Electroweak constraints in the Standard Model and beyond

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on behalf of the Gfitter collaboration

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Overview

Content:

The electroweak fit of the SM

New physics constraints

The 2-Higgs-Doublet Model (2HDM)

Outlook

The Electroweak Fit

- Gauge & scalar sector is determined by 4 parameters (choose α, G_F, M_Z, M_H)

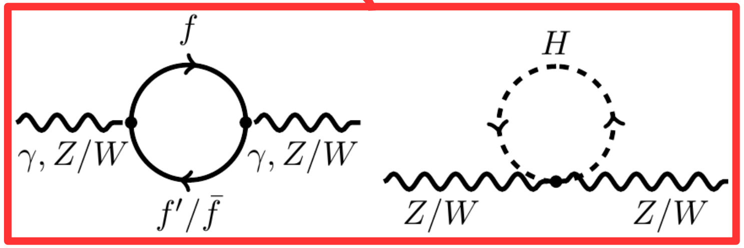
- Other parameters and observables related by theory

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \qquad M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\,G_F}$$

→ over-constrained theory allows consistency check and search for BSM

- Other SM parameters (quark masses, M_H, α_S) enter by radiative corrections

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



- α and G_F know with high precision → not varied in the fit

Theoretical Input

- Consistent set of full EW 2-loop calculations is available:
  - $\sin^2\Theta^f_{eff}$: effective weak mixing angle (from ratio g_V/g_A)
    (M. Awramik et al., PRL 93, 201805 (2004), JHEP 11, 048 (2006), Nucl. Phys. B813, 174 (2009))
  - M_W: mass of the W boson, includes QCD corrections at 4-loop level
    (M. Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002))
  - Γ_f: partial widths of the Z boson (A. Freitas, JHEP 04, 070 (2014))
  - Radiator functions to Γ_f: QED and QCD corrections up to N^3LO
    (Baikov et al., PRL 108, 222003 (2012))
  - (Γ_W: width of the W boson, only 1-loop EW corrections included)
    (Cho et al., JHEP 1111, 068 (2011))
- Estimate uncertainties due to unknown higher orders (using a geometric series):

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

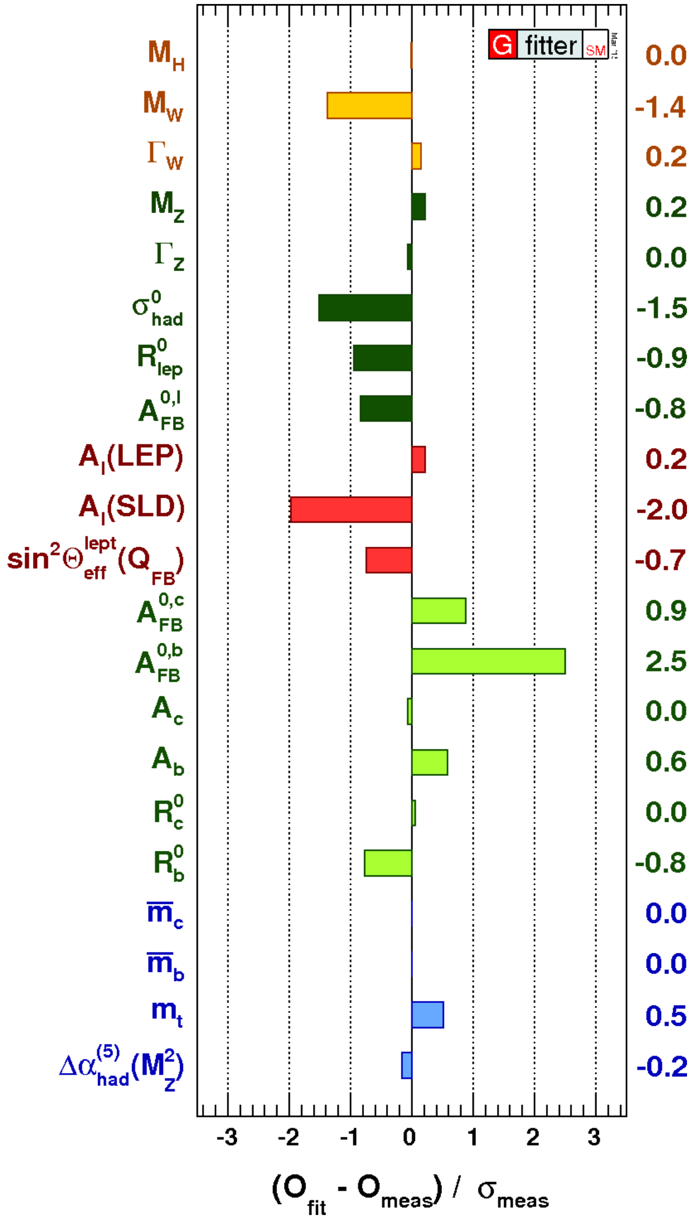
Uncertainty on m_t: Relation between m_{pole} and measured mass

Experimental Input

- All SM parameters measured in experiments
- Input from e^+e^- colliders (LEP+SLC):
  - M_Z, M_W, Γ_W, Γ_Z
  - (forward-backward) asymmetries
  - partial-Z-width ratios R
- Input from hadron colliders (LHC+Tevatron):
  - M_W, Γ_W
  - M_H
  - m_t
- $\alpha_s(M_Z^2)$ enters the fit as free parameter
- α evolving parameterized with $\Delta\alpha^{(5)}_{had}$

M_H [GeV]	125.14 ± 0.24
M_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
A_ℓ	0.1499 ± 0.0018
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.34 ± 0.76
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2757 ± 10

Results

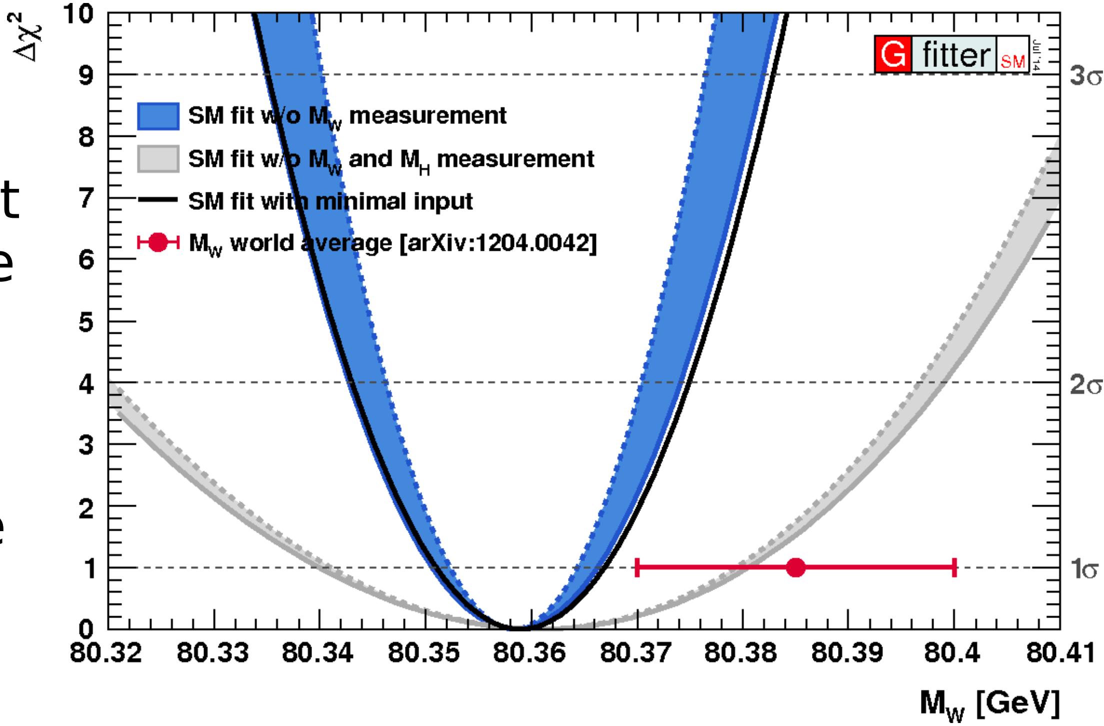


- Global χ^2=17.8 (for ndof = 14), p-value=0.21
- Predictions consistent with measurements
- Largest deviation for $A_{FB}^{0,b} \sim 2.5\sigma$

Indirect determination

- Perform fit without including direct measurement of observable in the fit

- Indirect determination of M_W more precise than direct measurement

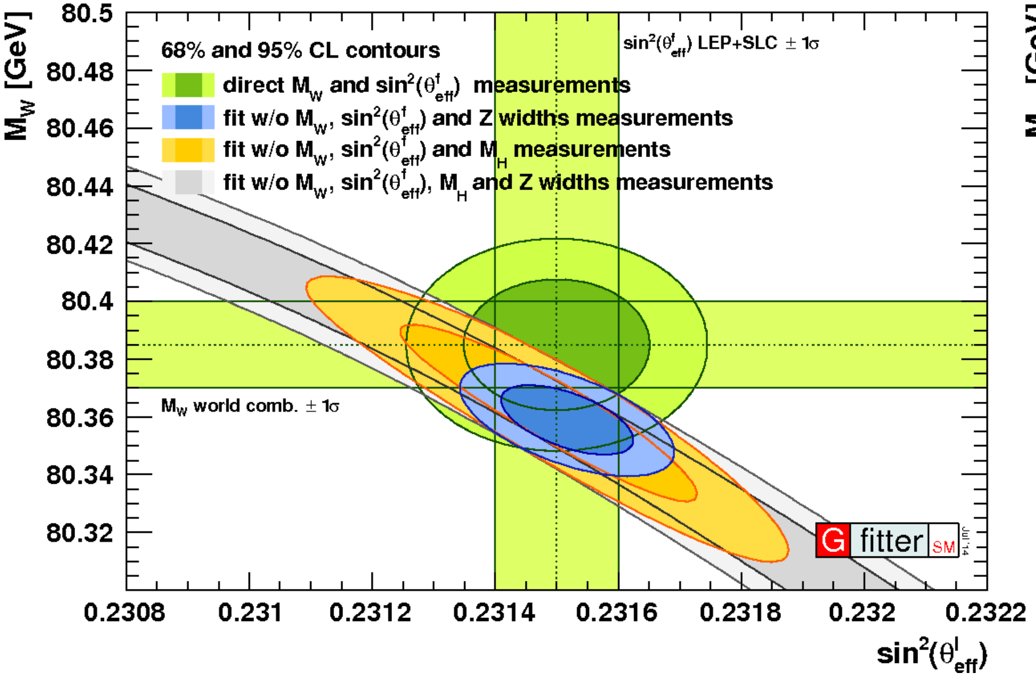


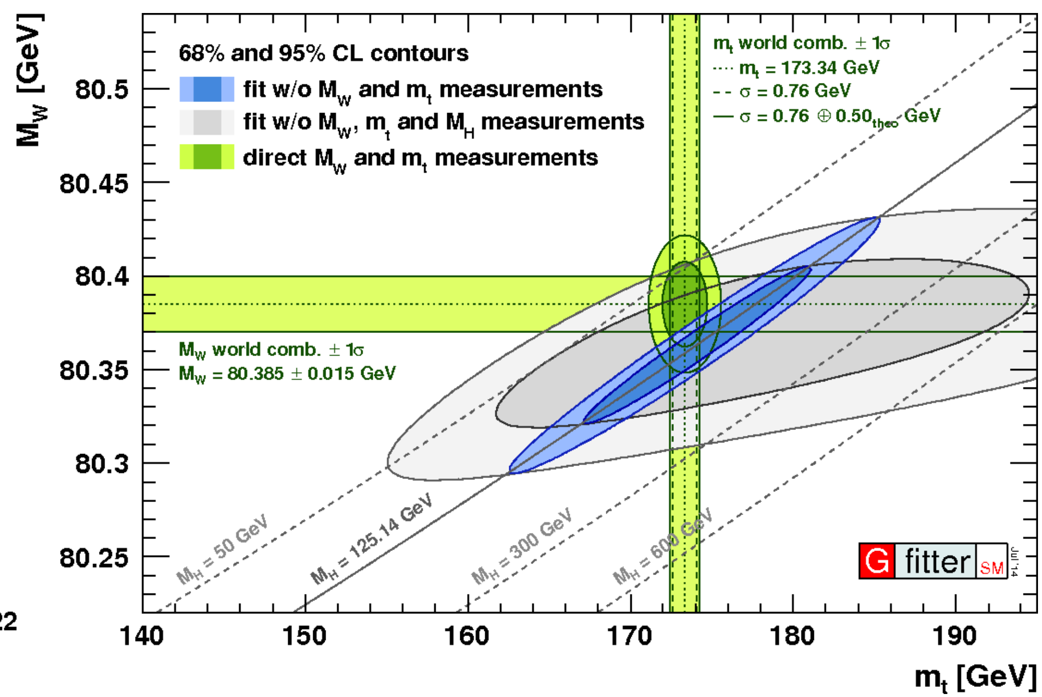
$$
\begin{aligned}
M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\
&\quad \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W}\ \text{GeV}\,, \\
&= 80.358 \pm 0.008_{\rm tot}\ \text{GeV}\,.
\end{aligned}
$$

compared to world average:
80.385 ± 0.015 GeV

2D Scans

- Testing simultaneously two sensitive observables to New Physics effects
- Determine χ^2 for each point in 2D space





- Increased precision due to knowledge of M_H
- Good consistency of SM predictions and measurements

Oblique Parameters

New Physics in electroweak sector parameterized with 3 parameters:

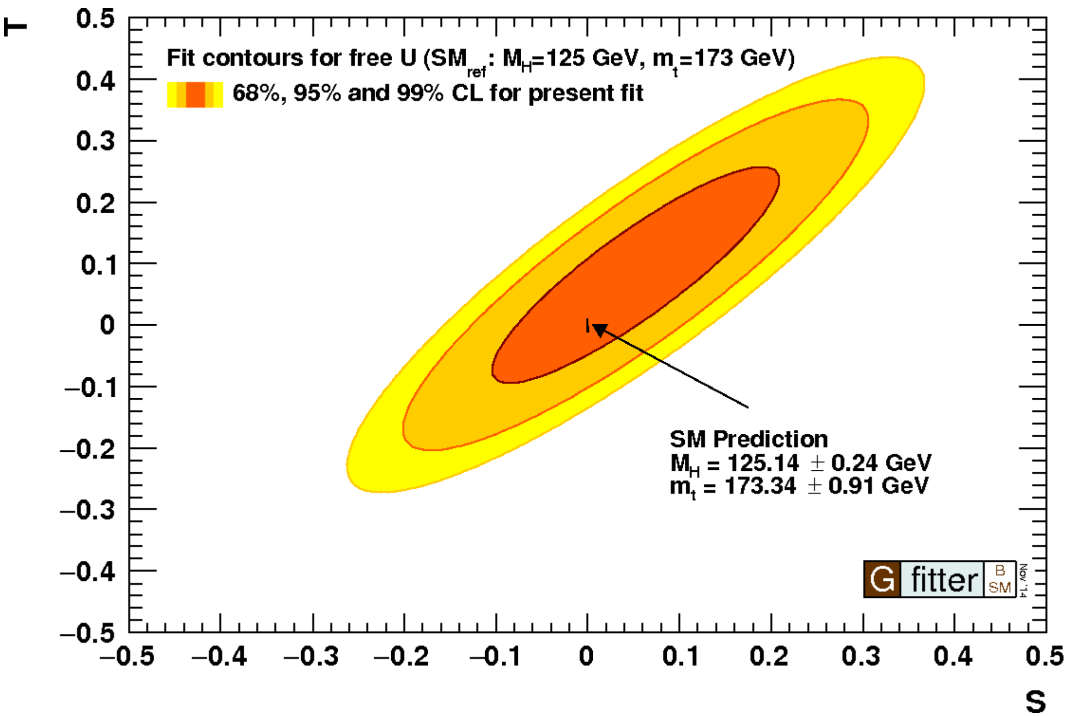
- S: changes to neutral currents
- T: changes to difference between charged and neutral currents
- U: changes to W width and mass

In SM: S=T=U=0

Fit result (for fixed M_H=125 GeV and m_t=173 GeV):

$$S = 0.05 \pm 0.11$$
$$T = 0.09 \pm 0.13$$
$$U = 0.01 \pm 0.11$$

(with large correlations)



No hint for New Physics but constraints on BSM models!

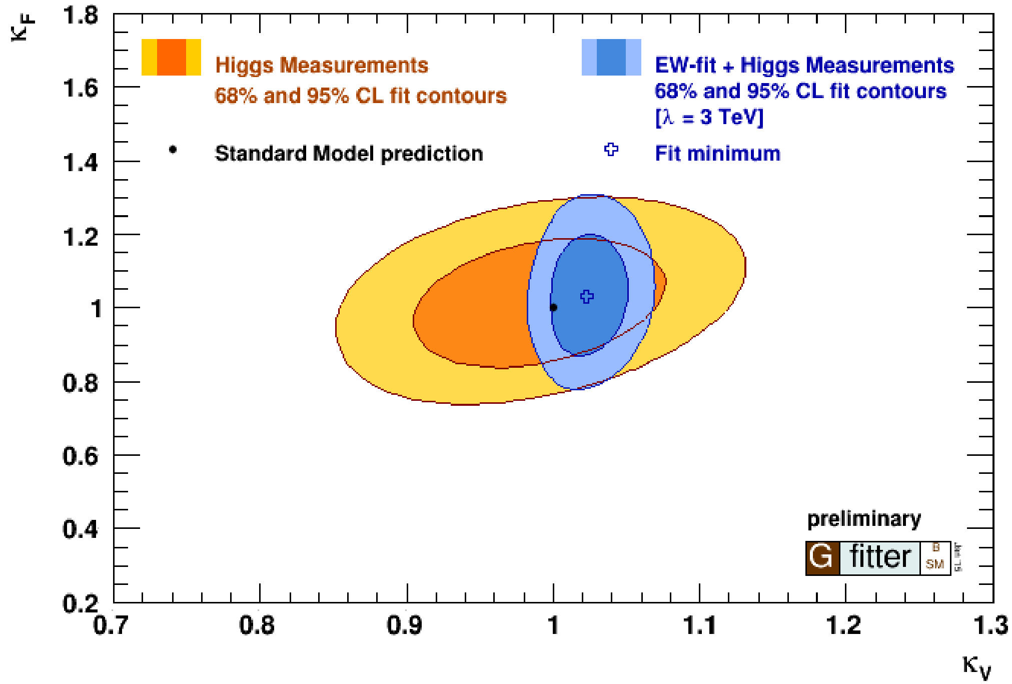
Higgs Couplings

- **New in Gfitter:** constraints from Higgs physics with interface to HiggsBounds & HiggsSignals (P. Bechtle et al., Eur.Phys.J C74 (2014) 2693 & 2711)
- Include latest Higgs branching ratio measurements from LHC
- Simple New Physics example:
  - Scale boson and fermion couplings with κ_V and κ_F
  - κ_V contributes to S, T:

$$S = \frac{1}{12\pi}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}$$

$$T = -\frac{3}{16\pi\cos^2\theta_{\rm eff}^{\ell}}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}$$

(S and T depend on scale Λ)



- Combination of Higgs and EW data improves sensitivity to New Physics

2HDM

The 2-Higgs-Doublet Model

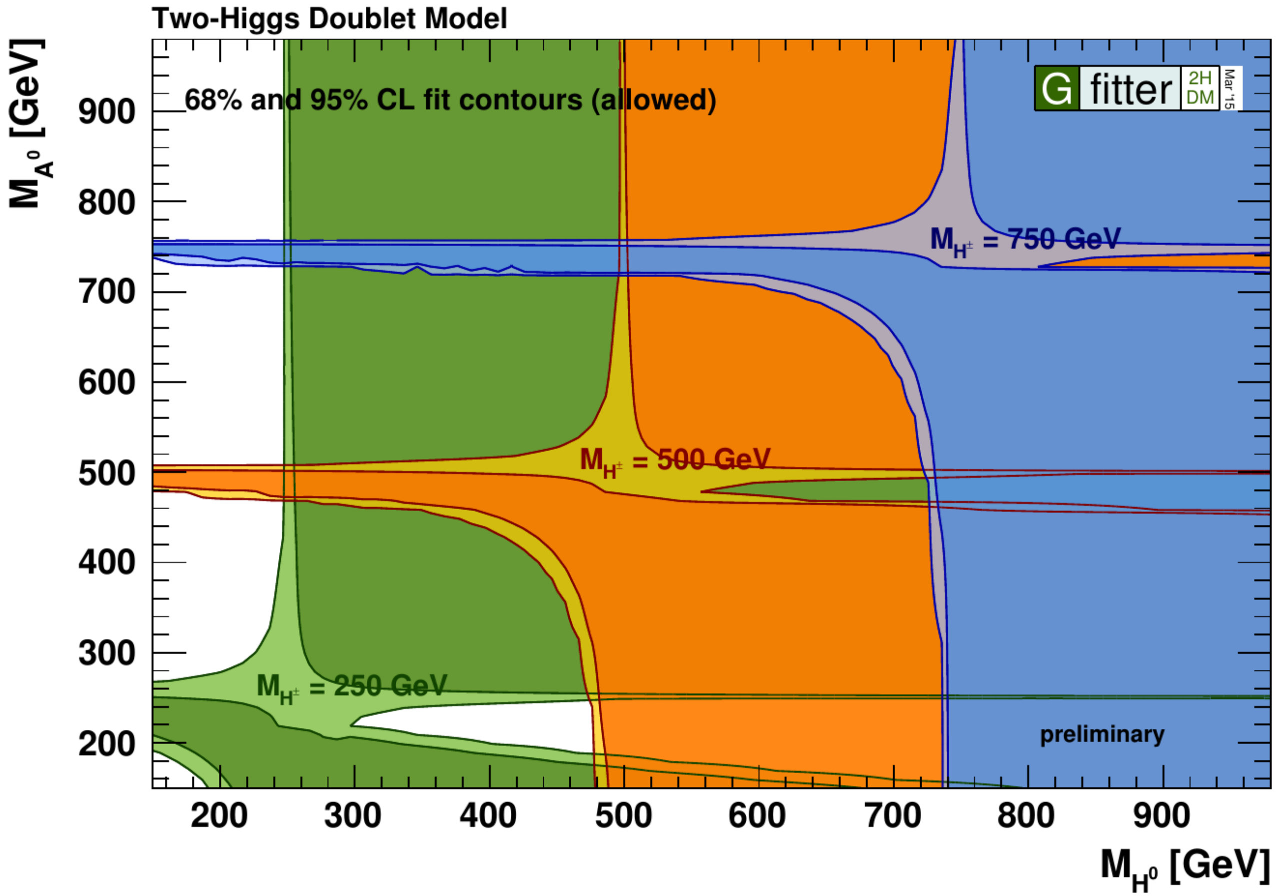
- Simplest extension of the SM Higgs sector
- One additional Higgs doublet → 5 Higgs bosons:

  h_0, H_0, A_0, H^+, H^-
- Additional free parameters:
  - $\tan\beta = v_2/v_1$
  - α: mixing angle of the neutral Higgs fields
  - M_{12}^2: mass parameter of the mixed term $\Phi_1^\dagger\Phi_2$, soft breaking scale

How is the 2HDM constrained by the EW fit and the measured Higgs boson?

2HDM: EW Constraints

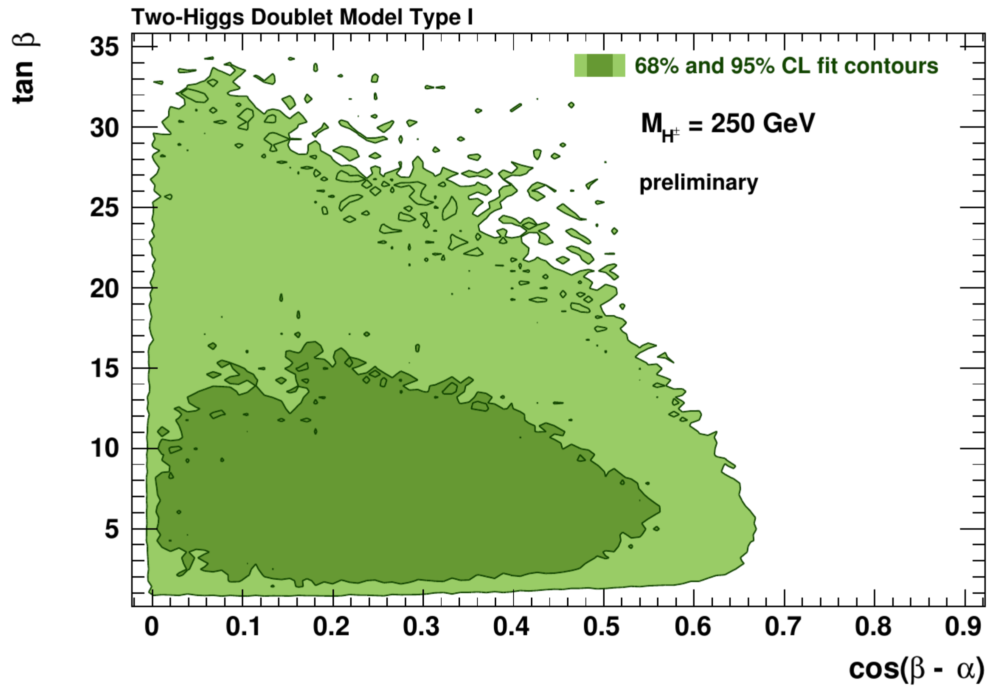
- Use STU formalism to constrain 2HDM
- Assume: discovered 125 GeV Higgs boson is light h_0
- Keep tan β and α free (not constraint by EW data)

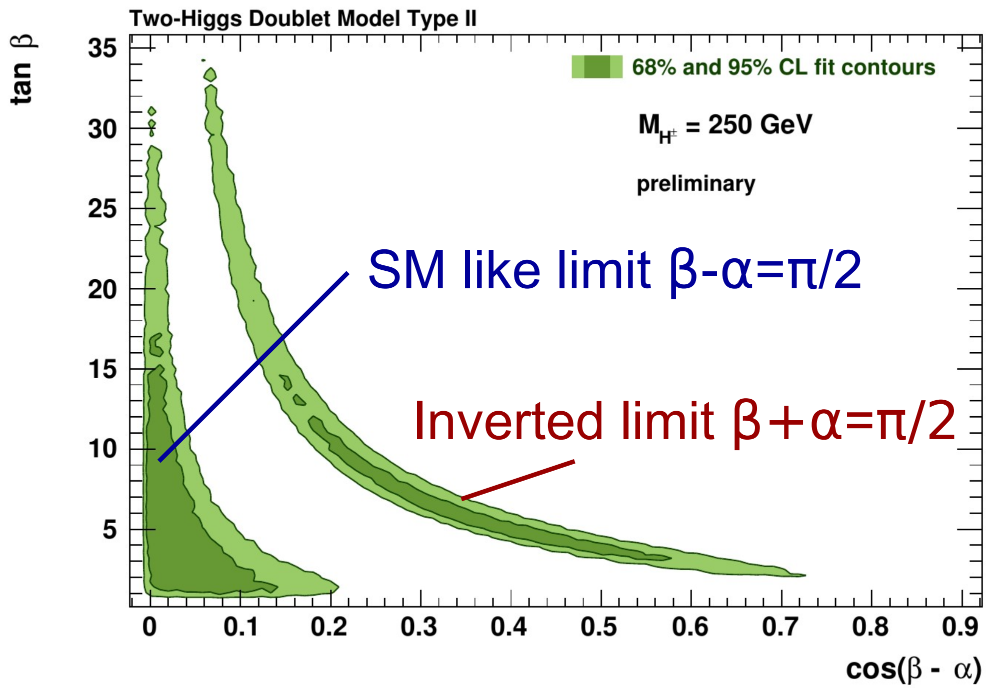


Only weak constraints on masses from electroweak data

2HDM: Higgs BRs

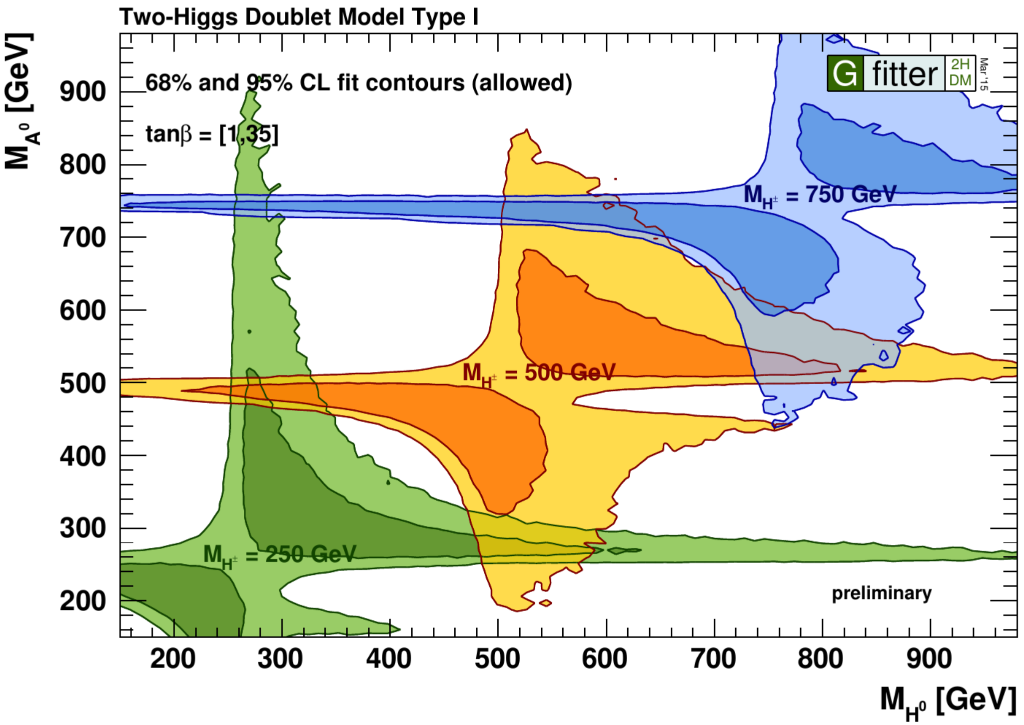
- Measured Higgs branching ratios can constrain 2HDM
- Predictions for Higgs BRs from 2HDMC (D. Eriksson et al., CPC 181, 189 (2010))
- Type I, Type II, flipped (Type III), lepton specific (Type IV) with different Yukawa couplings to light, heavy and charged Higgses
- Importance sampling algorithm MultiNest (F. Feroz et al., arXiv:1306.2144) used to scan parameter space

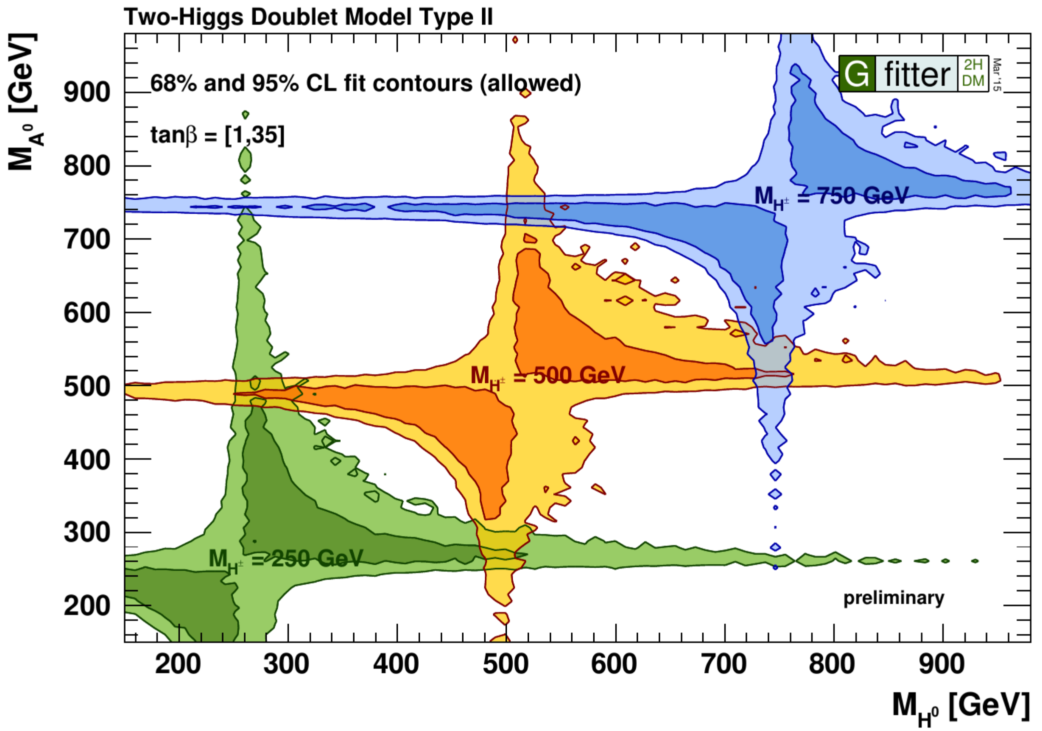




2HDM: Mass limits

Mass scans with constraints from Higgs BRs and EW data

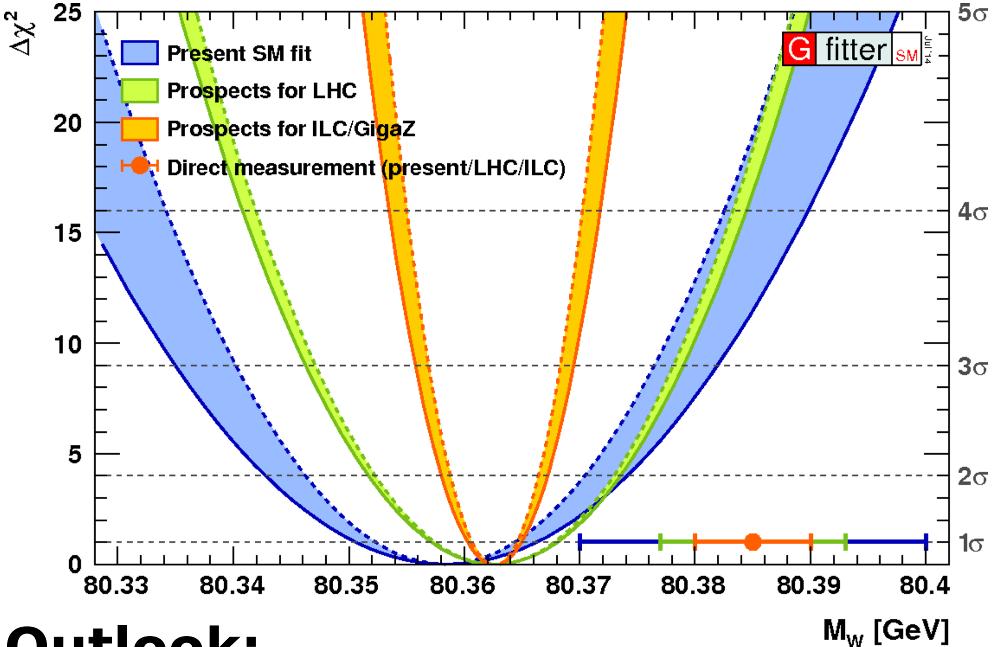


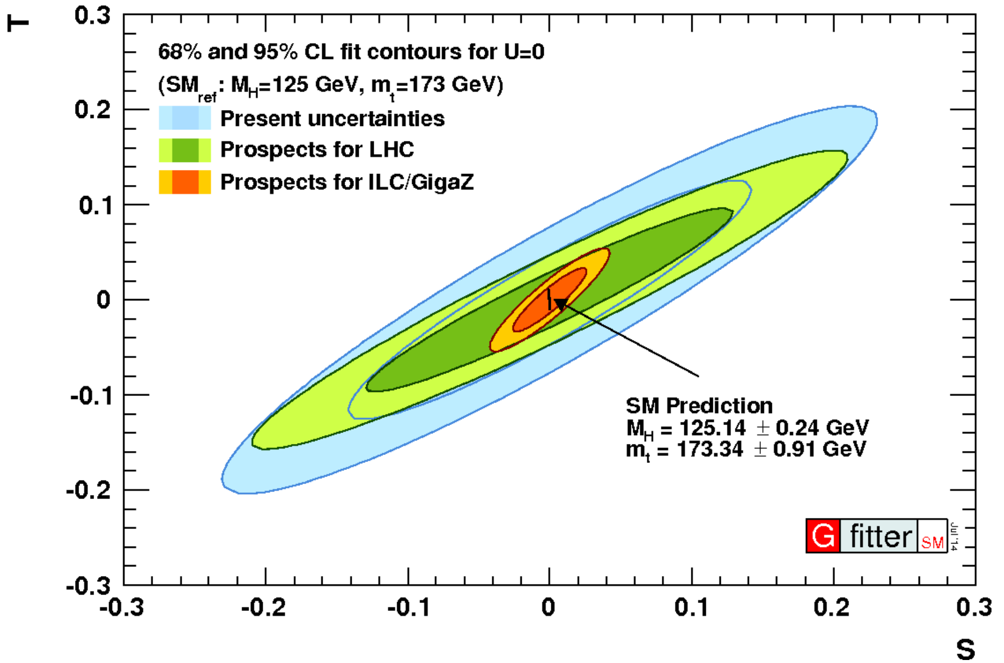


Not included so far: Constraints from flavor physics and direct searches

Conclusion & Outlook

- Electroweak fit probes SM at high precision
- Combination of EW and Higgs data can be used to constrain New Physics





Outlook:

- LHC and future e^+e^- colliders could improve measurements
- EW fit important to test SM with ultra-high precision in the future

BACKUP

Fit Results

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}	93^{+24}_{-20}
M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008	80.358 ± 0.006
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	91.1880 ± 0.0021	91.200 ± 0.011	91.2000 ± 0.010
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016	2.4945 ± 0.0016
σ^0_{had} [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026	20.721 ± 0.026
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001	0.01625 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007	0.23150 ± 0.00005
A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022	0.6680 ± 0.00016
A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004	0.93463 ± 0.00003
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003	0.0738 ± 0.0002
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004	0.1033 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011	0.21577 ± 0.00004
$\overline{m}_c$ [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]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\triangledown)}$	$177.0^{+2.3}_{-2.4}{}^{(\triangledown)}$	177.0 ± 2.3
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10	yes	2756 ± 10	2723 ± 44	2722 ± 42
$\alpha_s(M_Z^2)$	–	yes	0.1196 ± 0.0030	0.1196 ± 0.0030	0.1196 ± 0.0028

$^{(\circ)}$Average of the ATLAS and CMS measurements assuming no correlation of the systematic uncertainties.
$^{(\star)}$Average of the LEP and SLD A_ℓ measurements, used as two measurements in the fit.
$^{(\triangledown)}$The theoretical top mass uncertainty of 0.5 GeV is excluded.
$^{(\dagger)}$In units of 10^{-5}.
$^{(\triangle)}$Rescaled due to α_s dependence.

Indirect determination

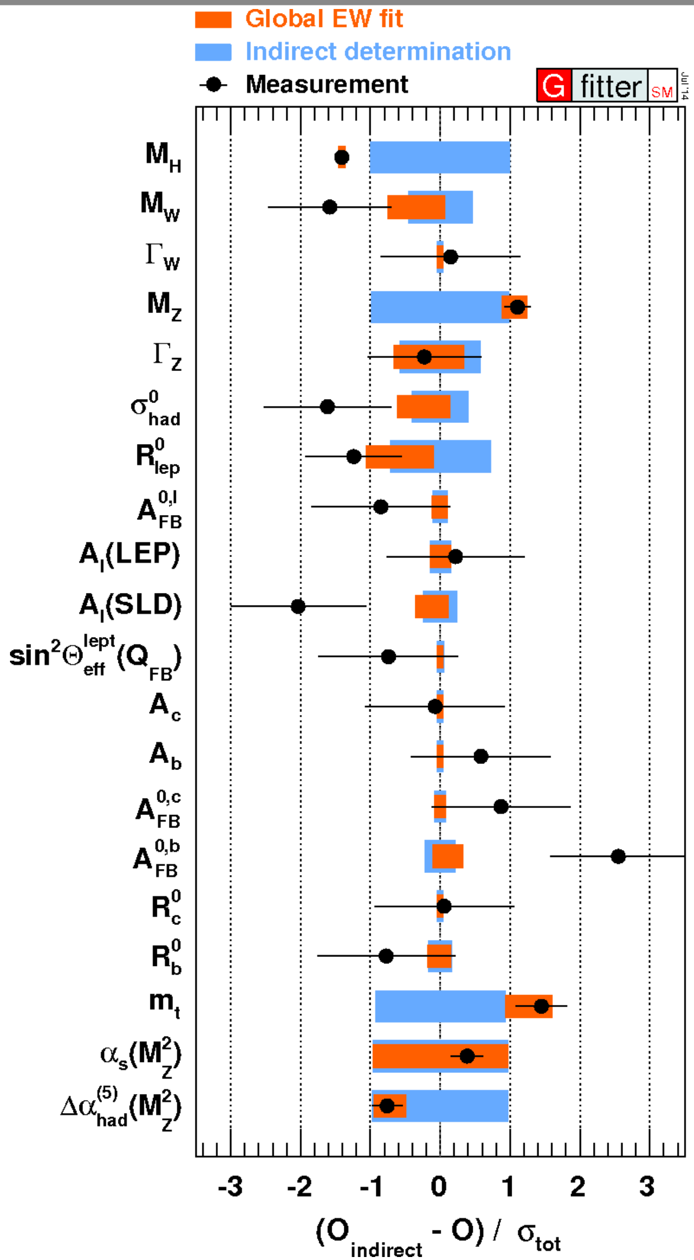
Other indirect determinations:

$$M_H = 93^{+25}_{-21}\ \mathrm{GeV}$$

direct value: 125.14 ± 0.24 GeV

$$m_t = 177.0^{+2.3}_{-2.4}\ \mathrm{GeV}$$

direct value: 173.34 ± 0.76 GeV

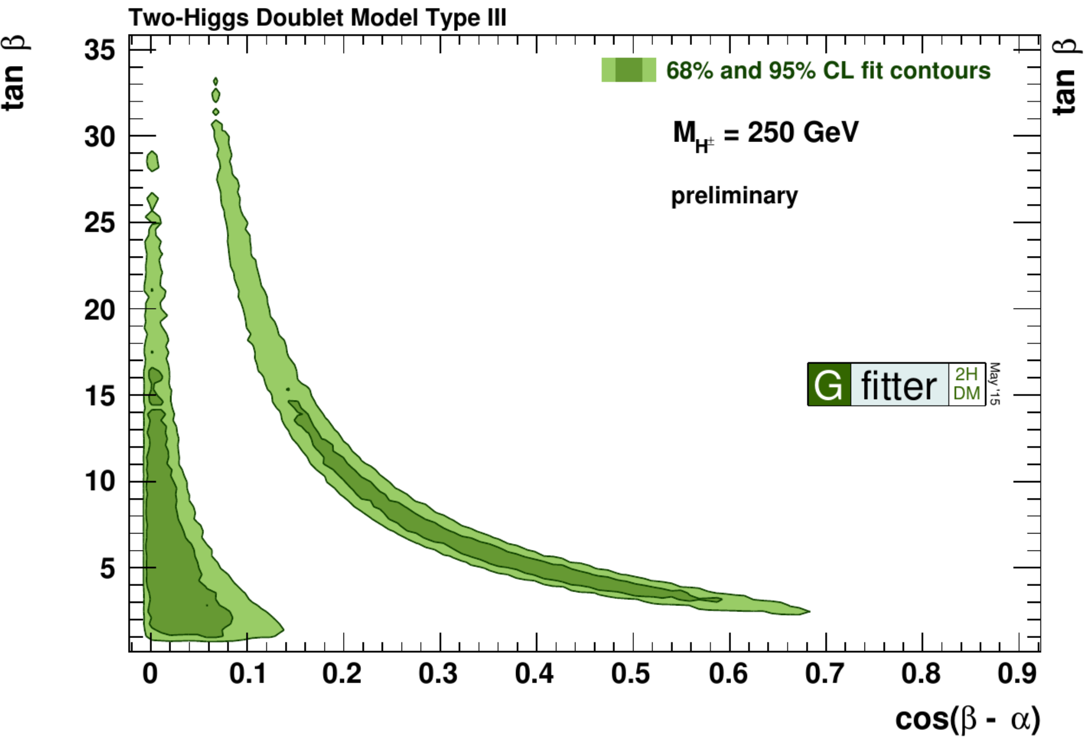


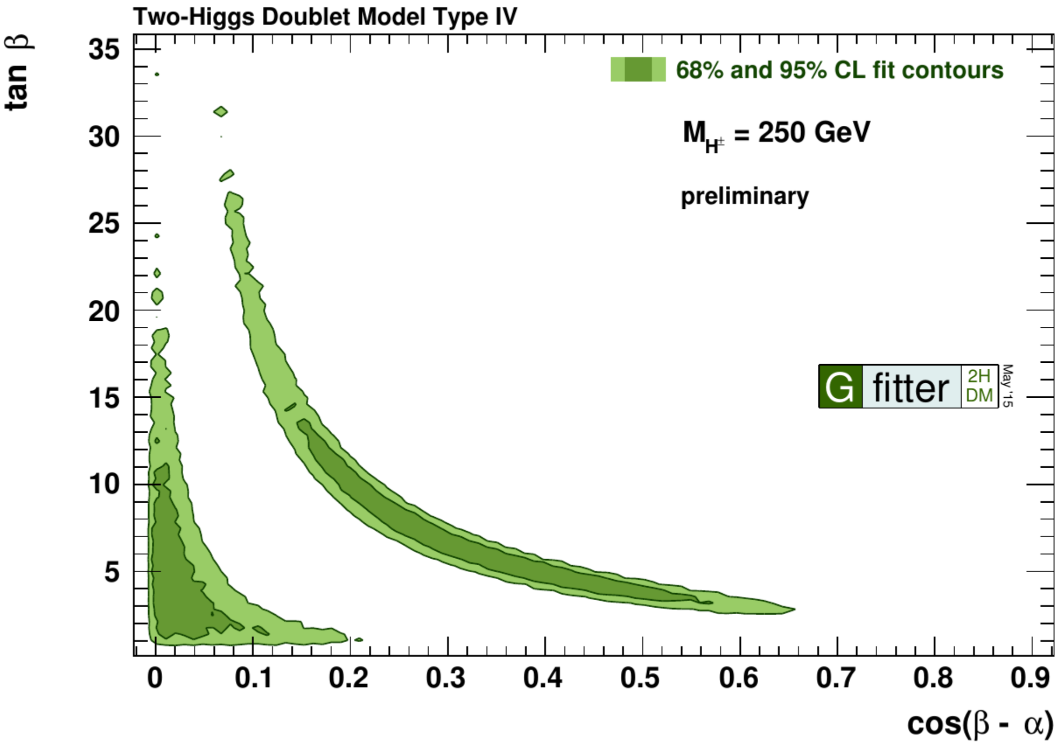
2HDM Types

Parameterization for various 2HDMs (taken from arXiv:1106.0034)

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

2HDM: Higgs Bounds

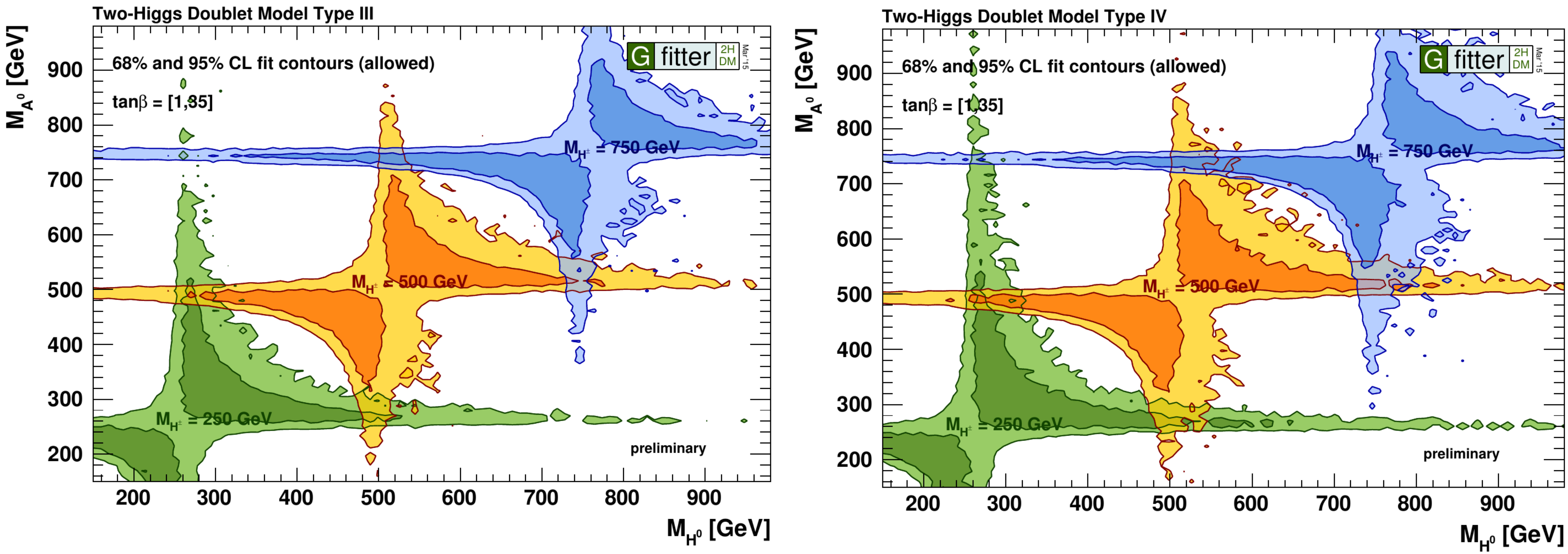




Similar constraints for models Type III and IV

2HDM: Mass Scans

Mass scans with constraints from Higgs BRs and EWPD for Type III and IV



Future Colliders

Parameter	δ_{meas}	δ_{fit}^{tot}	δ_{fit}^{theo}	δ_{fit}^{exp}	Experimental uncertainty source [$\pm 1\sigma$] δM_W	δM_Z	δm_t	$\delta \sin^2\theta_{eff}^{f}$	$\delta \Delta\alpha_{had}$	$\delta \alpha_S$
Present uncertainties										
M_H [GeV]	0.4	$^{+33}_{-27}$	$^{+10}_{-8}$	$^{+31}_{-26}$	$^{+28}_{-23}$	$^{+5}_{-4}$	$^{+10}_{-7}$	$^{+29}_{-23}$	$^{+7}_{-5}$	$^{+4}_{-3}$
M_W [MeV]	15	7.8	5.0	6.0	–	2.5	4.3	5.1	1.6	2.5
M_Z [MeV]	2.1	12.0	3.7	11.4	10.5	–	3.5	11.2	2.2	1.4
m_t [GeV]	0.8	2.5	0.6	2.4	2.3	0.4	–	2.3	0.5	0.6
$\sin^2\theta_{eff}^{\ell}$ $^{(\circ)}$	16	6.6	4.9	4.5	3.7	1.2	2.0	–	3.4	1.2
$\Delta\alpha_{had}$ $^{(\circ)}$	10	44	13	42	31	6	10	41	–	2
LHC prospects										
M_H [GeV]	< 0.1	$^{+21}_{-18}$	$^{+4}_{-3}$	$^{+20}_{-18}$	$^{+17}_{-14}$	$^{+6}_{-5}$	$^{+8}_{-7}$	$^{+18}_{-16}$	$^{+3}_{-2}$	$^{+5}_{-4}$
M_W [MeV]	8	5.5	1.8	5.2	–	2.5	3.5	4.8	0.8	2.6
M_Z [MeV]	2.1	7.2	1.4	7.0	6.0	–	2.8	5.9	0.8	1.9
m_t [GeV]	0.6	1.5	0.2	1.5	1.3	0.4	–	1.2	0.2	0.5
$\sin^2\theta_{eff}^{\ell}$ $^{(\circ)}$	16	3.0	1.1	2.8	2.5	1.1	1.4	–	1.5	0.9
$\Delta\alpha_{had}$ $^{(\circ)}$	4.7	36	6	36	25	9	12	35	–	5
ILC/GigaZ prospects										
M_H [GeV]	< 0.1	$^{+7.4}_{-7.0}$	$^{+2.5}_{-2.3}$	$^{+6.9}_{-6.6}$	$^{+3.9}_{-1.9}$	$^{+4.3}_{-4.1}$	$^{+0.9}_{-0.8}$	$^{+3.3}_{-3.0}$	$^{+4.3}_{-4.1}$	$^{+0.3}_{-0.3}$
M_W [MeV]	5	2.3	1.3	1.9	–	1.7	0.3	1.3	0.7	0.3
M_Z [MeV]	2.1	2.7	1.0	2.6	2.5	–	0.4	1.3	1.9	0.2
m_t [GeV]	0.1	0.8	0.2	0.7	0.6	0.5	–	0.3	0.4	0.2
$\sin^2\theta_{eff}^{\ell}$ $^{(\circ)}$	1.3	2.3	1.0	2.0	1.7	1.2	0.2	–	1.5	0.1
$\Delta\alpha_{had}$ $^{(\circ)}$	4.7	6.4	3.0	5.6	2.7	4.1	0.8	3.9	–	0.2

$^{(\circ)}$In units of 10^{-5}. $^{(\star)}$In units of 10^{-4}