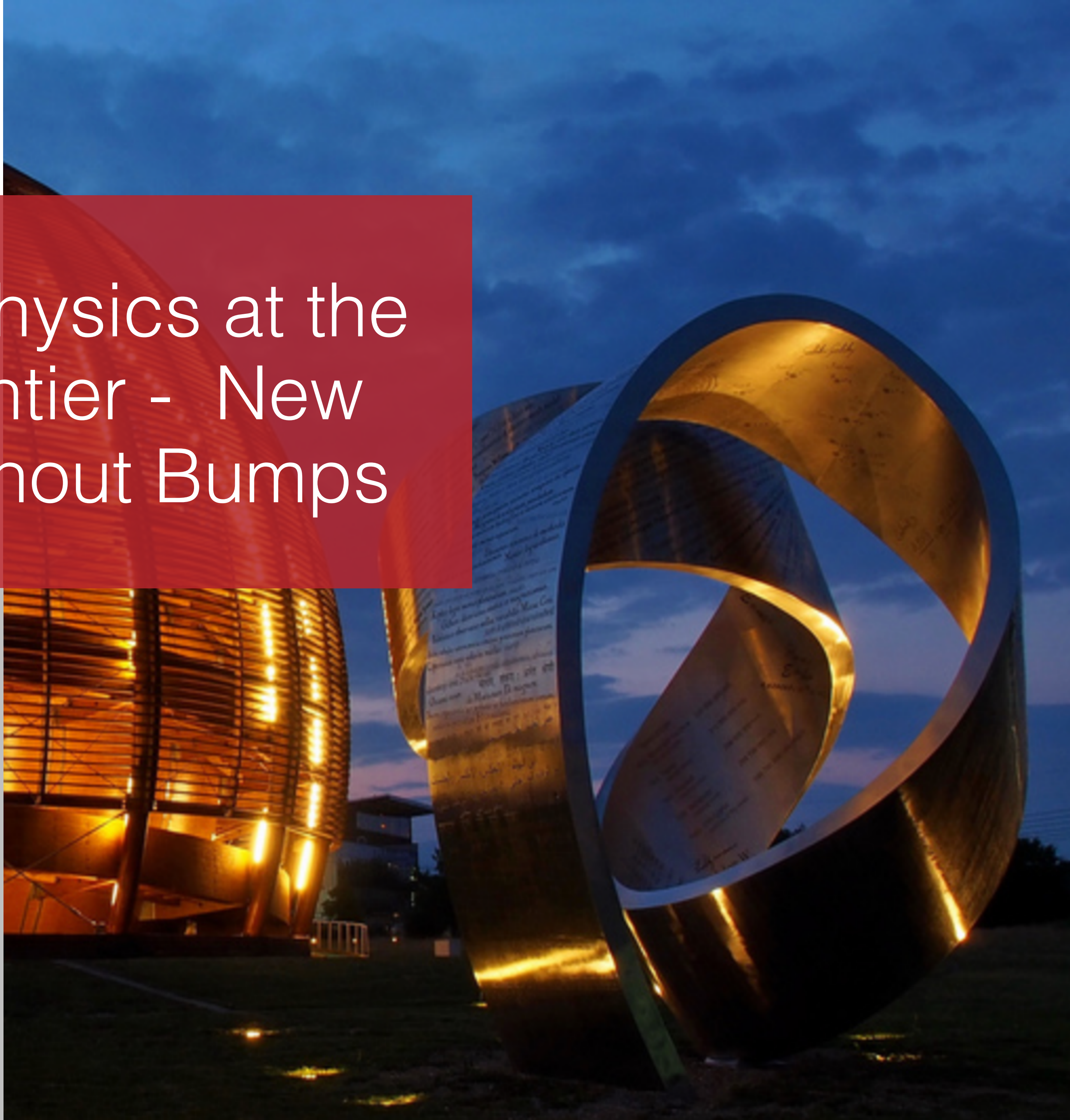
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Precision Physics at the Energy Frontier - New Physics without Bumps



Prof. Dr. Matthias Schott

My Academic Stations in one Slide


University of Erlangen


University of Cambridge


University of Munich

CERN, Geneva


University of Mainz


CERN


MIT, Cambridge

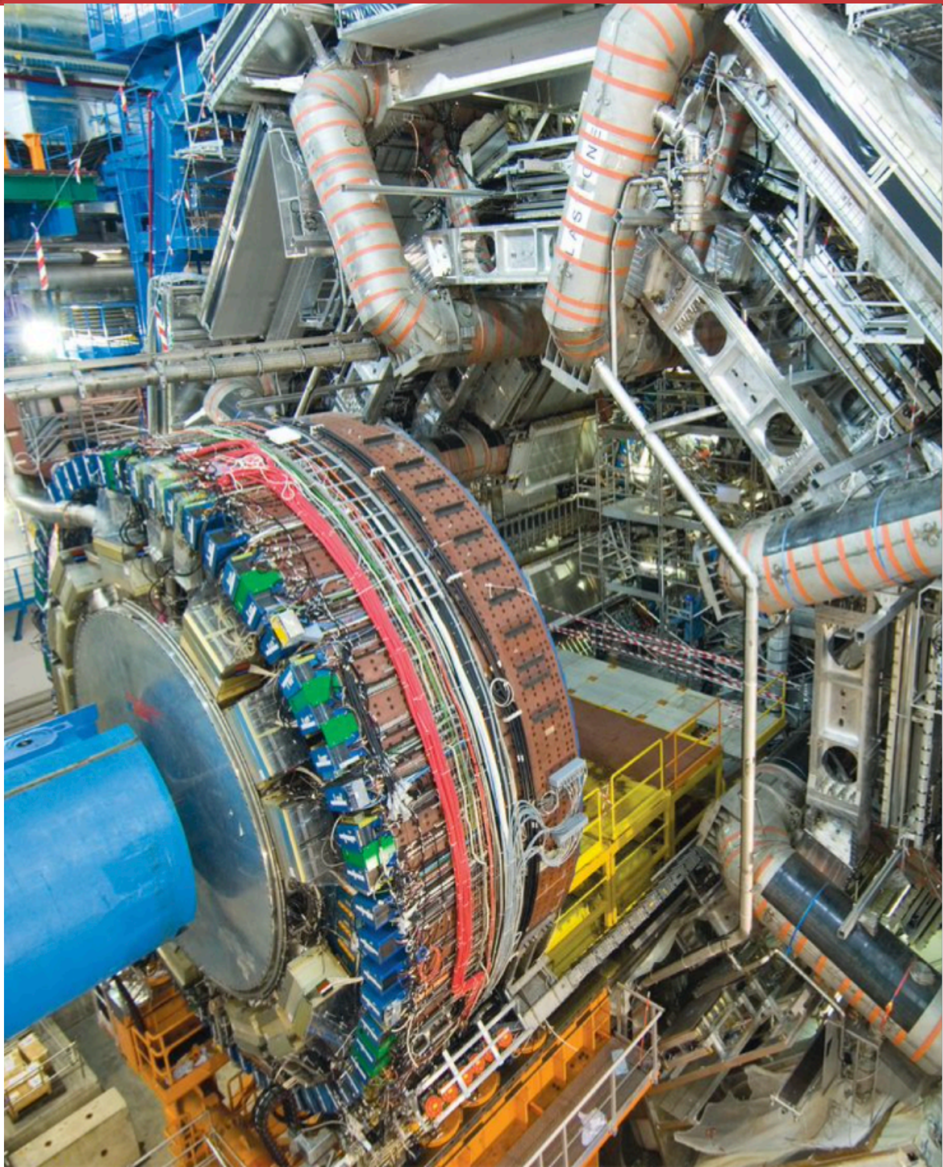

UCL, London

My Research Areas: Electroweak Precision Physics

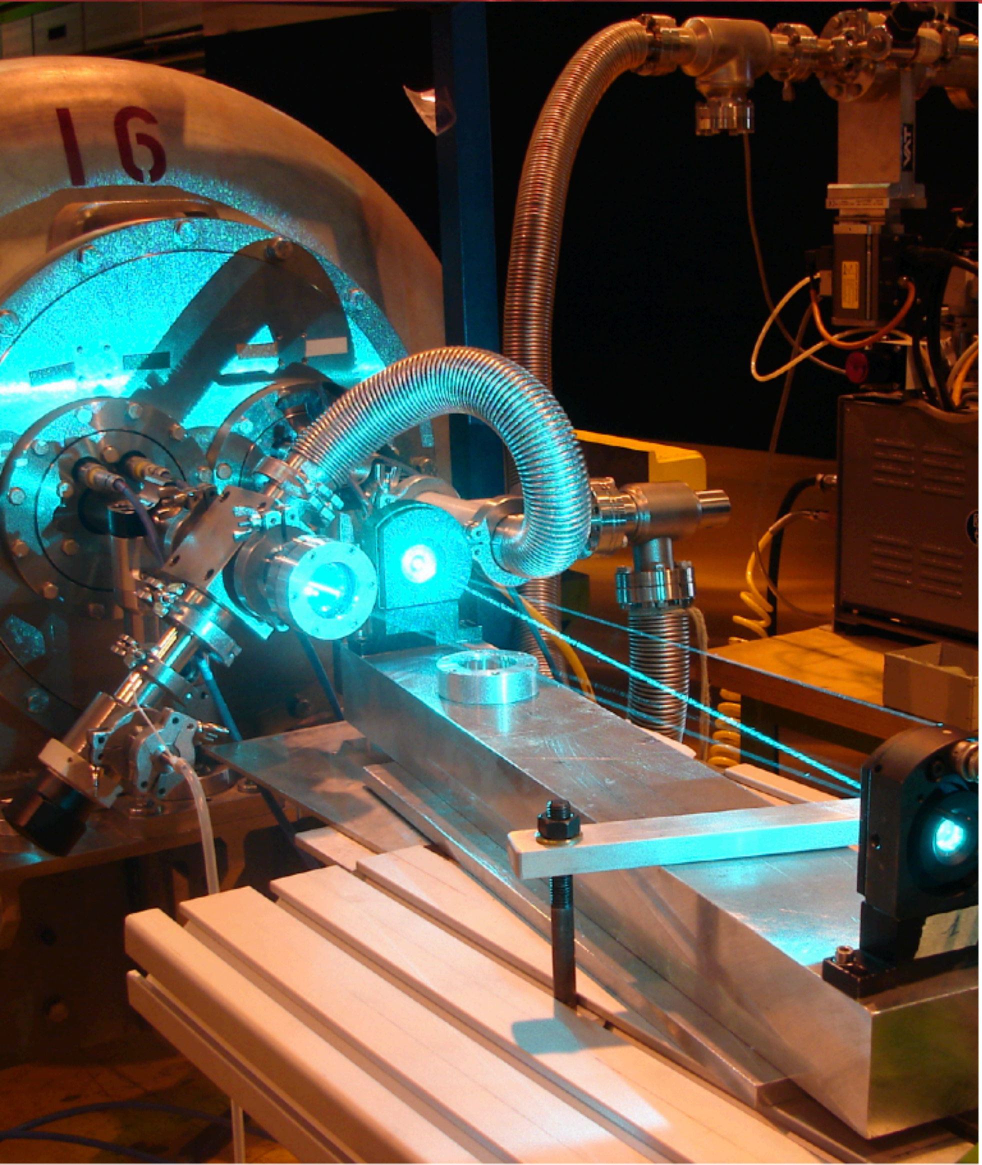
- Interpretation of the Electroweak Precision Measurements via the Global Electroweak Fit

- Measurement of the W boson mass with the ATLAS Detector (2011 - ongoing)
    - 5 years effort until first publication
    - Main topic of today’s talk

- Further high precision measurements to probe QCD
    - Most precise measurement of the differential W and Z boson cross-section at 7, 8 and 13 TeV
    - Underlying event measurements
    - Lots of detector calibration



My Research Areas: Search for Axion-Like Particles



- OSQAR Experiment
  - Responsible for everything ☺
- ALPS-II Experiment
  - Responsible for the signal photon detection (Transition Edge)
- (Baby)IAXO Experiment
  - Development of the X-ray detector as well as the cosmic muon veto
- FASER Experiment
  - Calibration of calorimeter modules
  - Development of Pre-shower detector
  - Support structure construction
- ATLAS Experiment
  - Light-by-Light and exotic Higgs-Decays

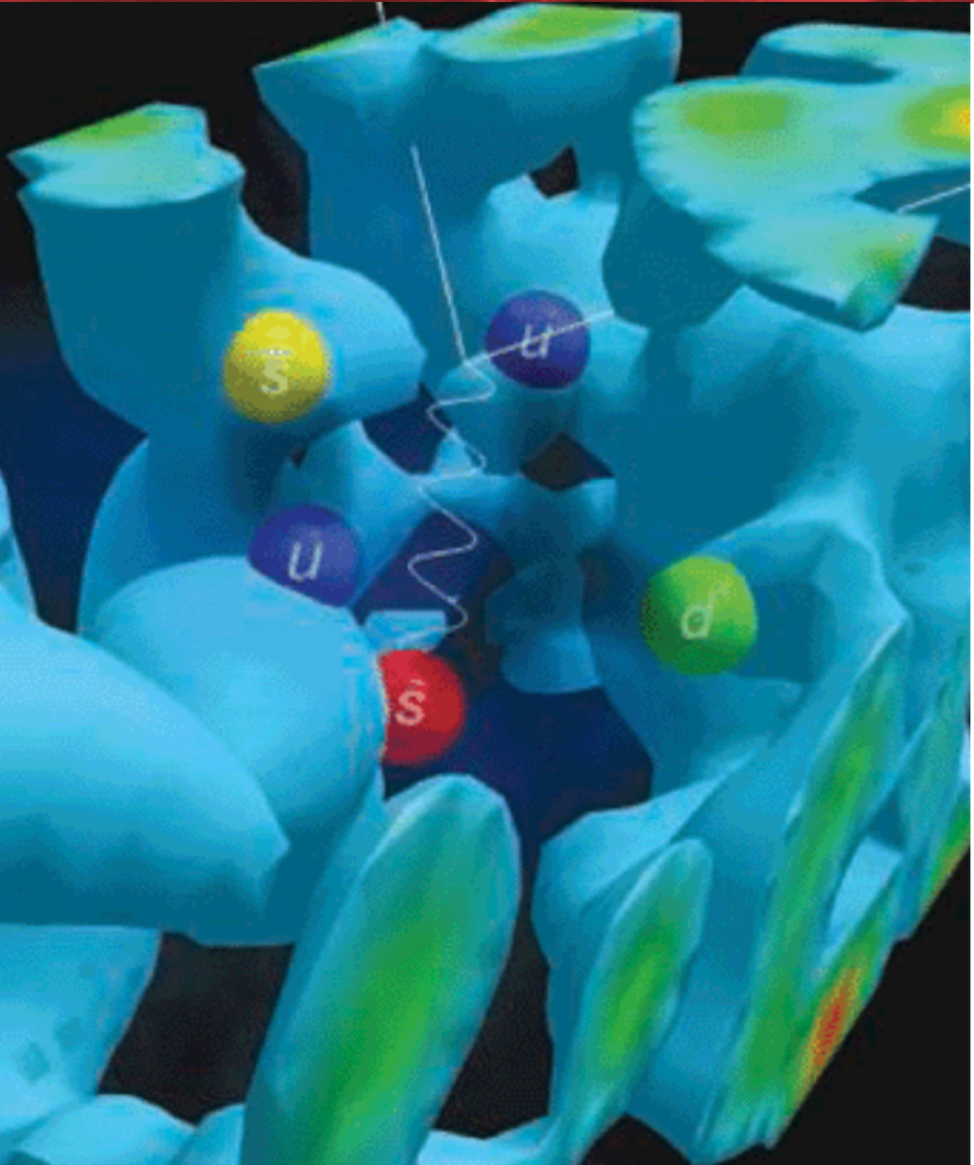
My Research Areas: Detector Research and Development

- Design, Construction and tests of the first fully functional prototype of the ATLAS New Small Wheel project

- Construction of >100m² of highly planar drift-panels for the ATLAS New Small Wheel project
  - ¼ of the world-wide production
  - Only group that finished according schedule ☺

- R&D of Micromegas Detectors for BabyIAXO
  - Xenon based detectors to enhance photon interaction probability

My Research Areas: Quantum Chromo Dynamics



- Measurement of the strong coupling constant using Z boson Production at the LHC

- Study of the hadronic contributions to $\Delta\alpha_{had}^{(5)}$ in the Electroweak Fit

- Study of hadronic contributions in light-by-light scattering at the LHC
  - Side-Effort: Probing $(g\text{-}2)_\tau$ of tau-Leptons

- Topological Effects (might be my future research focus)
  - QCD Instanton and Sphaleron Processes
  - Chiral Magnetic Effect

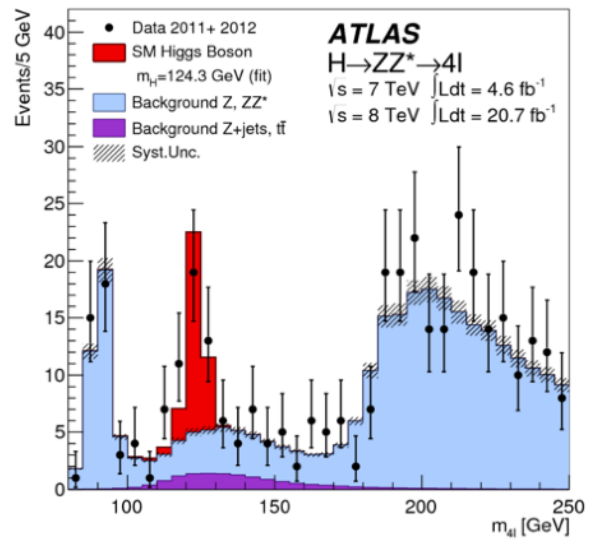
My Top Six of Open Questions in the Electroweak Theory

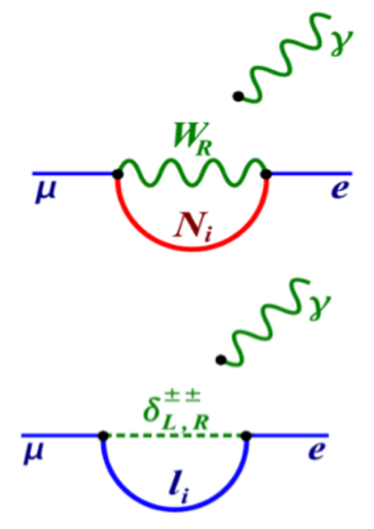
- What is Dark Matter?
- How to explain the matter-antimatter asymmetry?
- Is the Higgs-mass fine-tuned ?
- What is the physics behind dark energy?
- What is the origin of neutrino masses?

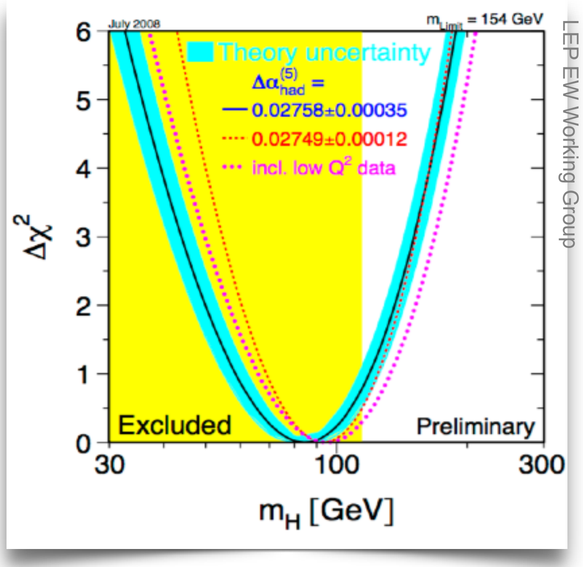
- And number seven as G. Zanderighi puts it: Are these the right questions?
  - Is naturalness a good argument?
    - It worked well in the past: electron self-energy => positron, pion-mass difference => rho resonance, K_S and K_L life time difference => charm mass prediction)
  - But it seems to fail at the LHC!

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

How to answer these Questions?







LEP EW Working Group

- Direct Searches
  - production of new particles (e.g. LHC)
  - Interaction of particles with detectors (e.g. XENON1T)
- 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

Why Precision Measurements?

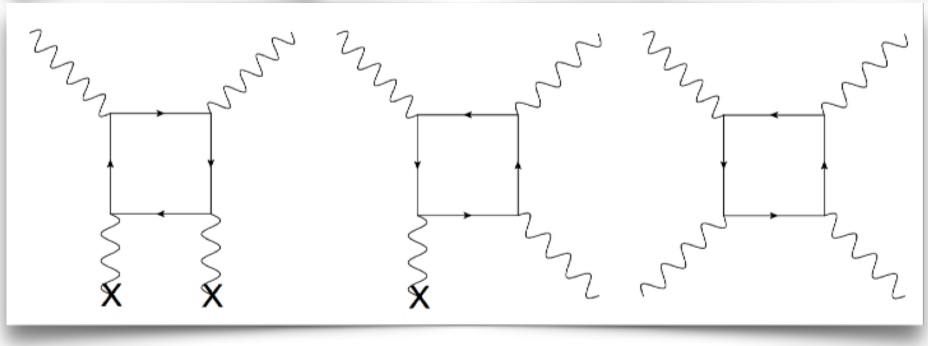
Simple Example: Loop Effects in QED

- Defining feature of Maxwell’s Equation: Super-position principle

- Euler and Heisenberg calculated already in 1935 QED corrections to Maxwell’s Equations, predicting

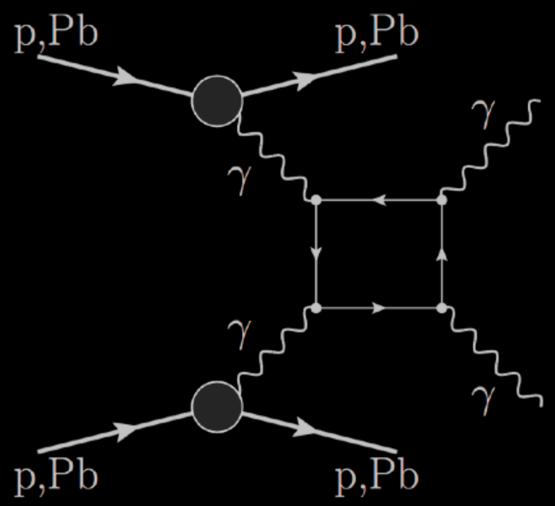
$$L_{eff}^{EHW} = L_0 + L_{eff}^{1} = \frac{1}{2}(E^2 - B^2)\cdot \frac{2\alpha^2}{45 m_e^4}\left[(E^2 - B^2)^2 + 7(\bar{E}\cdot\bar{B})^2\right]$$

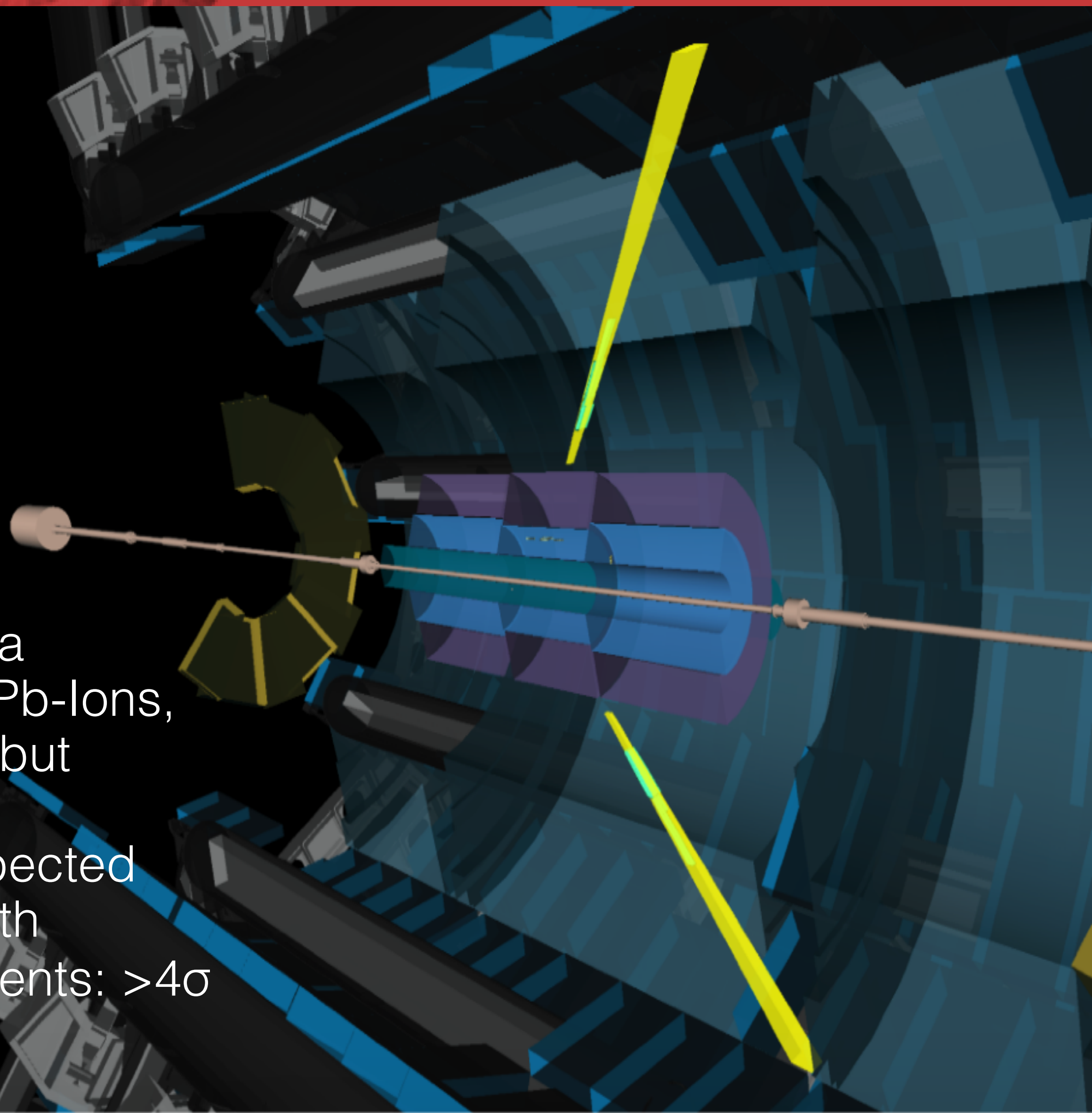
- Light-by-Light Scattering
- Photon-Splitting
- Vacuum Magnetic Birefringence



Light-by-Light Scattering at the LHC

https://arxiv.org/abs/1602.08088





- Use Heavy-Ion collision data
  - Look for events with two Pb-Ions, which are not diffractive, but radiate 2 photons
  - Very low background expected
  - ATLAS sees 13 events with roughly 3 background events: >4σ
  - Latest results: >7σ

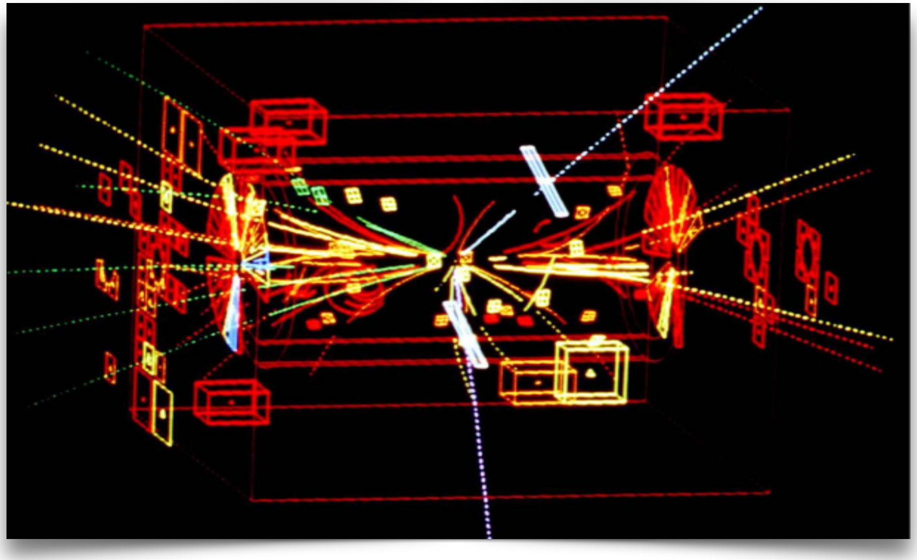
Let's move to the Electroweak Sector

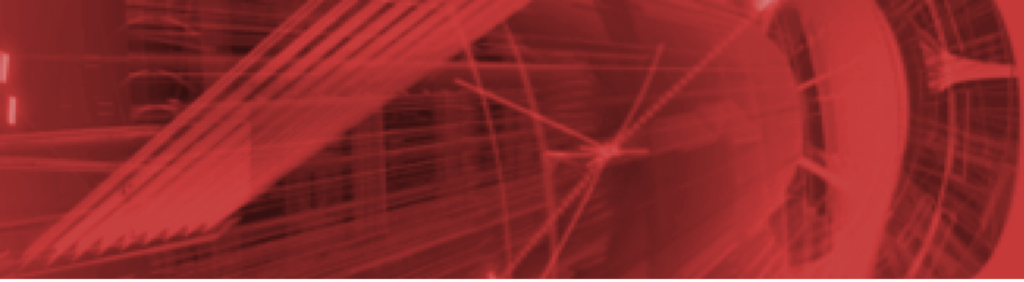
- The electroweak sector of the Standard Model has five parameters
  - α_{em}, G_F, m_W, m_Z, $\sin^2\theta_W$
  - (+ m_H for the scalar sector)

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

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

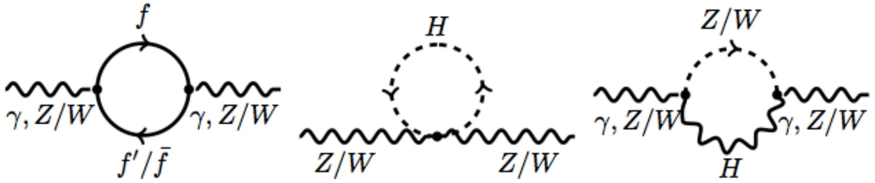
$$m_W^2 sin^2\theta_W = \frac{\pi}{\sqrt{2}}\frac{\alpha}{G_F}$$





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



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

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

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

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

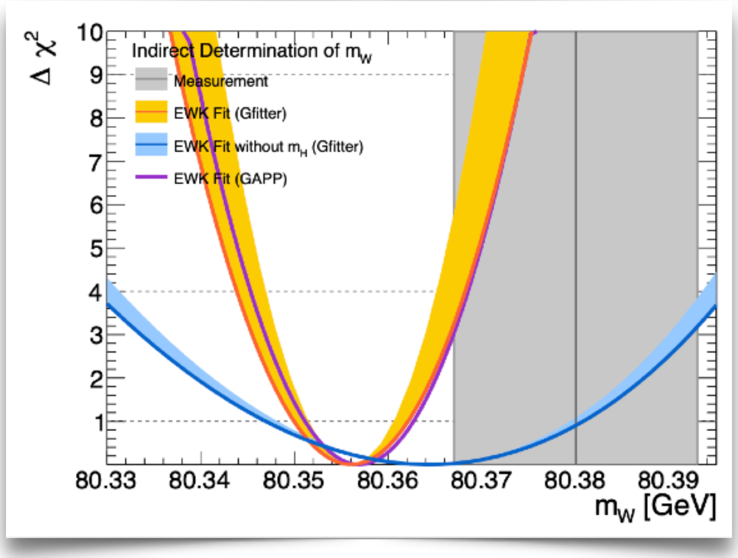
$$M_W\left(\ln(M_H), m^2_t, M_Z, \Delta\alpha^{(5)}_{\rm had}(M^2_Z), \alpha_S(M^2_Z)\right)$$

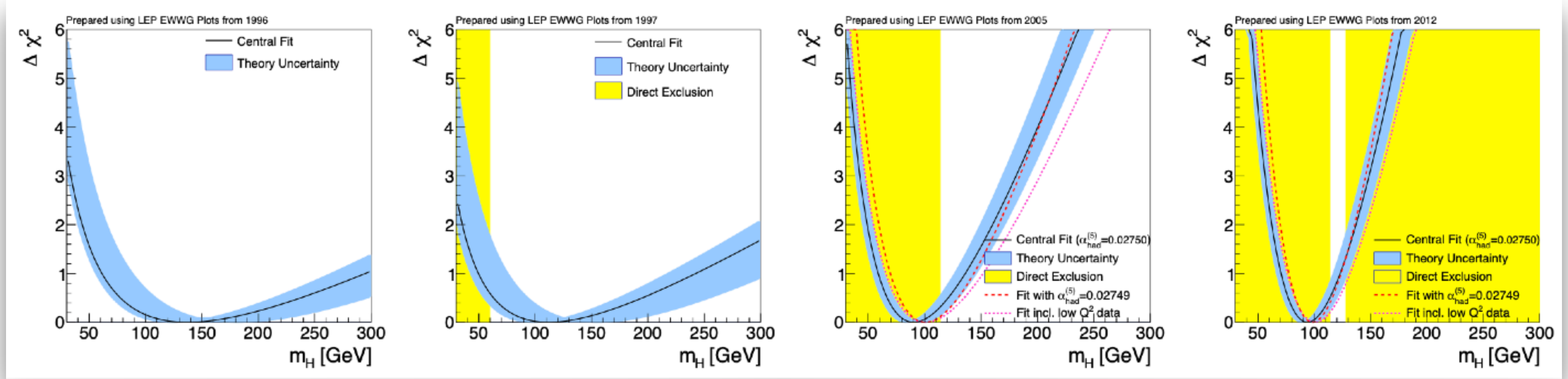
$$\sin^2\theta^f_{\rm eff}\left(\ln(M_H), M_H, m^2_t, M_Z, \Delta\alpha^{(5)}_{\rm had}(M^2_Z), \alpha_S(M^2_Z)\right)$$

Input and Outcome to the Electroweak Fit

- Input for the global 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

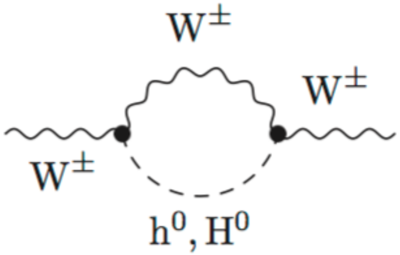


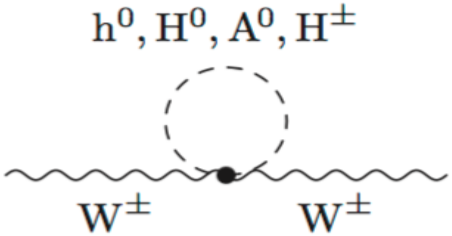


Want to learn more about the Global Electroweak Fit and its history? arXiv:1902.05142

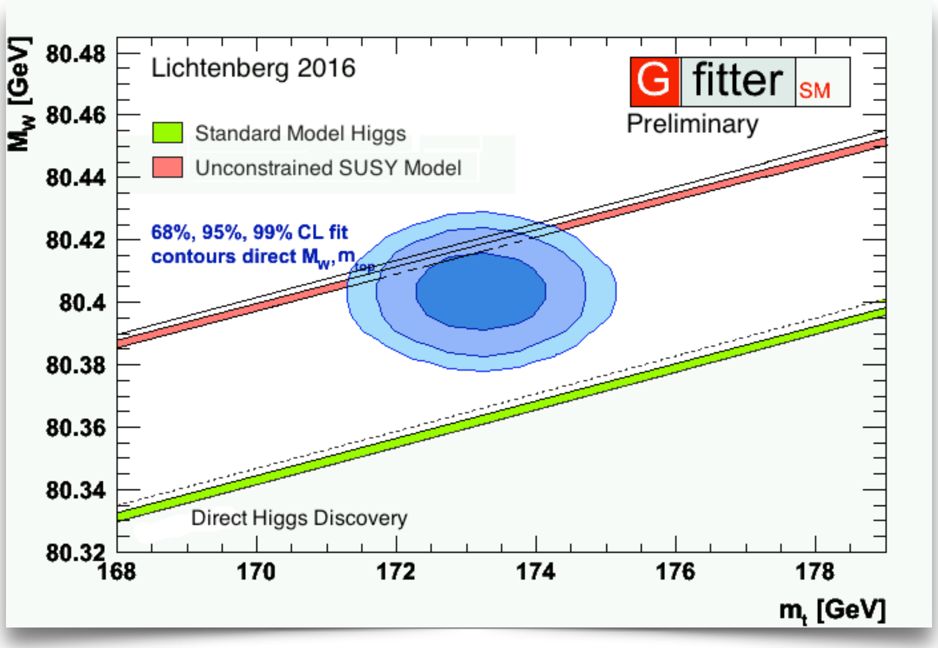
Why do we need that?

- 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]



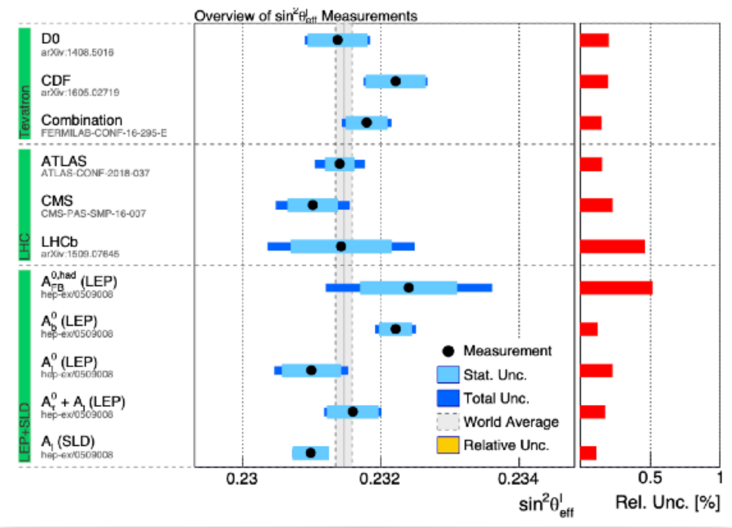
Where do we stand and what do we need?

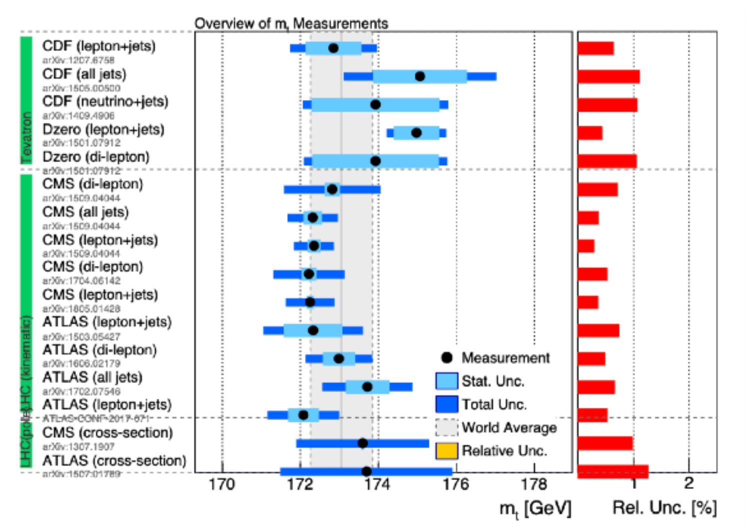
- Z boson observables: LEP was great; we can't do better (now)
    - Except the weak mixing angle

- Top-quark mass: huge progress; new approaches to overcome theoretical unc. on m_{top}
    - SM prediction ±2.5 GeV
    - measurement unc. <0.5 GeV

- Higgs mass: Only logarithmic dependence, hence not important

- W mass: SM prediction at 5 MeV precision, before LHC only known to 19 MeV!
    - Here we can gain a lot!





Measurement Strategy

Mass Sensitive Variables

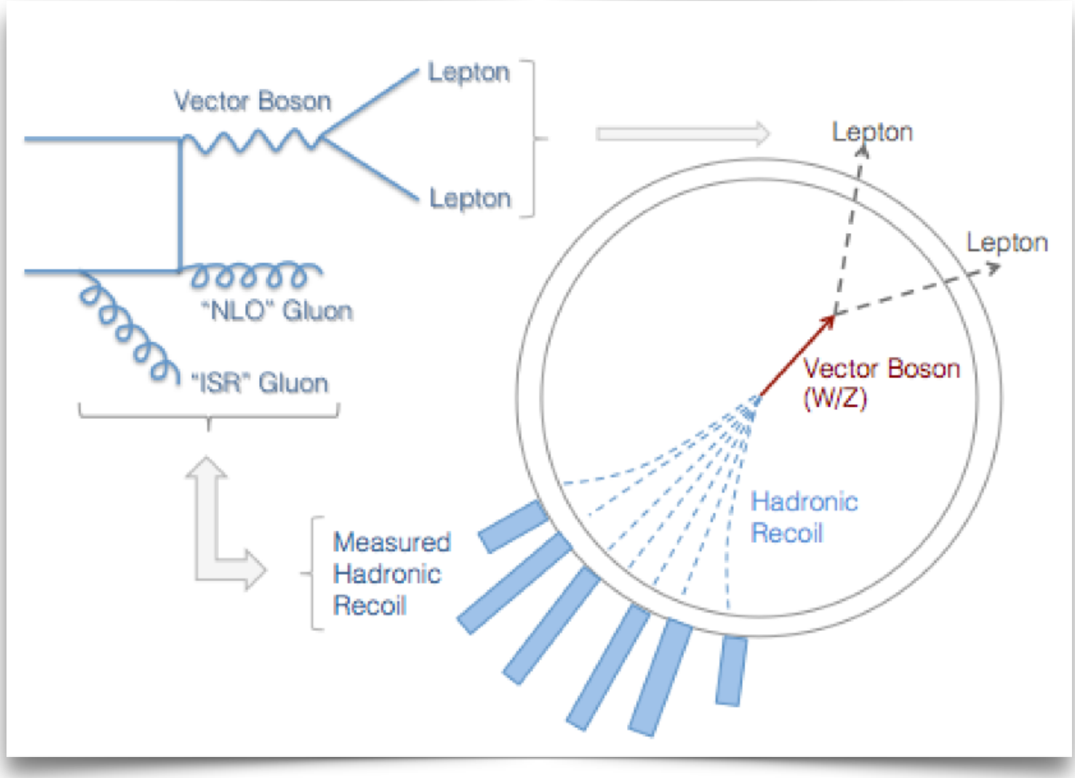
- Main signature: final state lepton (electron or muon): p_T(lepton)

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

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

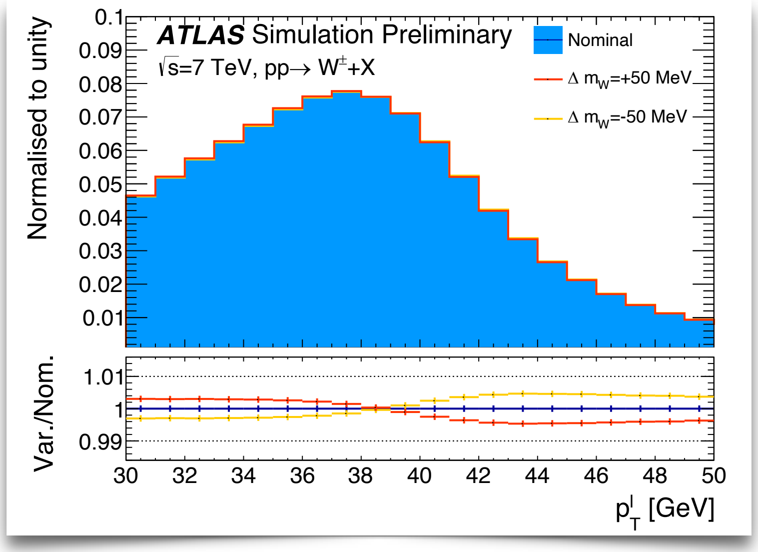
$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,l} + \vec{u}_T\right)$$

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

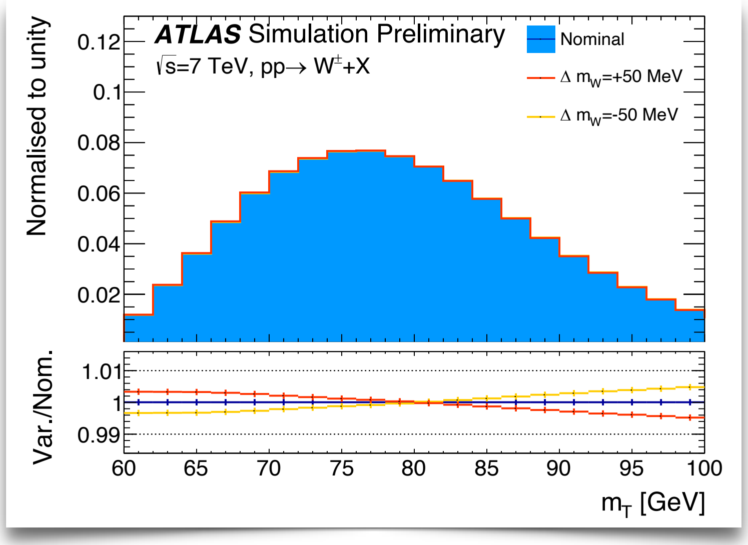


Mass Sensitive Variables

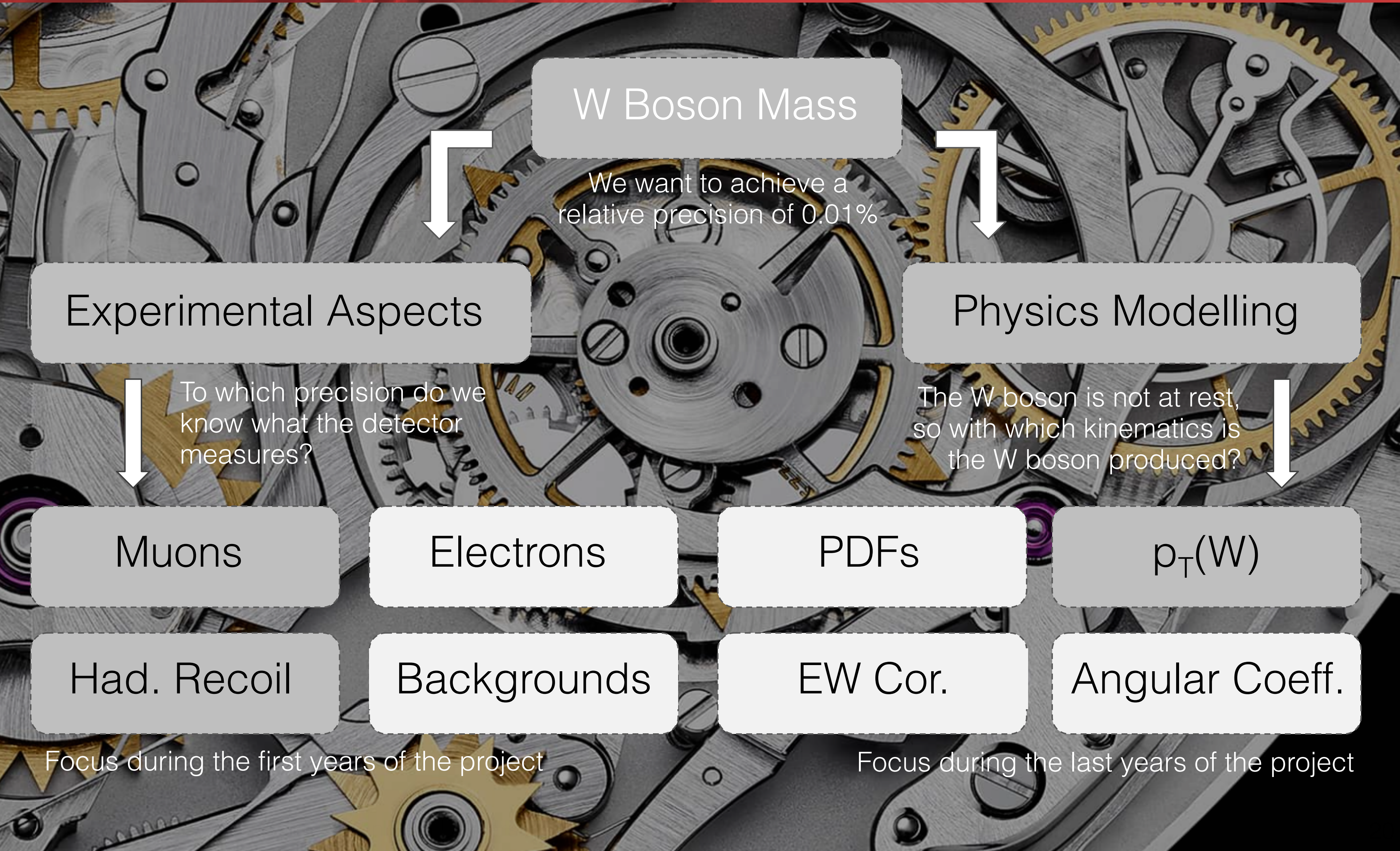
- Sensitive final state distributions:
  - Lepton transverse momentum $p_T(l)$
  - Transverse mass: m_T
  - Missing transverse energy ("neutrino p_T"): p_T^{miss}



- 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



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

- **Physics Modelling**

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

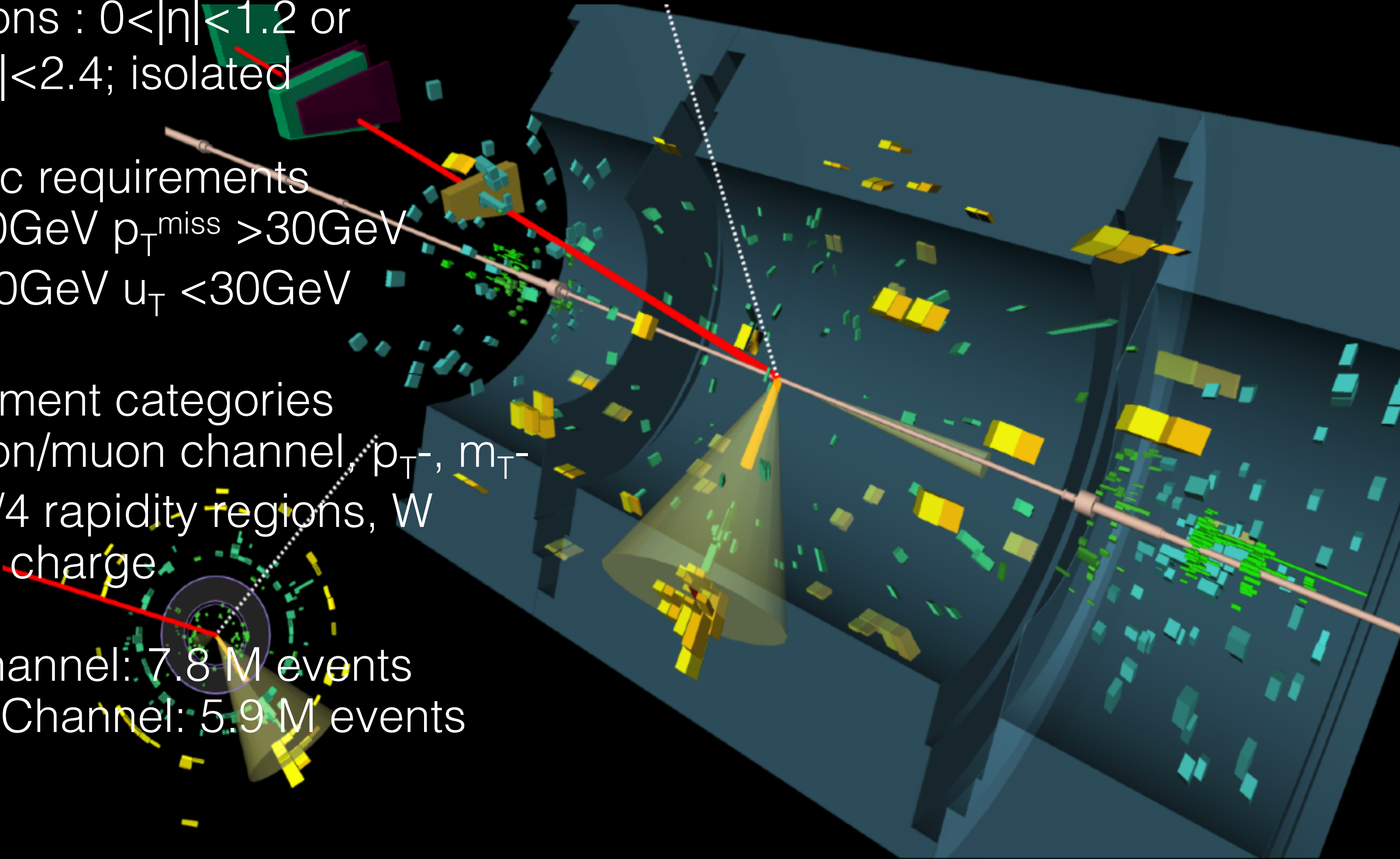
  - PDFs
  - $p_T(W)$
  - EW Cor.
  - Angular Coeff.

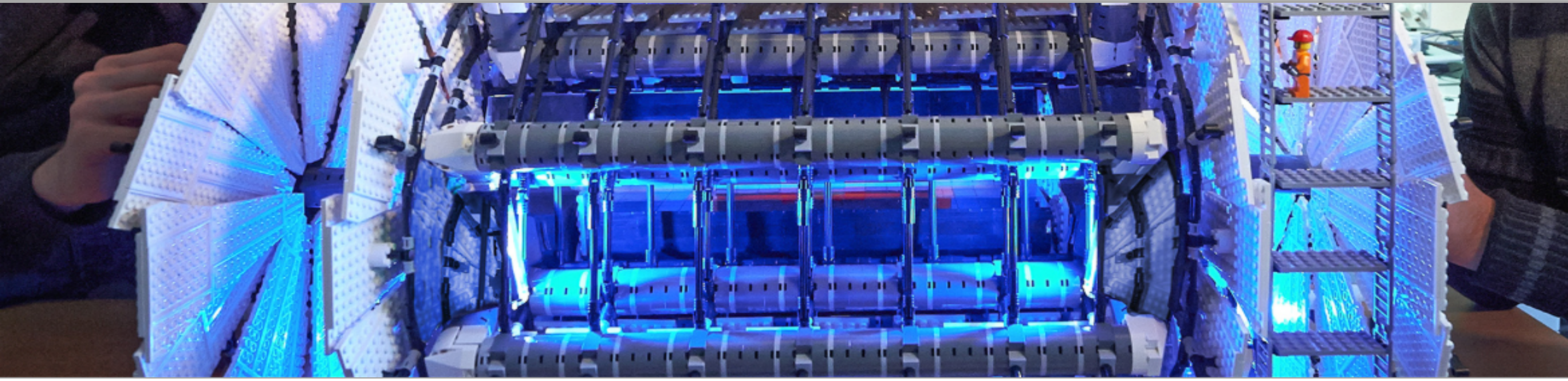
Focus during the first years of the project

Focus during the last years of the project

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
- 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

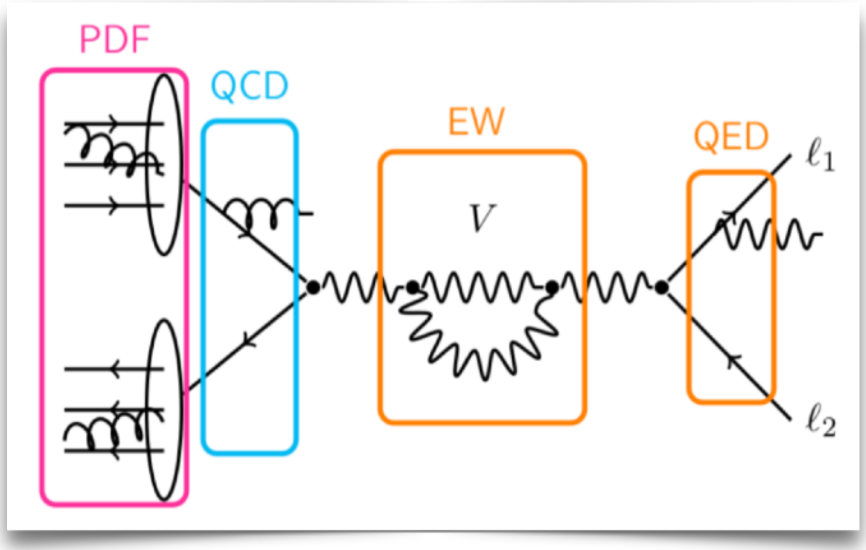




Physics Modelling

Physics Modelling

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



- QCD aspects
  - Rapidity, p_T distributions, angular distributions

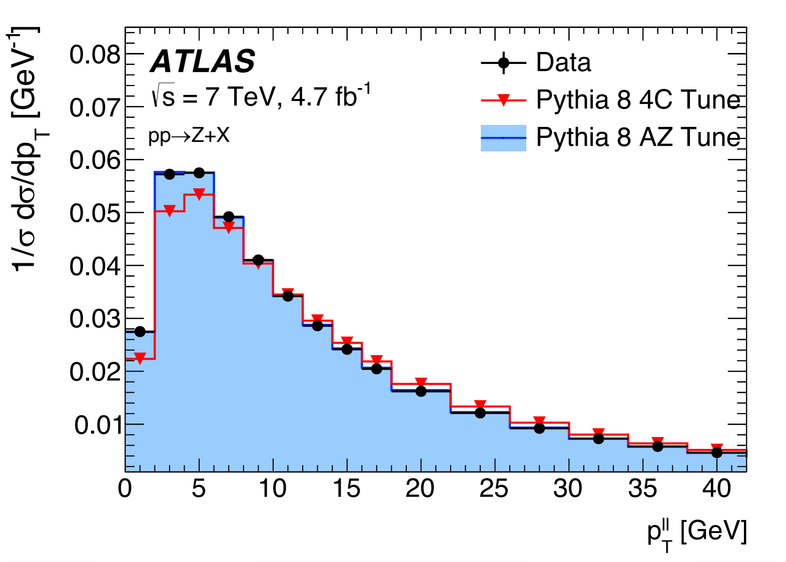
- EW aspects
  - ISR and FSR QED corrections, missing higher-order effects

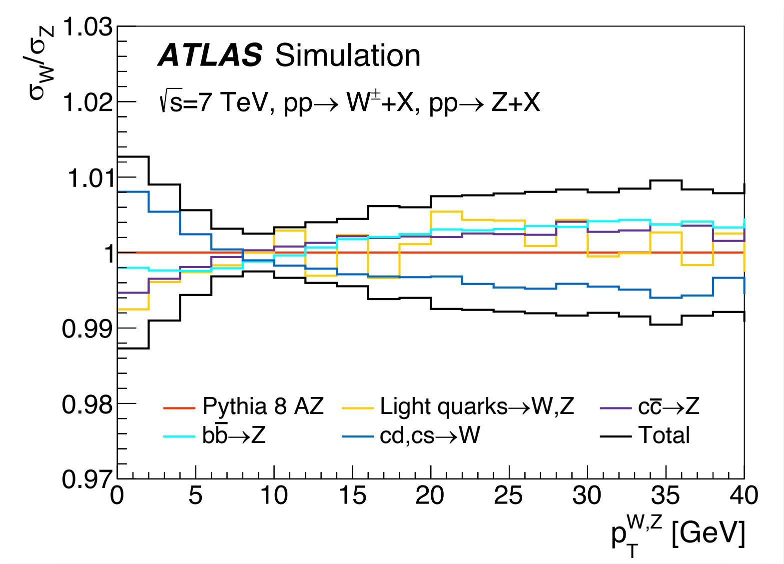
$$\frac{d\sigma}{dp_1dp_2} = \frac{d\sigma}{dm} \cdot \frac{d\sigma}{dy} \cdot \frac{d\sigma(p_t, y)}{dp_T} \cdot \frac{1}{\sigma(y)} \cdot \sum_i A_i(y, p_T)P_i(cos\theta, \phi)$$

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 Shower Variations and Z→W extrapolation : factorization scale variations (separately for light- and heavy-quark induced production), heavy quark masses

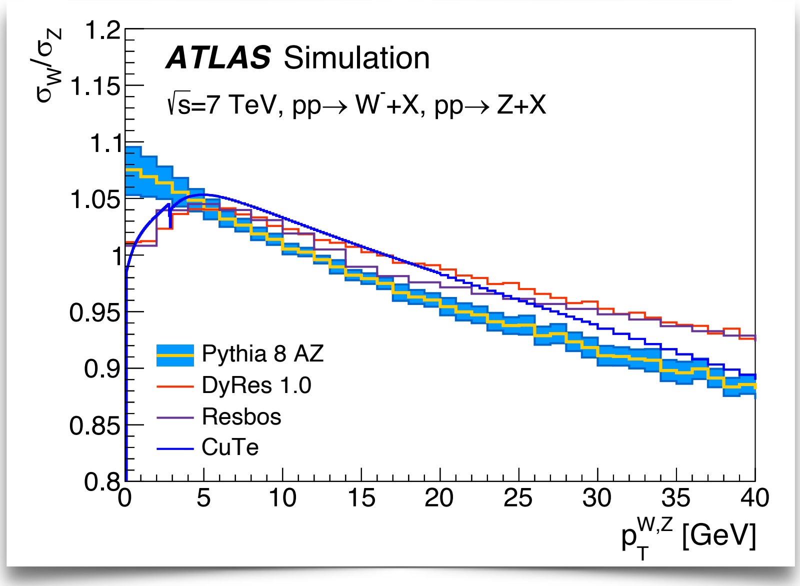


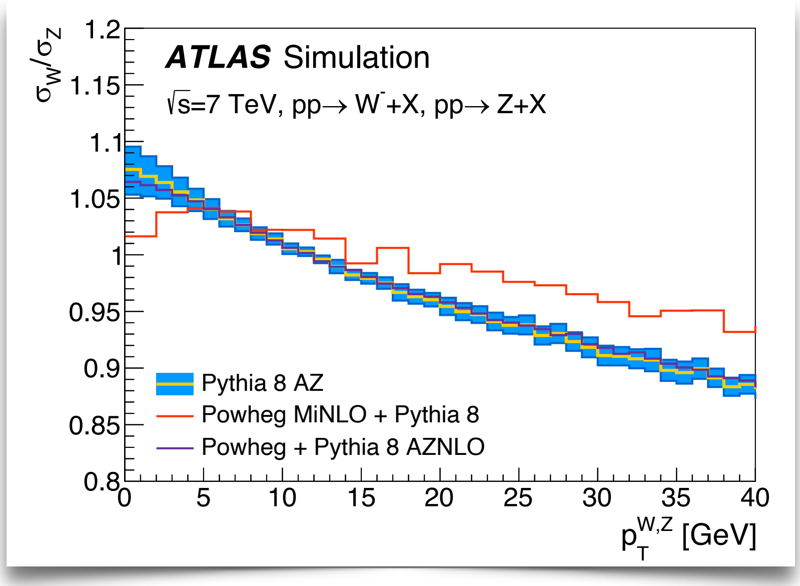


Transverse Momentum (A several years effort)

- 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)

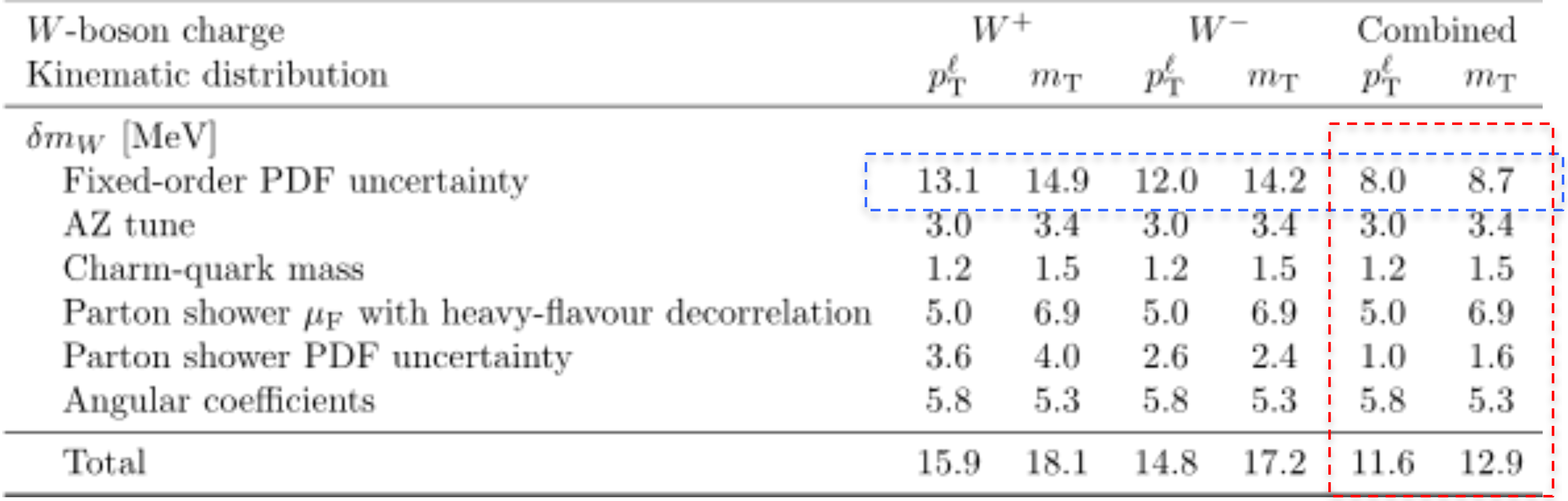




Overview of QCD Uncertainties

- 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



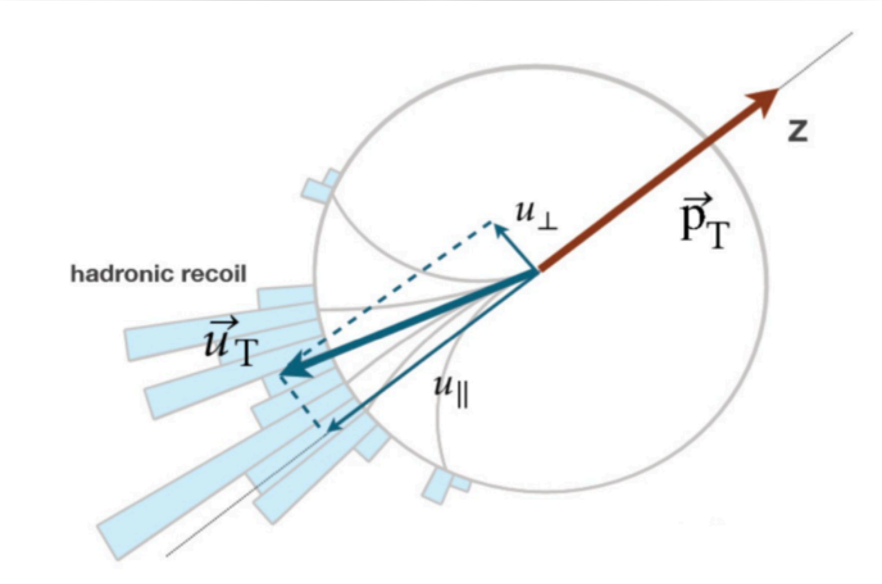
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	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

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

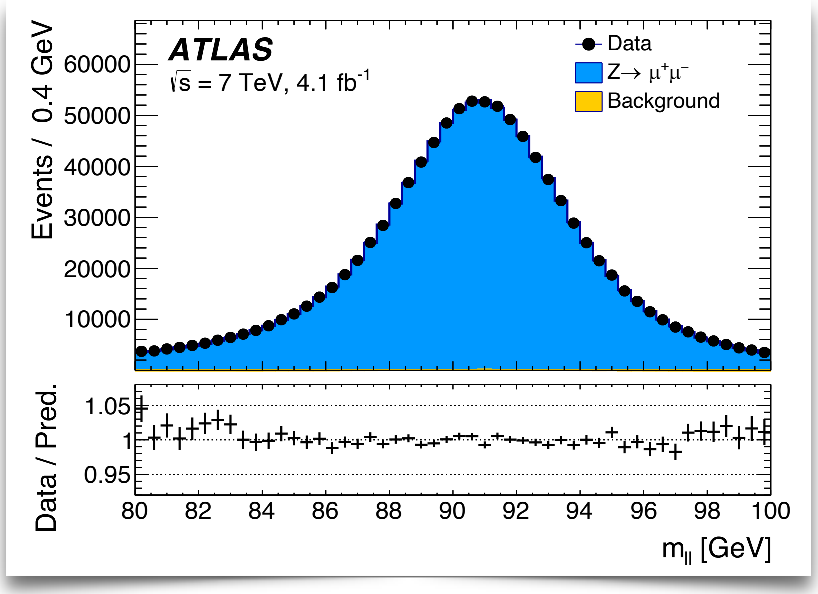


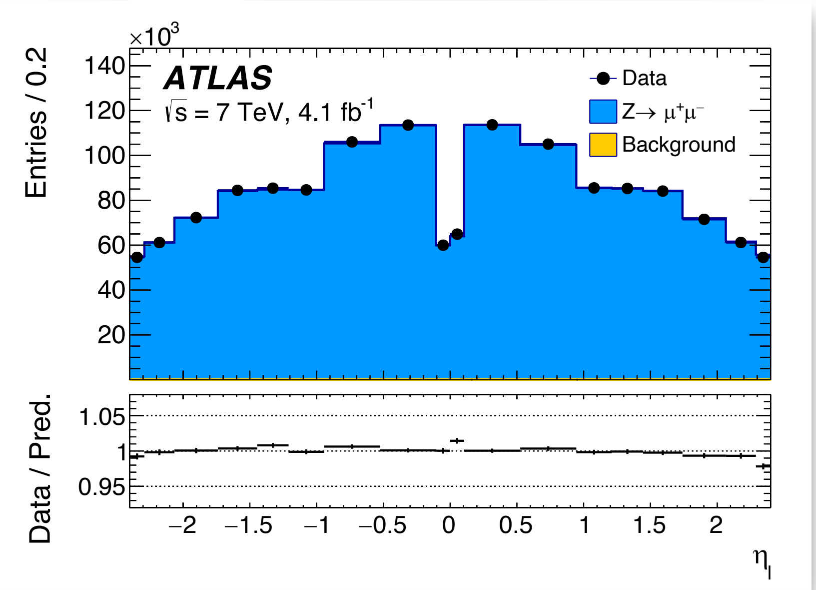
Muon Momentum and Efficiency Calibration

- Parameterization of momentum corrections:

$$p_T^{MC,corr} = p_T^{MC} \times [1 + \alpha(\eta,\phi)] \times [1 + \beta(\eta) \cdot G(0,1) \cdot p_T^{MC}]$$

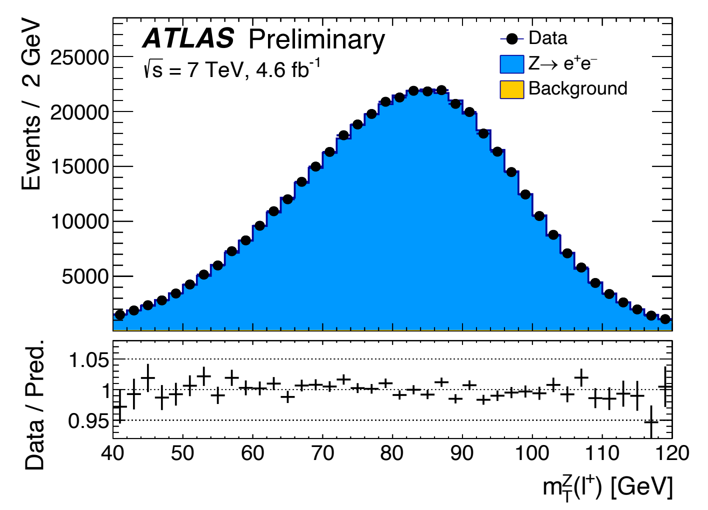
- Momentum scale and resolution corrections probed using Z→μμ events
- Also to correct: Track sagitta bias from rotational detector deformations
  - Using W→μν events for overall effect and Z→μμ for eta-calibration

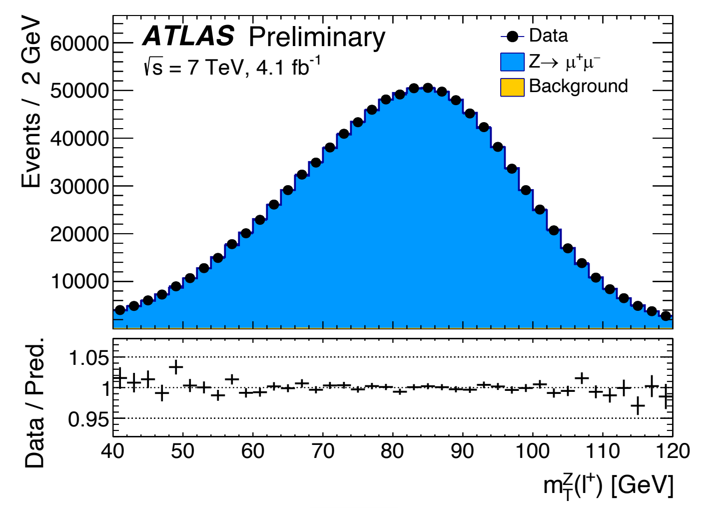




Can we learn even more from the Z Boson?

- Measurement of the Z boson mass via the invariant mass distribution closes by construction
- Treat one decay lepton as neutrino and mimic W boson decay
    - p_T and m_T fits
- Allows to test the full correction procedure, however without the transfer uncertainties to W bosons

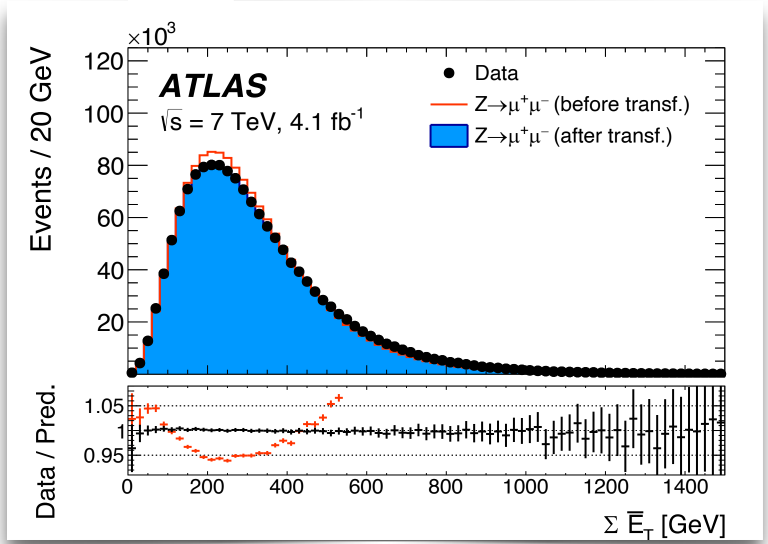


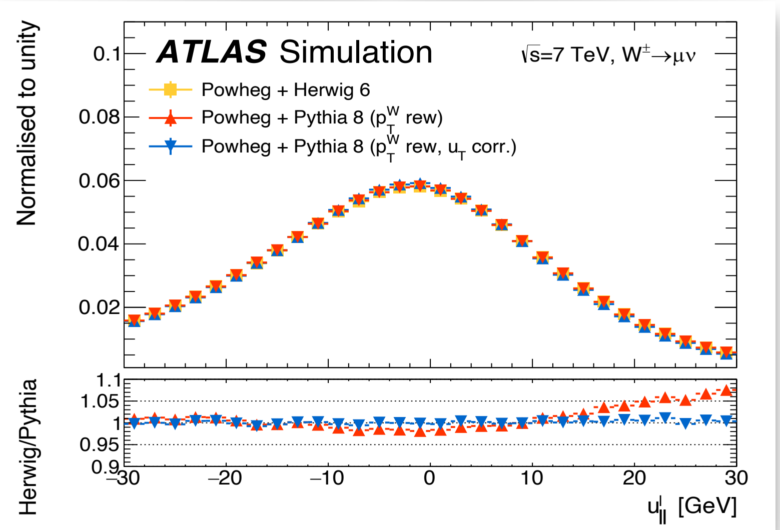


Hadronic Recoil Calibration

- 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

    correct u_T resolution due to imperfect event activity modeling
  - Can be done directly in W events – no extrapolation systematics
- MC based closure test!

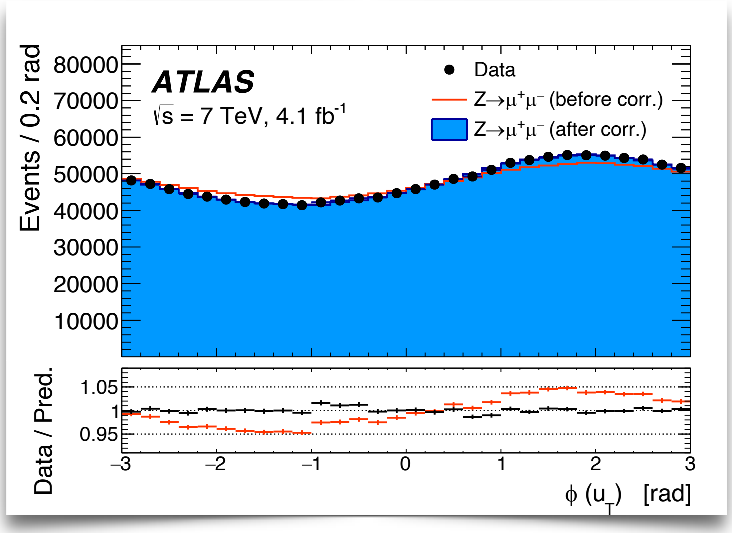


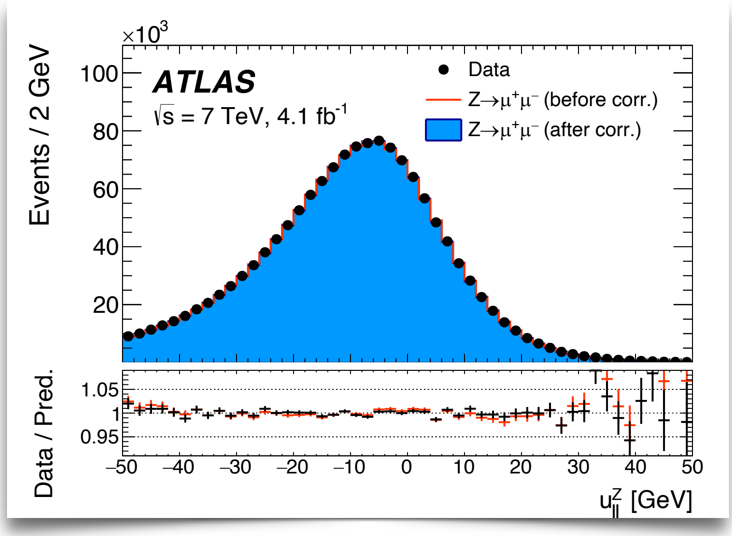


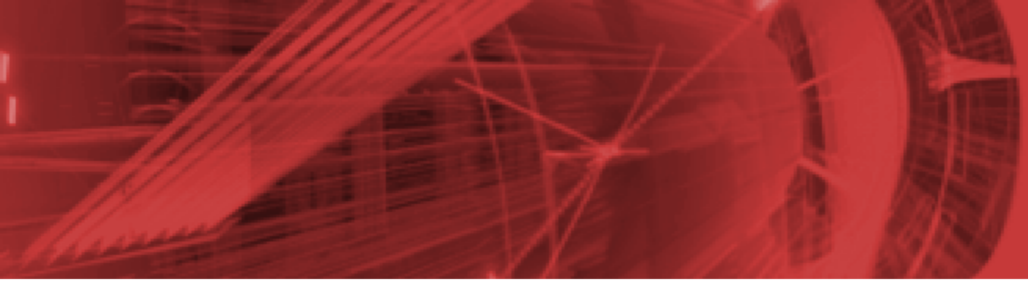
A distribution which took us months

- 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

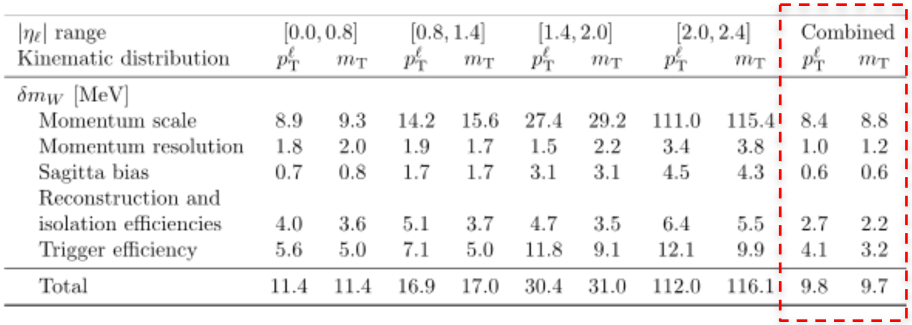




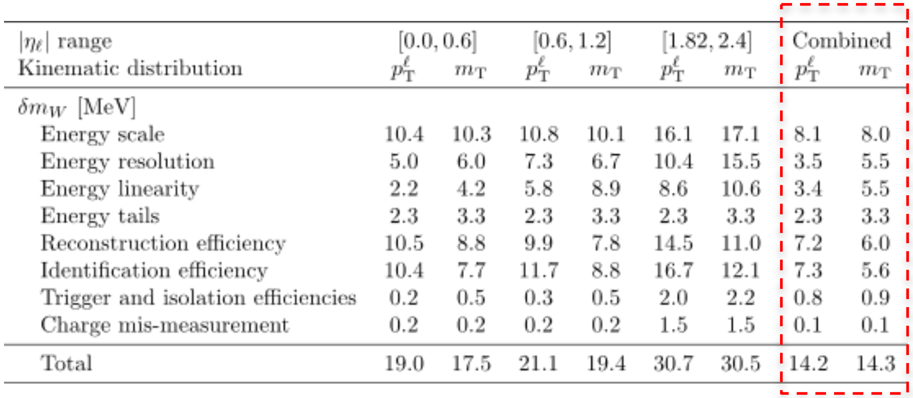


3 tables after 3 years of work

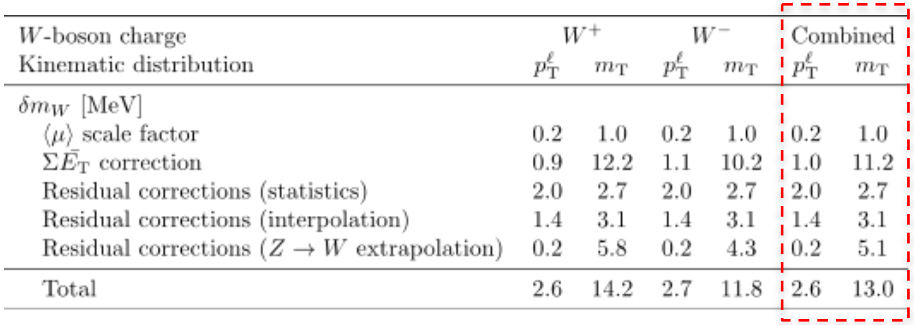
- Experimental uncertainty due to muon detector calibration on the 10 MeV level
  - In terms of average accuracy on the position resolution, this means μm-precision!
- Not even discussed here: How to estimate backgrounds
  - We control the background contributions on a rel. 5% level!
  - Final background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



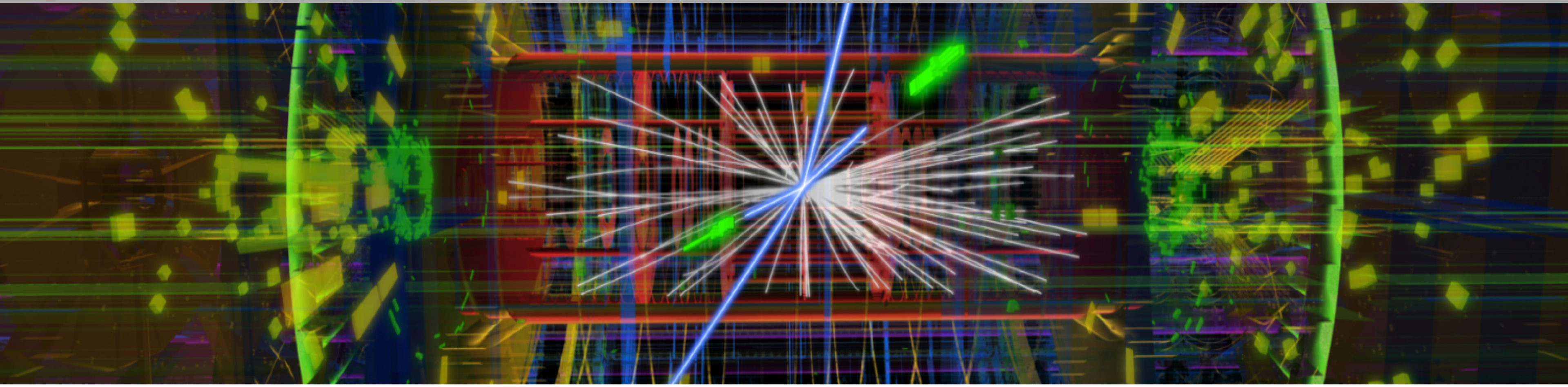
$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	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

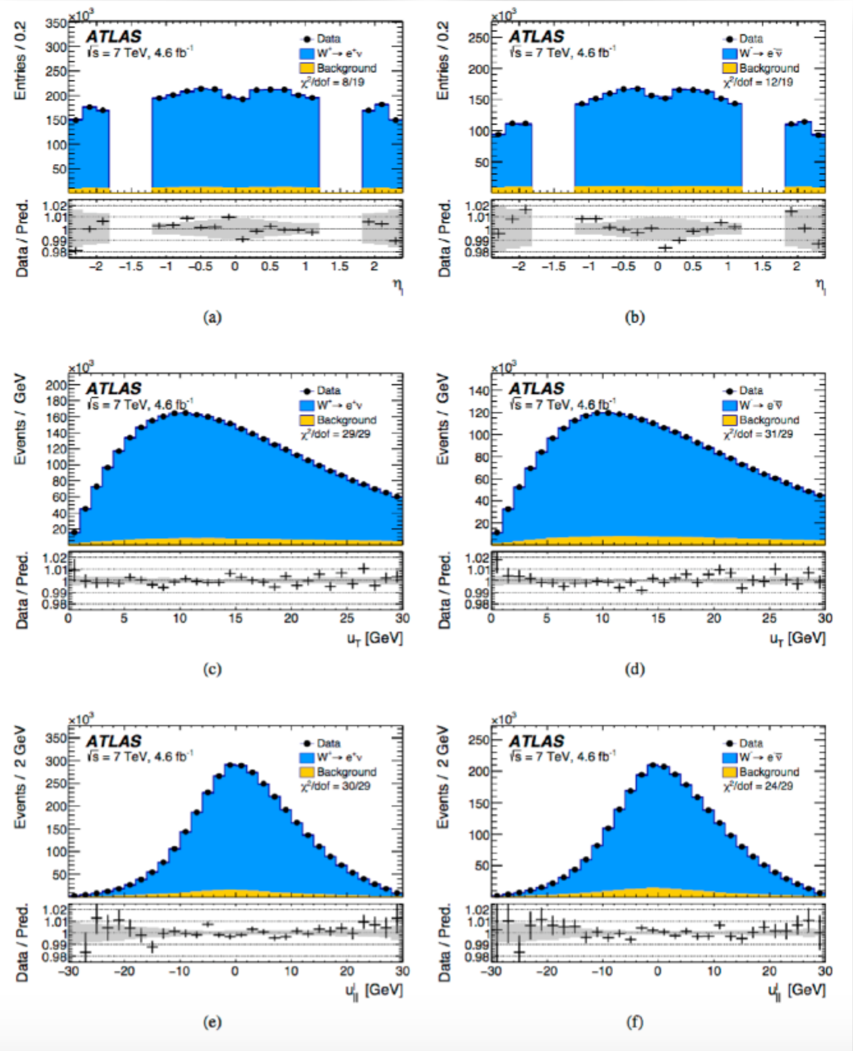


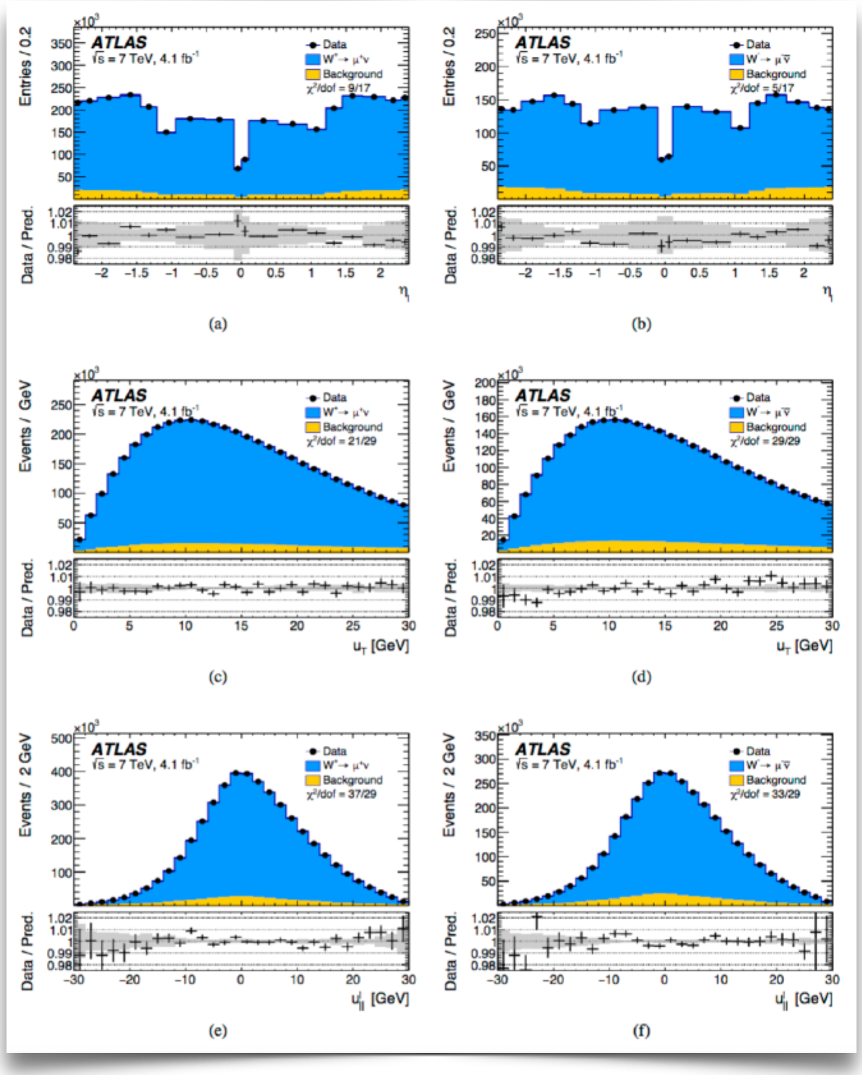
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)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

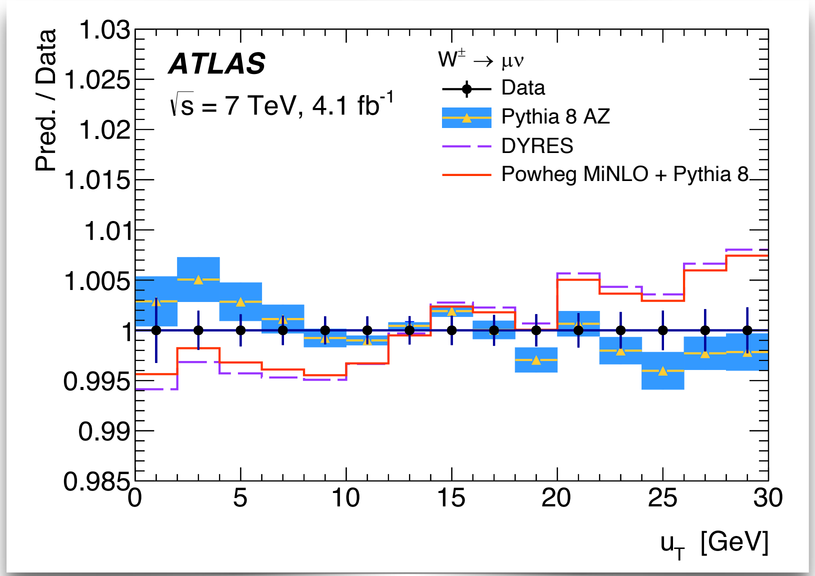


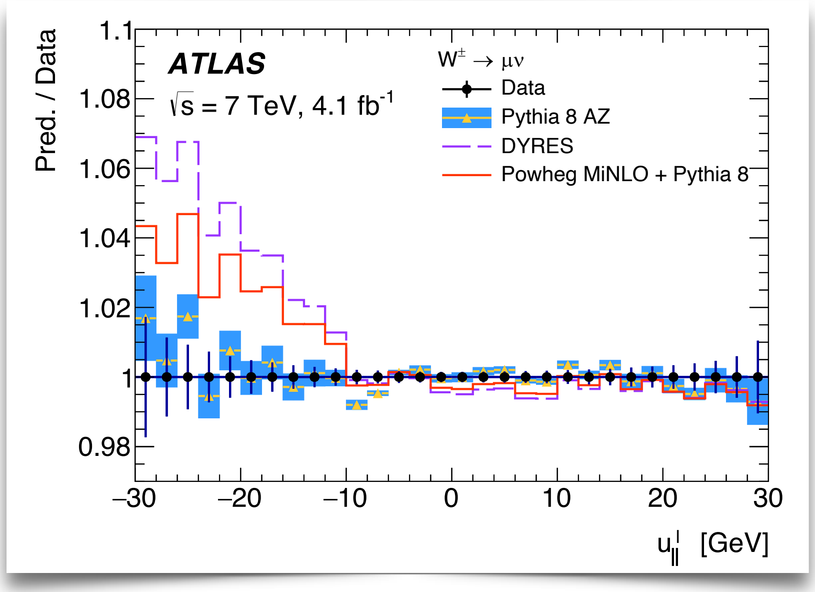


Crucial Test of $p_T(W)$ modelling

- 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?

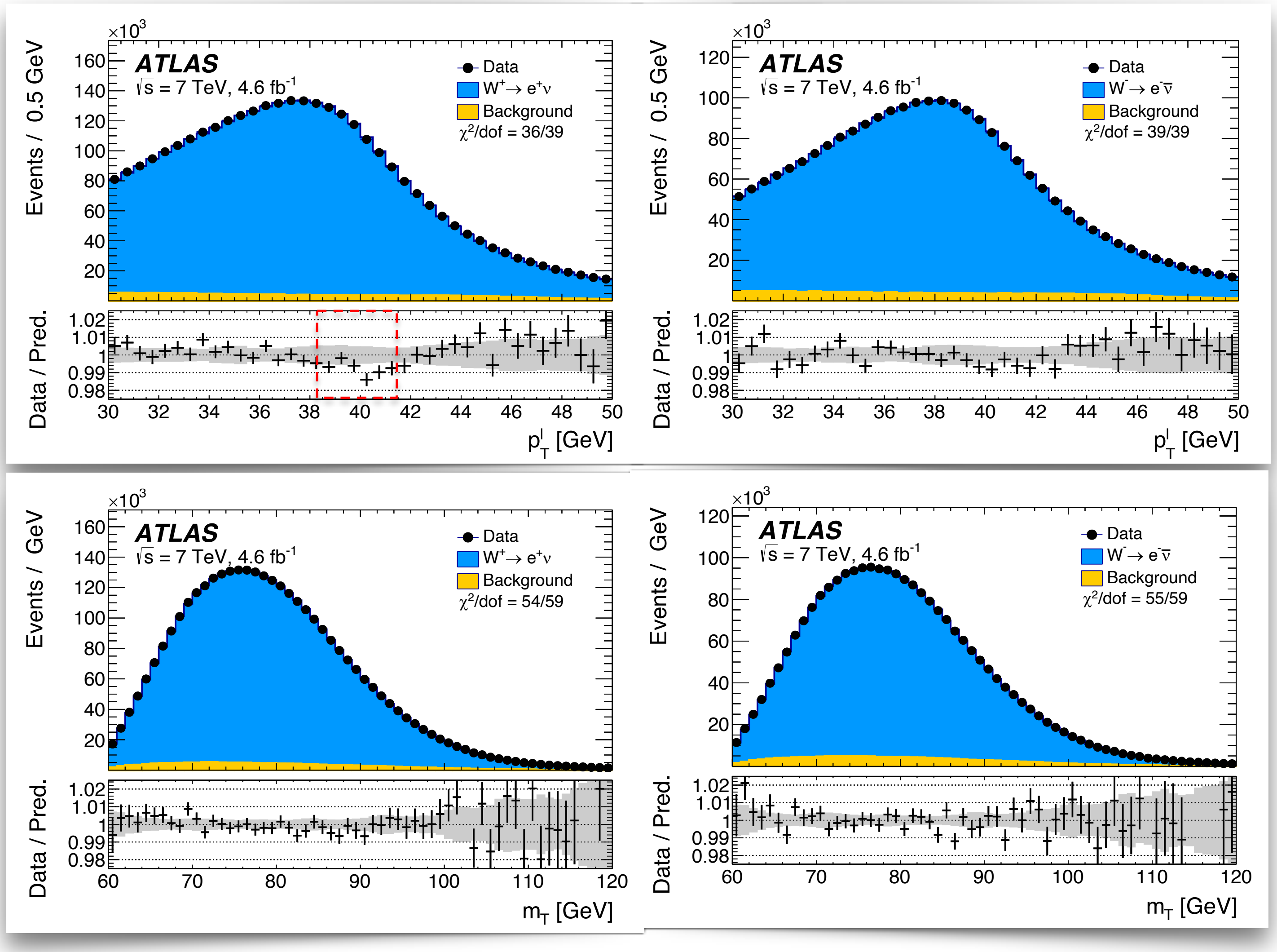
- The $u_{||}(l)$ distribution is very sensitive to the underlying $p_T(W)$ distribution
  - Can exploit this feature to verify the accuracy of our baseline model





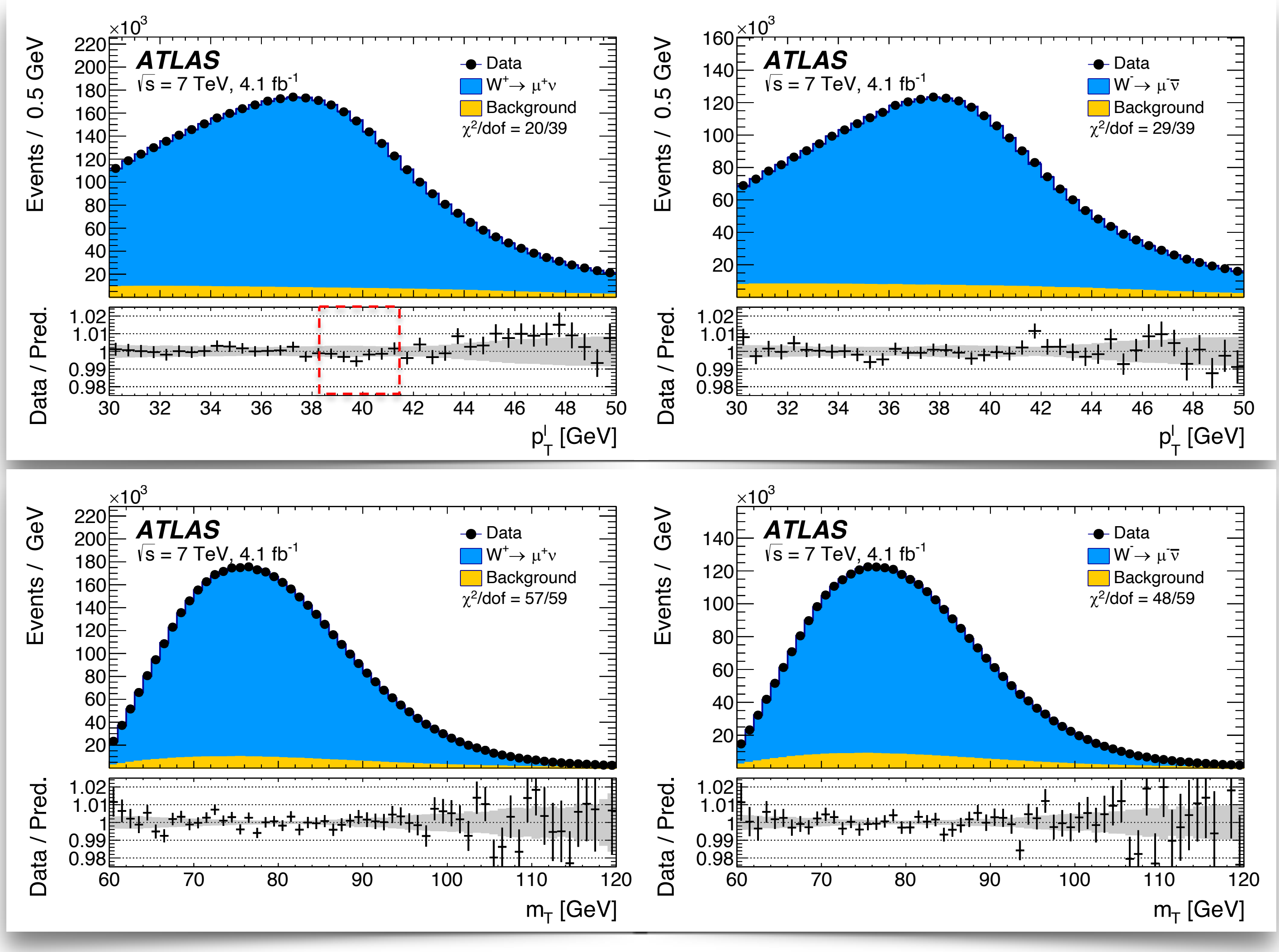
W-Mass Distributions: Electrons

- 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 m_W



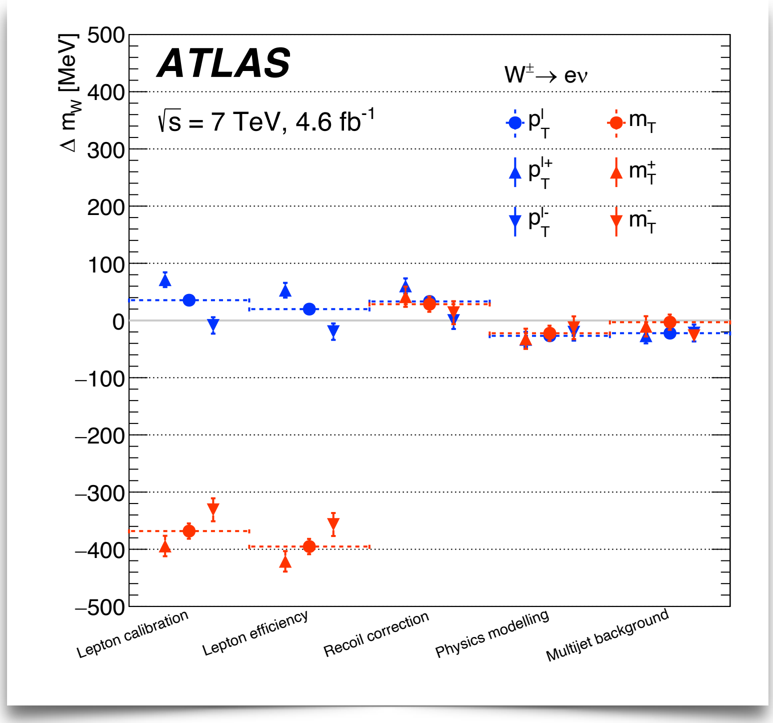
W-Mass Distributions: Muons

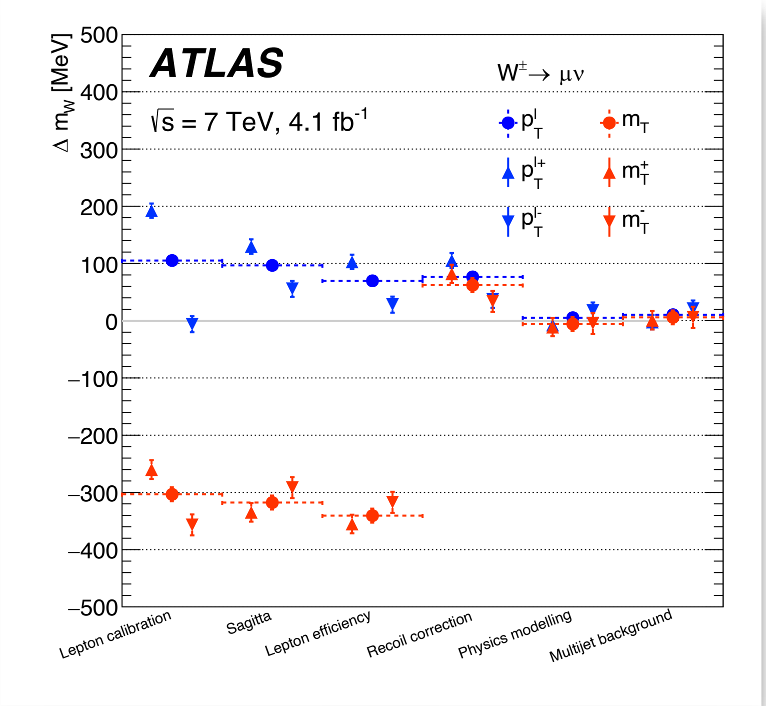
- Very good agreement for muons
- Overall: χ^2/n_{dof} probability distribution from 84 data/ prediction comparison
  - $\langle P \rangle = 0.54$



A Little Bit of History

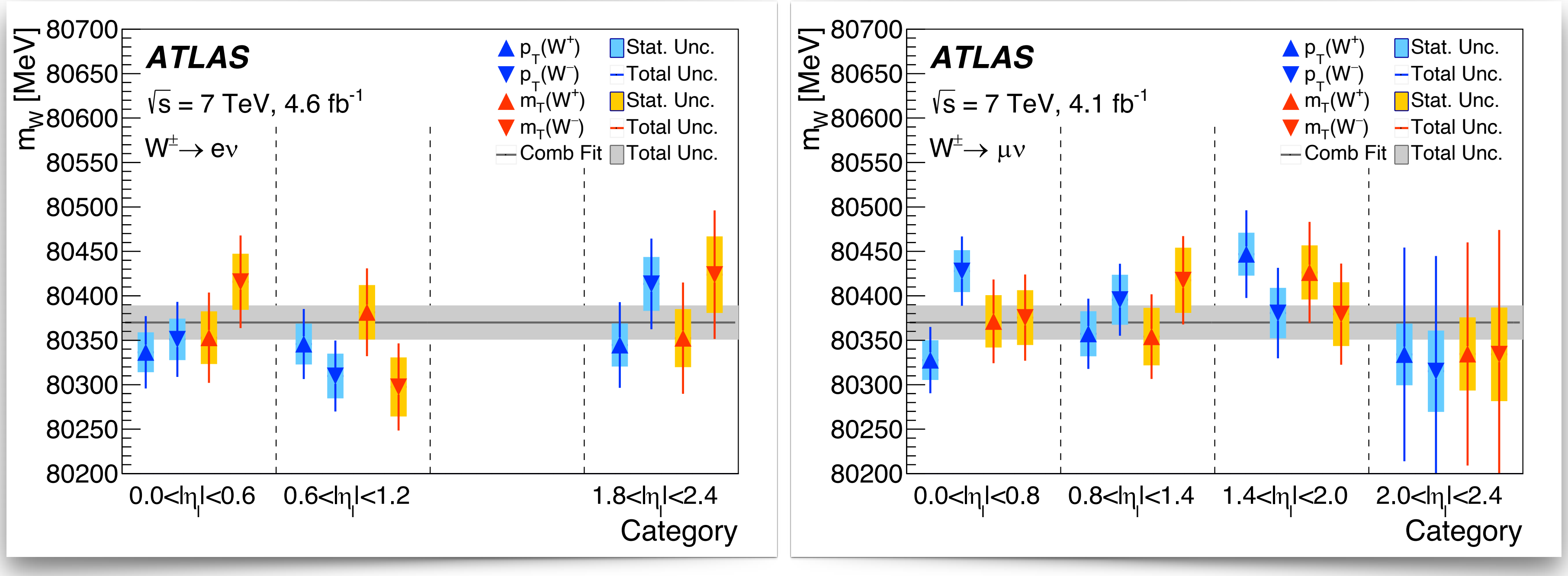
- Over many years we investigated differences in blinded m_W mass-fits in different channels, templates, categories
  - Only after all corrections applied (and all bugs where found), we achieved consistent results





Final Measurement

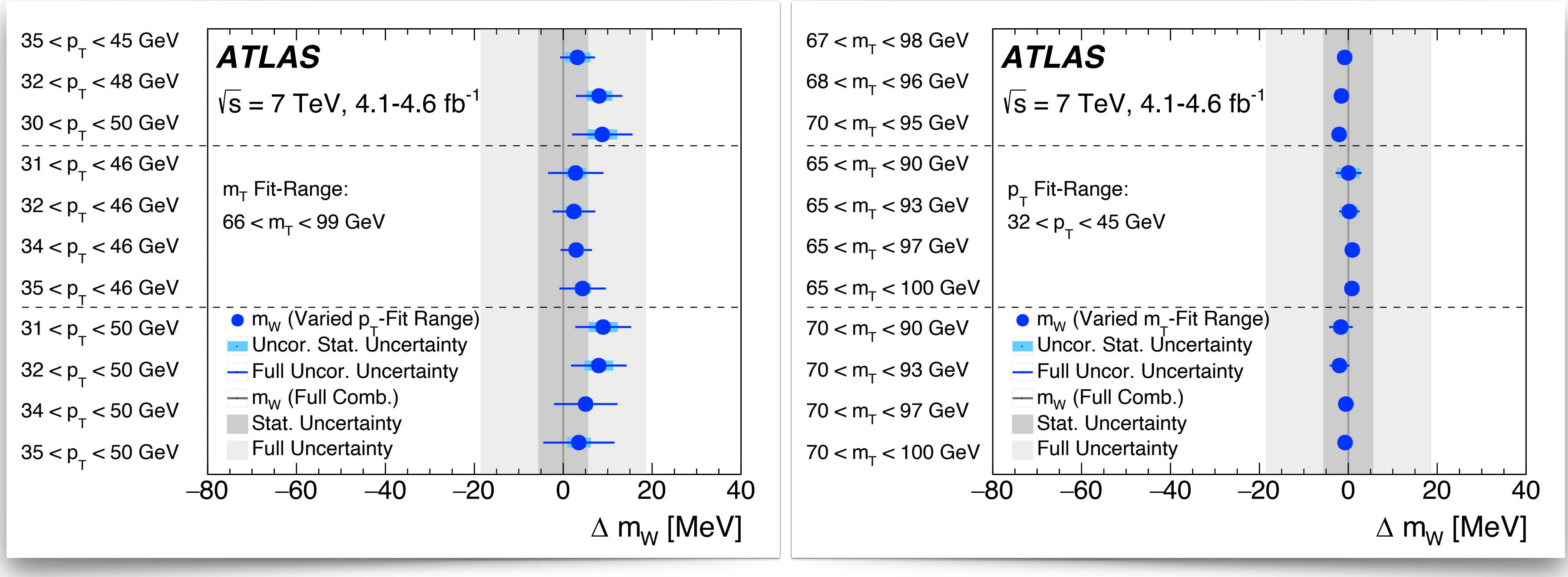
m_W Fit Results in Various Categories



- 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

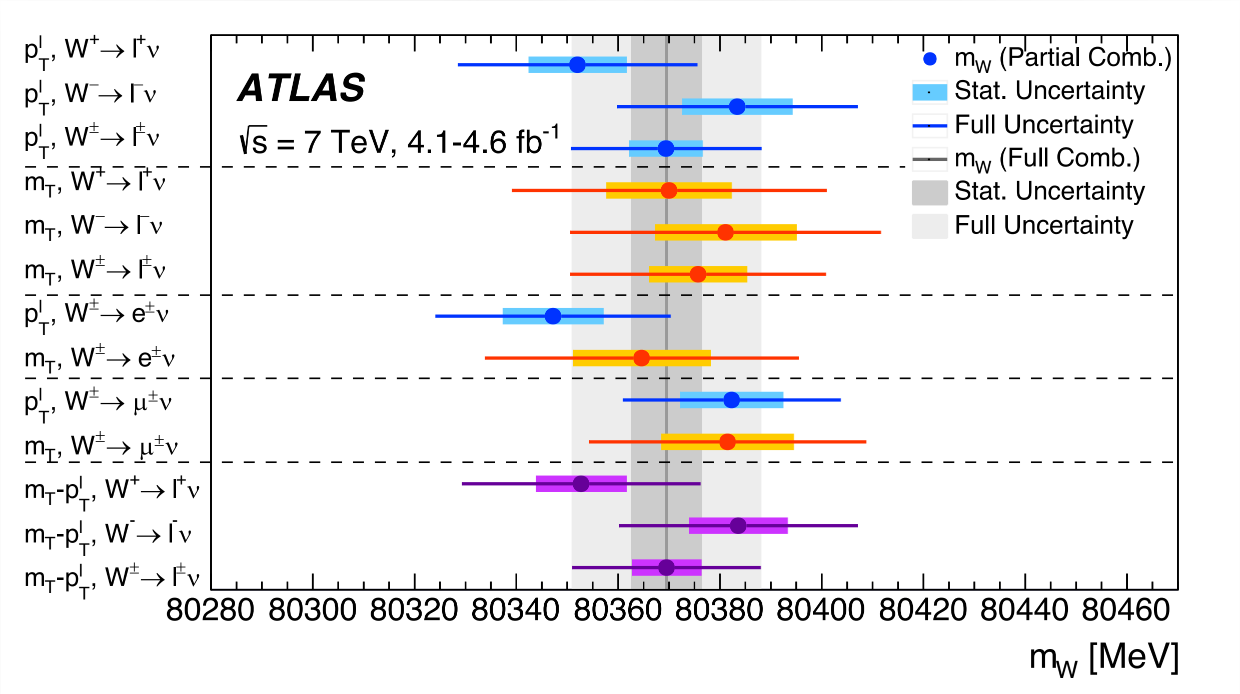
- Compatibility tests performed before unblinding: $\chi^2/n_{dof} = 29 / 27$

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

Final measured mass of the W boson:

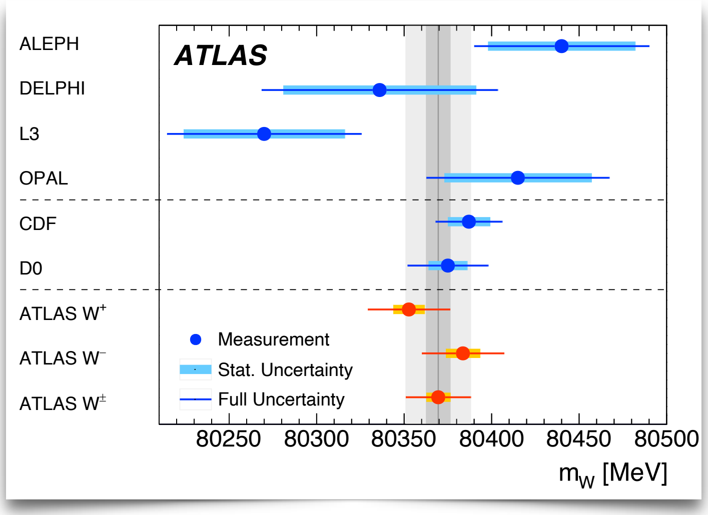
80370±7(stat.)±11(exp.)±14 (mod) MeV = 80370 ± 19 MeV

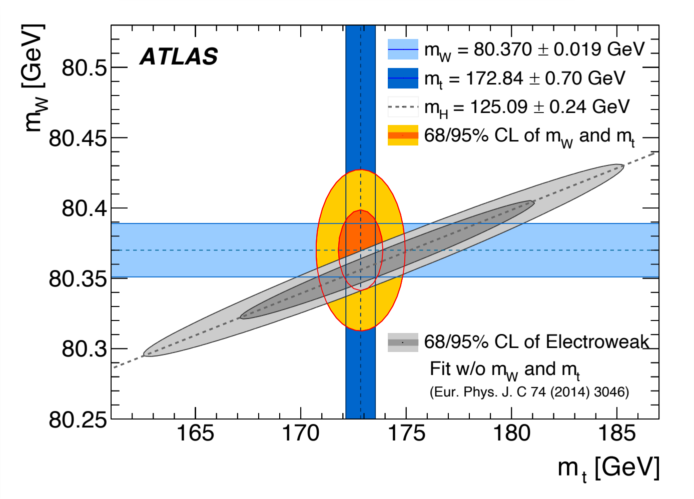
369.5 ± 18.5 MeV

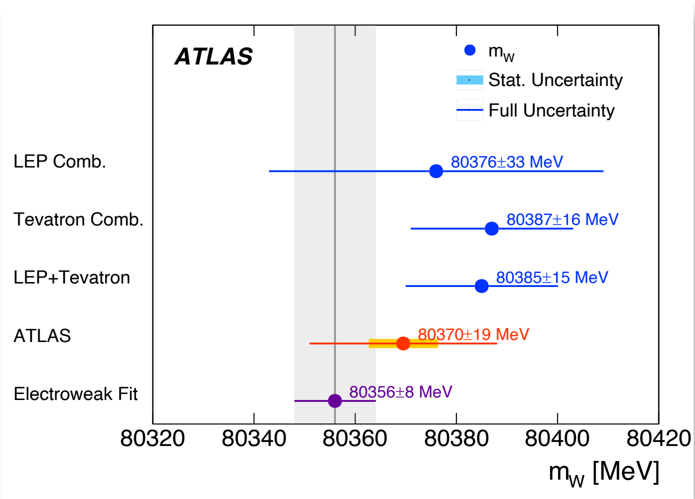
Comparison to previous measurements and the Global Electroweak Fit

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

- Bad news: We are even more Standard Model …

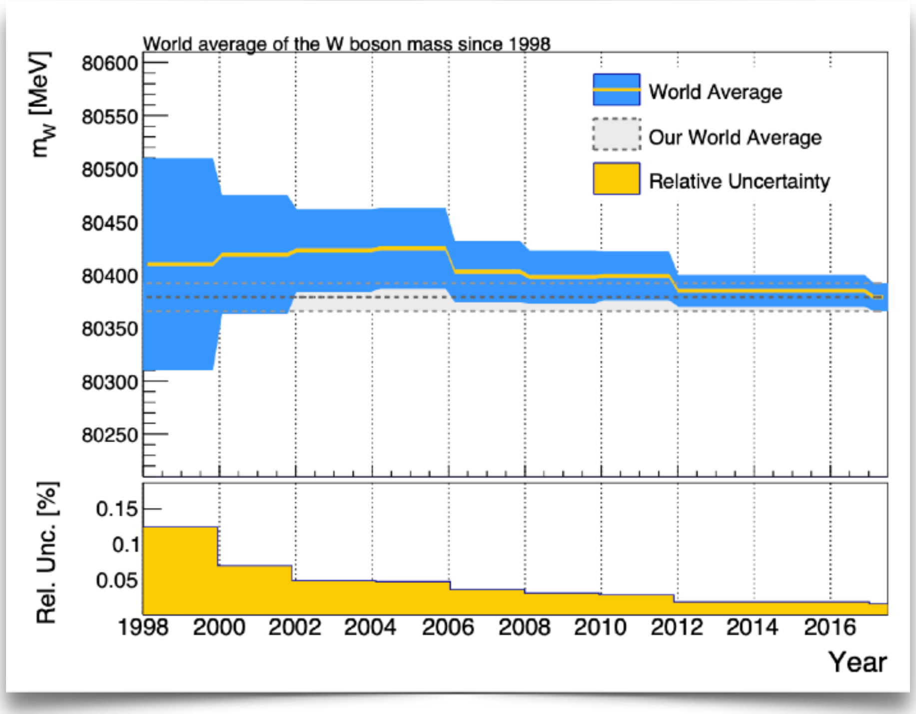






My Take on Electroweak Precision Physics in the next 3 years

- LHC
  - CMS will hopefully also publish soon a m_W measurement
  - ATLAS still has data-sets of 2012/2015/2016/2017/2018
  - Room for improvements on the theory and calibration
    - IMHO: 10 MeV is feasible
- Tevatron
  - x2-5 more statistics available
  - Use improved PDFs based on LHC measurements
    - They also could achieve 10 MeV uncertainty!



- We will have a world average of m_W<8 MeV until 2022
  - Uncertainty on the prediction is 8 MeV, so the measurement become less relevant

Summary

- Take away message for students
  - Do not get discouraged by reviewers
  - Talk to as many people as you can

- Precision Measurements allow for a search for new physics in a model independent way

- First W mass measurement at the LHC shows no signs of new physics
  - Large theory community working on improved predictions
  - I personally think that we reach a precision of <8 MeV in the next 3 years… and then we have to wait long before theory can catch up

Thanks to

- you for not falling asleep
- those who believe in my ideas and put lots of money over the past 8 years on the table
- and especially to those who do the real work: My Amazing Group

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European Research Council
Established by the European Commission
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