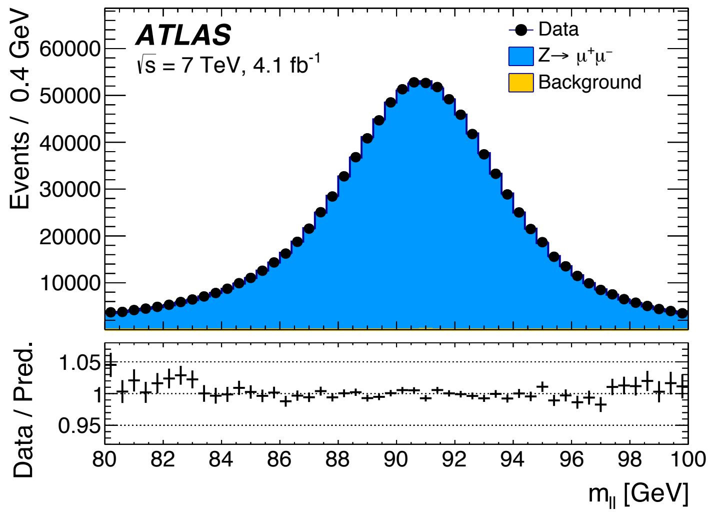
- Charge dependent corrections
- Scale and resolution corrections derived form Z boson line shape,
- Sagitta bias from E/p in W → en



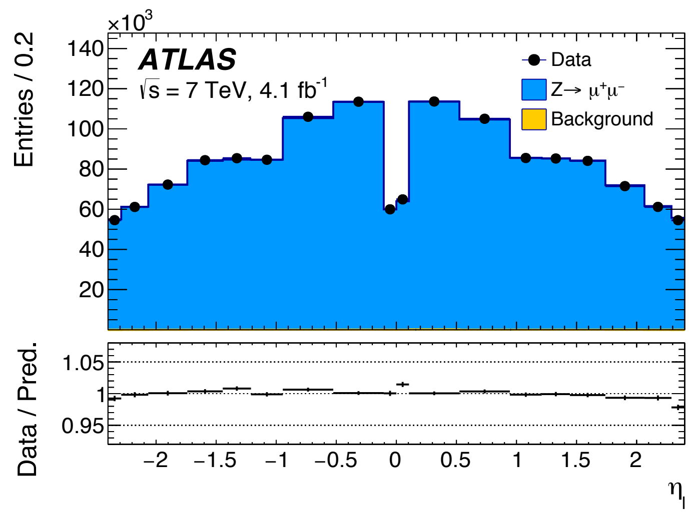


Muon Momentum and Efficiency Calibration

- Once the muon momentum is correctly calibrated, we observe a "perfect" Z boson line-shape
  - Need to study carefully momentum dependence of calibrations (e.g. via J/Psi)

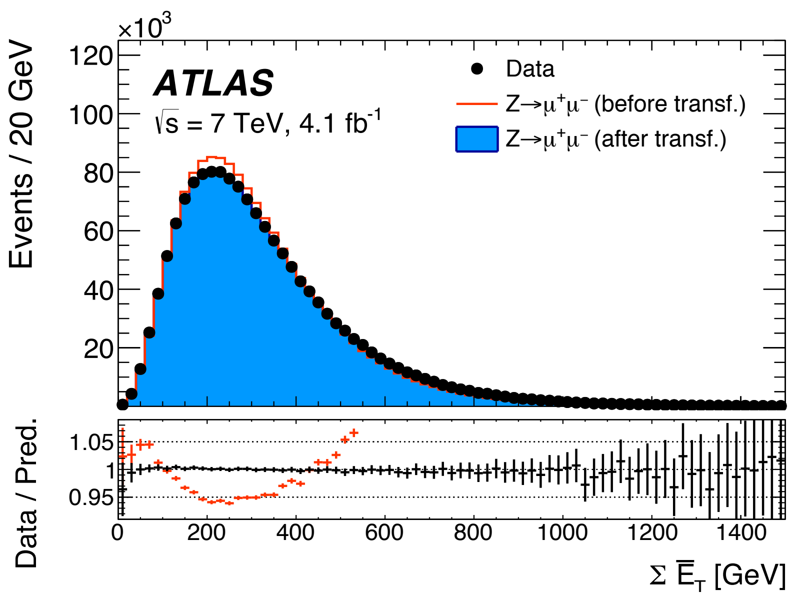


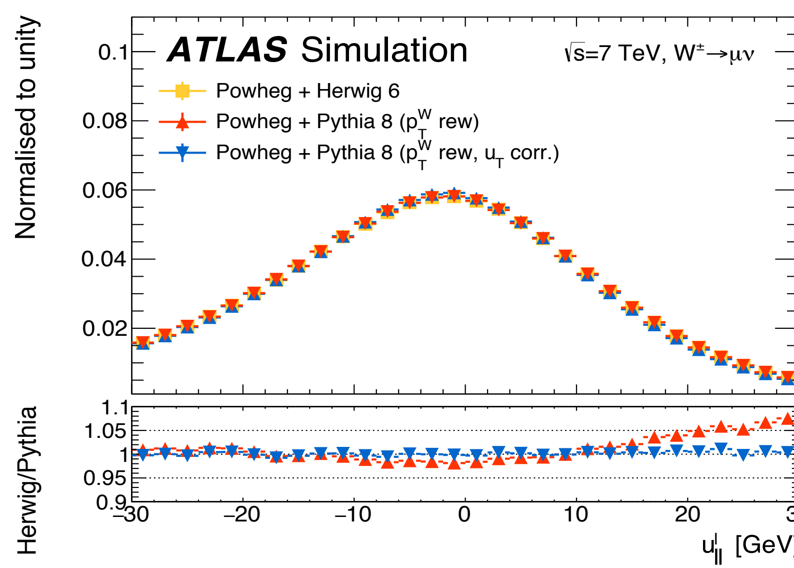
- Muon identification efficiencies with "Tag-and-Probe" method in four dimensions
  - Perfect lepton-η distribution after calibration (and one year of work)



Hadronic Recoil Calibration

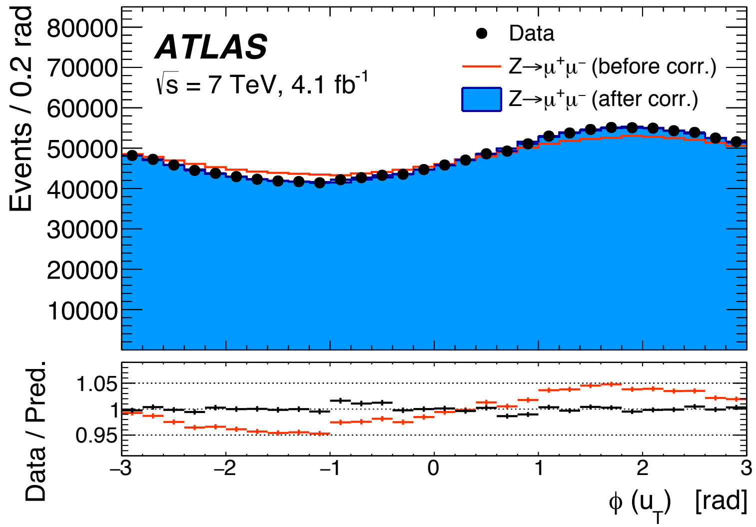
- Recoil correction steps
  - Step 1: Equalize pile-up multiplicity distribution in data and MC
  - Step 2: Correct for residual differences in the ΣE_T distribution
    - removes u_T resolution discrepancy due to imperfect event activity mis-modeling
  - Can be done directly in W events – no extrapolation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

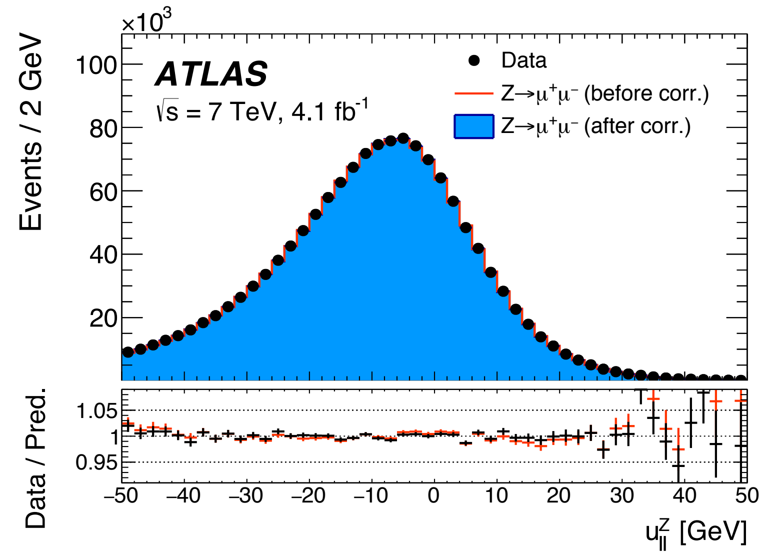




A distribution which took us months

- 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





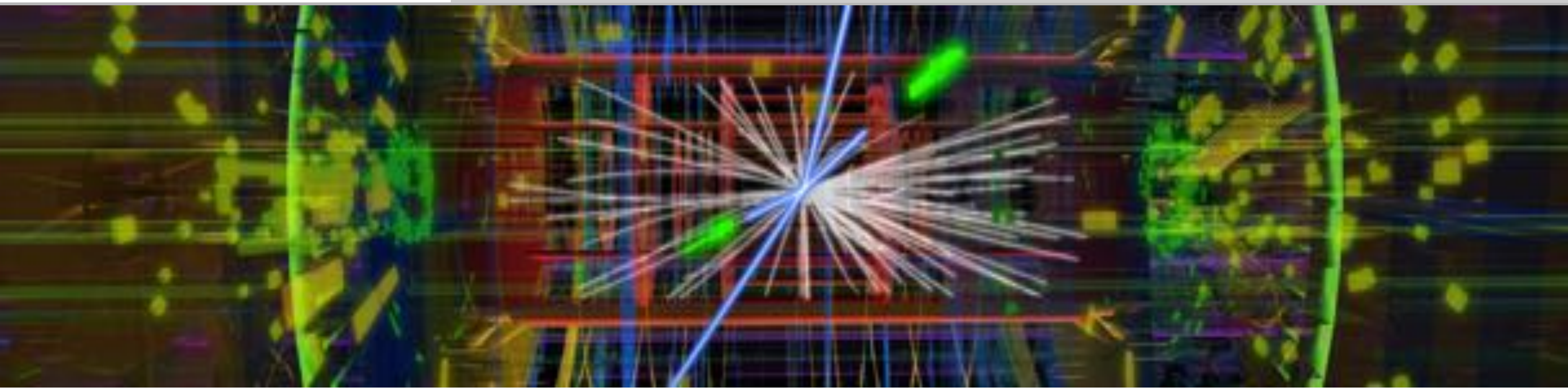
3 tables after 3 years of work

- 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)

$\lvert\eta_\ell\rvert$ 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

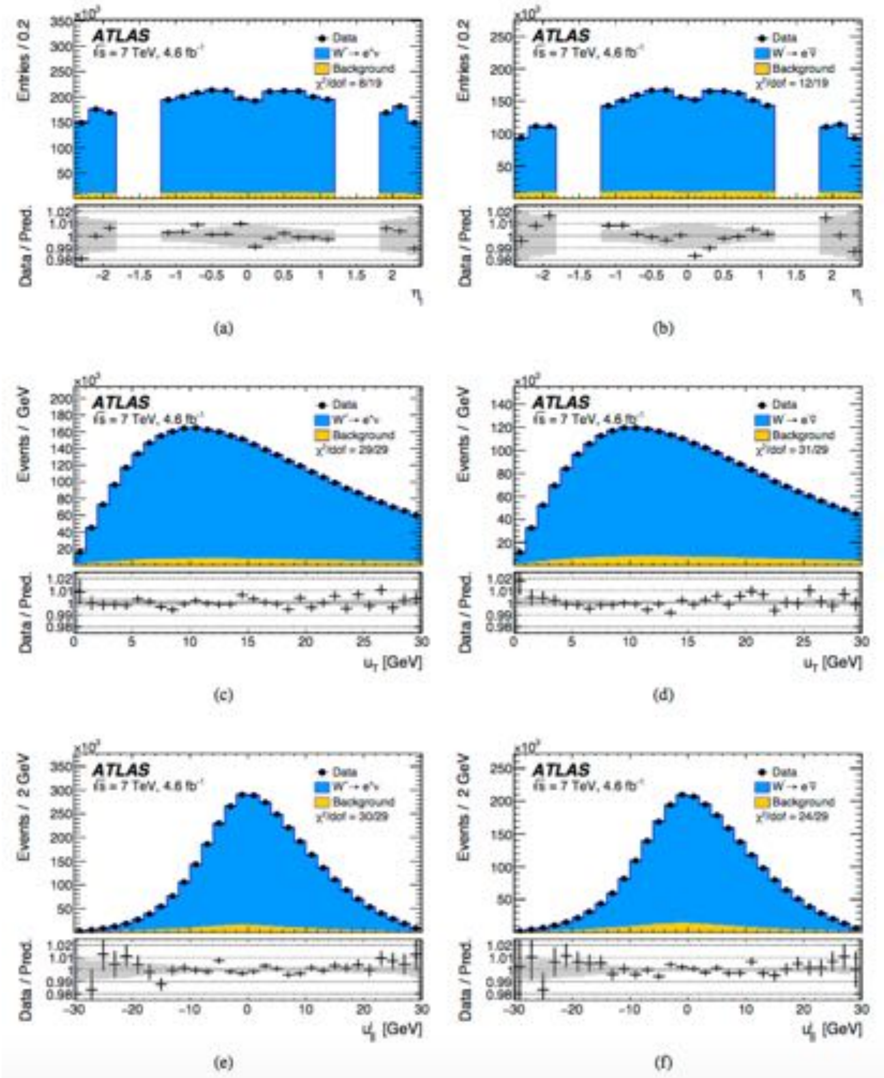
$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	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

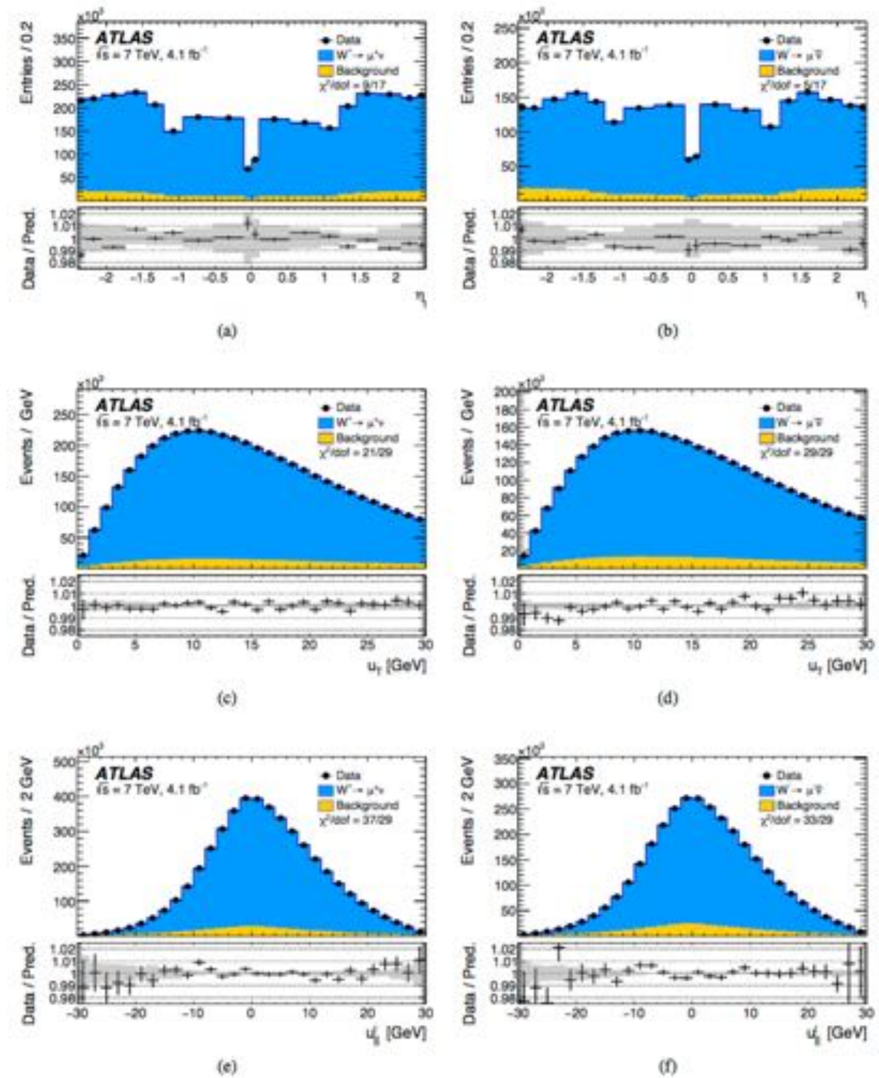
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	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



W Boson Analysis

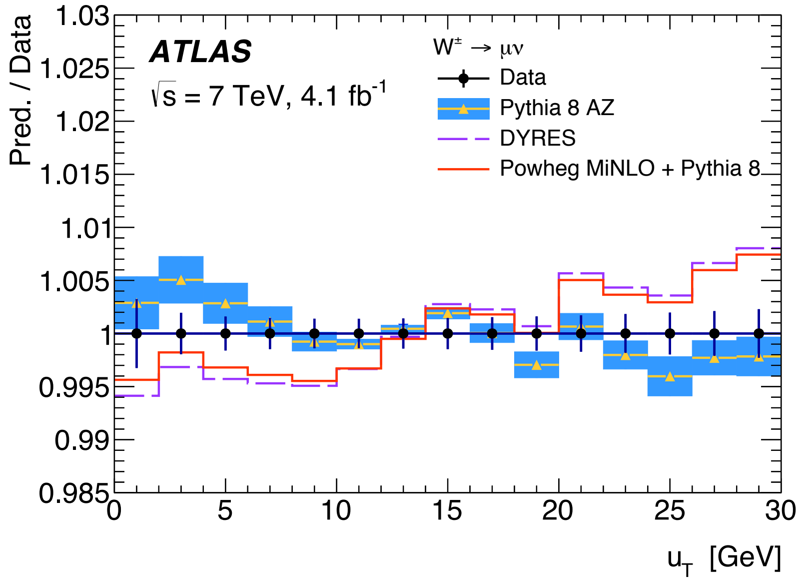
Control Distributions (non m_W sensitive)

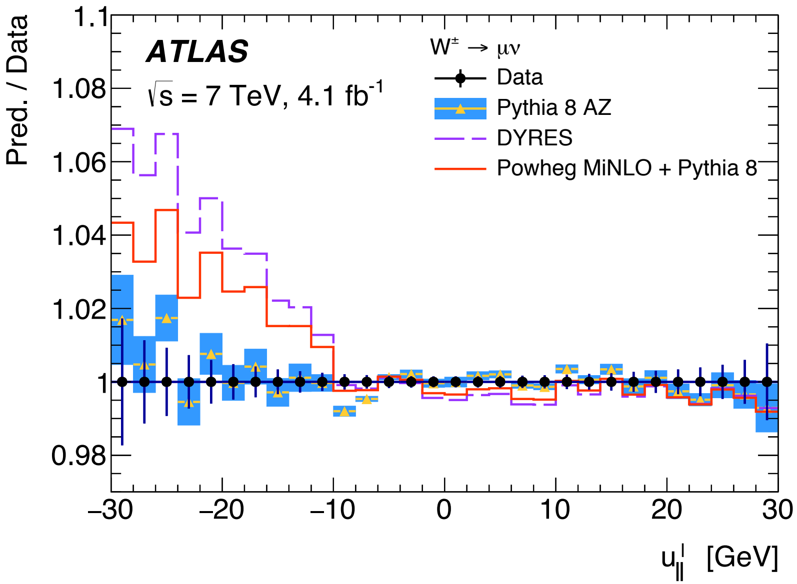




Crucial Test of $p_T(W)$ modelling

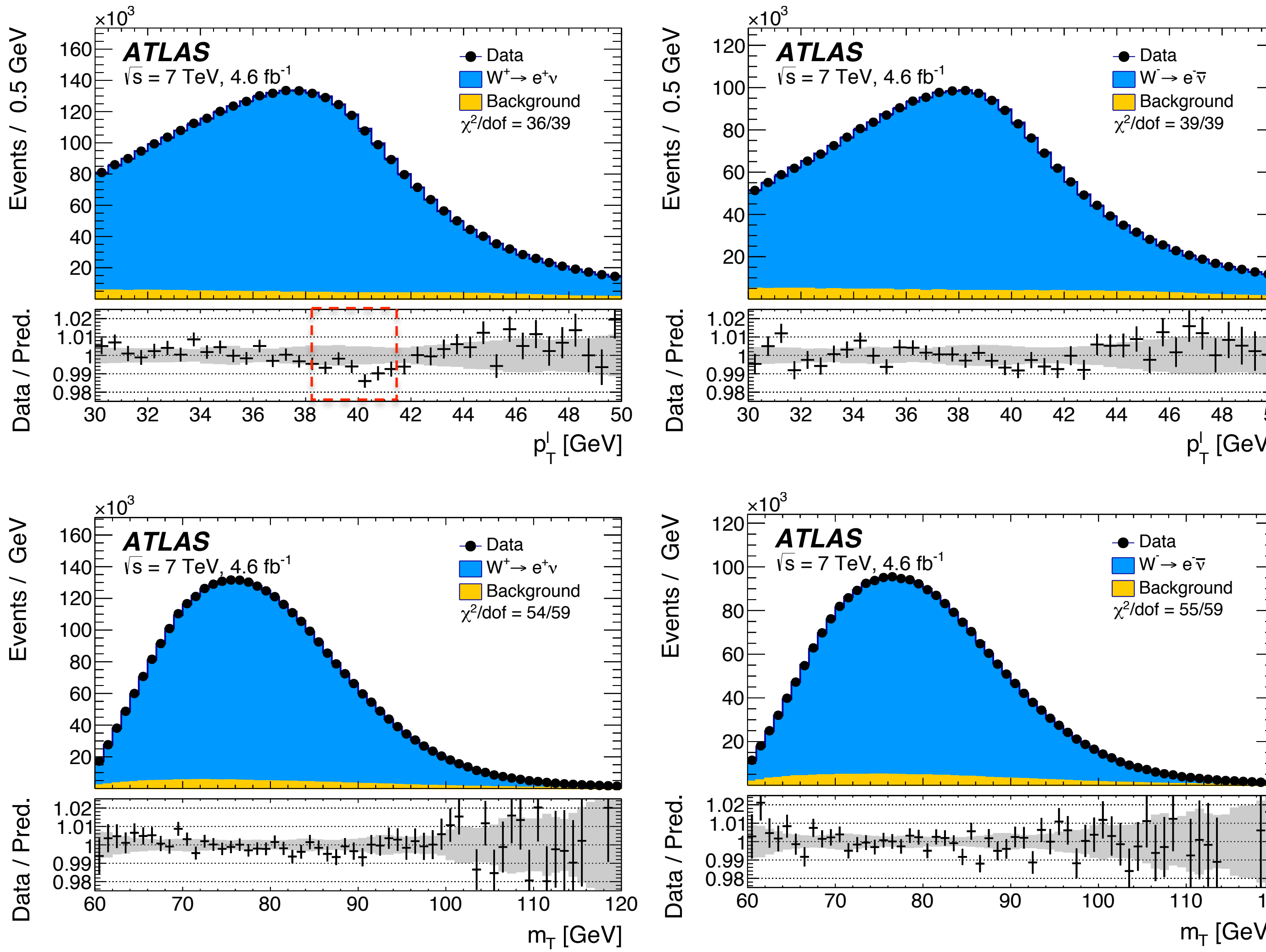
- Remember the problem with the $p_T(W)$ description?
  - How do we know, which MC generator to trust?
  - How do we know, that our assigned uncertainty makes sense?
- The $u_{||}(l)$ distribution is very sensitive to the underlying $p_T(W)$ distribution
  - Can exploit this feature to verify the accuracy of our baseline model, and compare to alternative calculations





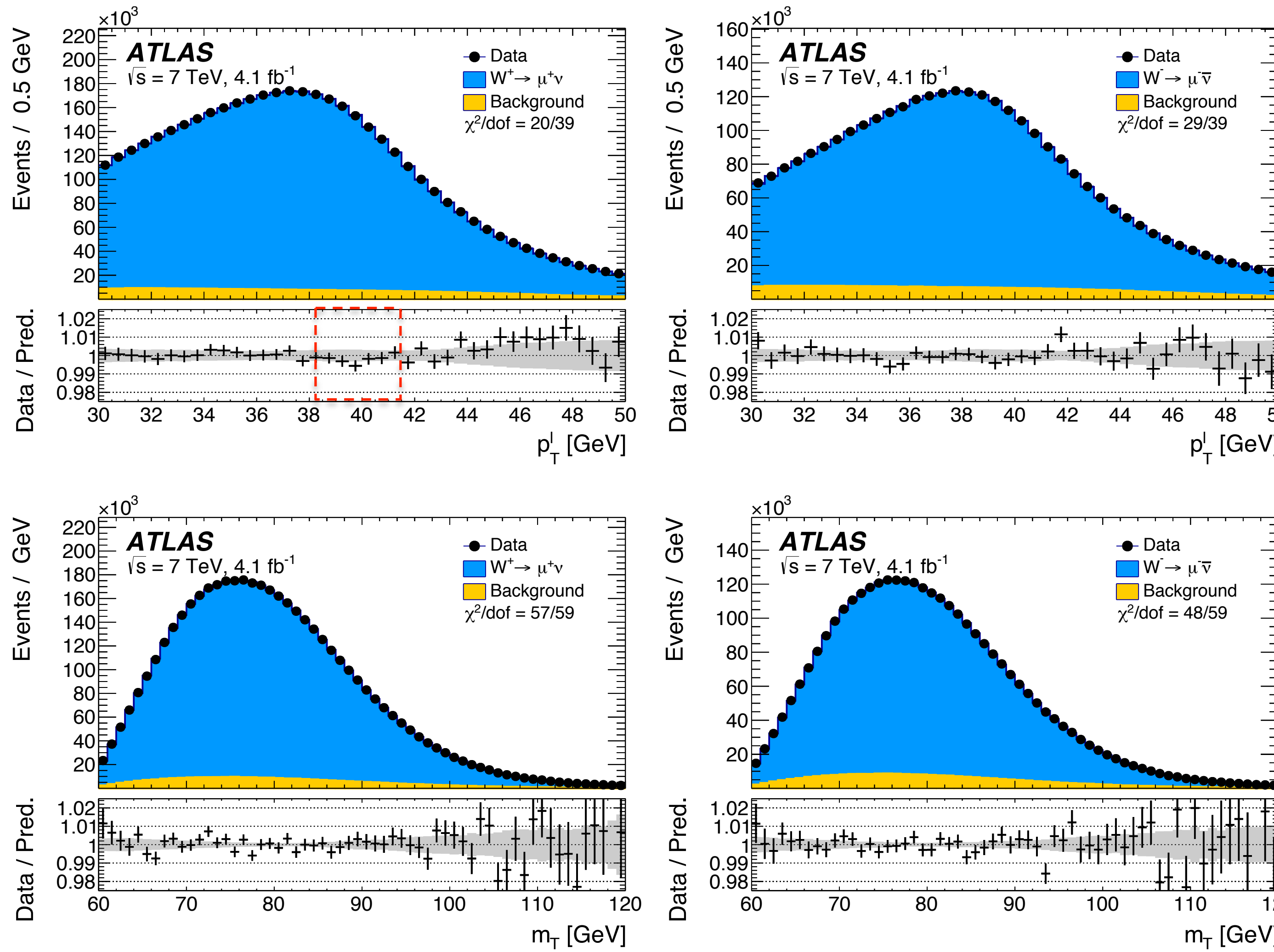
W-Mass Distributions: Electrons

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



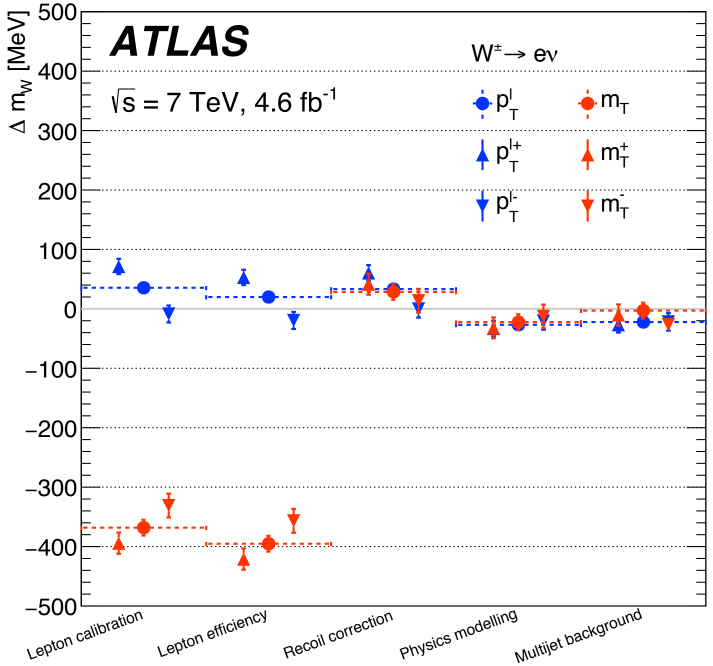
W-Mass Distributions: Muons

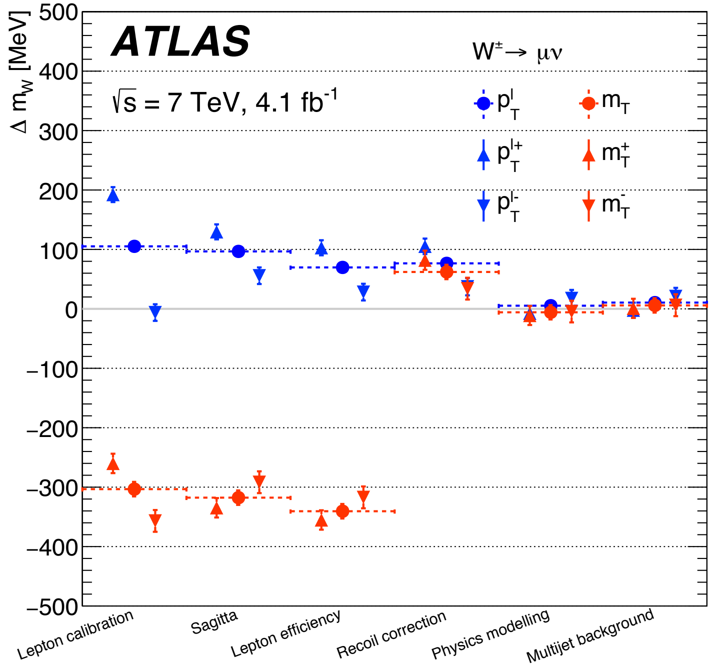
- Very good agreement for muons
- Overall: χ^2/n_{dof} probability distribution from 84 data/ prediction comparison
  - <P>= 0.54



A Little Bit of History

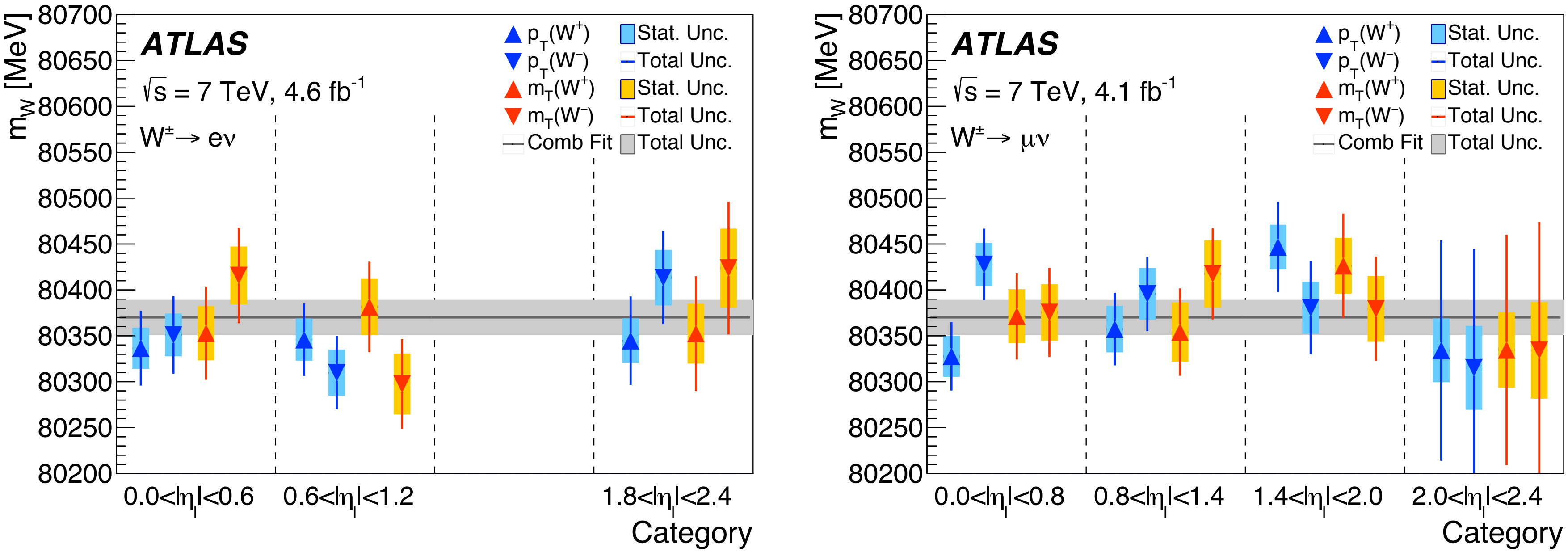
- Over many years we investigated differences in blinded m_W mass-fits in different channels, templates, categories
  - Only after all corrections applied (and all bugs where found), we achieved consistent results





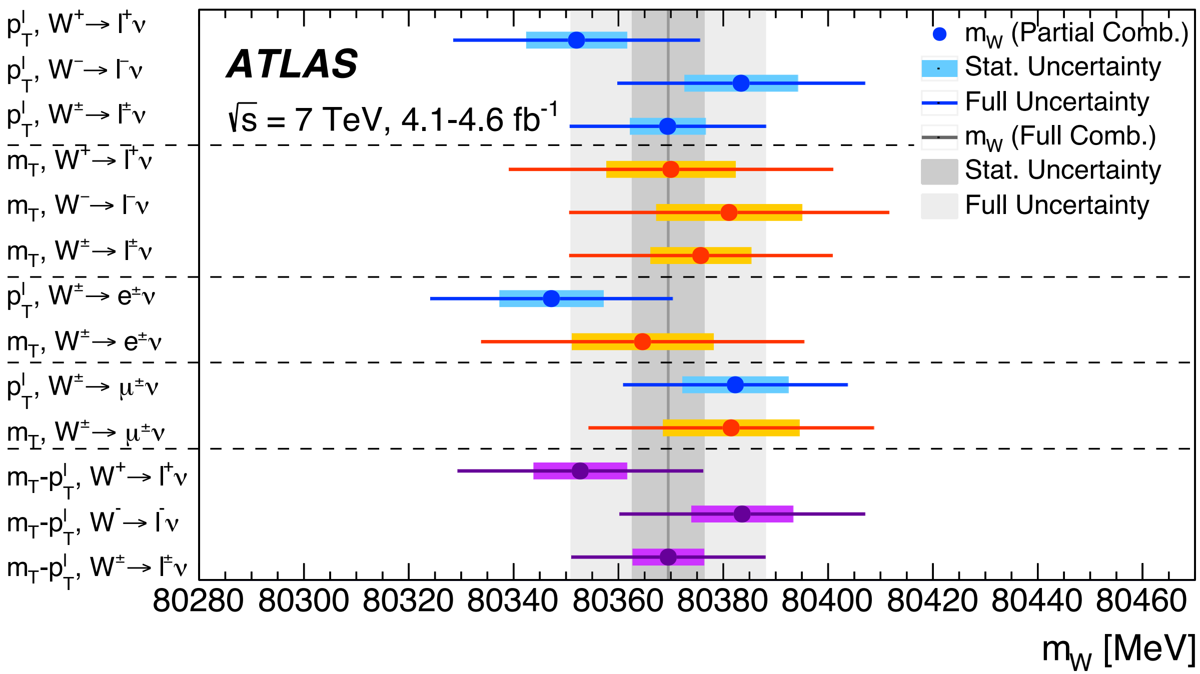
Final Measurement

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
- The fitting ranges have been optimized
  - 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!

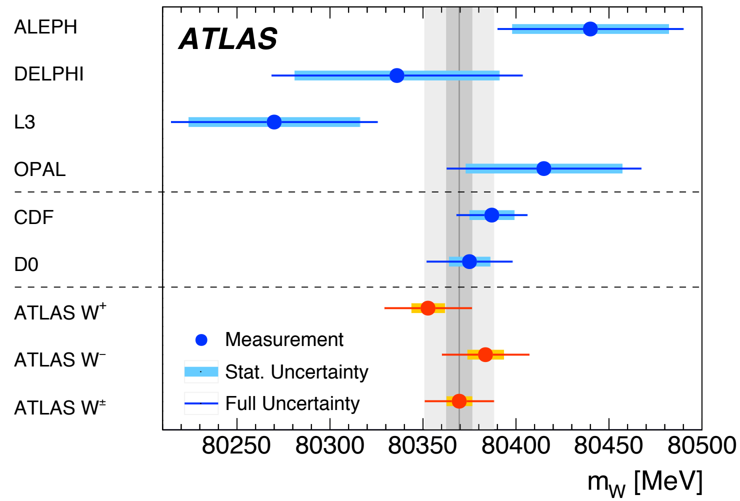
Final measured mass of the W boson:

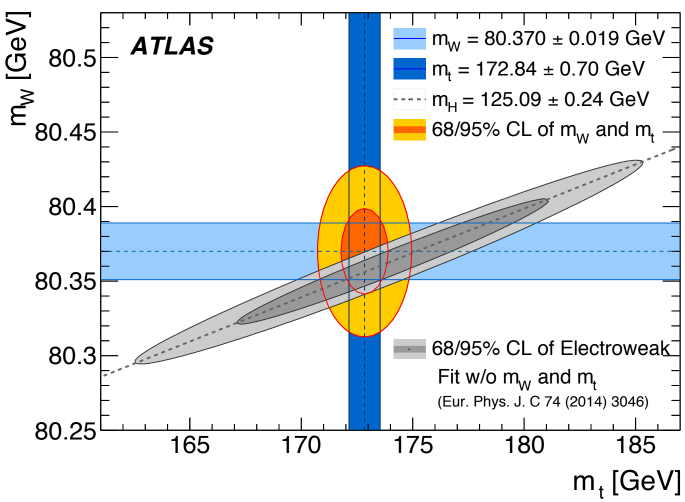
80370±7(stat.)±11(exp.)±14 (mod) MeV = 80370 ± 19 MeV

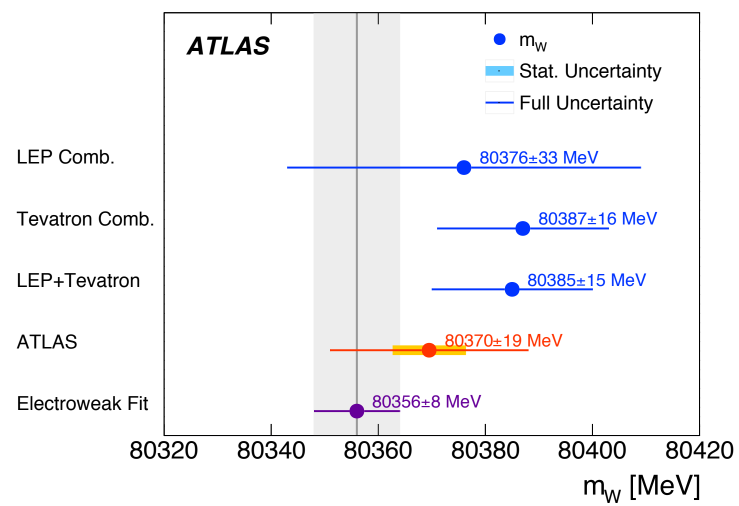
Comparison to previous measurements and the Global Electroweak Fit

- Good news: New measurement reaches precision of CDF and is now the world leading measurement

- Bad news: We are even more Standard Model …



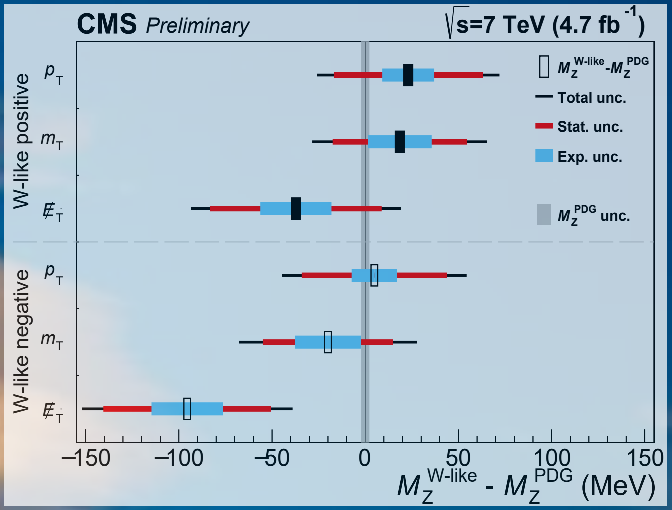


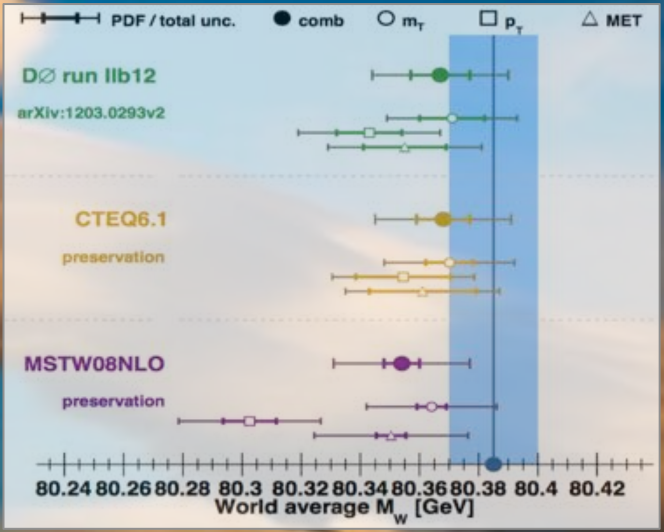


Outlook on EW precision at the LHC

- 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: 10-12 MeV is feasible**

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





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Summary

- Take away message for students
  - Do not get discouraged by reviewers
  - Talk to as many people as you can
- First W mass measurement at the LHC shows no signs of new physics
  - Need some “break-through” in the MC event generator developments
  - Final precision of <10 MeV seems in reach (in Combination with upcoming Tevatron results)
- The future of high energy physics lies (IMHO) in precision measurement and rare-decays