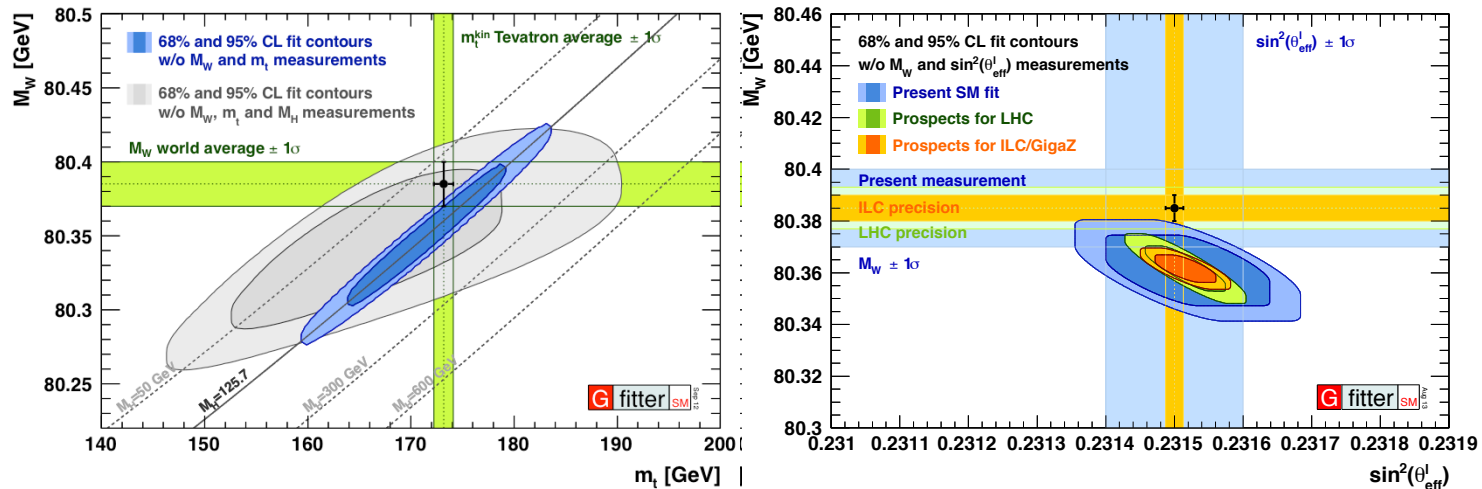




<http://cern.ch/Gfitter>

EPJC 72, 2205 (2012), arXiv:1209.2716

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



G **fit**ter

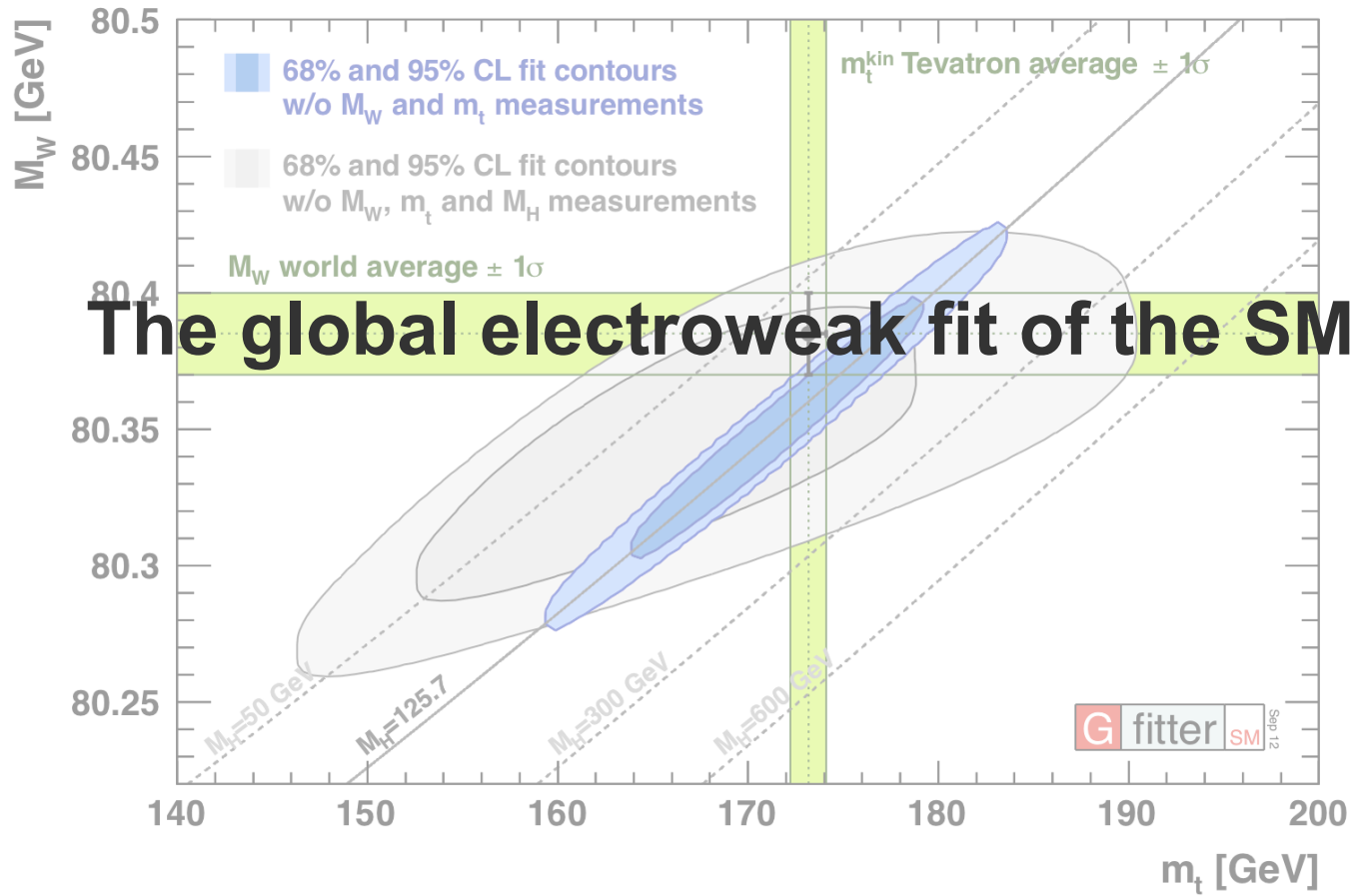
This presentation:

- 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



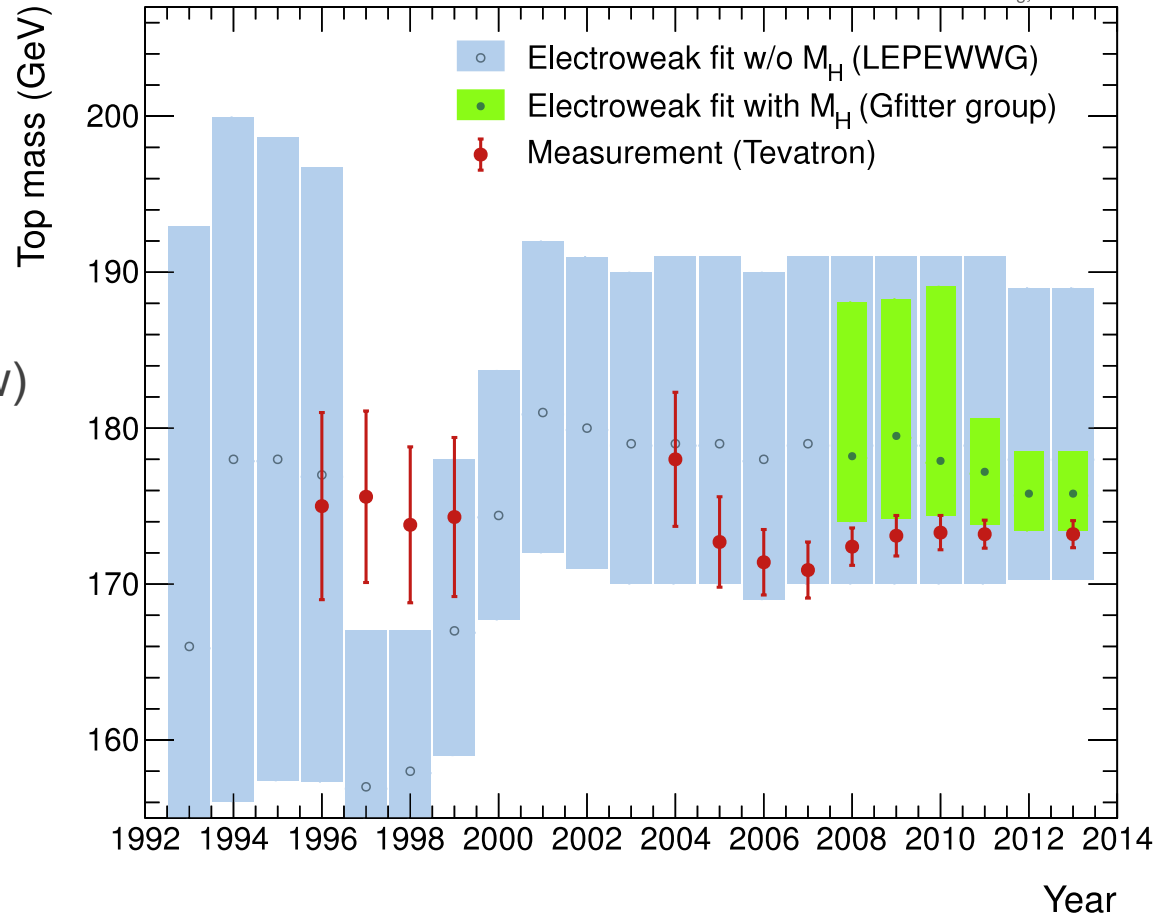
A **G**eneric **F**itter Project for HEP Model Testing

- 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, ...



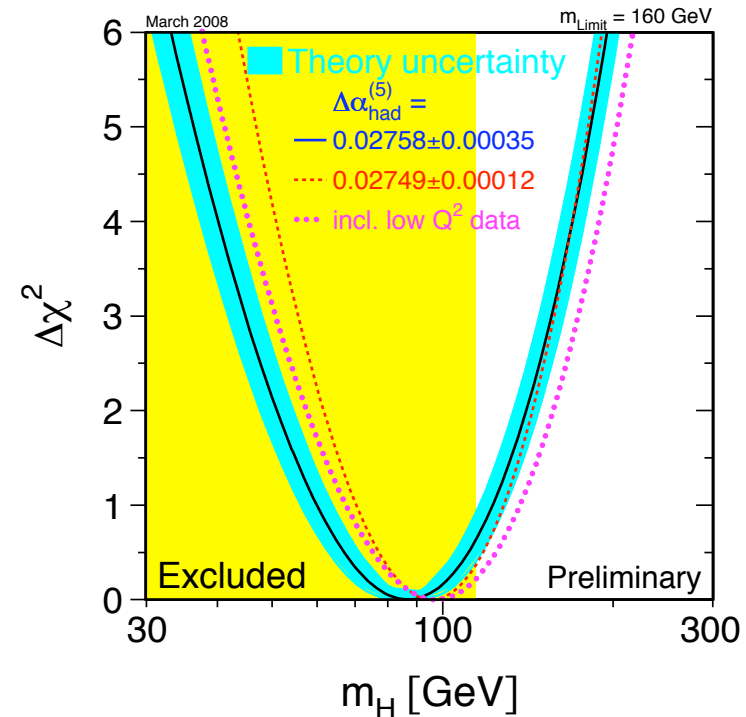
- ✓ Observables receive quantum loop corrections from ‘unseen’ virtual effects.
- ✓ If system is over-constrained, one can fit for unknown parameters or test the model’s self-consistency.
- ✓ If precision is better than typical loop factor ($\alpha \approx 1/137$), test the model or try to obtain info on new physics in loops.
 - For example, in the past EW fits were used to predict the Higgs mass.

- 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!

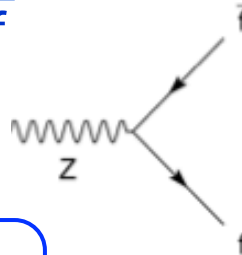
- EW fits performed by many groups in past and present.
 - D. Bardinet al. (ZFITTER), G. Passarino et al. (TOPAZ0), LEPEW WG (M. Grünewald, K. Mönig et al.), J. Erler (GAP), Bayesian fit (M. Ciuchini, L. Silvestrini et al.), etc ...
 - Important results obtained!
- Several groups pursuing global beyond-SM 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 $Z \rightarrow f\bar{f}$

- $$i\bar{f}\gamma^\mu (g_{V,f} - g_{A,f}\gamma_5) f Z_\mu$$

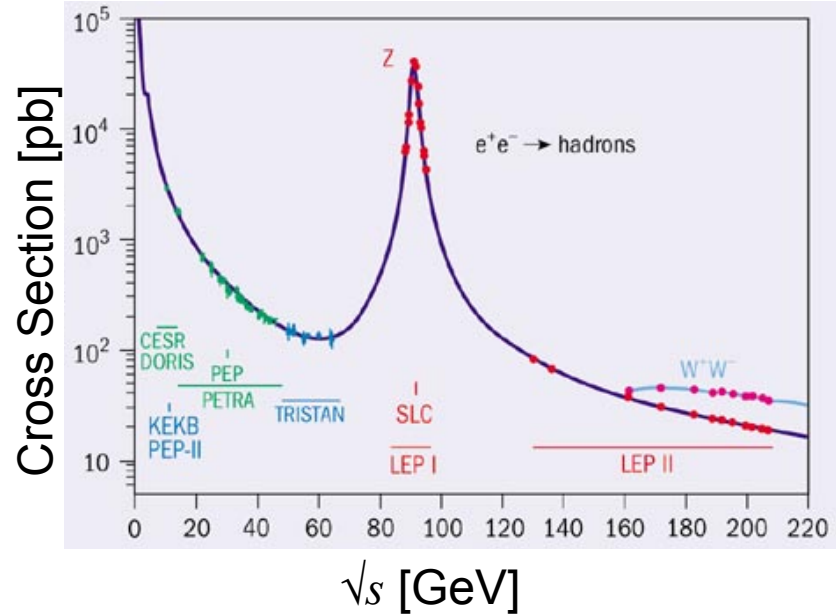


- Prediction EWSB at tree-level:

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

- The impact of loop corrections

- Absorbed into EW form factors: ρ , κ , Δr
- Effective couplings at the Z-pole
- Quadratically dependent on m_t , logarithmic dependence on M_H

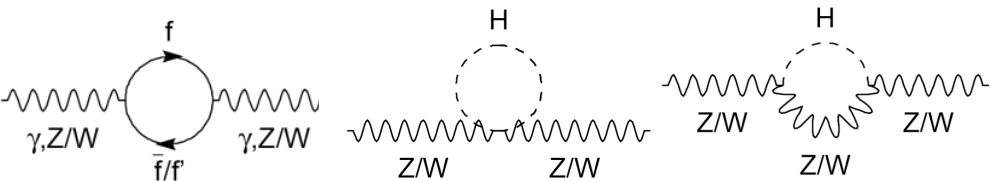


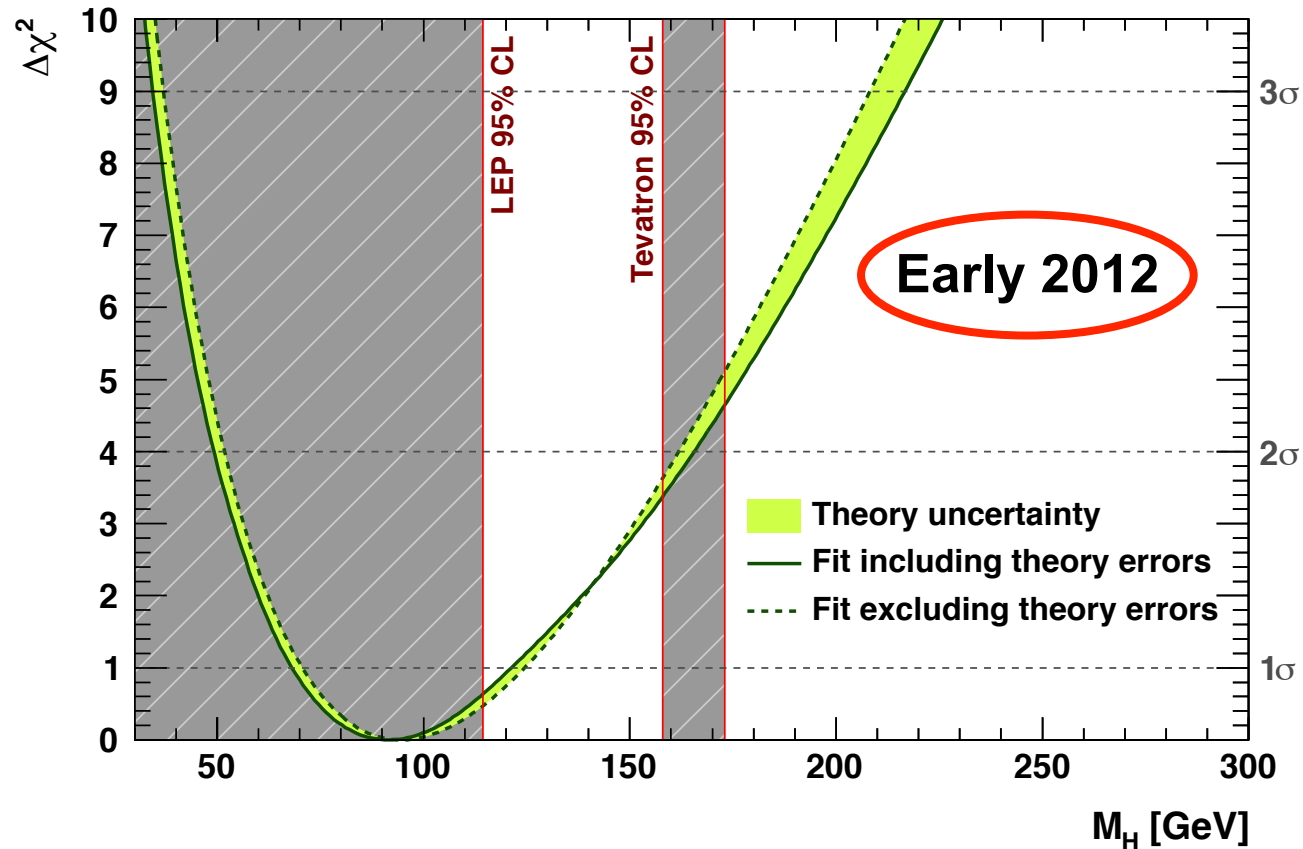
$$g_{V,f} = \sqrt{\rho_Z^f} (I_3^f - 2Q^f \sin^2 \theta_{\text{eff}}^f)$$

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

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

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



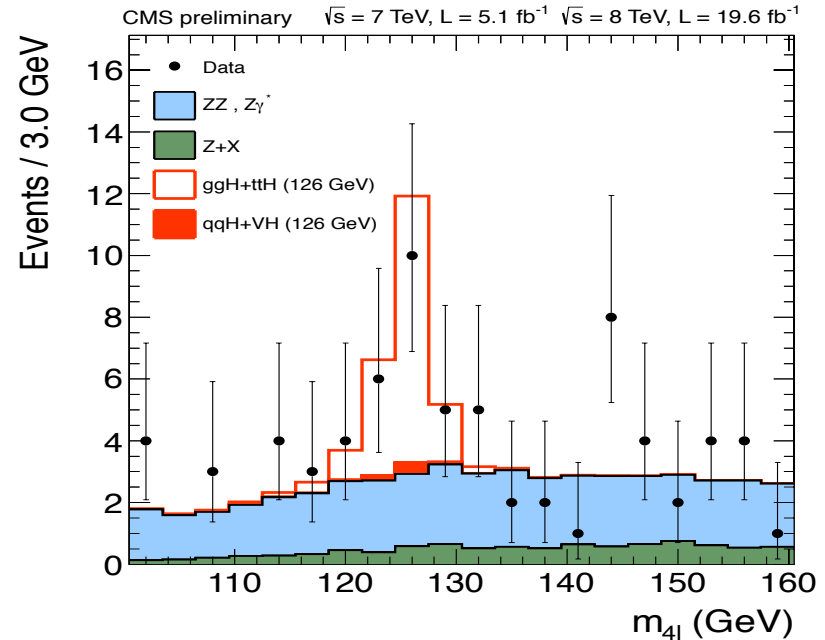
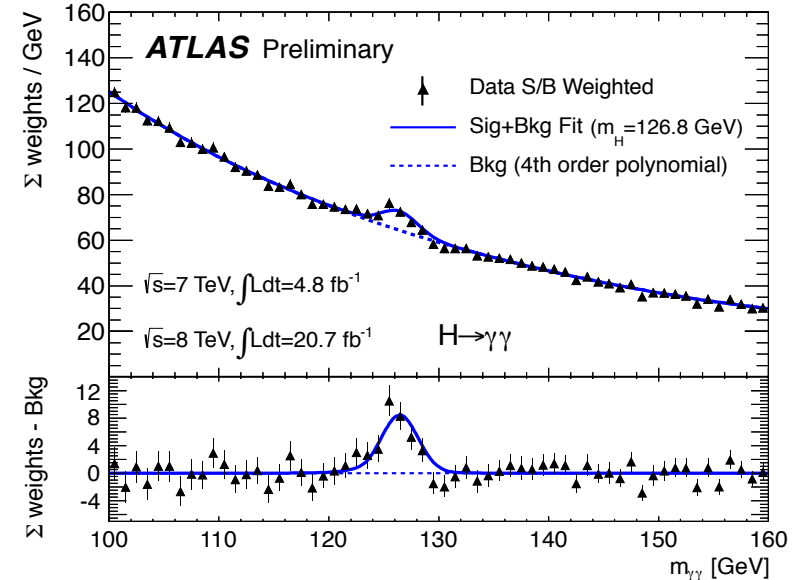


- M_H was last missing input parameter of the electroweak fit
- Indirect determination from EW fit (2012): $M_H = 96^{+31}_{-24}$ GeV
 - (Direct Higgs limits were of course also available in the EW fit.)

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: $\delta M_H : 0.4 \rightarrow 0.5$ GeV**



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 $Z \rightarrow f\bar{f}$

- Expressed in terms of partial decay width of initial and final width:

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

Corrected for QED radiation

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

- Set of input (width) parameters to EW fit:

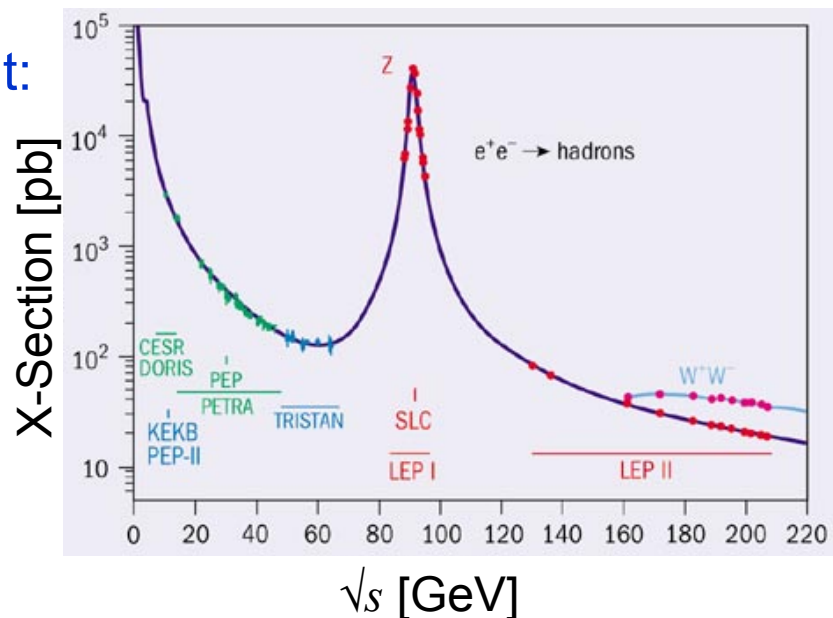
- Z mass and width: M_Z, Γ_Z
- Hadronic pole cross section:

$$\sigma_{\text{had}}^0 = 12\pi/M_Z^2 \cdot \Gamma_{ee}\Gamma_{\text{had}}/\Gamma_Z^2$$

- Three leptonic ratios (lepton univ.):

$$R_\ell^0 = R_e^0 = \Gamma_{\text{had}}/\Gamma_{ee} \quad (= R_\mu^0 = R_\tau^0)$$

- Hadronic-width ratios: R_b^0, R_c^0



Definition of Asymmetry

- Distinguish vector and axial-vector couplings of the Z

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

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

Observables

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

$$A_{FB}^f = \frac{N_F^f - N_B^f}{N_F^f + N_B^f}$$

$$A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

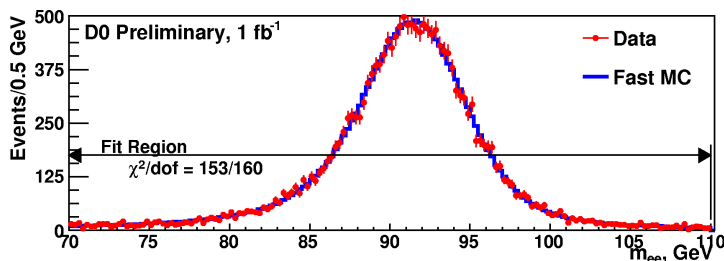
- Polarised beams (SLC), define *left/right asymmetry*:

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

- Measurements:

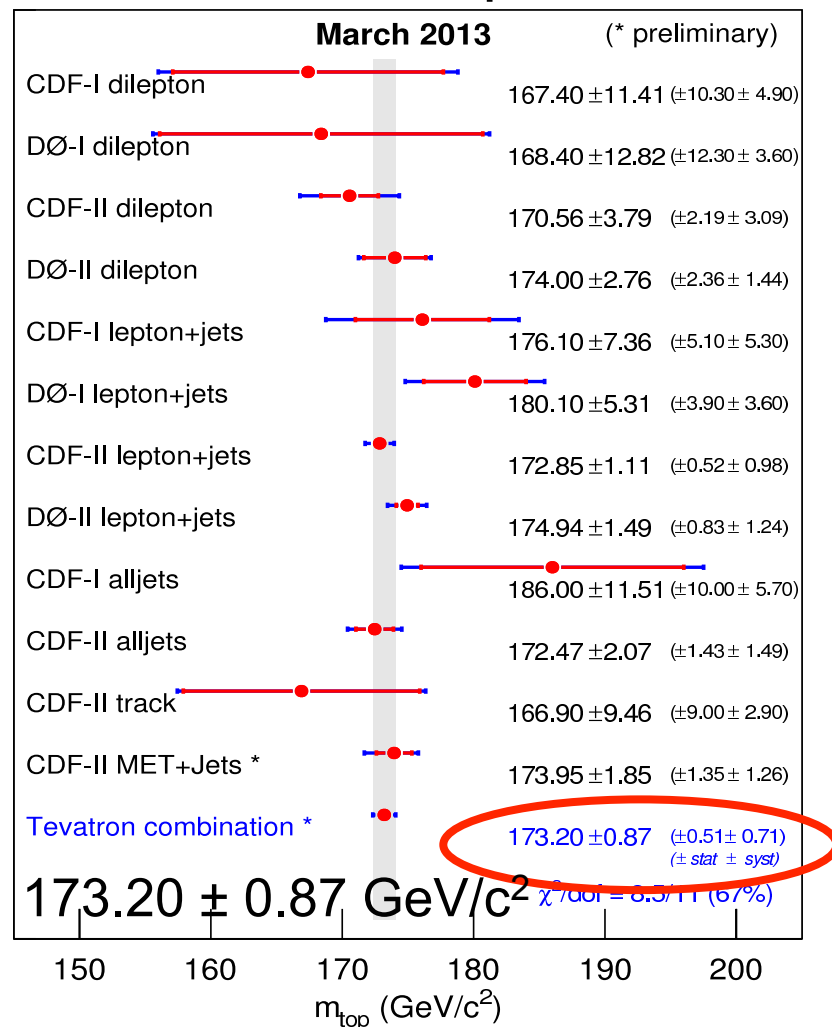
$$A_{FB}^{0,\ell}, A_{FB}^{0,c}, A_{FB}^{0,b}, A_\ell, A_c, A_b$$

Latest Tevatron result from: arXiv:1204.0042

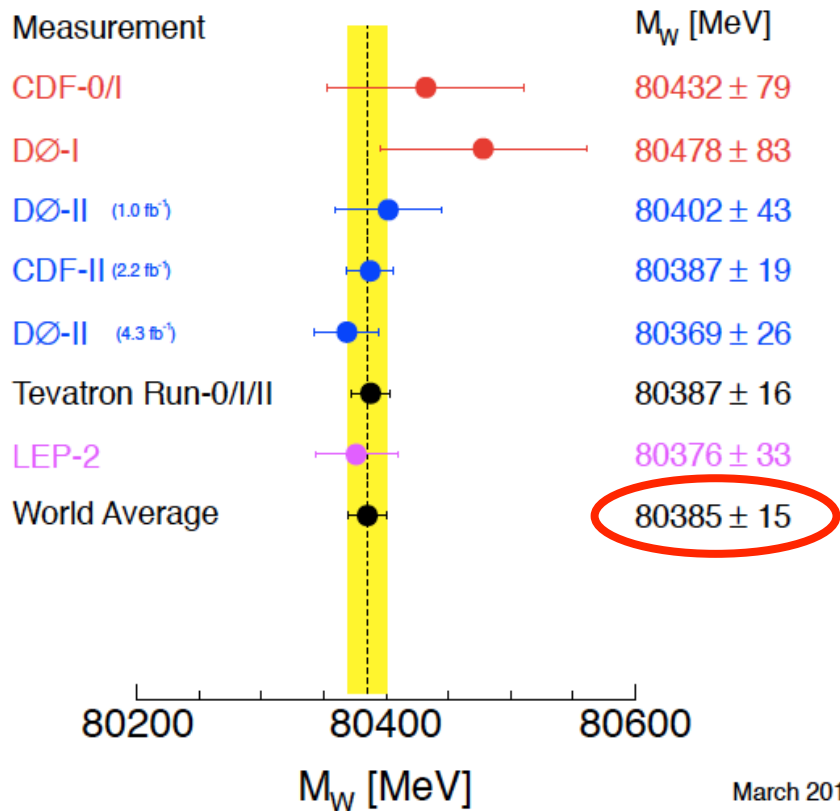


Tevatron result from: arXiv:1305.3929

Mass of the Top Quark



Mass of the W Boson



(LHC average: $173.29 \pm 0.95 \text{ GeV}/c^2$)

- 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 $\sin^2\theta_{\text{eff}}^f$
- Conventionally parametrized as ($\alpha(0)$ = fine structure constant) :

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

- Evolution with renormalization scale:

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

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- Leptonic term known up to *four* loops (for $q^2 \gg m_l^2$) [C.Sturm, arXiv: 1305.0581]
- Top quark contribution known up to 2 loops, *small*: -0.7×10^{-4} [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
- Similar analysis to evaluation of hadronic contribution to $(g-2)_\mu$

$$\Delta\alpha_{\text{had}}^{(5)}(M_Z) = (274.9 \pm 1.0) \cdot 10^{-4}$$

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

- 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: $M_W = (79.964 \pm 0.005) \text{ GeV}$
- Experiment: $M_W = (80.385 \pm 0.015) \text{ GeV}$

- 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)]

- $\sin^2\theta_{\text{eff}}^f$ 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 N³LO [P. A. Baikov et al., PRL108, 222003 (2012)]

- N³LO 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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- R_b Partial width of Z→bb [Freitas et al., JHEP08, 050 (2012)] ← **Update! EW 2-loop calc.**

- Two nuisance parameters in EW fit for theoretical uncertainties:

- $\delta M_W (4 \text{ MeV}), \delta \sin^2\theta_{\text{eff}}^f (4.7 \times 10^{-5})$

- The branching ratio $R_b^0 = \text{partial decay width of } Z \rightarrow bb \text{ to } Z \rightarrow qq$
- We use calculation with full EW 2-loop corrections of $Z \rightarrow bb$
 - From A. Freitas et al, JHEP 1208 (2012) 050, Erratum. 1305 (2013) 074.

Recently a mistake was found in this calculation.

- **Old:** Two-loop corrections to R_b^0 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_b^0 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_b^0 calculation.

- 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)]
 - **$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$** 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:
 - $M_H, M_Z, \alpha_S(M_Z^2), \Delta\alpha_{\text{had}}^{(5)}(M_Z^2), m_t, m_c, m_b$
 - 2 theory nuisance parameters
 - δM_W (4 MeV), $\delta \sin^2\theta_{\text{eff}}^l$ (4.7×10^{-5})

M_H [GeV] ^o	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	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
σ_{had}^0 [nb]	41.540 ± 0.037	
R_ℓ^0	20.767 ± 0.025	
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	SLC
A_ℓ (*)	0.1499 ± 0.0018	
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012	SLC
A_c	0.670 ± 0.027	
A_b	0.923 ± 0.020	LEP
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	Tevatron
R_c^0	0.1721 ± 0.0030	
R_b^0	0.21629 ± 0.00066	
\bar{m}_c [GeV]	$1.27^{+0.07}_{-0.11}$	Tevatron
\bar{m}_b [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.20 ± 0.87	
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ($\dagger\Delta$)	2756 ± 10	

Electroweak Fit – SM Fit Results



■ From the Gfitter Group, EPJC 72, 2205 (2012)

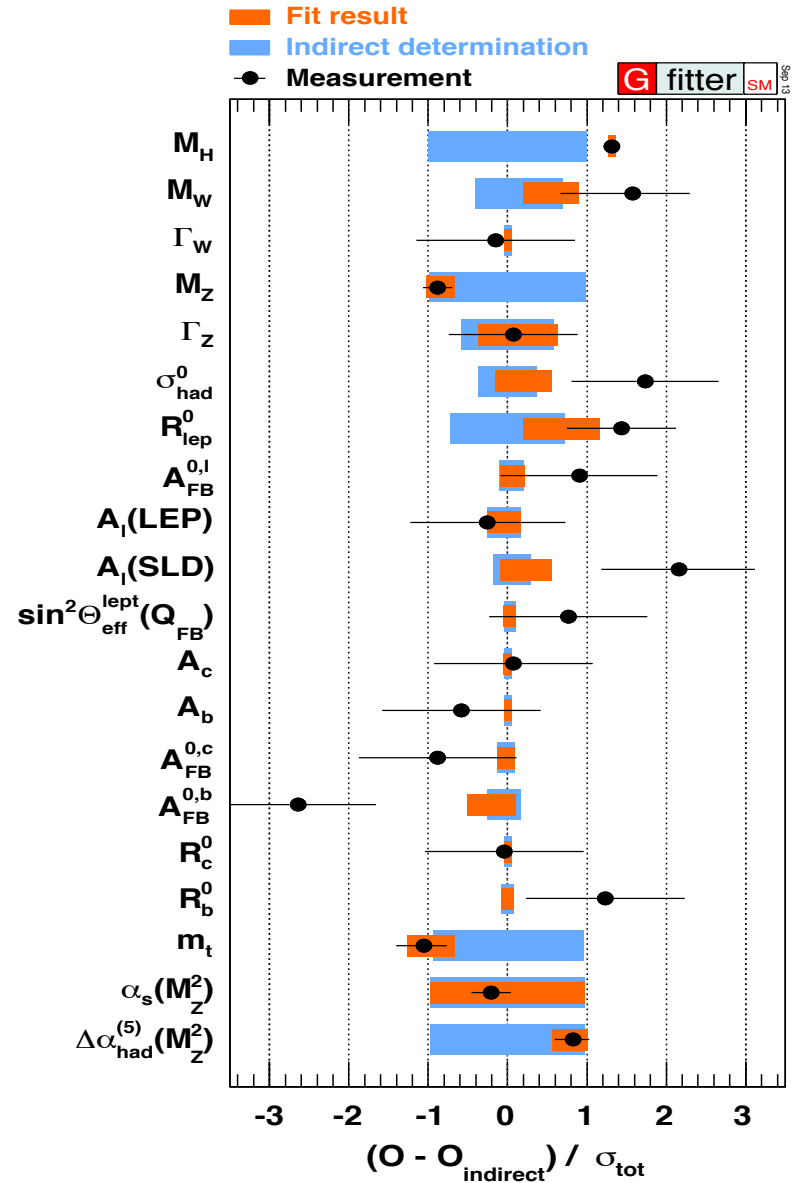
■ Left: full fit incl. M_H

■ Middle: not incl. M_H

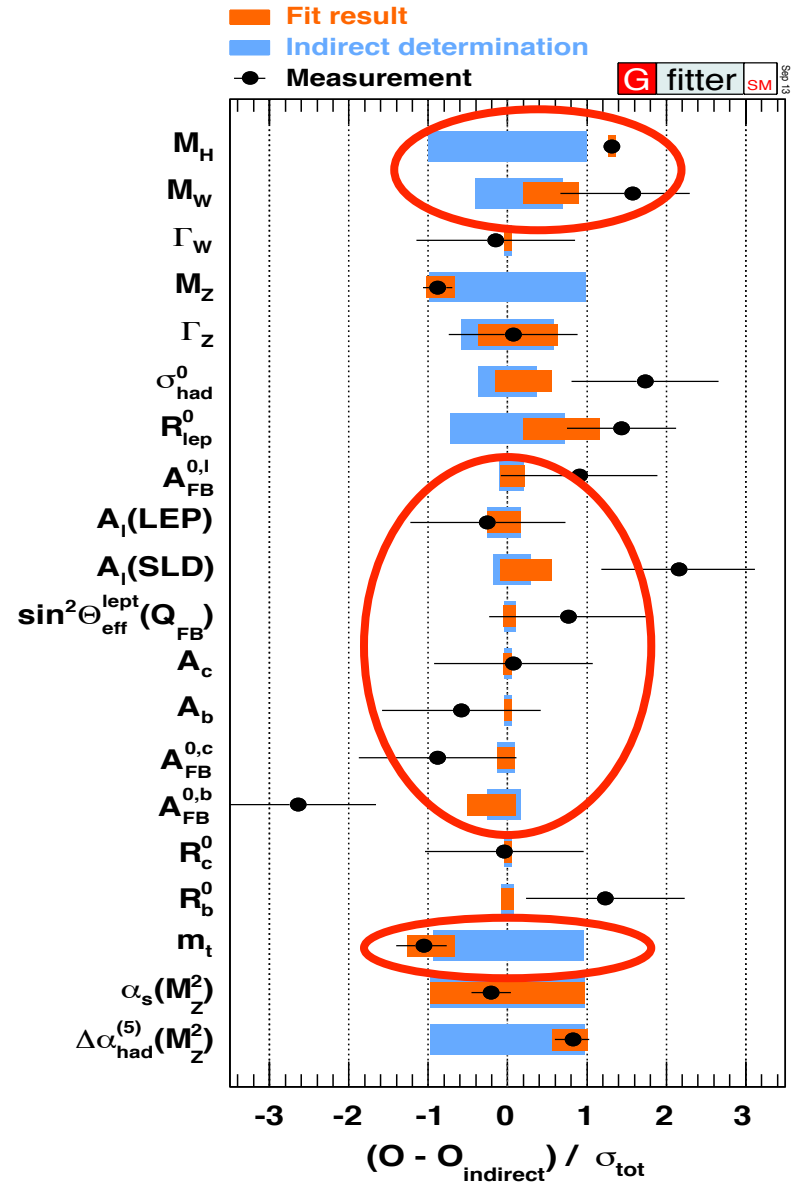
■ Right: fit incl M_H , not the row

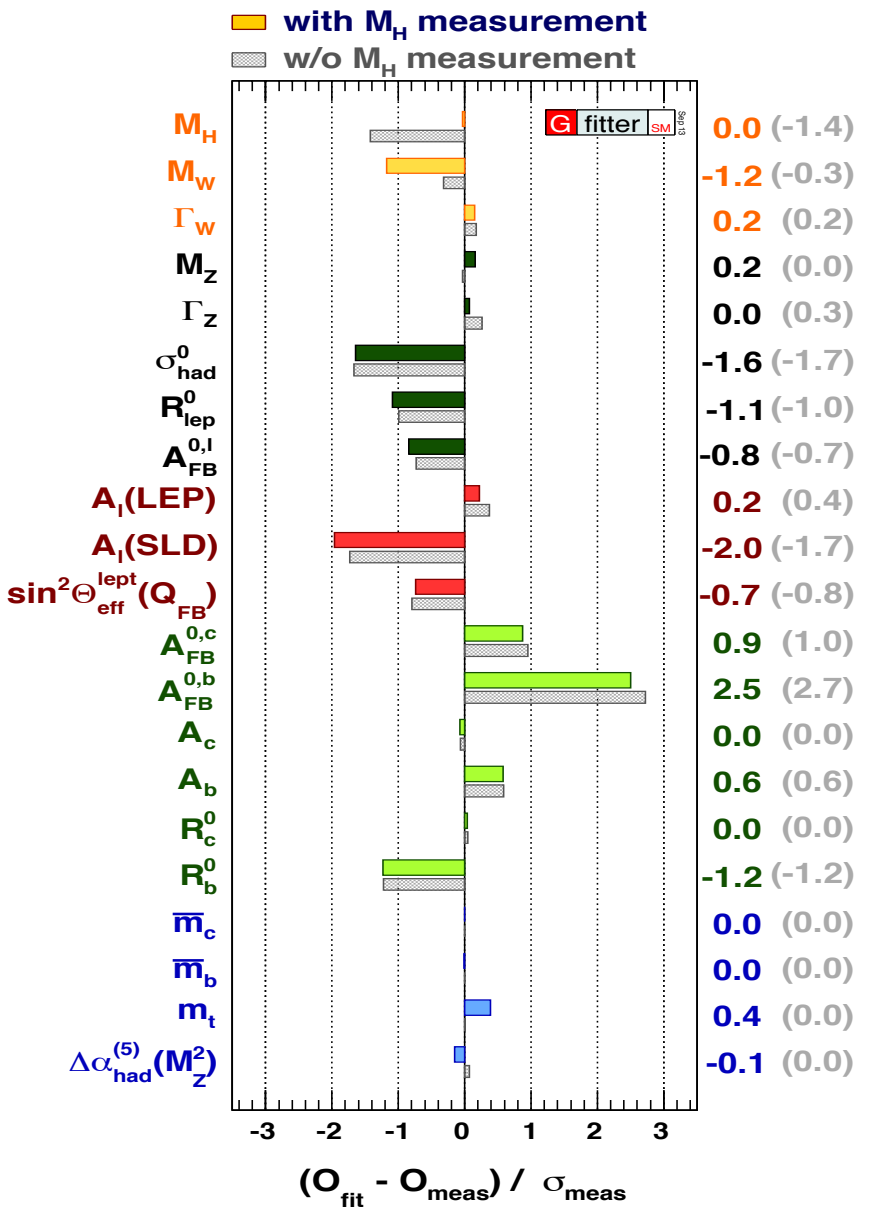
Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV] ^o	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.367^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	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_{had}^0 [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R_ℓ^0	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
$A_\ell^{(*)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	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
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R_c^0	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R_b^0	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	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ($\dagger\Delta$)	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	–
$\delta_{\text{th}}\sin^2\theta_{\text{eff}}^\ell$ (\dagger)	$[-4.7, 4.7]_{\text{theo}}$	yes	–0.6	–0.5	–

- 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!



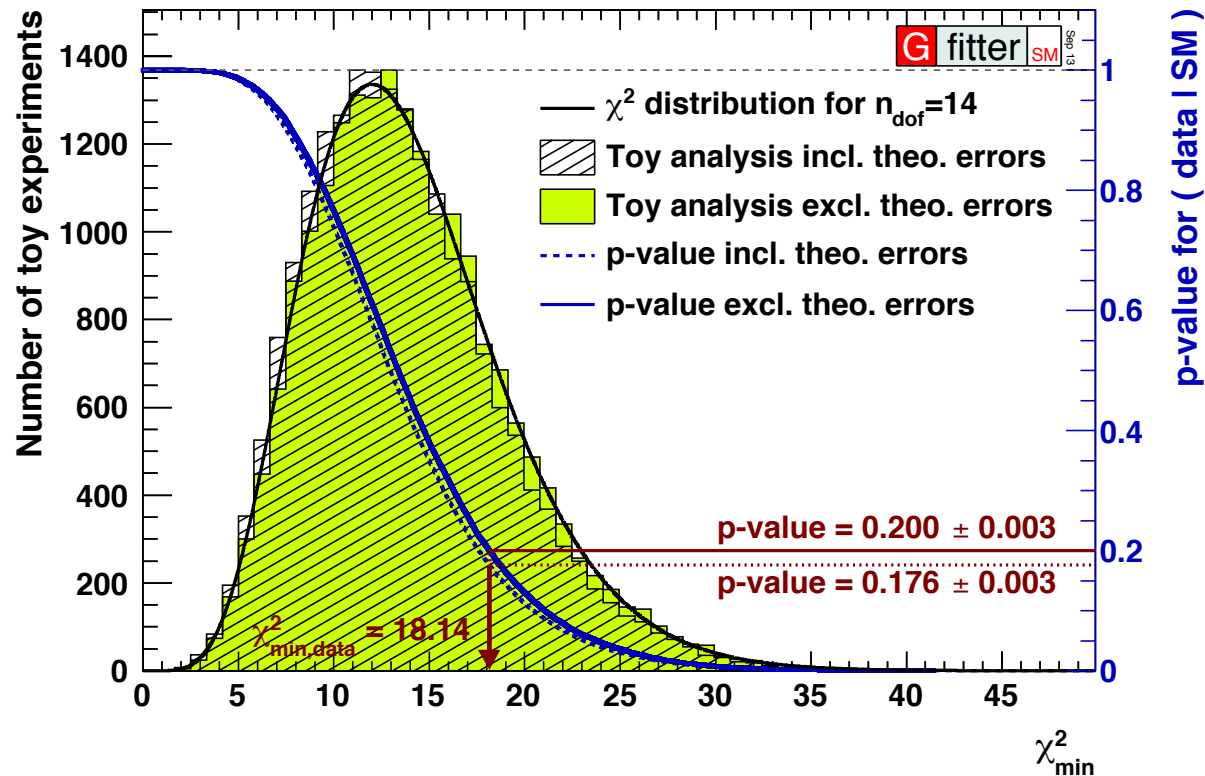
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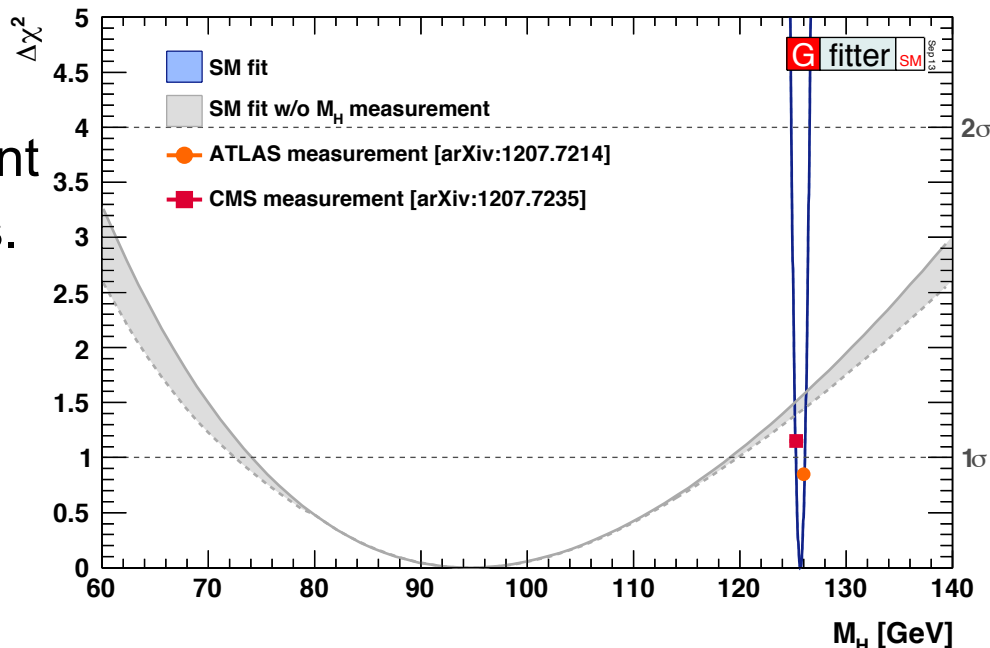
Plot inspired by Eberhardt et al. [arXiv:1209.1101]

- No individual value exceeds 3σ
- Small pulls for M_H , M_Z , $\Delta\alpha_{had}^{(5)}(M_Z^2)$, \bar{m}_c , \bar{m}_b indicate that input accuracies exceed fit requirements
- Largest deviations in b-sector: $A_{FB}^{0,b}$ with 2.5σ
 - \rightarrow largest contribution to χ^2
- R_b^0 using one-loop calculation -0.8σ
 - R_b^0 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.



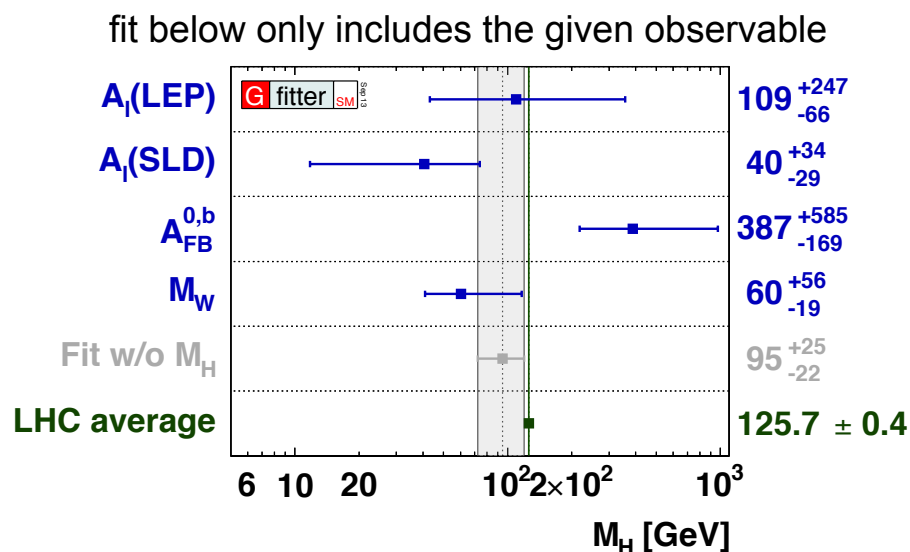
- Toy analysis: p-value for wrongly rejecting the SM = 18^{+2} (theo) %
 - p-value is equivalent to 0.9σ
 - Evaluated with 20k pseudo experiments – follows χ^2 with 14 d.o.f.
 - For comparison: $\chi^2_{\min} = 18.1 \rightarrow \text{Prob}(\chi^2_{\min}, 14) = 20\%$
- Large value of χ^2_{\min} *not*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

- 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.

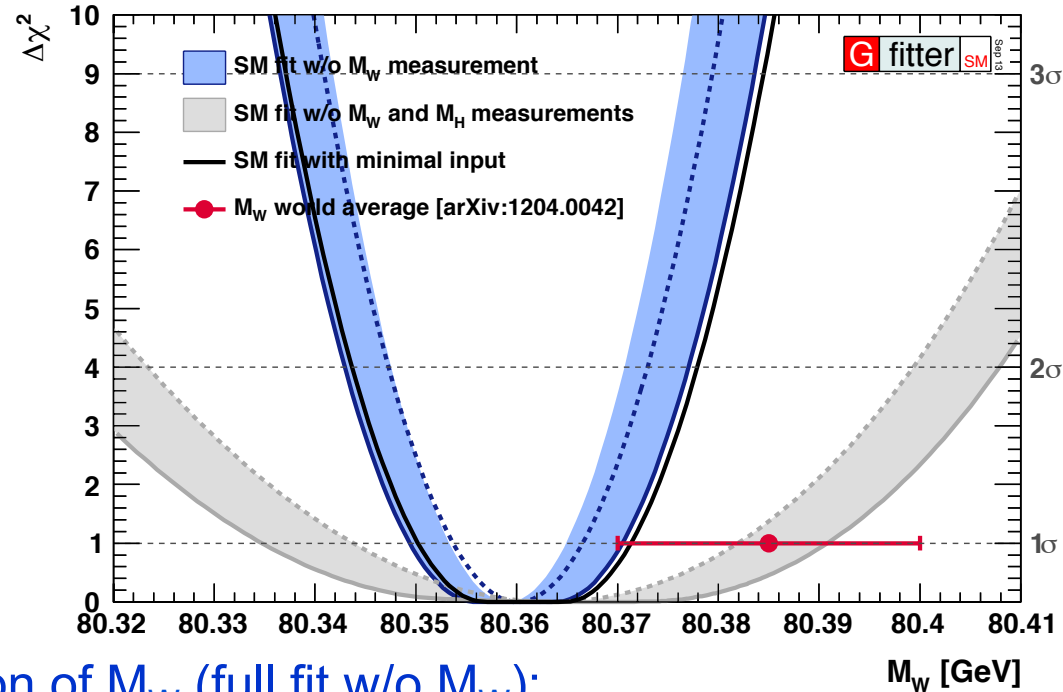


- Bottom plot: impact of other most sensitive Higgs observables

- Determination of M_H removing all sensitive observables except the given one.
- Known tension (2.5σ) between $A_1(\text{SLD})$, $A_{\text{FB}}^{0,b}$, and M_W clearly visible.



- Scan of $\Delta\chi^2$ profile versus M_W
 - Also shown: SM fit with minimal inputs: M_Z , G_F , $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, 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):



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

- **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 $\sin^2\theta_{\text{eff}}^l$
 - All sensitive measurements removed from the SM fit.
 - Also shown: SM fit with minimal inputs

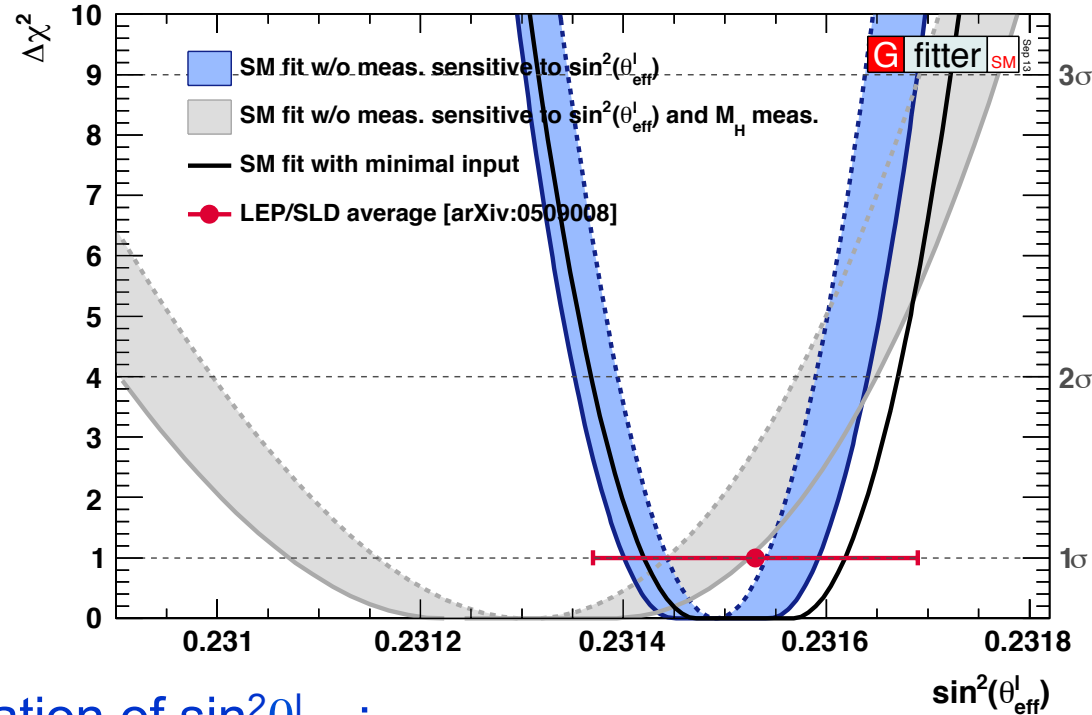
- M_H measurement allows for very precise constraint on $\sin^2\theta_{\text{eff}}^l$

- Fit result for indirect determination of $\sin^2\theta_{\text{eff}}^l$:

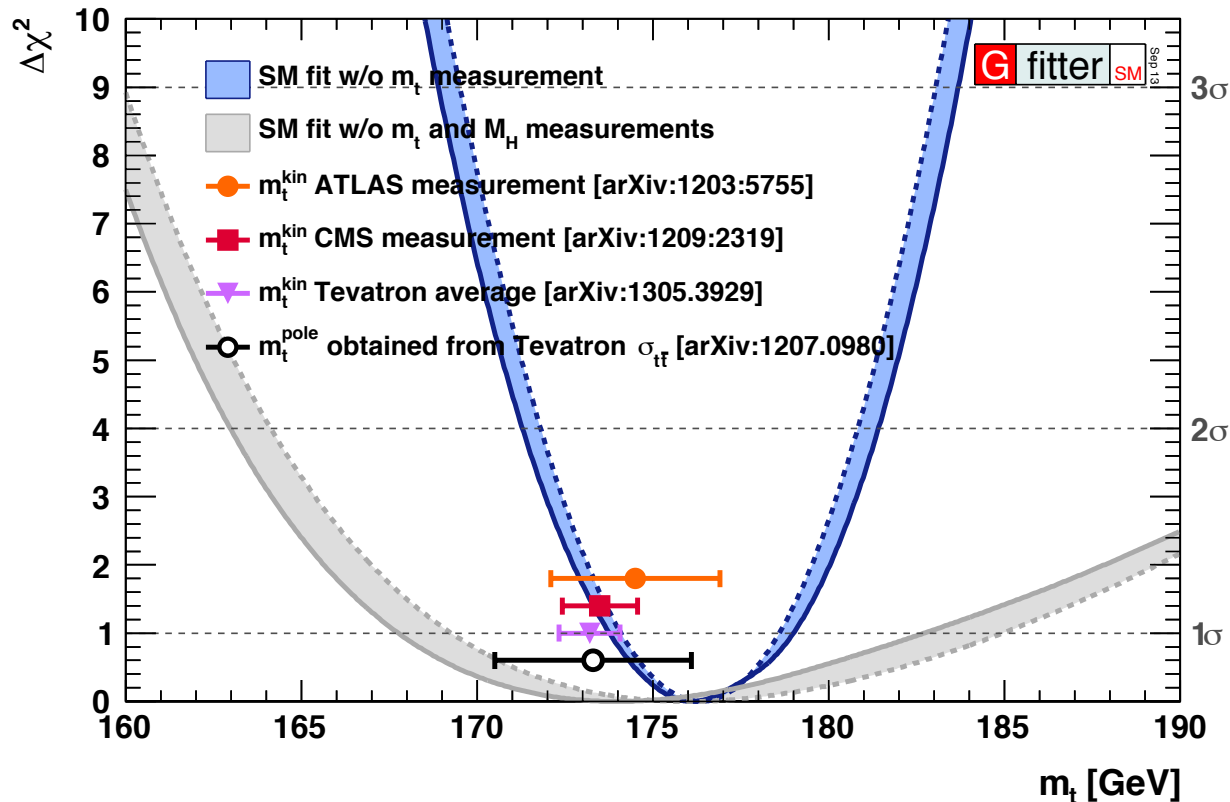
$$\begin{aligned} \sin^2\theta_{\text{eff}}^l &= 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\text{had}}} \\ &\quad \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\text{theo}}, \\ &= 0.23150 \pm 0.00010_{\text{tot}}, \end{aligned}$$

- More precise than direct determination (from LEP/SLD) !

- Uncertainty on LEP/SLD average: 1.6×10^{-4}



Indirect determination of top mass



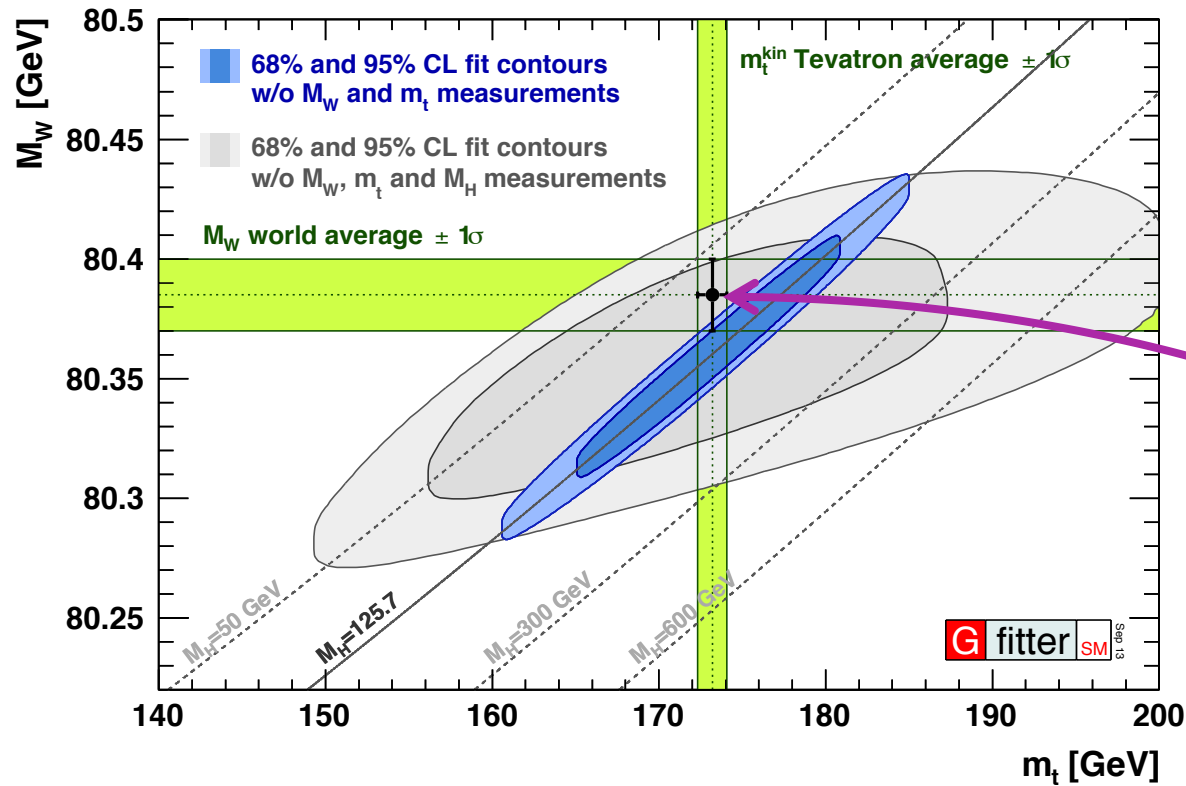
- Shown: scan of $\Delta\chi^2$ profile versus m_t (without m_t measurement)
 - M_H measurement allows for significant better constraint of m_t
 - Indirect determination consistent with direct measurements
 - Remember: fully obtained from loop corrections!

Indirect result: $m_t = 176.1^{+2.9}_{-2.4}$ GeV

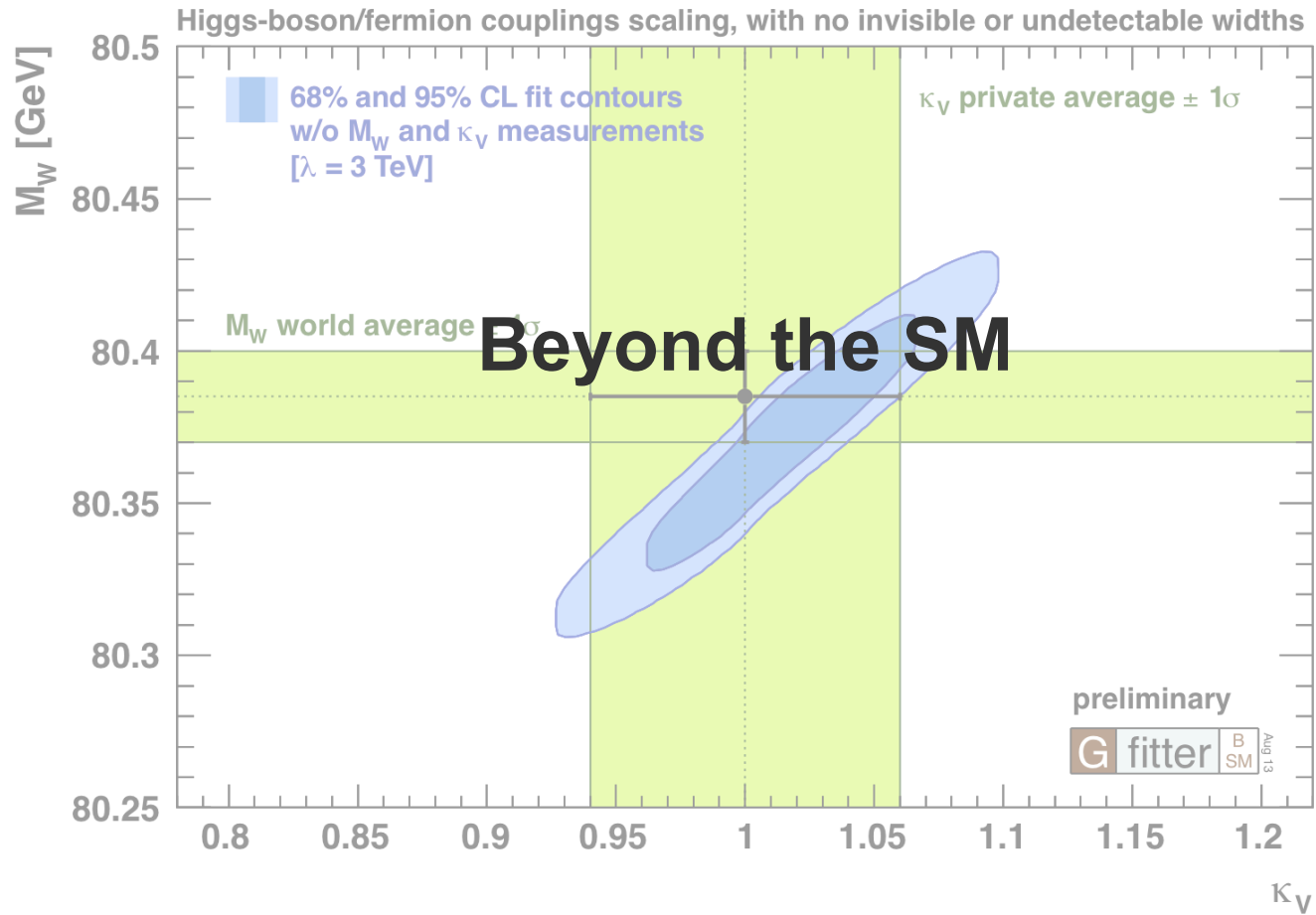
Tevatron: 173.2 ± 0.9 GeV
LHC: 173.3 ± 1.0 GeV

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 \rightarrow corners the SM!

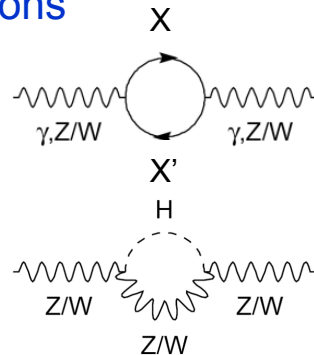


- Observed agreement demonstrates impressive consistency of the SM!





- 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 , $\sin^2\theta_{\text{eff}}$, 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)]

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

- **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 $Z \rightarrow bb$ 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: $M_H = 126 \text{ GeV}$, $m_t = 173 \text{ GeV}$
 - This defines $(S, T, U) = (0, 0, 0)$
- SM: S, T depend logarithmically on M_H

Fit result:

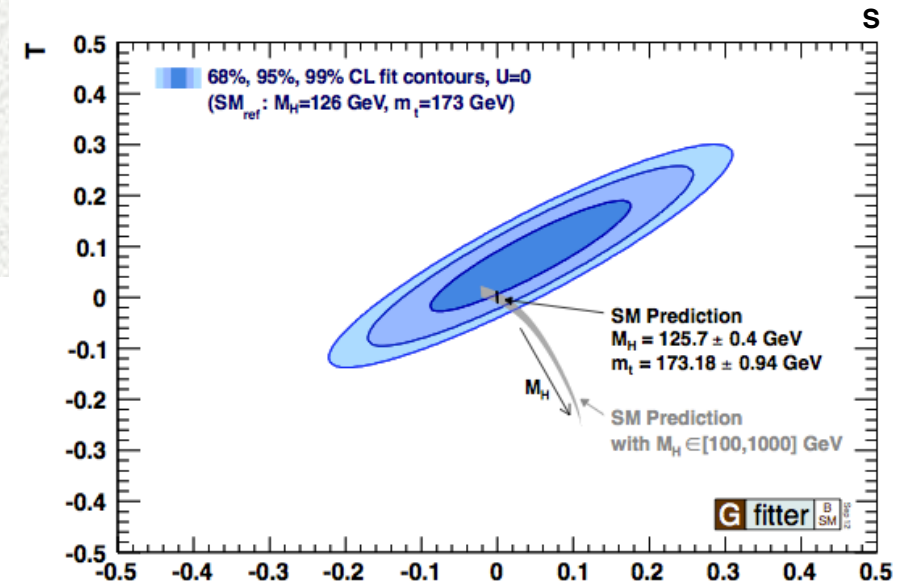
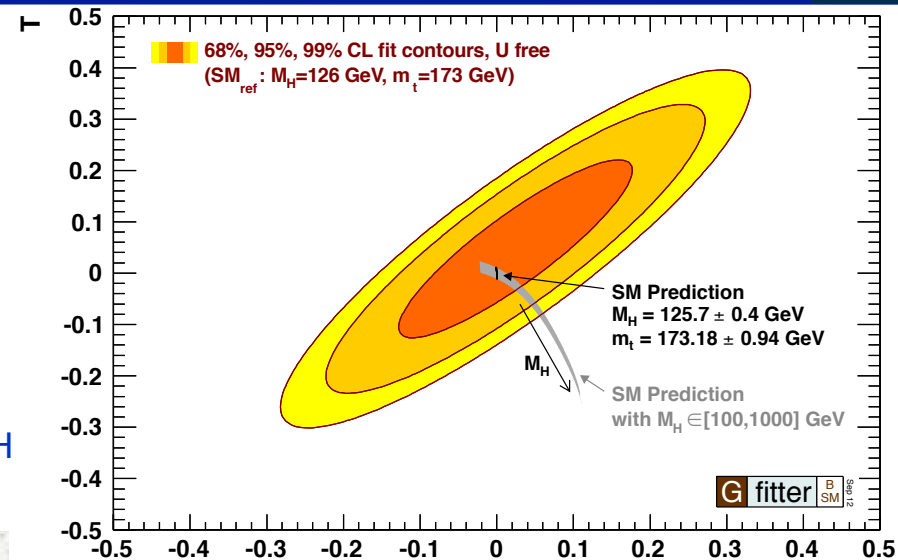
$$S = 0.03 \pm 0.10$$

$$T = 0.05 \pm 0.12$$

$$U = 0.03 \pm 0.10$$

	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 $Z \rightarrow b\bar{b}$ correction.
- **No indication for new physics.**
- Can now use this to constrain 4th gen, Ex-Dim, T-C, *Higgs couplings*, etc.



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

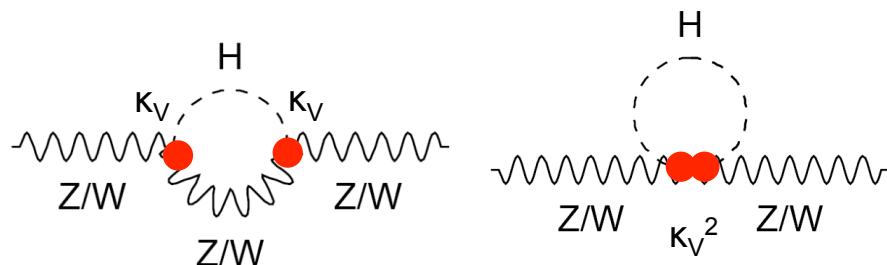
- Popular benchmark model:
 - Scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F)

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

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

- 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: $\kappa_V < 1$

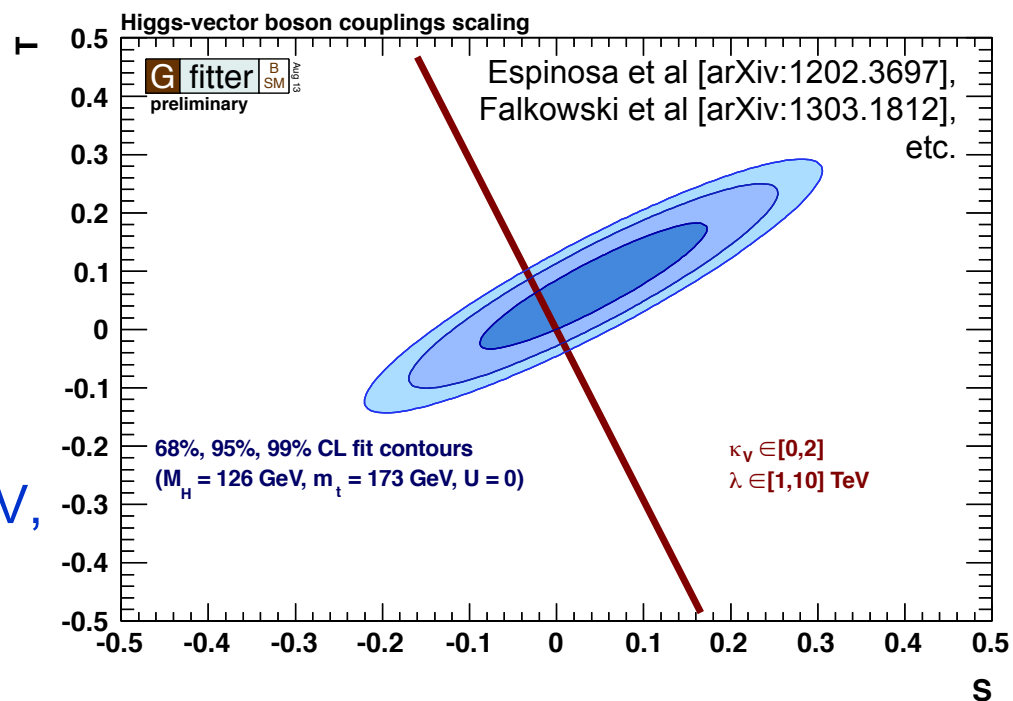
- Additional Higgses typically give *positive* contribution to M_{W} .

- Main effect on EWPO due to Higgs coupling to gauge bosons (κ_V).

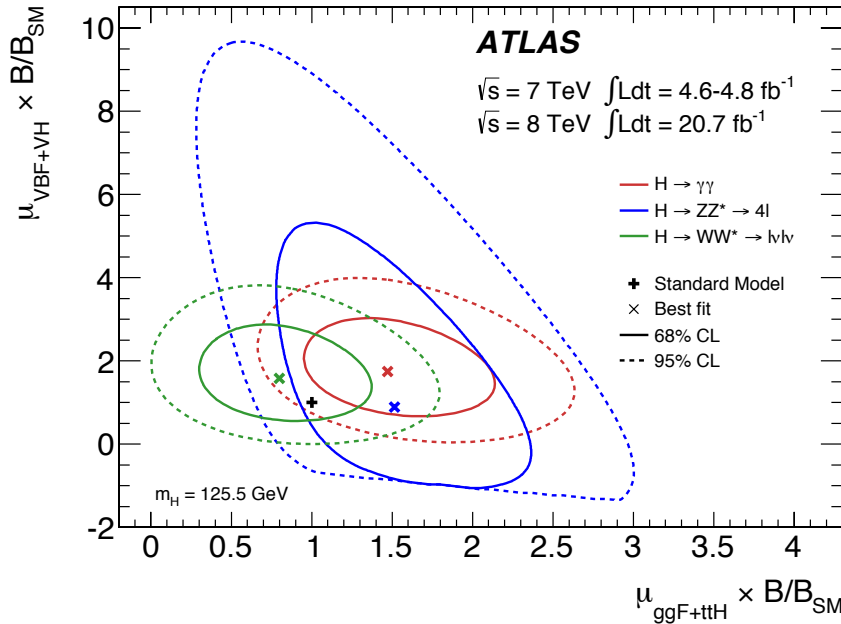
$$S = \frac{1}{12\pi} (1 - \kappa_V^2) \log \left(\frac{\Lambda^2}{M_H^2} \right), \quad T = -\frac{3}{16\pi c_W^2} (1 - \kappa_V^2) \log \left(\frac{\Lambda^2}{M_H^2} \right), \quad \Lambda = \frac{\lambda}{\sqrt{|1 - \kappa_V^2|}}$$

- Formulas from: Espinosa et al [arXiv:1202.3697]

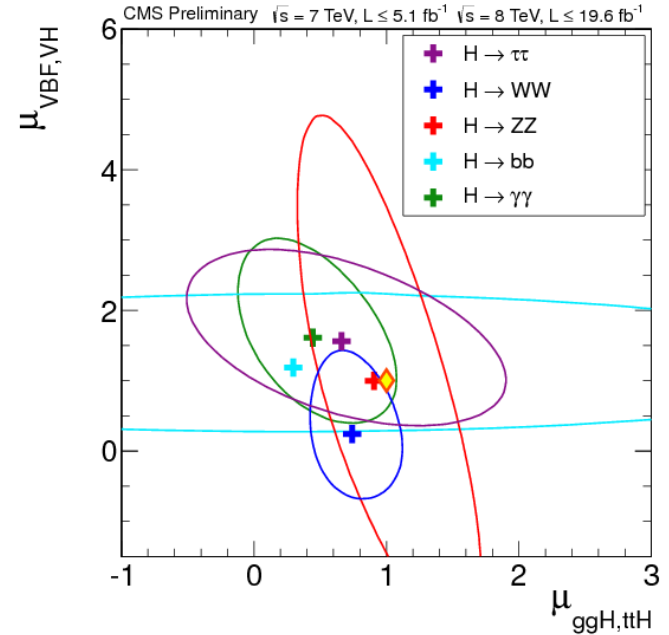
- Cut-off scale Λ represents mass scale of new states that unitarize longitudinal gauge-boson scattering.
- (As required in this model.)
- λ is varied between 1 and 10 TeV, nominally fixed to 3 TeV ($4\pi v$).



ATLAS arXiv:1307.1427

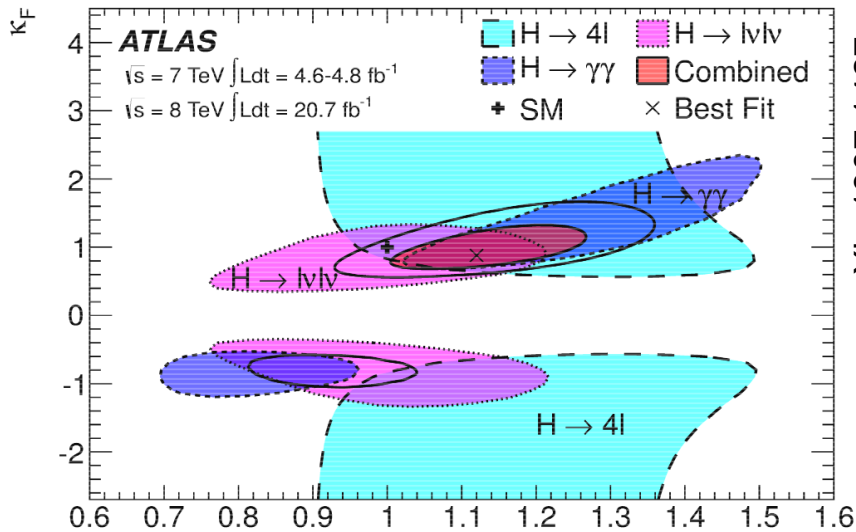


CMS PAS-HIG-13-005

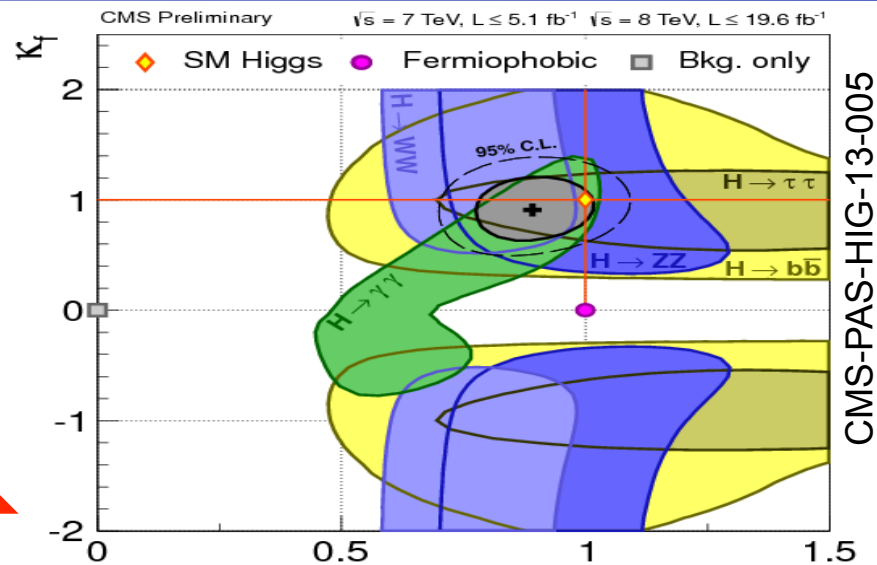


- Input: Higgs production times decay rate measurements (μ 's)
- Interpret as κ_V and κ_F using LHC HXSWG formalism.
- [arXiv:1209.0040]

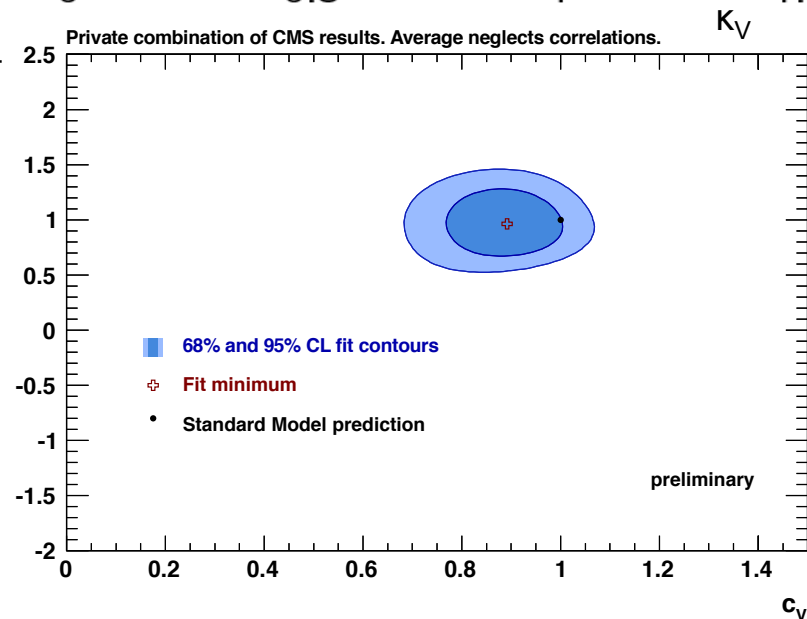
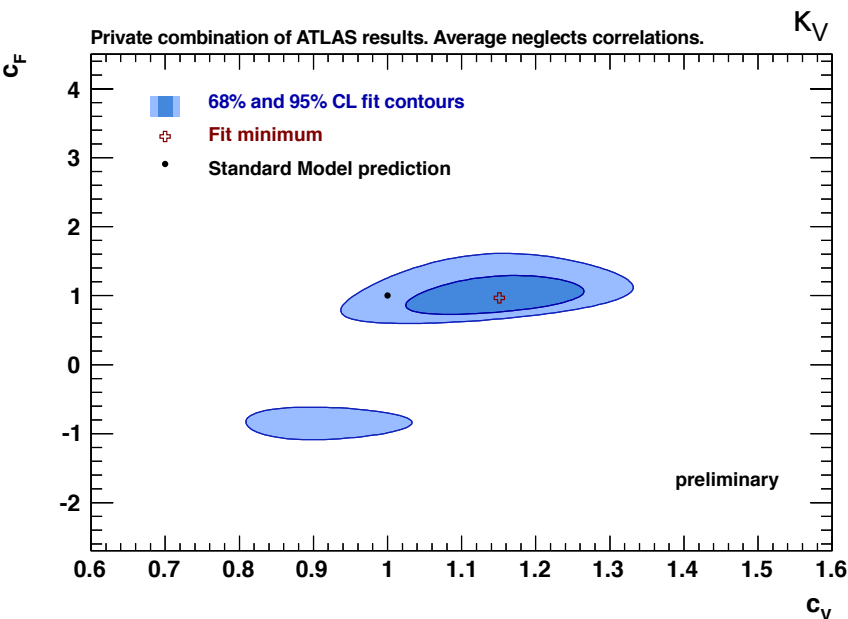
Reproduction of ATLAS and CMS results



arXiv:1307.1427



CMS-PAS-HIG-13-005



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

Private LHC combination:

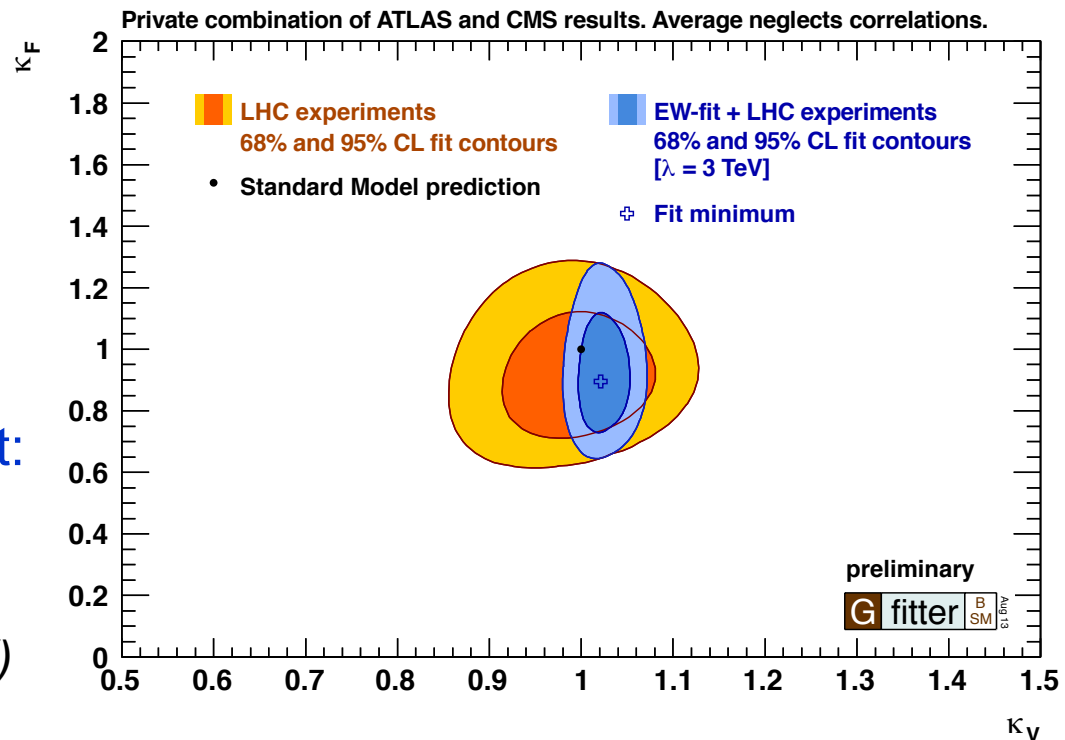
- $K_V = 1.00 \pm 0.06$
- $K_F = 0.89 \pm 0.13$
- Perfectly consistent with SM.

Result from stand-alone EW fit:

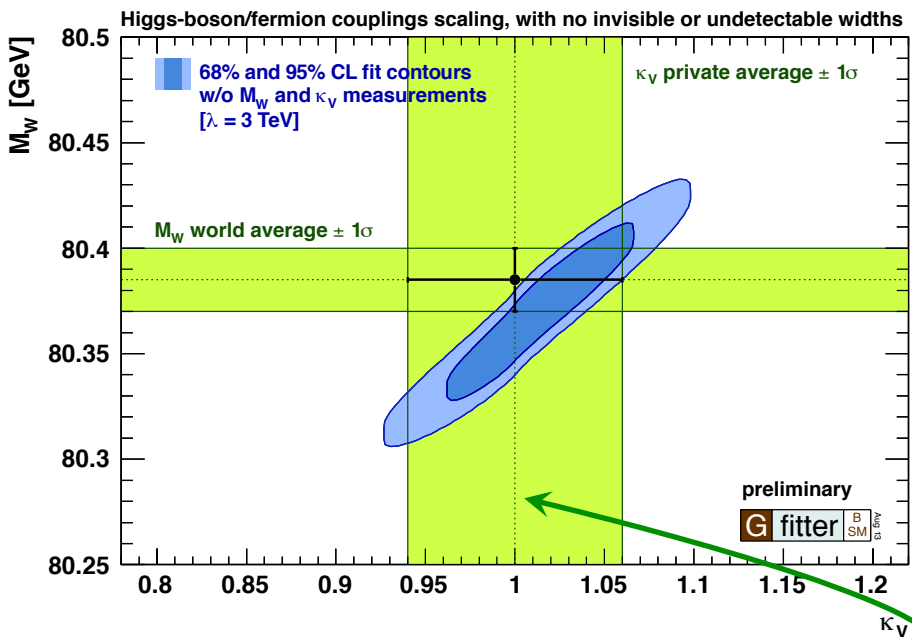
- $K_V = 1.032^{+0.036}_{-0.025}$ ($\lambda = 1$ TeV)
- $K_V = 1.024^{+0.024}_{-0.018}$ ($\lambda = 3$ TeV)
- $K_V = 1.019^{+0.019}_{-0.014}$ ($\lambda = 10$ TeV)

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

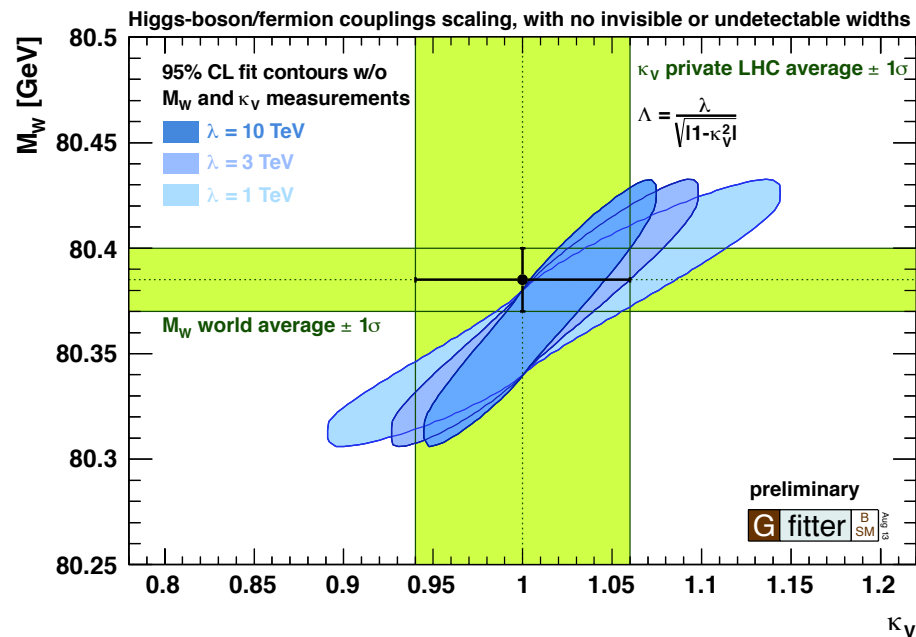
1. EW fit sofar more precise result for κ_V than current LHC experiments.
2. EW fit: positive deviation of κ_V from 1.0.
 - (Many BSM models: $\kappa_V < 1$)



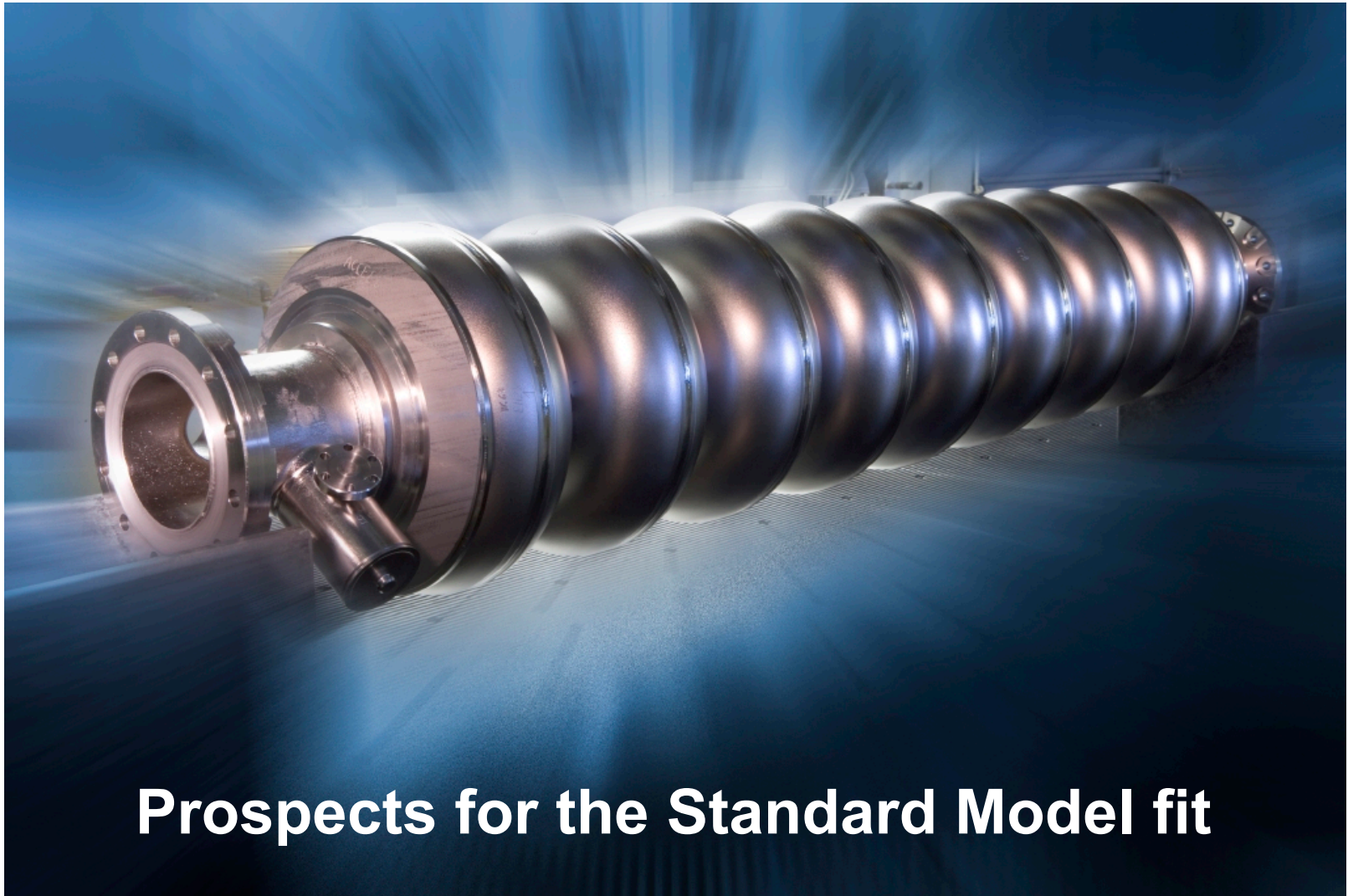
- EW fit: positive deviation of κ_V from one driven by small tension in W mass prediction versus measurement.



- 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

Prospects of EW fit tested for two scenarios:

1. LHC Run-2
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.)*

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

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

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

LHC Run-2

- *W mass measurement* : $\delta M_W : 15 \rightarrow 8$ MeV
- *Final top mass measurement* m_t : $\delta m_t : 0.9 \rightarrow 0.6$ GeV
- *H \rightarrow ZZ and H \rightarrow WW couplings*: measured at 4.5% precision.

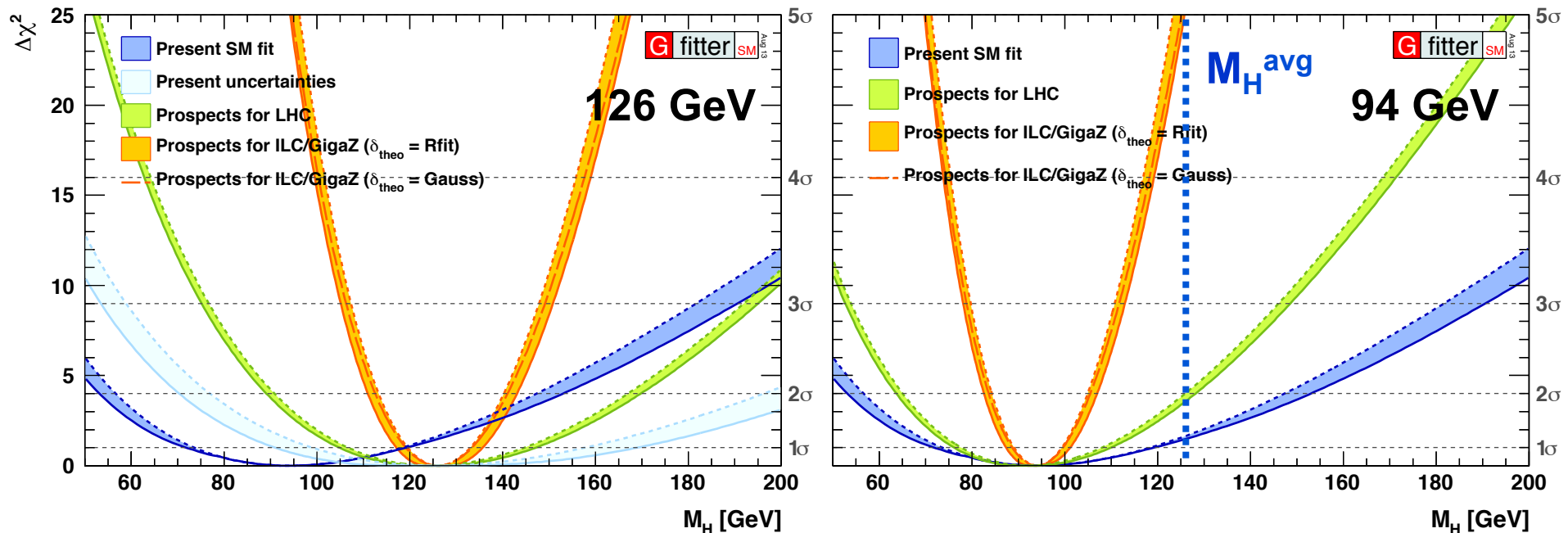
LHC prospects: possibly optimistic scenario, but not impossible.

LHC Run-2

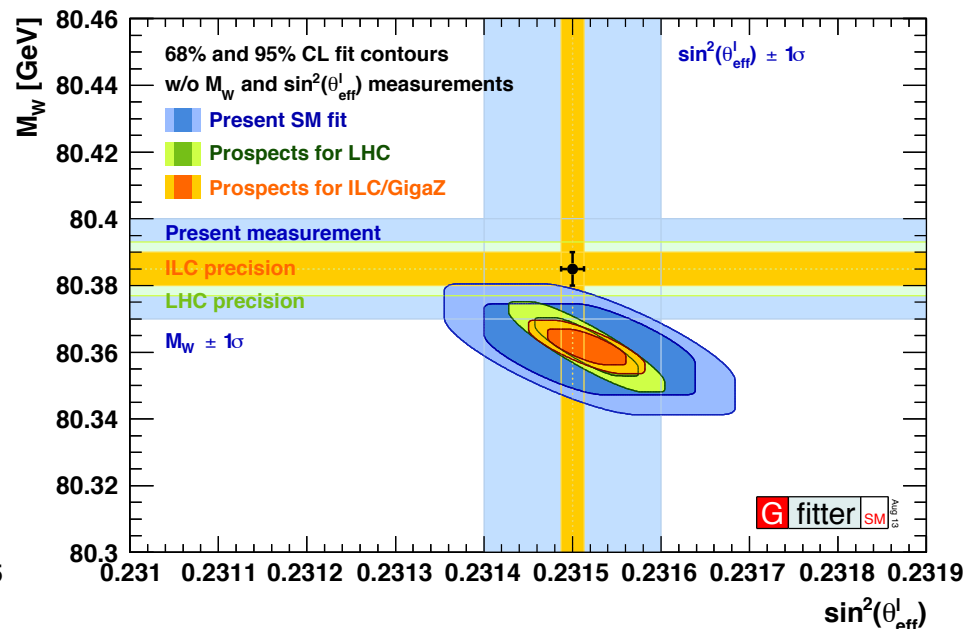
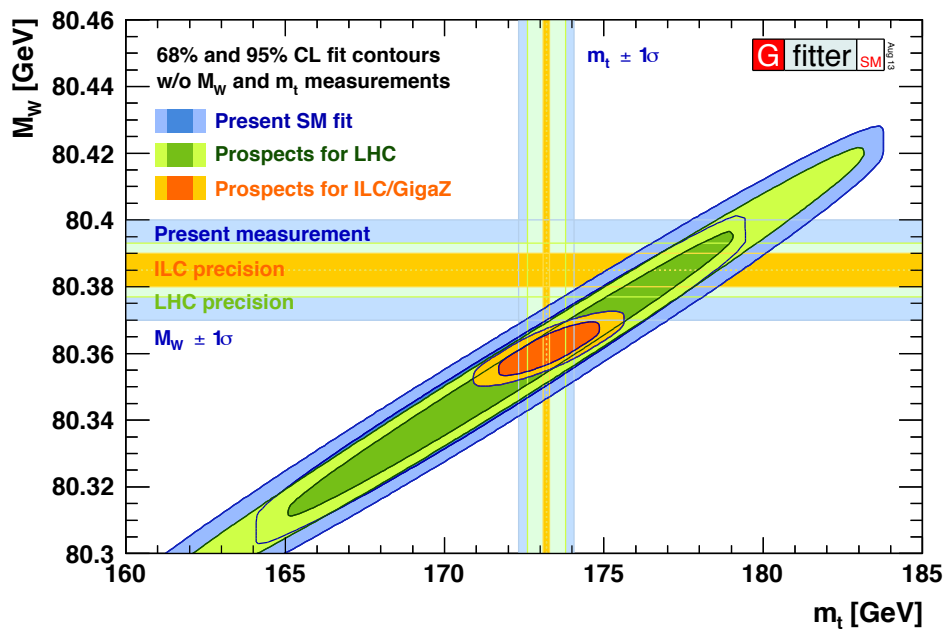
- *W mass measurement* : δM_W : 15 \rightarrow 8 MeV
- *Final top mass measurement* m_t : δm_t : 0.9 \rightarrow 0.6 GeV
- *H \rightarrow ZZ and H \rightarrow WW couplings*: measured at 4.5% precision.

For both LHC-300 and ILC:

- Low-energy data results to improve $\Delta\alpha_{\text{had}}$:
 - 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: $\Delta\alpha_{\text{had}}$: $10^{-4} \rightarrow 5 \cdot 10^{-5}$
- Assuming $\sim 25\%$ of today's theoretical uncertainties on M_W and $\sin^2\theta_{\text{eff}}^l$
 - Implies three-loop EW calculations!
 - δM_W (4 \rightarrow 1 MeV), $\delta \sin^2\theta_{\text{eff}}^l$ ($4.7 \times 10^{-5} \rightarrow 1 \times 10^{-5}$)
 - (Theoretical uncertainty estimates from recent Snowmass report)



- Logarithmic dependency on $M_H \rightarrow$ 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), $\sim 5\sigma$ discrepancy with measured Higgs mass.



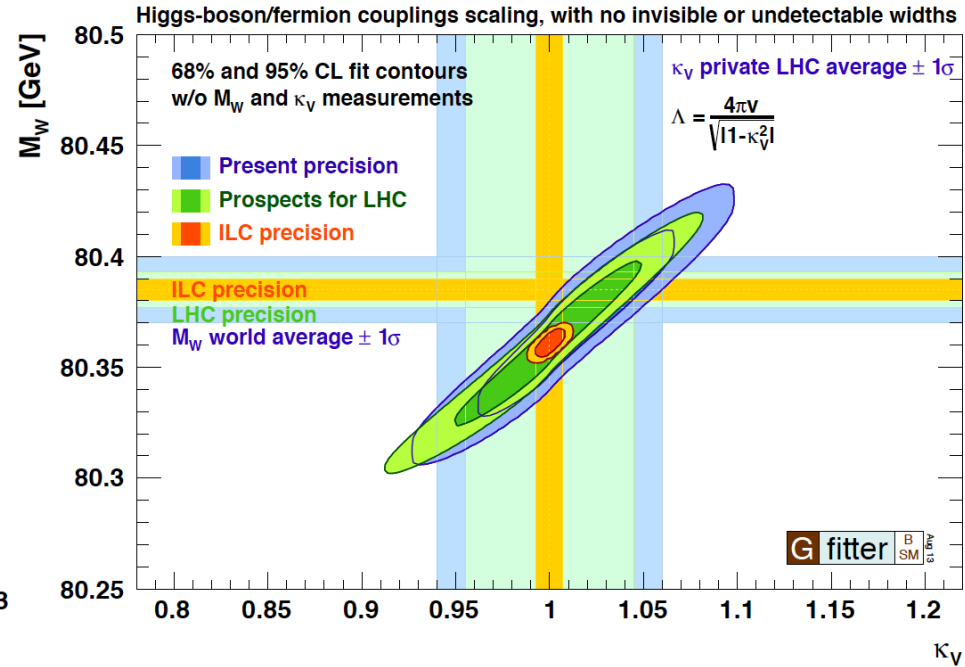
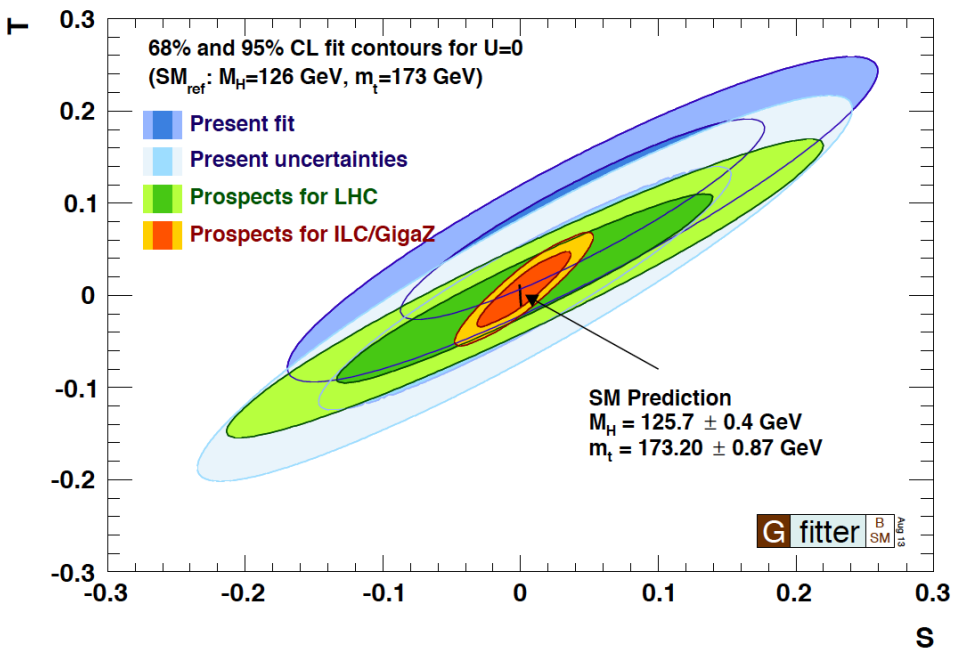
- Huge reduction of uncertainty on indirect determinations of m_t , m_W , and $\sin^2\theta_{\text{eff}}^l$, by a factor of 3 or more.
- Assuming central values of m_t and M_W do not change, (at ILC) a deviation between the SM prediction and the direct measurements would be prominently visible.

- Breakdown of predicted uncertainties for M_W and $\sin^2\theta_{\text{eff}}^l$

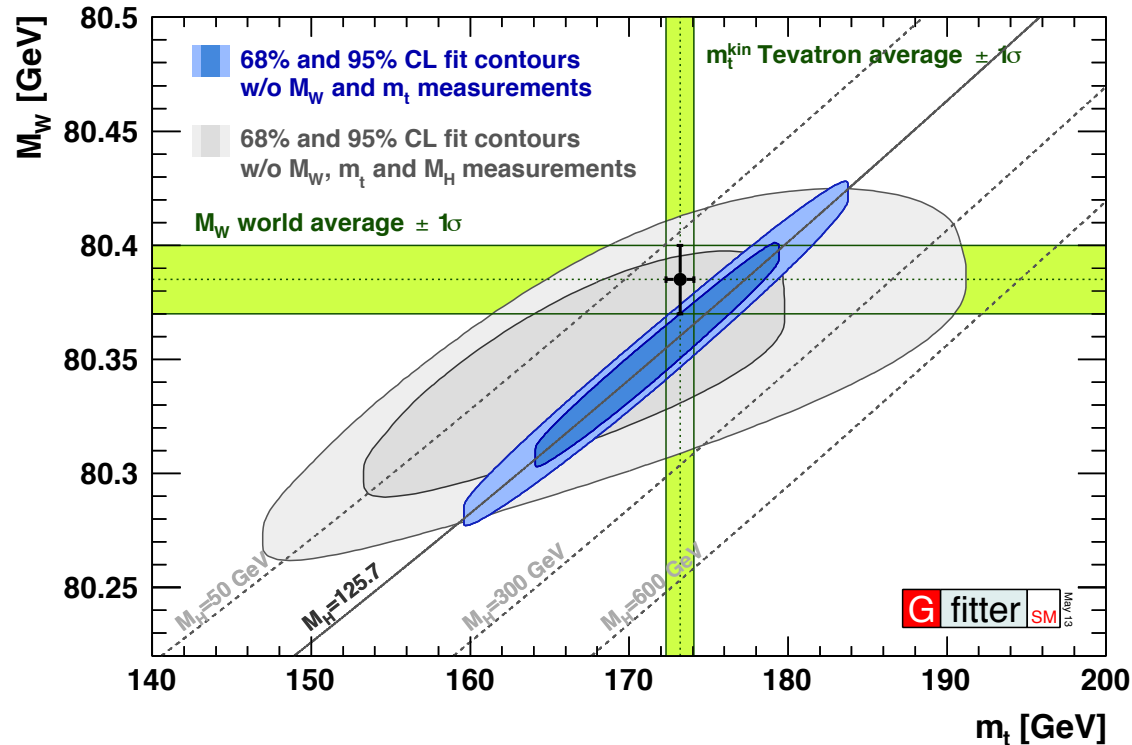
Parameter	Scenario	δ_{meas}	$\delta_{\text{pred tot (fit)}}$	error due to uncertainty ($\pm 1\sigma$)						
				$\delta_{\text{theo par}}$	δM_H	δM_Z	δm_t	$\delta \Delta\alpha_{\text{had}}$	$\delta \alpha_S$	
M_W [MeV]	Present	15	11.0	4.0	0.2	2.6	5.2	1.8	1.7	
	LHC	8	6.1	1.0	–	2.6	3.6	0.9	1.7	
	ILC	5	3.6	1.0	–	2.6	0.6	0.9	0.4	
$\sin^2\theta_{\text{eff}}^l$ ^(o)	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	

^(o)In units of 10^{-5} .

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



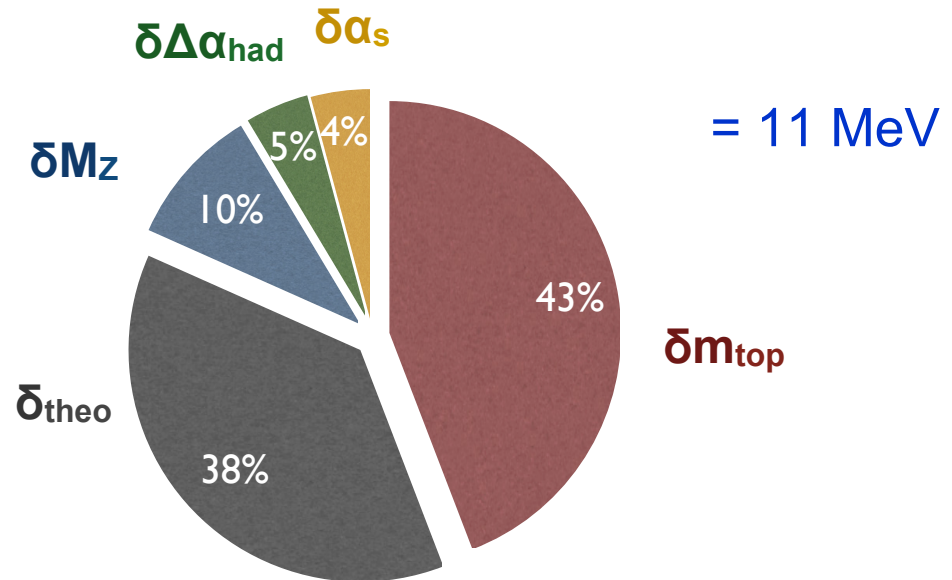
- For STU parameters, improvement of factor of >3 is possible at ILC.
- Again, at ILC a deviation between the SM predictions and direct measurements would be prominently visible.
- Competitive results between EW fit and Higgs coupling measurements!
 - (At level of 1%.)



- 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)

- 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), $\sin^2\theta_{\text{eff}}^l$ (2.3×10^{-5} → 1.0×10^{-5}), m_t (6.2 → 2.5 GeV)
 - Only surpassed so far by top mass measurement.

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



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

- 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!



A **G**eneric **F**itter Project for HEP Model Testing

Backup

Summary of indirect predictions



Parameter	Experimental input [$\pm 1\sigma$]			Indirect determination [$\pm 1\sigma_{\text{exp}} \pm 1\sigma_{\text{theo}}$]		
	Present	LHC	ILC/GigaZ	Present	LHC	ILC/GigaZ
M_H [GeV]	0.4	< 0.1	< 0.1	$^{+24}_{-20} \text{ } ^{+1}_{-2}$	$^{+20}_{-18} \text{ } ^{+2}_{-3}$	$^{+6.9}_{-6.6} \text{ } ^{+2.8}_{-2.3}$
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	$^{+2.3}_{-2.3} \text{ } ^{+0.4}_{-0.1}$	$^{+1.0}_{-1.8} \text{ } ^{+0.0}_{-0.4}$	$^{+0.7}_{-0.2} \text{ } ^{+0.3}_{-0.2}$
$\sin^2\theta_{\text{eff}}^\ell$ [$\cdot 10^{-5}$]	16	16	1.3	4.8 ± 4.7	2.7 ± 1.2	2.0 ± 1.2
$\Delta\alpha_{\text{had}}^5 M_Z^2$ [$\cdot 10^{-5}$]	10	4.7	4.7	$^{+42}_{-42} \text{ } ^{+7}_{-1}$	$^{+35}_{-35} \text{ } ^{+5}_{-4}$	6 ± 3
R_l^0 [$\cdot 10^{-3}$]	25	25	4	–	–	–
$\alpha_s(M_Z^2)$ [$\cdot 10^{-4}$]	–	–	–	27 ± 1	27 ± 1	4 ± 1
$S _{U=0}$	–	–	–	0.10	0.10	0.03
$T _{U=0}$	–	–	–	0.12	0.07	0.03

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

- 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_{beam} calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{\text{had}}$)	2495200 ± 2300	Z Line shape scan	8 keV	< 100 keV	E_{beam} calibration	QED corrections
R_t	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}	$\Delta\rho, \epsilon_3, \Delta\alpha_{\text{had}}$	0.1514 ± 0.0022	Z peak, polarized	0.000015	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho, \epsilon_3, \epsilon_2, \Delta\alpha_{\text{had}}$	80385 ± 15	WW threshold scan	0.3 MeV	< 0.5 MeV	E_{beam} , Statistics	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 MeV	< 10 MeV	Statistics	Theory interpretation

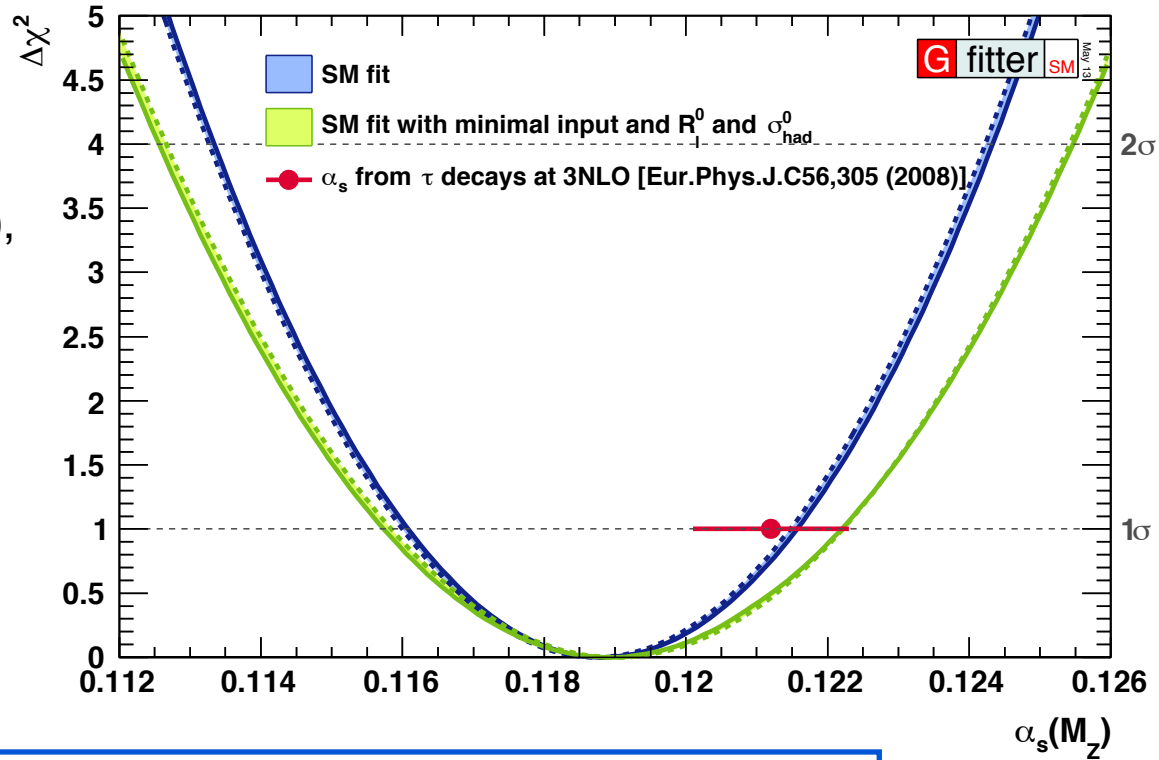
- Uncertainty estimates used:

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
$\sin^2\theta_{\text{eff}}^\ell$ [$\cdot 10^{-5}$]	16	16	1.3
$\Delta\alpha_{\text{had}}^5 M_Z^2$ [$\cdot 10^{-5}$]	10	4.7	4.7
R_l^0 [$\cdot 10^{-3}$]	25	25	4
$\alpha_s(M_Z^2)$ [$\cdot 10^{-4}$]	–	–	–

- 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 $Z \rightarrow \text{hadrons}$

- Scan of $\Delta\chi^2$ versus α_s
 - Also shown: SM fit with minimal inputs: M_Z , G_F , $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H , and fermion masses
- Determination of α_s at $N^3\text{LO}$.
 - Most sensitive through total hadronic cross-section σ_{had}^0 and partial leptonic width R_1^0



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

- Theory uncertainty at per-mille level (obtained by scale variation of Γ_{had}).
- *In good agreement with value from τ decays, also at $N^3\text{LO}$, and with WA.*
 - (Improvements in precision only expected with ILC/GigaZ. See later.)

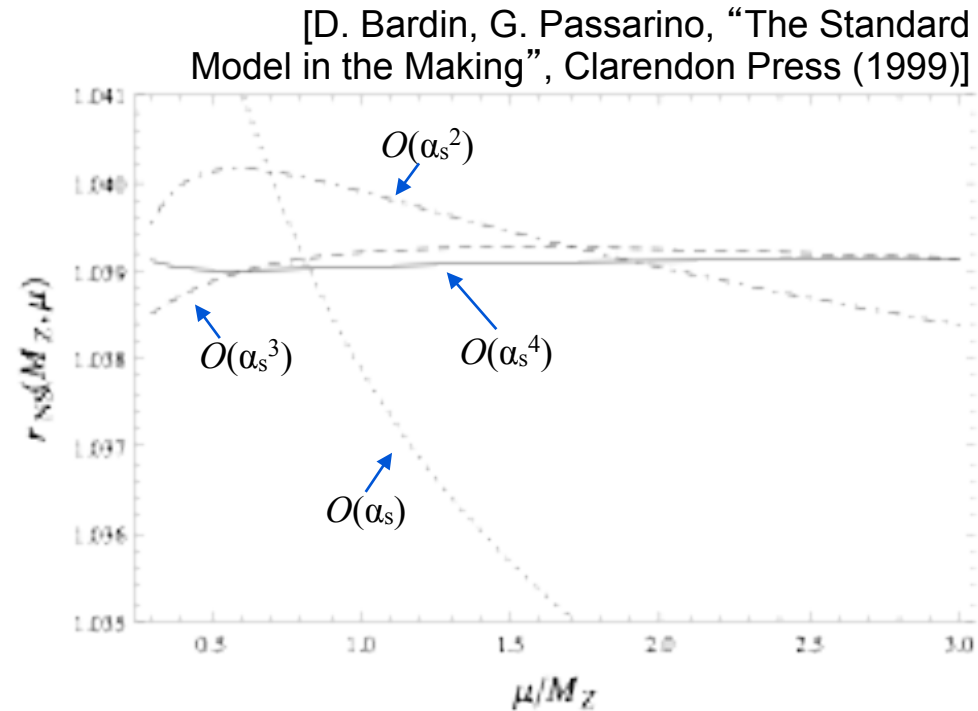
- The branching ratio R_b^0 : partial decay width of $Z \rightarrow bb$ to $Z \rightarrow qq$
- Freitas et al: full EW 2-loop calculation of $Z \rightarrow bb$
- Contribution of same terms as in the calculation of $\sin^2\theta_{\text{eff}}^{bb}$
→ cross-check of two results found good agreement
- Two-loop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

M_H [GeV]	1-loop EW and QCD correction to FSR $\mathcal{O}(\alpha) + \text{FSR}_{\alpha, \alpha_s, \alpha_s^2}$ [10^{-4}]	2-loop EW correction $\mathcal{O}(\alpha_{\text{ferm}}^2)$ [10^{-4}]	2-loop EW and 2+3-loop QCD correction to FSR $\mathcal{O}(\alpha_{\text{ferm}}^2) + \text{FSR}_{\alpha_s^3, \alpha\alpha_s, m_b^2\alpha_s, m_b^4}$ [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

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

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

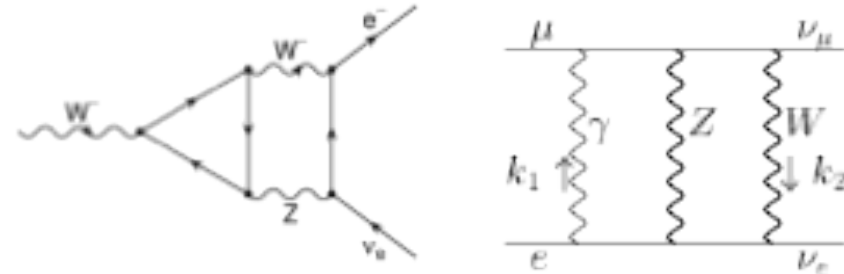
- High sensitivity to the strong coupling α_s
- Recently, full four-loop calculation of QCD Adler function became available (N³LO)
- Much-reduced scale dependence!
- Theoretical uncertainty of 0.1 MeV, compared with experimental uncertainty of 2.0 MeV.



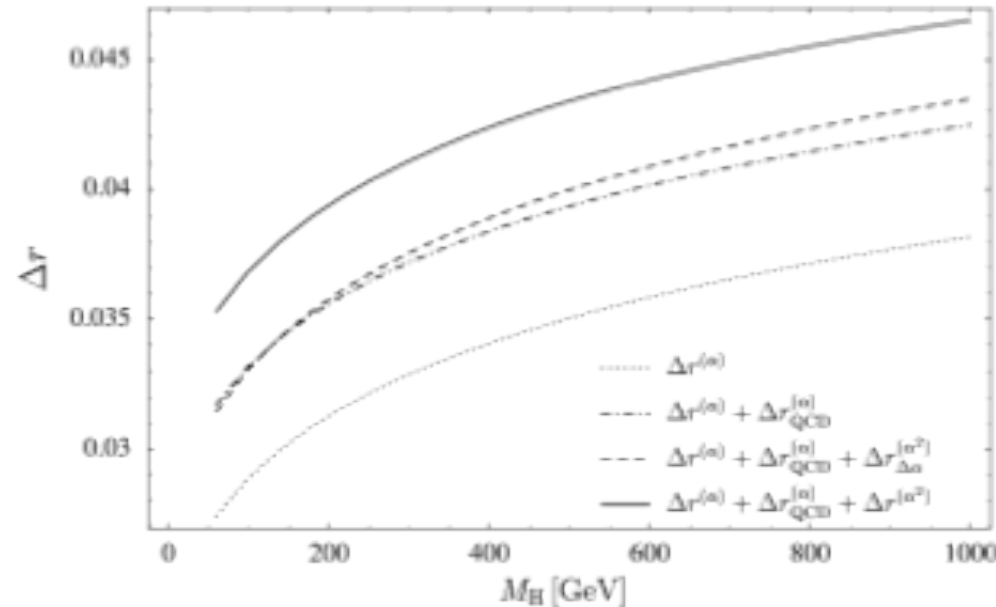
[P. Baikov et al., Phys. Rev. Lett. 108, 222003 (2012)]
 [P. Baikov et al Phys. Rev. Lett. 104, 132004 (2010)]

- 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 $O(\alpha)$, $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{\text{ferm}})$, $O(\alpha^2_{\text{bos}})$, $O(\alpha^2\alpha_s m_t^4)$, $O(\alpha^3 m_t^6)$
- Uncertainty estimate:
 - Missing terms of order $O(\alpha^2\alpha_s)$: about 3 MeV (from $O(\alpha^2\alpha_s m_t^4)$)
 - Electroweak three-loop correction $O(\alpha^3)$: < 2 MeV
 - Three-loop QCD corrections $O(\alpha_s^3)$: < 2 MeV
- Total: $\delta M_W \approx 4 \text{ MeV}$

[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 $\sin^2(\theta_{\text{eff}}^l)$

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

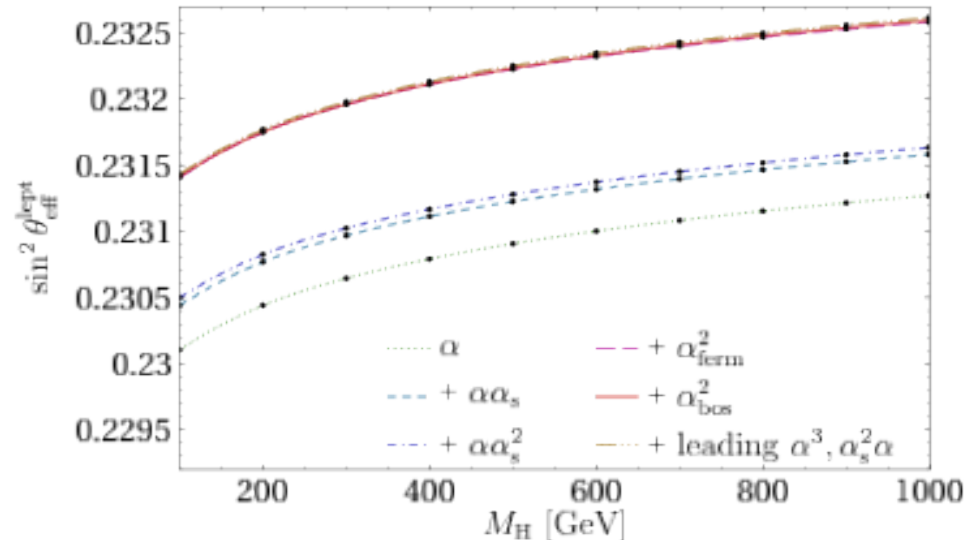
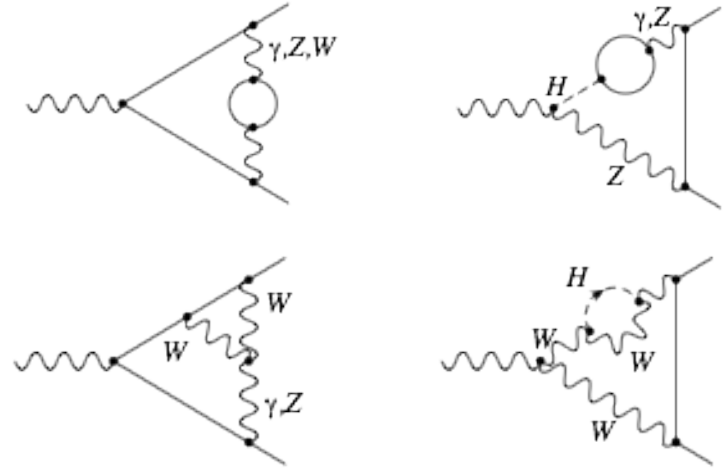
- Effective mixing angle:

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = (1 - M_W^2/M_Z^2) (1 + \Delta\kappa)$$

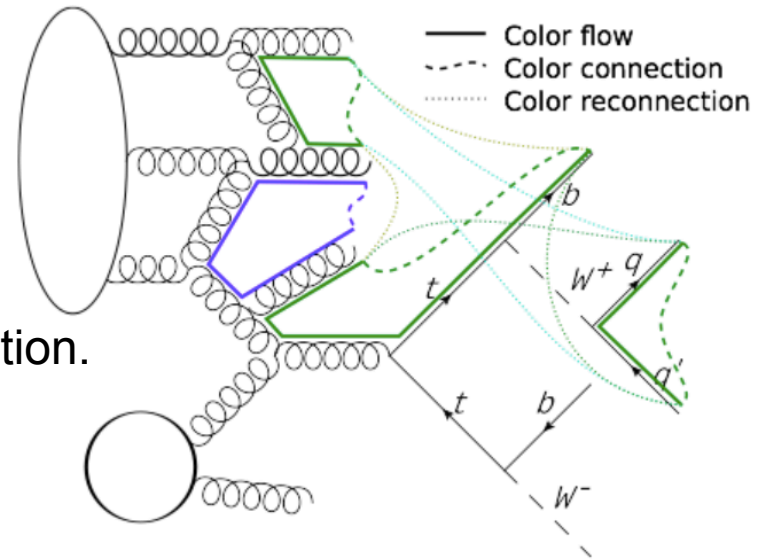
- Two-loop EW and QCD correction to $\Delta\kappa$ known, leading terms of higher order QCD corrections.

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

- Uncertainty estimate obtained with different methods, geometric progression, leading to total of: $\delta\sin^2(\theta_{\text{eff}}^l) = 4.7 \times 10^{-5}$



- 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 $\overline{\text{MS}}$ scheme.
 - Impact of finite top width effects.
- **Result: $m_t^{\text{exp}} \not\equiv m_t^{\text{pole}}$, and event-dependent.**
- The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_t) \sim 1 \text{ GeV}$
- Hard to estimate additional theo. uncertainties. With 0.5 GeV on m_t :
 - $M_H = 90^{+34}_{-21} \text{ GeV}$, $M_W = 80.359 \pm 0.013 \text{ GeV}$, $\sin^2 \theta_{\text{eff}}^l = 0.23148 \pm 0.00010$.
 - Only small deterioration in precision.



- 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] ^o	$125.7^{+0.4}_{-0.4}$	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_{had}^0 [nb]	41.540 ± 0.037	–	41.479 ± 0.014
R_ℓ^0	20.767 ± 0.025	–	20.740 ± 0.017
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$
$A_\ell^{(*)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	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	–	$0.93464^{+0.00005}_{-0.00007}$
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005
R_c^0	0.1721 ± 0.0030	–	0.17223 ± 0.00006
R_b^0	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
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ($\dagger\Delta$)	2757 ± 10	yes	2755 ± 11
$\alpha_s(M_Z^2)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$
$\delta_{\text{th}}M_W$ [MeV]	$[-4, 4]_{\text{theo}}$	yes	4
$\delta_{\text{th}}\sin^2\theta_{\text{eff}}^\ell$ (\dagger)	$[-4.7, 4.7]_{\text{theo}}$	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] ^o	$125.7^{+0.4}_{-0.4}$	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_{had}^0 [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014
R_ℓ^0	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$
$A_\ell^{(*)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	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	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93464^{+0.00005}_{-0.00007}$
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005
R_c^0	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006
R_b^0	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
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ($\dagger\Delta$)	2757 ± 10	yes	2755 ± 11	2755 ± 11
$\alpha_s(M_Z^2)$	–	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
$\delta_{\text{th}}\sin^2\theta_{\text{eff}}^\ell$ (\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] ^o	$125.7^{+0.4}_{-0.4}$	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_{had}^0 [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R_ℓ^0	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
$A_\ell^{(*)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	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
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R_c^0	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R_b^0	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	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)^{(\dagger\Delta)}$	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	–
$\delta_{\text{th}}\sin^2\theta_{\text{eff}}^\ell$ ^(†)	$[-4.7, 4.7]_{\text{theo}}$	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] ^o	$125.7^{+0.4}_{-0.4}$	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_{had}^0 [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R_ℓ^0	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
$A_\ell^{(*)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	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
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R_c^0	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R_b^0	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	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ($\dagger\Delta$)	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	–
$\delta_{\text{th}}\sin^2\theta_{\text{eff}}^\ell$ (\dagger)	$[-4.7, 4.7]_{\text{theo}}$	yes	–0.6	–0.5	–

Moriond 2011: Prediction for Higgs mass

LEP + Tevatron (Fall 2010) :

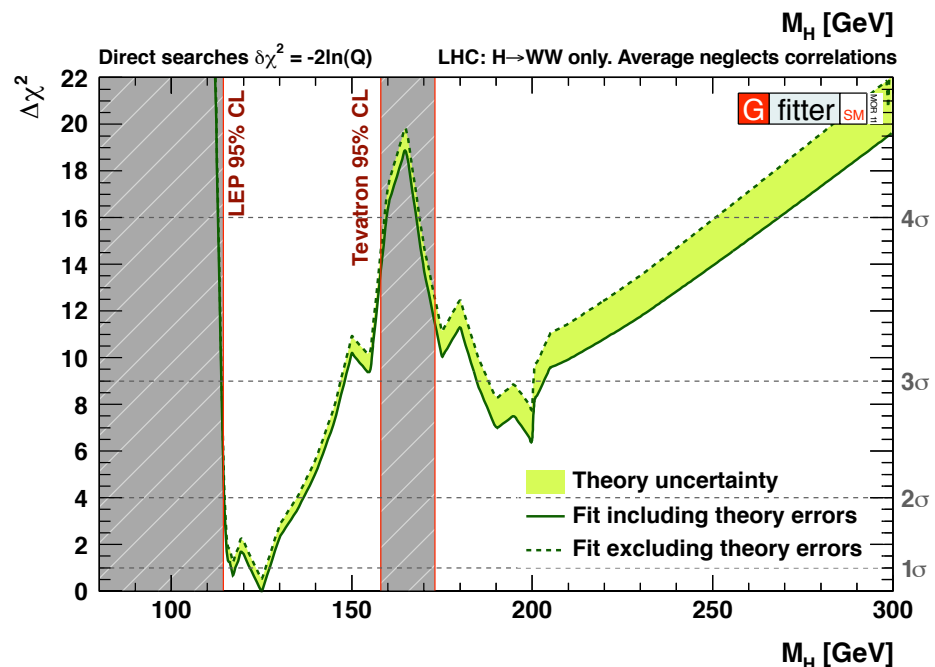
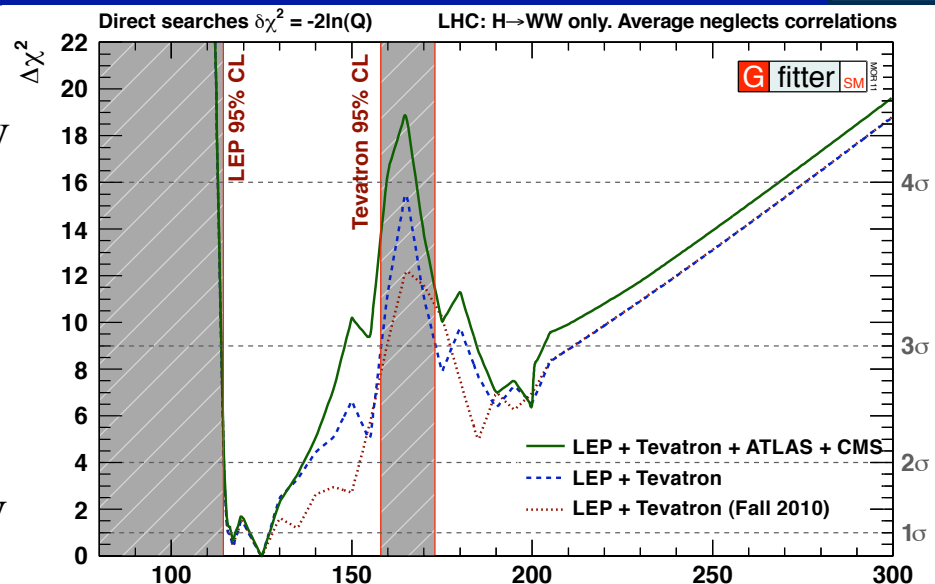
- CL_{s+b}^{2s} central value $\pm 1\sigma$: $M_H = 120.2_{-5.2}^{+17.9}$ GeV
- 2σ interval:
 $-2\ln Q$: [115,152] GeV
 $CL_{s+b}^{2-sided}$: [114,155] GeV

LEP + Tevatron (Moriond 2011) :

- CL_{s+b}^{2s} central value $\pm 1\sigma$: $M_H = 120.2_{-4.7}^{+12.3}$ GeV
- 2σ interval:
 $-2\ln Q$: [115,138] GeV
 $CL_{s+b}^{2-sided}$: [114,149] \cup [152,155] GeV

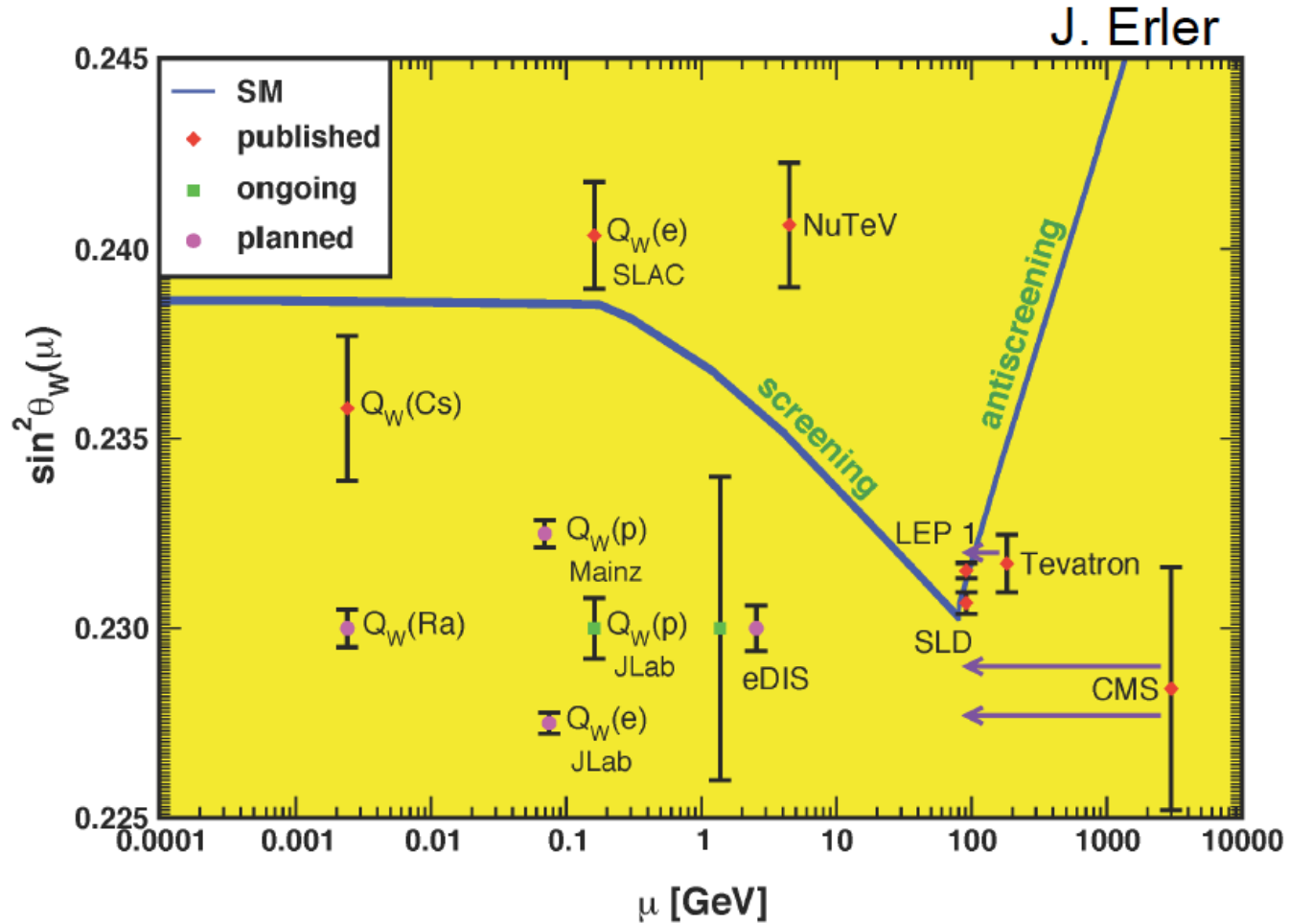
Fit with LEP + Tevatron + LHC (H \rightarrow WW) searches (Moriond 2011) :

- Central value unchanged
- 2σ interval:
 $-2\ln Q$: [115,137] GeV
 $CL_{s+b}^{2-sided}$: [114,14?] GeV



Low energy observables

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



- Input correlation coefficients between Z pole measurements

	M_Z	Γ_Z	σ_{had}^0	R_ℓ^0	$A_{\text{FB}}^{0,\ell}$		$A_{\text{FB}}^{0,c}$	$A_{\text{FB}}^{0,b}$	A_c	A_b	R_c^0	R_b^0
M_Z	1	-0.02	-0.05	0.03	0.06	$A_{\text{FB}}^{0,c}$	1	0.15	0.04	-0.02	-0.06	0.07
Γ_Z		1	-0.30	0.00	0.00	$A_{\text{FB}}^{0,b}$		1	0.01	0.06	0.04	-0.10
σ_{had}^0			1	0.18	0.01	A_c			1	0.11	-0.06	0.04
R_ℓ^0				1	-0.06	A_b				1	0.04	-0.08
$A_{\text{FB}}^{0,\ell}$					1	R_c^0					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].