Electroweak precision fit
and
model-independent constraints on new physics

Satoshi Mishima

Univ. of Rome "La Sapienza" & INFN Rome

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with Marco Ciuchini, Enrico Franco and Luca Silvestrini,
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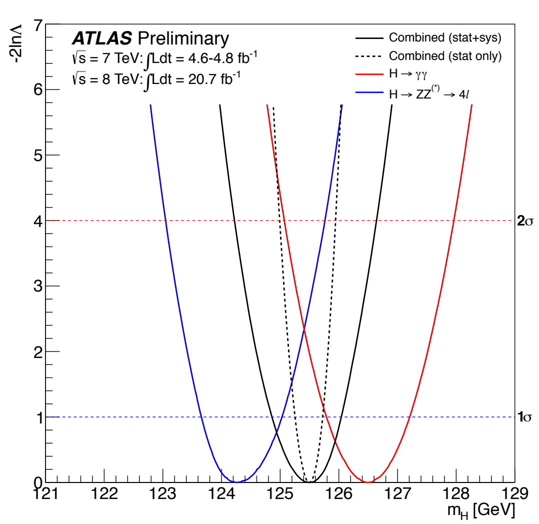
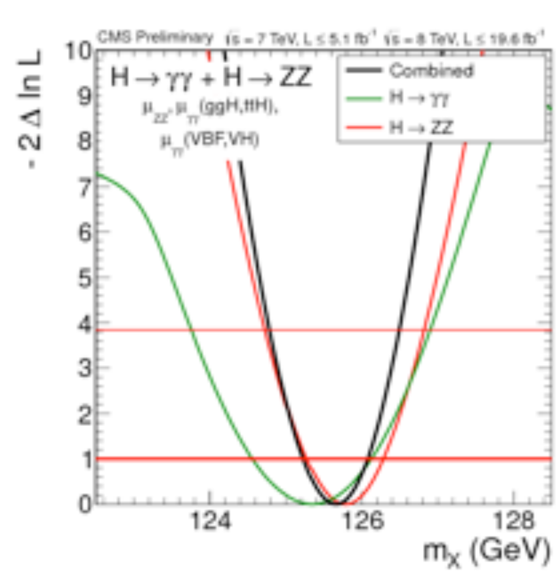
Contents

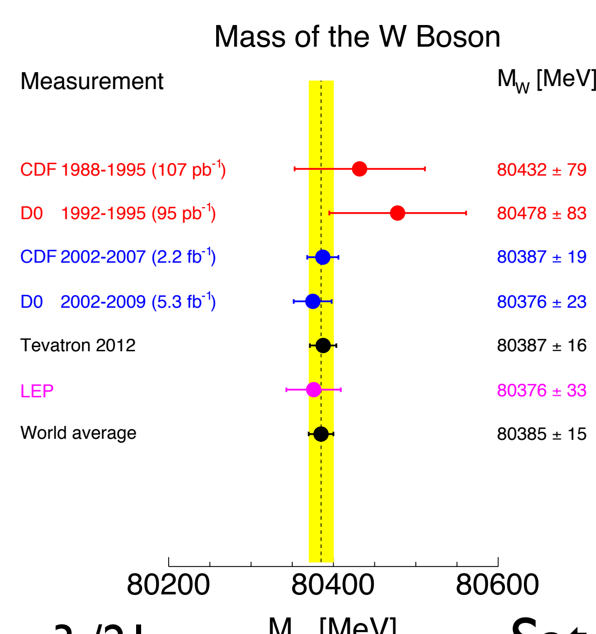
Model-indep. NP

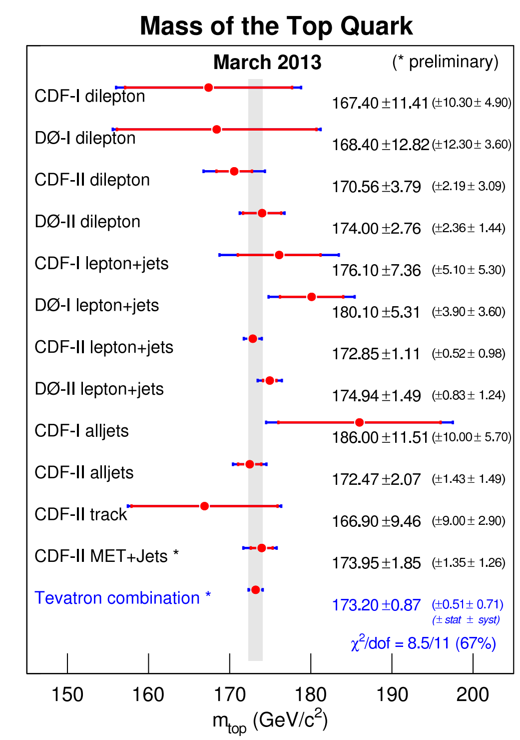
1. Introduction

- Electroweak precision fits have played a key role in constraining NP.
- The precise measurement of the Higgs mass at LHC as well as those of the W and top masses at Tevatron make improvement in EW fits.
- It is therefore phenomenologically relevant to reassess the constraining power of EW fits in the light of the recent exp. and theo. improvements.









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EW precision observables

- Precision observables:

$M_W,\ \Gamma_W$ and 13 Z-pole observables

(LEP2/Tevatron) (LEP/SLD)

- Z-pole obs' are given in terms of effective couplings:

$$\mathcal{L} = \frac{e}{2s_W c_W} Z_\mu \sum_f \bar{f}\left(g_V^f \gamma_\mu - g_A^f \gamma_\mu \gamma_5\right) f\,,$$
$$= \frac{e}{2s_W c_W} Z_\mu \sum_f \bar{f}\left[g_L^f \gamma_\mu (1-\gamma_5) + g_R^f \gamma_\mu (1+\gamma_5)\right] f\,,$$
$$= \frac{e}{2s_W c_W} \sqrt{\rho_Z^f}\, Z_\mu \sum_f \bar{f}\left[(I_3^f - 2Q_f \kappa_Z^f s_W^2)\gamma^\mu - I_3^f \gamma^\mu \gamma_5\right] f$$

$$\rho_Z^f = \left(\frac{g_A^f}{I_3^f}\right)^2 \quad (= 1 \text{ at tree level})$$

$$\kappa_Z^f = \frac{1}{4|Q_f| s_W^2}\left(1 - \frac{g_V^f}{g_A^f}\right)$$

$$A_{\rm LR}^{0,f} = \mathcal{A}_f = \frac{2\,\mathrm{Re}\left(g_V^f/g_A^f\right)}{1 + \left[\mathrm{Re}\left(g_V^f/g_A^f\right)\right]^2} \qquad A_{\rm FB}^{0,f} = \frac{3}{4}\mathcal{A}_e \mathcal{A}_f \qquad (f = \ell, c, b)$$

$$P_\tau^{\rm pol} = \mathcal{A}_\tau \qquad \sin^2\theta_{\rm eff}^{\rm lept} = \mathrm{Re}(\kappa_Z^\ell) s_W^2$$

$$\Gamma_f = \Gamma(Z \to f\bar{f}) \propto \left|\rho_Z^f\right| \left[\left|\frac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right] \Rightarrow \Gamma_Z,\ \sigma_h^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e \Gamma_h}{\Gamma_Z^2},\ R_\ell^0 = \frac{\Gamma_h}{\Gamma_\ell},\ R_{c,b}^0 = \frac{\Gamma_{c,b}}{\Gamma_h}$$

Theoretical status

- Mw has been calculated with full EW two-loop and leading higher-order contributions.

  Awramik, Czakon, Freitas & Weiglein (04)

- $\sin^2\theta^f_{\rm eff}$ (equivalent to κ^f_Z) have been calculated with full EW two-loop (bosonic is missing for b) and leading higher-order contributions.

  Awramik, Czakon & Freitas (06); Awramik, Czakon, Freitas & Kniehl (09)

- EW two-loop corrections to ρ^f_Z (normalization of Γ_f) were calculated in the large mt expansion.

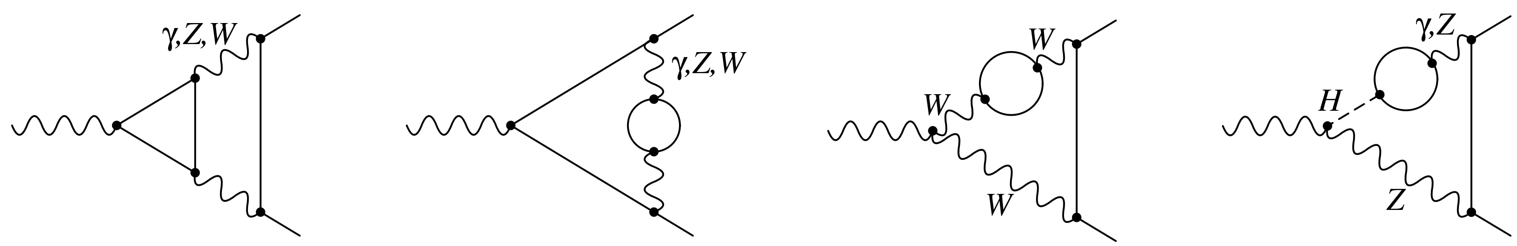
  Barbieri et al. (92,93); Fleischer et al. (93,95); Degrassi et al. (96,97,00)

see also Sirlin; Marciano&Sirlin; Bardin et al; Djouadi&Verzegnassi; Djouadi; Kniehl; Halzen&Kniehl; Kniehl&Sirlin; Djouadi&Gambino; Avdeev et al; Chetyrkin et al; Freitas et al; Awramik&Czakon; Onishchenko&Veretin; Van der Bij et al; Faisst et al; Awramik et al

Theoretical status

- Recently, the full fermionic EW two-loop corrections to $R_b^0 = \Gamma_b/\Gamma_h$ beyond the large mt expansion have been calculated.

  Freitas & Huang (12)



- Subleading power corrections are much larger than expected:

  cf. $(\Delta R_b^0)_{\mathrm{exp}} = \pm 0.00066$

$$R_b^0 = 0.21576 \to 0.21493 \; (\Delta R_b^0 = -0.00083)$$

- The results are available only for $\Gamma_{u,d}/\Gamma_b$, which allow us to compute $R_c^0 = \Gamma_c/\Gamma_h$ in addition to R_b^0.

- Subleading corr's: $\delta\rho_Z^{u(d)} - \delta\rho_Z^b \approx 0.0048(0.0044)$

  $\Gamma_f \propto |\rho_Z^f|$ $\quad (\delta\Gamma_Z, \delta\sigma_{\mathrm{h}}^0, \delta R_\ell^0)_{\mathrm{exp}} \sim 0.1\%$

⇨ We expect significant corrections also in Γ_Z, σ_{h}^0, R_ℓ^0!

2. SM fit

- Two options:
  1. "old Rb": use ρ_Z^f in the large mt expansion
  2. "new Rb": use $R^0_{c,b}$ from Freitas and Huang, introducing $\delta\rho_Z^{\nu,\ell,b}$ to account for possibly large unknown corrections.
- We adopt the on-shell renormalization scheme, and include up-to-date SM radiative corrections.
- We have developed our own codes for EWPO, tested against ZFITTER.
- We perform a Bayesian analysis with MCMC by using the Bayesian Analysis Toolkit (BAT) library.

Caldwell, Kollar & Kroninger

cf. Erler with GAPP for PDG $\overline{\text{MS}}$, frequentist

LEP EWWG with ZFITTER; Gfitter (Baak et al.); Eberhardt et al. with ZFITTER; and others...... on-shell, frequentist

SM input parameters

$G_\mu = 1.1663787 \times 10^{-5}\ \mathrm{GeV}^{-2}$ *PDG*

$\alpha = 1/137.035999074$ *PDG*

$\alpha_s(M_Z^2) = 0.1184 \pm 0.0006$ *PDG excl. EW*

$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) = 0.02750 \pm 0.00033$ *Burkhardt & Pietrzyk (11) (see also Davier et al(11); Hagiwara et al(11) ; Jegerlehner(11))*

measured with inclusive processes.

smaller uncertainty if using exclusive processes with pQCD, etc.

$M_Z = 91.1875 \pm 0.0021\ \mathrm{GeV}$ *LEP*

$m_t = 173.2 \pm 0.9\ \mathrm{GeV}$ *Tevatron (cf. LHC: $173.3 \pm 1.4\,\mathrm{GeV}$)*

$m_h = 125.6 \pm 0.3\ \mathrm{GeV}$ *ATLAS&CMS (naive average)*

$+\ \delta\rho_Z^\nu,\ \delta\rho_Z^\ell,\ \delta\rho_Z^b$ for "new Rb"

SM fit with the old Rb

	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1184 ± 0.0006	0.1184 ± 0.0006	0.1193 ± 0.0027	$+0.3$
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	0.02740 ± 0.00026	0.02725 ± 0.00042	-0.5
M_Z [GeV]	91.1875 ± 0.0021	91.1878 ± 0.0021	91.197 ± 0.012	$+0.8$
m_t [GeV]	173.2 ± 0.9	173.5 ± 0.8	176.3 ± 2.5	$+1.1$
m_h [GeV]	125.6 ± 0.3	125.6 ± 0.3	97.3 ± 26.9	-0.9
M_W [GeV]	80.385 ± 0.015	80.367 ± 0.007	80.362 ± 0.007	-1.4
Γ_W [GeV]	2.085 ± 0.042	2.0891 ± 0.0006	2.0891 ± 0.0006	$+0.1$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4953 ± 0.0004	2.4953 ± 0.0004	$+0.0$
σ_h^0 [nb]	41.540 ± 0.037	41.484 ± 0.004	41.484 ± 0.004	-1.5
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23145 ± 0.00009	0.23144 ± 0.00009	-0.8
$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1476 ± 0.0007	0.1477 ± 0.0007	$+0.3$
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1476 ± 0.0007	0.1471 ± 0.0008	-1.9
$\mathcal{A}_c$	0.670 ± 0.027	0.6682 ± 0.0003	0.6682 ± 0.0003	-0.1
$\mathcal{A}_b$	0.923 ± 0.020	0.93466 ± 0.00006	0.93466 ± 0.00006	$+0.6$
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0163 ± 0.0002	0.0163 ± 0.0002	-0.8
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.0740 ± 0.0004	0.0740 ± 0.0004	$+0.9$
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.1035 ± 0.0005	0.1039 ± 0.0005	$+2.8$
R_ℓ^0	20.767 ± 0.025	20.735 ± 0.004	20.734 ± 0.004	-1.3
R_c^0	0.1721 ± 0.0030	0.17223 ± 0.00002	0.17223 ± 0.00002	$+0.0$
R_b^0	0.21629 ± 0.00066	0.21575 ± 0.00003	0.21575 ± 0.00003	-0.8

← large deviation!

← old Rb

Fit: our fit results

Indirect: determined w/o using the corresponding experimental information

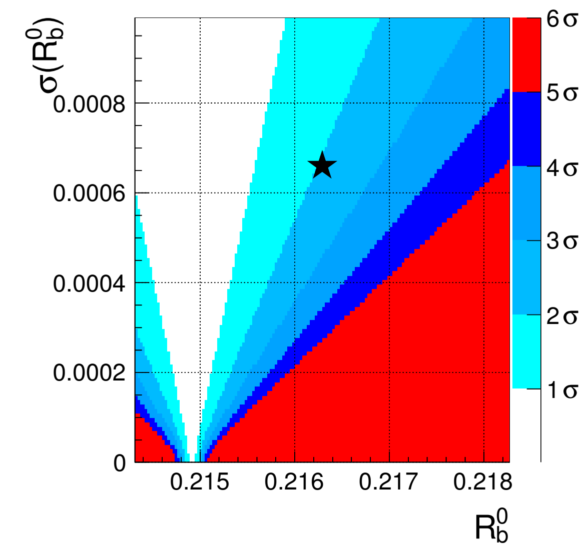
Pull: in units of standard deviations evaluated from the p.d.f.'s of "Data" and "Indirect"

SM fit with the new Rb

	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1184 ± 0.0006	0.1184 ± 0.0006	0.078 ± 0.024	-1.9
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	0.02742 ± 0.00026	0.02728 ± 0.00043	-0.4
M_Z [GeV]	91.1875 ± 0.0021	91.1878 ± 0.0021	91.204 ± 0.013	$+1.2$
m_t [GeV]	173.2 ± 0.9	173.5 ± 0.8	175.7 ± 2.6	$+0.9$
m_h [GeV]	125.6 ± 0.3	125.6 ± 0.3	98.5 ± 27.7	-0.8
$\delta\rho_Z^\nu$	—	-0.0052 ± 0.0031	—	—
$\delta\rho_Z^\ell$	—	-0.0002 ± 0.0010	—	—
$\delta\rho_Z^b$	—	-0.0021 ± 0.0011	—	—
M_W [GeV]	80.385 ± 0.015	80.366 ± 0.007	80.361 ± 0.007	-1.4
Γ_W [GeV]	2.085 ± 0.042	2.0890 ± 0.0006	2.0890 ± 0.0006	$+0.1$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952 ± 0.0023	—	—
σ_h^0 [nb]	41.540 ± 0.037	41.539 ± 0.037	—	—
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23145 ± 0.00009	0.23145 ± 0.00009	-0.8
$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1476 ± 0.0007	0.1476 ± 0.0007	$+0.3$
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1476 ± 0.0007	0.1470 ± 0.0008	-1.9
$\mathcal{A}_c$	0.670 ± 0.027	0.6681 ± 0.0003	0.6681 ± 0.0003	-0.1
$\mathcal{A}_b$	0.923 ± 0.020	0.93466 ± 0.00006	0.93466 ± 0.00006	$+0.6$
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0163 ± 0.0002	0.0163 ± 0.0002	-0.8
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.0739 ± 0.0004	0.0740 ± 0.0004	$+0.9$
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.1034 ± 0.0005	0.1038 ± 0.0005	$+2.7$
R_ℓ^0	20.767 ± 0.025	20.768 ± 0.025	—	—
R_c^0	0.1721 ± 0.0030	0.17247 ± 0.00002	0.17247 ± 0.00002	$+0.1$
R_b^0	0.21629 ± 0.00066	0.21492 ± 0.00003	0.21492 ± 0.00003	-2.1

← not precise! ($\alpha_s(M_Z^2)$)

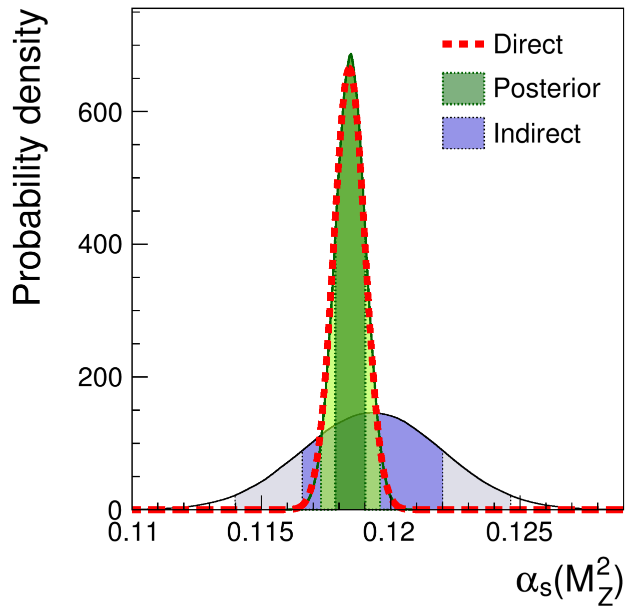
← new Rb (R_b^0)



- New Rb increases the pull from -0.8σ to -2.1σ.
- $\delta\rho_Z^{\nu,\ell,b}$ are of $O(10^{-3})$, compatible to Freitas & Huang.

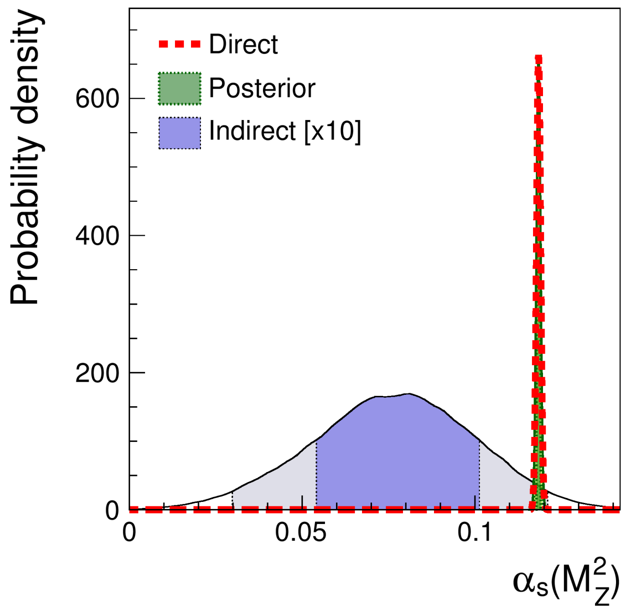
$\alpha_s(M_Z^2)$ from the EW fit

old Rb



$$\mathbf{0.1193 \pm 0.0027}$$

new Rb



$$\mathbf{0.078 \pm 0.024}$$

Not precise due to the inclusion of the unknown subleading corrections!

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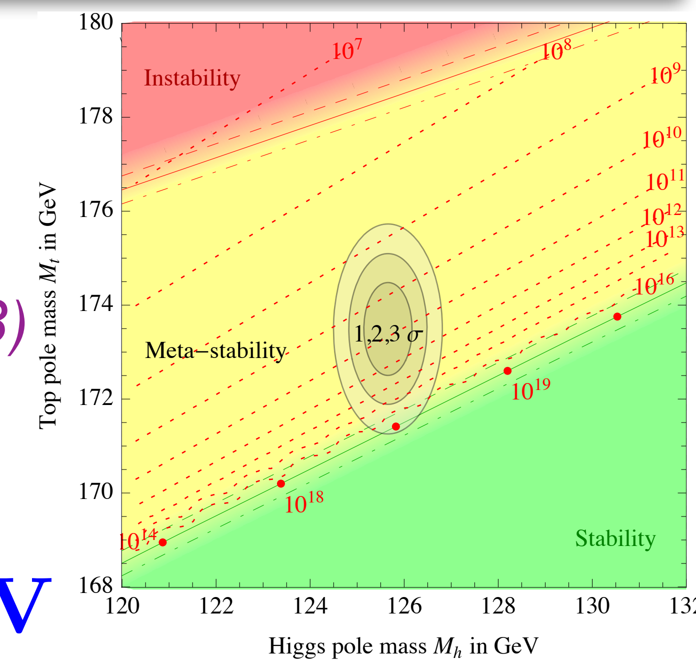
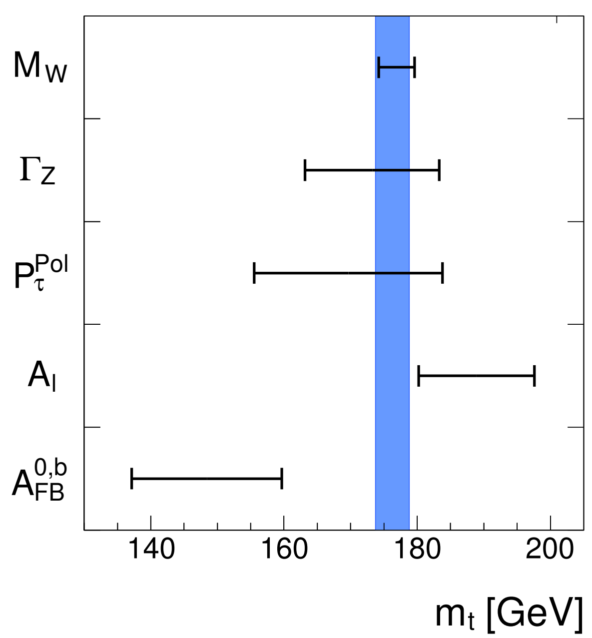
Top mass vs. (meta-)stability

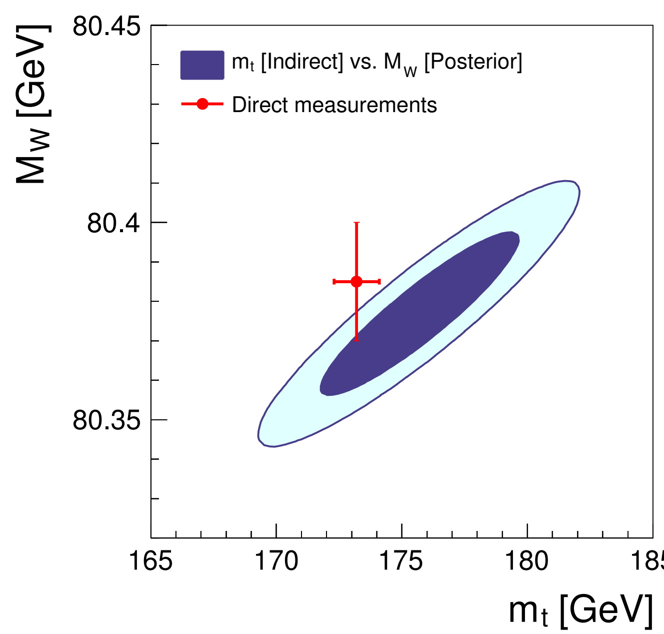


- The measurement of the top mass is crucial for testing the stability of the SM vacuum. *Degrassi et al.(12); Buttazzo et al.(13)*

$$m_t^{\text{pole}} < (171.36 \pm 0.46)\ \text{GeV}$$

- Tevatron pole(?) mass: 173.2 ± 0.9 GeV
- Pole from MSbar: 173.3 ± 2.8 GeV
- Indirect determination from EW fit: 175.7 ± 2.6 GeV





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On NP fits

"new Rb"

Significant subleading corrections in Γ_Z, σ_h^0, R_ℓ^0

We do not use them in NP fits with the new $R_{c,b}^0$.

"old Rb"

For comparison, we also present fit results with the old $R_{c,b}^0$ and Γ_Z, σ_h^0, R_ℓ^0 calculated using the large mt expansion.

3. Oblique parameters

- Suppose that dominant NP effects appear in the vacuum polarizations of the gauge bosons:

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

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

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

Kennedy & Lynn (89); Peskin & Takeuchi (90,92)

- EWPO depend on the combinations:

$$\delta M_W,\ \delta\Gamma_W \propto -S + 2c_W^2\, T + \frac{(c_W^2 - s_W^2)\, U}{2s_W^2}$$

$$\delta\Gamma_Z \propto -10(3 - 8s_W^2)\, S + (63 - 126 s_W^2 - 40 s_W^4)\, T$$

$$\text{others} \propto S - 4c_W^2 s_W^2\, T$$

- Cannot use Γ_Z with the new Rb.

  ⇨ cannot fit all S, T and U.

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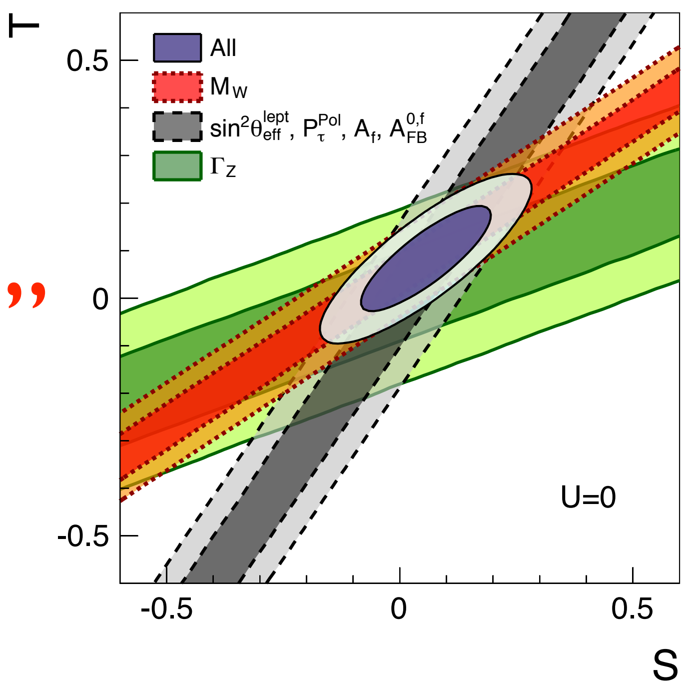
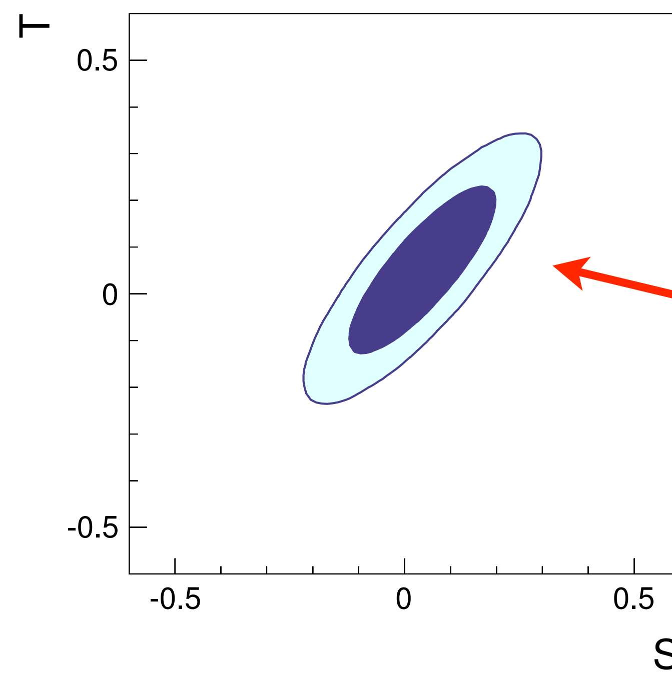
Oblique parameters

$U=0$ $U\neq0$

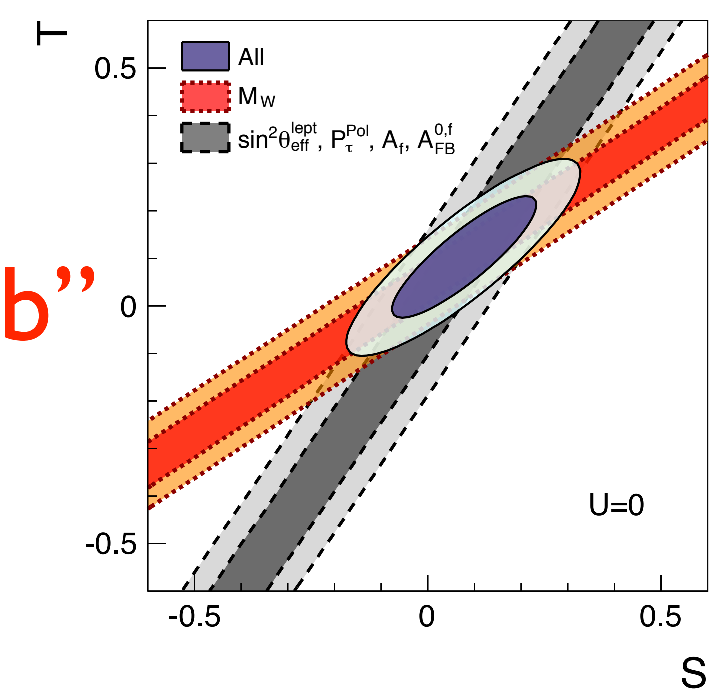
“old Rb”





68% & 95%

“new Rb”



	“old Rb”		“new Rb”
	$U\neq0$	$U=0$	$U=0$
S	0.04 ± 0.10	0.06 ± 0.09	0.08 ± 0.10
T	0.05 ± 0.12	0.08 ± 0.07	0.10 ± 0.08
U	0.03 ± 0.09	—	—

See also, e.g., Erler (12); Gfitter (12,13)

4. HVV coupling

- only a Higgs below cutoff + custodial symmetry:

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + \cdots\right) + \cdots$$

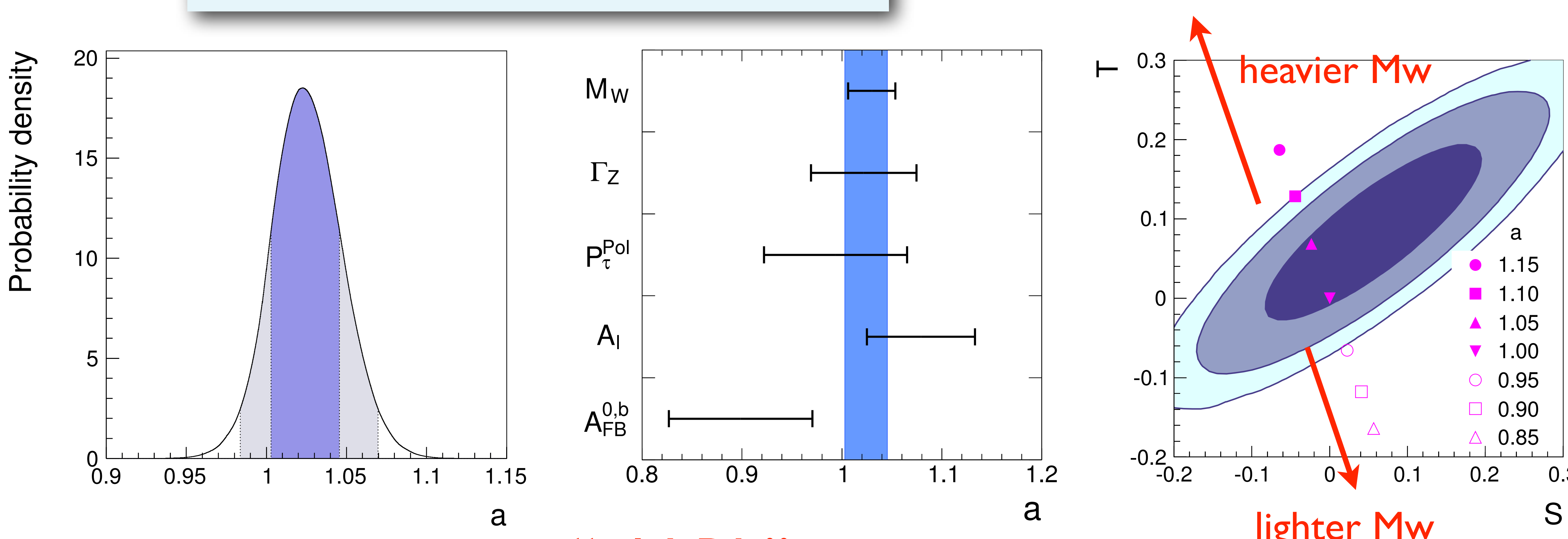
SM : $a = 1$

$$S = \frac{1}{12\pi}(1 - a^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right)$$

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

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

Barberi, Bellazzini, Rychkov & Varagnolo (07)



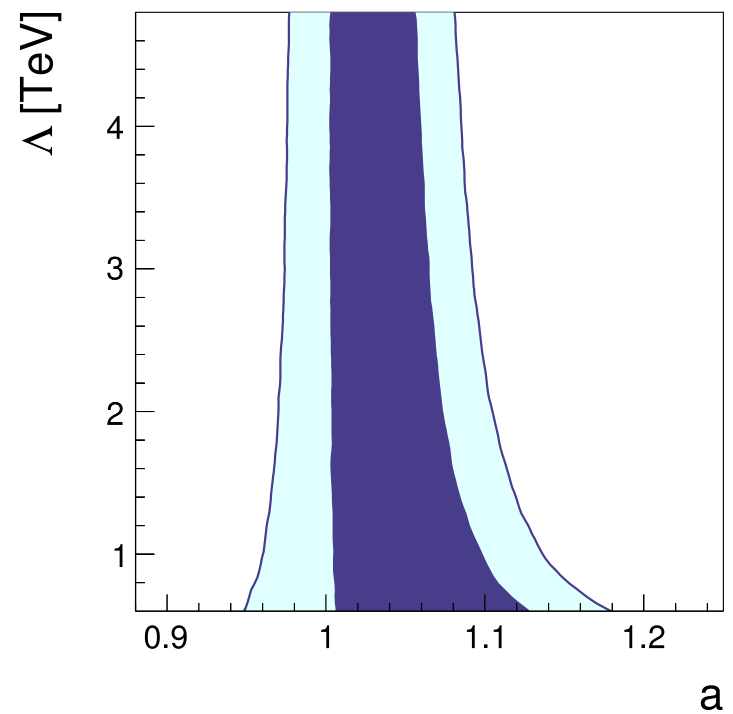
$a = 1.024 \pm 0.021$ "old Rb" ("new Rb" is similar)

Implication on composite Higgs models

- $a \in [0.98, 1.07]$ @ 95%

  ⇨ $\Lambda \gtrsim 16$ TeV @ 95%

$$\Lambda < \frac{4\pi v}{\sqrt{|1-a^2|}}$$



- Composite Higgs models typically generate $a < 1$.

$$\xi = \left(\frac{v}{f}\right)^2 = 1 - a^2$$

$a > 1$ ⇨ $W_L W_L$ scattering is dominated by isospin 2 channel

Falkowski, Rychkov & Urbano (12)

- Extra light states are required to fix the EW fit.

  Fermionic resonances can give desired shifts in S and T.

  Grojean et al. (13); Azatov et al. (13)

- The result is less sensitive to the current LHC data.

  See, e.g., Azatov et al. (13); Falkowski et al. (13); Giardino et al. (13).

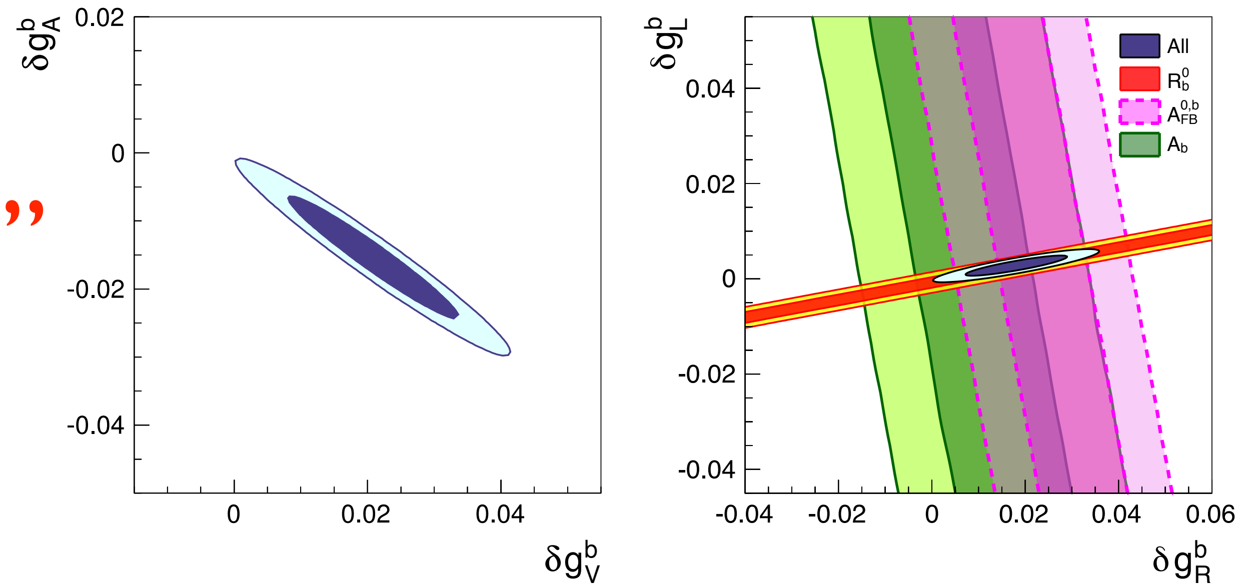
5. $Zb\bar{b}$ couplings

- Four solutions from Z-pole data, while two of them are disfavored by off Z-pole data for AFBb.

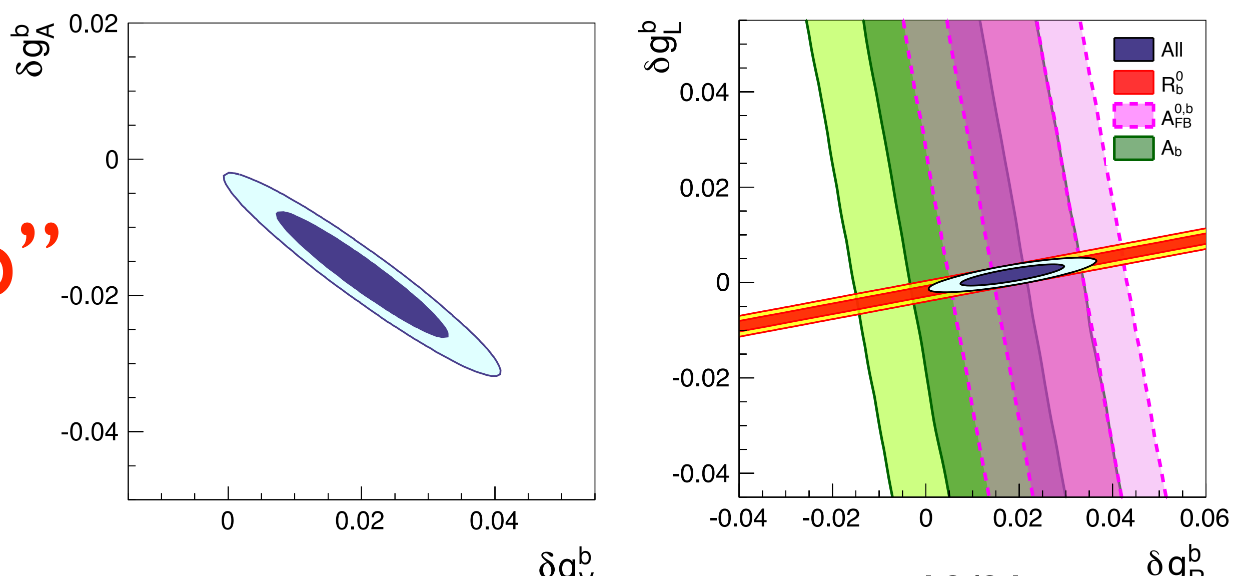
Choudhury et al. (02)

- The solution, closer to the SM:

"old Rb"



"new Rb"



	"old Rb"	"new Rb"
δg_R^b	0.018 ± 0.007	0.019 ± 0.007
δg_L^b	0.0028 ± 0.0014	0.0016 ± 0.0015
δg_V^b	0.021 ± 0.008	0.020 ± 0.008
δg_A^b	-0.015 ± 0.006	-0.017 ± 0.006

See also Batell et al. (13)

6. Dim. 6 operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

Barbieri & Strumia (99)

$$\mathcal{O}_{WB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu}\,, \qquad \mathcal{O}_H = |H^\dagger D_\mu H|^2\,,$$
$$\mathcal{O}_{LL} = \frac{1}{2}(\overline{L}\gamma_\mu \tau^a L)^2\,, \qquad \mathcal{O}'_{HL} = i(H^\dagger D_\mu \tau^a H)(\overline{L}\gamma^\mu \tau^a L)\,,$$
$$\mathcal{O}'_{HQ} = i(H^\dagger D_\mu \tau^a H)(\overline{Q}\gamma^\mu \tau^a Q)\,, \qquad \mathcal{O}_{HL} = i(H^\dagger D_\mu H)(\overline{L}\gamma^\mu L)\,,$$
$$\mathcal{O}_{HQ} = i(H^\dagger D_\mu H)(\overline{Q}\gamma^\mu Q)\,, \qquad \mathcal{O}_{HE} = i(H^\dagger D_\mu H)(\overline{E}\gamma^\mu E)\,,$$
$$\mathcal{O}_{HU} = i(H^\dagger D_\mu H)(\overline{U}\gamma^\mu U)\,, \qquad \mathcal{O}_{HD} = i(H^\dagger D_\mu H)(\overline{D}\gamma^\mu D)\,.$$

- Switching on one operator at a time:

	"old Rb"			"new Rb"		
	C_i/Λ^2 [TeV^{-2}]	Λ [TeV]		C_i/Λ^2 [TeV^{-2}]	Λ [TeV]	
Coefficient	at 95%	$C_i=-1$	$C_i=1$	at 95%	$C_i=-1$	$C_i=1$
C_{WB}	[−0.0096, 0.0042]	10.2	15.4	[−0.0095, 0.0045]	10.3	15.0
C_H	[−0.030, 0.007]	5.8	12.1	[−0.031, 0.008]	5.7	11.5
C_{LL}	[−0.011, 0.019]	9.5	7.2	[−0.016, 0.023]	8.0	6.6
C'_{HL}	[−0.012, 0.005]	9.2	14.1	[−0.017, 0.009]	7.6	10.8
C'_{HQ}	[−0.010, 0.015]	10.2	8.2	[−0.40, 0.20]	1.6	2.2
C_{HL}	[−0.007, 0.010]	12.2	10.0	[−0.034, 0.022]	5.5	6.7
C_{HQ}	[−0.023, 0.046]	6.6	4.7	[−0.01, 0.11]	11.7	3.0
C_{HE}	[−0.014, 0.008]	8.4	11.1	[−0.029, 0.019]	5.9	7.2
C_{HU}	[−0.061, 0.087]	4.0	3.4	[−0.37, 0.08]	1.6	3.5
C_{HD}	[−0.15, 0.05]	2.6	4.6	[−1.1, −0.2]	1.0	—

Constraints on dim. 6 operators

Fit multiple op's simultaneously:

Coefficient	"new Rb" C_i/Λ^2 [TeV^{-2}] at 95%
C_{WB}	$[-0.009,\ 0.021]$
C_H	$[-0.068,\ 0.016]$
C'_{HL}	$[-0.029,\ 0.006]$
C'_{HQ}	$[-0.34,\ 0.31]$
C_{HL}	—
C_{HQ}	$[-0.07,\ 0.12]$
C_{HE}	—
C_{HU}	$[-0.26,\ 0.49]$
C_{HD}	$[-1.2,\ -0.2]$
$C[\mathcal{A}_\ell]$	$[-0.0021,\ 0.0050]$
C'_{HL}	$[-0.029,\ 0.006]$
C_{HL}	—
C_{HE}	—
C_{HU_2}	$[-0.32,\ 0.55]$
C_{HD_3}	$[-1.2,\ -0.2]$
$C'_{HQ_1} + C'_{HQ_2}$	$[-0.68,\ 0.61]$
$C'_{HQ_2} - C_{HQ_2}$	$[-0.67,\ 0.55]$
$C'_{HQ_3} + C_{HQ_3}$	$[-0.77,\ 0.63]$
$C[\mathcal{A}_\ell]$	$[-0.0021,\ 0.0050]$
$C[\Gamma_{uds}]$	$[-0.42,\ 0.43]$

w/o quark-flavor universality:

	"new Rb"		
Coefficient	C_i/Λ^2 [TeV^{-2}] at 95%	Λ [TeV] $C_i=-1$	Λ [TeV] $C_i=1$
C'_{HQ_1}	$[-0.19,\ 0.01]$	2.3	11.9
C'_{HQ_2}	$[-0.20,\ 0.01]$	2.3	10.8
C'_{HQ_3}, C_{HQ_3}	$[0.00,\ 0.10]$	15.6	3.1
C_{HQ_1}	$[-1.9,\ 0.1]$	0.7	3.9
C_{HQ_2}	$[-0.25,\ 0.15]$	2.0	2.6
C_{HU_1}	$[-0.97,\ 0.03]$	1.0	5.6
C_{HU_2}	$[-0.39,\ 0.21]$	1.6	2.2
C_{HD_1}, C_{HD_2}	$[-0.1,\ 1.9]$	3.8	0.7
C_{HD_3}	$[-0.66,\ -0.13]$	1.2	—

Recent exp. improvements strengthen the bounds on NP!

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7. Summary

- We have updated the EW fit with the recent exp. and theo. improvements, discussing in detail the impact of the recently computed two-loop fermionic EW corrections to the $Zf\bar{f}$ couplings.
- We have derived constraints on oblique parameters, HVV coupling, $Zb\bar{b}$ couplings and dim. 6 operators.
- The constraining power of the EW fit have been improved.
- Full two-loop calculations of Γ_Z, σ_h^0, R_ℓ^0 need to be completed.
- Future data (LHC, ILC, LEP3/TLEP,...) strengthen greatly the power of the EW fit.

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Backup

Comparison to ZFITTER

- For a given set of the input parameters,

	ZFITTER	OURS	$\frac{\text{OURS}-\text{ZFITTER}}{\text{ZFITTER}} * 100$	Exp uncertainty
M_W	80.362216	80.362499	0.00035 %	0.02 %
Γ_W	2.0906748	2.0887391	−0.093 %	2.0 %
Γ_Z	2.4953142	2.4951814	−0.0053 %	0.09 %
σ_h^0	41.479103	41.483516	0.011 %	0.09 %
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	0.23149326	0.23149297	−0.00012 %	0.52 %
P_τ^{Pol}	0.14724705	0.14724926	0.0015 %	2.2 %
A_ℓ	0.14724705	0.14724926	0.0015 %	1.4 %
A_c	0.66797088	0.66799358	0.0034 %	4.0 %
A_b	0.93460981	0.93464051	0.0033 %	2.2 %
$A_{\text{FB}}^{0,\ell}$	0.016261269	0.016261758	0.0030 %	5.5 %
$A_{\text{FB}}^{0,c}$	0.073767554	0.073771169	0.0049 %	5.0 %
$A_{\text{FB}}^{0,b}$	0.10321390	0.10321884	0.0048 %	1.6 %
R_ℓ^0	20.739702	20.735130	−0.022 %	0.12 %
R_c^0	0.17224054	0.17222362	−0.0098 %	1.7 %
R_b^0	0.21579927	0.21578277	−0.0077 %	0.31 %

Our results are in agreement with ZFITTER v6.43.

Impact of parametric uncertainties

	Prediction	α_s	$\Delta\alpha^{(5)}_{\rm had}$	M_Z	m_t
M_W [GeV]	80.362 ± 0.008	± 0.000	± 0.006	± 0.003	± 0.005
Γ_Z [GeV]	2.4951 ± 0.0005	± 0.0003	± 0.0003	± 0.0002	± 0.0002
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1472 ± 0.0009	± 0.0000	± 0.0009	± 0.0001	± 0.0002
$A_{\rm FB}^{0,b}$	0.1032 ± 0.0007	± 0.0000	± 0.0006	± 0.0001	± 0.0002
R_b^0	0.21493 ± 0.00004	± 0.00001	± 0.00000	± 0.00000	± 0.00003

- $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ and mt are the most important sources of parametric uncertainty.
- The theoretical uncertainty from missing higher-order corrections has been estimated as $\delta M_W^{\rm theo} \sim 4\ {\rm MeV}$. *Awramik et al. (04)*

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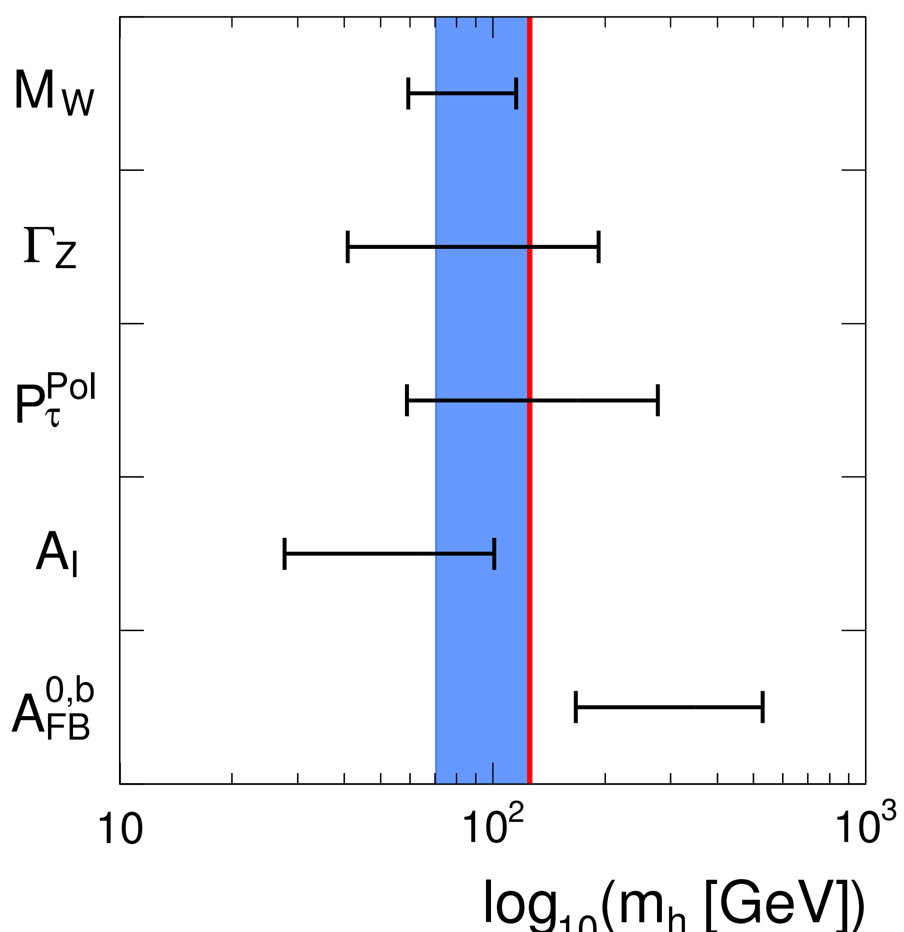
Individual constraints on the Higgs mass

indirect determination from the EW fit:

$$m_h = 97.3 \pm 26.9\,\mathrm{GeV}$$

direct measurement at LHC (ATLAS & CMS):

$$m_h = 125.6 \pm 0.3\,\mathrm{GeV}$$



"old Rb"

- Mw gives the most stringent constraint.
- Tension between Al(SLD) and AFBb.

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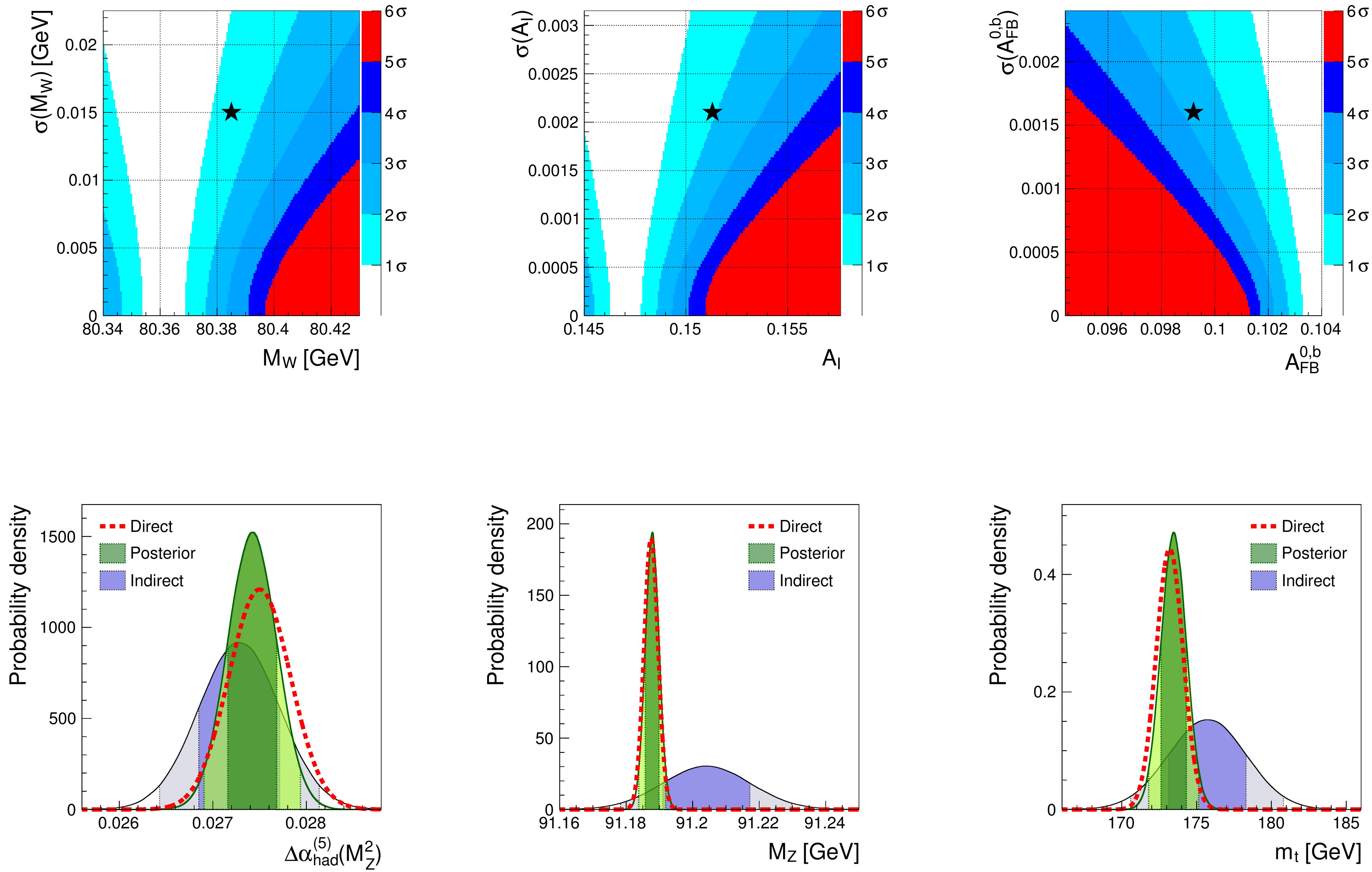
Other plots in the SM fit



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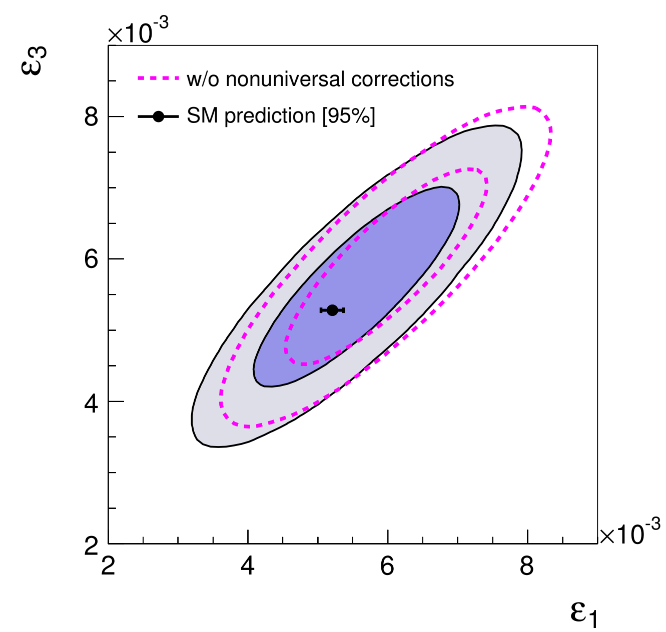
Constraints on the epsilon parameters

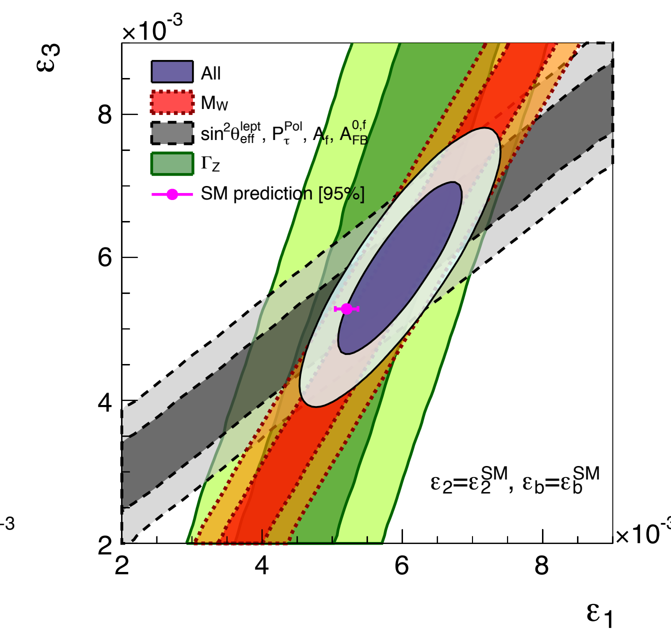
- Unlike STU, the epsilon parameters involve SM contributions.

Altarelli et al. (91,92,93)

➡ **Flavour non-universal VCs in the SM have to be taken into account.**

Parameter	"old Rb" $\epsilon_{1,2,3,b}$ fit	"old Rb" $\epsilon_{1,3}$ fit
ϵ_1 $[10^{-3}]$	5.6 ± 1.0	6.0 ± 0.6
ϵ_2 $[10^{-3}]$	-7.8 ± 0.9	—
ϵ_3 $[10^{-3}]$	5.6 ± 0.9	5.9 ± 0.8
ϵ_b $[10^{-3}]$	-5.8 ± 1.3	—





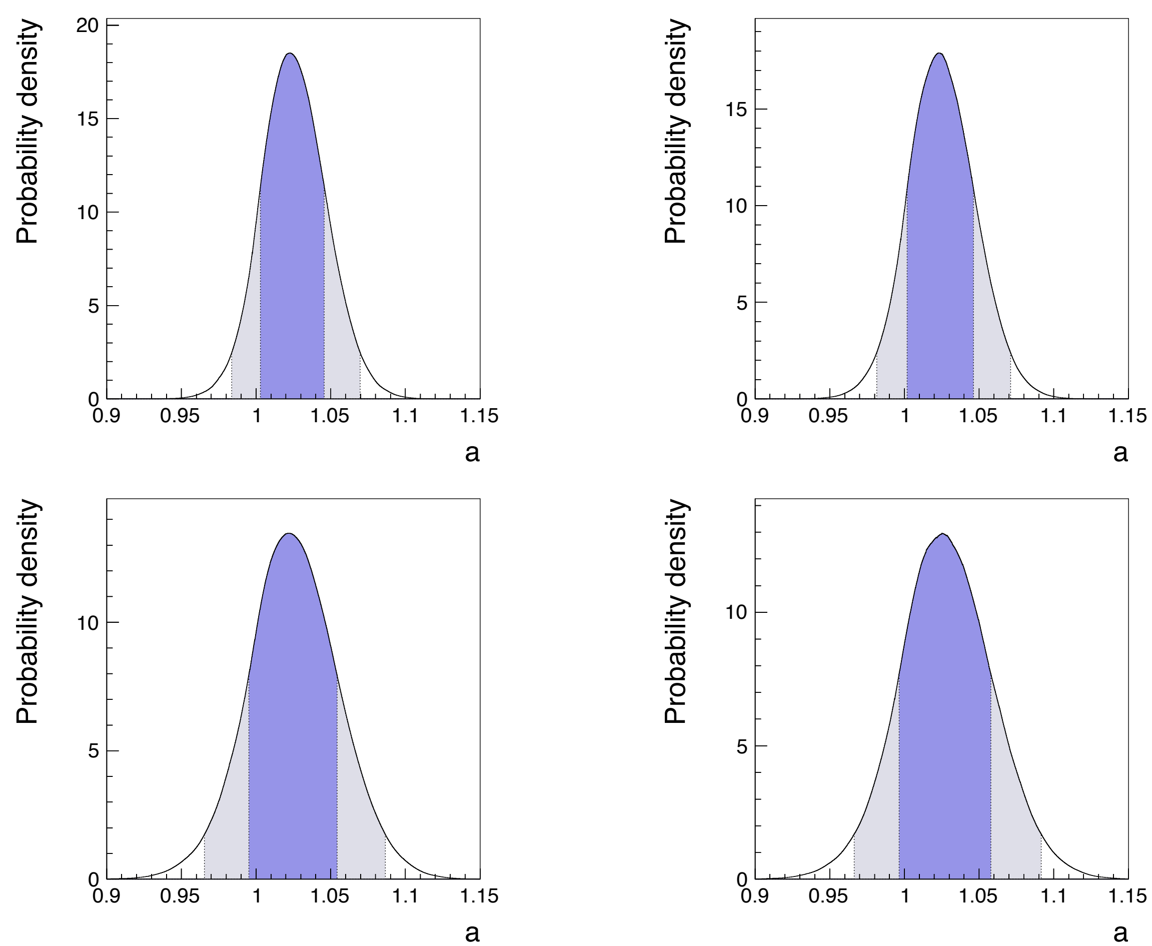
Top mass uncertainty for HVV

- If using the pole mass derived from the $\overline{\text{MS}}$ mass,

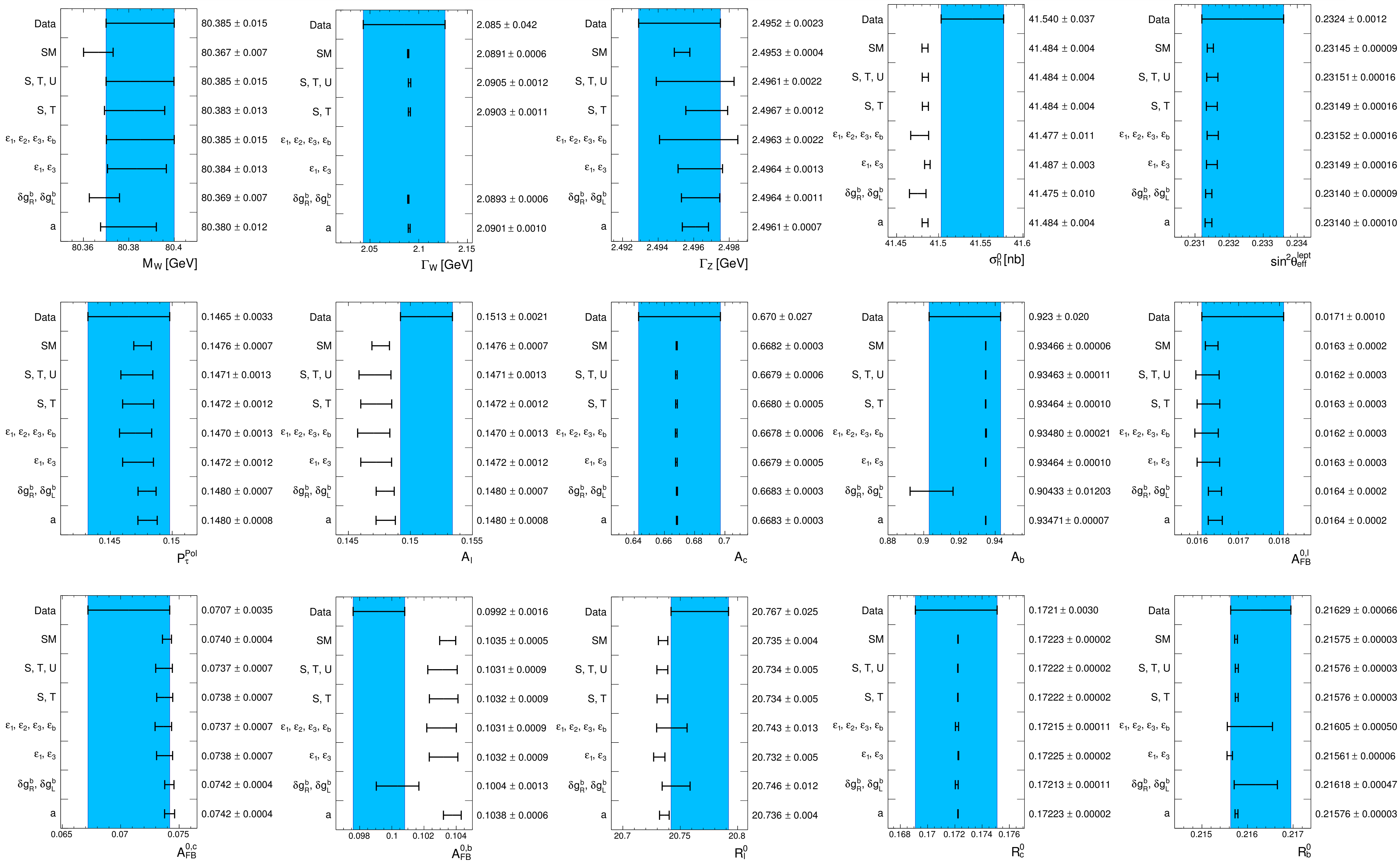
$$m_t^{\overline{\text{MS}}} \text{ from total } \sigma_{t\bar{t}} \Rightarrow m_t^{\text{pole}} = 173.3 \pm 2.8\,\text{GeV}$$

Alekhin et al. (12)

m_t [GeV]	"old Rb"	"new Rb"
173.2 ± 0.9	1.024 ± 0.021	1.024 ± 0.022
173.3 ± 2.8	1.025 ± 0.030	1.027 ± 0.031



Summary of fit results w/o new Rb



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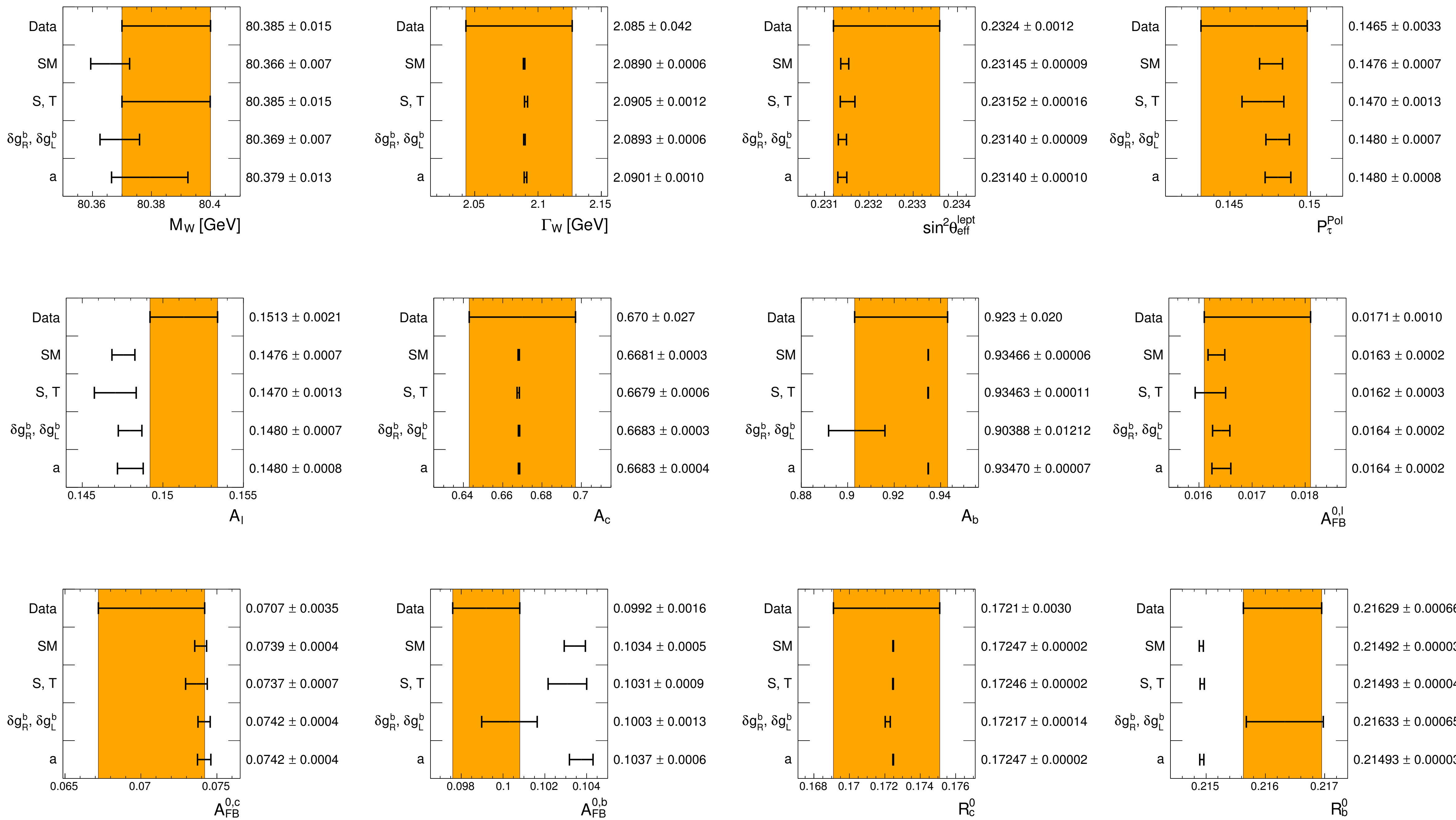
Summary of fit results with new Rb



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