Electroweak precision fit
and
model-independent constraints on new physics

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Update of the global fits in JHEP 08 (2013) 106 [arXiv:1306.4644[hep-ph]] with M. Ciuchini, E. Franco and L. Silvestrini.

4. Future sensitivity to NP

working with M. Bona, M. Ciuchini, E. Franco, M. Pierini and L. Silvestrini

5. Summary

1. Introduction

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

- 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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Our codes

- We have developed our own C++ codes for EWPO with up-to-date formulae for radiative corrections in the on-shell scheme.
- We perform a Bayesian analysis with MCMC by using the Bayesian Analysis Toolkit (BAT) library.

  Caldwell, Kollar & Kroninger

- Our fit results are in agreement with those from other groups:

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

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

  and others......

- Our EW codes will be released to the public soon!

EW precision observables

M_W, Γ_W and 13 Z-pole observables
(LEP2/Tevatron) (LEP/SLD)

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

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

$$\rho_Z^f = \left(\frac{g_A^f}{I_3^f}\right)^2$$

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

$$\left.\begin{aligned} &A_{\rm LR}^{0,f} = \mathcal{A}_f = \frac{2\,{\rm Re}\left(g_V^f/g_A^f\right)}{1+\left[{\rm Re}\left(g_V^f/g_A^f\right)\right]^2} \qquad A_{\rm FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad (f=\ell,c,b)\\ &P_\tau^{\rm pol} = \mathcal{A}_\tau \qquad \sin^2\theta_{\rm eff}^{\rm lept} = {\rm Re}(\kappa_Z^\ell)s_W^2 \end{aligned}\right\}\ \kappa_Z^f$$

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

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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)

- $\sin^2\theta_{\mathrm{eff}}^f$ (equivalent to κ_Z^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)

- Recently, full fermionic EW two-loop corrections to ρ_Z^f have been calculated with a numerical integration method.

  Freitas & Huang (12); Freitas (13)

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 others

Huge 2-loop corrections to R_b^0 ?

$$(R_b^0)_{\rm exp} = 0.21629 \pm 0.00066$$

- Freitas and Huang found that the subleading two-loop EW corrections to R_b^0 are very large:

Freitas & Huang (12)

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

$\Rightarrow$ $\gtrsim 2\sigma$ deviation!

- They have then found a mistake in their calculation, and the corrected result shows smaller subleading two-loop corrections.

$$R_b^0 = 0.21550 \ (\Delta R_b^0 = -0.00026)$$

2-loop corrections to other observables

- Moreover, Freitas has calculated full fermionic EW two-loop corrections to $\Gamma_Z, \ \sigma_h^0$.

R_b^0	*Freitas & Huang (12)*
R_c^0	*Freitas, private communication*
$\Gamma_Z, \ \sigma_h^0$	*Freitas (13)*
R_ℓ^0	Still missing!

2. SM fit

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*

$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) = 0.02750 \pm 0.00033$ *measured with inclusive processes.*

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

smaller uncertainty if using exclusive processes with pQCD, etc.
0.02757 ± 0.00010

but discrepancy between inclusive and exclusive in low-energy data

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

SM fit

Updated from Ciuchini, Franco, Mishima & Silvestrini (13)

Fit: our fit results

Indirect: determined w/o using the corresponding experimental information

	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1184 ± 0.0006	0.1185 ± 0.0006	0.1197 ± 0.0028	$+0.5$
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	0.02739 ± 0.00026	0.02721 ± 0.00042	-0.5
M_Z [GeV]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.012	$+1.0$
m_t [GeV]	173.2 ± 0.9	173.5 ± 0.8	176.2 ± 2.6	$+1.1$
m_h [GeV]	125.6 ± 0.3	125.6 ± 0.3	95.5 ± 26.9	-0.9
M_W [GeV]	80.385 ± 0.015	80.367 ± 0.007	80.363 ± 0.007	-1.3
Γ_W [GeV]	2.085 ± 0.042	2.0891 ± 0.0006	2.0891 ± 0.0006	$+0.1$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4943 ± 0.0004	2.4942 ± 0.0004	-0.4
σ_h^0 [nb]	41.540 ± 0.037	41.479 ± 0.003	41.479 ± 0.003	-1.6
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	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	0.1472 ± 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	0.93467 ± 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	20.735 ± 0.004	-1.3
R_c^0	0.1721 ± 0.0030	0.17236 ± 0.00002	0.17236 ± 0.00002	$+0.1$
R_b^0	0.21629 ± 0.00066	0.21549 ± 0.00003	0.21549 ± 0.00003	-1.2

$-2.1\sigma \rightarrow -1.2\sigma$

Parametric and theoretical uncertainties

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

	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]	2.4941 ± 0.0005	± 0.0003	± 0.0003	± 0.0002	± 0.0001
$\mathcal{A}_\ell$	0.1472 ± 0.0009	± 0.0000	± 0.0009	± 0.0001	± 0.0002
$A^{0,b}_{\rm FB}$	0.1032 ± 0.0007	± 0.0000	± 0.0006	± 0.0001	± 0.0002
R^0_b	0.21550 ± 0.00003	± 0.00001	± 0.00000	± 0.00000	± 0.00003

- The theoretical uncertainties from missing higher-order corrections have been estimated as

$$\delta M_W^{\rm theo} \sim 0.004\ \mathrm{GeV}$$

Awramik et al. (04)

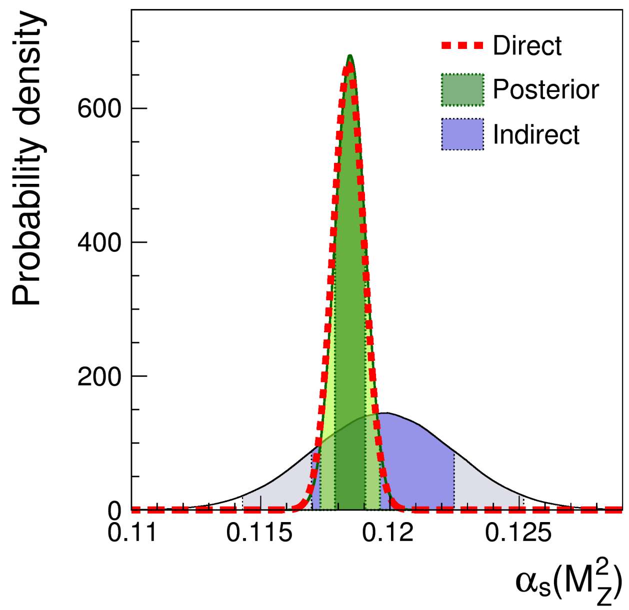
$$\delta\Gamma_Z^{\rm theo} \sim 0.0005\ \mathrm{GeV}$$

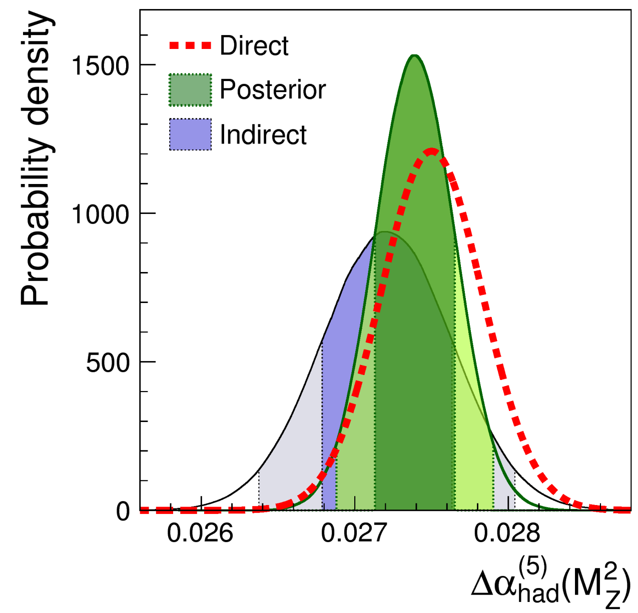
Freitas (13)

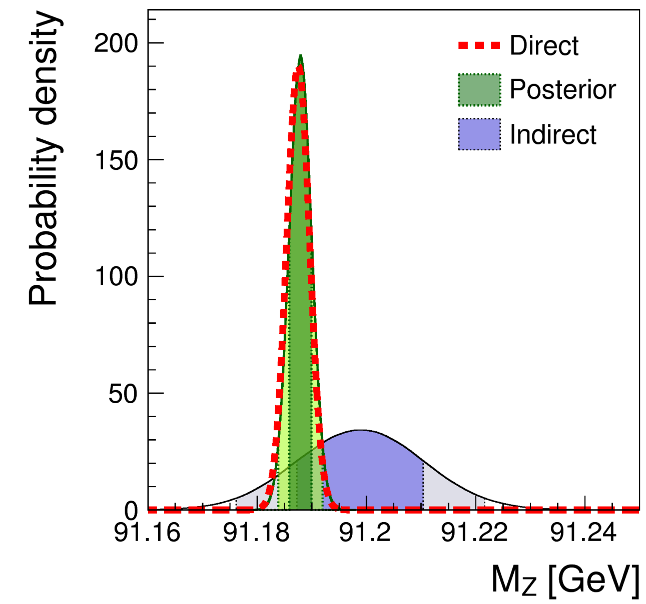
$$\delta\mathcal{A}_\ell^{\rm theo} \sim 0.00037 \quad (\delta \sin^2\theta_{\rm eff}^{\rm lept} = 4.7\times 10^{-5})$$

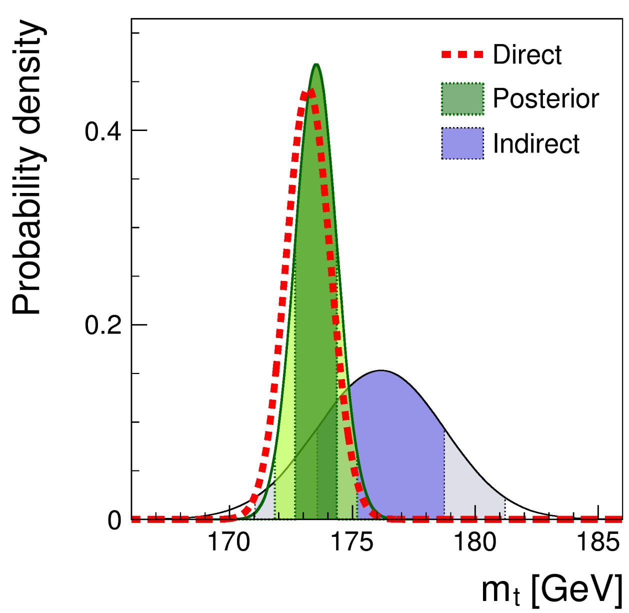
Awramik et al. (06)

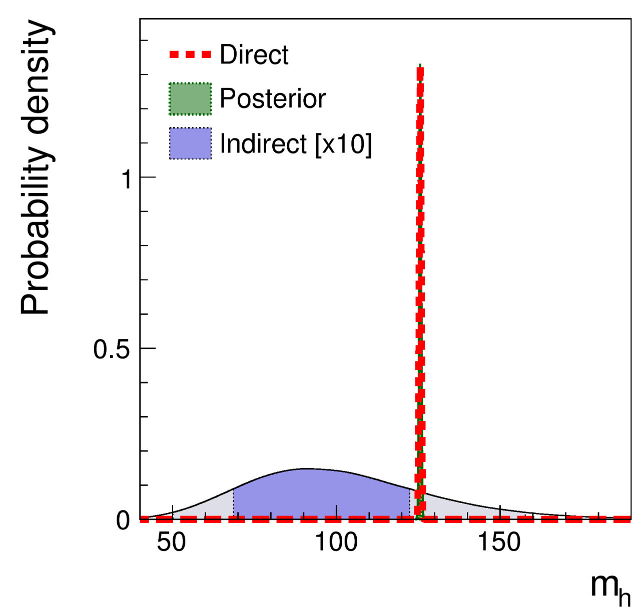
Direct and indirect measurements











68% & 95% prob. regions

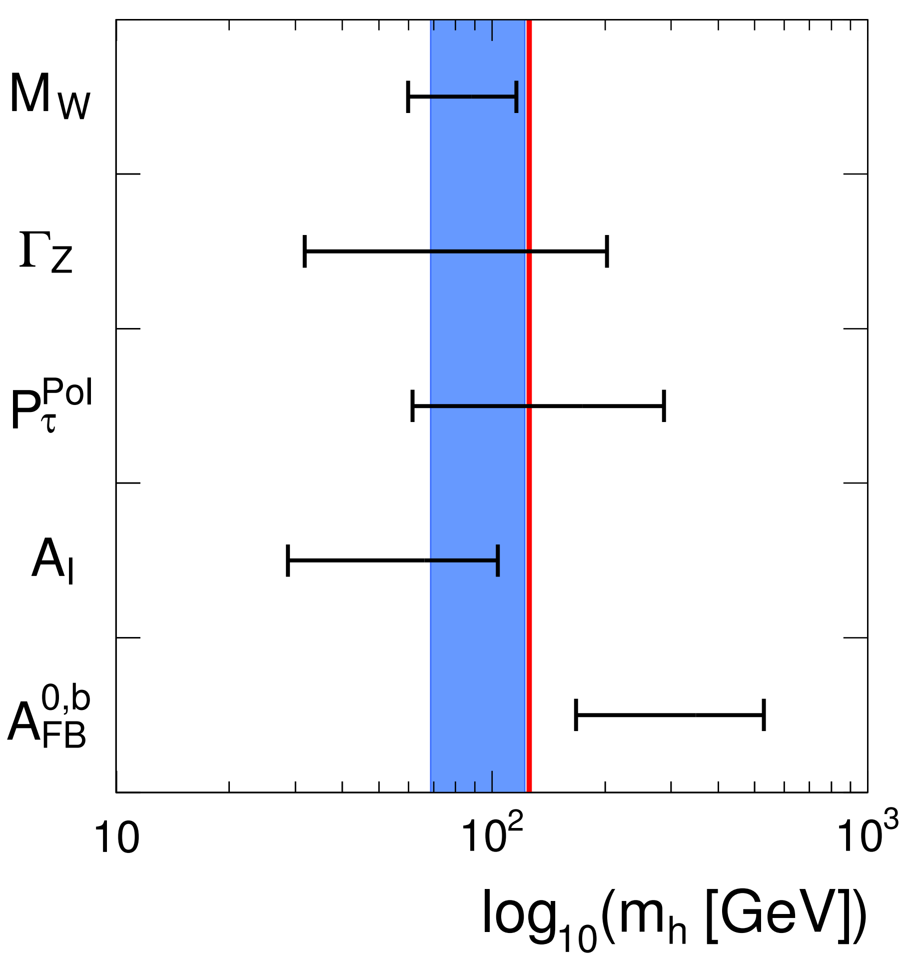
Individual constraints on the Higgs mass

indirect determination from the EW fit:

$$m_h = \mathbf{95.5 \pm 26.9\ GeV}$$

direct measurement at LHC (ATLAS & CMS):

$$m_h = \mathbf{125.6 \pm 0.3\ GeV}$$



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

3. Model-independent NP fits

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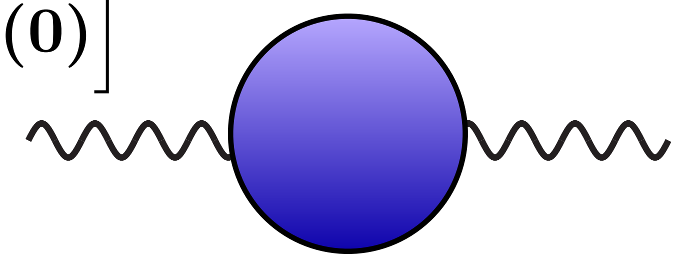
Oblique parameters

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

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

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

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



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

- When the EW symmetry is realized linearly, U is associated with a dim. 8 operator and thus small.
- EWPO depend on the three combinations:

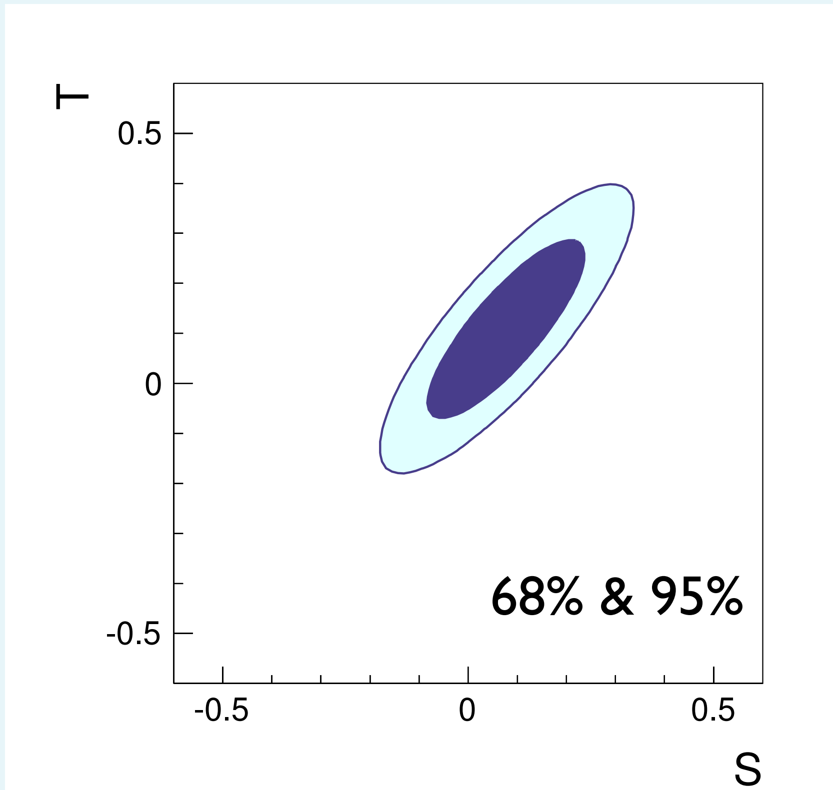
$$\delta M_W,\ \delta\Gamma_W \propto -S + 2c_W^2\, T + \frac{(c_W^2 - s_W^2)\, U}{2s_W^2}$$

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

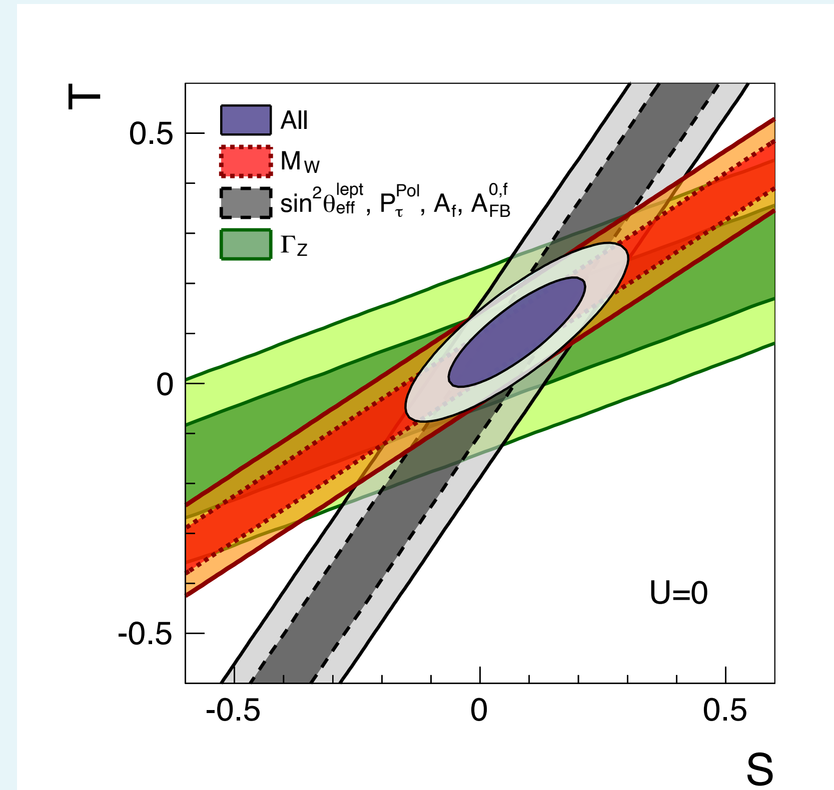
$$\text{others} \propto S - 4c_W^2 s_W^2\, T$$

Oblique parameters

$U \neq 0$



$U = 0$



	Fit result	Correlations		
S	0.08 ± 0.10	1		
T	0.11 ± 0.12	0.85	1	
U	-0.01 ± 0.09	-0.48	-0.79	1

	Fit result	Correlations	
S	0.07 ± 0.09	1	
T	0.10 ± 0.07	0.86	1

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

No evidence for NP!

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)

$$s_W^2 c_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\, G_\mu M_Z^2 (1 - \Delta r_W)}$$

$$\sqrt{\mathrm{Re}\,\rho_Z^e} = 1 + \frac{\Delta\rho'}{2}$$

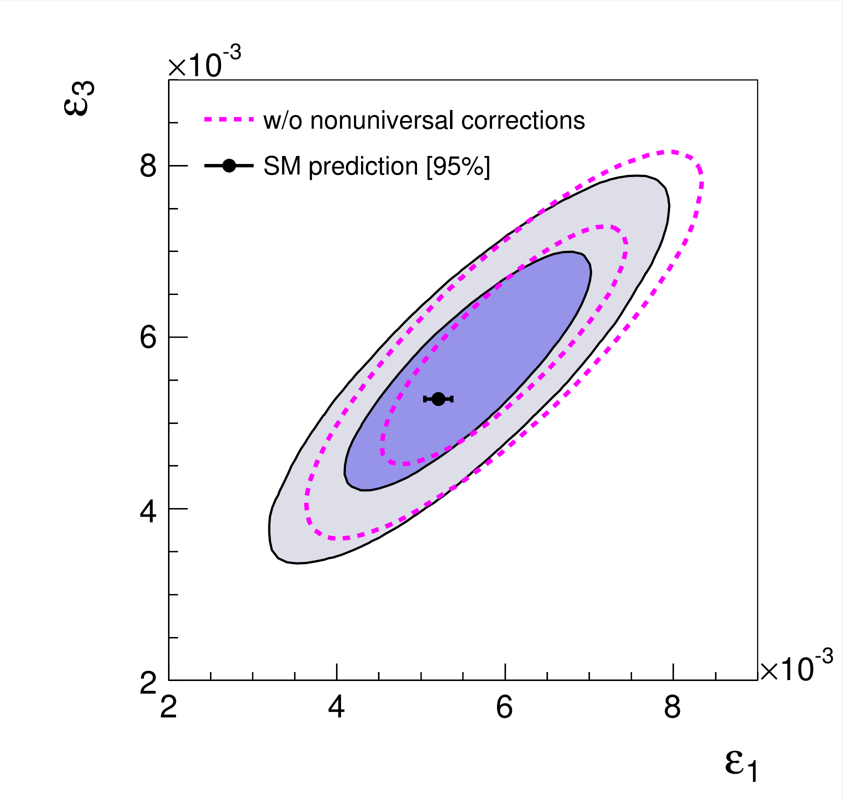
$$\sin^2\theta_{\mathrm{eff}}^e = (1 + \Delta\kappa')\, s_0^2$$

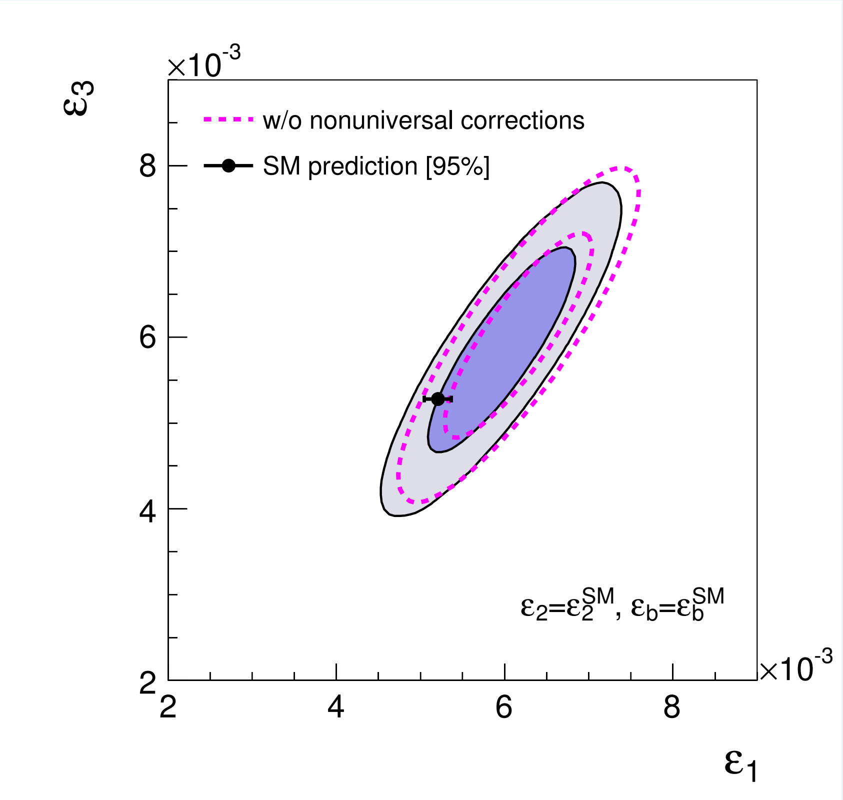
$$s_0^2\, c_0^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2} G_\mu M_Z^2}$$

- Unlike STU, the epsilon parameters involve SM contributions, including the vertex corrections.

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

Epsilon parameters



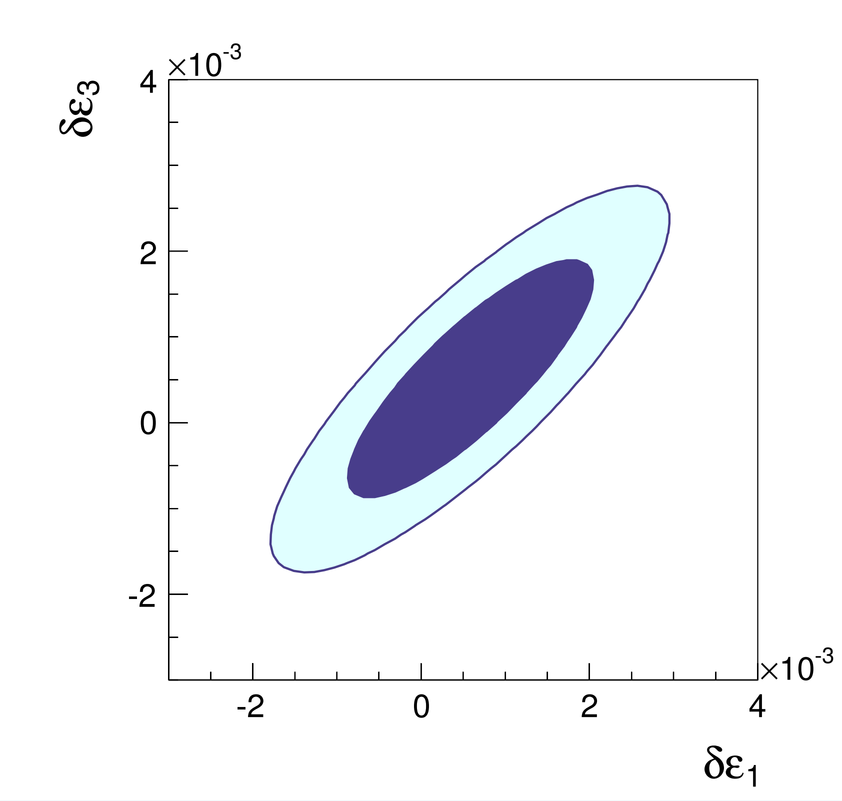


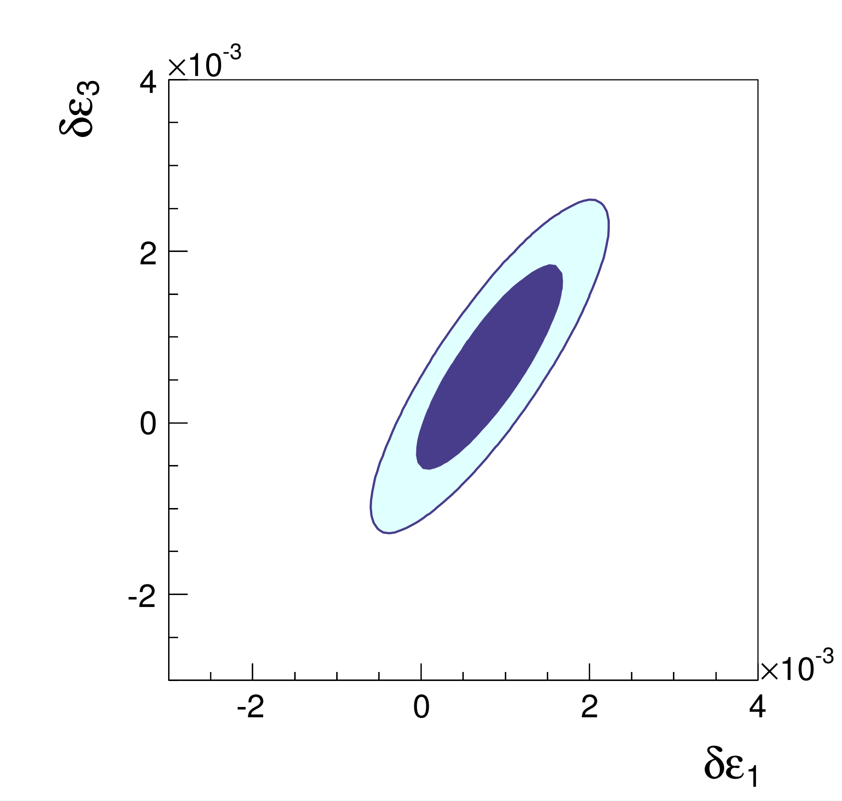
	Fit result	Correlations			
ϵ_1	0.0056 ± 0.0010	1.00			
ϵ_2	-0.0078 ± 0.0009	0.79	1.00		
ϵ_3	0.0056 ± 0.0009	0.86	0.50	1.00	
ϵ_b	-0.0058 ± 0.0013	-0.32	-0.31	-0.21	1.00

	Fit result	Correlations	
ϵ_1	0.0060 ± 0.0006	1.00	
ϵ_3	0.0059 ± 0.0008	0.87	1.00

Epsilon parameters

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





	Fit result	Correlations			
$\delta\epsilon_1$	0.0006 ± 0.0010	1.00			
$\delta\epsilon_2$	-0.0002 ± 0.0009	0.80	1.00		
$\delta\epsilon_3$	0.0005 ± 0.0009	0.86	0.51	1.00	
$\delta\epsilon_b$	0.0011 ± 0.0013	-0.33	-0.32	-0.21	1.00

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

HVV coupling

- Only a Higgs below cutoff + custodial symmetry:

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

Σ : Goldstone bosons

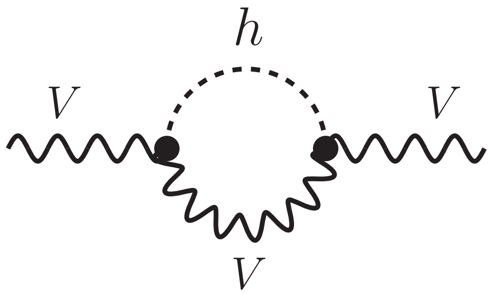
$a = 1$ in the SM

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

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

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

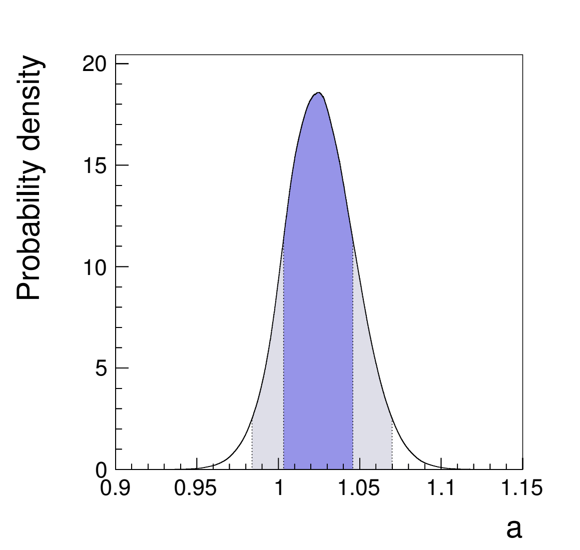
$$\Lambda = 4\pi v/\sqrt{|1 - a^2|}$$



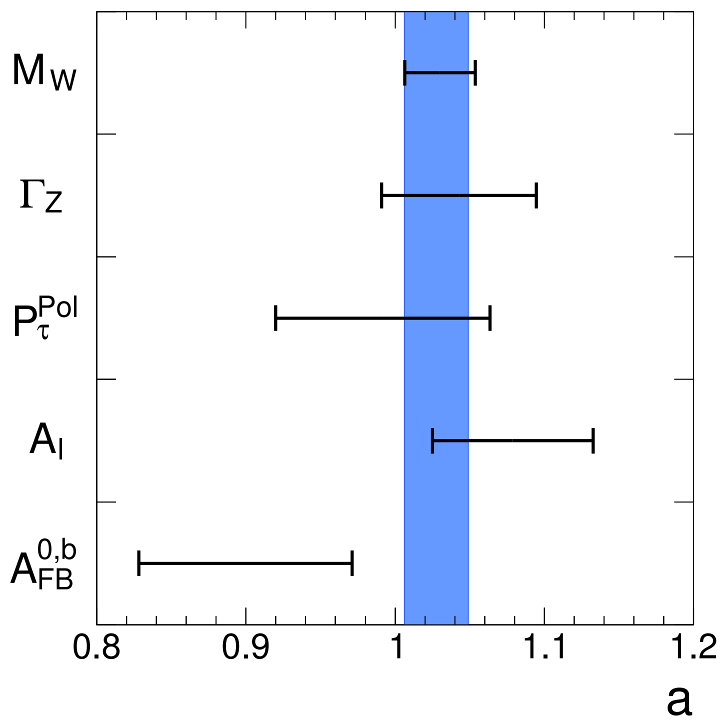
Barberi, Bellazzini, Rychkov & Varagnolo (07)

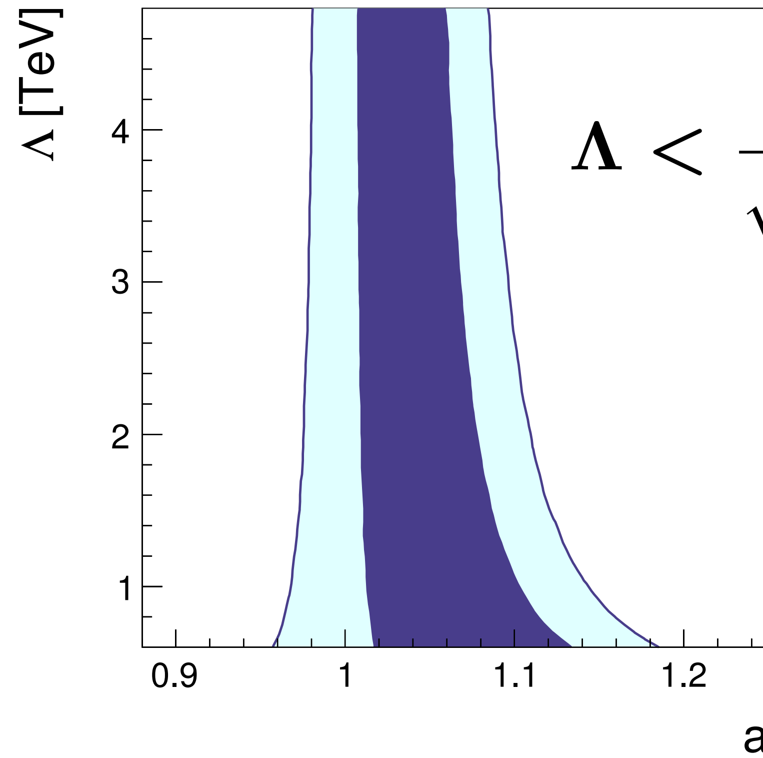
$$a = 1.028 \pm 0.021$$

$$\Lambda \gtrsim 19\ \mathrm{TeV}\ @\,95\%\ \text{for}\ a < 1$$

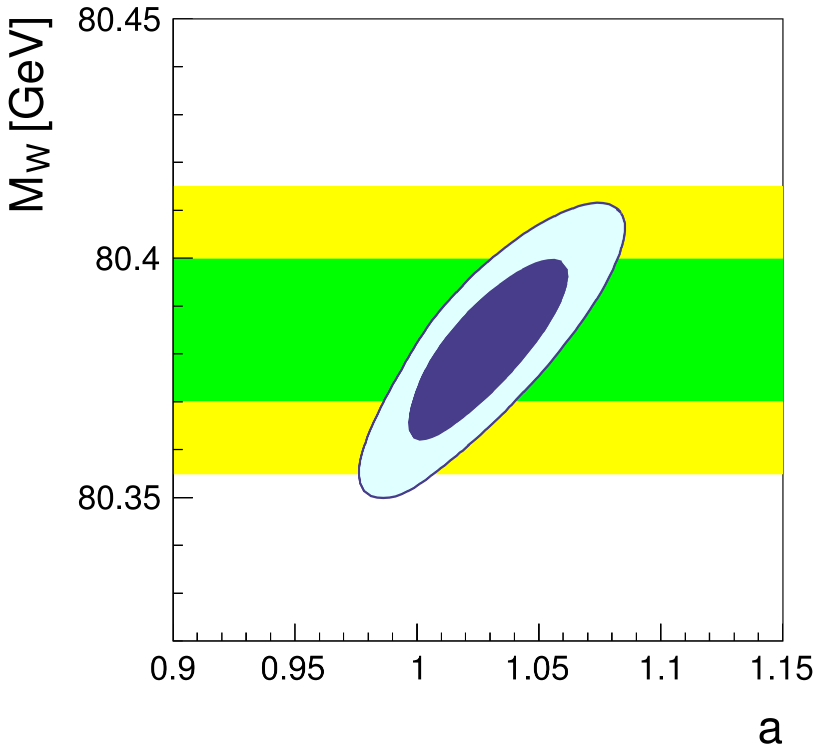


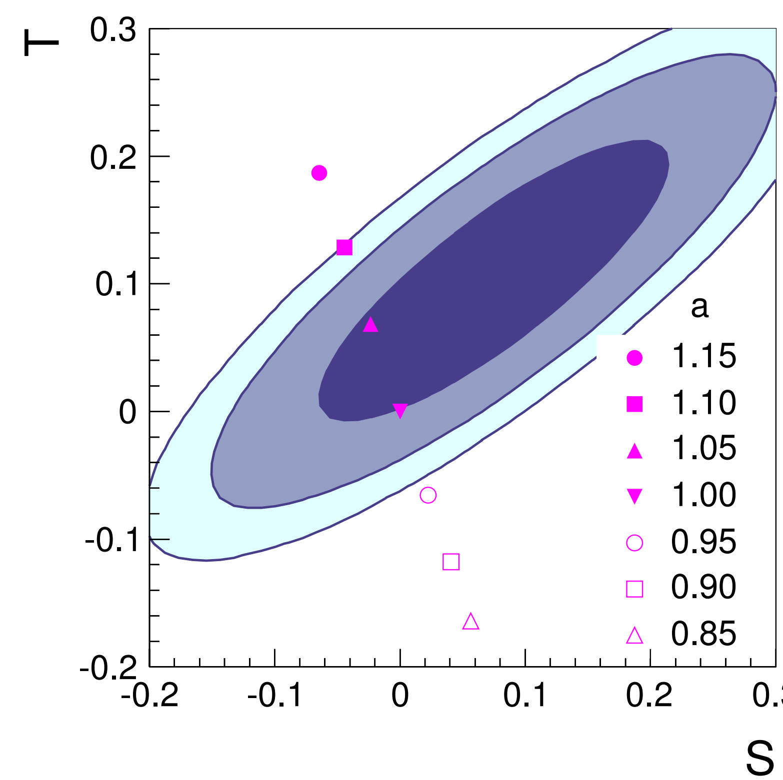
HVV coupling





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





68%, 95% & 99%

Implication on composite Higgs models

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

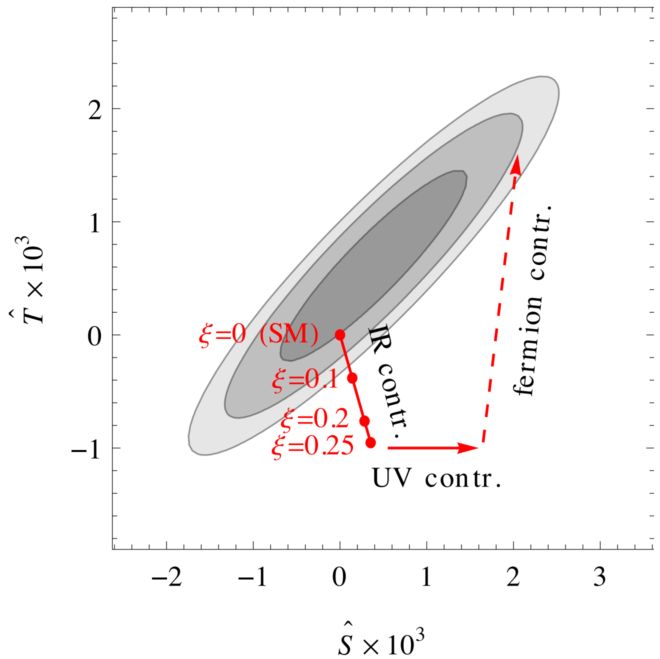
  Falkowski, Rychkov & Urbano (12)

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

$$\xi = \left(\frac{v}{f}\right)^2 = 1 - a^2$$ in minimal composite Higgs models

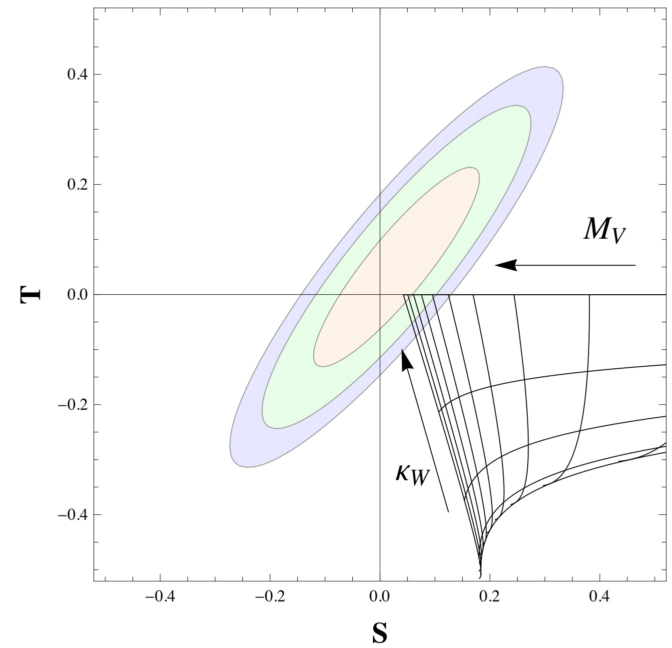
- Extra contributions to S and T are required to fix the EW fit under $a < 1$.

fermionic resonances



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

vector/axial-vector resonances



$M_V = 1.5, \ldots, 6.0$ TeV

$\kappa_W = \frac{M_V^2}{M_A^2} = 0, \ldots, 1$

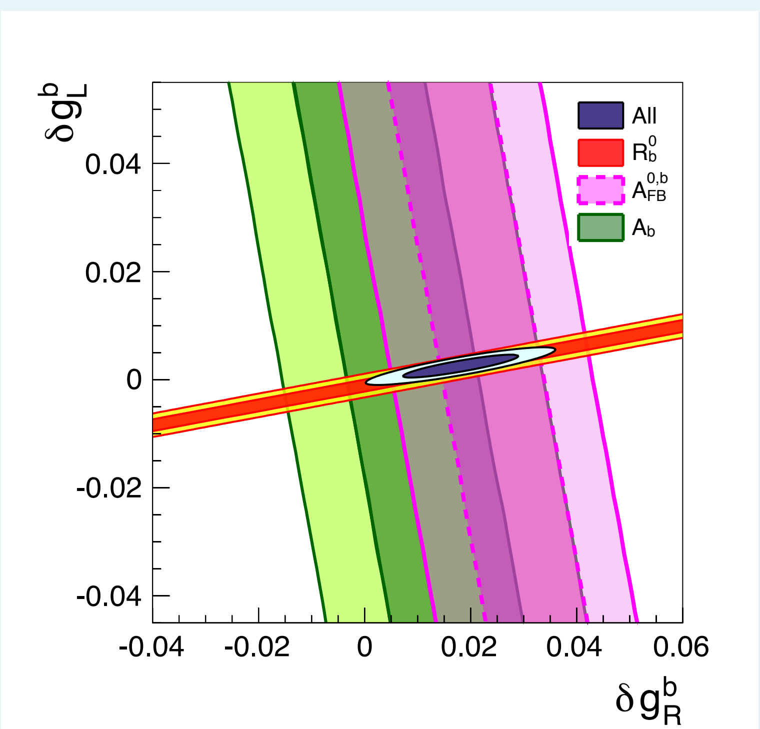
Pich et al. (13)

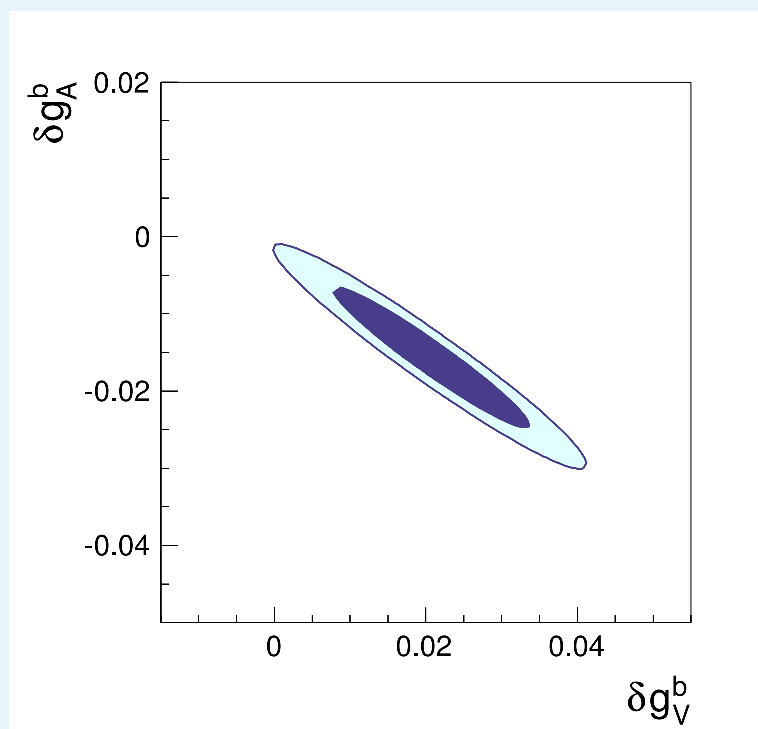
$Zb\bar{b}$ couplings

- 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:





$$g^b_{V,A} = (g^b_{V,A})_{\rm SM} + \delta g^b_{V,A}$$

Parameter	Fit result	Correlations	
δg_R^b	0.018 ± 0.007	1.00	
δg_L^b	0.0025 ± 0.0014	0.90	1.00
δg_V^b	0.021 ± 0.008	1.00	
δg_A^b	-0.016 ± 0.006	-0.99	1.00

See also Batell et al. (13)

- Deviation from the SM due to $A_{\rm FB}^{0,b}$

Dim. 6 operators

- We consider NP-induced dimension six operators:

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

Barbieri & Strumia (99)

$$\begin{aligned}
\mathcal{O}_{WB} &= (H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu} && \to \text{ S parameter} \\
\mathcal{O}_{H} &= |H^\dagger D_\mu H|^2 && \to \text{ T parameter} \\
\mathcal{O}_{LL} &= \frac{1}{2}(\overline{L}\gamma_\mu \tau^a L)^2 \\
\mathcal{O}'_{HL} &= i(H^\dagger D_\mu \tau^a H)(\overline{L}\gamma^\mu \tau^a L) \\
\mathcal{O}'_{HQ} &= i(H^\dagger D_\mu \tau^a H)(\overline{Q}\gamma^\mu \tau^a Q) \\
\mathcal{O}_{HL} &= i(H^\dagger D_\mu H)(\overline{L}\gamma^\mu L) \\
\mathcal{O}_{HQ} &= i(H^\dagger D_\mu H)(\overline{Q}\gamma^\mu Q) \\
\mathcal{O}_{HE} &= i(H^\dagger D_\mu H)(\overline{E}\gamma^\mu E) \\
\mathcal{O}_{HU} &= i(H^\dagger D_\mu H)(\overline{U}\gamma^\mu U) \\
\mathcal{O}_{HD} &= i(H^\dagger D_\mu H)(\overline{D}\gamma^\mu D)
\end{aligned}$$

$\mathcal{O}_{LL}$, $\mathcal{O}'_{HL}$ → *Fermi constant*

$\mathcal{O}'_{HL}$, $\mathcal{O}'_{HQ}$, $\mathcal{O}_{HL}$, $\mathcal{O}_{HQ}$ → *Left-handed $Zf\bar{f}$ couplings*

$\mathcal{O}_{HE}$, $\mathcal{O}_{HU}$, $\mathcal{O}_{HD}$ → *Right-handed $Zf\bar{f}$ couplings*

- assume lepton-flavour universality.
- switch on one operator at a time.

Dim. 6 operators

with quark-flavour universality

Coefficient	C_i/Λ^2 [TeV^{-2}] at 95%	Λ [TeV] $C_i=-1$	Λ [TeV] $C_i=1$
C_{WB}	[−0.0098, 0.0040]	10.1	15.7
C_H	[−0.031, 0.005]	5.7	14.2
C_{LL}	[−0.008, 0.022]	10.9	6.8
C'_{HL}	[−0.013, 0.004]	8.9	15.3
C'_{HQ}	[−0.008, 0.016]	10.9	7.8
C_{HL}	[−0.006, 0.011]	13.2	9.6
C_{HQ}	[−0.016, 0.052]	7.9	4.4
C_{HE}	[−0.016, 0.007]	8.0	12.2
C_{HU}	[−0.058, 0.090]	4.2	3.3
C_{HD}	[−0.17, 0.04]	2.5	5.3

without quark-flavour universality

Coefficient	C_i/Λ^2 [TeV^{-2}] at 95%	Λ [TeV] $C_i=-1$	Λ [TeV] $C_i=1$
C'_{HQ_1}	[−0.025, 0.035]	6.3	5.3
C'_{HQ_2}	[−0.025, 0.035]	6.4	5.3
C'_{HQ_3}, C_{HQ_3}	[−0.017, 0.061]	7.7	4.0
C_{HQ_1}	[−0.25, 0.35]	2.0	1.7
C_{HQ_2}	[−0.16, 0.18]	2.5	2.4
C_{HU_1}	[−0.12, 0.18]	2.8	2.4
C_{HU_2}	[−0.10, 0.17]	3.1	2.4
C_{HD_1}, C_{HD_2}	[−0.35, 0.25]	1.7	2.0
C_{HD_3}	[−0.41, −0.01]	1.6	—

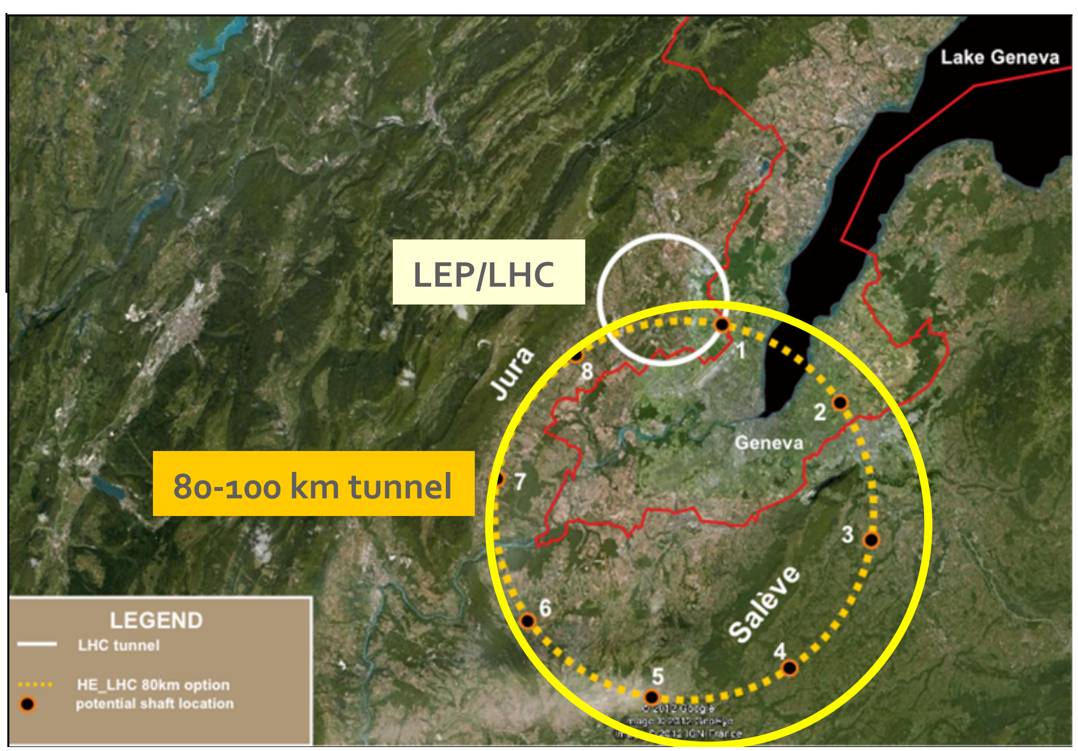
- Recent exp. improvements strengthen the bounds on NP!

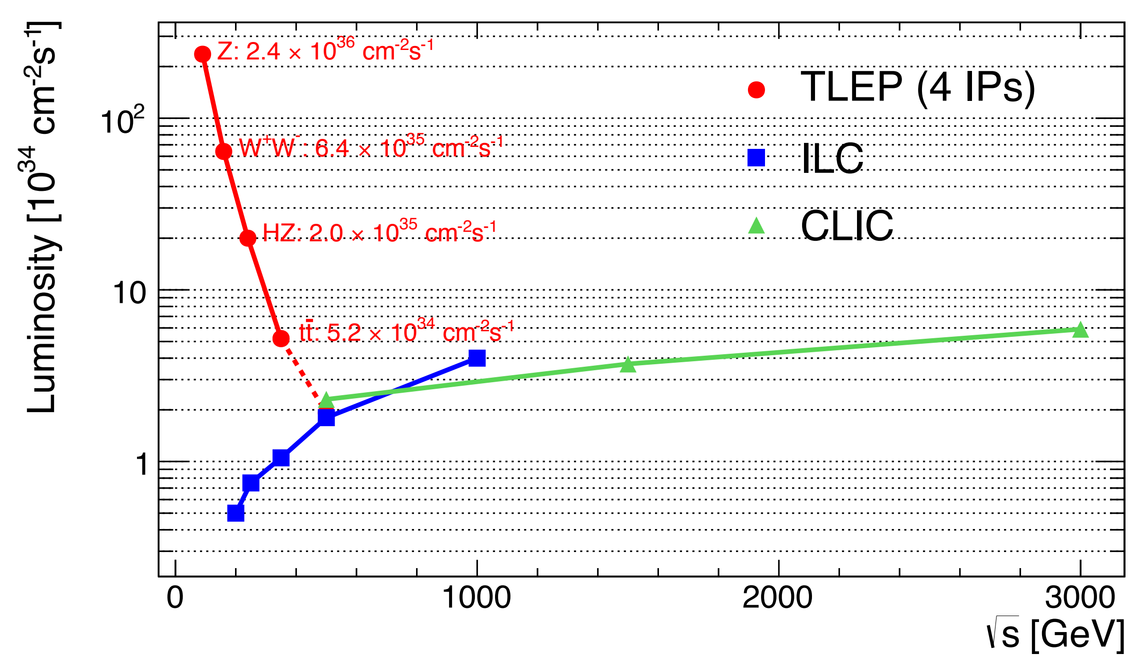
4. Future sensitivity to NP

A plan for TLEP

TLEP Design Study Working Group, arXiv:1308.6176

- TLEP = Triple LEP (80km) or Tetra LEP (100km).
- A high-luminosity circular e^+e^- collider.
- Produces $10^{12}\,Z$, $10^8\,W^+W^-$, $10^6\,Zh$ and $10^6\,t\bar{t}$.
- The same tunnel will be used for VHE-LHC (a 100 TeV hadron collider) later.
- Physics run from 2030?





TLEP precision

ILC TDR vol. 2

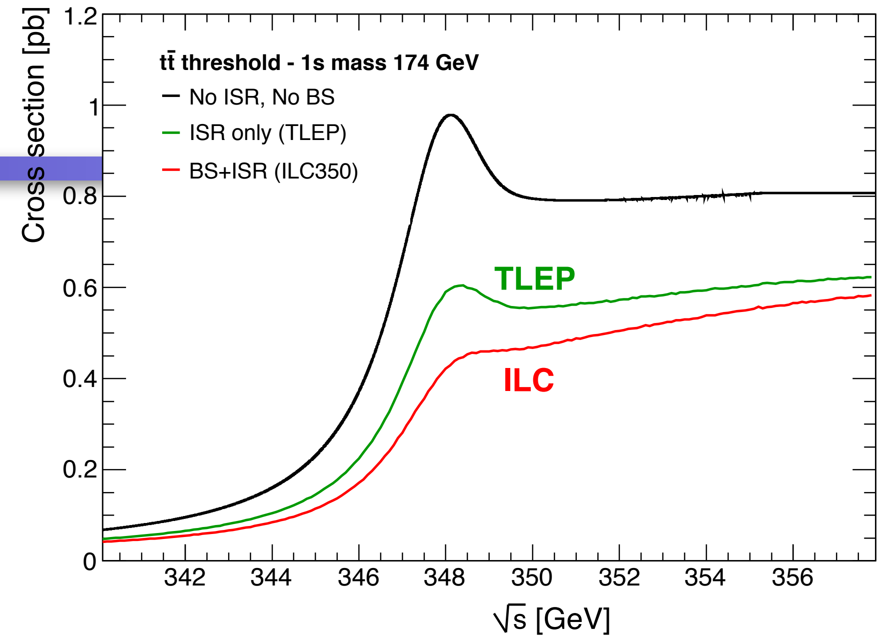
TLEP Design Study Working Group, arXiv:1308.6176

	Current data	LHC	low e^+e^-	ILC	TLEP-Z	TLEP-Z (pol.)	TLEP-W	TLEP-t
$\alpha_s(M_Z^2)$	0.1184 ± 0.0006							
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	0.02750 ± 0.00033		± 0.00005					
M_Z [GeV]	91.1875 ± 0.0021			± 0.0016	± 0.0001			
m_t [GeV]	173.2 ± 0.9	± 0.6		± 0.1				± 0.016
m_h [GeV]	125.6 ± 0.3	± 0.15		± 0.032				
M_W [GeV]	80.385 ± 0.015	± 0.008		± 0.006			± 0.00064	
Γ_W [GeV]	2.085 ± 0.042						± 0.030	
Γ_Z [GeV]	2.4952 ± 0.0023			± 0.0008	± 0.0001			
σ_h^0 [nb]	41.540 ± 0.037				± 0.025			
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012				± 0.0001			
$P_\tau^{\rm pol}$	0.1465 ± 0.0033				± 0.0002			
$\mathcal{A}_\ell$	0.1513 ± 0.0021			± 0.0001		± 0.000021		
$\mathcal{A}_c$	0.670 ± 0.027					± 0.010		
$\mathcal{A}_b$	0.923 ± 0.020			± 0.001		± 0.007		
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010				± 0.0001			
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035				± 0.0003			
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016				± 0.0001			
R_ℓ^0	20.767 ± 0.025				± 0.001			
R_c^0	0.1721 ± 0.0030				± 0.0003			
R_b^0	0.21629 ± 0.00066			± 0.00014	± 0.00006			

red = our estimates

- TLEP-Z: one-year scan of the Z resonance
- TLEP-Z (pol.): one year at the Z pole with long.-polarized beams
- TLEP-W: one-year (or two years) scan of the WW threshold
- TLEP-t: five-year scan of the ttbar threshold

TLEP-t precision on m_t



- The top-quark mass is measured through top-pair productions near threshold.

- Estimate by the TLEP design study working group:

  stat. error: 10 (12) MeV for 4 (2) IPs
  syst. error: < 10 MeV

- The latter requires the better knowledge of the beam-energy spectrum, the precise measurement of α_s at TLEP-W, etc., and reduction of theoretical uncertainties.

Current uncertainty in the conversion of $E_{\rm res}$ into m_t:

$$\delta\alpha_s = 0.0006 \ \rightarrow \ \delta m_t \sim 23 \text{ MeV}$$

$$\text{scale variation} \ \rightarrow \ \delta m_t \gtrsim 20 \text{ MeV}$$

Penin & Steinhauser (02)

Parametric and theoretical uncertainties

- We assume that theoretical uncertainties will be reduced by calculating subleading three-loop contributions of $O(\alpha^2\alpha_s)$ and $O(\alpha^3)$.

	TLEP	Parametric uncertainty						Theoretical uncertainty	
	direct	α_s	$\Delta\alpha_{\rm had}^{(5)}$	M_Z	m_t	m_h	Total	current	future
δM_W [MeV]	± 0.64	± 0.36	± 0.91	± 0.13	± 0.10	± 0.14	± 1.00	± 4	± 1
$\delta \Gamma_Z$ [MeV]	± 0.1	± 0.3	± 0.0	± 0.0	± 0.0	± 0.0	± 0.3	± 0.5	± 0.1
$\delta \mathcal{A}_\ell$ [10^{-5}]	± 2.1	± 1.6	± 13.7	± 0.6	± 0.4	± 0.9	± 13.9	± 37.0	± 11.8

$\delta \sin^2\theta_{\rm eff}^{\rm lept} = 1.5 \times 10^{-5}$

- Parametric uncertainties are dominated by $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$.

- Theoretical calculations at three-loop level and beyond are necessary to reach the TLEP precision.

Our strategy

- For the TLEP study, we do not assume the ILC results.
- We neglect possible correlations among the data.
- We consider two scenarios:

  SM scenario:

  apply the current SM-fit results to the central values of "future data", used in studying TLEP sensitivity to NP.

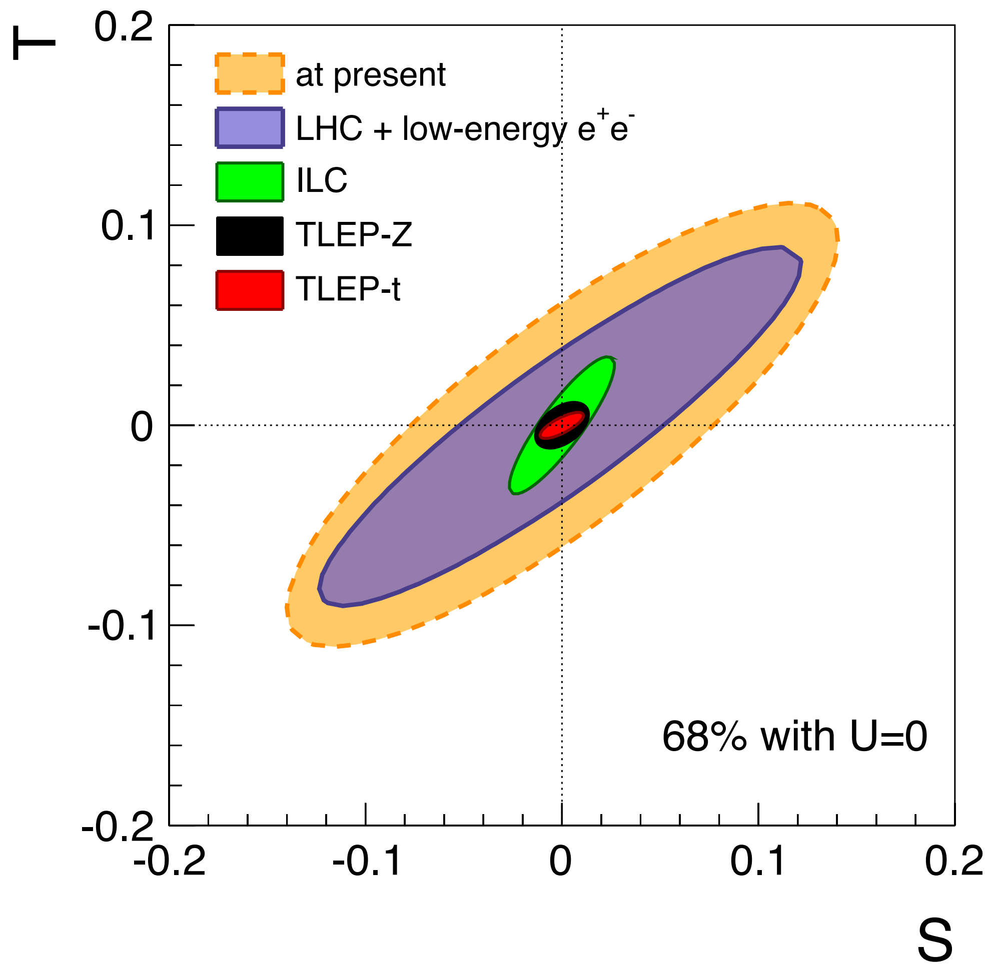
  NP scenario:

  apply current NP-fit results to the central values of "future data" and demonstrate the power of TLEP in NP searches.

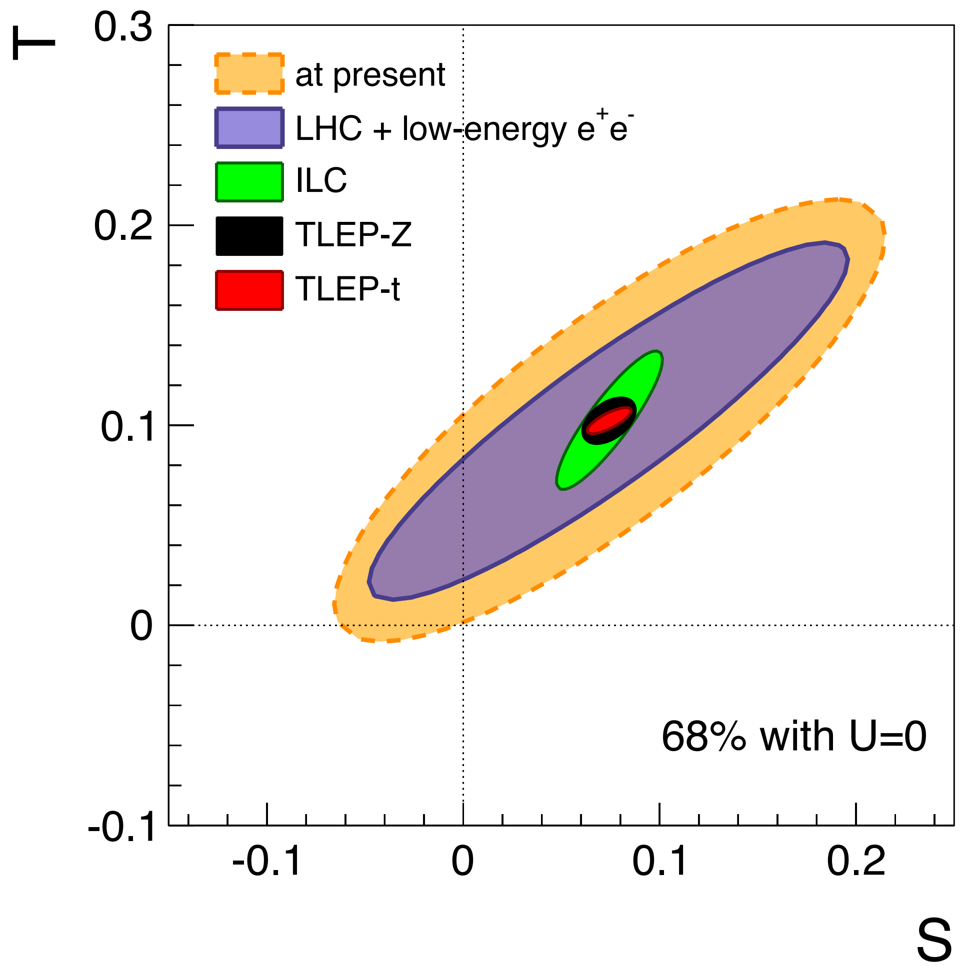
TLEP sensitivity to S and T ($U = 0$)

- ILC and TLEP improve the sensitivity to NP.

SM scenario



NP scenario

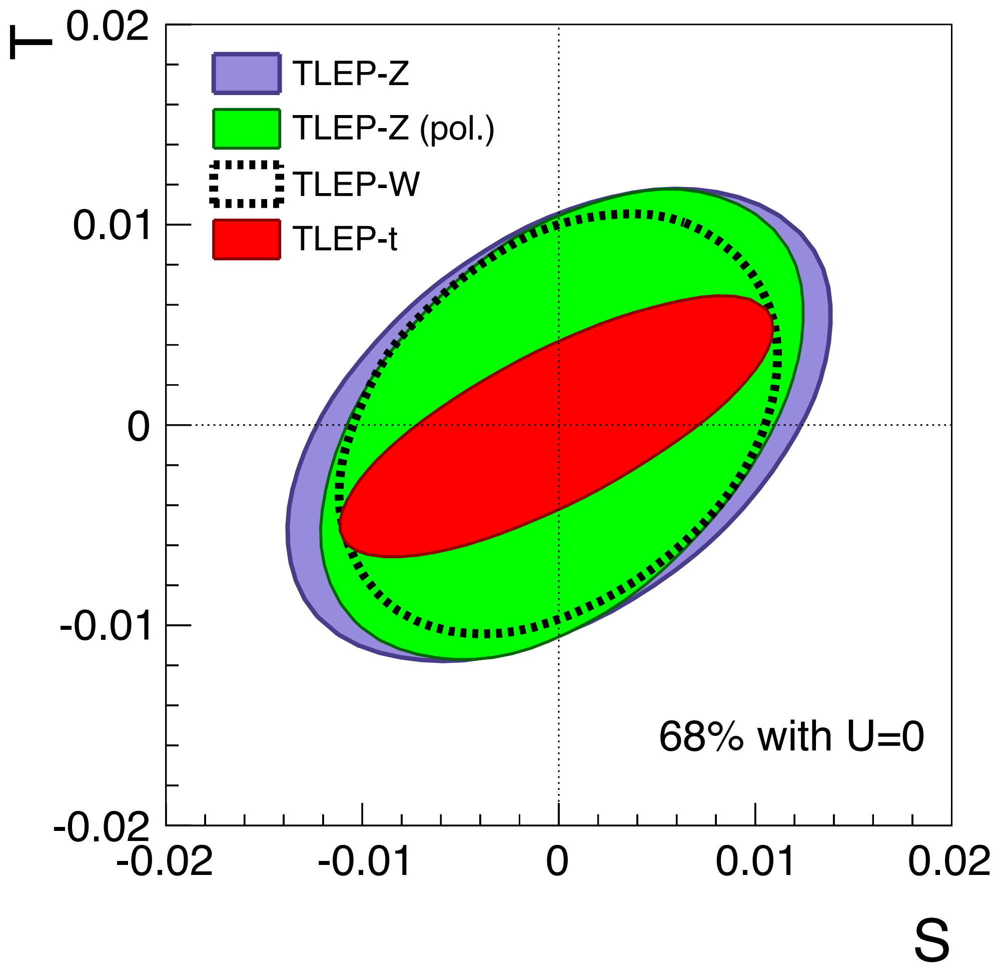


TLEP sensitivity to S and T ($U = 0$)

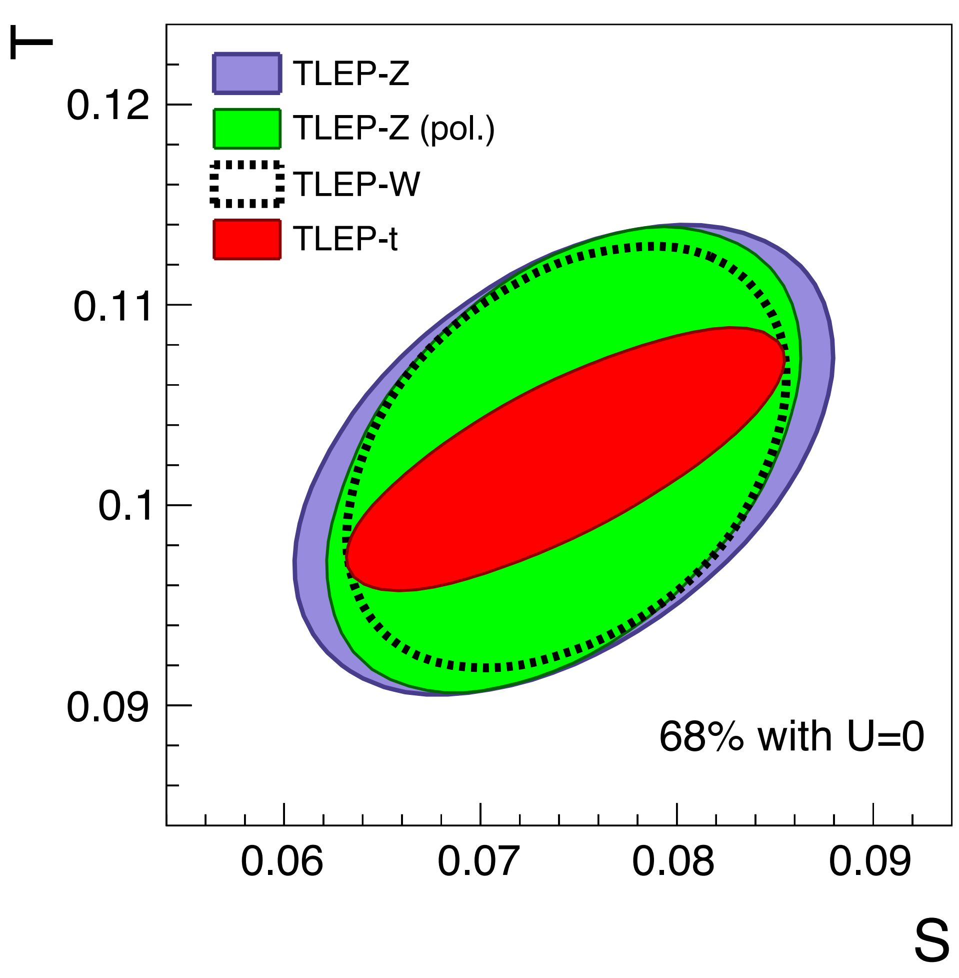
- In the case of $U = 0$,

$$\delta S \sim 7 \times 10^{-3}, \quad \delta T \sim 4 \times 10^{-3}$$

SM scenario



NP scenario



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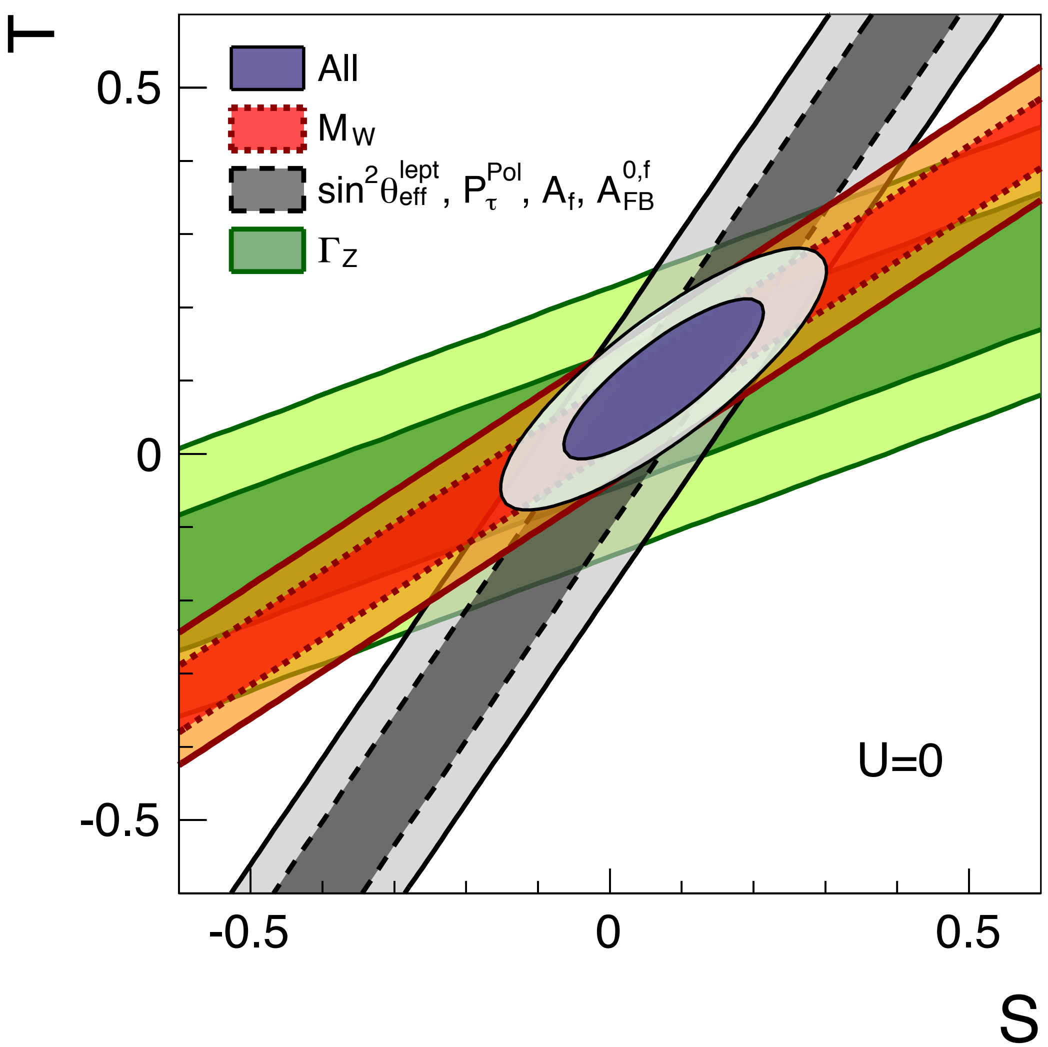
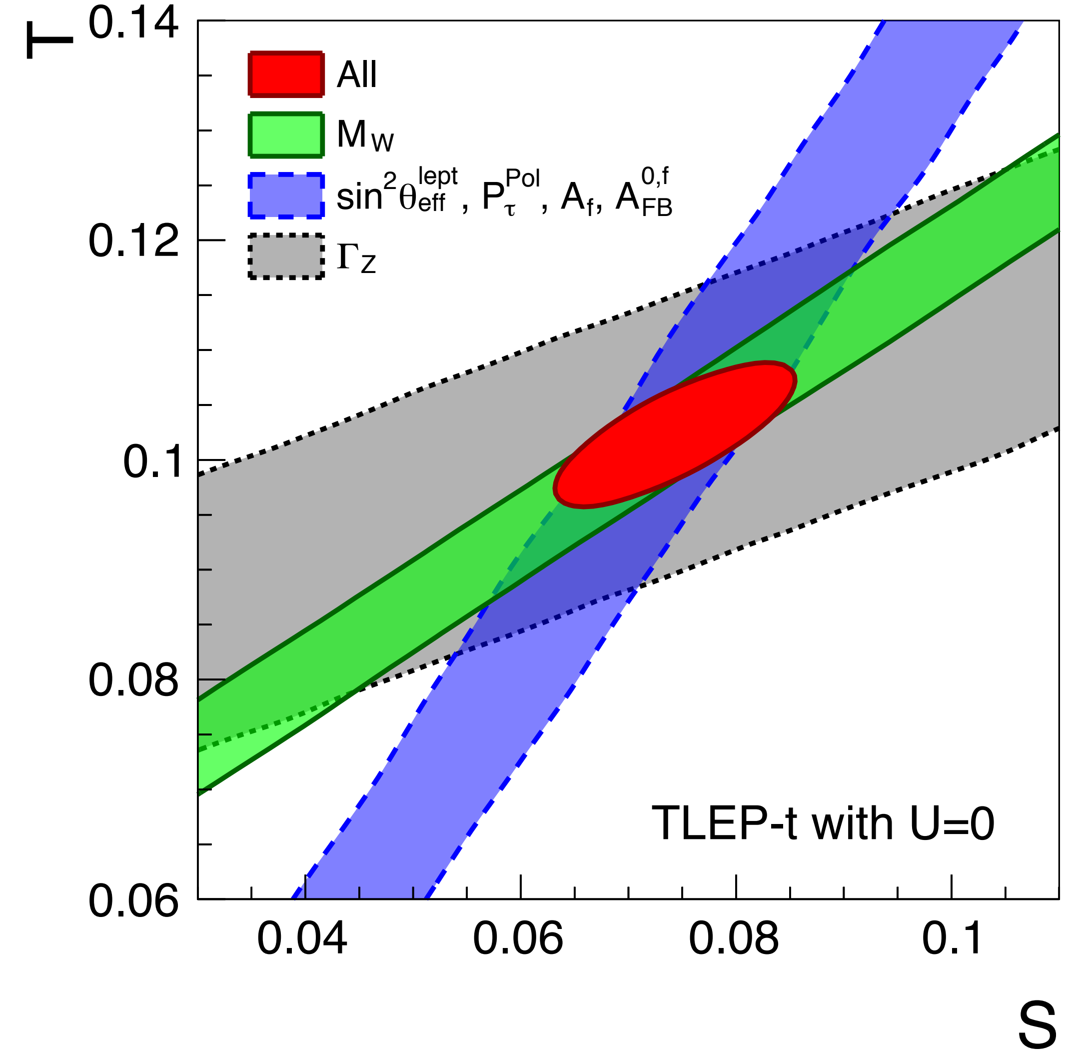
Individual constraints on S and T ($U = 0$)

At present



68% & 95%

NP scenario



only 68 %

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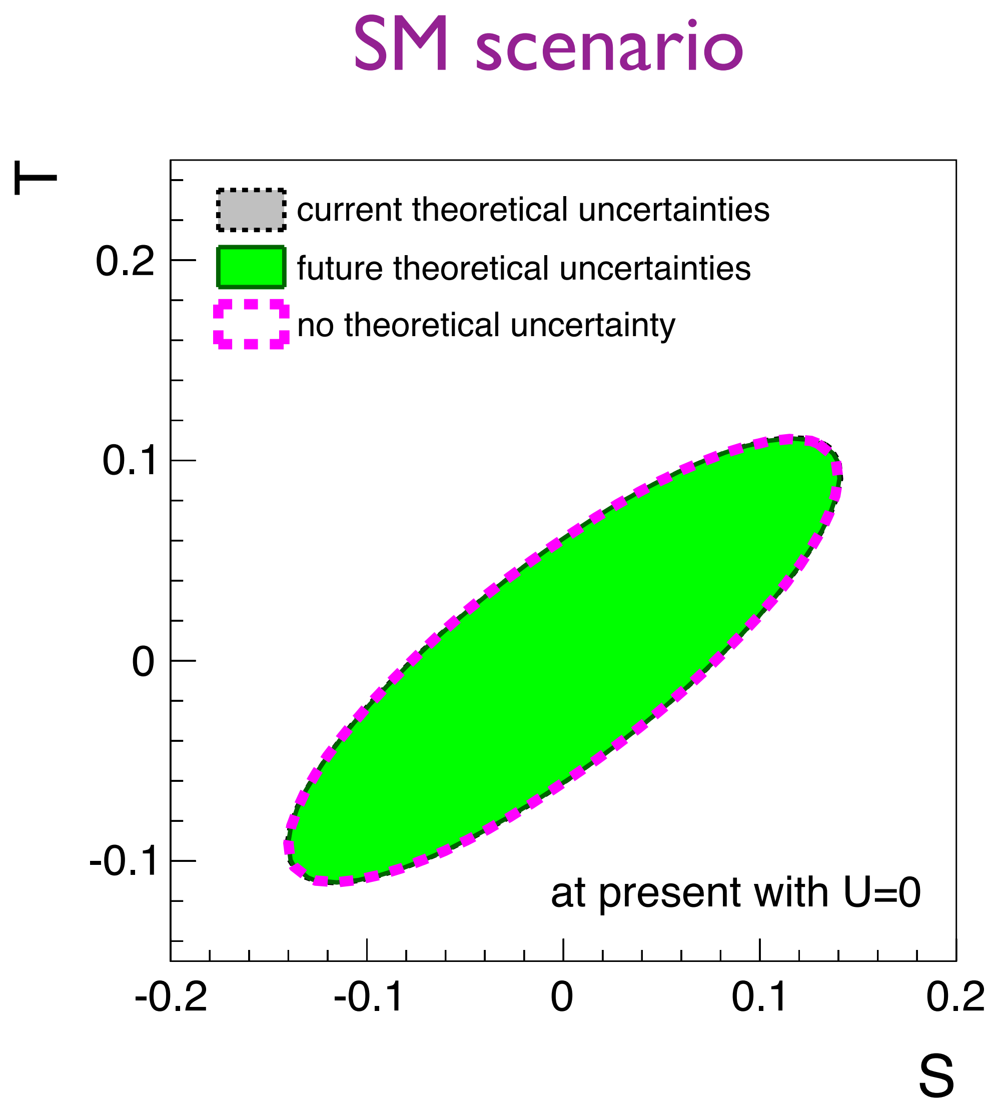
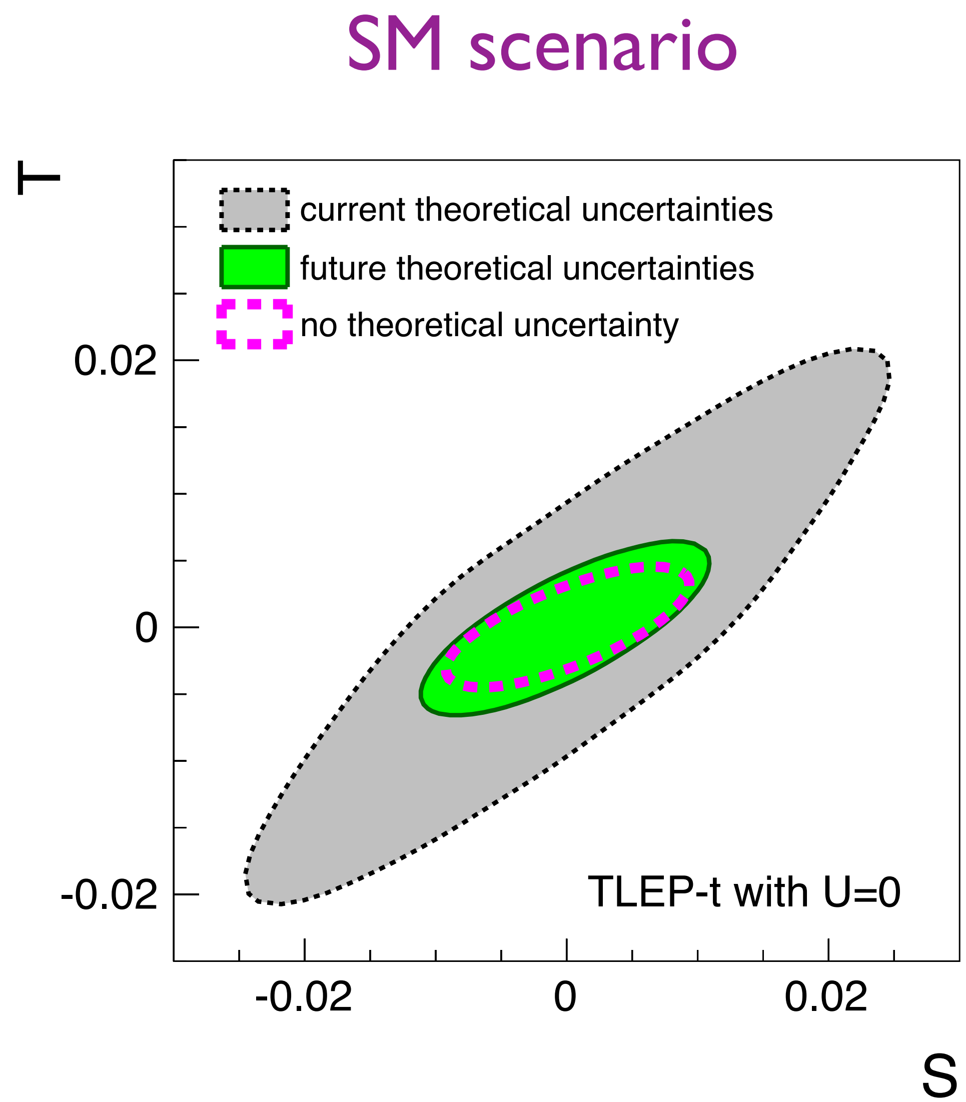
Impact of theoretical uncertainties ($U = 0$)





Theoretical effort to reduce uncertainties is required to achieve a precision of $\lesssim 10^{-2}$.

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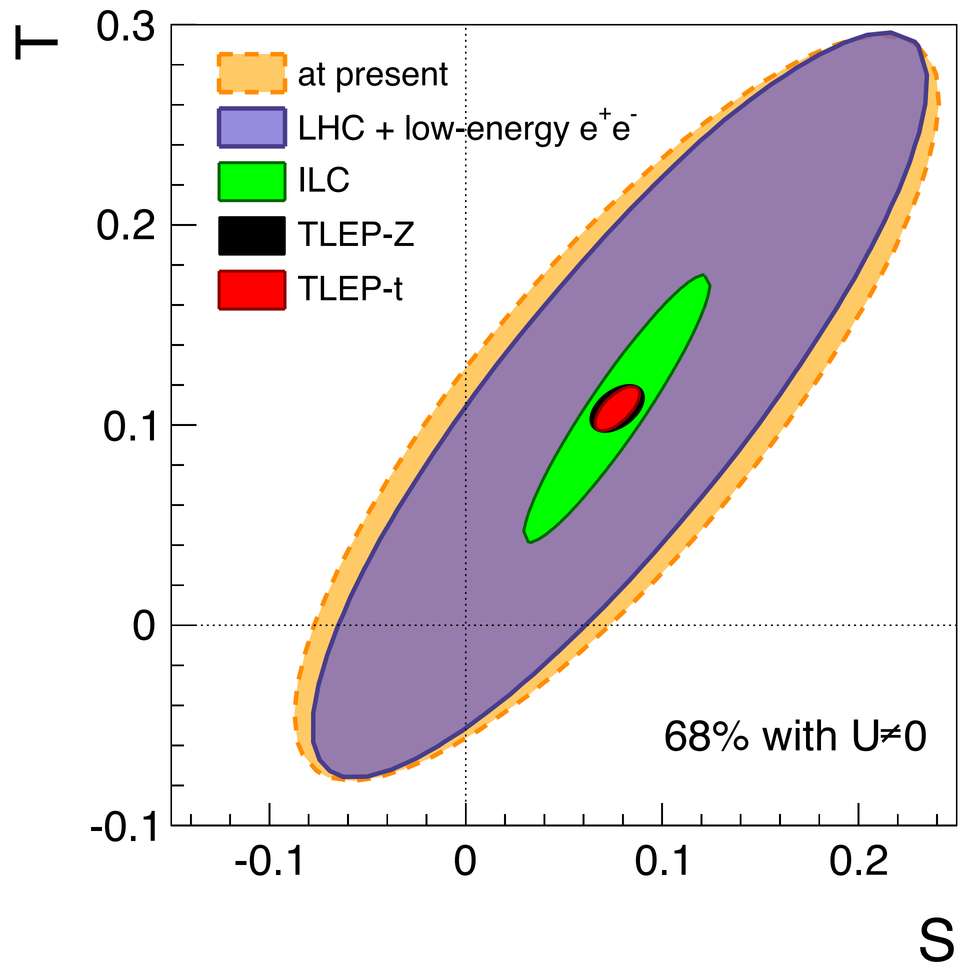
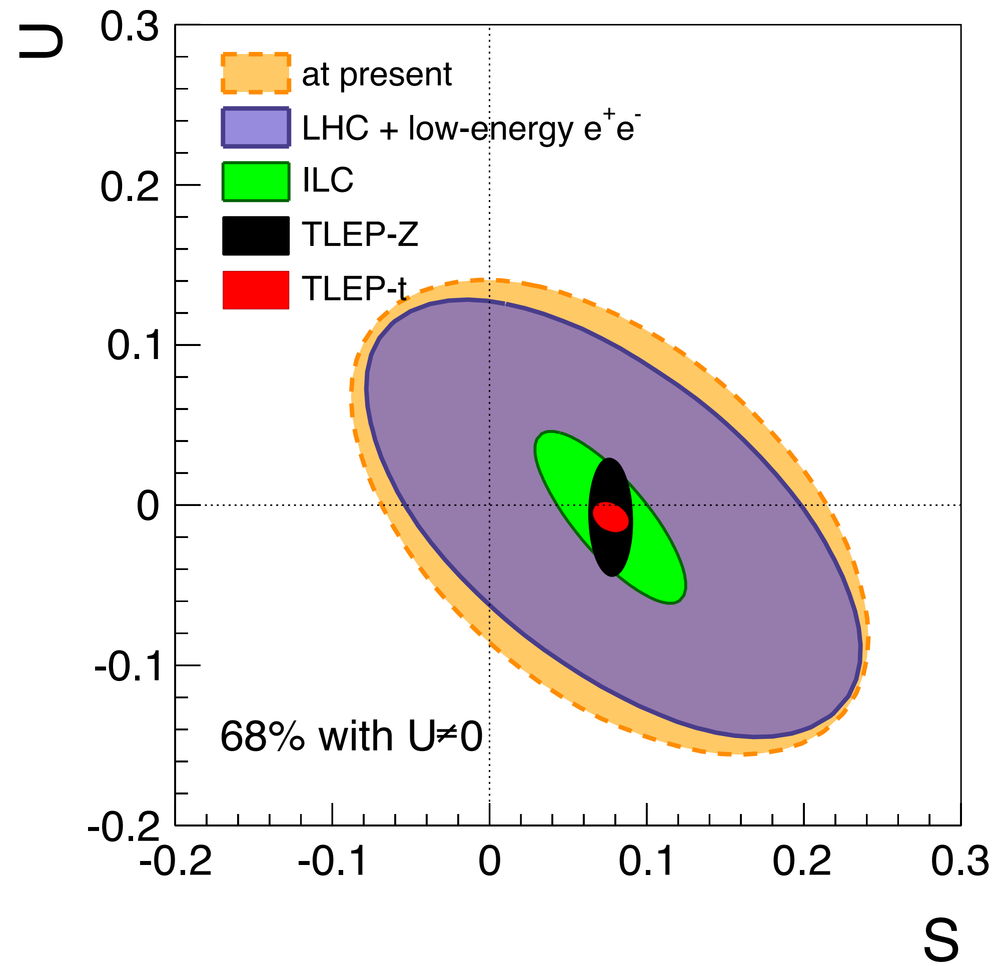
Future sensitivity to S, T and U ($U \neq 0$)

NP scenario



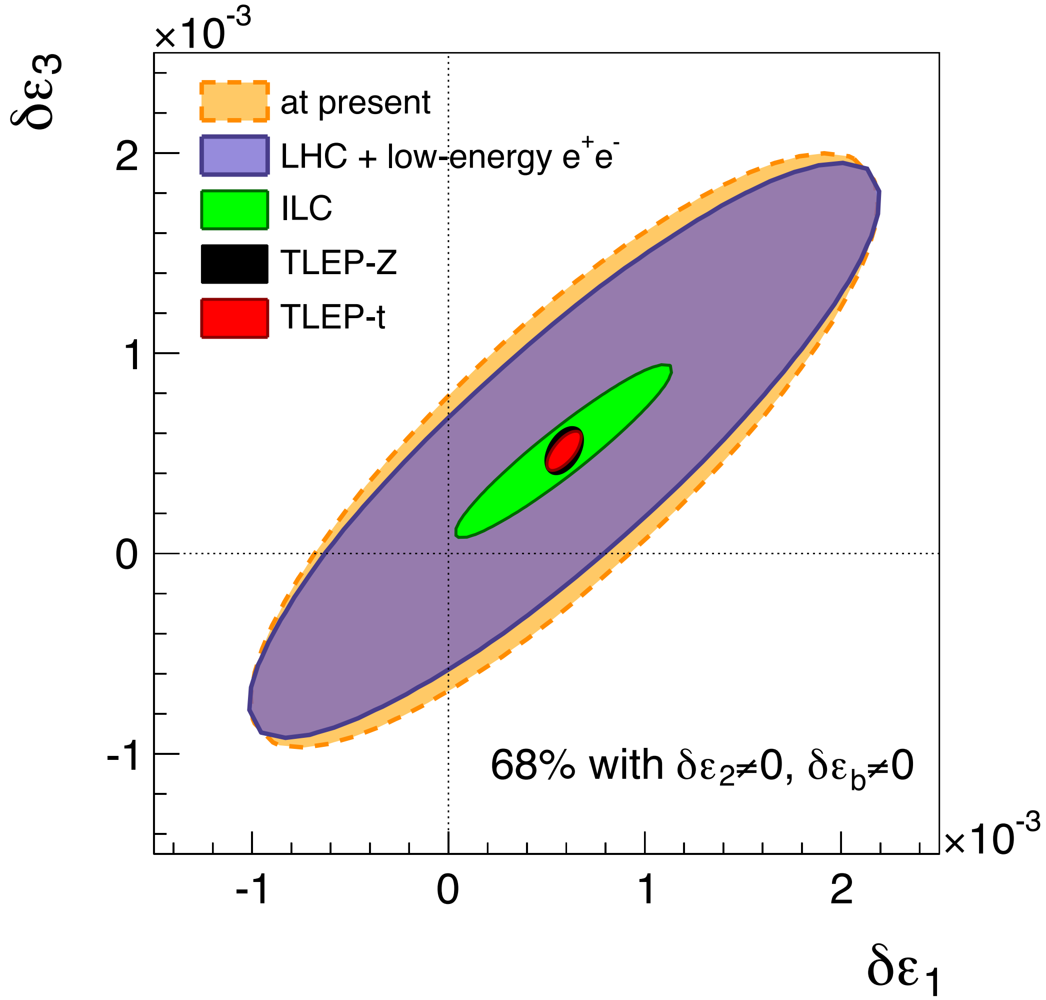
NP scenario



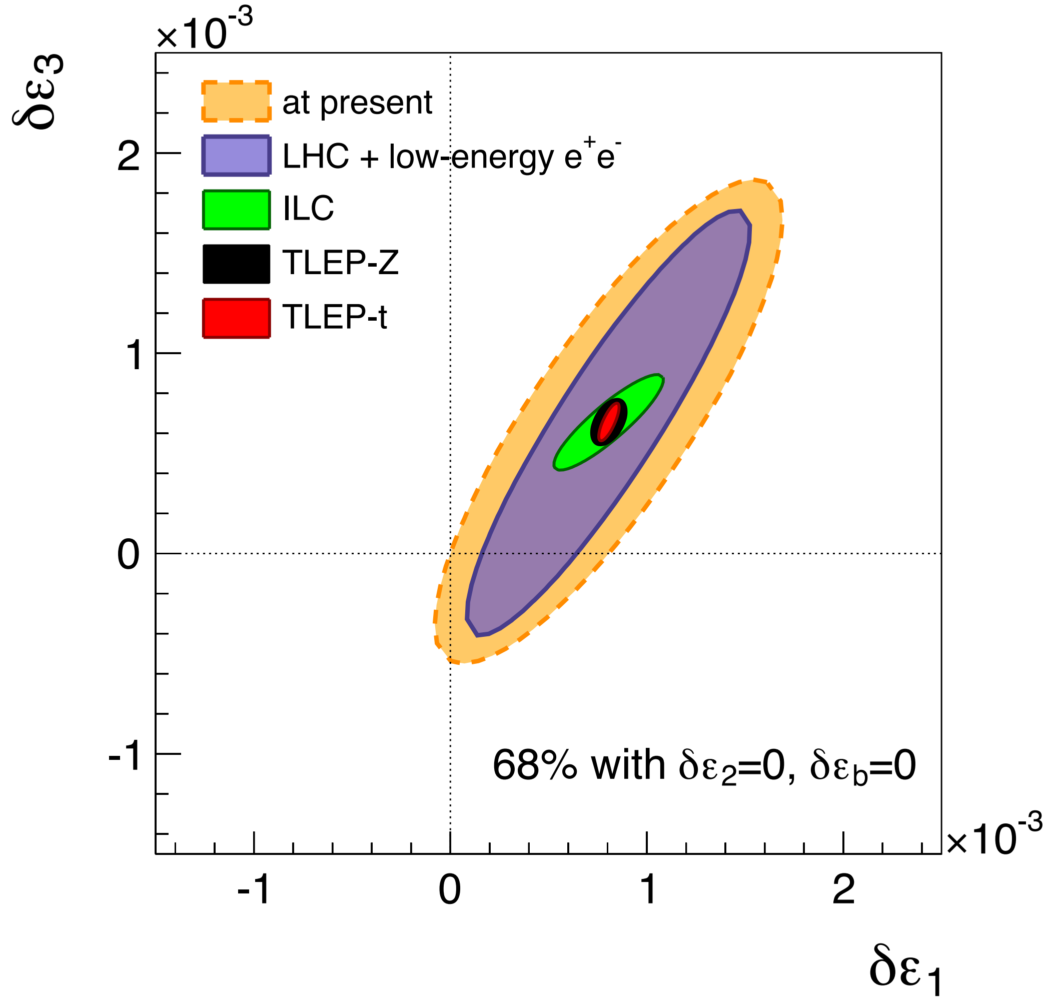
⇨ $\delta S \sim 7 \times 10^{-3}, \quad \delta T \sim 7 \times 10^{-3}, \quad \delta U \sim 6 \times 10^{-3}$

Future sensitivity to Epsilons

NP scenario



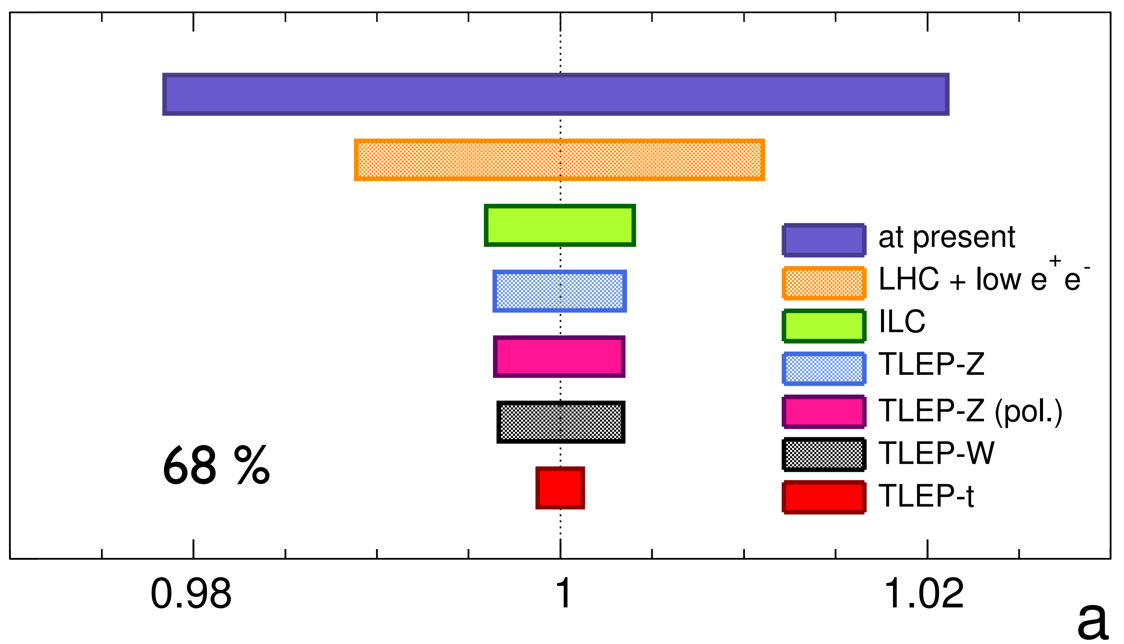
NP scenario



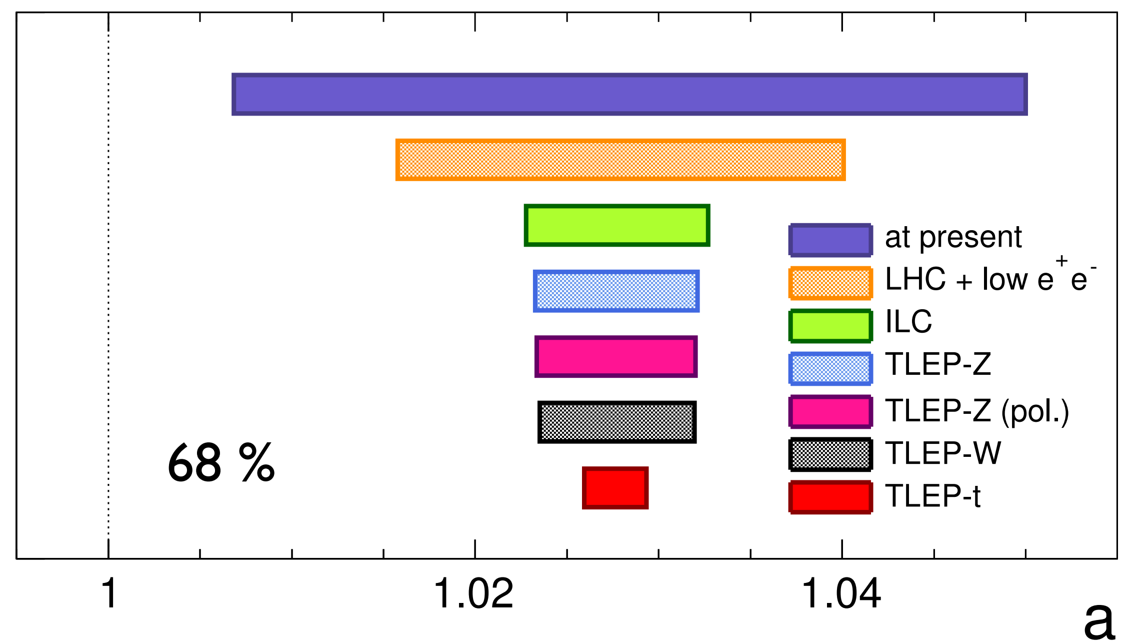
$$\Rightarrow \quad \delta(\delta\epsilon_{1,3}) \sim O(10^{-5})$$

Future sensitivity to the HVV coupling

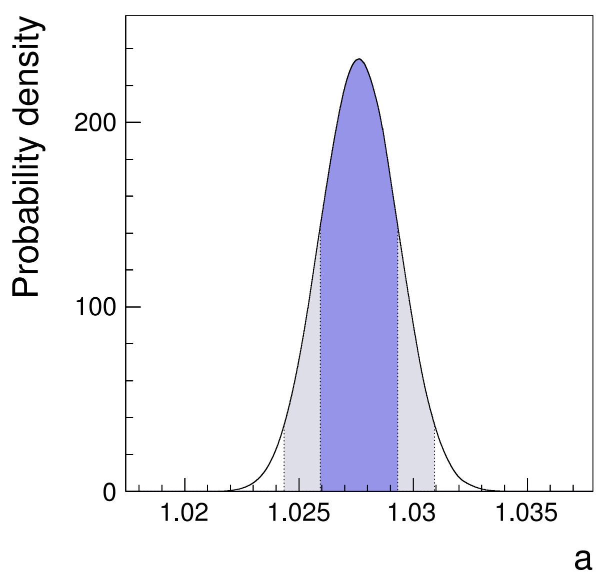
SM scenario



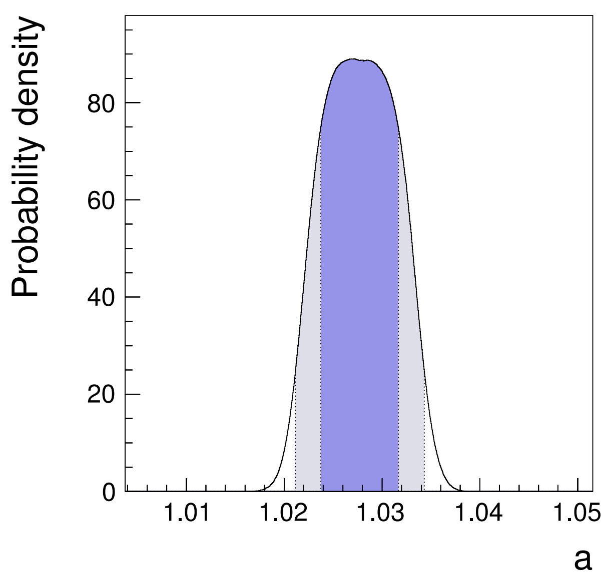
NP scenario



The HVV coupling can be measured with a precision of $\lesssim \mathbf{2 \times 10^{-3}}$.

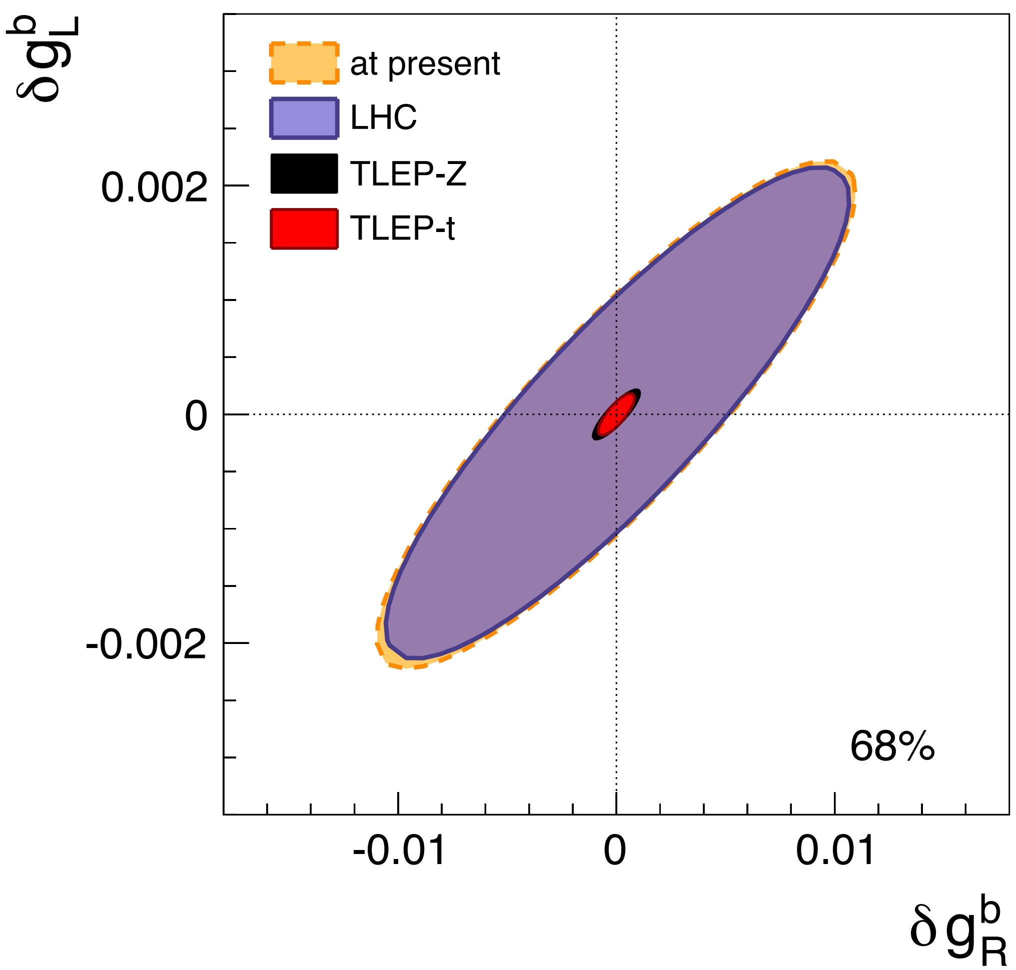


if no theory progress

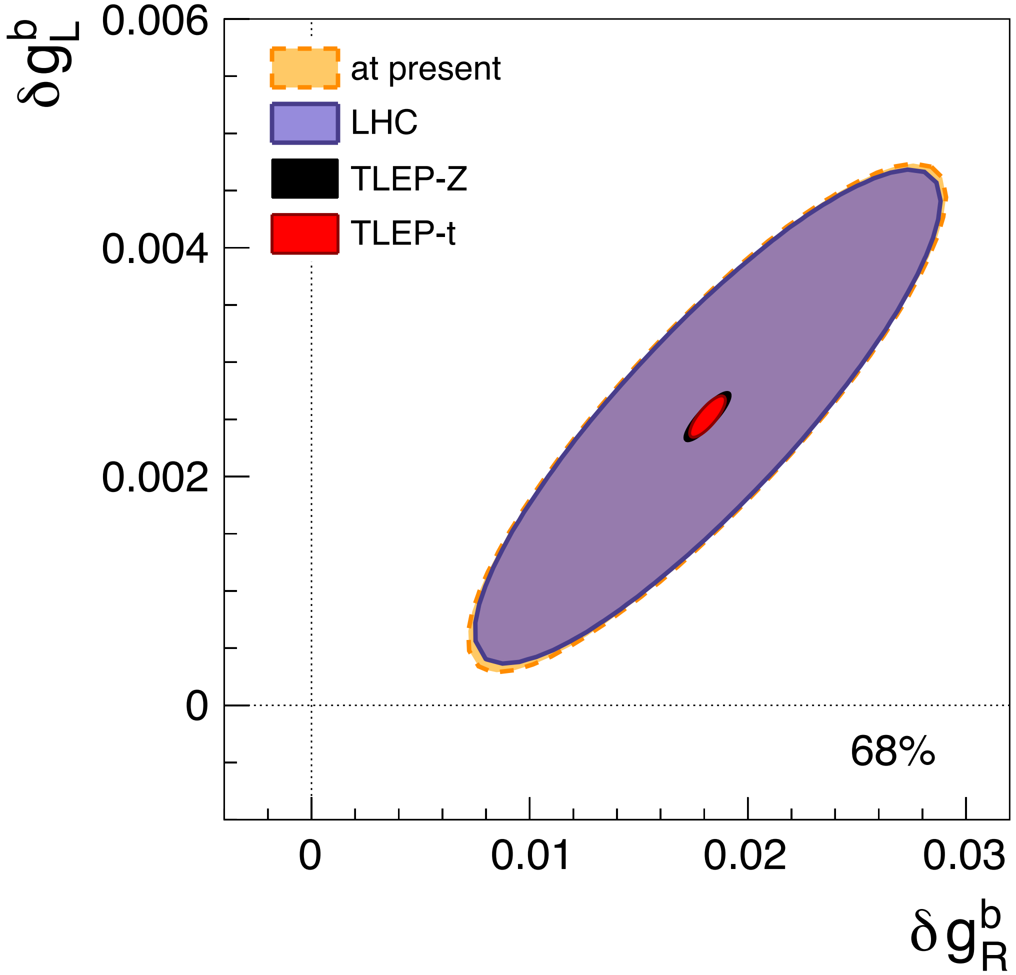


Future sensitivity to $Zb\bar{b}$ couplings

SM scenario



NP scenario



$$\delta(\delta g^b_{R,L}) \sim O(10^{-4})$$

Caveat: Future theory uncertainty $\delta R_b^0 \sim 1 \times 10^{-4}$ has not been taken into account in the above plots.

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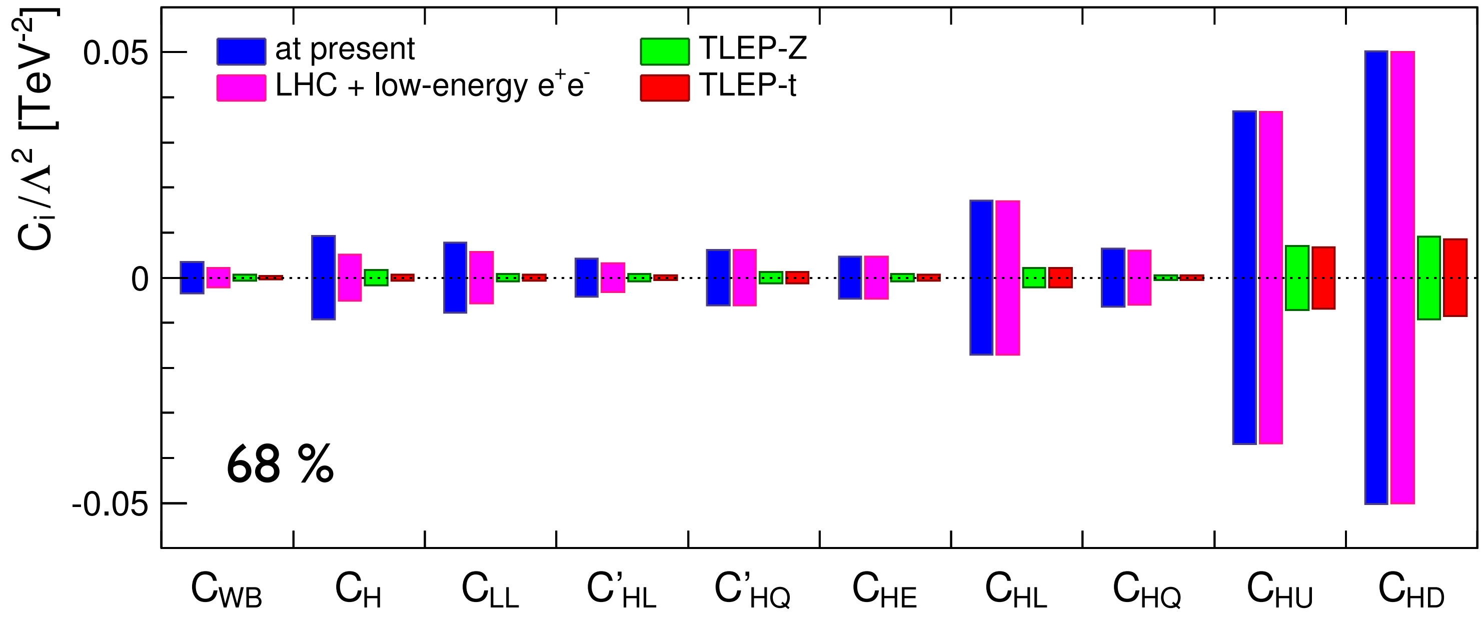
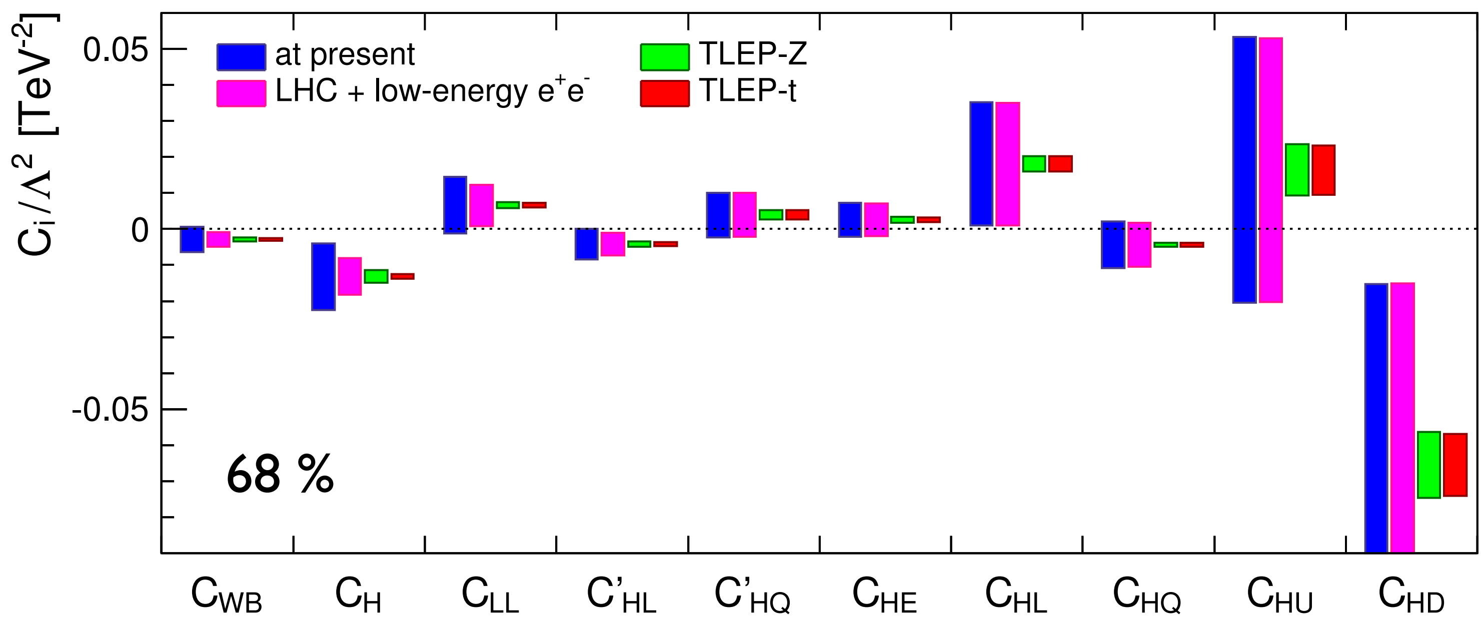
Future sensitivity to dim. 6 operators

SM scenario



NP scenario



Improvements by a factor of 5 to 10!

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Future sensitivity to NP scale

- The fit result for C_i/Λ^2 can be interpreted as a lower bound on the NP scale by fixing the coupling.

SM scenario, in units of TeV

Coefficient	at present $C_i=-1$	at present $C_i=1$	LHC + low e^+e^- $C_i=-1$	LHC + low e^+e^- $C_i=1$	TLEP-Z $C_i=-1$	TLEP-Z $C_i=1$	TLEP-t $C_i=-1$	TLEP-t $C_i=1$
C_{WB}	12.0	12.0	15.5	15.5	28.9	28.8	38.5	39.0
C_H	7.4	7.4	9.9	9.9	17.1	17.2	27.8	27.9
C_{LL}	8.1	8.1	9.4	9.4	24.3	24.3	27.6	27.6
C'_{HL}	10.9	10.9	12.7	12.7	25.1	25.1	31.2	31.3
C'_{HQ}	9.1	9.1	9.1	9.1	19.7	19.6	20.0	20.0
C_{HL}	10.4	10.4	10.5	10.5	24.8	24.7	28.2	28.3
C_{HQ}	5.5	5.5	5.5	5.5	15.2	15.2	15.3	15.3
C_{HE}	8.9	8.9	9.2	9.2	29.5	29.5	31.1	31.2
C_{HU}	3.7	3.7	3.7	3.7	8.4	8.4	8.6	8.6
C_{HD}	3.2	3.2	3.2	3.2	7.5	7.5	7.7	7.7

⇨ The TLEP measurements would push up the lower bound of the NP scale significantly!

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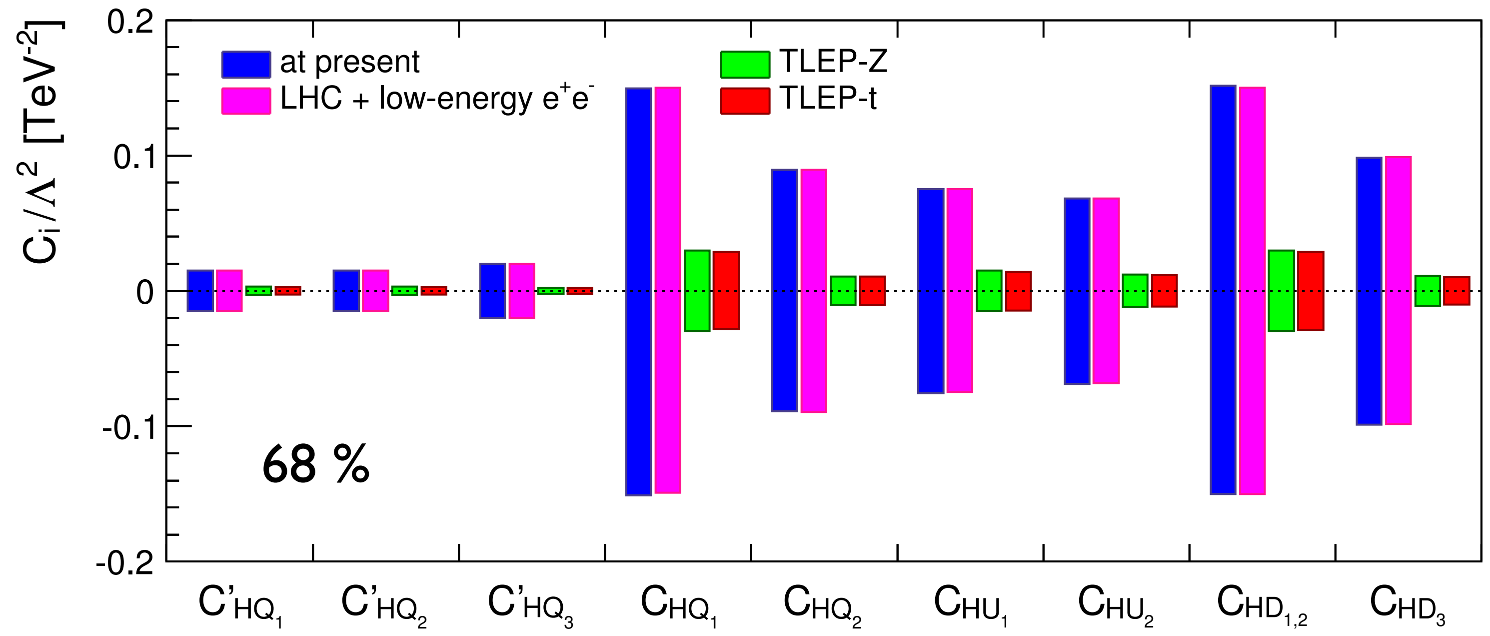
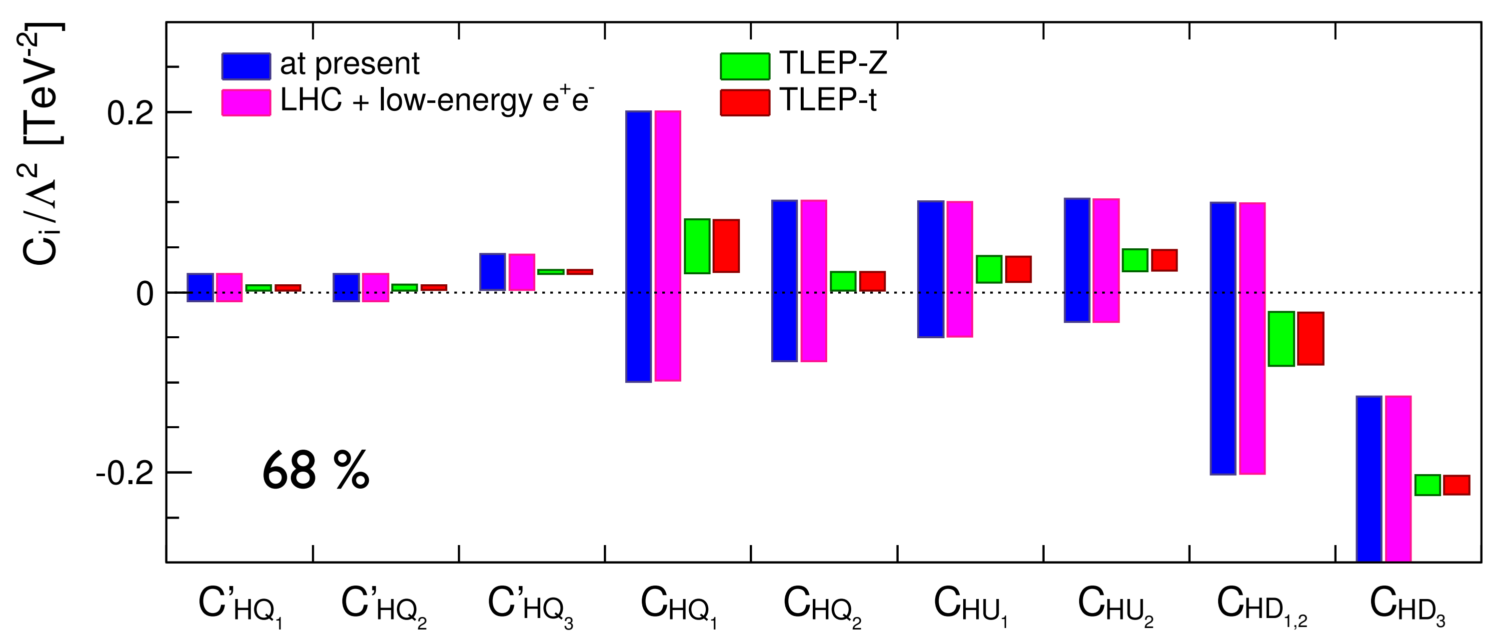
Future sensitivity to dim. 6 operators

Without quark-flavour universality

SM scenario



NP scenario



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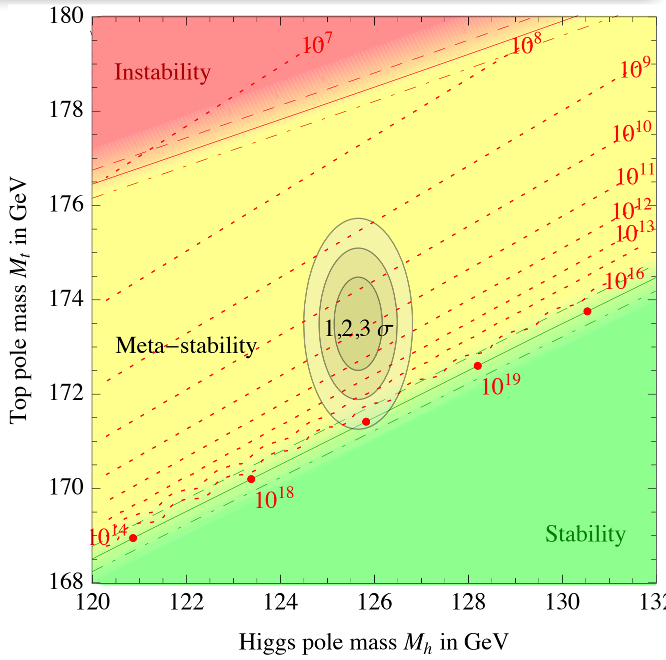
Top mass vs. (meta-)stability

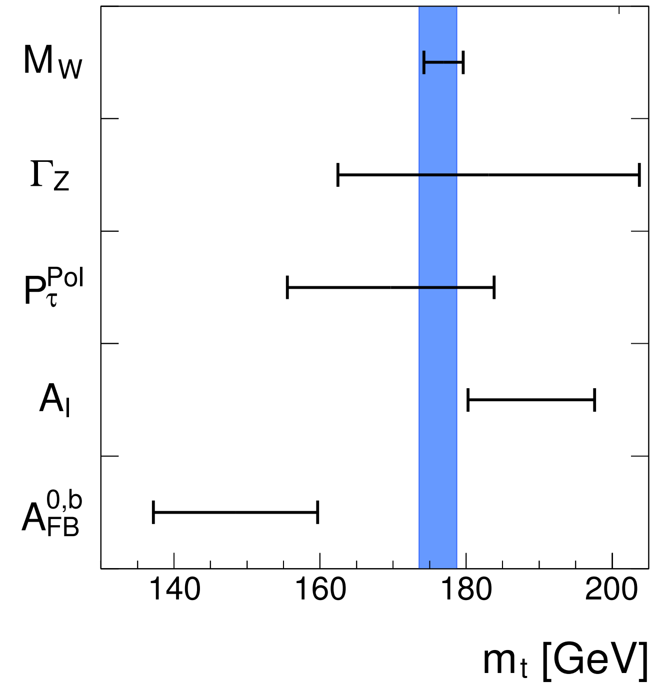
- The measurement of the top mass is crucial for testing the stability of the SM vacuum. *Degrassi et al.(12); Buttazzo et al.(13)*

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



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

$$176.2 \pm 2.6\ {\rm GeV}$$



- At TLEP:

$$\delta m_t^{\rm direct} \sim \pm 0.016\ {\rm GeV} \qquad \delta m_t^{\rm indirect} \sim \pm 0.2\ {\rm GeV}$$

5. Summary

- We have updated the EW fit with the recent exp. data and the recently computed fermionic EW 2-loop corrections to the $Zf\bar{f}$ couplings.

- We have derived constraints on oblique parameters, epsilon parameters, HVV coupling, $Zb\bar{b}$ couplings and dim. 6 operators.

- The constraining power of the EW fit have been improved by the recent experimental progresses.

- Future data (ILC/TLEP) will strengthen greatly the power of the EW fit.

Backup

Comparison to ZFITTER

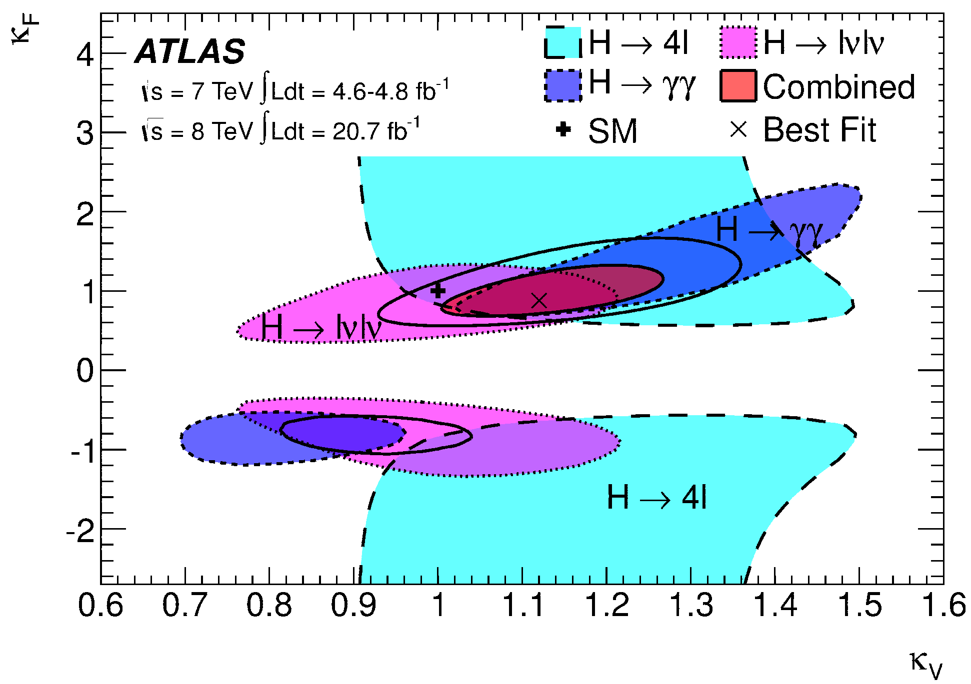
- With a given set of the input parameters and without using the new formulae for the partial Z widths:

	ZFITTER	OURS	Difference	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 %
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.23149326	0.23149297	−0.00012 %	0.52 %
$P_\tau^{\rm Pol}$	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 %
$A_{\rm FB}^{0,\ell}$	0.016261269	0.016261758	0.0030 %	5.5 %
$A_{\rm FB}^{0,c}$	0.073767554	0.073771169	0.0049 %	5.0 %
$A_{\rm FB}^{0,b}$	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 %

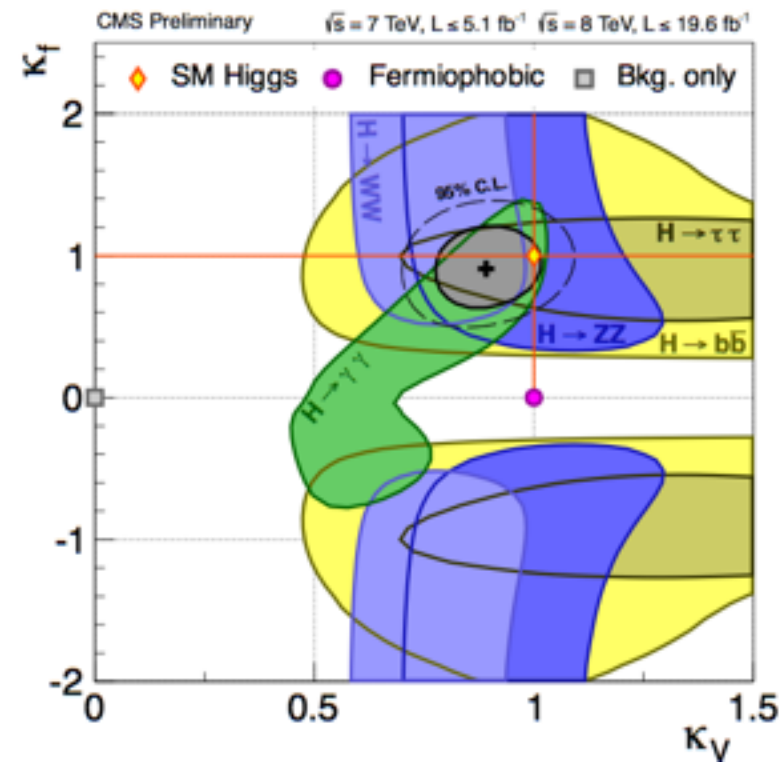
Our results are in agreement with ZFITTER v6.43.

Other measurements of HVV couplings

- Current LHC measurements:



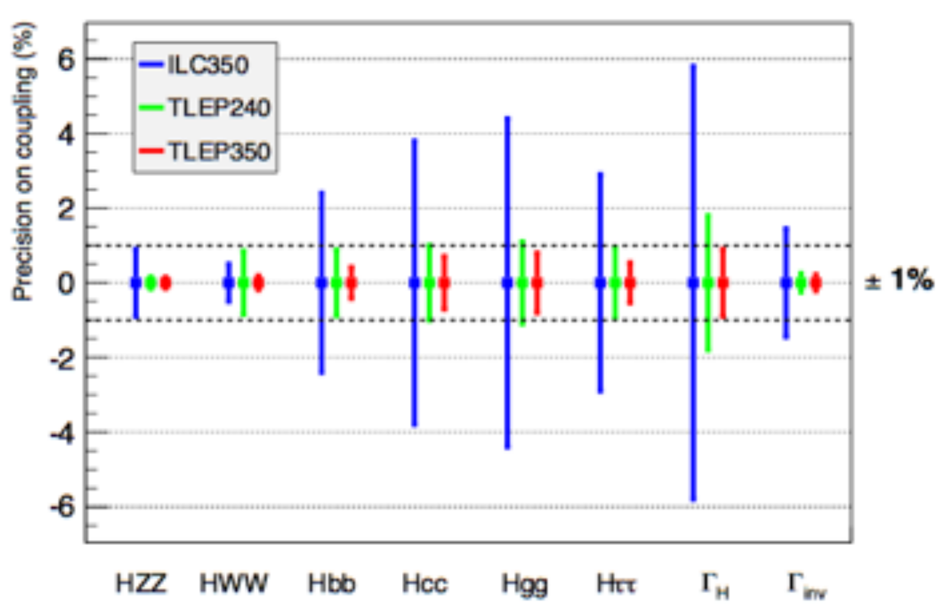
$\kappa_V \in [1.05,\ 1.22]$ @ 68%



$\kappa_V \in [0.81,\ 0.97]$ @ 68%

- Measurements of Higgs decays at TLEP

TLEP Design Study Working Group (13)



Similar precision to the EW precision fit

⇨ Compare two measurements!