[http://cern.ch/gfitter]

Reference paper
[EPJC72, 2205(2012), arXiv:1209.2716]
Accepted by EPJC
[arXiv:1407.3792]

The global electroweak fit at NNLO and prospects for the LHC and ILC

M. Baak[1], **J. Cúth**[2], J. Haller[3], A. Hoecker[1], R. Kogler[3], K. Mönig[4], M. Schott[2], J. Stelzer[5]

[1]CERN, Switzerland; [2]U. Mainz, Germany; [3]U. Hamburg, Germany; [4]DESY, Germany; [5]Michigan State, USA

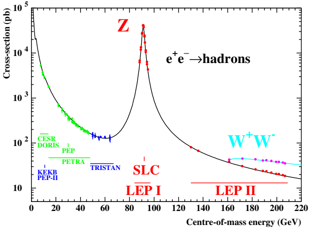
BSM fit workingshop, DESY–Hamburg, September 29th 2014

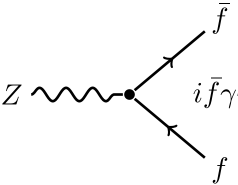
Gfitter

Outline

1. Global electroweak fit
2. Current status and BSM tests
3. Future prospects

- The Standard Model was proving it's predictive power for decades





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

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

- Precision electroweak fits are used as testing tools since LEP era
- We are using Gfitter – generic fitter package

Electroweak sector

Gfitter

- Tree level relations are not sufficient – radiative corrections are needed
- The impact of corrections stored in EW form factors helps to define effective coupling at Z-pole
- Quadratic dependence on m_t, logarithmic dependece on M_H

$$M_W^{\text{tree level}} = (79.964 \pm 0.005)\ \text{GeV}$$

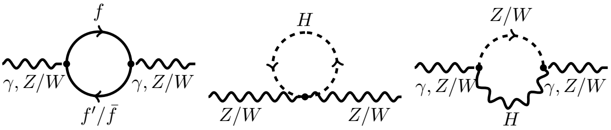
$$M_W^{\text{meas}} = (80.385 \pm 0.015)\ \text{GeV}$$

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

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

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

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



- The relation between SM parameters appears

$$M_W\left(\ln(M_H), m_t^2, M_Z, \Delta\alpha_{\text{had}}^{(5)}(M_Z^2), \alpha_S(M_Z^2)\right)$$

$$\sin^2\theta^f_{\text{eff}}\left(\ln(M_H), M_H, m_t^2, M_Z, \Delta\alpha_{\text{had}}^{(5)}(M_Z^2), \alpha_S(M_Z^2)\right)$$

Current predictions

G fitter

- Gfitter is using state-of-the-art EW calculations:
  - M_W – mass of W bosson in full two loop + beyond-two-loop corrections

    [M. Awramik et al., Phys. Rev. D69, 053006 (2004)]
  - $\sin^2\theta^f_{\rm eff}$ – effective weak mixing angle same as M_W

    [M. Awramik et al., JHEP 0611, 048 (2006); M. Awramik et al., Nucl.Phys.B813:174-187 (2009)]
  - Γ_{had} – QCD Adler function at N3LO

    [P. A. Baikov et al., Phys.Rev.Lett. 108, 222003 (2012)]
  - $\Gamma_Z, \ldots$ – new full two-loop partial and total Z width

    [A. Freitas, JHEP 1404, 070 (2014)]
  - R^0_b – Electroweak two-loop corrections

    [Freitas and Huang, arXiv:1205.0299, v3]
- nuisance parameters for theoretical uncertainties used EW fit:

$\delta_{\rm th} M_W$	4 MeV	$\delta_{\rm th}\Gamma_{u,c}$	0.12 MeV
$\delta_{\rm th}\sin^2\theta^f_{\rm eff}$	4.7×10^{-5}	$\delta_{\rm th}\Gamma_b$	0.21 MeV
$\delta_{\rm th}\Gamma_{e,\mu,\tau}$	0.012 MeV	$\delta_{\rm th}\sigma^0_{\rm had}$	6 pb
$\delta_{\rm th}\Gamma_\nu$	0.014 MeV	$\delta_{\rm th}\mathcal{R}_{V,A}$	$\sim\mathcal{O}(\alpha_s^4)$
$\delta_{\rm th}\Gamma_{d,s}$	0.09 MeV	$\delta_{\rm th} m_t$	0.5 GeV

- Gaussian treatment of theoretical uncertainties

Experimental inputs

G fitter

M_H [GeV]	♣	125.14 ± 0.24	LHC
M_W [GeV]		80.385 ± 0.015	Tevatron / LEP
Γ_W [GeV]		2.085 ± 0.042	Tevatron / LEP
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		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]	♣	173.34 ± 0.76	Comb
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	♣	2757 ± 10	

♣ free in fit

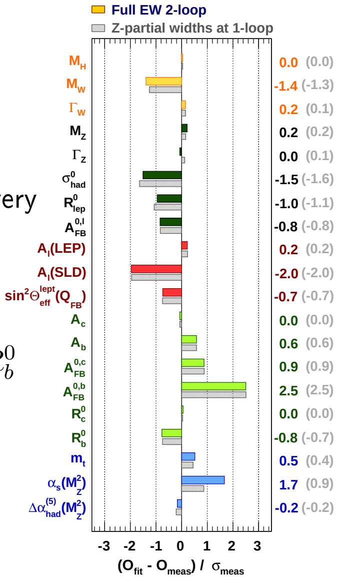
- Z-pole observables: from LEP / SLC
  [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
- M_W and Γ_W from LEP/Tevatron
  [arXiv:1204.0042, arXiv:1302.3415]
- m_t latest Tevatron+LHC combination
  [arXiv:1403.4427]
- $\overline{m}_c$, $\overline{m}_b$ world averages (PDG)
  [Phys. Rev. D86, 010001(2012)]
- $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ including α_S dependency
  [Davier et al., EPJC 71, 1515 (2011)]
- M_H latest ATLAS + CMS
  [arXiv:1406.3827, CMS-PAS-HIG-14-009]

Status of EW fit – improved calculations

- no observable exceeds 3σ with $\chi^2_{\min} = 17.8$

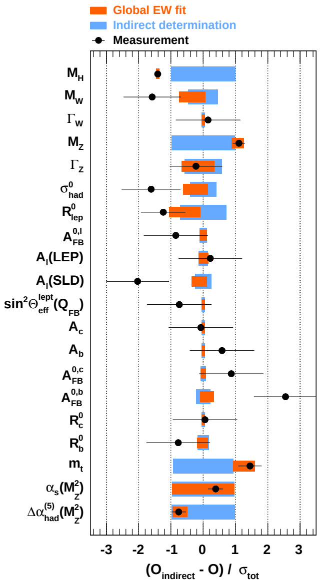
- the system is over constrain since Higgs discovery
- most affected M_W with shift of 13 MeV

- comparing new two-loop calculation main differencies are from corrected calculation of R_b^0
- two loop partial Γ_Z decrease value of $\chi^2_{\min}$
- four loop QCD M_W increase value of $\chi^2_{\min}$



Status of EW fit – measurement vs fit precission

Gfitter

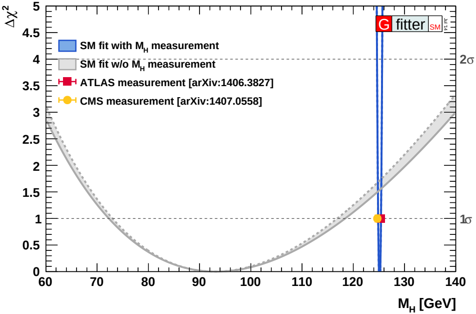


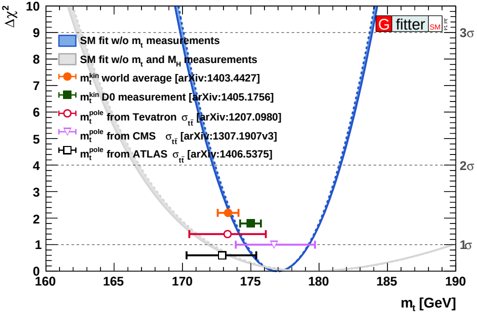
- fit results drawn as pull: deviation from indirect determination divided by total error
- total error = direct measurement $\oplus$ inderect determination

- black: experimental measurement
- orange : full fit result
- blue : fit without input in row

- many indirect determinations are more precise than measurement

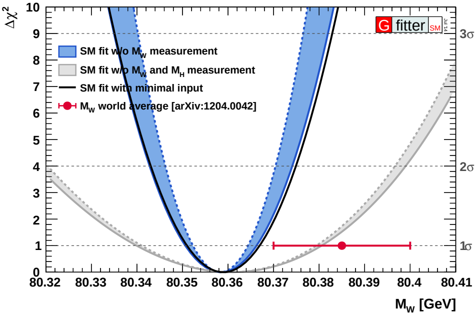
Fitting observables – 1D scans

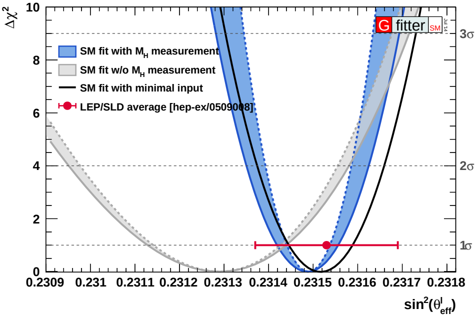




- Higgs measurement made strong impact on indirect determination
- further improvement of M_H precision would have small effect (log dependence)

Fitting observables – 1D scans

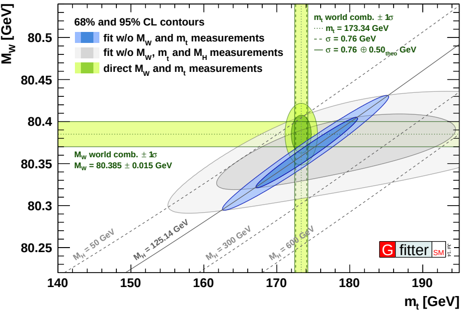


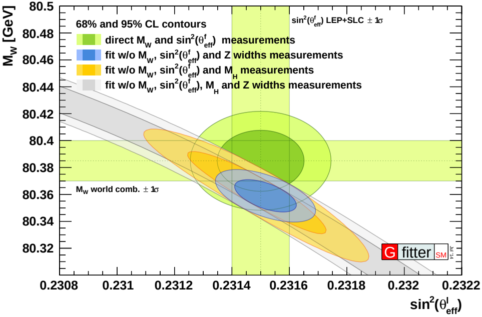


$$
\begin{aligned}
M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\text{had}}} \\
&\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W} \ \text{GeV}\,, \\
&= 80.358 \pm 0.008_{\text{tot}} \ \text{GeV}\,.
\end{aligned}
$$

$$
\begin{aligned}
\sin^2\theta^\ell_{\text{eff}} &= 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\text{theo}} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\text{had}}} \\
&\qquad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\text{theo}} \sin^2\theta^f_{\text{eff}}}\,, \\
&= 0.23149 \pm 0.00007_{\text{tot}}
\end{aligned}
$$

Status of SM – 2D scans

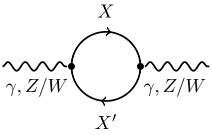


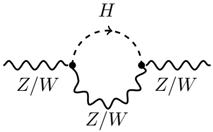


- new m_t measurement – LHC+Tevatron
- M_W vs $\sin^2\theta^f_{\mathrm{eff}}$ – sensitive probes for new physics (both are tree level SM predictions)
- the constrain is higher from Higgs than Zwidths measurements

Oblique parameters

- NP has higher energy scale however could contribute to EW in vacuum polarization corrections
- oblique parameters in SM are hidden into EW radiative form factors $\Delta\rho$, $\Delta\kappa$, Δr appearing in M_W^2, M_Z^2, $\sin^2\theta_{\text{eff}}$, G_F, α ...
- fit is sensible to BSM model – similar to top and Higgs loops





- we are using Peskin-Takeuchi STU parametrization, which measures the deviation from SM

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

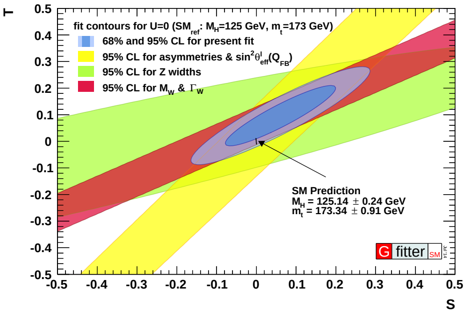
$$O_{\text{meas}} = O_{\text{SMref}}(M_H, m_t) + c_S S + c_T T + c_U U$$

- S: new physics in neutral currents
- T: neutral–charged difference – weak isospin violation
- U: charged currents (with S), sensitive to M_W and Γ_W, usually small

- closely related to $\varepsilon_{1,2,3}$

STU fitting

- STU are derived from EW observables
- the SM reference: $M_H = 125\,\text{GeV}$ and $m_t = 173\,\text{GeV}$, which defines (S,T,U) = (0,0,0)
- log dependence on M_H



- fit results : results show consistency with SM

$S = 0.05 \pm 0.11$

$T = 0.09 \pm 0.13$

$U = 0.01 \pm 0.11$

	S	T	U
S	1	+0.9	-0.59
T		1	-0.83
U			1

$S_{U=0} = 0.06 \pm 0.09$

$T_{U=0} = 0.10 \pm 0.07$

$\text{corr}_{U=0}(S,T) = +0.91$

Higgs couplings

G fitter

- NP potencialy couples to Higgs field.
- Popular benchmark model [LHC HXSWG: 1307.1347] originating from effective Lagrangian
  - considering only leading corrections
  - Higgs–vector boson (κ_V) and Higgs–fermion (κ_f) scalling
  - no additional loops in production
  - no invisible decays

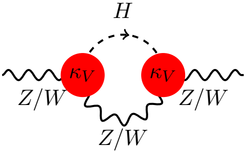
- main effect with gauge bosson coupling κ_V
- Most BSM models implies $\kappa_V < 1$: additional give positive contribution to M_W

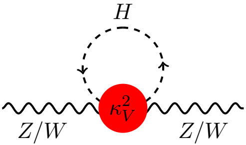
$$\kappa_V (= \kappa_W = \kappa_Z),\ \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau),$$

$$\kappa_\gamma = \kappa_\gamma(\kappa_f, \kappa_f, \kappa_f, \kappa_V),$$

$$\kappa_G = \kappa_f, \quad \kappa_H = \kappa_H(\kappa_i)$$

	$H \to \gamma\gamma$	$H \to VV^*$	$H \to f\bar{f}$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \kappa_\gamma^2}{\kappa_H^2}$	$\frac{\kappa_f^2 \kappa_V^2}{\kappa_H^2}$	$\frac{\kappa_f^2 \kappa_f^2}{\kappa_H^2}$
VBF V+H	$\frac{\kappa_V^2 \kappa_\gamma^2}{\kappa_H^2}$	$\frac{\kappa_V^2 \kappa_V^2}{\kappa_H^2}$	$\frac{\kappa_V^2 \kappa_f^2}{\kappa_H^2}$



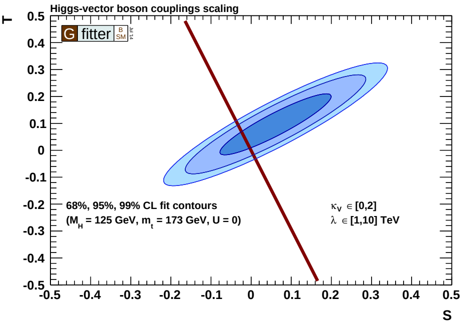


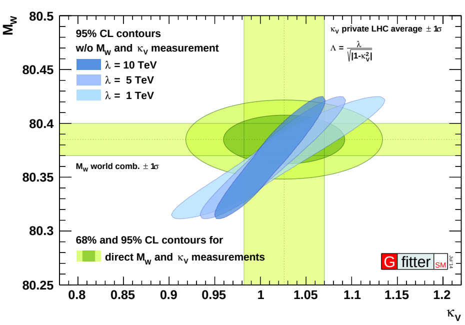
Modified Higgs couplings

- Modified Higgs coupling via gauge boson scaling κ_V [Espinosa et al arXiv:1202.3697]

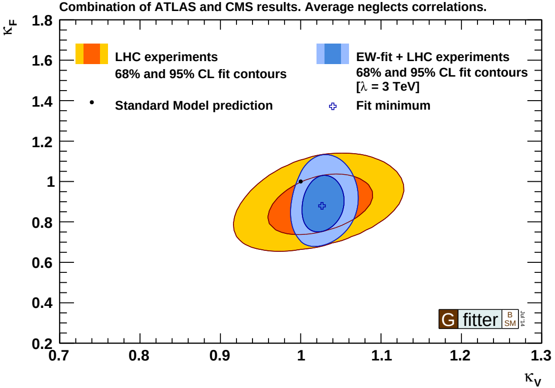
$$S = \frac{1}{12\pi}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right), \quad T = \frac{-3}{16\pi c_W^2}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right), \quad \Lambda = \frac{\lambda}{\sqrt{|1-\kappa_V^2|}}$$

- λ is varied between (1-10) TeV, normally fixed 3 TeV ($4\pi v$) $\Rightarrow$ NP$\gtrsim$ 13 TeV





Higgs couplings resutlts



- Private LHC combination

  $\kappa_V = 1.026^{+0.042}_{-0.044}$

  $\kappa_f = 0.88^{+0.1}_{-0.09}$

- EW fit results with fixed λ

λ	κ_V
1 TeV	$1.037^{+0.029}_{-0.026}$
3 TeV	$1.027^{+0.020}_{-0.019}$
10 TeV	$1.021^{+0.015}_{-0.014}$

- Higgs coupling measurement from LHC compatible with SM
- EW fit so far more precise than current experiments

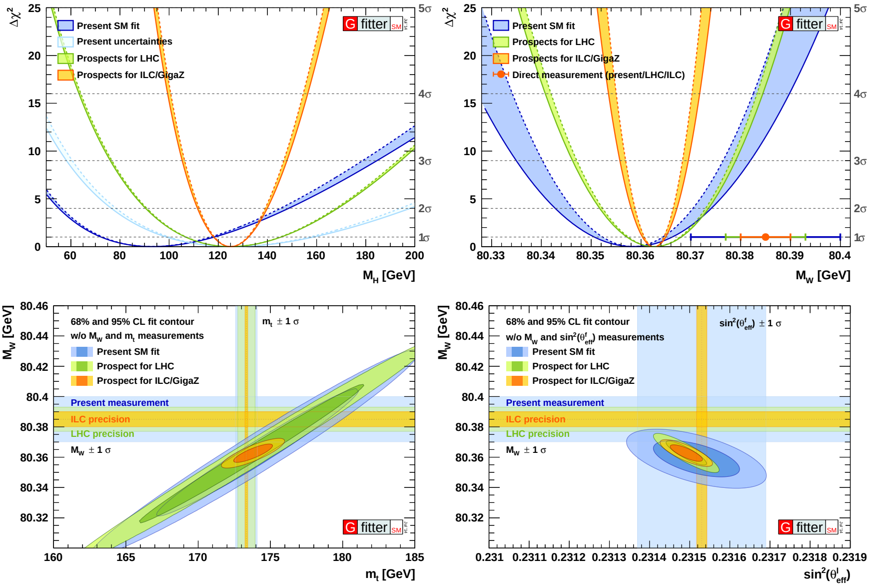
Prospects for future colliders

Parameter	Experimental input [$\pm 1\sigma_{\text{exp}}$] Present	LHC	ILC/GigaZ
M_H [GeV]	0.2 →	< 0.1	< 0.1
M_W [MeV]	15 →	8 →	5
M_Z [MeV]	2.1	2.1	2.1
m_t [GeV]	0.8 →	0.6	0.1
Γ_Z [MeV]	2.3	2.3 →	0.8
$\sin^2\theta^\ell_{\text{eff}}$ [10^{-5}]	16	16 →	1.3
R^0_l [10^{-3}]	25	25 →	4
$\Delta\alpha^5_{\text{had}}(M^2_Z)$ [10^{-5}]	10 →	4.7	4.7
$\delta_{\text{th}} M_W$ [MeV]	4 →	1	1
$\delta_{\text{th}} \sin^2\theta^\ell_{\text{eff}}$ [$\cdot 10^{-4}$]	4.7 →	1	1
κ_V ($\lambda = 3$ TeV)	0.05 →	0.03 →	0.01

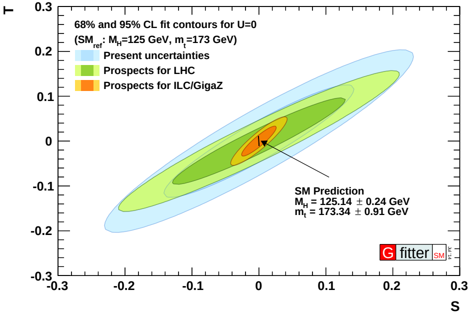
- future measurements: LHC
  - Run 2+3, i.e. 300 fb^{-1}
  - numbers from LHC studies
- future colliders: ILC

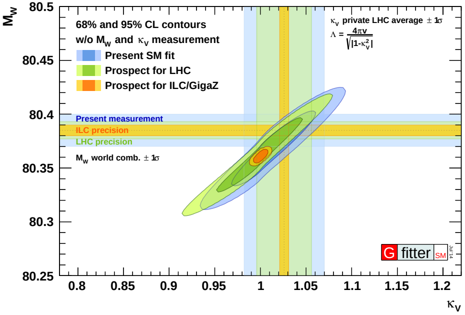
  [H. Baer et al., 1306.6352]
  - GigaZ: scan of WW, $t\bar{t}$ thresholds and Z-pole (M_Z not improve)
  - precise determination of Higgs couplings
- future theory: multi-loop calculation (25% of today)
- pulls are forced to be zero for future prospects
- present uncertanties – current uncertainties with pull = 0

Future of EW fits



Higgs couplings and STU prospects





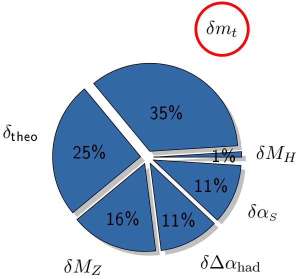
- For STU parameters, improvement of factor of >3 is possible at ILC.
- At ILC a deviation between the SM predictions and direct measurements would be prominently visible.
- Competitive results between EW fit and Higgs coupling measurements!

Conclusion

- as far as we can see SM is consistent (according to EW fits)
- the BSM test (STU + Higgs couplings) looks compatible with SM as well
- posibility to new discoveries and hint with future data and theoretical predictions

- smoking gun M_W : needed measurement with higher precision

$$\delta^{\text{direct}} M_W = 15\,\text{MeV}$$
$$\delta^{\text{indirect}} M_W = 8\,\text{MeV}$$
$$\Delta M_W \sim 1.8\sigma$$



- new paper available [arXiv:1407.3792] , latest results on [http://cern.ch/gfitter]

Thank you for your attention.