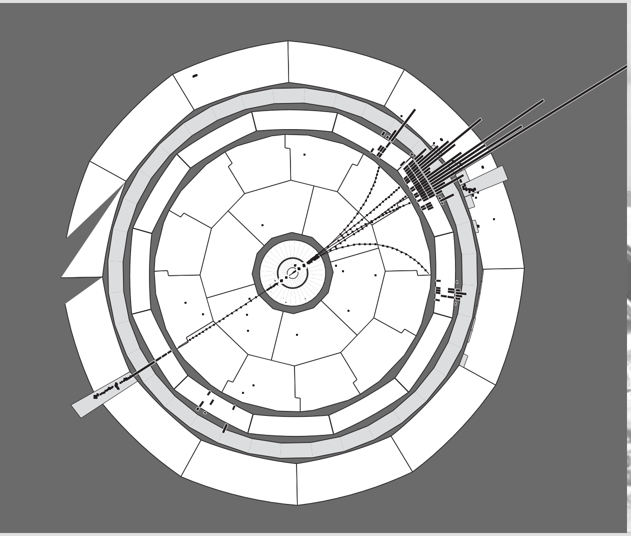
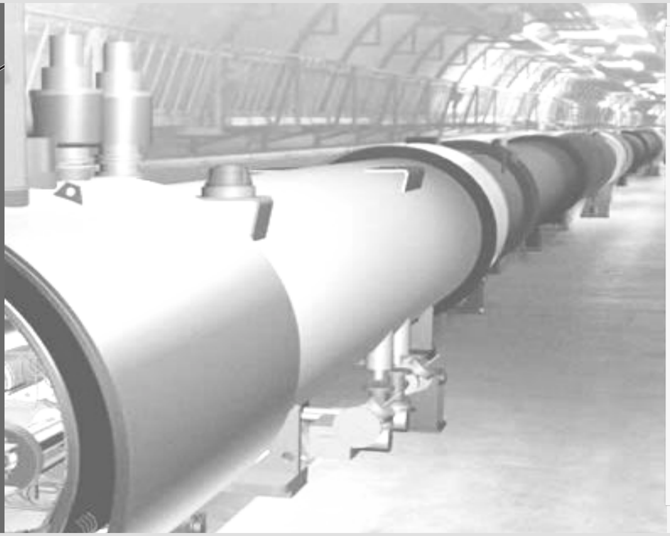
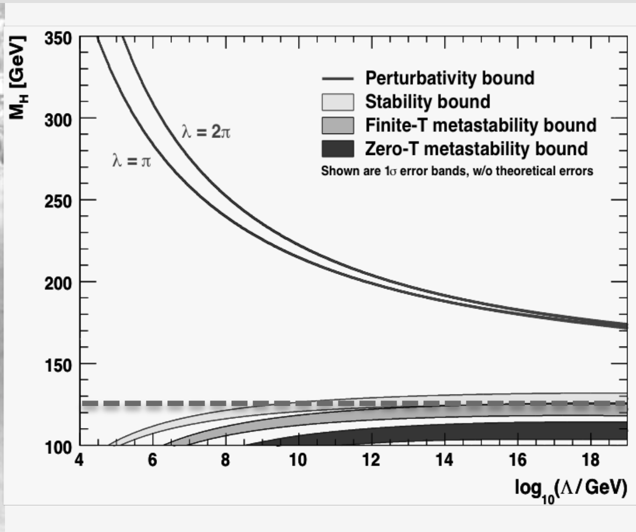
The electroweak fit of the Standard Model after the discovery of an SM-like scalar boson

Andreas Hoecker (CERN)

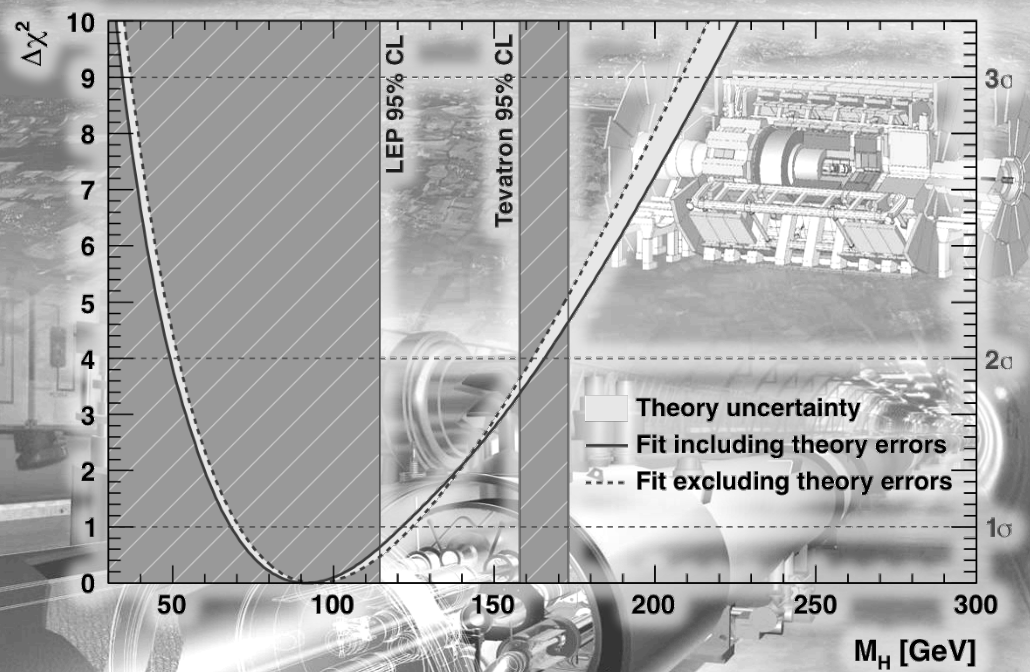
Solvay workshop “*Facing the Scalar Sector*”, May 29-31, 2013







Introduction



Predictive power of the Standard Model

Electroweak physics at the Z-pole

Vector and axial-vector couplings for $Z \rightarrow ff$ in SM at tree level:

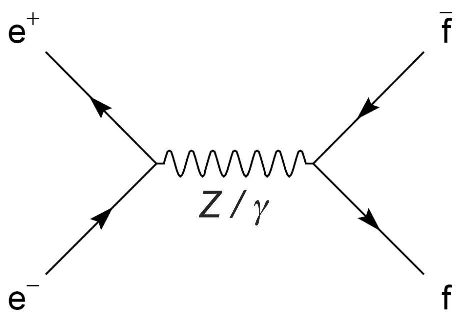
$$g_{V,f}^{(0)} \equiv g_{L,f}^{(0)} + g_{R,f}^{(0)} = I_3^f - 2Q^f \sin^2\theta_W \,, \quad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

$$g_{A,f}^{(0)} \equiv g_{L,f}^{(0)} - g_{R,f}^{(0)} = I_3^f$$

Electroweak unification: relation between weak and electromagnetic couplings:

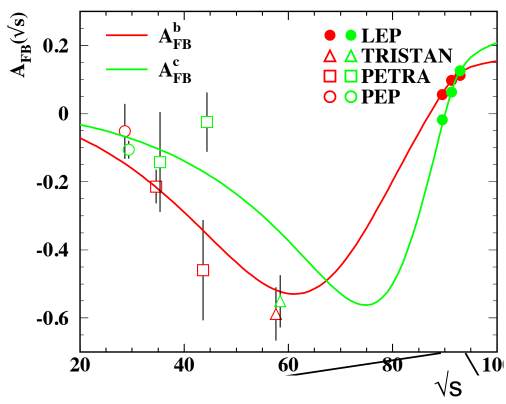
$$G_F = \frac{\pi\alpha(0)}{\sqrt{2}M_W^2\left(1 - M_W^2/M_Z^2\right)} \,, \quad M_W^2 = \frac{M_Z^2}{2}\cdot\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Gauge sector of SM on tree level is given by three free parameters, *e.g.*: α, M_Z, G_F (best known!)



Z–lepton coupling almost pure axial-vector

(γ pure vector → large off-peak interference → could establish Z-fermion coupling at PETRA, interesting for Z' searches via interference)



Predictive power of the Standard Model

Electroweak physics at the Z-pole

Radiative corrections -
modifying propagators and vertices

Significance of radiative corrections can be illustrated by verifying tree level relation:

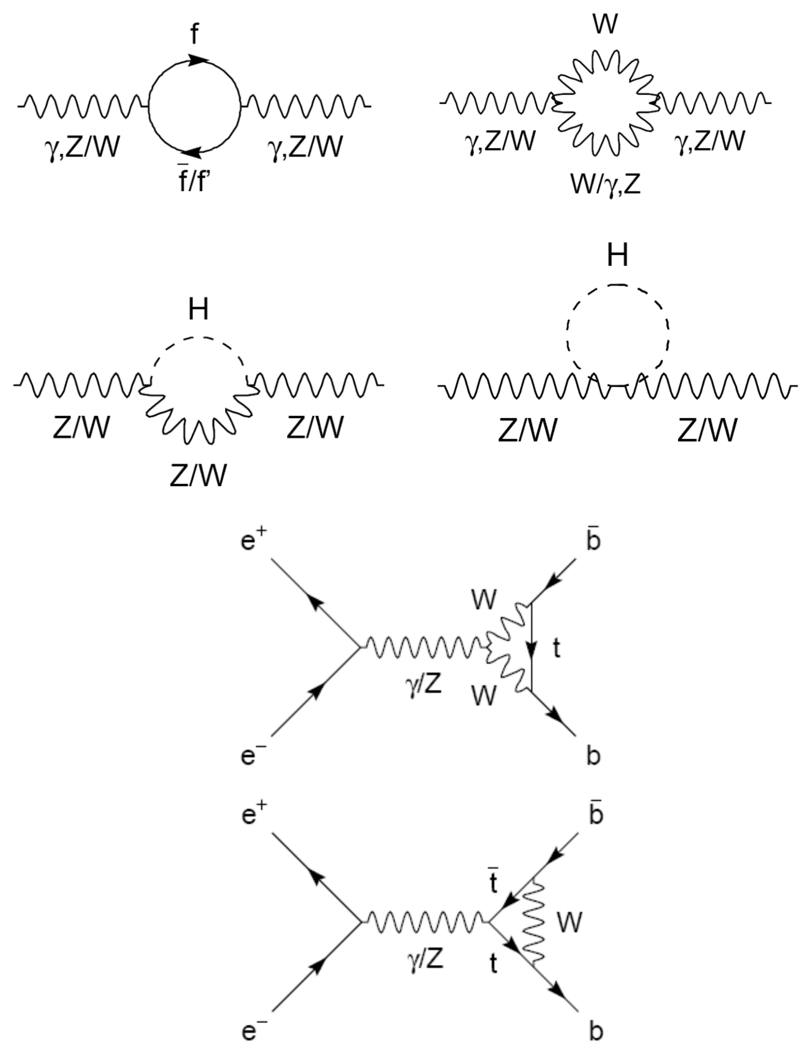
$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

Using the measurements:

$$M_W = (80.399 \pm 0.023)\ \mathrm{GeV}$$
$$M_Z = (91.1875 \pm 0.0021)\ \mathrm{GeV}$$

one predicts: $\sin^2\theta_W = 0.22284 \pm 0.00045$

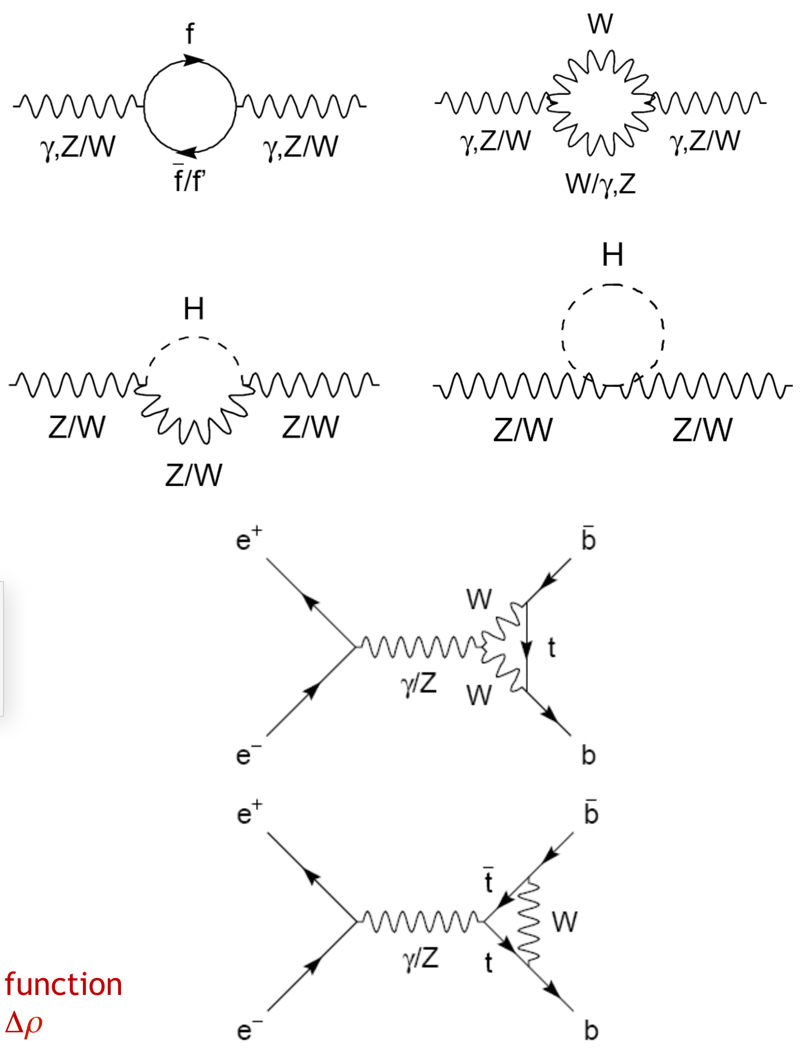
which is 18 σ away from the experimental value obtained by combining all asymmetry measurements: $\sin^2\theta_W = 0.23153 \pm 0.00016$



Predictive power of the Standard Model

Electroweak physics at the Z-pole

Radiative corrections - modifying propagators and vertices



Parametrisation of radiative corrections: "electroweak form-factors": ρ, κ, Δr

- Modified ("effective") couplings at the Z pole:

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

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

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

ρ : overall scale

κ : on-shell mixing angle

- Modified W mass:

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

Δr function of $\Delta\rho$

Predictive power of the Standard Model

Electroweak physics at the *Z*-pole

Radiative corrections - modifying propagators and vertices

Leading order terms ($M_W \ll M_H$)

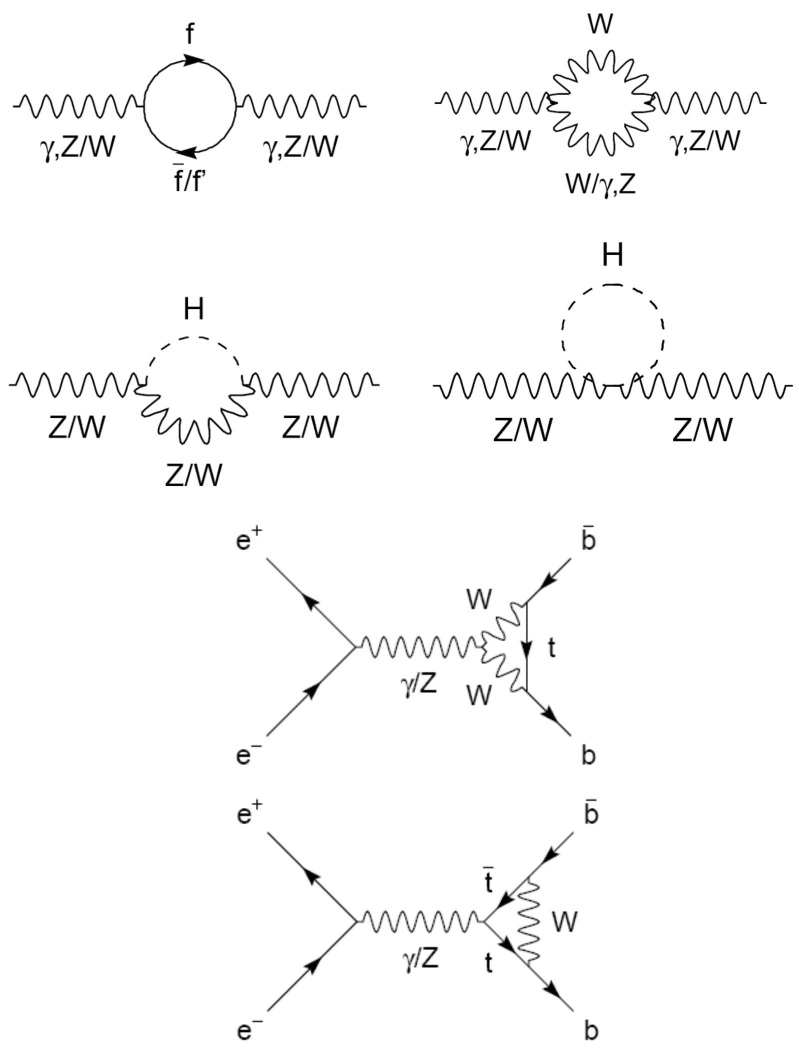
- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

$$\Delta\rho_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{M_W^2} - \tan^2\theta_W\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots\right]$$

$$\Delta\kappa_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{M_W^2}\cot^2\theta_W - \frac{10}{9}\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots\right]$$

- and flavour-specific vertex corrections, which are very small, except for top quarks, owing to large mass and $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \ldots$$



Predictive power of the Standard Model

Electroweak physics at the *Z*-pole

Radiative corrections -
modifying propagators and vertices

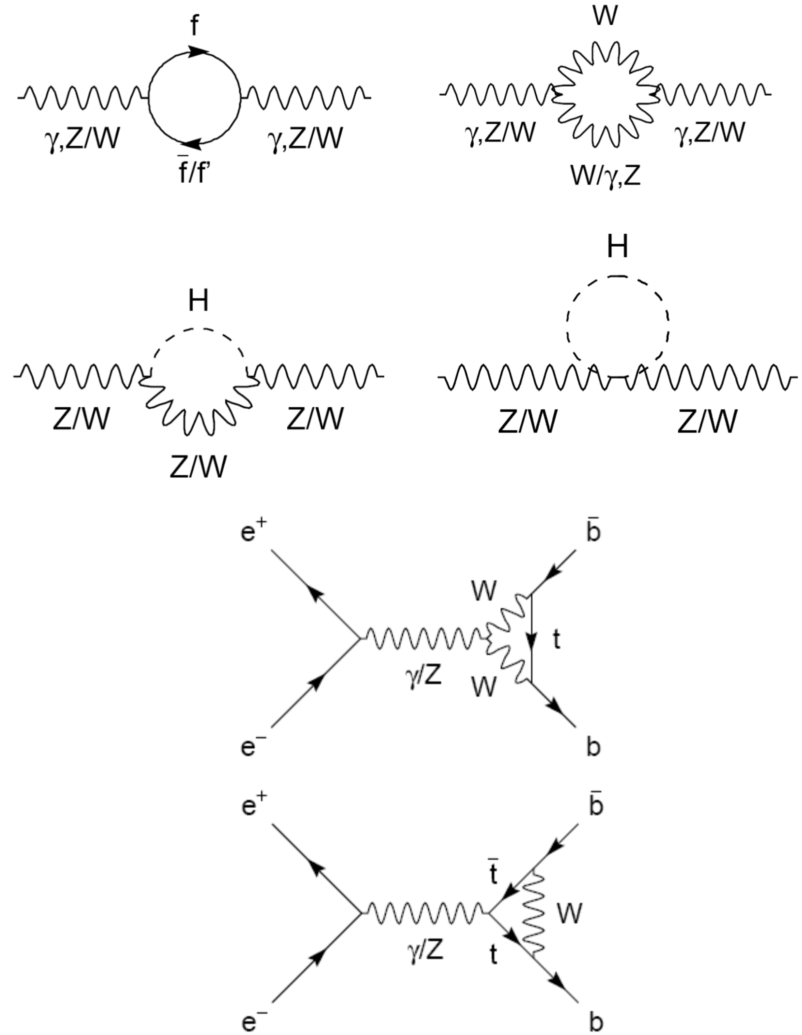
Leading order terms ($M_W \ll M_H$)

- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

Radiative corrections allow us to test the SM and to constrain unknown SM parameters

- and flavour-specific vertex corrections, which are very small, except for top quarks, owing to large mass and $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \ldots$$



Predictive power of the Standard Model

Electroweak physics at the *Z*-pole

Observables computed using ρ_Z^f, κ_Z^f, Δr and QED/QCD *radiator functions* $R_{A,f}$, $R_{V,f}$

Asymmetries:
$$A_f = \frac{2\,\mathrm{Re}\left(g_{V,f}/g_{A,f}\right)}{1+\left[\mathrm{Re}\left(g_{V,f}/g_{A,f}\right)\right]^2}, \quad \text{where} \quad \frac{\mathrm{Re}(g_{V,f})}{\mathrm{Re}(g_{A,f})} = 1 - 4\left|Q_f\right|\sin^2\theta_{\mathrm{eff}}^f$$

Measured asymmetries (forward-backward, left-right [+ FB] (SLD), tau polarisation) can be expressed as functions of different A_f

Partial widths:
$$\Gamma_f = N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi}\left|\rho_Z^f\right|\left(I_3^f\right)^2\left(\left|\frac{g_{V,f}^2}{g_{A,f}^2}\right| R_{V,f}(M_Z^2) + R_{A,f}(M_Z^2)\right)$$

Radiator functions for leptonic (hadronic) width involve QED (EW+QCD) corrections;
→ dependence on $\alpha_{\mathrm{QED}}(M_Z)$ and $\alpha_S(M_Z)$

Partial widths are highly correlated set of parameters. **For EW fit, use**:

- *Z* mass and width: M_Z (2×10^{-5} accuracy!), Γ_Z
- Hadronic pole cross section: σ^0_{had}
- Three leptonic ratios (use lepton-univ.): $R_\ell^0 = R_e^0 = \Gamma_{\mathrm{had}}/\Gamma_{ee}$, R_μ^0, R_τ^0
- Hadronic width ratios: $R_b^0 = \Gamma_{b\bar{b}}/\Gamma_{\mathrm{had}}$, R_c^0

Predictive power of the Standard Model

Electroweak physics at the Z-pole

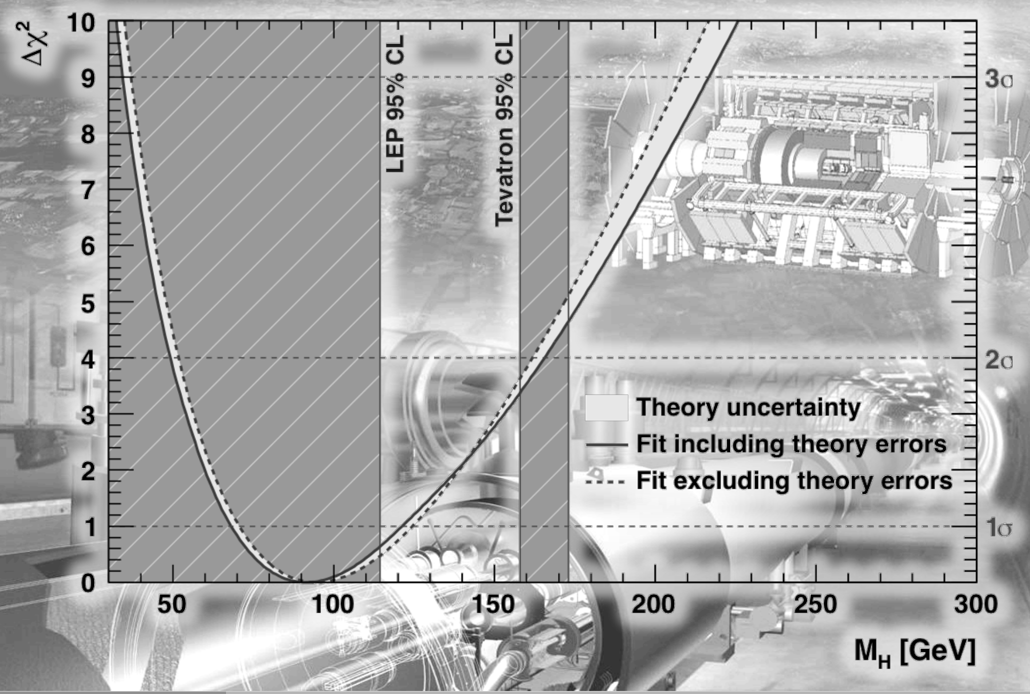
Observables computed using ρ_Z^f, κ_Z^f, Δr and QED/QCD *radiator functions* $R_{A,f}$, $R_{V,f}$

Latest calculations for observables used

- M_W — **mass of the W boson**
  $O(\alpha^2)$, $O(\alpha\alpha_s)$, $O(G_F\alpha_s^2 m_t^2)$, $O(G_F^2\alpha_s m_t^4)$, $O(G_F^3 m_t^6)$ — [Awramik et al, PRD 69, 053006 (2004)*]
  $\delta_{theo}M_W$ = 4 MeV
- $\sin^2\theta^l_{eff}$ — **effective weak mixing angle**
  $O(\alpha^2)$, $O(G_F^2\alpha_s m_t^4)$, $O(G_F^3 m_t^6)$ — [Awramik et al, JHEP 11, 048, NP 813, 174 (2009)*]
  $\delta_{theo}\sin^2\theta^l_{eff} = 4.7 \times 10^{-5}$
- Γ_Z , Γ_W — **Total widths of Z and W** — [Cho et al, arXiv:1104*]
- R_l — **leptonic width ratio**
  QCD Adler functions at 3NLO — [Baikov et al., PRL 108, 222003 (2012)*]
  $\alpha_{QED}(M_Z)$ from newest hadronic data — [Davier et al., EPJ.C71, 1515 (2011)]
- R_b — **$Z \to bb$ width ratio**
  Full two-loop fermionic correction (sizable: theoretical uncertainties larger than expected?) — [Freitas et al, JHEP 08, 050 (2012)*]

**References only those used directly by Gfitter.*
Full list of theoretical calculations referenced given in 0811.0009.

The electroweak fit



Electroweak fits

Several groups perform these fits with regular updates (LEPEWWG, PDG, Gfitter, BSM groups)

LEP: Phys. Rept. 427 (2006) 257, Gfitter: EPJ C72 (2012) 2003

A long tradition

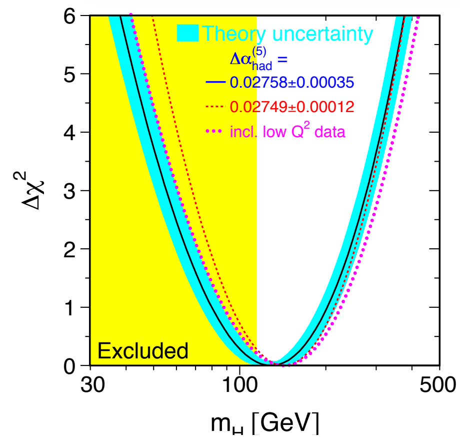
- Precision measurements crucial. After LEP/SLC era, results from Tevatron & soon also LHC
- Huge & pioneering work to compute loop corrections to two-loop order or higher

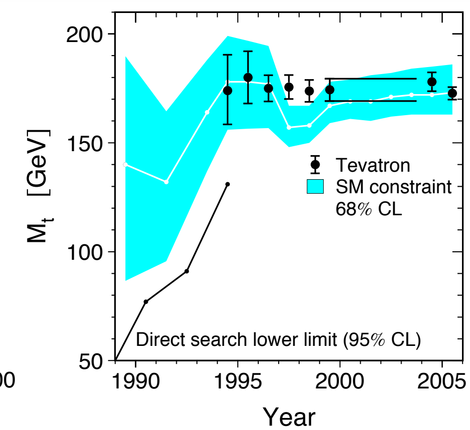
Brout-Englert-Higgs hunting

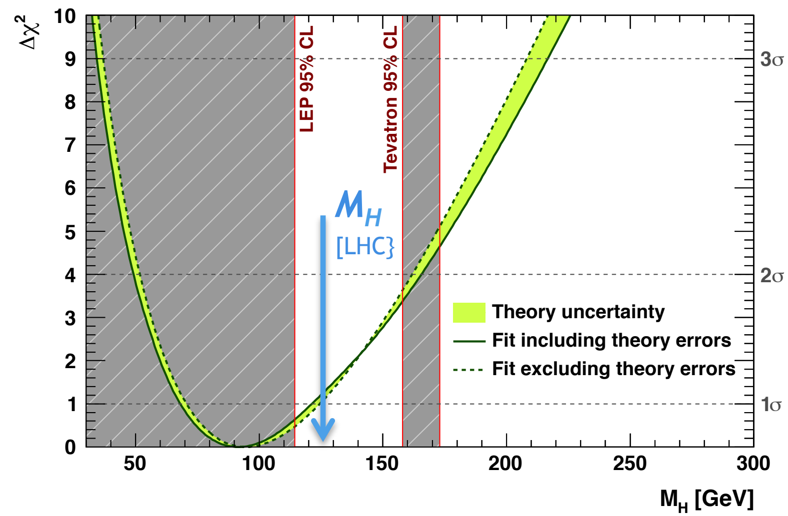
- M_H last missing parameter of the SM
- Indirect determination (2011): $M_H = 96^{+31}_{-24}$ GeV
- Exclusion limits were incorporated in EW fits

Discovery of new boson in July 2012

- The cross section and branching ratios are (so far) compatible with the SM scalar boson
- Assume in the following that the boson is the SM scalar: M_H = 125.7 ± 0.4 GeV*







*Exact value and uncertainty irrelevant for EW fit in SM

Experimental observables

Several groups perform these fits with regular updates (LEPEWWG, PDG, Gfitter, BSM groups)

Experimental inputs:

- Z-pole observables: LEP/SLD results (corrected for ISR/FSR QED effects) [ADLO & SLD, Phys. Rept. 427, 257 (2006)]
  - Total and partial cross sections around Z: M_Z, Γ_Z, σ^0_{had}, R_l^0, R_c^0, R_b^0
  - Asymmetries on the Z pole: $A_{FB}^{0,l}$, $A_{FB}^{0,b}$, $A_{FB}^{0,c}$, A_l, A_c, A_b, $\sin^2\theta^l_{eff}$ (Q_{FB})
- M_W and Γ_W : LEP + Tevatron average [arXiv:1204:0042]
- m_t: latest Tevatron average [CDF & D0, new combination, arXiv:1305.3929]
- m_c, m_b: world averages [PDG, Phys. Lett. B667, 1 (2008) and 2009 partial update for the 2010 edition]
- $\Delta\alpha_{had}(M_Z)$: data + QCD-driven [Davier et al., EPJ.C71, 1515 (2011) + rescaling mechanism to account for α_s dependency]
- M_H : LHC [arXiv:1207.7214 , arXiv:1207.7235]

Fit parameters

- $\Delta\alpha_{had}(M_Z)$, $\alpha_S(M_Z)$, M_Z, M_H, m_c, m_b, m_t + theory uncertainty parameters $\delta_{theo}M_W$/ $\sin^2\theta^l_{eff}$
- Other parameters well enough known and fixed in fit

Experimental Input

Parameter	Input value	
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

Parameter	Input value	
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron & LEP
Γ_W [GeV]	2.085 ± 0.042	Tevatron & LEP
$\overline{m}_c$ [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
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\nabla)}$	2757 ± 10	
$\alpha_s(M_Z^2)$	$-$	
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	

Correlations for observables from Z lineshape fit

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

Correlations for heavy-flavour observables at Z pole

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

Experimental Input and Fit Results

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]$^{\circ}$	125.7 ± 0.4	yes	125.7 ± 0.4	94.1^{+25}_{-22}	94.1^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.380^{+0.011}_{-0.012}$	80.360 ± 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 ± 0.0115
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4953 ± 0.0014	2.4957 ± 0.0015	2.4949 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.480 ± 0.014	41.479 ± 0.014	41.472 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.739 ± 0.017	20.741 ± 0.017	20.713 ± 0.026
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	$0.01627^{+0.0001}_{-0.0002}$	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	$0.1477^{+0.0009}_{-0.0008}$	–
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	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	–	$0.6681^{+0.00021}_{-0.00042}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93468^{+0.00008}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	$0.0740^{+0.0005}_{-0.0004}$	0.0738 ± 0.0004
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	$0.1036^{+0.0007}_{-0.0006}$	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17222^{+0.00006}_{-0.00005}$	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21491 ± 0.00005	0.21492 ± 0.00005	0.21490 ± 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	173.49 ± 0.82	173.17 ± 0.86	$175.83^{+2.74}_{-2.42}$
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ $^{(\dagger\triangle)}$	2756 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	$0.1188^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1188 ± 0.0027
$\delta_{\mathrm{th}} M_W$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	yes	4	4	–
$\delta_{\mathrm{th}} \sin^2\theta^\ell_{\mathrm{eff}}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\mathrm{theo}}$	yes	-1.4	4.7	–

$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (sys)) and CMS ($M_H = 125.3 \pm 0.4$ (stat) ± 0.5 (sys)) measurements assuming no correlation of the systematic uncertainties. $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474^{+0.0005}_{-0.0009}$ ($A_\ell = 0.1467^{+0.0006}_{-0.0004}$). $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

http://gfitter.desy.de/Standard_Model/

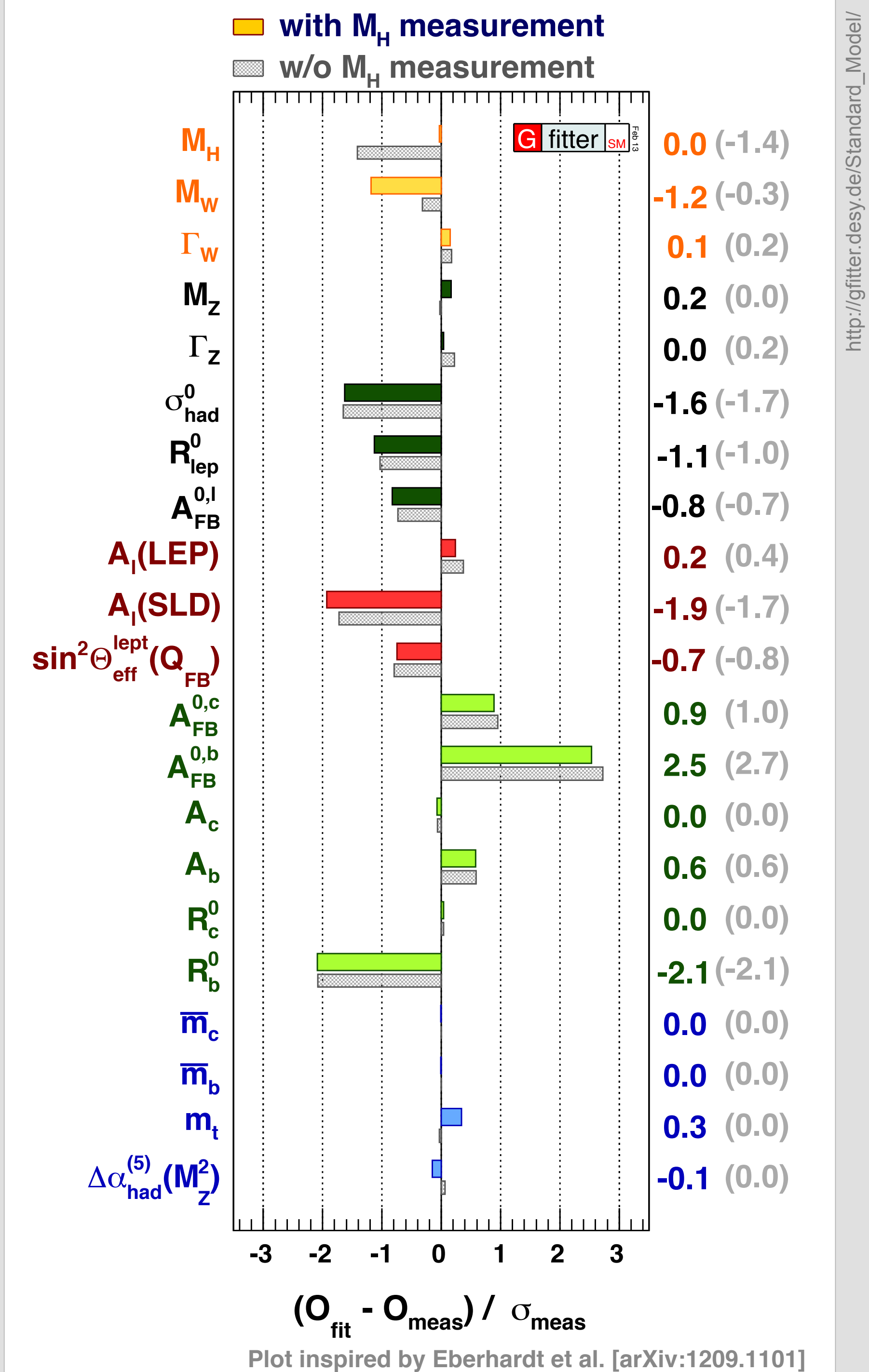
Goodness-of-fit:

χ^2_{min}/n_{dof} = 20.7/14 → p-value = $0.09_{toy\text{-}MC}$

- large value of χ^2_{min} not due to M_H measurement
- Without M_H measurement:
  χ^2_{min}/n_{dof} = 19.3/13 → p-value ~ 0.11

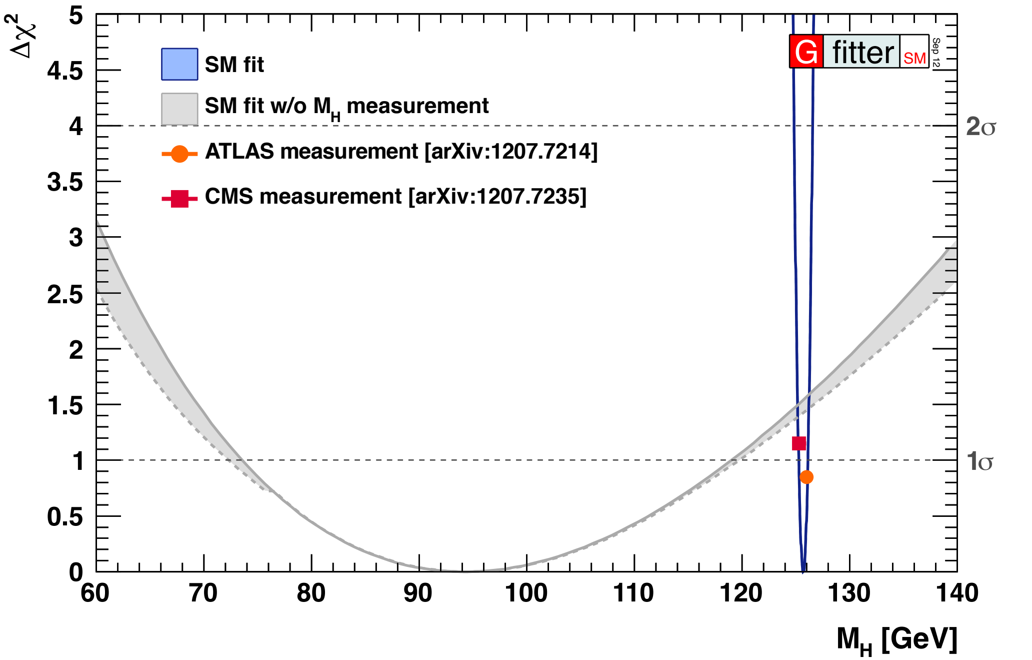
Pull values after fit:

- No pull value exceeds deviation of more than 3σ (consistency of SM)
- Small pulls for M_H, A_c, R^0_c, m_c and m_b indicate that their input accuracies exceed the fit requirements
- Largest pulls in b-sector: $A^{0,b}_{FB}$ and R^0_b with 2.5σ and −2.1σ (little dependence on M_H)
- For comparison: R^0_b using one fermionic loop calculation: 0.8σ



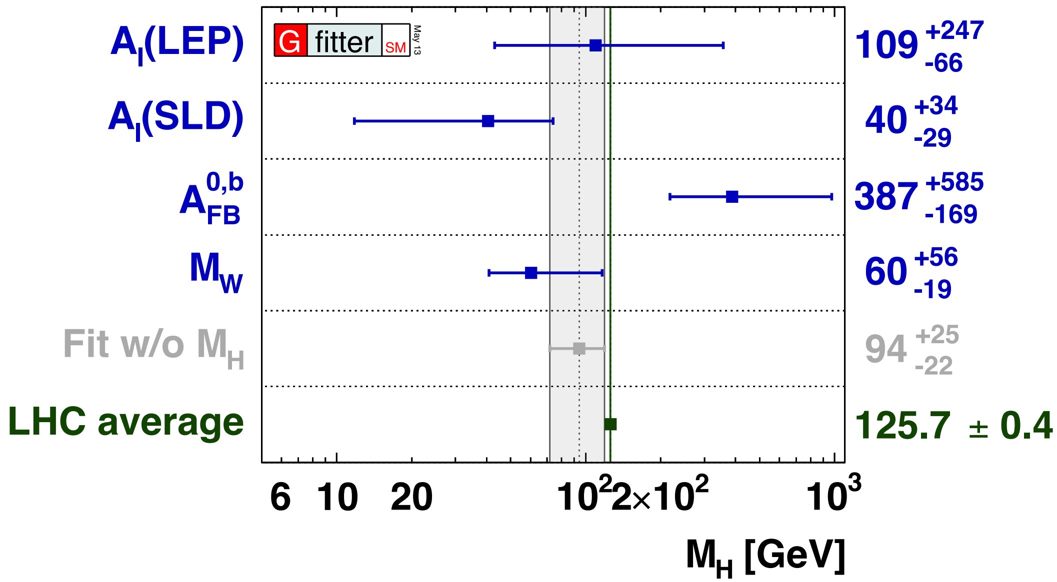
Scan of the $\Delta\chi^2$ profile versus M_H

- Blue line: full SM fit
- Grey band: fit without M_H measurement
- Fit without MH input gives $M_H = 94^{+25}_{-22}$ GeV
- Consistent within 1.3σ with measurement



Tension in M_H fit ?

- Determination of M_H removing all sensitive observables except the given one
- Tension (2.5σ - from toy MC) between $A^{0,b}_{FB}$, A_l(SLD) and M_W



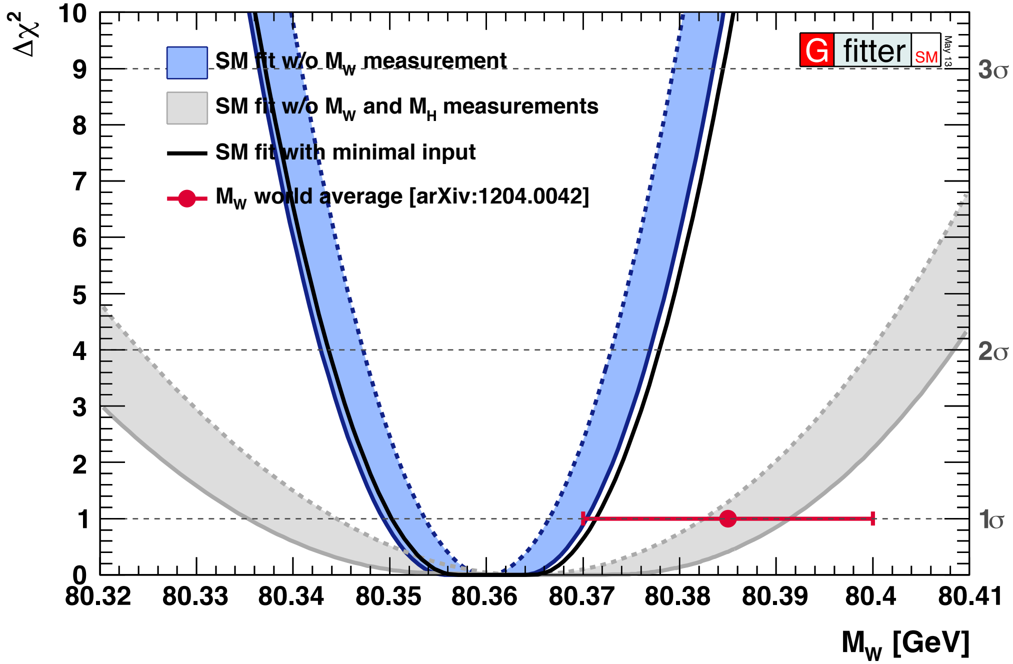
http://gfitter.desy.de/Standard_Model/

Global fit results

Indirect determination of the W boson mass

Scan of $\Delta\chi^2$ profile versus M_W

- M_H measurement allows for precise constraint of M_W
- Also shown SM fit with minimal input: M_Z, G_F, $\Delta\alpha_{had}(M_Z)$, $\alpha(M_Z)$, M_H and fermion masses
- Consistency between total fit and SM fit with minimal input



Fit results in the indirect determination :

$$M_W = 80.3603 \pm 0.0056(m_{top}) \pm 0.0026(M_Z) \pm 0.0018(\Delta\alpha_{had}) \pm 0.0027(\alpha_S) \pm 0.0002(M_H) \pm 0.0040(\text{theo})\ \text{GeV}$$

$= 80.360 \pm 0.011(\text{tot})$ GeV, *more precise than experimental value*

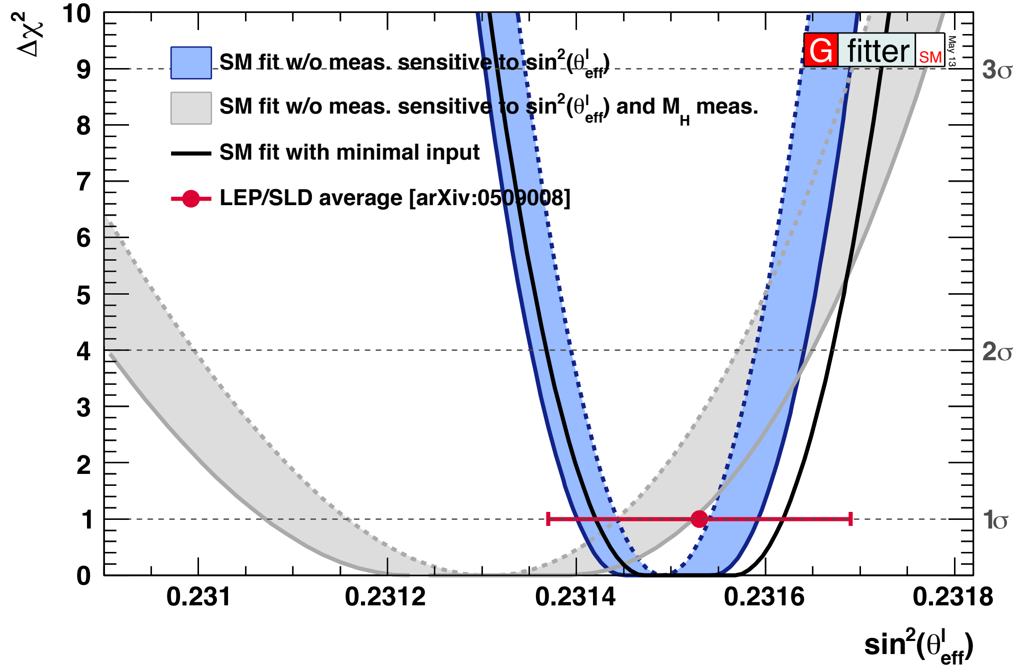
$= 80.385 \pm 0.015(\text{exp})$ GeV [Tevatron/LEP: arXiv:1204.0042]

Global fit results

Effective weak mixing angle

Scan of $\Delta\chi^2$ profile versus $\sin^2\theta^l_{eff}$

- All observables sensitive to $\sin^2\theta^l_{eff}$ removed from fit
- M_H measurement allows for precise constraint
- Also shown SM fit with minimal input



Fit results in the indirect determination :

$$\sin^2\theta^l_{eff} = 0.231496 \pm 0.000030(m_{top}) \pm 0.000015(M_Z) \pm 0.000035(\Delta\alpha_{had}) \pm 0.000010(\alpha_S) \pm 0.000002(M_H) \pm 0.000047(\text{theo})$$

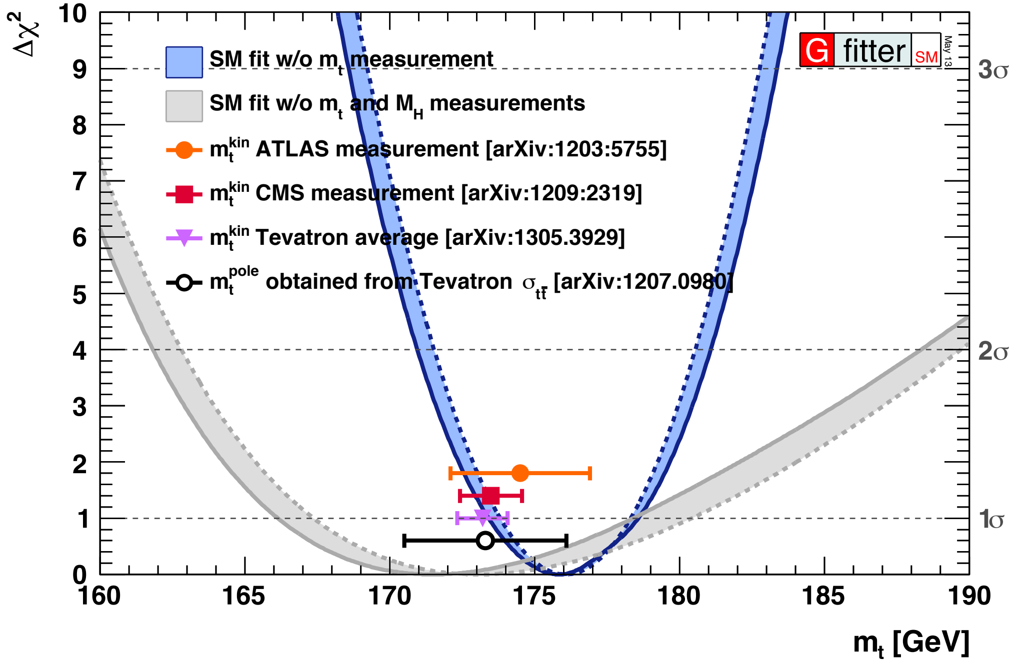
$= 0.23150 \pm 0.00010(\text{tot})$, *more precise than LEP/SLD average*

$= 0.23153 \pm 0.00016(\text{exp})$ [LEP/SLD: Phys Rept 427 (2006) 257]

Global fit results

Top mass

Scan of $\Delta\chi^2$ profile versus m_{top}



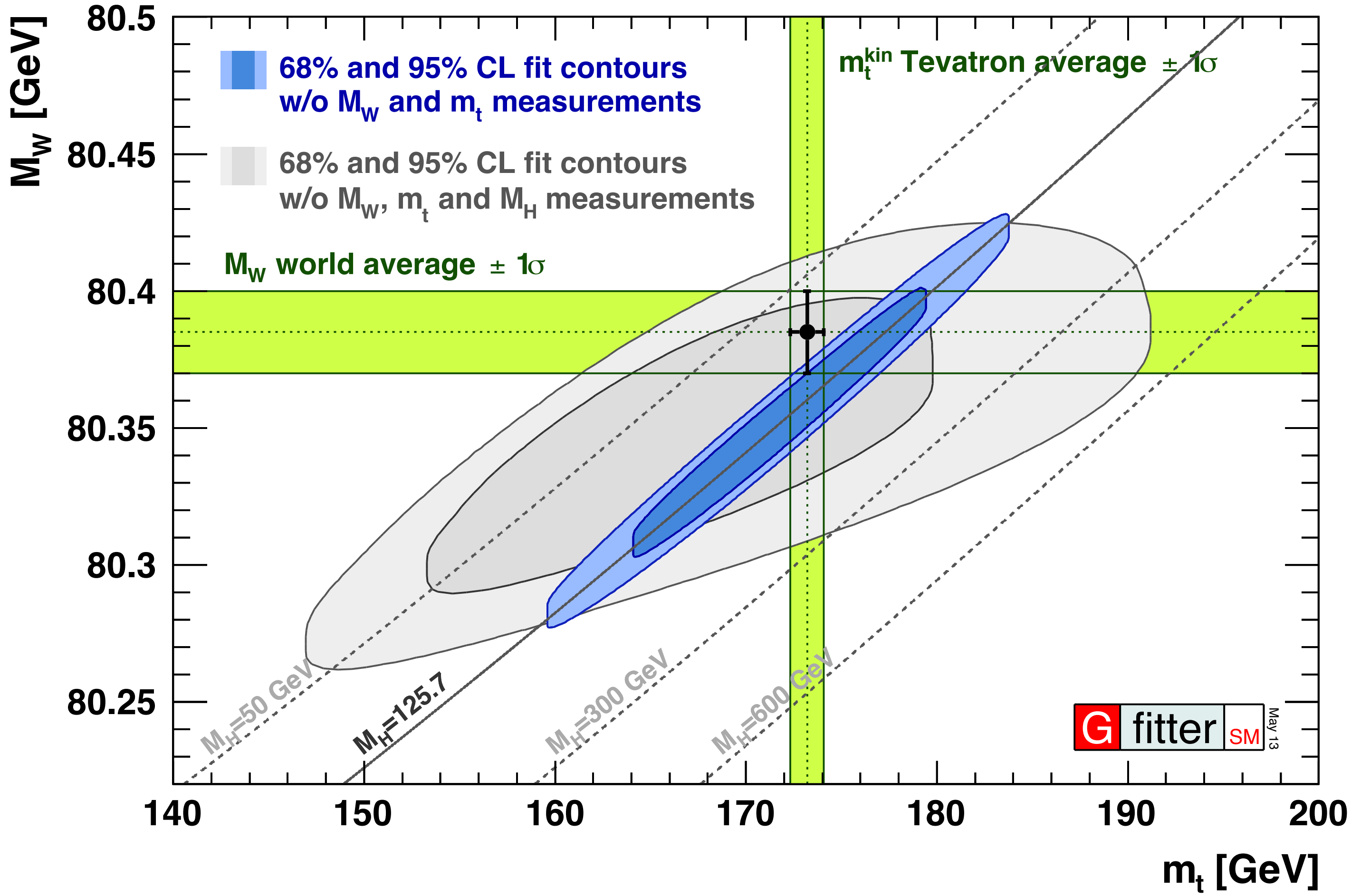
Fit results in the indirect determination :

$m_{top} = 175.8\,^{+2.7}_{-2.4}$ (tot) GeV

$= 173.2 \pm 0.9$ (exp) [Tevatron: arXiv:1207.0980]

Global fit results

W boson and top mass correlation — impressive consistency of the SM



Once M_H fixed, the SM is cornered

Effects of new physics can enter through loop corrections

→ Improve measurements of EW precision observables

Global fit results

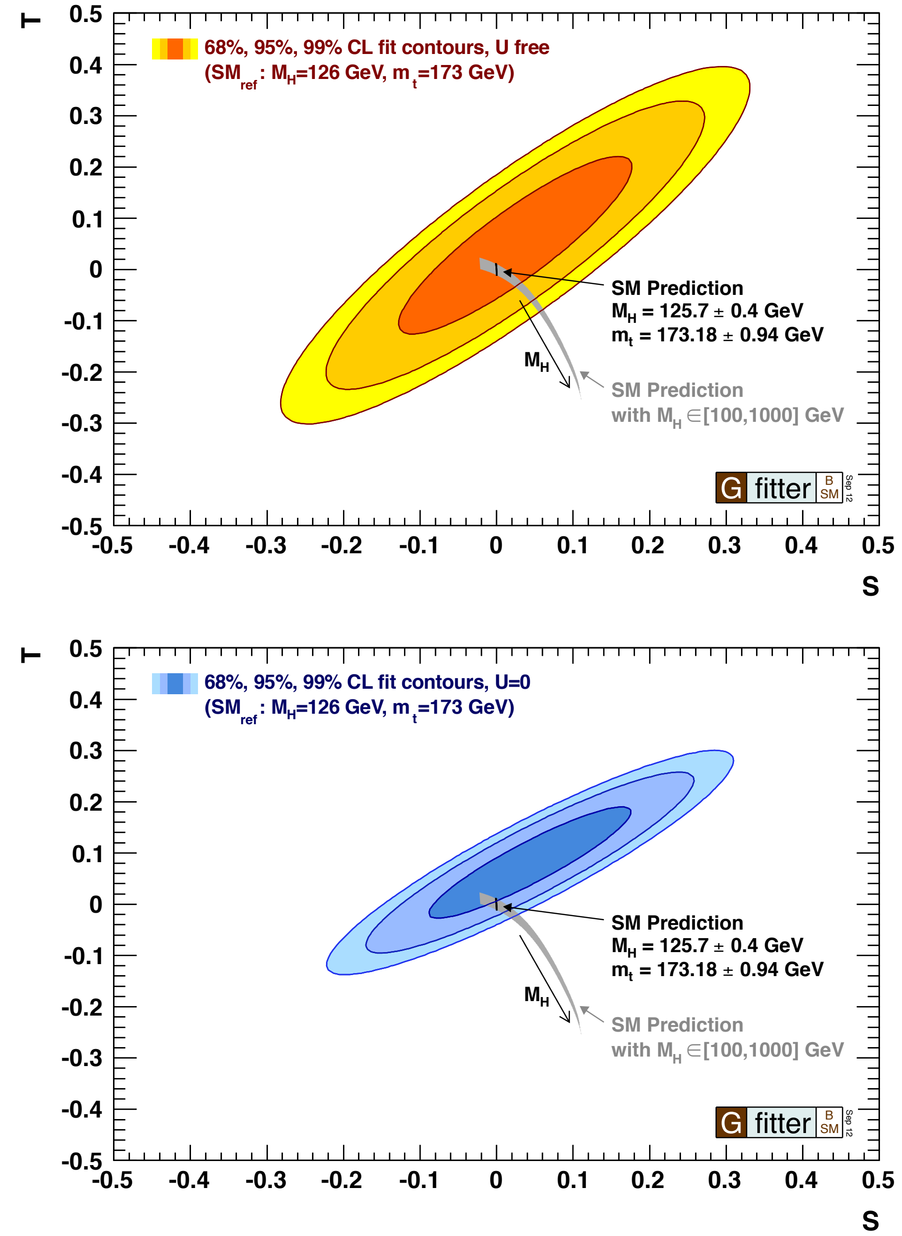
Constraints on new physics

Parametrise contributions from vacuum polarisation

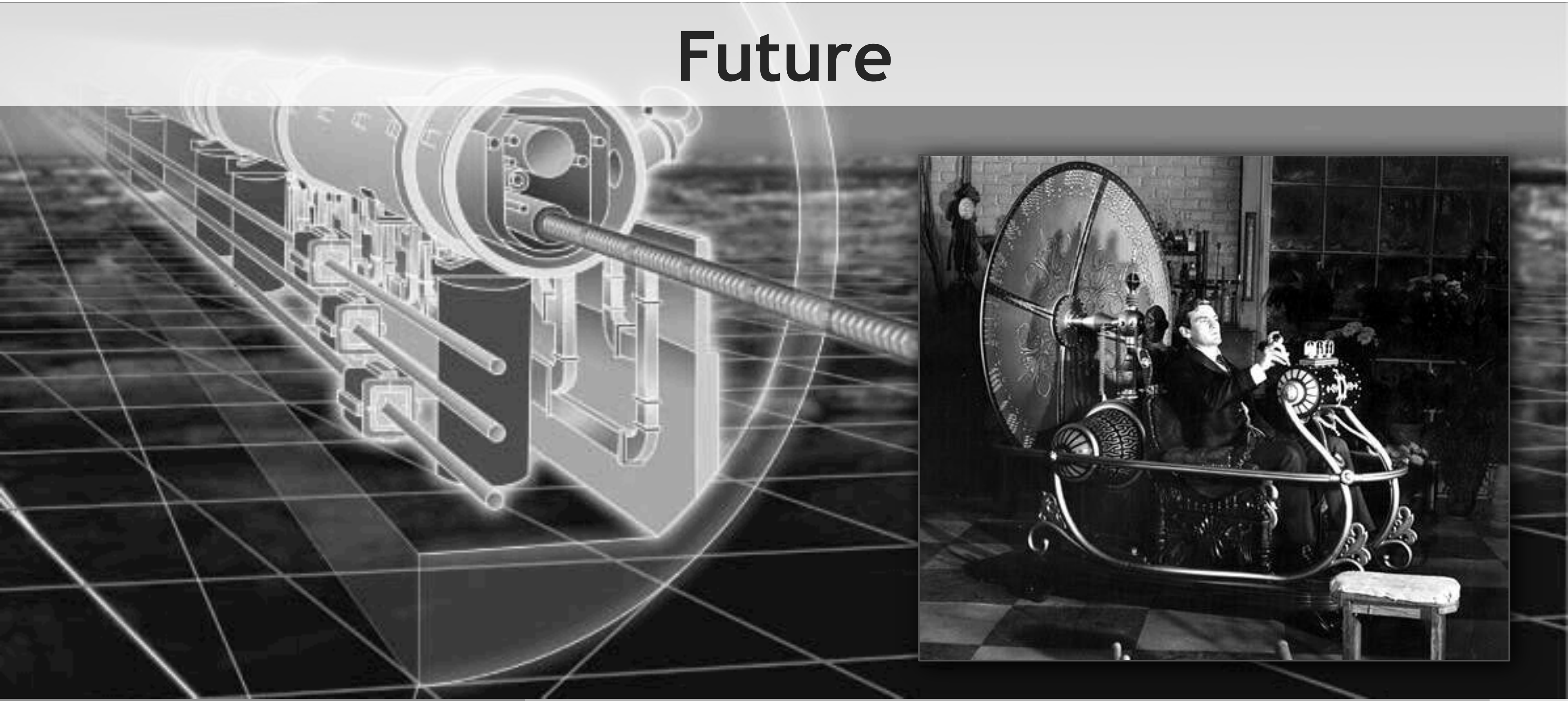
- Sensitivity to new physics
- SM reference chosen to be $M_{H,\text{ref}} = 126$ GeV, $m_{t,\text{ref}} = 173$ GeV
- S, T depend logarithmically on M_H
- Fit result:

  $S = 0.03 \pm 0.10$
  $T = 0.05 \pm 0.12$
  $U = 0.03 \pm 0.10$

  with large correlation between S and T
- Stronger constraints from fit with $U = 0$
- S, T, U fit used to constrain new physics models (Little Higgs, 2HDM, SUSY, universal extra dimensions, Technicolor, …)



Future

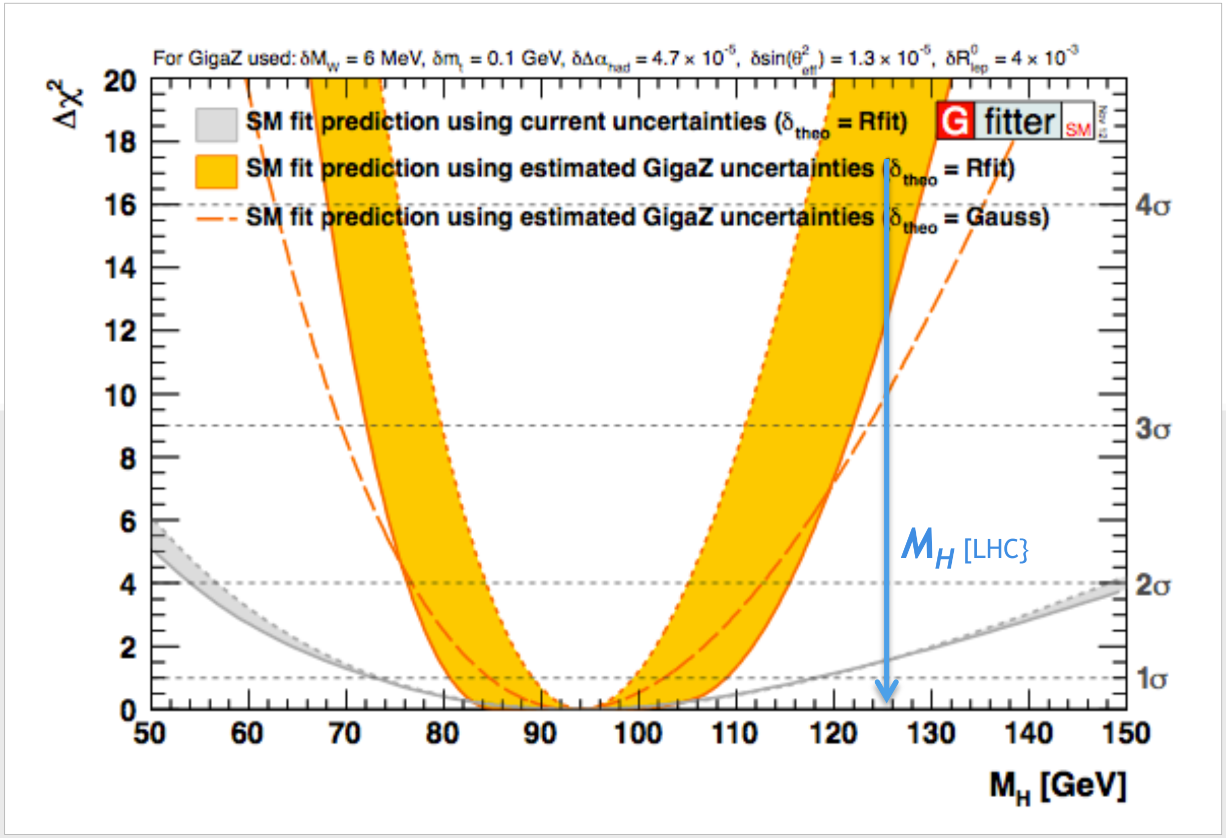


ILC with GigaZ

- tt threshold: obtain m_{top} from production cross section: $\delta(m_{top}) \sim 0.1$ GeV
- Z peak measurements
  - Polarised beams, uncertainty $\delta A^{0,f}_{LR}$: $10^{-3} \rightarrow 10^{-4}$ translates into $\delta\sin^2\theta^l_{eff}$: $10^{-4} \rightarrow 1.3\times10^{-5}$
  - High statistics: 10^9 Z decays: δR^0_l : $2.5\times10^{-2} \rightarrow 4\times10^{-3}$
- WW threshold: from threshold scan: $\delta M_W = 15 \rightarrow 6$ MeV
- Low energy data: $\Delta\alpha_{had}$: more precise cross section data for low energy ($\sqrt{s} < 1.8$ GeV) and around cc resonance (BES-III), improved α_S, improvements in theory: $1.0\times10^{-4} \rightarrow 0.5\times10^{-4}$

A future linear collider could tremendously improve the precision of the electroweak observables

Current theorey uncertainties



Prospects for ILC with GigaZ

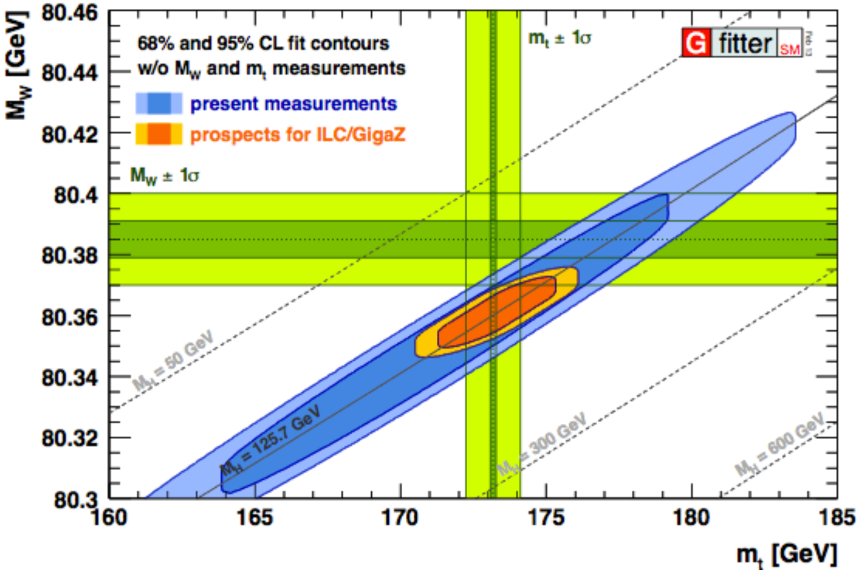
No theory uncertainty: $M_H = 94.2\,^{+5.3}_{-5.0}\,\left[^{+23}_{-19}\right]$ GeV

*R*fit scheme: $M_H = 92.3\,^{+17}_{-12}\,\left[^{+36}_{-23}\right]$ GeV

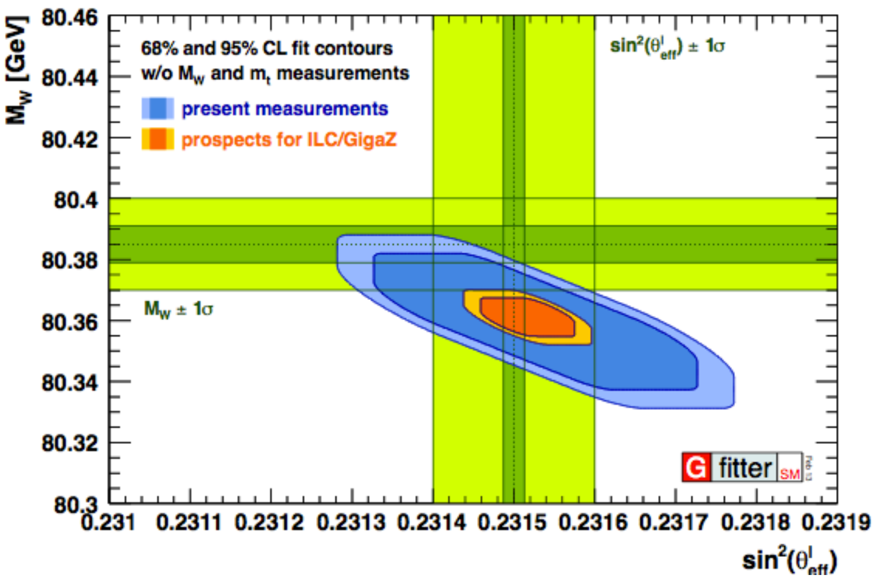
In brackets the 4σ uncertainties

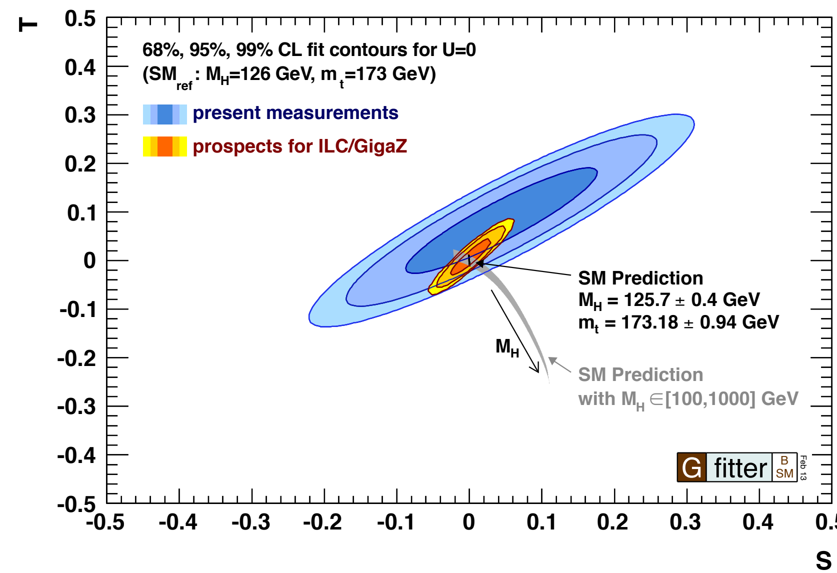
A future linear collider could tremendously improve the precision of the electroweak observables

Prospects for ILC with GigaZ



- Assume 50% of today's theoretical uncertainty (implies three-loop EW calculations), treated *à la R*fit
- Fit features huge uncertainty reduction for indirect determinations
- Strong constraints on *S*, *T*, *U*





Summary

Knowledge of M_H over-constrains EW fit allowing a precise prediction of observables

http://gfitter.desy.de/Standard_Model

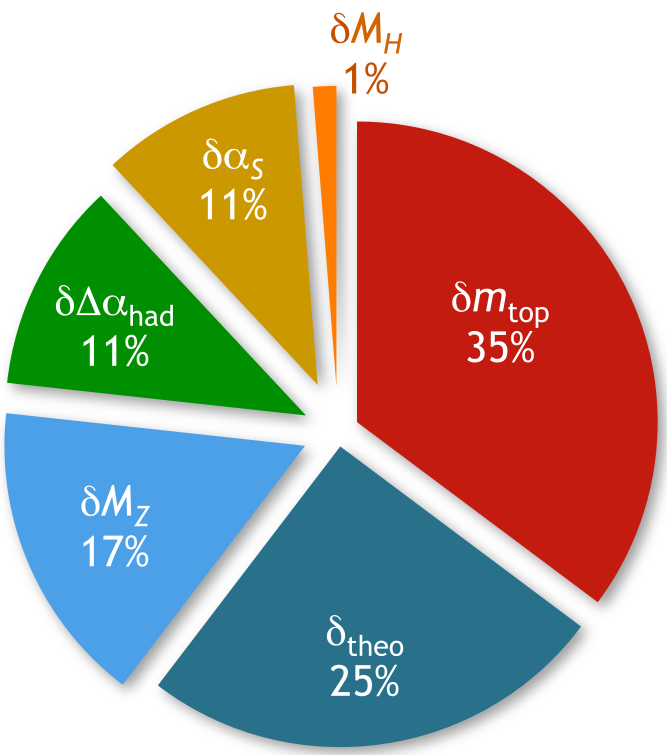
SM Fit with *p*-value of 0.07

- Incentive to revisit $Z \to bb$ experimentally and theoretically !
- Incentive also to compute higher order contributions to other partial width observables

Significant improvement in SM prediction of key observables with M_H

- M_W : 28 $\to$ 11 MeV
- $\sin2\theta^l_{eff}$: 2.3 $\to$ 1.0 × 10^{-5}
- m_{top} : 6.2 $\to$ 2.5 GeV

δM_W =



= 11 MeV

(exp: 15 MeV)

Improved accuracy sets benchmark for new direct measurements

Extra slides…

ILC with GigaZ projection

Parameter	Input value	Free in fit	Predicted fit result
M_H [GeV]	125.8 ± 0.1	yes	125.0^{+12}_{-10}
M_W [GeV]	80.378 ± 0.006	–	80.361 ± 0.005
Γ_W [GeV]	–	–	2.0910 ± 0.0004
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0046
Γ_Z [GeV]	–	–	2.4953 ± 0.0003
σ^0_{had} [nb]	–	–	41.479 ± 0.003
R^0_l	20.742 ± 0.003	–	–
$A^{0,l}_{\mathrm{FB}}$	–	–	0.01622 ± 0.00002
A_ℓ	–	–	0.14706 ± 0.00010
$\sin^2\theta^\ell_{\mathrm{eff}}$	0.231385 ± 0.000013	–	0.23152 ± 0.00004
A_c	–	–	0.66791 ± 0.00005
A_b	–	–	0.93462 ± 0.00002
$A^{0,c}_{\mathrm{FB}}$	–	–	0.07367 ± 0.00006
$A^{0,b}_{\mathrm{FB}}$	–	–	0.10308 ± 0.00007
R^0_c	–	–	0.17223 ± 0.00001
R^0_b	–	–	0.214746 ± 0.000004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	–
m_t [GeV]	173.18 ± 0.10	yes	173.3 ± 1.2
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ $^{(\triangle)}$	2757.0 ± 4.7	yes	2757 ± 10
$\alpha_s(M_Z^2)$	–	yes	0.1190 ± 0.0005
$\delta_{\mathrm{th}}\, M_W$ [MeV]	$[-2.0, 2.0]_{\mathrm{theo}}$	yes	–
$\delta_{\mathrm{th}}\, \sin^2\theta^\ell_{\mathrm{eff}}$ $^{(\triangle)}$	$[-1.5, 1.5]_{\mathrm{theo}}$	yes	–

$^{(\triangle)}$In units of 10^{-5}. $^{(\triangledown)}$Rescaled due to α_s dependency.

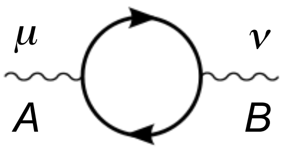
http://gfitter.desy.de/Standard_Model/

Oblique Corrections

Parametrising new physics contributions to electroweak precision observables

At low energies, BSM physics appears dominantly through vacuum polarisation

- Aka, oblique corrections



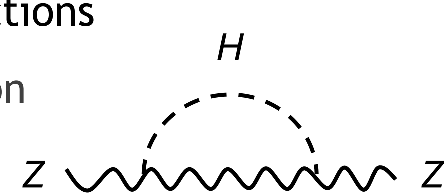
$$= i\Pi^{\mu\nu}_{AB=\{W,Z,\gamma\}}(q)$$

- Direct corrections (vertex, box, brems-strahlung) generally suppressed by m_f/Λ

Oblique corrections reabsorbed into electroweak parameters $\Delta\rho$, $\Delta\kappa$, Δr

Electroweak fit sensitive to BSM physics through oblique corrections

- In direct competition with Higgs loop corrections



- Oblique corrections from New Physics described through "*STU* parameters"

[Peskin-Takeuchi, Phys. Rev. D46, 381 (1992)]

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

S : (*S*+*U*) New Physics contributions to neutral (charged) currents

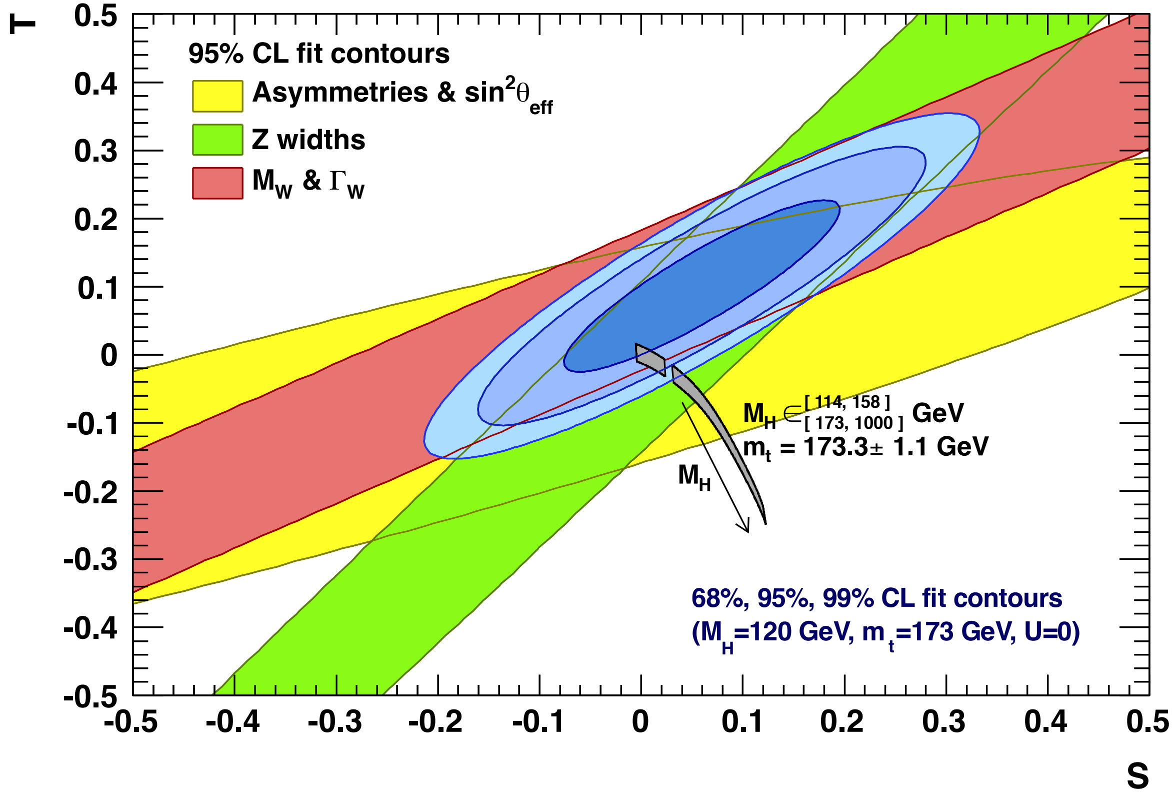
T : Difference between neutral and charged current processes – sensitive to weak isospin violation

U : Constrained by M_W and Γ_W. Usually very small in NP models (often: *U*=0)

Oblique Corrections

Parametrising new physics contributions to electroweak precision observables

At low energies, BSM physics appears dominantly through vacuum polarisation



Illustrations of constraints on S, T

[arXiv:1107.0975]

Oblique Corrections

Parametrising new physics contributions to electroweak precision observables

Definitions of S, T, U, V, W, X :

[STU parameters suffice when (q/M)2 small, so that linear approximation is accurate]

[Burgess et al., PLB 326, 276 (1994), PRD 49, 6115 (1994)]

$$\frac{\alpha S}{4 s_W^2 c_W^2} = \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2}\right] - \frac{\left(c_W^2 - s_W^2\right)}{s_W c_W}\,\delta\Pi'_{Z\gamma}(0) - \delta\Pi'_{\gamma\gamma}(0)\ ,$$

$$\alpha T = \frac{\delta\Pi_{WW}(0)}{M_W^2} - \frac{\delta\Pi_{ZZ}(0)}{M_Z^2}\ ,$$

$$\frac{\alpha U}{4 s_W^2} = \left[\frac{\delta\Pi_{WW}(M_W^2) - \delta\Pi_{WW}(0)}{M_W^2}\right] - c_W^2\left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2}\right] - s_W^2\,\delta\Pi'_{\gamma\gamma}(0) - 2 s_W c_W\,\delta\Pi'_{Z\gamma}(0)\ ,$$

$$\alpha V = \delta\Pi'_{ZZ}(M_Z^2) - \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2}\right]\ ,$$

$$\alpha W = \delta\Pi'_{WW}(M_W^2) - \left[\frac{\delta\Pi_{WW}(M_W^2) - \delta\Pi_{WW}(0)}{M_W^2}\right]\ ,$$

$$\alpha X = -s_W c_W\left[\frac{\delta\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \delta\Pi'_{Z\gamma}(0)\right]\ .$$

Oblique Corrections

Parametrising new physics contributions to electroweak precision observables

Dependence of electroweak observables on S,T,U,V,W,X.

[The numerical values are based on $\alpha^{-1}(M_Z)$ = 128 and $\sin^2\theta_W$ = 0.23]

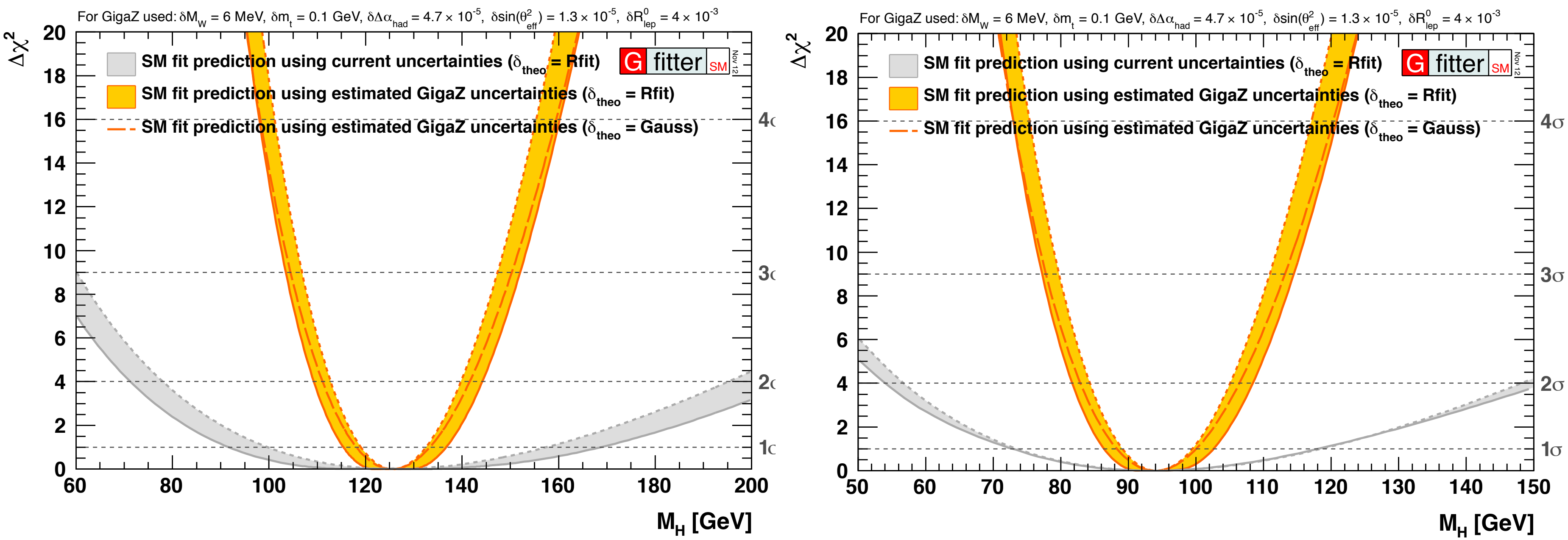
$$\Gamma_Z = (\Gamma_Z)_{SM} - 0.00961S + 0.0263T + 0.0194V - 0.0207X \text{ [GeV]}$$
$$\Gamma_{bb} = (\Gamma_{bb})_{SM} - 0.00171S + 0.00416T + 0.00295V - 0.00369X \text{ [GeV]}$$
$$\Gamma_{\ell^+\ell^-} = (\Gamma_{\ell^+\ell^-})_{SM} - 0.000192S + 0.000790T + 0.000653V - 0.000416X \text{ [GeV]}$$
$$\Gamma_{had} = (\Gamma_{had})_{SM} - 0.00901S + 0.0200T + 0.0136V - 0.0195X \text{ [GeV]}$$
$$A_{FB(\mu)} = (A_{FB(\mu)})_{SM} - 0.00677S + 0.00479T - 0.0146X$$
$$A_{pol(\tau)} = (A_{pol(\tau)})_{SM} - 0.0284S + 0.0201T - 0.0613X$$
$$A_{e(P\tau)} = (A_{e(P\tau)})_{SM} - 0.0284S + 0.0201T - 0.0613X$$
$$A_{FB(b)} = (A_{FB(b)})_{SM} - 0.0188S + 0.0131T - 0.0406X$$
$$A_{FB(c)} = (A_{FB(c)})_{SM} - 0.0147S + 0.0104T - 0.03175X$$
$$A_{LR} = (A_{LR})_{SM} - 0.0284S + 0.0201T - 0.0613X$$
$$M_W^2 = (M_W^2)_{SM}\,(1 - 0.00723S + 0.0111T + 0.00849U)$$
$$\Gamma_W = (\Gamma_W)_{SM}\,(1 - 0.00723S - 0.00333T + 0.00849U + 0.00781W)$$
$$g_L^2 = (g_L^2)_{SM} - 0.00269S + 0.00663T$$
$$g_R^2 = (g_R^2)_{SM} + 0.000937S - 0.000192T$$
$$g^e_{V,(\nu e\to\nu e)} = (g^e_V)_{SM} + 0.00723S - 0.00541T$$
$$g^e_{A,(\nu e\to\nu e)} = (g^e_A)_{SM} - 0.00395T$$
$$Q_W(^{133}_{55}\text{Cs}) = Q_W(\text{Cs})_{SM} - 0.795S - 0.0116T$$

[Burgess et al., PLB 326, 276 (1994), PRD 49, 6115 (1994)]

ILC with GigaZ

Prospects for M_H fit at ILC with GigaZ

Central values of input observables chosen to agree with their SM prediction for a Higgs mass of 126 GeV (left) and 94 GeV (right), respectively.



New R^0_b calculation

[A. Freitas et al., J … 208, 050 (2012)]

Status: Moriond QCD, 2013

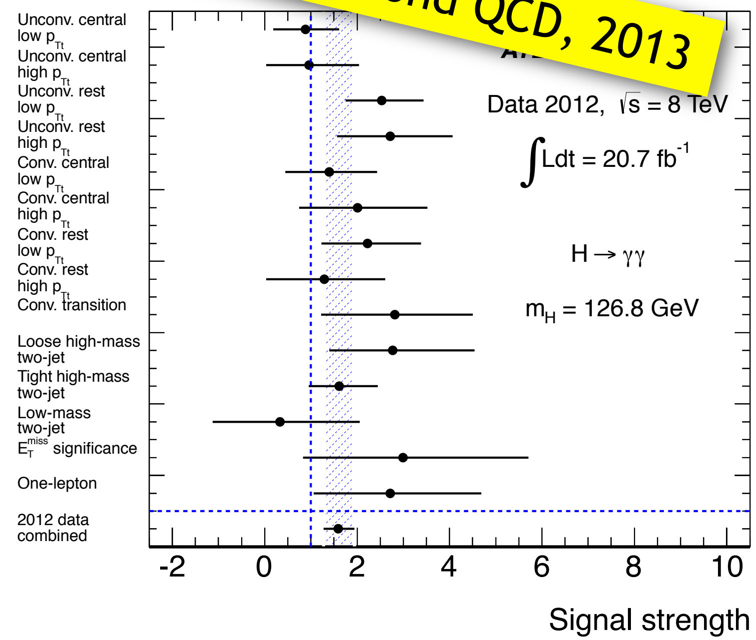
- The branching ratio R^0_b: partial decay width of $Z \to bb$ to $Z \to qq$
- Freitas et al: full 2-loop calculation of $Z \to bb$
- Contribution of same terms as in the calculation of $\sin^2\theta^{bb}_{eff}$
  $\to$ cross-check of two results found good agreement
- Two-loop corrections comparable 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]	$\mathcal{O}(\alpha) + \mathrm{FSR}_{1-\mathrm{loop}}$ $[10^{-3}]$	$\mathcal{O}(\alpha^2_{\mathrm{ferm}})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\mathrm{ferm}}) + \mathrm{FSR}_{>1-\mathrm{loop}}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_s, \alpha\alpha_s^2)$ $[10^{-4}]$
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

Higgs couplings in the EW fit

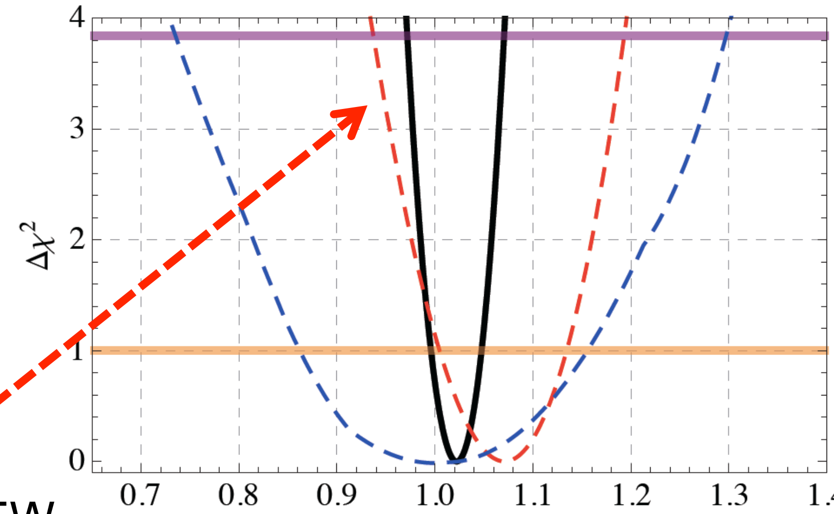
Status: Moriond QCD, 2013

- 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: $\rho_0 = \frac{M_{W_0}^2}{M_{Z_0}^2 c_W^2} = 1 + \alpha T$
  - $\alpha T \approx \frac{3 g_Y^2}{32\pi^2} (c_V^2 - 1) \log(\Lambda / m_Z)$
  - 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