Electroweak Precision Observables in the Standard Model and Beyond: Present & Future

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arXiv: 1604.XXASAP [hep-ph]

HEPfit COLLABORATION

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Istituto Nazionale di Fisica Nucleare

Electroweak precision observables: present

- Very precise measurements of Z & W boson properties:

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$

Z-pole obs. (SLD/LEP) 0.002-O(1)%

$$M_W,\ \Gamma_W$$

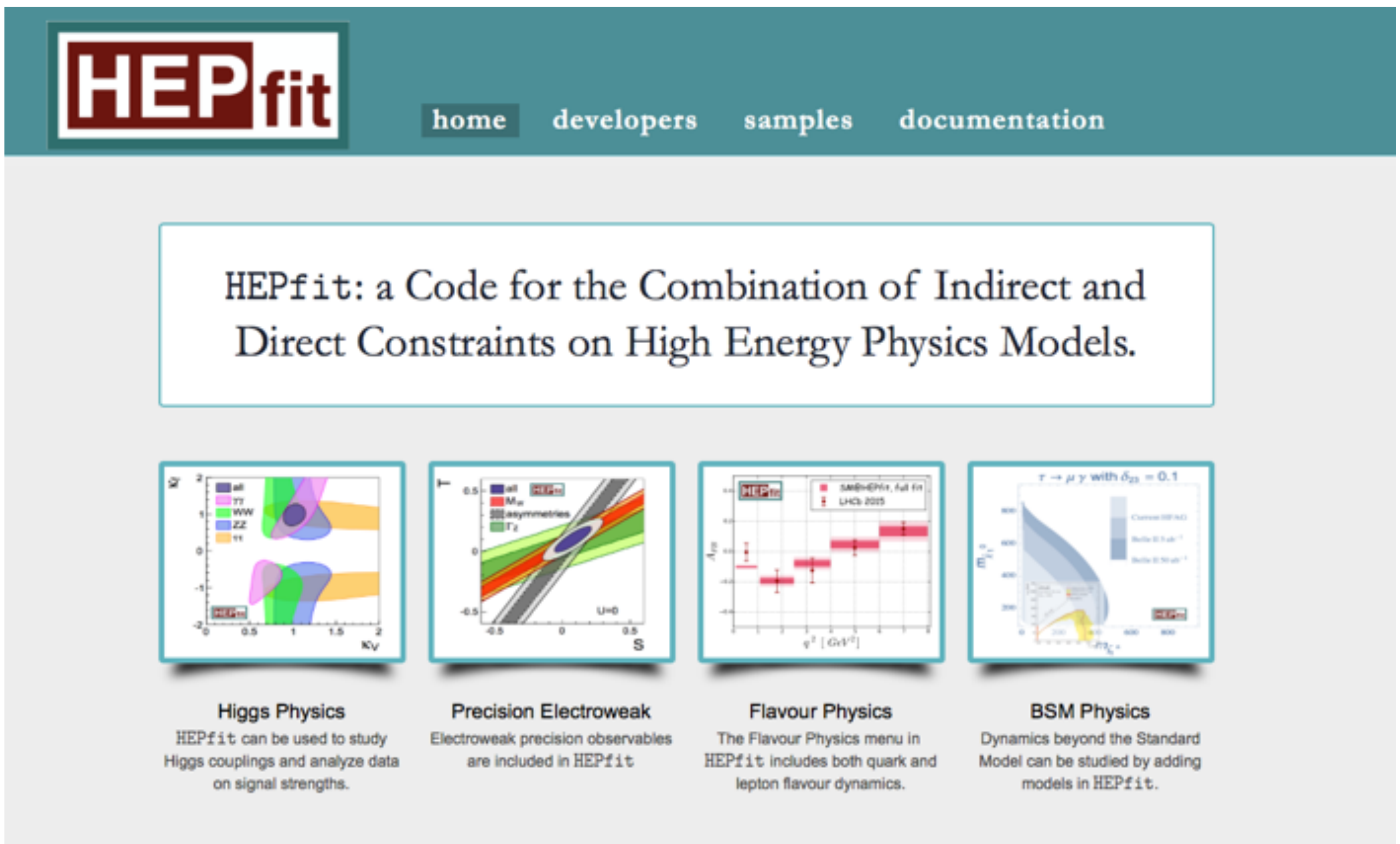
W obs. (LEP2/Tevatron) 0.02-O(1)%

- EW precision observables can test the SM to the level of radiative corrections → Indirect determination of top & Higgs masses …
- After Higgs discovery → strong (unambiguous) constraints on new physics modifying the electroweak sector (e.g. solutions to the hierarchy problem)
- Several groups/codes for the EW fit: ZFITTER, GAPP, Gfitter, …

Also part of HEPfit

THE HEPfit CODE

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on github)
  https://github.com/silvest/HEPfit
- Webpage: http://hepfit.roma1.infn.it



THE HEPfit CODE

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics:
  - Written in C++. Support for MPI parallelization.
  - Dependencies: ROOT, GSL, Boost, Bayesian Analysis Toolkit (BAT)
    Beaujean, Caldwell, Greenwald, Kollar, Kröninger, Schulz
  - Bayesian Statistical Analysis
  - Stand-alone and library modes to compute observables in a given model
  - Add new models and/or observables as external modules
- Preparing for first official release…

THE HEPfit CODE

Already in the code:

Models

- Standard Model
- Oblique pars: S,T,U
- ε_i parameters
- Modified *Zbb* couplings
- Modified Higgs coup: κ_V, κ_f
- SMEFT dim 6
- General THDM

⇐Tested

- SUSY

⇐WiP

Observables

- EWPO
- Higgs signal strengths
- Flavor: ΔF=2, UT, B decays
- LFV

⇐Tested

- LEP 2 cross sections

⇐WiP

Already in HEPfit:

Models

- Standard Model
- Oblique pars: S,T,U
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In this talk

Observables

- EWPO
- Higgs signal strengths
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- LFV

⇐Tested

- LEP 2 cross sections

⇐WiP

EW precision observables:

- Written from scratch
- SM EWPO validated against ZFITTER

Akhundov, Arbuzov, Riemann & Riemann

EW precision observables in the SM

- Input parameters: $\{G_\mu,\ \alpha_{\rm em}\}$ (Fixed)

$$\left\{m_h,\ m_t,\ M_Z,\ \alpha_s(M_Z^2),\ \Delta\alpha_{\rm had}^{(5)}(M_Z^2)\right\}$$ (Floating)

- W mass parametrized in terms of Δr

$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}(1+\Delta r)}\right)$$

- Z-pole observables parametrized in terms of effective Zff couplings

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

$$\rho_Z^f = \left(\frac{g_A^f}{I_3^f}\right)^2 \qquad \kappa_Z^f = \frac{1}{4|Q_f|s_W^2}\left(1-\frac{g_V^f}{g_A^f}\right) \qquad s_W^2 = 1-\frac{M_W^2}{M_Z^2}$$

On-shell ren. scheme

EW precision observables in the SM

- Z-pole observables parametrized in terms of Effective Zff couplings

Left-Right and Forward-Backward Asymmetries

$$A_{L,R}^{0,f} = A_f = \frac{2\mathrm{Re}\left\{\frac{g_V^f}{g_A^f}\right\}}{1+\mathrm{Re}\left\{\frac{g_V^f}{g_A^f}\right\}^2} \qquad A_{FB}^{0,f} = \frac{3}{4}A_e A_f \qquad (f=\ell, c, b)$$

Effective electroweak mixing angle

$$\sin^2\theta_{\mathrm{Eff}}^{\mathrm{lept}} = \mathrm{Re}\left\{\kappa_Z^\ell\right\} s_W^2$$

Decay widths (and ratios), hadronic cross section

$$\Gamma_f \propto \left|\rho_Z^f\right| \left[\left|\frac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right]$$

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

EW precision observables in the SM

- Theory status:
  - M_W : Full EW 2-loop + leading 3-loop & some 4-loop contrib.
    M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Phys. Rev D69 (2004) 053006
  - $\sin^2\theta^f_{\rm Eff}$: Full EW 2-loop + leading higher order contrib.
    M. Awramik, M. Czakon, A. Freitas, JHEP 0611 (2006) 048
    M. Awramik, M. Czakon, A. Freitas, B.A. Kniehl, Nucl. Phys. B813 (2009) 174-187
  - Γ^f_Z : Full fermionic EW 2-loop
    A. Freitas, JHEP 1404 (2014) 070
  - Γ_W: Only EW one loop
    D.Y. Bardin, P.K. Khristova, O. Fedorenko, Nucl. Phys B197 (1982) 1-44
    D.Y. Bardin, S. Riemann, T. Riemann, Z. Phys C32 (1986) 121-125
- Experimental vs Theoretical uncertainties: Present

	$M_{\rm W}$	$\Gamma_{\rm Z}$	$\sigma^0_{\rm had}$	$R_{\rm b}$	$\sin^2\theta^\ell_{\rm eff}$
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}

A. Freitas, **PoS(LL2014)050** [arXiv: 1406.6980]

EW precision observables in the SM

	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1185±0.0005	0.1185±0.0005	0.1184±0.0028	−0.0
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750±0.00033	0.02741±0.00026	0.02725±0.00042	−0.5
M_Z[GeV]	91.1875±0.0021	91.1879±0.0020	91.199±0.011	+1.0
m_t[GeV]	173.34±0.76	173.6±0.7	176.9±2.5	+1.3
m_h[GeV]	125.09±0.24	125.09±0.24	97.40±25.59	−0.9
M_W[GeV]	80.385±0.015	80.365±0.006	80.361±0.007	−1.4
Γ_W[GeV]	2.085±0.042	2.0890±0.0005	2.0890±0.0005	+0.1
Γ_Z[GeV]	2.4952±0.0023	2.4945±0.0004	2.4945±0.0004	−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	0.1477±0.0007	0.1477±0.0007	+0.4
A_ℓ(SLD)	0.1513±0.0021	0.1477±0.0007	0.1472±0.0008	−1.9
A_c	0.670±0.027	0.6682±0.0003	0.6682±0.0003	−0.1
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	0.0164±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	20.752±0.003	20.752±0.003	−0.6
R_c^0	0.1721±0.0030	0.17224±0.00001	0.17224±0.00001	+0.0
R_b^0	0.21629±0.00066	0.21578±0.00003	0.21578±0.00003	−0.8

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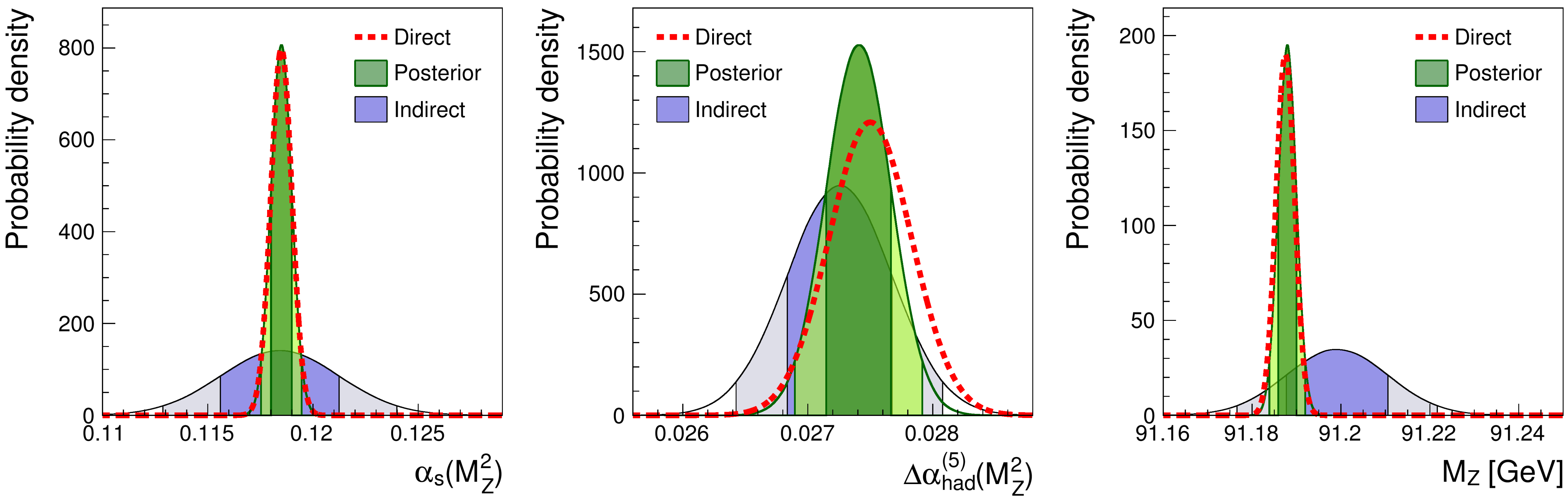
Only 1 significant discrepancy

EW precision observables in the SM

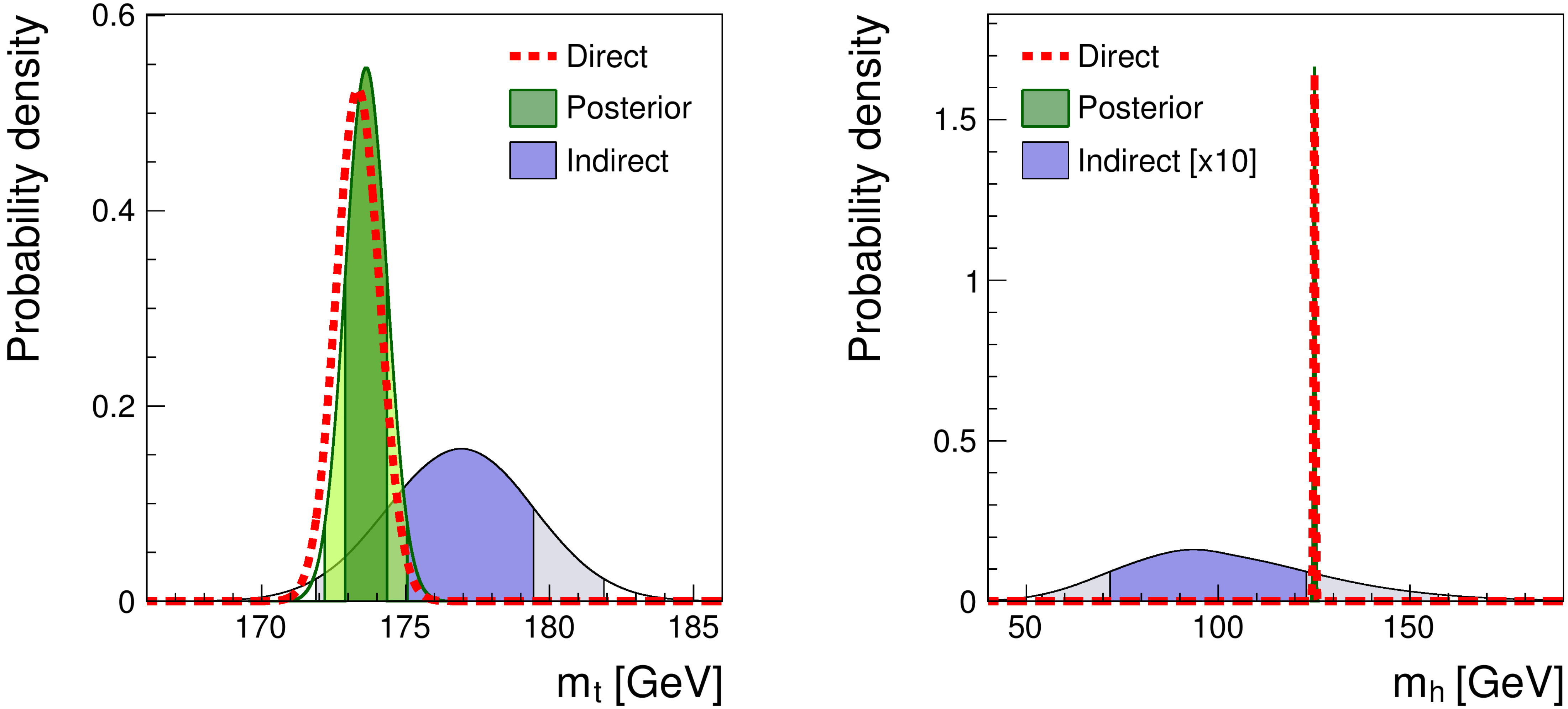
- Good agreement between direct and indirect determinations of the values of the input parameters



Indirect: Best-fit value, excluding the direct exp. measurement from the fit

EW precision observables in the SM

- Good agreement between direct and indirect determinations of the values of the input parameters



Indirect: Best-fit value, excluding the direct exp. measurement from the fit

EW precision observables in the SM

- Parametric uncertainties dominated by $\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = 0.02750 \pm 0.00033$

H. Burkhardt, B. Pietrzyk, Phys. Rev. D84 (2011) 037502

	Prediction	$\alpha_s(M_Z^2)$	$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	M_Z	m_t
M_W [GeV]	80.361±0.008	±0.000	±0.006	±0.003	±0.005
Γ_W [GeV]	2.0887±0.0007	±0.0002	±0.0005	±0.0002	±0.0004
Γ_Z [GeV]	2.4943±0.0005	±0.0002	±0.0003	±0.0002	±0.0002
σ_h^0 [nb]	41.488±0.003	±0.002	±0.000	±0.002	±0.001
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.23149±0.00012	±0.00000	±0.00012	±0.00001	±0.00002
$P_\tau^{\rm pol}$	0.1473±0.0009	±0.0000	±0.0009	±0.0001	±0.0002
A_ℓ(SLD)	0.1473±0.0009	±0.0000	±0.0009	±0.0001	±0.0002
A_c	0.6680±0.0004	±0.0000	±0.0004	±0.0001	±0.0001
A_b	0.93464±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
$A_{\rm FB}^{0,c}$	0.0738±0.0005	±0.0000	±0.0005	±0.0001	±0.0001
$A_{\rm FB}^{0,b}$	0.1033±0.0007	±0.0000	±0.0006	±0.0001	±0.0001
R_ℓ^0	20.752±0.004	±0.003	±0.002	±0.000	±0.000
R_c^0	0.17223±0.00001	±0.00001	±0.00001	±0.00000	±0.00001
R_b^0	0.21579±0.00003	±0.00001	±0.00000	±0.00000	±0.00003

- Measured with inclusive processes. Smaller uncertainty if using exclusive with pQCD, etc.

Assume $\delta(\Delta\alpha_{\rm had}^{(5)}(M_Z^2)) \approx 0.0005$ in Future analyses

EW precision observables at the FCCee

- Physics at the FCCee: Several projected runs

	Z pole	WW threshold	HZ threshold	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}(ab^{-1}/year)$	86	15	3.5	1.0	1.0
Years of run	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	6×10^{7}	2×10^{6}	2×10^{5}	7.5×10^{4}

- Each run will bring improvements on the precision of different sectors of Electroweak precision observables

EW precision observables at the FCCee

- Expected sensitivities to EWPO

	Current Data	Before FCC	FCCee-Z (no pol.)	FCCee-Z	FCCee-WW	FCCee-HZ	FCCee-$t\bar{t}$
$\alpha_s(M_Z^2)$	0.1185 ± 0.0005		±0.0002				
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	±0.00005 (?)					
M_Z[GeV]	91.1875 ± 0.0021		±0.0001				
m_t[GeV]	173.34 ± 0.76	±0.6					±0.014
m_h[GeV]	125.09 ± 0.24	±0.05				±0.007	
M_W[GeV]	80.385 ± 0.015	±0.011			±0.001		
Γ_W[GeV]	2.085 ± 0.042				±0.005		
Γ_Z[GeV]	2.4952 ± 0.0023		±0.0001				
σ_h^0[nb]	41.540 ± 0.037		±0.025				
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.2324 ± 0.0012		±0.0001				
$P_\tau^{\rm pol}$	0.1465 ± 0.0033		±0.0002				
A_ℓ	0.1513 ± 0.0021			±0.000021			
A_c	0.670 ± 0.027			±0.01			
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$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010		±0.0001				
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TLEP WG, arXiv: 1308.6176 [hep-ex]

EW PRECISION OBSERVABLES AT THE FCCEE

- Expected sensitivities to EWPO and Higgs observables

	Current Data	Before FCC	FCCee-Z (no pol.)	FCCee-Z	FCCee-WW	FCCee-HZ	FCCee-$t\bar{t}$
$\alpha_s(M_Z^2)$	0.1185±0.0005		±0.0002				
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	0.02750±0.00033	±0.00005 (?)					
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M_W[GeV]	80.385±0.015	±0.011			±0.001		
Γ_W[GeV]	2.085±0.042						
Γ_Z[GeV]	2.4952±0.0023		±0.00				
σ_h^0[nb]	41.540±0.037		±0.02				
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	0.2324±0.0012		±0.00				
P_τ^{pol}	0.1465±0.0033		±0.00				
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R_b^0	0.21629±0.00066		±0.000				

	Before FCC	FCCee-HZ
σ_{HZ}		0.4%
$\sigma_{HZ}\,\text{Br}(H\to b\bar{b})$	$\sim$ 10%	0.2%
$\sigma_{HZ}\,\text{Br}(H\to c\bar{c})$		1.2%
$\sigma_{HZ}\,\text{Br}(H\to gg)$		1.4%
$\sigma_{HZ}\,\text{Br}(H\to W^\pm W^{\mp *})$	$\sim$ 5-10%	0.9%
$\sigma_{HZ}\,\text{Br}(H\to \tau^+\tau^-)$	$\sim$ 15%	0.7%
$\sigma_{HZ}\,\text{Br}(H\to ZZ^*)$	$\sim$ 5-15%	3.1%
$\sigma_{HZ}\,\text{Br}(H\to \gamma\gamma)$	$\sim$ 5-10%	3.0%
$\sigma_{HZ}\,\text{Br}(H\to \mu^+\mu^-)$	$\sim$ 15-20%	13%

TLEP WG, arXiv: 1308.6176 [hep-ex]

EW precision observables in the SM: Future

- Experimental vs Theoretical uncertainties:

Present

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	4.5	16
Γ_Z [MeV]	0.5	2.3
R_b [10^{-5}]	15	66

Future

Quantity	ILC	FCC-ee	CEPC	Projected theory error
M_W [MeV]	3–4	1	3	1
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	1	0.6	2.3	1.5
Γ_Z [MeV]	0.8	0.1	0.5	0.2
R_b [10^{-5}]	14	6	17	5–10

A. Freitas, arXiv: 1604.00406

Theoretical effort necessary to achieve FCCee precision

EWPD limits on physics Beyond the SM: present vs. future

(preliminary results)

EWPD limits on physics Beyond the SM

- New Physics beyond the Standard Model: Several model-independent NP scenarios implemented within HEPfit
  - Oblique parameters
  - Non-Standard *Zbb* couplings
  - Modified Higgs couplings
  - Dim 6 SMEFT
- General strategy for the calculation of future sensitivities:
  - Assume theoretical uncertainties will be reduced as needed to reach FCCee precision
  - Use SM best-fit results as central values for future data. Limits provide FCCee sensitivity to New Physics.

EW limits on NP: S, T, U

- Oblique Parameters: New Physics contributing to gauge boson self-energies. EWPD depends only on 3 parameters

M.E. Peskin, T. Takeuchi, Phys. Rev. D46 (1992) 381-409

$$\alpha S = 4e^2 \left[\Pi_{33}^{\rm NP}{}'(0) - \Pi_{3Q}^{\rm NP}{}'(0)\right]$$

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

$$\alpha U = 4e^2 \left[\Pi_{11}^{\rm NP}{}'(0) - \Pi_{33}^{\rm NP}{}'(0)\right]$$

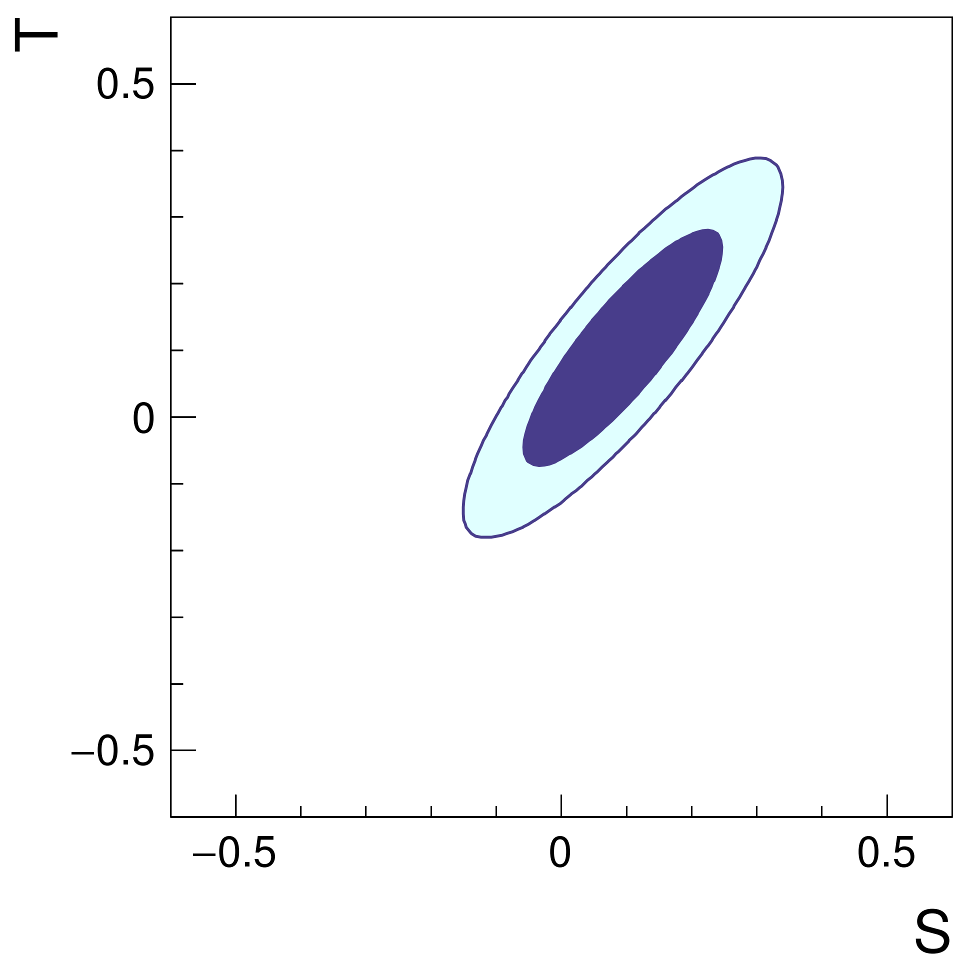
- In models where EWSB is realized linearly, U is expected to be << S,T

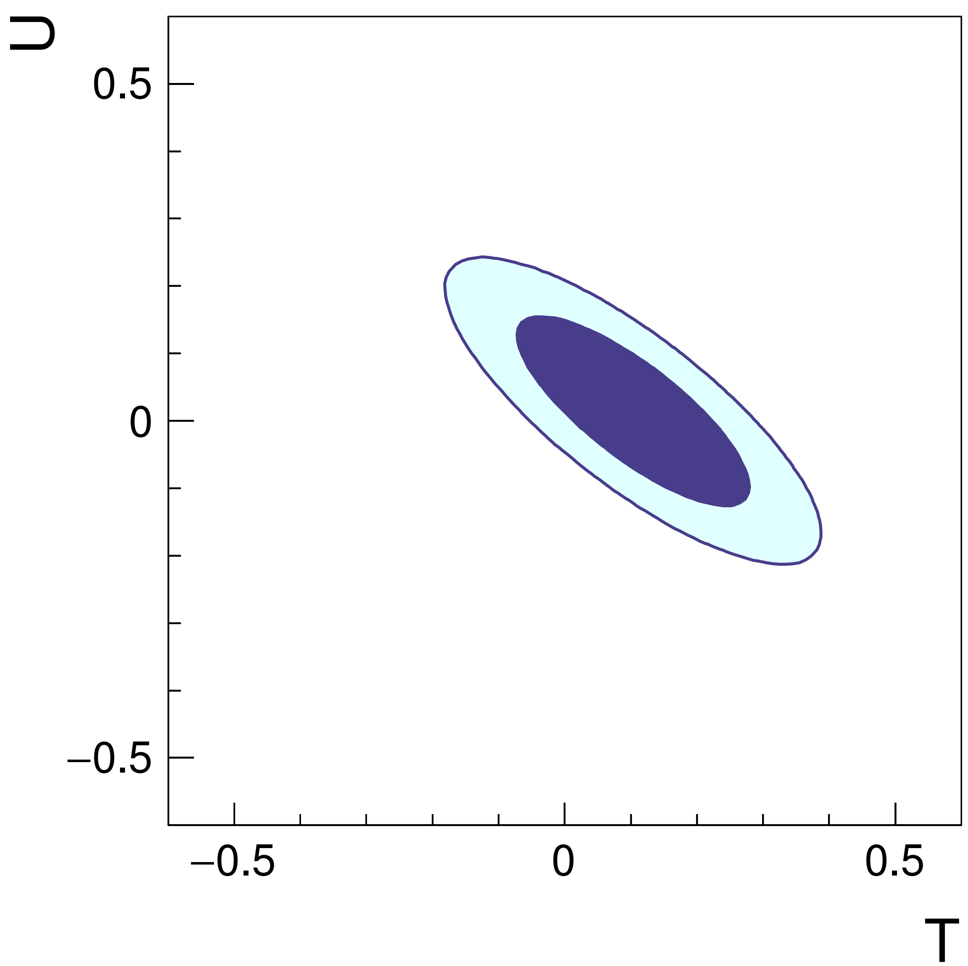
U: dim 8

S,T: dim 6

EW limits on NP: S, T, U

- Oblique Parameters: Present

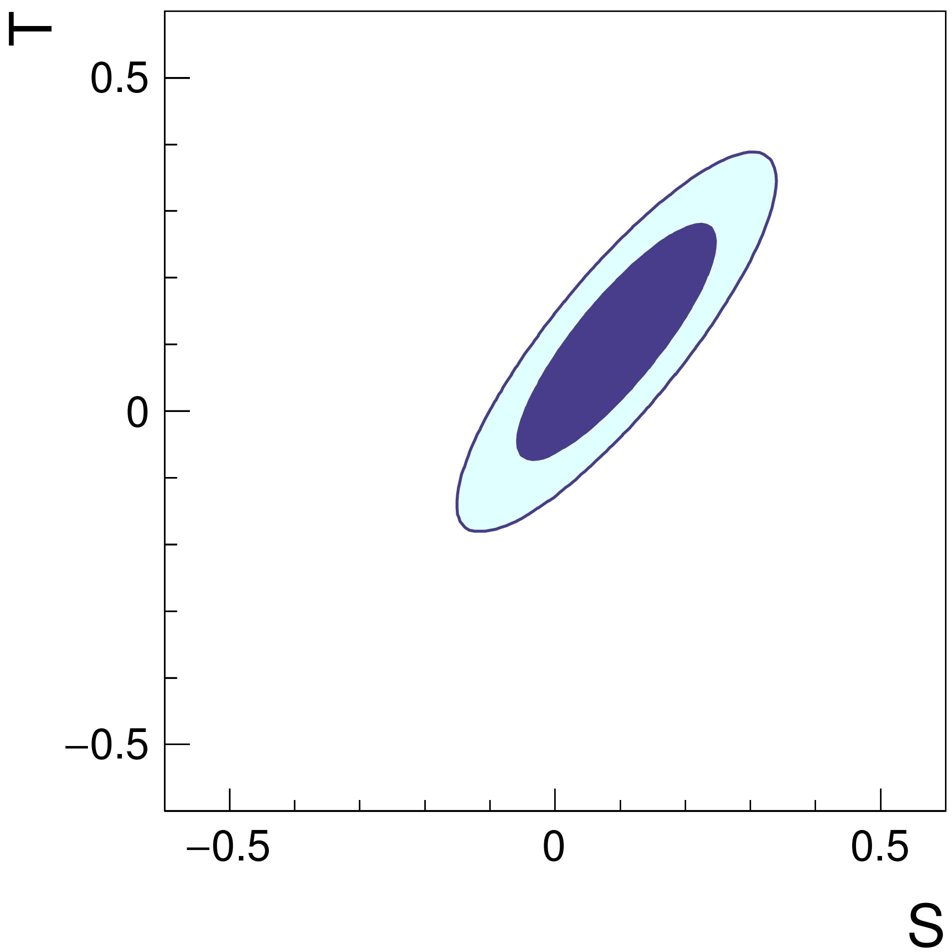




	Fit result	Correlations		
S	0.09 ± 0.10	1.00		
T	0.10 ± 0.12	0.86	1.00	
U	0.02 ± 0.09	-0.54	-0.81	1.00

EW limits on NP: S, T, U

- Oblique Parameters: **Present vs. Future**



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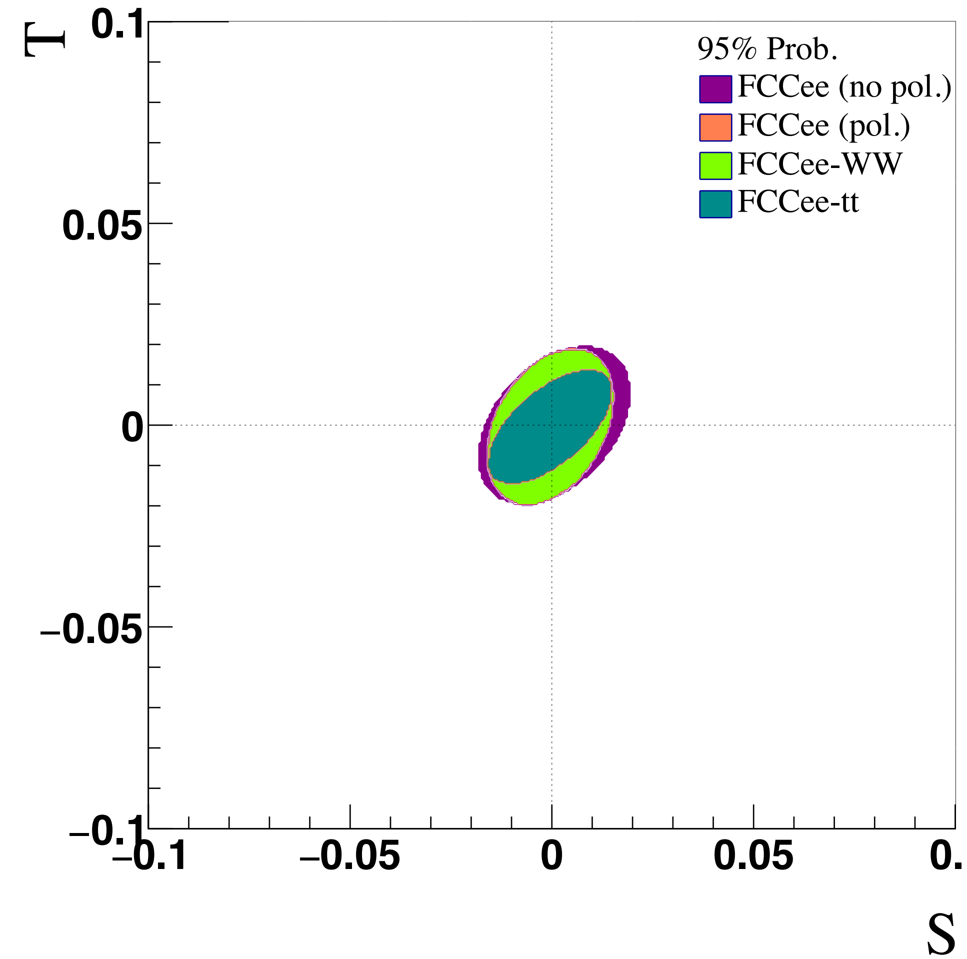
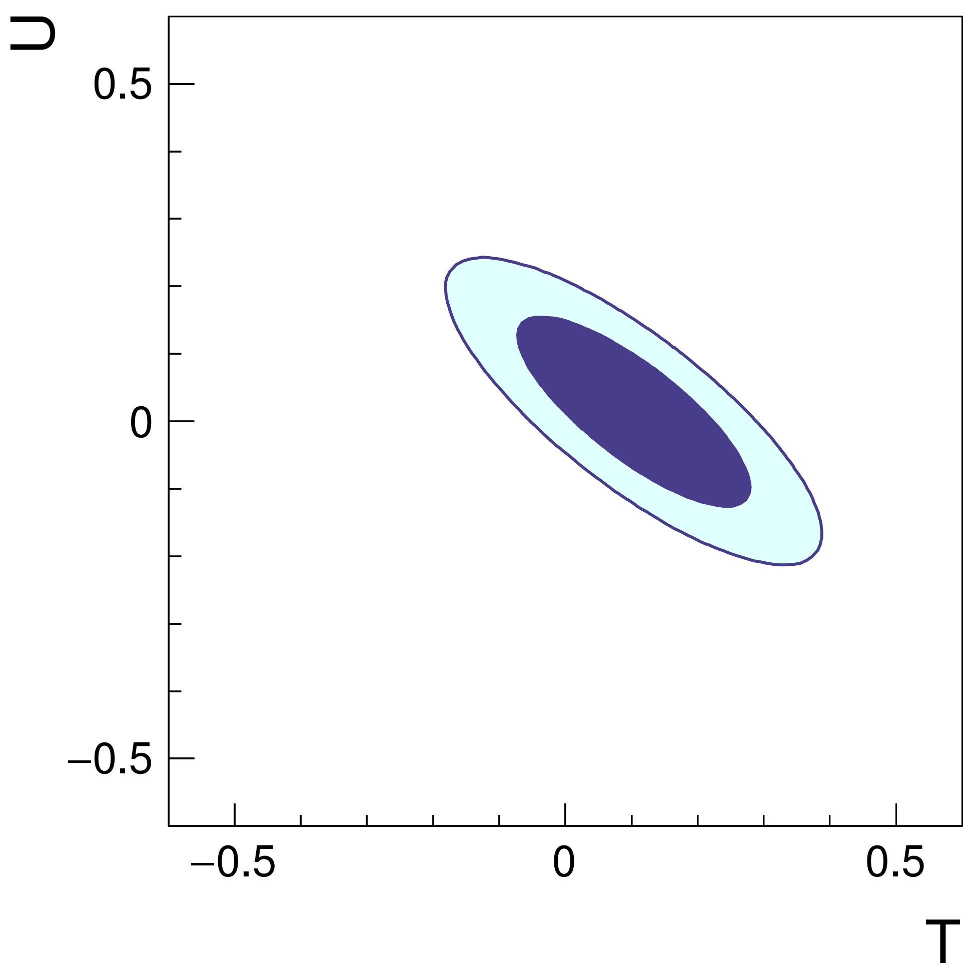


FCCee

$$\delta S,\ \delta T \sim 0.006$$

EW LIMITS ON NP: S, T, U

- Oblique Parameters: **Present vs. Future**



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T	0.10 ± 0.12	0.86	1.00	
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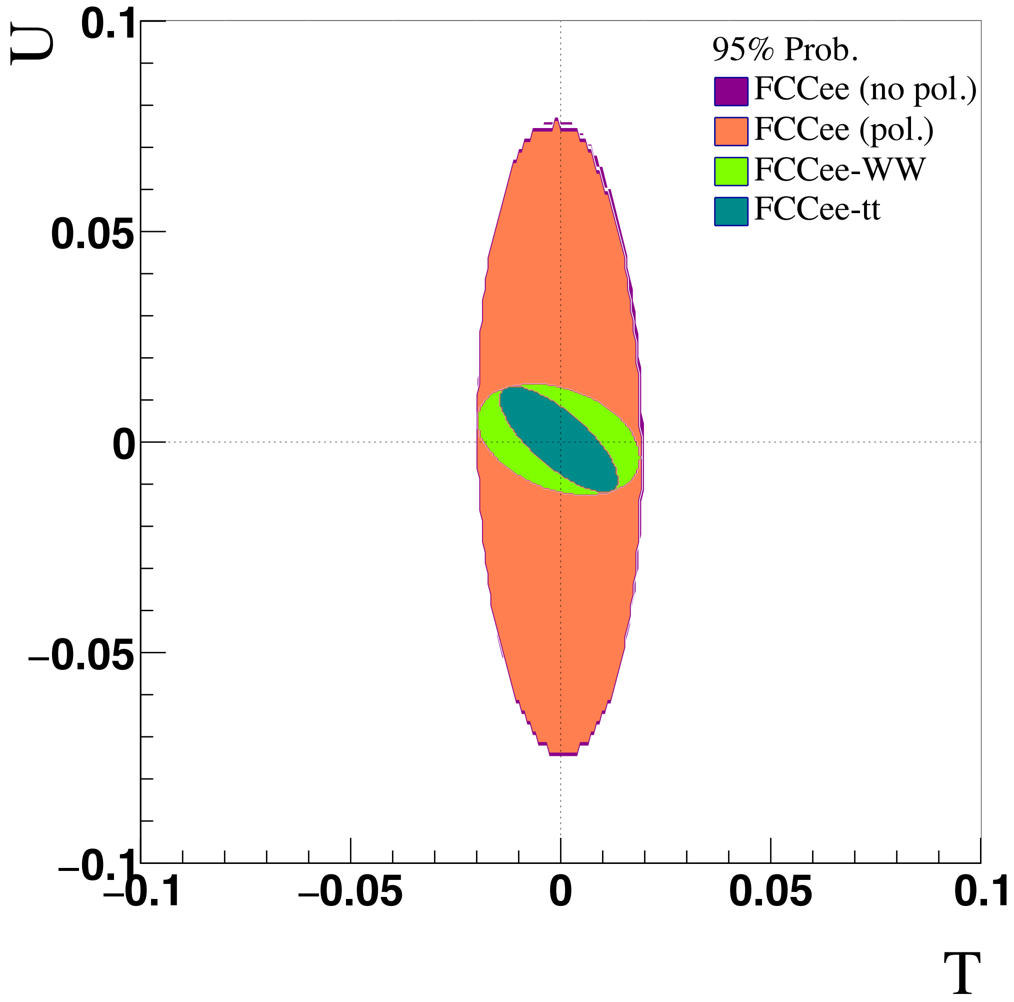


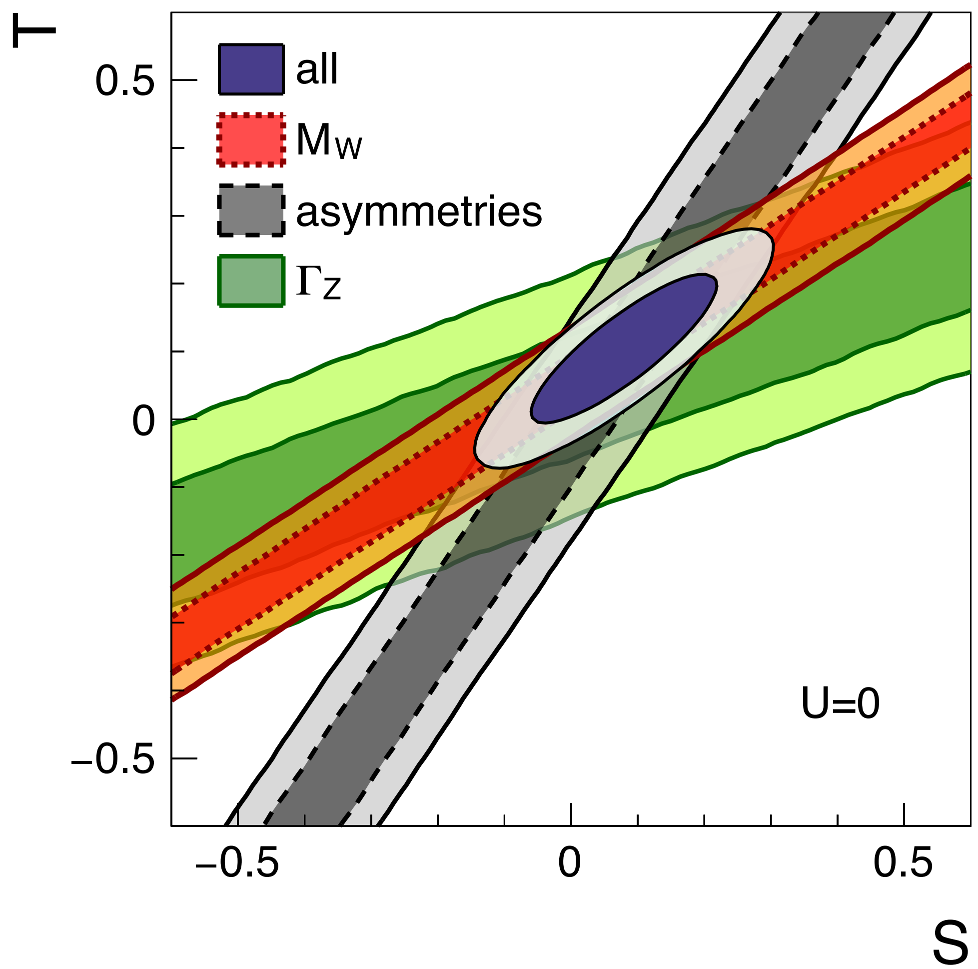
FCCee

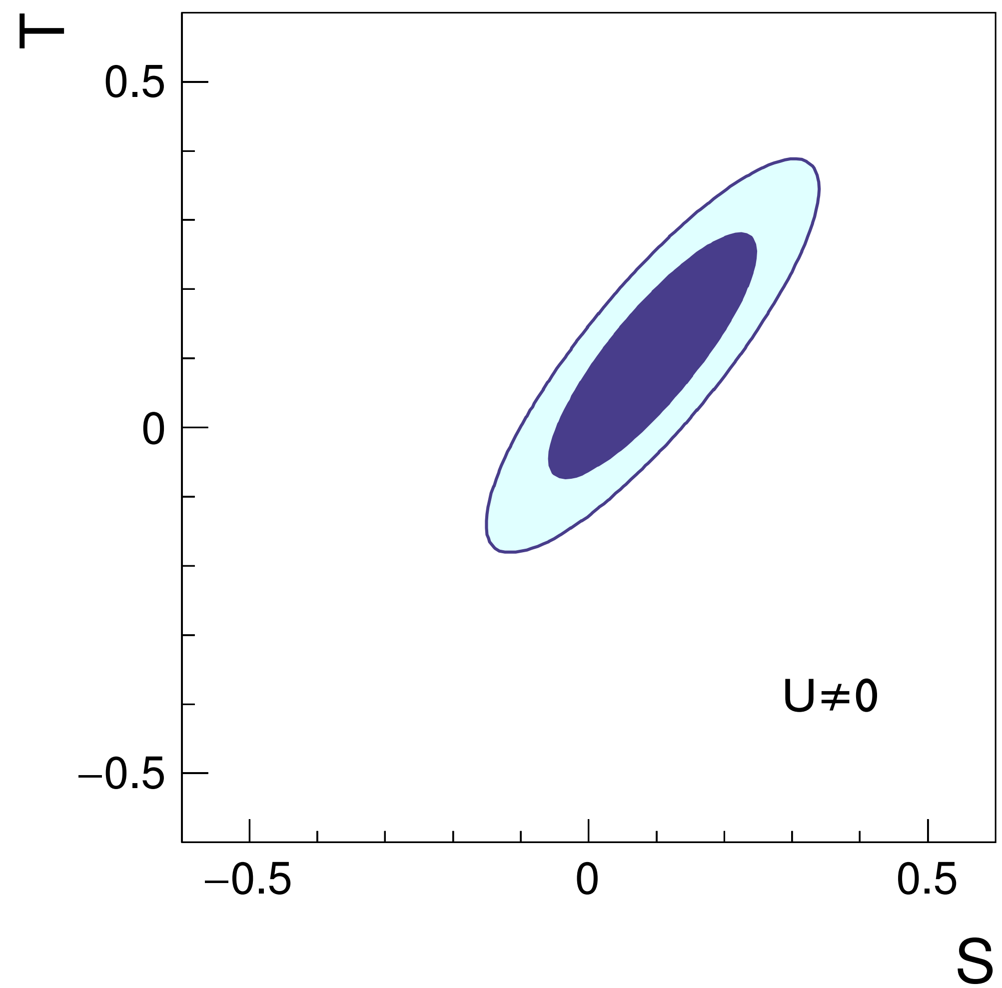
$\delta U \sim 0.005$

Major improvement on U at FCCee-WW

EW limits on NP: S, T (U=0)

- Oblique Parameters: Present

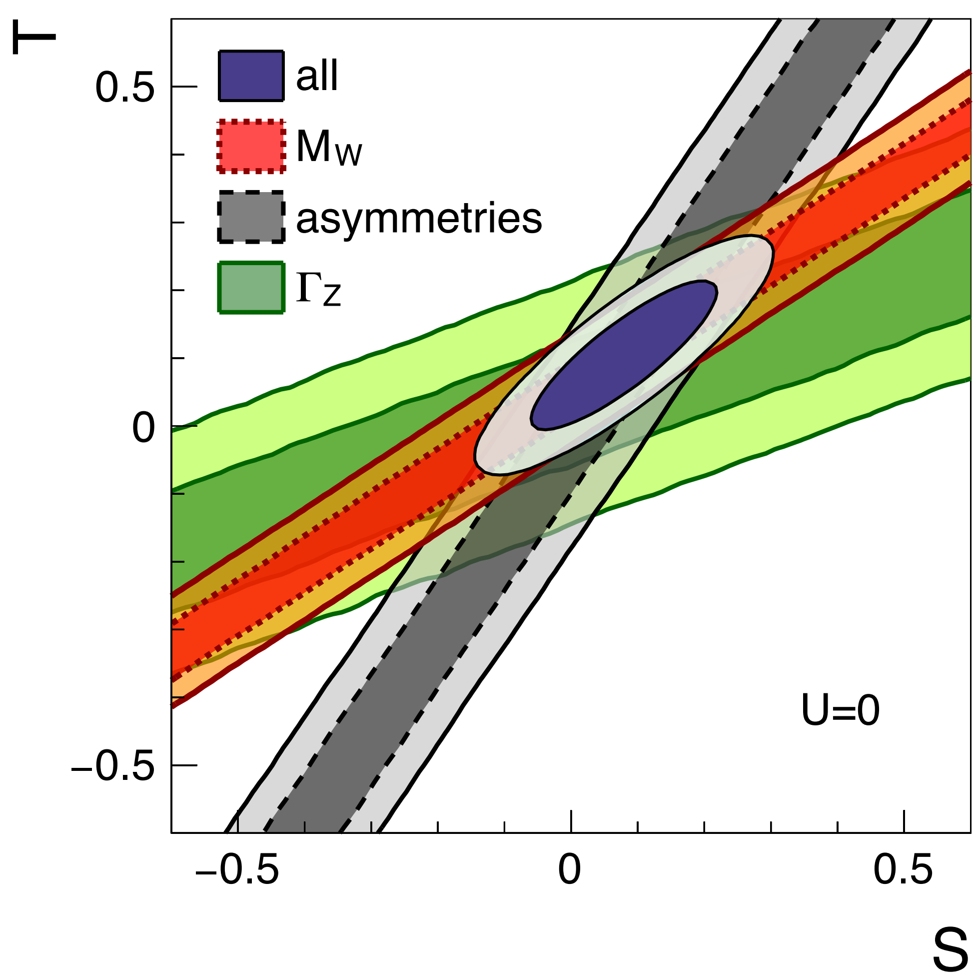




	Fit result	Correlations	
S	0.10 ± 0.08	1.00	
T	0.12 ± 0.07	0.85	1.00

EW LIMITS ON NP: S, T (U=0)

- Oblique Parameters: **Present vs. Future**



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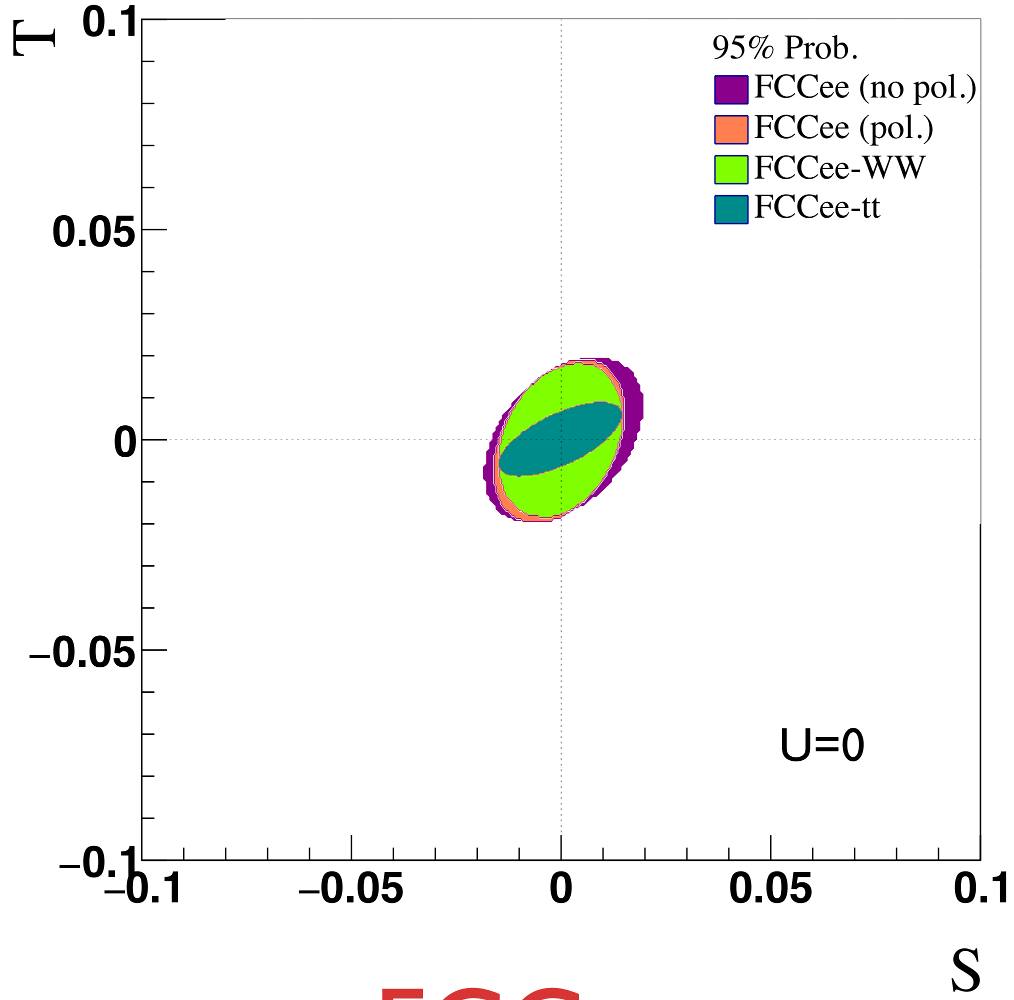


FCCee

$\delta S \sim 0.006$

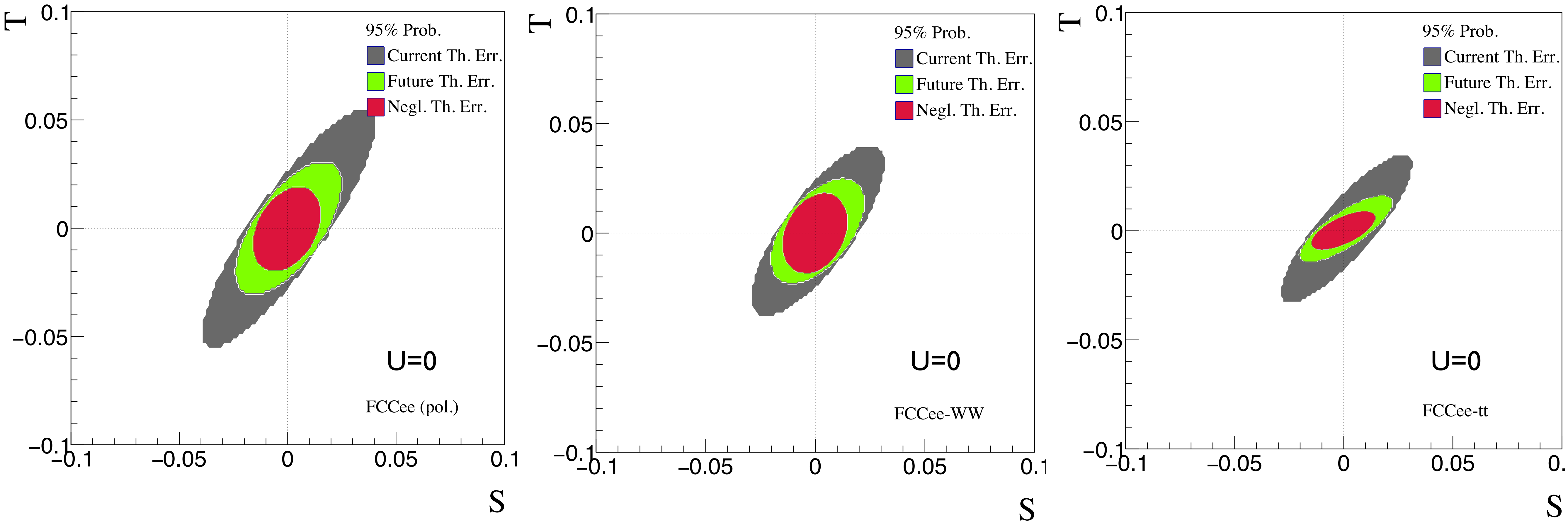
$\delta T \sim 0.004$

$(U=0)$

EW limits on NP: S, T (U=0)

- Oblique Parameters: **Present vs. Future**

Impact of theory uncertainties



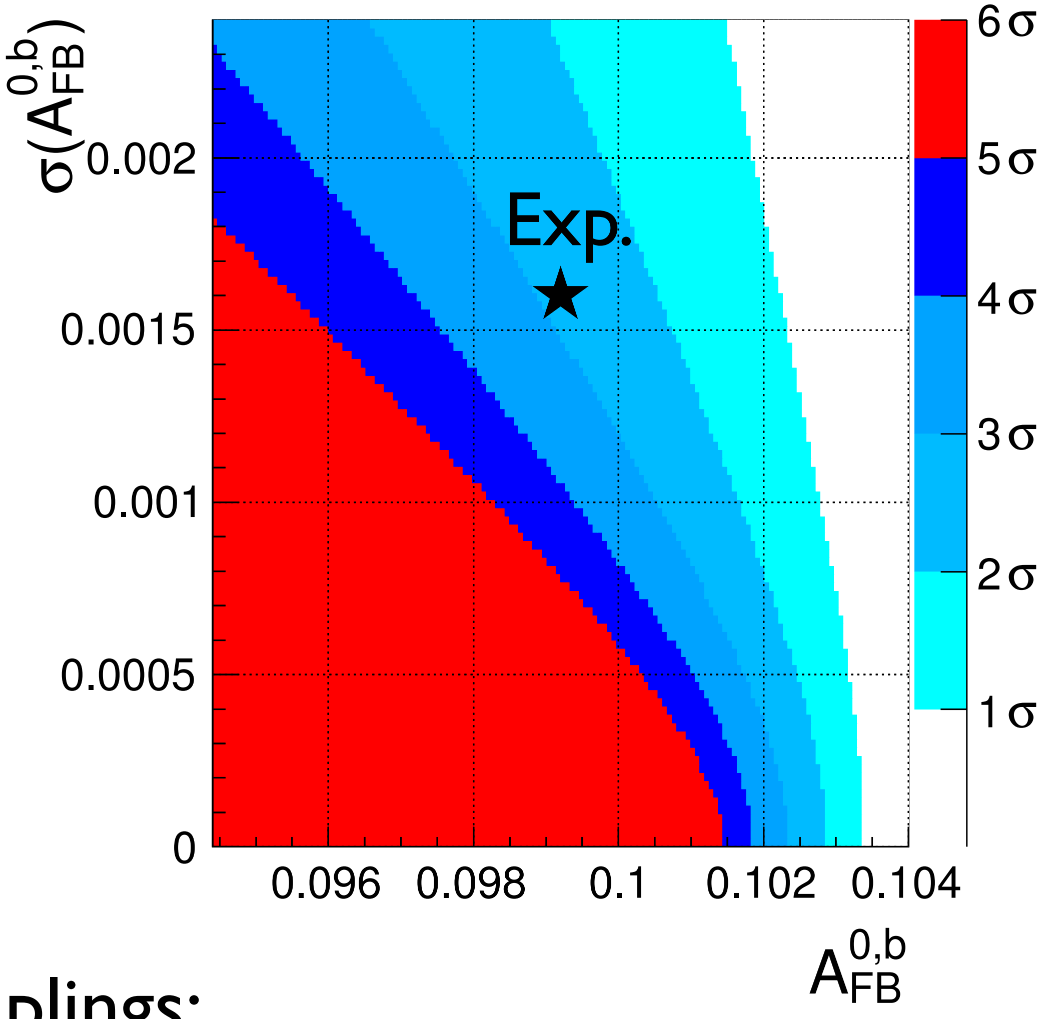
Current theoretical calculations insufficient for FCCee -precision physics

EW limits on NP: Non-standard *Zbb* couplings

- Non-standard *Zbb* couplings

- One significant discrepancy in the SM fit:

$$A_{FB}^{0,b} \sim 2.8\ \sigma$$

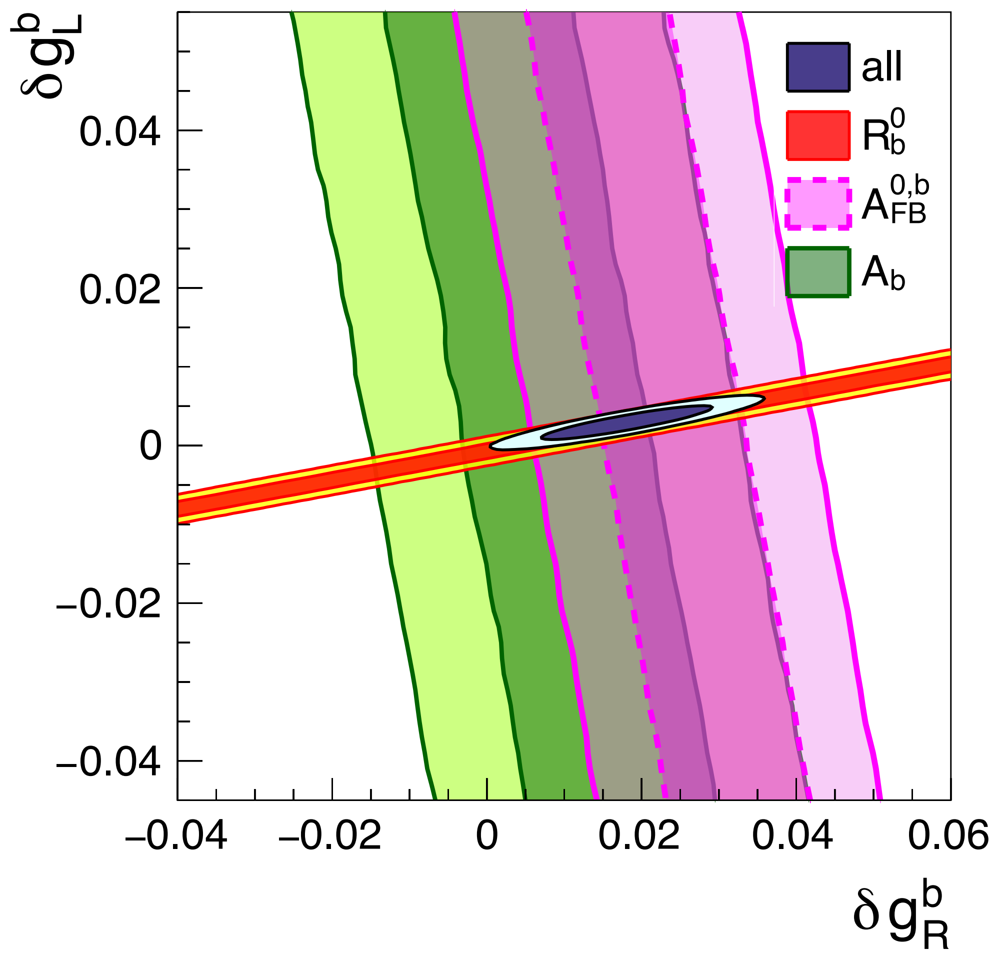


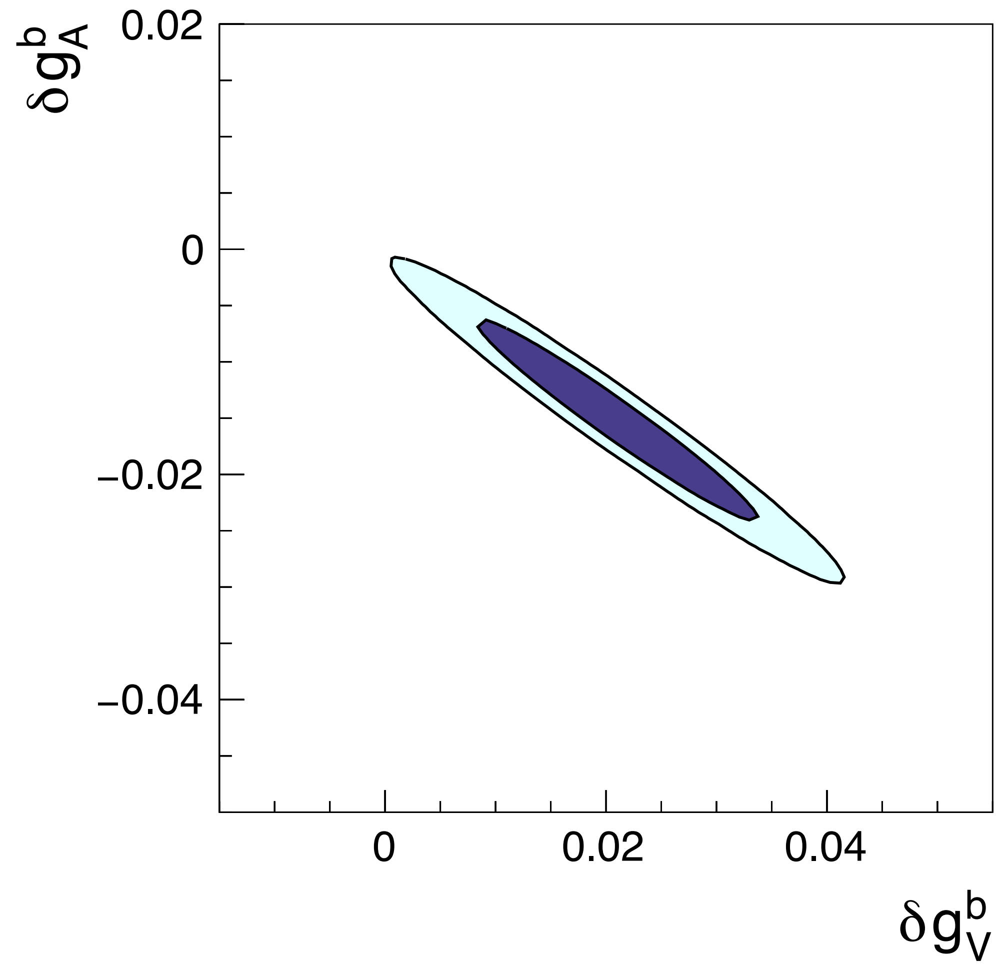
- Requires NP corrections to *Zbb* couplings:

$$g_{L,R}^{b} = g_{L,R}^{b\,\mathrm{SM}} + \delta g_{L,R}^{b}$$

EW limits on NP: Non-standard Zbb couplings

- Non-standard Zbb couplings: Present

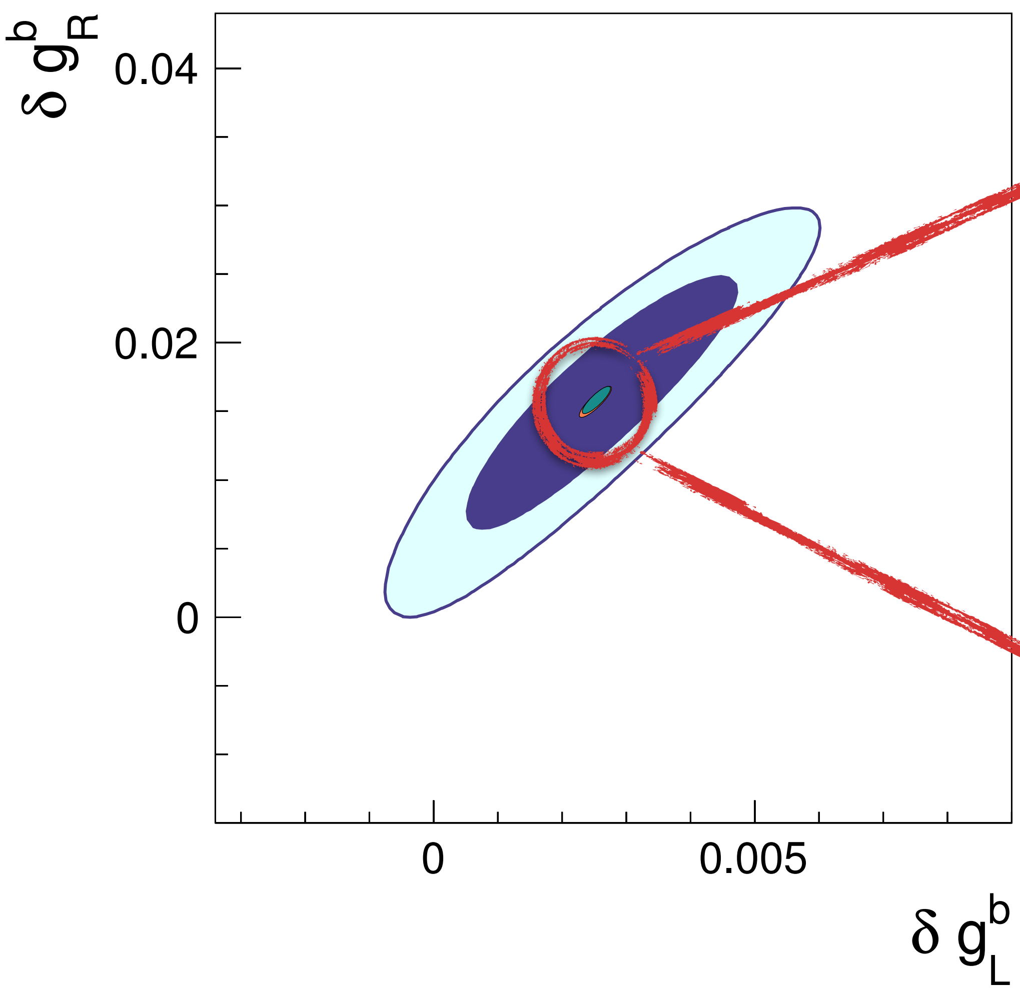


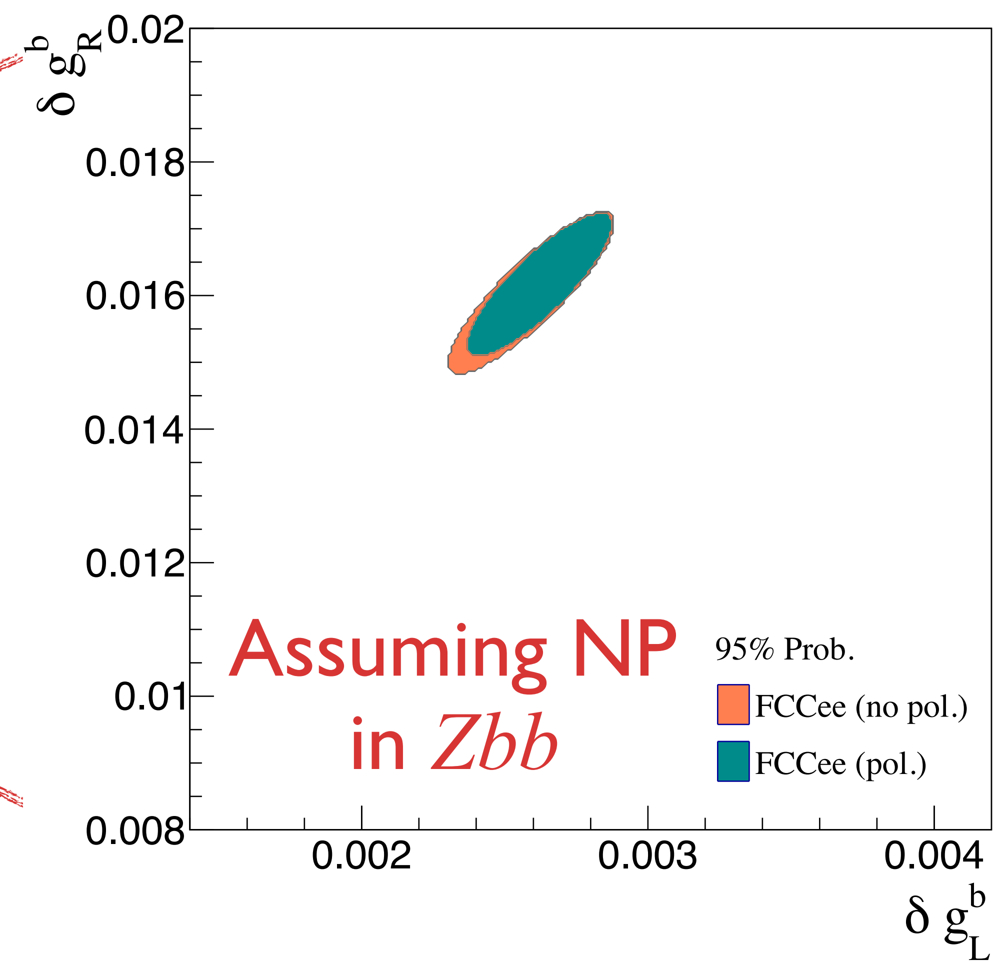


	Fit result	Correlations	
δg_R^b	0.016 ± 0.006	1.00	
δg_L^b	0.0025 ± 0.0014	0.90	1.00
δg_V^b	0.018 ± 0.007	1.00	
δg_A^b	-0.013 ± 0.005	-0.98	1.00

Closest solution to the SM

- Non-standard *Zbb* couplings: **Present vs. Future**





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δg_A^b	-0.013 ± 0.005	-0.98	1.00

FCCee

$$\delta g_L^b \sim 0.0001$$

$$\delta g_R^b \sim 0.0005$$

EW limits on NP: Modified Higgs couplings

- Non-standard Higgs couplings
- Effective Lagrangian for a light Higgs+Approximate custodial symmetry

Rescaled *hVV* couplings

$$\mathcal{L}_{\mathrm{Eff}} = \frac{v^2}{4}\mathrm{Tr}\left[D_\mu\Sigma^\dagger\Sigma\right]\left(1 + 2\kappa_V\frac{h}{v} + \ldots\right)$$
$$-m_i\bar{f}_L^i\left(1 + 2\kappa_f\frac{h}{v} + \ldots\right)f_R^i$$

Rescaled *hff* couplings

- EWPO: One-loop contribution to S & T

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

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

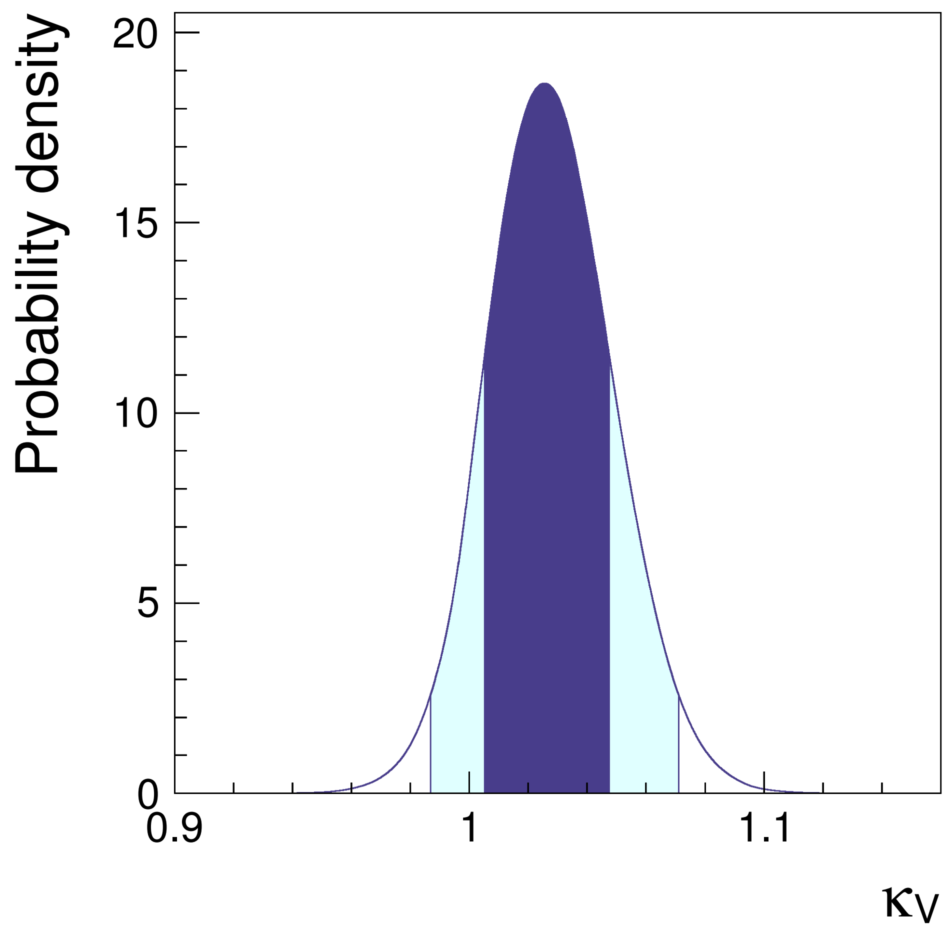
$$\Lambda = \frac{4\pi v}{\sqrt{\left|1-\kappa_V^2\right|}}$$

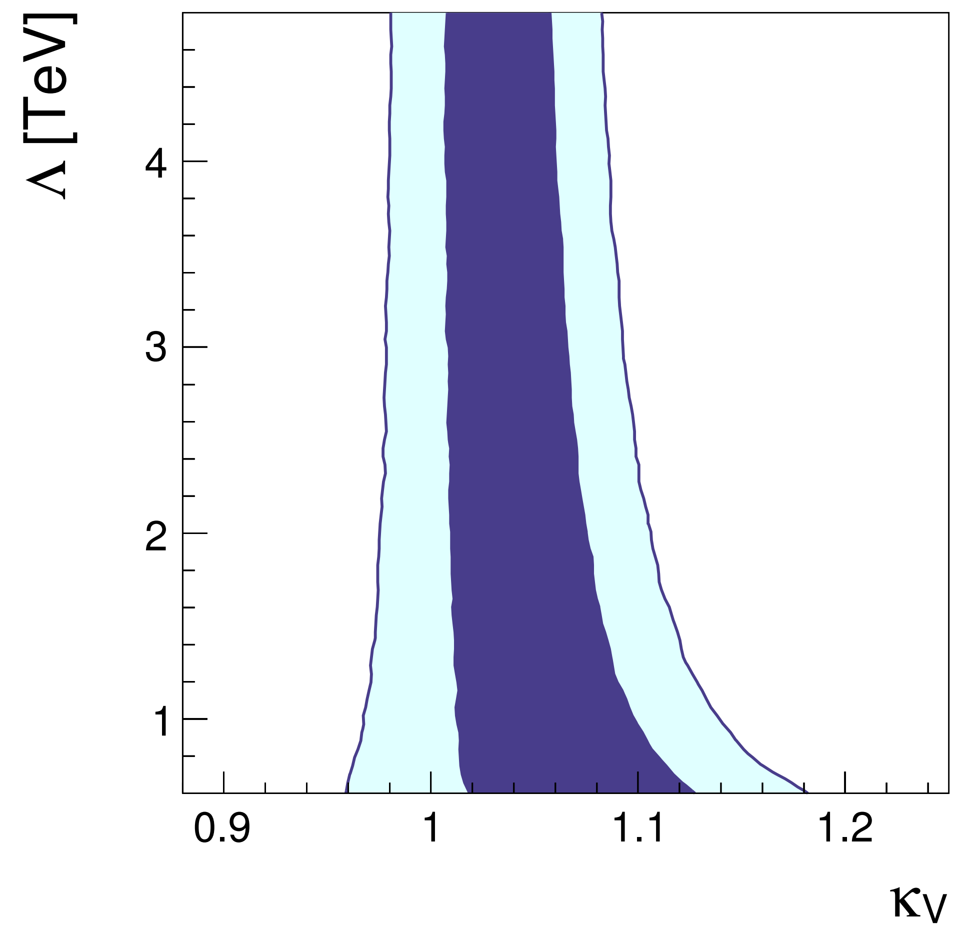
Cut-off of the Higgs Eff. Lag.

- Non-standard Higgs couplings: Present

	68%	95%
κ_V	1.025 ± 0.021	$[0.981,\ 1.072]$

$$\Lambda > 13\ \text{TeV} \quad (\kappa_V < 1)$$
$$\Lambda > 8.5\ \text{TeV} \quad (\kappa_V > 1)$$





Implications for composite Higgs (κ_V<1):

Extra contrib. to *S*, *T* required to agree with EWPD fit

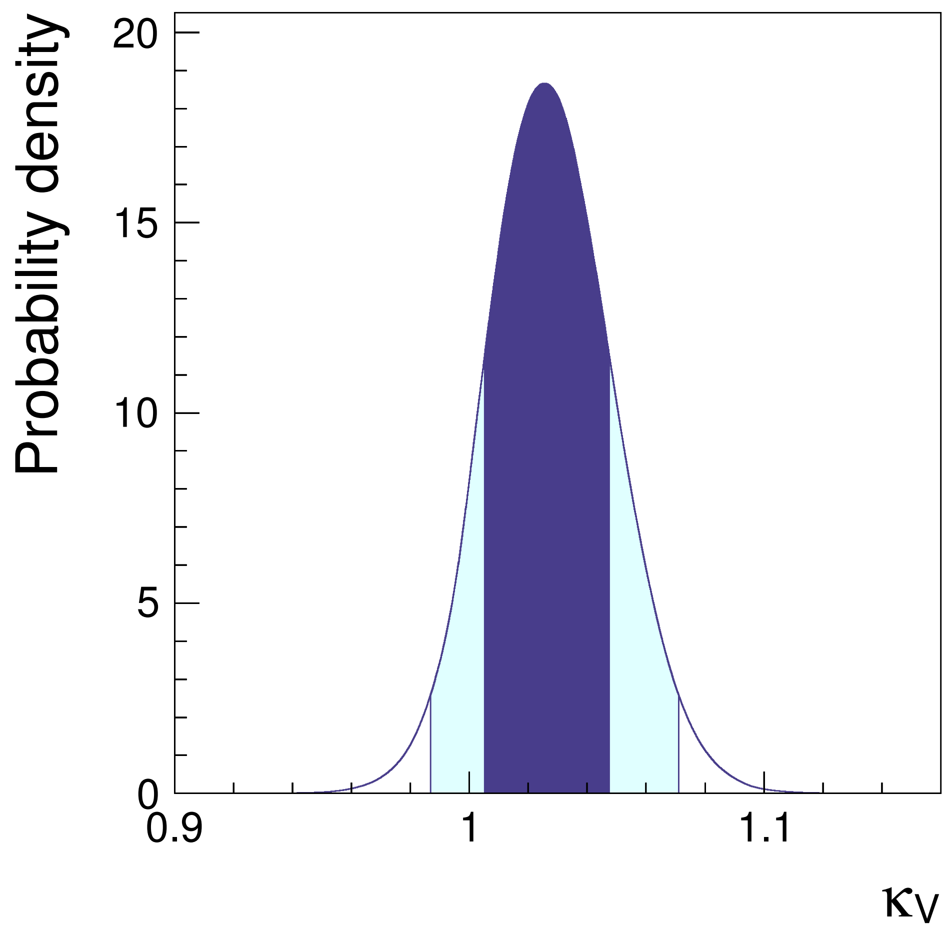
Allowing for: $\Lambda < \frac{4\pi v}{\sqrt{|1-\kappa_V^2|}}$

→Constraints in the Λ-κ_V plane

EW limits on NP: Modified Higgs couplings

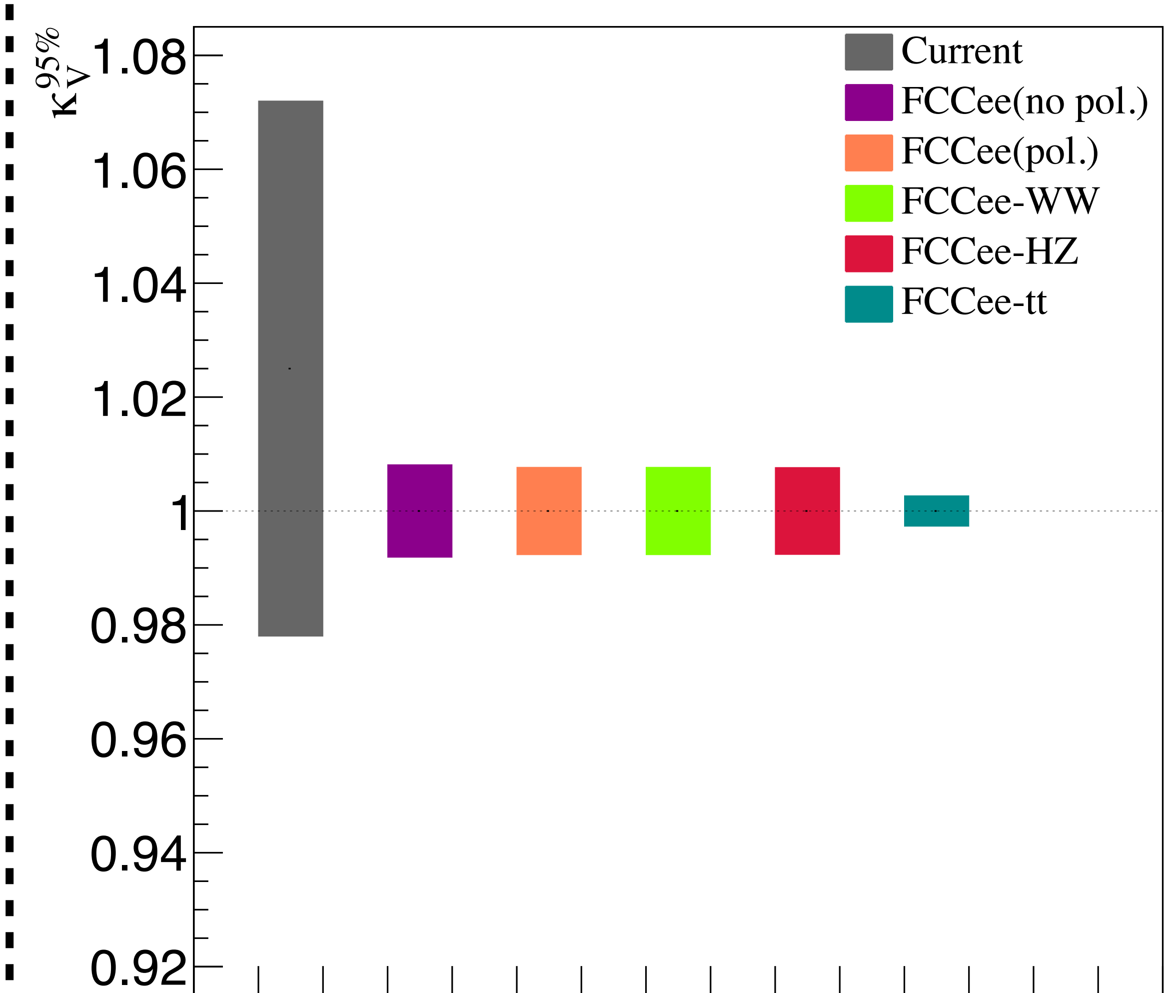
- Non-standard Higgs couplings: **Present vs. Future**

	68%	95%
κ_V	1.025 ± 0.021	$[0.981,\ 1.072]$



FCCee

$\delta\kappa_V \sim 0.001$



EW limits on NP: dimension 6 SMEFT

- The SM as an Effective Theory

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

- General parametrization compatible with assumptions
- Provides an ordering principle (Power counting)
- Provides (Lorentz & Gauge invariance) correlations between different types of observables
- Dim 5: 1 operator — S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566
- Dim 6: 59 operators — W. Buchmüller, D. Wyler, Nucl. Phys. B268 (1986) 621
  C. Arzt, M.B. Einhorn, J. Wudka, Nucl. Phys. B433 (1995) 41
  B.Grzadkowski, M.Iskrynski, M.Misiak, J.Rosiek, JHEP 1010 (2010) 085

We use the GIMR/Warsaw basis

EW limits on NP: dimension 6 SMEFT

- EWPO sensitive to:
  - Oblique corrections

$$\mathcal{O}_{HD} = \left|H^\dagger i D_\mu H\right|^2 \qquad \mathcal{O}_{HWB} = (H^\dagger \sigma_a H) W^a_{\mu\nu} B^{\mu\nu}$$

$$T = -\frac{1}{2\alpha} C_{HD} \frac{v^2}{\Lambda^2} \qquad S = \frac{4 s_W c_W}{\alpha} C_{HWB} \frac{v^2}{\Lambda^2}$$

  - Corrections to EW *Vff* couplings

$$\mathcal{O}_{Hf}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{f}\gamma^\mu f) \qquad \mathcal{O}_{Hf}^{(3)} = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{f}\gamma^\mu \sigma_a f)$$

$$\delta g_L^{u(\nu),d(e)} = -\frac{1}{2}\left(C^{(1)}_{Hq(l)} \mp C^{(3)}_{Hq(l)}\right)\frac{v^2}{\Lambda^2} \qquad \delta g_R^{u,d,e} = -\frac{1}{2} C^{(1)}_{Hu,d,e} \frac{v^2}{\Lambda^2}$$

$$\delta V_L^{q,l} = C^{(3)}_{Hq,l} \frac{v^2}{\Lambda^2}$$

  - Also sensitive to $\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$ through indirect effects (It affects the extraction of G_F from μ decay)

EW limits on NP: dimension 6 SMEFT

- Dimension six SMEFT: Present

1 operator at a time. Flavor universal.

		95% prob. bound on			
		$\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	Λ [TeV]		
Operator			$C_i = 1$	$C_i = -1$	$C_i = \pm 1$
$\mathcal{O}_{HWB}$	$(H^\dagger \sigma_a H)\, W^a_{\mu\nu} B^{\mu\nu}$	[−0.009, 0.003]	16(17%)	11(83%)	12
$\mathcal{O}_{HD}$	$\left\|H^\dagger D_\mu H\right\|^2$	[−0.027, 0.004]	11(7%)	6.5(93%)	6.6
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	[−0.005, 0.012]	9.7(82%)	13(18%)	9.9
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	[−0.011, 0.005]	14(21%)	10(79%)	10
$\mathcal{O}_{He}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$	[−0.015, 0.007]	11(19%)	8.6(81%)	8.6
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	[−0.027, 0.043]	5.1(67%)	5.9(33%)	5.3
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	[−0.011, 0.015]	8.9(56%)	9.6(44%)	9.1
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	[−0.071, 0.081]	3.7(54%)	3.9(46%)	3.7
$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	[−0.14, 0.070]	3.7(22%)	2.8(78%)	2.9
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	[−0.0096, 0.023]	7.0(77%)	9.8(23%)	7.3

NP scale > 3-16 TeV ($C_i \sim 1$)

EW limits on NP: dimension 6 SMEFT

- Dimension six SMEFT: Present

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-}2] (All EW operator at the same time)	95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-}2] (1 operator at a time)
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	$[-0.013, 0.038]$	$[-0.005, 0.012]$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	$[-0.065, 0.010]$	$[-0.011, 0.005]$
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$	$[-0.026, 0.015]$	$[-0.015, 0.007]$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	$[-0.108, 0.077]$	$[-0.027, 0.043]$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.190, 0.005]$	$[-0.011, 0.015]$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	$[-0.230, 0.440]$	$[-0.071, 0.081]$
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.2, -0.140]$	$[-0.14, 0.070]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.090, 0.030]$	$[-0.0096, 0.023]$

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. Remove $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EW limits on NP: dimension 6 SMEFT

- Dimension six SMEFT: Present

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	$[-0.013, 0.038]$	$[-0.005, 0.012]$
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$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	$[-0.230, 0.440]$	$[-0.071, 0.081]$
$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.2, -0.140]$	$[-0.14, 0.070]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.090, 0.030]$	$[-0.0096, 0.023]$

~30-50% correlations

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. Remove $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EW limits on NP: dimension 6 SMEFT

- Dimension six SMEFT: Present

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	$[-0.013, 0.038]$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	$[-0.065, 0.010]$
$\mathcal{O}_{He}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$	$[-0.026, 0.015]$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	$[-0.108, 0.077]$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.190, 0.005]$
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	$[-0.230, 0.440]$
$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.2, -0.140]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.090, 0.030]$

~80-90% correlations

95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]
$[-0.005, 0.012]$
$[-0.011, 0.005]$
$[-0.015, 0.007]$
$[-0.027, 0.043]$
$[-0.011, 0.015]$
$[-0.071, 0.081]$
$[-0.14, 0.070]$
$[-0.0096, 0.023]$

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. Remove $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EW limits on NP: dimension 6 SMEFT

- <u>Dimension six SMEFT: Present</u>

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ $[\mathrm{TeV}^{-2}]$	95% prob. bound on $\frac{C_i}{\Lambda^2}$ $[\mathrm{TeV}^{-2}]$
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	$[-0.013, 0.038]$	$[-0.005, 0.012]$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^a H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	$[-0.065, 0.010]$	$[-0.011, 0.005]$
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$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^a H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.190, 0.005]$	$[-0.011, 0.015]$
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	$[-0.230, 0.440]$	$[-0.071, 0.081]$
$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.2, -0.140]$	$[-0.14, 0.070]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.090, 0.030]$	$[-0.0096, 0.023]$

~10-80% correlations

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. Remove $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EW limits on NP: dimension 6 SMEFT

- Dimension six SMEFT: **Present vs. Future**

1 operator at a time. Flavor universal.

	Operator	95% present bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	Λ [TeV] $C_i=\pm1$	95% projected bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	Λ [TeV] $C_i=\pm1$
$\mathcal{O}_{HWB}$	$(H^\dagger\sigma_a H)\, W^a_{\mu\nu}B^{\mu\nu}$	$[-0.009,\ 0.003]$	12	$[-0.0001, 0.0001]$	93
$\mathcal{O}_{HD}$	$\left\|H^\dagger D_\mu H\right\|^2$	$[-0.027,\ 0.004]$	6.6	$[-0.0005, 0.0005]$	45
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{l_L}\gamma^\mu l_L)$	$[-0.005,\ 0.012]$	9.9	$[-0.0003, 0.0003]$	56
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)\,(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$[-0.011,\ 0.005]$	10	$[-0.0002, 0.0002]$	70
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{e_R}\gamma^\mu e_R)$	$[-0.015,\ 0.007]$	8.6	$[-0.0003, 0.0003]$	58
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{q_L}\gamma^\mu q_L)$	$[-0.027,\ 0.043]$	5.3	$[-0.0018, 0.0018]$	24
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)\,(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$[-0.011,\ 0.015]$	9.1	$[-0.0005, 0.0005]$	44
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{u_R}\gamma^\mu u_R)$	$[-0.071,\ 0.081]$	3.7	$[-0.0035,\ 0.0035]$	17
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{d_R}\gamma^\mu d_R)$	$[-0.14,\ 0.070]$	2.9	$[-0.0046,\ 0.0046]$	15
$\mathcal{O}_{ll}$	$(\bar l\gamma_\mu l)(\bar l\gamma^\mu l)$	$[-0.0096,\ 0.023]$	7.3	$[-0.0003, 0.0003]$	61

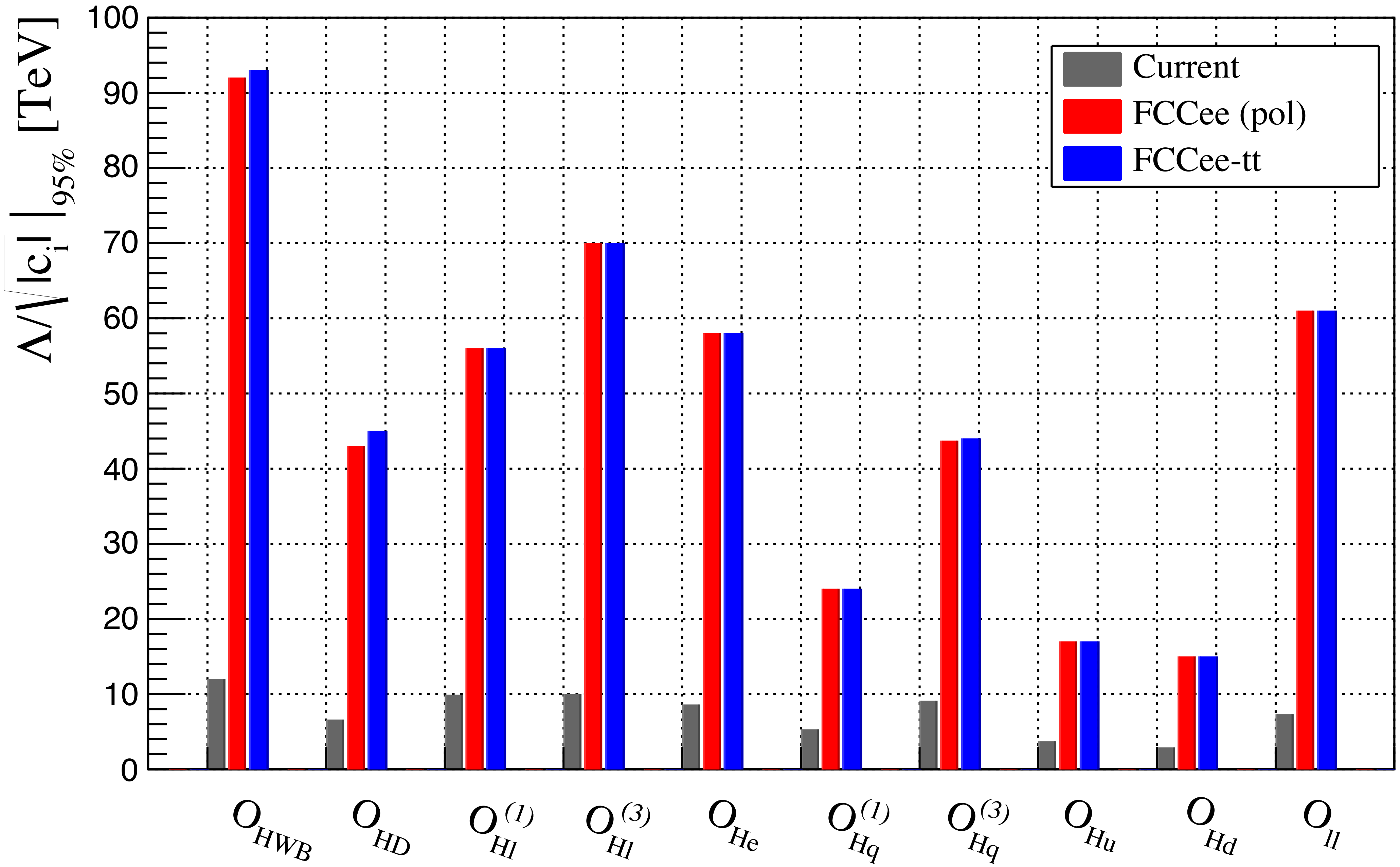
Preliminary

FCCee: NP scale >15-90 TeV ($C_i \sim 1$)

EW limits on NP: dimension 6 SMEFT

- Dimension six SMEFT: **Present vs. Future**

1 operator at a time. Flavor universal.



Preliminary

FCCee: NP scale >15-90 TeV ($C_i \sim 1$)

Conclusions

- Current EWPD fit shows good agreement with the SM predictions

  $\Rightarrow$ **Bounds on the scale of NP ~ 3-15 TeV**

- FCCee would strengthen greatly the constraining/discriminating power of the EWPD fit…

- … but a significant **improvement in theoretical calculations is required** in order to bring the SM predictions down to the FCCee precision, and optimize NP searches.

FCCee projections

	Expected sensitivity	Improvement
$S,\ T,\ U$	$\delta S,\ \delta T \sim 6 \cdot 10^{-3},\quad \delta U \sim 5 \cdot 10^{-3}$	20x
$\delta g^b_{L,R}$	$\delta g^b_L \sim 10^{-4},\quad \delta g^b_R \sim 5 \cdot 10^{-4}$	10x
$\delta g_{hVV}\ (\kappa_V)$	$\delta \kappa_V \sim 0.001$	20x
$\mathcal{L}^{d=6}_{\mathrm{SMEFT}}$	$\Lambda_{NP} \gtrsim 15 - 90$ TeV ($C_i \sim 1$)	$\sim$ 10x