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

EPS 2013, Stockholm,
18th-24th July 2013

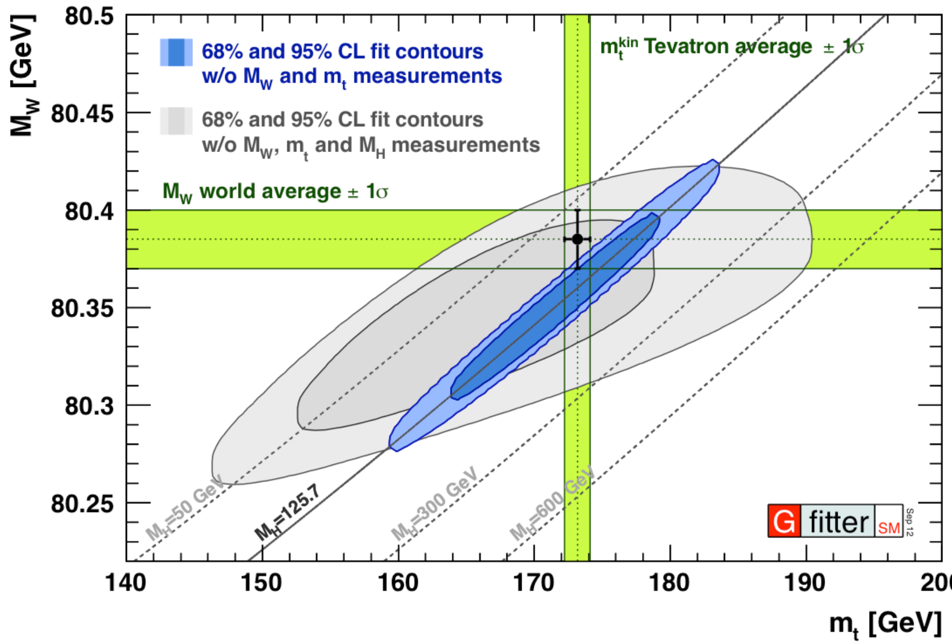
http://cern.ch/Gfitter

EPJC 72, 2205 (2012), arXiv:1209.2716

The ElectroWeak fit of the Standard Model and Beyond

Outline:

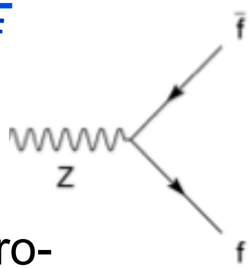
- ✓ The Electroweak Fit
- ✓ Higgs couplings
- ✓ Prospects for ILC

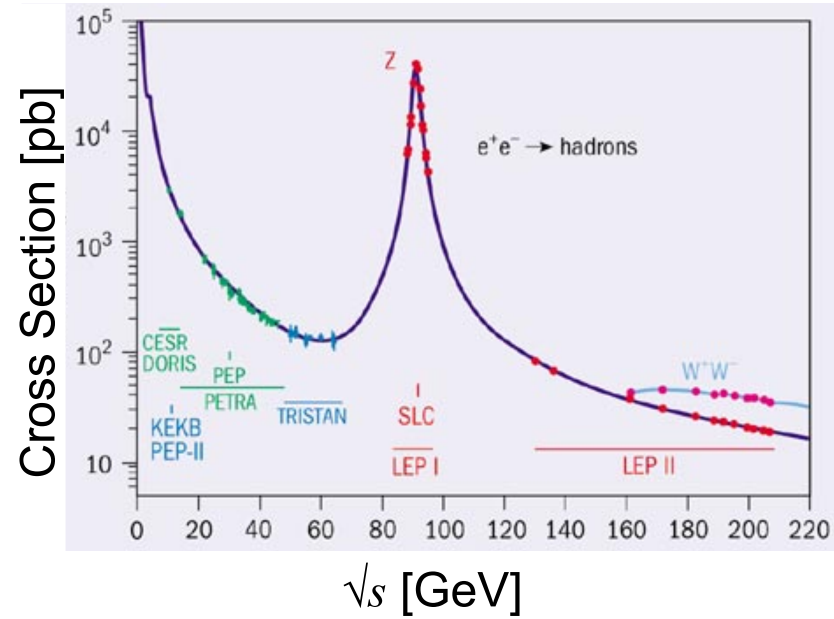


(*) M. Baak, J. Haller, A. Höcker, R. Kogler, K. Mönig, M. Schott, J. Stelzer

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 $Z \to f\bar{f}$
  - $i\bar{f}\gamma^{\mu}\left(g_{V,f} - g_{A,f}\gamma_5\right) f Z_{\mu}$
  - Unification connects the electro-magnetic and weak couplings





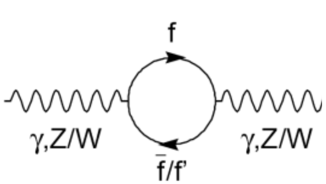
- The impact of loop corrections
  - Absorbed into EW form factors: ρ, κ, Δr
  - Effective couplings at the Z-pole
  - Quadraticly dependent on m_t, *logarithmic* dependence on M_H

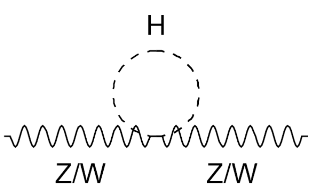
$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\text{eff}}^f\right)$$

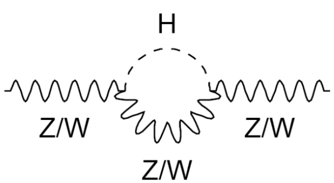
$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

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

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



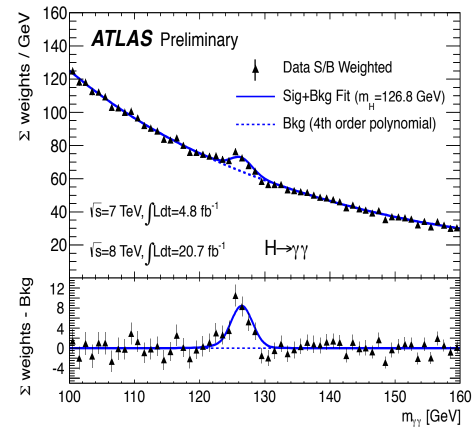


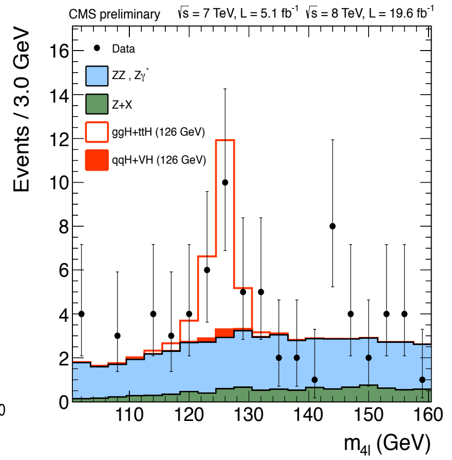


The SM fit with Gfitter, including the Higgs

- Discovery of Higgs-like boson by LHC
  - Cross section x branching ratios, spin, parity, compatible with SM Higgs boson
  - This talk: assume boson is SM Higgs.
  - Use in EW fit: $M_H = 125.7 \pm 0.4$ GeV
  - Change between fully uncorrelated and fully correlated systematic uncertainties is minor: δM_H : 0.4 → 0.5 GeV

[arXiv:1207.7214, arXiv:1207.7235]





- *EW observables precisely predicted at loop level → test consistency of SM!*

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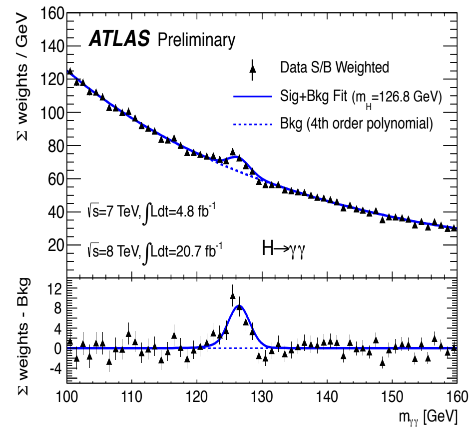
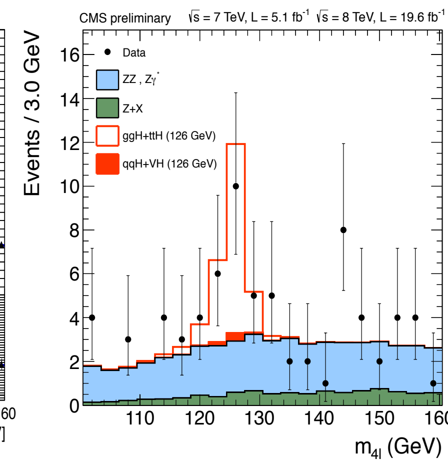




- *EW observables precisely predicted at loop level → test consistency of SM!*

- 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)]
  - $\sin^2\theta^f_{eff}$ 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 N³LO [P. A. Baikov et al., PRL108, 222003 (2012)]
    - N³LO prediction of the hadronic cross section
  - R_b Partial width of Z→b$\bar{b}$ [Freitas et al., JHEP08, 050 (2012)]

← **Update!** (*)
EW 2-loop calc.

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_Z, M_H, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, m_c, m_b
  - 2 theory nuisance parameters
    - δM_W (4 MeV), $\delta \sin^2\theta^l_{eff}$ (4.7×10^{-5})

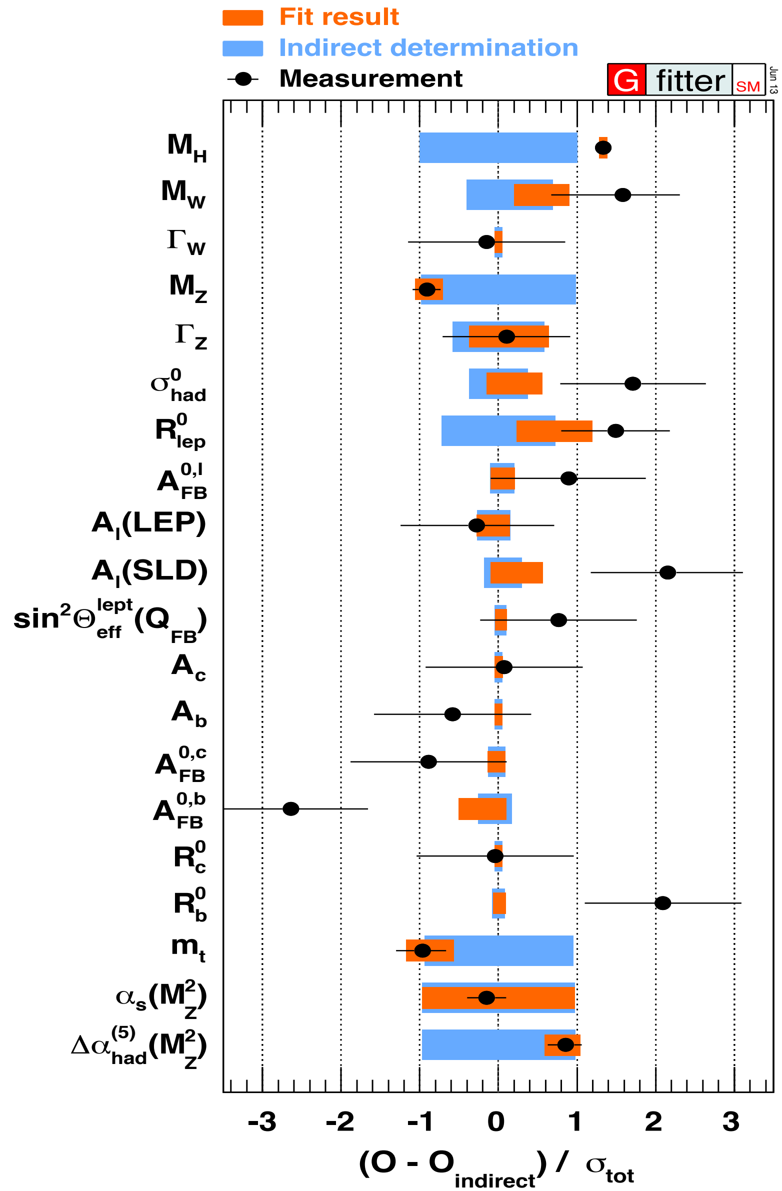
M_H [GeV]°	125.7 ± 0.4	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	Tevatron
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP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

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

- 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.*

- The prediction is often better than the measurement!



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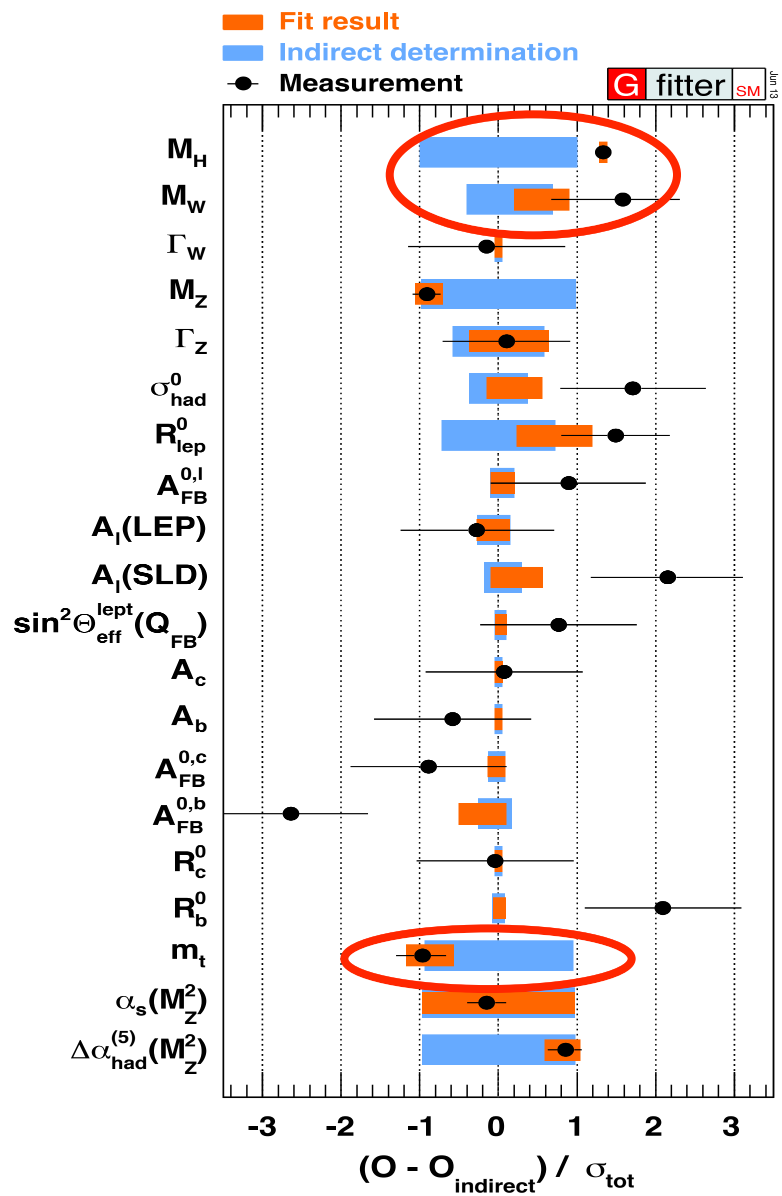

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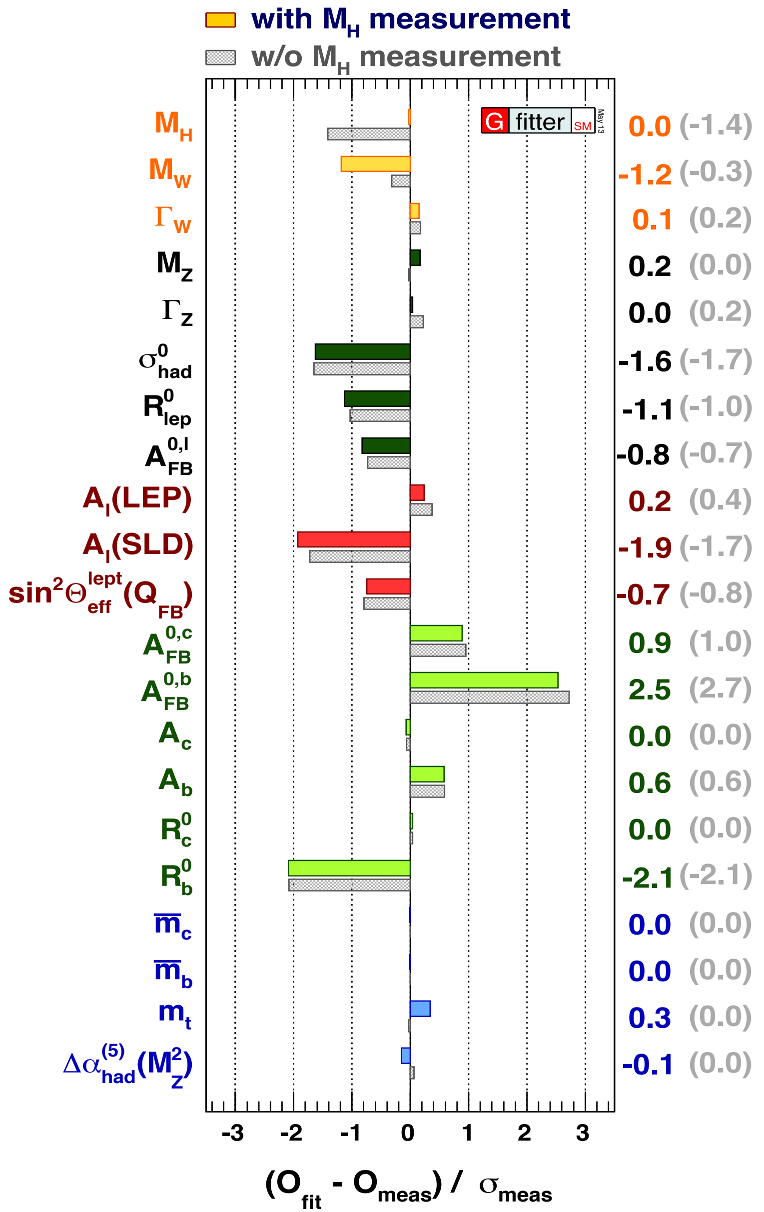
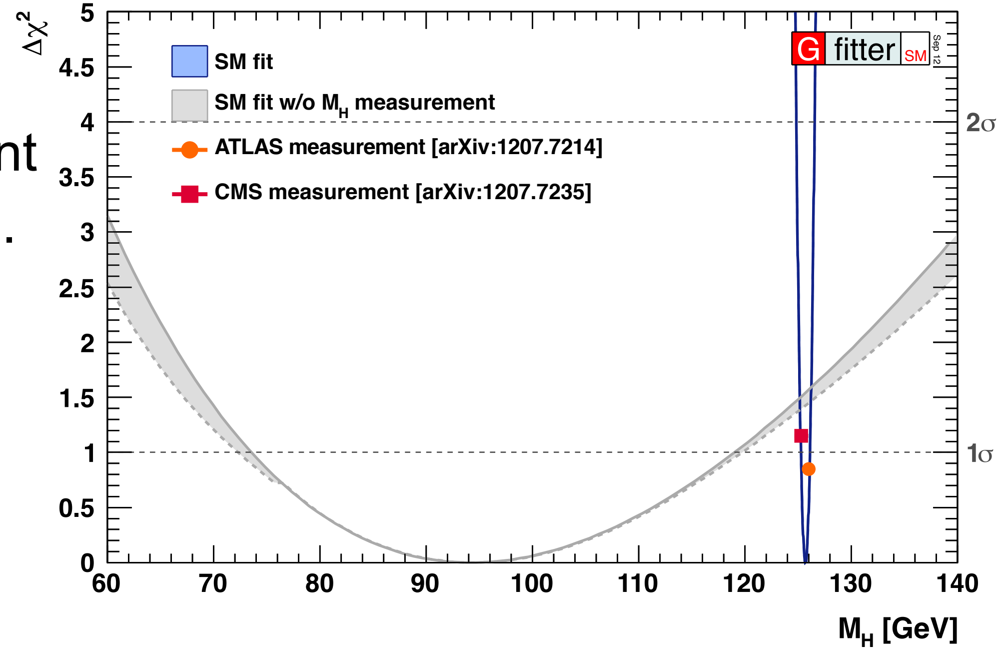


Plot inspired by Eberhardt et al. [arXiv:1209.1101]

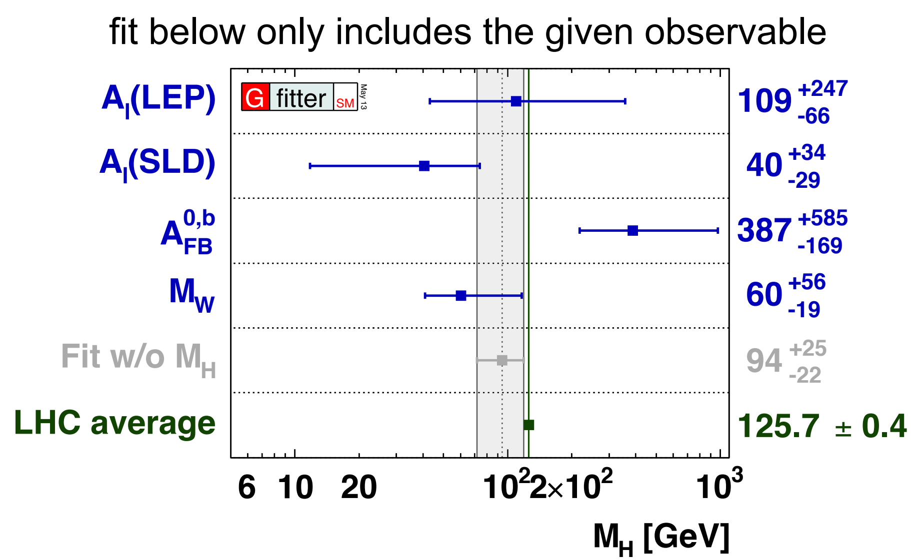
- Pull values of full fit (with M_H)
  - No individual value exceeds 3σ
  - Small pulls for M_H, M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$ indicate that input accuracies exceed fit requirements
  - Largest deviations in b-sector: $A^{0,b}_{FB}$ and R^0_b with 2.5σ and -2.1σ → 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:
  - Shift in predicted M_W value of 13 MeV.
- Goodness of fit – p-value:
  - χ^2_{min}= 20.7 → Prob(χ^2_{min}, 14) = 11%
  - From pseudo experiments: 9^{+2} %
    - Large value of χ^2_{min} not due to inclusion of M_H measurement.
    - Without M_H measurement: χ^2_{min}= 19.3 → Prob(χ^2_{min}, 13) = 11%

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.

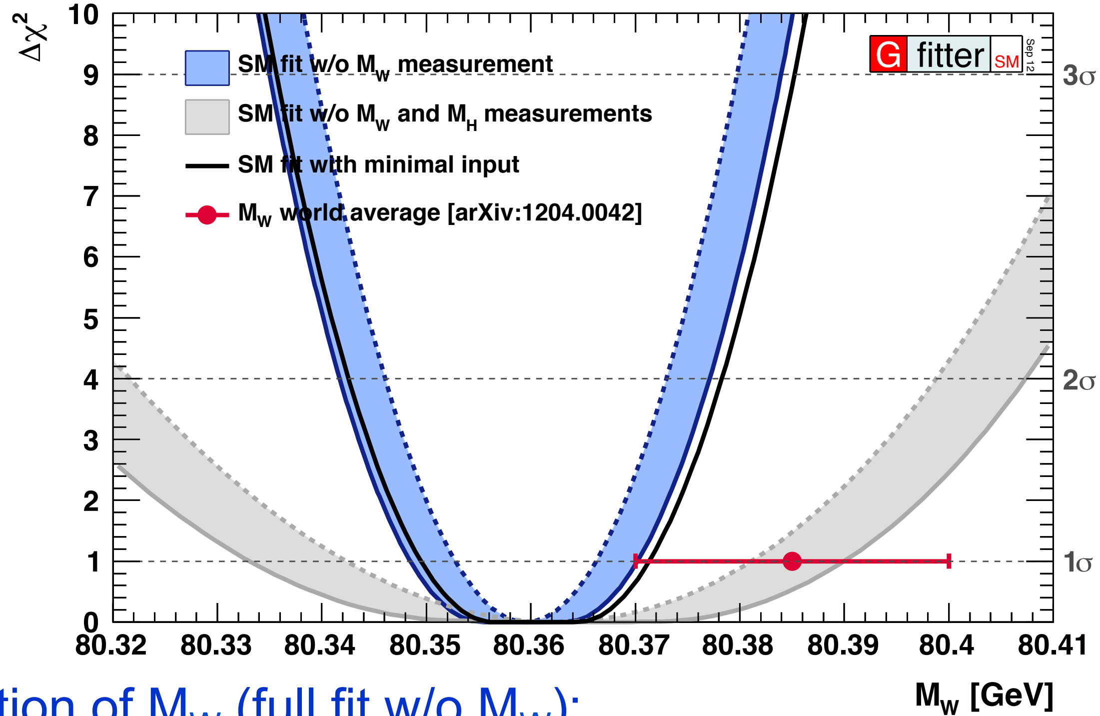


- Bottom plot: impact of other most sensitive Higgs observables
  - Determination of M_H removing all sensitive observables except the given one.
  - Known tension (2.5σ) between A_l(SLD), $A^{0,b}_{FB}$, and M_W clearly visible.



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



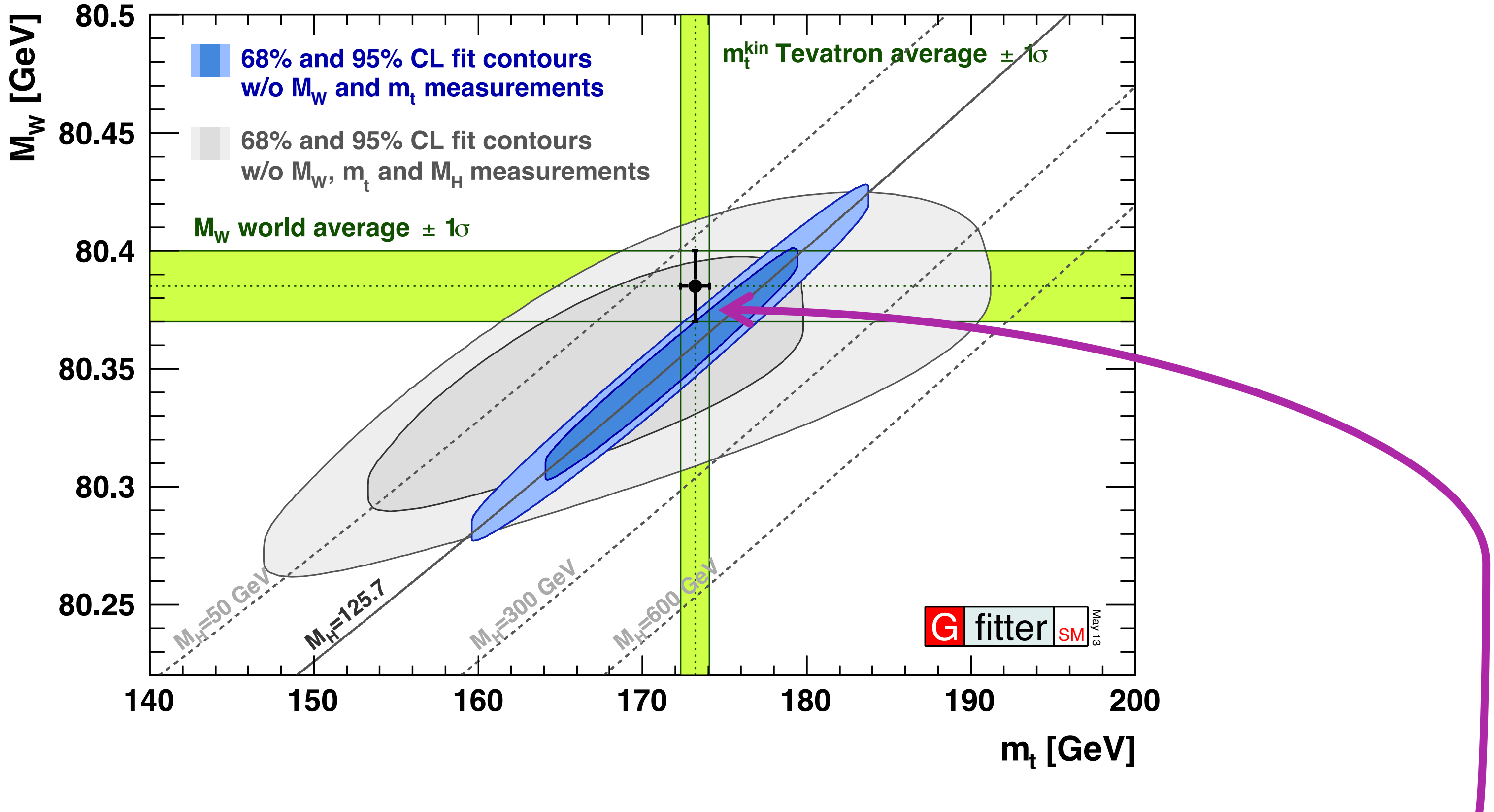
- M_H measurement allows for precise constraint on M_W
  - Agreement at 1.4σ
- Fit result for indirect determination of M_W (full fit w/o M_W):

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

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

State of the SM: W versus top mass

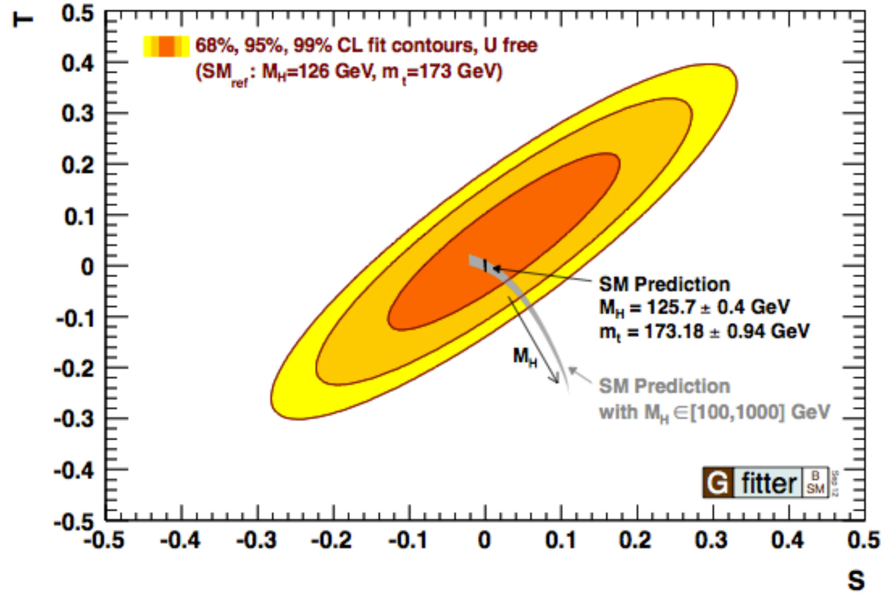
- Scan of M_W vs m_t, with the direct measurements excluded from the fit.
- Results from Higgs measurement significantly reduces allowed indirect parameter space → corners the SM!



- Observed agreement demonstrates impressive consistency of the SM!

Constraints on BSM models

- If energy scale of NP is high, BSM physics appears dominantly through vacuum polarization corrections.
- Described with STU parametrization
  [Peskin and Takeuchi, Phys. Rev. D46, 1 (1991)]
- SM: M_H = 125.7 GeV, m_t = 173.2 GeV
  - This defines (S,T,U) = (0,0,0)
- S, T depend logarithmically on M_H



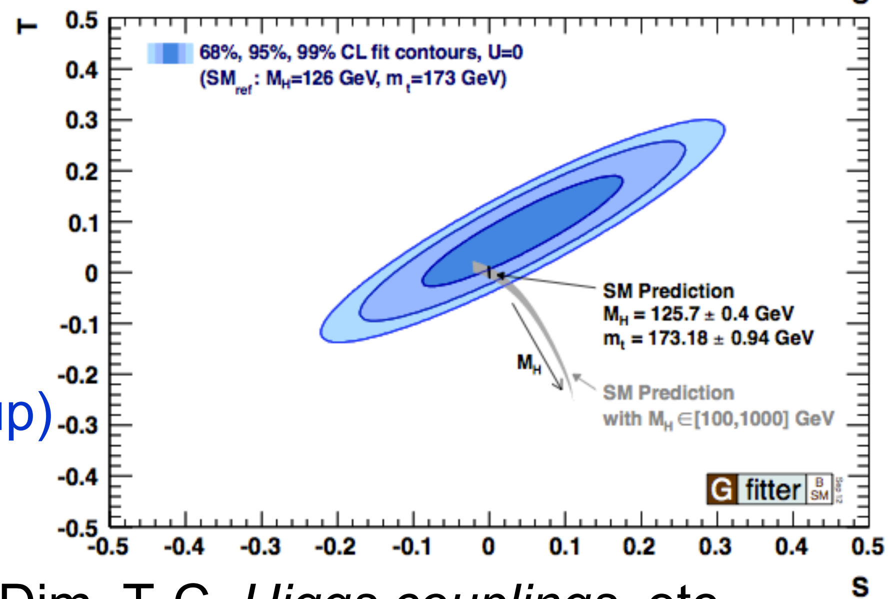
- Fit result:

  S = 0.03 ± 0.10

  T = 0.05 ± 0.12

  U = 0.03 ± 0.10

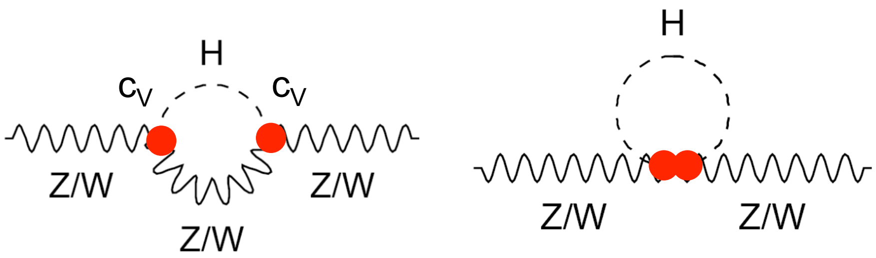
	S	T	U
S	1	+0.89	-0.54
T		1	-0.83
U			1

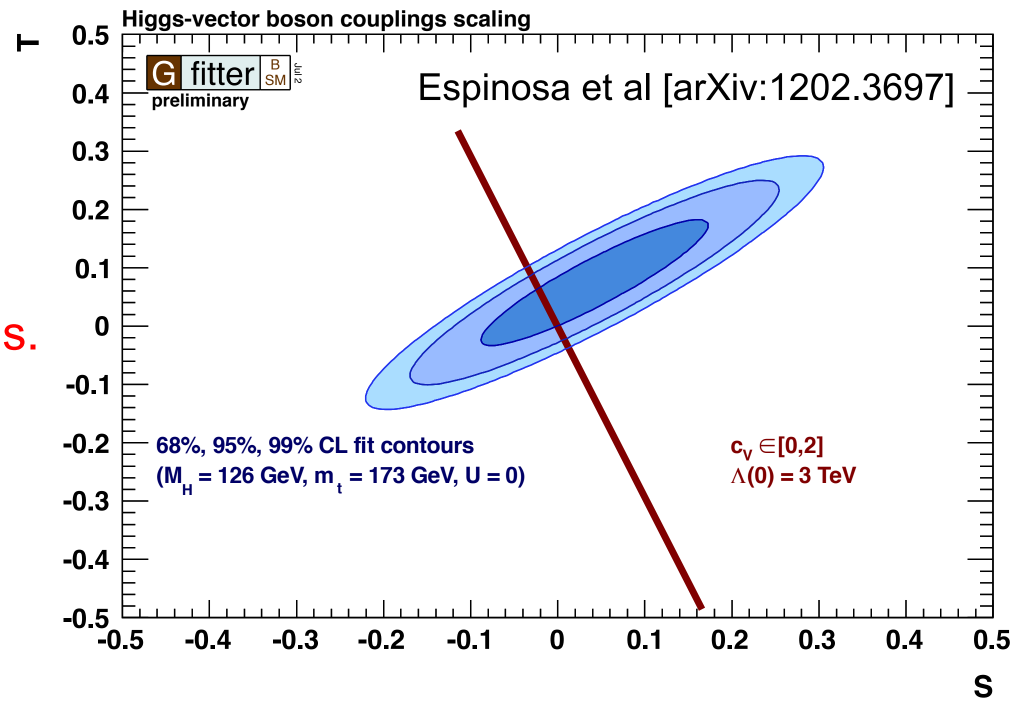


- Stronger constraints from fit with U=0.
- Also results for Z→b$\bar{b}$ correction (backup)
- No indication for new physics.
- Can now use this constrain 4th gen, Ex-Dim, T-C, *Higgs couplings*, etc.

Modified Higgs couplings

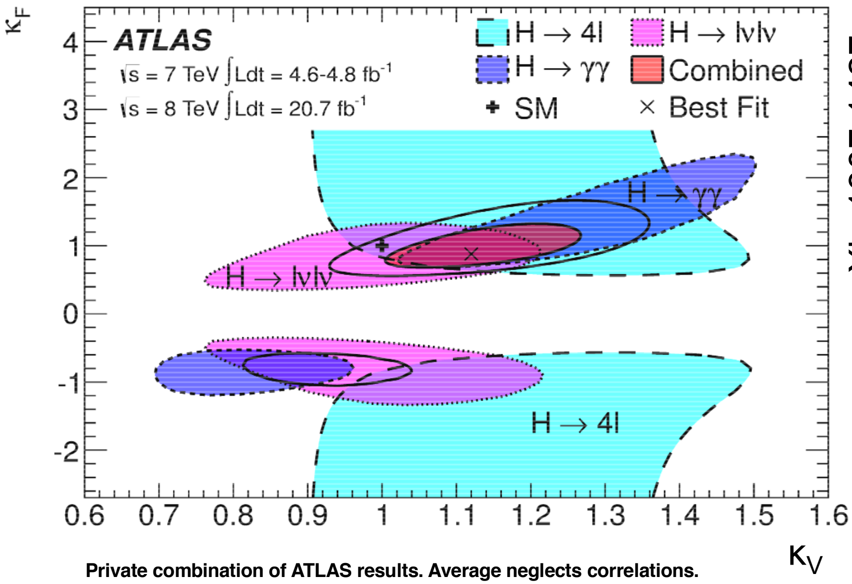
- Study of potential deviations of Higgs couplings from SM.
- BSM modeled as extension of SM through effective Lagrangian.
  - Consider leading corrections only.
- Model considered here:
  - Scaling of Higgs-vector boson (c_V) and Higgs-fermion couplings (c_F), with no invisible/undetectable widths.
  - (Custodial symmetry is assumed.)
- Main effect on EWPO due to modified Higgs coupling to gauge bosons (c_V).
  - Espinosa et al [arXiv:1202.3697], Falkowski et al [arXiv:1303.1812], etc.



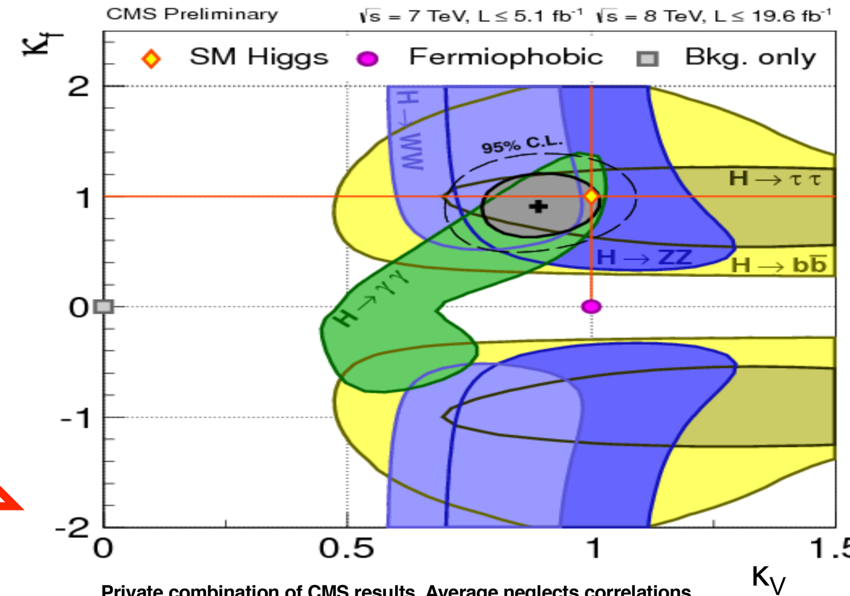


$$S = \frac{1}{12\pi}(1-c_V^2)\log\left(\frac{\Lambda^2}{m_h^2}\right), \quad T = -\frac{3}{16\pi c_W^2}(1-c_V^2)\log\left(\frac{\Lambda^2}{m_h^2}\right), \quad \Lambda = 4\pi v/\sqrt{|1-c_V^2|}$$

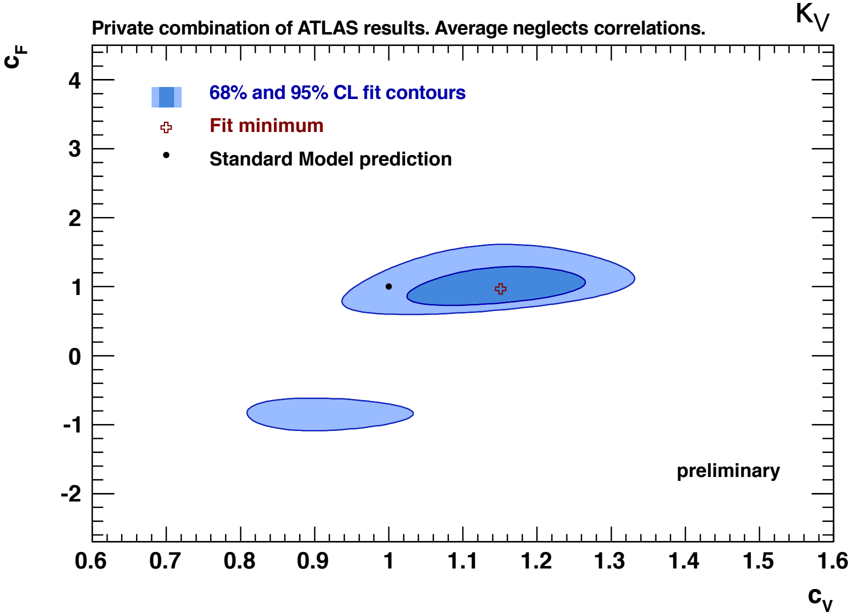
Reproduction of ATLAS and CMS results

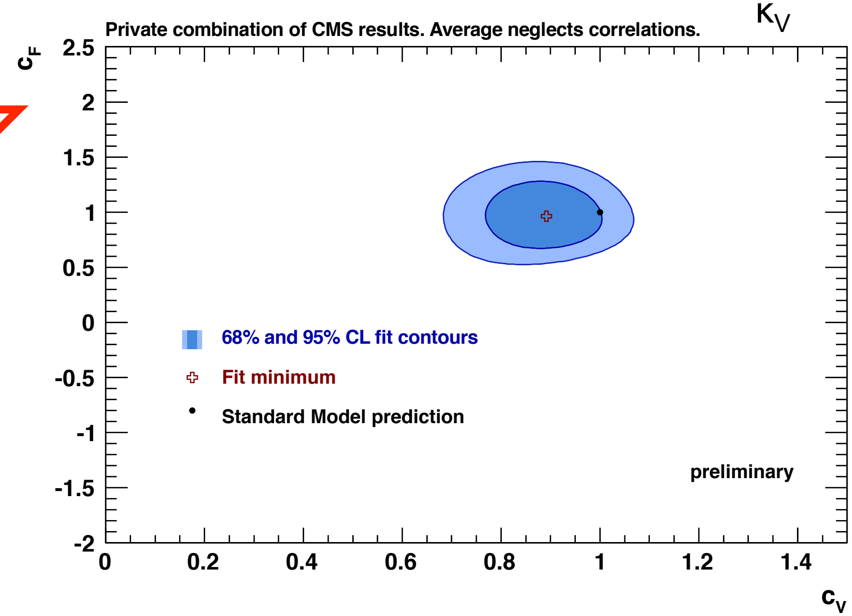


arXiv:1307.1427



CMS-PAS-HIG-13-005

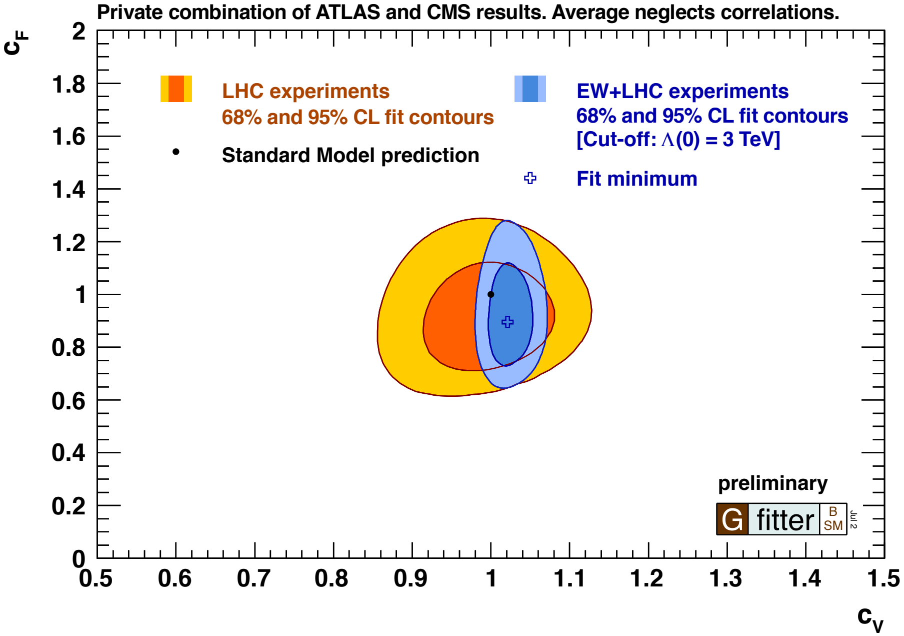


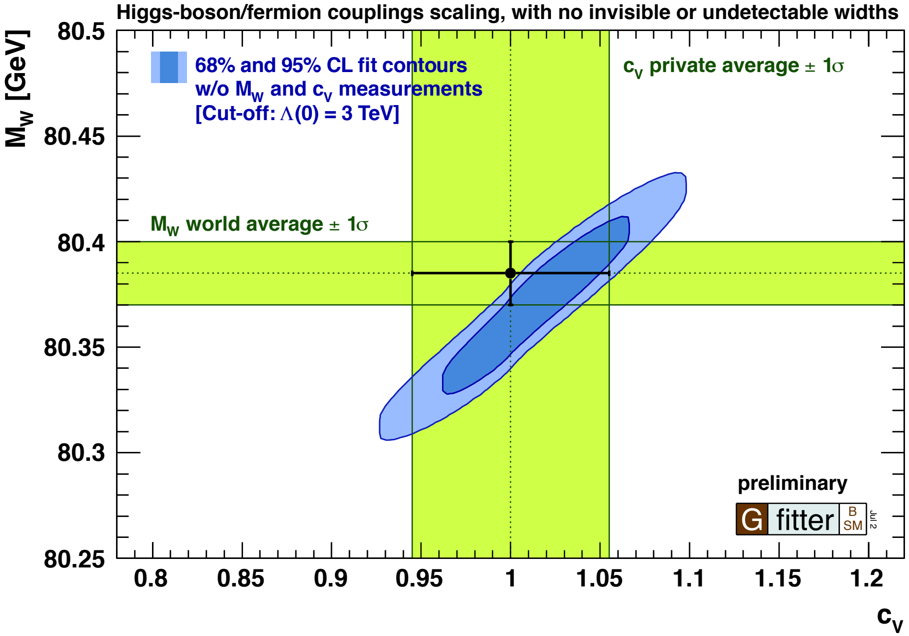


- Decent reproduction of ATLAS and CMS results within limited public-info available.

Higgs coupling results

- Private LHC combination:
  - $c_V = 1.00 \pm 0.06$
  - $c_F = 0.89 \pm 0.13$
- Result from stand-alone EW fit:
  - $c_V = 1.02 \pm 0.02$
  - *(Using cutoff scale: $\Lambda(0)$ = 3 TeV)*





- EW fits gives more precise result than current LHC experiments for c_V.
- EW fit: deviation of c_V from one driven by small tension in W mass prediction versus measurement.

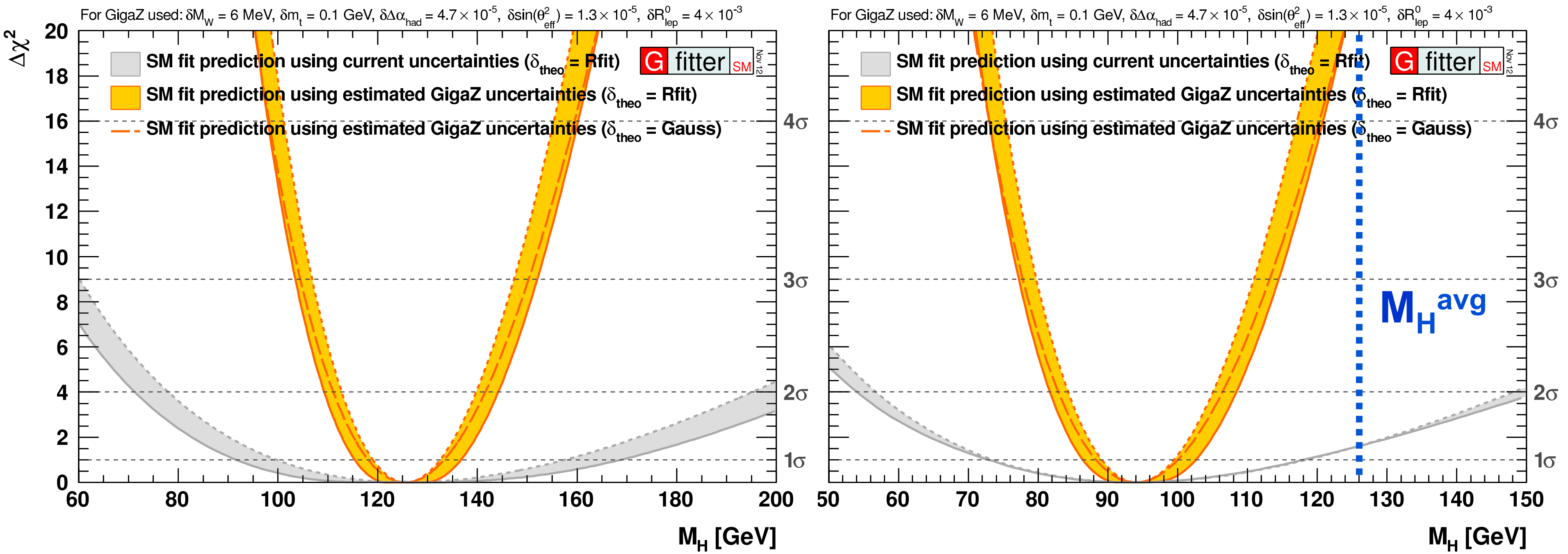
Prospects of EW fit for ILC with Giga Z

- Future Linear Collider can improve precision of EWPO's tremendously.
  - *WW threshold, to obtain M_W*
    - from threshold scan: δM_W : 15 → 6 MeV
  - *ttbar threshold, 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.

- Low-energy data results to improve $\Delta\alpha_{had}$:
  - ISR-based (BABAR) and KLOE-II (both low energy), and BESIII e^+e^- cross-section measurements, in particular around cc resonance.
  - Plus: improved α_s, improvements in theory: $\Delta\alpha_{had}$: $10^{-4} \rightarrow 5 \cdot 10^{-5}$

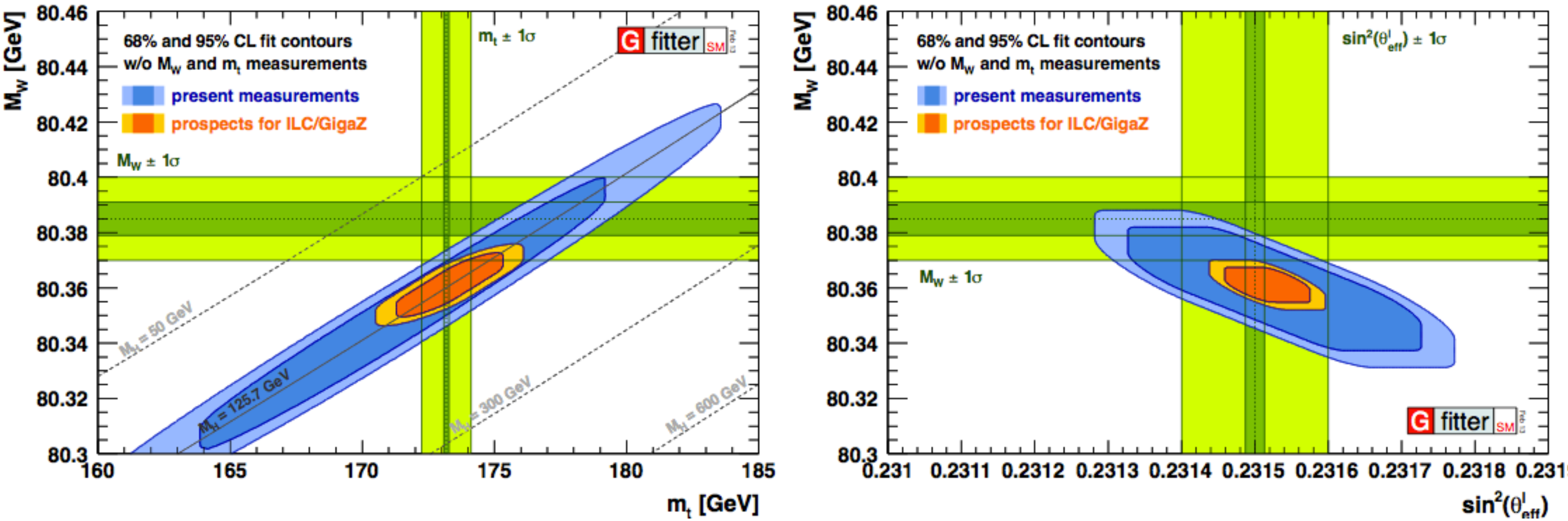
- Assuming 50% of today's theoretical uncertainties on M_W and $\sin^2\theta^l_{eff}$
  - Implies three-loop EW calculations!
  - δM_W (4→2 MeV), $\delta \sin^2\theta^l_{eff}$ ($4\times10^{-5} \rightarrow 2\times10^{-5}$)

Prospects for ILC with Giga Z



- 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
  - R-fit scheme: $M_H = 126^{+12}_{-10}$ 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), >4σ discrepancy with measured Higgs mass.

Prospects for ILC with Giga Z

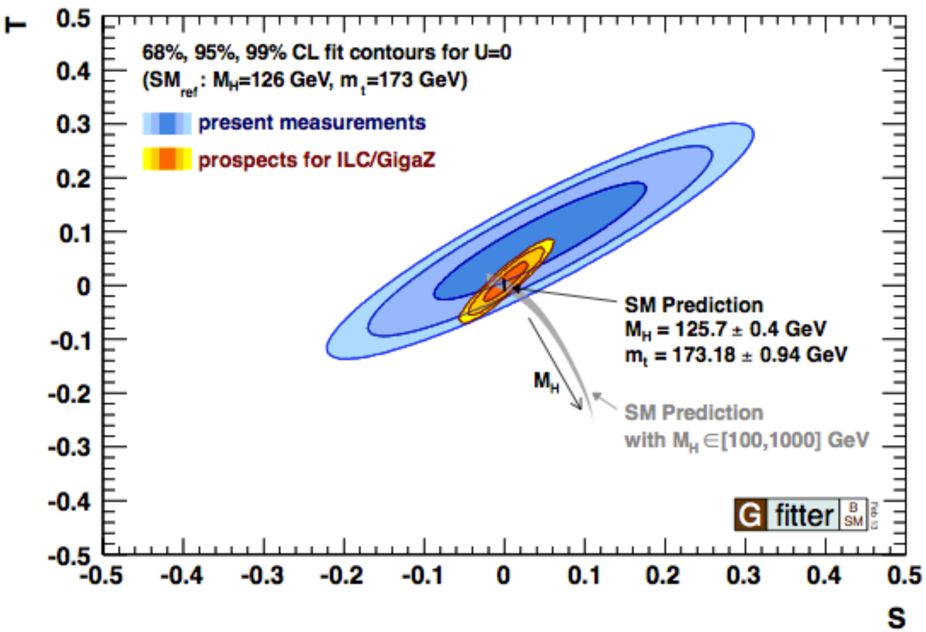


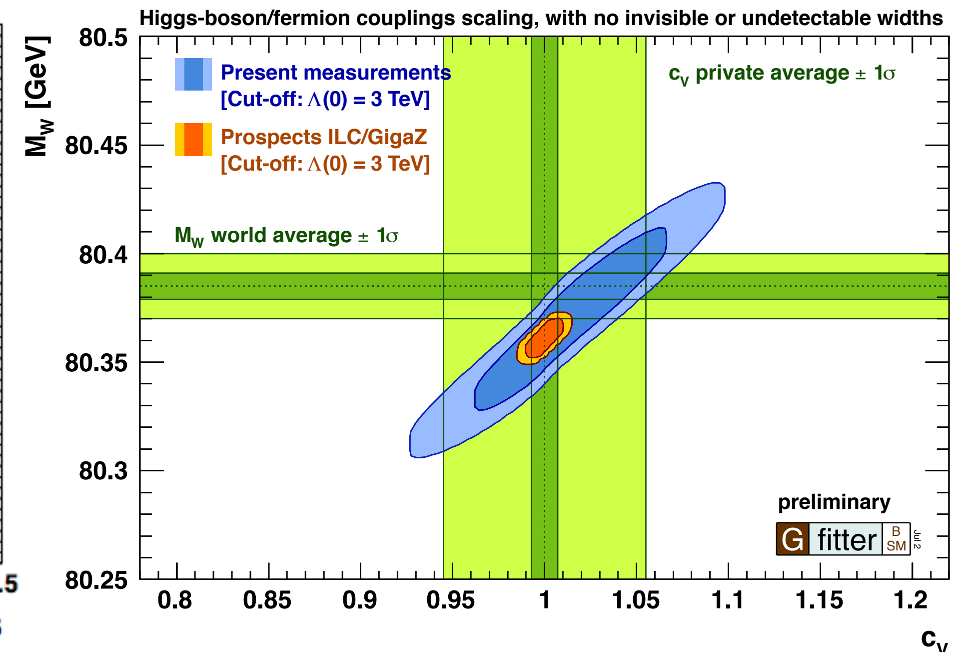
current precision

prospects for direct ILC measurements

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

Prospects for ILC with Giga Z





current precision
prospects for direct ILC measurements

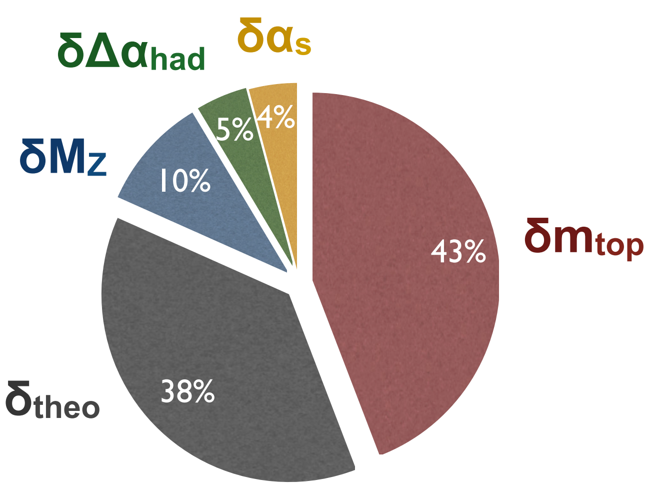
- For STU parameters, improvement of factor of >3 is possible.
- Again, at ILC a deviation between the SM predictions and direct measurements would be prominently visible.
- Competitive results between EW fit and Higgs coupling measurements!
  - [Note: model-dependency for Higgs coupling predictions from EW fit.]

Conclusion and Today's prospects

- Including M_H measurement, for first time SM is fully over-constrained!
  - M_H consistent at 1.3σ with indirect prediction from EW fit.
- p-Value of global electroweak fit of SM: 9% (pseudo-experiments)
  - Would be great to revisit $Z \rightarrow b\bar{b}$, both theoretically and experimentally

- Knowledge of M_H dramatically improves SM prediction of key observables
  - M_W (28→11 MeV), $\sin^2\theta^l_{eff}$ ($2.3\times10^{-5} \rightarrow 1.0\times10^{-5}$), m_t (6.2→2.5 GeV)
- Improved accuracies set benchmark for new direct measurements!

- δM_W (indirect) = 11 MeV
  - Large contributions to δM_W from top and unknown higher-order EW corrections
- δM_W (direct) = 15 MeV



- Including new data electroweak fits remain very interesting in the next years!
- Latest results always available at: http://cern.ch/Gfitter

Thanks!