EW THEORY & GLOBAL FIT

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- Introduction
- Theoretical status & R_b
- SM fit & uncertainties
- EWPO beyond the SM and model-independent constraints on NP
- Conclusions and Outlook

Preliminary results from M. Ciuchini, E. Franco, S. Mishima & L.S.

INTRODUCTION

The Standard Model works beautifully up to a few hundred GeV's, but it must be an effective theory valid up to a scale $\Lambda \leq M_{planck}$:

$$\mathcal{L}(M_W) = \Lambda^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{1}{\Lambda}\mathcal{L}^5 + \frac{1}{\Lambda^2}\mathcal{L}^6 + \ldots$$

EW scale

Spontaneously broken renormalizable theory: tree-level relations, accidental symmetries

Violates tree-level relations and accidental symmetries

INTRODUCTION - II

Spontaneous breaking of $SU(2)_L \otimes U(1)_Y$ via Higgs vev & renormalizability imply

1) Tree-level relations in EW sector (ex. $M_W = M_Z \cos\theta_W$)

2) Calculable loop corrections to tree-level relations

$\Rightarrow$ EWPO extremely sensitive to NP!!

INTRODUCTION - III

Qualitative change in the EW fit with the exp. observation of the Higgs boson:

- Before:
  - indirect evidence of a light Higgs boson
  - interplay between SM and NP in EWPO
- After:
  - SM predictions fully computable
  - constraints on NP (including Higgs couplings)

THEORETICAL STATUS

- We use as SM input parameters:
  - G_μ=1.1663787 10^{-5} GeV^{-2}, α=1/137.035999074 (PDG)
  - M_Z = 91.1875 ± 0.0021 GeV (LEP)
  - m_h=(125.6±0.3) GeV (naïve average of Atlas & CMS)
  - $\alpha_s(M_Z^2)$=0.1184±0.0006 (PDG excluding EW)
  - $\Delta\alpha^5_{had}(M_z^2)$ = 0.02750±0.00033 (Burkhardt & Pietrzyk; see also Davier et al, Hagiwara et al, Jegerlehner)
  - m_t = 173.2 ± 0.9 GeV (TeVatron average; LHC has 173.3 ± 1.4 GeV)

THEORETICAL STATUS II

- Radiative corrections induce deviations from tree-level relations:
  - $M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}(1+\Delta r)}\right)$
  - $g_A^f = \sqrt{\rho_Z^f}\, I_3^f$
  - $g_V^f = \sqrt{\rho_Z^f}\,(I_3^f - 2Q_f \kappa_Z^f \sin^2\theta_W)$

  where $\sin^2\theta_W = 1 - M_W^2/M_Z^2$.
- Define $\sin^2\theta_{eff}^f = \mathrm{Re}(\kappa_Z^f)\,\sin^2\theta_W$

THEORETICAL STATUS III

- EWPO computable from $\rho_Z{}^f$ and $\kappa_Z{}^f$, plus additional QED/QCD corrections (radiators, FSI):

$$\mathcal{A}_f = \frac{2\,\mathrm{Re}\left(g_V^f/g_A^f\right)}{1+\left[\mathrm{Re}\left(g_V^f/g_A^f\right)\right]^2}$$

$$A_{\mathrm{LR}}^0 = \mathcal{A}_e\,,\qquad A_{\mathrm{FB}}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f\,,\qquad P_\tau^{\mathrm{pol}} = \mathcal{A}_\tau\,.$$

$$\Gamma_\ell = \Gamma_0|\rho_Z^f|\sqrt{1-\frac{4m_\ell^2}{M_Z^2}}\left[\left(1+\frac{2m_\ell^2}{M_Z^2}\right)\left(\left|\frac{g_V^\ell}{g_A^\ell}\right|^2+1\right)-\frac{6m_\ell^2}{M_Z^2}\right]\left(1+\frac{3}{4}\frac{\alpha(M_Z^2)}{\pi}Q_\ell^2\right)$$

$$\Gamma_q = N_c\Gamma_0|\rho_Z^q|\left[\left|\frac{g_V^q}{g_A^q}\right|^2 R_V^q(M_Z^2)+R_A^q(M_Z^2)\right]+\Delta_{\mathrm{EW/QCD}}$$

$$R_\ell^0 = \frac{\Gamma_h}{\Gamma_\ell}\,,R_q^0 = \frac{\Gamma_q}{\Gamma_h}\,,\sigma_h^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_h}{\Gamma_Z^2}$$

LEPEWWG;ZFITTER;Chetyrkin et al;Baikov et al;Czarknecki&Kuhn;Harlander et al.Bardin et al

THEORETICAL STATUS IV

- Available calculations:
  - Δr: numerical expression including $O(\alpha)$, $O(\alpha\alpha_s)$, $O(G_\mu \alpha_s^2 m_t^2(1+m_t^2/M_Z^2+m_t^4/M_Z^4)$, $O(\alpha^2)$, $O(G_\mu^2 \alpha_s m_t^4)$, $O(G_\mu^3 m_t^6)$; th. err.<4 MeV (neglected)
  - κ_Z^f: numerical expression including $O(\alpha^2)$, $O(G_\mu^2 \alpha_s m_t^4)$, $O(G_\mu^3 m_t^6)$ (bosonic 2-loop missing for b); th. err.<2 10^{-4} (neglected)

Sirlin;Marciano&Sirlin;Djouadi&Verzegnassi;Djouadi;Kniehl;Halzen&Kniehl;Kniehl&Sirlin;Djouadi&Gambino; Avdeev et al.;Chetyrkin et al.;Barbieri et al.;Fleischer et al.;Degrassi et al.;Freitas et al.;Awramik&Czakon; Onishchenko&Veretin;Van der Biji et al.;Faisst et al.;Awramik et al.

A PROBLEM WITH R_b^0

- A problem with ρ_Z^f:
  - complete two-loop corrections still missing;
  - two-loop fermionic corrections to $R_b^0=\Gamma_b/\Gamma_h$ recently computed by Freitas & Huang;
  - result much larger than expected: 0.21576 $\rightarrow$ 0.21493 (comparable to 1-loop!)
  - results only available for Γ_u/Γ_b and Γ_d/Γ_b, not enough to extract all ρ_Z^f
  - independent computation of all ρ_Z^f needed!!!

- Cannot use Γ_u/Γ_b and Γ_d/Γ_b from Freitas & Huang and "old" formulae for all other ρ_Z^f-related observables (R_l^0, Γ_Z, σ_{had}^0)! See e.g. Gfitter...
- expect large two-loop corrections to all $\rho_Z^f \rightarrow$ add additional large th uncertainty.
- Two fit options:
  - "Old R_b": use $O(\alpha^2 m_t^4/M_W^4)$ & $O(\alpha^2 m_t^2/M_W^2)$
  - "New R_b": use Freitas & Huang plus $\Delta\rho_Z^{b,l,\nu}$ to account for possibly large unknown 2-loop fermionic corrections, with $|\Delta\rho_Z^{b,l,\nu}|<5\ 10^{-3}$

THEORETICAL STATUS V

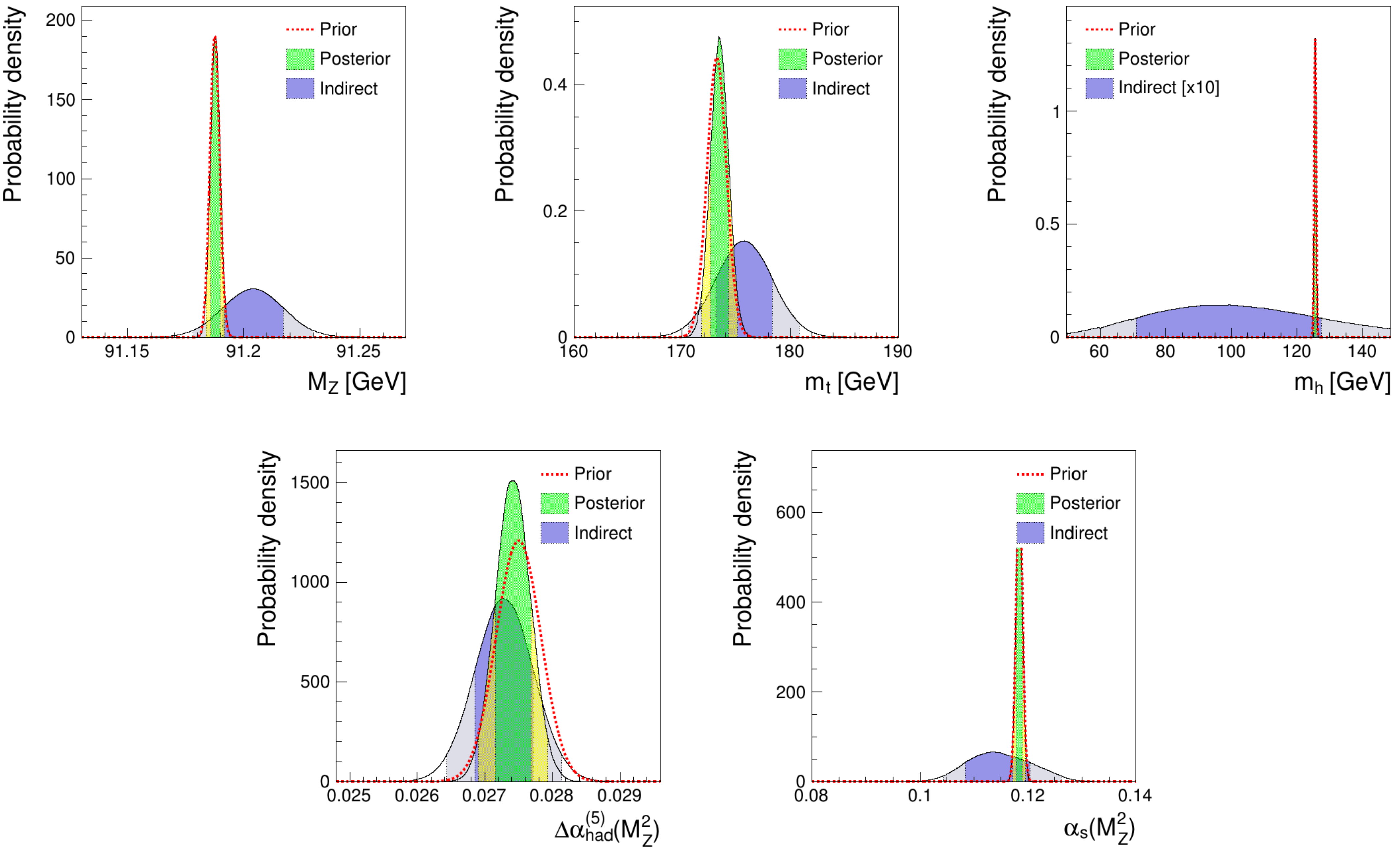
- Numerical implementation:
  - Bayesian analysis (exp likelihood used as prior for all input parameters)
  - MCMC implemented using BAT
  - All expressions coded from scratch and validated against ZFITTER (thanks to the ZFITTER coll.!)
  - Part of "SusyFit" HEP model fitting project
  - Official release of the code to appear soon

See GFitter and Erler for other recent analyses

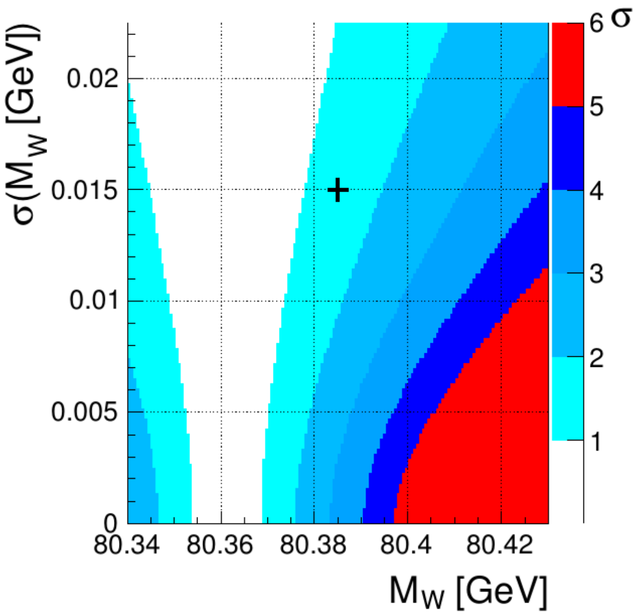
SM FIT RESULTS - "new R_b"

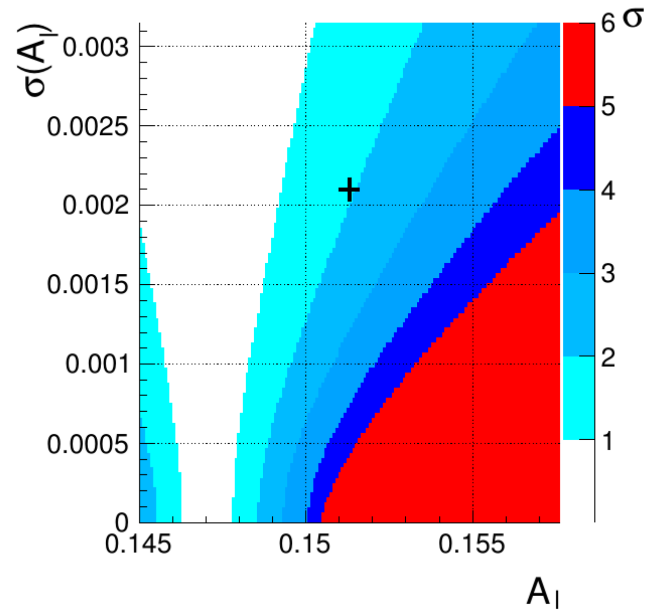
		Data	Fit	Indirect	Pull
	$\alpha_s(M_Z^2)$	0.1184 ± 0.0006	0.1184 ± 0.0006	0.1144 ± 0.0060	$-0.6\,\sigma$
	$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	0.02742 ± 0.00026	0.02728 ± 0.00043	$-0.4\,\sigma$
LEP	M_Z [GeV]	91.1875 ± 0.0021	91.1877 ± 0.0021	91.1998 ± 0.0126	$+1.0\,\sigma$
TeVatron	m_t [GeV]	173.2 ± 0.9	173.5 ± 0.8	175.6 ± 2.6	$+0.9\,\sigma$
LHC	m_h [GeV]	125.6 ± 0.3	125.6 ± 0.3	99.5 ± 28.5	$-0.8\,\sigma$
	$\delta\rho_Z^\nu$	—	-0.0035 ± 0.0015	—	—
	$\delta\rho_Z^\ell$	—	0.0002 ± 0.0009	—	—
	$\delta\rho_Z^b$	—	-0.0024 ± 0.0011	—	—
TeVatron	M_W [GeV]	80.385 ± 0.015	80.366 ± 0.007	80.361 ± 0.007	$-1.4\,\sigma$
LEPII TeV	Γ_W [GeV]	2.085 ± 0.042	2.0890 ± 0.0006	2.0890 ± 0.0006	$+0.1\,\sigma$
LEP	Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0021	2.4979 ± 0.0035	$+0.5\,\sigma$
LEP	σ_h^0 [nb]	41.540 ± 0.037	41.518 ± 0.028	41.445 ± 0.073	$-1.2\,\sigma$
LEP	$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23145 ± 0.00009	0.23145 ± 0.00009	$-0.8\,\sigma$
LEP	$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1476 ± 0.0007	0.1476 ± 0.0007	$+0.3\,\sigma$
SLD	$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1476 ± 0.0007	0.1470 ± 0.0008	$-1.9\,\sigma$
SLD	$\mathcal{A}_c$	0.670 ± 0.027	0.6681 ± 0.0003	0.6681 ± 0.0003	$-0.1\,\sigma$
SLD	$\mathcal{A}_b$	0.923 ± 0.020	0.93466 ± 0.00006	0.93466 ± 0.00006	$+0.6\,\sigma$
LEP	$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0163 ± 0.0002	0.0163 ± 0.0002	$-0.8\,\sigma$
LEP	$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.0739 ± 0.0004	0.0740 ± 0.0004	$+0.9\,\sigma$
LEP	$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.1034 ± 0.0005	0.1038 ± 0.0005	$+2.7\,\sigma$
LEP	R_ℓ^0	20.767 ± 0.025	20.755 ± 0.020	20.713 ± 0.043	$-1.1\,\sigma$
LEP SLD	R_c^0	0.1721 ± 0.0030	0.17243 ± 0.00002	0.17243 ± 0.00002	$+0.1\,\sigma$
LEP SLD	R_b^0	0.21629 ± 0.00066	0.21498 ± 0.00003	0.21498 ± 0.00003	$-2.0\,\sigma$

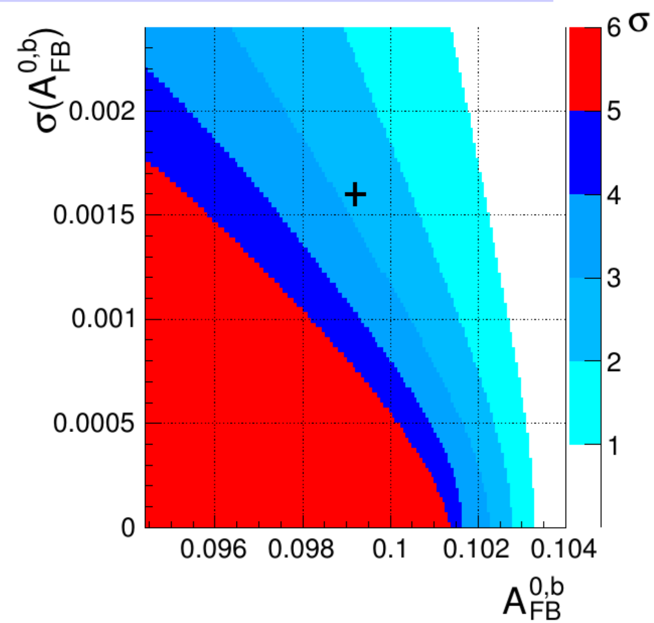
SM PARAMETERS



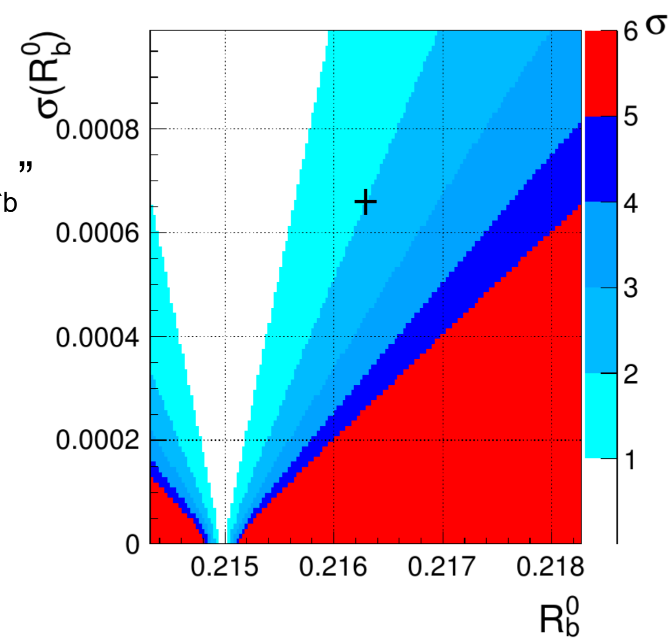
COMPATIBILITY PLOTS

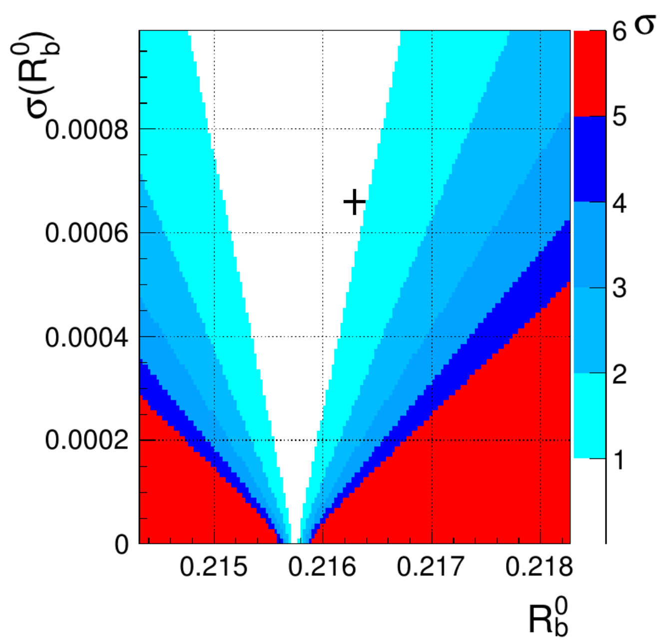






"New R_b"





"Old R_b"

PREDICTIONS

	Prediction	α_s	$\Delta\alpha_{\rm had}^{(5)}$	M_Z	m_t
M_W [GeV]	80.3625 ± 0.0085	± 0.0004	± 0.0060	± 0.0026	± 0.0054
Γ_W [GeV]	2.0888 ± 0.0007	± 0.0002	± 0.0005	± 0.0002	± 0.0004
Γ_Z [GeV]	2.5014 ± 0.0060 *	± 0.0004	± 0.0003	± 0.0001	± 0.0002
σ_h^0 [nb]	41.425 ± 0.123 *	± 0.004	± 0.000	± 0.001	± 0.000
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.23149 ± 0.00012	± 0.00000	± 0.00012	± 0.00001	± 0.00003
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.14725 ± 0.00094	± 0.00002	± 0.00091	± 0.00012	± 0.00022
$\mathcal{A}_c$	0.6680 ± 0.0004	± 0.0000	± 0.0004	± 0.0001	± 0.0001
$\mathcal{A}_b$	0.9346 ± 0.0001	± 0.0000	± 0.0001	± 0.0000	± 0.0000
$A_{\rm FB}^{0,\ell}$	0.01626 ± 0.00021	± 0.00000	± 0.00020	± 0.00003	± 0.00005
$A_{\rm FB}^{0,c}$	0.07377 ± 0.00052	± 0.00001	± 0.00050	± 0.00006	± 0.00012
$A_{\rm FB}^{0,b}$	0.10322 ± 0.00067	± 0.00001	± 0.00064	± 0.00008	± 0.00016
R_ℓ^0	20.808 ± 0.090 *	± 0.004	± 0.002	± 0.001	± 0.000
R_c^0	0.17242 ± 0.00002	± 0.00001	± 0.00001	± 0.00000	± 0.00001
R_b^0	0.214991 ± 0.000036	± 0.000009	± 0.000004	± 0.000001	± 0.000035

* completely dominated by unknown corrections to ρ_Z^f!

SM FIT - OLD R_b

	Data	Fit	Prediction	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1184 ± 0.0006	0.1184 ± 0.0006	–	0.1193 ± 0.0027	$+0.3\,\sigma$
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	0.02741 ± 0.00026	–	0.02725 ± 0.00043	$-0.5\,\sigma$
M_Z [GeV]	91.1875 ± 0.0021	91.1878 ± 0.0020	–	91.1968 ± 0.0118	$+0.8\,\sigma$
m_t [GeV]	173.2 ± 0.9	173.5 ± 0.8	–	176.3 ± 2.5	$+1.1\,\sigma$
m_h [GeV]	125.6 ± 0.3	125.6 ± 0.3	–	97.9 ± 27.6	$-0.8\,\sigma$
M_W [GeV]	80.385 ± 0.015	80.367 ± 0.006	80.363 ± 0.008	80.362 ± 0.007	$-1.4\,\sigma$
Γ_W [GeV]	2.085 ± 0.042	2.0891 ± 0.0006	2.0888 ± 0.0007	2.0891 ± 0.0006	$+0.1\,\sigma$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4953 ± 0.0004	2.4951 ± 0.0005	2.4953 ± 0.0004	$+0.0\,\sigma$
σ_h^0 [nb]	41.540 ± 0.037	41.484 ± 0.004	41.484 ± 0.004	41.484 ± 0.004	$-1.5\,\sigma$
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23145 ± 0.00009	0.23149 ± 0.00012	0.23144 ± 0.00009	$-0.8\,\sigma$
$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1476 ± 0.0007	0.1472 ± 0.0009	0.1477 ± 0.0007	$+0.4\,\sigma$
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1476 ± 0.0007	0.1472 ± 0.0009	0.1471 ± 0.0008	$-1.9\,\sigma$
$\mathcal{A}_c$	0.670 ± 0.027	0.6682 ± 0.0003	0.6680 ± 0.0004	0.6682 ± 0.0003	$-0.1\,\sigma$
$\mathcal{A}_b$	0.923 ± 0.020	0.9347 ± 0.0001	0.9346 ± 0.0001	0.9347 ± 0.0001	$+0.6\,\sigma$
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0163 ± 0.0002	0.0163 ± 0.0002	0.0163 ± 0.0002	$-0.8\,\sigma$
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.0740 ± 0.0004	0.0738 ± 0.0005	0.0740 ± 0.0004	$+0.9\,\sigma$
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.1035 ± 0.0005	0.1032 ± 0.0007	0.1039 ± 0.0005	$+2.8\,\sigma$
R_ℓ^0	20.767 ± 0.025	20.735 ± 0.004	20.734 ± 0.004	20.734 ± 0.004	$-1.3\,\sigma$
R_c^0	0.1721 ± 0.0030	0.17223 ± 0.00002	0.17222 ± 0.00002	0.17223 ± 0.00002	$+0.0\,\sigma$
R_b^0	0.21629 ± 0.00066	0.21575 ± 0.00003	0.21576 ± 0.00003	0.21575 ± 0.00003	$-0.8\,\sigma$

EWPO BEYOND THE SM

- Consider several NP scenarios:
  - Oblique: NP contributes mainly to gauge-boson self-energies;
  - Modified Zbb couplings;
  - Non-standard (composite) Higgs: modified Higgs couplings
  - Effective Lagrangian for EWPO: generic NP contributions to EWPO from dim. 6 op.'s

See also parallel talks by de Blas and Rosell

OBLIQUE NP

- Assume that NP mainly contributes to gauge boson self-energies:

$$S = -16\pi\Pi'_{30}(0) = 16\pi\left[\Pi^{\mathrm{NP}\prime}_{33}(0) - \Pi^{\mathrm{NP}\prime}_{3Q}(0)\right],$$

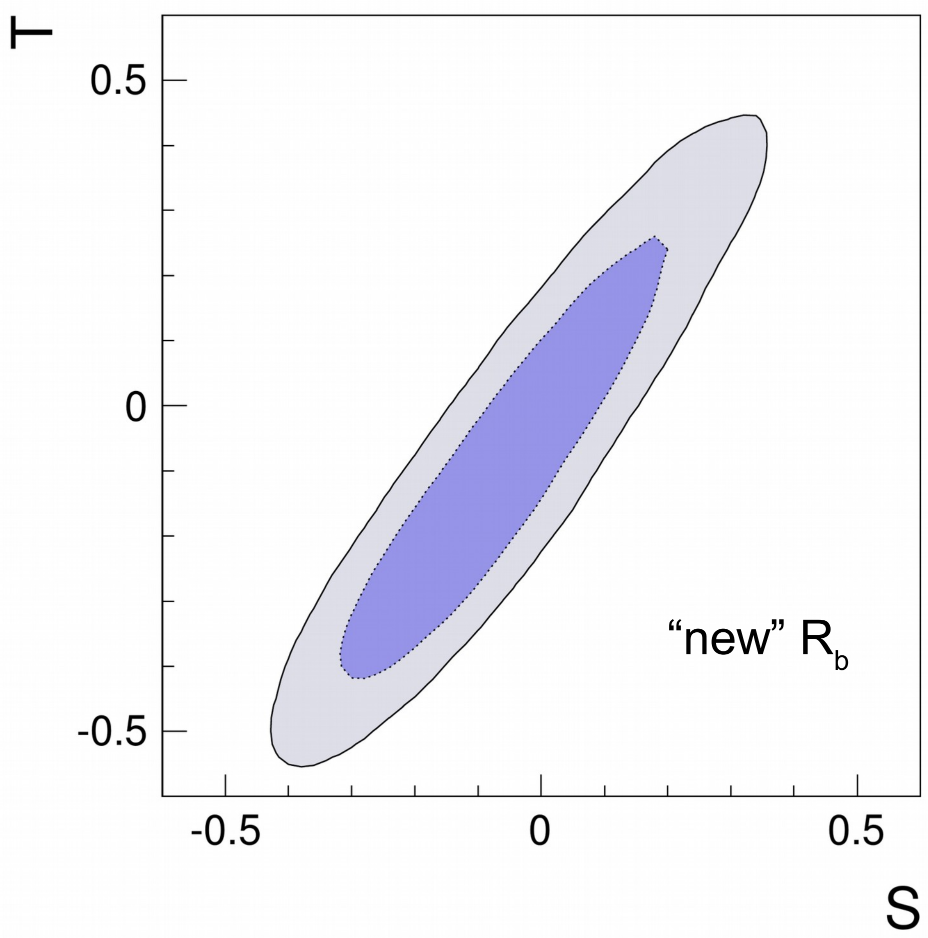
$$T = \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi^{\mathrm{NP}}_{11}(0) - \Pi^{\mathrm{NP}}_{33}(0)\right],$$

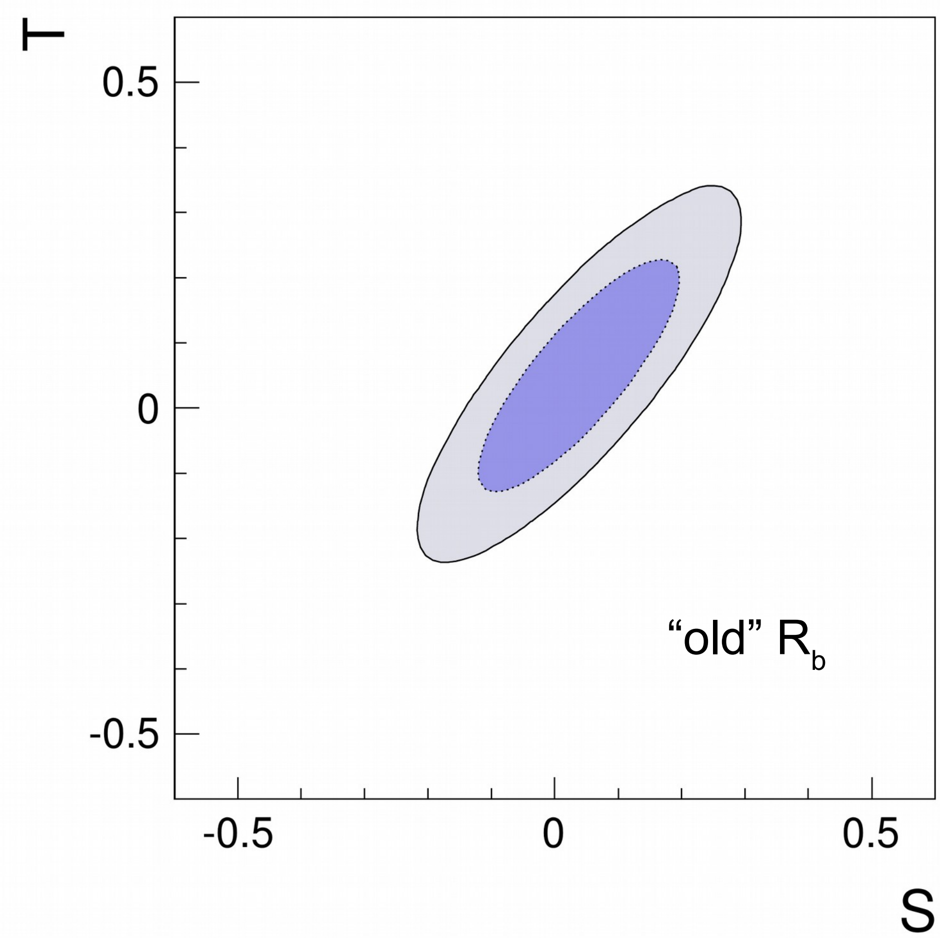
$$U = 16\pi\left[\Pi^{\mathrm{NP}\prime}_{11}(0) - \Pi^{\mathrm{NP}\prime}_{33}(0)\right],$$

- fit for SM parameters + S, T, U

Kennedy&Lynn;Kennedy et al.;Peskin&Takeuchi;Maksymyk et al.;Burgess et al.;Altarelli et al.

CONSTRAINTS ON S,T,U

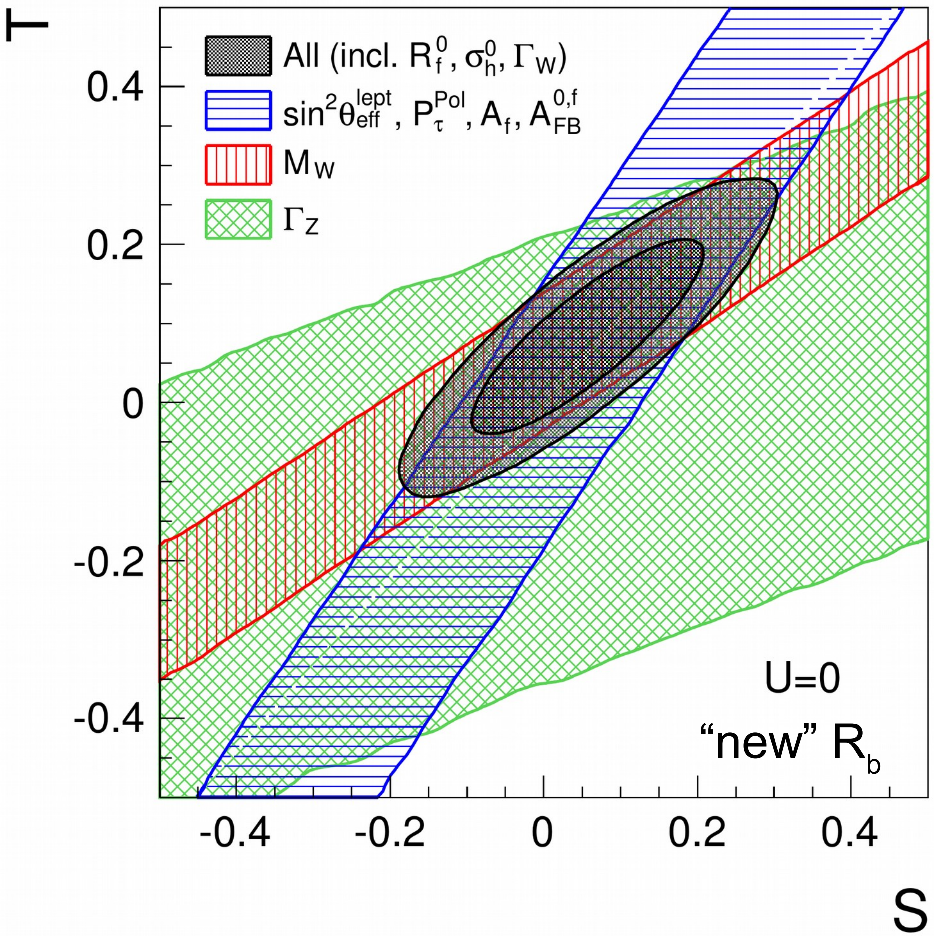


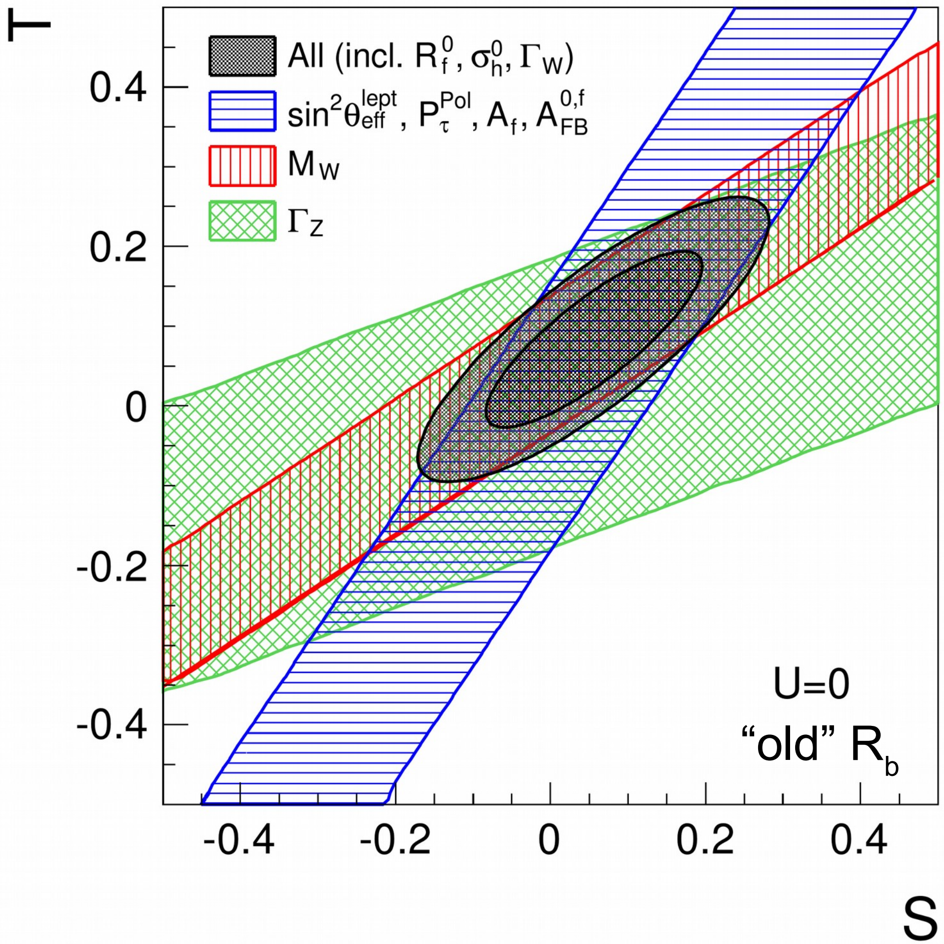


For U≠0, the uncertainty on ρ_Z^f has a very large impact, due to Γ_Z

See also Gfitter, Erler, ...

CONSTRAINTS ON S,T FOR U=0





$S = 0.05 \pm 0.10$, $T = 0.08 \pm 0.08$
corr. 0.88

$S = 0.06 \pm 0.09$, $T = 0.08 \pm 0.07$
corr. 0.86

See also Gfitter, Erler, ...

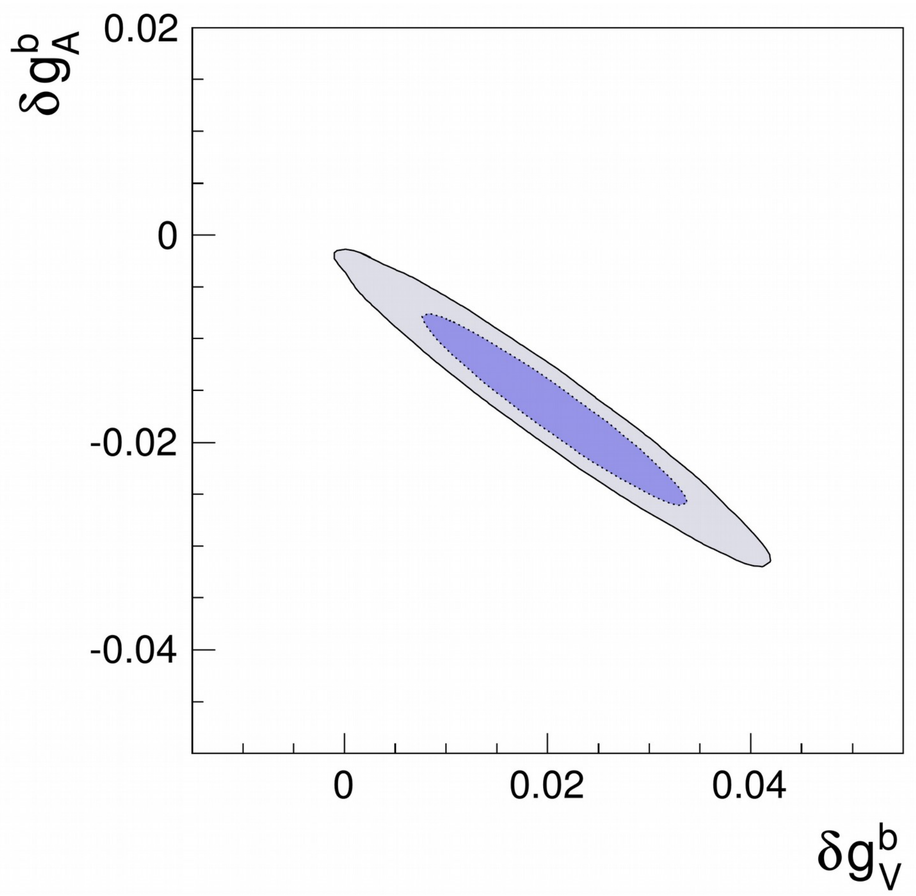
MODIFIED Zbb COUPLINGS

- Long-standing pull in $A_{FB}^{0,b}$ and (if confirmed) more recent one in R_b^0 may be due to NP in Zbb vertex
- NP may couple mainly to the third generation
- Parameterize possible NP contributions as

$$g_V^b = (g_V^b)_{\rm SM} + \delta g_V^b \,, \qquad g_A^b = (g_A^b)_{\rm SM} + \delta g_A^b$$

Bamert et al.;Haber&Logan;Choudhury et al.;Kumar et al.;Batell, Gori & Wang;...

CONSTRAINTS ON δg_V^b, δg_A^b



- $\delta g_A^b = -0.017 \pm 0.006$,

  $\delta g_V^b = 0.021 \pm 0.009$
- $\delta g_L^b = 0.002 \pm 0.001$,

  $\delta g_R^b = 0.019 \pm 0.007$
- Tensions in $A_{FB}^{0,b}$ and in R_b^0 solved

THE NATURE OF THE HIGGS

- Consider an extension of the SM in which:
  - the only new light state below the cutoff is the Higgs boson
  - there is a custodial symmetry
  - there is no new source of flavour violation

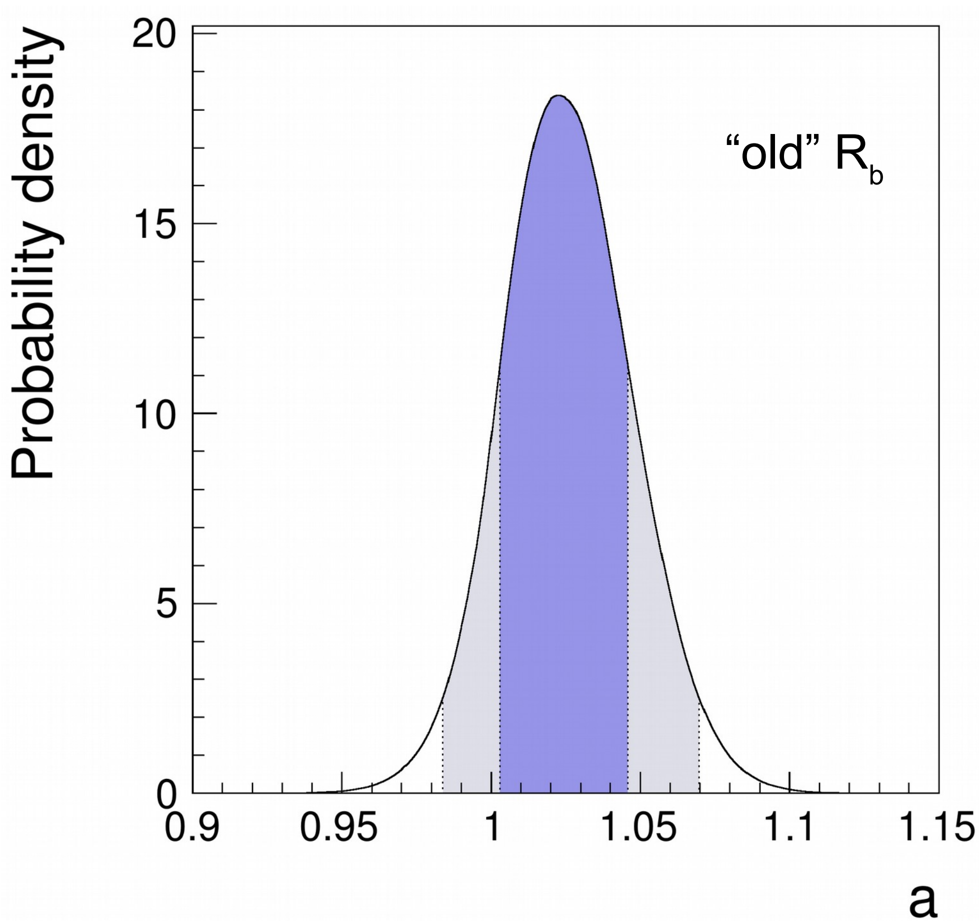
Giudice et al;Contino et al;Azatov et al;Contino et al

- the main effect in EWPO is due to a possibly modified Higgs coupling a to vectors (GB's):

$$S = \frac{1}{12\pi}(1-a^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right), \quad T = -\frac{3}{16\pi c_W^2}(1-a^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right),$$

$$\Lambda = 4\pi v/\sqrt{|1-a^2|}$$

CONSTRAINTS ON a AND Λ



See also Falkowski,Riva&Urbano; Contino et al.;Pich et al

- $a = 1.02 \pm 0.02$
- $a \in [0.98, 1.07]$@95%
- Composite Higgs models typically generate $a < 1$

Falkowski,Rychkov&Urbano

- for $a < 1$, $\Lambda > 15$ TeV
- need additional light states to fix EW fit!

Barbieri et al

EWPO AND THE SCALE OF NP

- Consider the most general set of D=6 op.'s relevant for EWPO:

Buchmuller&Wyler;Grzadkowski et al;Aguilar-Saavedra;del Aguila et al;Barbieri & Strumia; del Aguila &de Blas; Contino et al

Dimension 6 operators			Effects on precision observables		
$\mathcal{O}_{WB}$	$=$	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	$\delta e_3 = 2/\tan\theta_{\rm W}$		
$\mathcal{O}_H$	$=$	$\|H^\dagger D_\mu H\|^2$	$\delta e_1 = -1$		
$\mathcal{O}_{LL}$	$=$	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	$\delta G_{\rm VB} = 2$		
$\mathcal{O}'_{HL}$	$=$	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	$\delta g_{Ve} = \delta g_{Ae} = -1$	$\delta g_{V\nu} = \delta g_{A\nu} = +1,$	$\delta G_{\rm VB} = 4$
$\mathcal{O}'_{HQ}$	$=$	$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	$\delta g_{Vd} = \delta g_{Ad} = -1$	$\delta g_{Vu} = \delta g_{Au} = +1$	
$\mathcal{O}_{HL}$	$=$	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	$\delta g_{Ve} = \delta g_{Ae} = -1$	$\delta g_{V\nu} = \delta g_{A\nu} = -1$	
$\mathcal{O}_{HQ}$	$=$	$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	$\delta g_{Vd} = \delta g_{Ad} = -1$	$\delta g_{Vu} = \delta g_{Au} = -1$	
$\mathcal{O}_{HE}$	$=$	$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	$\delta g_{Ve} = -\delta g_{Ae} = -1$		
$\mathcal{O}_{HU}$	$=$	$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	$\delta g_{Vu} = -\delta g_{Au} = -1$		
$\mathcal{O}_{HD}$	$=$	$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	$\delta g_{Vd} = -\delta g_{Ad} = -1$		

Table 2: *Dimensions 6 operators affecting the electroweak precision tests, with their contributions, up to a common factor $c_i(v/\Lambda)^2$, to the various form factors. The effect of the hermitian conjugate to the operators from $\mathcal{O}'_{HL}$ to $\mathcal{O}_{HD}$ is included.*

Barbieri & Strumia

- Switch on one operator at a time and get a bound on c_i for fixed Λ (or on Λ for fixed c_i)

EWPO AND THE SCALE OF NP

Operator	c_i with $\Lambda = 1$ TeV	Λ [TeV] at 68% $c_i = +1$	Λ [TeV] at 68% $c_i = -1$	Λ [TeV] at 95% $c_i = +1$	Λ [TeV] at 95% $c_i = -1$
$\mathcal{O}_{WB}$	$(-2.7 \pm 3.5) \times 10^{-3}$	34.9	12.7	15.4	10.2
$\mathcal{O}_{H}$	$(-1.2 \pm 0.9) \times 10^{-2}$	—	6.9	12.2	5.8
$\mathcal{O}_{LL}$	$(4.1 \pm 7.7) \times 10^{-3}$	9.2	16.6	7.2	9.5
$\mathcal{O}'_{HL}$	$(-3.4 \pm 4.3) \times 10^{-3}$	33.8	11.4	14.1	9.2
$\mathcal{O}'_{HQ}$	$(2.7 \pm 6.3) \times 10^{-3}$	10.6	16.7	8.2	10.1
$\mathcal{O}_{HL}$	$(1.7 \pm 4.2) \times 10^{-3}$	13.0	19.9	10.0	12.3
$\mathcal{O}_{HQ}$	$(1.1 \pm 1.7) \times 10^{-2}$	5.9	12.9	4.7	6.6
$\mathcal{O}_{HE}$	$(-3.0 \pm 5.6) \times 10^{-3}$	19.3	10.8	11.1	8.4
$\mathcal{O}_{HU}$	$(1.3 \pm 3.8) \times 10^{-2}$	4.5	6.3	3.4	4.0
$\mathcal{O}_{HD}$	$(-5.3 \pm 5.1) \times 10^{-2}$	—	3.1	4.6	2.6

- NP scale for c_i=1 beyond the LHC reach, while TeV NP possible if perturbative

"old" R_b

CONCLUSIONS

- Indirect searches for NP as relevant as ever after the LHC 7-8 TeV run
- m_h completes the set of SM parameters
- Need more theoretical progress on fermionic two-loop contributions to ρ_Z^f
- Overall consistency of the SM fit is very good

CONCLUSIONS II

- EWPO very effective in constraining EW-related NP:
  - Updated constraints on oblique NP
  - Updated constraints on modified Zbb
  - Composite Higgs models disfavoured unless additional light (fermionic) states present
  - Generic nonperturbative NP scale beyond the LHC reach

OUTLOOK

- Order-of-magnitude experimental progress (and theoretical improvements) in the EW fit would allow us to
  - constrain the Lagrangian of any NP directly seen at next LHC run or
  - indirectly probe scales up to 100 TeV
- Strong motivation for TLEP!

BACKUP SLIDES

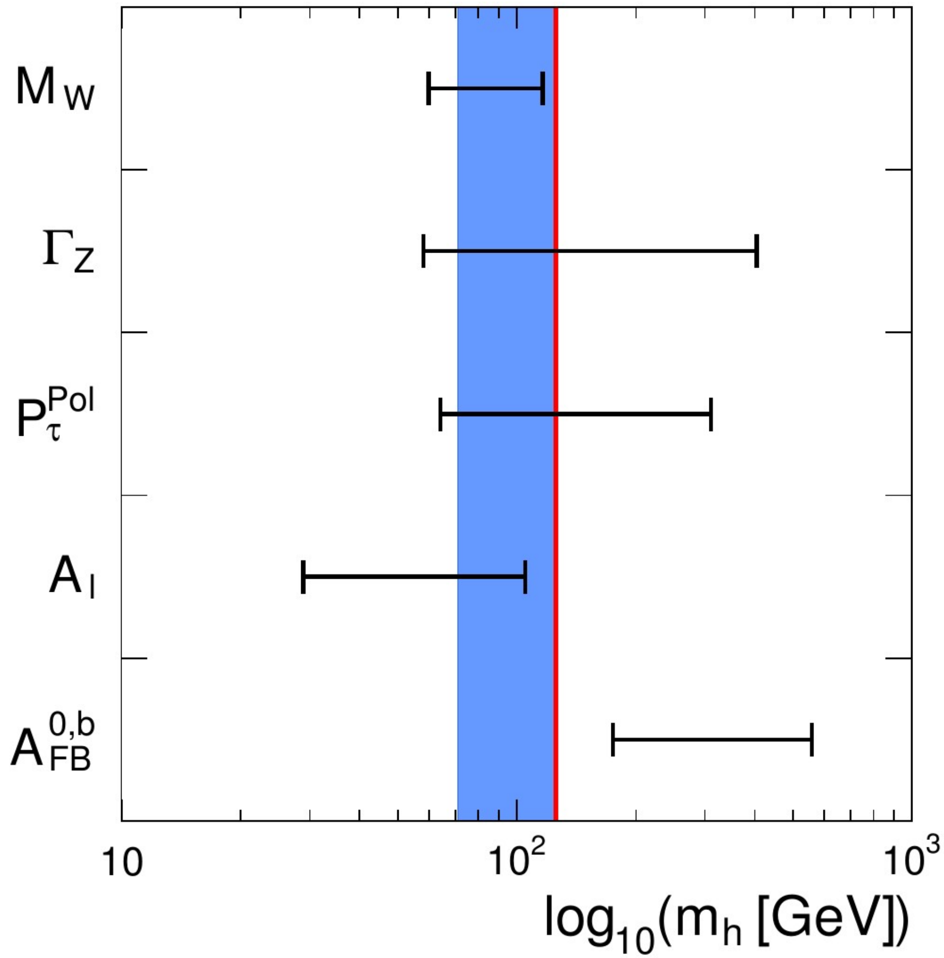
CORRELATION MATRIX FOR SM

Parameter	α_s	$\Delta\alpha^{(5)}_{\mathrm{had}}$	M_Z	m_t	m_h	$\delta\rho^{\nu}_Z$	$\delta\rho^{\ell}_Z$	$\delta\rho^{b}_Z$
α_s	1.00							
$\Delta\alpha^{(5)}_{\mathrm{had}}$	−0.01	1.00						
M_Z	0.00	0.08	1.00					
m_t	0.01	0.18	−0.05	1.00				
m_h	0.00	−0.01	0.00	0.00	1.00			
$\delta\rho^{\nu}_Z$	0.00	−0.01	−0.05	−0.02	0.00	1.00		
$\delta\rho^{\ell}_Z$	0.00	0.02	−0.11	−0.07	0.00	0.49	1.00	
$\delta\rho^{b}_Z$	−0.18	0.10	−0.03	−0.06	0.00	−0.28	0.38	1.00

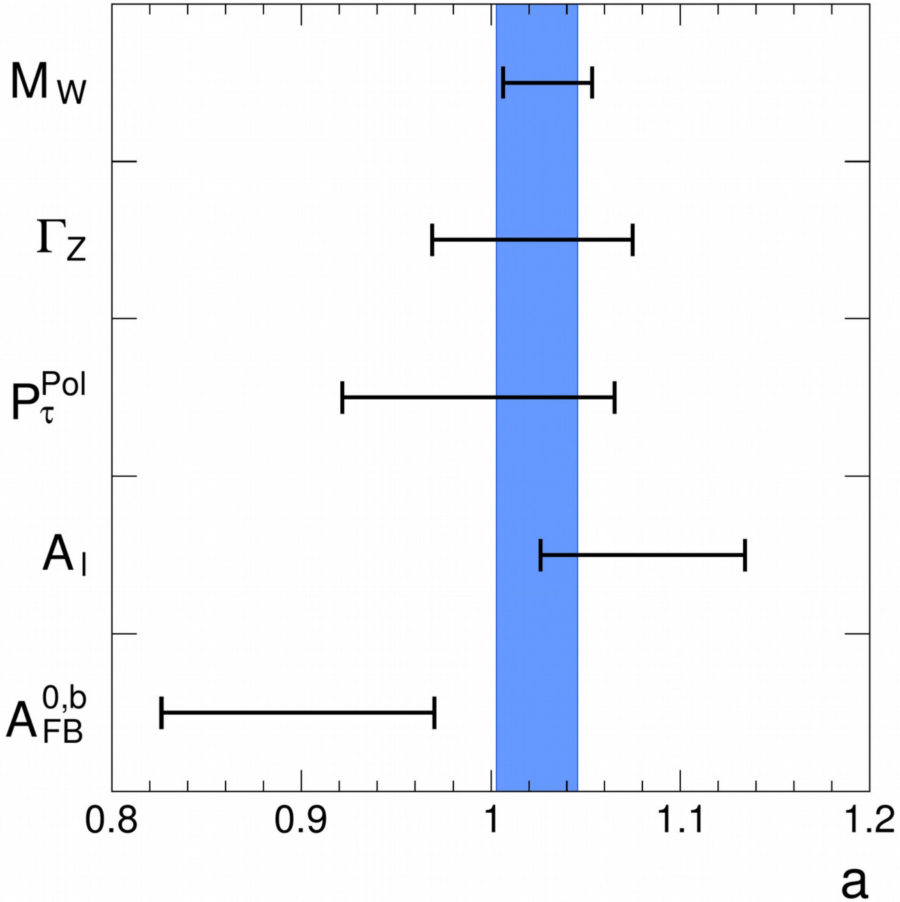
PREDICTIONS FOR "old R_b"

	Prediction	α_s	$\Delta\alpha^{(5)}_{\rm had}$	M_Z	m_t
M_W [GeV]	80.3625 ± 0.0085	± 0.0004	± 0.0060	± 0.0026	± 0.0054
Γ_W [GeV]	2.0889 ± 0.0007	± 0.0002	± 0.0005	± 0.0002	± 0.0004
Γ_Z [GeV]	2.4951 ± 0.0052	± 0.0003	± 0.0003	± 0.0002	± 0.0002
σ_h^0 [nb]	41.484 ± 0.004	± 0.003	± 0.000	± 0.002	± 0.001
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.23149 ± 0.00012	± 0.00000	± 0.00012	± 0.00001	± 0.00003
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.14725 ± 0.00094	± 0.00002	± 0.00091	± 0.00012	± 0.00022
$\mathcal{A}_c$	0.6680 ± 0.0004	± 0.0000	± 0.0004	± 0.0001	± 0.0001
$\mathcal{A}_b$	0.9346 ± 0.0001	± 0.0000	± 0.0001	± 0.0000	± 0.0000
$A_{\rm FB}^{0,\ell}$	0.01626 ± 0.00021	± 0.00000	± 0.00020	± 0.00003	± 0.00005
$A_{\rm FB}^{0,c}$	0.07377 ± 0.00052	± 0.00001	± 0.00050	± 0.00006	± 0.00012
$A_{\rm FB}^{0,b}$	0.10322 ± 0.00067	± 0.00001	± 0.00064	± 0.00008	± 0.00016
R_ℓ^0	20.734 ± 0.044	± 0.004	± 0.002	± 0.000	± 0.000
R_c^0	0.17222 ± 0.00002	± 0.00001	± 0.00001	± 0.00000	± 0.00001
R_b^0	0.215762 ± 0.000033	± 0.000002	± 0.000004	± 0.000007	± 0.000032

INDIRECT HIGGS MASS

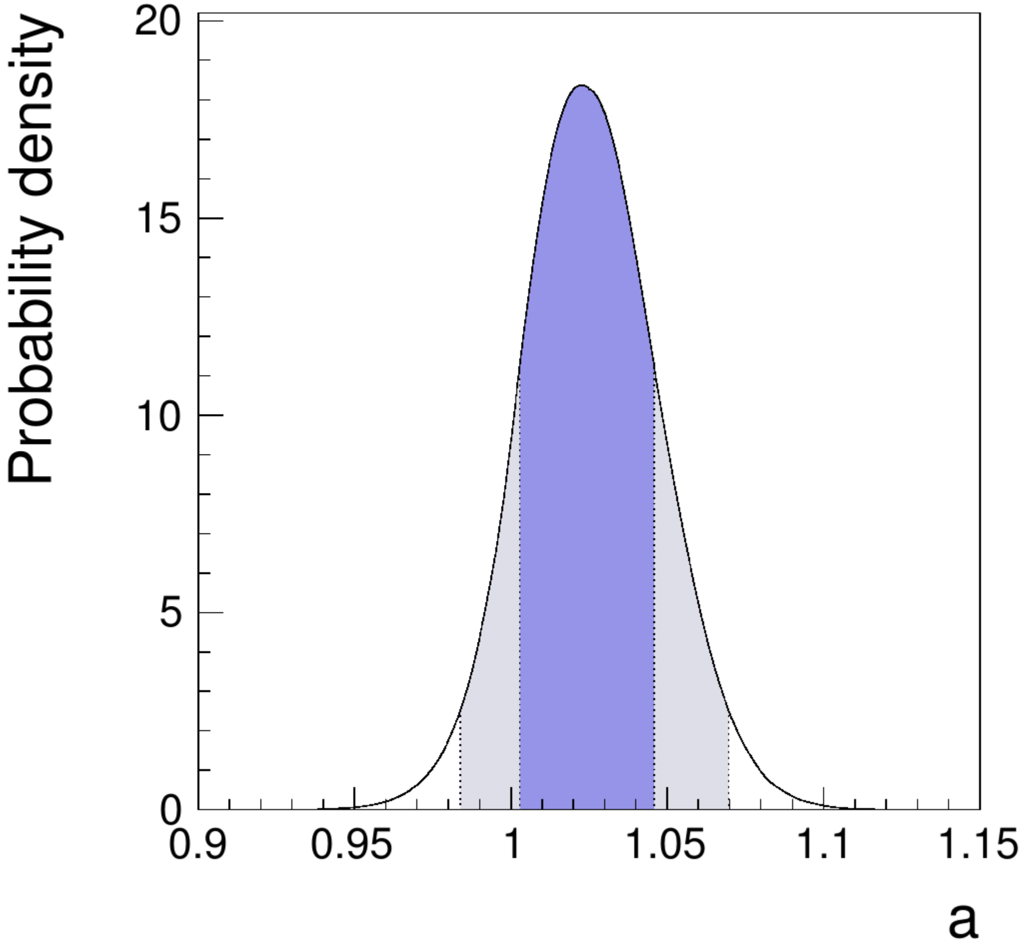


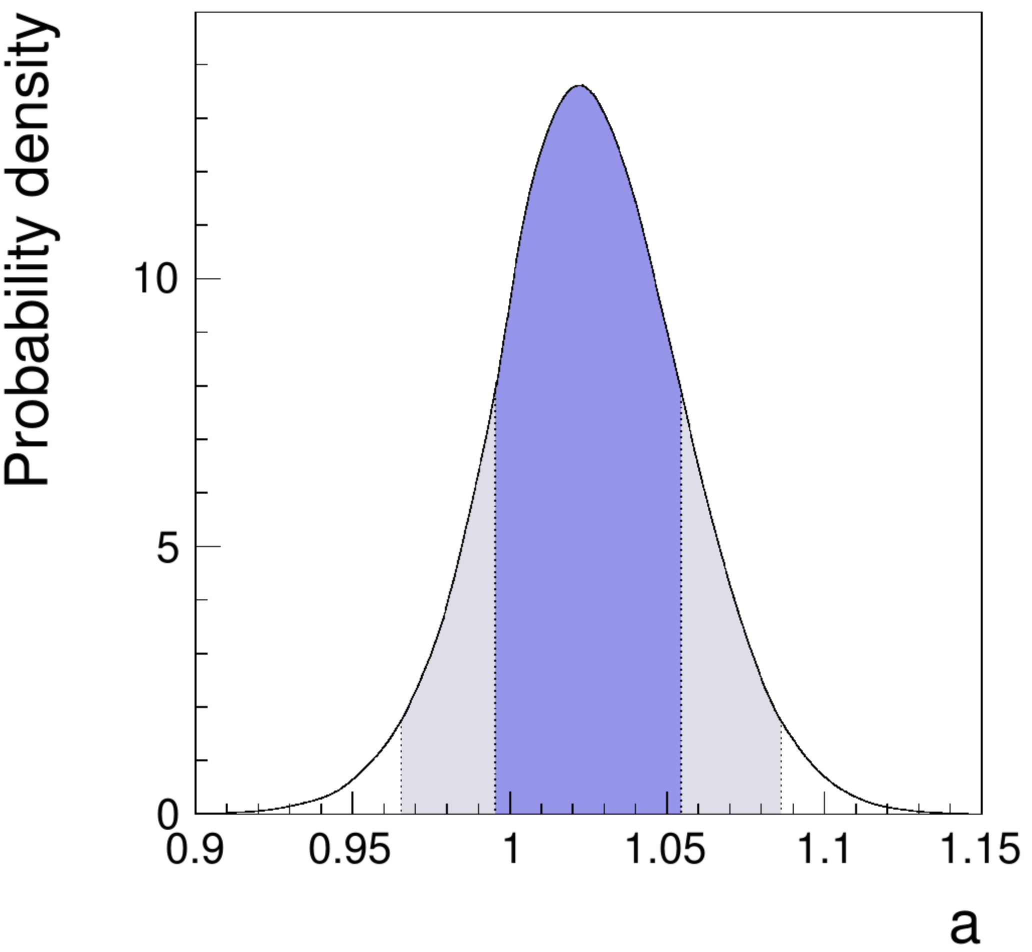
WHAT CONSTRAINS a?



- Apply one of the constraints M_W, Γ_Z, P_τ^{Pol}, A_l and $A_{FB}^{0,b}$ at a time, and compare with the full fit (blue band)

STABILITY OF a VS m_t





$m_t = 173.2 \pm 0.9$ $\quad a \in [0.98, 1.07]$

$m_t = 173.3 \pm 2.8$ $\quad a \in [0.97, 1.09]$

$$
\begin{aligned}
M_{W,\mathrm{NP}} &= -\frac{\alpha(M_Z^2)\, c_W\, M_Z}{4(c_W^2 - s_W^2)} \left(S - 2\, c_W^2\, T - \frac{(c_W^2 - s_W^2)\, U}{2\, s_W^2} \right), \\
\Gamma_{W,\mathrm{NP}} &= -\frac{3\, \alpha^2(M_Z^2)\, c_W\, M_Z}{8\, s_W^2\, (c_W^2 - s_W^2)} \left(S - 2\, c_W^2\, T - \frac{(c_W^2 - s_W^2)\, U}{2\, s_W^2} \right), \\
\Gamma_{Z,\mathrm{NP}} &= \frac{\alpha^2(M_Z^2)\, M_Z}{72\, c_W^2 s_W^2\, (c_W^2 - s_W^2)} \left[-10(3 - 8\, s_W^2)\, S + (63 - 126\, s_W^2 - 40\, s_W^4)\, T \right], \\
\sigma^0_{h,\mathrm{NP}} &= -\frac{72\pi\alpha(M_Z^2)\, (729 - 4788\, s_W^2 + 8352\, s_W^4 - 6176\, s_W^6 + 640\, s_W^8)}{M_Z^2\, (63 - 120\, s_W^2 + 160\, s_W^4)^3 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff,NP}} &= \frac{\alpha(M_Z^2)}{4(c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
P^{\mathrm{pol}}_{\tau,\mathrm{NP}} &= -\frac{4\, \alpha(M_Z^2)\, s_W^2}{(1 - 4\, s_W^2 + 8\, s_W^4)^2} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
\mathcal{A}_{\ell,\mathrm{NP}} &= -\frac{4\, \alpha(M_Z^2)\, s_W^2}{(1 - 4\, s_W^2 + 8\, s_W^4)^2} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
\mathcal{A}_{c,\mathrm{NP}} &= -\frac{48\, \alpha(M_Z^2)\, s_W^2\, (3 - 4\, s_W^2)}{(9 - 24\, s_W^2 + 32\, s_W^4)^2 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
\mathcal{A}_{b,\mathrm{NP}} &= -\frac{12\, \alpha(M_Z^2)\, s_W^2\, (3 - 2\, s_W^2)}{(9 - 12\, s_W^2 + 8\, s_W^4)^2 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
A^{0,\ell}_{\mathrm{FB,NP}} &= -\frac{6\, \alpha(M_Z^2)\, s_W^2\, (1 - 4\, s_W^2)}{(1 - 4\, s_W^2 + 8\, s_W^4)^3} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
A^{0,c}_{\mathrm{FB,NP}} &= -\frac{9\, \alpha(M_Z^2)\, s_W^2\, (39 - 310\, s_W^2 + 992\, s_W^4 - 1600\, s_W^6 + 1024\, s_W^8)}{(1 - 4\, s_W^2 + 8\, s_W^4)^2 (9 - 24\, s_W^2 + 32\, s_W^4)^2 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
A^{0,b}_{\mathrm{FB,NP}} &= -\frac{18\, \alpha(M_Z^2)\, s_W^2\, (15 - 76\, s_W^2 + 152\, s_W^4 - 160\, s_W^6 + 64\, s_W^8)}{(1 - 4\, s_W^2 + 8\, s_W^4)^2 (9 - 12\, s_W^2 + 8\, s_W^4)^2 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
R^0_{\ell,\mathrm{NP}} &= \frac{8\, \alpha(M_Z^2)\, (3 - 2\, s_W^2)(1 - 5\, s_W^2)}{3(1 - 4\, s_W^2 + 8\, s_W^4)^2 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
R^0_{c,\mathrm{NP}} &= -\frac{9\, \alpha(M_Z^2)\, (9 - 36\, s_W^2 + 16\, s_W^4)}{(45 - 84\, s_W^2 + 88\, s_W^4)^2 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right), \\
R^0_{b,\mathrm{NP}} &= \frac{6\, \alpha(M_Z^2)\, (9 - 36\, s_W^2 + 16\, s_W^4)}{(45 - 84\, s_W^2 + 88\, s_W^4)^2 (c_W^2 - s_W^2)} \left(S - 4\, c_W^2 s_W^2\, T \right),
\end{aligned}
\tag{B.1}
$$

where s_W^2 and c_W^2 denote their SM values, and $c_W = \sqrt{c_W^2}$.

$$\sin^2\theta_{\rm eff}^{\rm lept} = \sin^2\theta_{\rm eff,SM}^{\rm lept} - \frac{1}{4}\,\delta\left(\frac{g_V^e}{g_A^e}\right),$$

$$\mathcal{A}_f = \mathcal{A}_{f,{\rm SM}} - \frac{2\left[(g_V^f)^2 - (g_A^f)^2\right]\,(g_A^f)^2}{G_f^2}\,\delta\left(\frac{g_V^f}{g_A^f}\right), \tag{355}$$

$$A_{\rm FB}^{0,f} = A_{\rm FB,SM}^{0,f} - \frac{3\,g_V^f\,g_A^f\left[(g_V^e)^2 - (g_A^e)^2\right]\,(g_A^e)^2}{G_f G_e^2}\delta\left(\frac{g_V^e}{g_A^e}\right) - \frac{3\,g_V^e\,g_A^e\left[(g_V^f)^2 - (g_A^f)^2\right]\,(g_A^f)^2}{G_e G_f^2}\delta\left(\frac{g_V^f}{g_A^f}\right), \tag{356}$$

$$\Gamma_Z = \Gamma_{Z,{\rm SM}} + \frac{\alpha(M_Z^2)M_Z}{12 s_W^2 c_W^2}\sum_f N_c^f\,\delta G_f\,, \tag{357}$$

$$\sigma_h^0 = \sigma_{h,{\rm SM}}^0 + \frac{12\pi}{M_Z^2}\frac{G_e\left(\sum_q N_c^q\,G_q\right)}{\left(\sum_f N_c^f\,G_f\right)^2}\left(\frac{\delta G_e}{G_e} + \frac{\sum_q \delta G_q}{\sum_q G_q} - \frac{2\sum_f N_c^f\,\delta G_f}{\sum_f N_c^f\,G_f}\right), \tag{358}$$

$$R_\ell^0 = R_{\ell,{\rm SM}}^0 + \frac{\sum_q N_c^q\,\delta G_q}{G_\ell} - \frac{\left(\sum_q N_c^q\,G_q\right)\delta G_\ell}{G_\ell^2}, \tag{359}$$

$$R_c^0 = R_{c,{\rm SM}}^0 + \frac{\delta G_c}{\sum_q G_q} - \frac{G_c\sum_q \delta G_q}{\left(\sum_q G_q\right)^2}, \tag{360}$$

$$R_b^0 = R_{b,{\rm SM}}^0 + \frac{\delta G_b}{\sum_q G_q} - \frac{G_b\sum_q \delta G_q}{\left(\sum_q G_q\right)^2}, \qquad G_f \equiv (g_V^f)^2 + (g_A^f)^2, \tag{361}$$

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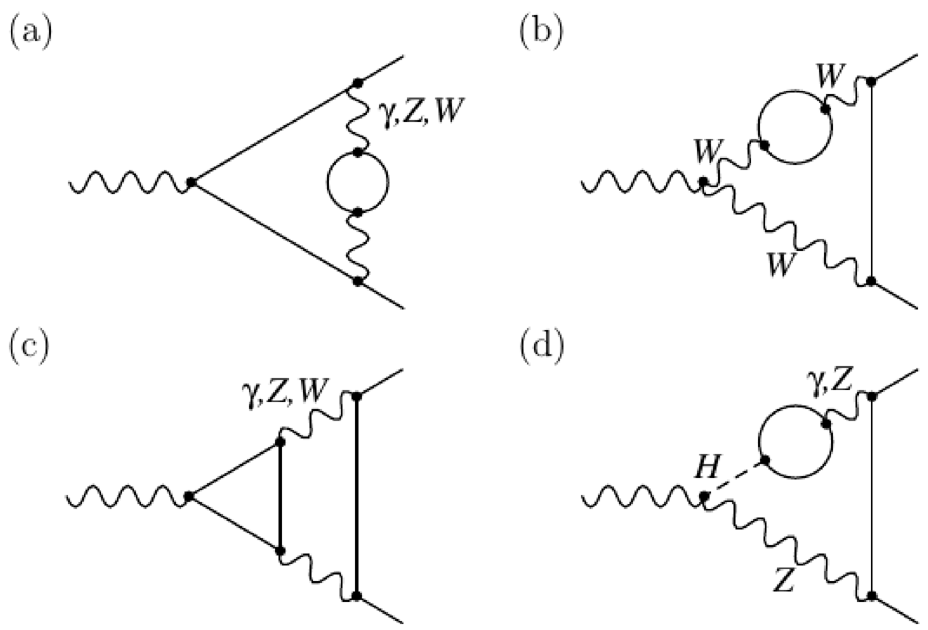

M_H [GeV]	$\mathcal{O}(\alpha)+\mathrm{FSR}_{\alpha,\alpha_s,\alpha_s^2}$ $[10^{-3}]$	$\mathcal{O}(\alpha^2_{\mathrm{ferm}})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\mathrm{ferm}})+\mathrm{FSR}_{\alpha_s^3,\alpha\alpha_s,m_b^2\alpha_s,m_b^4}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_s,\alpha\alpha_s^2)$ $[10^{-4}]$
100	−3.566	−6.583	−8.214	−0.404
200	−3.585	−6.587	−8.216	−0.404
400	−3.609	−6.595	−8.220	−0.404
600	−3.624	−6.594	−8.216	−0.404
1000	−3.645	−6.582	−8.201	−0.404