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Messages from EW tests after the Higgs discovery (and beyond)

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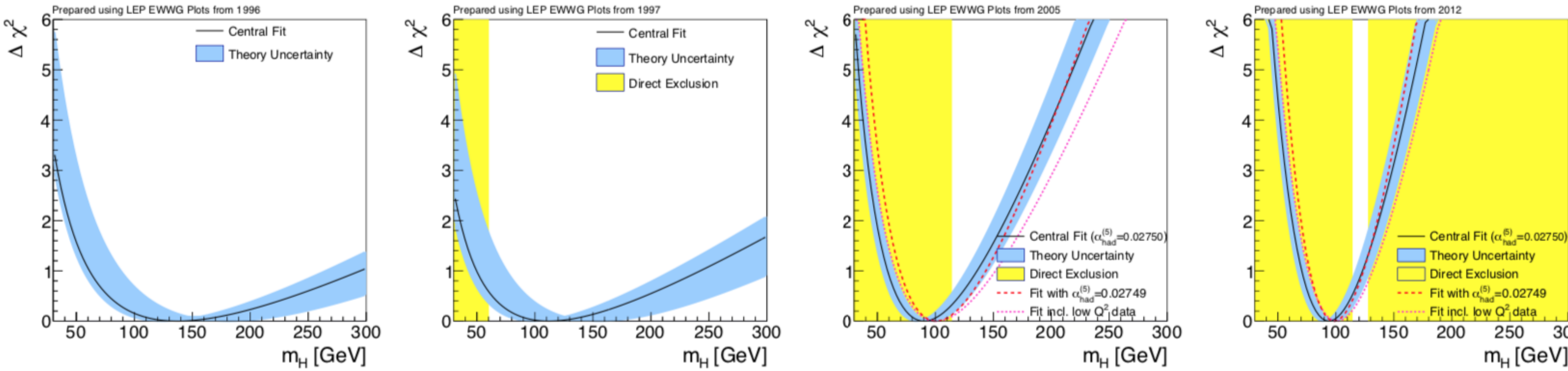
Setting the Stage



- Very powerful idea of the global electroweak fit enabled prediction of m_{Top} and m_H before their discoveries
  - Measure different observables
  - Calculate the relations between those observables

- In this talk: Review where we currently stand after the Higgs (arXiv:1902.05142) and where the FCCee will bring us

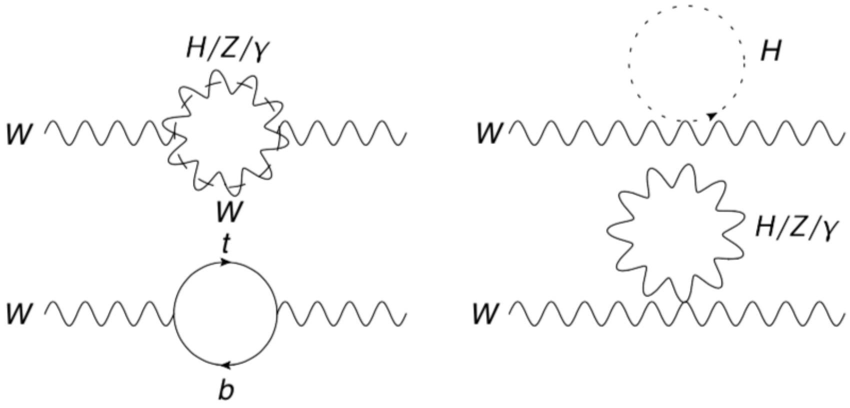
$$
\begin{aligned}
M_W^2 &= \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right), \\
\sin^2\theta_{\text{eff}}^f &= \kappa_Z^f \sin^2\theta_W , \\
g_V^f &= \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f\sin^2\theta_{\text{eff}}^f\right), \\
g_A^f &= \sqrt{\rho_Z^f}\, I_3^f ,
\end{aligned}
$$

Where do we stand with the theory? - W Boson mass

- Already known in the 1980s
  - full one-loop calculations
  - mixed EW/QCD corrections: $O(\alpha\alpha_s m_t^2)$, $O(\alpha\alpha_s)$

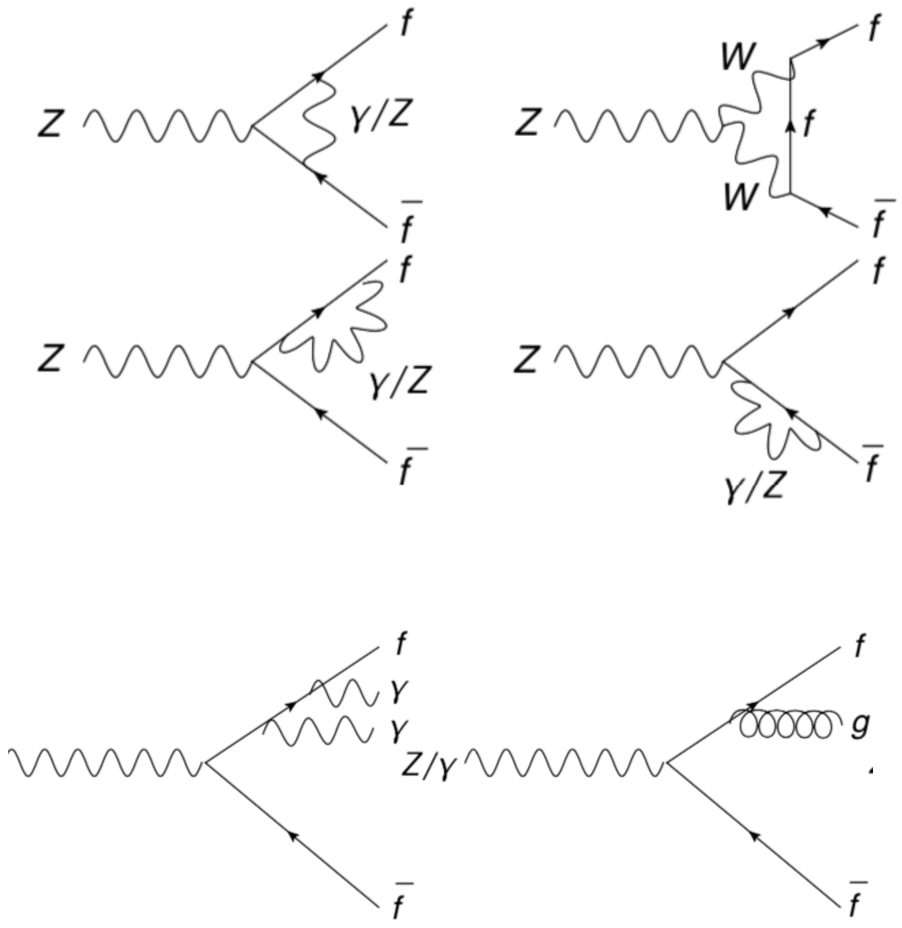
- 2015: full $O(\alpha^2)$ results

- Enhanced three-loop contributions are also important
  - $O(\alpha\alpha_s^2 m_t^2)$ correction reduces m_W by about 10 MeV
  - shift is almost entirely due to the use of the pole mass definition, and amounts to less than 3 MeV if the definition based on the MS scheme is employed instead.



Where do we stand with the theory? – weak mixing angle and decay rates

- most important radiative corrections are related to those in M_W, entering through $\Delta\alpha$ and $\Delta\rho$
  - two-loop $O(\alpha^2)$ fermionic and bosonic corrections are fully known
- $\sin^2\theta^f_{eff}$ of the four light quarks differ slightly from the prediction for charged leptons.
  - flavor dependent corrections of $O(\alpha\alpha_s)$ that do not factorize in the total Z width and need to be include.
  - for bottom quarks additional $O(\alpha m_t^2)$ and $O(\alpha^2 m_t^4)$ enhanced effects enter the Zbb-vertex
    - Also complete at 2-loop since 2018 https://arxiv.org/pdf/1804.10236.pdf

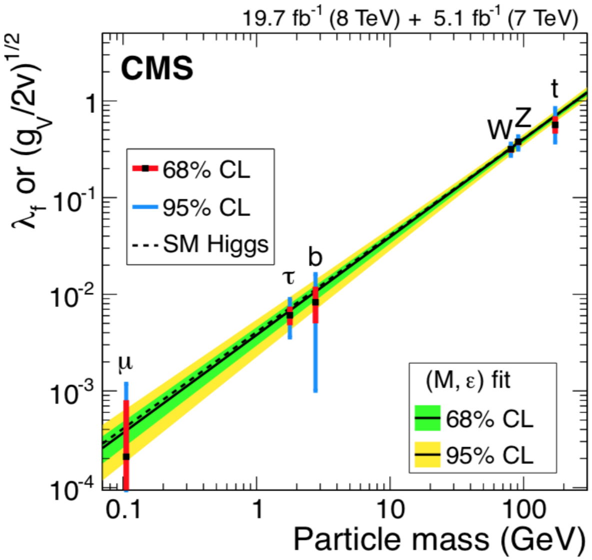


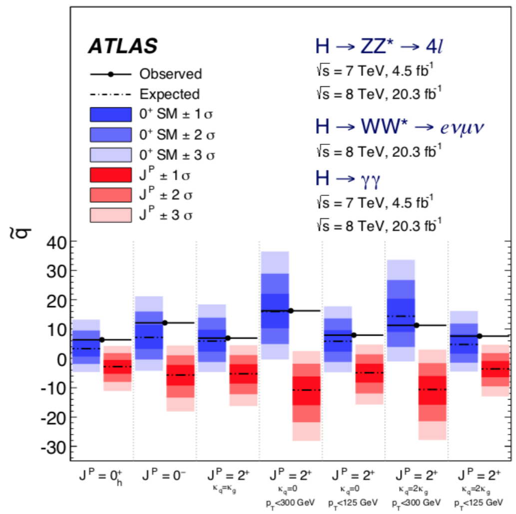
Unknown higher order corrections

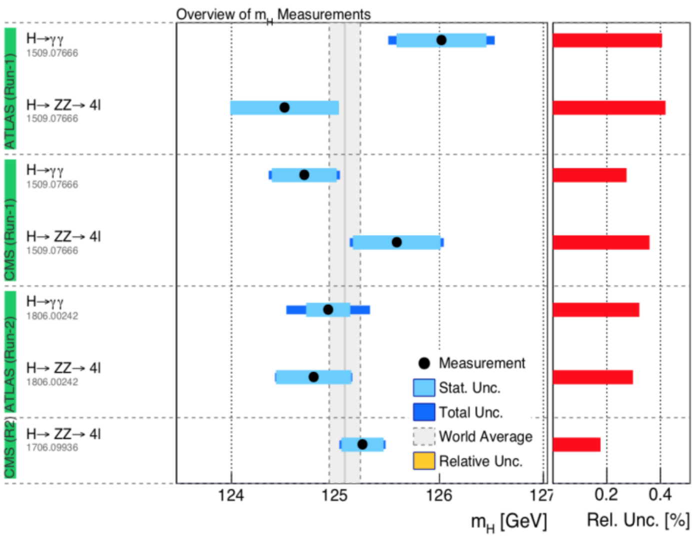
- theoretical uncertainties in M_W, $\sin^2\theta_{l,eff}$, and Γ_Z, due to unknown higher-order electroweak corrections, arise from W and Z boson self-energies, in the
  - vertex corrections
  - box corrections,
  - further non-factorizable corrections, i.e., those that are not captured by the improved Born approximation

	$\Delta T = \pm 0.0073$	$\Delta S = \pm 0.0034$	$\Delta U = \pm 0.0051$	$\delta_{\mathrm{PQCD/EW}}$	BW	total
M_W	± 3.3 MeV	∓ 0.6 MeV	± 1.8 MeV	—	—	3.8 MeV
$\sin^2\theta^l_{\mathrm{eff}}$	$\mp 1.9 \times 10^{-5}$	$\pm 1.2 \times 10^{-5}$	0	—	—	2.2×10^{-5}
$\hat{\rho}$	$\pm 5.9 \times 10^{-5}$	0	$\pm 4.4 \times 10^{-5}$	—	—	7.4×10^{-5}
Γ_Z	± 0.19 MeV	∓ 0.03 MeV	0	± 0.22 MeV	—	0.29 MeV
R_ℓ	$\pm 0.3 \times 10^{-3}$	$\mp 0.2 \times 10^{-3}$	0	$\pm 2.6 \times 10^{-3}$	—	2.6×10^{-3}
σ^0_{had}	∓ 0.1 pb	± 0.1 pb	0	∓ 2.1 pb	± 1.2 pb	2.4 pb

Experimental Status: Higgs Boson Mass





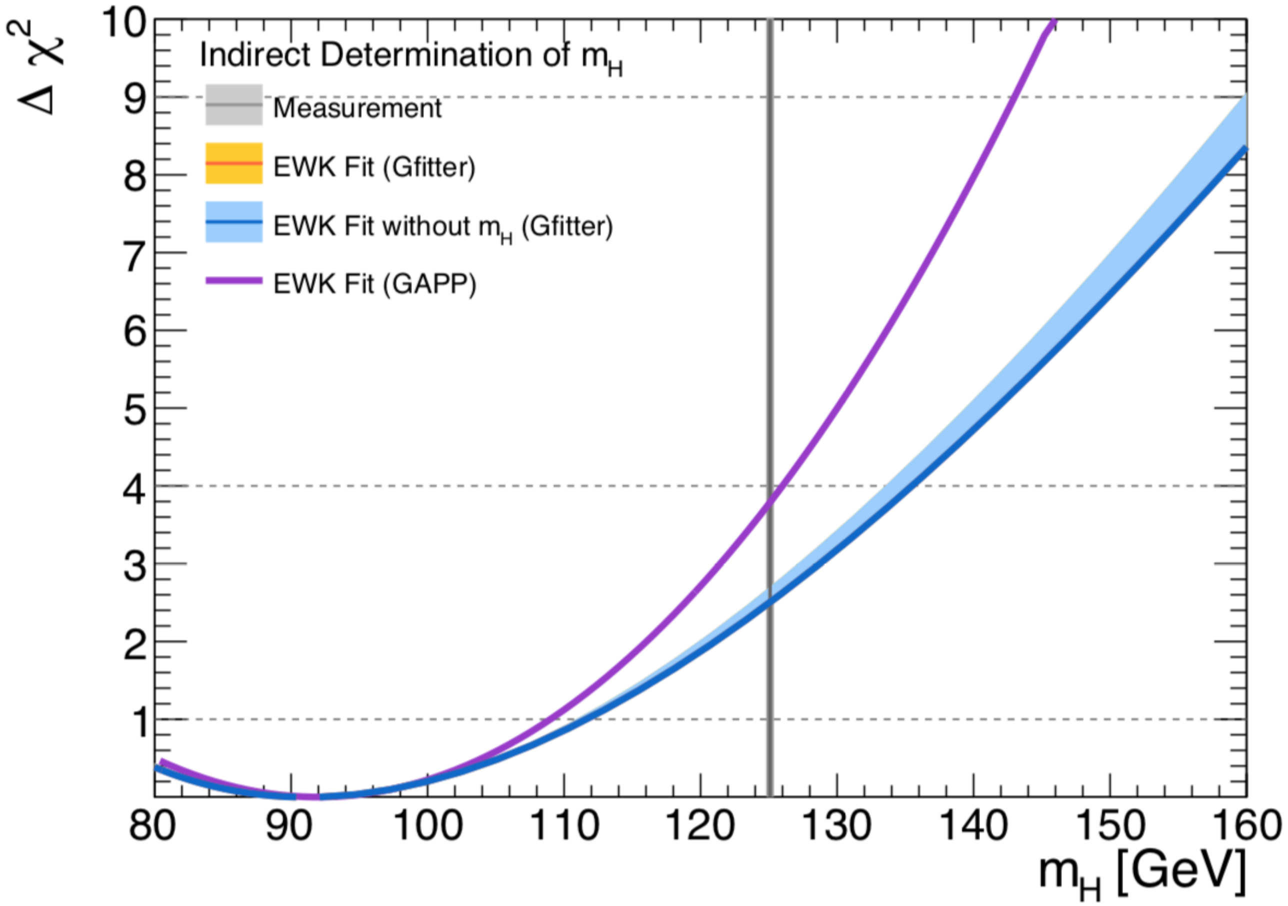


- Only the mass parameter of the Higgs enters the fit
  - have to assume that the "Higgs" is really the Standard Model Higgs boson
    - Coupling and JPC measurement look pretty much like a SM-Higgs
- Inofficial combination of latest measurements, yield
  - M_H = 125.10 ± 0.14 GeV
  - with a χ2/n.d.f. = 8.9/6
- Change of precision from 0.1 GeV to 1.0 GeV, changes the χ^2 of the fit by only 0.005

Interpretation in the context of the Electroweak Fit

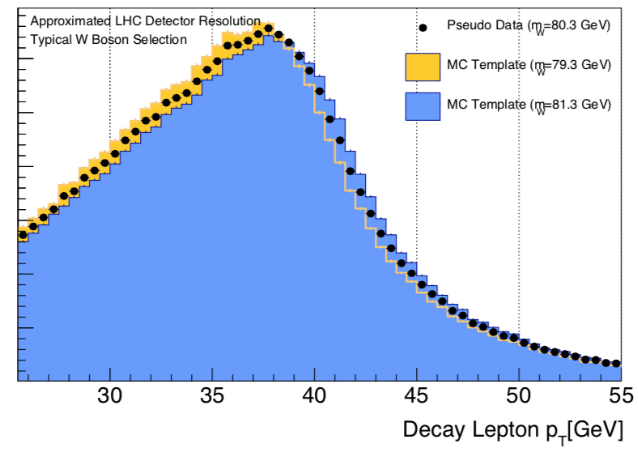
- Indirect prediction of the Higgs boson mass is
  - M_H=92.0±20 GeV

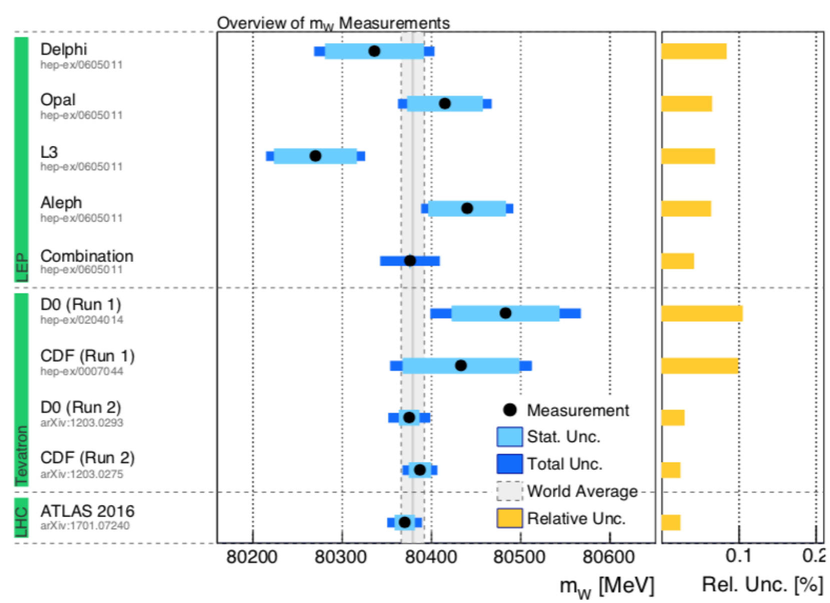
- Perfect knowledge of m_W and/or $\sin^2\theta_{eff}$ would reduce uncertainty to 10 GeV



Experimental Status: W Boson Mass

- Same basic measurement principle at Tevatron and LHC
  - Using a template fit approach to the decay lepton kinematics
- Uncertainties dominated by model-uncertainties
  - PDFs, angular coefficients
  - Transverse momentum spectrum of the W boson
- Tevatron and LHC results currently at similar level of precision
  - Significant improvements expected from new runs at LHC and and further refinements (also “new” data) from the Tevatron

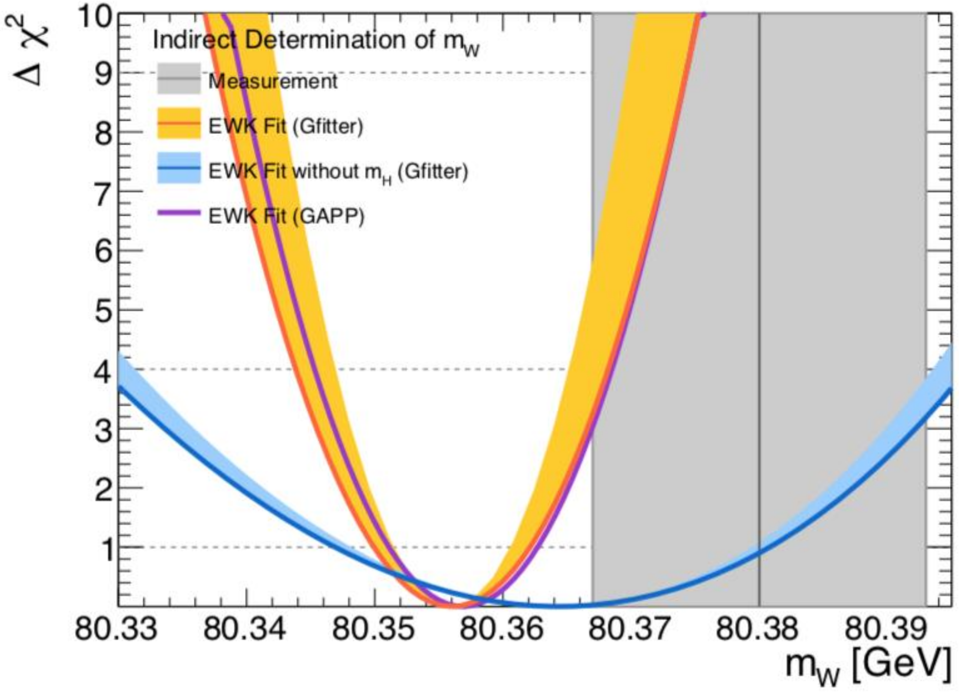




Interpretation in the context of the Electroweak Fit

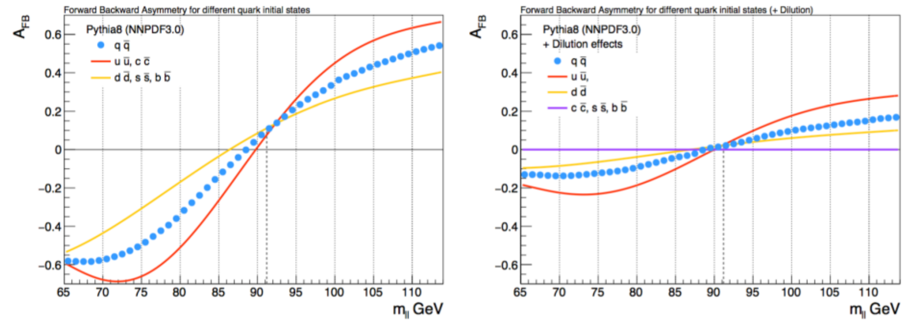
- Unofficial combination yields a value of
  - M_W = 80380±13 MeV, with a p-value of 0.74
  - Several PDF correlation scenarios tested and results are stable

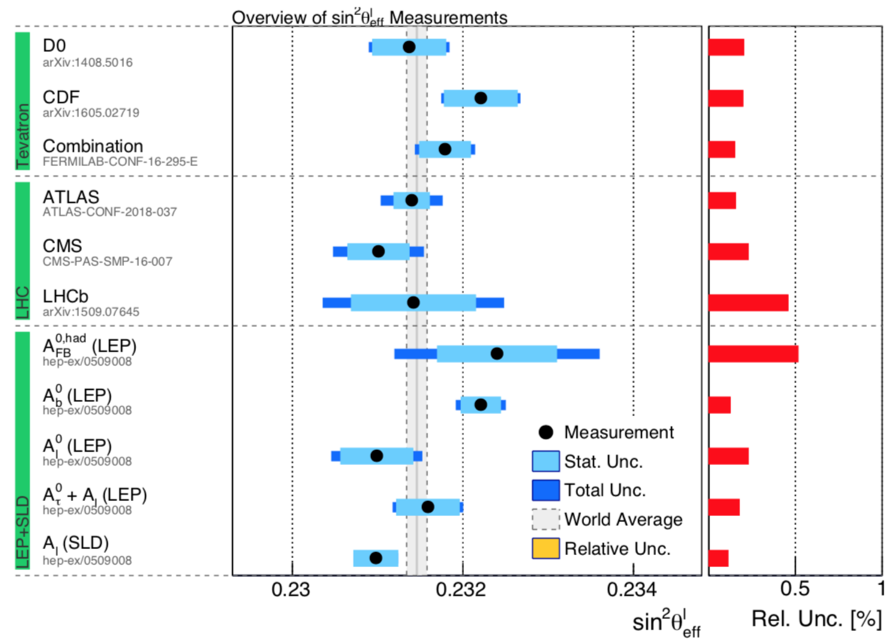
- Predicted value of the electroweak fit
  - M_W = 80356±6 MeV
  - 1.6σ "tension" with the SM prediction
  - Dominated by m_{top} and m_Z uncertainty, contributing 2.6 and 2.5 MeV
  - Without m_H: M_W=80364±17MeV



Experimental Status: Weak Mixing Angle

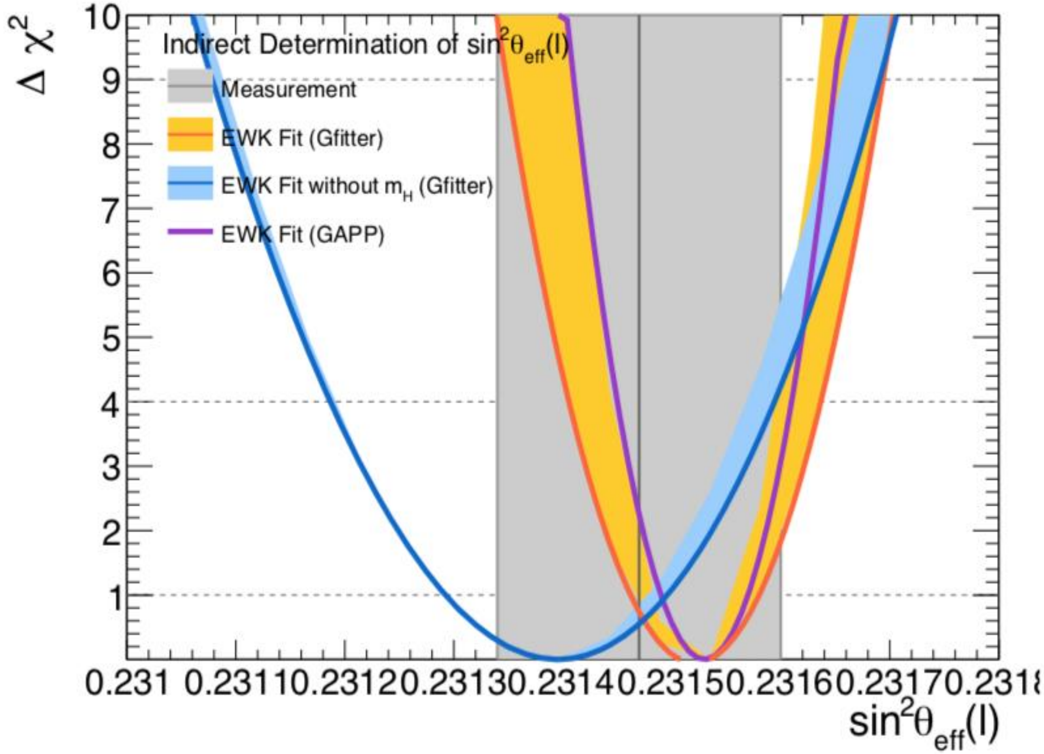
- Discrepancy of LEP and SLD measurement on $\sin^2\theta_W$ triggered quite some interest in recent years
- Problem at Hadron colliders: Do not know incoming fermion direction on an event-by-event basis
  - Problem reduced at Tevatron, very prominent at LHC
- Use (variation) of template fit approaches to extract $\sin^2\theta_W$
- Combination at hadron colliders
  - $\sin^2\theta_{eff} = 0.23140 \pm 0.00023$
  - Level of LEP and SLD
  - Disagreement between LEP and SLD might be just a statistical effect





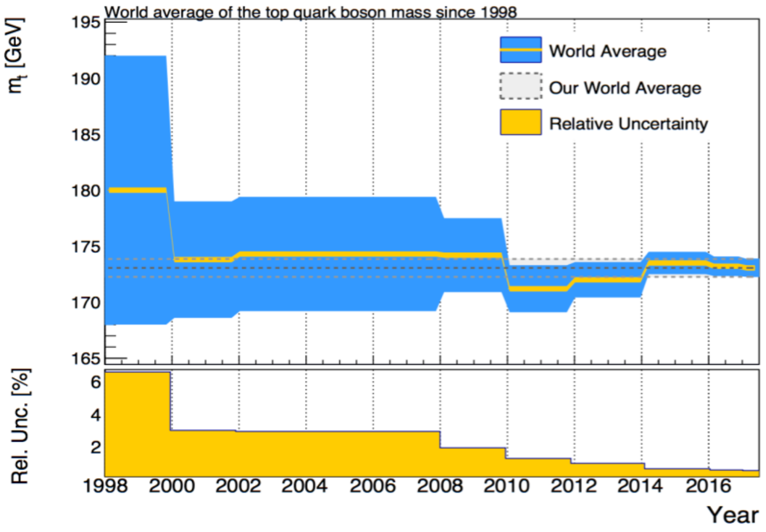
Interpretation in the context of the Electroweak Fit

- Indirect Determination
  - $\sin^2\theta_{eff}$ = 0.23151±0.00006
  - Without m_H: 0.23140+0.00010
- World average
  - $\sin^2\theta_{eff}$ = 0.23151±0.00014
- Hadron Collider average
  - $\sin^2\theta_{eff}$ = 0.23140 ± 0.00023
  - Maybe this can improved further by a factor of two when including new PDF-constraining measurements and a combination of all LHC experiments (e.g. also LHCb)

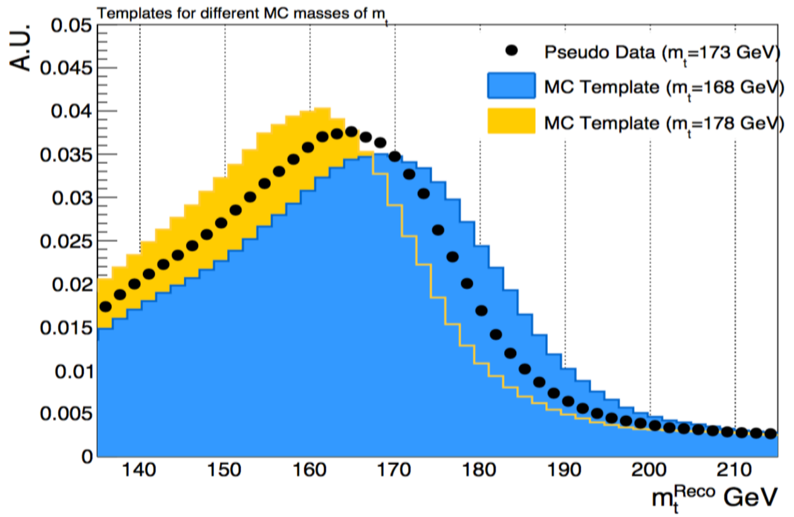


Experimental Status: Top Quark Mass (1/2)

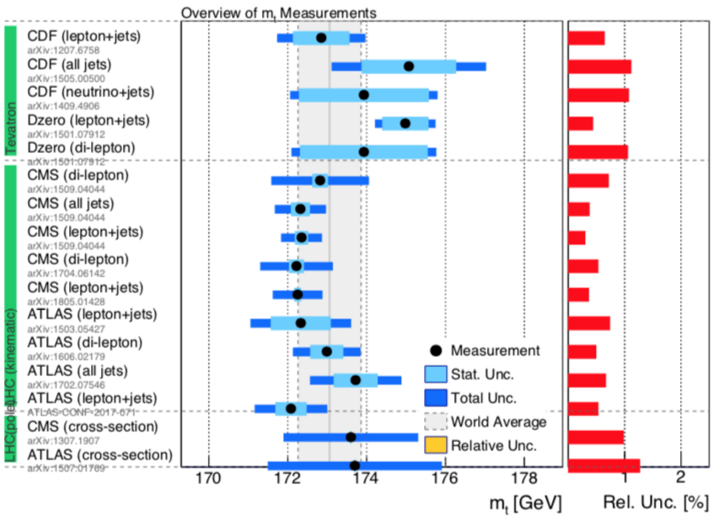
- Several approaches to measure the kinematic top-quark mass (template-method, matrix-element method, ...)
  - Most precise measurements performed in the lepton+jets channel
  - Significant differences in assigned model uncertainties of different experiments;



- 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)



Experimental Status: Top Quark Mass (2/2)



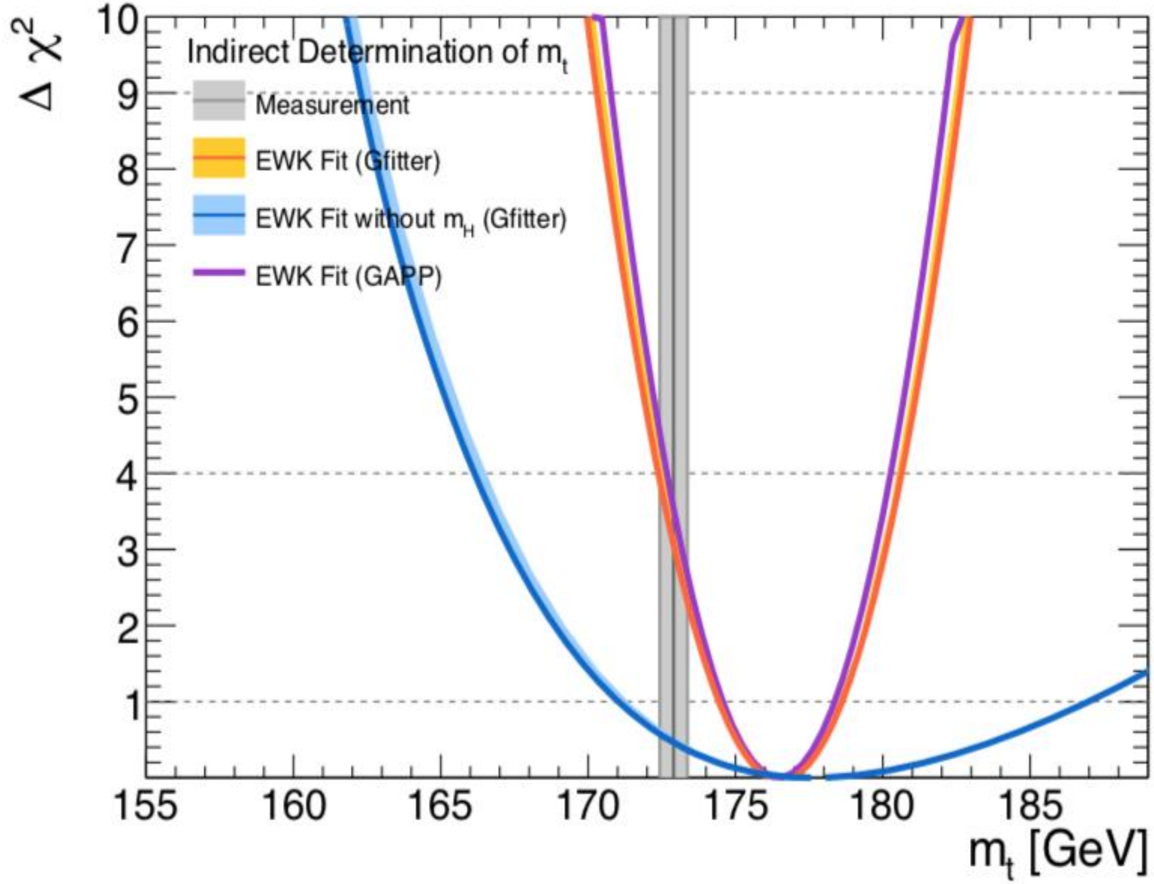
Experiment	Channel	Method	Value [GeV]	Stat. Unc. [GeV]	Sys. Unc. [GeV]	Total Unc. [GeV]	Jet Unc. [GeV]	Exp. Unc. [GeV]	Model Unc. [GeV]	UE + Color [GeV]	Had. Unc. [GeV]
CDF	l+jets	Template	172.85	0.71	0.85	1.11	0.55	0.60	0.1	0.22	0.57
CDF	ν+jets	Template	173.93	1.64	0.87	1.86	0.48	0.56	0.32	0.33	0.36
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

- No official combination of latest ATLAS and Tevatron results
  - Correlations are estimated from previous official combinations
  - 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 ± 0.47 GeV.with a p-value of 4.1%
- Recent ATLAS of m_{pole} measurement (ATLAS-CONF-2017-044): m_t^{pole} = 173.2±0.9±0.8±1.2
  - Significant future improvements expected with differential (N^X)LO calculations

Interpretation in the context of the Electroweak Fit

- 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: without m_H we get m_{top}=177.6±8 GeV

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

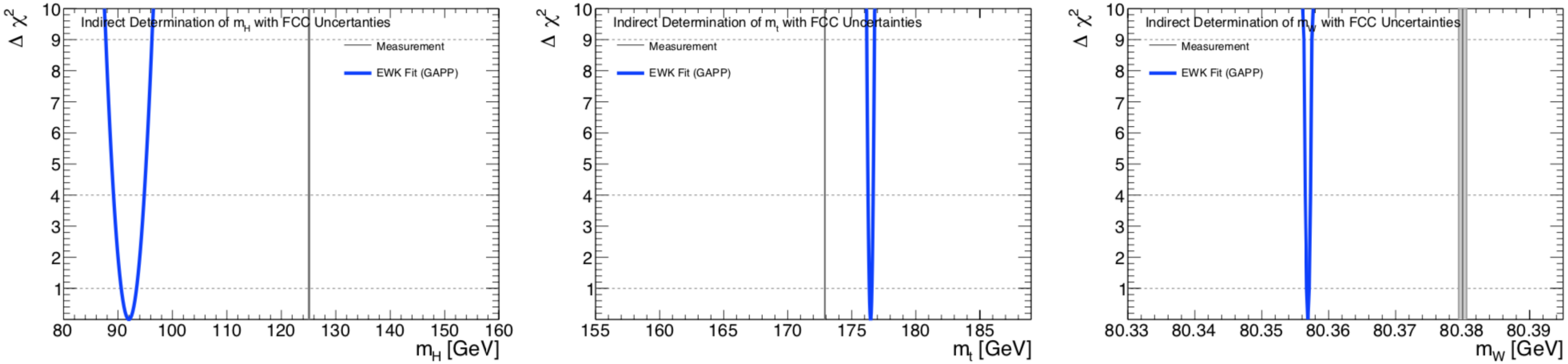


Uncertainties at the end of the LHC and FCCee

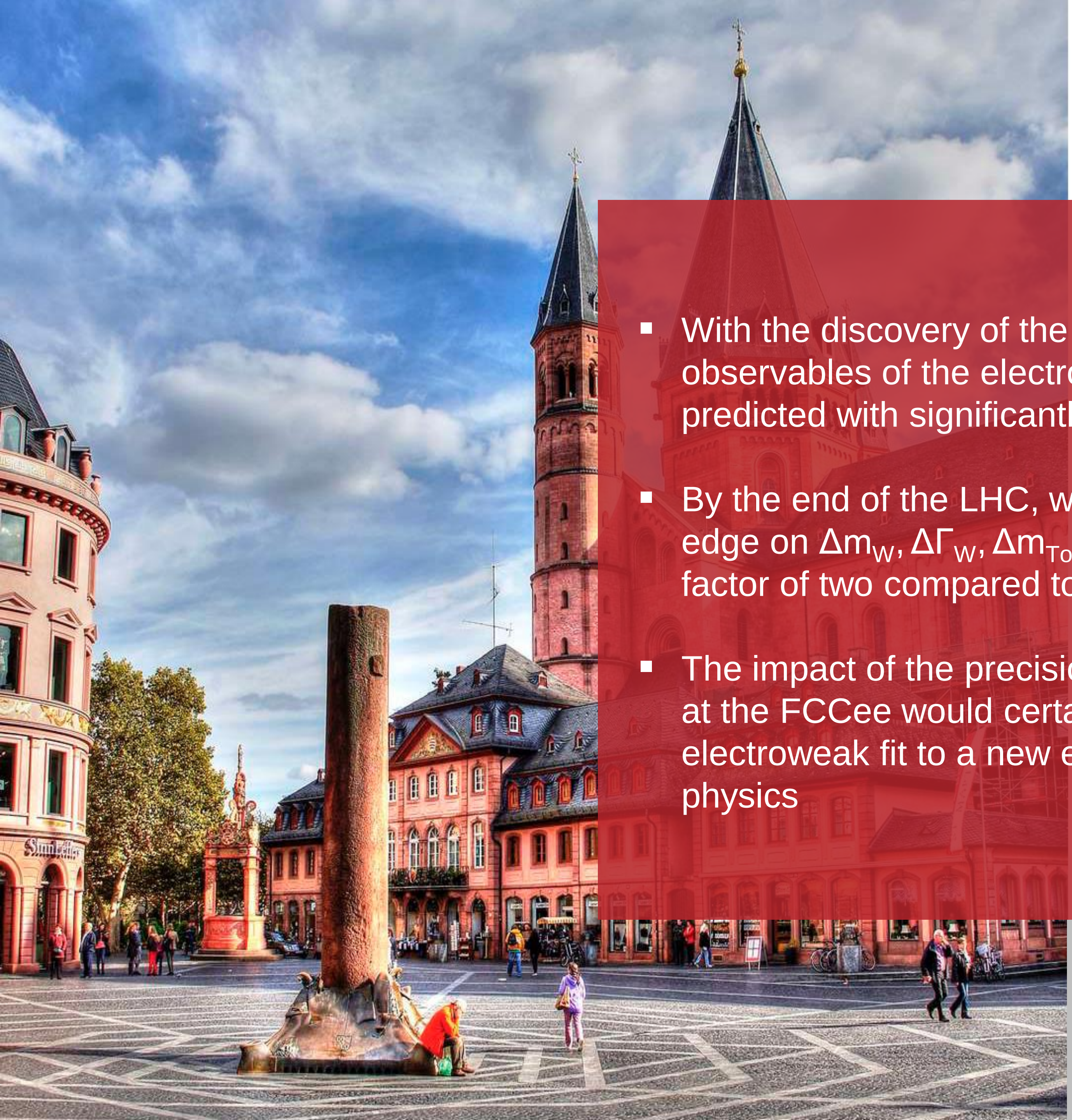
parameter	current value	FCC-ee unc.-target	parameter	current value	FCC-ee unc-target
M_H	125.09 ± 0.15 GeV	± 0.1 GeV	M_Z	91.1875 ± 0.0021 GeV	< 0.1 MeV
M_W	80.380 ± 0.013 GeV	± 0.6 MeV	Γ_Z	2.4952 ± 0.0023 GeV	< 0.1 MeV
Γ_W	2.085 ± 0.042 GeV	± 1.0 MeV	σ^0_{had}	41.540 ± 0.037 nb	0.004 nb
m_{top}	172.90 ± 0.47 GeV	± 15 MeV	R_b	0.21629 ± 0.00066	< 0.00006
$\Delta\alpha_{had}[\times 10^{-5}]$	2758 ± 10	± 2	$A^{FB}_{LR}(b)$	0.0992 ± 0.0016	± 0.0001

- By the end of the LHC, we might have (take it as „somehow educated guesses“)
  - $\Delta m_H \approx 100$ MeV
  - $\Delta m_W \approx 8$ MeV
  - $\Delta \Gamma_W \approx 20$ MeV
  - $\Delta m_{Top} \approx$ 200-500 MeV (as pole-mass via cross-sections personal guess of MS)
  - $\Delta \sin^2\Theta_W \approx 0.00006$
- Dramatic improvements expected for all relevant observables at the LCCee
  - Often my more than a order of magnitude

Impact on the global electroweak Fit



- 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!
- Similar studies for other future collider options previously done
  - e.g. by Gfitter Eur. Phys. J., C74:3046, 2014



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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