Global analysis of Higgs couplings with dimension-six operators

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M. Ciuchini, E. Franco, S.M. & L. Silvestrini, JHEP 08, 106 (2013);
+ M. Pierini and L. Reina, in preparation;
+ J. de Blas and D. Ghosh, in preparation

1. Introduction

- We have found only a Higgs and no other new particle so far at the LHC.
- Experimental data suggest that the NP scale is well above the EW scale.
- We consider an effective theory built exclusively from the SM fields with the SM gauge symmetries.

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Contributions from higher-dimensional operators are suppressed by powers of the NP scale.

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_j C_j^{(6)} O_j^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

Effective field theory approach

- Model-independent
- Correlations among observables are induced by gauge-invariant operators.

  ➡ *Useful guide to look for NP effects*

- Constraints on the Wilson coefficients will give us clues for constructing the UV theory.

Dim-6 operators

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_j C_j^{(6)} O_j^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

- Dim-5 operators violate B and/or L.
- Dim-6 operators contribute to EW/Higgs physics.

Buchmuller & Wyler, NPB268, 621(1986)

A list of the dim-6 operators was presented.

80 op's (for one generation) that respect B/L.

⇩

Grzadkowski, Iskrzynski, Misiak & Rosiek, JHEP10, 085 (2010)

Redundant operators have been removed with the equations of motion. *59 independent op's*

Complete list of the dim-6 operators

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{L}eH)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{Q}u\widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{Q}dH)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$(H^\dagger H)G_{\mu\nu}^AG^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{L}\sigma^{\mu\nu}e)\tau^IHW_{\mu\nu}^I$	$\mathcal{O}_{HL}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$
$\mathcal{O}_{H\widetilde{G}}$	$(H^\dagger H)\widetilde{G}_{\mu\nu}^AG^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{L}\sigma^{\mu\nu}e)HB_{\mu\nu}$	$\mathcal{O}_{HL}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{L}\tau^I\gamma^\mu L)$
$\mathcal{O}_{HW}$	$(H^\dagger H)W_{\mu\nu}^IW^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{Q}\sigma^{\mu\nu}T^Au)\widetilde{H}G_{\mu\nu}^A$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{H\widetilde{W}}$	$(H^\dagger H)\widetilde{W}_{\mu\nu}^IW^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{Q}\sigma^{\mu\nu}u)\tau^I\widetilde{H}W_{\mu\nu}^I$	$\mathcal{O}_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{HB}$	$(H^\dagger H)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{Q}\sigma^{\mu\nu}u)\widetilde{H}B_{\mu\nu}$	$\mathcal{O}_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{Q}\tau^I\gamma^\mu Q)$
$\mathcal{O}_{H\widetilde{B}}$	$(H^\dagger H)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{Q}\sigma^{\mu\nu}T^Ad)HG_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{HWB}$	$(H^\dagger\tau^IH)W_{\mu\nu}^IB^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{Q}\sigma^{\mu\nu}d)\tau^IHW_{\mu\nu}^I$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{H\widetilde{W}B}$	$(H^\dagger\tau^IH)\widetilde{W}_{\mu\nu}^IB^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{Q}\sigma^{\mu\nu}d)HB_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}\gamma^\mu d)$

EDMs, g-2,etc.

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{LL}$	$(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$	$\mathcal{O}_{ee}$	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$	$\mathcal{O}_{Le}$	$(\bar{L}\gamma_\mu L)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{QQ}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{uu}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{Lu}$	$(\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{QQ}^{(3)}$	$(\bar{Q}\gamma_\mu\tau^IQ)(\bar{Q}\gamma^\mu\tau^IQ)$	$\mathcal{O}_{dd}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$	$\mathcal{O}_{Ld}$	$(\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{LQ}^{(1)}$	$(\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{eu}$	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{Qe}$	$(\bar{Q}\gamma_\mu Q)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{LQ}^{(3)}$	$(\bar{L}\gamma_\mu\tau^IL)(\bar{Q}\gamma^\mu\tau^IQ)$	$\mathcal{O}_{ed}$	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$	$\mathcal{O}_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$	$\mathcal{O}_{Qu}^{(8)}$	$(\bar{Q}\gamma_\mu T^AQ)(\bar{u}\gamma^\mu T^Au)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^Au)(\bar{d}\gamma^\mu T^Ad)$	$\mathcal{O}_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
				$\mathcal{O}_{Qd}^{(8)}$	$(\bar{Q}\gamma_\mu T^AQ)(\bar{d}\gamma^\mu T^Ad)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{LedQ}$	$(\bar{L}^je)(\bar{d}Q^j)$	$\mathcal{O}_{duQ}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha)^TCu^\beta\right]\left[(Q^{\gamma j})^TCL^k\right]$
$\mathcal{O}_{QuQd}^{(1)}$	$(\bar{Q}^ju)\varepsilon_{jk}(\bar{Q}^kd)$	$\mathcal{O}_{QQu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(Q^{\alpha j})^TCQ^{\beta k}\right]\left[(u^\gamma)^TCe\right]$
$\mathcal{O}_{QuQd}^{(8)}$	$(\bar{Q}^jT^Au)\varepsilon_{jk}(\bar{Q}^kT^Ad)$	$\mathcal{O}_{QQQ}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(Q^{\alpha j})^TCQ^{\beta k}\right]\left[(Q^{\gamma m})^TCL^n\right]$
$\mathcal{O}_{LeQu}^{(1)}$	$(\bar{L}^je)\varepsilon_{jk}(\bar{Q}^ku)$	$\mathcal{O}_{QQQ}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(Q^{\alpha j})^TCq^{\beta k}\right]\left[(Q^{\gamma m})^TCL^n\right]$
$\mathcal{O}_{LeQu}^{(3)}$	$(\bar{L}^j\sigma_{\mu\nu}e)\varepsilon_{jk}(\bar{Q}^k\sigma^{\mu\nu}u)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha)^TCu^\beta\right]\left[(u^\gamma)^TCe\right]$

Grzadkowski, Iskrzynski, Misiak & Rosiek (10)

- Consider 18 CP-even op's for EW and Higgs physics.
- To avoid dangerous FCNP, we assume *flavor universality.*

  (Alternatively, *MFV* will also be considered in the paper.)
- Other choices of the basis are possible.

  direct connections to observables

  operator mixing in the RG running

  See, e.g., Giudice et al. (07); Contino et al. (13)

Global fitting tool

M. Ciuchini, E. Franco, S.M., L. Silvestrini and others …

- We have been developing a computational framework to calculate various observables in the SM or in its extensions, and to constrain their parameter space.
- The codes are written in C++, supporting MPI.
- One can use our tool as a stand-alone program to perform a Bayesian statistical analysis with MCMC based on the Bayesian Analysis Toolkit (BAT).

  Caldwell, Kollar & Kroninger
- Alternatively, one can use it as a library to compute observables in a given model.
- One can add his/her favorite models as well as observables to our tool as external modules.

Global fitting tool

M. Ciuchini, E. Franco, S.M., L. Silvestrini and others …

- Models (parameters, RGEs, effective couplings, etc):
  - Standard Model (tested)
  - Some NP extensions for model-independent studies of EW and Higgs (tested)
  - general MSSM (under testing)
- Observables:
  - EW precision observables (tested)
  - Higgs signal strengths (tested)
  - Flavor: $\Delta F = 2,\ \mathrm{UT},\ b \to s\gamma,\ b \to s\ell\ell$ (under testing)
  - LEP2 x-sections, LFV obs' (under construction/testing)
- EW+Higgs codes will be released soon.

Statistical approaches

- Frequentist:

  model parameter: constant true value

  data: random variables

  68% confidence interval of a parameter:

  The interval covers the true value with a probability of 68%.

- Bayesian:

$$P(\vec{\theta}\,|\,\mathrm{Data}) = \frac{L(\mathrm{Data}\,|\,\vec{\theta})\,\pi(\vec{\theta})}{\int d\vec{\theta}'\,L(\mathrm{Data}\,|\,\vec{\theta}')\,\pi(\vec{\theta}')}$$

  prior p.d.f. for parameters $\vec{\theta}$

  model parameter: random variable

  68% credible interval:

  The parameter is in the interval with a probability of 68%.

2. EW precision fit in the SM

EW precision physics

- Electroweak precision observables (EWPO) offer a very powerful handle on the mechanism of EWSB and allow us to strongly constrain NP models relevant to solve the hierarchy problem.

- The precise measurements of the Higgs/W/top masses at Tevatron and LHC improve EW fits.

  ⇨ No free SM parameter in the fit

- Theoretical calculations have been improved in recent years.

EW precision observables

$M_W, \;\; \Gamma_W$ and 13 Z-pole observables
(LEP2/Tevatron) (LEP/SLD)

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

$$\mathcal{L} = \frac{e}{2 s_W c_W} Z_\mu \bar{f} \left(g_V^f \gamma_\mu - g_A^f \gamma_\mu \gamma_5 \right) f$$

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

$$P_\tau^{\rm pol} = \mathcal{A}_\tau \qquad \sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4|Q_\ell|}\left[1 - {\rm Re}\left(\frac{g_V^\ell}{g_A^\ell}\right)\right]$$

$\Big\}\; g_V^f / g_A^f$

$$\Gamma_f = \Gamma(Z \to f\bar{f}) \propto |g_A^f|^2 \left[\left|\frac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right]$$

$$\Rightarrow \quad \Gamma_Z, \; \sigma_h^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_h}{\Gamma_Z^2}, \; R_\ell^0 = \frac{\Gamma_h}{\Gamma_\ell}, \; R_{c,b}^0 = \frac{\Gamma_{c,b}}{\Gamma_h}$$

$\Big\}\; g_V^f, \; g_A^f$

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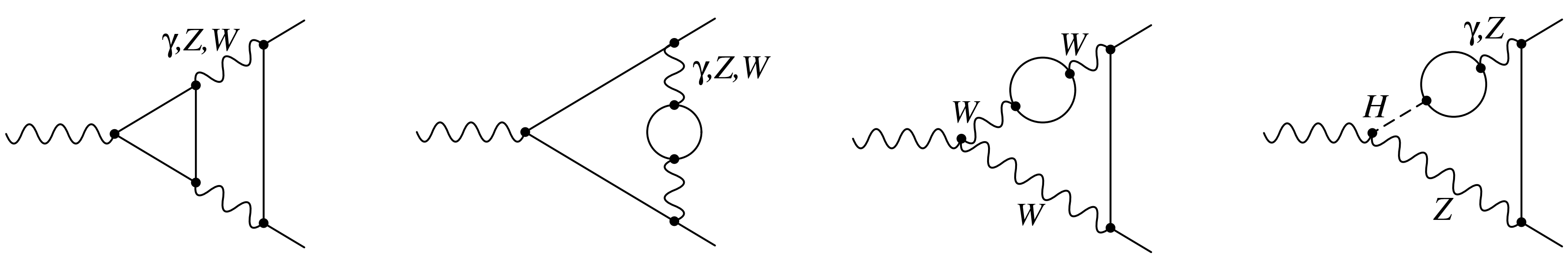
Theoretical status

- Mw has been calculated with full EW two-loop and leading higher-order contributions. *Awramik, Czakon, Freitas & Weiglein (04)*

- $\sin^2\theta_{\rm eff}^f$ have been calculated with full EW two-loop (bosonic is missing for f=b) and leading higher-order contributions. *Awramik, Czakon & Freitas (06); Awramik, Czakon, Freitas & Kniehl (09)*

- Full fermionic EW two-loop corrections to the Z-boson partial widths have been calculated recently. *Freitas & Huang (12); Freitas (13); Freitas (14)*



- Up-to-date formulae are available in on-shell scheme.

See also Sirlin; Marciano&Sirlin; Bardin et al; Djouadi&Verzegnassi; Djouadi; Kniehl; Halzen&Kniehl; Kniehl&Sirlin; Barbieri et al; Fleischer et al; Djouadi&Gambino; Degrassi et al; Avdeev et al; Chetyrkin et al; Freitas et al; Awramik&Czakon; Onishchenko&Veretin; Van der Bij et al; Faisst et al; Awramik et al, and many other works

Theoretical status

A. Freitas, 1406.6980

	M_W	Γ_Z	σ^0_{had}	R_b	$\sin^2\theta^\ell_{eff}$
Exp. error	15 MeV	2.3 MeV	37 pb	6.6×10^{-4}	1.6×10^{-4}
Theory error	4 MeV	0.5 MeV	6 pb	1.5×10^{-4}	0.5×10^{-4}

Theory errors from missing higher-order corrections are safely below current experimental errors.

EW precision fit

- Erler et al. (for PDG) *http://www.fisica.unam.mx/erler/GAPPP.html*

  GAPP (Global Analysis of Particle Properties)

  MSbar scheme & frequentist

- Gfitter group

  Gfitter (Generic fitting package) *http://gfitter.desy.de*

  on-shell scheme & frequentist

- Many other groups with ZFITTER *http://zfitter.com*

  on-shell scheme

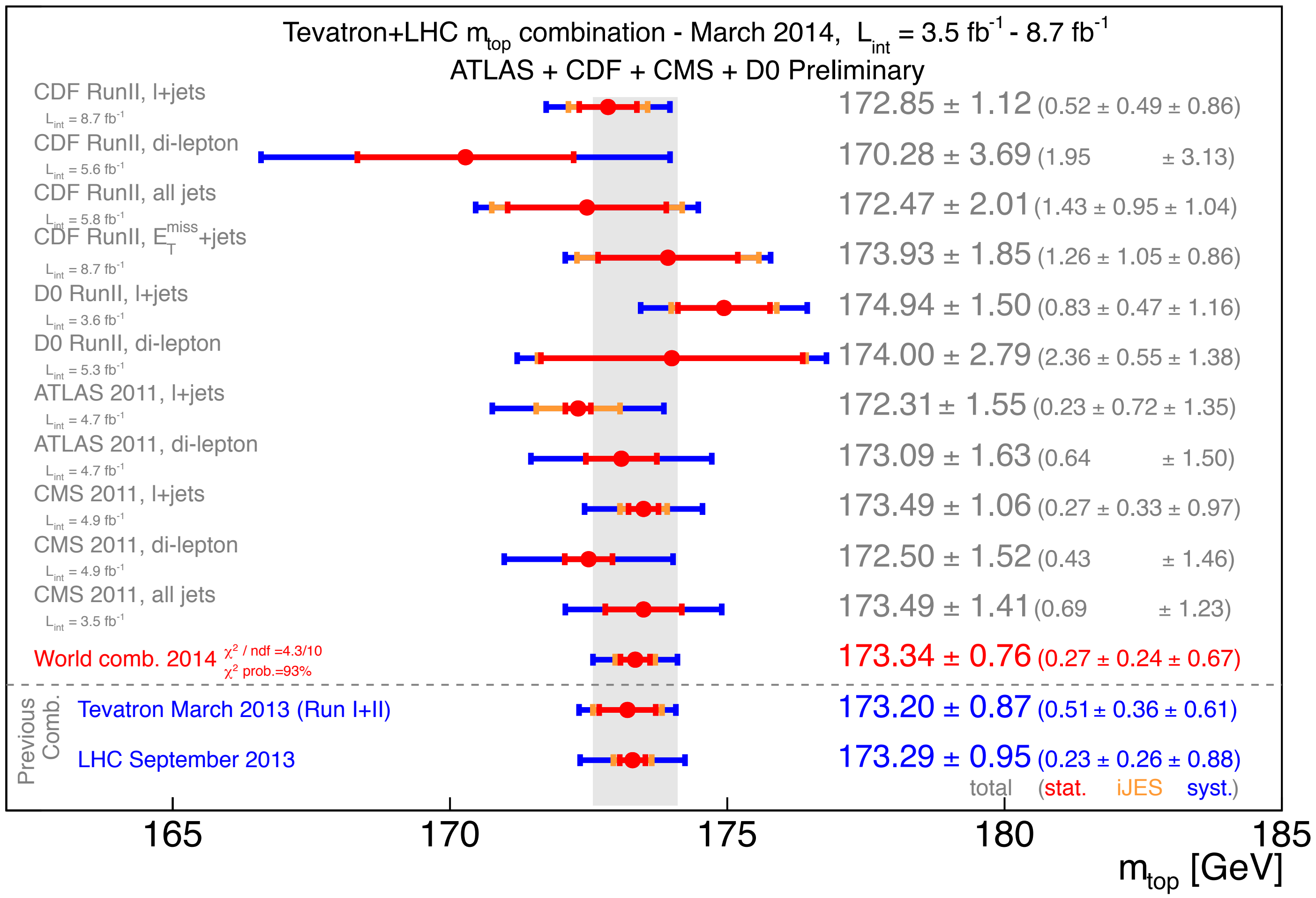
- Our group *M. Ciuchini, E. Franco, S.M., L. Silvestrini and others …*

  on-shell scheme & Bayesian

Measurements of the top pole mass

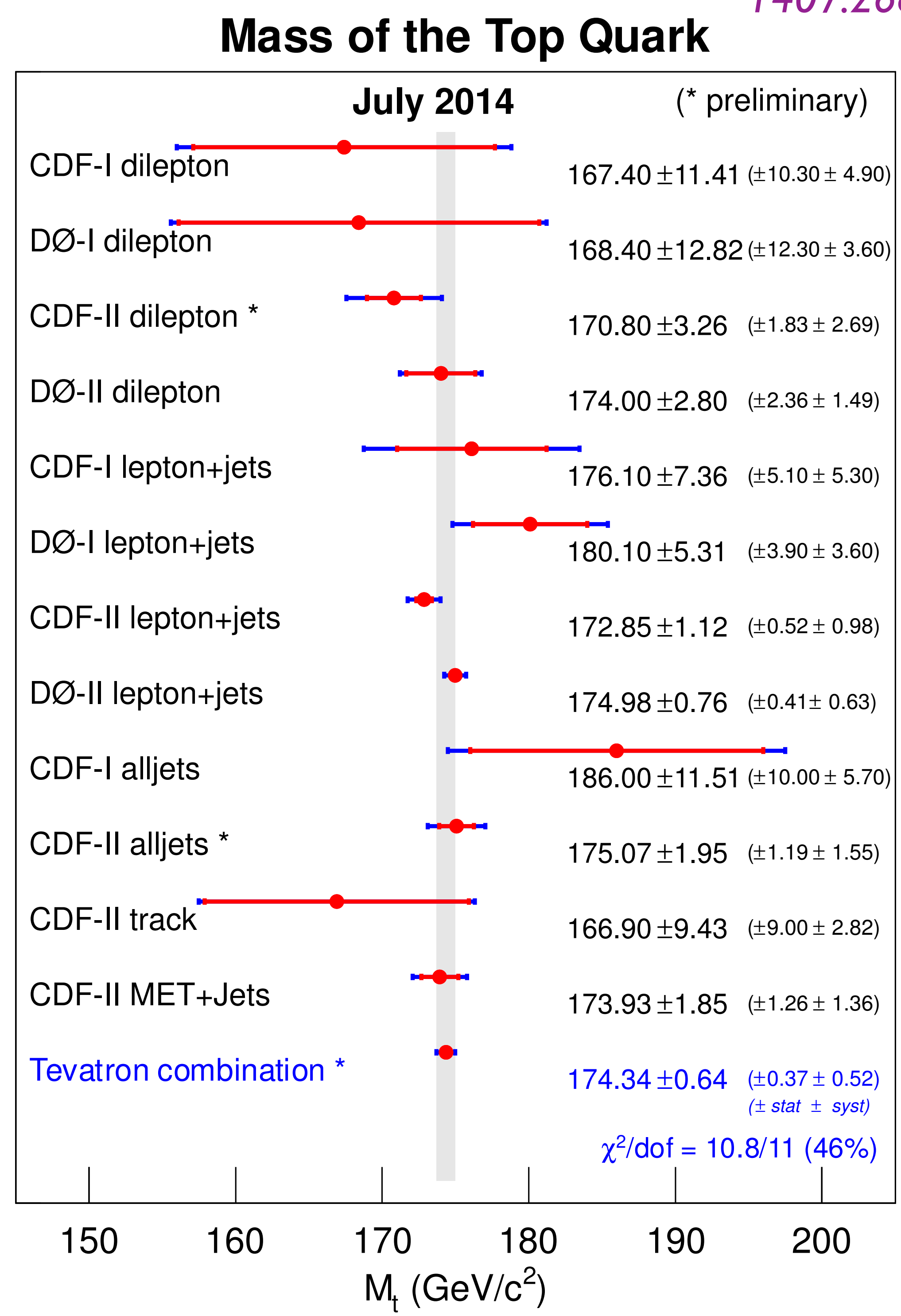
Tevatron +LHC combination

1403.4427



New Tevatron combination

1407.2682



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Ambiguity in the top pole mass

- The measurements of the pole mass of the top quark at Tevatron and LHC suffer from ambiguities:

parton shower models, color reconnections, …

M. Mangano at TOP2013:

"All in all I believe that it is justified to assume that MC mass parameter is interpreted as m_{pole} within the ambiguity intrinsic in the definition of m_{pole}, thus at the level of ~250-500 MeV."

Moch et al., 1405.4781 (report on the 2014 MITP scientific program):

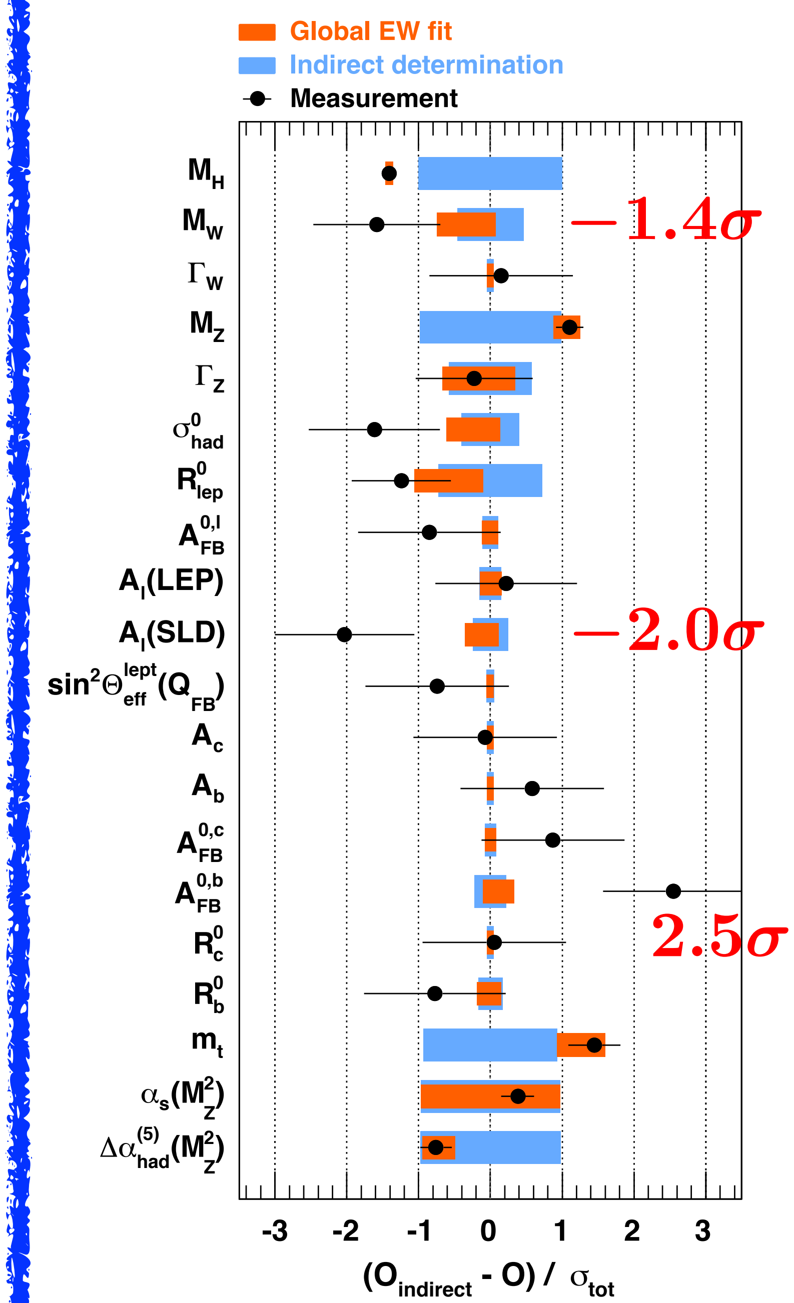
"The uncertainty on the translation from the MC mass definition to a theoretically well defined short-distance mass definition at a low scale is currently estimated to be of the order of 1 GeV." (There is an additional uncertainty originating from the conversion of the short-distance mass to pole mass.)

- We take a naive combination of Tevatron/LHC, and assume the additional uncertainty of 1 GeV.

SM fit

	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1185 ± 0.0005	0.1185 ± 0.0005	0.1186 ± 0.0028	$+0.0$
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	0.02745 ± 0.00026	0.02737 ± 0.00043	-0.2
M_Z [GeV]	91.1875 ± 0.0021	91.1878 ± 0.0020	91.195 ± 0.012	$+0.7$
m_t [GeV]	$174.01 \pm 0.53 \pm 1.00$	174.3 ± 0.8	176.6 ± 2.6	$+1.2$
m_h [GeV]	125.14 ± 0.24	125.14 ± 0.24	105.80 ± 28.28	-0.5
M_W [GeV]	80.385 ± 0.015	80.371 ± 0.007	80.367 ± 0.007	-1.1
Γ_W [GeV]	2.085 ± 0.042	2.0894 ± 0.0005	2.0894 ± 0.0005	$+0.1$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4946 ± 0.0005	2.4946 ± 0.0005	-0.3
σ_h^0 [nb]	41.540 ± 0.037	41.488 ± 0.003	41.488 ± 0.003	-1.4
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23144 ± 0.00009	0.23144 ± 0.00009	-0.8
$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1476 ± 0.0007	0.1477 ± 0.0007	$+0.4$
$\mathcal{A}_\ell$ (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	20.751 ± 0.003	20.751 ± 0.003	-0.6
R_c^0	0.1721 ± 0.0030	0.17225 ± 0.00001	0.17225 ± 0.00001	$+0.0$
R_b^0	0.21629 ± 0.00066	0.21576 ± 0.00003	0.21576 ± 0.00003	-0.8
δM_W [GeV]	$[-0.004,\ 0.004]$			
$\delta\sin^2\theta_{\rm eff}^{\rm lept}$	$[-4.7,\ 4.7]\cdot 10^{-5}$			
$\delta\Gamma_Z$ [GeV]	$[-5,\ 5]\cdot 10^{-4}$			

Gfitter, 1407.3792



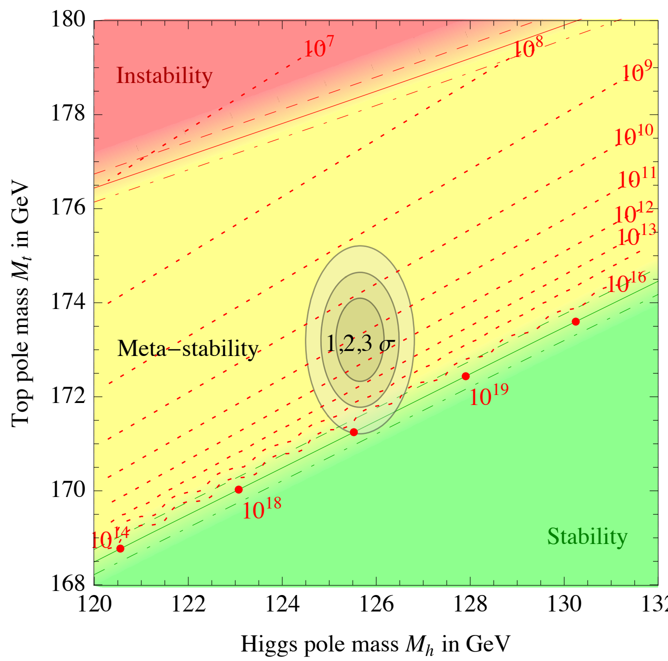
$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = 0.02757 \pm 0.00010$$

Indirect: determined w/o using the corresponding experimental information

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)*

$$m_t^{\rm pole} < 171.53 \pm 0.42\ {\rm GeV}$$



- Tevatron/LHC measurements:

  174.34 ± 0.64 GeV (Tevatron)

  173.29 ± 0.95 GeV (LHC)

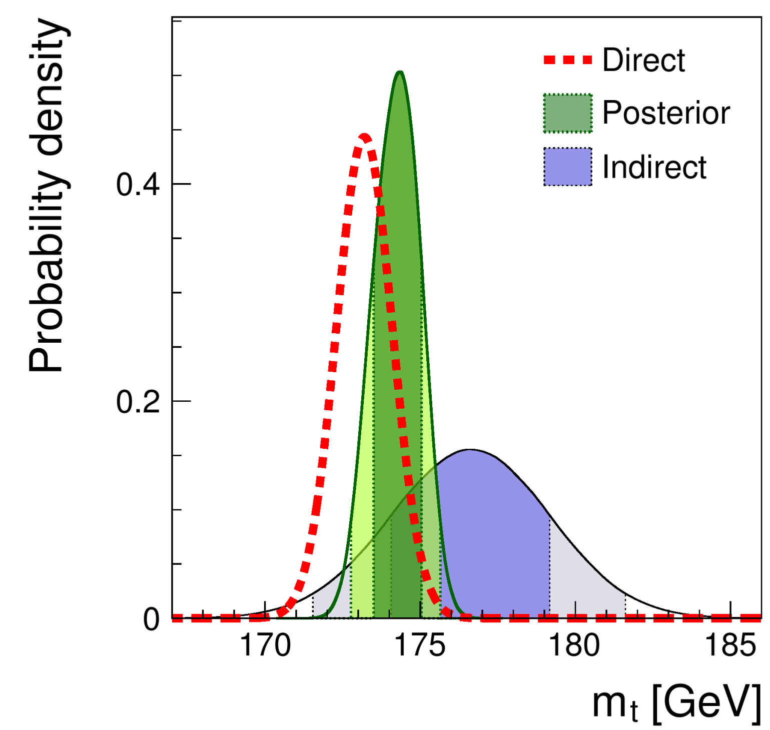
  extra uncertainty of O(1 GeV)

- Pole from MSbar: 171.2 ± 2.4 GeV

  1405.4781

- Indirect determination from EW fit:

$$176.6 \pm 2.6\ {\rm GeV}$$



- Caveat: Threshold corrections at the Planck scale alter the phase diagram.

Branchina & Messina (13); Branchina, Messina & Platania (14)

3. Constraints on the coefficients of dim-6 operators

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Indirect and direct contributions

$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$$
$$= \frac{v^2}{4}\left(1 + \frac{2h}{v} + \frac{h^2}{v^2}\right)(\partial^\mu h)(\partial_\mu h) + \frac{g^2 v^4}{16 c_W^2} Z^\mu Z_\mu \left(1 + \frac{4h}{v} + \frac{6h^2}{v^2} + \frac{4h^3}{v^3} + \frac{h^4}{v^4}\right)$$

- Indirect contribution via input parameters:

$$M_Z^2 = M_{Z,\mathrm{SM}}^2 \left(1 + \frac{v^2}{2\Lambda^2} C_{HD}\right)$$

⇨ contributes to EW/Higgs observables.

- Direct contribution:

$$\mathcal{L}_{\mathrm{eff}} = \frac{M_Z^2}{v} \left(1 + \frac{v^2}{\Lambda^2} C_{HD}\right) Z_\mu Z^\mu h$$

Indirect and direct contributions

Indirect contributions | **Direct contributions**

Operator	Kinetic terms					SM param's			Direct contribution to interactions						
	G^A	W^I	B	W^3B	H	M_Z	v	Y_f	WWV	$Wf\bar{f}'$	$Zf\bar{f}$	hVV	$hf\bar{f}$	$hVq\bar{q}$	4ℓ
$\mathcal{O}_{HG}$	√											√			
$\mathcal{O}_{HW}$		√										√			
$\mathcal{O}_{HB}$			√									√			
$\mathcal{O}_{HWB}$				√					√			√			
$\mathcal{O}_{HD}$					√	√						√			
$\mathcal{O}_{H\Box}$					√										
$\mathcal{O}_{HL}^{(1)}$											√				
$\mathcal{O}_{HL}^{(3)}$										√	√				
$\mathcal{O}_{HQ}^{(1)}$											√			√	
$\mathcal{O}_{HQ}^{(3)}$										√	√			√	
$\mathcal{O}_{He}$											√				
$\mathcal{O}_{Hu}$											√			√	
$\mathcal{O}_{Hd}$											√			√	
$\mathcal{O}_{Hud}$										√				√	
$\mathcal{O}_{eH}$								√					√		
$\mathcal{O}_{uH}$								√					√		
$\mathcal{O}_{dH}$								√					√		
$\mathcal{O}_{LL}$															√

$$\mathcal{O}_{HG} = (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H) W^I_{\mu\nu} W^{I\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$
$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$
$$\mathcal{O}_{HL}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$$
$$\mathcal{O}_{HL}^{(3)} = (H^\dagger i \overleftrightarrow{D}{}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L)$$
$$\mathcal{O}_{HQ}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{O}_{HQ}^{(3)} = (H^\dagger i \overleftrightarrow{D}{}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$$
$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$$
$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$$
$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}\, e_R H)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\, u_R \widetilde{H})$$
$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}\, d_R H)$$
$$\mathcal{O}_{LL} = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$$

Dim-6 contributions to EWPO

$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$ → *S parameter (W_3-B mixing)*

$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$ → *T parameter (M_Z)*

$$\mathcal{O}_{LL} = (\overline{L}\gamma_\mu L)(\overline{L}\gamma^\mu L)$$

$$\mathcal{O}^{(3)}_{HL} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{L}\tau^I \gamma^\mu L)$$

$\mathcal{O}_{LL}$, $\mathcal{O}^{(3)}_{HL}$ → *Fermi constant*

$$\mathcal{O}^{(1)}_{HL} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{L}\gamma^\mu L)$$

$$\mathcal{O}^{(3)}_{HQ} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{Q}\tau^I \gamma^\mu Q)$$

$$\mathcal{O}^{(1)}_{HQ} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{Q}\gamma^\mu Q)$$

$\mathcal{O}^{(3)}_{HL}$, $\mathcal{O}^{(1)}_{HL}$, $\mathcal{O}^{(3)}_{HQ}$, $\mathcal{O}^{(1)}_{HQ}$ → *Left-handed $Zf\bar{f}$*

$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e}_R\gamma^\mu e_R)$$

$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u}_R\gamma^\mu u_R)$$

$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d}_R\gamma^\mu d_R)$$

$\mathcal{O}_{He}$, $\mathcal{O}_{Hu}$, $\mathcal{O}_{Hd}$ → *Right-handed $Zf\bar{f}$*

- There are flat directions in the fit. *See, e.g., Han & Skiba (05)*
- switch on one operator at a time to avoid the flat directions and accidental cancellations.

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Higgs data

- We use the ATLAS/CMS (and CDF/D0) data for the Higgs signal strengths relative to the SM expectations.

  $ZZ,\ W^+W^-,\ \gamma\gamma,\ \tau^+\tau^-,\ b\bar{b}$ channels

  divided into different categories to improve sensitivity to each production mechanism

- We assume that the efficiency of event selection for a given category is similar to that in the SM. This assumption is valid for small deviations from the SM couplings, which do not modify kinematic distributions significantly.

Fit results at 95% in units of $1/\Lambda^2\ \mathrm{TeV}^{-2}$

Coefficient	EW	Higgs	EW+Higgs
C_{HG}	—	$[-0.0077, 0.0066]$	$[-0.0077, 0.0066]$
C_{HW}	—	$[-0.039, 0.012]$	$[-0.039, 0.012]$
C_{HB}	—	$[-0.011, 0.003]$	$[-0.011, 0.003]$
C_{HWB}	$[-0.0094, 0.0055]$	$[-0.006, 0.020]$	$[-0.0063, 0.0066]$
C_{HD}	$[-0.029, 0.009]$	$[-5.3, 8.5]$	$[-0.029, 0.009]$
$C_{H\Box}$	—	$[-1.2, 2.0]$	$[-1.2, 2.0]$
$C_{HL}^{(1)}$	$[-0.005, 0.011]$	—	$[-0.005, 0.011]$
$C_{HL}^{(3)}$	$[-0.011, 0.007]$	$[-1.5, 0.5]$	$[-0.011, 0.007]$
$C_{HQ}^{(1)}$	$[-0.027, 0.041]$	$[-28, 15]$	$[-0.027, 0.041]$
$C_{HQ}^{(3)}$	$[-0.011, 0.013]$	$[-0.6, 2.2]$	$[-0.011, 0.013]$
C_{He}	$[-0.017, 0.006]$	—	$[-0.017, 0.006]$
C_{Hu}	$[-0.071, 0.076]$	$[-5, 11]$	$[-0.071, 0.077]$
C_{Hd}	$[-0.14, 0.06]$	$[-33, 15]$	$[-0.14, 0.06]$
C_{Hud}	—	—	—
C_{eH}	—	$[-0.071, 0.024]$	$[-0.071, 0.024]$
C_{uH}	—	$[-0.50, 0.59]$	$[-0.50, 0.59]$
C_{dH}	—	$[-0.072, 0.078]$	$[-0.072, 0.078]$
C_{LL}	$[-0.012, 0.021]$	$[-1.0, 3.0]$	$[-0.012, 0.021]$

$$\mathcal{O}_{HG} = (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H) W^I_{\mu\nu} W^{I\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$
$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$
$$\mathcal{O}_{HL}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$$
$$\mathcal{O}_{HL}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I \gamma^\mu L)$$
$$\mathcal{O}_{HQ}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{O}_{HQ}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I \gamma^\mu Q)$$
$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$
$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$$
$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$$
$$\mathcal{O}_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_R \gamma^\mu d_R)$$
$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}\, e_R H)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\, u_R \widetilde{H})$$
$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}\, d_R H)$$
$$\mathcal{O}_{LL} = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$$

$gg \to h$ (one-loop in the SM)

$$\mathcal{L}_{\rm NP} = \left(\frac{v}{\Lambda^2} C_{HG} + \cdots\right) G^A_{\mu\nu} G^{A\mu\nu} h$$

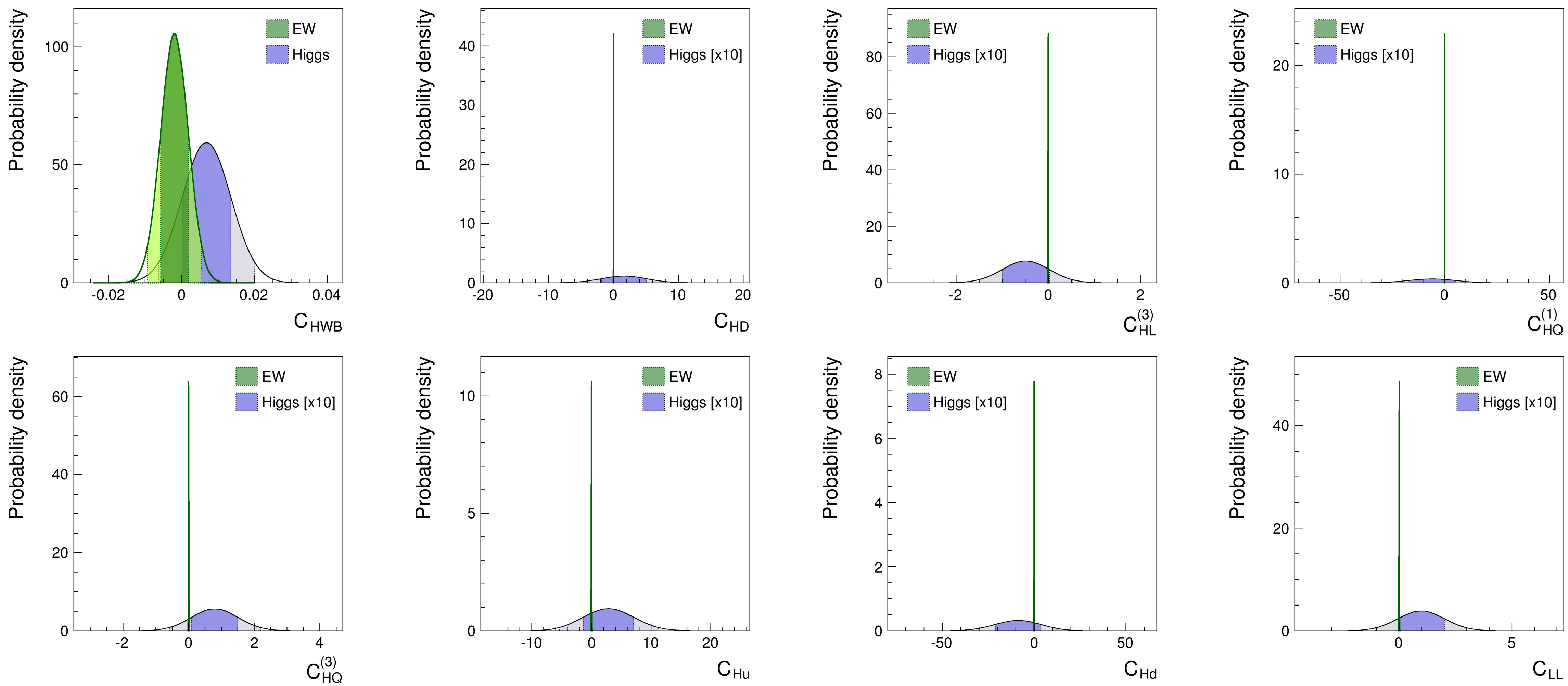
$h \to \gamma\gamma$ (one-loop in the SM)

$$\mathcal{L}_{\rm NP} = \frac{v}{\Lambda^2}(s_W^2 C_{HW} + c_W^2 C_{HB} - s_W c_W C_{HWB}) F_{\mu\nu} F^{\mu\nu} h$$

$h \to f\bar{f}$ (suppressed by mf for light fermions in the SM)

$$\mathcal{L}_{\rm NP} = \frac{v^2}{\sqrt{2}\Lambda^2} C_{fH} \bar{f}_L f_R h + \mathrm{h.c.}$$

EW vs. Higgs



- Except for C_{HWB}, the constraints from the Higgs data are much weaker than those from the EW data.

  ➡ Those operators do not yield significant deviations in the Higgs couplings.

Lower bounds on the NP scale in TeV

Coefficient	EW $C_i=-1$	EW $C_i=1$	Higgs $C_i=-1$	Higgs $C_i=1$	EW+Higgs $C_i=-1$	EW+Higgs $C_i=1$
C_{HG}	—	—	11.4	12.3	11.4	12.3
C_{HW}	—	—	5.1	9.1	5.1	9.1
C_{HB}	—	—	9.6	17.2	9.6	17.2
C_{HWB}	10.3	13.4	12.6	7.1	12.6	12.3
C_{HD}	5.9	10.8	0.4	0.3	5.9	10.8
$C_{H\Box}$	—	—	0.9	0.7	0.9	0.7
$C_{HL}^{(1)}$	13.9	9.3	—	—	13.9	9.3
$C_{HL}^{(3)}$	9.7	11.9	0.8	1.4	9.6	11.9
$C_{HQ}^{(1)}$	6.1	4.9	0.2	0.3	6.1	4.9
$C_{HQ}^{(3)}$	9.4	8.7	1.3	0.7	9.4	8.7
C_{He}	7.7	13.4	—	—	7.7	13.4
C_{Hu}	3.8	3.6	0.4	0.3	3.8	3.6
C_{Hd}	2.7	4.0	0.2	0.3	2.7	4.0
C_{Hud}	—	—	—	—	—	—
C_{eH}	—	—	3.8	6.4	3.8	6.4
C_{uH}	—	—	1.4	1.3	1.4	1.3
C_{dH}	—	—	3.7	3.6	3.7	3.6
C_{LL}	9.3	7.0	1.0	0.6	9.3	7.0

$$\mathcal{O}_{HG} = (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H) W^I_{\mu\nu} W^{I\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$
$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$
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$$\mathcal{O}_{HL}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L)$$
$$\mathcal{O}_{HQ}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{O}_{HQ}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$$
$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$$
$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$$
$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}\, e_R H)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\, u_R \widetilde{H})$$
$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}\, d_R H)$$
$$\mathcal{O}_{LL} = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$$

Lower bounds are multi-TeV to 17 TeV.

4. Summary

- We have presented an updated fit to the EW precision data in the SM, and that to the EW precision and Higgs data in the effective theory approach.
- The constraints from EW precision data and Higgs data are complementary to each other.
- Some of the results presented in this talk (especially those with the Higgs data) are still very preliminary.

  - estimates of theoretical uncertainties

  - inclusion of more data in the fit

    e.g., measurements of TGCs
    kinematic distributions in H+V associated production

    J. Ellis, V. Sanz & T. You (14)

    ⇨ remove flat directions in the fit

Backup

Hadronic corrections to the EM coupling

- We adopt a conservative value:

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = 0.02750 \pm 0.00033$$

measured with inclusive processes.

Burkhardt & Pietrzyk (11)
(see also Davier et al(11); Hagiwara et al(11) ; Jegerlehner(11))

Note: Smaller uncertainty has been obtained if using exclusive processes with pQCD:

$$\delta\big(\Delta\alpha^{(5)}_{\rm had}(M_Z^2)\big) \sim \pm 0.00010$$

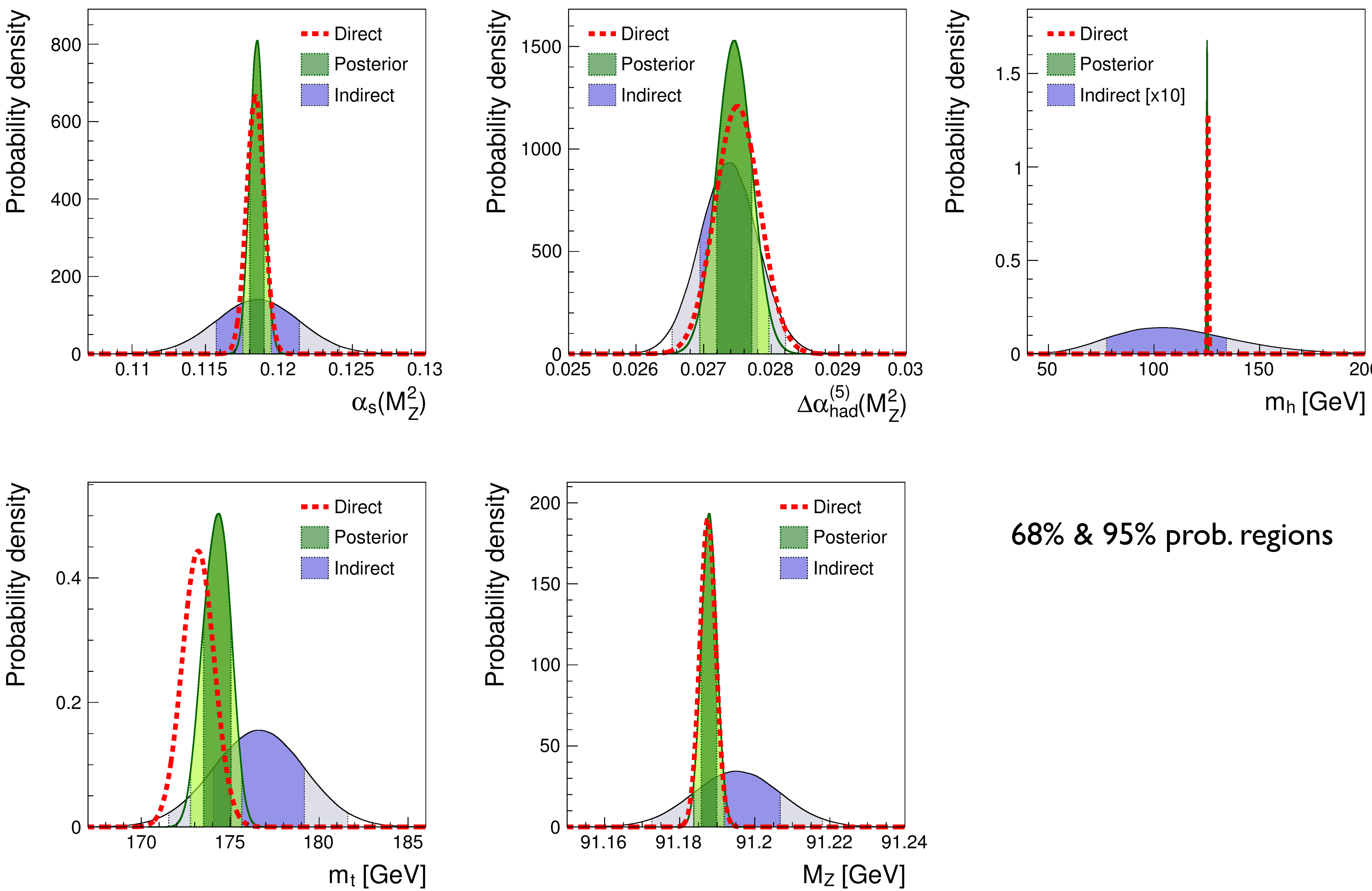
but discrepancy has been observed between inclusive and exclusive in low-energy data.

Parametric uncertainties

- $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ and m_t are the most important sources of parametric uncertainty.

	Prediction	α_s	$\Delta\alpha^{(5)}_{\rm had}$	M_Z	m_t
M_W [GeV]	80.368 ± 0.008	± 0.000	± 0.006	± 0.003	± 0.005
Γ_W [GeV]	2.0892 ± 0.0007	± 0.0002	± 0.0005	± 0.0002	± 0.0004
Γ_Z [GeV]	2.4945 ± 0.0006	± 0.0002	± 0.0003	± 0.0002	± 0.0002
σ_h^0 [nb]	41.489 ± 0.003	± 0.002	± 0.000	± 0.002	± 0.001
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.23147 ± 0.00012	± 0.00000	± 0.00012	± 0.00001	± 0.00003
$P_\tau^{\rm pol}$	0.1475 ± 0.0010	± 0.0000	± 0.0009	± 0.0001	± 0.0002
$\mathcal{A}_\ell$ (SLD)	0.1475 ± 0.0010	± 0.0000	± 0.0009	± 0.0001	± 0.0002
$\mathcal{A}_c$	0.6681 ± 0.0004	± 0.0000	± 0.0004	± 0.0001	± 0.0001
$\mathcal{A}_b$	0.93465 ± 0.00008	± 0.00000	± 0.00007	± 0.00001	± 0.00001
$A_{\rm FB}^{0,\ell}$	0.0163 ± 0.0002	± 0.0000	± 0.0002	± 0.0000	± 0.0000
$A_{\rm FB}^{0,c}$	0.0739 ± 0.0005	± 0.0000	± 0.0005	± 0.0001	± 0.0001
$A_{\rm FB}^{0,b}$	0.1034 ± 0.0007	± 0.0000	± 0.0006	± 0.0001	± 0.0001
R_ℓ^0	20.751 ± 0.004	± 0.003	± 0.002	± 0.000	± 0.000
R_c^0	0.17224 ± 0.00001	± 0.00001	± 0.00001	± 0.00000	± 0.00001
R_b^0	0.21577 ± 0.00003	± 0.00001	± 0.00000	± 0.00000	± 0.00003

Direct and indirect measurements



68% & 95% prob. regions

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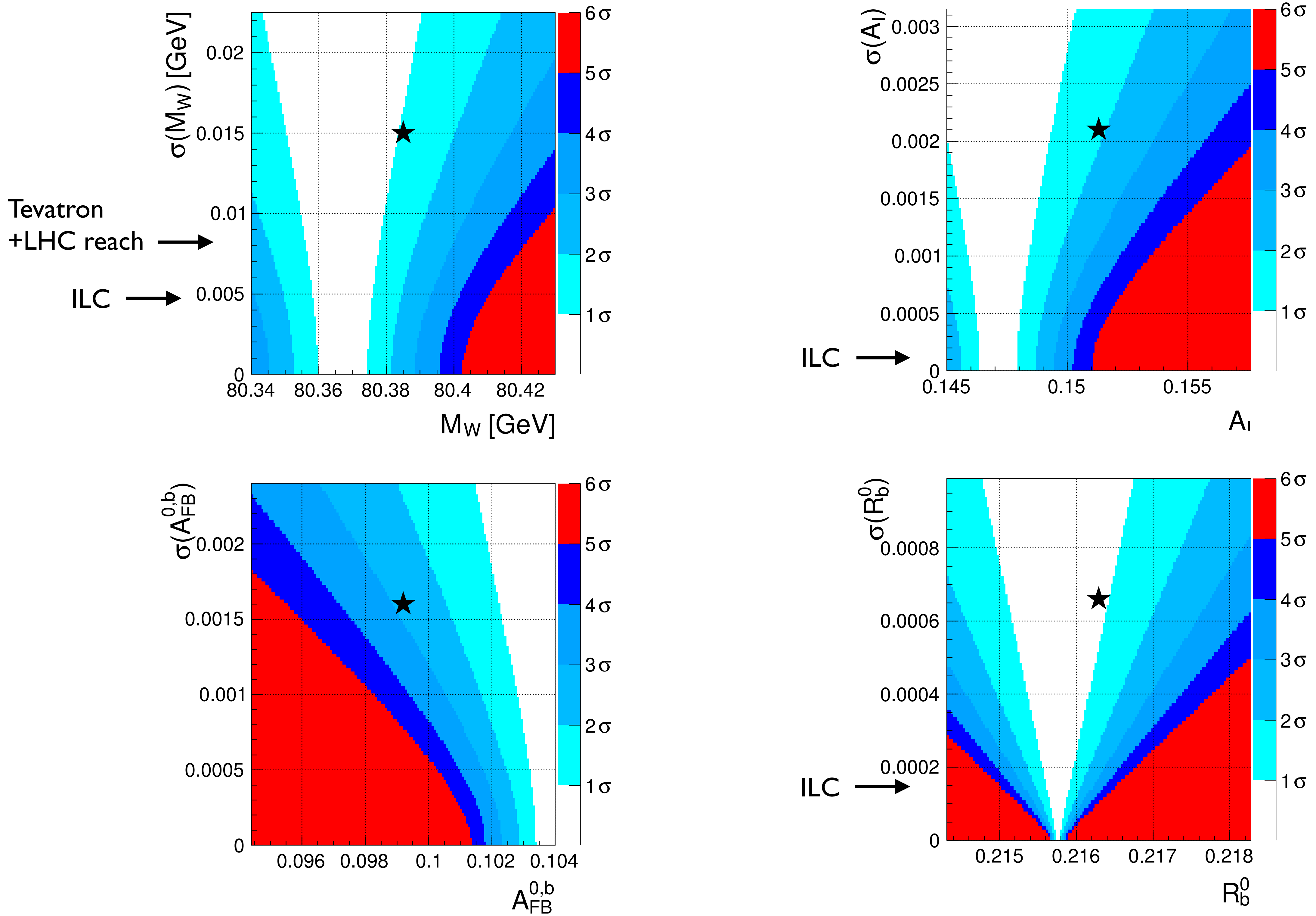
Future prospect



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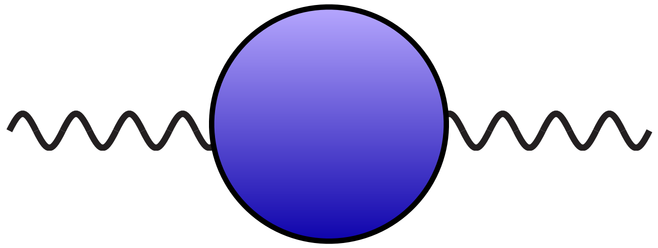
Oblique parameters

- 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 three combinations:

$$\delta M_W,\ \delta\Gamma_W \propto -S + 2c_W^2\, T + \frac{(c_W^2 - s_W^2)\, U}{2 s_W^2}$$
$$\delta\Gamma_Z \propto -10(3 - 8 s_W^2)\, S + (63 - 126 s_W^2 - 40 s_W^4)\, T$$
$$\text{others} \propto S - 4 c_W^2 s_W^2\, T$$

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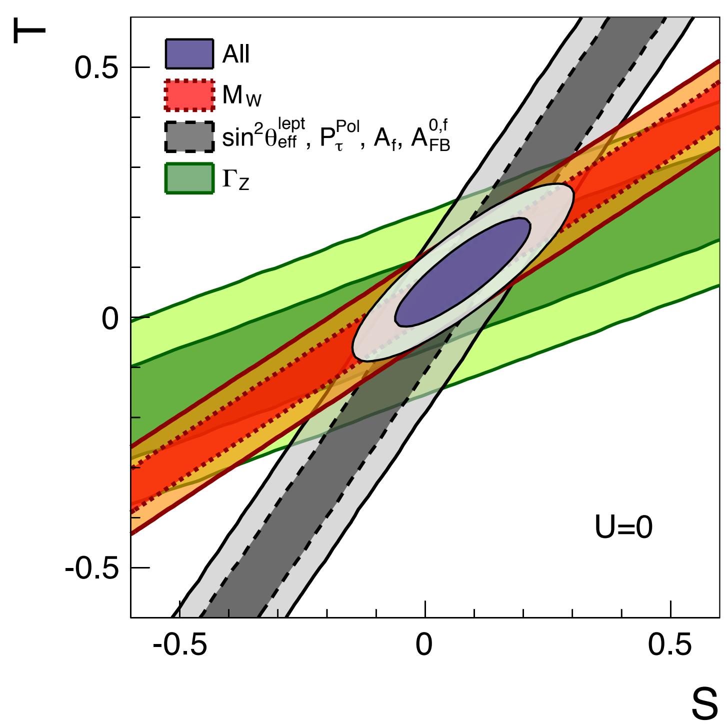
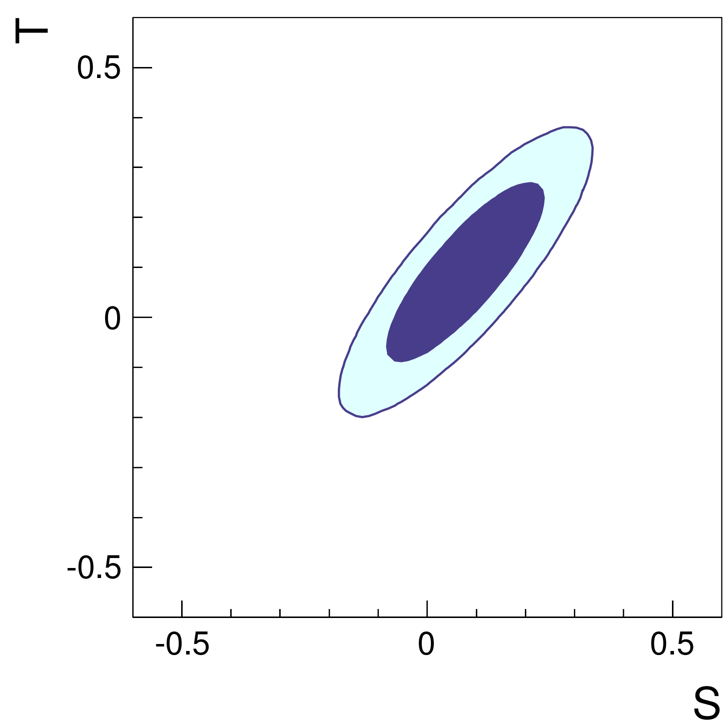
Fit results for oblique parameters

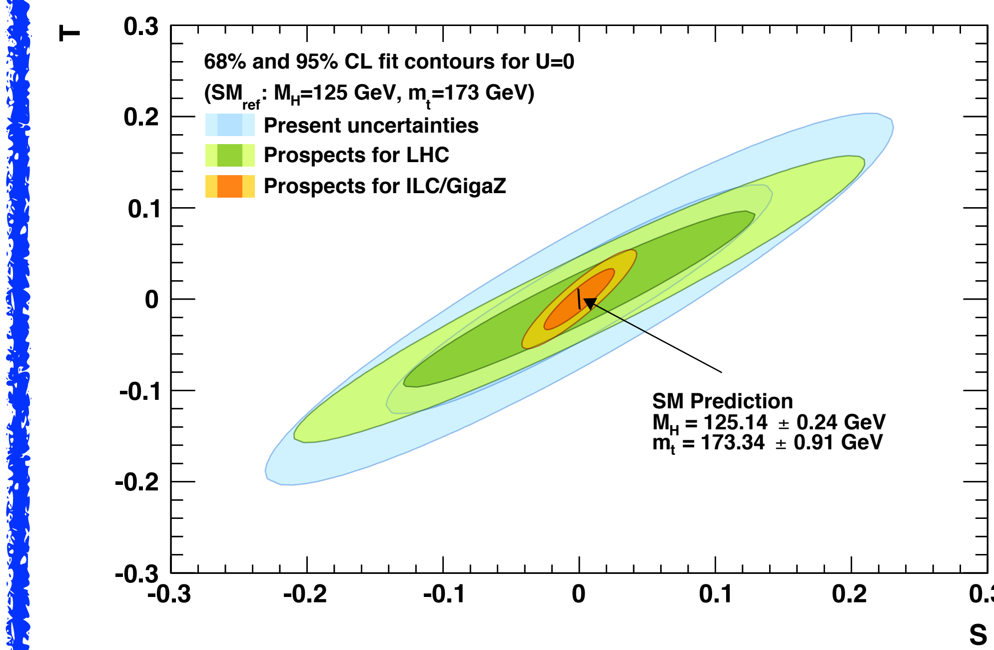


	Fit result	Correlations	
S	0.08 ± 0.09	1.00	
T	0.09 ± 0.07	0.87	1.00



	Fit result	Correlations		
S	0.08 ± 0.10	1.00		
T	0.09 ± 0.12	0.85	1.00	
U	0.00 ± 0.09	-0.48	-0.79	1.00

Gfitter, 1407.3792



	Fit result	Correlations	
S	0.06 ± 0.09	1.00	
T	0.10 ± 0.07	0.91	1.00

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Epsilon parameters

$$\epsilon_1 = \Delta\rho'$$
$$\epsilon_2 = c_0^2\Delta\rho' + \frac{s_0^2}{c_0^2 - s_0^2}\Delta r_W - 2s_0^2\Delta\kappa'$$
$$\epsilon_3 = c_0^2\Delta\rho' + (c_0^2 - s_0^2)\Delta\kappa'$$

and ϵ_b

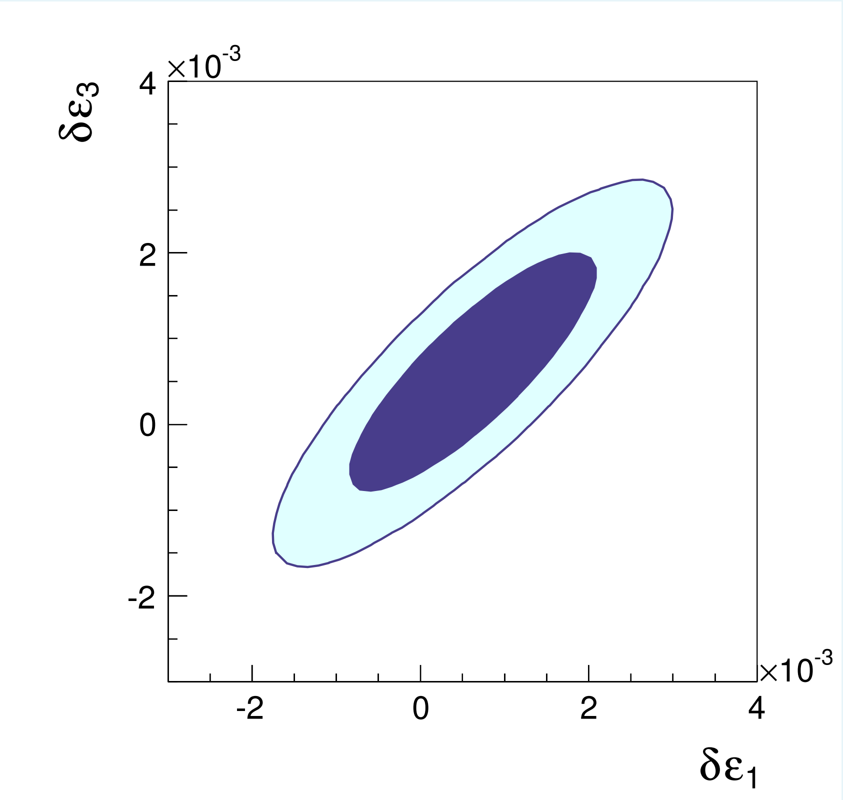
Altarelli et al. (91,92,93)

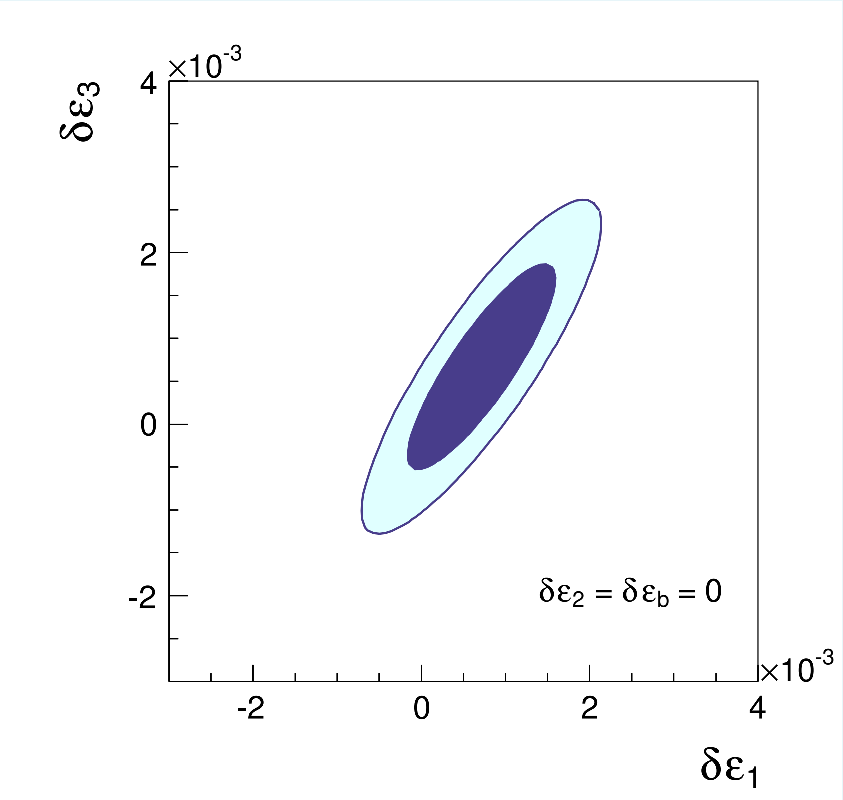
$$s_W^2 c_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_\mu M_Z^2(1-\Delta r_W)}$$
$$\sqrt{\mathrm{Re}\,\rho_Z^e} = 1 + \frac{\Delta\rho'}{2}$$
$$\sin^2\theta_{\mathrm{eff}}^e = (1+\Delta\kappa')\,s_0^2$$
$$s_0^2\,c_0^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_\mu M_Z^2}$$

- ϵ_i involve the oblique corrections beyond S,T and U.
  i.e., W, Y, …
- Unlike STU, ϵ_i involve non-oblique vertex corrections.
- Moreover, ϵ_i also involve SM contributions.

⇨ $$\delta\epsilon_i = \epsilon_i - \epsilon_i^{\mathrm{SM}}$$

Epsilon parameters





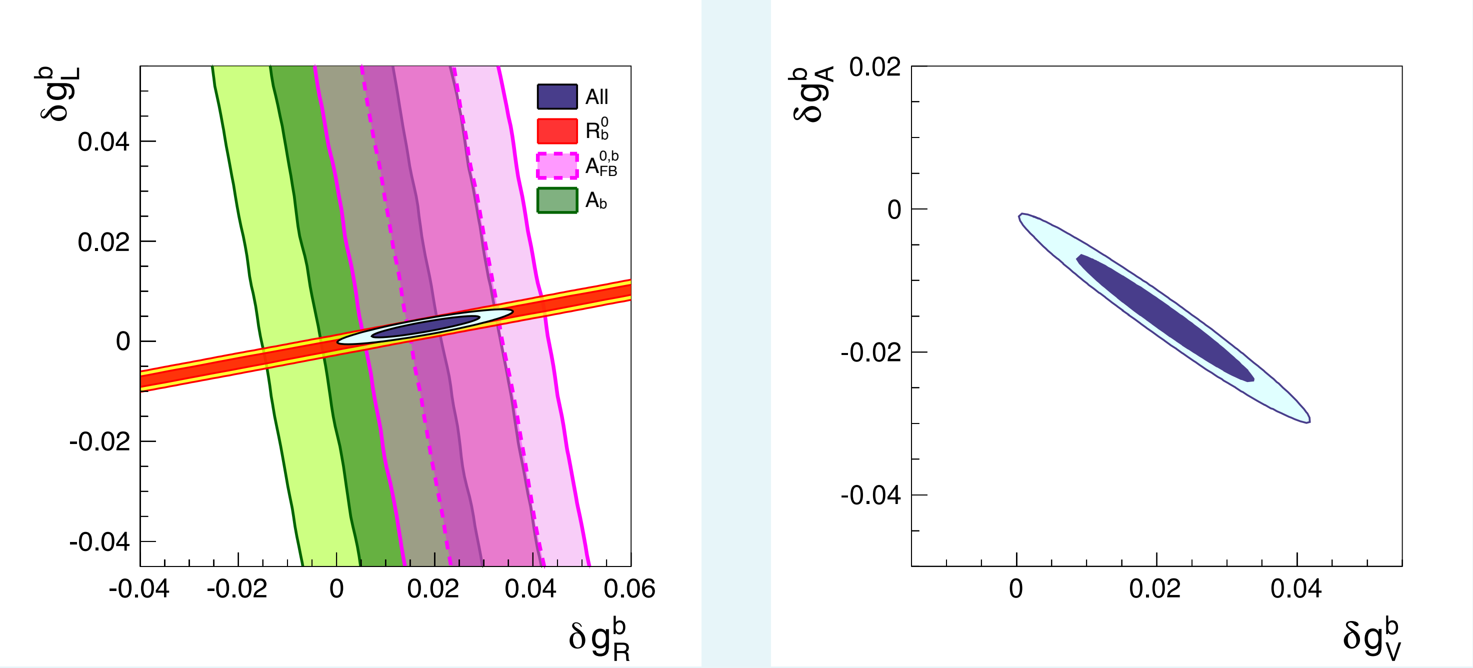
	Fit result	Correlations			
$\delta\epsilon_1$	0.0006 ± 0.0010	1.00			
$\delta\epsilon_2$	-0.0001 ± 0.0009	0.80	1.00		
$\delta\epsilon_3$	0.0006 ± 0.0009	0.85	0.50	1.00	
$\delta\epsilon_b$	0.0004 ± 0.0013	-0.33	-0.32	-0.21	1.00

	Fit result	Correlations	
$\delta\epsilon_1$	0.0007 ± 0.0006	1.00	
$\delta\epsilon_3$	0.0007 ± 0.0008	0.87	1.00

$Zb\bar{b}$ 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:



$$g_i^b = (g_i^b)_{\rm SM} + \delta g_i^b$$

	Fit result	Correlations	
δg_R^b	0.018 ± 0.007	1.00	
δg_L^b	0.0029 ± 0.0014	0.90	1.00
δg_V^b	0.021 ± 0.008	1.00	
δg_A^b	-0.015 ± 0.006	-0.99	1.00

- Deviation from the SM due to $A_{\rm FB}^{0,b}$ *See also Batell et al. (13)*

EW chiral Lagrangian

- No new state below cutoff + custodial symmetry:

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

Σ : Goldstone bosons

$\kappa_V = 1$ in the SM

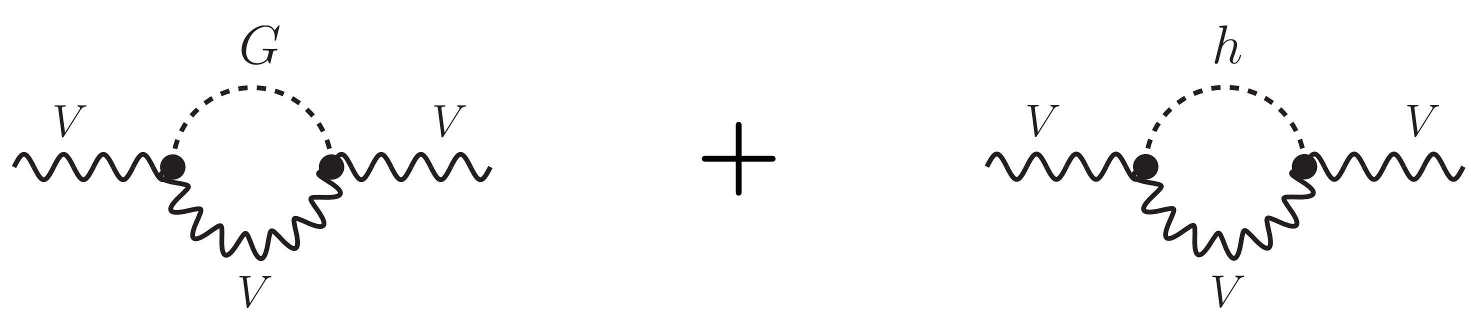
➡ The HVV coupling contributes to S and T at one-loop.

Barberi, Bellazzini, Rychkov & Varagnolo (07)

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

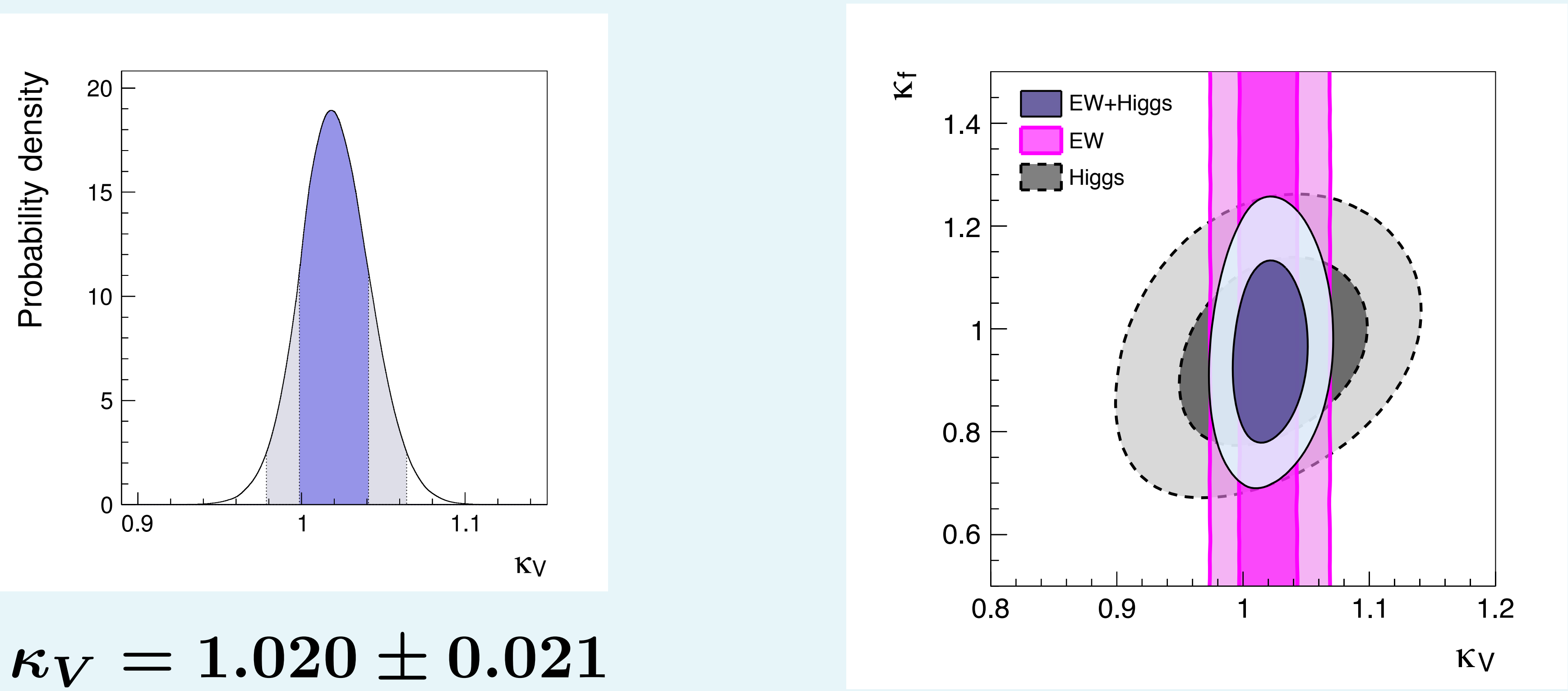
$$T = -\frac{3}{16\pi c_W^2}(1 - \kappa_V^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right)$$

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



$$\ln(\Lambda^2/M_Z^2) - \kappa_V^2 \ln(\Lambda^2/m_h^2)$$

EW chiral Lagrangian



$\kappa_V = 1.020 \pm 0.021$

- EWPO constraint on Kv is stronger than Higgs one, but no constraint on Kf.
- $\kappa_V > 1$ ⇨ WLWL scattering is dominated by isospin 2 channel

$$1 - \kappa_V^2 = \frac{v^2}{6\pi}\int_0^\infty \frac{ds}{s}\left(2\sigma^{\rm tot}_{I=0}(s) + 3\sigma^{\rm tot}_{I=1}(s) - 5\sigma^{\rm tot}_{I=2}(s)\right)$$

Falkowski, Rychkov & Urbano (12)

- $\Lambda \gtrsim 15\ \mathrm{TeV}\ @\,95\%\ \text{ for } \kappa_V < 1$

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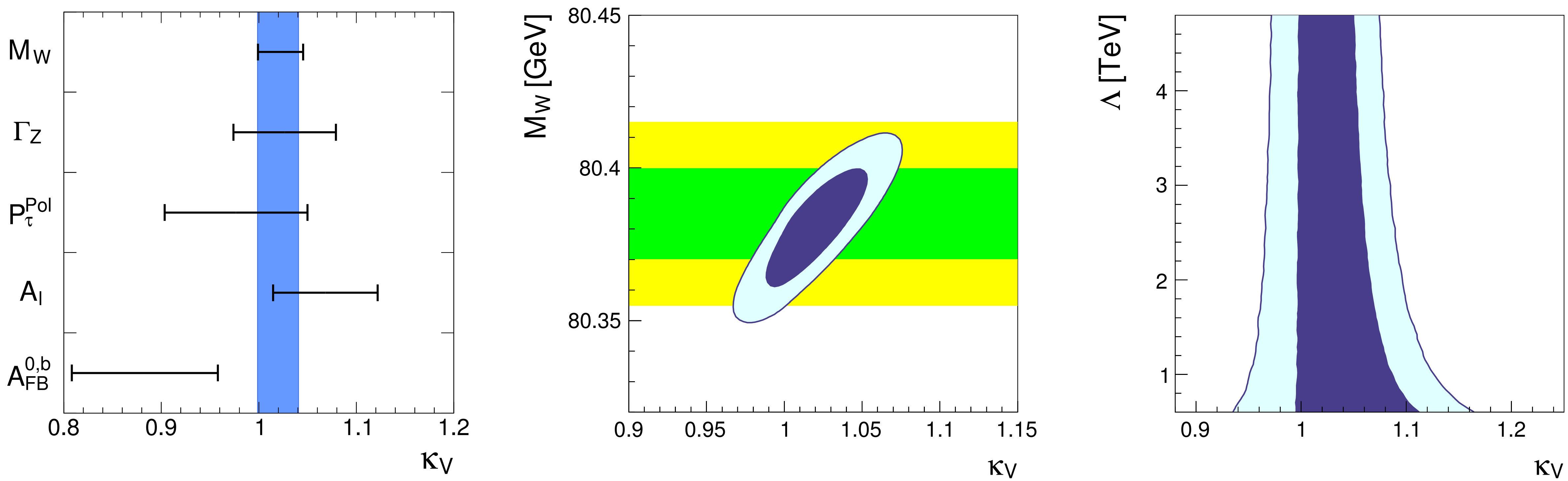
EW chiral Lagrangian



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

- smaller Mw ➩ smaller Kv
- Kv is tightly constrained for the scale compatible with direct searches.

Composite Higgs models

- Composite Higgs models typically generate $\kappa_V < 1$.

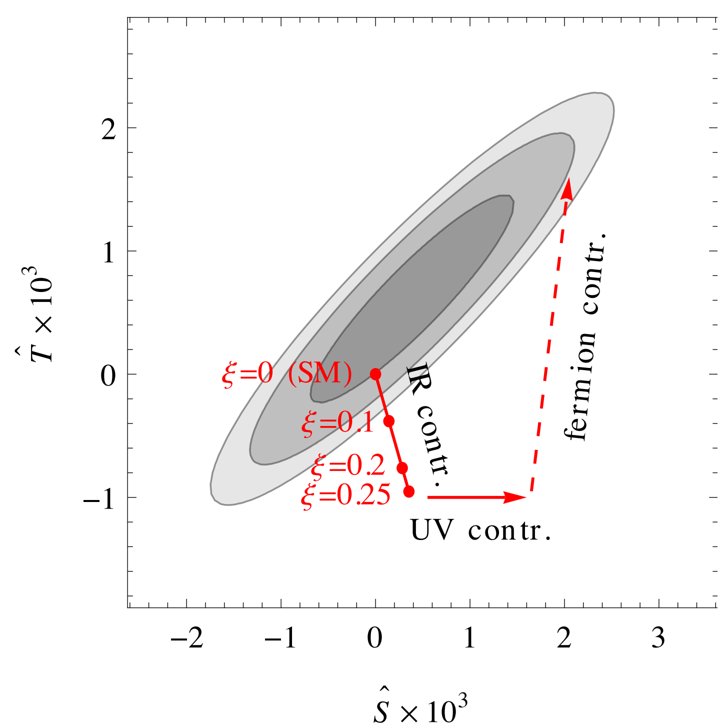
  e.g. Minimal Composite Higgs Models (MCHM) based on SO(5)/SO(4)

  Agashe, Contino & Pomarol (05)

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

f: scale of compositeness

- Extra contributions to S and T are required to fix the EW fit under $\kappa_V < 1$.



Grojean et al. (13)

IR contribution

+

UV cont' from heavy vector resonances

+

Fermionic resonances