Global Electroweak Fits: Where do we stand?

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(Summarized from the materials from the GFitter group and Jens Erler[1])

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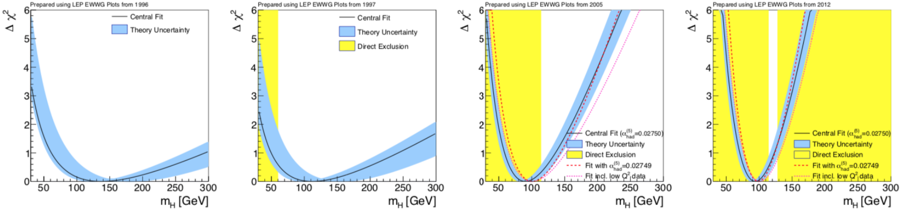
February 24th 2023

Setting the Stage



- The global electroweak fit – A very powerful idea
  (Enable predictions of M_H before its discovery)
  - Measure different observables
  - Consider the theoretical constrains
- LEP saga hasn't been over yet
  (Possible underestimation of its luminosity)[1]

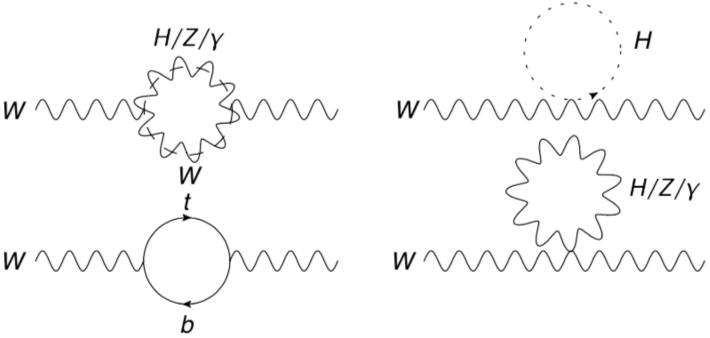
$$
\begin{aligned}
M_W^2 &= \frac{M_Z^2}{2}\left(1+\sqrt{\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right) \\
\sin^2\theta_{\text{eff}}^f &= \kappa_f \sin^2\theta_W \\
g_V^f &= \sqrt{\rho^f}(I_3^f - 2Q^f \sin^2\theta_{\text{eff}}^f) \\
g_A^f &= \sqrt{\rho^f}\, I_3^f
\end{aligned} \quad (1)
$$

- This talk: review where we currently stand after the Higgs[2] and where we might stand in 2035

[1] Physics Letters B 800 (2020) 135068
[2] Progress in Particle and Nuclear Physics 106 (2019) 68-119

Where do we stand with the theory? – M_W

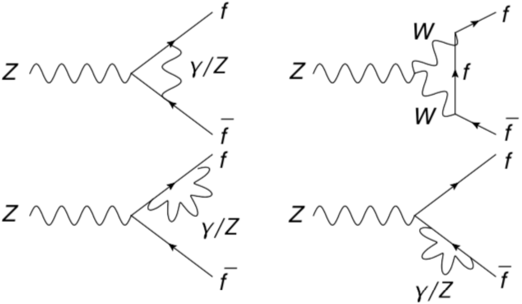
- In the 1980s
  - Full one-loop calculation
  - Mixed EQ/QCD corrections: $\mathcal{O}(\alpha\alpha_s m_t^2)$, $\mathcal{O}(\alpha\alpha_s)$
- In 2015
  - Full $\mathcal{O}(\alpha^2)$ results



- Enhanced three-loop contributions
  - Impact from $\mathcal{O}(\alpha\alpha_s^2 m_t^2)$: $\Delta M_W \simeq -10$ MeV
  - Almost entirely due to the use of the pole mass definition
  - Amount to less than 3 MeV if the definition based on MS scheme is employed

Where do we stand with the theory? – $\sin^2\theta_W$

- Most important radiative corrections are related to those in M_W
  - $\Delta\alpha$: the scale dependence of α (QED running)
  - $\Delta\rho$: the impact on the ratio of neutral-current to charged-current interaction strengths
- For $\sin^2\theta_W$, two-loop $\mathcal{O}(\alpha^2)$ fermionic and bosonic corrections are fully known since 2018[1]



- $\sin^2\theta_{\text{eff}}^{u,d,s,c}$ are slightly different from $\sin^2\theta_{\text{eff}}^{\ell}$
  - Flavor dependent correction, $\mathcal{O}(\alpha\alpha_s)$, is not factorized in the total Z width (need to be include)
  - For b quark, additional $\mathcal{O}(\alpha m_t^2)$ and $\mathcal{O}(\alpha^2 m_t^4)$ enhanced effects

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[1] Physics Letters B, 783 (2018) 86-94

Unknown higher order corrections

- Theoretical uncertainty due to the unknown higher order electroweak corrections arises from the self-energies of the boson
  - Vector Corrections
  - Box Corrections
  - Further non-factorizable corrections
    (Those cannot be expressed into the form of Enhanced Born Approximation of IBA)

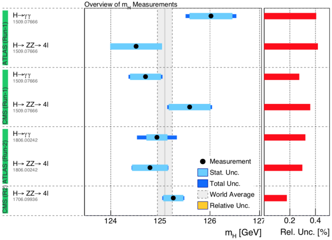
	$\Delta T = \pm 0.0073$	$\Delta S = \pm 0.0034$	$\Delta U = \pm 0.0051$	$\delta_{\text{PQCD/EW}}$	BW	total
M_W	± 3.3 MeV	∓ 0.6 MeV	± 1.8 MeV	—	—	3.8 MeV
$\sin^2\theta^l_{\text{eff}}$	$\mp 1.9 \times 10^{-5}$	$\pm 1.2 \times 10^{-5}$	0	—	—	2.2×10^{-5}
$\hat{\rho}$	$\pm 5.9 \times 10^{-5}$	0	$\pm 4.4 \times 10^{-5}$	—	—	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

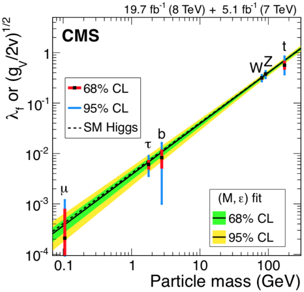
Table 2.1: Uncertainties from missing higher-order electroweak corrections to precision observables. The parameter $\hat{\rho}$ is a high-energy variant [128] of the parameter $\rho = 1 + \alpha T$. The uncertainties within each column are fully correlated, while those between columns are treated as independent and uncorrelated.

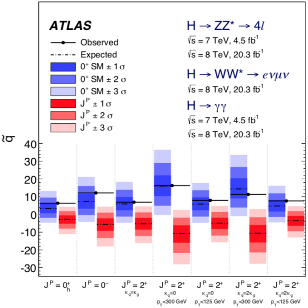
Experimental Status – M_H

- Only M_H considered in the fitting
  - Assume the "Higgs" is really the SM Higgs
    (Coupling and JPC measurement look pretty much like a SM Higgs)

- Inofficial combination of the latest measurements
  (Latest CMS measurement in 09.2019 not included)
  - $M_H = 125.10 \pm 0.14$ GeV
  - $\chi^2/ndf = 8.9/6$
- χ^2 of the fit not sensitive to its precision
  (Change σ_{M_H} to 1 GeV, the χ^2 changed by 5×10^{-3})

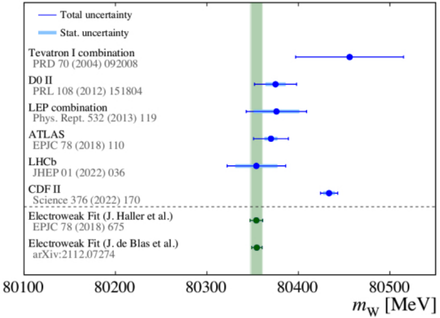






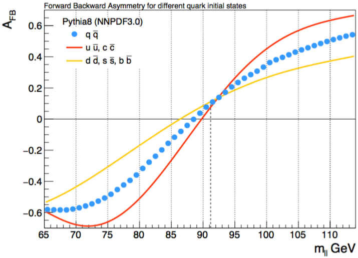
- Discrepancy between the recent CDF measurements and other measurements
  - Precision at 10 MeV level
    (Close to the uncertainty of the prediction)
  - Urgently need a measurement from a single experiment with a similar precision
- An on-going combination with Tevatron and LHC measurements
  (Quantify the discrepancy, $> 3\sigma$)

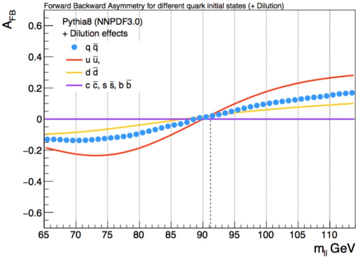
- M_W can be extracted from m_T, p_T^ℓ and E_T^{Miss} distributions
  - Tevatron: m_T has the most sensitivity
  - LHC: p_T^ℓ has the most sensitivity
    (The resolution of the hadronic recoil)
- On-going ATLAS measurements
  (With low-μ dataset)
  - Similar precision as the recent CDF results expected from ATLAS
    (7 TeV Reanalysis + low-*mu*)



- Assuming a combined value: $M_W = 80380 \pm 13$ MeV
  (Without the recent CDF measurement)

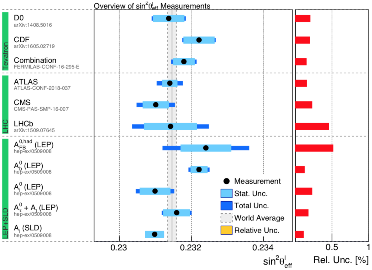
- Discrepancy between LEP and SLD measurements on $\sin^2\theta_W$
  - A precision similar to LEP achieved in Tevatron



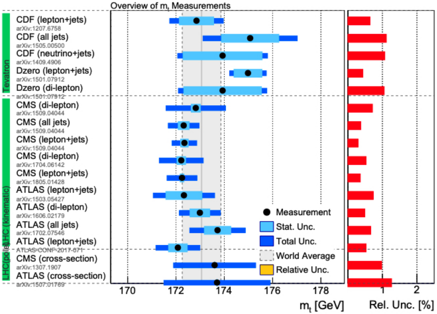


- In the future, a direct comparison (Between the measurement and the prediction)
  - Sensitivity reduction due to the dilution effect (Direction of the incoming fermion unknown)

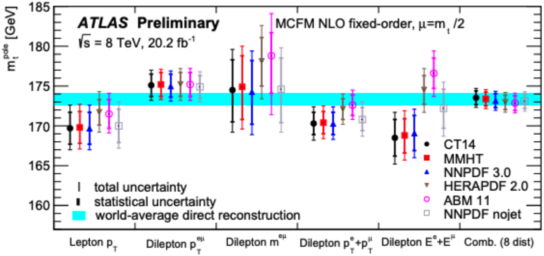
- Combination at hadron colliders
  - $\sin^2\theta^{\ell}_{\text{eff}} = 0.23140 \pm 0.00023$
  - Precision at the level of LEP and SLD

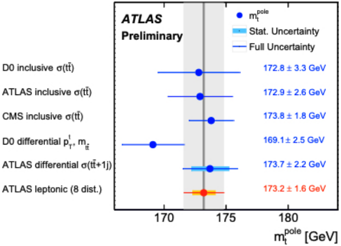


- The electroweak fit needs pole mass of top-quark, m_{top}^{pole}, as input (m_{top} measured at Tevatron and LHC is a MC parameter)
- Measurements of the kinematic top-quark mass, m_{top}^{MC}
  - Several different approaches to measure the kinematic top-quark mass (Template, Matrix-element, Ideogram, AMWT)
  - Most precise measurements from $\ell +$ jets channel (A good signal to background ratio and a fully reconstructed event kinematics)
  - Additional uncertainty around 400 MeV since $m_{top}^{MC} \neq m_{top}^{pole}$ (Which is caused by top quark self-energy corrections)
  - Model uncertainties significantly differ between experiments
- Combine the measurements from D0, CDF, ATLAS and CMS
  - $m_{top}^{MC} = 172.90 \pm 0.35$ GeV (p-value $= 4.1\%$, 3σ between D0 and others)
  - Additional 0.32 GeV theory uncertainty
  - $m_{top}^{pole} = 172.90 \pm 0.47$ GeV



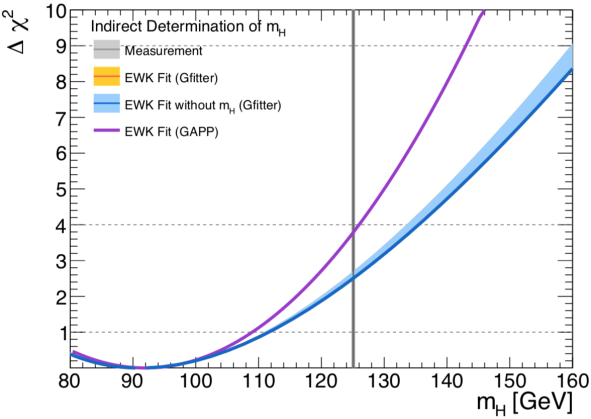
- Measurement of the pole mass of top-quark, $m_{\text{top}}^{\text{pole}}$
  - The mass dependence of the $t\bar{t}$ production cross section
  - ATLAS: $m_{\text{top}}^{\text{pole}} = 173.2 \pm 1.6$ GeV
  - CMS: $m_{\text{top}}^{\text{pole}} = 173.6 \pm 1.7$ GeV
  - Need differential NNLO calculations to reduce the theoretical uncertainty





Interpretation in the context of the electroweak fit – M_H

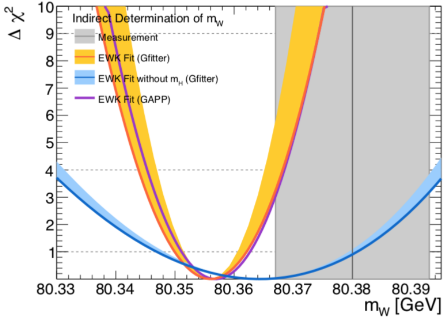
- Inofficial combination: $M_H = 125.10 \pm 0.14$ GeV
- Predictions from the electroweak fit: $M_H = 92 \pm 20$ GeV $\rightarrow 1.66\sigma$
(To reduce the uncertainty to 10 GeV, with a better precision of M_W or $\sin^2\theta_{\text{eff}}$)

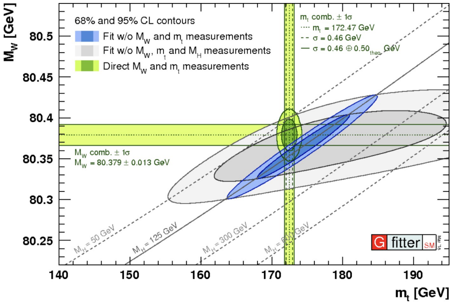


Interpretation in the context of the electroweak fit – M_W

- Assuming a combined value: $M_W = 80380 \pm 13$ MeV
  (Several PDF correction scenarios tested and results are stable, $p - value = 0.74$)

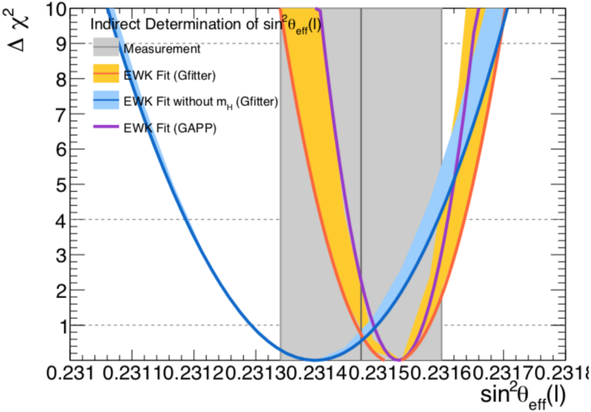
- Predictions from the electroweak fit
  - $M_W = 80356 \pm 6$ MeV $\rightarrow 1.67\sigma$
    (Dominated by the uncertainties due to m_{top} (2.6 MeV)and M_Z(2.5 MeV))
  - Without M_H: $M_W = 80364 \pm 17$ MeV $\rightarrow 0.75\sigma$





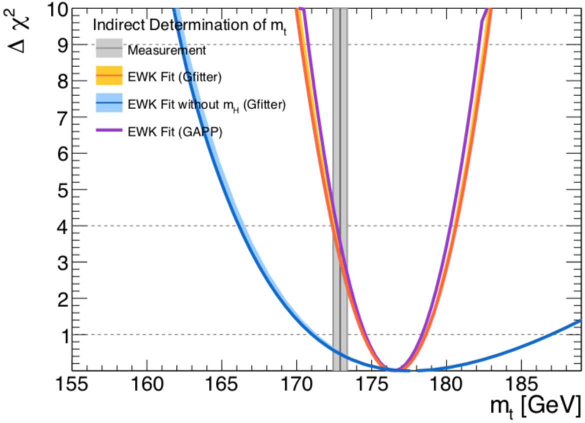
Interpretation in the context of the electroweak fit – $\sin^2\theta_W$

- World average: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23151 \pm 0.00014$
- Hadron collider average: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23140 \pm 0.00023$
  (Precision around 0.00011 by new PDF constraining measurements and a LHC combination)
- Predictions from the electroweak fit
  - $\sin^2\theta^{\ell}_{\text{eff}} = 0.23151 \pm 0.00006$
  - Without M_H: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23140 \pm 0.00010$

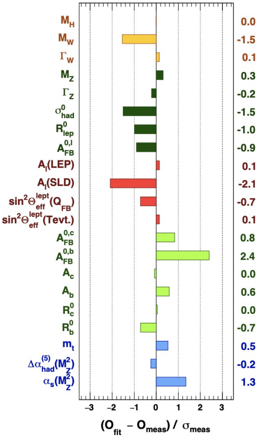


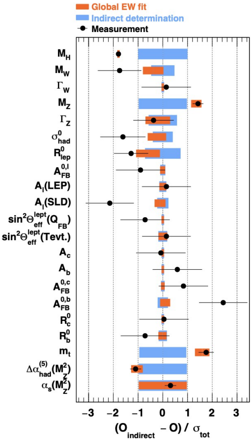
Interpretation in the context of the electroweak fit – m_{top}

- LHC-Tevatron Combination: $m_{top}^{pole} = 172.90 \pm 0.47$ GeV
  (Experimental uncertainty: 0.35 GeV, Theoretical uncertainty: 0.32 GeV)
- Predictions from the electroweak fit
  - $m_{top}^{pole} = 176.5 \pm 2.1$ GeV $\rightarrow 1.67\sigma$
    (Dominated by the uncertainty due to M_W(1.9 GeV))
  - Without M_H: $m_{top}^{pole} = 178 \pm 8$ GeV

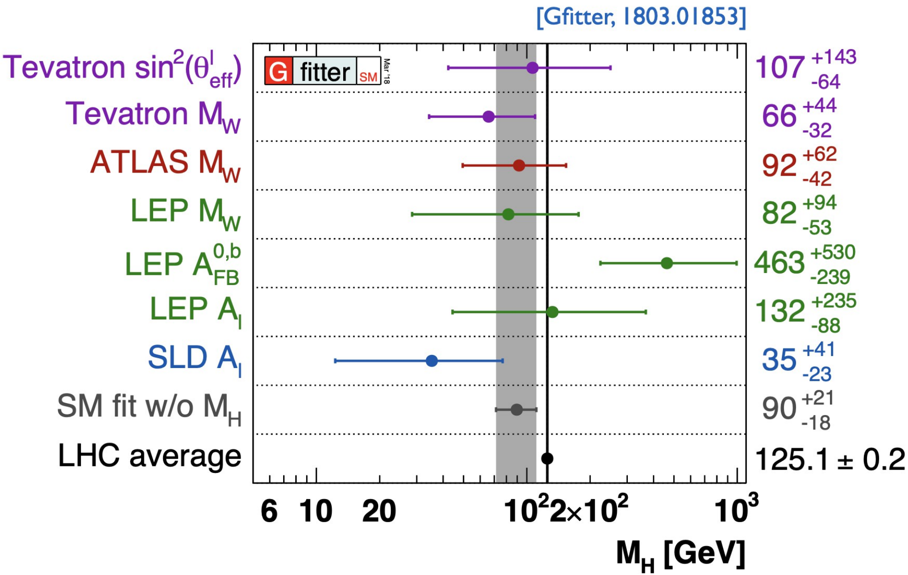


- Input parameters – slightly different from the previous result
  - $m_{top}^{pole} = 172.47 \pm 0.68$ GeV
  - $M_H = 125.1 \pm 0.2$ GeV
  - $M_W = 80379 \pm 13$ MeV
  - $\sin^2\theta^{\ell}_{eff} = 0.23148 \pm 0.00033$
- Conclusions stay the same
  - $\chi^2_{min} = 18.6,\ p - value = 0.23$
  - $\chi^2_{min}(\text{old } m_{texttop}) = 17.3$
  - $\chi^2_{min}(\text{old } m_W) = 19.3$





Predict M_H with GFitter



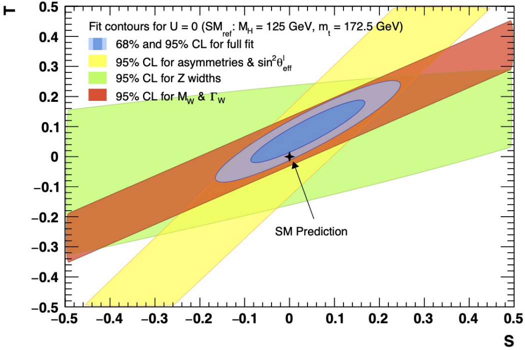
- Predictions from GFitter:

$$S = 0.04 \pm 0.11$$
$$T = 0.09 \pm 0.14$$
$$U = -0.02 \pm 0.11$$

- Predictions when U is fixed to 0:

$$S = 0.04 \pm 0.08$$
$$T = 0.08 \pm 0.07$$

  - Correlation: $\rho = 92\%$



Where will we stand in 10 years? – Prospects of the electroweak fit

- Future developments for the global electroweak fit
  - $\Delta\alpha_{\text{had}}^{(5)}$: Low energy data, especially $\pi^+\pi^-$, also pQCD/lattice
  - M_W: LHC measurements, Theory uncertainty of 4 MeV
  - m_t: Experimental progress and theoritical interpretations
  - $\sin^2\theta_{\text{eff}}$: Already close to LEP precision
  - A_{FB}^{0b}: $Z+b$ production at LHC[1]

- Extensions of the scalar sector
  - $B\to Xs\gamma$, $B_s\to\mu\mu$, $(g-2)_\mu$, $\cdots$, precision Higgs coupling measurements
  - Direct search in all possible final states

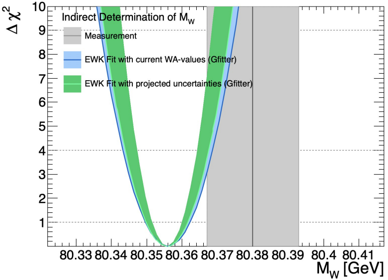
- General extension with the SMEFT
  - EWPO, LEP2 data, flavor data[2]
  - Differential Higgs measurements, also sensitive to Higgs self-coupling λ

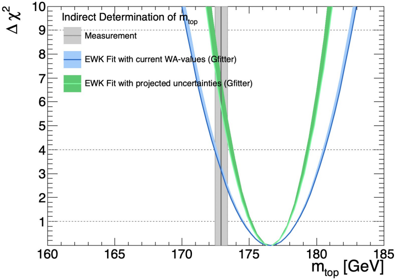
[1] Physics Letter B, 730 (2014) 149

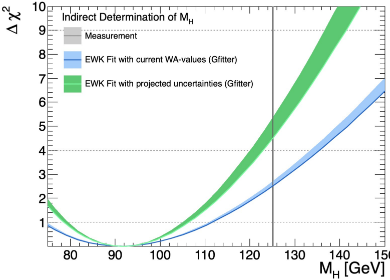
[2] Journal of High Energy Physics 06 (2018) 149

Where will we stand in 10 years? – With an ultimate precision at the LHC

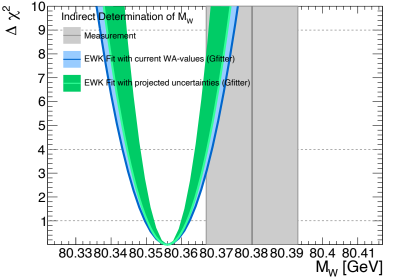
- By the end of the LHC, we might have:
  - $\Delta M_W \simeq 8$ MeV
  - $\Delta m_t \simeq 300$ MeV
  - $\Delta \sin^2 \theta_W \simeq 0.00012$
- Indirect determination:
  - $\Delta M_W \simeq 4$ MeV
  - $\Delta m_t \simeq 1.3$ GeV
  - $\Delta M_H \simeq 13$ GeV

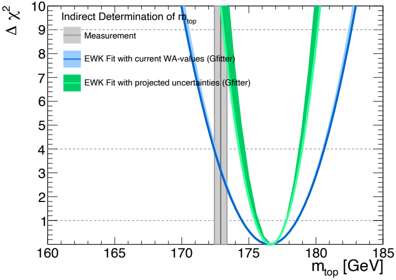


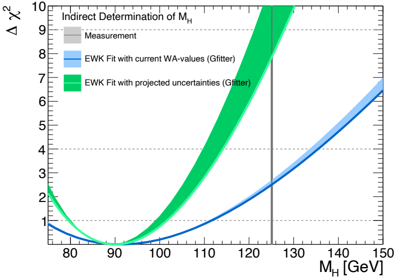




- By the end of the LHC, we might have:
  - $\Delta M_W \simeq 5$ MeV
  - $\Delta m_t \simeq 200$ MeV
  - $\Delta \sin^2 \theta_W \simeq 0.00008$
- Indirect determination:
  - $\Delta M_W \simeq 4$ MeV
  - $\Delta m_t \simeq 1.0$ GeV
  - $\Delta M_H \simeq 9$ GeV







- See the detailed study from GFitter in 2014[3]

[3] The European Physical Journal C 74 (2014) 3046

Summary

- With the precision measurement of M_H, several key observables of the electroweak sector could be predicted with significantly reduced uncertainties
- This makes the electroweak precision measurements in the future LHC more challenging
- By the end of the LHC, we expect to improve out edge on M_W, m_{top} and $\sin^2\theta^{\ell}_{\text{eff}}$ by a factor of 2 compared to the world average now
- A direct comparison between the measurements and the predictions would be possible, especially for M_W and $\sin^2\theta^{\ell}_{\text{eff}}$