

ELECTROWEAK PRECISION OBSERVABLES IN THE STANDARD MODEL AND BEYOND: PRESENT AND FUTURE

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IN COLLABORATION WITH:

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ELECTROWEAK PRECISION OBSERVABLES

- Very precise measurements of Z & W boson properties:

M_Z , Γ_Z , σ_{had}^0 , $\sin^2 \theta_{\text{Eff}}^{\text{lept}}$, P_τ^{pol} , A_f , $A_{FB}^{0,f}$, R_f^0

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

M_W , Γ_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 EWPD fit: ZFITTER, GAPP, Gfitter, ...

Also part of **HEPfit**

- General High Energy Physics **fitting** 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>

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.

Higgs Physics
HEPfit can be used to study Higgs couplings and analyze data on signal strengths.

Precision Electroweak
Electroweak precision observables are included in HEPfit

Flavour Physics
The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.

BSM Physics
Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics:
- Flexible open-source C++ code
- Stand-alone and library modes to compute observables in a given model
- Add new models and/or observables as external modules
- Optional Bayesian Statistical Analysis framework
(supports MPI parallelization)
- Dependencies: ROOT, GSL, Boost, Bayesian Analysis Toolkit (BAT)
Beaujean, Caldwell, Greenwald, Kollar, Kröninger, Schulz
- First official release is coming soon...

Already in the code:

Models

Standard Model
Oblique pars: S,T,U
 ϵ_i parameters

Modified Zbb couplings
Modified Higgs coup: Kv, Kf
SMEFT dim 6
General THDM

↔Tested

SUSY
LR models

↔WiP

Observables

EWPO
Higgs signal strengths
Flavor: $\Delta F=2$, UT, B decays
LFV

↔Tested

LEP 2 cross sections

↔WiP

Already in the code:

Models

In this talk



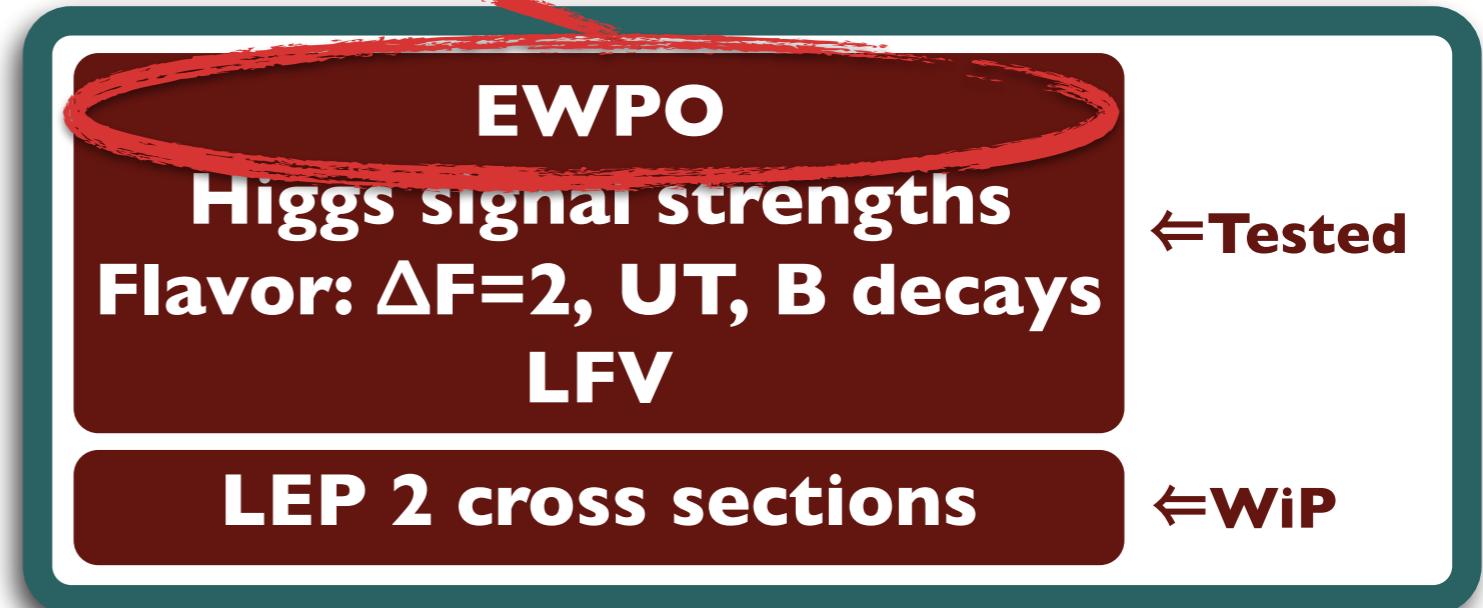
Observables

EW precision observables:

- Written from scratch
- SM EWPO validated against

ZFITTER

Akhundov, Arbuzov, Riemann & Riemann



Already in the code:

Models

See my previous talk
on thursday
(Higgs session)



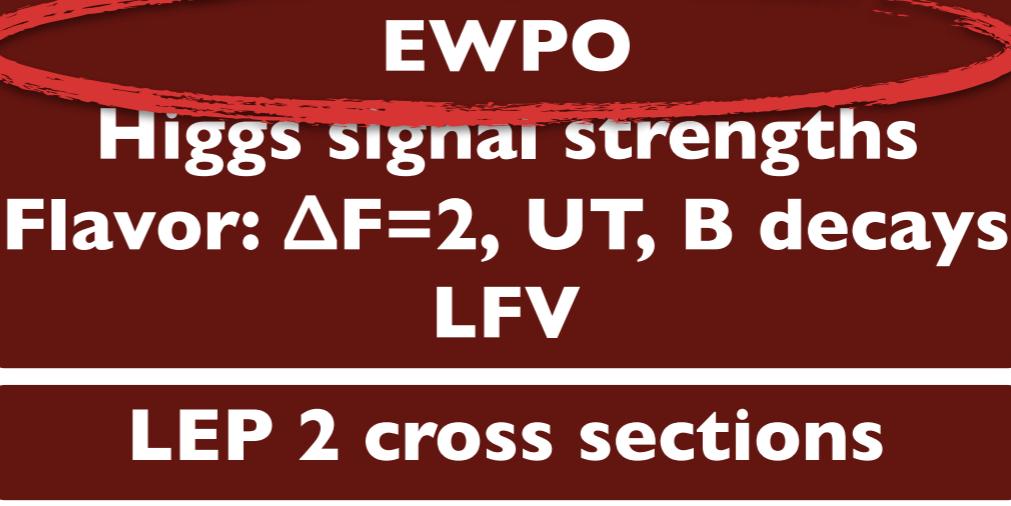
↔Tested
↔WiP

Observables

EW precision observables:

- Written from scratch
- SM EWPO validated against ZFITTER

Akhundov, Arbuzov, Riemann & Riemann



↔Tested
↔WiP

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
 - $\sin^2 \theta_{\text{Eff}}^f$: 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_Z^f : 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:

	M_W	Γ_Z	σ_{had}^0	R_b	$\sin^2 \theta_{\text{eff}}^\ell$
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

	Measurement	Posterior	Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	0.1179 ± 0.0012	0.1180 ± 0.0011	0.1185 ± 0.0028	-0.2	
$\Delta\alpha_{\text{had}}^{(5)}(M_Z)$	0.02750 ± 0.00033	0.02747 ± 0.00025	0.02743 ± 0.00038	0.04	
M_Z [GeV]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.011	-1.0	
m_t [GeV]	173.34 ± 0.76	173.61 ± 0.73	176.6 ± 2.5	-1.3	
m_H [GeV]	125.09 ± 0.24	125.09 ± 0.24	102.8 ± 26.3	0.8	
M_W [GeV]	80.385 ± 0.015	80.3644 ± 0.0061	80.3604 ± 0.0066	1.5	
Γ_W [GeV]	2.085 ± 0.042	2.08872 ± 0.00064	2.08873 ± 0.00064	-0.2	
$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	0.2324 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.000090	0.8	
$P_\tau^{\text{pol}} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14748 ± 0.00068	0.14752 ± 0.00069	-0.4	
Γ_Z [GeV]	2.4952 ± 0.0023	2.49420 ± 0.00063	2.49405 ± 0.00068	0.5	
σ_h^0 [nb]	41.540 ± 0.037	41.4903 ± 0.0058	41.4912 ± 0.0062	1.3	0.7
R_ℓ^0	20.767 ± 0.025	20.7485 ± 0.0070	20.7472 ± 0.0076	0.8	
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	0.01631 ± 0.00015	0.01628 ± 0.00015	0.8	
\mathcal{A}_ℓ (SLD)	0.1513 ± 0.0021	0.14748 ± 0.00068	0.14765 ± 0.00076	1.7	
\mathcal{A}_c	0.670 ± 0.027	0.66810 ± 0.00030	0.66817 ± 0.00033	0.02	
\mathcal{A}_b	0.923 ± 0.020	0.934650 ± 0.000058	0.934663 ± 0.000064	-0.6	
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	0.07390 ± 0.00037	0.07399 ± 0.00042	-0.9	1.5
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	0.10338 ± 0.00048	0.10350 ± 0.00054	-2.6	
R_c^0	0.1721 ± 0.0030	0.172228 ± 0.000023	0.172229 ± 0.000023	-0.05	
R_b^0	0.21629 ± 0.00066	0.215790 ± 0.000028	0.215788 ± 0.000028	0.7	
$\sin^2 \theta_{\text{eff}}^{ee}$	0.23248 ± 0.00052			2.1	
$\sin^2 \theta_{\text{eff}}^{\mu\mu}$	0.2315 ± 0.0010			0.07	
$\sin^2 \theta_{\text{eff}}^{ee}$	0.23146 ± 0.00047	0.231464 ± 0.000087	0.231435 ± 0.000090	0.1	
$\sin^2 \theta_{\text{eff}}^{ee,\mu\mu}$	0.2308 ± 0.0012			-0.5	
$\sin^2 \theta_{\text{eff}}^{\mu\mu}$	0.2287 ± 0.0032			-0.8	
$\sin^2 \theta_{\text{eff}}^{\mu\mu}$	0.2314 ± 0.0011			-0.1	

EW PRECISION OBSERVABLES IN THE SM

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LHC & Tevatron measurements of
the eff. weak mixing angle

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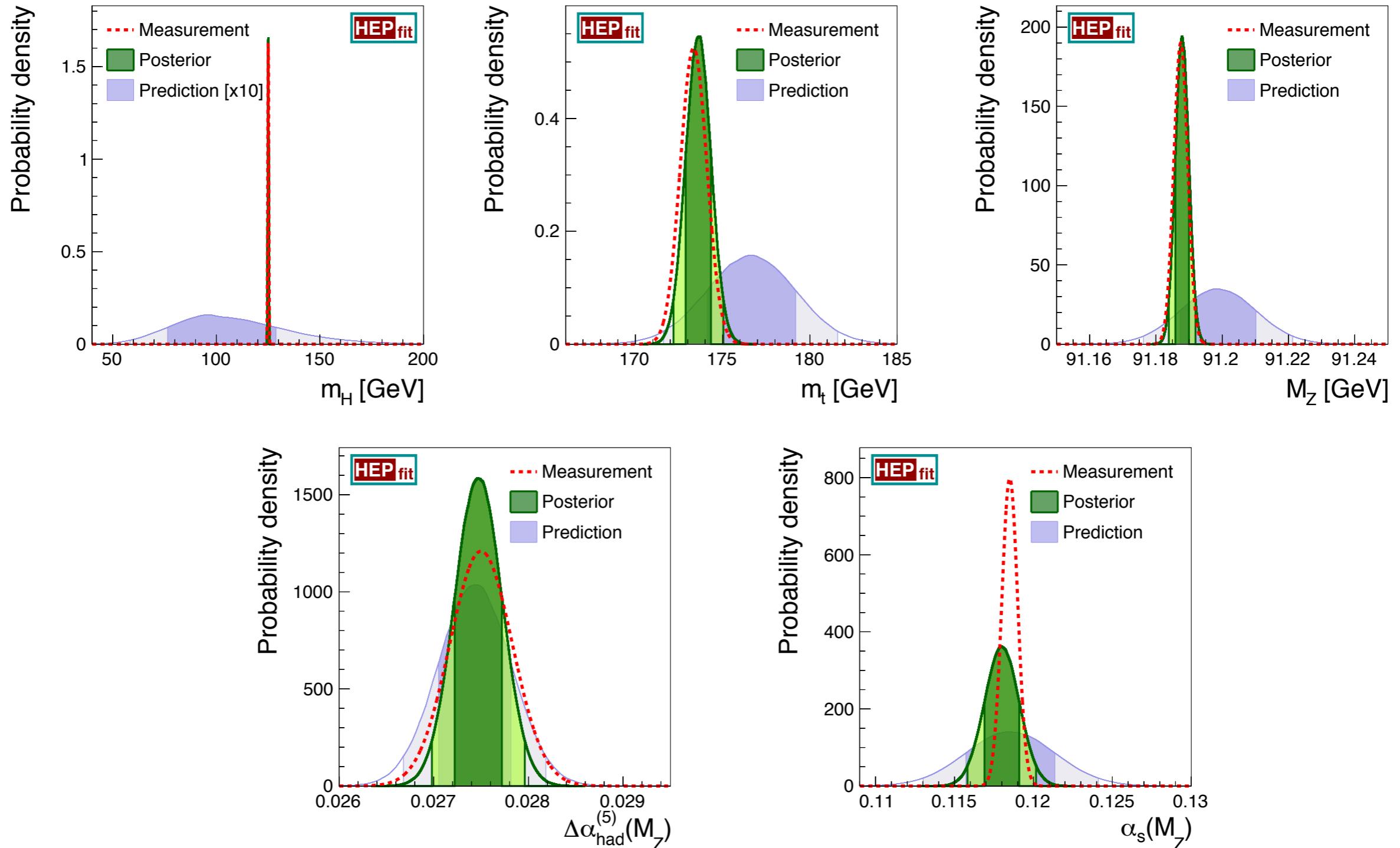
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Only I significant discrepancy

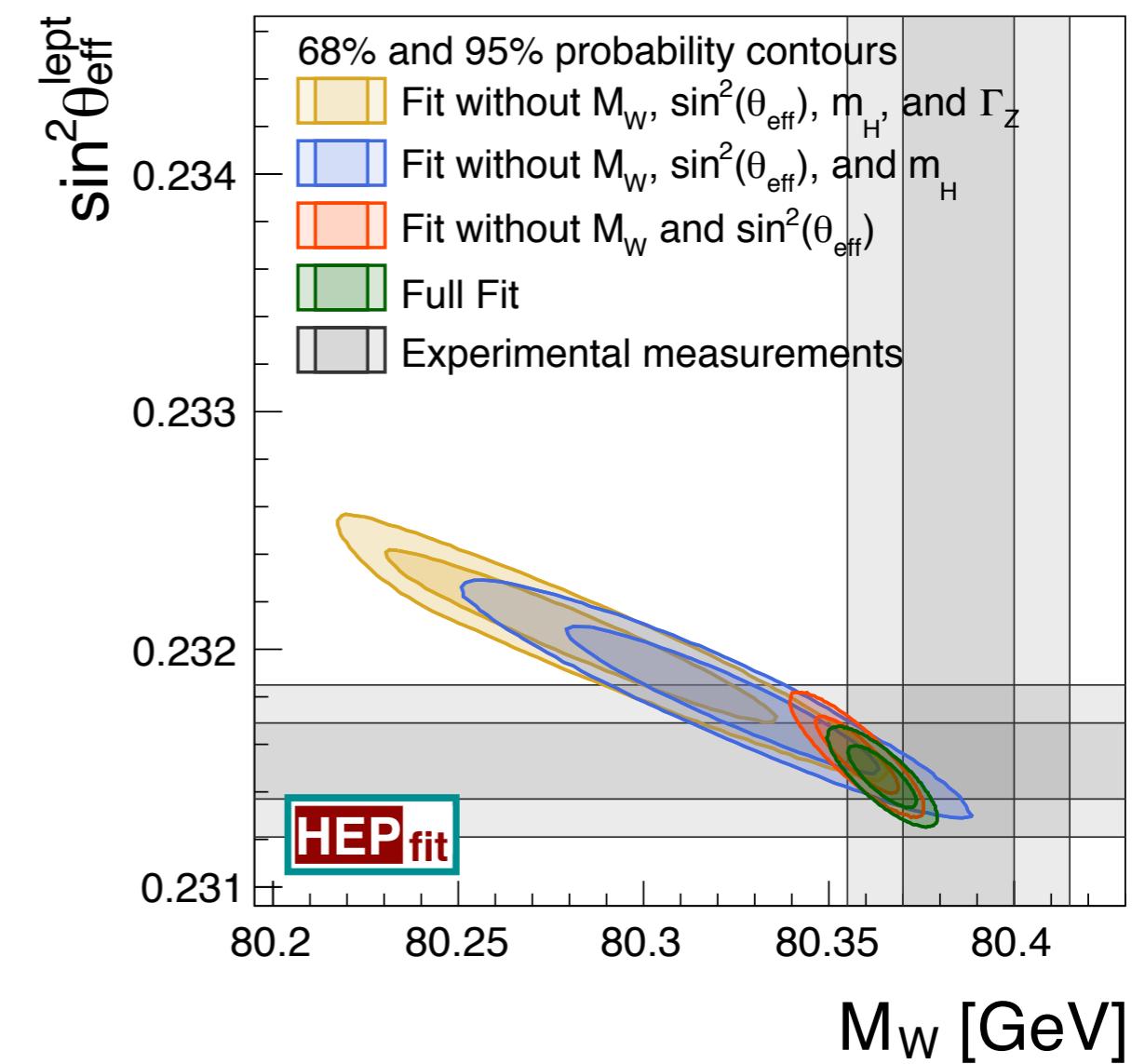
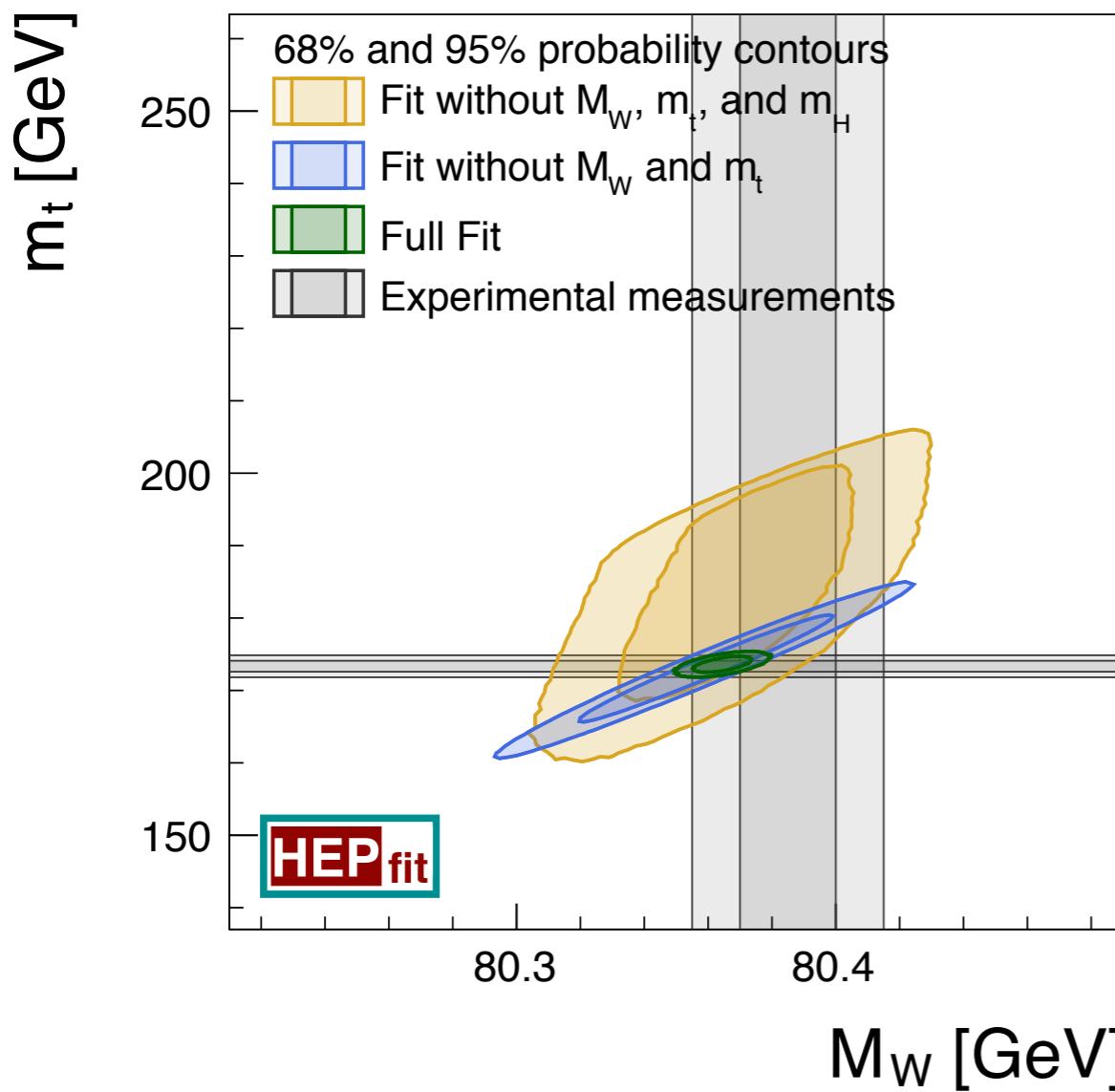
EW PRECISION OBSERVABLES IN THE SM

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



EW PRECISION OBSERVABLES IN THE SM

- Good agreement between direct and indirect determinations of the EWPO, e.g.



EW PRECISION OBSERVABLES IN THE SM

● Parametric uncertainties

$$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) = 0.02750 \pm 0.00033$$

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

	Prediction	α_s	$\Delta\alpha_{\text{had}}^{(5)}$	M_Z	m_t
M_W [GeV]	80.3618 ± 0.0080	± 0.0008	± 0.0060	± 0.0026	± 0.0046
Γ_W [GeV]	2.08849 ± 0.00079	± 0.00048	± 0.00047	± 0.00021	± 0.00036
Γ_Z [GeV]	2.49403 ± 0.00073	± 0.00059	± 0.00031	± 0.00021	± 0.00017
σ_h^0 [nb]	41.4910 ± 0.0062	± 0.0059	± 0.0005	± 0.0020	± 0.0005
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.23148 ± 0.00012	± 0.00000	± 0.00012	± 0.00002	± 0.00002
$P_\tau^{\text{pol}} = \mathcal{A}_\ell$	0.14731 ± 0.00093	± 0.00003	± 0.00091	± 0.00012	± 0.00019
\mathcal{A}_c	0.66802 ± 0.00041	± 0.00001	± 0.00040	± 0.00005	± 0.00008
\mathcal{A}_b	0.934643 ± 0.000076	± 0.000003	± 0.000075	± 0.000010	± 0.000005
$A_{\text{FB}}^{0,\ell}$	0.01627 ± 0.00021	± 0.00001	± 0.00020	± 0.00003	± 0.00004
$A_{\text{FB}}^{0,c}$	0.07381 ± 0.00052	± 0.00002	± 0.00050	± 0.00007	± 0.00010
$A_{\text{FB}}^{0,b}$	0.10326 ± 0.00067	± 0.00002	± 0.00065	± 0.00008	± 0.00013
R_ℓ^0	20.7478 ± 0.0077	± 0.0074	± 0.0020	± 0.0003	± 0.0003
R_c^0	0.172222 ± 0.000026	± 0.000023	± 0.000007	± 0.000001	± 0.000009
R_b^0	0.215800 ± 0.000030	± 0.000013	± 0.000004	± 0.000000	± 0.000026

$(\delta(\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)) \approx 0.00005 \text{ in near future experiments})$

EW PRECISION OBSERVABLES IN THE SM

- Parametric uncertainties

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0012$$

PDG average (Excluding EW fit determination)

	Prediction	α_s	$\Delta\alpha_{\text{had}}^{(5)}$	M_Z	m_t
M_W [GeV]	80.3618 ± 0.0080	± 0.0008	± 0.0060	± 0.0026	± 0.0046
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($\delta\alpha_s(M_Z^2) \approx 0.0002$ future lattice projection)

EWPO AT FUTURE E⁺ E⁻ COLLIDERS

- Several projects for future e⁺ e⁻ colliders: ILC, FCC, CEPC...
- Physics at the FCCee:

	Z pole	WW threshold	HZ threshold	t <bar>t</bar> threshold	Above t <bar>t</bar> 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 improves the precision of different sectors of EWPO and/or Higgs observables

- Physics at the ILC: Optimized for a precise determination of Higgs properties. Operation at 250, 350, 500 (and 1000?) GeV
- Physics at the CEPC: designed as a Z and H factory (Z-pole and HZ runs)

EWPO AT FUTURE E⁺ E⁻ COLLIDERS

● Expected sensitivities to EWPO

	Current Data	HL-LHC	ILC	FCCee (Run)	CEPC
$\alpha_s(M_Z^2)$	0.1179 ± 0.0012				
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	0.02750 ± 0.00033				
$M_Z[\text{GeV}]$	91.1875 ± 0.0021			± 0.0001 (FCCee-Z)	± 0.0005
$m_t[\text{GeV}]$	173.34 ± 0.76	± 0.6	± 0.017	± 0.014 (FCCee-t <bar>t)</bar>	
$m_H[\text{GeV}]$	125.09 ± 0.24	± 0.05	± 0.015	± 0.007 (FCCee-HZ)	± 0.0059
$M_W[\text{GeV}]$	80.385 ± 0.015	± 0.011	± 0.0024	± 0.001 (FCCee-WW)	± 0.003
$\Gamma_W[\text{GeV}]$	2.085 ± 0.042			± 0.005 (FCCee-WW)	
$\Gamma_Z[\text{GeV}]$	2.4952 ± 0.0023			± 0.0001 (FCCee-Z)	± 0.0005
$\sigma_h^0[\text{nb}]$	41.540 ± 0.037			± 0.025 (FCCee-Z)	± 0.037
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.2324 ± 0.0012			± 0.0001 (FCCee-Z)	± 0.000023
P_τ^{pol}	0.1465 ± 0.0033			± 0.0002 (FCCee-Z)	
A_ℓ	0.1513 ± 0.0021			± 0.000021 (FCCee-Z [pol])	
A_c	0.670 ± 0.027			± 0.01 (FCCee-Z [pol])	
A_b	0.923 ± 0.020			± 0.007 (FCCee-Z [pol])	
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010			± 0.0001 (FCCee-Z)	± 0.0010
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035			± 0.0003 (FCCee-Z)	
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016			± 0.0001 (FCCee-Z)	± 0.00014
R_ℓ^0	20.767 ± 0.025			± 0.001 (FCCee-Z)	± 0.007
R_c^0	0.1721 ± 0.0030			± 0.0003 (FCCee-Z)	
R_b^0	0.21629 ± 0.00066			± 0.00006 (FCCee-Z)	± 0.00018

- Experimental vs Theoretical uncertainties:

Present

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2 \theta_{\text{eff}}^\ell$ [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
$\sin^2 \theta_{\text{eff}}^\ell$ [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

EW PRECISION OBSERVABLES IN THE SM: FUTURE

- Experimental vs Theoretical uncertainties:

Present

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2 \theta_{\text{eff}}^\ell$ [10^{-5}]	4.5	16
Γ_Z [MeV]	0.5	2.3
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R_b [10^{-5}]	14	6	17	5–10

A. Freitas, arXiv: 1604.00406

Theoretical effort necessary to achieve future experimental precision

EWPD LIMITS ON PHYSICS BEYOND THE SM: PRESENT VS. FUTURE

- 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 \Rightarrow See my previous talk on thursday (Higgs Session)
- General strategy for the calculation of future sensitivities:
 - Assume theoretical uncertainties will be reduced as needed to reach future experimental precision
(Also use the future expected uncertainties $\delta(\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)) \approx 0.00005$)
$$\delta\alpha_s(M_Z^2) \approx 0.0002$$
 - Use SM best-fit results as central values for future data. Limits provide future sensitivity to New Physics.

EWPD 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

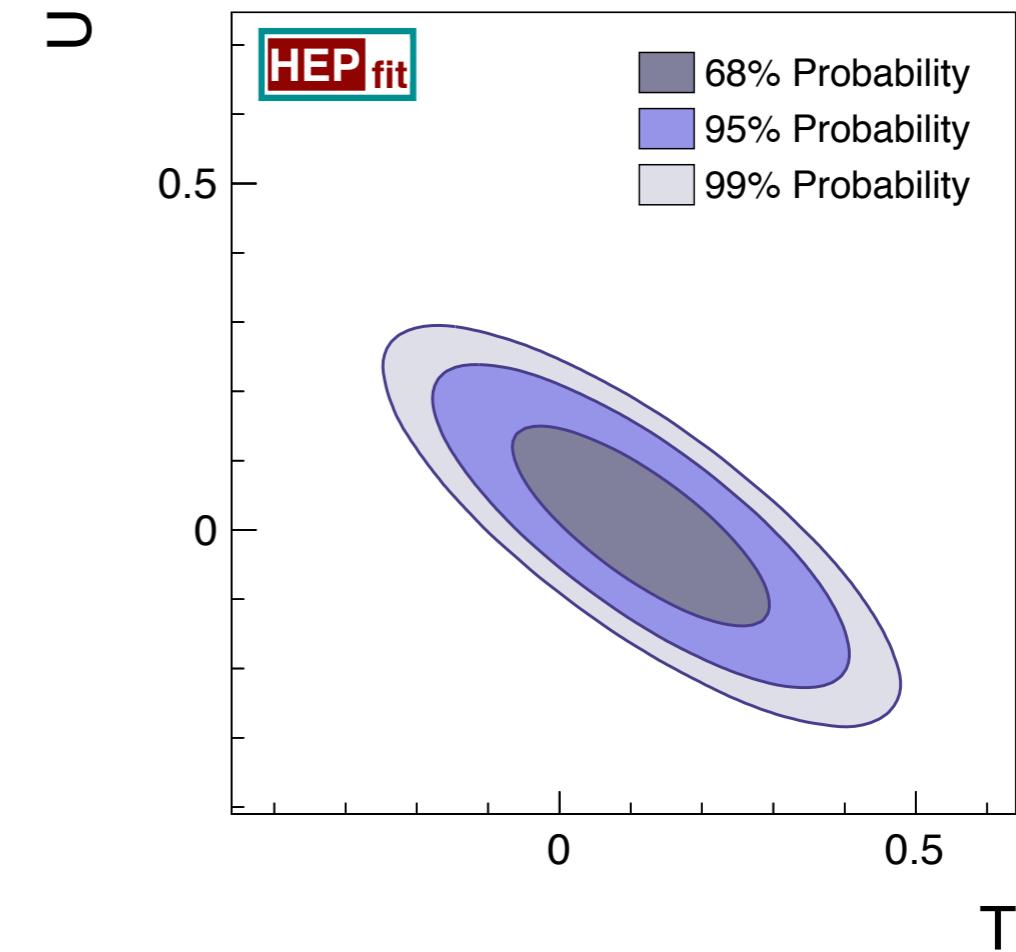
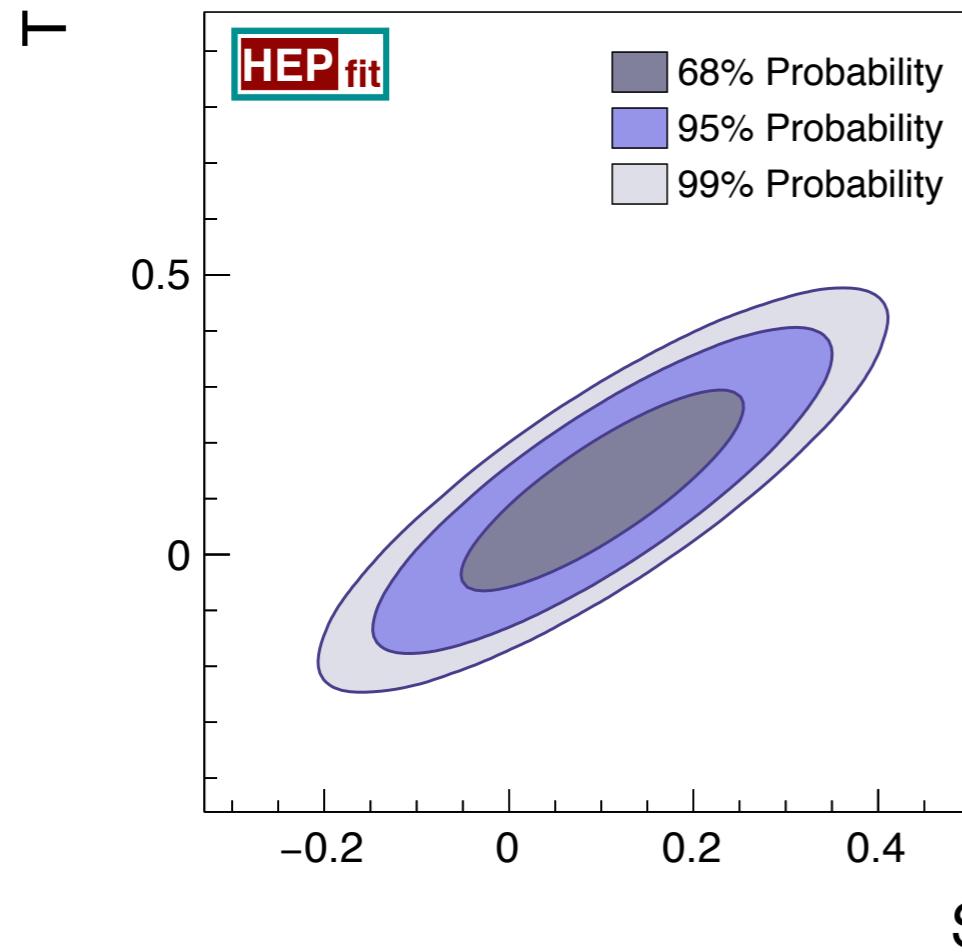
$$\begin{aligned}\alpha S &= 4e^2 \left[\Pi_{33}^{\text{NP}}'(0) - \Pi_{3Q}^{\text{NP}}'(0) \right] \\ \alpha T &= \frac{e^2}{s_W^2 c_W^2 M_Z^2} \left[\Pi_{11}^{\text{NP}}(0) - \Pi_{33}^{\text{NP}}(0) \right] \\ \alpha U &= 4e^2 \left[\Pi_{11}^{\text{NP}}'(0) - \Pi_{33}^{\text{NP}}'(0) \right]\end{aligned}$$

- In models where EWSB is realized linearly, U is expected to be $\ll S, T$



EWPD LIMITS ON NP: S, T, U

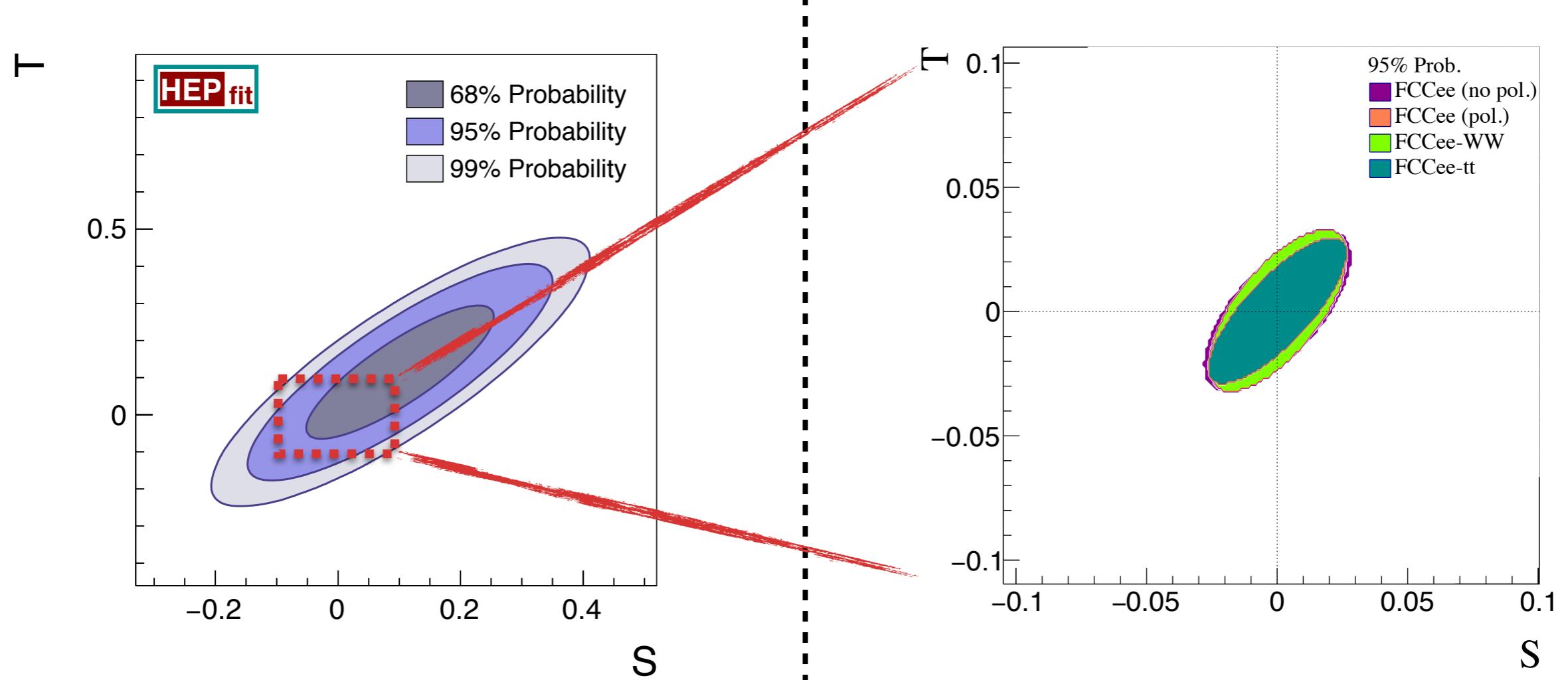
- Oblique Parameters: Present



Fit result	Correlations		
S 0.09 ± 0.10	1.00		
T 0.10 ± 0.12	0.86	1.00	
U 0.01 ± 0.09	-0.54	-0.81	1.00

EWPD LIMITS ON NP: S, T, U

- Oblique Parameters: Present vs. Future

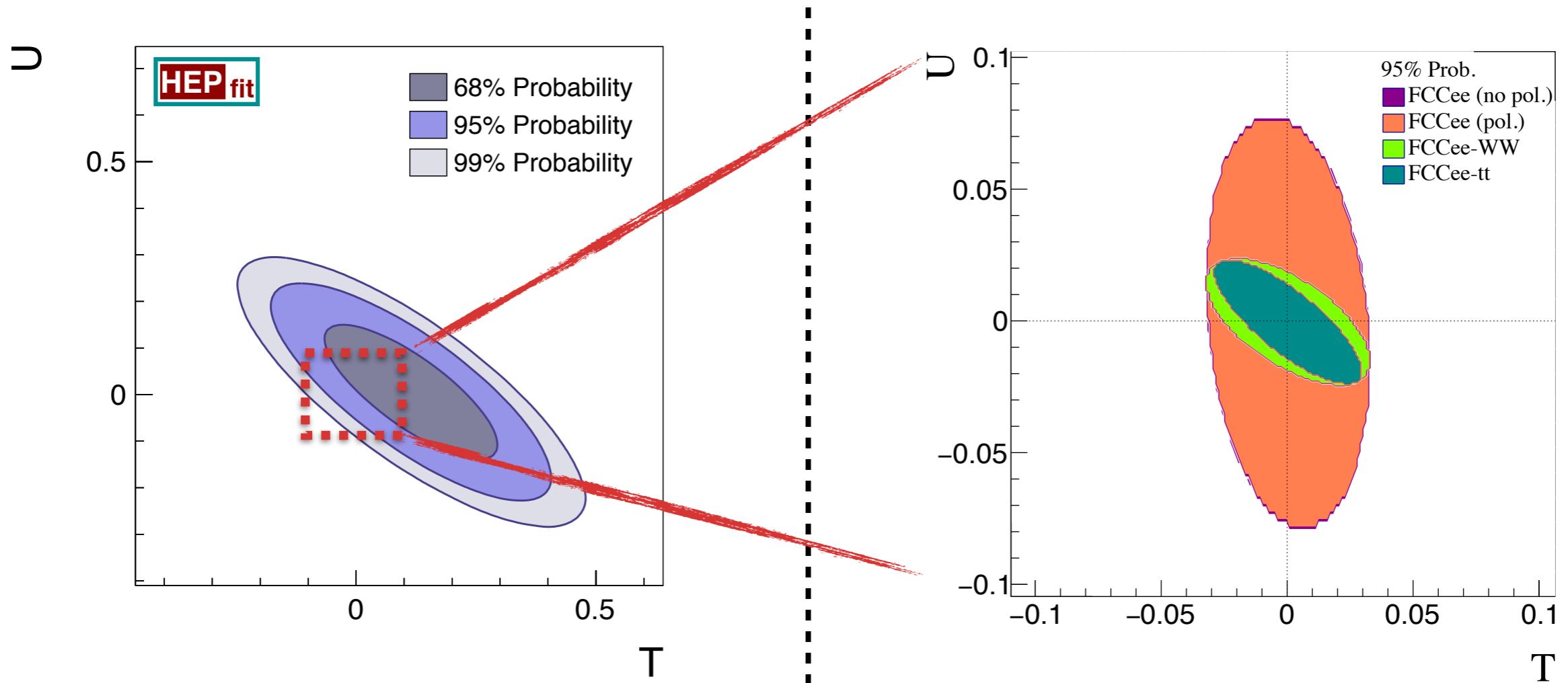


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T	0.10 ± 0.12	0.86	1.00
U	0.01 ± 0.09	-0.54	-0.81
			1.00

FCCee
 $\Delta S, \Delta T, \Delta U \sim 0.01$

EWPD LIMITS ON NP: S, T, U

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

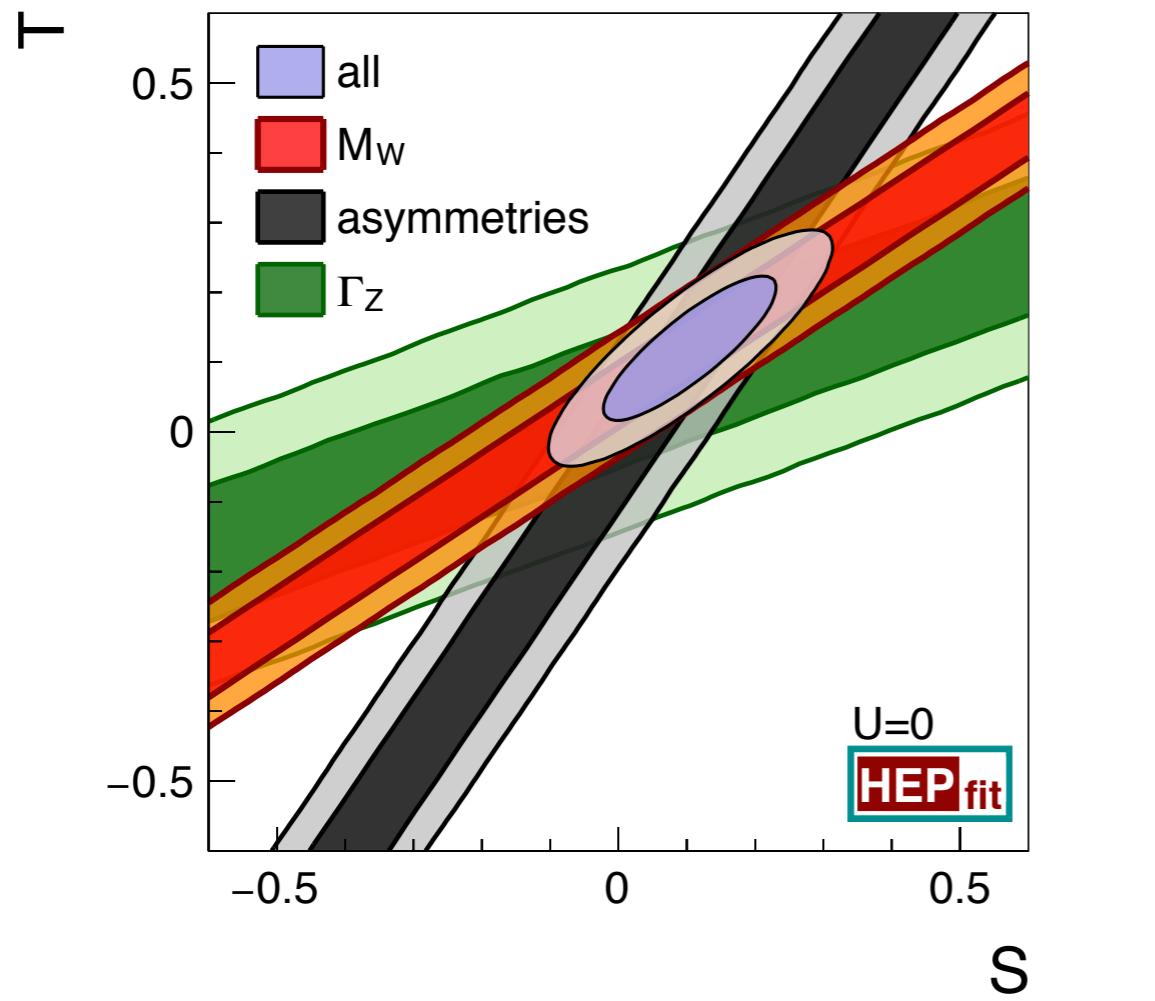


Fit result	Correlations		
S	0.09 ± 0.10	1.00	
T	0.10 ± 0.12	0.86	1.00
U	0.01 ± 0.09	-0.54	-0.81
			1.00

FCCee
 $\Delta S, \Delta T, \Delta U \sim 0.01$
Major improvement on U
at FCCee-WW

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

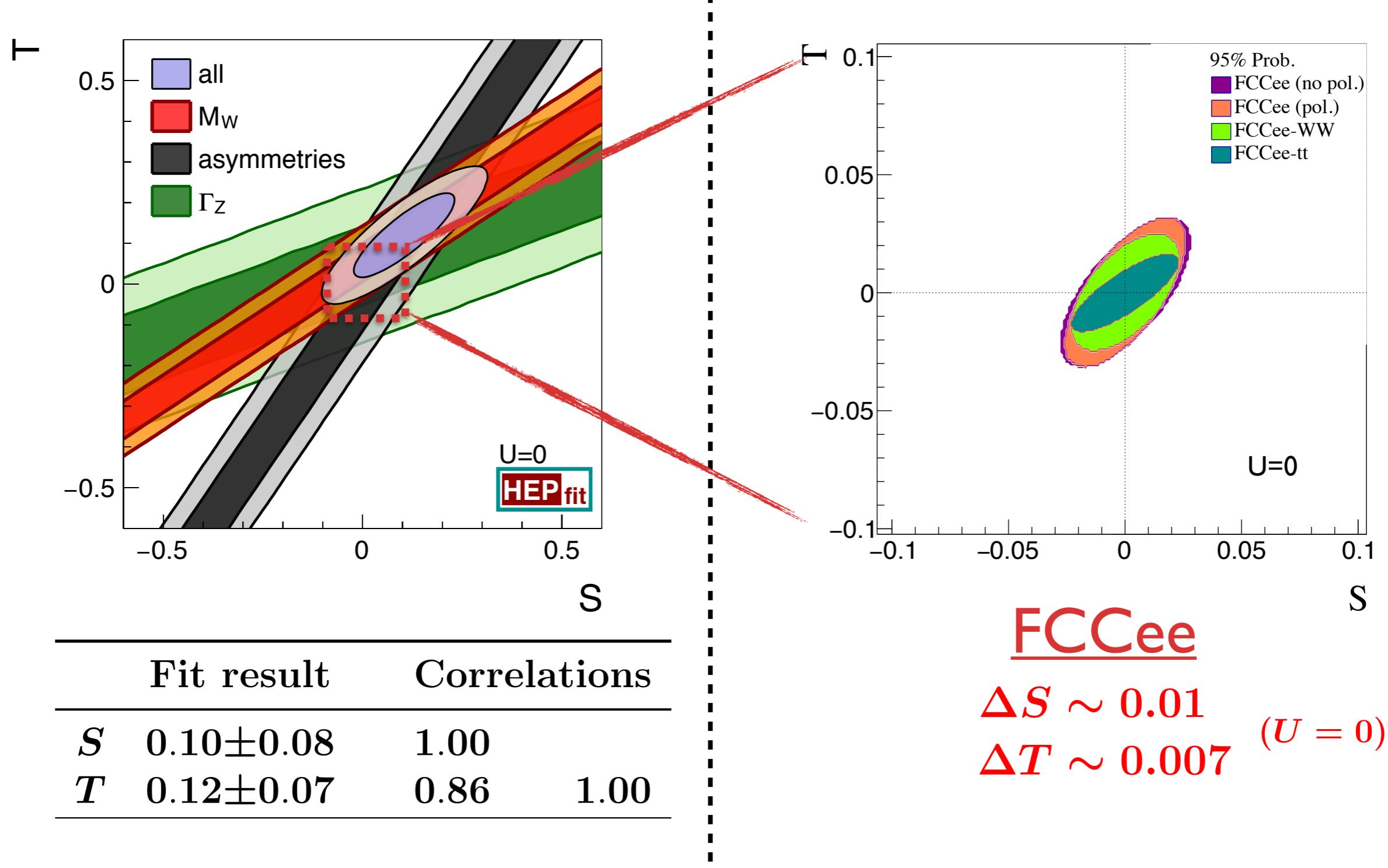
- Oblique Parameters: Present



Fit result	Correlations	
S 0.10 ± 0.08	1.00	
T 0.12 ± 0.07	0.86	1.00

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

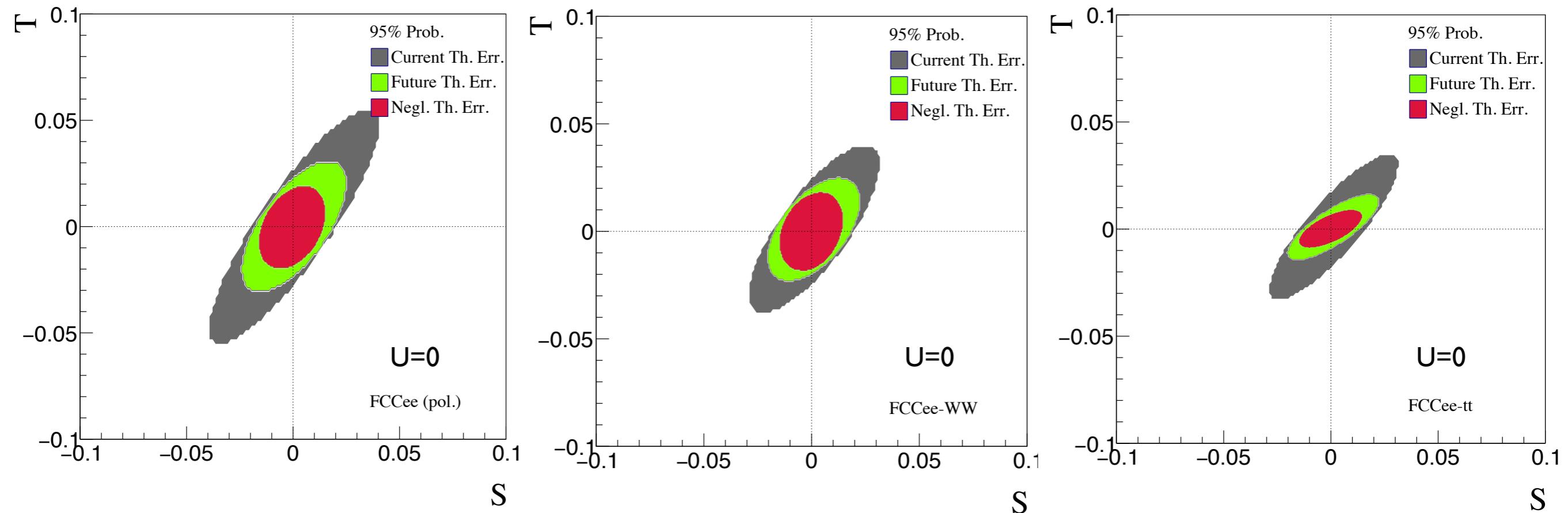
- Oblique Parameters: Present vs. Future



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

- Oblique Parameters: Present vs. Future

Impact of theory uncertainties

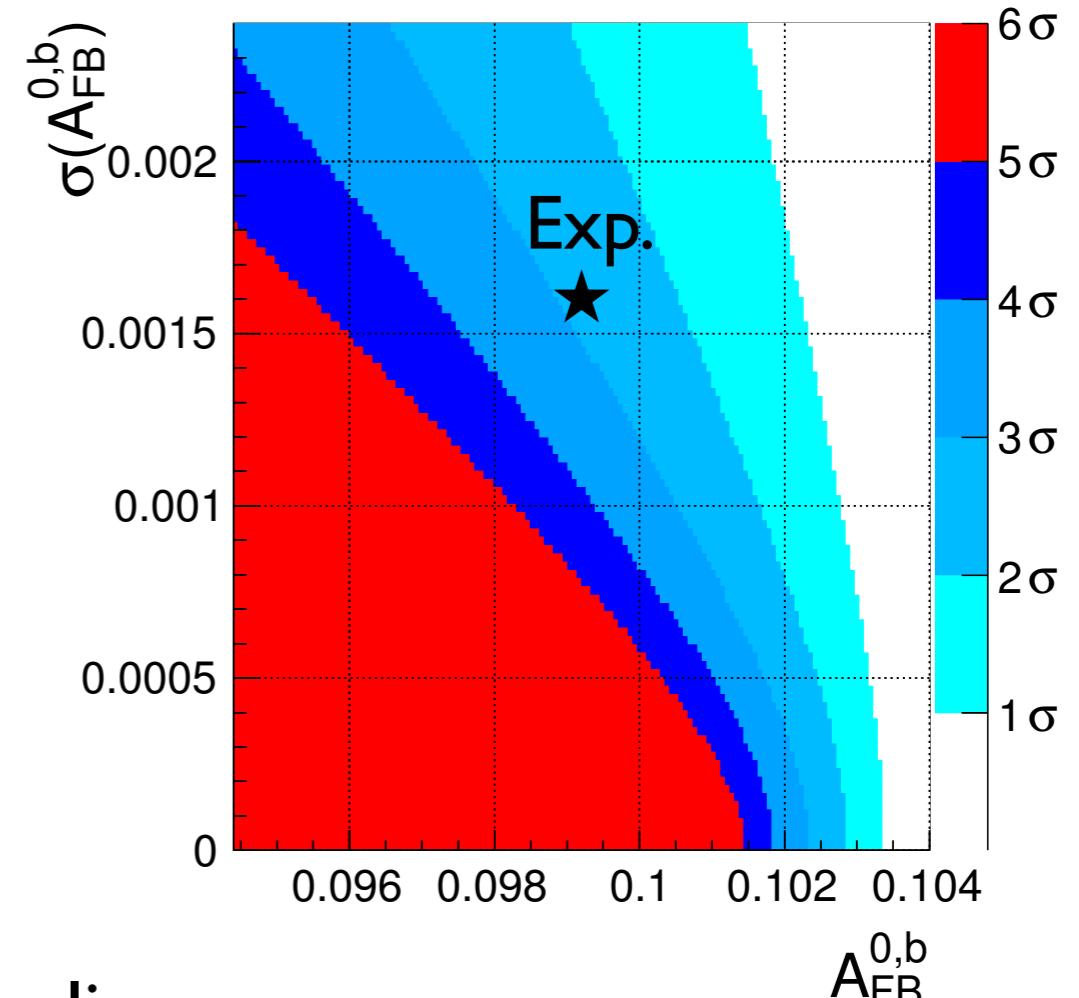


Current theoretical calculations insufficient for FCCee -precision physics

EWPD LIMITS ON NP: NON-STANDARD Zbb _COUP.

- Non-standard Zbb couplings
- One significant discrepancy in the SM fit:

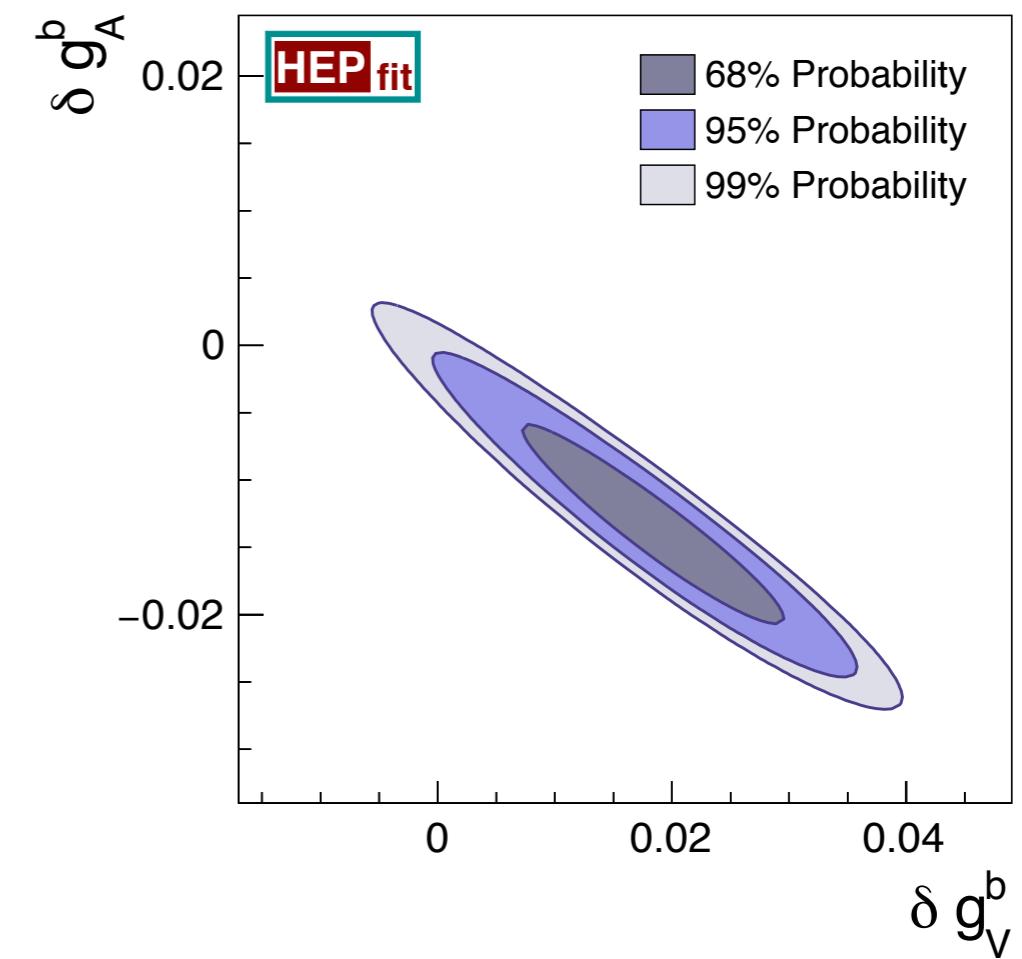
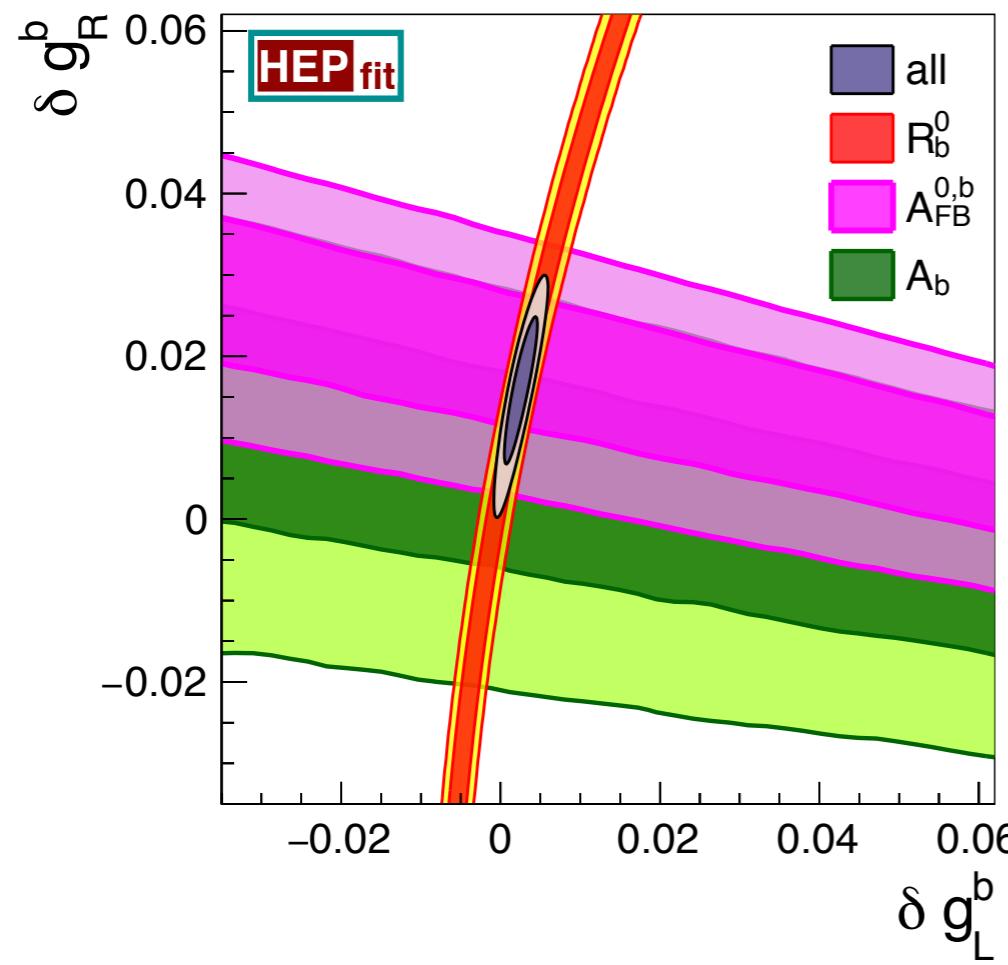
$$A_{FB}^{0,b} \sim -2.6\sigma$$



- Requires NP corrections to Zbb couplings:

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

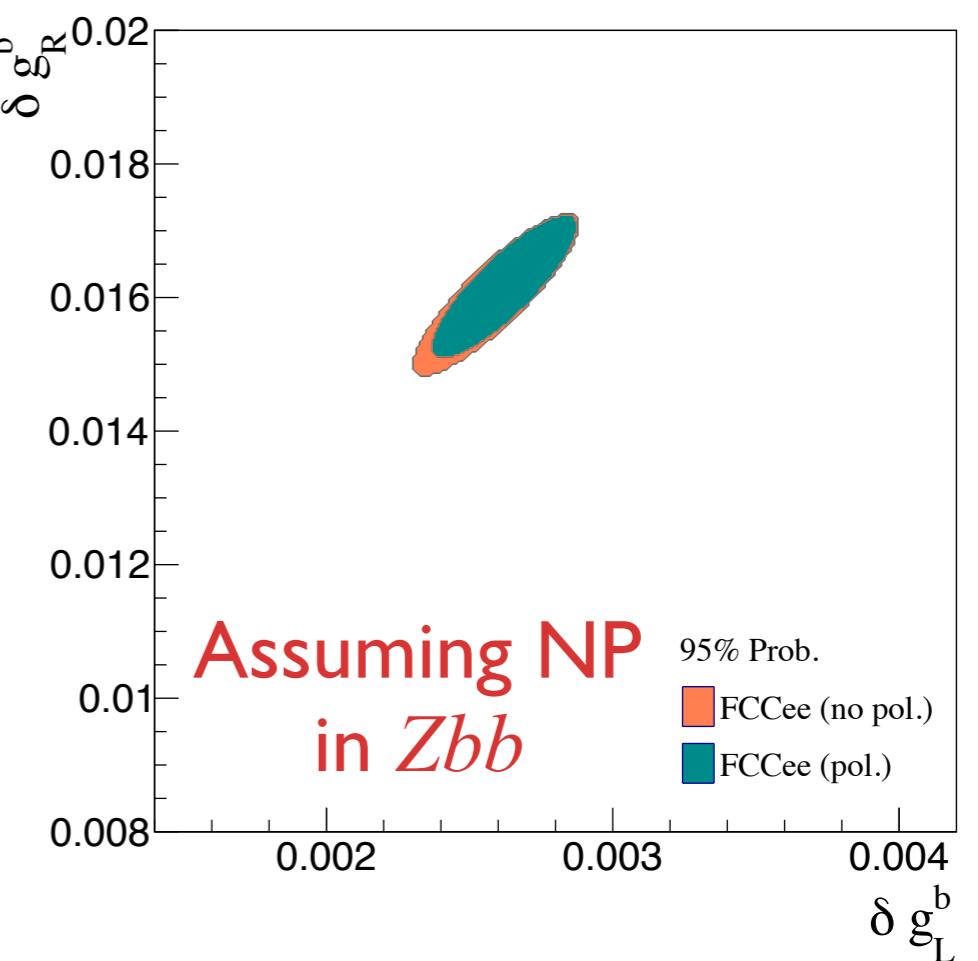
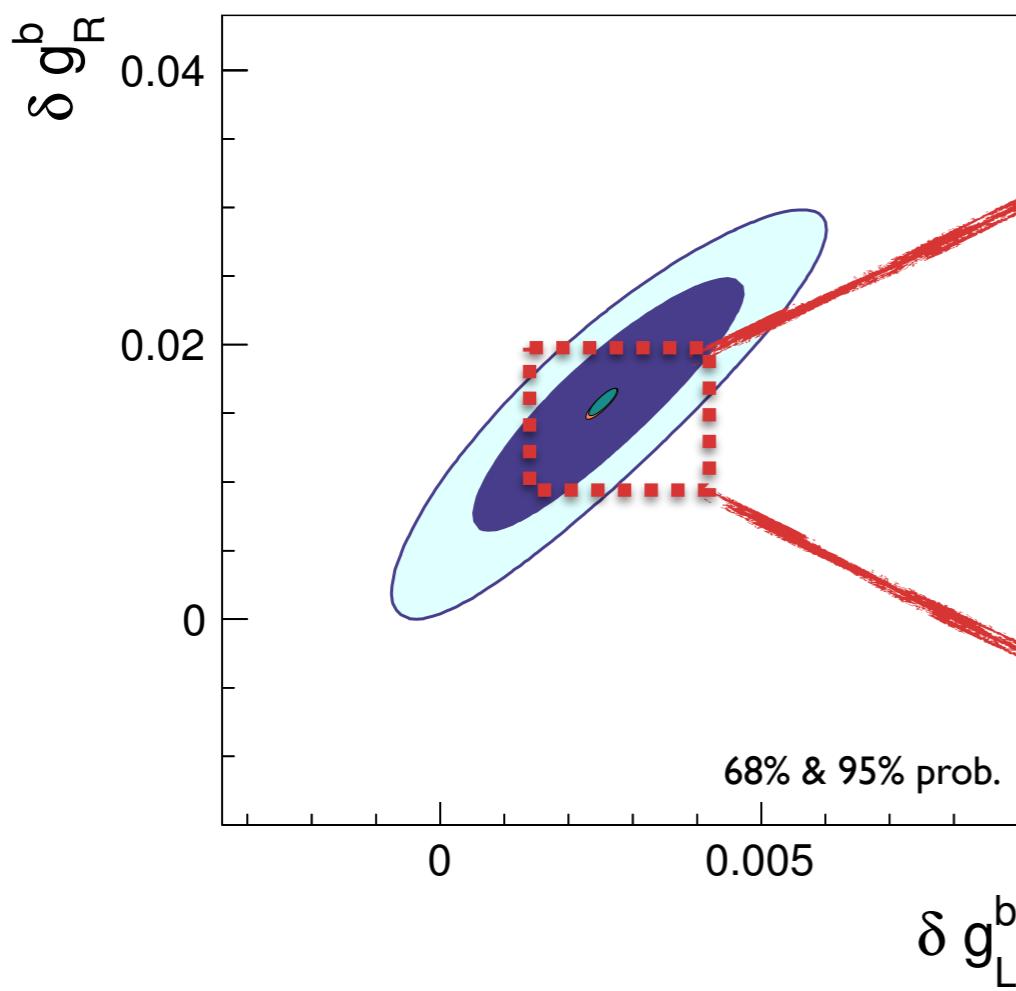
- Non-standard Zbb couplings: Present



	Fit result	Correlations	
δg_R^b	0.016 ± 0.006	1.00	
δg_L^b	0.003 ± 0.001	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



Fit result	Correlations		
δg_R^b	0.016 ± 0.006	1.00	
δg_L^b	0.003 ± 0.001	0.90	1.00
δg_V^b	0.018 ± 0.007	1.00	
δg_A^b	-0.013 ± 0.005	-0.98	1.00

FCCee

$$\Delta(\delta g_L^b) \sim 0.0001$$

$$\Delta(\delta g_R^b) \sim 0.0005$$

EWPD LIMITS ON NP: MODIFIED HIGGS COUPLINGS

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

Rescaled hVV couplings

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

Rescaled hff couplings

- EWPO: One-loop contribution to S & T

$$S = \frac{1}{12\pi} (1 - \kappa_V^2) \log \frac{\Lambda^2}{m_h^2}$$
$$T = -\frac{3}{16\pi c_W^2} (1 - \kappa_V^2) \log \frac{\Lambda^2}{m_h^2}$$

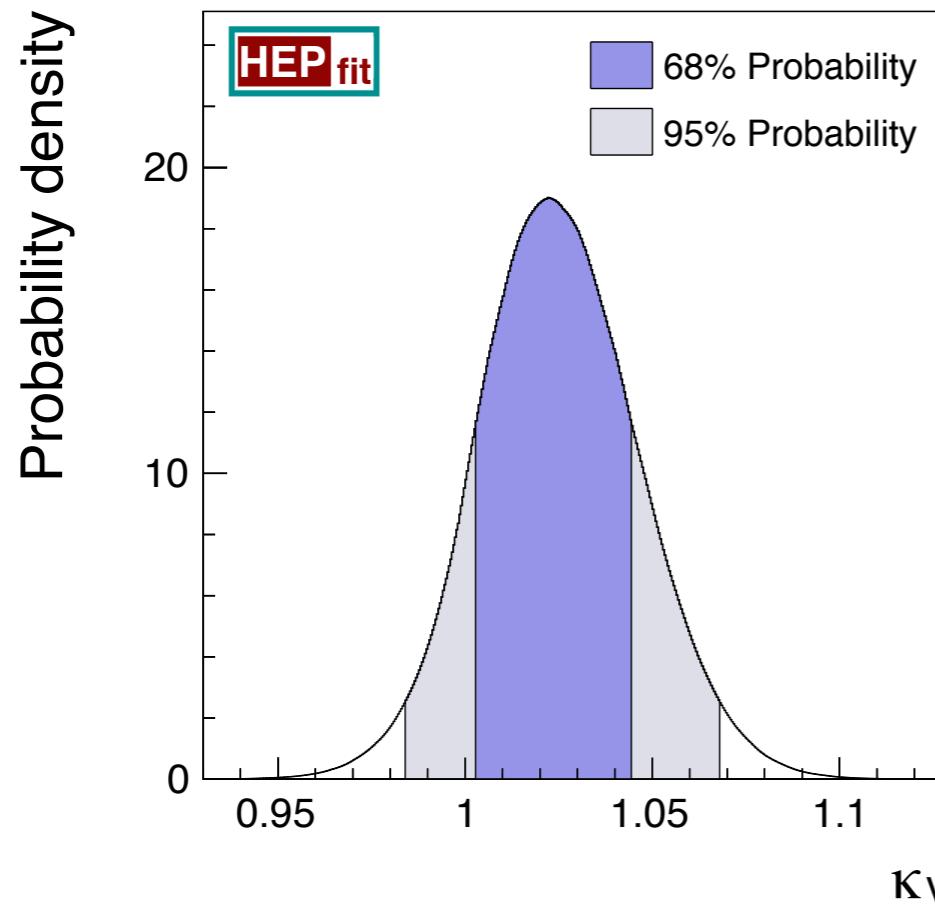
$$\Lambda = \frac{4\pi v}{\sqrt{|1 - \kappa_V^2|}}$$

Cut-off of the Higgs Eff. Lag.

- Modified Higgs couplings: Present

	Fit result	95% Prob.
κ_V	1.02 ± 0.02	[0.98, 1.07]

$$\left(\begin{array}{ll} \Lambda > 13 \text{ TeV} & (\kappa_V < 1) \\ \Lambda > 8.7 \text{ TeV} & (\kappa_V > 1) \end{array} \right)$$

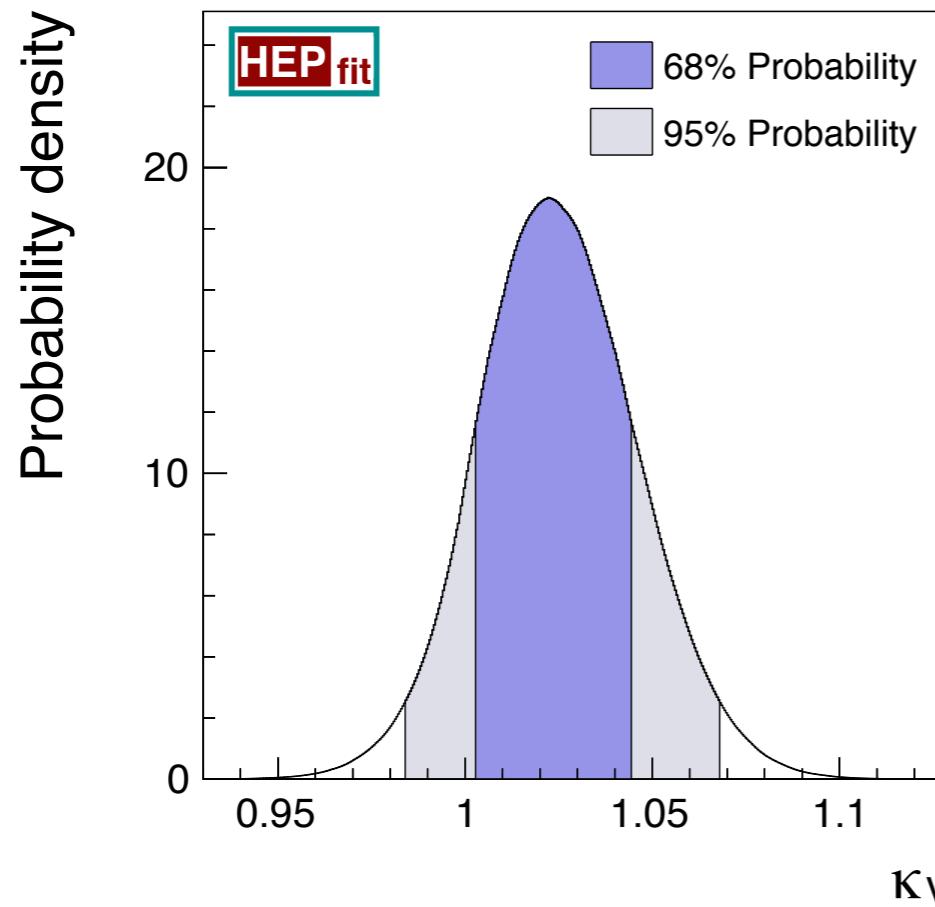


Implications for composite Higgs ($\kappa_V < 1$):
 Extra contrib. to S, T required to agree with
 EWPD fit

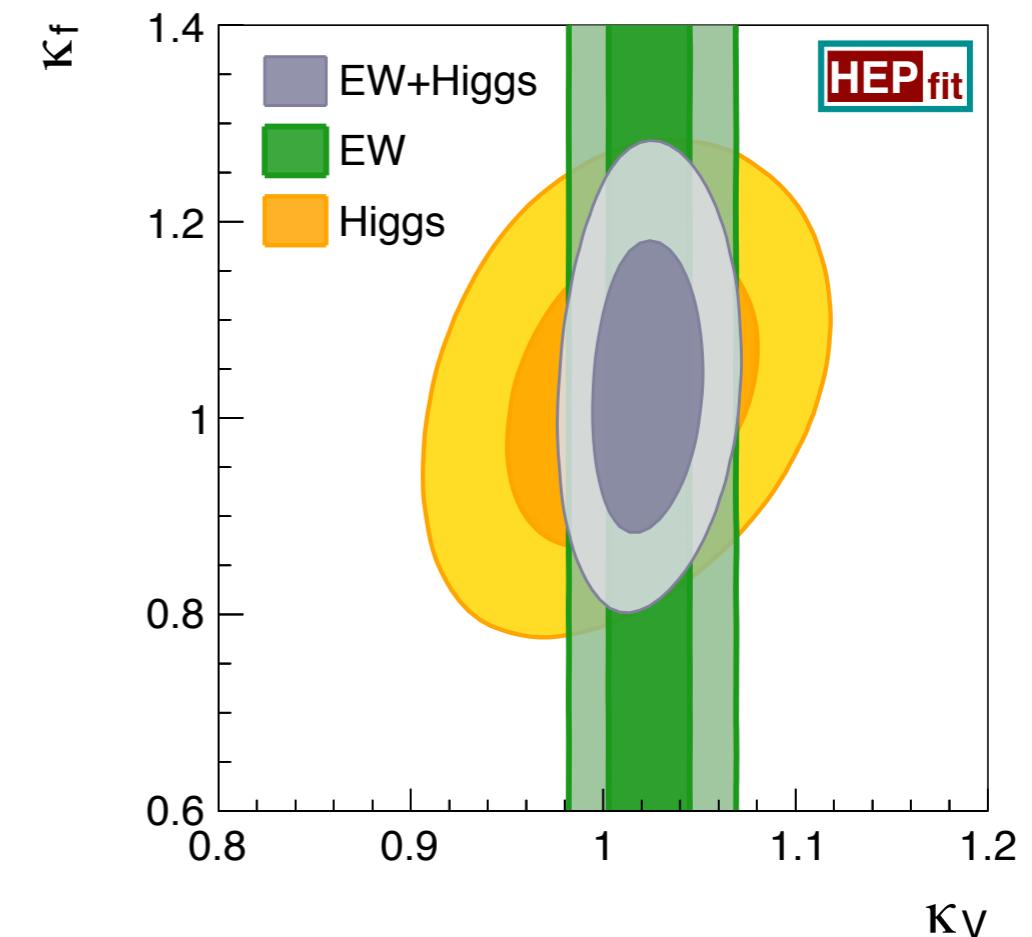
- Modified Higgs couplings: Present

Fit result	95% Prob.
κ_V 1.02 ± 0.02	[0.98, 1.07]

$$\begin{aligned} (\Lambda &> 13 \text{ TeV} \quad (\kappa_V < 1)) \\ (\Lambda &> 8.7 \text{ TeV} \quad (\kappa_V > 1)) \end{aligned}$$



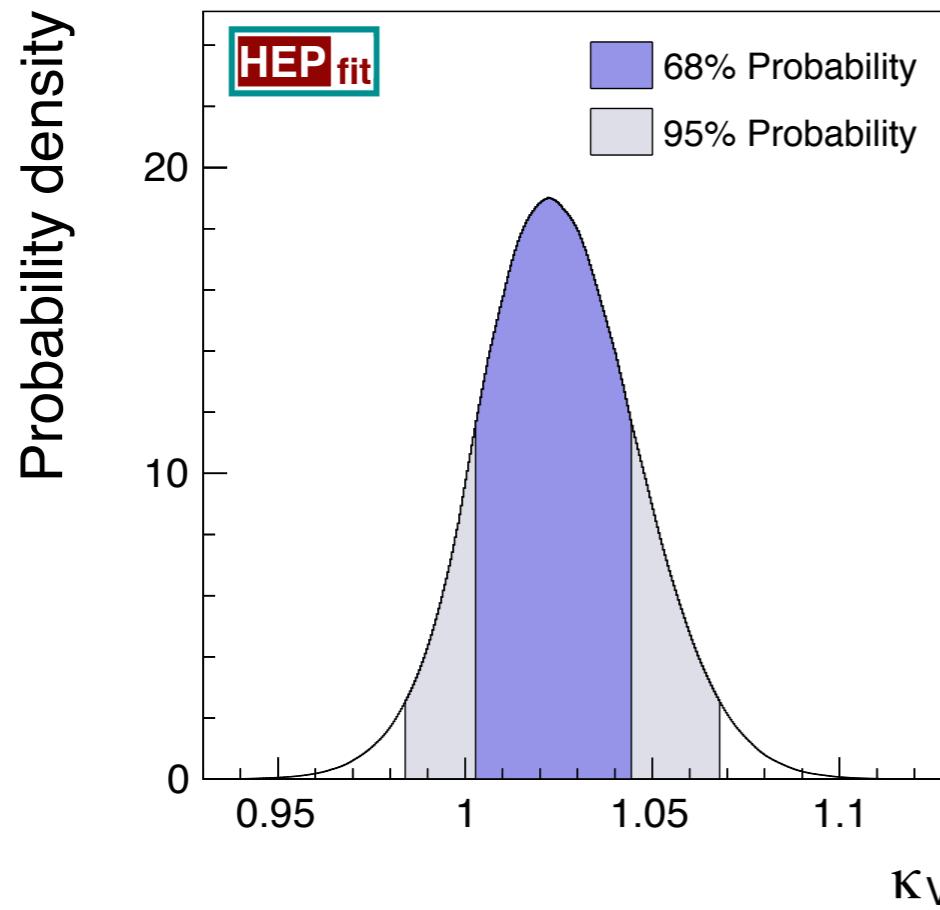
Implications for composite Higgs ($\kappa_V < 1$):
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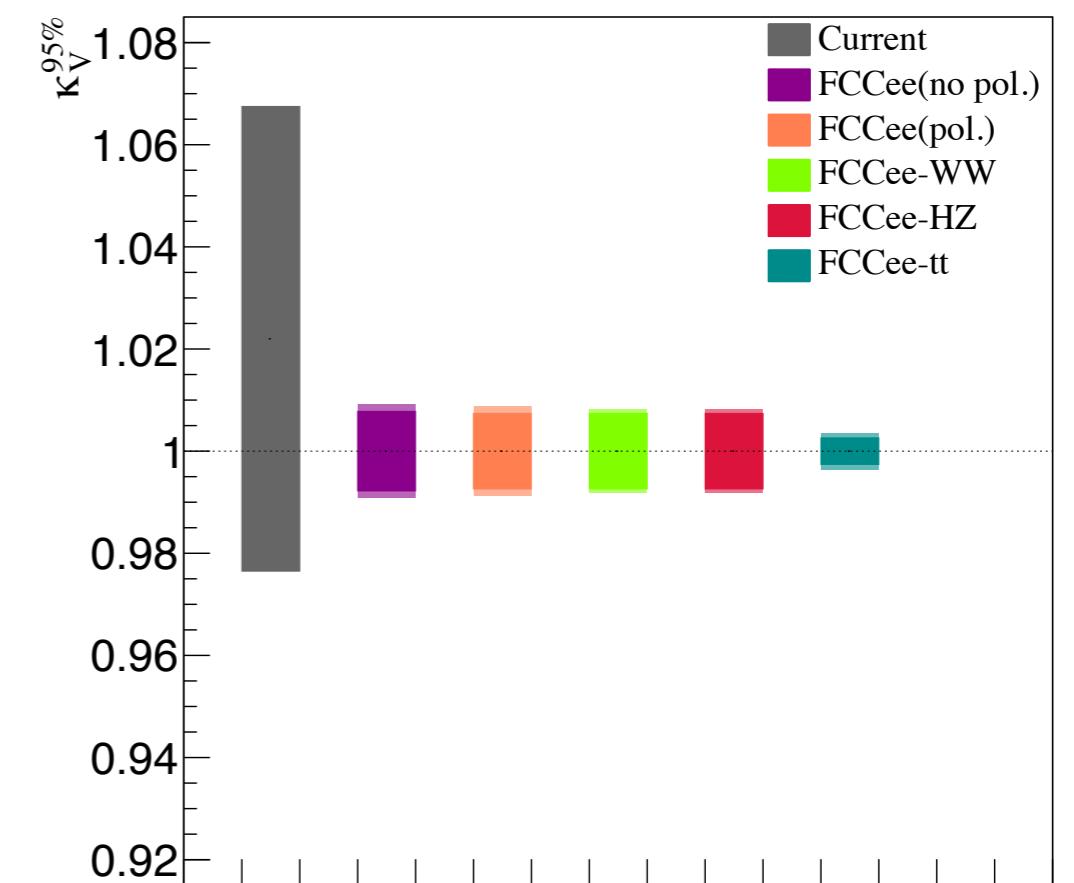
EWPD bounds (κ_V)
 stronger than Higgs limits

- Modified Higgs couplings: Present vs. Future

Fit result	95% Prob.
κ_V	1.02 ± 0.02 [0.98, 1.07]



Implications for composite Higgs ($\kappa_V < 1$):
 Extra contrib. to S, T required to agree with
 EWPD fit



FCCee
 $\Delta\kappa_V \sim 0.002$

- NP sensitivity at future colliders: **Summary & Comparison**

	Current	HL-LHC	ILC				FCCee				CEPC			
			Z (no pol)		Z (pol)		WW		$t\bar{t}$					
ΔS [$\times 10^{-3}$]	100	99	99	99	12	7.8	11	6.4	11	6.4	11	6.3	21	19
ΔT [$\times 10^{-3}$]	120	120	120	120	13	8.1	13	7.9	13	7.9	12	5.8	28	26
ΔU [$\times 10^{-3}$]	95	87	83	82	32	31	32	31	9.8	5.4	9.6	5.2	21	20
ΔS [$\times 10^{-3}$]	91	81	79	79	12	7.8	11	6.4	9.5	6.1	9.5	6	14	12
ΔT [$\times 10^{-3}$]	72	63	52	52	13	8.1	13	7.9	10	7.4	6.8	3.6	16	15
($U = 0$)														
$\Delta \epsilon_1^{\text{NP}}$ [$\times 10^{-5}$]	96	96	96	95	11	7.3	11	7.2	11	7.2	9.5	4.7	25	23
$\Delta \epsilon_2^{\text{NP}}$ [$\times 10^{-5}$]	86	81	77	76	29	28	28	28	8.6	4.8	8.5	4.7	21	19
$\Delta \epsilon_3^{\text{NP}}$ [$\times 10^{-5}$]	91	87	88	87	9.9	6.6	9.3	5.5	9.2	5.5	9.3	5.5	20	18
$\Delta \epsilon_b^{\text{NP}}$ [$\times 10^{-5}$]	130	130	130	130	15	12	15	12	15	12	14	11	41	37
$\Delta \delta g_L^b$ [$\times 10^{-4}$]	14	14	14	14	1.5	1.3	1.2	1.1	1.2	1.1	1.2	1.1	2.4	2.2
$\Delta \delta g_R^b$ [$\times 10^{-4}$]	72	70	70	70	7.1	6.6	5.3	5.3	5.3	5.3	5.3	5.3	8.9	8.6
$\Delta \kappa_V$ [$\times 10^{-3}$]	22	14	4.5	4.4	4.6	3.9	4.4	3.7	4.1	3.7	1.8	1.3	5	4.7

 Including future theory errors

 Assuming subdominant theory errors

EWPD LIMITS ON NP

- NP sensitivity at future colliders: **Summary & Comparison**

	Current	HL-LHC		ILC		FCCee						CEPC		
		Z (no pol)	Z (pol)	WW	t̄t									
ΔS [$\times 10^{-3}$]	100	99	99	99	12	7.8	11	6.4	11	6.4	11	6.3	21	19
ΔT [$\times 10^{-3}$]	120	120	120	120	13	8.1	13	7.9	13	7.9	12	5.8	28	26
ΔU [$\times 10^{-3}$]	95	87	83	82	32	31	32	31	9.8	5.4	9.6	5.2	21	20
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ΔT [$\times 10^{-3}$]	72	63	52	52	13	8.1	13	7.9	10	7.4	6.8	3.6	16	15
($U = 0$)														
$\Delta \epsilon_1^{\text{NP}}$ [$\times 10^{-5}$]	96	96	96	95	11	7.3	11	7.2	11	7.2	9.5	4.7	25	23
$\Delta \epsilon_2^{\text{NP}}$ [$\times 10^{-5}$]	86	81	77	76	29	28	28	28	8.6	4.8	8.5	4.7	21	19
$\Delta \epsilon_3^{\text{NP}}$ [$\times 10^{-5}$]	91	87	88	87	9.9	6.6	9.3	5.5	9.2	5.5	9.3	5.5	20	18
$\Delta \epsilon_b^{\text{NP}}$ [$\times 10^{-5}$]	130	130	130	130	15	12	15	12	15	12	14	11	41	37
$\Delta \delta g_L^b$ [$\times 10^{-4}$]	14	14	14	14	1.5	1.3	1.2	1.1	1.2	1.1	1.2	1.1	2.4	2.2
$\Delta \delta g_R^b$ [$\times 10^{-4}$]	72	70	70	70	7.1	6.6	5.3	5.3	5.3	5.3	5.3	5.3	8.9	8.6
$\Delta \kappa_V$ [$\times 10^{-3}$]	22	14	4.5	4.4	4.6	3.9	4.4	3.7	4.1	3.7	1.8	1.3	5	4.7

Sizable impact of future theory uncertainties at FCCee
(up to a factor ~2)

Including future theory errors

Assuming subdominant theory errors

CONCLUSIONS

- Current EWPD fit shows good agreement with the SM
 ⇒ **Strong constraints on NP at the TeV scale**
(Guide and complement the information from LHC direct searches)
- Future e^+e^- colliders would strengthen the constraining/discriminating power of the EWPD fit. Significant **improvement in theoretical calculations is required** to match future exp. precision of EWPO.
- Projected sensitivities to NP (EWPO at FCCee):

	Expected sensitivity	Improvement
S, T, U	$\Delta S, \Delta T, \Delta U \sim 5\text{-}10 \cdot 10^{-3}$	10-20x
$\delta g_{L,R}^b$	$\Delta \delta g_L^b \sim 10^{-4}, \quad \Delta \delta g_R^b \sim 5 \cdot 10^{-4}$	10x
κ_V	$\Delta \kappa_V \sim 0.001\text{-}0.002$	10-20x

BACKUP SLIDES

EFF. LAG. DESCRIPTION OF NP IN EWPO

- To dim 6 EWPO are sensitive to 10 ops. (we use the “Warsaw” basis):
- Oblique corrections

$$\mathcal{O}_{HD} = |H^\dagger iD_\mu H|^2 \quad \mathcal{O}_{HWB} = (H^\dagger \sigma_a H) W_{\mu\nu}^a B^{\mu\nu}$$

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

- Corrections to EW Vff couplings

$$\mathcal{O}_{Hf}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{f}\gamma^\mu f) \quad \mathcal{O}_{Hf}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^a H)(\bar{f}\gamma^\mu \sigma_a f)$$

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

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

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

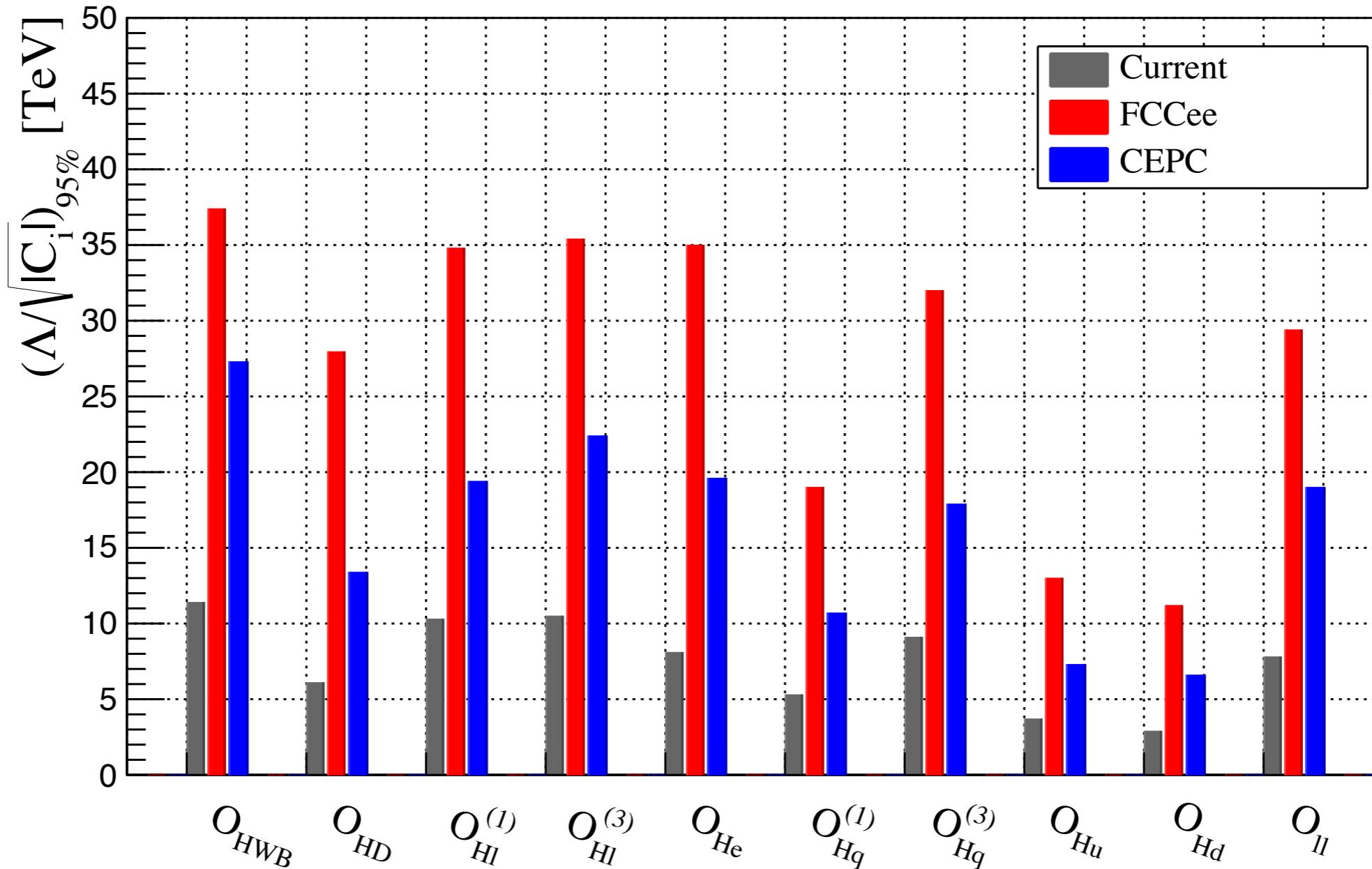
$$\delta_{G_F} = \left((C_{H\ell}^{(3)})_{11} + (C_{H\ell}^{(3)})_{22} - \frac{1}{2} ((C_{\ell\ell})_{1221} + (C_{\ell\ell})_{2112}) \right) \frac{v^2}{\Lambda^2}$$

EWPD LIMITS ON NP: DIM 6 SMEFT

Preliminary

- Dimension six SMEFT: Present vs. Future

| operator at a time. Flavor universal.



EWPO at future colliders: NP scale >5-40 TeV ($C_i \sim 1$)

See my previous talk on thursday for details
(Higgs session)