Electroweak Precision Observables and Higgs signal strengths in the SM and beyond: present and future

Luca Silvestrini
INFN, Rome

Based on:

M. Ciuchini, E. Franco, S. Mishima & LS, JHEP 08 (2013) 106
J. de Blas, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina & LS, JHEP 12 (2016) 135 + in preparation

Special thanks to Laura Reina and Jorge de Blas

OUTLINE

- Introduction
- EW fits with current data:
  - SM
  - oblique corrections
  - modified Z couplings
  - modified Higgs couplings
  - Constraints on D=6 operators
- Future prospects
- Conclusions

INTRODUCTION

- $SU(2)_L$ X $U(1)_Y$ symmetry hidden at low energies, but restored in the UV
  - tree-level relations among weak couplings and masses corrected by finite and calculable loop corrections
  - precision measurements of masses and couplings
    - test the quantum structure of the SM
    - probe NP through its virtual effects

INTRODUCTION II

- What is the scale Λ of NP?
  - consider the SM as an effective theory valid up to the NP scale Λ:

$$\mathscr{L} = \mathscr{L}_{SM} + \Lambda^2 |\phi|^2 + \mathscr{L}_5/\Lambda + \mathscr{L}_6/\Lambda^2 + \ldots$$

determines the EW scale

break SM accidental symmetries; modify SM predictions

- Precision measurements in the EW sector are a very powerful probe of Λ

EW PHYSICS IN THE LHC ERA

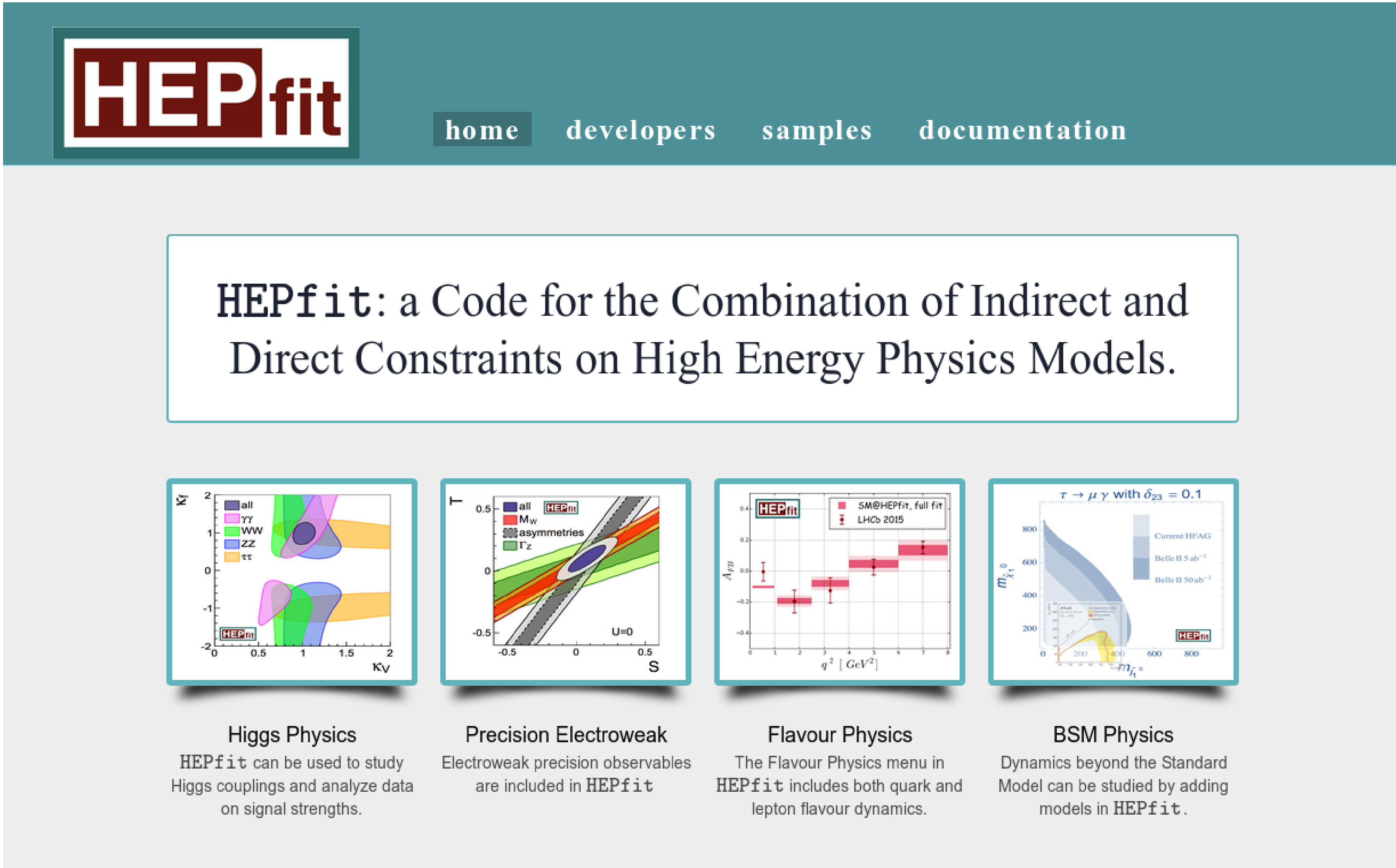
- The measurement of the Higgs mass completes the knowledge of $\mathscr{L}_{SM}$
  - all EWPO now fully computable in the SM
- Higgs signal strengths directly probe electroweak symmetry breaking
  - test SM Higgs couplings
- Combine EWPO and Higgs signal strengths to constrain extensions of the SM

EWPO FIT

- SM input parameters:
  - G_F, α, M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}^{(5)}$
- state-of-the-art computation of EWPO
- parametrize possible NP effects (modified couplings, additional loop contributions, D=6 operators)
- perform a fit to experimental data
  - GAPP (Erler)
  - ZFITTER (Akhundov, Arbuzov, S. & T. Riemann)
  - Gfitter (Baak, Cúth, Haller, Hoecker, Kogler, Mönig, Schott, Stelzer)
  - us, using the HEPfit public code

HEPfit developer repository: https://github.com/silvest/HEPfit

HEPfit webpage: http://hepfit.roma1.infn.it



HEPfit

home developers samples documentation

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.

EW FITS WITH HEPfit

- Both electroweak and Higgs observables are calculated as a SM core plus corrections:
  - the SM core includes all existing higher order corrections
  - NP corrections are at the lowest order in all SM couplings
- Experimental results are taken from the most recent published analyses
- The fit procedure uses BAT (Bayesan Analysis Toolkit) with flat priors for all input parameters, and posteriors calculated using a Markov Chain Monte Carlo
- Stand-alone or library mode to compute observables in a given model:
  - Implemented models:
    - SM, Oblique parameters (S,T,U), ε_i parameters, modified $Zb\bar{b}$ couplings, Modified Higgs couplings (κ_i), SMEFT (D=6), 2HDM
  - Implemented observables:
    - EWPO, Flavour ($\Delta F = 2$, UT, rare B decays)

	Ref.	Measurement	Posterior	Prediction	1D Pull	nD Pull	
$\alpha_s(M_Z)$	[10]	0.1179 ± 0.0012	0.1180 ± 0.0011	0.1185 ± 0.0028	-0.2		PDG
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	[13]	0.02750 ± 0.00033	0.02747 ± 0.00025	0.02743 ± 0.00038	0.04		Burkhardt et al
M_Z [GeV]	[14]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.011	-1.0		LEP
m_t [GeV]	[15]	173.34 ± 0.76	173.61 ± 0.73	176.6 ± 2.5	-1.3		TeVatron + LHC
m_H [GeV]	[16]	125.09 ± 0.24	125.09 ± 0.24	102.8 ± 26.3	0.8		Atlas + CMS
M_W [GeV]	[17]	80.385 ± 0.015	80.3644 ± 0.0061	80.3604 ± 0.0066	1.5		CDF + D0
Γ_W [GeV]	[18]	2.085 ± 0.042	2.08872 ± 0.00064	2.08873 ± 0.00064	-0.2		TeV + LEP + SLD
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	[14]	0.2324 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.000090	0.8		LEP
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	[14]	0.1465 ± 0.0033	0.14748 ± 0.00068	0.14752 ± 0.00069	-0.4		LEP
Γ_Z [GeV]	[14]	2.4952 ± 0.0023	2.49420 ± 0.00063	2.49405 ± 0.00068	0.5		
σ^0_h [nb]	[14]	41.540 ± 0.037	41.4903 ± 0.0058	41.4912 ± 0.0062	1.3	0.7	LEP
R^0_ℓ	[14]	20.767 ± 0.025	20.7485 ± 0.0070	20.7472 ± 0.0076	0.8		
$A^{0,\ell}_{\rm FB}$	[14]	0.0171 ± 0.0010	0.01631 ± 0.00015	0.01628 ± 0.00015	0.8		
$\mathcal{A}_\ell$ (SLD)	[14]	0.1513 ± 0.0021	0.14748 ± 0.00068	0.14765 ± 0.00076	1.7		
$\mathcal{A}_c$	[14]	0.670 ± 0.027	0.66810 ± 0.00030	0.66817 ± 0.00033	0.02		
$\mathcal{A}_b$	[14]	0.923 ± 0.020	0.934650 ± 0.000058	0.934663 ± 0.000064	-0.6		
$A^{0,c}_{\rm FB}$	[14]	0.0707 ± 0.0035	0.07390 ± 0.00037	0.07399 ± 0.00042	-0.9	1.5	LEP + SLD
$A^{0,b}_{\rm FB}$	[14]	0.0992 ± 0.0016	0.10338 ± 0.00048	0.10350 ± 0.00054	-2.6		
R^0_c	[14]	0.1721 ± 0.0030	0.172228 ± 0.000023	0.172229 ± 0.000023	-0.05		
R^0_b	[14]	0.21629 ± 0.00066	0.215790 ± 0.000028	0.215788 ± 0.000028	0.7		
$\sin^2\theta^{ee}_{\rm eff}$	[19]	0.23248 ± 0.00052			2.1		CDF
$\sin^2\theta^{\mu\mu}_{\rm eff}$	[20]	0.2315 ± 0.0010			0.07		CDF
$\sin^2\theta^{ee}_{\rm eff}$	[21]	0.23146 ± 0.00047			0.1		D0
$\sin^2\theta^{ee,\mu\mu}_{\rm eff}$	[22]	0.2308 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.000090	-0.5		ATLAS
$\sin^2\theta^{\mu\mu}_{\rm eff}$	[23]	0.2287 ± 0.0032			-0.8		CMS
$\sin^2\theta^{\mu\mu}_{\rm eff}$	[24]	0.2314 ± 0.0011			-0.1		LHCb

	Ref.	Measurement	Posterior	Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	[10]	0.1179 ± 0.0012	0.1180 ± 0.0011	0.1185 ± 0.0028	-0.2	
$\Delta\alpha^{(5)}_{\text{had}}(M_Z)$	[13]	0.02750 ± 0.00033	0.02747 ± 0.00025	0.02743 ± 0.00038	0.04	
M_Z [GeV]	[14]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.011	-1.0	
m_t [GeV]	[15]	173.34 ± 0.76	173.61 ± 0.73	176.6 ± 2.5	-1.3	
m_H [GeV]	[16]	125.09 ± 0.24	125.09 ± 0.24	102.8 ± 26.3	0.8	
M_W [GeV]	[17]	80.385 ± 0.015	80.3644 ± 0.0061	80.3604 ± 0.0066	1.5	
Γ_W [GeV]	[18]	2.085 ± 0.042	2.08872 ± 0.00064	2.08873 ± 0.00064	-0.2	
$\sin^2\theta^{\text{lept}}_{\text{eff}}(Q^{\text{had}}_{\text{FB}})$	[14]	0.2324 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.000090	0.8	
$P^{\text{pol}}_\tau = \mathcal{A}_\ell$	[14]	0.1465 ± 0.0033	0.14748 ± 0.00068	0.14752 ± 0.00069	-0.4	
Γ_Z [GeV]	[14]	2.4952 ± 0.0023	2.49420 ± 0.00063	2.49405 ± 0.00068	0.5	
σ^0_h [nb]	[14]	41.540 ± 0.037	41.4903 ± 0.0058	41.4912 ± 0.0062	1.3	0.7
R^0_ℓ	[14]	20.767 ± 0.025	20.7485 ± 0.0070	20.7472 ± 0.0076	0.8	
$A^{0,\ell}_{\text{FB}}$	[14]	0.0171 ± 0.0010	0.01631 ± 0.00015	0.01628 ± 0.00015	0.8	
$\mathcal{A}_\ell$ (SLD)	[14]	0.1513 ± 0.0021	0.14748 ± 0.00068	0.14765 ± 0.00076	1.7	
$\mathcal{A}_c$	[14]	0.670 ± 0.027	0.66810 ± 0.00030	0.66817 ± 0.00033	0.02	
$\mathcal{A}_b$	[14]	0.923 ± 0.020	0.934650 ± 0.000058	0.934663 ± 0.000064	-0.6	
$A^{0,c}_{\text{FB}}$	[14]	0.0707 ± 0.0035	0.07390 ± 0.00037	0.07399 ± 0.00042	-0.9	1.5
$A^{0,b}_{\text{FB}}$	[14]	0.0992 ± 0.0016	0.10338 ± 0.00048	0.10350 ± 0.00054	-2.6	
R^0_c	[14]	0.1721 ± 0.0030	0.172228 ± 0.000023	0.172229 ± 0.000023	-0.05	
R^0_b	[14]	0.21629 ± 0.00066	0.215790 ± 0.000028	0.215788 ± 0.000028	0.7	
$\sin^2\theta^{ee}_{\text{eff}}$	[19]	0.23248 ± 0.00052	0.231464 ± 0.000087	0.231435 ± 0.000090	2.1	
$\sin^2\theta^{\mu\mu}_{\text{eff}}$	[20]	0.2315 ± 0.0010			0.07	
$\sin^2\theta^{ee}_{\text{eff}}$	[21]	0.23146 ± 0.00047			0.1	
$\sin^2\theta^{ee,\mu\mu}_{\text{eff}}$	[22]	0.2308 ± 0.0012			-0.5	
$\sin^2\theta^{\mu\mu}_{\text{eff}}$	[23]	0.2287 ± 0.0032			-0.8	
$\sin^2\theta^{\mu\mu}_{\text{eff}}$	[24]	0.2314 ± 0.0011			-0.1	

Correlated Observables

Correlated Observables

	Ref.	Measurement	Posterior	Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	[10]	0.1179 ± 0.0012	0.1180 ± 0.0011	0.1185 ± 0.0028	-0.2	[illegible]
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	[13]	0.02750 ± 0.00033	0.02747 ± 0.00025	0.02743 ± 0.00038	0.04	[illegible]
M_Z [GeV]	[14]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.011	-1.0	[illegible]
m_t [GeV]	[15]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
m_H [GeV]	[16]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M_W [GeV]	[17]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Γ_W [GeV]	[18]	2.085 ± 0.042	2.08872 ± 0.0006[illegible]	[illegible]	[illegible]	[illegible]
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	[14]	0.2324 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.00009[illegible]	[illegible]	[illegible]
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	[14]	0.1465 ± 0.0033	0.14748 ± 0.00068	0.14752 ± 0.00069	[illegible]	[illegible]
Γ_Z [GeV]	[14]	2.4952 ± 0.0023	2.49420 ± 0.00063	2.49405 ± 0.00068	[illegible]	[illegible]
σ^0_h [nb]	[14]	41.540 ± 0.037	41.4903 ± 0.0058	41.4912 ± 0.0062	[illegible]	[illegible]
R^0_ℓ	[14]	20.767 ± 0.025	20.7485 ± 0.0070	20.7472 ± 0.0076	0.8	[illegible]
$A^{0,\ell}_{\rm FB}$	[14]	0.0171 ± 0.0010	0.01631 ± 0.00015	0.01628 ± 0.00015	0.8	[illegible]
$\mathcal{A}_\ell$ (SLD)	[14]	0.1513 ± 0.0021	0.14748 ± 0.00068	0.14765 ± 0.00076	1.7	
$\mathcal{A}_c$	[14]	0.670 ± 0.027	0.66810 ± 0.00030	0.66817 ± 0.00033	0.02	
$\mathcal{A}_b$	[14]	0.923 ± 0.020	0.934650 ± 0.000058	0.934663 ± 0.000064	-0.6	
$A^{0,c}_{\rm FB}$	[14]	0.0707 ± 0.0035	0.07390 ± 0.00037	0.07399 ± 0.00042	-0.9	1.5
$A^{0,b}_{\rm FB}$	[14]	0.0992 ± 0.0016	0.10338 ± 0.00048	0.10350 ± 0.00054	-2.6	
R^0_c	[14]	0.1721 ± 0.0030	0.172228 ± 0.000023	0.172229 ± 0.000023	-0.05	
R^0_b	[14]	0.21629 ± 0.00066	0.215790 ± 0.000028	0.215788 ± 0.000028	0.7	
$\sin^2\theta^{ee}_{\rm eff}$	[19]	0.23248 ± 0.00052			2.1	
$\sin^2\theta^{\mu\mu}_{\rm eff}$	[20]	0.2315 ± 0.0010			0.07	
$\sin^2\theta^{ee}_{\rm eff}$	[21]	0.23146 ± 0.00047			0.1	
$\sin^2\theta^{ee,\mu\mu}_{\rm eff}$	[22]	0.2308 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.000090	-0.5	
$\sin^2\theta^{\mu\mu}_{\rm eff}$	[23]	0.2287 ± 0.0032			-0.8	
$\sin^2\theta^{\mu\mu}_{\rm eff}$	[24]	0.2314 ± 0.0011			-0.1	

Measurement: Experimental value used as input

Posterior: Result of the global fit

Prediction: Result of the fit not using the corresponding measurement

1D Pull: Difference between measurement and prediction in units of σ, neglecting correlations for correlated observables

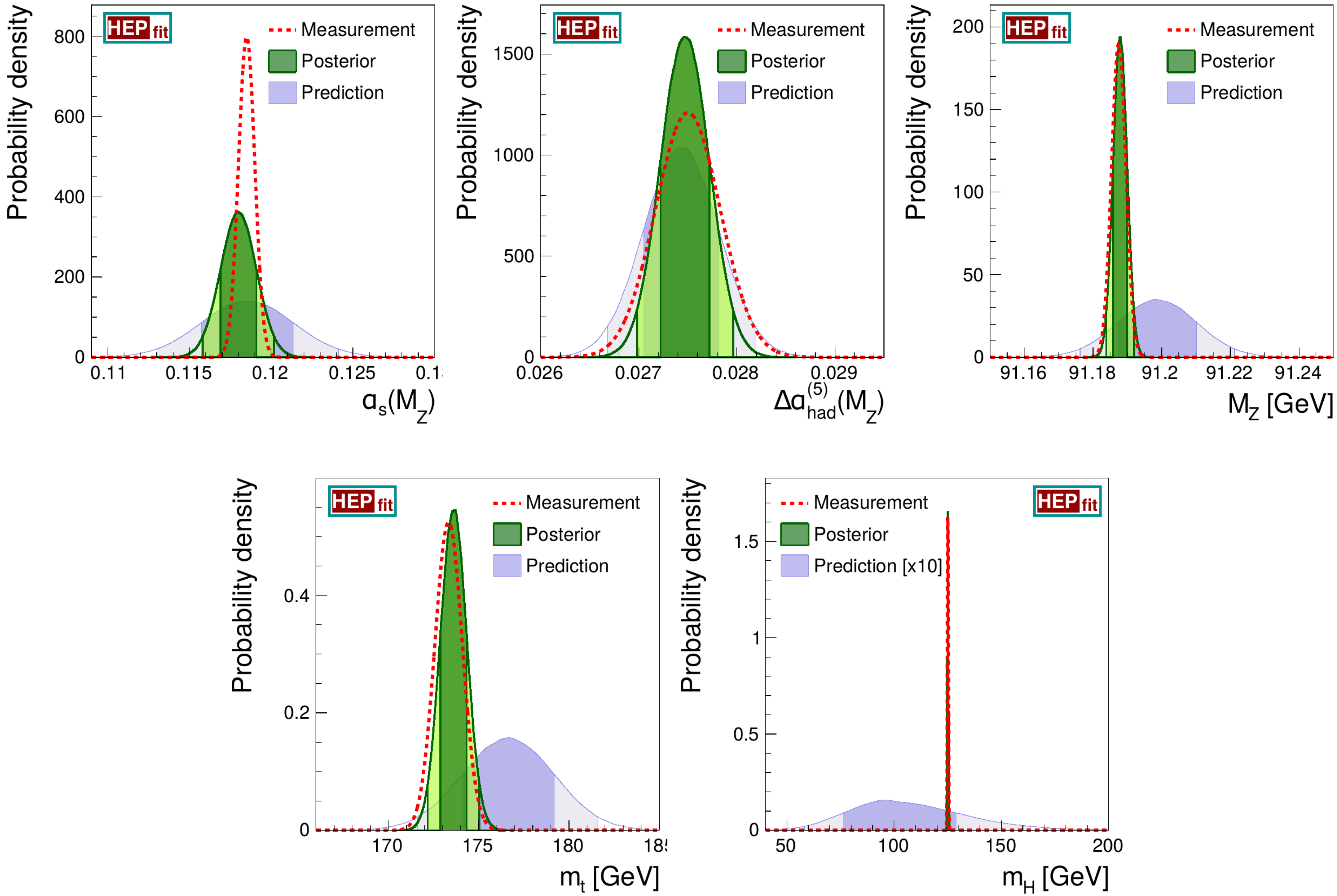
nD Pull: Difference between measurement and prediction in units of σ, taking all correlations (theoretical and experimental) properly into account

	Ref.	Measurement	Posterior	Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	[10]	0.1179 ± 0.0012	0.1180 ± 0.0011	0.1185 ± 0.0028	-0.2	
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$	[13]	0.02750 ± 0.00033	0.02747 ± 0.00025	0.02743 ± 0.00038	0.04	
M_Z [GeV]	[14]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.011	-1.0	
m_t [GeV]	[15]	173.34 ± 0.76	173.61 ± 0.73	176.6 ± 2.5	-1.3	
m_H [GeV]	[16]	125.09 ± 0.24	125.09 ± 0.24	102.8 ± 26.3	0.8	
M_W [GeV]	[17]	80.385 ± 0.015	80.3644 ± 0.0061	80.3604 ± 0.0066	1.5	
Γ_W [GeV]	[18]	2.085 ± 0.042	2.08872 ± 0.00064	2.08873 ± 0.00064	-0.2	
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	[14]	0.2324 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.000090	0.8	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	[14]	0.1465 ± 0.0033	0.14748 ± 0.00068	0.14752 ± 0.00069	-0.4	
Γ_Z [GeV]	[14]	2.4952 ± 0.0023	2.49420 ± 0.00063	2.49405 ± 0.00068	0.5	
σ_h^0 [nb]	[14]	41.540 ± 0.037	41.4903 ± 0.0058	41.4912 ± 0.0062	1.3	0.7
R_ℓ^0	[14]	20.767 ± 0.025	20.7485 ± 0.0070	20.7472 ± 0.0076	0.8	
$A_{\rm FB}^{0,\ell}$	[14]	0.0171 ± 0.0010	0.01631 ± 0.00015	0.01628 ± 0.00015	0.8	
$\mathcal{A}_\ell$ (SLD)	[14]	0.1513 ± 0.0021	0.14748 ± 0.00068	0.14765 ± 0.00076	1.7	
$\mathcal{A}_c$	[14]	0.670 ± 0.027	0.66810 ± 0.00030	0.66817 ± 0.00033	0.02	
$\mathcal{A}_b$	[14]	0.923 ± 0.020	0.934650 ± 0.000058	0.934663 ± 0.000064	-0.6	
$A_{\rm FB}^{0,c}$	[14]	0.0707 ± 0.0035	0.07390 ± 0.00037	0.07399 ± 0.00042	-0.9	1.5
$A_{\rm FB}^{0,b}$	[14]	0.0992 ± 0.0016	0.10338 ± 0.00048	0.10350 ± 0.00054	-2.6	
R_c^0	[14]	0.1721 ± 0.0030	0.172228 ± 0.000023	0.172229 ± 0.000023	-0.05	
R_b^0	[14]	0.21629 ± 0.00066	0.215790 ± 0.000028	0.215788 ± 0.000028	0.7	
$\sin^2\theta_{\rm eff}^{ee}$	[19]	0.23248 ± 0.00052			2.1	
$\sin^2\theta_{\rm eff}^{\mu\mu}$	[20]	0.2315 ± 0.0010			0.07	
$\sin^2\theta_{\rm eff}^{ee}$	[21]	0.23146 ± 0.00047			0.1	
$\sin^2\theta_{\rm eff}^{ee,\mu\mu}$	[22]	0.2308 ± 0.0012	0.231464 ± 0.000087	0.231435 ± 0.000090	-0.5	
$\sin^2\theta_{\rm eff}^{\mu\mu}$	[23]	0.2287 ± 0.0032			-0.8	
$\sin^2\theta_{\rm eff}^{\mu\mu}$	[24]	0.2314 ± 0.0011			-0.1	

2016 PDG average for $\alpha_s(M_Z)$ has doubled the error due to unweighted average of Lattice results; FLAG gives same error but based on estimate of truncation of perturbative series.

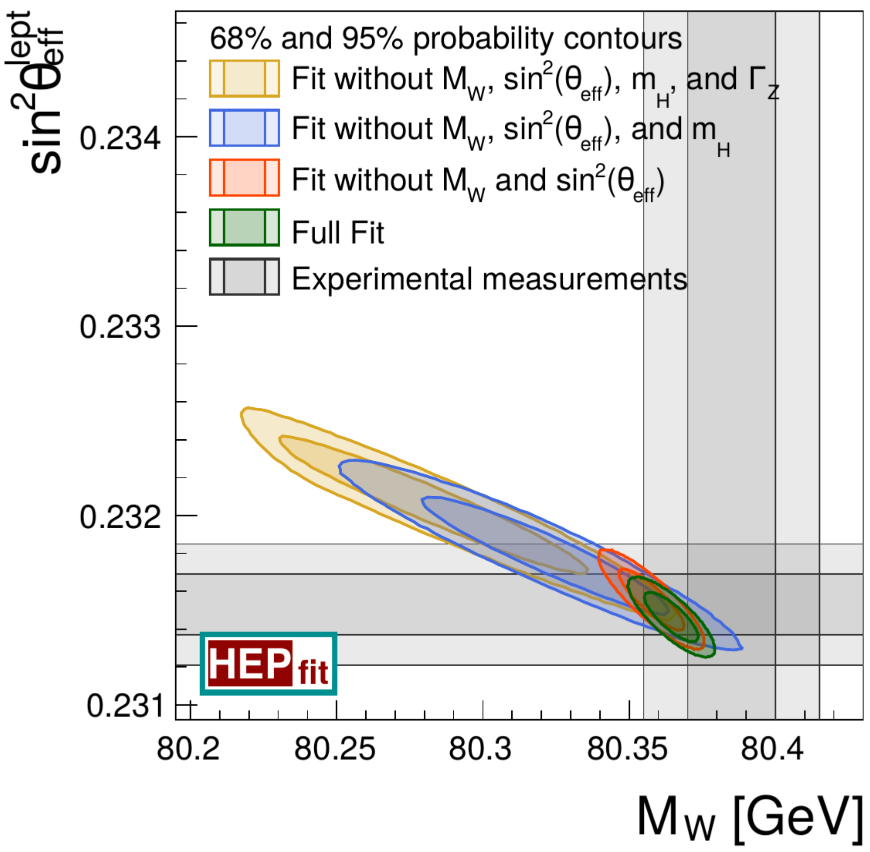
	Prediction	α_s	$\Delta\alpha^{(5)}_{\rm had}$	M_Z	m_t
M_W [GeV]	80.3618 ± 0.0080	± 0.0008	± 0.0060	± 0.0026	± 0.0046
Γ_W [GeV]	2.08849 ± 0.00079	± 0.00048	± 0.00047	± 0.00021	± 0.00036
Γ_Z [GeV]	2.49403 ± 0.00073	± 0.00059	± 0.00031	± 0.00021	± 0.00017
σ_h^0 [nb]	41.4910 ± 0.0062	± 0.0059	± 0.0005	± 0.0020	± 0.0005
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.23148 ± 0.00012	± 0.00000	± 0.00012	± 0.00002	± 0.00002
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	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
$A_{\rm FB}^{0,\ell}$	0.01627 ± 0.00021	± 0.00001	± 0.00020	± 0.00003	± 0.00004
$A_{\rm FB}^{0,c}$	0.07381 ± 0.00052	± 0.00002	± 0.00050	± 0.00007	± 0.00010
$A_{\rm FB}^{0,b}$	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

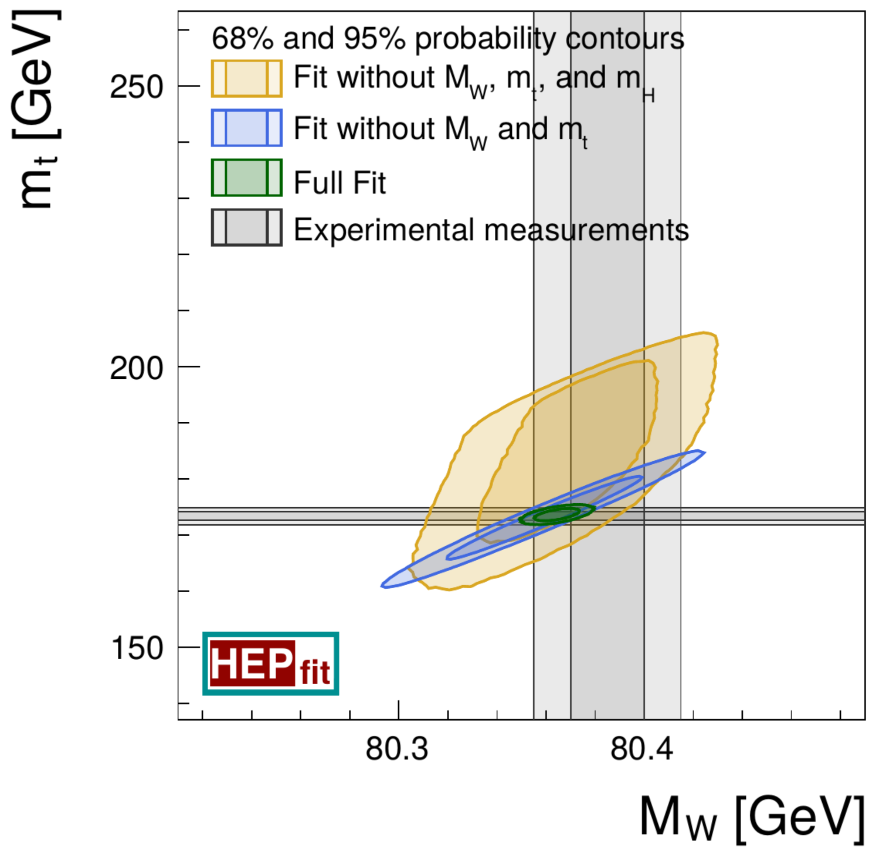
Parametric error budget for theoretical predictions (no fit)



Excellent agreement between full, direct and indirect determinations of input parameters

IMPACT OF m_H, m_t, M_W, $\sin^2\theta$ & Γ_Z



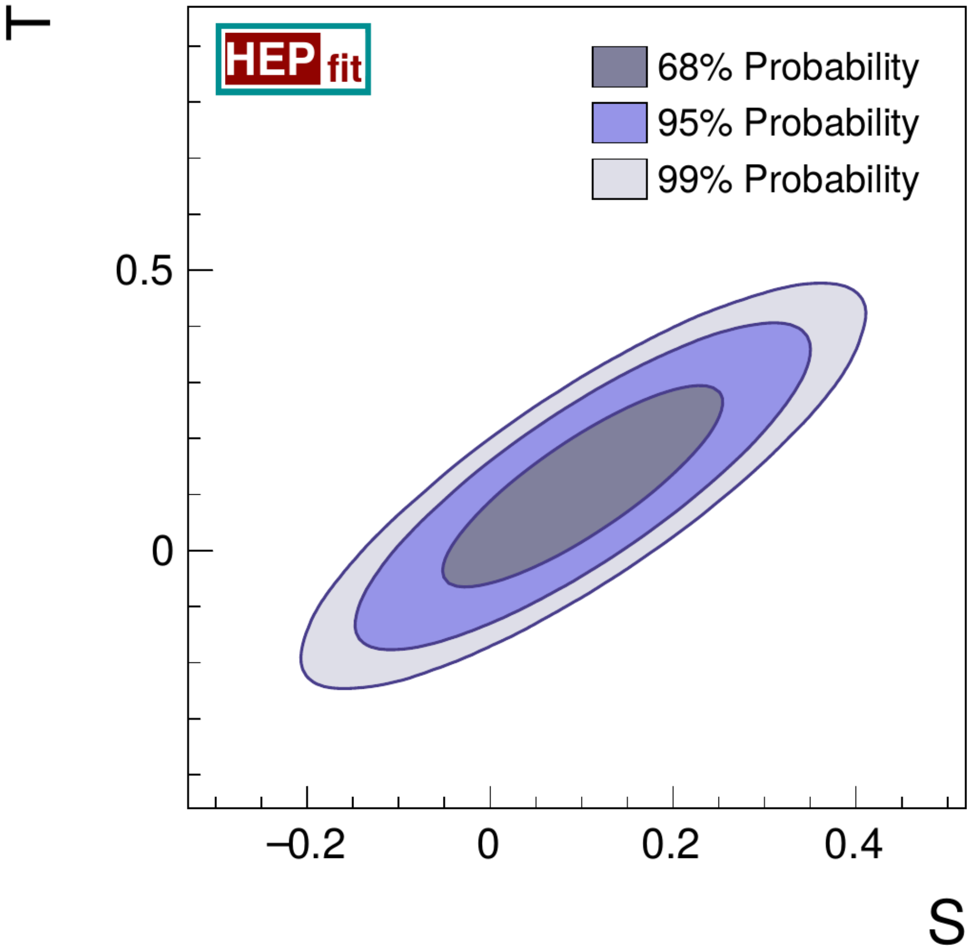


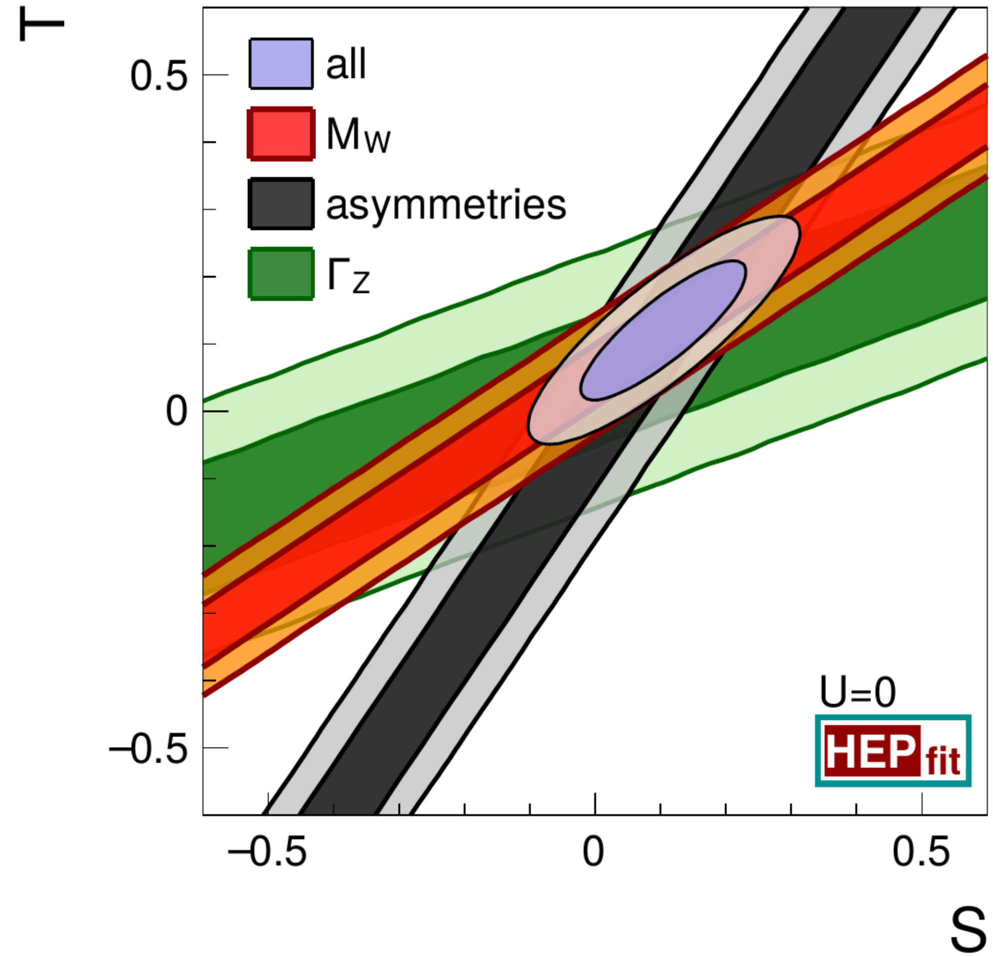
EW FIT BEYOND THE SM

- Oblique corrections
  - S, T, U; $\delta\varepsilon_{1,2,3}$
- Modified Zbb couplings
  - $\delta g^b_{L,R}$; $\delta\varepsilon_b$
- Modified Higgs couplings
  - $\kappa_{V,f}$
- Effective theory with D=6
  - C_i

OBLIQUE CORRECTIONS

- Parameterize dominant NP effects in gauge-boson vacuum polarization:
  - S,T,U [Peskin & Takeuchi '90,'92]
  - $\varepsilon_{1,2,3} \to \delta\varepsilon_{1,2,3}$ now that m_t and m_H are known precisely [Altarelli & Barbieri '91; + Jadach '92; + Caravaglios '93]
- $U \ll S,T$ ($\delta\varepsilon_2 \ll \delta\varepsilon_{1,3}$) in many NP models (linearly realized EWSB)



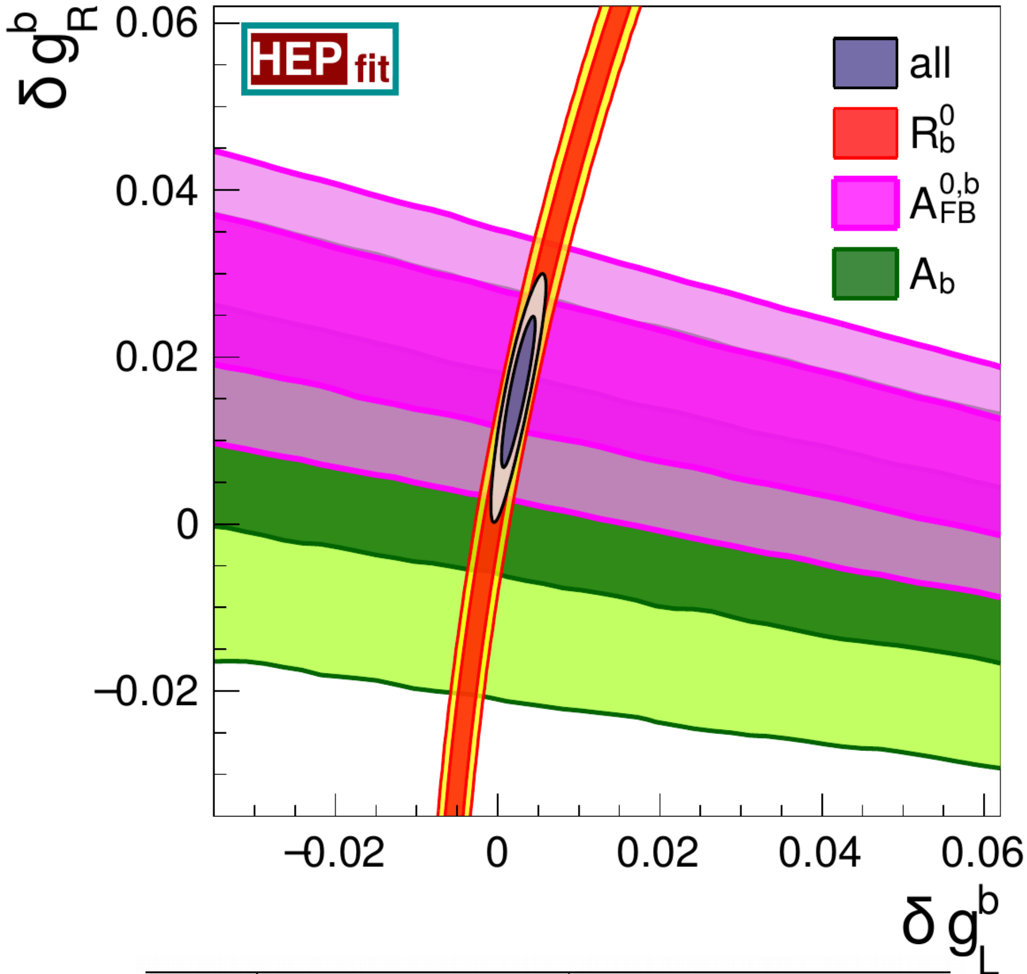


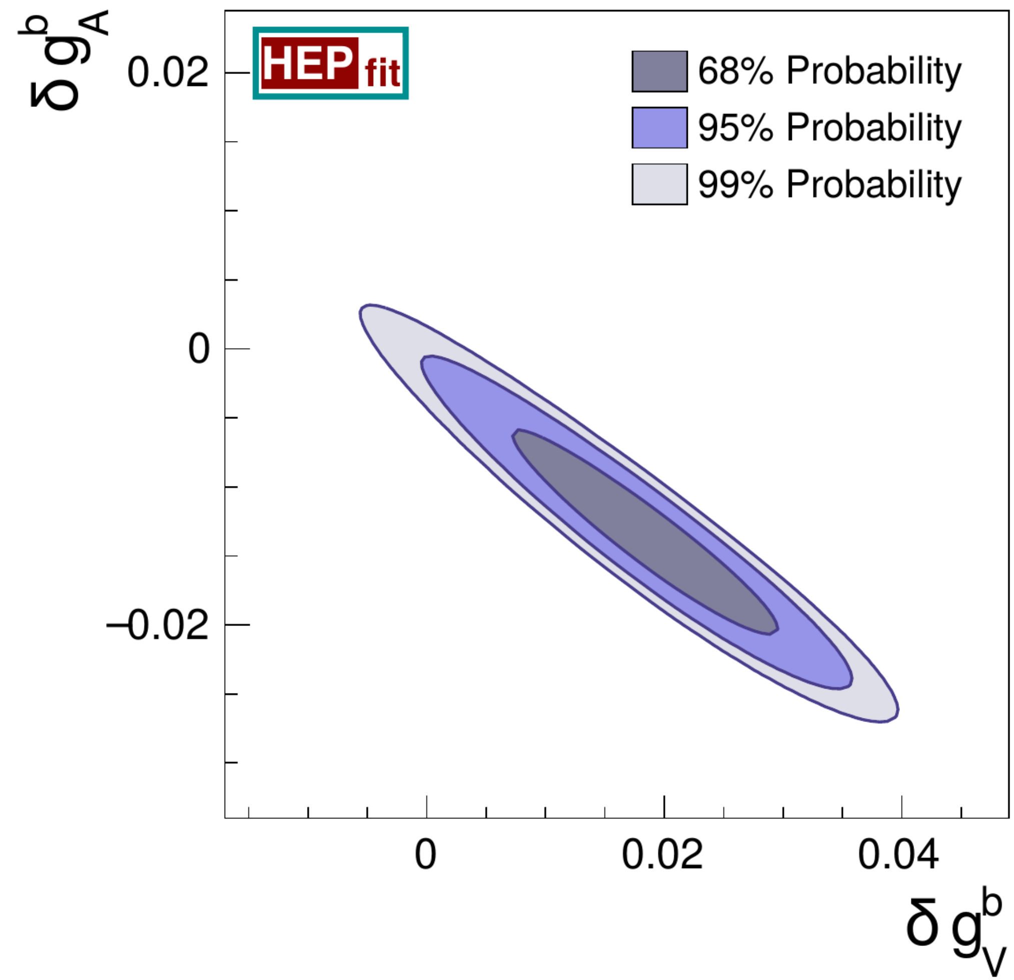
	Result	Correlation Matrix		
S	0.09 ± 0.10	1.00		
T	0.10 ± 0.12	0.86	1.00	
U	0.01 ± 0.09	−0.54	−0.81	1.00

	Result	Correlation Matrix	
S	0.10 ± 0.08	1.00	
T	0.12 ± 0.07	0.86	1.00

	Result	Correlation Matrix			
$\delta\varepsilon_1$	0.0007 ± 0.0010	1.00			
$\delta\varepsilon_2$	-0.0002 ± 0.0008	0.82	1.00		
$\delta\varepsilon_3$	0.0007 ± 0.0009	0.87	0.56	1.00	
$\delta\varepsilon_b$	0.0004 ± 0.0013	−0.34	−0.32	−0.24	1.00

Modified Zbb couplings

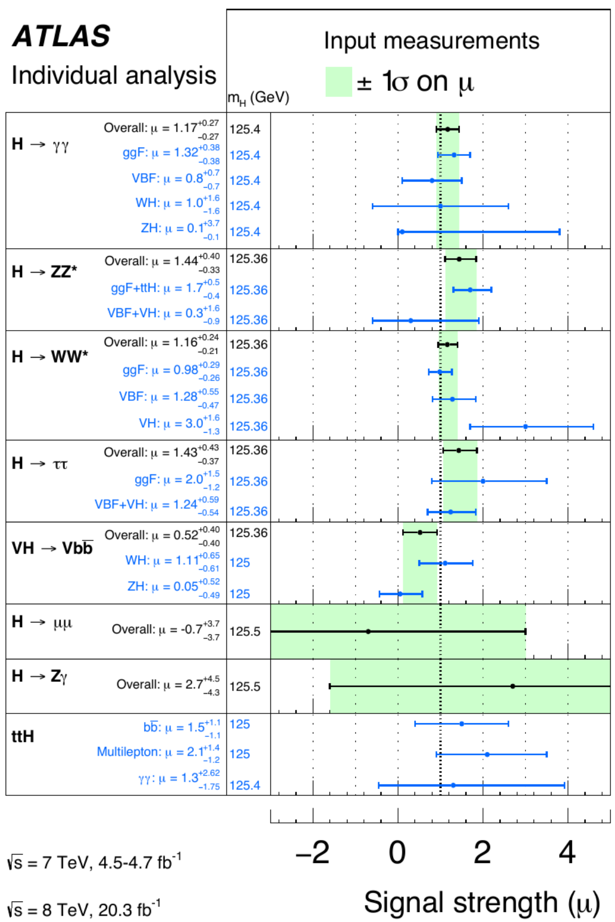




	Result	Correlation Matrix	
δg_R^b	0.016 ± 0.006	1.00	
δg_L^b	0.002 ± 0.001	0.90	1.00
δg_V^b	0.018 ± 0.007	1.00	
δg_A^b	-0.013 ± 0.005	-0.98	1.00

	Result	Correlation Matrix			
S	0.04 ± 0.09	1.00			
T	0.08 ± 0.07	0.86	1.00		
δg_L^b	0.003 ± 0.001	-0.24	-0.15	1.00	
δg_R^b	0.017 ± 0.008	-0.29	-0.22	0.91	1.00

Higgs Couplings Analysis



ATLAS: arXiv:1507.04548

$\mu = \sum_i w_i r_i$ where

$$w_i = \frac{[\sigma\times\mathrm{Br}]_i}{[\sigma_{\mathrm{SM}}\times\mathrm{Br}_{\mathrm{SM}}]_i}$$

$$r_i = \frac{\epsilon_i[\sigma_{\mathrm{SM}}\times\mathrm{Br}_{\mathrm{SM}}]_i}{\sum_j \epsilon_j^{\mathrm{SM}}[\sigma_{\mathrm{SM}}\times\mathrm{Br}_{\mathrm{SM}}]_j}$$

$$\sigma_i = \sigma_i^{\mathrm{SM}} + \delta\sigma_i$$

$$\Gamma_j = \Gamma_j^{\mathrm{SM}} + \delta\Gamma_j$$

$\sigma_i^{\mathrm{SM}}, \Gamma_j^{\mathrm{SM}} \to$ YR of HXSWG

$\delta\sigma_i \to$ FR+Madgraph+Kfactors

$\delta\Gamma_j \to$ eHdecay

$h\gamma\gamma$: ATLAS(1408.7084), CMS(1407.0558)

$h\tau\tau$: ATLAS(1501.04943), CMS(1401.5041)

hZZ: ATLAS(1408.5191), CMS(1412.8662)

hWW: ATLAS(1412.2641,1506.06641), CMS(1312.1129)

hbb: ATLAS(1409.6212, 1503.05066), CMS(1310.3687, 1408.1682), CDF (1301.6668), D0 (1303.0823)

Non-standard Higgs boson couplings

- Minimal assumptions (inspired by strong-dynamics EWSB models):
  - only one Higgs boson below the cutoff Λ
  - custodial symmetry approximately realized
  - NP corrections flavour-diagonal and universal

$$\mathcal{L}_{\rm eff} = \frac{v^2}{4}{\rm tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2\kappa_V \frac{H}{v} + \cdots\right) - m_i \bar{f}^i_L \left(1 + 2\kappa_f \frac{H}{v} + \cdots\right) f^i_R + \cdots,$$

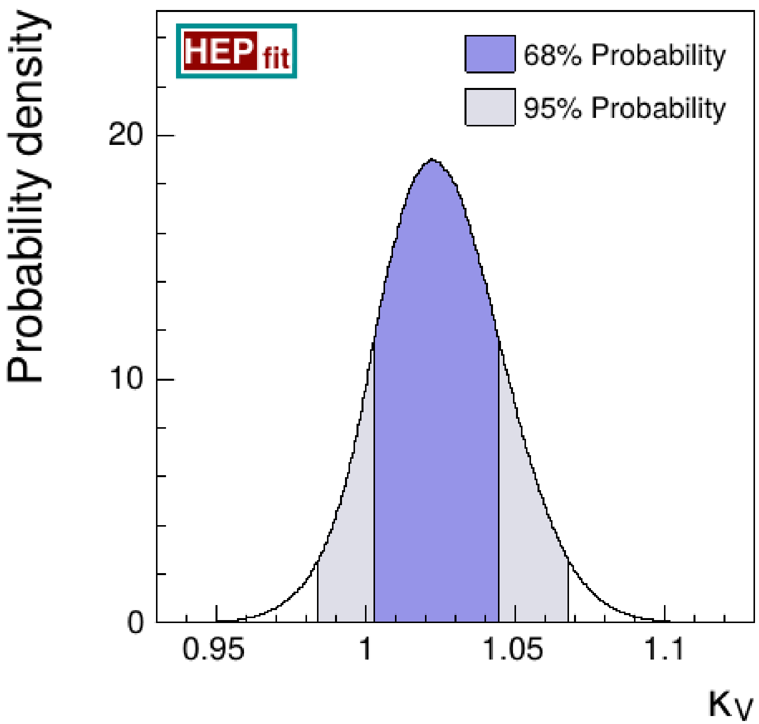
  where $\Sigma(x) = \exp i\sigma^a \chi^a(x)/v$ → W/Z longitudinal pol
  - SM given by $\kappa_V, \kappa_f \to 1$

κ_V ONLY

$$S = \frac{1}{12\pi}(1-\kappa_V^2)\ln\left(\frac{\Lambda^2}{m_H^2}\right), \qquad T = -\frac{3}{16\pi c_W^2}(1-\kappa_V^2)\ln\left(\frac{\Lambda^2}{m_H^2}\right),$$

[Barbieri et al., PRD 76 (2007) 115008

- set cutoff Λ to scale of perturbative unitarity violation: $\Lambda = 4\pi v/\sqrt{|1-\kappa_V^2|}$

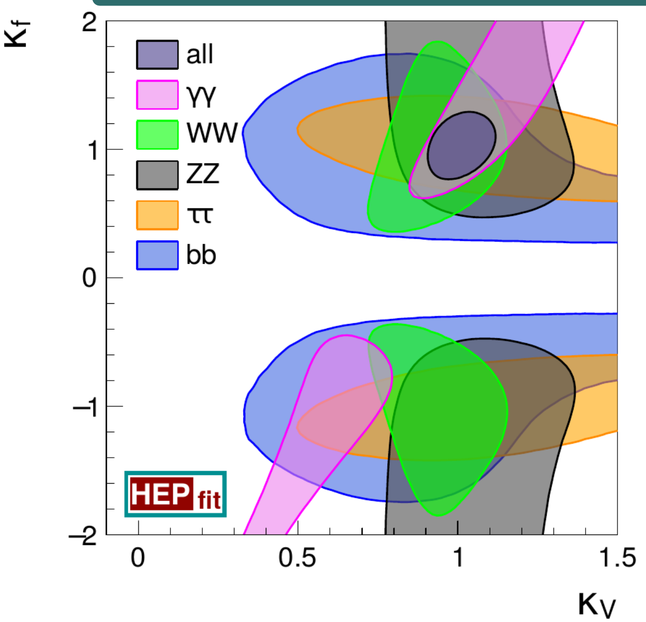


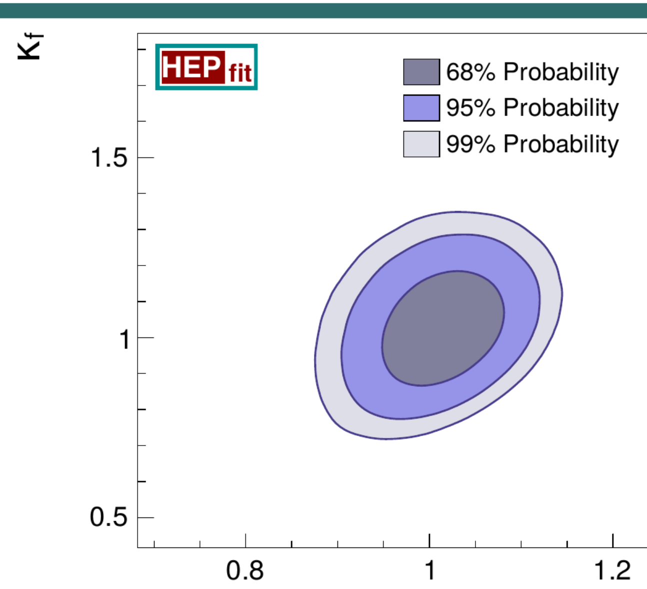
	Result	95% Prob.
κ_V	1.02 ± 0.02	[0.98, 1.07]

κ_V < 1 predicted in composite Higgs models disfavoured ⇒ need additional contributions

[Grojean et al; Azatov et al; Pich et al]

κ_V and κ_f



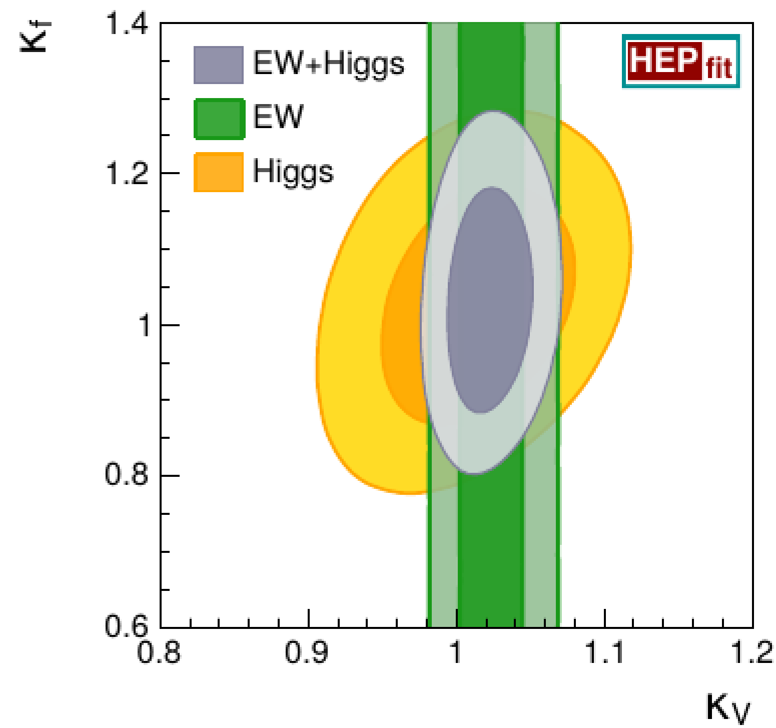


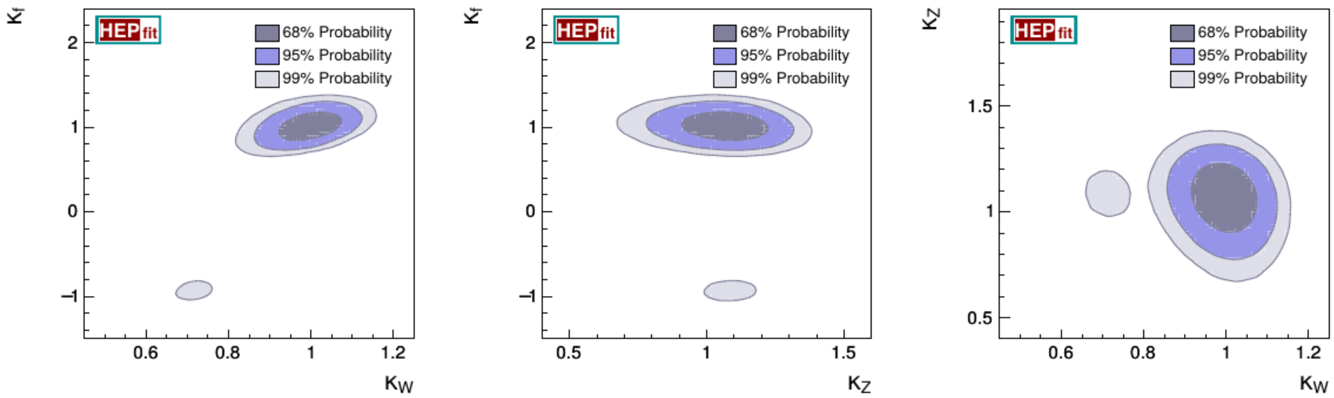
Higgs data only

	Result	95% Prob.	Correlation Matrix	
κ_V	1.01 ± 0.04	$[0.93, 1.10]$	1.00	
κ_f	1.03 ± 0.10	$[0.83, 1.23]$	0.31	1.00

Higgs + EWPO

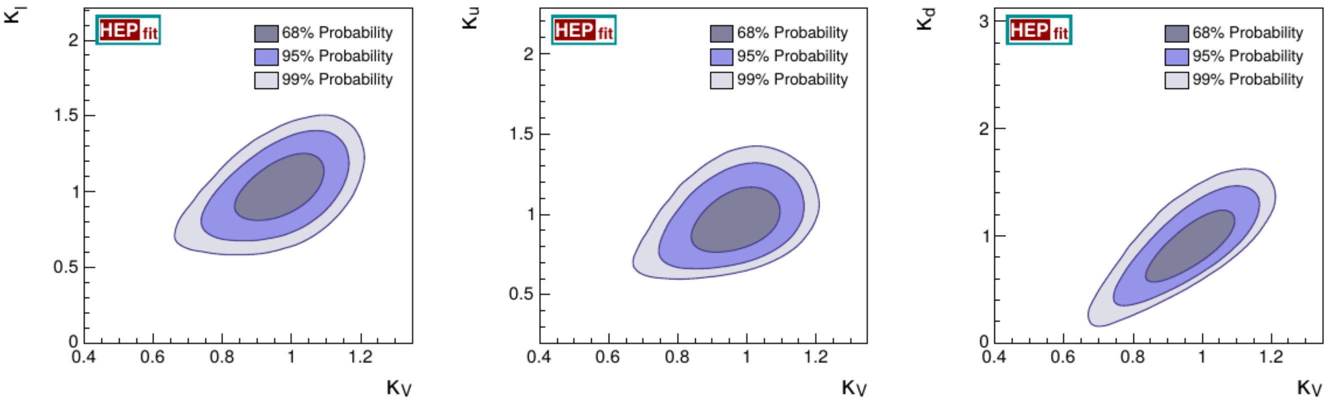
	Result	95% Prob.	Correlation Matrix	
κ_V	1.02 ± 0.02	$[0.99, 1.06]$	1.00	
κ_f	1.03 ± 0.10	$[0.85, 1.23]$	0.14	1.00





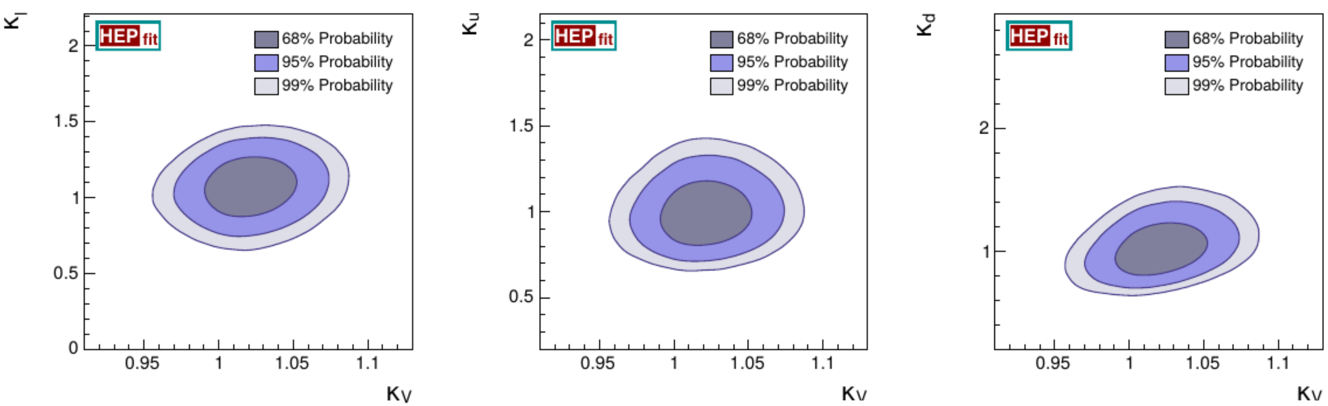
Higgs data only

	Result	95% Prob.	Correlation Matrix		
κ_W	1.00 ± 0.05	$[0.89, 1.10]$	1.00		
κ_Z	1.07 ± 0.11	$[0.85, 1.27]$	-0.17	1.00	
κ_f	1.01 ± 0.11	$[0.80, 1.22]$	0.41	-0.14	1.00



Higgs data only

	Result	95% Prob.	Correlation Matrix			
κ_V	0.97 ± 0.08	$[0.80, 1.13]$	1.00			
κ_ℓ	1.01 ± 0.14	$[0.73, 1.30]$	0.54	1.00		
κ_u	0.97 ± 0.13	$[0.73, 1.25]$	0.42	0.41	1.00	
κ_d	0.91 ± 0.21	$[0.48, 1.35]$	0.81	0.61	0.77	1.00



Higgs + EWPO

	Result	95% Prob.	Correlation Matrix			
κ_V	1.02 ± 0.02	$[0.98, 1.06]$	1.00			
κ_ℓ	1.07 ± 0.12	$[0.82, 1.32]$	0.15	1.00		
κ_u	1.01 ± 0.12	$[0.79, 1.27]$	0.10	0.24	1.00	
κ_d	1.01 ± 0.13	$[0.76, 1.30]$	0.31	0.38	0.78	1.00

	Result	95% Prob.	Correlation Matrix				
κ_W	0.94 ± 0.10	$[0.73, 1.13]$	1.00				
κ_Z	1.03 ± 0.13	$[0.77, 1.28]$	0.34	1.00			
κ_ℓ	1.02 ± 0.15	$[0.73, 1.33]$	0.55	0.22	1.00		
κ_u	0.95 ± 0.13	$[-0.96, -0.72] \cup [0.68, 1.28]$	0.49	0.04	0.44	1.00	
κ_d	0.91 ± 0.22	$[0.46, 1.36]$	0.81	0.36	0.62	0.78	1.00

Higgs data only

The SM as an effective theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d, \quad \text{with} \quad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i, \quad [\mathcal{O}_i] = d\,,$$

- d=6 only, one Higgs doublet, SU(2)xU(1), B, L
- with flavour universality/conservation, 59 operators (we use GIMR basis) [Grzadkowski et al.]
- contributing to EWPO + μ_i : 18 operators
- take C_i at EW scale, no running included

[See also Corbett et al, Ellis et al, Falkowski & Riva, ...]

One operator at a time - **Preliminary**

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]		
		Only EW	Only Higgs	EW + Higgs
$\mathcal{O}_{HG}$	$(H^\dagger H)\, G^A_{\mu\nu} G^{A\,\mu\nu}$	—	$[-0.005, 0.009]$	$[-0.005, 0.009]$
$\mathcal{O}_{HW}$	$(H^\dagger H)\, W^a_{\mu\nu} W^{a\,\mu\nu}$	—	$[-0.033, 0.015]$	$[-0.033, 0.015]$
$\mathcal{O}_{HB}$	$(H^\dagger H)\, B_{\mu\nu} B^{\mu\nu}$	—	$[-0.009, 0.004]$	$[-0.009, 0.004]$
$\mathcal{O}_{HWB}$	$(H^\dagger \sigma_a H)\, W^a_{\mu\nu} B^{\mu\nu}$	$[-0.010,\ 0.004]$	$[-0.008, 0.017]$	$[-0.007, 0.005]$
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H \right\rvert^2$	$[-0.032,\ 0.006]$	$[-1.38, 1.35]$	$[-0.032, 0.005]$
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\, \Box\, (H^\dagger H)$	—	$[-1.12, 1.72]$	$[-1.12, 1.72]$
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\, (\overline{l_L} \gamma^\mu l_L)$	$[-0.006,\ 0.011]$	—	$[-0.006,\ 0.011]$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)\, (\overline{l_L} \gamma^\mu \sigma_a l_L)$	$[-0.013,\ 0.006]$	$[-0.64, 0.49]$	$[-0.013, 0.006]$
$\mathcal{O}_{He}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\, (\overline{e_R} \gamma^\mu e_R)$	$[-0.017,\ 0.006]$	—	$[-0.017,\ 0.006]$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\, (\overline{q_L} \gamma^\mu q_L)$	$[-0.025,\ 0.046]$	$[-4.3, 1.3]$	$[-0.026, 0.046]$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)\, (\overline{q_L} \gamma^\mu \sigma_a q_L)$	$[-0.011,\ 0.016]$	$[-0.35, 0.18]$	$[-0.011, 0.015]$
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\, (\overline{u_R} \gamma^\mu u_R)$	$[-0.069,\ 0.088]$	$[-1.9, 2.2]$	$[-0.068, 0.088]$
$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\, (\overline{d_R} \gamma^\mu d_R)$	$[-0.16,\ 0.058]$	$[-6.2, 7]$	$[-0.160, 0.055]$
$\mathcal{O}_{eH}$	$(H^\dagger H)\, (\overline{l_L} H e_R)$	—	$[-0.053, 0.027]$	$[-0.053, 0.027]$
$\mathcal{O}_{uH}$	$(H^\dagger H)\, \left(\overline{q_L} \tilde{H} u_R\right)$	—	$[-0.350, 0.510]$	$[-0.350, 0.510]$
$\mathcal{O}_{dH}$	$(H^\dagger H)\, (\overline{q_L} H d_R)$	—	$[-0.036, 0.086]$	$[-0.036, 0.086]$
$\mathcal{O}_{ll}$	$(\bar{l} \gamma_\mu l)(\bar{l} \gamma^\mu l)$	$[-0.010,\ 0.023]$	$[-0.970, 1.26]$	$[-0.010, 0.022]$

One operator at a time – Preliminary

	Operator	95% prob. bound on Λ [TeV] Only EW $\lvert C_i\rvert = 1$	Only Higgs $\lvert C_i\rvert = 1$	EW + Higgs $\lvert C_i\rvert = 1$
$\mathcal{O}_{HG}$	$(H^\dagger H)\, G^A_{\mu\nu} G^{A\,\mu\nu}$	—	12	12
$\mathcal{O}_{HW}$	$(H^\dagger H)\, W^a_{\mu\nu} W^{a\,\mu\nu}$	—	5.9	5.9
$\mathcal{O}_{HB}$	$(H^\dagger H)\, B_{\mu\nu} B^{\mu\nu}$	—	12	12
$\mathcal{O}_{HWB}$	$(H^\dagger \sigma_a H)\, W^a_{\mu\nu} B^{\mu\nu}$	11	8.2	12
$\mathcal{O}_{HD}$	$\lvert H^\dagger D_\mu H\rvert^2$	5.9	0.9	6.0
$\mathcal{O}_{H\Box}$	$(H^\dagger H) \Box (H^\dagger H)$	—	0.8	0.8
$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	10	—	10
$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	9.4	1.3	9.7
$\mathcal{O}_{He}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$	8.2	—	8.2
$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	5.0	0.5	5.0
$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	8.6	1.8	8.7
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	3.5	0.7	3.5
$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	2.7	0.4	2.6
$\mathcal{O}_{eH}$	$(H^\dagger H)(\overline{l_L} H e_R)$	—	4.7	4.7
$\mathcal{O}_{uH}$	$(H^\dagger H)(\overline{q_L} \tilde{H} u_R)$	—	1.5	1.5
$\mathcal{O}_{dH}$	$(H^\dagger H)(\overline{q_L} H d_R)$	—	3.7	3.7
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	7.1	0.9	7.1

Future Prospects: data sets

FCCee	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]	88	15	3.5	1.0	1.0
Years of operation	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	10^8	2×10^6	2.1×10^5	7.5×10^4

[Talk by P. Azzi @ 2016 FCC week]

ILC	Phase 1			Phase 2 (Luminosity upgrade)		
$\sqrt{s}$ [GeV]	250	500	1000	250	500	100
$\int \mathcal{L}\, dt$ [ab^{-1}]	0.25	0.5	1	1.15	1.6	2.5
$\int dt$ (10^7 s)	3	3	3	3	3	3

[S. Dawson et al., 1310.8361]

plus CepC: 10^6 H @ 240 GeV + 10^{11} Z @ M_Z

[CepC-SPPC preliminary CDR, 2015]

Future Prospects: EWPO

	Current Data	HL-LHC	ILC	FCCee	(Run)	CepC
$\alpha_s(M_Z)$	0.1179 ± 0.0012					
$\Delta\alpha^{(5)}_{\text{had}}(M_Z)$	0.02750 ± 0.00033					
M_Z [GeV]	91.1875 ± 0.0021			± 0.0001	(FCCee-Z)	± 0.0005
m_t [GeV]	173.34 ± 0.76	± 0.6	± 0.017	± 0.014	(FCCee-$t\bar{t}$)	
m_H [GeV]	125.09 ± 0.24	± 0.05	± 0.015	± 0.007	(FCCee-HZ)	± 0.0059
M_W [GeV]	80.385 ± 0.015	± 0.011	± 0.0024	± 0.001	(FCCee-WW)	± 0.003
Γ_W [GeV]	2.085 ± 0.042			± 0.005	(FCCee-WW)	
Γ_Z [GeV]	2.4952 ± 0.0023			± 0.0001	(FCCee-Z)	± 0.0005
σ^0_h [nb]	41.540 ± 0.037			± 0.025	(FCCee-Z)	
$\sin^2\theta^{\text{lept}}_{\text{eff}}$	0.2324 ± 0.0012			± 0.0001	(FCCee-Z)	± 0.000023
P^{pol}_τ	0.1465 ± 0.0033			± 0.0002	(FCCee-Z)	
$\mathcal{A}_\ell$	0.1513 ± 0.0021			± 0.000021	(FCCee-Z [pol])	
$\mathcal{A}_c$	0.670 ± 0.027			± 0.01	(FCCee-Z [pol])	
$\mathcal{A}_b$	0.923 ± 0.020			± 0.007	(FCCee-Z [pol])	
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010			± 0.0001	(FCCee-Z)	± 0.0010
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035			± 0.0003	(FCCee-Z)	
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016			± 0.0001	(FCCee-Z)	± 0.00014
R^0_ℓ	20.767 ± 0.025			± 0.001	(FCCee-Z)	± 0.007
R^0_c	0.1721 ± 0.0030			± 0.0003	(FCCee-Z)	
R^0_b	0.21629 ± 0.00066			± 0.00006	(FCCee-Z)	± 0.00018

Future Prospects: Higgs + Th

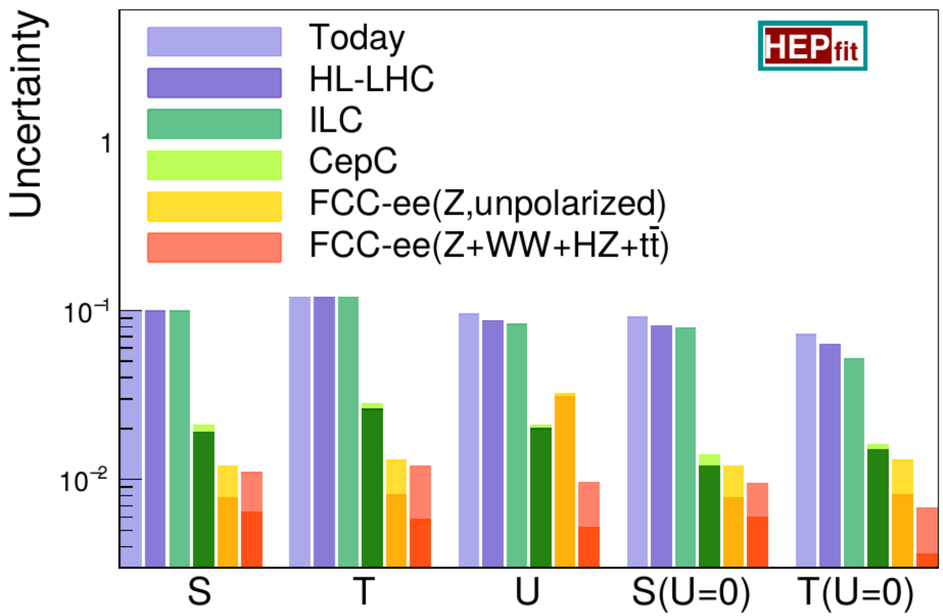
	Current	HL-LHC	ILC						FCCee	CepC
			Phase 1			Phase 2				
			250	500	1000	250	500	1000		
$H \to b\bar{b}$	$\gtrsim 23\%$	5-36%	1.2%	1.8-28%	0.3-6%	0.56%	0.37-16%	0.3-3.8%	0.2-0.6%	0.28%
$H \to c\bar{c}$			8.3%	6.2-13%	3.1%	3.9%	3.5-7.2%	2%	1.2%	2.2%
$H \to gg$			7%	4.1-11%	2.3%	3.3%	2.3-6%	1.4%	1.4%	1.6%
$H \to WW$	$\gtrsim 15\%$	4-11%	6.4%	2.4-9.2%	1.6%	3%	1.3-5.1%	1%	0.9%	1.5%
$H \to \tau\tau$	$\gtrsim 25\%$	5-15%	4.2%	5.4-9%	3.1%	2%	3-5%	2%	0.7%	1.2%
$H \to ZZ$	$\gtrsim 24\%$	4-17%	19%	8.2-25%	4.1%	8.8%	4.6-14%	2.6%	3.1%	4.3%
$H \to \gamma\gamma$	$\gtrsim 20\%$	4-28%	38%	20-38%	7%	16%	13-19%	5.4%	3.0%	9%
$H \to Z\gamma$		10-27%								
$H \to \mu\mu$		14-23%			31%			20%	13%	17%

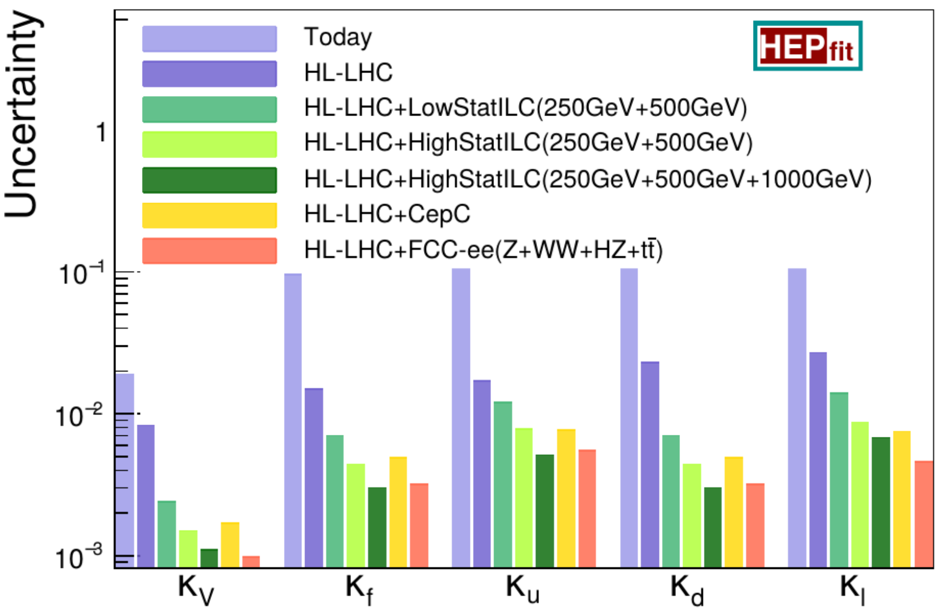
Observable	Current Th. Error	Future Th. Error	Current Exp. Error	ILC	FCC-ee	CepC
M_W [MeV]	4	1	15	$3-4$	1	3
$\sin^2\theta_{\rm eff}^{\rm lept}$ $[10^{-5}]$	4.5	1.5	16		0.6	2.3
Γ_Z [MeV]	0.5	0.2	2.3		0.1	0.5
R_b^0 $[10^{-5}]$	15	10	66		6	17

[Freitas et al., 1307.3962; A. Freitas, 1406.6980, 1604.00406]

+ $\delta\Delta\alpha^{(5)}_{had}$ = 5 10^{-5} from R; $\delta\alpha_s(M_Z)$ = 2 10^{-4} from LQCD

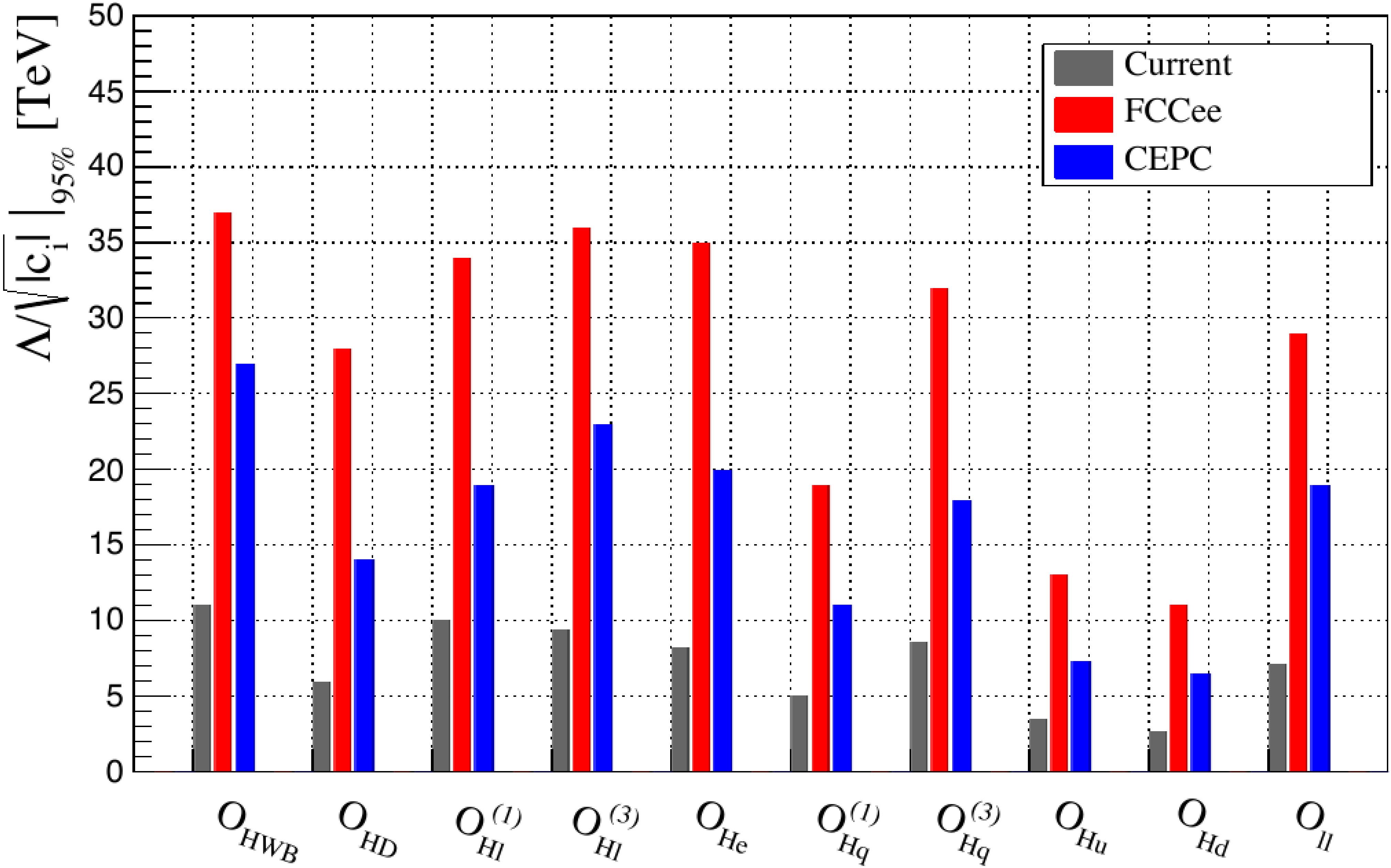
Future Prospects: NP analyses



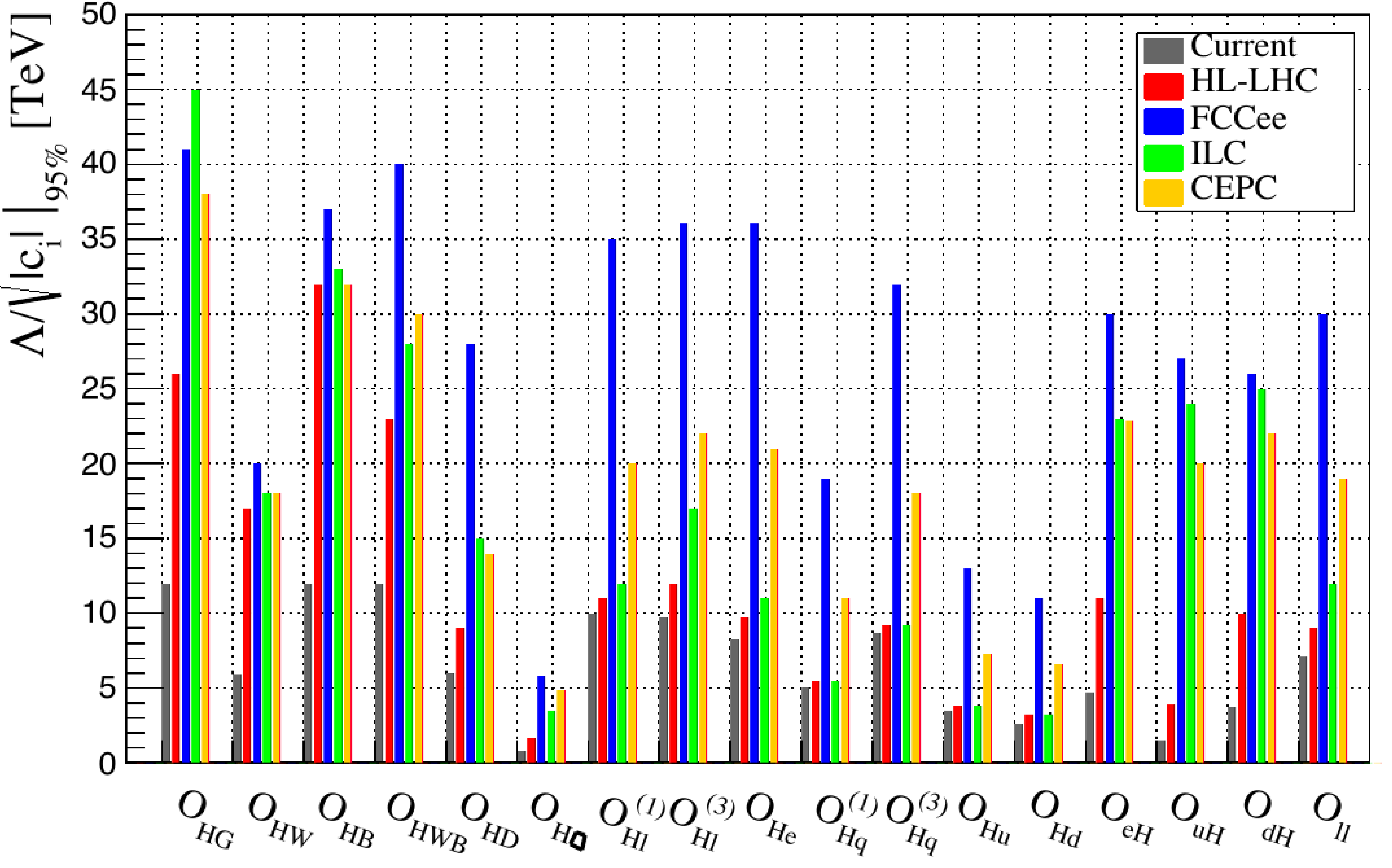


Lighter: incl. th. error;
darker: no theory error

Future Prospects: Λ from EWPO



Future Prospects: Λ from EWPO, μ_i



Conclusions

- Remarkable experimental progress on EWSB with measurements of m_H & μ_i
- Combined with EWPO: high sensitivity to NP, currently probing scales up to 12 TeV
- Impressive progress foreseen with future facilities will allow us to challenge further the SM and hopefully see some NP effect, with order-of-magnitude improvements in the sensitivity to NP