Max Baak (CERN),
on behalf of the Gfitter group (*)

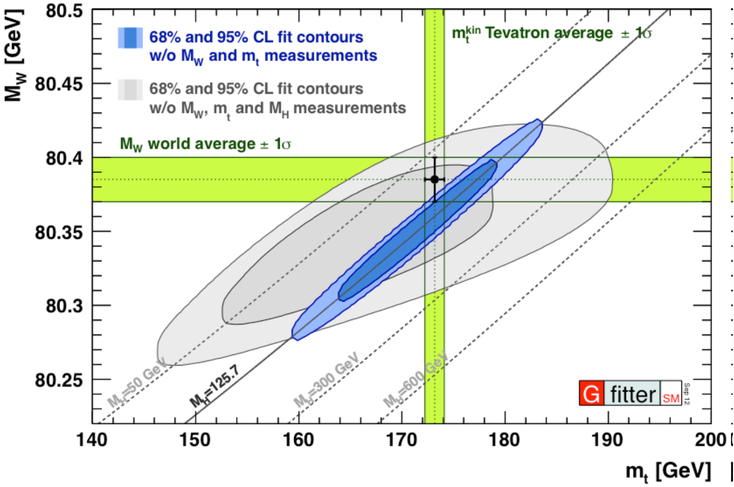
CERN seminar, Geneva,
23rd September, 2013

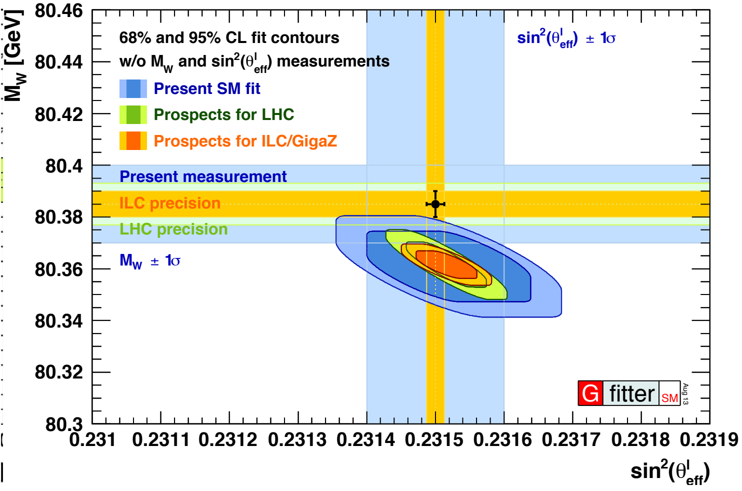
G fitter

http://cern.ch/Gfitter

EPJC 72, 2205 (2012), arXiv:1209.2716

After the Higgs: Status and Prospects of The ElectroWeak fit of the SM and Beyond





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(*) M. Baak, J. Cuth, J. Haller, A. Höcker, R. Kogler, K. Mönig, M. Schott, J. Stelzer

Outline

This presentation:

- Introduction to the Electroweak Fit
  - Inputs to the electroweak fit
- ✓ After the Higgs: predictions for key observables
- ✓ BSM: Modified Higgs couplings
- ✓ Prospects for LHC-300 and ILC/GigaZ
- Conclusion & Outlook

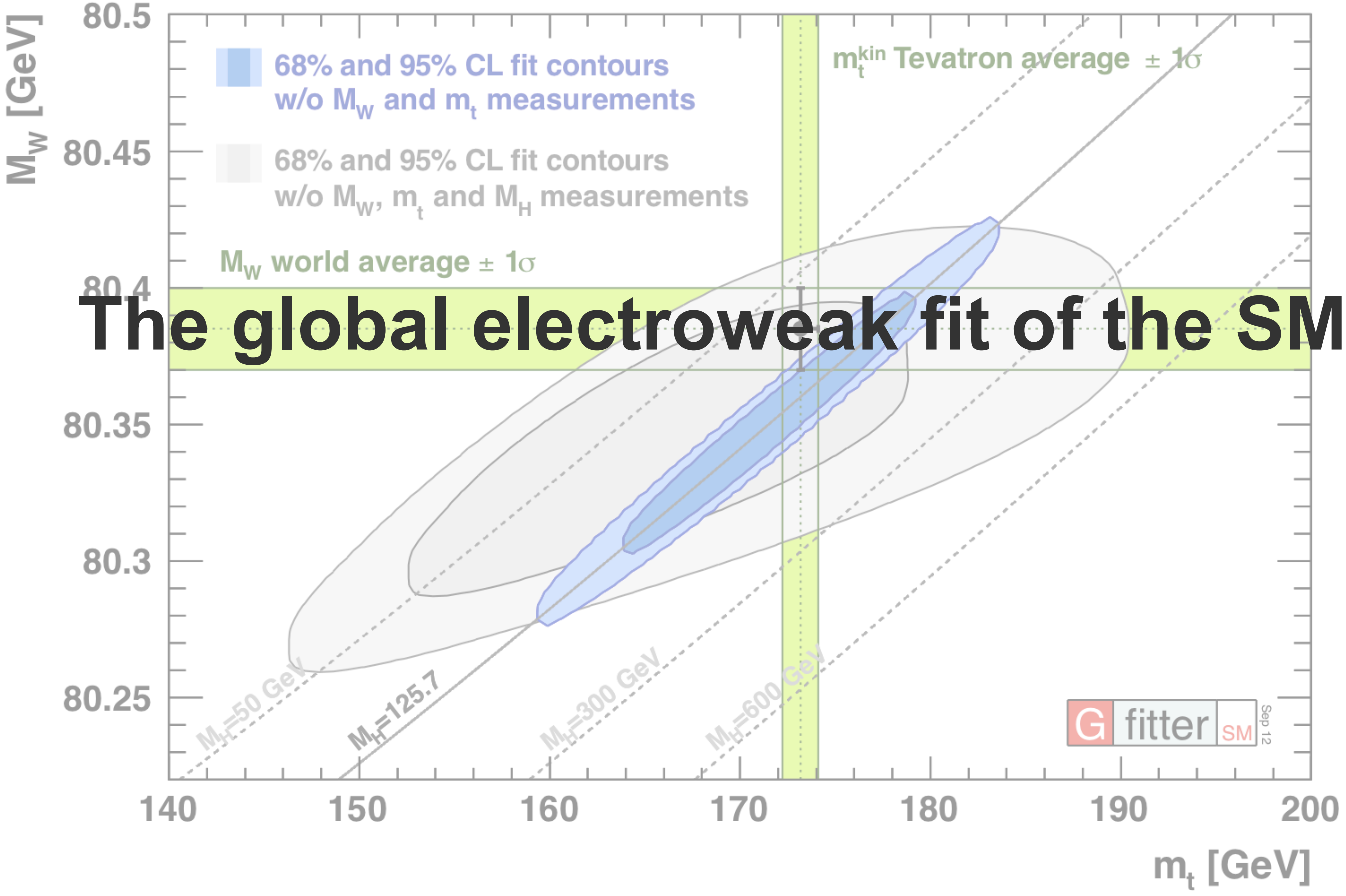
The Gfitter Project – Introduction

G fitter

A Generic Fitter Project
for HEP Model Testing

- Gfitter = state-of-the-art HEP model testing tool for LHC era
- Latest results always available at: http://cern.ch/Gfitter
  - *(Most) results of this presentation: EPJC 72, 2205 (2012)*
  - *LHC-300 and ILC/GigaZ prospects paper to appear on arXiv this week !*
- Gfitter software and features:
  - Modular, object-oriented C++, relying on ROOT, XML, python, etc.
  - Core package with data-handling, fitting, and statistics tools
  - Independent "plug-in" physics libraries: SM, 2HDM, multiple BSM models, ...

The global electroweak fit of the SM



Idea behind electroweak fits

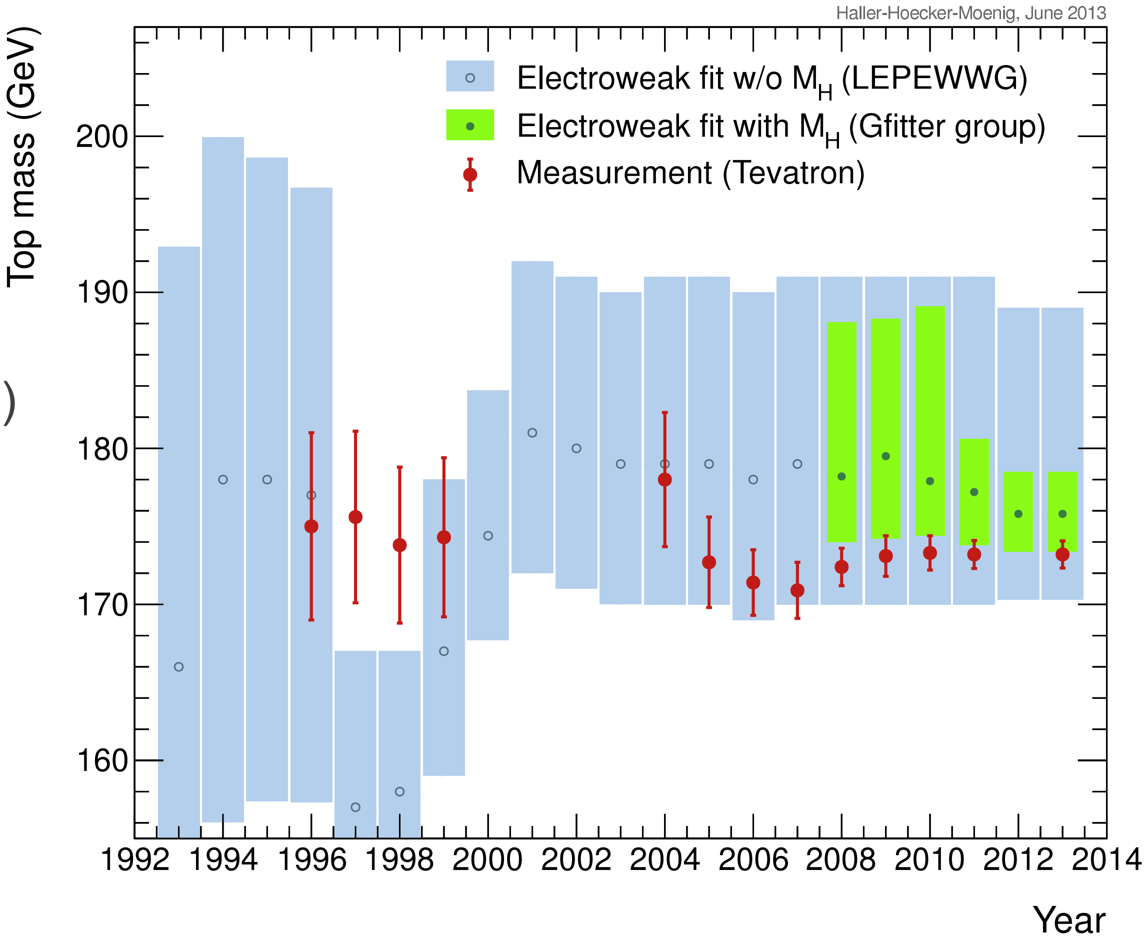
- ✓ Observables receive quantum loop corrections from ‘unseen’ virtual effects.

- ✓ If system is over-constrained, one can fit for unknown parameters or test the model’s self-consistency.

- ✓ If precision is better than typical loop factor (α≈1/137), test the model or try to obtain info on new physics in loops.
  - For example, in the past EW fits were used to predict the Higgs mass.

Global EW fits: a long history

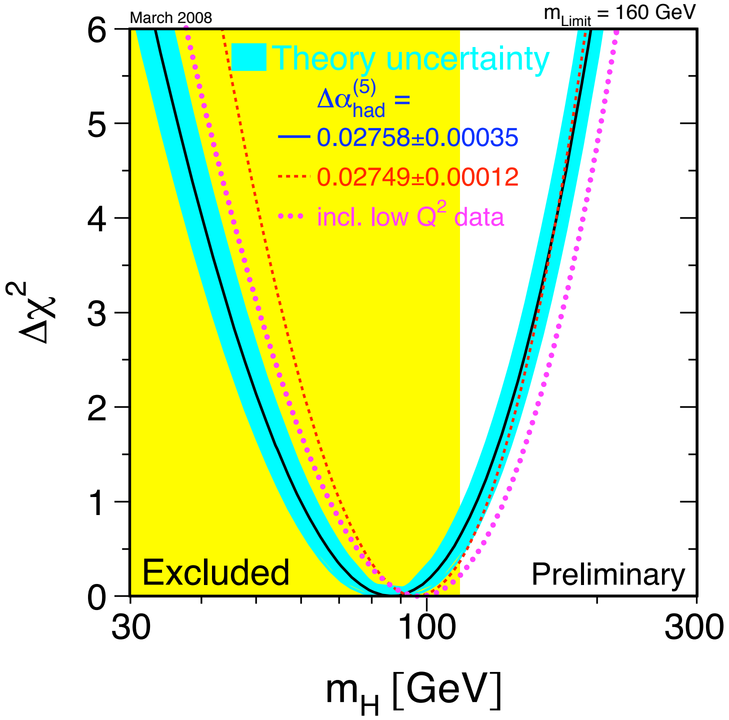
- Huge amount of pioneering work by many!
  - Needed to understand importance of loop corrections
    - Important observables (now) known at least at two-loop order, sometimes more.
  - High-precision Standard Model (SM) predictions and measurements required
    - First from LEP/SLC, then Tevatron, now LHC.



- Top mass predictions from loop effects available since ~1990.
  - Official LEPEW fit since 1993.
- The EW fits have always been able to predict the top mass correctly!

Global EW fits: many fit codes

- EW fits performed by many groups in past and present.
  - D. Bardinet al. (ZFITTER), G. Passarino et al. (TOPAZ0), LEPEW WG (M. Grünewald, K. Mönig et al.), J. Erler (GAP), Bayesian fit (M. Ciuchini, L. Silvestrini et al.), etc …
  - Important results obtained!
- Several groups pursuing global beyond-SM fits, especially SUSY.
- Global SM fits also used at lower energies [CKM-matrix].

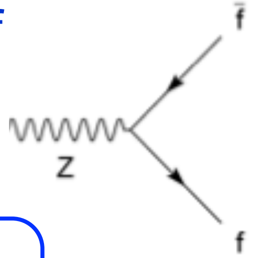


- Fits of the different groups agree very well.

- Some differences in treatment of theory errors, which just start to matter.
  - E.g. Gfitter uses “R-fit prescription”: theoretical uncertainties included in χ^2 with flat likelihood in allowed ranges
    - I.e. theoretical and experimental errors added linearly (= conservative).

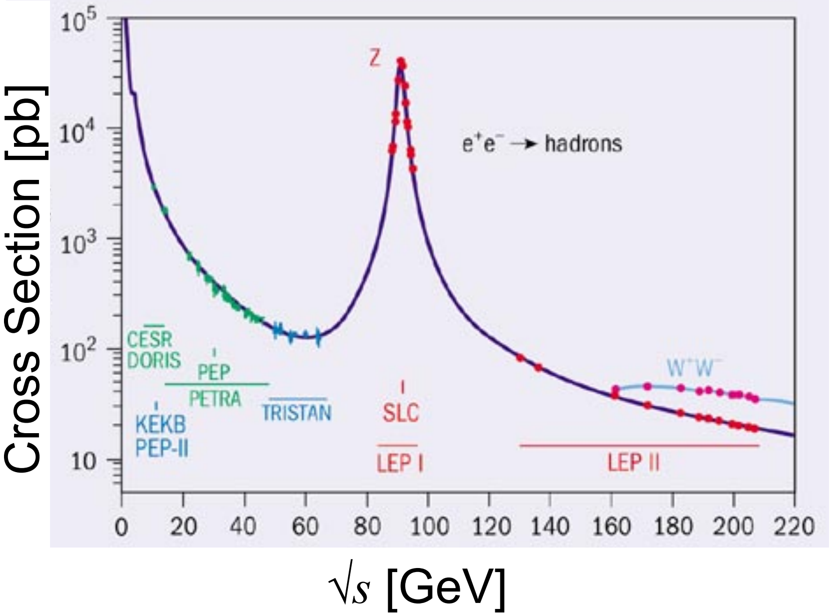
The predictive power of the SM

- As the Z boson couples to all fermions, it is ideal to measure & study both the electroweak and strong interactions.
- Tree level relations for Z→f$\bar{f}$
  - $i\bar{f}\gamma^{\mu}\left(g_{V,f}-g_{A,f}\gamma_5\right)fZ_{\mu}$



- Prediction EWSB at tree-level:

$$\boxed{\frac{M_W^2}{M_Z^2 c_W^2}=1}$$



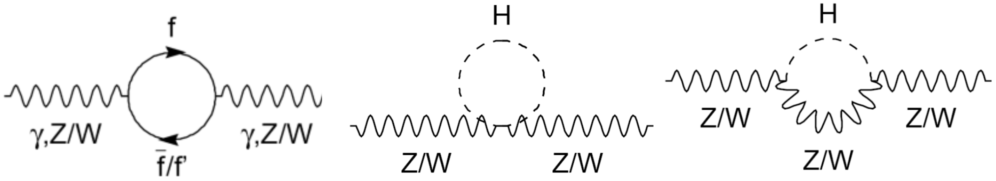
- The impact of loop corrections
  - Absorbed into EW form factors: ρ, κ, Δr
  - Effective couplings at the Z-pole
  - Quadraticly dependent on m_t, *logarithmic* dependence on M_H

$$g_{V,f}=\sqrt{\rho_Z^f}\left(I_3^f-2Q^f\sin^2\theta_{\mathrm{eff}}^f\right)$$

$$g_{A,f}=\sqrt{\rho_Z^f}I_3^f$$

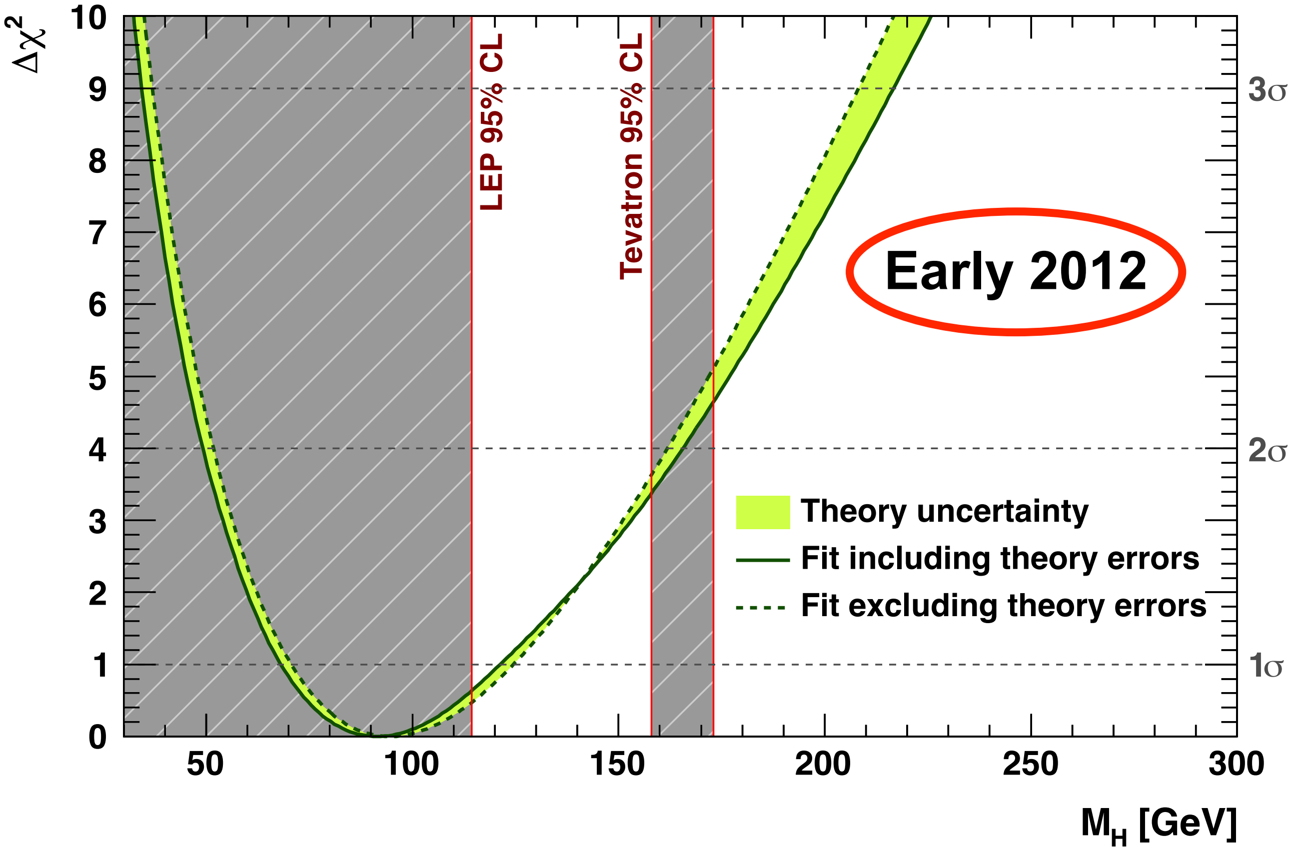
$$\sin^2\theta_{\mathrm{eff}}^f=\kappa_Z^f\sin^2\theta_W$$

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



Hunt for the Higgs

Gfitter group, EPJC 72, 2003 (2012)



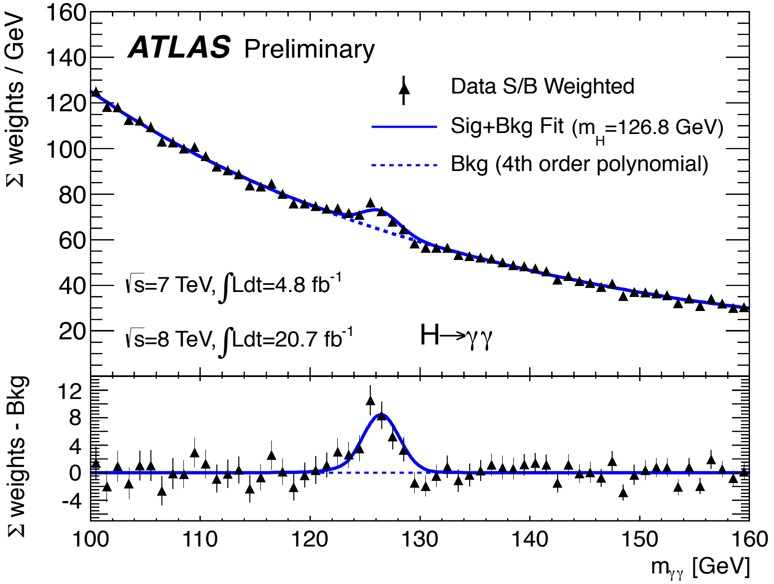
- M_H was last missing input parameter of the electroweak fit
- Indirect determination from EW fit (2012): $M_H = 96^{+31}_{-24}$ GeV
  - (Direct Higgs limits were of course also available in the EW fit.)

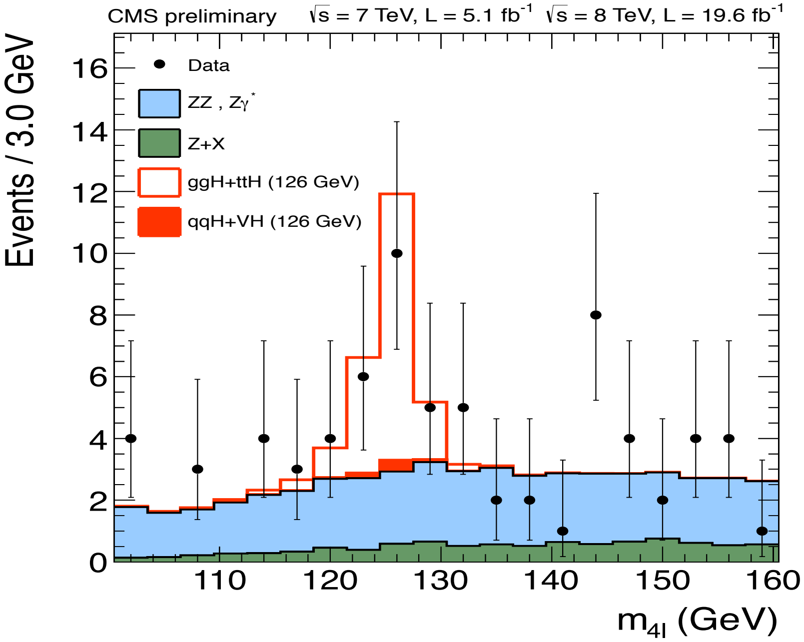
The SM fit with Gfitter, including the Higgs

- Discovery of Higgs-like boson at LHC
  - Cross section, production rate time branching ratios, spin, parity sofar compatible with SM Higgs boson.
- This talk: assume boson is SM Higgs.
- Use in EW fit: $M_H = 125.7 \pm 0.4$ GeV
  - ATLAS: $M_H = 126.0 \pm 0.4 \pm 0.4$ GeV
  - CMS: $M_H = 125.3 \pm 0.4 \pm 0.5$ GeV

    [arXiv:1207.7214, arXiv:1207.7235]
- Change in average between fully uncorrelated and fully correlated systematic uncertainties is minor:

  δM_H : 0.4 → 0.5 GeV





The SM fit with Gfitter, including the Higgs

Unique situation:

- *For first time SM is fully over-constrained.*
- *And for first time electroweak observables can be unambiguously predicted at loop level.*
- *Powerful predictions of key observables now possible, much better than w/o* M_H

Can now test for:

→ Self-consistency of SM

→ Possible contributions from BSM models

- The focus of this talk …

Measurements at the Z-pole (1/2)

- Total cross-section of $Z \to f\bar{f}$
  - Expressed in terms of partial decay width of initial and final width:

$$\boxed{\sigma^{Z}_{f\bar{f}} = \sigma^{0}_{f\bar{f}} \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \frac{1}{R_{\mathrm{QED}}} \quad \text{with} \quad \sigma^{0}_{f\bar{f}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}}$$

Corrected for QED radiation

  - Full width: $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{inv}}$
  - (Correlated set of measurements.)

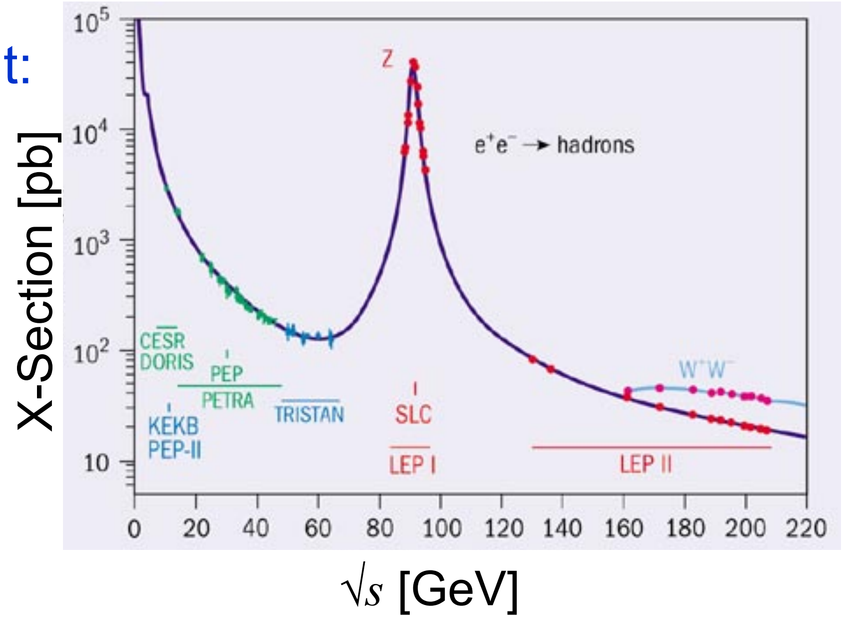
- Set of input (width) parameters to EW fit:
  - Z mass and width: $\boxed{M_Z}$, $\boxed{\Gamma_Z}$
  - Hadronic pole cross section:

$$\boxed{\sigma^0_{\mathrm{had}}} = 12\pi/M_Z^2 \cdot \Gamma_{ee}\Gamma_{\mathrm{had}}/\Gamma_Z^2$$

  - Three leptonic ratios (lepton univ.):

$$\boxed{R^0_\ell} = R^0_e = \Gamma_{\mathrm{had}}/\Gamma_{ee} \left(= R^0_\mu = R^0_\tau\right)$$

  - Hadronic-width ratios: $\boxed{R^0_b}$, $\boxed{R^0_c}$



Measurements at the Z-pole (2/2)

- Definition of Asymmetry
  - Distinguish vector and axial-vector couplings of the Z

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = \frac{2 g_{V,f}\, g_{A,f}}{g_{V,f}^2 + g_{A,f}^2}$$

  - Directly related to: $\sin^2\theta_{\mathrm{eff}}^{f\bar{f}} = \frac{1}{4Q_f}\left(1 + \mathcal{R}e\left(\frac{g_{V,f}}{g_{A,f}}\right)\right)$

- Observables
  - In case of no beam polarisation (LEP) use final state angular distribution to define *forward/backward asymmetry:*

$$A_{FB}^f = \frac{N_F^f - N_B^f}{N_F^f + N_B^f} \qquad A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

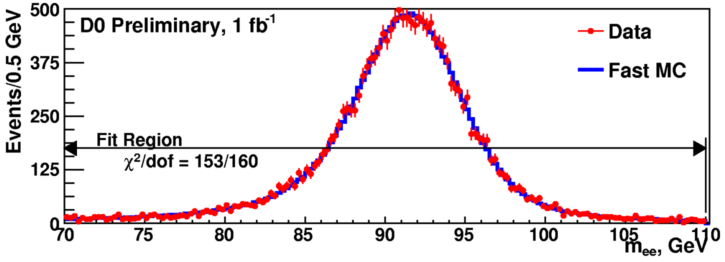
  - Polarised beams (SLC), define *left/right asymmetry:*

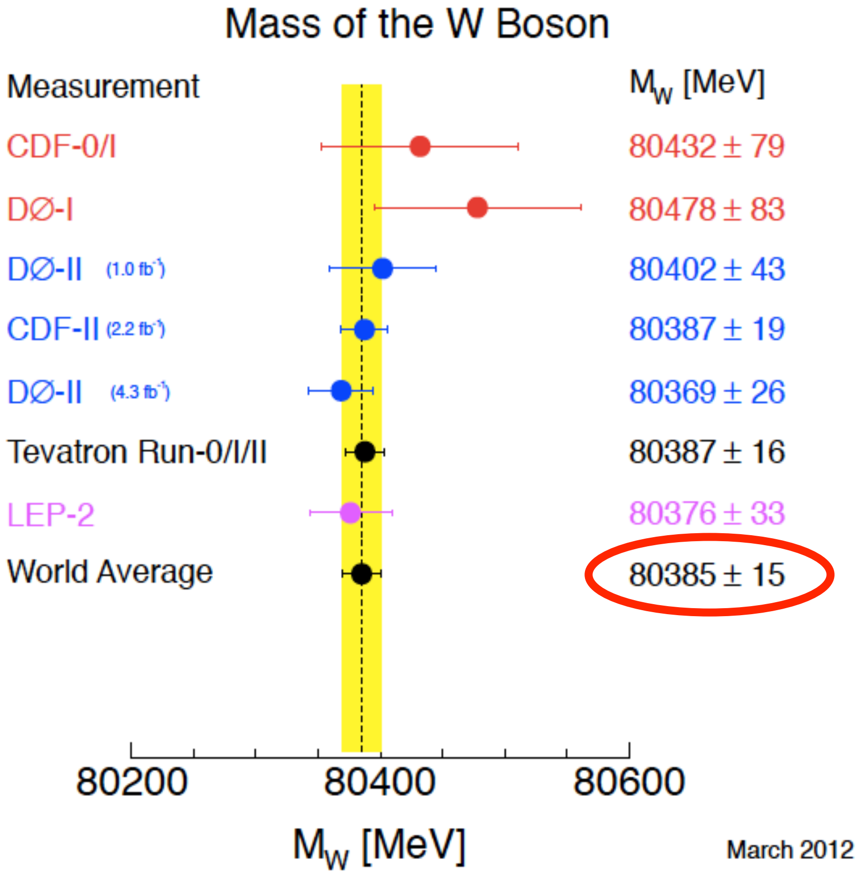
$$A_{LR}^f = \frac{N_L^f - N_R^f}{N_L^f + N_R^f}\,\frac{1}{\langle |P|_e \rangle} \qquad A_{LR}^0 = A_e$$

  - Measurements: $\boxed{A_{FB}^{0,\ell}}$ $\boxed{A_{FB}^{0,c}}$ $\boxed{A_{FB}^{0,b}}$ $\boxed{A_\ell}$ $\boxed{A_c}$ $\boxed{A_b}$

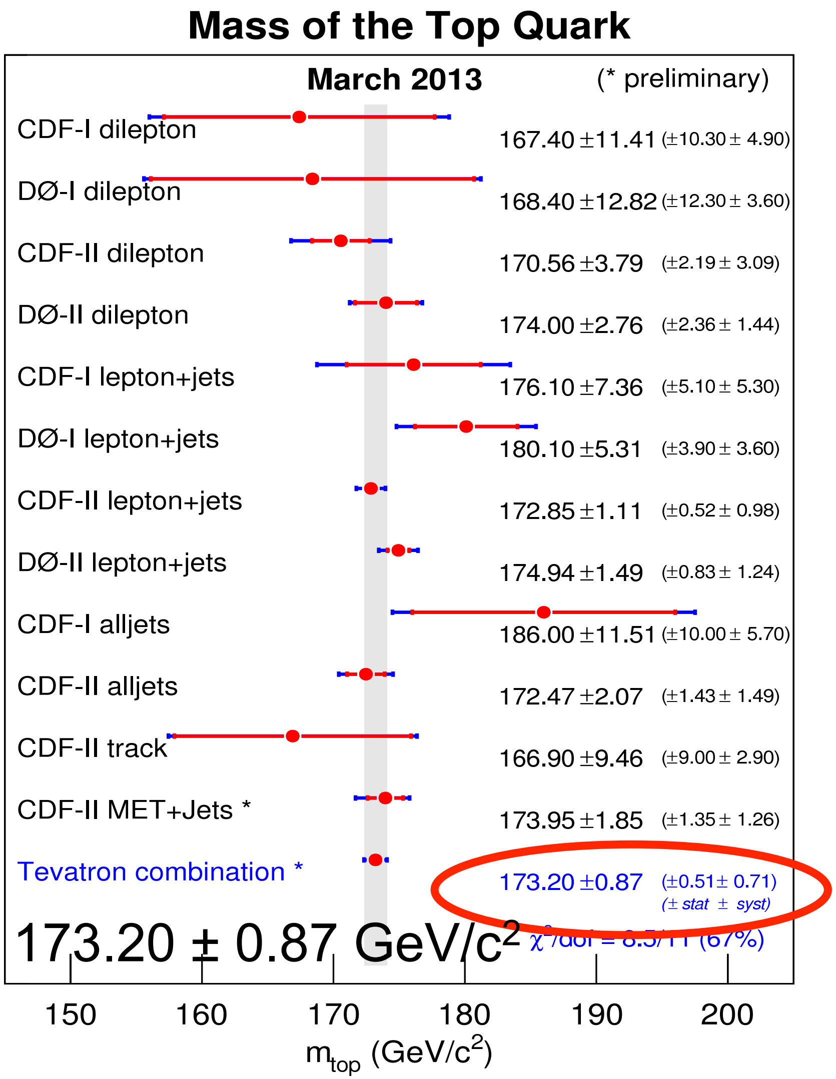
Latest averages for M_W and m_{top}

Latest Tevatron result from: arXiv:1204.0042





Tevatron result from: arXiv:1305.3929



173.20 ± 0.87 GeV/c^2

(LHC average: 173.29 ± 0.95 GeV/c^2)

The electromagnetic coupling

- The EW fit requires precise knowledge of $\alpha(M_Z)$ – better than 1% level
  - Enters various places: hadr. radiator functions, predictions of M_W and $\sin^2\theta^f_{eff}$
- Conventionally parametrized as ($\alpha(0)$ = fine structure constant) :

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)}$$

- Evolution with renormalization scale:

$$\Delta\alpha(s) = \Delta\alpha_{\mathrm{lep}}(s) + \Delta\alpha^{(5)}_{\mathrm{had}}(s) + \Delta\alpha_{\mathrm{top}}(s)$$

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- Leptonic term known up to *four* loops (for $q^2 \gg m_l^2$)
- Top quark contribution known up to 2 loops, *small: -0.7x10^{-4}*

[C.Sturm, arXiv: 1305.0581]

[M. Steinhauser, PLB 429, 158 (1998)]

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- Hadronic contribution (from the 5 light quarks) completely dominates overall uncertainty on $\alpha(M_Z)$.
- Difficult to calculate, cannot be obtained from pQCD alone.
  - Analysis of low-energy e^+e^- data
  - Usage of pQCD if lack of data

$$\boxed{\Delta\alpha^{(5)}_{had}(M_Z) = (274.9 \pm 1.0)\cdot 10^{-4}}$$

- Similar analysis to evaluation of hadronic contribution to $(g-2)_\mu$

[M. Davier et al., Eur. Phys. J. C71, 1515 (2011)]

Theoretical inputs

- Radiative corrections are important!
  - E.g. consider tree-level EW unification relation:
    $$M_W^2\Big|_{\text{tree-level}} = \frac{M_Z^2}{2}\cdot\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$
    - This predicts: $M_W = (79.964 \pm 0.005)$ GeV
    - Experiment: $M_W = (80.385 \pm 0.015)$ GeV
- Without loop corrections: shift of 400 MeV, 27σ discrepancy!

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- In EW fit with Gfitter we use state-of-the-art calculations:
  - M_W Mass of the W boson [M. Awramik et al., Phys. Rev. D69, 053006 (2004)]
  - $\sin^2\theta^f_{\mathrm{eff}}$ Effective weak mixing angle [M. Awramik et al., JHEP 11, 048 (2006), M. Awramik et al., Nucl.Phys.B813:174-187 (2009)]
    - Full two-loop + leading beyond-two-loop form factor corrections
  - Γ_{had} QCD Adler functions at N^3LO [P. A. Baikov et al., PRL108, 222003 (2012)]
    - N^3LO prediction of the hadronic cross section
  - R_b Partial width of Z→bb [Freitas et al., JHEP08, 050 (2012)] ← **Update!**

EW 2-loop calc.

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- Two nuisance parameters in EW fit for theoretical uncertainties:
  - δM_W *(4 MeV)*, $\delta\sin^2\theta^l_{\mathrm{eff}}$ *(4.7x10^{-5})*

Updated calculation of R_b

- The branching ratio R^0_b = partial decay width of $Z \rightarrow bb$ to $Z \rightarrow qq$

- We use calculation with full EW 2-loop corrections of $Z \rightarrow bb$
  - From A. Freitas etal, JHEP 1208 (2012) 050, Erratum. 1305 (2013) 074.

Recently a mistake was found in this calculation.

- ***Old:*** Two-loop corrections to R^0_b comparable to experimental uncertainty (6.6×10^{-4})
  - Moved theoretical prediction by 1.5σ
    - Much more than the originally estimated theory uncertainty!
- ***New:*** bug in calculation of R^0_b has been corrected, resulting in a sizable reduction of the size of the two-loop correction.

- All results shown here and on Gfitter homepage use the corrected R^0_b calculation.

Electroweak Fit – Experimental inputs

- Latest experimental inputs:
  - Z-pole observables: from LEP / SLC
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - M_W and Γ_W from LEP/Tevatron
    [arXiv:1204.0042, arXiv:1302.3415]
  - m_{top} latest avg from Tevatron
    [arXiv:1305.3929]
  - m_c, m_b world averages (PDG)
    [PDG, J. Phys. G33,1 (2006)]
  - $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency
    [Davier et al., EPJC 71, 1515 (2011)]
  - M_H from LHC
    [arXiv:1207.7214, arXiv:1207.7235]
- 7 (+2) free fit parameters:
  - M_H, M_Z, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, m_c, m_b
  - 2 theory nuisance parameters
    - δM_W (4 MeV), $\delta\sin^2\theta^l_{eff}$ (4.7×10^{-5})

M_H [GeV]°	125.7 ± 0.4	**LHC**
M_W [GeV]	80.385 ± 0.015	**Tevatron**
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	**LEP**
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	**SLC**
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	**SLC**
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	**LEP**
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	
m_t [GeV]	173.20 ± 0.87	**Tevatron**
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2756 ± 10	

Electroweak Fit – SM Fit Results

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: not incl. M_H
- Right: fit incl M_H, not the row

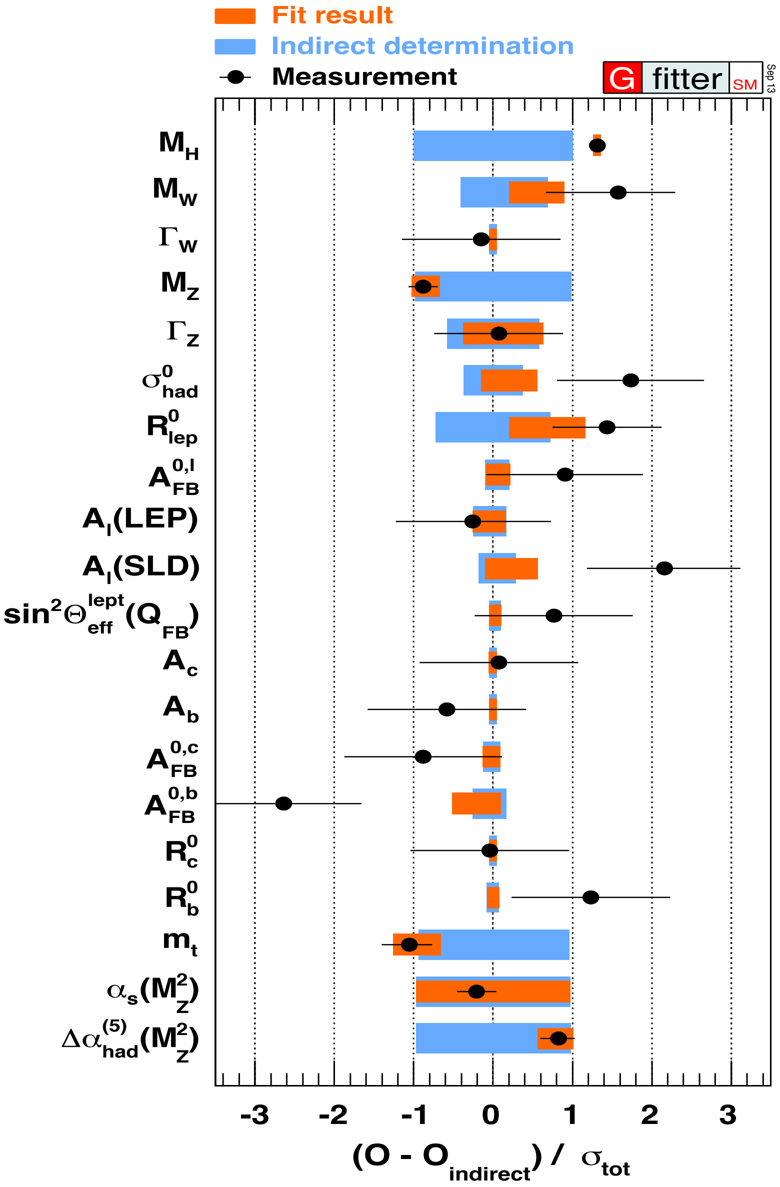
Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]$^{\circ}$	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.367^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021	91.1978 ± 0.0114
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014	2.4950 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012	–	$0.23149^{+0.00010}_{-0.00008}$	$0.23149^{+0.00010}_{-0.00008}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6679^{+0.00034}_{-0.00028}$	$0.6679^{+0.00034}_{-0.00028}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93464^{+0.00005}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005	0.21547 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11	2718^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1190 ± 0.0027
$\delta_{\text{th}} M_W$ [MeV]	$[-4, 4]_{\text{theo}}$	yes	4	4	–
$\delta_{\text{th}} \sin^2\theta^\ell_{\text{eff}}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\text{theo}}$	yes	-0.6	-0.5	–

Electroweak Fit – SM Fit Results

- Results drawn as *pull values:* → deviations to the *indirect* determinations, divided by *total error*.
- Total error: *error of direct measurement plus error from indirect determination.*

- Black: direct measurement (data)
- Orange: full fit
- Light-blue: fit excluding input from the row

- The prediction (light blue) is often more precise than the measurement!

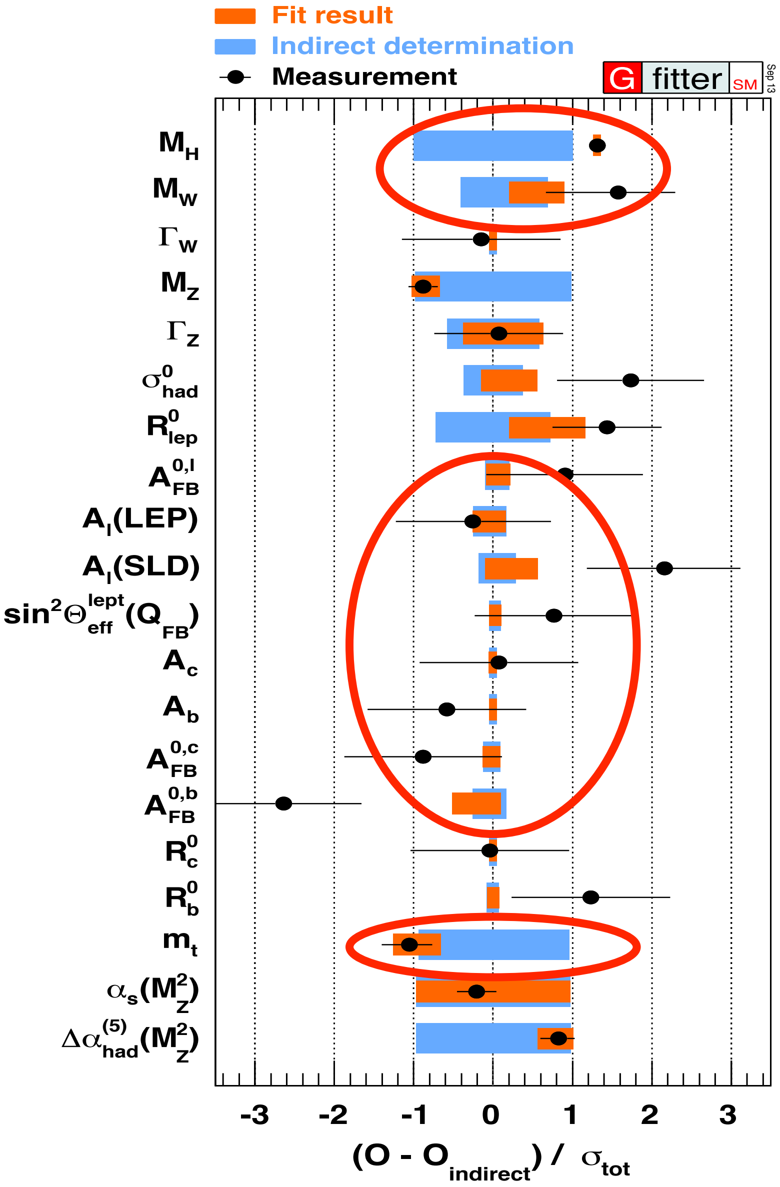


Electroweak Fit – SM Fit Results

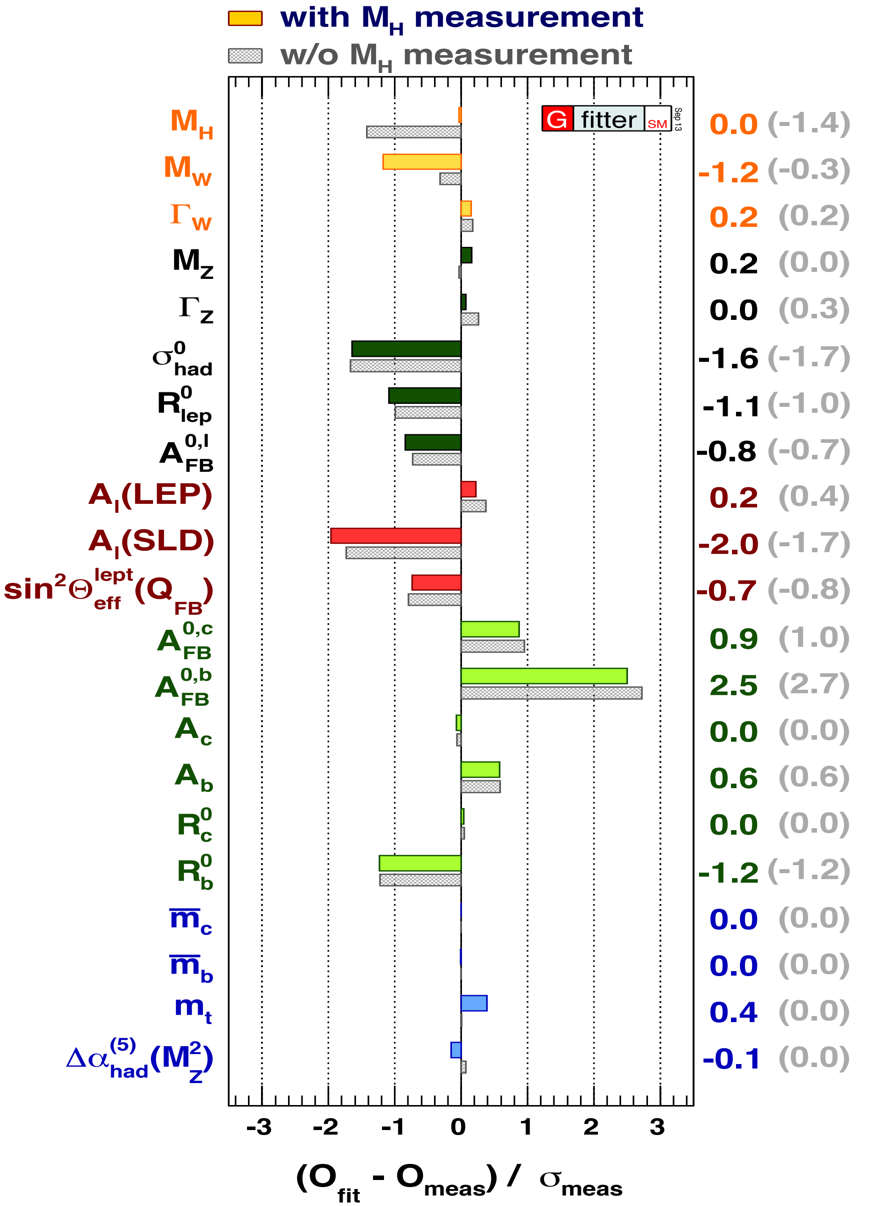
- Results drawn as *pull values:* → deviations to the *indirect* determinations, divided by *total error*.
- Total error: *error of direct measurement plus error from indirect determination.*

- Black: direct measurement (data)
- Orange: full fit
- Light-blue: fit excluding input from the row

- The prediction (light blue) is often more precise than the measurement!



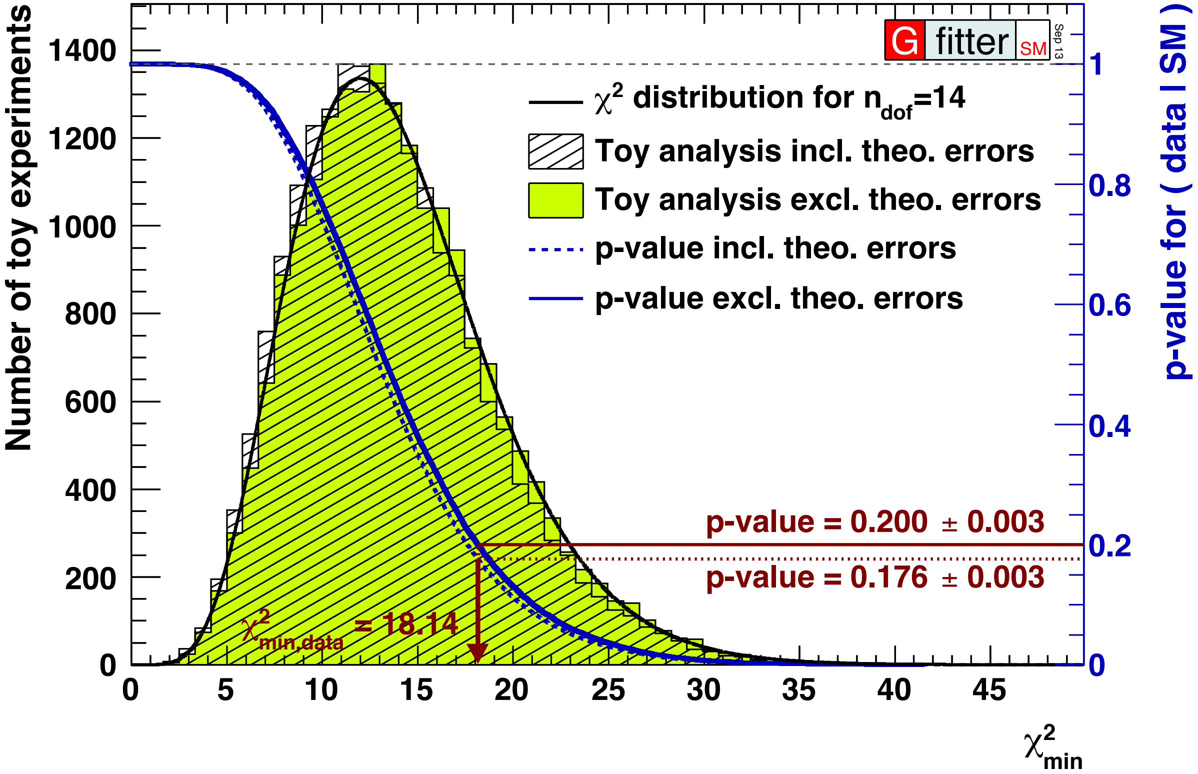
Electroweak Fit – SM Fit Results



Plot inspired by Eberhardt et al. [arXiv:1209.1101]

- No individual value exceeds 3σ
- Small pulls for M_H, M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$ indicate that input accuracies exceed fit requirements
- Largest deviations in b-sector: $A^{0,b}_{FB}$ with 2.5σ
  - → largest contribution to χ^2
- R^0_b using one-loop calculation -0.8σ
  - R^0_b has only little dependence on M_H
- Most affected when including M_H : M_W prediction:
  - Shift in predicted M_W value of ~13 MeV.

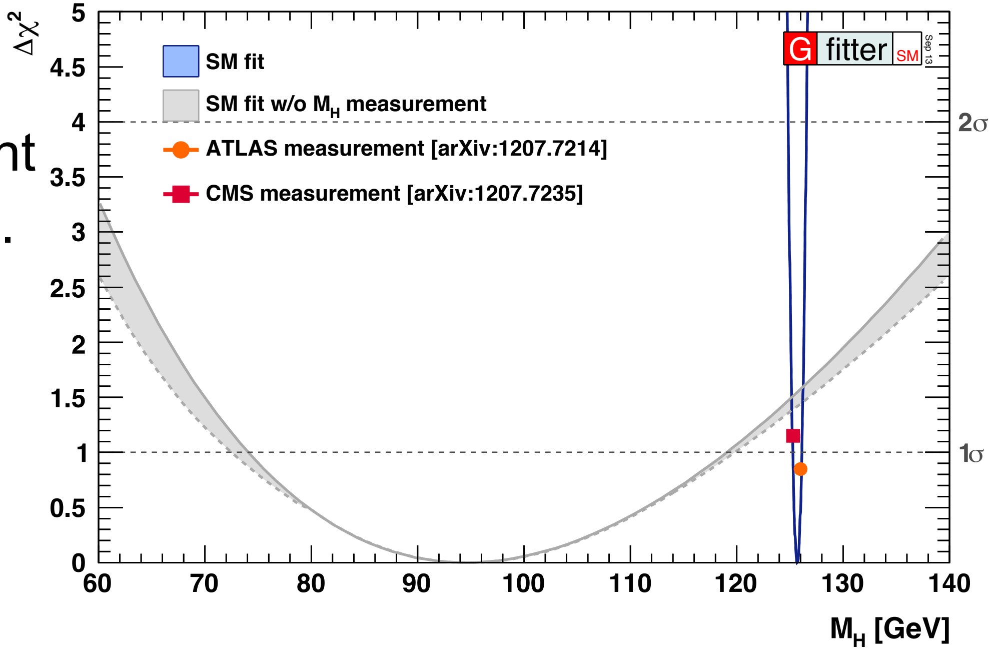
Goodness of Fit



- Toy analysis: p-value for wrongly rejecting the SM = $18^{+2\ (\mathrm{theo})}$ %
  - p-value is equivalent to 0.9σ
  - Evaluated with 20k pseudo experiments – follows χ^2 with 14 d.o.f.
  - For comparison: χ^2_{min}= 18.1 → Prob(χ^2_{min}, 14) = 20 %
- Large value of χ^2_{min} *not* due to inclusion of M_H measurement.
  - Without M_H measurement: χ^2_{min}= 16.7 → Prob(χ^2_{min}, 13) = 21%

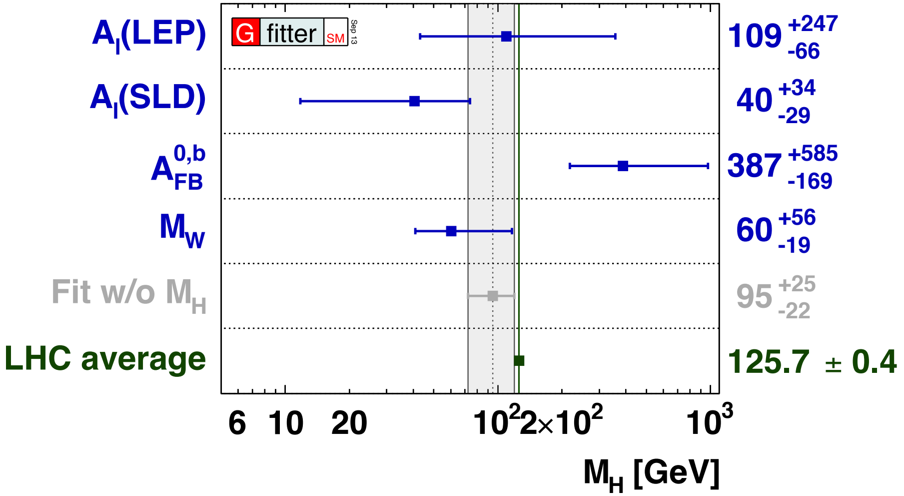
Higgs results of the EW fit

- Scan of $\Delta\chi^2$ profile versus M_H
  - Grey band: fit w/o M_H measurement
  - Blue line: full SM fit, with M_H meas.
  - Fit w/o M_H measurement gives: $M_H = 94^{+25}_{-22}$ GeV
  - Consistent at 1.3σ with LHC measurement.



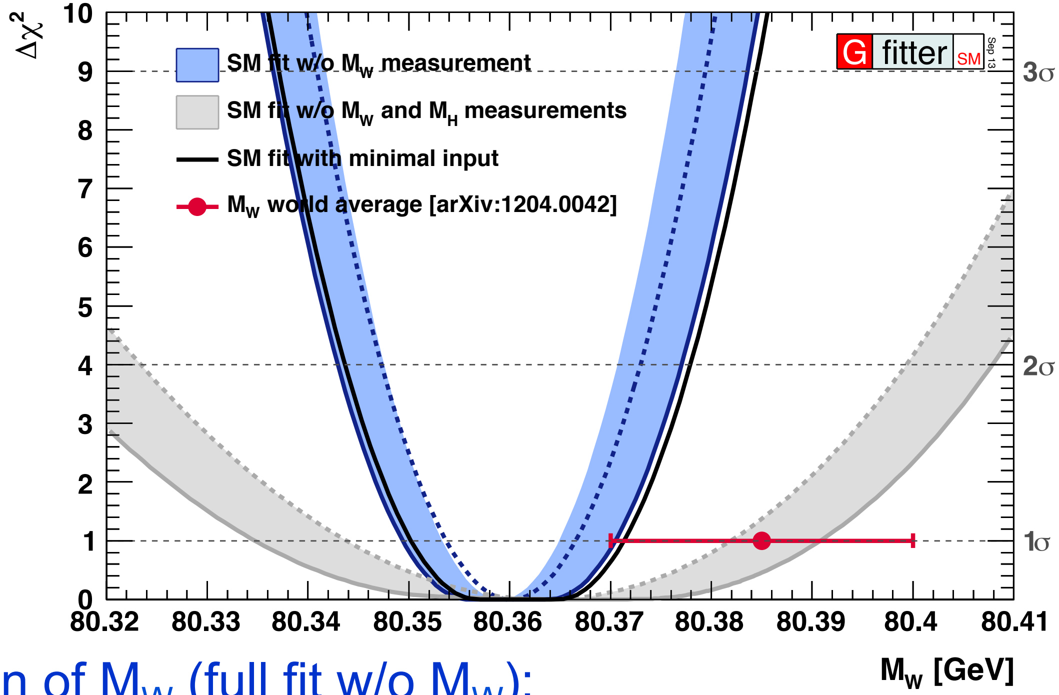
- Bottom plot: impact of other most sensitive Higgs observables
  - Determination of M_H removing all sensitive observables except the given one.
  - Known tension (2.5σ) between A_l(SLD), $A^{0,b}_{FB}$, and M_W clearly visible.

fit below only includes the given observable



Indirect determination of W mass

- Scan of $\Delta\chi^2$ profile versus M_W
  - Also shown: SM fit with minimal inputs: M_Z, G_F, $\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H, and fermion masses
  - Good consistency between total fit and SM w/ minimal inputs



- M_H measurement allows for precise constraint on M_W
  - Agreement at 1.4σ
- Fit result for indirect determination of M_W (full fit w/o M_W):

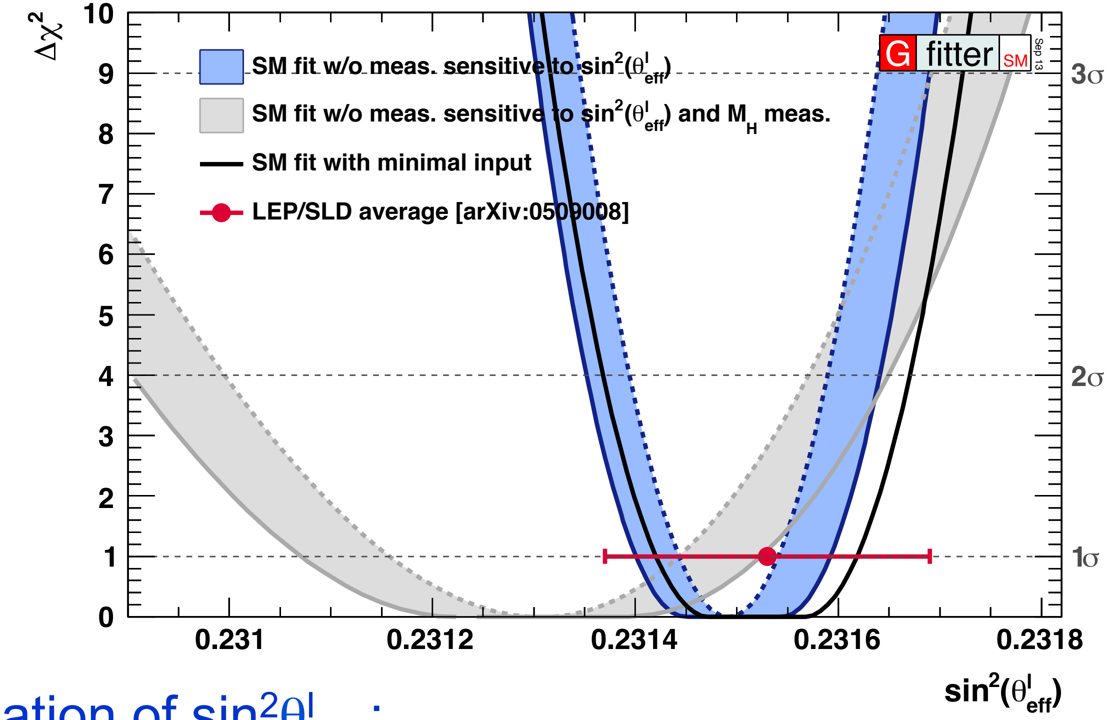
$$
\begin{aligned}
M_W &= 80.3593 \pm \boxed{0.0056_{m_t}} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\
&\quad \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm \boxed{0.0040_{\rm theo}} \\
&= 80.359 \pm 0.011_{\rm tot} \,,
\end{aligned}
$$

- More precise estimate of M_W than the direct measurements!
  - Uncertainty on world average measurement: 15 MeV

Indirect effective weak mixing angle

- Right: scan of $\Delta\chi^2$ profile versus $\sin^2\theta^l_{eff}$
  - All sensitive measurements removed from the SM fit.
  - Also shown: SM fit with minimal inputs

- M_H measurement allows for very precise constraint on $\sin^2\theta^l_{eff}$

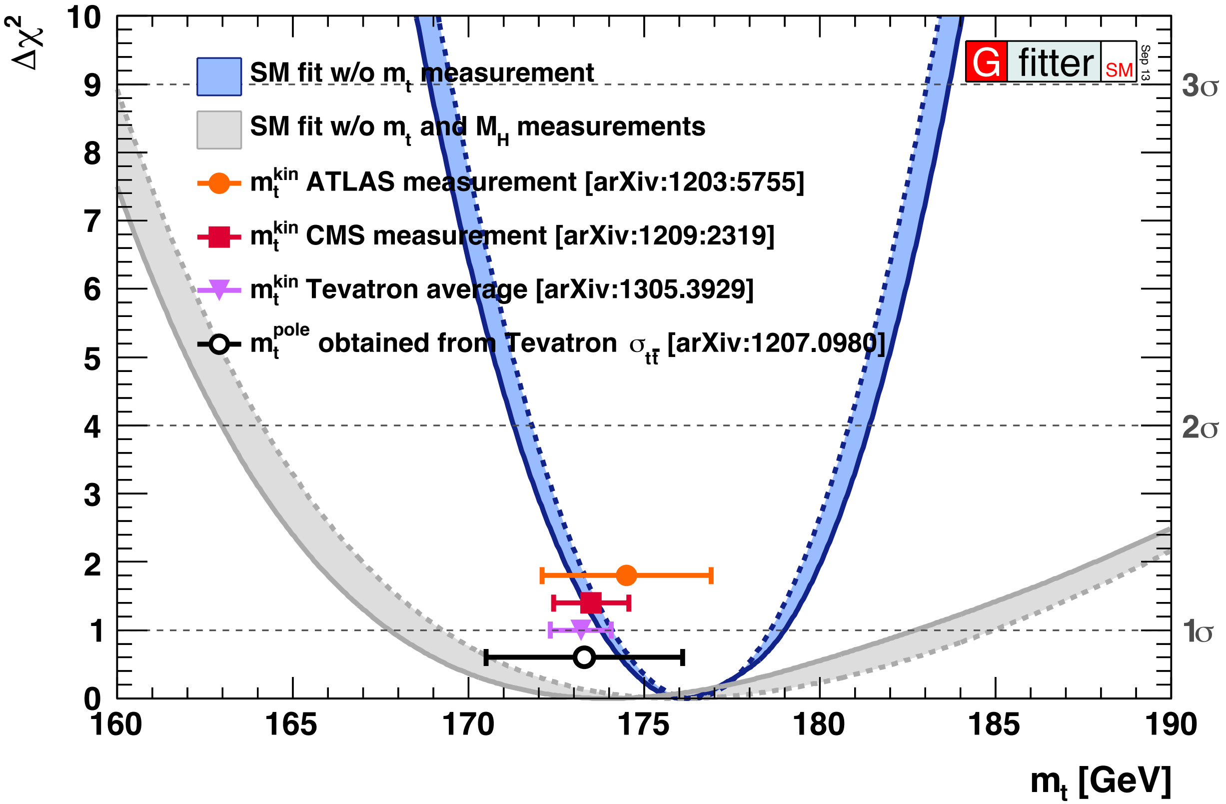


- Fit result for indirect determination of $\sin^2\theta^l_{eff}$:

$$
\begin{aligned}
\sin^2\theta^\ell_{\rm eff} &= 0.231496 \pm \boxed{0.000030_{m_t}} \pm 0.000015_{M_Z} \pm \boxed{0.000035_{\Delta\alpha_{\rm had}}} \\
&\quad \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm \boxed{0.000047_{\rm theo}} \,, \\
&= 0.23150 \pm 0.00010_{\rm tot} \,,
\end{aligned}
$$

- More precise than direct determination (from LEP/SLD) !
  - Uncertainty on LEP/SLD average: $1.6\text{x}10^{-4}$

Indirect determination of top mass

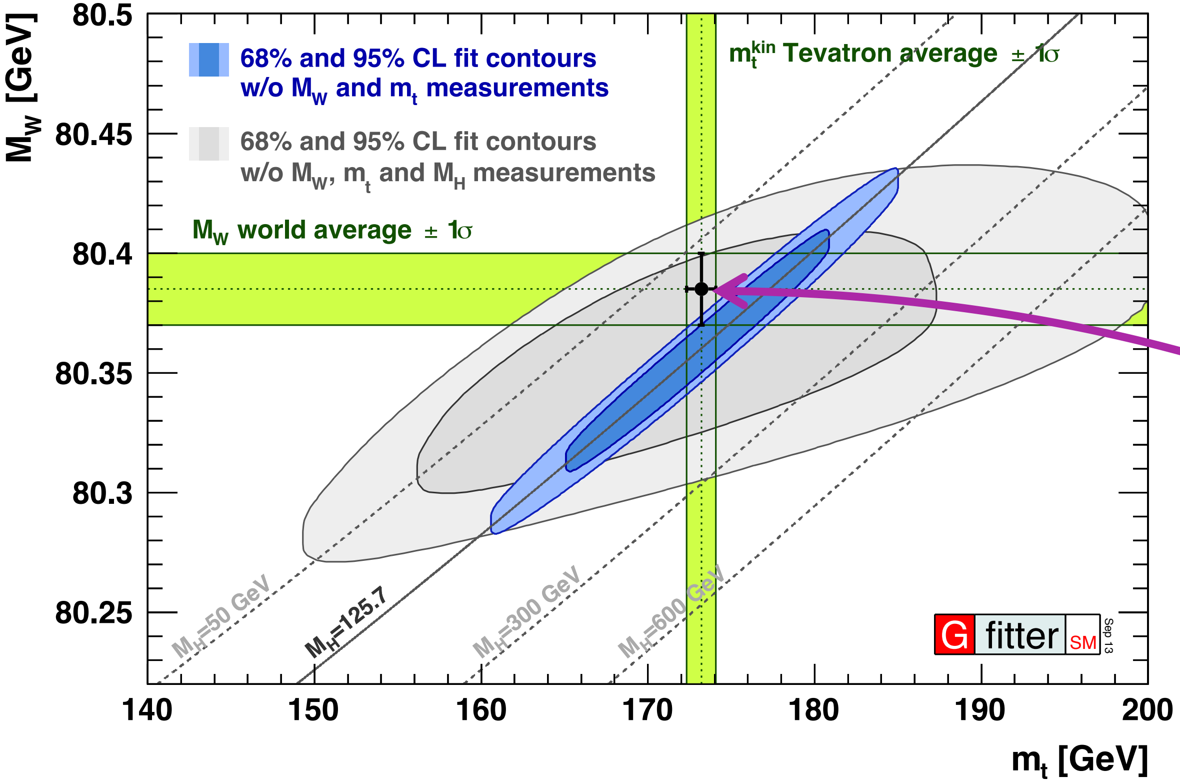


- Shown: scan of $\Delta\chi^2$ profile versus m_t (without m_t measurement)
  - M_H measurement allows for significant better constraint of m_t
  - Indirect determination consistent with direct measurements
    - Remember: fully obtained from loop corrections!
- Indirect result: $m_t = 176.1^{+2.9}_{-2.4}$ GeV

Tevatron: 173.2 ± 0.9 GeV
LHC: 173.3 ± 1.0 GeV

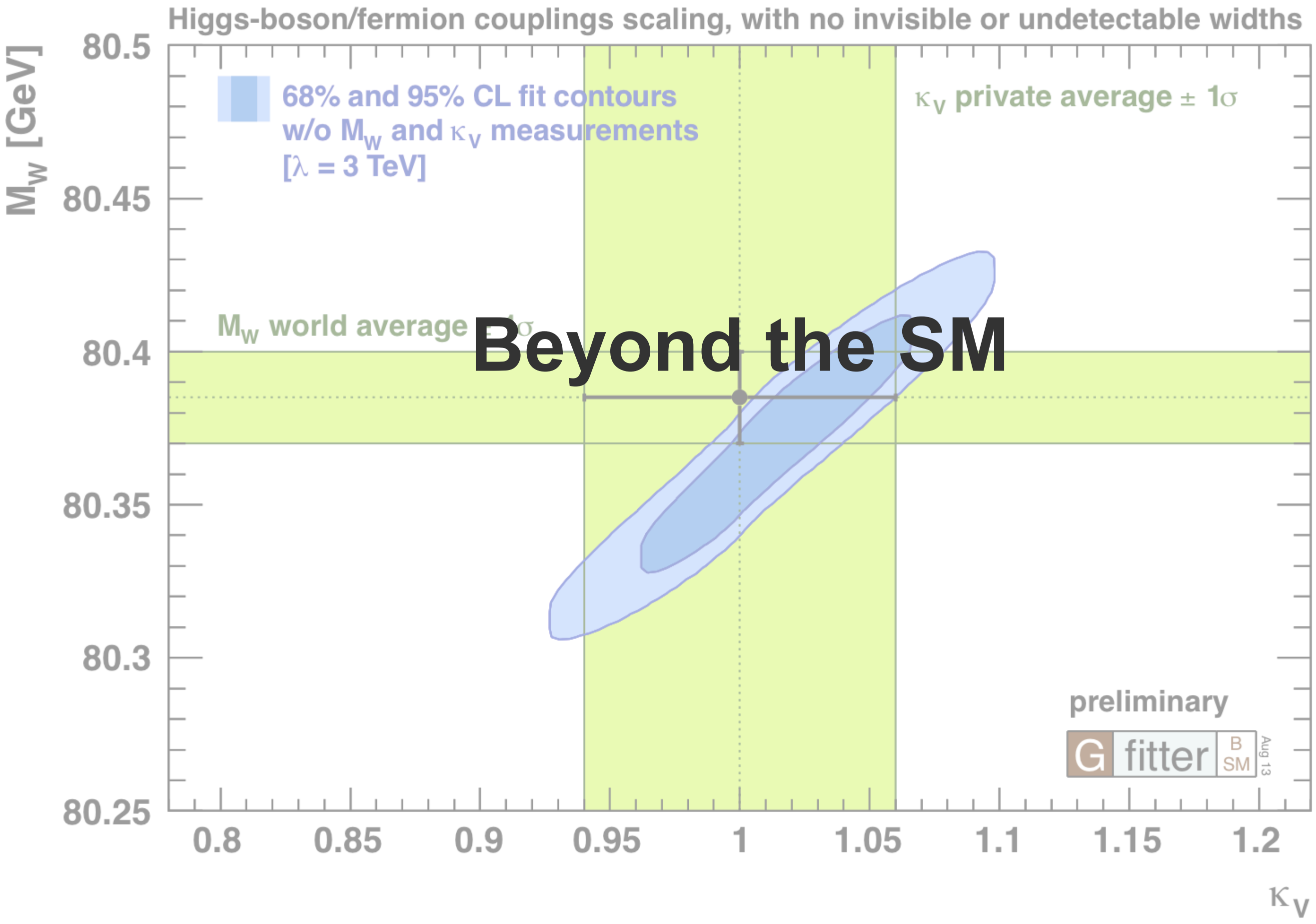
State of the SM: W versus top mass

- Scan of M_W vs m_t, with the direct measurements excluded from the fit.
- Results from Higgs measurement significantly reduces allowed indirect parameter space → corners the SM!



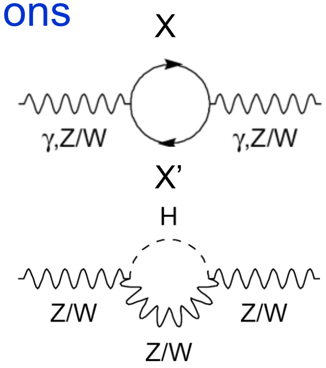
- Observed agreement demonstrates impressive consistency of the SM!

Beyond the SM



Constraints on Oblique Corrections

- If energy scale of NP is high, BSM physics appears dominantly through vacuum polarization corrections
  - Aka, “oblique corrections”
- Oblique corrections reabsorbed into electroweak form factors
  - $\Delta\rho$, $\Delta\kappa$, Δr parameters, appearing in: M_W^2, $\sin^2\theta_{eff}$, G_F, α, etc.
- Electroweak fit sensitive to BSM physics through oblique corrections
  - Similar to sensitivity to top and Higgs loop corrections.



- Oblique corrections from New Physics described through STU parametrization

[Peskin and Takeuchi, Phys. Rev. D46, 1 (1991)]

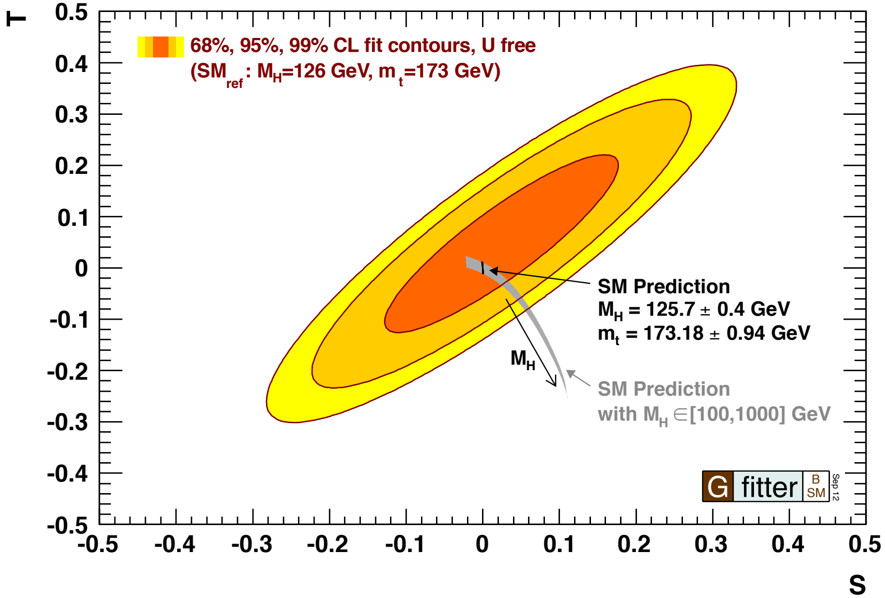
$$\boxed{O_{meas} = O_{SM,REF}(m_H,m_t) + c_S S + c_T T + c_U U}$$

- S : New Physics contributions to neutral currents
- T : Difference between neutral and charged current processes – sensitive to weak isospin violation
- U : (+S) New Physics contributions to charged currents. U only sensitive to W mass and width, usually very small in NP models (often: U=0)

- Also implemented: extended parameters (VWX), correction to Z→bb couplings.

[Burgess et al., Phys. Lett. B326, 276 (1994)]
[Burgess et al., Phys. Rev. D49, 6115 (1994)]

Fit results for S, T, U



- S,T,U obtained from fit to the EW observables
- SM: M_H = 126 GeV, m_t = 173 GeV
    - This defines (S,T,U) = (0,0,0)
- SM: S, T depend logarithmically on M_H
- Fit result:

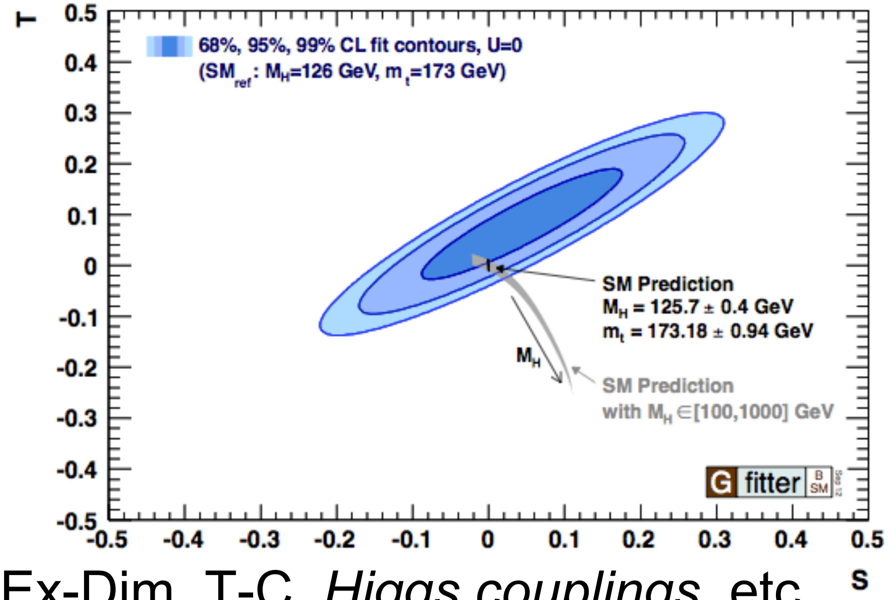
$S = 0.03 \pm 0.10$

$T = 0.05 \pm 0.12$

$U = 0.03 \pm 0.10$

	S	*T*	*U*
S	1	+0.89	-0.54
T		1	-0.80
U			1

- Stronger constraints from fit with U=0.
- Also available for Z→bb correction.



- No indication for new physics.
- Can now use this to constrain 4th gen, Ex-Dim, T-C, *Higgs couplings*, etc.

Modified Higgs couplings

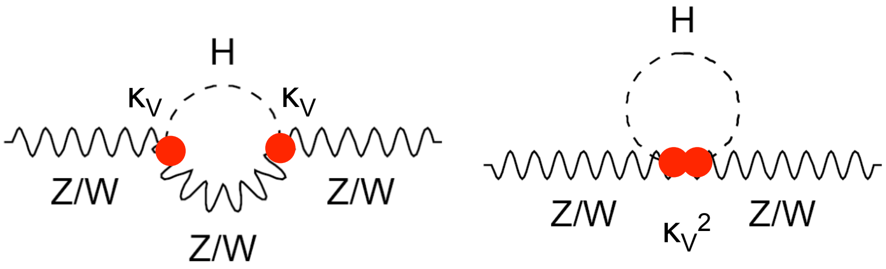
- Study of potential deviations of Higgs couplings from SM.
- BSM modeled as extension of SM through effective Lagrangian.
  - Consider leading corrections only.

$$L_V = \frac{h}{v}\left(2\boxed{\kappa_V} m_W^2\, W_\mu W^\mu + \boxed{\kappa_V} m_Z^2\, Z_\mu Z^\mu\right)$$

$$L_F = -\frac{h}{v}\left(\boxed{\kappa_F} m_t\, \bar{t}t + \boxed{\kappa_F} m_b\, \bar{b}b + \boxed{\kappa_F} m_\tau\, \bar{\tau}\tau\right)$$

- Popular benchmark model:
  - Scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F)
  - No additional loops in the production or decay of the Higgs, no invisible Higgs decays and undetectable width.

- Main effect on EWPO due to modified Higgs coupling to gauge bosons (κ_V)
  - Involving the longitudinal d.o.f.



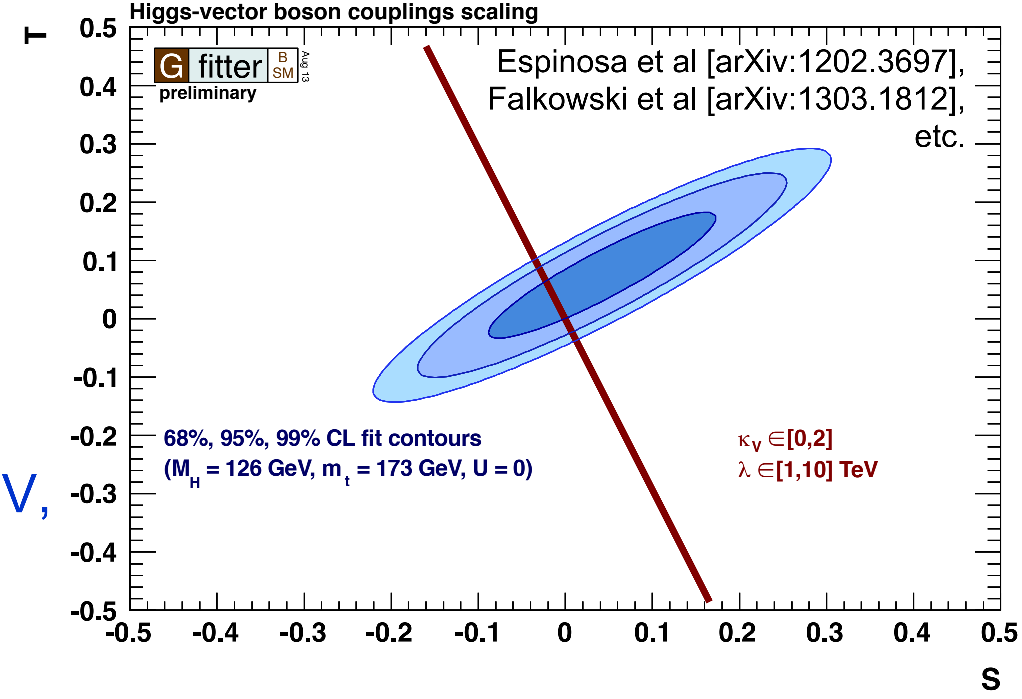
- Most BSM models: $\kappa_V < 1$
  - Additional Higgses typically give *positive* contribution to M_W.

Modified Higgs couplings

- Main effect on EWPO due to Higgs coupling to gauge bosons (κ_V).
  - $S = \frac{1}{12\pi}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right)\,,\quad T = -\frac{3}{16\pi c_W^2}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right)\,,\quad \Lambda = \frac{\lambda}{\sqrt{|1-\kappa_V^2|}}$
  - Formulas from: Espinosa et al [arXiv:1202.3697]

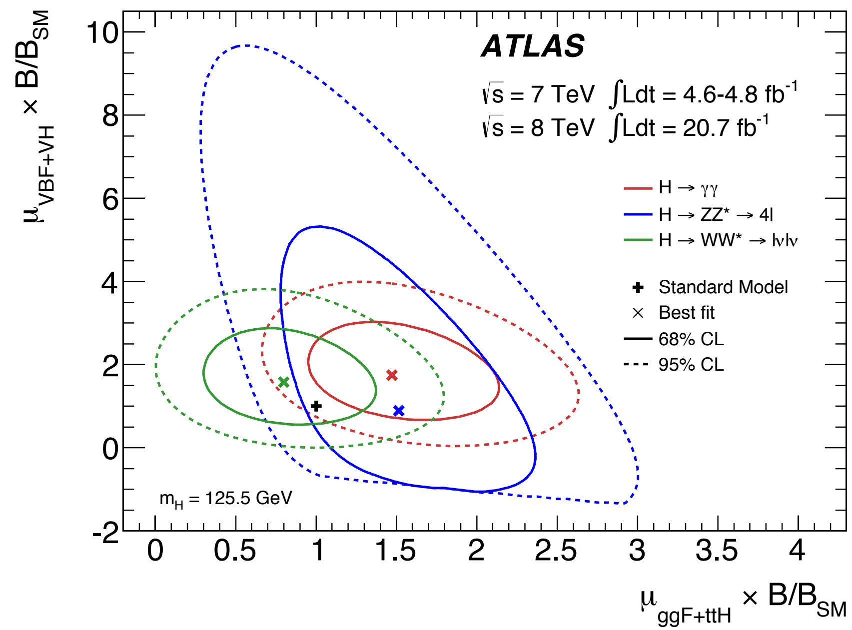
- Cut-off scale Λ represents mass scale of new states that unitarize longitudinal gauge-boson scattering.
  - (As required in this model.)

- λ is varied between 1 and 10 TeV, nominally fixed to 3 TeV (4πv).

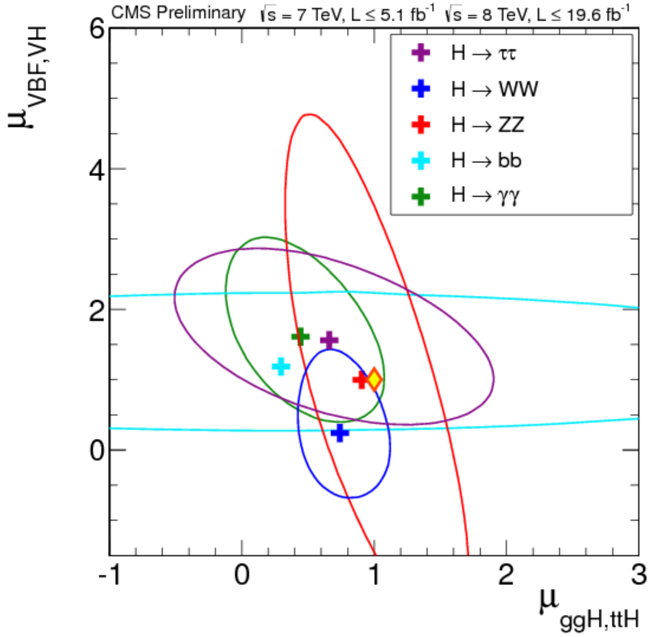


Higgs coupling results by ATLAS and CMS

ATLAS arXiv:1307.1427

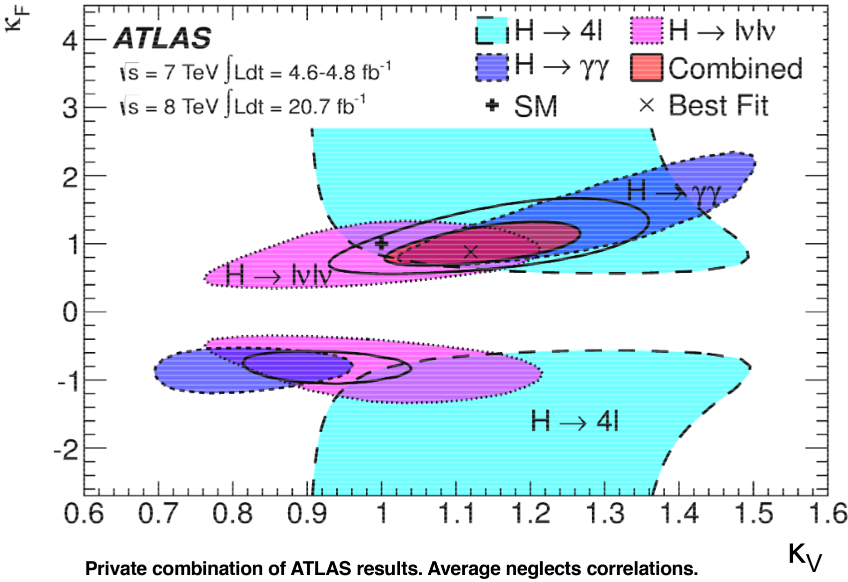


CMS PAS-HIG-13-005

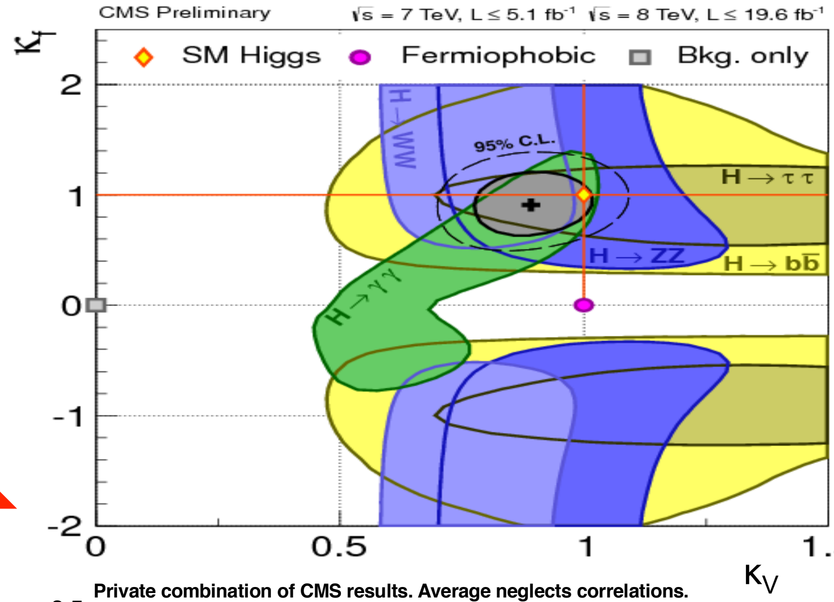


- Input: Higgs production times decay rate measurements (μ's)
- Interpret as κ_V and κ_F using LHC HXSWG formalism.
  - [arXiv:1209.0040]

Reproduction of ATLAS and CMS results

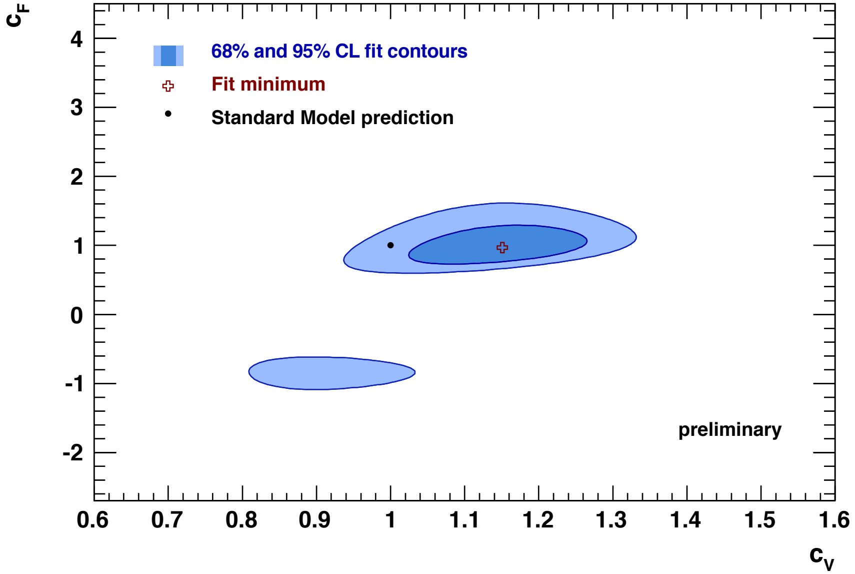


arXiv:1307.1427

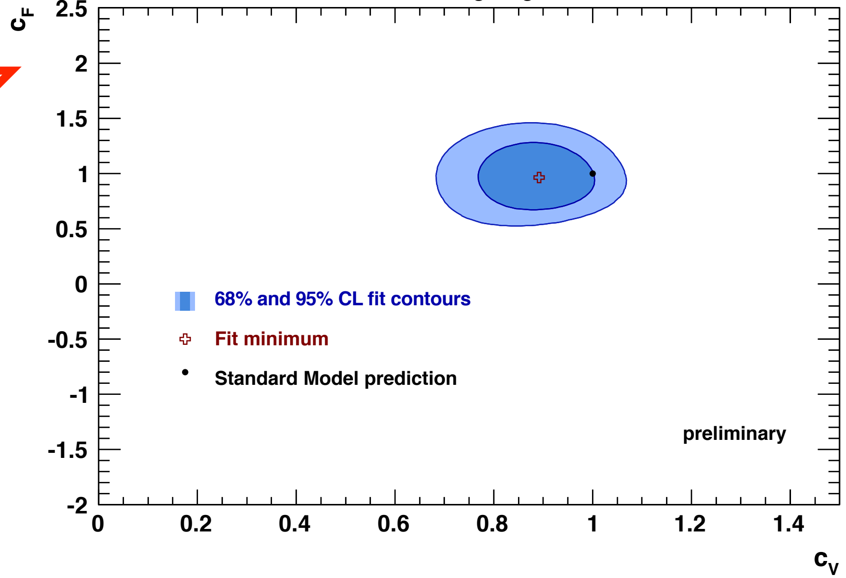


CMS-PAS-HIG-13-005

Private combination of ATLAS results. Average neglects correlations.



Private combination of CMS results. Average neglects correlations.

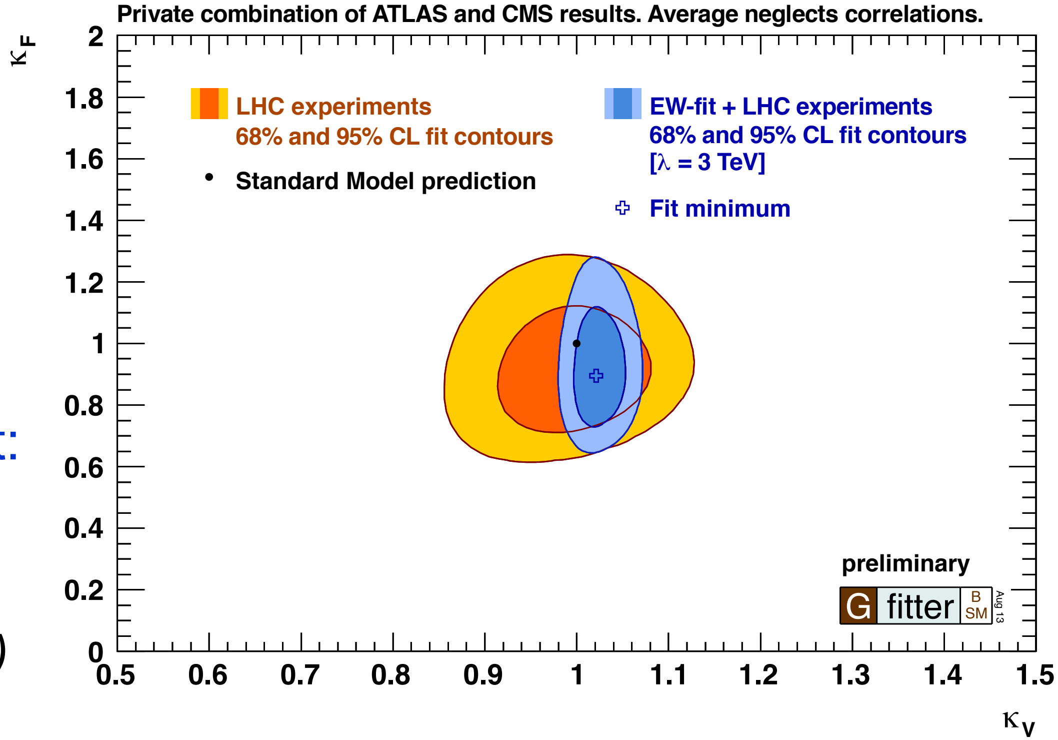


- Decent reproduction of ATLAS and CMS results within limited public-info available.

Higgs coupling results

- Private LHC combination:
  - $\kappa_V = 1.00 \pm 0.06$
  - $\kappa_F = 0.89 \pm 0.13$
  - Perfectly consistent with SM.

- Result from stand-alone EW fit:
  - $\kappa_V = 1.032^{+0.036}_{-0.025}$ (λ = 1 TeV)
  - $\kappa_V = 1.024^{+0.024}_{-0.018}$ (λ = 3 TeV)
  - $\kappa_V = 1.019^{+0.019}_{-0.014}$ (λ = 10 TeV)

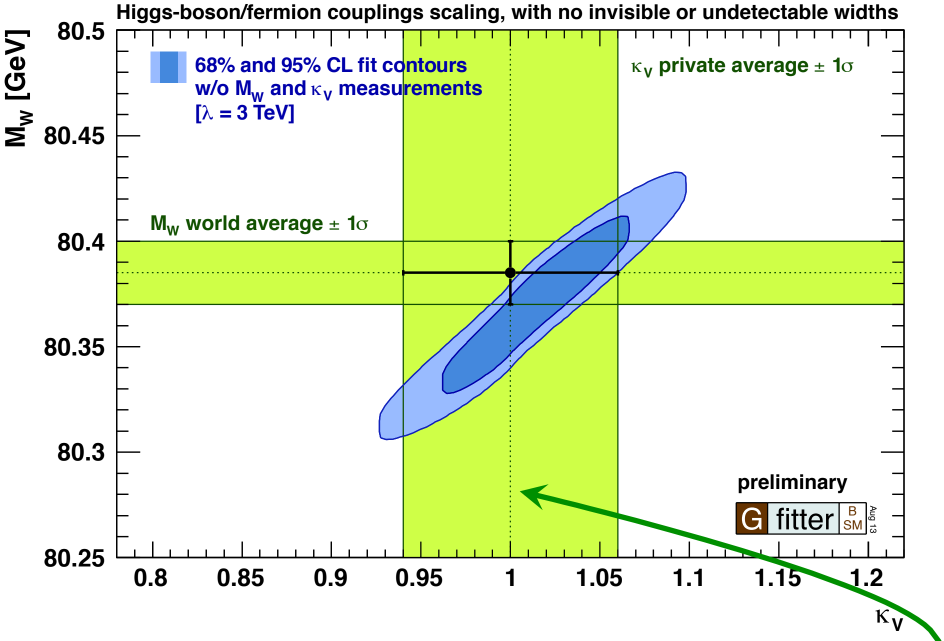

Private combination of ATLAS and CMS results. Average neglects correlations.

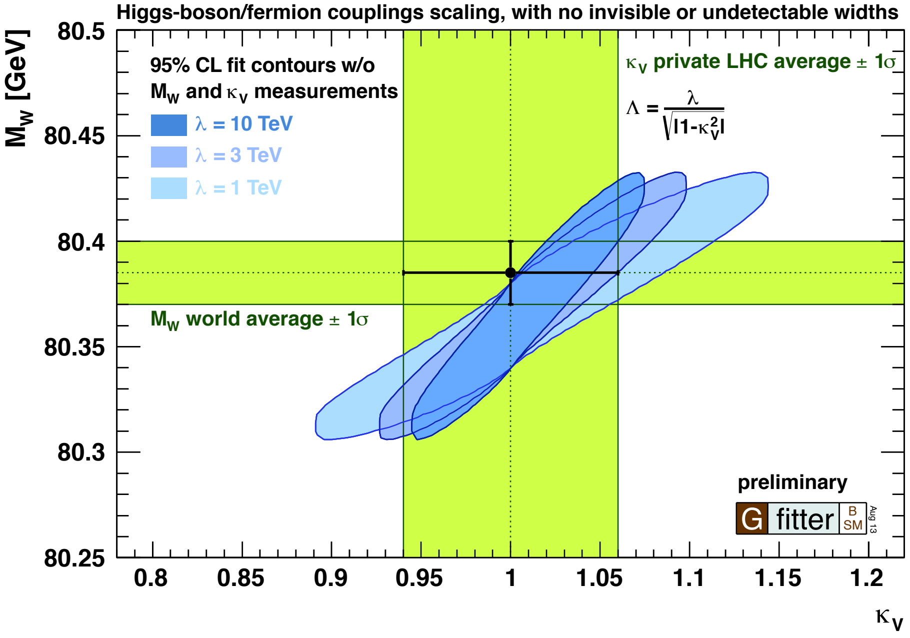
- Note: some dependency in central value and error on cut-off scale λ.

1. EW fit sofar more precise result for κ_V than current LHC experiments.
2. EW fit: positive deviation of κ_V from 1.0.
   - (Many BSM models: $\kappa_V < 1$)

EW fit: Higgs coupling results

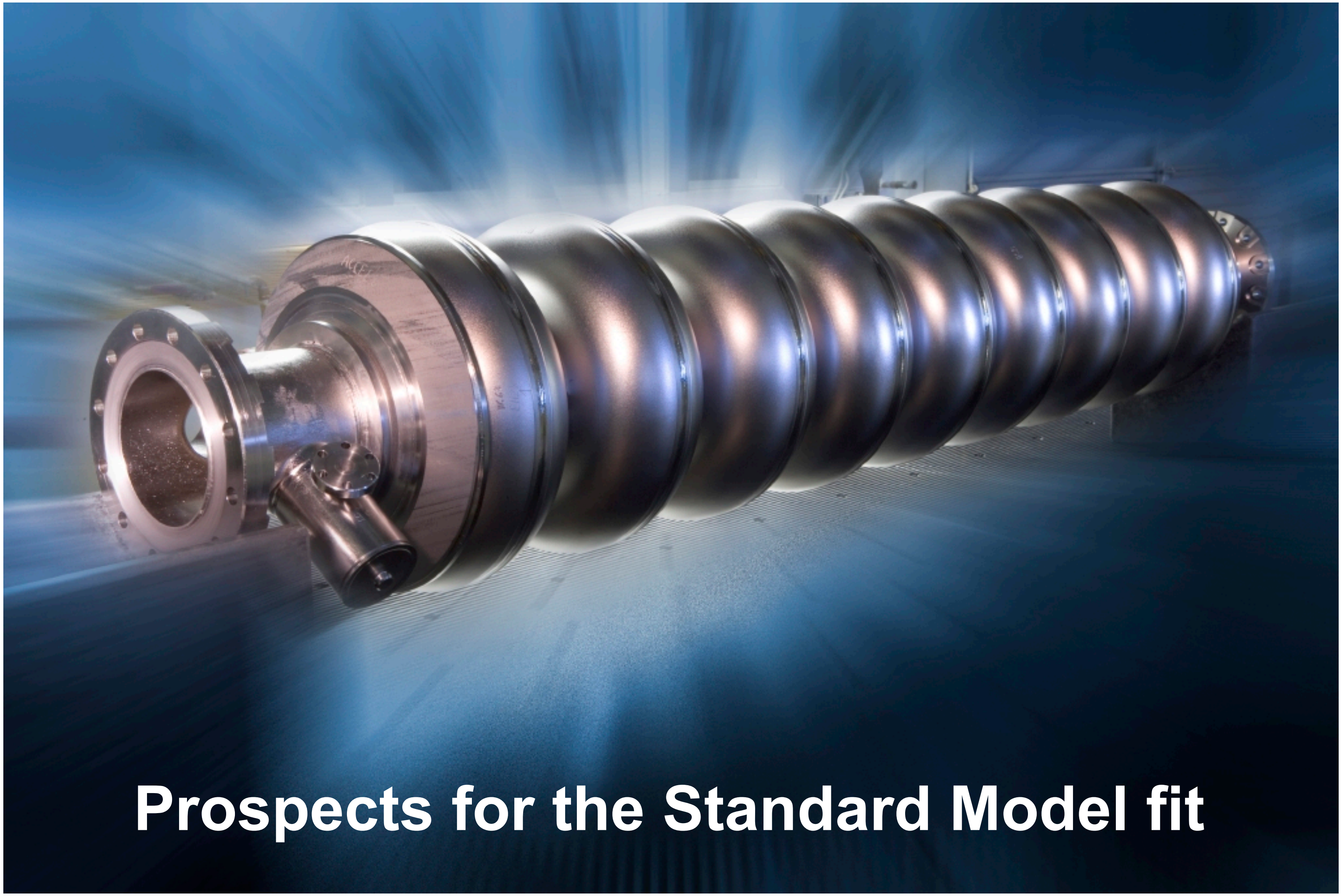
- EW fit: positive deviation of κ_V from one driven by small tension in W mass prediction versus measurement.





- Private LHC combination:
  - $\kappa_V = 1.00 \pm 0.06$
  - $\kappa_F = 0.89 \pm 0.13$

- Above: dependency on λ
- (Will be interesting to see how these measurements develop.)



Prospects for the Standard Model fit

Two prospects scenarios: LHC-300, ILC/GigaZ

Prospects of EW fit tested for two scenarios:

1. LHC Run-2+3
2. ILC with GigaZ(*)

(*) GigaZ:

- Operation of ILC at lower energies like Z-pole or WW threshold.
  - Allows to perform precision measurements of EW sector of the SM.
- At Z-pole, several billion Z's can be studied within 1-2 months.
- Physics of LEP1 and SLC can be revisited with few days of data.

In following studies:
Central values of input measurements adjusted to M_H = 126 GeV.

- *(Except where indicated.)*

Prospects of EW fit for: ILC with Giga Z

Future Linear Collider can improve precision of EWPO's tremendously.

- *WW threshold scan + kinematic reconstruction, to obtain M_W*
  - From threshold scan: δM_W : 15 → 5 MeV
- *ttbar threshold scan, to obtain m_t*
  - Obtain m_t indirectly from production cross section: δm_t : 0.9 → 0.1 GeV
- *Z pole measurements*
  - High statistics: 10^9 Z decays: $\delta R^0_{lep} : 2.5 \cdot 10^{-2} \rightarrow 4 \cdot 10^{-3}$
  - With polarized beams, uncertainty on $\delta A^{0,f}_{LR}$: $10^{-3} \rightarrow 10^{-4}$, which translates to $\delta \sin^2\theta^l_{eff} : 1.6 \cdot 10^{-4} \rightarrow 1.3 \cdot 10^{-5}$
- *H→ZZ and H→WW couplings*: measured at 1% precision.

ILC prospects: from ILC TDR (Vol-2).

Prospects of EW fit for: LHC Run-2

LHC Run-2+3 (300/fb)

- *W mass measurement* : δM_W : 15 → 8 MeV
- *Final top mass measurement m_t* : δm_t : 0.9 → 0.6 GeV
- *H→ZZ and H→WW couplings*: measured at 4.5% precision.

LHC prospects: possibly optimistic scenario, but not impossible.

Prospects of EW fit

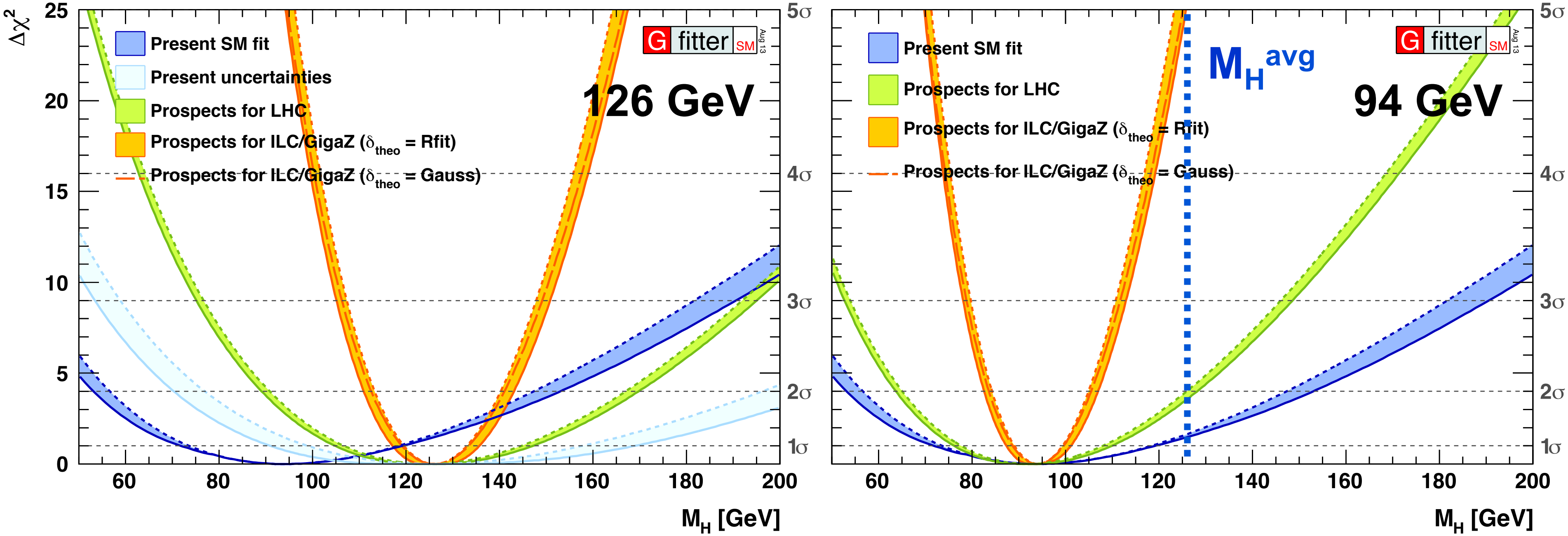
LHC Run-2+3 (300/fb)

- *W mass measurement* : δM_W : 15 → 8 MeV
- *Final top mass measurement m_t* : δm_t : 0.9 → 0.6 GeV
- *H→ZZ and H→WW couplings*: measured at 4.5% precision.

For both LHC-300 and ILC:

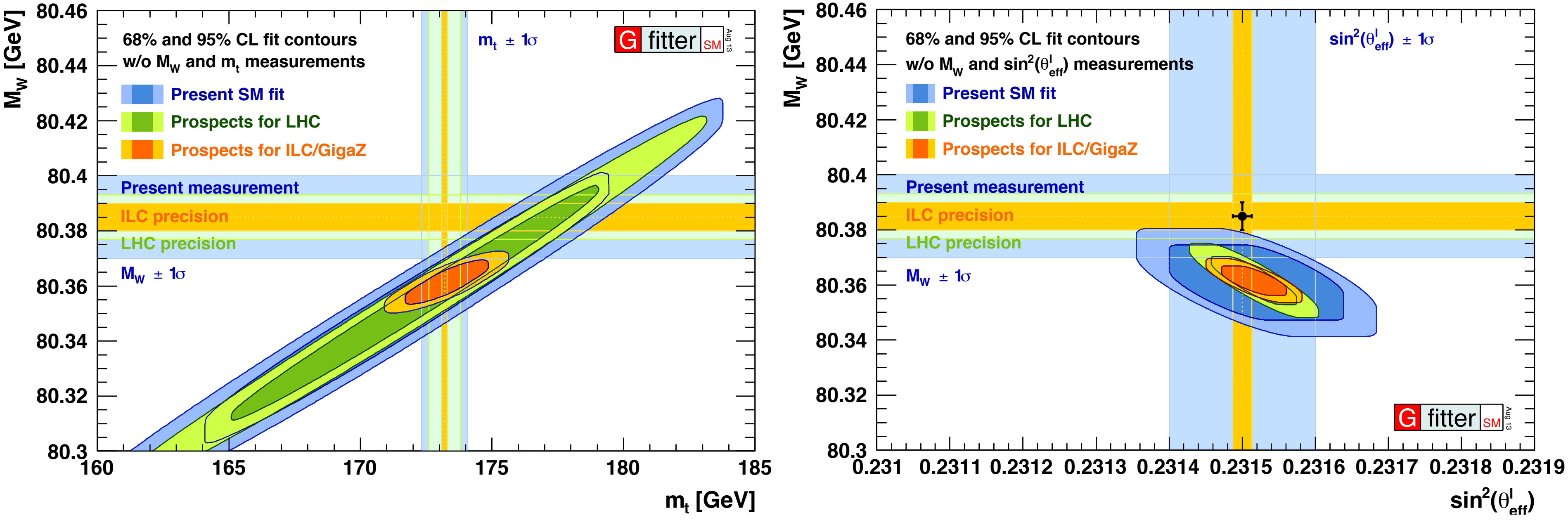
- Low-energy data results to improve $\Delta\alpha_{had}$:
  - ISR-based (BABAR), KLOE-II, VEPP-2000 (at energy below cc resonance), and BESIII e^+e^- cross-section measurements, in particular around cc resonance.
  - Plus: improved α_s, improvements in theory: $\Delta\alpha_{had}$: $10^{-4} \rightarrow 5 \cdot 10^{-5}$
- Assuming ~25% of today's theoretical uncertainties on M_W and $\sin^2\theta^l_{eff}$
  - Implies three-loop EW calculations!
  - δM_W (4→1 MeV), $\delta\sin^2\theta^l_{eff}$ ($4.7\times10^{-5} \rightarrow 1\times10^{-5}$)
  - (Theoretical uncertainty estimates from recent Snowmass report)

Prospects of EW fit



- Logarithmic dependency on M_H → cannot compete with direct M_H meas.
- Indirect prediction M_H dominated by theory uncertainties.
  - No theory uncertainties: $M_H = 126 \pm 7$ GeV
  - With theory errors (R-fit scheme): $M_H = 126^{+10}_{-9}$ GeV
  - Present day theory uncertainties: $M_H = 126^{+20}_{-17}$ GeV
- If EWP-data central values unchanged, i.e. keep favoring low value of Higgs mass (94 GeV), ~5σ discrepancy with measured Higgs mass.

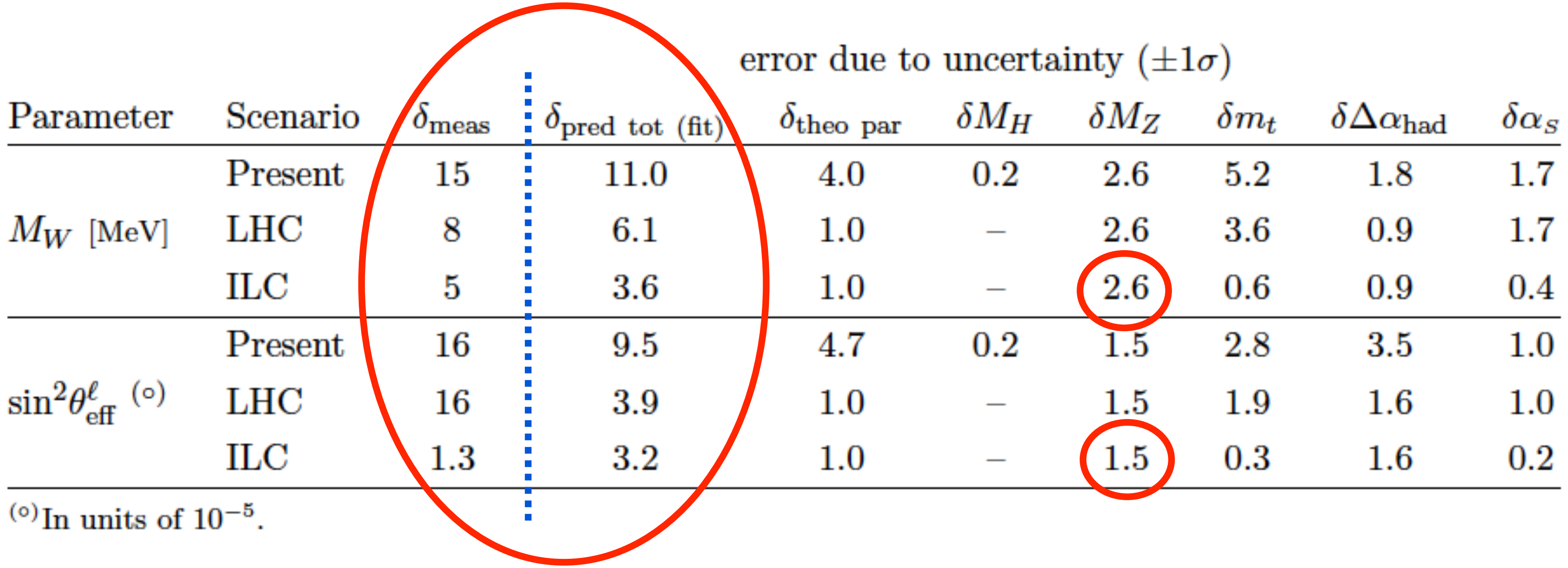
Prospects of EW fit



- Huge reduction of uncertainty on indirect determinations of m_t, m_W, and $\sin^2\theta^l_{eff}$, by a factor of 3 or more.
- Assuming central values of m_t and M_W do not change, (at ILC) a deviation between the SM prediction and the direct measurements would be prominently visible.

Confrontation of measurement and prediction

- Breakdown of predicted uncertainties for M_W and $\sin^2\theta^l_{eff}$

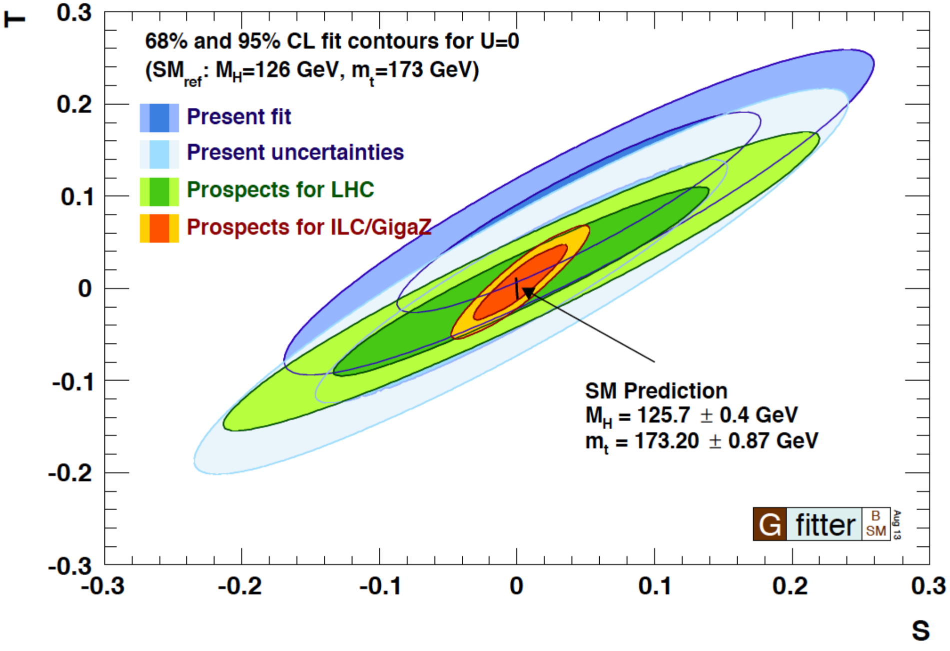


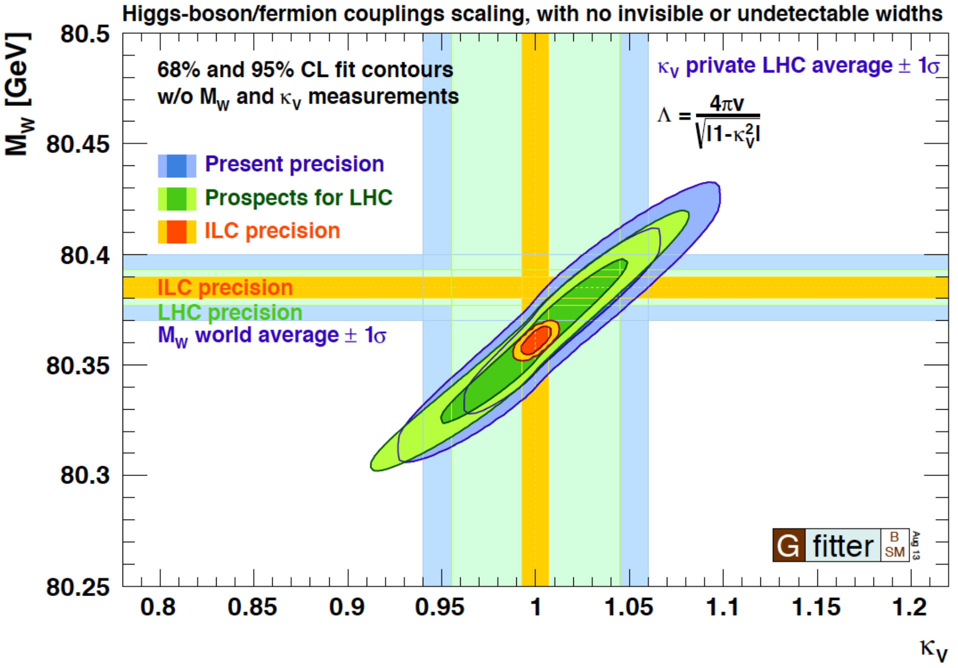
Parameter	Scenario	$\delta_{\rm meas}$	$\delta_{\rm pred\ tot\ (fit)}$	error due to uncertainty ($\pm1\sigma$)					
				$\delta_{\rm theo\ par}$	δM_H	δM_Z	δm_t	$\delta\Delta\alpha_{\rm had}$	$\delta\alpha_S$
M_W [MeV]	Present	15	11.0	4.0	0.2	2.6	5.2	1.8	1.7
	LHC	8	6.1	1.0	–	2.6	3.6	0.9	1.7
	ILC	5	3.6	1.0	–	2.6	0.6	0.9	0.4
$\sin^2\theta^\ell_{\rm eff}$ (∘)	Present	16	9.5	4.7	0.2	1.5	2.8	3.5	1.0
	LHC	16	3.9	1.0	–	1.5	1.9	1.6	1.0
	ILC	1.3	3.2	1.0	–	1.5	0.3	1.6	0.2

(∘)In units of 10^{-5}.

- M_W and $\sin^2\theta^l_{eff}$ are (and will be) sensitive probes of new physics!

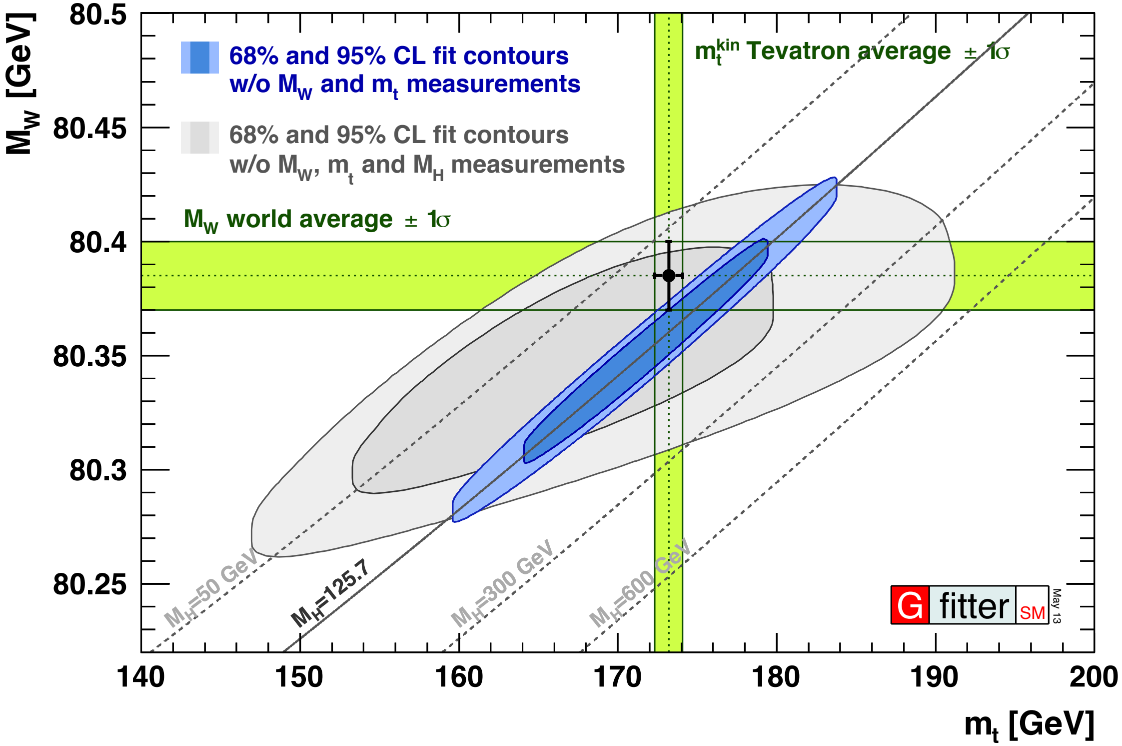
Prospects of EW fit





- For STU parameters, improvement of factor of >3 is possible at ILC.
- Again, at ILC a deviation between the SM predictions and direct measurements would be prominently visible.
- Competitive results between EW fit and Higgs coupling measurements!
  - (At level of 1%.)

Conclusions 1/2

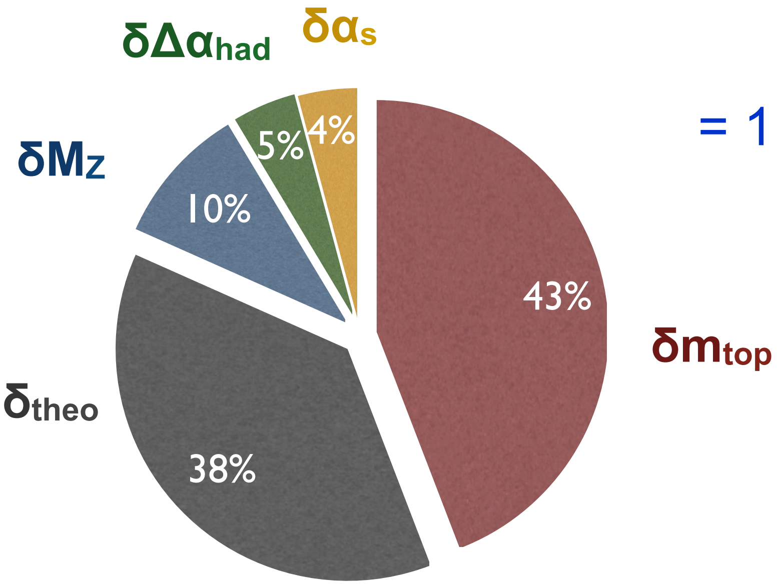


- Including M_H measurement, precise predictions of EW observables at loop level are possible for the first time.
- Overall consistency of the SM fit is very good.
  - M_H consistent at 1.3σ with indirect prediction from EW fit.
  - p-Value of global electroweak fit of SM: 18^{+2} % (pseudo-experiments)

Conclusions 2/2

- Paradigm shift for EW fit: from Higgs mass prediction to consistency tests of the Standard Model.
- Knowledge of M_H dramatically improves SM prediction of key observables
  - M_W (28→11 MeV), $\sin^2\theta^l_{eff}$ ($2.3\times10^{-5}\rightarrow1.0\times10^{-5}$), m_t (6.2→2.5 GeV)
  - Only surpassed sofar by top mass measurement.

- δM_W (indirect) = = 11 MeV
  - Large contributions to δM_W (and $\delta\sin^2\theta^l_{eff}$) from top and unknown higher-order EW corrections.
- δM_W (direct) = 15 MeV



- Improved accuracies set benchmark for new direct measurements!
  - M_W, $\sin^2\theta^l_{eff}$ (and Higgs couplings) sensitive probes of new physics.

Outlook

- Next step is evident: further exploration of Higgs couplings in the EW fit.
  - (Several groups already doing this. Gfitter too.)

- Prospects: including new data electroweak fits remain very interesting in coming years!
  - In particular ILC provides excellent New Physics sensitivity.

- Latest results always available at: http://cern.ch/Gfitter
  - Results of this presentation: EPJC 72, 2205 (2012)
  - *LHC-300 and ILC/GigaZ prospects paper to appear on arXiv this week !*

Thanks!

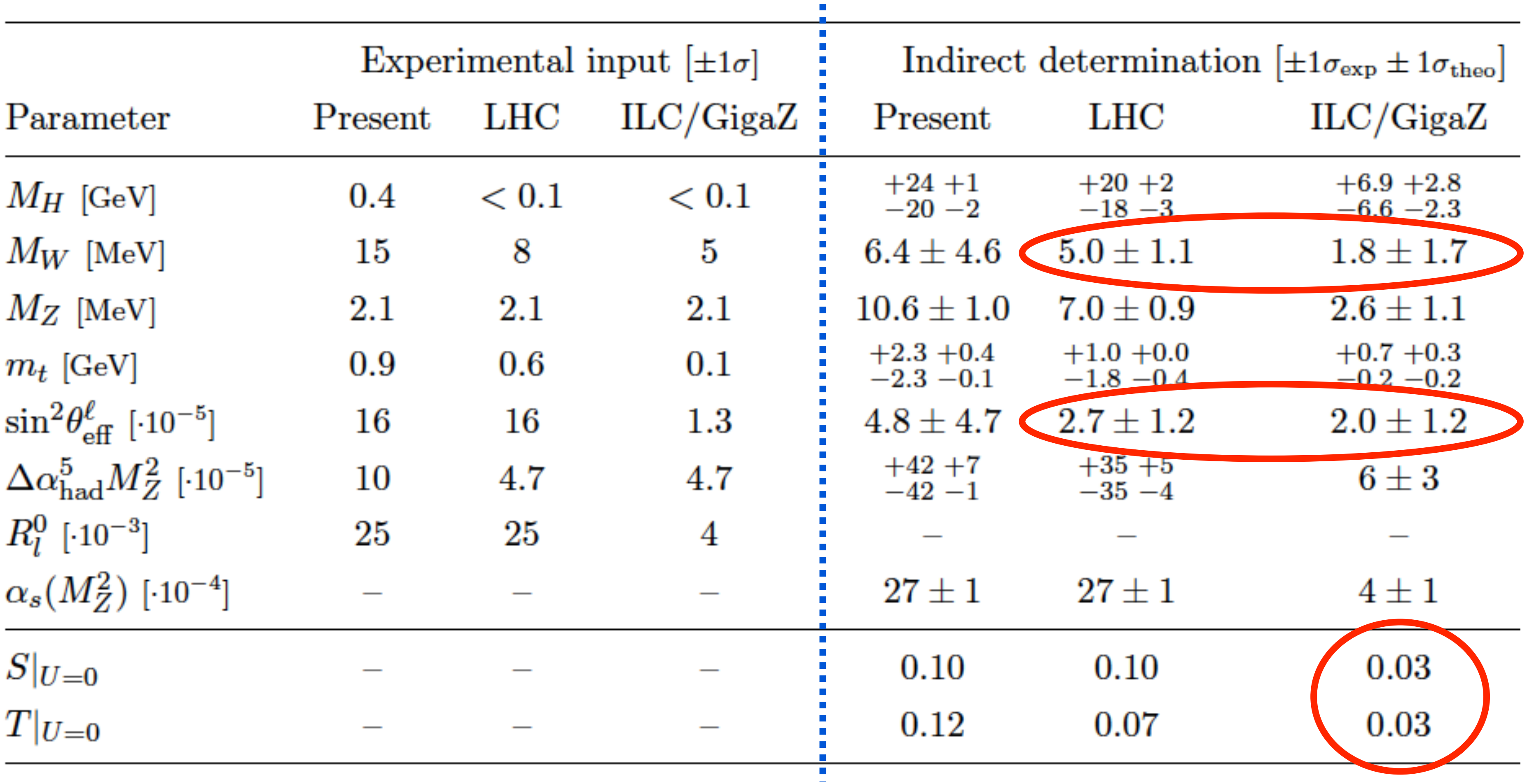
Backup

G fitter

A Generic Fitter Project for HEP Model Testing

Backup

Summary of indirect predictions



	Experimental input [$\pm 1\sigma$]			Indirect determination [$\pm 1\sigma_{\mathrm{exp}} \pm 1\sigma_{\mathrm{theo}}$]		
Parameter	Present	LHC	ILC/GigaZ	Present	LHC	ILC/GigaZ
M_H [GeV]	0.4	< 0.1	< 0.1	${}^{+24}_{-20}\,{}^{+1}_{-2}$	${}^{+20}_{-18}\,{}^{+2}_{-3}$	${}^{+6.9}_{-6.6}\,{}^{+2.8}_{-2.3}$
M_W [MeV]	15	8	5	6.4 ± 4.6	5.0 ± 1.1	1.8 ± 1.7
M_Z [MeV]	2.1	2.1	2.1	10.6 ± 1.0	7.0 ± 0.9	2.6 ± 1.1
m_t [GeV]	0.9	0.6	0.1	${}^{+2.3}_{-2.3}\,{}^{+0.4}_{-0.1}$	${}^{+1.0}_{-1.8}\,{}^{+0.0}_{-0.4}$	${}^{+0.7}_{-0.2}\,{}^{+0.3}_{-0.2}$
$\sin^2\theta^{\ell}_{\mathrm{eff}}$ [$\cdot 10^{-5}$]	16	16	1.3	4.8 ± 4.7	2.7 ± 1.2	2.0 ± 1.2
$\Delta\alpha^5_{\mathrm{had}} M_Z^2$ [$\cdot 10^{-5}$]	10	4.7	4.7	${}^{+42}_{-42}\,{}^{+7}_{-1}$	${}^{+35}_{-35}\,{}^{+5}_{-4}$	6 ± 3
R^0_l [$\cdot 10^{-3}$]	25	25	4	–	–	–
$\alpha_s(M_Z^2)$ [$\cdot 10^{-4}$]	–	–	–	27 ± 1	27 ± 1	4 ± 1
$S\vert_{U=0}$	–	–	–	0.10	0.10	0.03
$T\vert_{U=0}$	–	–	–	0.12	0.07	0.03

- M_W and $\sin^2\theta^l_{\mathrm{eff}}$ are (and will be) sensitive probes of new physics!

TLEP prospects

- From: arXiv:1308.6176

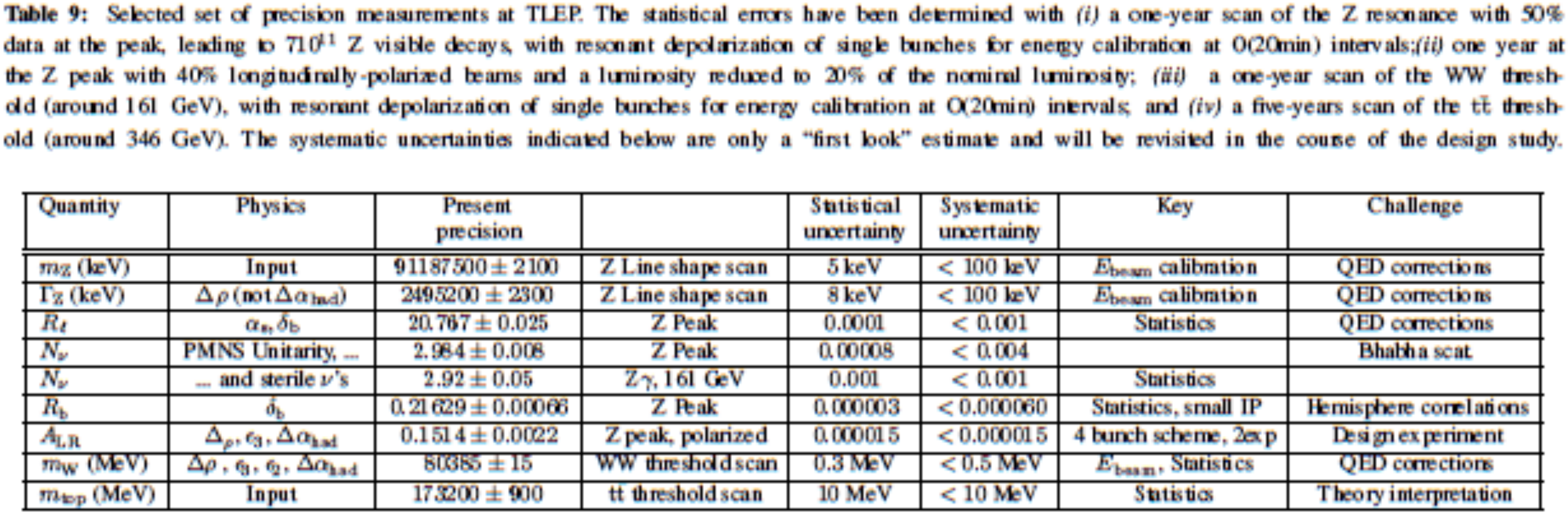
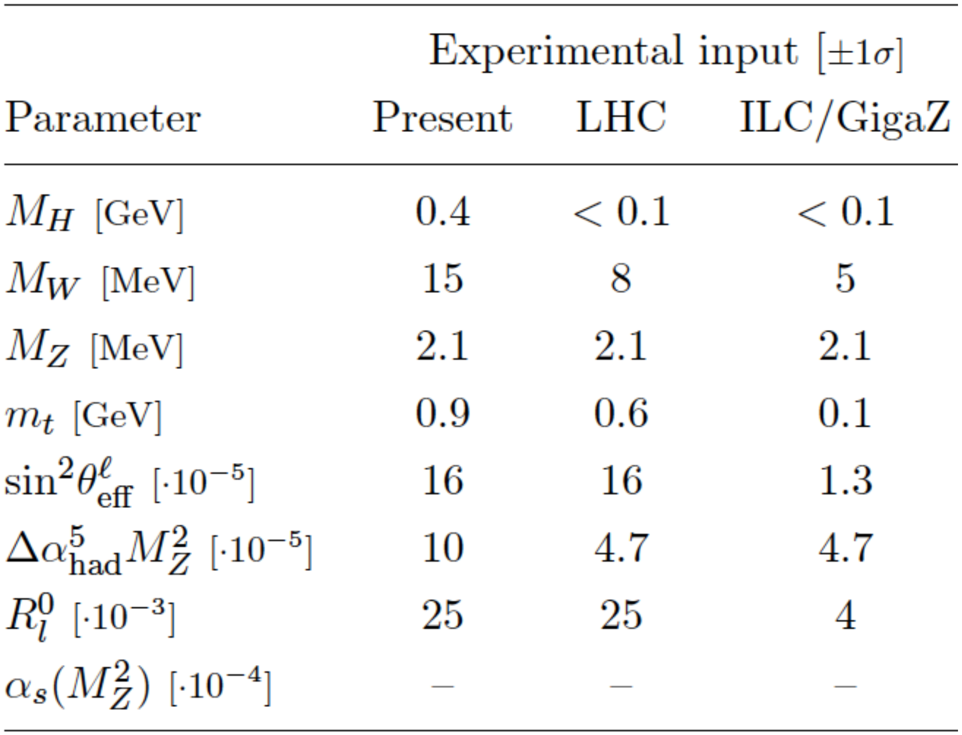


Table 9: Selected set of precision measurements at TLEP. The statistical errors have been determined with *(i)* a one-year scan of the Z resonance with 50% data at the peak, leading to 710^{11} Z visible decays, with resonant depolarization of single bunches for energy calibration at O(20min) intervals;*(ii)* one year at the Z peak with 40% longitudinally-polarized beams and a luminosity reduced to 20% of the nominal luminosity; *(iii)* a one-year scan of the WW threshold (around 161 GeV), with resonant depolarization of single bunches for energy calibration at O(20min) intervals; and *(iv)* a five-years scan of the $t\bar{t}$ threshold (around 346 GeV). The systematic uncertainties indicated below are only a "first look" estimate and will be revisited in the course of the design study.

Quantity	Physics	Present precision		Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 keV	< 100 keV	$E_{\rm beam}$ calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{\rm had}$)	2495200 ± 2300	Z Line shape scan	8 keV	< 100 keV	$E_{\rm beam}$ calibration	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	< 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008	< 0.004		Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.001	< 0.001	Statistics	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003	< 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta_\rho, \epsilon_3, \Delta\alpha_{\rm had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{\rm had}$	80385 ± 15	WW threshold scan	0.3 MeV	< 0.5 MeV	$E_{\rm beam}$, Statistics	QED corrections
$m_{\rm top}$ (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 MeV	< 10 MeV	Statistics	Theory interpretation

Two prospects scenarios: LHC-300, ILC/GigaZ

- Uncertainty estimates used:

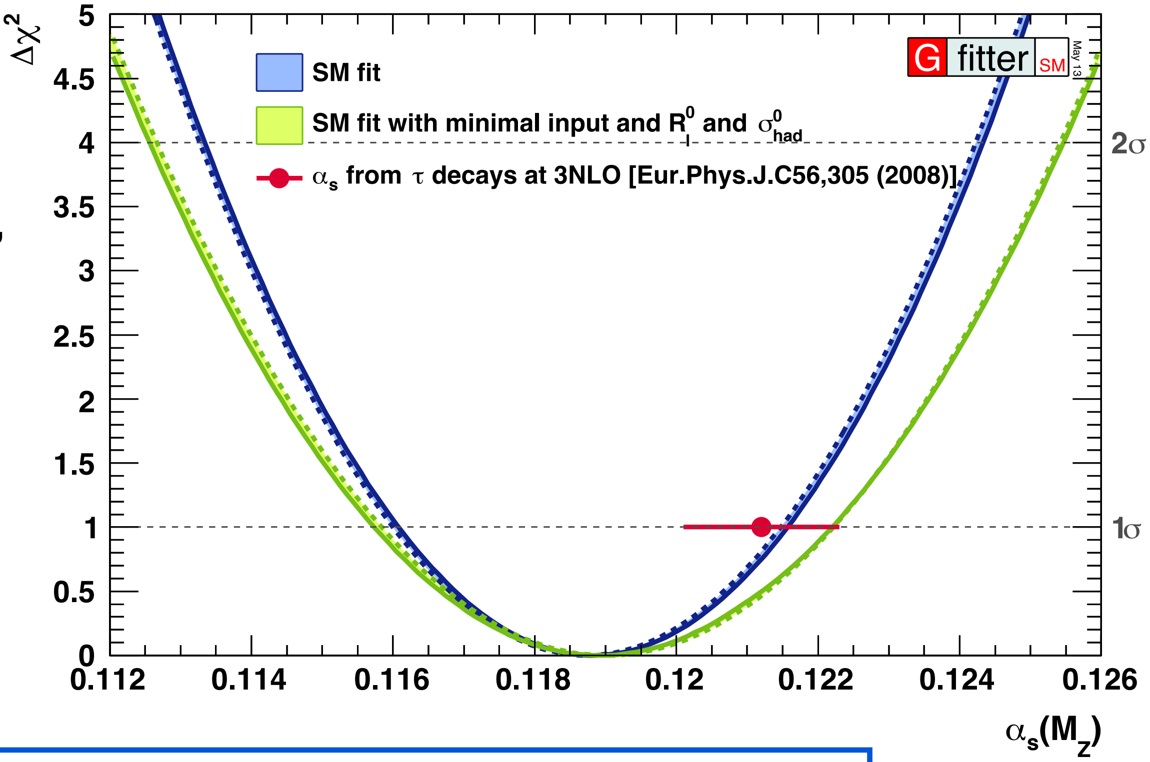


Parameter	Experimental input [$\pm 1\sigma$] Present	LHC	ILC/GigaZ
M_H [GeV]	0.4	< 0.1	< 0.1
M_W [MeV]	15	8	5
M_Z [MeV]	2.1	2.1	2.1
m_t [GeV]	0.9	0.6	0.1
$\sin^2\theta^{\ell}_{\mathrm{eff}}$ [$\cdot 10^{-5}$]	16	16	1.3
$\Delta\alpha^5_{\mathrm{had}} M^2_Z$ [$\cdot 10^{-5}$]	10	4.7	4.7
R^0_l [$\cdot 10^{-3}$]	25	25	4
$\alpha_s(M^2_Z)$ [$\cdot 10^{-4}$]	–	–	–

  - ILC prospects from: ILC TDR (Vol-2).
  - Theoretical uncertainty estimates from recent Snowmass report
- Central values of input measurements adjusted to M_H = 126 GeV.

Prediction for $\alpha_s(M_Z)$ from Z→hadrons

- Scan of $\Delta\chi^2$ versus α_s
  - Also shown: SM fit with minimal inputs: M_Z, G_F, $\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H, and fermion masses
- Determination of α_s at N^{3}LO.
  - Most sensitive through total hadronic cross-section σ^0_{had} and partial leptonic width R^0_l



$$\alpha_s(M_Z) = 0.1190^{+0.0028}_{-0.0027}\,(\mathrm{exp.}) \pm 0.0001\,(\mathrm{theo.})$$

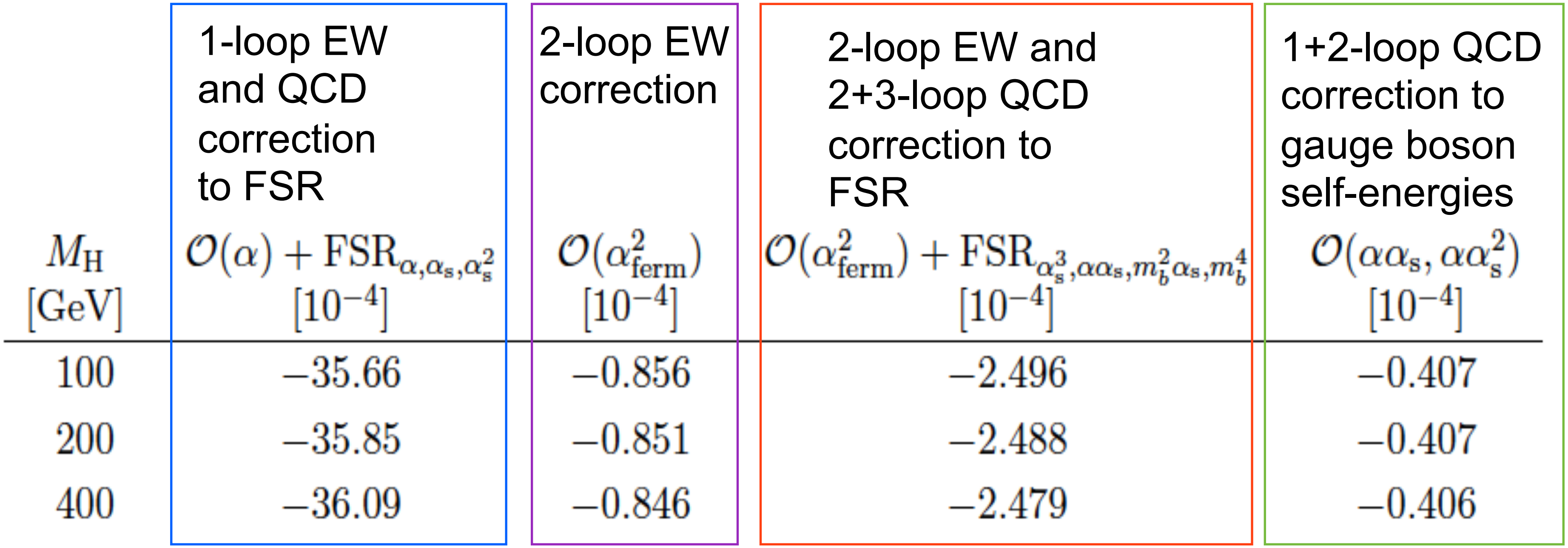
  - Theory uncertainty at per-mille level (obtained by scale variation of Γ_{had}).

- *In good agreement with value from τ decays, also at N^{3}LO, and with WA.*
  - (Improvements in precision only expected with ILC/GigaZ. See later.)

New R^0_b calculation

[A. Freitas et al., JHEP 1208, 050 (2012)]

- The branching ratio R^0_b: partial decay width of Z→bb to Z→qq
- Freitas et al: full EW 2-loop calculation of Z→bb
- Contribution of same terms as in the calculation of $\sin^2\theta^{bb}_{eff}$
→ cross-check of two results found good agreement
- Two-loop EW corrections now much smaller than experimental uncertainty (6.6×10^{-4})



$M_{\rm H}$ [GeV]	1-loop EW and QCD correction to FSR $\mathcal{O}(\alpha)+\mathrm{FSR}_{\alpha,\alpha_s,\alpha_s^2}$ [10^{-4}]	2-loop EW correction $\mathcal{O}(\alpha^2_{\rm ferm})$ [10^{-4}]	2-loop EW and 2+3-loop QCD correction to FSR $\mathcal{O}(\alpha^2_{\rm ferm})+\mathrm{FSR}_{\alpha_s^3,\alpha\alpha_s,m_b^2\alpha_s,m_b^4}$ [10^{-4}]	1+2-loop QCD correction to gauge boson self-energies $\mathcal{O}(\alpha\alpha_s,\alpha\alpha_s^2)$ [10^{-4}]
100	−35.66	−0.856	−2.496	−0.407
200	−35.85	−0.851	−2.488	−0.407
400	−36.09	−0.846	−2.479	−0.406

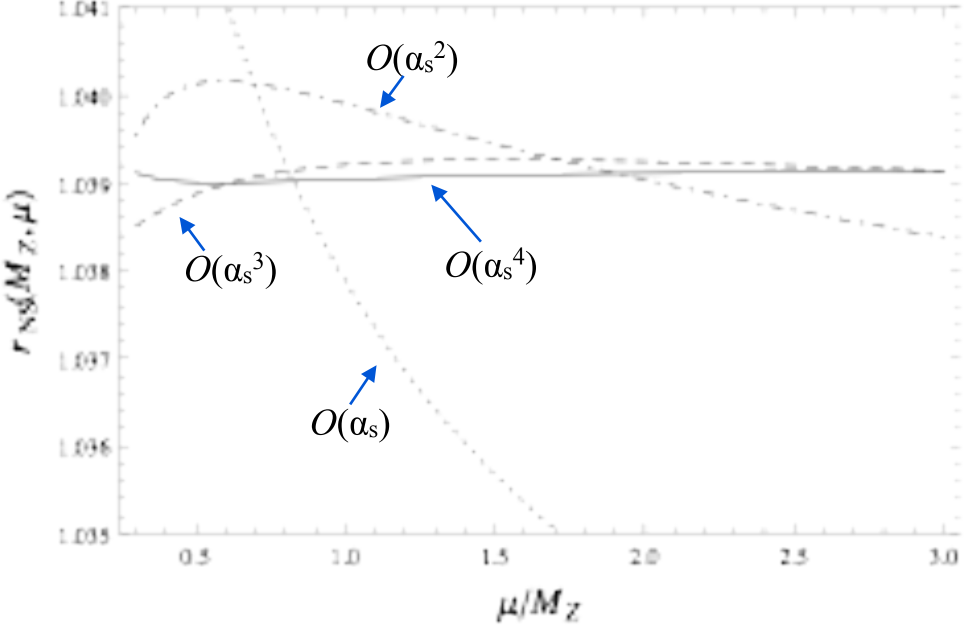
Radiator Functions

- Partial widths are defined inclusively: contain both QCD and QED contributions.
- Corrections expressed as so-called radiator functions $R_{A,f}$ and $R_{V,f}$

$$\Gamma_{f\bar{f}} = N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi} \left(|g_{A,f}|^2 R_{A,f} + |g_{V,f}|^2 R_{V,f} \right)^2$$

[D. Bardin, G. Passarino, “The Standard Model in the Making”, Clarendon Press (1999)]

- High sensitivity to the strong coupling α_s
- Recently, full four-loop calculation of QCD Adler function became available (N^3LO)
- Much-reduced scale dependence!
- Theoretical uncertainty of 0.1 MeV, compared with experimental uncertainty of 2.0 MeV.

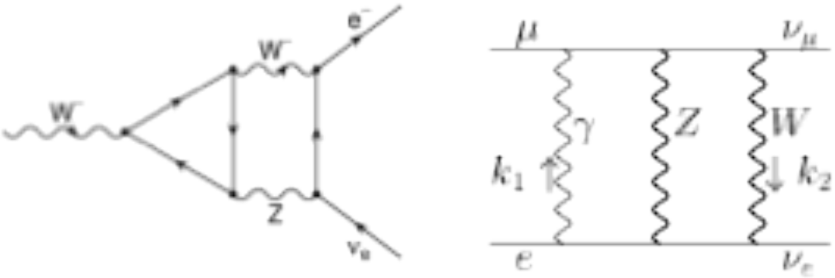


[P. Baikov et al., Phys. Rev. Lett. 108, 222003 (2012)]
[P. Baikov et al Phys. Rev. Lett. 104, 132004 (2010)]

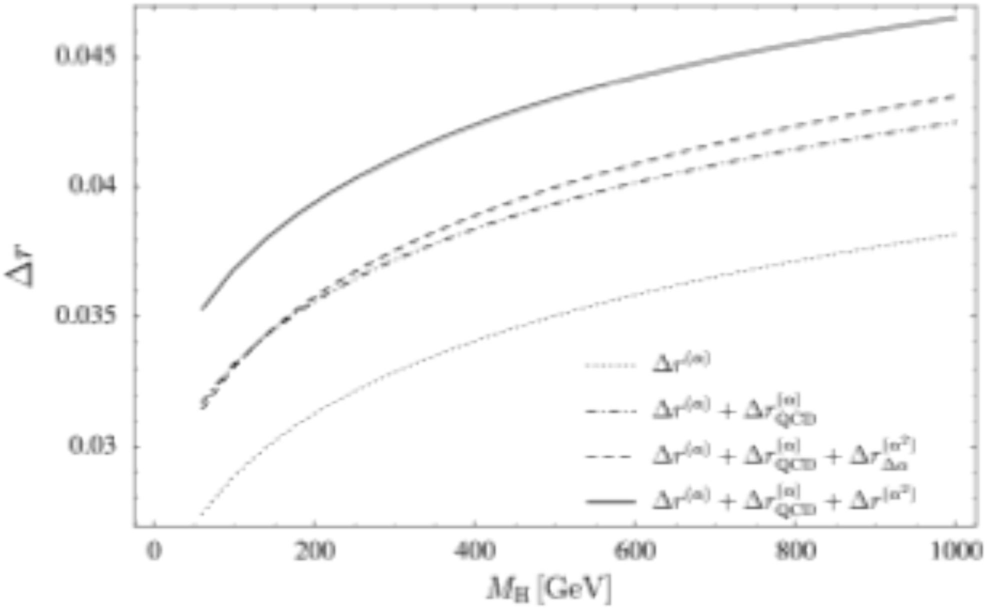
Calculation of M_W

- Full EW one- and two-loop calculation of fermionic and bosonic contributions.
- One- and two-loop QCD corrections and leading terms of higher order corrections.
- Results for Δr include terms of order $O(\alpha)$, $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{ferm})$, $O(\alpha^2_{bos})$, $O(\alpha^2\alpha_s m_t^4)$, $O(\alpha^3 m_t^6)$
- Uncertainty estimate:
  - Missing terms of order $\mathbf{O(\alpha^2\alpha_s)}$: about 3 MeV (from $O(\alpha^2\alpha_s m_t^4)$)
  - Electroweak three-loop correction $\mathbf{O(\alpha^3)}$: < 2 MeV
  - Three-loop QCD corrections $\mathbf{O(\alpha_s^3)}$: < 2 MeV
- Total: $\delta M_W \approx 4$ MeV

[M Awramik et al., Phys. Rev. D69, 053006 (2004)]
[M Awramik et al., Phys. Rev. Lett. 89, 241801 (2002)]



[A Freitas et al., Phys. Lett. B495, 338 (2000)]



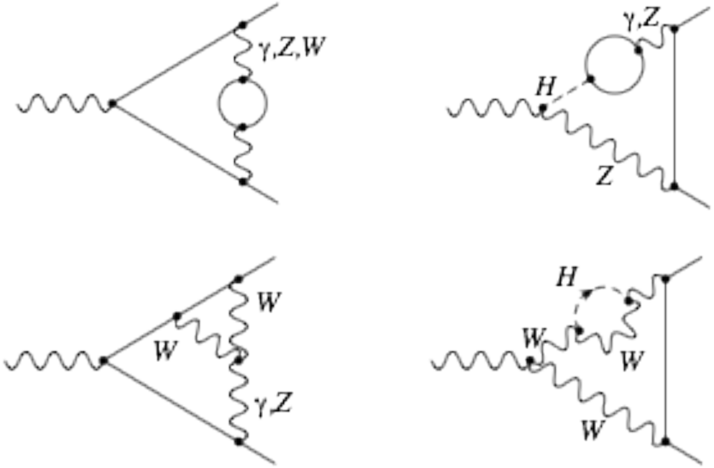
Calculation of $\sin^2(\theta^l_{eff})$

[M Awramik et al, Phys. Rev. Lett. 93, 201805 (2004)]
[M Awramik et al., JHEP 11, 048 (2006)]

- Effective mixing angle:

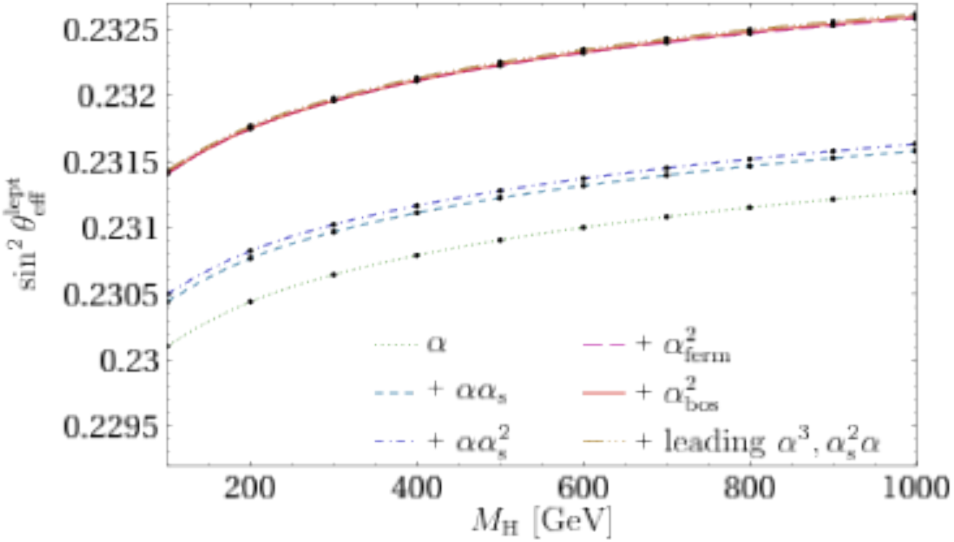
$$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = \left(1 - M_W^2/M_Z^2\right)(1 + \Delta\kappa)$$

- Two-loop EW and QCD correction to Δκ known, leading terms of higher order QCD corrections.



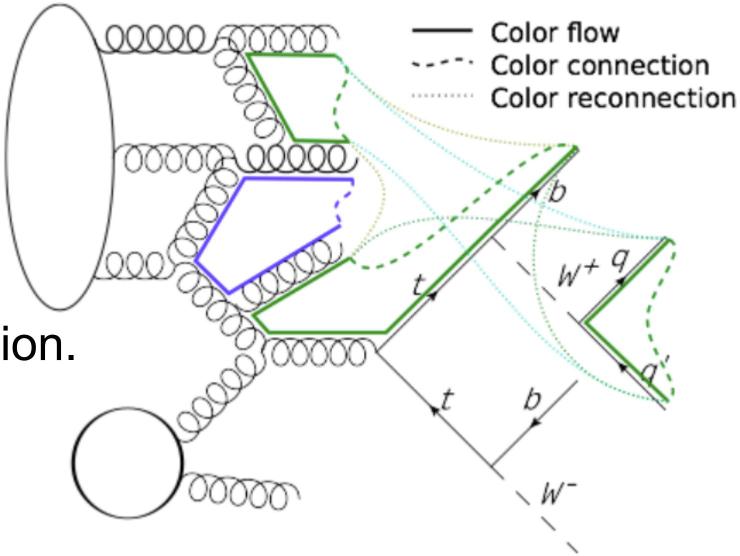
- Fermionic two-loop correction about 10^{-3}, whereas bosonic one 10^{-5}.

- Uncertainty estimate obtained with different methods, geometric progression, leading to total of: $\delta\sin^2(\theta^l_{eff}) = 4.7\mathrm{x}10^{-5}$



Uncertainty in Top mass definition

- Difficult to define a pole mass for heavy, unstable and colored particle.
  - Single top decays before hadronizing. To have colorless final states, additional quarks needed.
  - *Non-perturb.* color-reconnection effects in fragmentation → biases in simulation.
  - ‘Renormalon’ ambiguity in top mass definition.
    - For pole mass, not for MS-bar scheme.
  - Impact of finite top width effects.



- Result: $m_t^{exp} \neq m_t^{pole}$, and event-dependent.
- The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_t)$ ~ 1 GeV

- Hard to estimate additional theo. uncertainties. With 0.5 GeV on m_t:
  - $M_H = 90^{+34}_{-21}$ GeV, $M_W = 80.359 \pm 0.013$ GeV, $\sin^2\theta^l_{eff} = 0.23148 \pm 0.00010$.
  - Only small deterioration in precision.

Electroweak Fit – SM Fit Results

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H

Parameter	Input value	Free in fit	Fit Result
M_H [GeV]°	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014
σ^0_{had} [nb]	41.540 ± 0.037	–	41.479 ± 0.014
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	$0.23149^{+0.00010}_{-0.00008}$
A_c	0.670 ± 0.027	–	$0.6679^{+0.00034}_{-0.00028}$
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11
$\alpha_s(M_Z^2)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$
$\delta_{\mathrm{th}} M_W$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	yes	4
$\delta_{\mathrm{th}} \sin^2\theta^\ell_{\mathrm{eff}}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\mathrm{theo}}$	yes	-0.6

Electroweak Fit – SM Fit Results

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: not incl. M_H

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements
M_H [GeV]°	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367\,^{+0.006}_{-0.007}$	$80.367\,^{+0.006}_{-0.007}$
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014
σ^0_{had} [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	–	$0.01626\,^{+0.0001}_{-0.0002}$	$0.01626\,^{+0.0001}_{-0.0002}$
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012	–	$0.23149\,^{+0.00010}_{-0.00008}$	$0.23149\,^{+0.00010}_{-0.00008}$
A_c	0.670 ± 0.027	–	$0.6679\,^{+0.00034}_{-0.00028}$	$0.6679\,^{+0.00034}_{-0.00028}$
A_b	0.923 ± 0.020	–	$0.93464\,^{+0.00005}_{-0.00007}$	$0.93464\,^{+0.00005}_{-0.00007}$
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	yes	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	yes	$4.20\,^{+0.17}_{-0.07}$	$4.20\,^{+0.17}_{-0.07}$
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82
$\Delta\alpha^{(5)}_{\text{had}}(M^2_Z)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11
$\alpha_s(M^2_Z)$	–	yes	$0.1190\,^{+0.0028}_{-0.0027}$	$0.1190\,^{+0.0028}_{-0.0027}$
$\delta_{\text{th}} M_W$ [MeV]	$[-4, 4]_{\text{theo}}$	yes	4	4
$\delta_{\text{th}} \sin^2\theta^\ell_{\text{eff}}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\text{theo}}$	yes	-0.6	-0.5

Electroweak Fit – SM Fit Results

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: not incl. M_H
- Right: fit incl M_H, not the row

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]°	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367\,^{+0.006}_{-0.007}$	$80.367\,^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021	91.1978 ± 0.0114
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014	2.4950 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	$0.01626\,^{+0.0001}_{-0.0002}$	$0.01626\,^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
$A_\ell\ ^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	$0.23149\,^{+0.00010}_{-0.00008}$	$0.23149\,^{+0.00010}_{-0.00008}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6679\,^{+0.00034}_{-0.00028}$	$0.6679\,^{+0.00034}_{-0.00028}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464\,^{+0.00005}_{-0.00007}$	$0.93464\,^{+0.00005}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005	0.21547 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	yes	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	yes	$4.20\,^{+0.17}_{-0.07}$	$4.20\,^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82	$176.11\,^{+2.88}_{-2.35}$
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)\ ^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11	2718^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	$0.1190\,^{+0.0028}_{-0.0027}$	$0.1190\,^{+0.0028}_{-0.0027}$	0.1190 ± 0.0027
$\delta_{\mathrm{th}} M_W$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	yes	4	4	–
$\delta_{\mathrm{th}} \sin^2\theta^\ell_{\mathrm{eff}}\ ^{(\dagger)}$	$[-4.7, 4.7]_{\mathrm{theo}}$	yes	-0.6	-0.5	–

Electroweak Fit – SM Fit Results

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: not incl. M_H
- Right: fit incl M_H, not the row

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]°	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.367^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021	91.1978 ± 0.0114
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014	2.4950 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23149^{+0.00010}_{-0.00008}$	$0.23149^{+0.00010}_{-0.00008}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6679^{+0.00034}_{-0.00028}$	$0.6679^{+0.00034}_{-0.00028}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93464^{+0.00005}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005	0.21547 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11	2718^{+49}_{-43}
$\alpha_s(M^2_Z)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1190 ± 0.0027
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-0.6	-0.5	–

Moriond 2011: Prediction for Higgs mass

- LEP + Tevatron (Fall 2010) :
  - CL^{2s}_{s+b} central value ±1σ: $M_H = 120.2^{+17.9}_{-5.2}$ GeV
  - 2σ interval:

$$-2\ln Q: \quad [115,152]\ \mathrm{GeV}$$

$$CL^{2-sided}_{s+b}: \quad [114,155]\ \mathrm{GeV}$$

- LEP + Tevatron (Moriond 2011) :
  - CL^{2s}_{s+b} central value ±1σ: $M_H = 120.2^{+12.3}_{-4.7}$ GeV
  - 2σ interval:

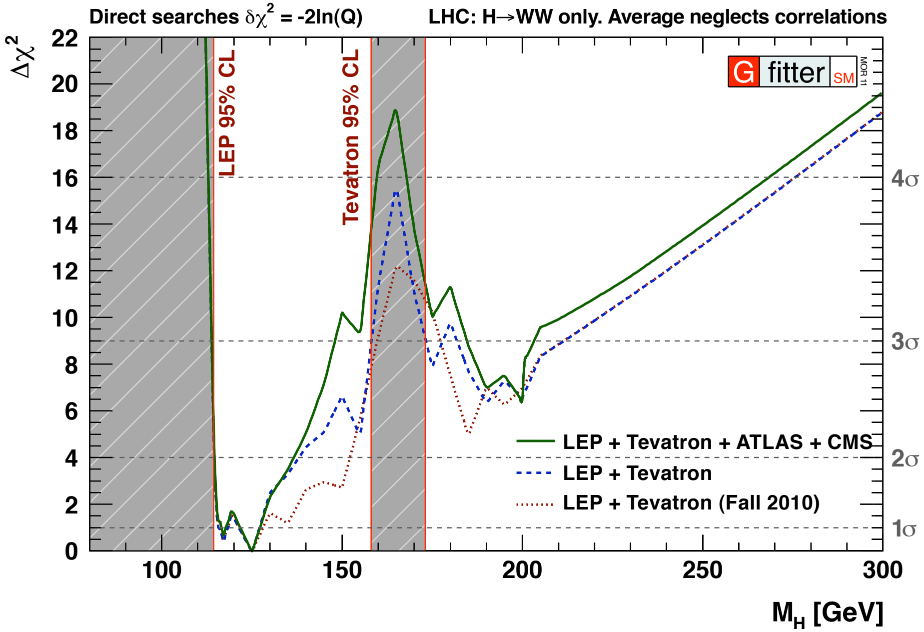
$$-2\ln Q: \quad [115,138]\ \mathrm{GeV}$$

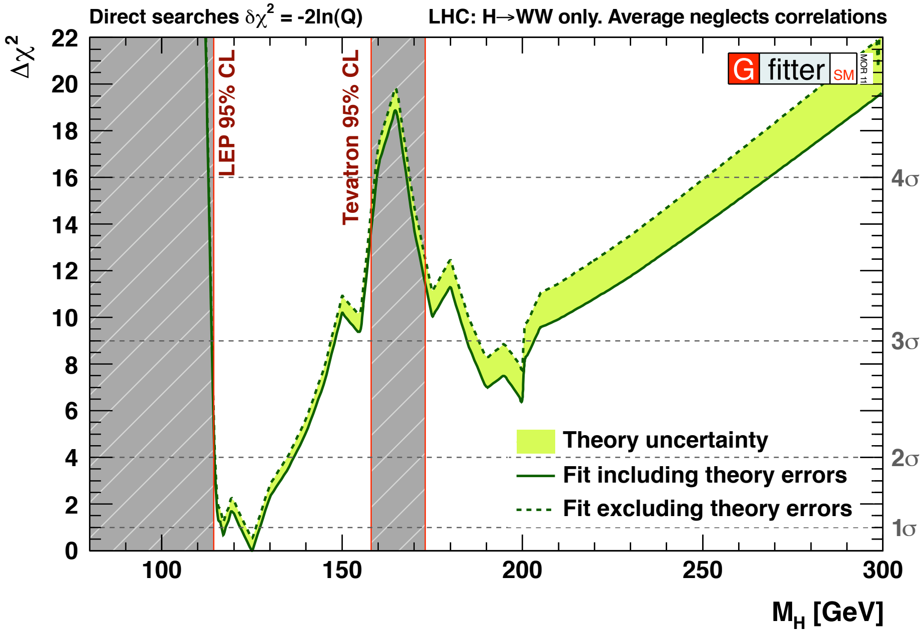
$$CL^{2-sided}_{s+b}: \quad [114,149] \cup [152,155]\ \mathrm{GeV}$$

- Fit with LEP + Tevatron + LHC (H➔WW) searches (Moriond 2011) :
  - Central value unchanged
  - 2σ interval:

$$-2\ln Q: \quad [115,137]\ \mathrm{GeV}$$

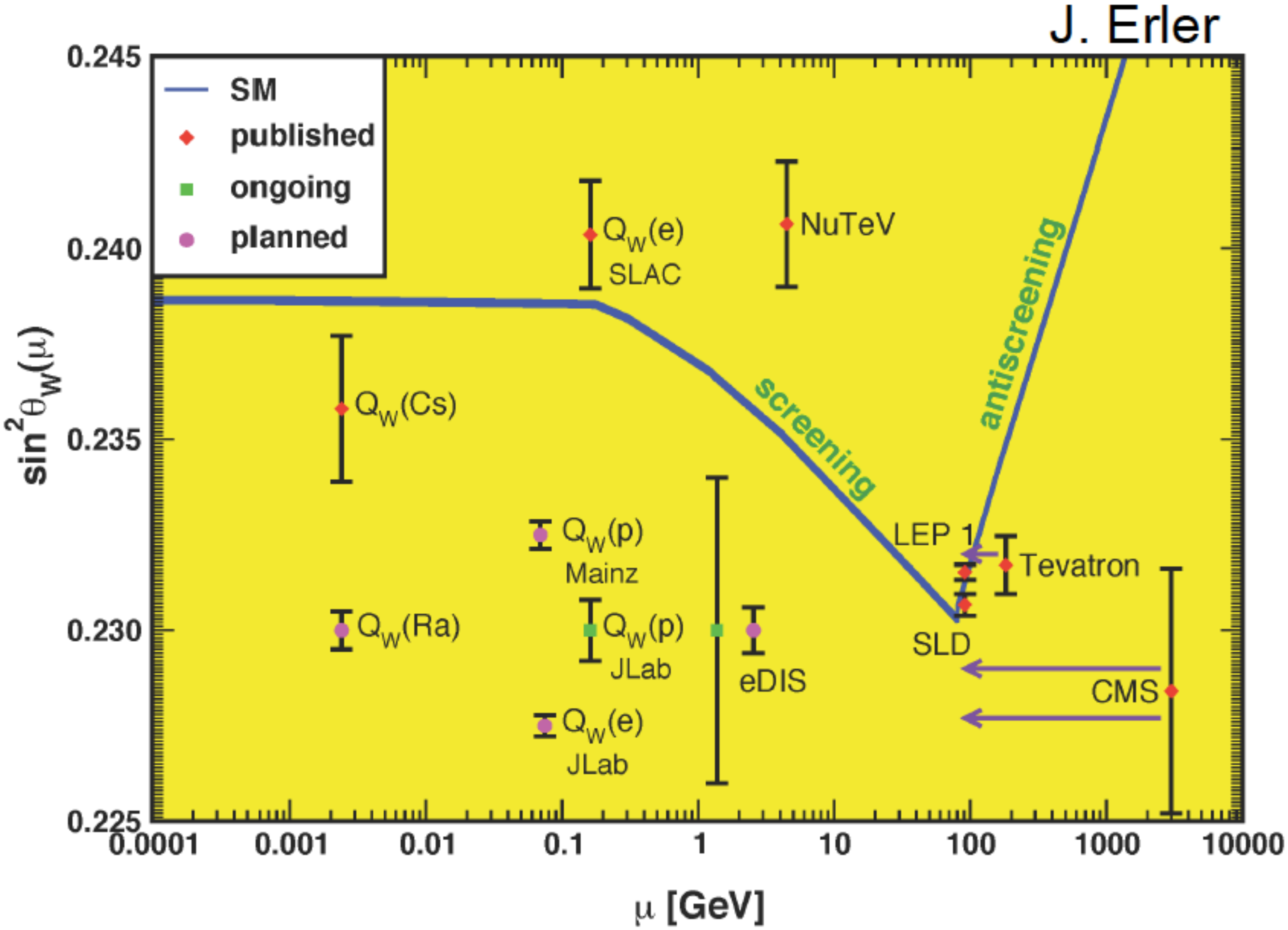
$$CL^{2-sided}_{s+b}: \quad [114,14?]\ \mathrm{GeV}$$





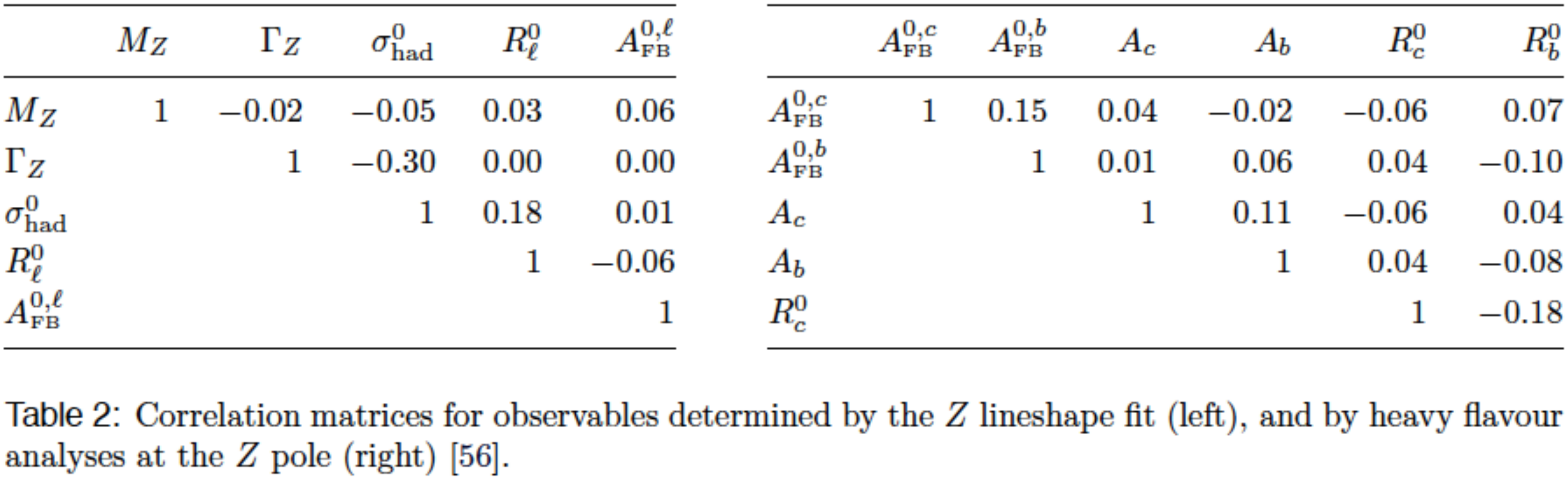
Low energy observables

- Low energy observables with interesting precision will soon become available.



Input correlations of the EW fit

- Input correlation coefficients between Z pole measurements



	M_Z	Γ_Z	σ^0_{had}	R^0_ℓ	$A^{0,\ell}_{\mathrm{FB}}$
M_Z	1	-0.02	-0.05	0.03	0.06
Γ_Z		1	-0.30	0.00	0.00
σ^0_{had}			1	0.18	0.01
R^0_ℓ				1	-0.06
$A^{0,\ell}_{\mathrm{FB}}$					1

	$A^{0,c}_{\mathrm{FB}}$	$A^{0,b}_{\mathrm{FB}}$	A_c	A_b	R^0_c	R^0_b
$A^{0,c}_{\mathrm{FB}}$	1	0.15	0.04	-0.02	-0.06	0.07
$A^{0,b}_{\mathrm{FB}}$		1	0.01	0.06	0.04	-0.10
A_c			1	0.11	-0.06	0.04
A_b				1	0.04	-0.08
R^0_c					1	-0.18

Table 2: Correlation matrices for observables determined by the Z lineshape fit (left), and by heavy flavour analyses at the Z pole (right) [56].