Global Electroweak Fits: Where do we stand?

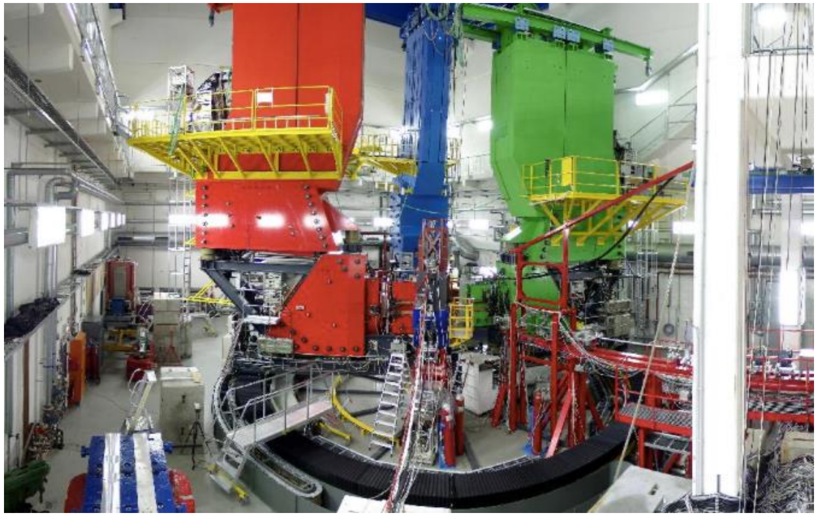
Matthias Schott

Some facts about Mainz

- Mainz is small town, but capital of Rhineland-Palatinate
  - Next to the river Rhine (with some quite nice castles)
  - 20 Minutes from Frankfurt International Airport
  - Founded by romans 2K years ago
  - The cathedral is only 1000 years old (and burnt down several times)
- Time-Magazine's man of the millennium:
  - Johannes Gutenberg, who invented the printing press in Mainz

Johannes Gutenberg University

- Founded in 1477 and reopened by the French occupation forces in 1946
  - 37.000 students for all subjects (bachelor, master, PhD)
  - German cluster of excellence PRISMA for fundamental physics
- Own electron accelerator MAMI and research reactor
  - 60 physics professors and research groups: LHC, IceCube, Xenon, SOX, NA62, JUNO, ALPS,



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Electroweak Precision Physics

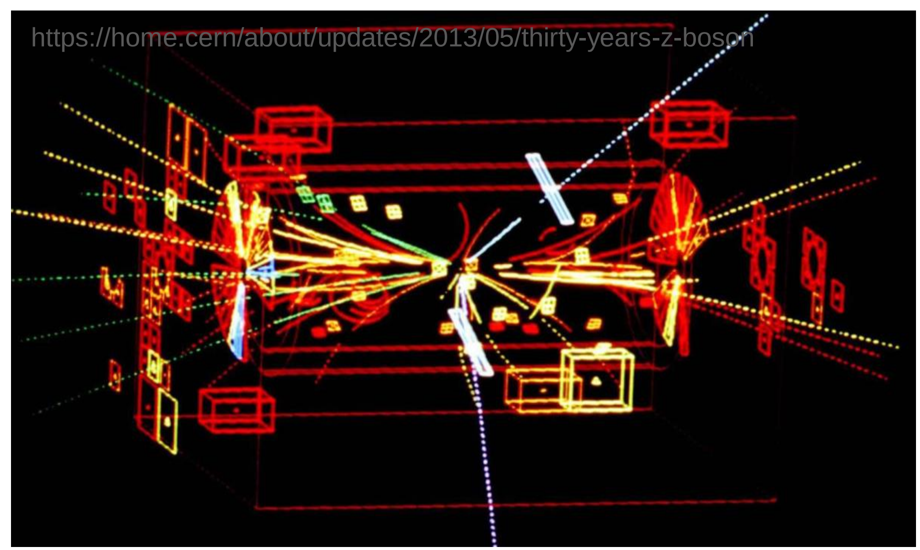
Summary of the Electroweak Sector

- 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

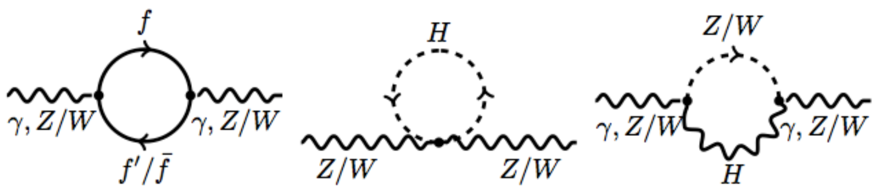
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

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



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**

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

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

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

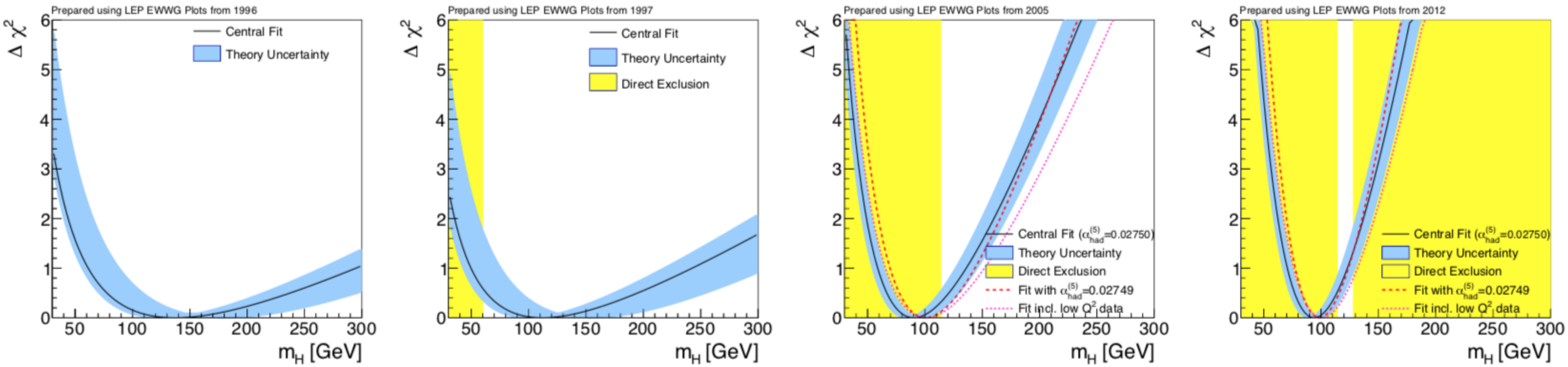
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

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

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

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

Input to the Electroweak Fit

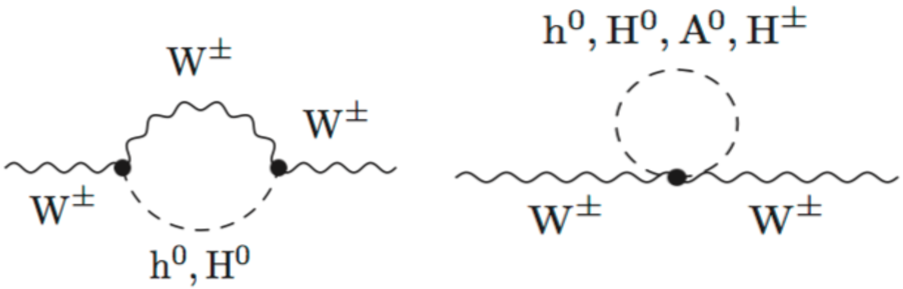


- Success of the Fit: **Amazing predictions!**
  - Top-Quark mass before its discovery
  - Higgs-Boson mass before its discovery and the funding argument for the LHC

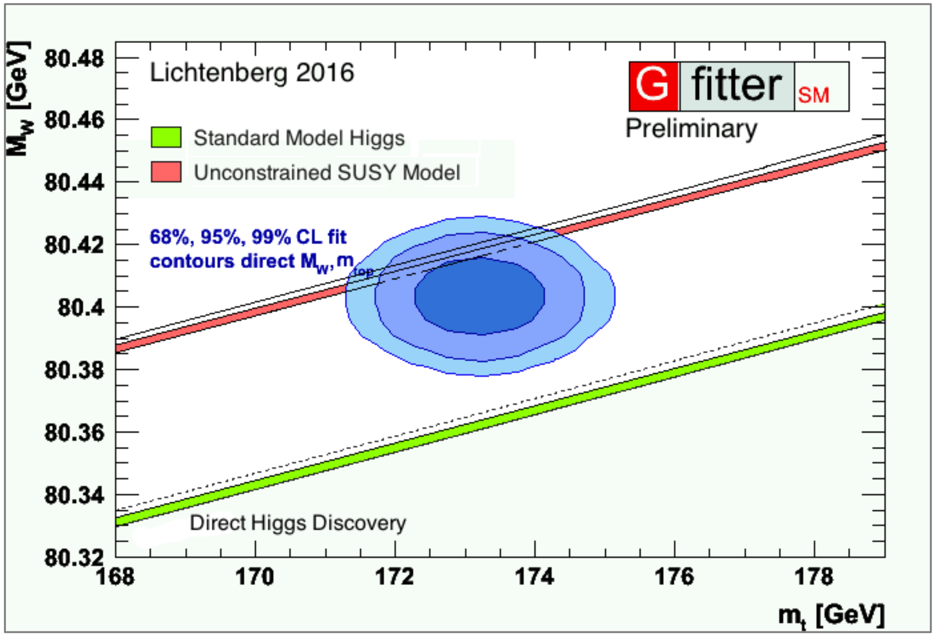
- Main inputs to the gobal electroweak fit
  - LEP: Z boson observables
  - Tevatron: W boson mass, top quark mass
  - LHC (**today's focus**)
    - Higgs boson mass
    - Top quark mass
    - Electroweak mixing angle
    - W boson mass

Why is the fit still interesting?

- So far a "simple" thing: test consistency of the SM
  - Current **p-value = 0.24**
- 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

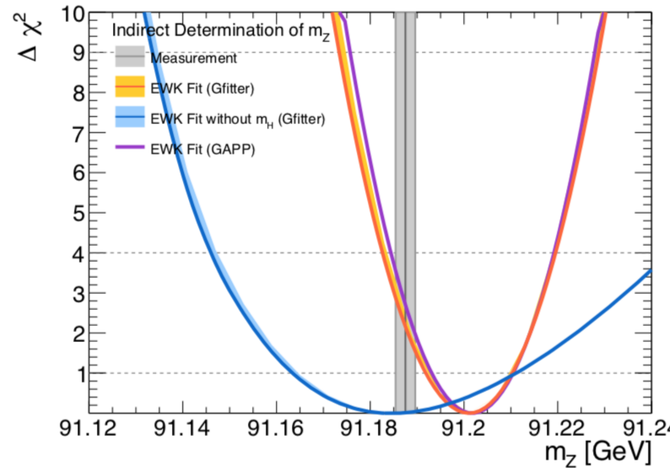


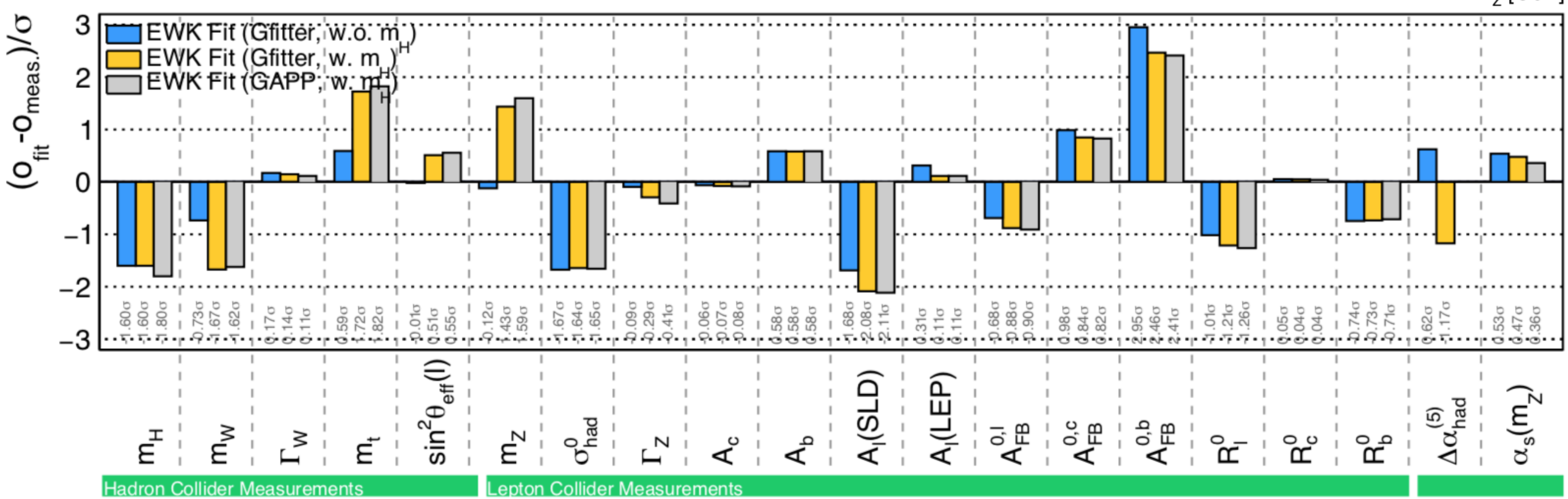
Inspired by [S. Heinemeyer et. al. arXiv:1311.1663]



Why is the fit still interesting?

- General idea: predict a certain observable with the global electroweak fit and compare to the direct measurement
  - When we find a significant tension, then this could be a hint to new physics





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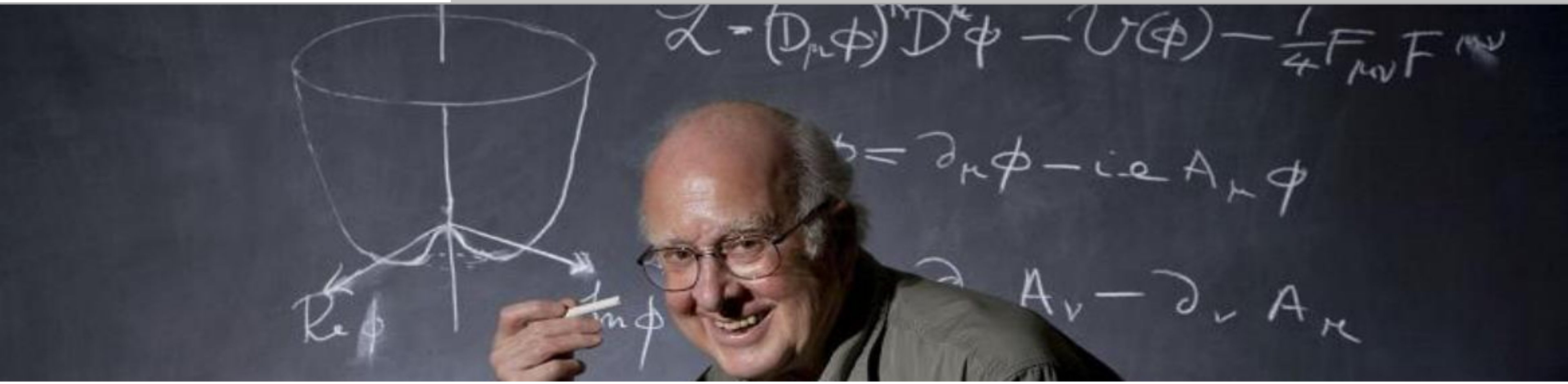
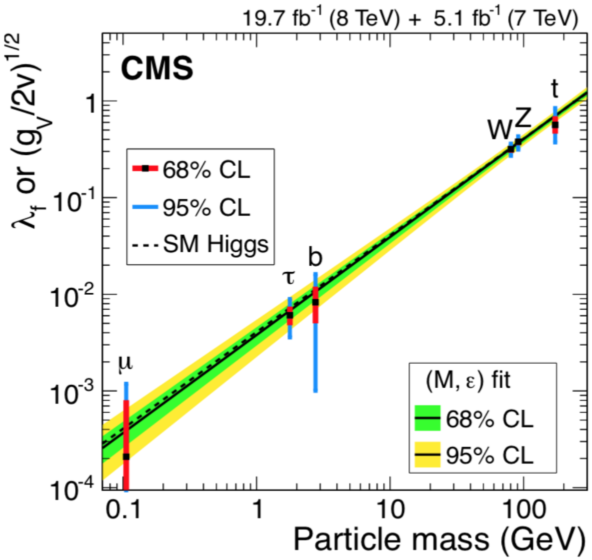
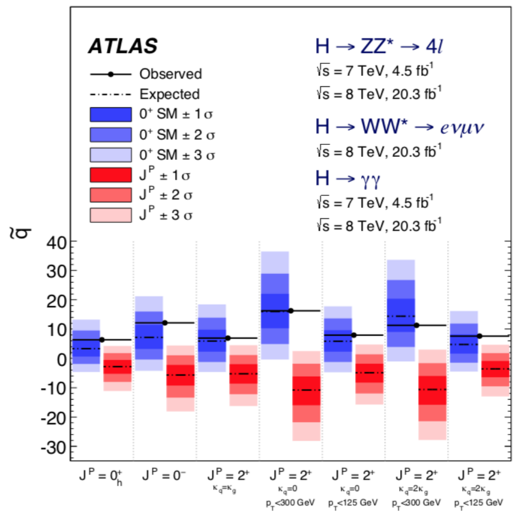
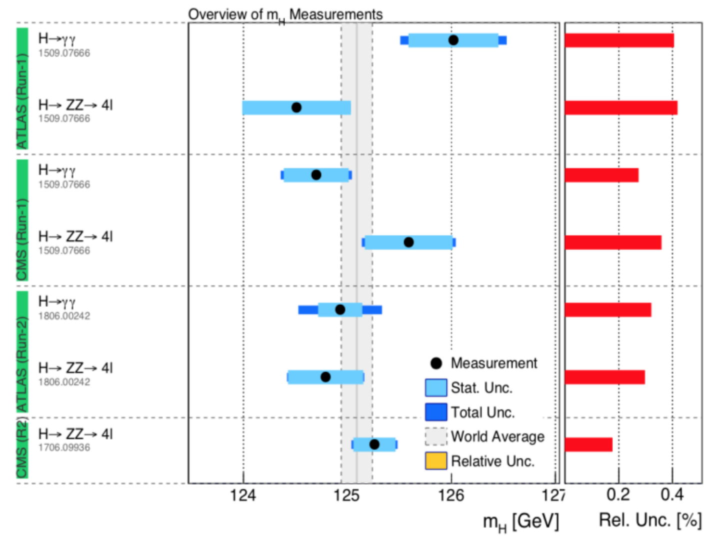


The Higgs Boson Mass

Higgs Boson Mass







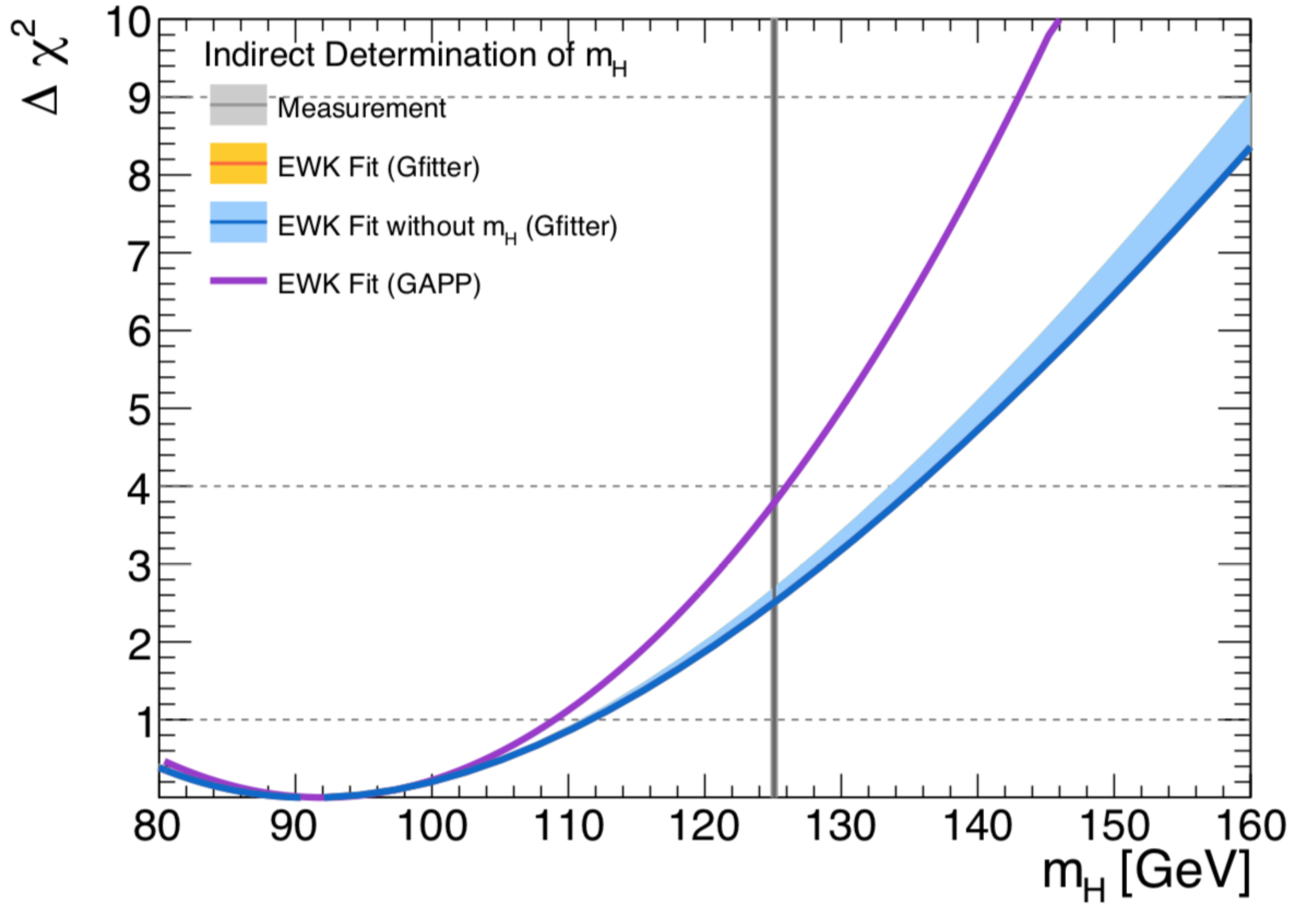
- Only the mass parameter of the Higgs enters the fit
  - have to assume that the “Higgs” is really the Standard Model Higgs boson
    - Coupling and JPC measurement look pretty much like a SM-Higgs

- Inofficial combination of latest measurements, yield to
  - M_H = 125.10 ± 0.14 GeV
  - with a χ2/n.d.f. = 8.9/6

- Change of precision from 0.1GeV to 1.0 GeV, changes the χ^2 of the fit by only 0.005

Interpretation of the Higgs Boson Mass

- Indirect prediction of the Higgs boson mass is
  - M_H=92.0±20 GeV
- Perfect knowledge of m_W and/or $\sin^2\theta_{eff}$ would reduce uncertainty to 10 GeV



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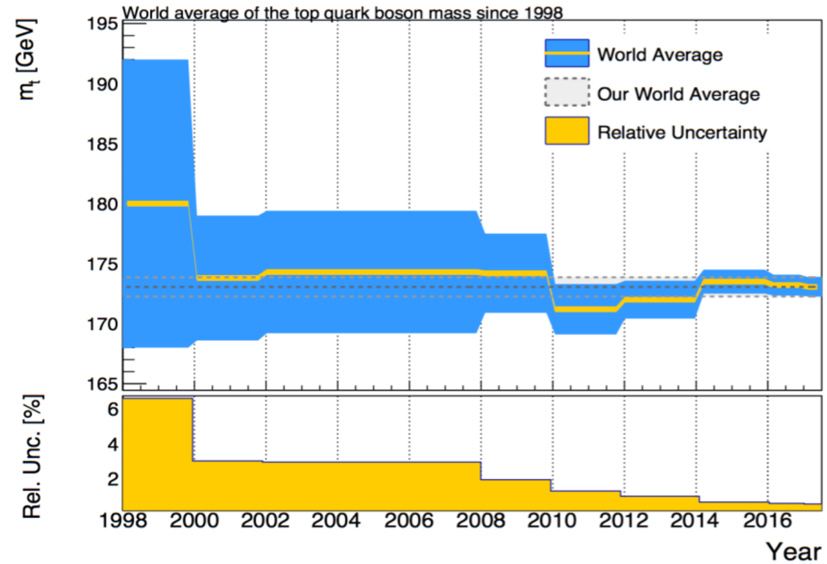
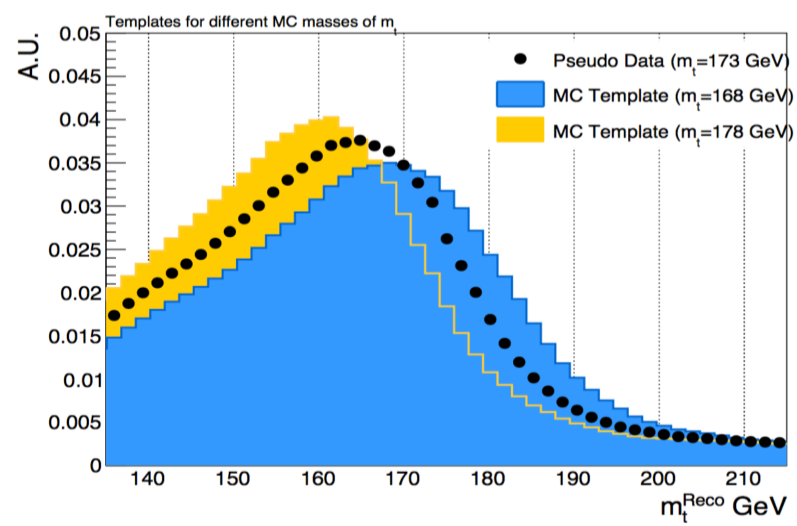
Top Quark Mass

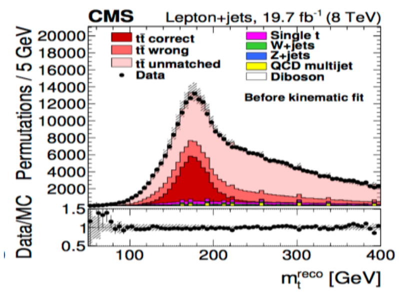
Measurement of the Top Quark Mass (1/3)

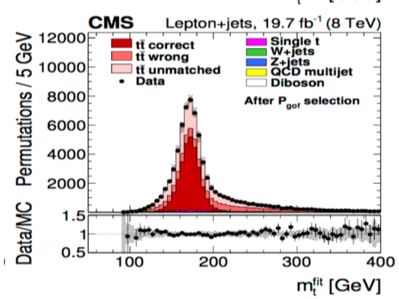
- Several approaches to measure the kinematic top-quark mass (template-method, matrix-element method, ideogram method, ...)
- World average dominated until 2011 by Tevatron, then LHC started to play crucial role
- Important: EW-fit needs pole mass of top-quark as input, but measured m_{top} at Tevatron and LHC is a MC parameter
  - Assume additional uncertainty of 300-500 MeV (not known if this is conservative)





Measurement of the Top Quark Mass (2/3)





Experiment	Channel	Method	Value [GeV]	Stat. Unc. [GeV]	Sys. Unc. [GeV]	Total Unc. [GeV]	Jet Unc. [GeV]	Exp. Unc. [GeV]	Model Unc. [GeV]	UE + Color [GeV]	Had. Unc. [GeV]
CDF	l+jets	Template	172.85	0.71	0.85	1.11	0.55	0.60	0.1	0.22	0.57
CDF	ν+jets	Template	173.93	1.64	0.87	1.86	0.48	0.56	0.32	0.33	0.36
DØ	l+jets	M.E.	174.98	0.58	0.49	0.76	0.29	0.32	0.19	0.12	0.26
CMS	l+jets	AMWM	172.82	0.19	1.22	1.23	0.34	0.81	0.84	0.11	0.79
CMS	l+jets	Ideogram	172.35	0.16	0.48	0.51	0.12	0.43	0.15	0.08	0.33
CMS	l+jets	Template	172.22	0.18	$^{+0.89}_{-0.93}$	$^{+0.91}_{-0.95}$	0.45	0.17	0.46	0.17	0.51
ATLAS	l+jets	Template	172.33	0.75	1.03	1.27	0.64	0.62	0.48	0.19	0.18
DØ	semi-lep.	Matrix	173.93	1.61	0.88	1.83	0.67	0.42	0.36	0.15	0.31
ATLAS	semi-lep.	Template	172.99	0.41	0.74	0.85	0.62	0.30	0.25	0.11	0.22
ATLAS	semi-lep.	Template	172.08	0.39	0.82	0.91	0.56	0.43	0.20	0.21	0.15
CMS	semi-lep.	Ideogram	172.25	0.08	0.62	0.62	0.39	0.19	0.27	0.32	0.10
CDF	full.had.	Template	175.07	1.19	1.55	1.95	1.12	0.98	0.28	0.32	0.29
ATLAS	full.had.	Template	173.72	0.55	1.01	1.15	0.69	0.68	0.2	0.2	0.64
CMS	full.had.	Ideogram	172.32	0.25	0.59	0.64	0.28	0.41	0.24	0.21	0.3

- Most precise measurements performed in the lepton+jets channel
  - Significant differences in assigned model uncertainties of different experiments;

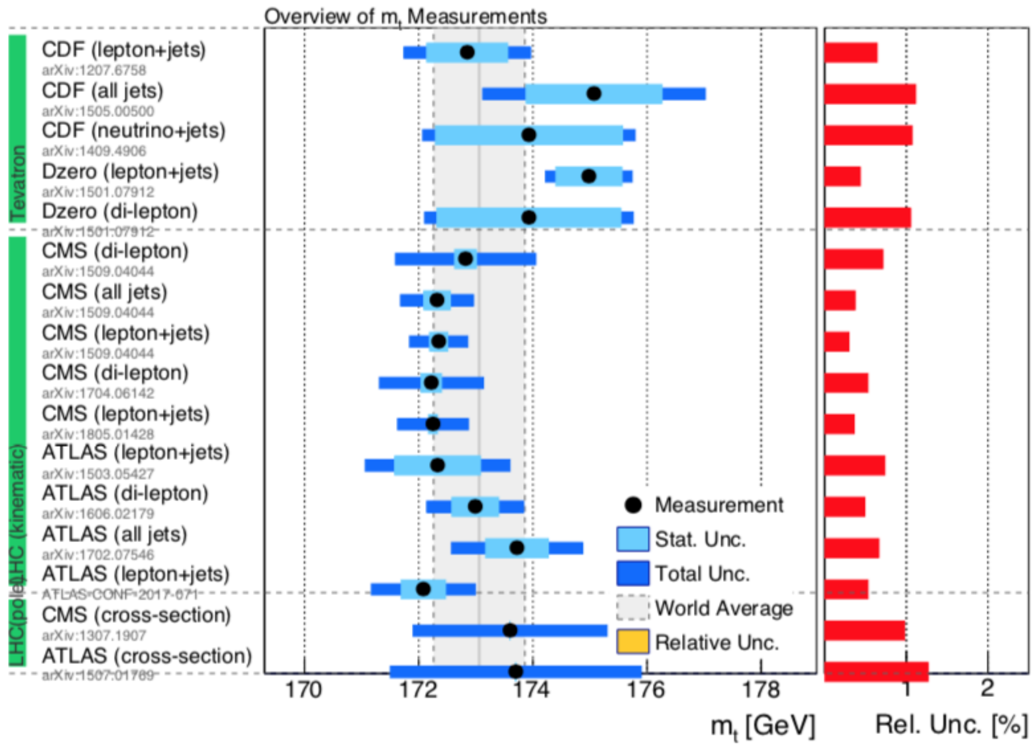
- Most precise value from CMS(arXiv:1509.04044): m_t^{MC} = 172.35±0.51 GeV
- ATLAS combination (8 TeV semi-leptonic+others): m_t^{MC} = 172.69±0.48 GeV
  - Already close to 300-500 MeV theory uncertainty level

- Recent ATLAS of m_{pole} measurement (ATLAS-CONF-2017-044): m_t^{pole} = 173.2±0.9±0.8±1.2

Measurement of the Top Quark Mass (3/3)

- No official combination of latest ATLAS and Tevatron results

- Preliminary combination
  - Correlations are estimated from previous official combinations
  - Take individual combinations from all four experiments as well as new 13 TeV measurements into account
  - Observe tension between D0 and LHC by 2.5σ
    - driven by D0 lepton + jets measurement



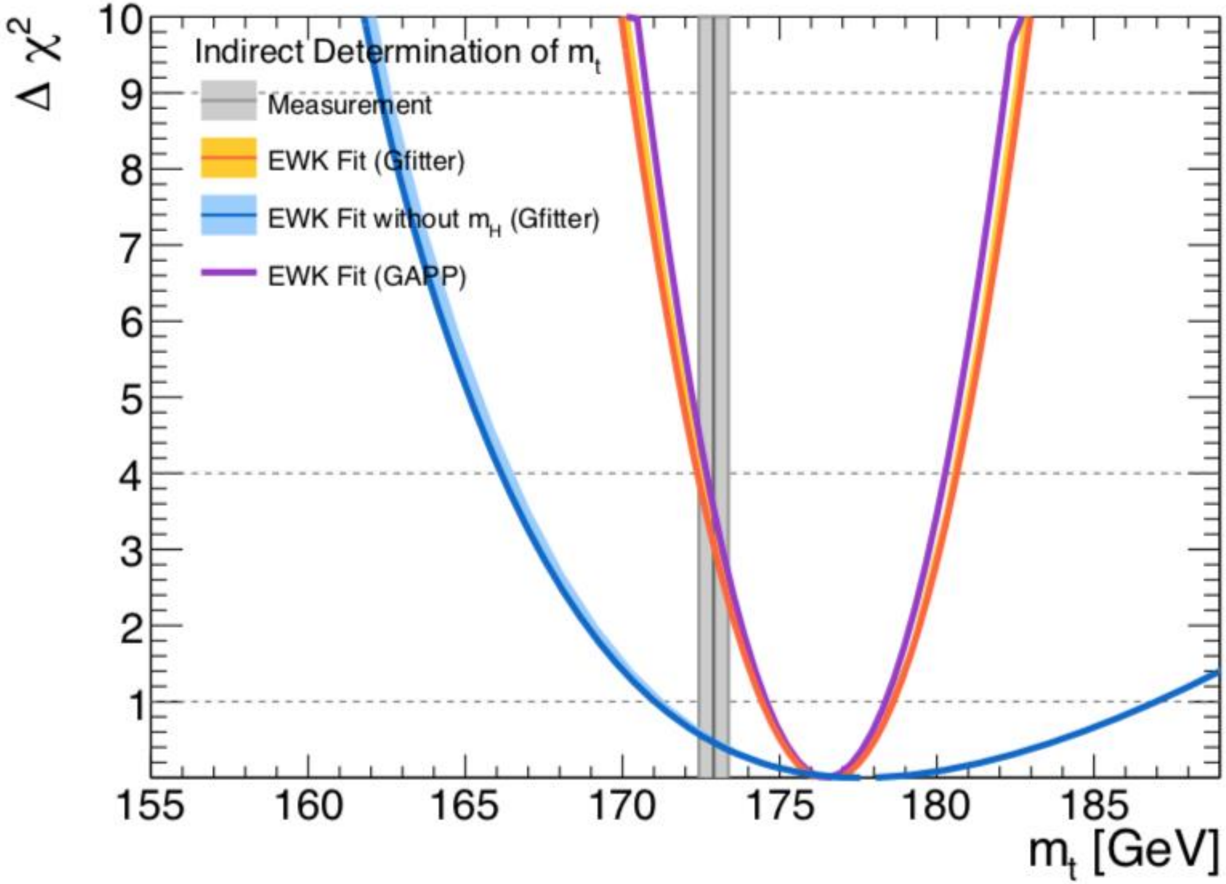
- Assuming additional 320 MeV for m_{pole} vs m_{MC} interpretation, leads to
  - $m_t^{pole} = 172.90 \pm 0.47$ GeV.

  with a p-value of 4.1%

Interpretation of the Top Quark Mass

- Indirect prediction of the top quark mass
  - m_{top}=176.5±2.1 GeV
  - Uncertainty on M_W contributes 1.9 GeV
  - Significant improvement when including m_H in the fit

- Experimental uncertainty on m_{top} is already close to theory limit



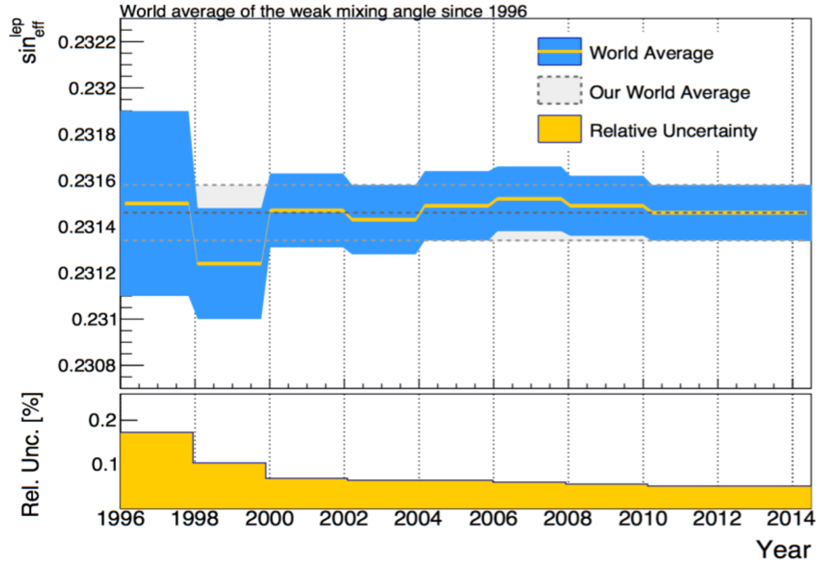
The Electroweak Mixing Angle

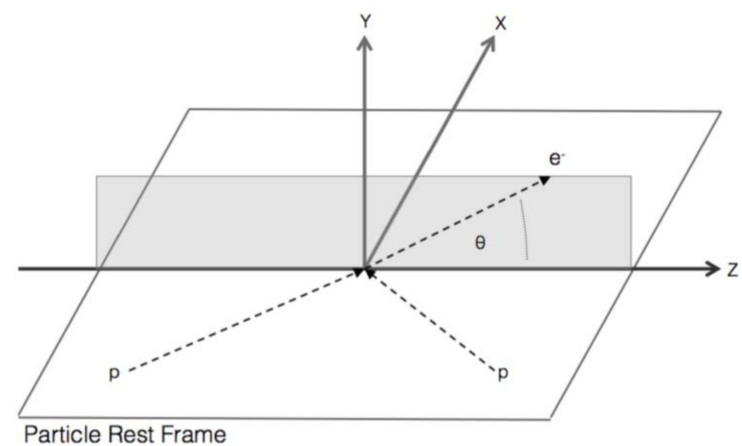
Measurement of the Electroweak Mixing Angle (1/3)

- Discrepancy of LEP and SLD measurement on $\sin^2\theta_W$ triggered quite some interest in recent years

- Problem at Hadron colliders: Do not know incoming fermion direction on an event-by-event basis
  - Problem reduced at Tevatron, very prominent at LHC
  - Significant $p_T(Z)$ due to ISR
  - Need reference frame to define forward- and background angle θ
    - Colins Soper frame

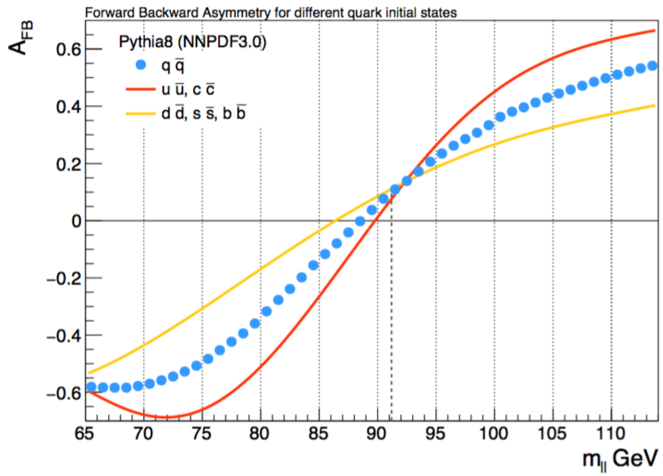
- Use (variation) of template fit approach to extract $\sin^2\theta_W$

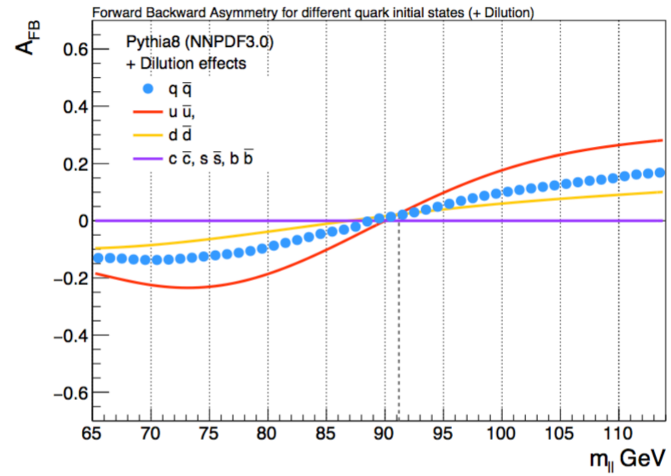




Measurement of the Electroweak Mixing Angle (2/3)

- Forward backward asymmetry also induced by Z/γ interference
- Need to integrate over all initial state quarks
- Knowledge on PDFs is essential!
- Tevatron stat. limited
- LHC limited by PDFs





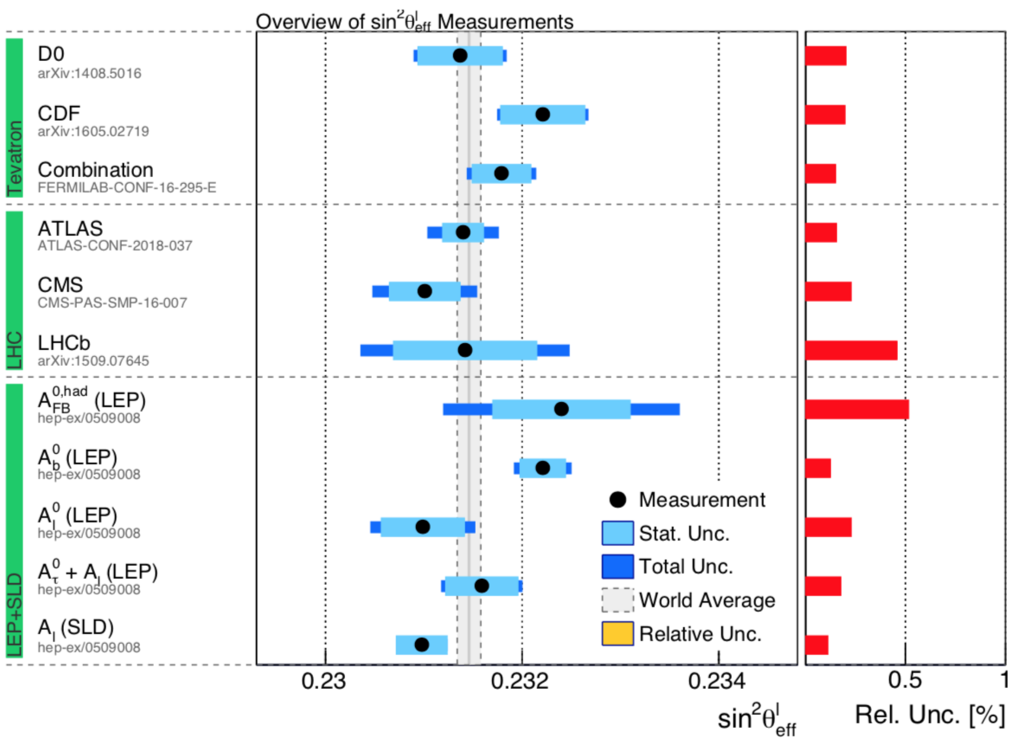
$sin^2\theta^{lep}_{eff}$	Value	Stat. Unc.	Exp. Unc.	PDF Unc.	Model Unc.	Total Unc.
D0	0.23095	0.00035	0.00007	0.00019	0.00008	0.00047
CDF	0.23221	0.00043	0.00003	0.00016	0.00006	0.00046
Tevatron (Comb.)	0.23148	0.00027	0.00005	0.00018	0.00006	0.00033
CMS	0.23101	0.00036	0.00018	0.00030	0.00016	0.00053
ATLAS (central)	0.23119	0.00031	0.00018	0.00033	0.00006	0.00049
ATLAS (forward)	0.23166	0.00029	0.00021	0.00022	0.00010	0.00043
ATLAS (combined)	0.23140	0.00021	0.00014	0.00024	0.00007	0.00036
LHCb	0.23142	0.00073	0.00052	0.00043*	0.00036*	0.00106
$A_{FB}^{0,had}$ (LEP)	0.23240	0.00070	0.00100	-	-	0.00120
A_l^0 (LEP)	0.23099	0.00042*	0.00032*	-	-	0.00053
$A_\tau + A_e$ (LEP)	0.23159	0.00037*	0.00018*	-	-	0.00041
$A_{FB}^{0,b}$ (LEP)	0.23221	0.00023*	0.00017*	-	-	0.00029
A_l (SLD)	0.23098	0.00026*	0.00000*	-	-	0.00026

Measurement of the Electroweak Mixing Angle (3/3)

- Hadron collider results
  - Measurements at Tevatron and CMS employ a template fit of A_{FB} in the C.S.-frame
  - ATLAS employs a template fittig procedure of the angular coefficients and extracts $\sin^2\theta_W$ from A4
  - CMS and ATLAS employ PDF-profiling

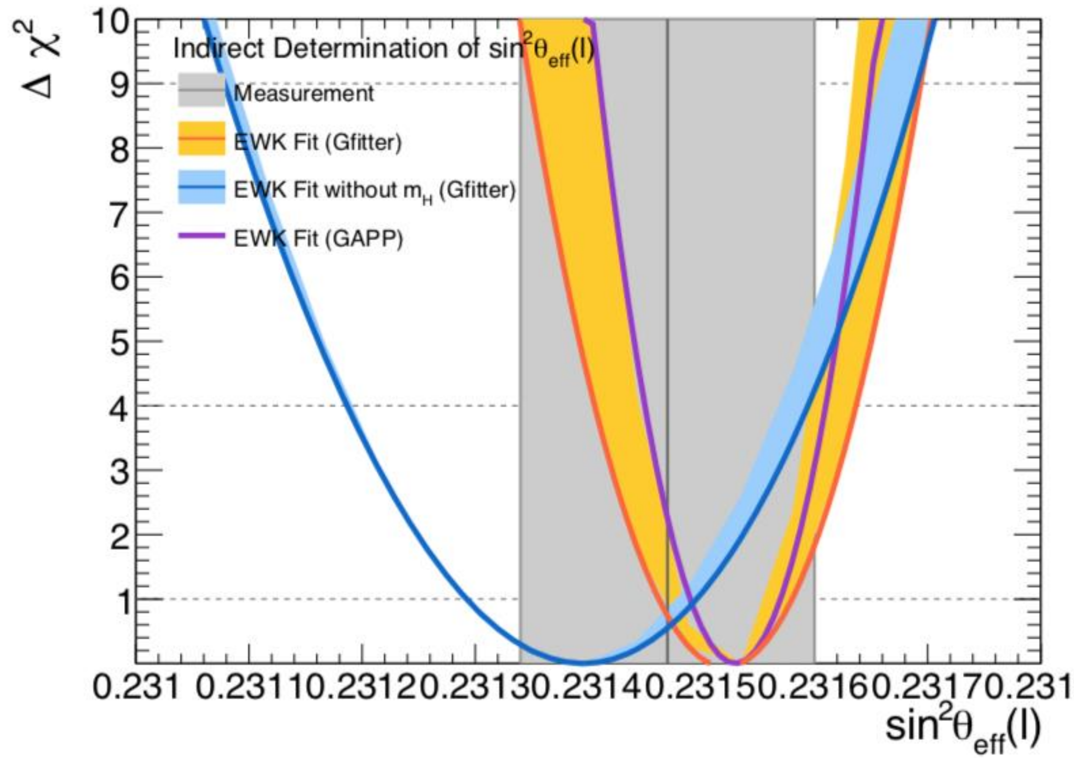
$$\frac{d\sigma}{dp_T^2\,dy\,d\cos\theta\,d\phi} = \frac{d\sigma_{unpol}}{dp_T^2\,dy} \Big((1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2(\theta)) + A_1\sin(2\theta)\cos(\phi)$$
$$+A_2\frac{1}{2}\sin^2(\theta)\cos(2\phi) + A_3\sin(\theta)\cos(\phi) + A_4\cos(\theta)$$
$$+A_5\sin^2(\theta)\sin(2\phi) + A_6\sin(2\theta)\sin(\phi) + A_7\sin(\theta)\sin(\phi)\Big),$$

- Combination of hadron collider results
  - $\sin^2\theta_{eff} = 0.23140 \pm 0.00023$
  - Level of LEP and SLD
  - Disagreement between LEP and SLD might be just a statistical effect



Interpretation in the context of the Electroweak Fit

- Indirect Determination
  - $\sin^2\theta_{eff} = 0.23151 \pm 0.00006$
- World average
  - $\sin^2\theta_{eff} = 0.23151 \pm 0.00014$
  - More precise than prediction
  - Does it make sense to improve the measurement?
- Hadron Collider average
  - $\sin^2\theta_{eff} = 0.23140 \pm 0.00023$
  - Assuming an improvement by a factor of two (and a central value within 2σ to the current w.a. would still show no tension above 1.5σ)



W-Boson Mass Measurement

Mass Sensitive Variables

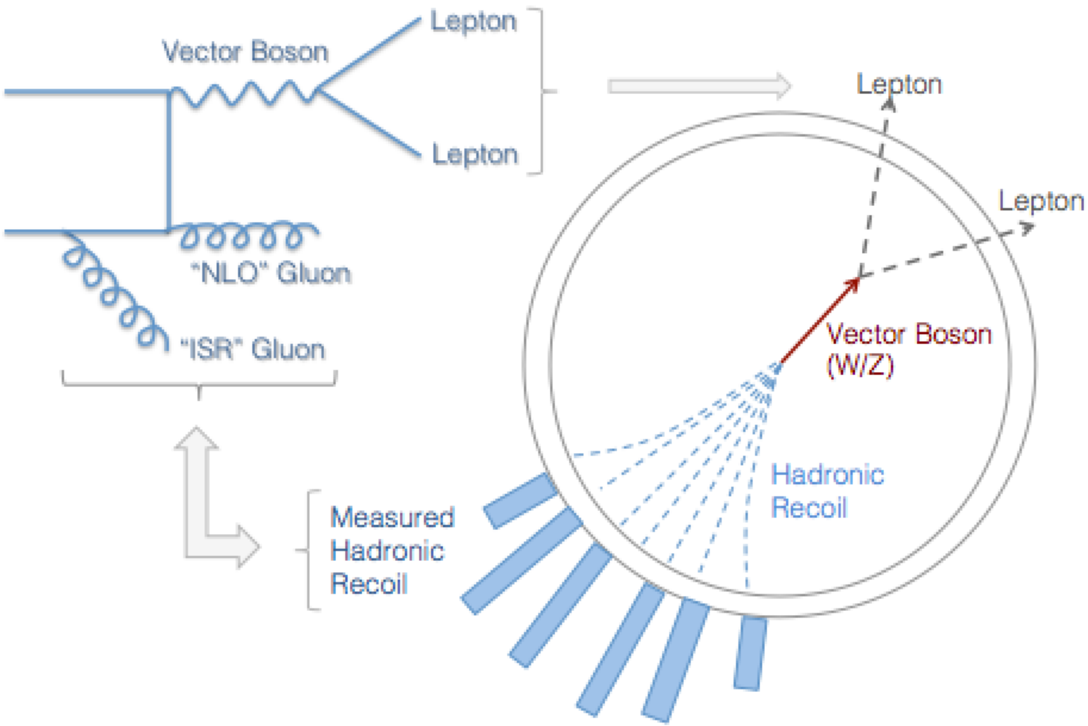
- **Main signature**: final state lepton (electron or muon): p_T(lepton)

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

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

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

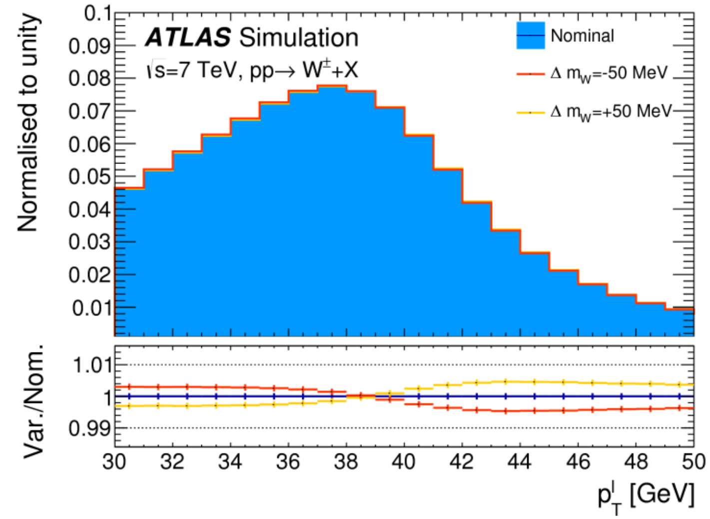
$$m_T = \sqrt{2 p_T^l p_T^{miss} (1 - \cos\Delta\phi)}$$

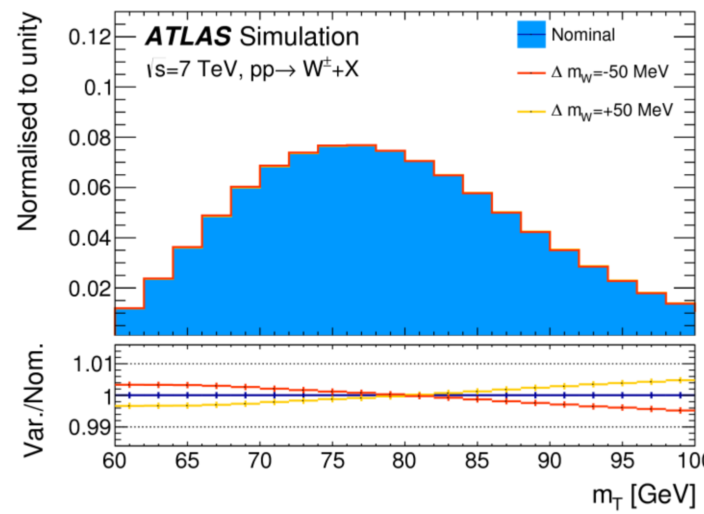


Mass Sensitive Variables

- 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.

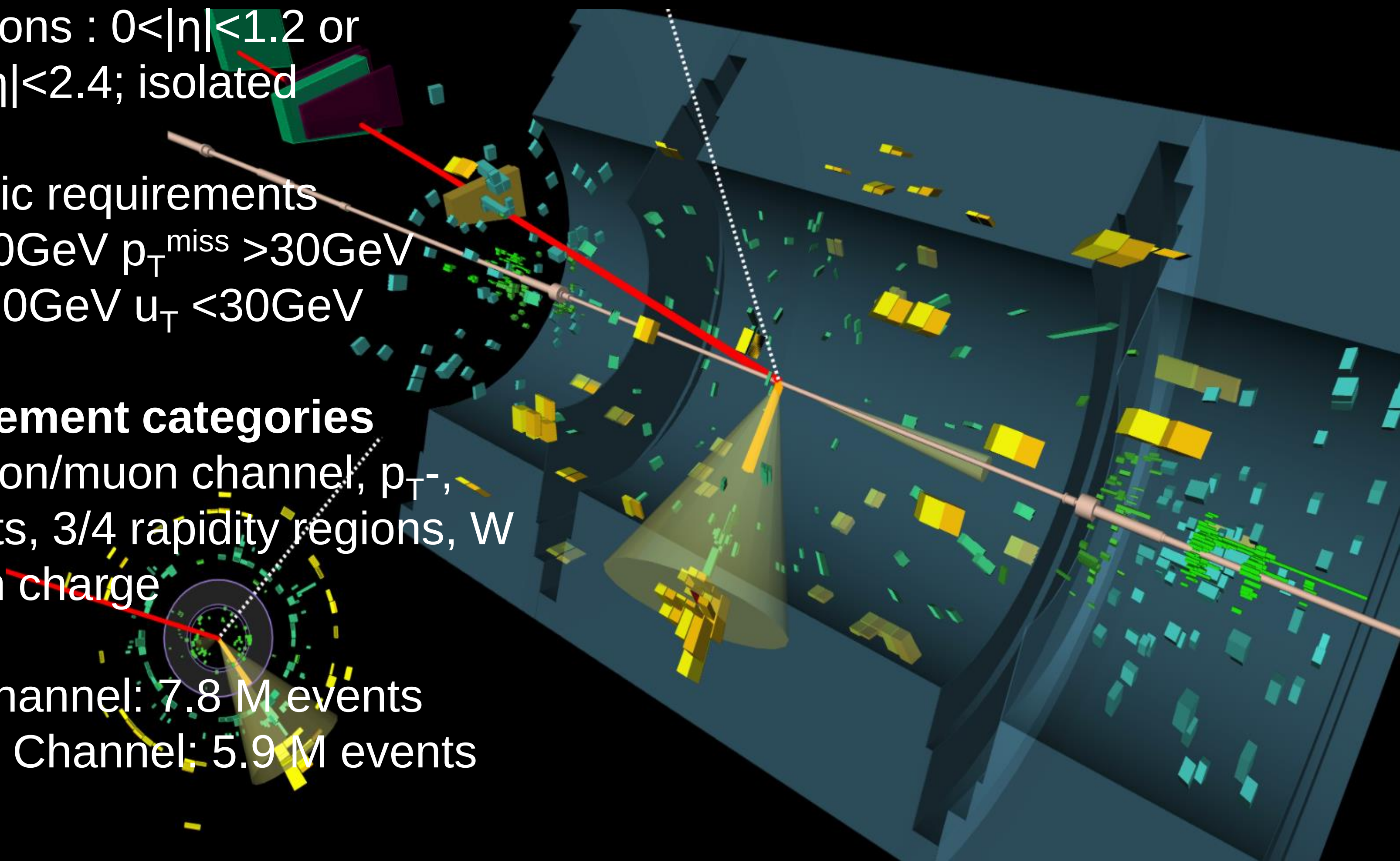
Angular Coeff.

Focus during the first years of the project

Focus during the last years of the project

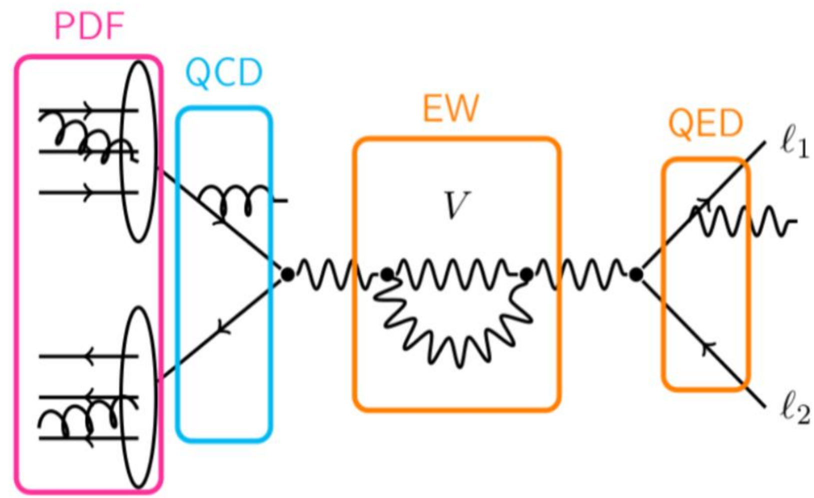
Signal Selection and Measurement Regions

- 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

- **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

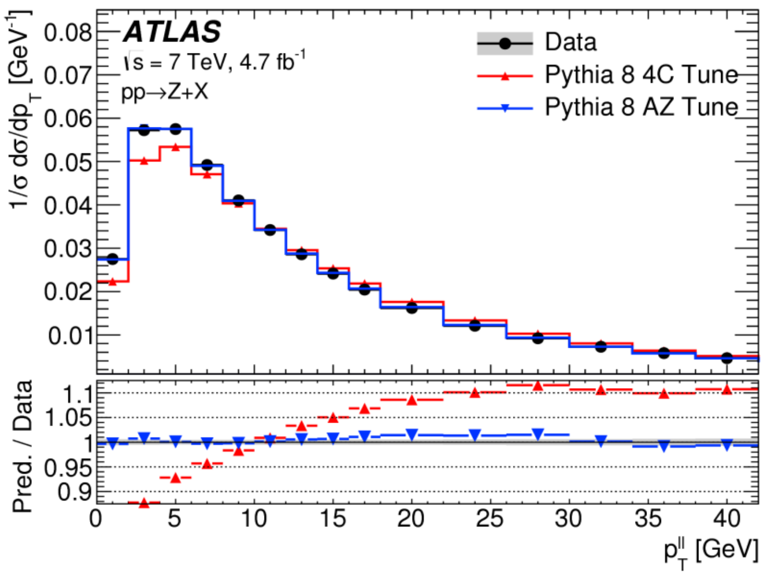
- **EW aspects**
  - ISR and FSR QED corrections
    Missing higher-order effects

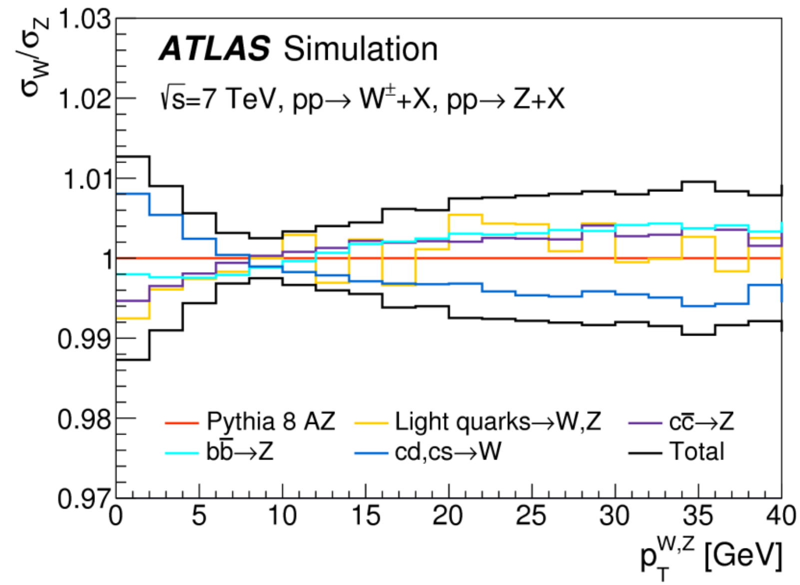
$$\frac{d\sigma}{dp_1 dp_2} = \left(\frac{d\sigma}{dm}\right)\left(\frac{d\sigma}{dy}\right)\left(\frac{d\sigma(p_t,y)}{dpt}\frac{1}{\sigma(y)}\right)\cdot$$
$$\times\left(\sum_i A_i(y,p_t)P_i(\cos\theta,\phi)\right)$$

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

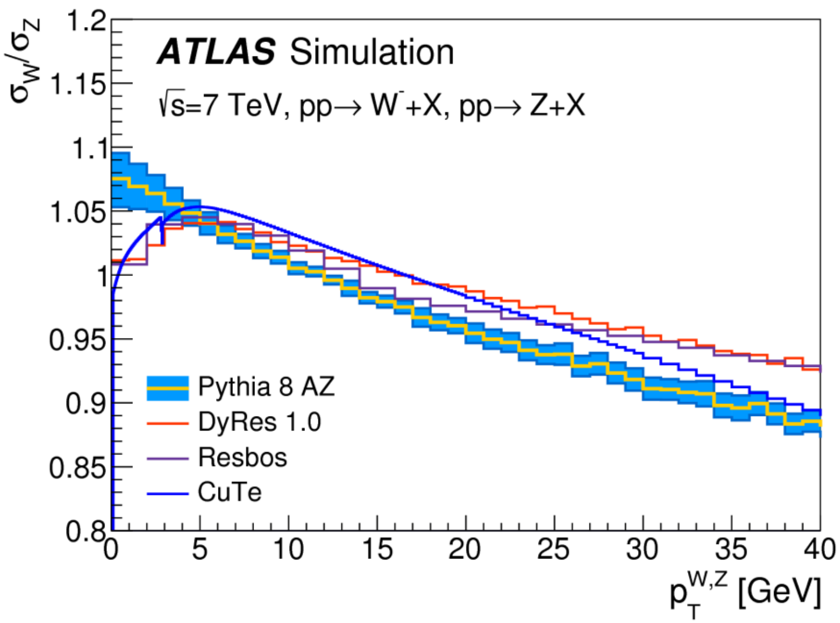


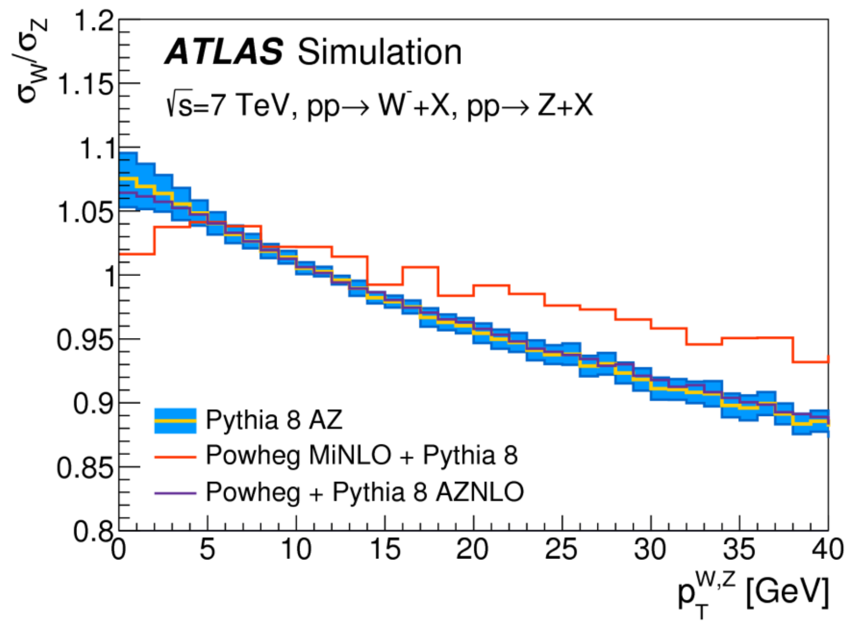


Transverse Momentum (A several years effort)

- 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^-**!

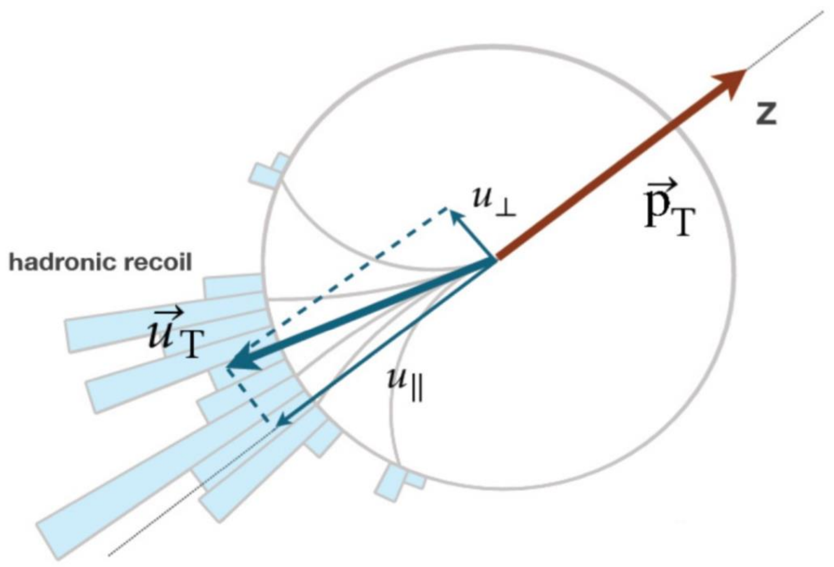
- AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
- **A_i uncertainties from Z data**; envelope for A_2 discrepancy

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

Mass Sensitive Variables

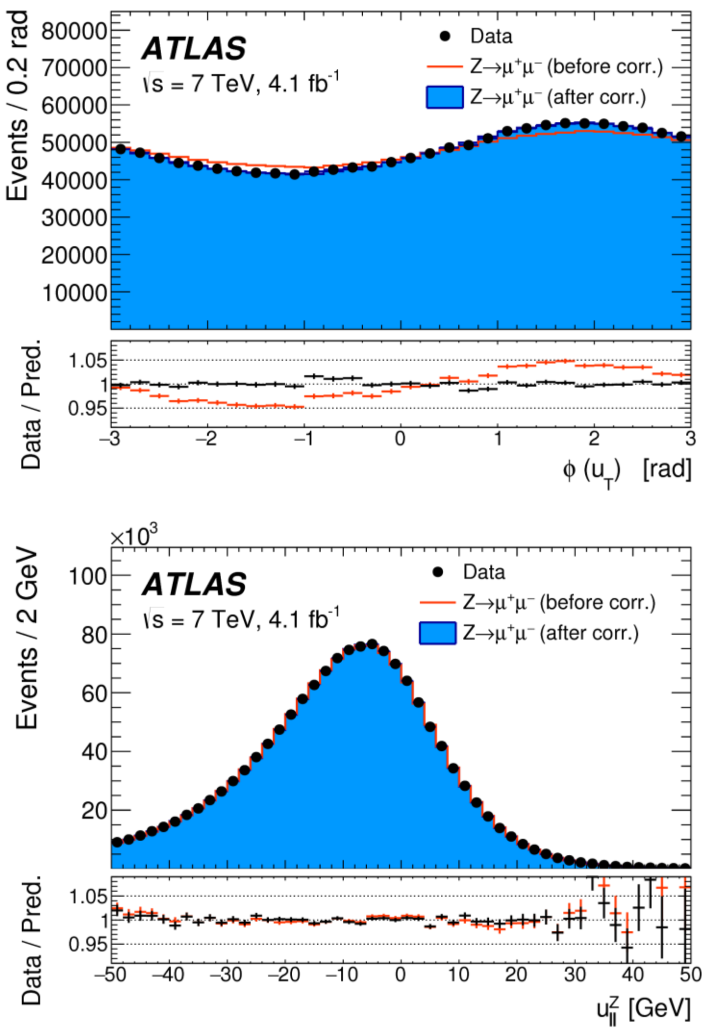
- **Lepton calibration**
  - momentum calibration using the Z peak
  - efficiency corrections (reconstruction, identification, trigger) rederived via tag- and probe-method in 3 dimensions

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



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

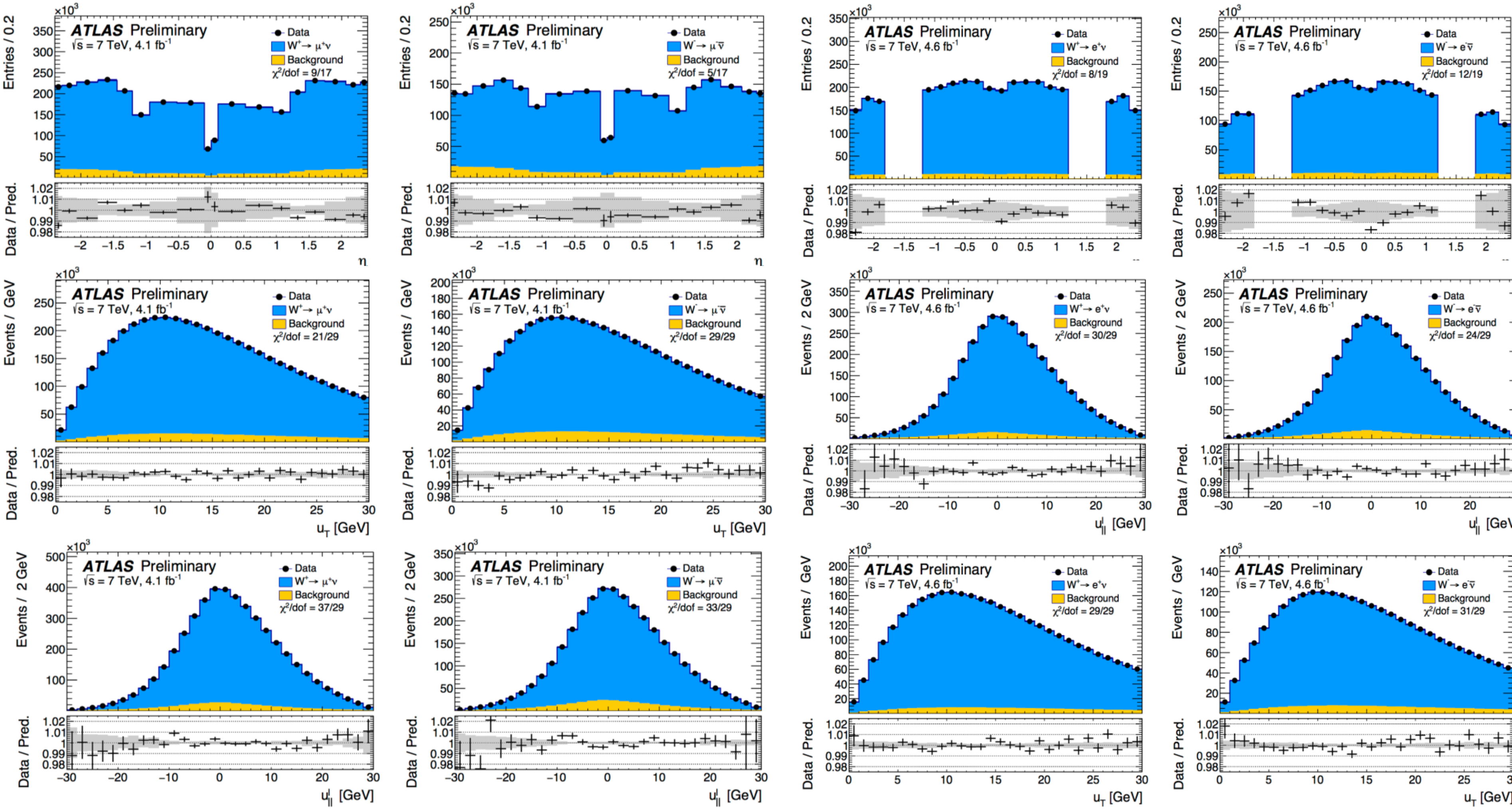
- Experimental uncertainty due to muon detector calibration on the 10 MeV level
  - In terms of average accuracy on the position resolution, this means µm-precision!
- Not even discussed here: **How to estimate backgrounds**
  - We control the background contributions on **a rel. 5% level!**
  - Final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

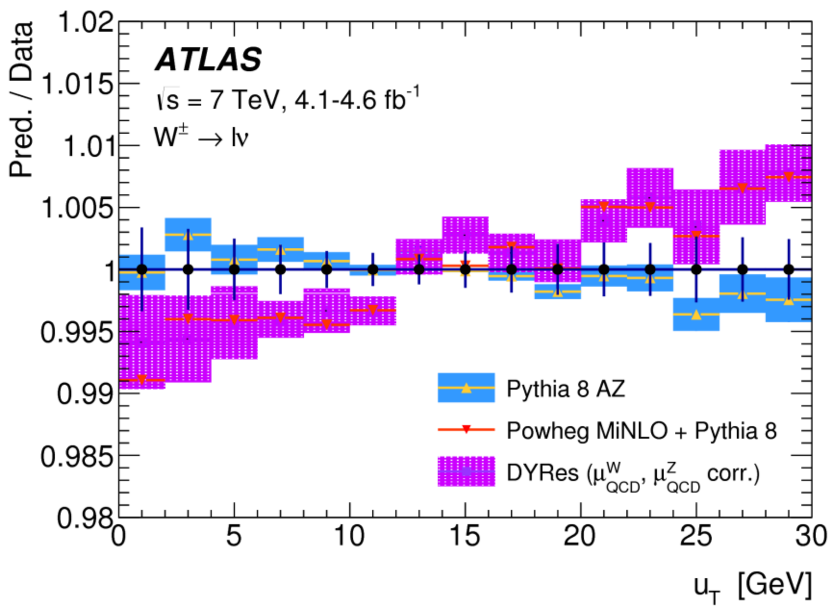
Control Distributions (non m_W sensitive)

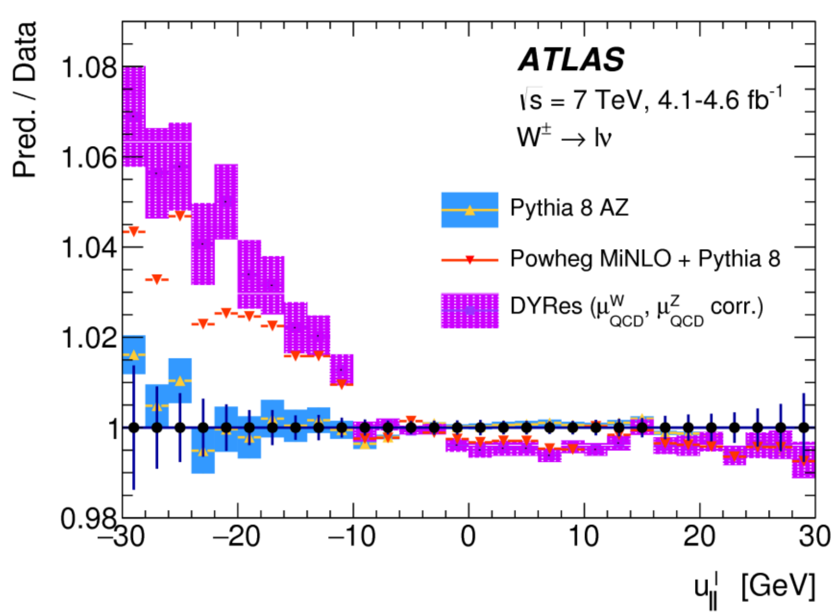


Crucial Test of $p_T(W)$ modelling

- **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?

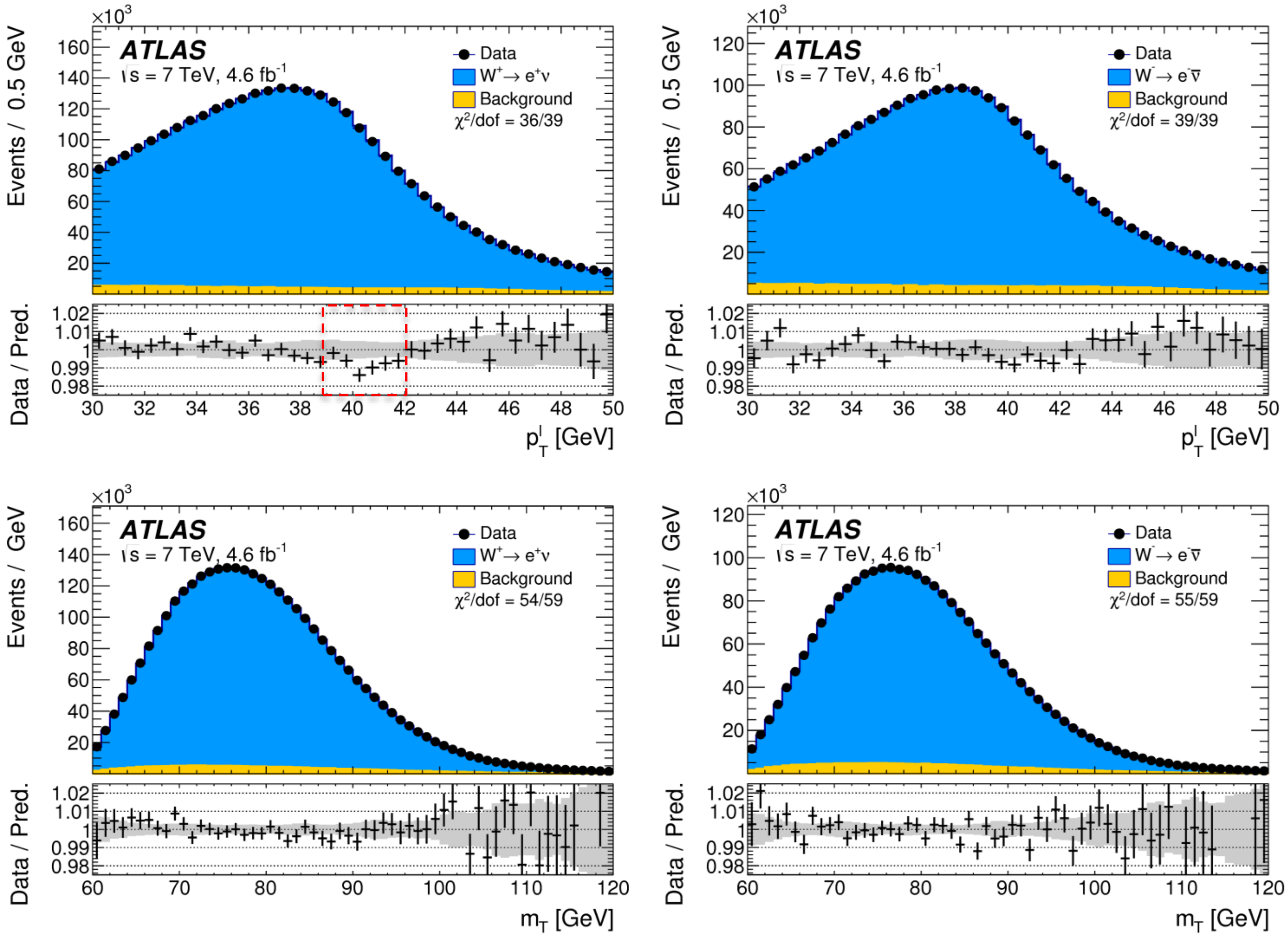
- The **$u_{||}(l)$ distribution is very sensitive** to the underlying $p_T(W)$ distribution
  - Can exploit this feature to verify the accuracy of our baseline model, and





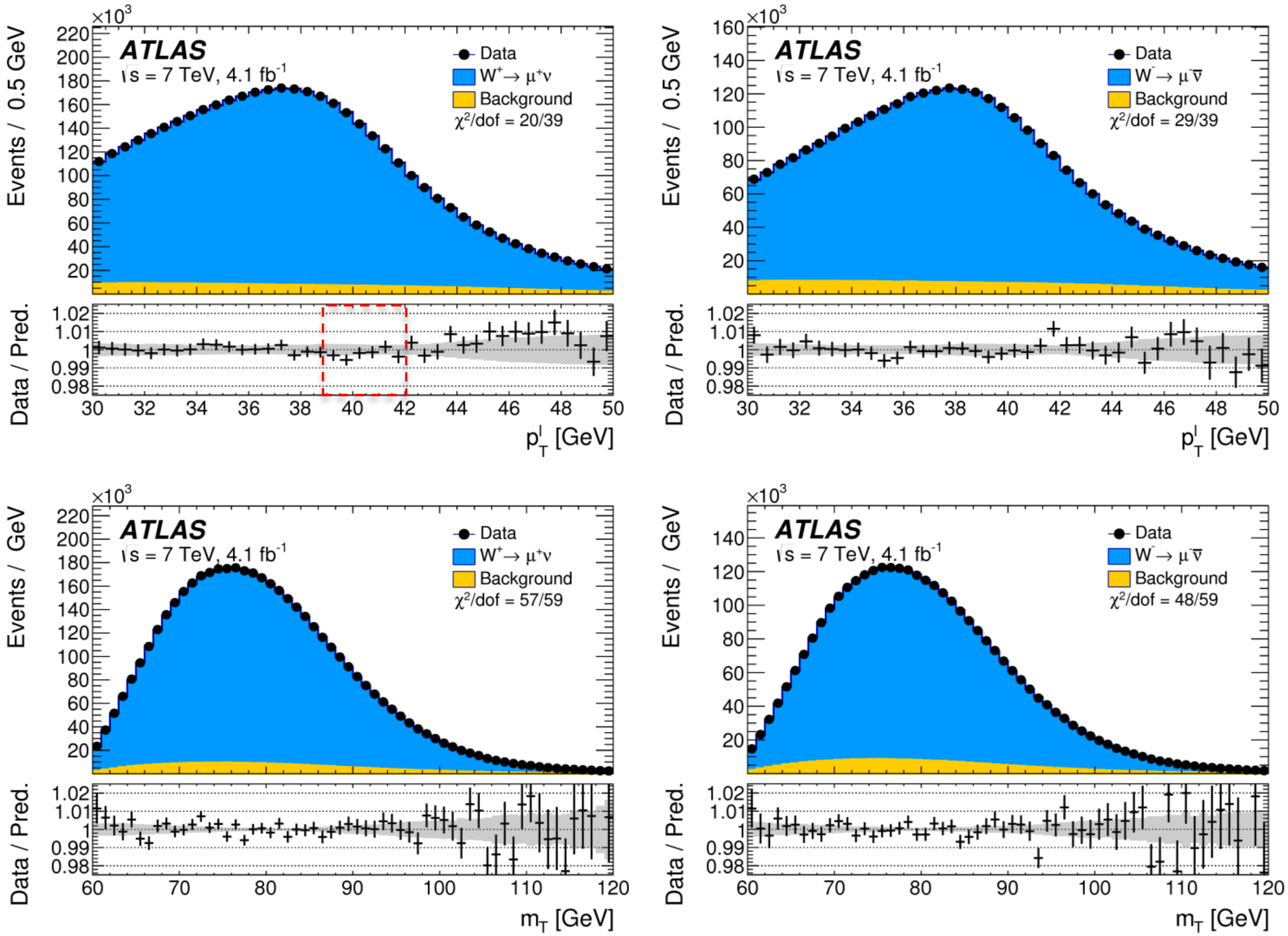
W-Mass Distributions: Electrons

- 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

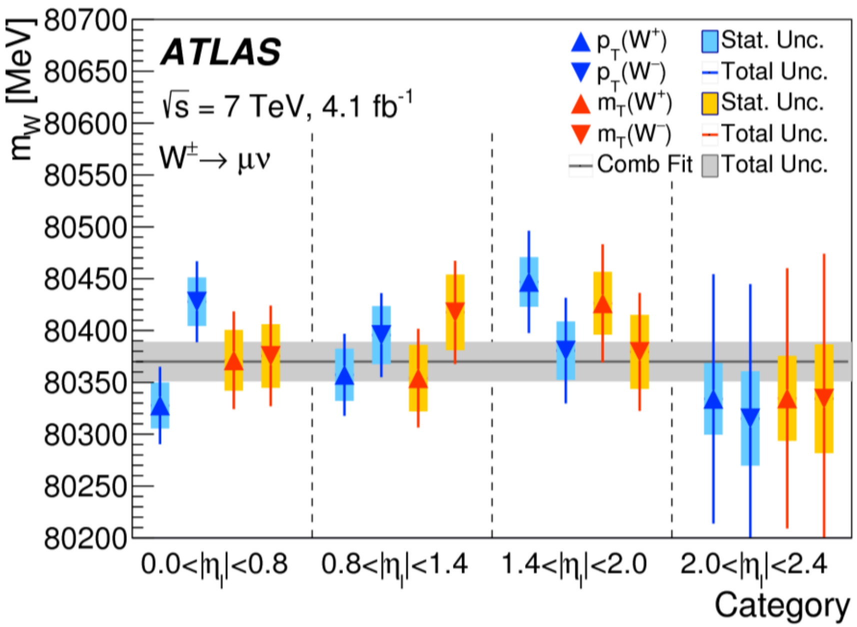


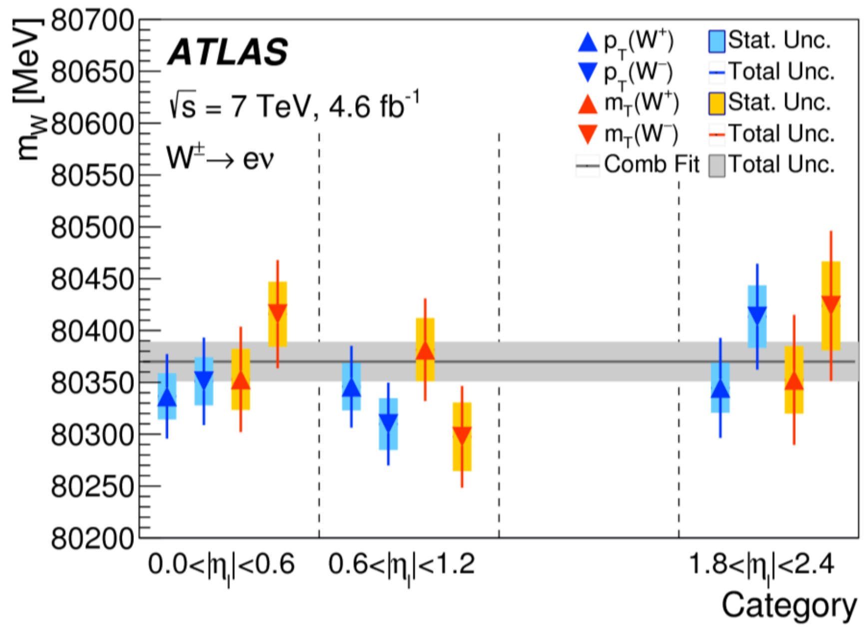
W-Mass Distributions: Muons

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



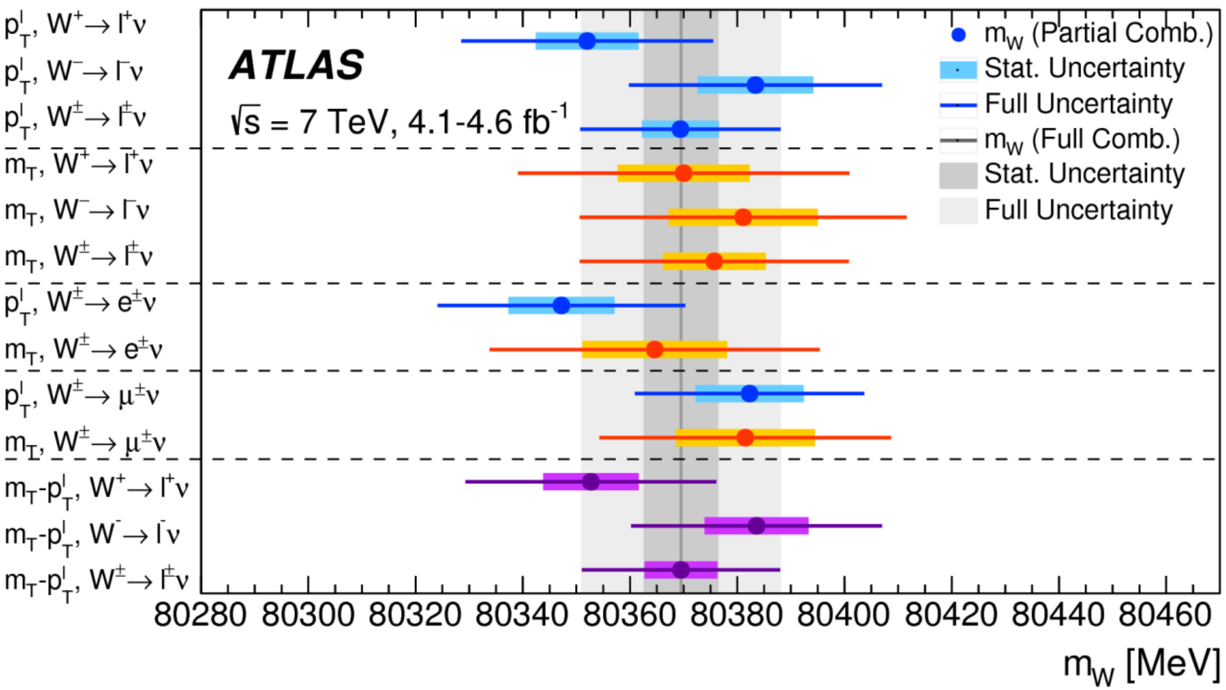
m_W Fit Results in Various Categories





- 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**

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

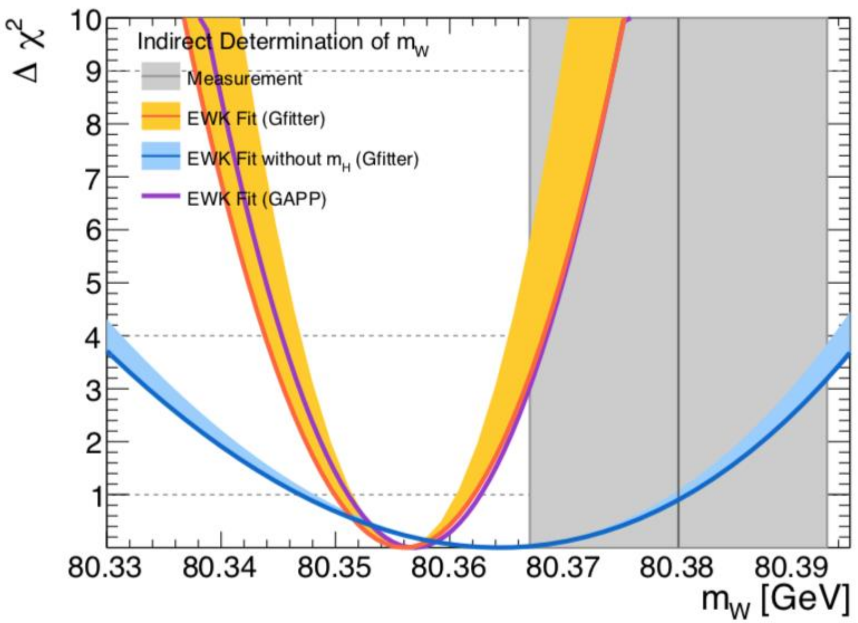
Nobody cares about your method. People remember only your last number!

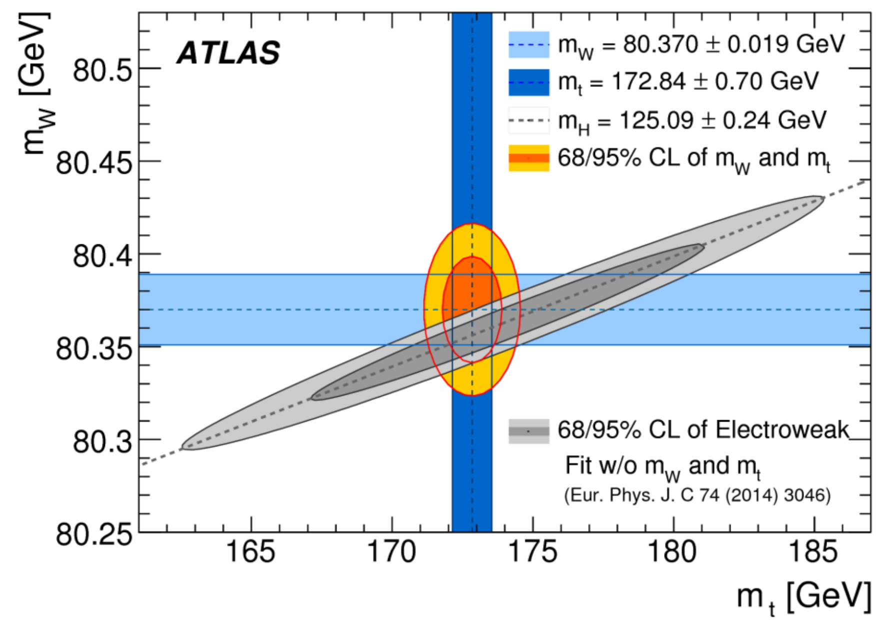
Final measured mass of the W boson

$= 80.370 \pm 0.007(\text{stat.}) \pm 0.011(\text{exp.}) \pm 0.014\ (\text{mod})\ \text{GeV}$

$= \mathbf{80.370 \pm 0.019\ GeV}$

Interpretation in the context of the 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** …

- Unofficial combination yields a value of
  - M_W =80380±13 MeV,

  with a p-value of 0.74
- 1.6σ “tension” with the SM

Where will we stand in 10 years?

Prospects of the EW Fit

- Future Developments for the Global Electroweak Fit
  - $\Delta\alpha^{(5)}_{had}$: Low energy data (esp. $\pi+\pi-$), also pQCD/lattice
  - M_W: LHC Measurements! Theory uncertainty of 4 MeV!
  - m_t: Experimental progress and theoretical interpretations
  - $\sin^2\theta_{leff}$: We are already now at LEP precision
  - A^{FB}_{0b} Z+b production at LHC, [M. Beccaria et al., PLB 730, 149 (2014)]

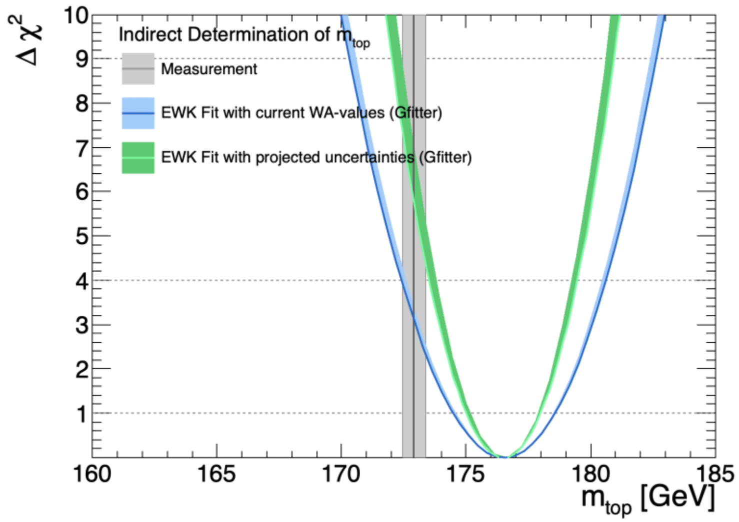
- Extensions of the scalar sector
  - $B\to Xs\gamma$, $B_s\to\mu\mu$, $(g-2)_\mu$..., precision H coupling measurements
  - Direct searches: cover all possible final states

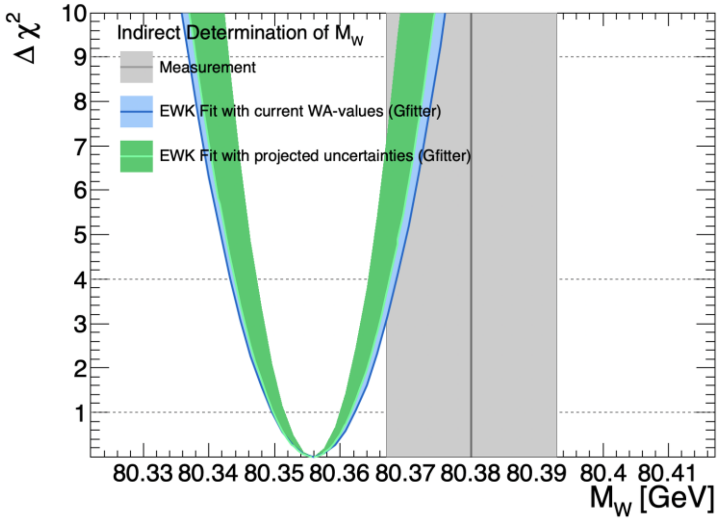
- General extension with the SMEFT
  - EWPO, LEP 2 data, flavour data [J. Ellis et al., 1803.03252]
  - Differential H measurements, also sensitivity to H self-coupling λ!

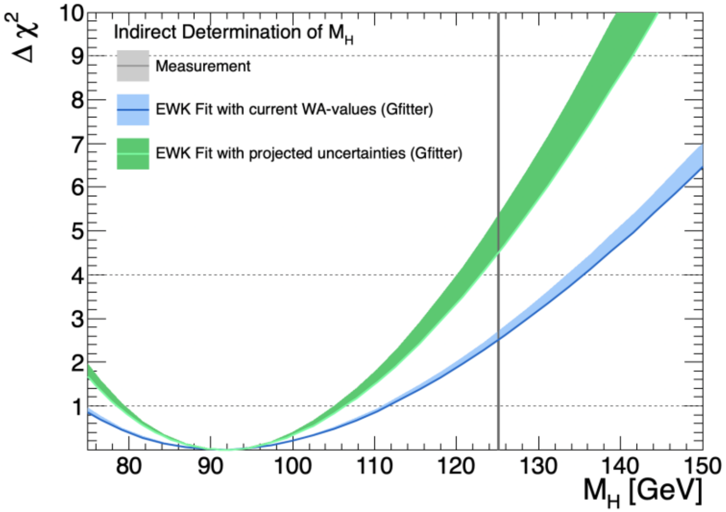
Where will we stand in 10 Years with an Ultimate Precision at the LHC?

- By the end of the LHC, we (being optimistic) might have
  - $\Delta m_W \approx 8$ MeV
  - $\Delta m_{Top} \approx 300$ MeV
  - $\Delta \sin^2\Theta_W \approx 0.00012$

- … results in indirect precisions of
  - $\Delta m_W \approx 4$ MeV, $\Delta m_{Top} \approx 1.3$ GeV, $\Delta m_H \approx 13$ GeV
  - See also a detailed studfy from Gfitter from 2014: https://arxiv.org/abs/1407.3792



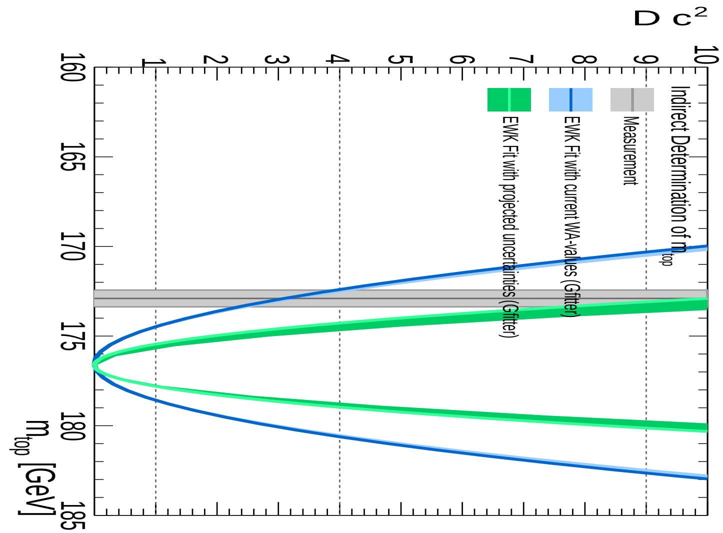


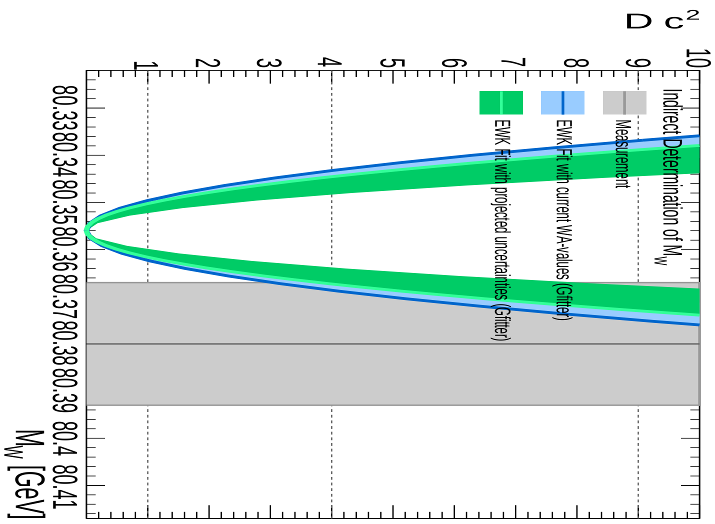


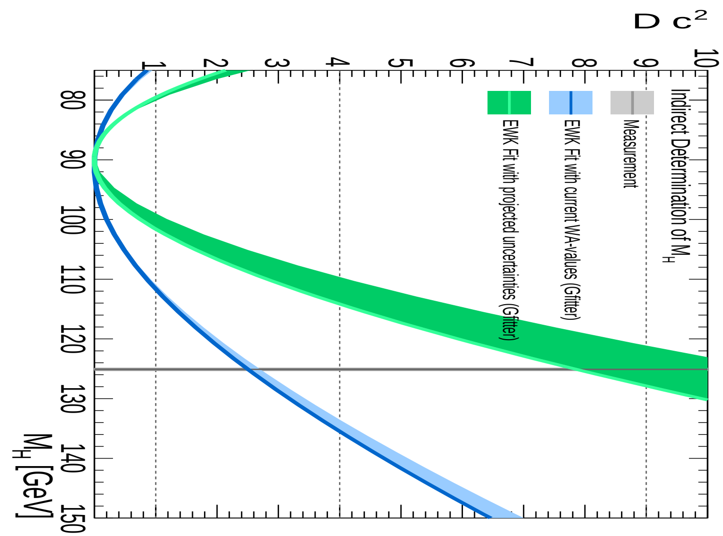
Where will we stand in 10 Years with an Ultimate Precision at the LHC?

- By the end of the LHC, we (being super optimistic) might have
  - $\Delta m_W \approx 5$ MeV
  - $\Delta m_{Top} \approx 200$ MeV
  - $\Delta \sin^2\Theta_W \approx 0.00008$

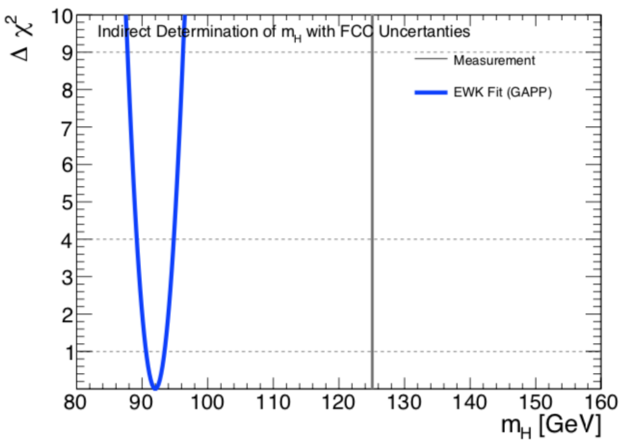
- … results in indirect precisions of
  - $\Delta m_W \approx 4$ MeV, $\Delta m_{Top} \approx 1.0$ GeV, $\Delta m_H \approx 9$ GeV

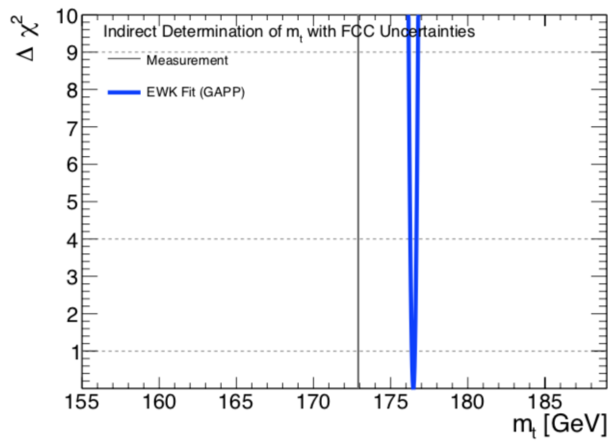


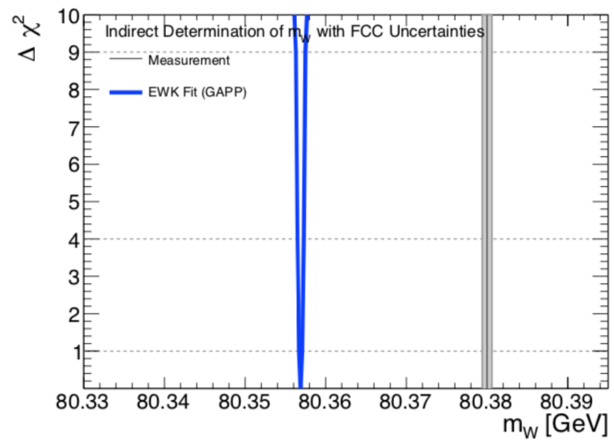




Where will we stand with an Electron-Positron Collider (e.g. FCCee)?



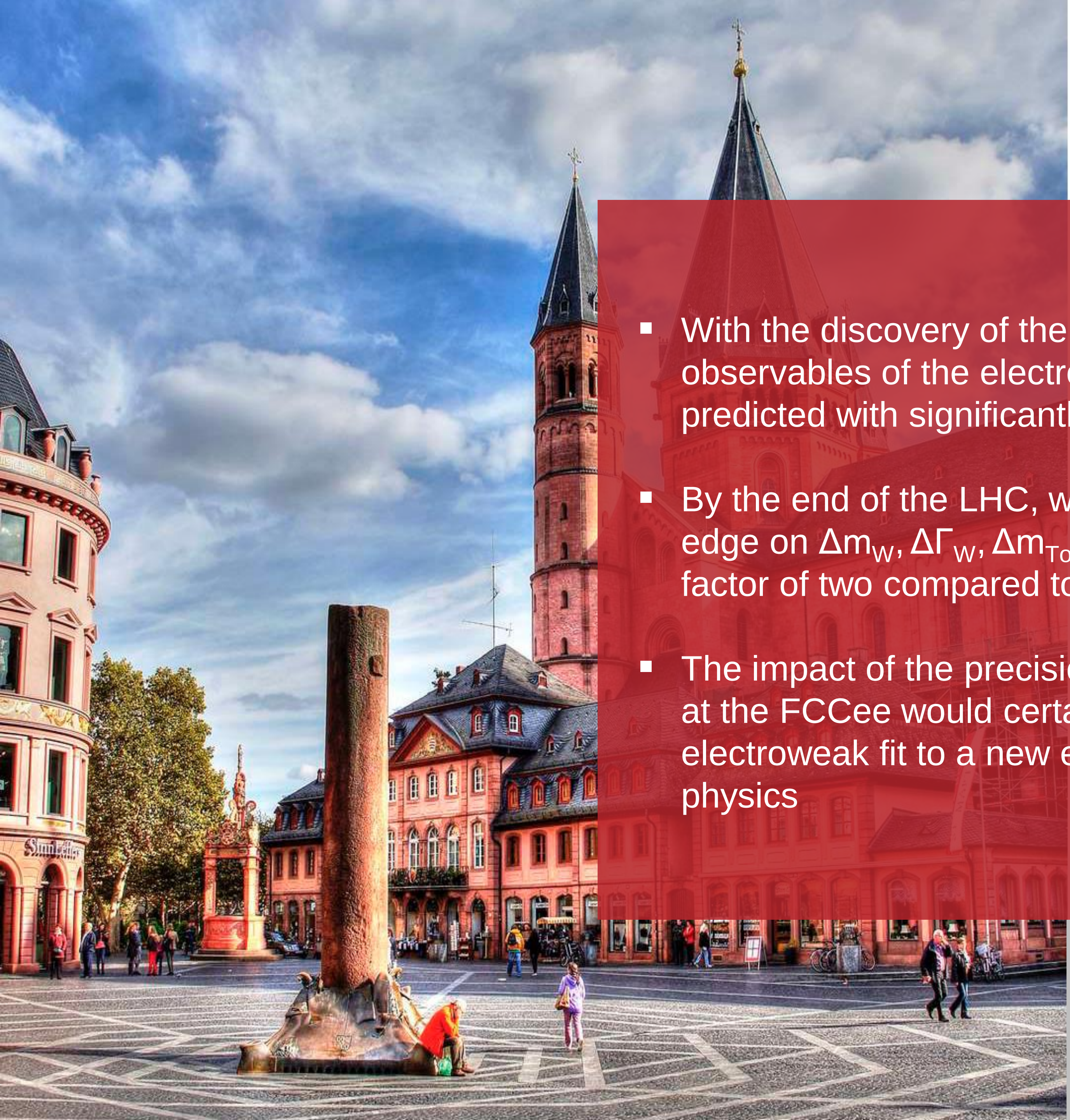




- Repeating the electroweak fit with the expected FCCee uncertainties using the GAPP framework, we find
  - $\Delta m_H^{indirect} \approx 1.4$ GeV
  - $\Delta m_W^{indirect} \approx 0.2$ MeV
  - $\Delta m_{Top}^{indirect} \approx 0.1$ GeV
- Improvements on the indirect predictions by more than a factor of 10
  - Theory uncertainties dominante!

parameter	current value	FCC-ee unc.-target
M_H	125.09 ± 0.15 GeV	± 0.1 GeV
M_W	80.380 ± 0.013 GeV	± 0.6 MeV
Γ_W	2.085 ± 0.042 GeV	± 1.0 MeV
m_{top}	172.90 ± 0.47 GeV	± 15 MeV
$\Delta\alpha_{had}[\times 10^{-5}]$	2758 ± 10	± 2

parameter	current value	FCC-ee unc-target
M_Z	91.1875 ± 0.0021 GeV	< 0.1 MeV
Γ_Z	2.4952 ± 0.0023 GeV	< 0.1 MeV
σ^0_{had}	41.540 ± 0.037 nb	0.004 nb
R_b	0.21629 ± 0.00066	< 0.00006
$A_{LR}^{FB}(b)$	0.0992 ± 0.0016	± 0.0001



JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Summary

- With the discovery of the Higgs, several key observables of the electroweak sector could be predicted with significantly reduced uncertainties
- By the end of the LHC, we expect to improve our edge on Δm_W, $\Delta\Gamma_W$, Δm_{Top} and $\Delta \sin^2\Theta_W$ by up to a factor of two compared to the world averages now
- The impact of the precision observables measured at the FCCee would certainly bring the global electroweak fit to a new era of sensitivity to BSM physics