EW fits @ HL-LHC

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HEPfit

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EW PHYSICS IN THE (HL-)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

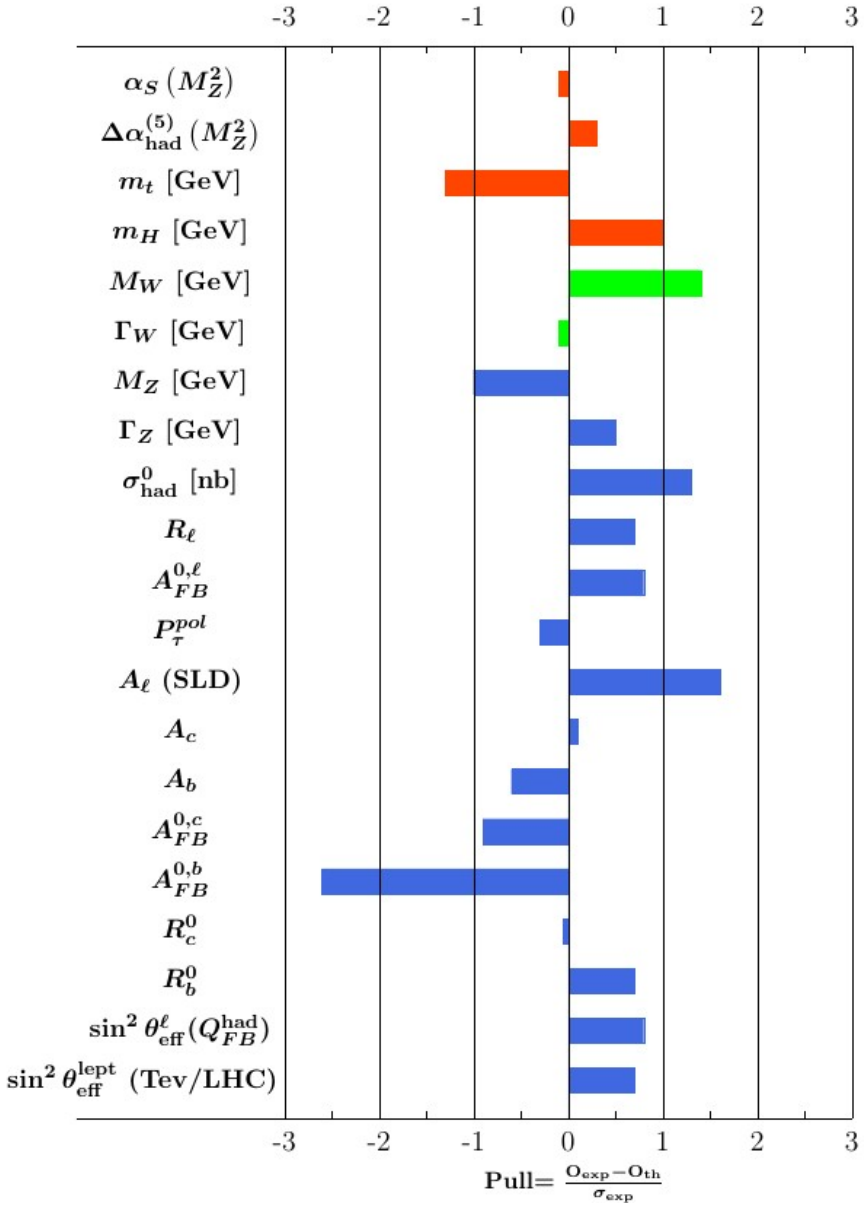
EWPO FIT

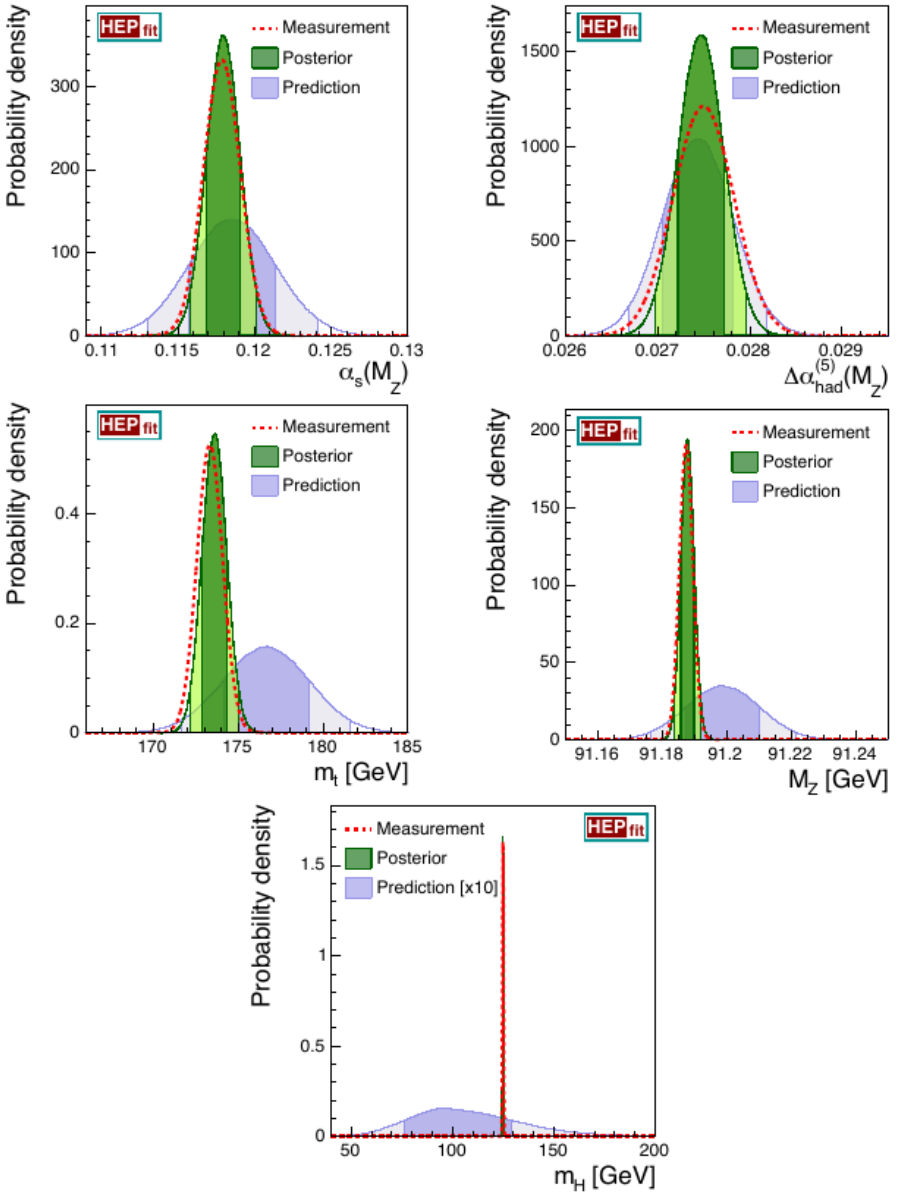
- SM input parameters:
  - G_F, α, M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}^{(5)}$
- state-of-the-art computation of EWPO
- parametrize possible NP effects (modified couplings, additional loop contributions, D=6 operators)
- perform a fit to experimental data
  - GAPP (Erler)
  - ZFITTER (Akhundov, Arbuzov, S. & T. Riemann)
  - Gfitter
  - us, using the HEPfit public code available from http://hepfit.roma1.infn.it

EW & HIGGS FITS WITH HEPfit

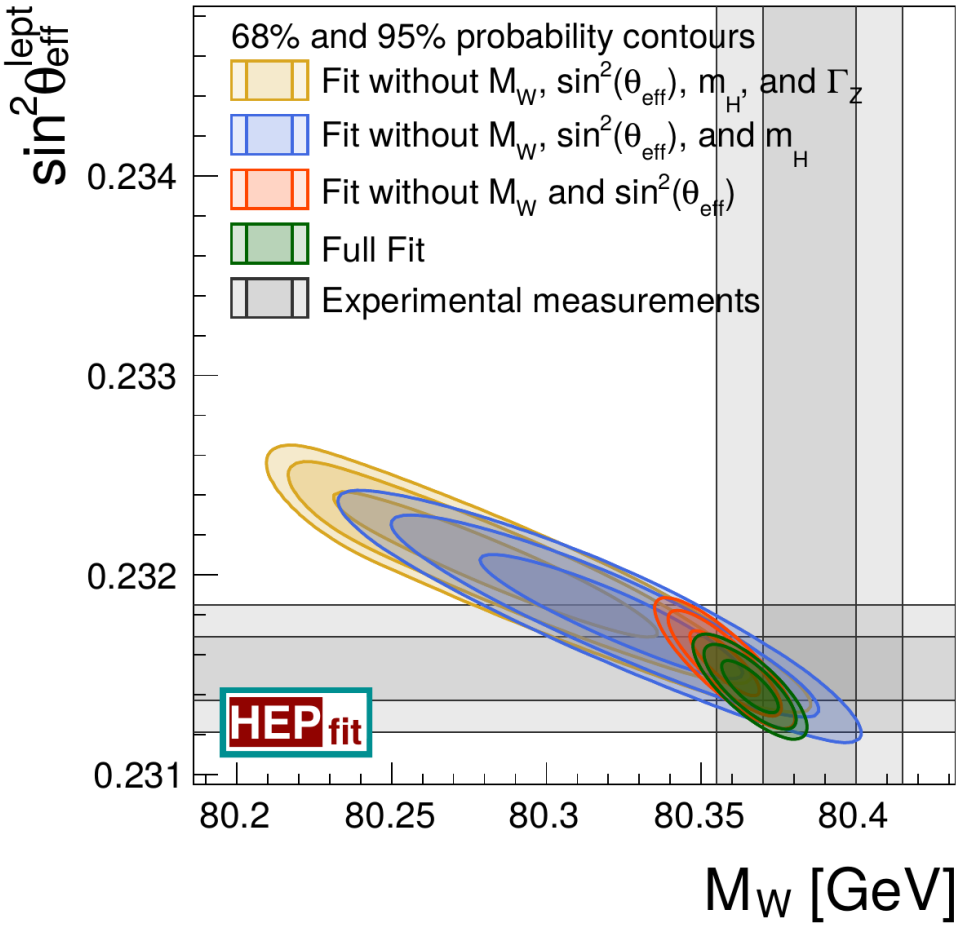
- Both electroweak and Higgs observables are calculated as a SM core plus corrections:
  - the SM core includes all existing higher order corrections
  - NP corrections are at the lowest order in all SM couplings
  - Higgs observables from Madgraph w. our UFO + eHdecay
- Experimental results are taken 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, LUV in $b \to s$ transitions
  - Implemented observables:
    - EWPO, Higgs signal strengths, Flavour ($\Delta F = 2$, UT, rare B decays)

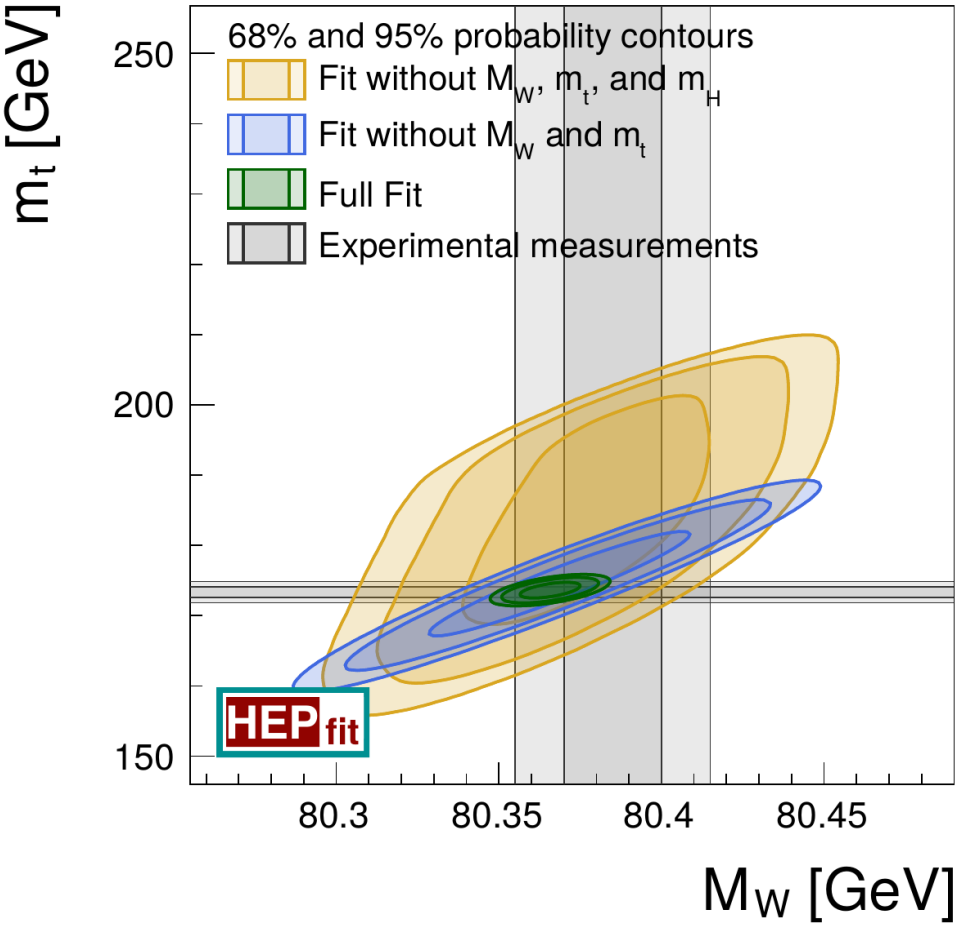
CURRENT SM FIT RESULTS





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



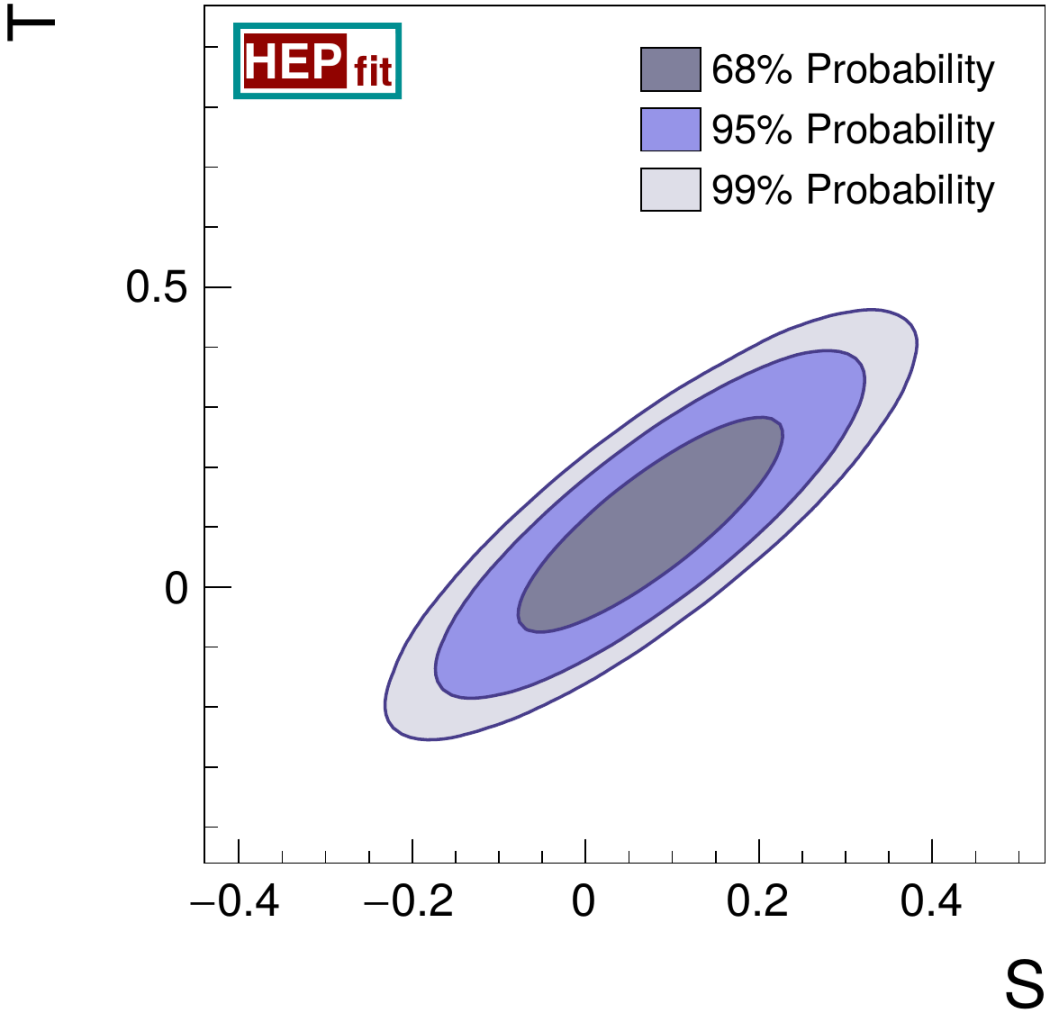


EW FIT BEYOND THE SM

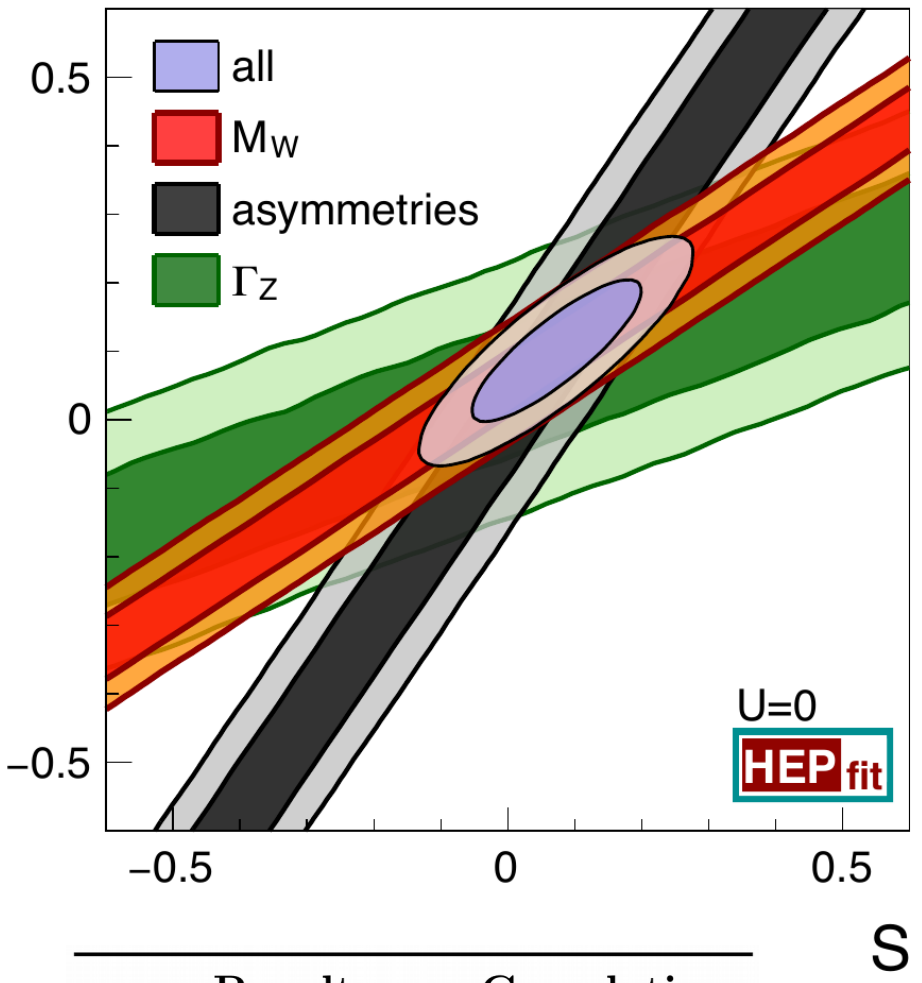
- Oblique corrections
  - S, T, U; $\delta\varepsilon_{1,2,3,b}$
- Modified Zbb couplings – see backup
- Modified Higgs couplings
  - $\kappa_{V,f}$
- Effective theory with D=6
  - C_i

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	0.08±0.10	1.00		
T	0.1±0.12	0.86	1.00	
U	0.00±0.09	−0.55	−0.81	1.00



	Result	Correlation	
S	0.07±0.08	1.00	
T	0.10±0.07	0.85	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	0.57	1.00	
$\delta\varepsilon_b$	0.0004 ± 0.0013	−0.32	−0.30	−0.23	1.00

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

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

where $\Sigma(x) = \exp i\sigma^a \chi^a(x)/v$ → W/Z longitudinal pol

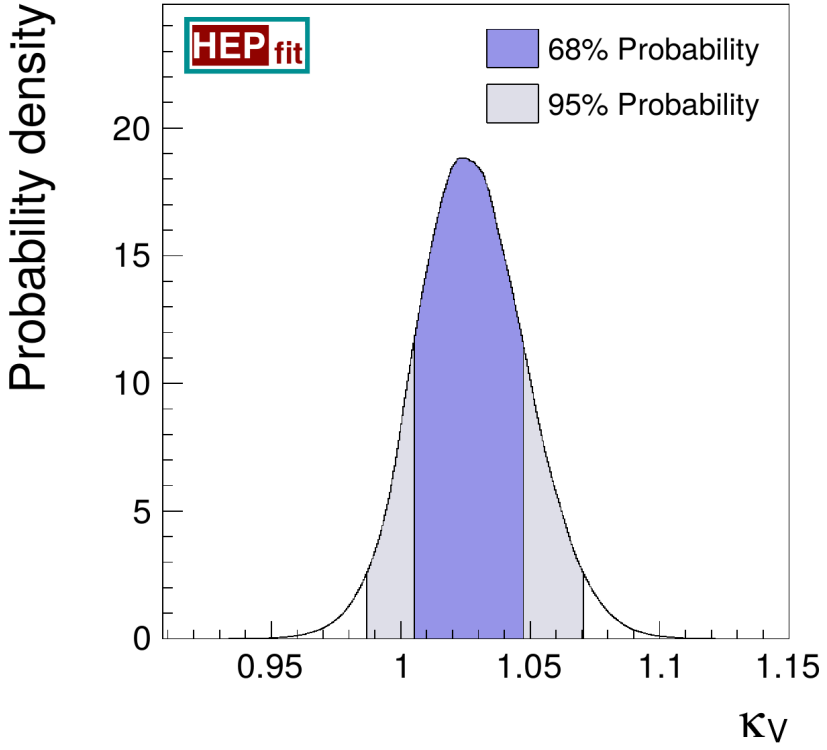
  - SM given by $\kappa_V, \kappa_f \to 1$

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

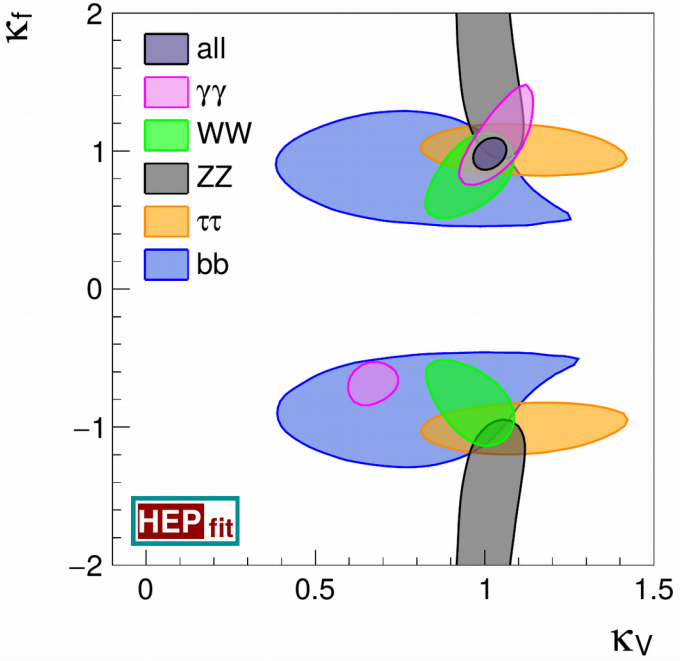


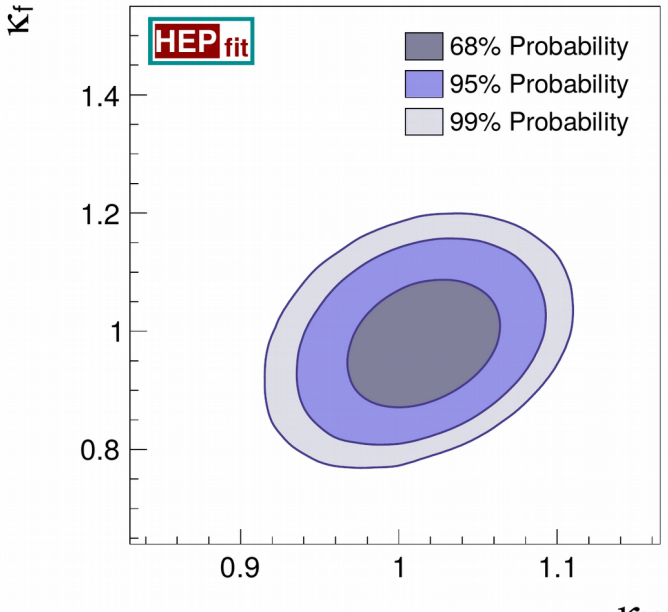
	Result	95% Prob.
κ_V	1.02 ± 0.02	$[0.99, 1.07]$

$\kappa_V < 1$ predicted in composite Higgs models disfavoured ⇒ need additional contributions

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

κ_V and κ_f



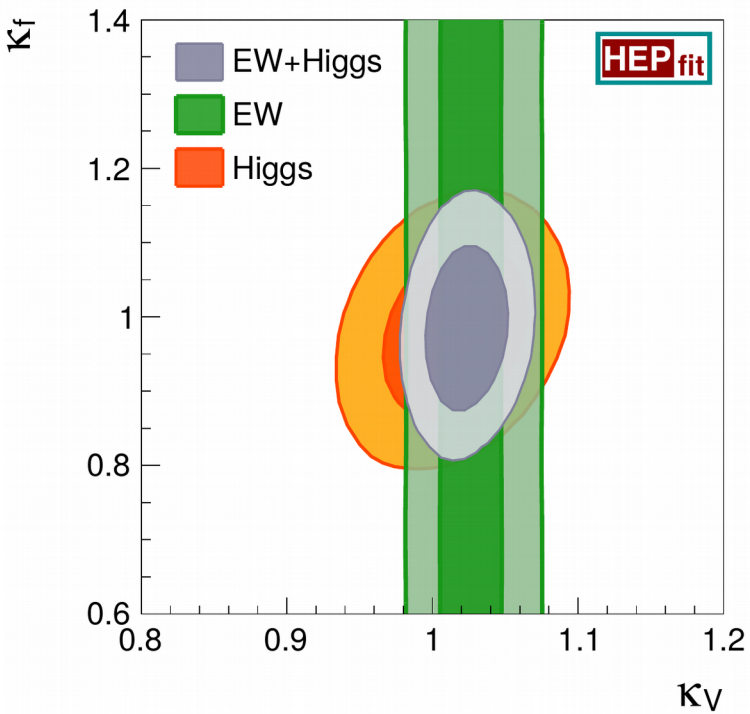


Higgs data only

	Result	95% Prob.	Correlation	
κ_V	1.01 ± 0.03	$[0.95, 1.07]$	1.00	
κ_f	0.98 ± 0.07	$[0.86, 1.12]$	0.29	1.00

Higgs + EWPO

	Result	95% Prob.	Correlation	
κ_V	1.02 ± 0.02	$[0.99, 1.06]$	1.00	
κ_f	0.99 ± 0.07	$[0.86, 1.12]$	0.17	1.00



MOST GENERAL FRAMEWORK: SMEFT

- Assume SM field content and a mass gap between the EW scale and the NP scale Λ
- Assume NP does not break SU(2)xU(1) and decouples

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

determines the EW scale

has accidental symmetries; gets log corrections

break SM accidental symmetries; modify SM predictions

SMEFT BASICS II

- Effects of $\mathscr{L}_6$ in SM processes suppressed by $\frac{(v,p)^2}{\Lambda^2}$ at linear order
- Truncation of the expansion at D=6 implies $(v,p) \ll \Lambda$ (to be checked a posteriori)
- Higher energy can compensate for lower precision (e.g. LEPII vs LEP); requires detailed knowledge of process kinematics - beware of overflow bins!

Contino et al.

RELEVANT SMEFT OP'S...

$$\mathcal{O}_{\phi G} = (\phi^\dagger\phi)\, G^A_{\mu\nu} G^{A\mu\nu} \ ,$$
$$\mathcal{O}_{\phi W} = (\phi^\dagger\phi)\, W^I_{\mu\nu} W^{I\mu\nu} \ ,$$
$$\mathcal{O}_{\phi B} = (\phi^\dagger\phi)\, B_{\mu\nu} B^{\mu\nu} \ ,$$
$$\mathcal{O}_{\phi WB} = (\phi^\dagger\sigma_I\phi)\, W^I_{\mu\nu} B^{\mu\nu} \ ,$$
$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu\phi)^* (\phi^\dagger D_\mu\phi) \ ,$$
$$\mathcal{O}_{\phi\Box} = (\phi^\dagger\phi)\Box(\phi^\dagger\phi)$$

$$\mathcal{O}_{e\phi} = (\phi^\dagger\phi)(\bar{L}\, e_R\phi)$$
$$\mathcal{O}_{u\phi} = (\phi^\dagger\phi)(\bar{Q}\, u_R\widetilde{\phi})$$
$$\mathcal{O}_{d\phi} = (\phi^\dagger\phi)(\bar{Q}\, d_R\phi)$$

$$\mathcal{O}^{(1)}_{\phi L} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{L}\gamma^\mu L) \ ,$$
$$\mathcal{O}^{(3)}_{\phi L} = (\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)(\overline{L}\,\sigma_I\gamma^\mu L) \ ,$$
$$\mathcal{O}_{\phi e} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{e}_R\gamma^\mu e_R) \ ,$$
$$\mathcal{O}^{(1)}_{\phi Q} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{Q}\gamma^\mu Q) \ ,$$
$$\mathcal{O}^{(3)}_{\phi Q} = (\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)(\overline{Q}\,\sigma_I\gamma^\mu Q) \ ,$$
$$\mathcal{O}_{\phi u} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{u}_R\gamma^\mu u_R) \ ,$$
$$\mathcal{O}_{\phi d} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{d}_R\gamma^\mu d_R) \ ,$$

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

AND THEIR EFFECTS IN EWPD

$$\delta g_L^u = -\frac{1}{2}\left(C_{\phi q}^{(1)} - C_{\phi q}^{(3)}\right)\frac{v^2}{\Lambda^2}, \qquad \delta g_R^u = -\tfrac{1}{2} C_{\phi u}\frac{v^2}{\Lambda^2},$$

$$\delta g_L^d = -\frac{1}{2}\left(C_{\phi q}^{(1)} + C_{\phi q}^{(3)}\right)\frac{v^2}{\Lambda^2}, \qquad \delta g_R^d = -\tfrac{1}{2} C_{\phi d}\frac{v^2}{\Lambda^2},$$

$$\delta g_L^\nu = -\frac{1}{2}\left(C_{\phi l}^{(1)} - C_{\phi l}^{(3)}\right)\frac{v^2}{\Lambda^2},$$

$$\delta g_L^e = -\frac{1}{2}\left(C_{\phi l}^{(1)} + C_{\phi l}^{(3)}\right)\frac{v^2}{\Lambda^2}, \qquad \delta g_R^e = -\tfrac{1}{2} C_{\phi e}\frac{v^2}{\Lambda^2},$$

$$\delta V_{ud} = C_{\phi q}^{(3)}\frac{v^2}{\Lambda^2}, \qquad \delta U_{e\nu} = \left(C_{\phi l}^{(3)}\right)^\dagger \frac{v^2}{\Lambda^2}$$

$$\Delta S = \frac{4 s_W c_W}{\alpha_{\rm em}(M_Z)}\frac{v^2}{\Lambda^2} C_{\phi WB}\ ,$$

$$\Delta T = -\frac{1}{2\alpha_{\rm em}(M_Z)}\frac{v^2}{\Lambda^2} C_{\phi D}\ ,$$

BOUNDS ON SMEFT COEFF'S

- Working in GIMR basis, obtain bounds from
  - EWPO only
  - Higgs only
  - EWPO + Higgs combined
- working at linear order, fit one operator at a time or all relevant op's simultaneously
- take C_i at EW scale, no running included

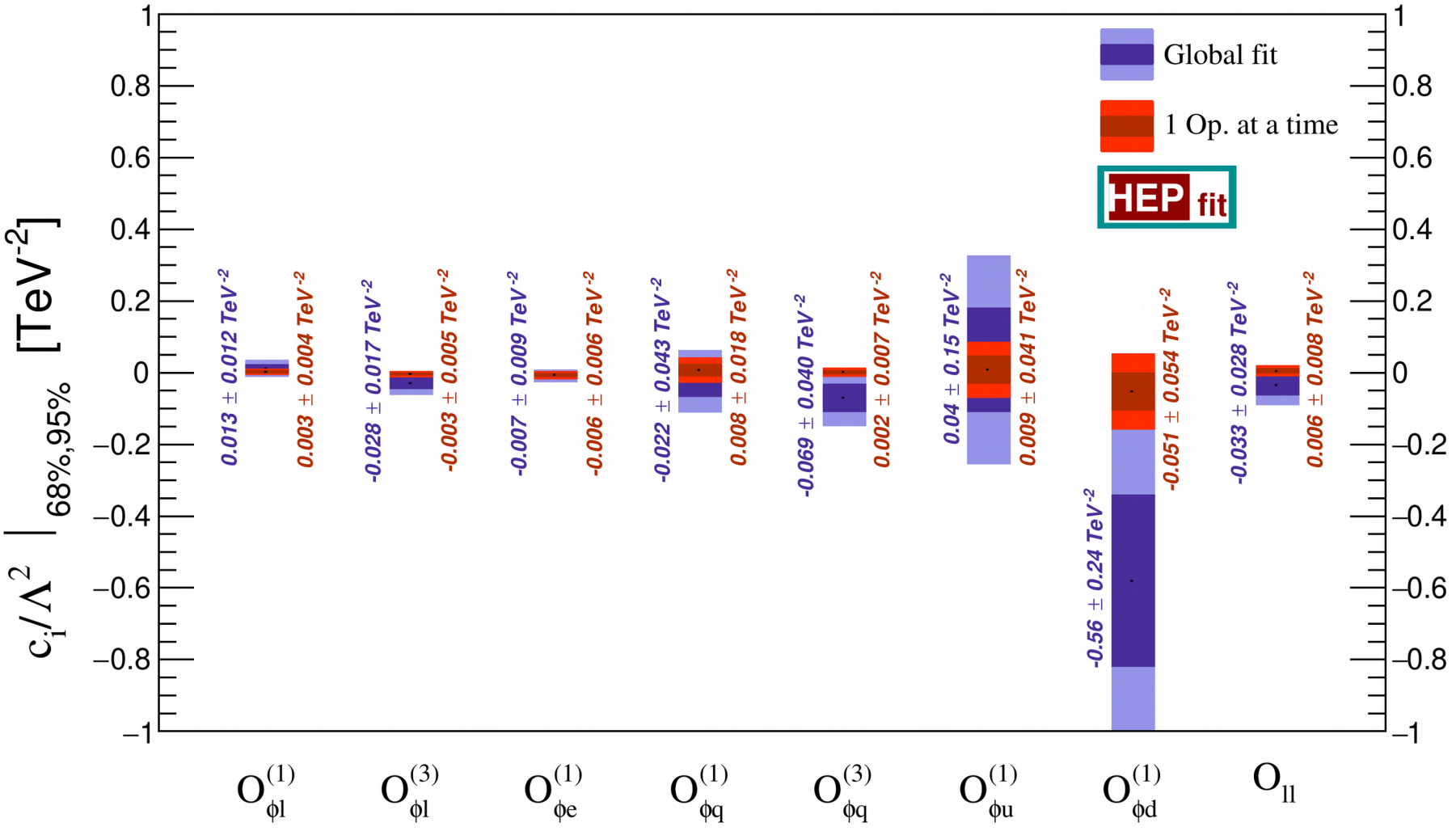
[See also Corbett et al, Ellis et al, Falkowski & Riva, ...]

Bounds from EWPO

Operator	95% prob. range $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. lower bound on Λ [TeV] ($\lvert C_i\rvert = 1$)
$C_{\phi WB}$	$[-0.0095, 0.0038]$	10
$C_{\phi D}$	$[-0.028, 0.0036]$	6.0
$C_{\phi l}^{(1)}$	$[-0.0058, 0.011]$	9.6
$C_{\phi l}^{(3)}$	$[-0.012, 0.0051]$	9.1
$C_{\phi e}^{(1)}$	$[-0.017, 0.005]$	7.7
$C_{\phi Q}^{(1)}$	$[-0.026, 0.044]$	4.8
$C_{\phi Q}^{(3)}$	$[-0.011, 0.015]$	8.2
$C_{\phi u}$	$[-0.066, 0.087]$	3.4
$C_{\phi d}$	$[-0.15, 0.054]$	2.5
C_{LL}	$[-0.0093, 0.021]$	6.8

PRELIMINARY

1 OP AT A TIME VS GLOBAL FIT



PRELIMINARY

BOUNDS FROM HIGGS

Operator	95% prob. range $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. lower bound on Λ [TeV] ($\lvert C_i\rvert = 1$)
$C_{\phi G}$	$[-0.00078, 0.0062]$	13
$C_{\phi W}$	$[-0.018, 0.0083]$	7.5
$C_{\phi B}$	$[-0.0053, 0.0026]$	14
$C_{\phi WB}$	$[-0.0047, 0.0097]$	10
$C_{\phi D}$	$[-1.5, 0.31]$	0.83
$C_{\phi\Box}$	$[-0.12, 1.6]$	0.80
$C_{\phi l}^{(3)}$	$[-0.62, 0.10]$	1.3
$C_{\phi Q}^{(1)}$	$[-3.1, 1.2]$	0.57
$C_{\phi Q}^{(3)}$	$[-0.14, 0.22]$	2.1
$C_{\phi u}$	$[-1.2, 1.4]$	0.86
$C_{\phi d}$	$[-3.7, 3.5]$	0.52
$C_{e\phi}$	$[-0.036, 0.020]$	5.2
$C_{u\phi}$	$[-2.1, 0.17]$	0.69
$C_{d\phi}$	$[-0.00065, 0.066]$	3.9
C_{LL}	$[-0.21, 1.2]$	0.90

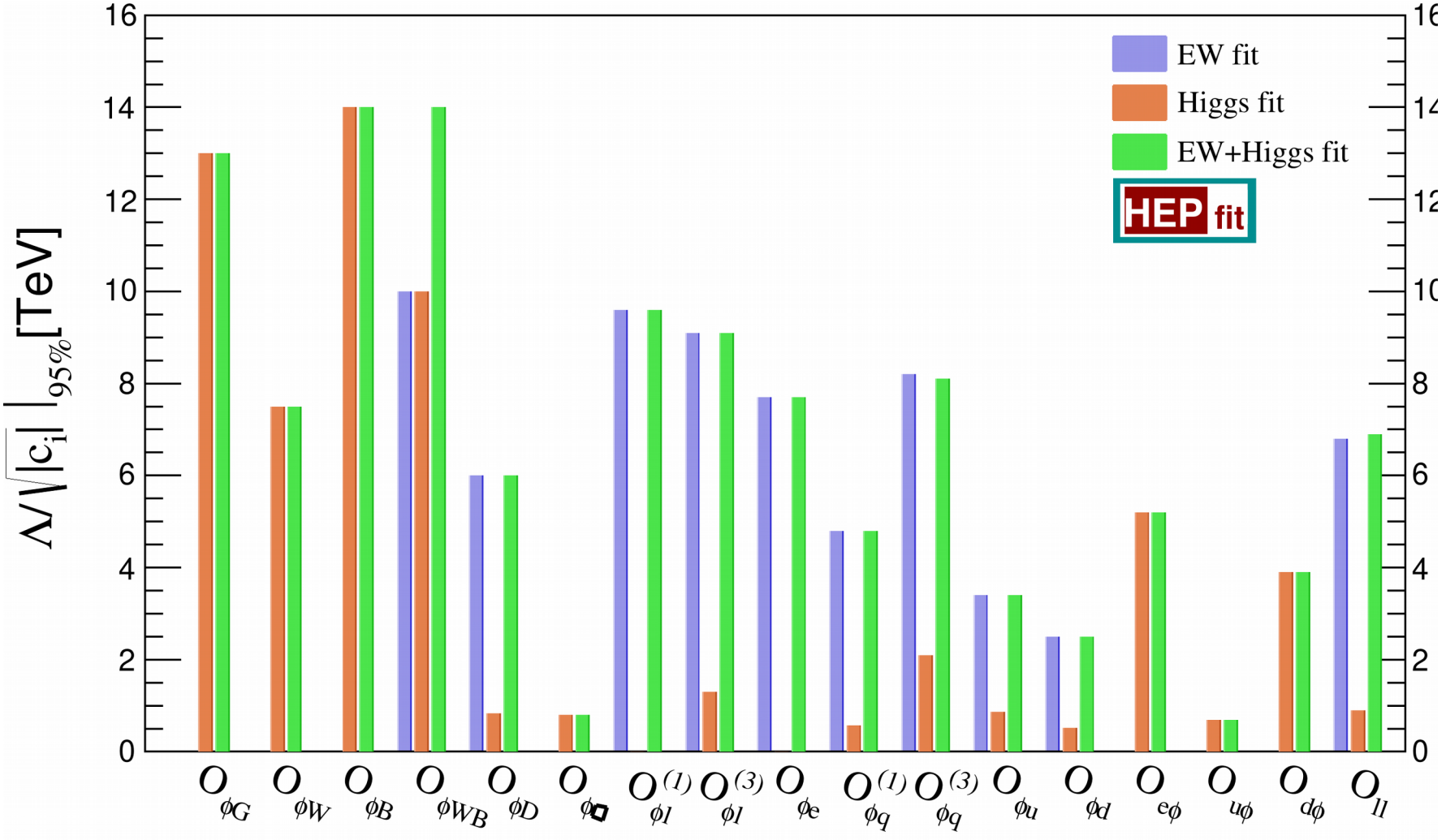
PRELIMINARY

BOUNDS FROM EWPO + HIGGS

Operator	95% prob. range $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. lower bound on Λ [TeV] ($\lvert C_i\rvert = 1$)
$C_{\phi G}$	$[-0.00076, 0.0063]$	13
$C_{\phi W}$	$[-0.018, 0.0084]$	7.5
$C_{\phi B}$	$[-0.0053, 0.0025]$	14
$C_{\phi WB}$	$[-0.0052, 0.0045]$	14
$C_{\phi D}$	$[-0.028, 0.0035]$	6.0
$C_{\phi\Box}$	$[-0.12, 1.6]$	0.80
$C_{\phi l}^{(1)}$	$[-0.0058, 0.011]$	9.6
$C_{\phi l}^{(3)}$	$[-0.012, 0.0052]$	9.1
$C_{\phi e}^{(1)}$	$[-0.017, 0.0051]$	7.7
$C_{\phi Q}^{(1)}$	$[-0.026, 0.044]$	4.8
$C_{\phi Q}^{(3)}$	$[-0.010, 0.015]$	8.1
$C_{\phi u}$	$[-0.066, 0.087]$	3.4
$C_{\phi d}$	$[-0.15, 0.055]$	2.5
$C_{e\phi}$	$[-0.037, 0.020]$	5.2
$C_{u\phi}$	$[-2.1, 0.16]$	0.69
$C_{d\phi}$	$[-0.0006, 0.066]$	3.9
C_{LL}	$[-0.0093, 0.021]$	6.9

PRELIMINARY

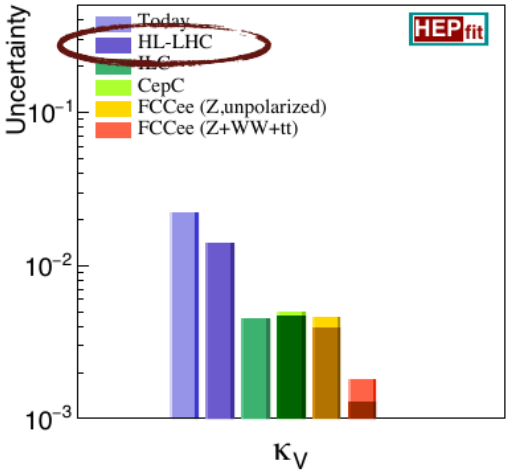
Bounds from EWPO + Higgs

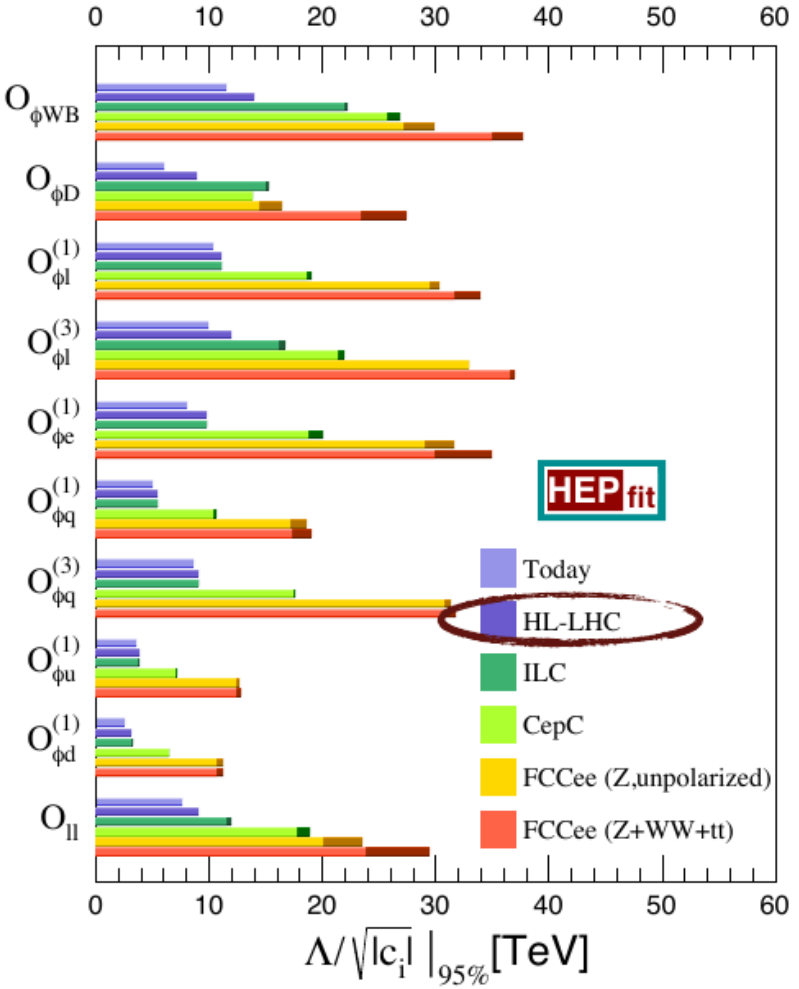


PRELIMINARY

EXTRAPOLATION TO HL-LHC

- "Old" HL-LHC extrapolation using only δM_W=10 MeV
- to be updated with new estimates for M_W, asymmetries, m_t
- complementary info from WG2





CONCLUSIONS

- Ready for extrapolating with new updated HL-LHC projections
- Need to agree on additional inputs such as α_s
- Define possible overlap with WG2/WG3
- Anything more?