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

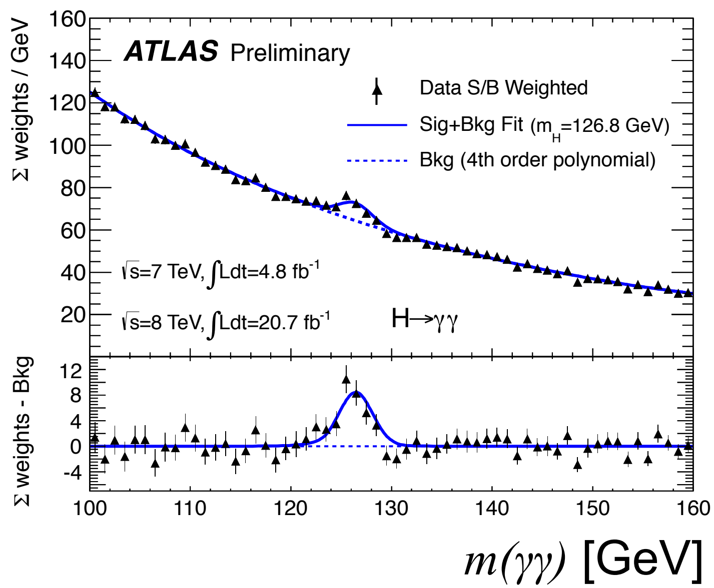
Rencontres de Moriond QCD
La Thuile, 9th-15th March 2013

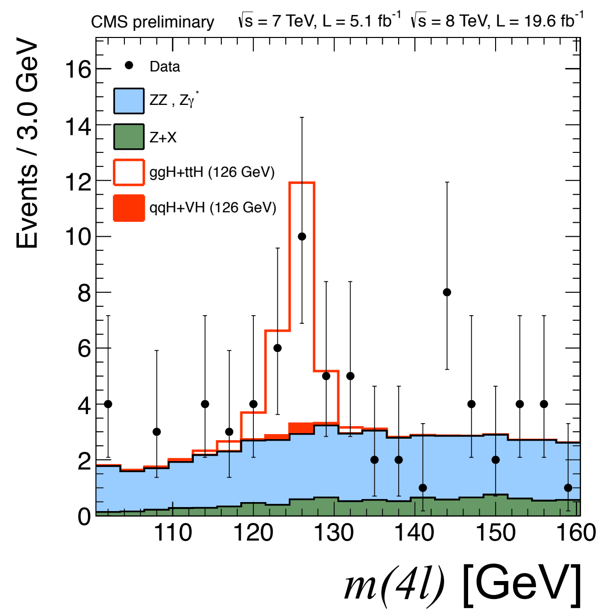
Gfitter

http://cern.ch/Gfitter

EPJC 72, 2205 (2012), arXiv:1209.2716

The ElectroWeak fit of Standard Model after the Discovery of the Higgs-like boson

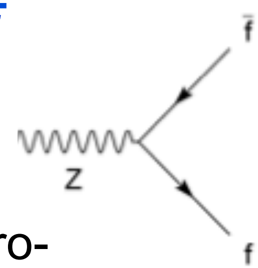


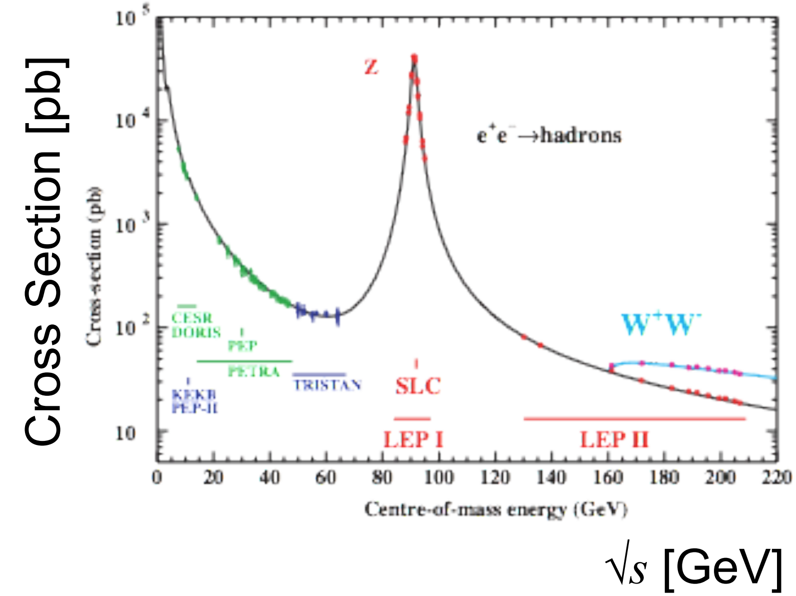


(*) M. Baak, J. Haller, A. Höcker, R. Kogler, K. Mönig, M. Schott, J. Stelzer

Reminder: the predictive power of the SM

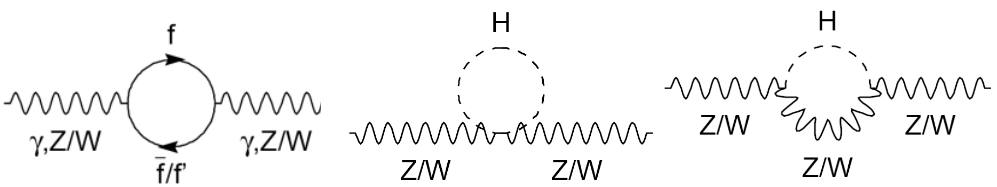
- Tree level relations for $Z \to f\bar{f}$
  - $$i\bar{f}\gamma^{\mu}\left(g_{V,f} - g_{A,f}\gamma_5\right) f Z_{\mu}$$
  - Unification connects the electro-magnetic and weak couplings
  - E.g. M_W can be expressed as function of M_Z and G_F





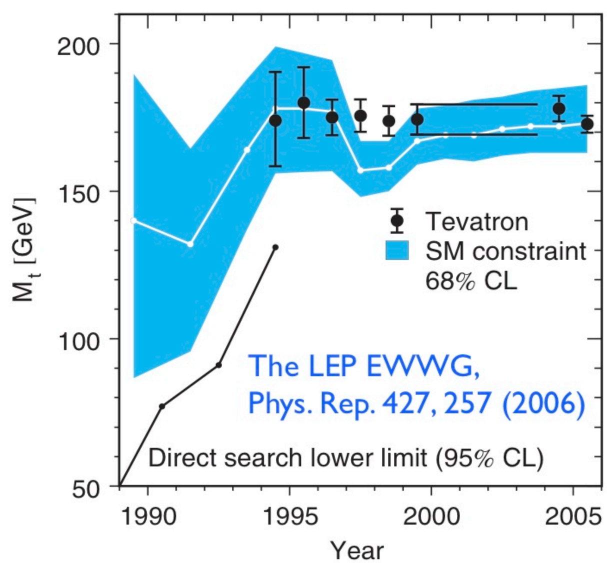
- The impact of radiative corrections
  - Absorbed into EW form factors: ρ, κ, Δr
  - Effective couplings at the Z-pole
  - Quadraticly dependent on m_t, *logarithmic* dependence on M_H

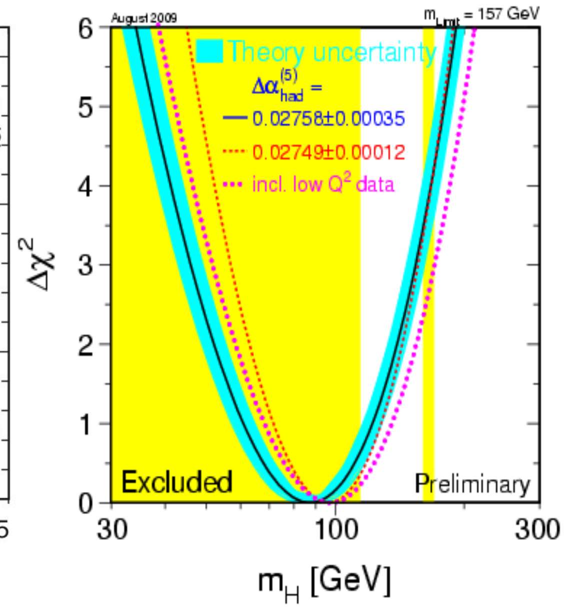
$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\rm eff}^f\right)$$
$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$
$$\sin^2\theta_{\rm eff}^f = \kappa_Z^f \sin^2\theta_W$$
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$



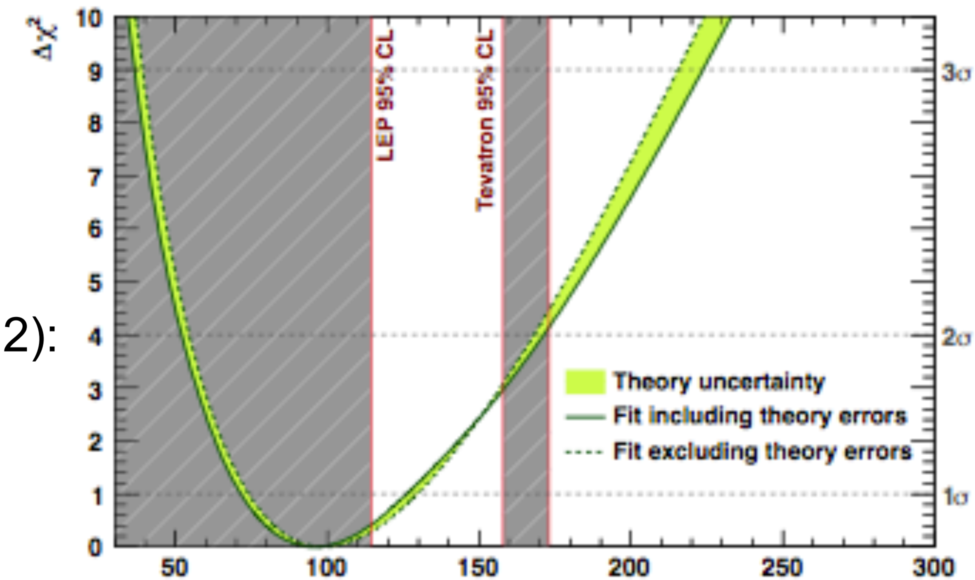
Global EW fits: a long tradition

- EW fits: a long tradition
  - Huge amount of pioneering work by many!
  - Precision measurements crucial, first from LEP/SLC, then Tevatron and now LHC.
  - Precise understanding of loop corrections essential.
    - Observables known at least at two-loop order, sometimes more.





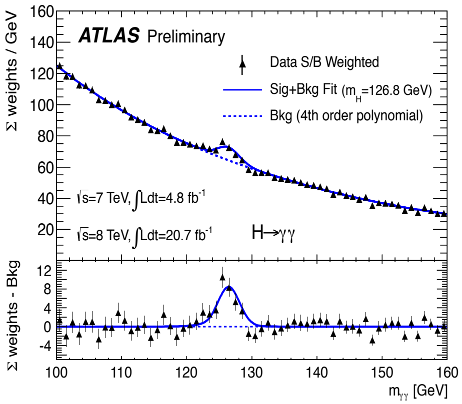
- Hunt for the Higgs
  - M_H last missing input parameter
  - Indirect determination from EW fit (2012): $M_H = 96^{+31}_{-24}$ GeV
  - (Direct exclusion limits also incorporated in EW fits.)

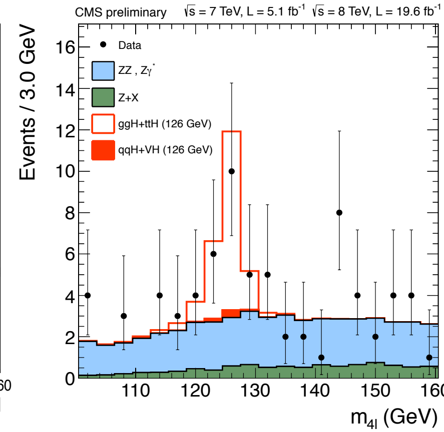


Gfitter group, EPJC 72, 2003 (2012)

The SM fit with Gfitter, including the Higgs

- Discovery of Higgs-like boson by LHC
  - Cross section and branching ratios 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
  - Change between fully uncorrelated and fully correlated systematic uncertainties is minor: δM_H : 0.4 → 0.5 GeV





- *For first time SM is fully over-constrained → test its self-consistency!*

- 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)]
  - Γ_Z, Γ_W Partial and total widths of the Z and W [Cho et. al, arXiv:1104.1769]
  - $\sin^2\theta^f_{eff}$ Effective weak mixing angle [M. Awramik et al., JHEP 11, 048 (2006), M. Awramik et al., Nucl.Phys.B813:174-187 (2009)]
  - Γ_{had} QCD Adler functions at N3LO [P. A. Baikov et al., PRL108, 222003 (2012)]
  - R_b Partial width of $Z \to b\bar{b}$ [Freitas et al., JHEP08, 050 (2012)] ← **New! full 2-loop calc.**

Electroweak fit – Experimental inputs

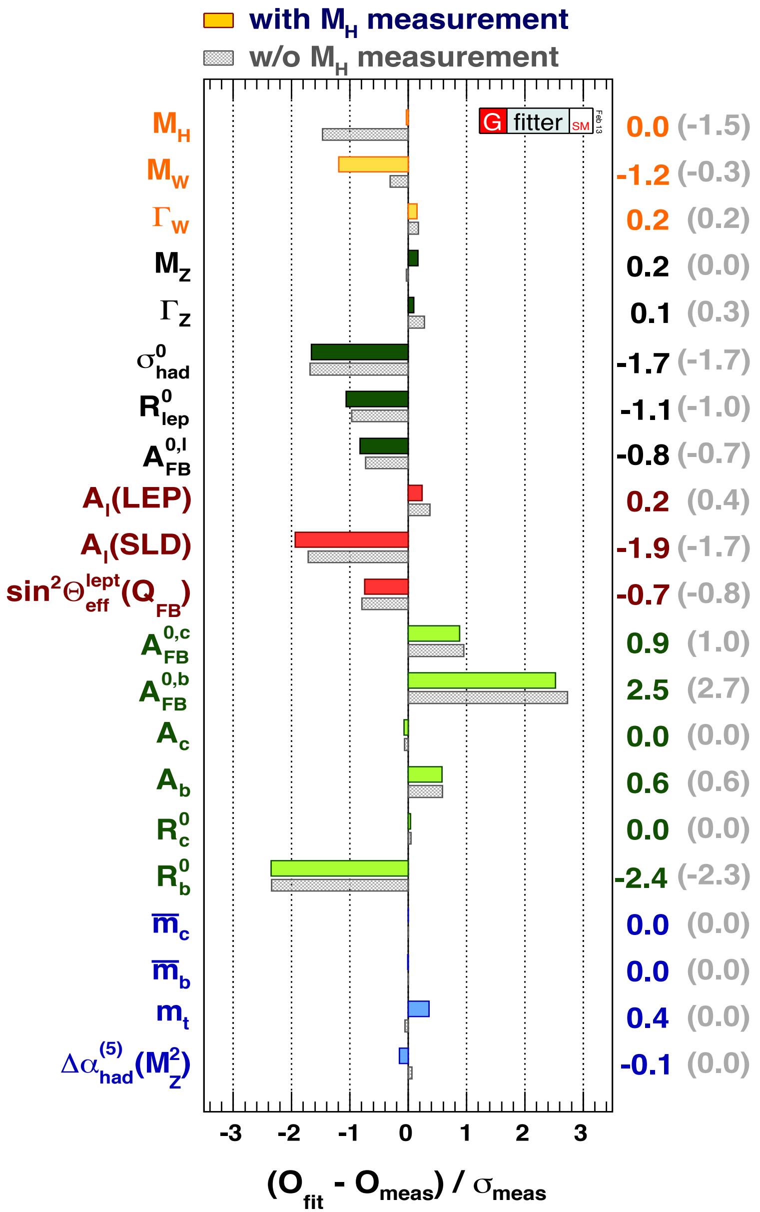
- **Latest experimental inputs:**
  - Z-pole observables: from LEP / SLC
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - M_W and Γ_W from LEP/Tevatron
    [arXiv:1204.1069]
  - m_{top} : average from Tevatron
    [arXiv:1207.1069]
  - m_c, m_b world averages
    [PDG, J. Phys. G33,1 (2006)]
  - $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency
    [Davier et al., EPJC 71, 1515 (2011)]
  - M_H from LHC
    [arXiv:1207.7214, arXiv:1207.7235]
- **7 free fit parameters:**
  - M_Z, M_H, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, $\overline{m}_c$, $\overline{m}_b$
  - Two nuisance parameters for theoretical uncertainties: *δM_W (4 MeV), $\delta \sin^2\theta^l_{eff}$ (4.7×10^{-5})*

M_H [GeV]$^{(\circ)}$	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	LHC
Γ_Z [GeV]	2.4952 ± 0.0023	LHC
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LHC
R^0_ℓ	20.767 ± 0.025	LHC
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LHC
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LHC / SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LHC
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]	173.18 ± 0.94	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\nabla)}$	2757 ± 10	

Electroweak Fit – SM Fit Results

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

Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680^{+0.00025}_{-0.00038}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
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	–	0.21474 ± 0.00003	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [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]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\bigtriangledown)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

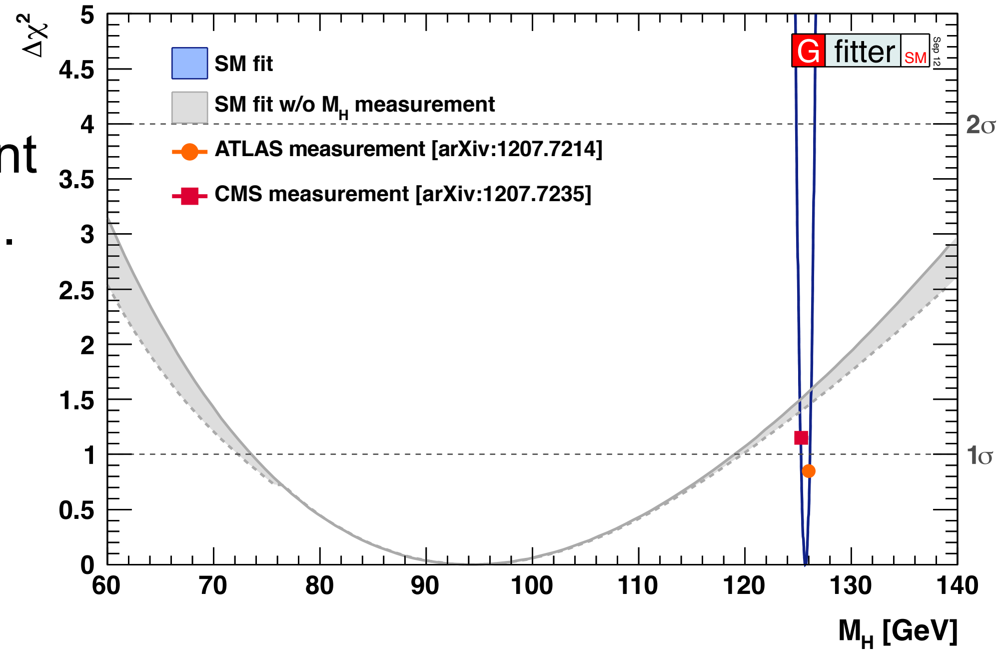


Plot inspired by Eberhardt et al. [arXiv:1209.1101]

- 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 -2.4σ → largest contribution to χ^2
  - R^0_b using one-loop calculation -0.8σ
    - R^0_b has only little dependence on M_H

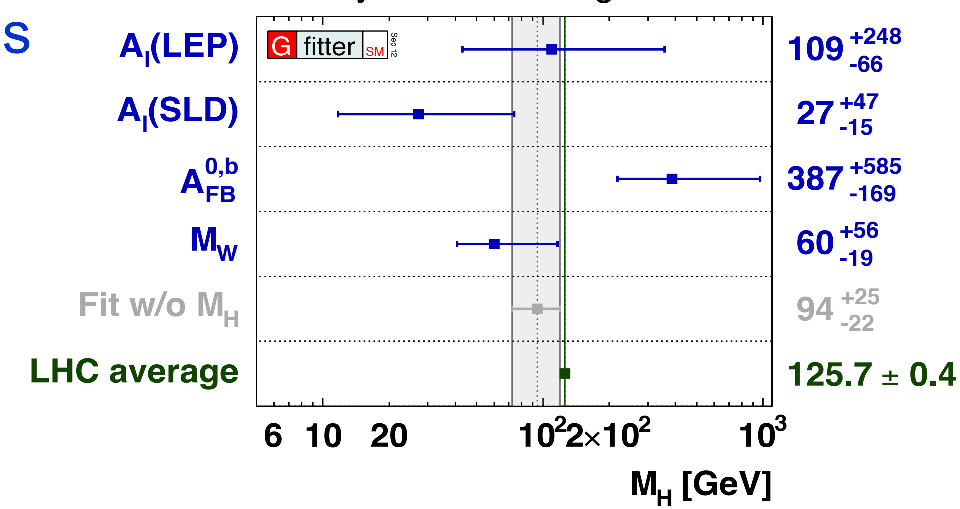
- Goodness of fit – p-value:
  - χ^2_{min}= 21.8 → Prob(χ^2_{min}, 14) = 8 %
  - From pseudo experiments: 7±1%
    - Large value of χ^2_{min} not due to inclusion of M_H measurement.
    - Without M_H measurement: χ^2_{min}= 20.3 → Prob(χ^2_{min}, 13) = 9%

- 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.



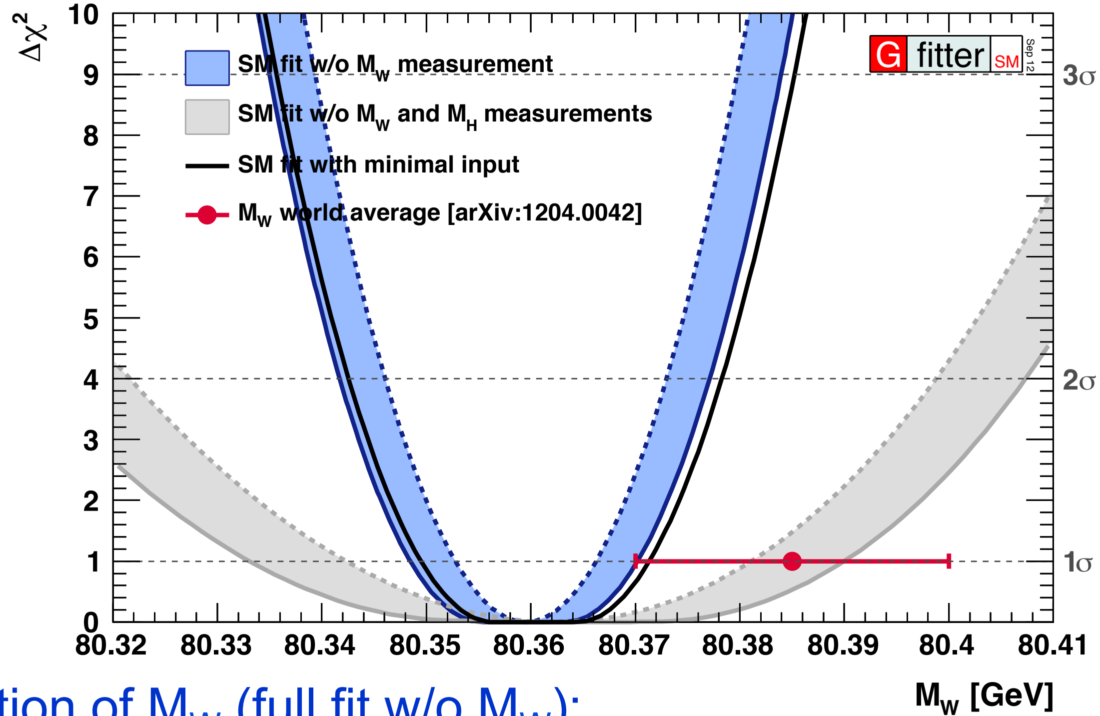
- Bottom plot: impact of other most sensitive Higgs observables
  - Determination of M_H removing all sensitive observables except the given one.
  - Known tension (2.5σ) between A_l(SLD), $A^{0,b}_{FB}$, and M_W clearly visible.

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



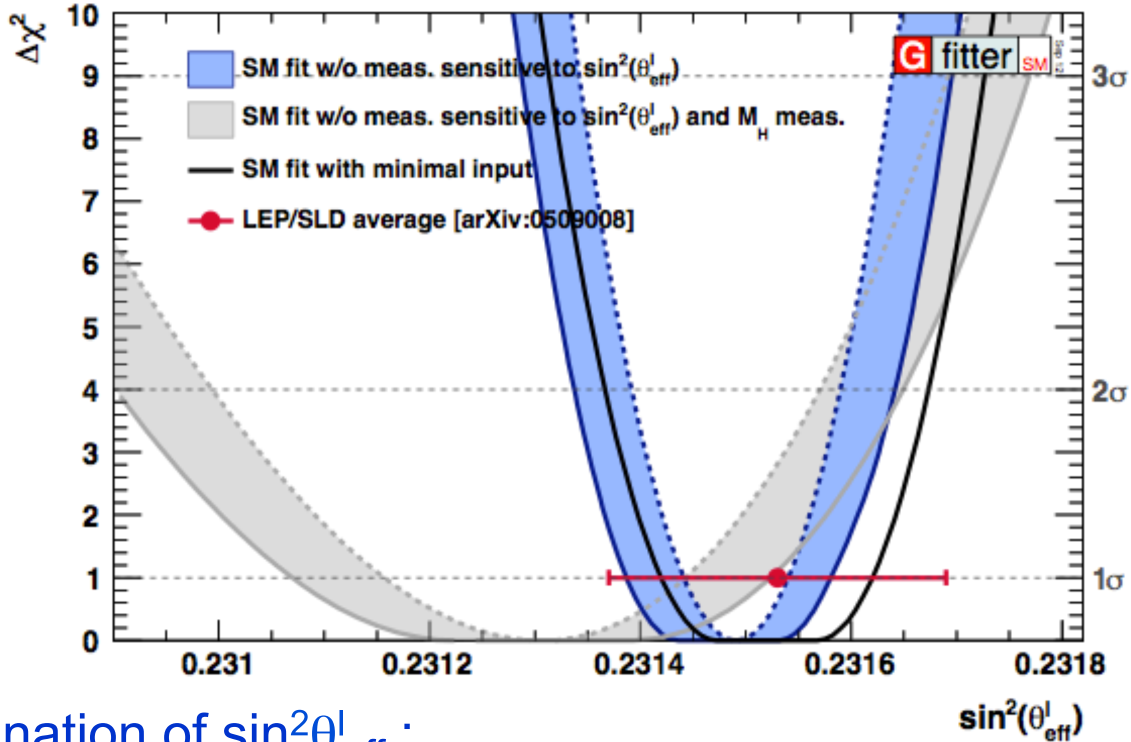
- M_H measurement allows for precise constraint on M_W
  - Agreement at 1.4σ
- Fit result for indirect determination of M_W (full fit w/o M_W):

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

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

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



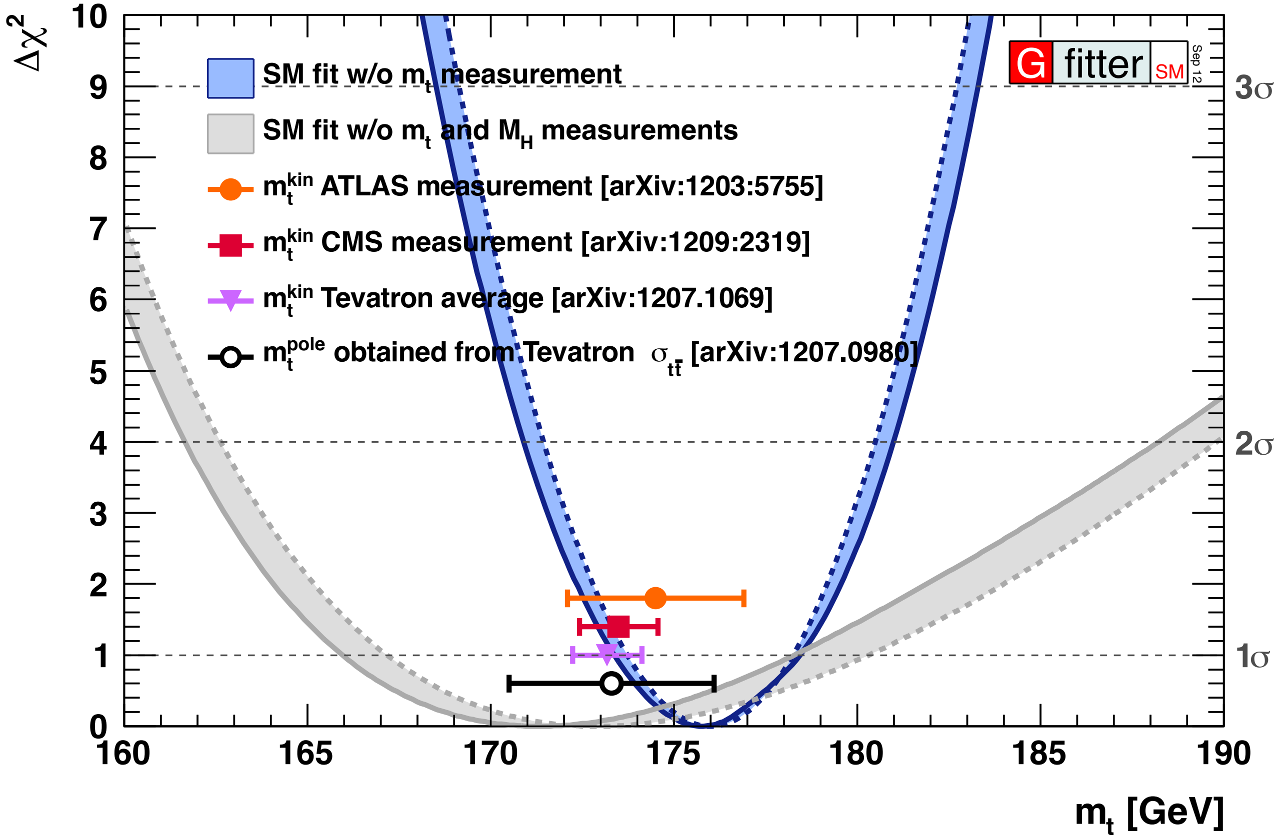
- M_H measurement allows for very precise constraint on $\sin^2\theta^l_{eff}$

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

$$\sin^2\theta^\ell_{\rm eff} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo} \,,$$

$$= 0.23150 \pm 0.00010_{\rm tot} \,,$$

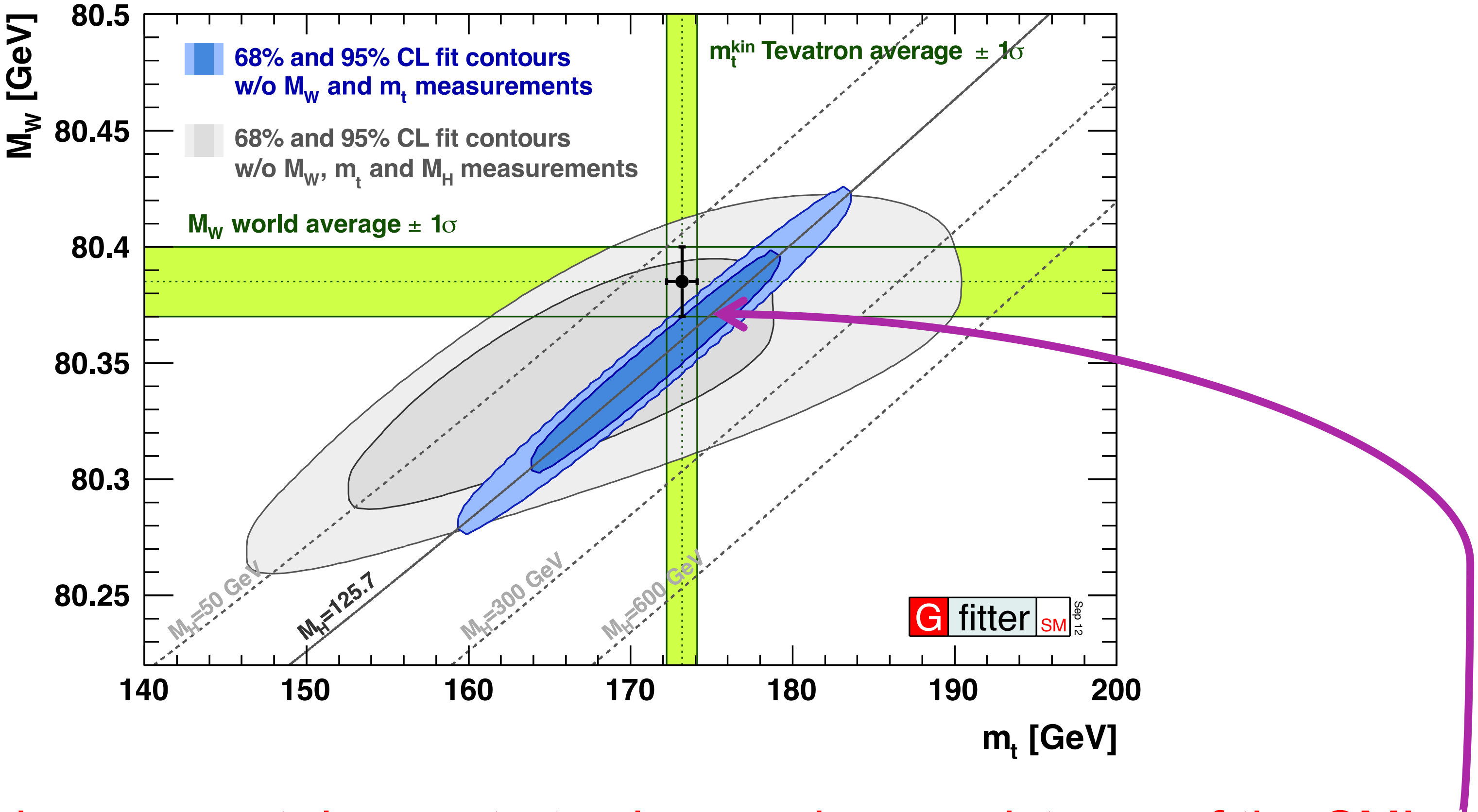
- More precise than direct determination (from LEP/SLD) !
  - Uncertainty on LEP/SLD average: $1.7\text{x}10^{-4}$



- 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
  - Indirect result: $m_t = 175.8^{+2.7}_{-2.4}$ GeV (Tevatron average: 173.2 ± 0.9 GeV)

State of the SM: W versus top mass

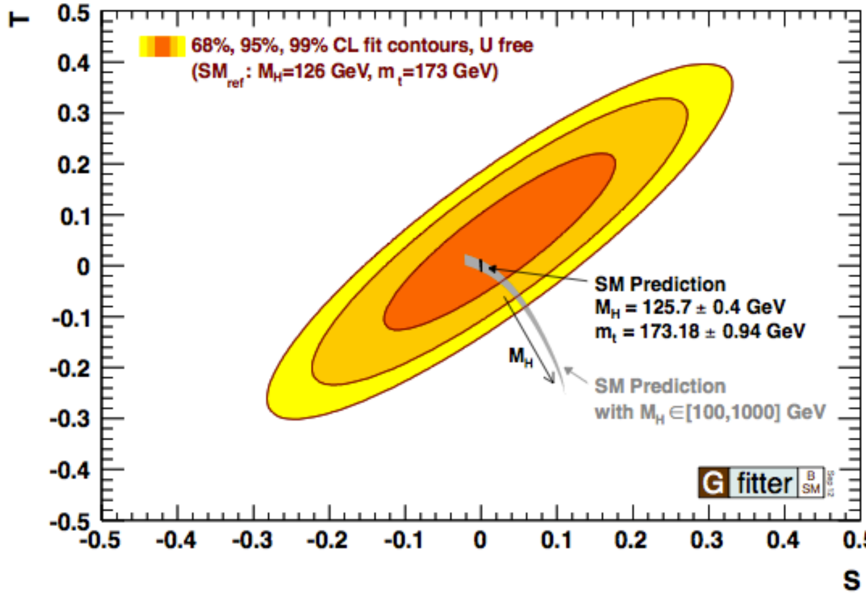
- Scan of M_W vs m_t, with the direct measurements excluded from the fit.
- Results from Higgs measurement significantly reduces allowed indirect parameter space → corners the SM!



- Observed agreement demonstrates impressive consistency of the SM!

Constraints on S, T, U

- Electroweak fit sensitive to BSM physics through vacuum polarization corrections (also absorbed in ρ, κ, Δr).
- 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:

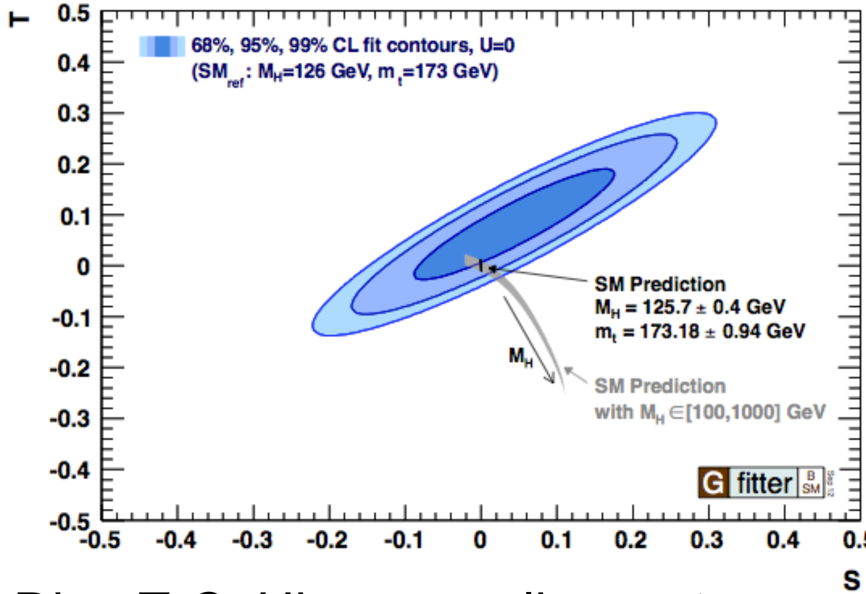
  S = 0.03 ± 0.10

  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



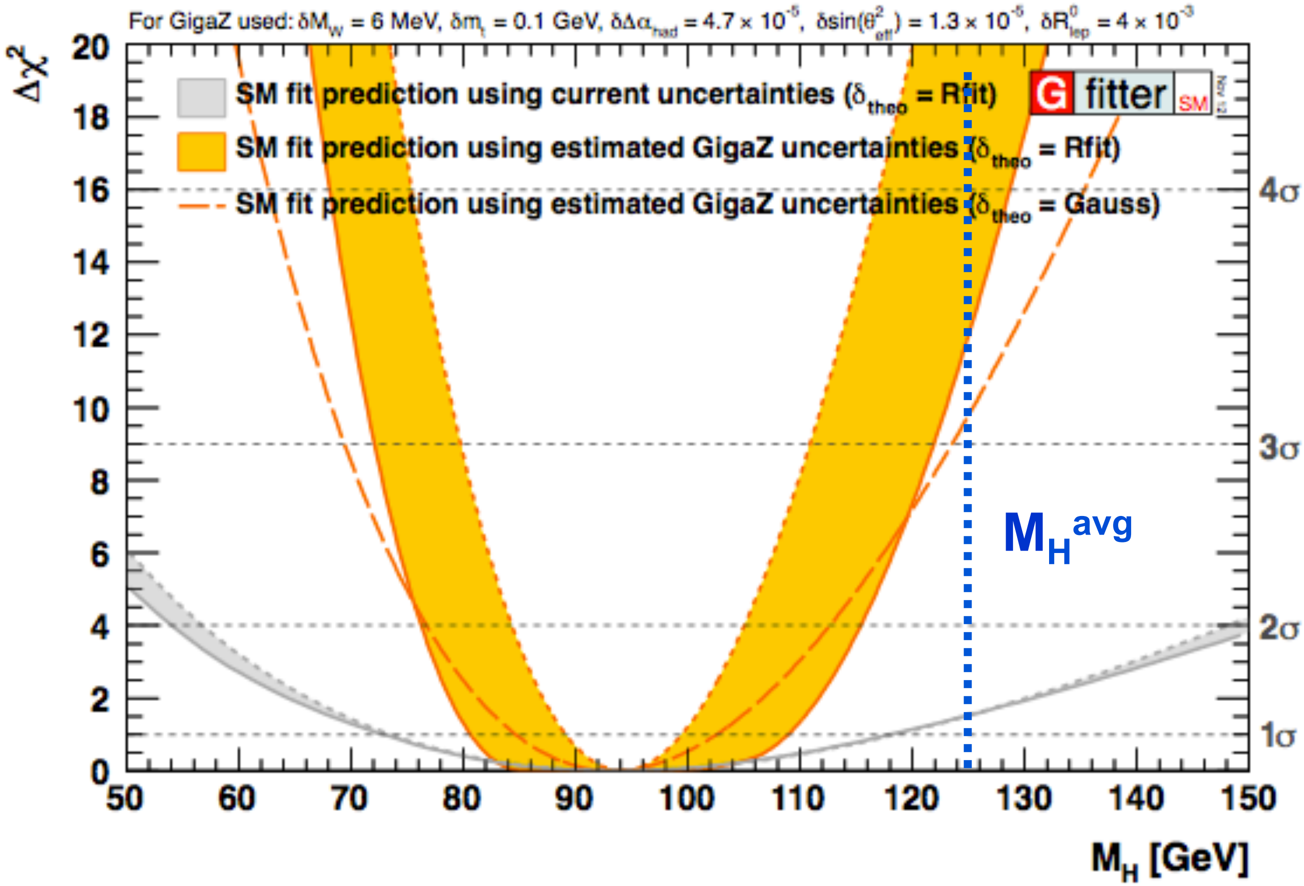
- No indication for new physics.
- Can now use this constrain 4th gen, Ex-Dim, T-C, Higgs couplings, etc.

Prospects for ILC with Giga Z

- Future Linear Collider could improve precision of EW observables 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: δR^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 $\delta \sin^2\theta^l_{eff}$: $1.6 \cdot 10^{-4} \rightarrow 1.3 \cdot 10^{-5}$

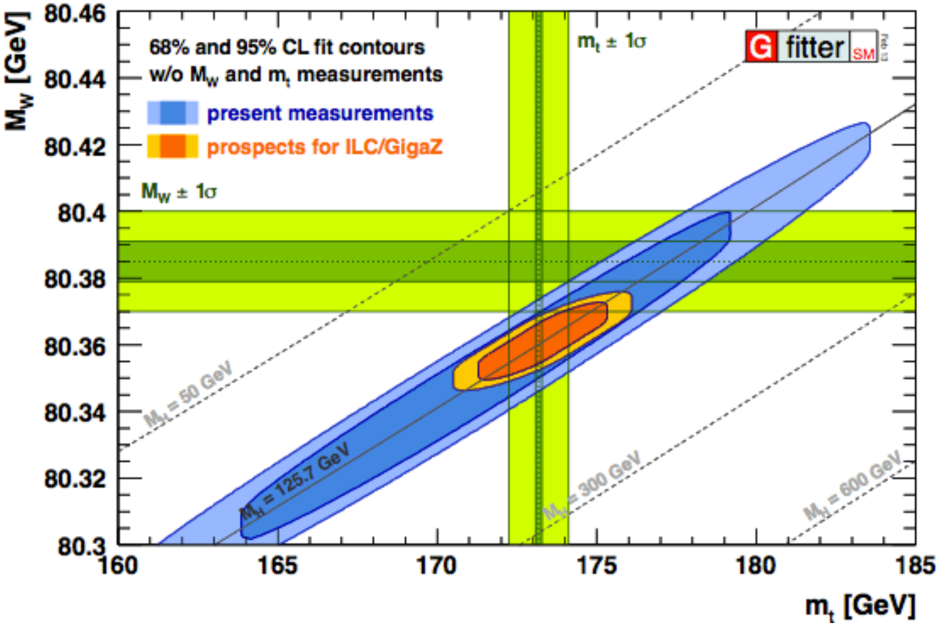
- Low-energy data results
  - *For $\Delta\alpha_{had}$:*
    - more precise e^+e^- cross section results for low energy ($\sqrt{s}$ < 1.8 GeV) and around cc resonance (KLOE-II, BaBar-ISR, BES-III), improved α_s, improvements in theory: $\Delta\alpha_{had}$: $10^{-4} \rightarrow 5 \cdot 10^{-5}$

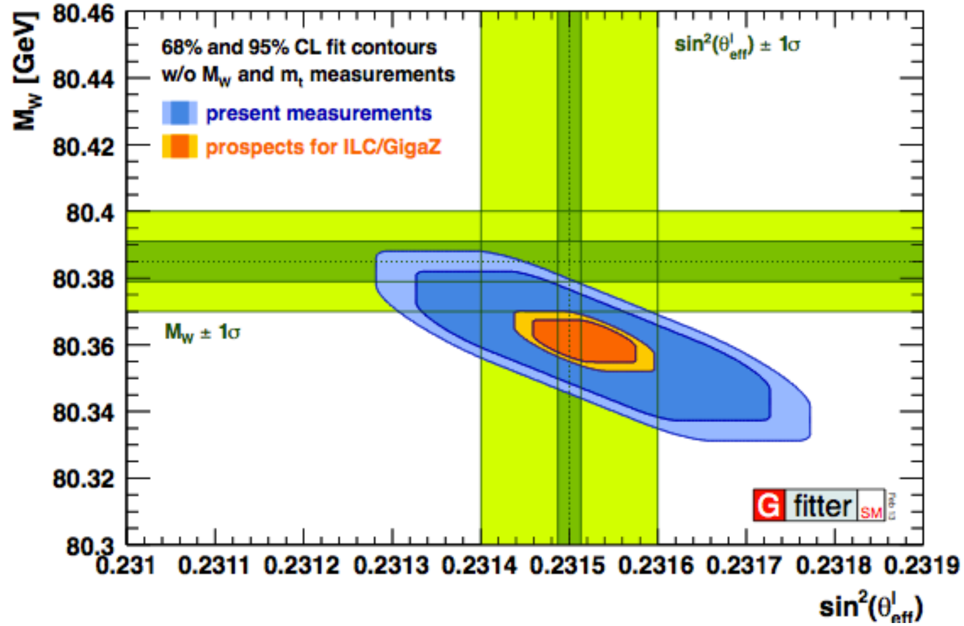
Prospects for ILC with Giga Z



- Logarithmic dependency on M_H → cannot compete with direct M_H meas.
- Indirect prediction M_H dominated by theory uncertainties.
  - No theory uncertainty: $M_H = 94.2^{+5.3}_{-5.0}$ GeV
  - Rfit scheme: $M_H = 92.3^{+16.6}_{-11.6}$ GeV

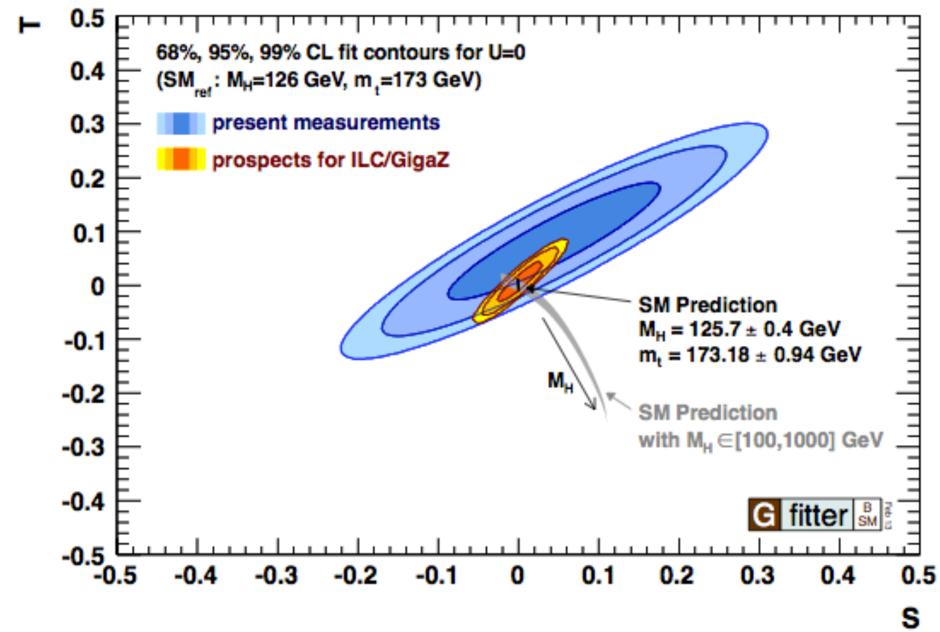
Prospects for ILC with Giga Z





- current precision
- prospects for direct ILC measurements

- *Assuming also 50% of today's theoretical uncertainties*
  - Implies three-loop EW calculations!
- Huge reduction of uncertainty on indirect determinations
- Also strong constraints on S, T, U

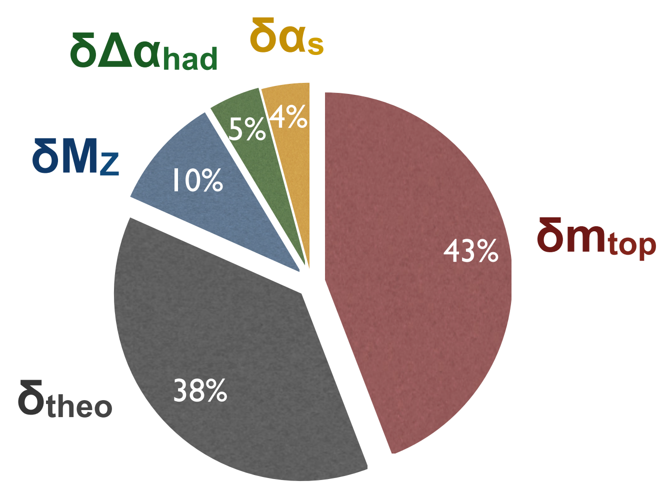


Conclusion and Today's Prospects

- 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: 7% (pseudo-experiments)
  - Would be great to revisit $Z \to b\bar{b}$, both theoretically and experimentally

- Knowledge of M_H dramatically improves SM prediction of key observables
  - M_W (28→11 MeV), $\sin^2\theta^l_{eff}$ ($2.3\times10^{-5} \to 1.0\times10^{-5}$), 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 (and $\delta\sin^2\theta^l_{eff}$) from top and unknown higher-order EW corrections
- δM_W (direct) = 15 MeV



- Latest results always available at: http://cern.ch/Gfitter
  - Results in this presentation: EPJC 72, 2205 (2012)

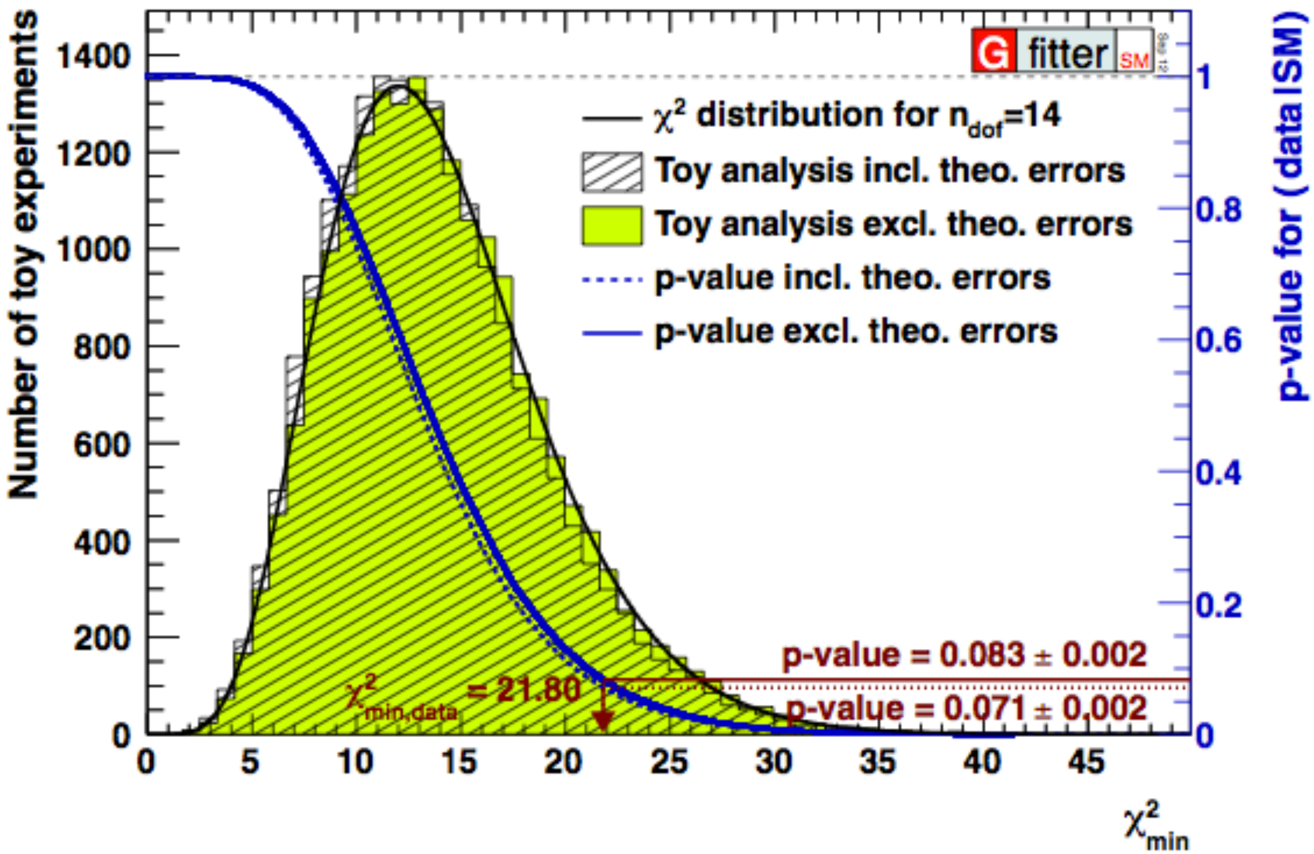
G fitter

A Generic Fitter Project for HEP Model Testing

Backup

Goodness of Fit

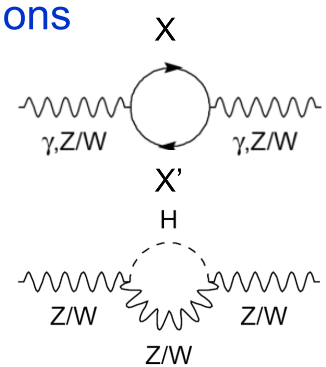
- Toy analysis with 20k pseudo experiments
  - p-value = probability of getting $\chi^2_{min,\,toy}$ larger than χ^2_{min} from data
  - i.e probability of incorrectly rejecting the SM as false = 0.07 ± 0.01 (theo)



A Gfitter package for Oblique Corrections

Gfitter BSM

- At low energies, BSM physics appears dominantly through vacuum polarization corrections
  - Aka, “oblique corrections”
- Oblique corrections reabsorbed into electroweak parameters
  - $\Delta\rho$, $\Delta\kappa$, Δr parameters, appearing in: M_W^2, $\sin^2\theta_{eff}$, G_F, α, etc
- Electroweak fit sensitive to BSM physics through oblique corrections
  - In direct competition with sensitivity to Higgs loop corrections



- Oblique corrections from New Physics described through STU parametrization
  [Peskin and Takeuchi, Phys. Rev. D46, 1 (1991)]

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

- 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: correction to Z→bb coupling, extended parameters (VWX)
  [Burgess et al., Phys. Lett. B326, 276 (1994)]
  [Burgess et al., Phys. Rev. D49, 6115 (1994)]

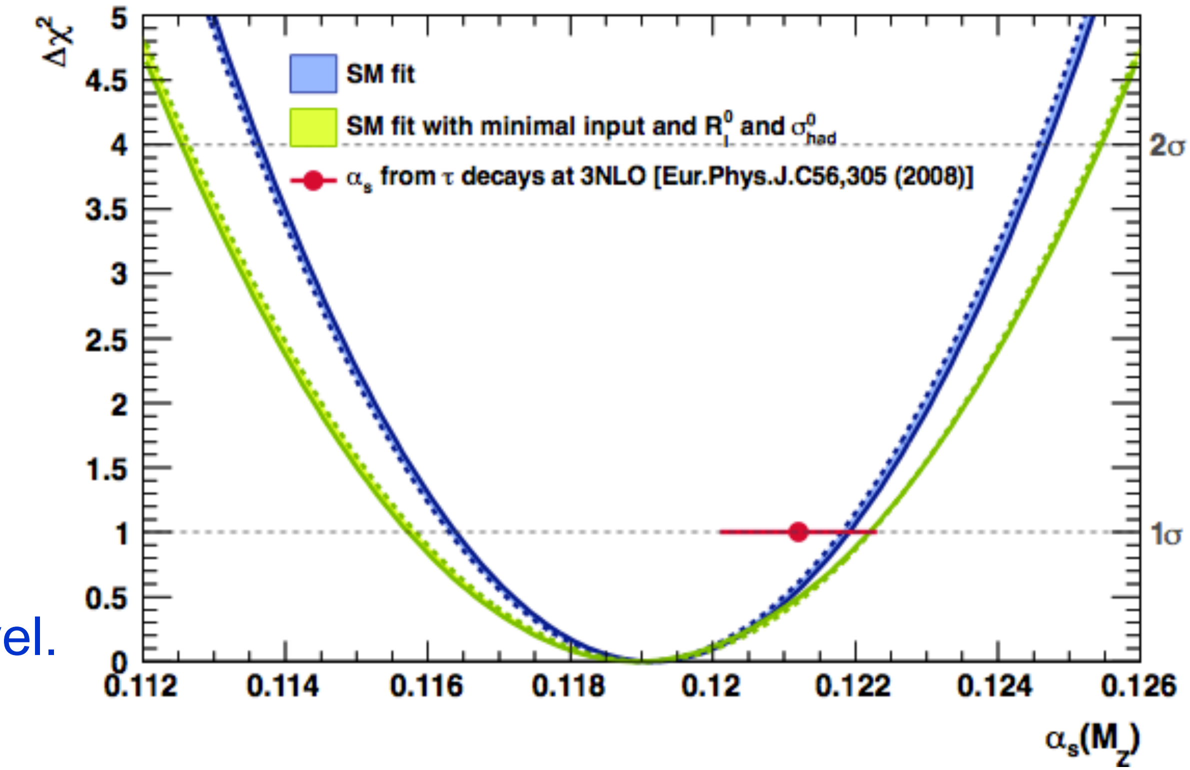
New R^0_b calculation [A. Freitas et al., JHEP 1208, 050 (2012)]

- The branching ratio R^0_b: partial decay width of Z→bb to Z→qq
- Freitas et al: full 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 corrections comparable to experimental uncertainty (6.6×10^{-4})

	1-loop EW and QCD correction to FSR	2-loop EW correction	2-loop EW and 2+3-loop QCD correction to FSR	1+2-loop QCD correction to gauge boson self-energies
M_H [GeV]	$\mathcal{O}(\alpha) + \text{FSR}_{1-\text{loop}}$ $[10^{-3}]$	$\mathcal{O}(\alpha^2_{\text{ferm}})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\text{ferm}}) + \text{FSR}_{>1-\text{loop}}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_s, \alpha\alpha_s^2)$ $[10^{-4}]$
100	−3.632	−6.569	−9.333	−0.404
200	−3.651	−6.573	−9.332	−0.404
400	−3.675	−6.581	−9.331	−0.404

$\alpha_s(M_Z)$ from Z→hadrons

- Determination of α_s at N3LO.
- Most sensitive through total hadronic cross-section σ^0_{had} and partial leptonic width R^0_l
- Theory uncertainty obtained by scale variation, at per-mille level.



$$\alpha_s(M_Z) = 0.1191 \pm 0.0028\,(\text{exp.}) \pm 0.0001\,(\text{theo.})$$

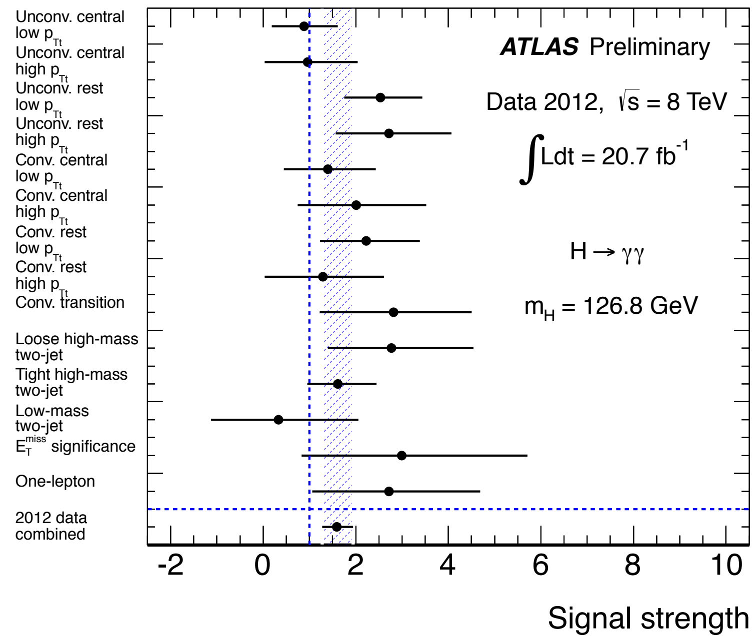
- Good agreement with value from t decays, also at N3LO.
- Improvements in precision only expected with ILC/GigaZ

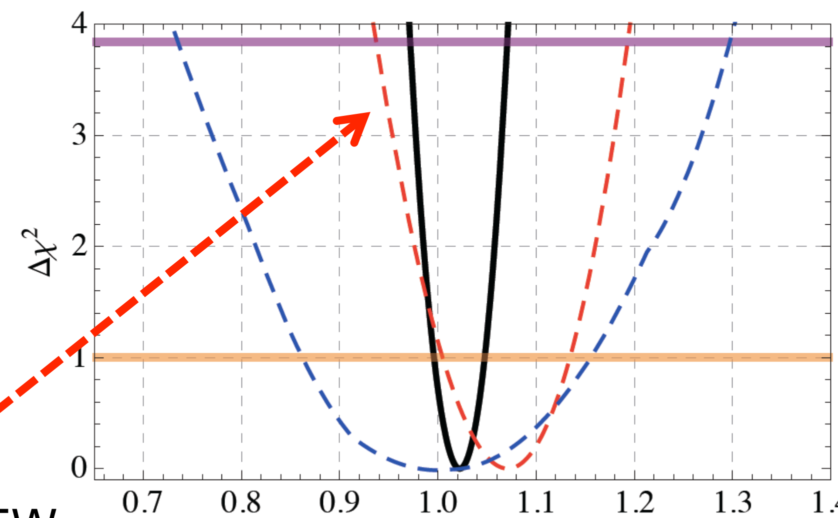
Higgs couplings in the EW fit

- In latest ATLAS H→γγ, 2.3σ deviation seen from SM μ (≡1.0)
- Interpret.: H→VV couplings scaled with c_V

From: Falkowski et al, arXiv:1303.1812

- Modified Higgs couplings can be constrained by EW fit through extended STU formalism.
- Result of c_V driven by limit on T parameter.
  - Tree-level relation: $\rho_0 = \frac{M_{W_0}^2}{M_{Z_0}^2 c_W^2} = 1 + \alpha T$
  - $\alpha T \approx \frac{3g_Y^2}{32\pi^2}(c_V^2 - 1)\log(\Lambda/m_Z)$
  - Reminder: T = 0.05 ± 0.12 (Gfitter)
- EW-fit Falkowski et al: $c_V \simeq 1.08 \pm 0.07$
  - Blue dashed: c_V from μ's, black: comb. w/ EW





Falkowski et al, arXiv:1303.1812