

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

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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 Jorge de Blas,  
Ayan Paul and Maurizio Pierini



# INTRODUCTION

- $SU(2)_L \times U(1)_Y$  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

# EW PHYSICS IN THE LHC ERA

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

# EWPO FIT

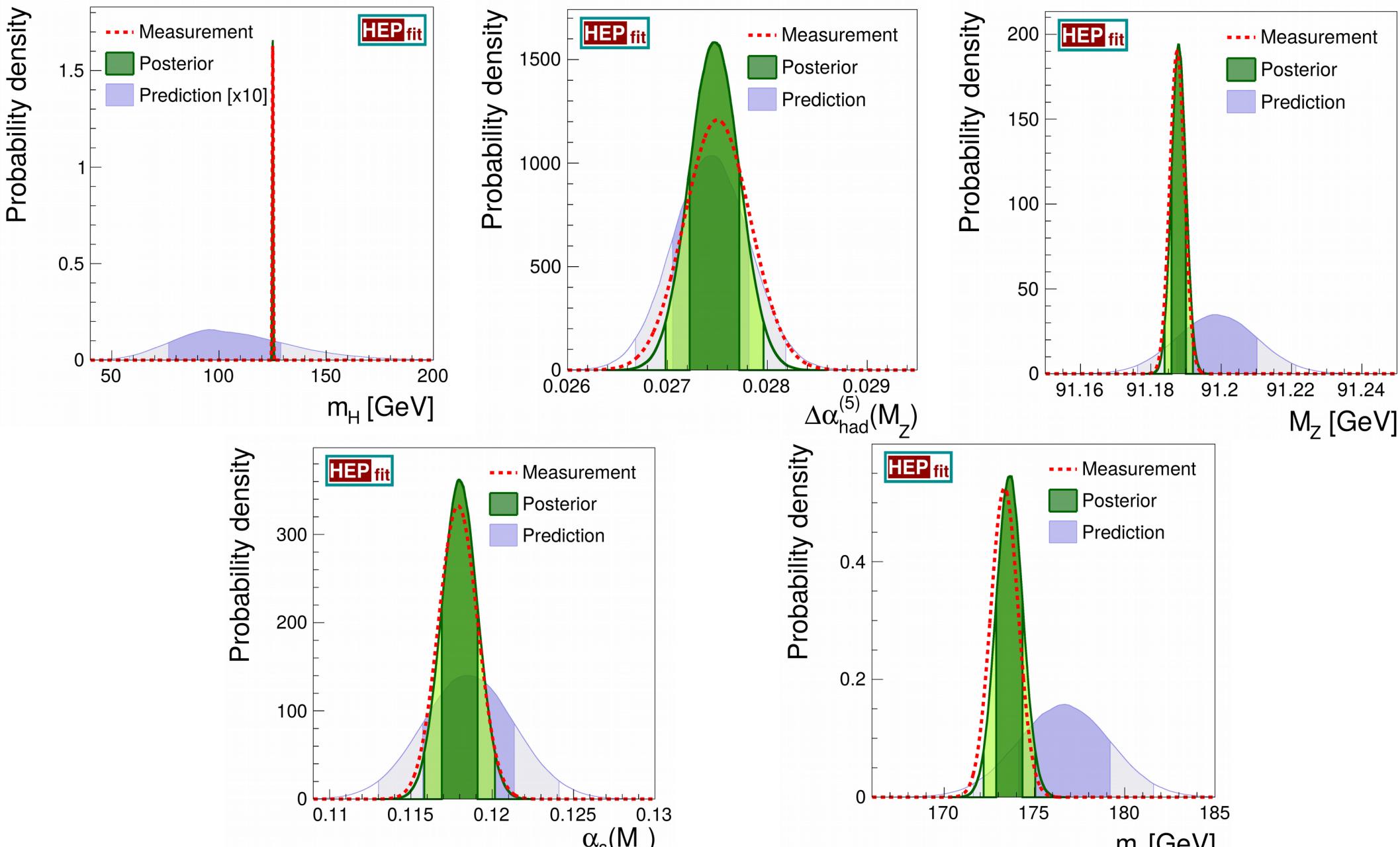
- SM input parameters:
  - $G_F, \alpha, M_Z, M_H, m_t, \alpha_s(M_Z), \Delta\alpha_{had}^{(5)}$
- state-of-the-art computation of EWPO
- parametrize possible NP effects (modified couplings, additional loop contributions, D=6 operators)
- perform a fit to experimental data
  - GAPP (Erler)
  - ZFITTER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

# EW FITS WITH



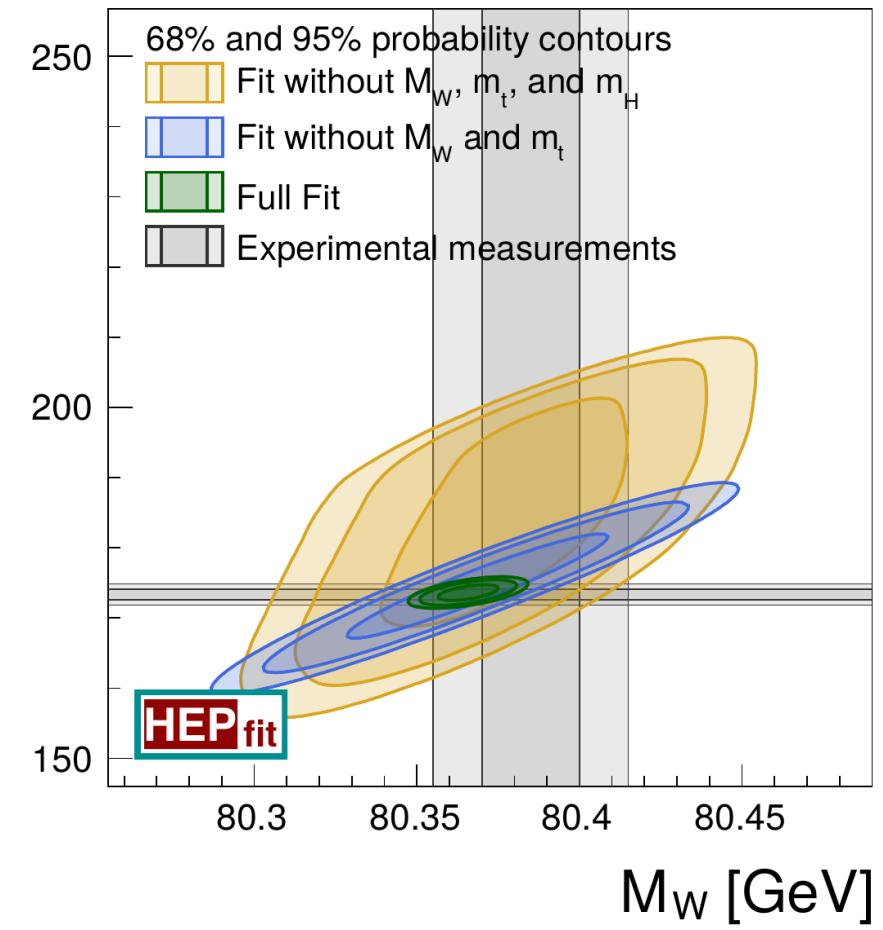
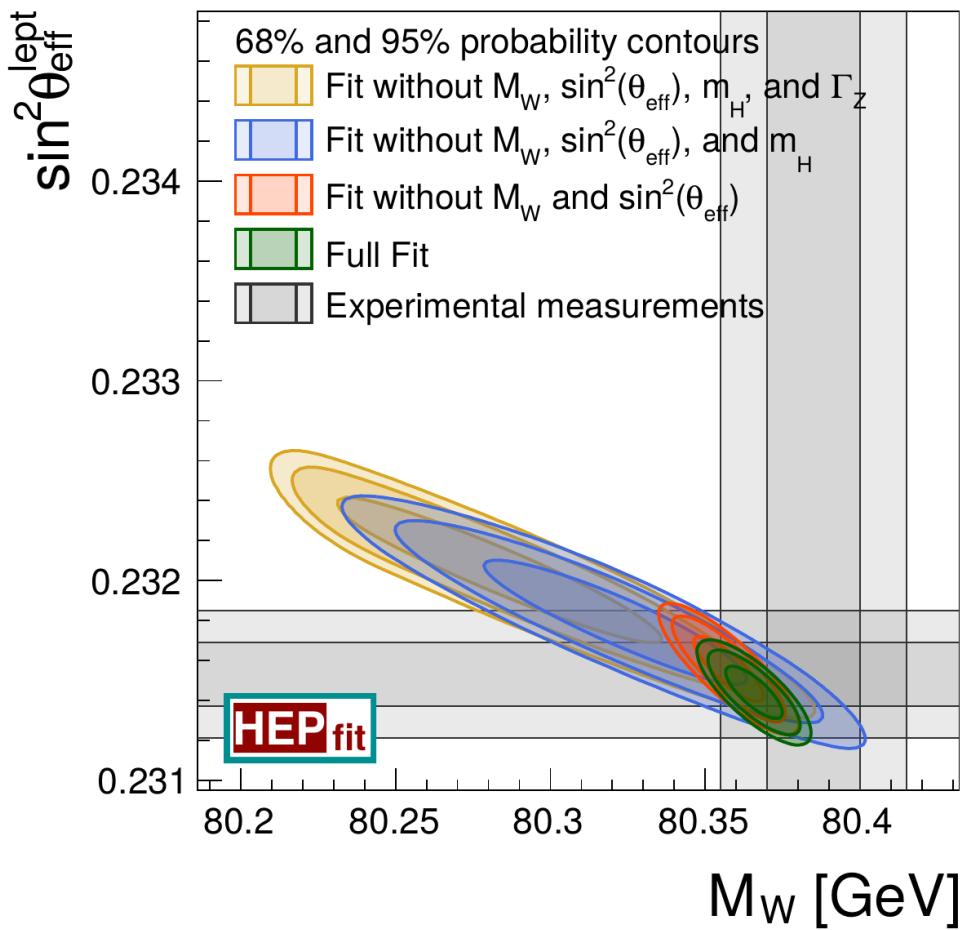
- Both electroweak and Higgs observables are calculated as a SM core plus corrections:
  - the SM core includes all existing higher order corrections
  - NP corrections are at the lowest order in all SM couplings
- Experimental results are taken from the most recent published analyses
- The fit procedure uses BAT (Bayesian 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 ( $S, T, U$ ),  $\varepsilon_i$  parameters, modified  $Z b\bar{b}$  couplings, Modified Higgs couplings ( $\kappa_i$ ), SMEFT ( $D=6$ ), 2HDM, LUV in  $b \rightarrow s$  transitions
  - Implemented observables:
    - EWPO, Higgs signal strengths, Flavour ( $\Delta F = 2$ , UT, rare B decays)

	Measurement	Posterior	Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	$0.1180 \pm 0.0010$	$0.1181 \pm 0.0009$	$0.1184 \pm 0.0028$	-0.1	
$\Delta\alpha_{\text{had}}^{(5)}(M_Z)$	$0.02750 \pm 0.00033$	$0.02740 \pm 0.00025$	$0.02730 \pm 0.00038$	0.4	
$M_Z$ [GeV]	$91.1875 \pm 0.0021$	$91.1879 \pm 0.0021$	$91.199 \pm 0.011$	-1.0	
$m_t$ [GeV]	$173.34 \pm 0.76$	$173.62 \pm 0.73$	$176.8 \pm 2.5$	-1.3	
$m_H$ [GeV]	$125.09 \pm 0.24$	$125.09 \pm 0.24$	$104 \pm 27$	0.8	
$M_W$ [GeV]	$80.385 \pm 0.015$	$80.366 \pm 0.006$	$80.362 \pm 0.007$	1.4	
$\Gamma_W$ [GeV]	$2.085 \pm 0.042$	$2.0889 \pm 0.0006$	$2.0889 \pm 0.0006$	-0.1	
$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	$0.2324 \pm 0.0012$	$0.231440 \pm 0.000086$	$0.231434 \pm 0.000086$	0.8	
$P_\tau^{\text{pol}} = \mathcal{A}_\ell$	$0.1465 \pm 0.0033$	$0.14767 \pm 0.00067$	$0.14772 \pm 0.00069$	-0.4	
$\Gamma_Z$ [GeV]	$2.4952 \pm 0.0023$	$2.4943 \pm 0.0006$	$2.4942 \pm 0.0006$	0.4	
$\sigma_h^0$ [nb]	$41.540 \pm 0.037$	$41.490 \pm 0.005$	$41.491 \pm 0.005$	1.3	0.7
$R_\ell^0$	$20.767 \pm 0.025$	$20.749 \pm 0.006$	$20.748 \pm 0.006$	0.7	
$A_{\text{FB}}^{0,\ell}$	$0.0171 \pm 0.0010$	$0.01635 \pm 0.00015$	$0.01632 \pm 0.00015$	0.8	
$\mathcal{A}_\ell$ (SLD)	$0.1513 \pm 0.0021$	$0.14767 \pm 0.00067$	$0.14789 \pm 0.00075$	1.5	
$\mathcal{A}_c$	$0.670 \pm 0.027$	$0.6682 \pm 0.0003$	$0.6683 \pm 0.0003$	0.06	
$\mathcal{A}_b$	$0.923 \pm 0.020$	$0.93479 \pm 0.00006$	$0.93481 \pm 0.00006$	-0.6	
$A_{\text{FB}}^{0,c}$	$0.0707 \pm 0.0035$	$0.07400 \pm 0.00037$	$0.07412 \pm 0.00041$	-1.0	1.5
$A_{\text{FB}}^{0,b}$	$0.0992 \pm 0.0016$	$0.10353 \pm 0.00048$	$0.10368 \pm 0.00053$	-2.7	
$R_c^0$	$0.1721 \pm 0.0030$	$0.17223 \pm 0.00002$	$0.17223 \pm 0.00002$	-0.04	
$R_b^0$	$0.21629 \pm 0.00066$	$0.21579 \pm 0.00003$	$0.21579 \pm 0.00003$	0.8	
$\sin^2 \theta_{\text{eff}}^{ee}$ (CDF)	$0.23248 \pm 0.00053$			1.9	
$\sin^2 \theta_{\text{eff}}^{\mu\mu}$	$0.2315 \pm 0.0010$			0.06	
$\sin^2 \theta_{\text{eff}}^{ee}$ (D0)	$0.23147 \pm 0.00047$			0.06	
$\sin^2 \theta_{\text{eff}}^{\mu\mu}$	$0.23002 \pm 0.00066$	$0.231440 \pm 0.000086$	$0.231440 \pm 0.000090$	-2.1	
$\sin^2 \theta_{\text{eff}}^{ee,\mu\mu}$ (ATLAS)	$0.2308 \pm 0.0012$			-0.5	
$\sin^2 \theta_{\text{eff}}^{\mu\mu}$ (CMS)	$0.2287 \pm 0.0032$			-0.9	
$\sin^2 \theta_{\text{eff}}^{\mu\mu}$ (LHCb)	$0.2314 \pm 0.0011$			-0.04	



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

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

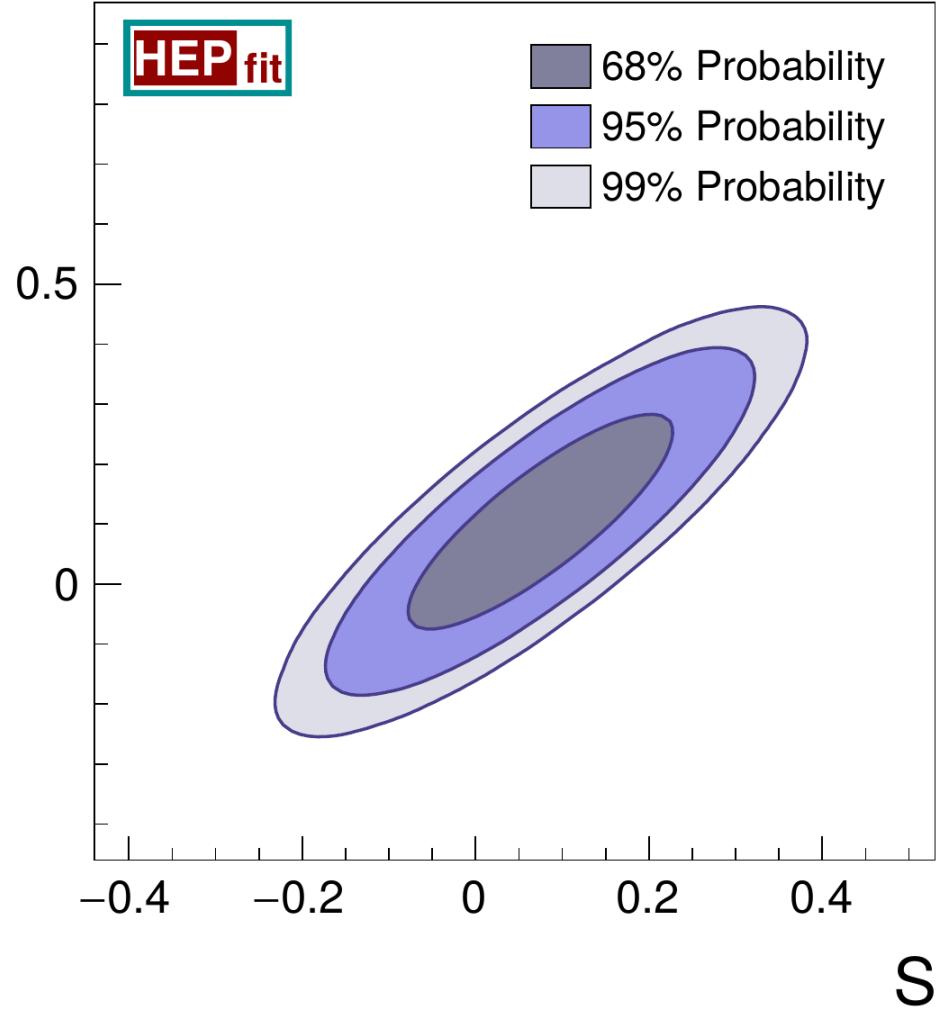


# EW FIT BEYOND THE SM

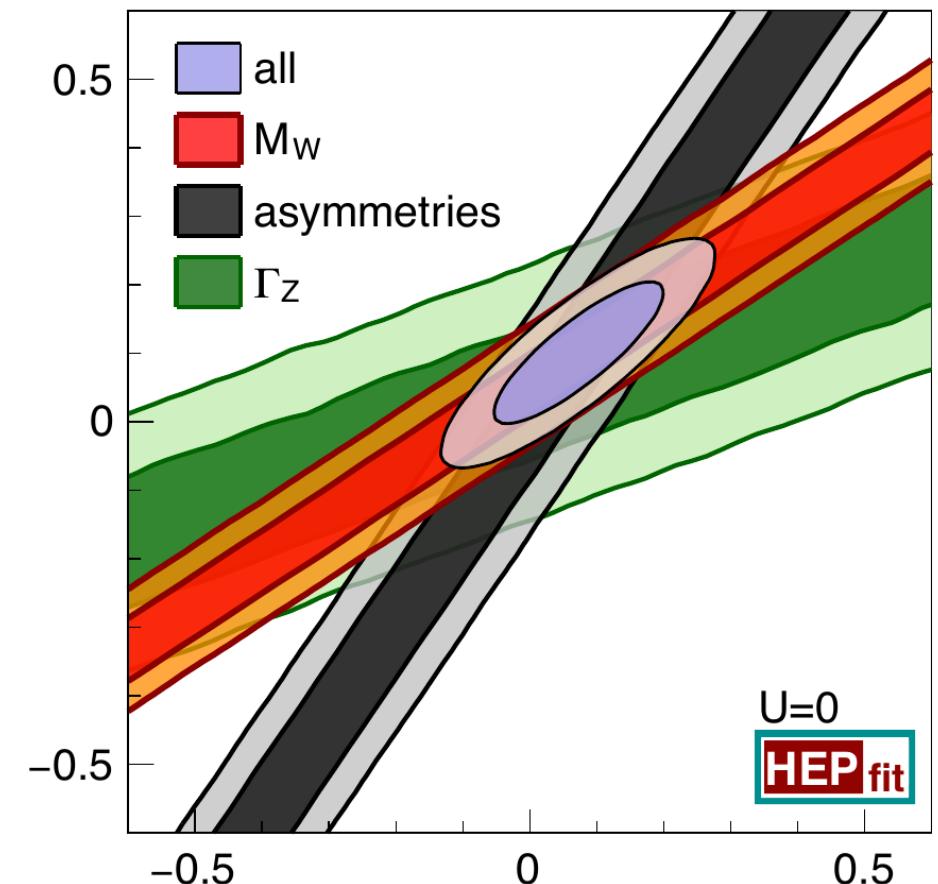
- Oblique corrections
  - $S, T, U; \delta\epsilon_{1,2,3,b}$
- Modified Zbb couplings - see backup
- Modified Higgs couplings
  - $\kappa_{V,f}$
- Effective theory with D=6
  - $C_i$

# OBLIQUE CORRECTIONS

- Parameterize dominant NP effects in gauge-boson vacuum polarization:
  - $S, T, U$  [Peskin & Takeuchi '90, '92]
  - $\varepsilon_{1,2,3} \rightarrow \delta\varepsilon_{1,2,3}$  now that  $m_+$  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		
$S$	$0.08 \pm 0.10$	1.00		
$T$	$0.1 \pm 0.12$	0.86	1.00	
$U$	$0.00 \pm 0.09$	-0.55	-0.81	1.00



Result		Correlation Matrix			
$S$	$0.07 \pm 0.08$	1.00			
$T$	$0.10 \pm 0.07$	0.85	1.00		
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Result		Correlation Matrix			
$\delta\varepsilon_1$	$0.0007 \pm 0.0010$	1.00			
$\delta\varepsilon_2$	$-0.0002 \pm 0.0008$	0.82	1.00		
$\delta\varepsilon_3$	$0.0007 \pm 0.0009$	0.87	0.57	1.00	
$\delta\varepsilon_b$	$0.0004 \pm 0.0013$	-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  $\Lambda$
  - custodial symmetry approximately realized
  - NP corrections flavour-diagonal and universal

$$\mathcal{L}_{\text{eff}} = \frac{v^2}{4} \text{tr} \left( D_\mu \Sigma^\dagger D^\mu \Sigma \right) \left( 1 + 2\kappa_V \frac{H}{v} + \dots \right) - m_i \bar{f}_L^i \left( 1 + 2\kappa_f \frac{H}{v} + \dots \right) f_R^i + \dots ,$$

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

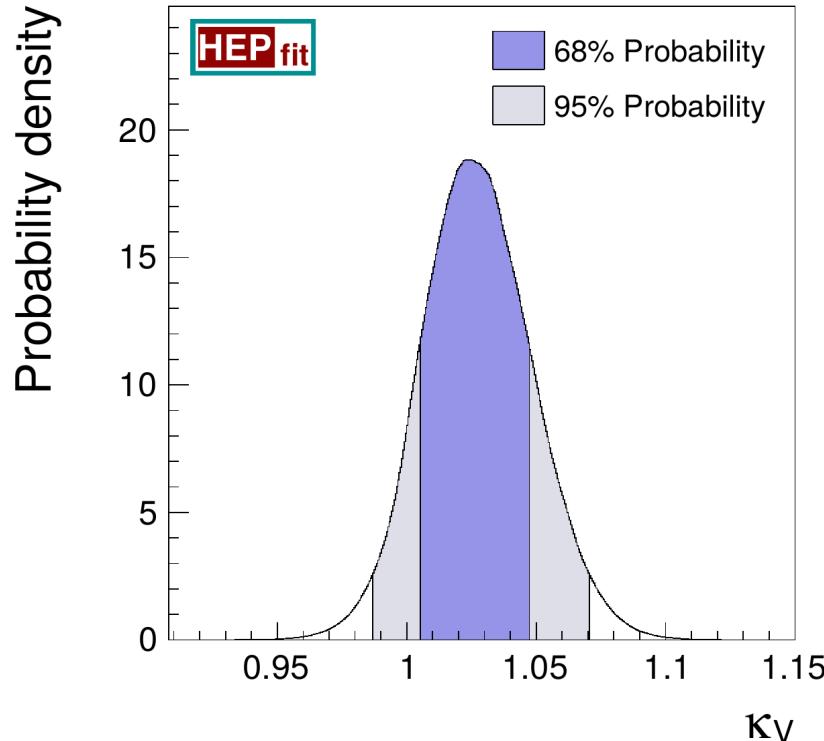
- SM given by  $\kappa_V, \kappa_f \rightarrow 1$

# $\kappa_V$ ONLY

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

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

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

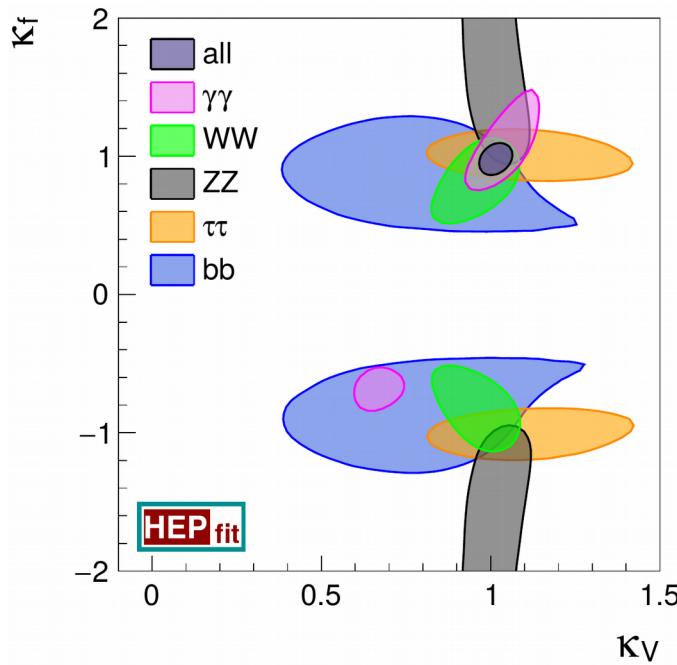


	Result	95% Prob.
$\kappa_V$	$1.02 \pm 0.02$	[0.99, 1.07]

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

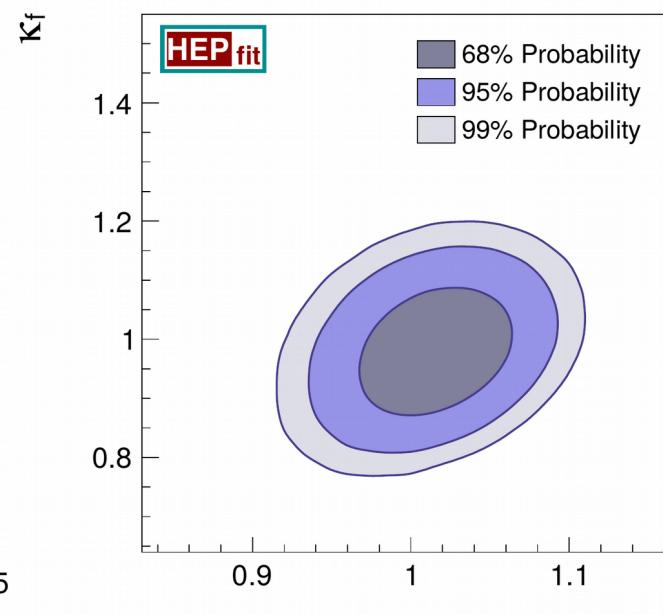
[Grojean et al; Azatov et al; Pich et al]

# $\kappa_V$ and $\kappa_f$



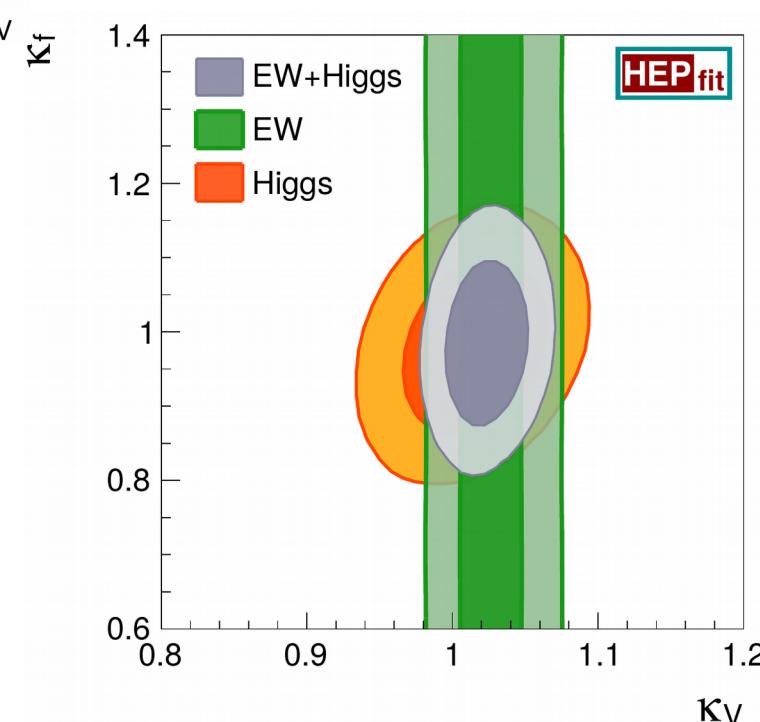
Higgs + EWPO

Result	95% Prob.	Correlation
$\kappa_V$	$1.02 \pm 0.02$	[0.99, 1.06]
$\kappa_f$	$0.99 \pm 0.07$	[0.86, 1.12]



Higgs data only

Result	95% Prob.	Correlation
$\kappa_V$	$1.01 \pm 0.03$	[0.95, 1.07]
$\kappa_f$	$0.98 \pm 0.07$	[0.86, 1.12]



# The SM as an effective theory

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

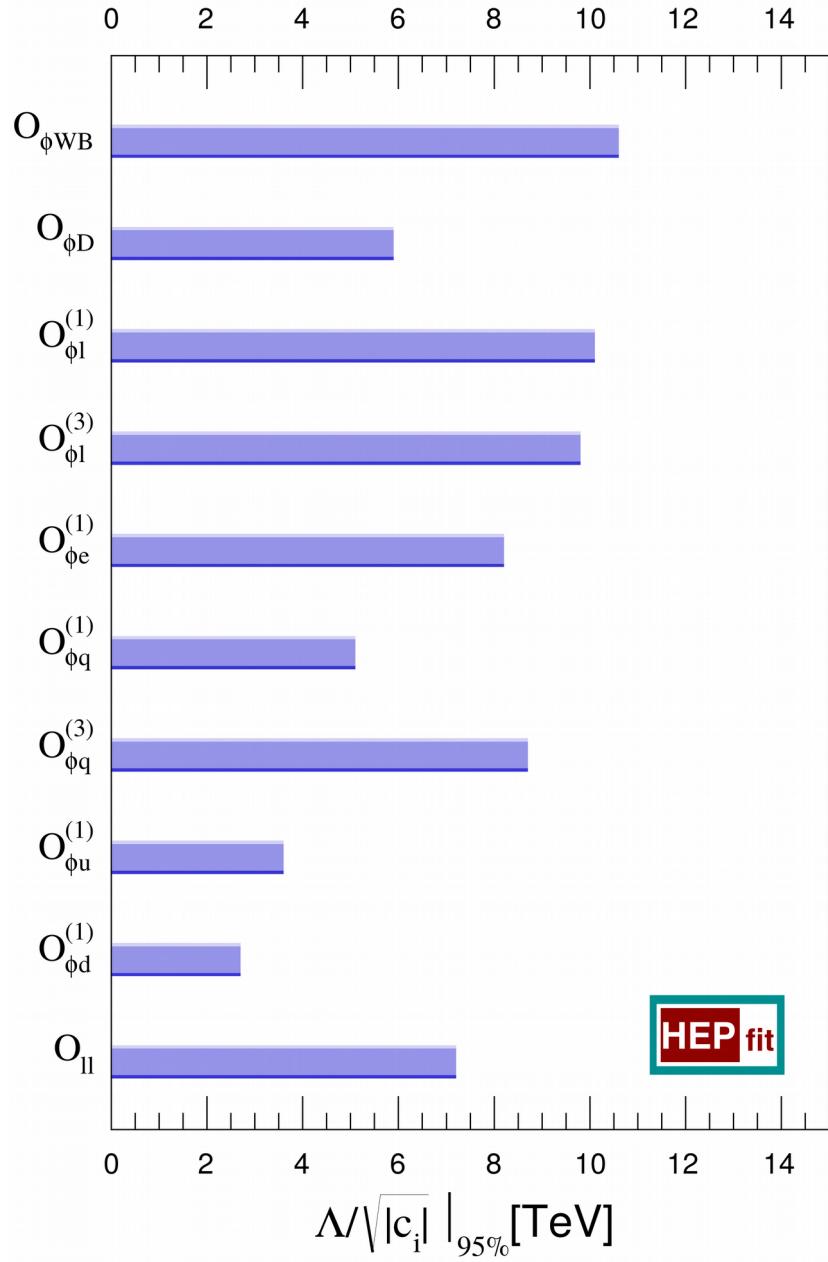
- $d=6$  only, one Higgs doublet,  $SU(2) \times U(1)$ ,  $B, L$
- with flavour universality/conservation, 59 operators (we use GIMR basis) [Grzadkowski et al.]
- contributing to EWPO +  $\mu_i$ : 18 operators
- take  $C_i$  at EW scale, no running included

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

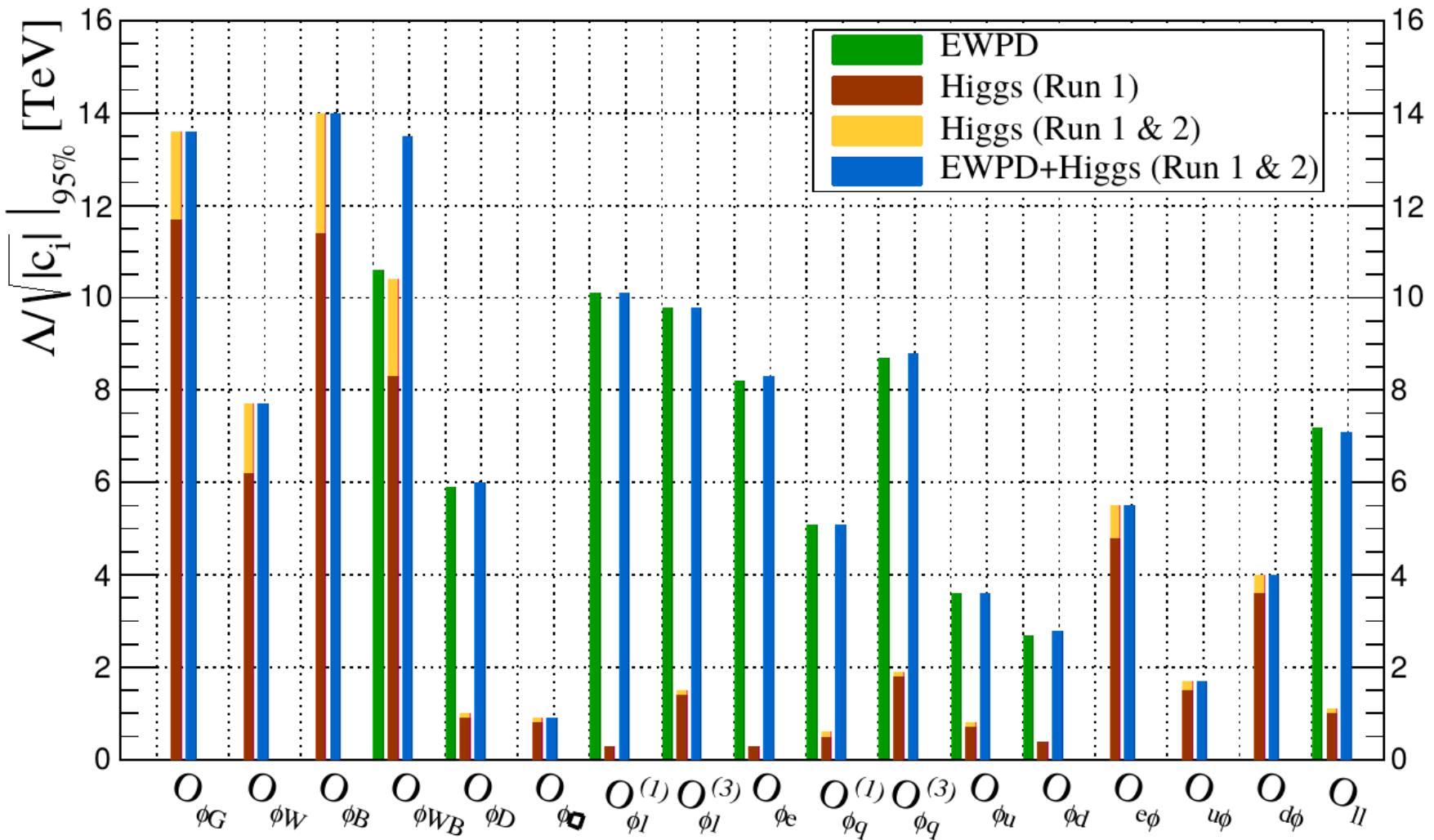
# Bounds from EWPO

Operator	95% prob. bound on		
	$\frac{C_i}{\Lambda^2}$ [TeV $^{-2}$ ]	$\Lambda$ [TeV]	$C_i = \pm 1$
$\mathcal{O}_{\phi WB}$	( $\phi^\dagger \sigma_a \phi$ ) $W_{\mu\nu}^a B^{\mu\nu}$	[-0.010, 0.005]	11
$\mathcal{O}_{\phi D}$	$ \phi^\dagger D_\mu \phi ^2$	[-0.032, 0.006]	5.9
$\mathcal{O}_{\phi l}^{(1)}$	( $\phi^\dagger i \overset{\leftrightarrow}{D}_\mu \phi$ ) ( $\bar{l}_L \gamma^\mu l_L$ )	[-0.006, 0.011]	10
$\mathcal{O}_{\phi l}^{(3)}$	( $\phi^\dagger i \overset{\leftrightarrow}{D}_\mu^a \phi$ ) ( $\bar{l}_L \gamma^\mu \sigma_a l_L$ )	[-0.013, 0.006]	9.8
$\mathcal{O}_{\phi e}^{(1)}$	( $\phi^\dagger i D_\mu \phi$ ) ( $\bar{e}_R \gamma^\mu e_R$ )	[-0.017, 0.006]	8.2
$\mathcal{O}_{\phi q}^{(1)}$	( $\phi^\dagger i \overset{\leftrightarrow}{D}_\mu \phi$ ) ( $\bar{q}_L \gamma^\mu q_L$ )	[-0.026, 0.044]	5.1
$\mathcal{O}_{\phi q}^{(3)}$	( $\phi^\dagger i \overset{\leftrightarrow}{D}_\mu^a \phi$ ) ( $\bar{q}_L \gamma^\mu \sigma_a q_L$ )	[-0.010, 0.015]	8.7
$\mathcal{O}_{\phi u}^{(1)}$	( $\phi^\dagger i \overset{\leftrightarrow}{D}_\mu \phi$ ) ( $\bar{u}_R \gamma^\mu u_R$ )	[-0.068, 0.086]	3.6
$\mathcal{O}_{\phi d}^{(1)}$	( $\phi^\dagger i \overset{\leftrightarrow}{D}_\mu \phi$ ) ( $\bar{d}_R \gamma^\mu d_R$ )	[-0.151, 0.058]	2.7
$\mathcal{O}_{ll}$	( $\bar{l} \gamma_\mu l$ ) ( $\bar{l} \gamma^\mu l$ )	[-0.010, 0.022]	7.2

One operator at a time



# Bounds from EWPO + Higgs



# 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	$10^{12}/10^{13}$	$10^8$	$2 \times 10^6$	$2.1 \times 10^5$	$7.5 \times 10^4$

[Talk by P. Azzi @ 2016 FCC week]

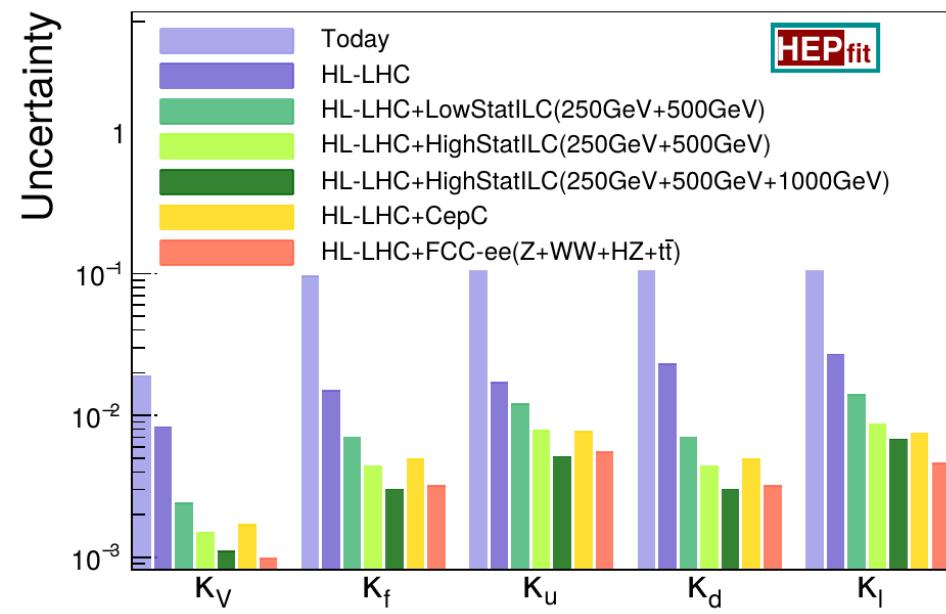
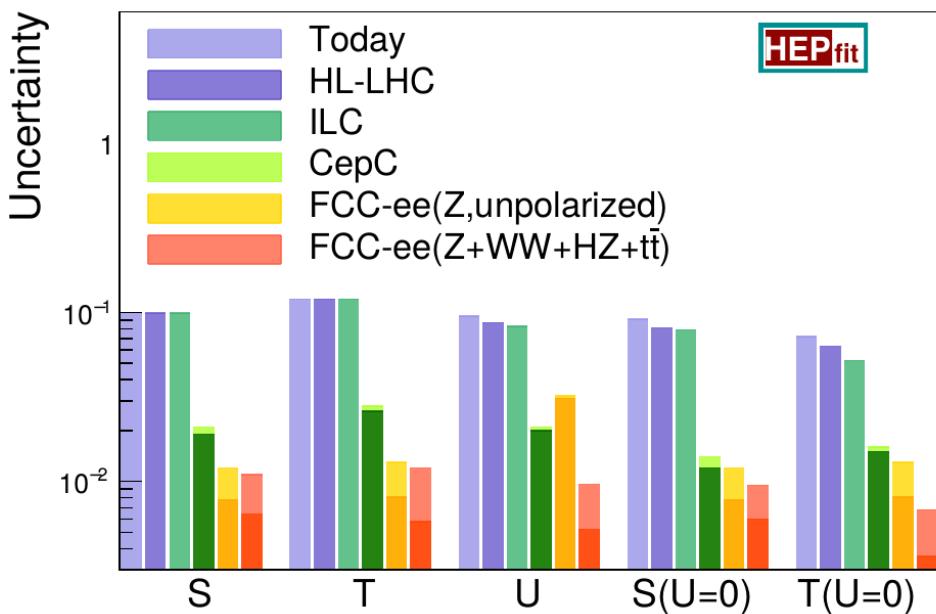
ILC	Phase 1			Phase 2 (Luminosity upgrade)		
$\sqrt{s}$ [GeV]	250	500	1000	250	500	100
$\int \mathcal{L} dt$ [ab $^{-1}$ ]	0.25	0.5	1	1.15	1.6	2.5
$\int dt$ ( $10^7$ s)	3	3	3	3	3	3

[S. Dawson et al., 1310.8361]

EPS-H plus CepC:  $10^6 H$  @ 240 GeV +  $10^{11} Z$  @  $M_Z$  18

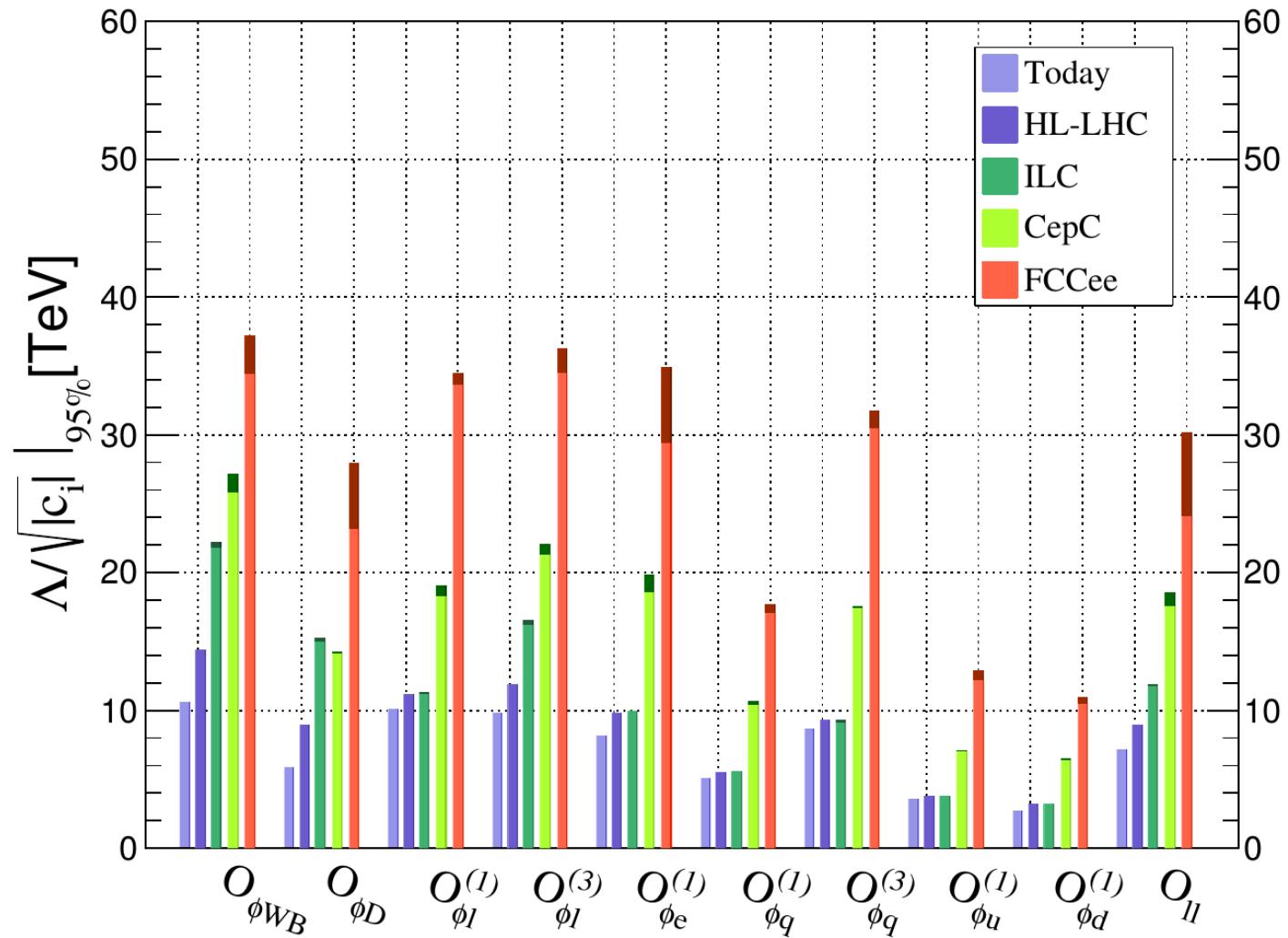
[CepC-SPPC preliminary CDR, 2015]

# Future Prospects: NP analyses

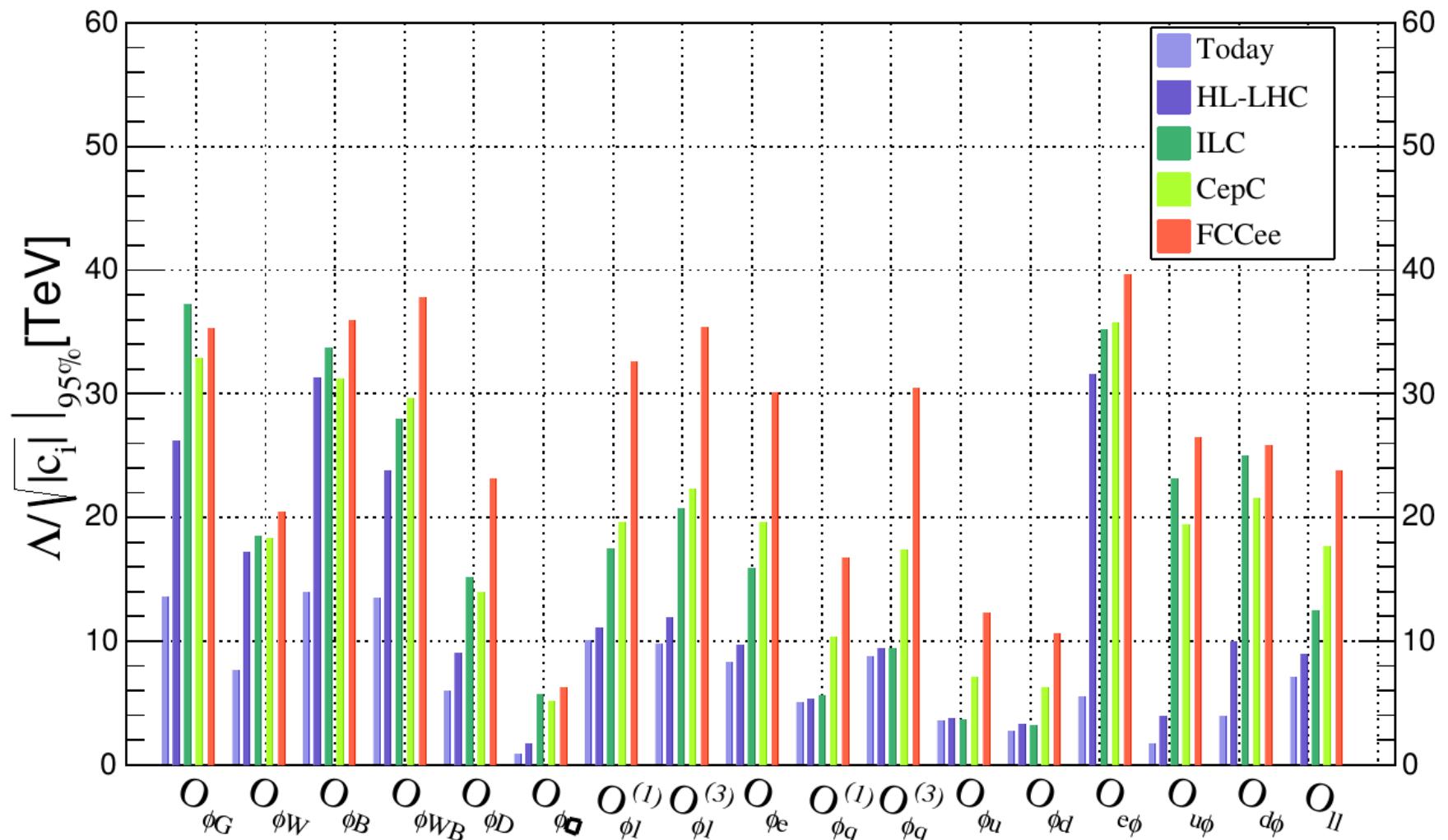


Lighter: incl. th. error;  
darker: no theory error

# Future Prospects: $\Lambda$ from EWPO



# Future Prospects: $\Lambda$ from EWPO, $\mu_i$

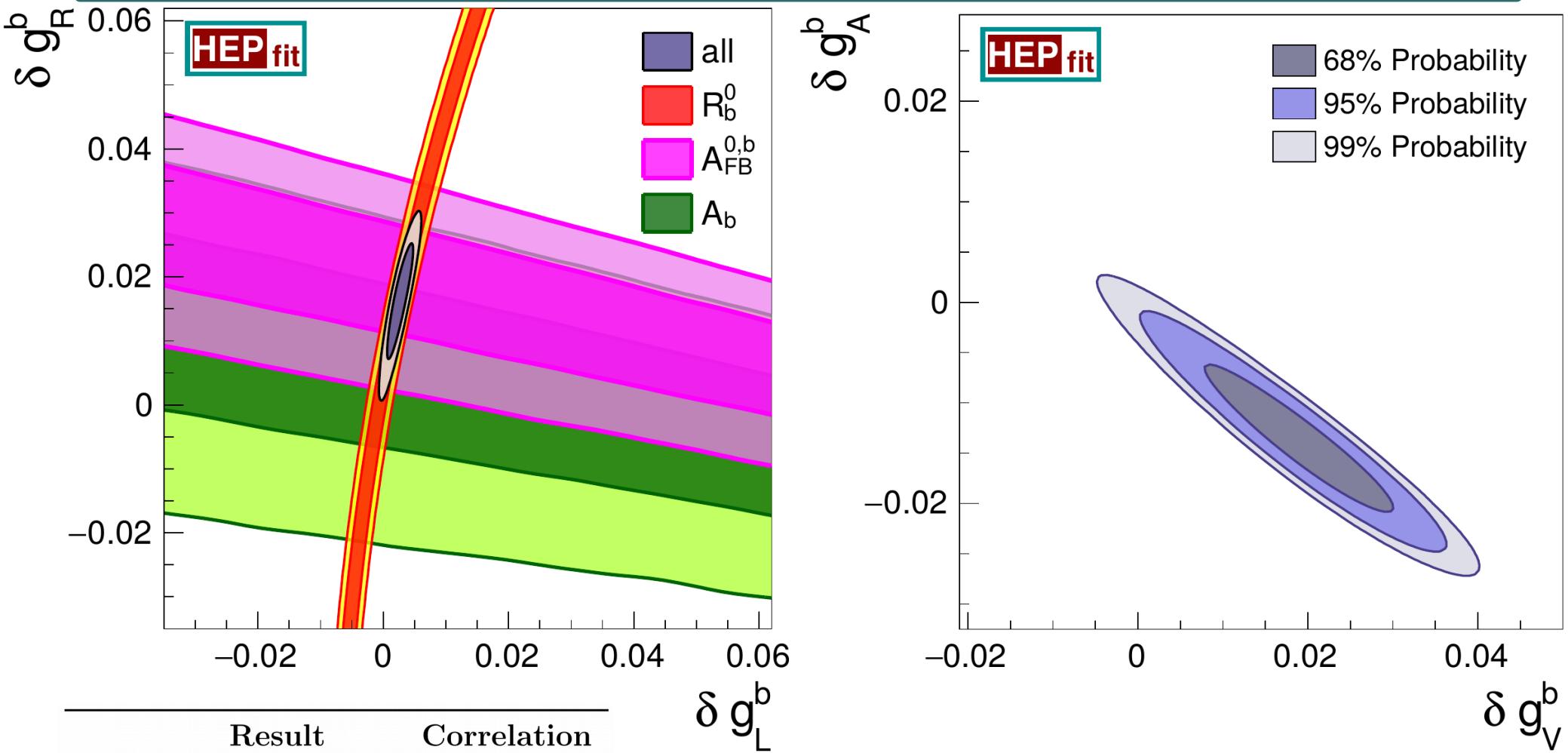


# Conclusions

- Remarkable experimental progress on EWSB with measurements of  $m_H$  &  $\mu_i$
- Combined with EWPO: high sensitivity to NP, currently probing scales up to 14 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

# BACKUP SLIDES

# Modified Zbb couplings



	Result	Correlation	
$\delta g_R^b$	$0.016 \pm 0.006$	1.00	
$\delta g_L^b$	$0.003 \pm 0.001$	0.89	1.00
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$\delta g_V^b$	$0.019 \pm 0.007$	1.00	
$\delta g_A^b$	$-0.013 \pm 0.005$	-0.98	1.00

	Result	Correlation Matrix		
$S$	$0.01 \pm 0.09$	1.00		
$T$	$0.06 \pm 0.07$	0.86	1.00	
Luca Si				
$\delta g_L^b$	$0.003 \pm 0.002$	-0.23	-0.14	1.00
$\delta g_R^b$	$0.019 \pm 0.008$	-0.28	-0.22	0.90
		1.00		

	Prediction	$\alpha_s$	$\Delta\alpha_{\text{had}}^{(5)}$	$M_Z$	$m_t$
$M_W$ [GeV]	$80.3618 \pm 0.0080$	$\pm 0.0007$	$\pm 0.0060$	$\pm 0.0026$	$\pm 0.0046$
$\Gamma_W$ [GeV]	$2.08849 \pm 0.00074$	$\pm 0.00040$	$\pm 0.00047$	$\pm 0.00021$	$\pm 0.00036$
$\Gamma_Z$ [GeV]	$2.49403 \pm 0.00065$	$\pm 0.00050$	$\pm 0.00031$	$\pm 0.00021$	$\pm 0.00017$
$\sigma_h^0$ [nb]	$41.4910 \pm 0.0053$	$\pm 0.0049$	$\pm 0.0005$	$\pm 0.0020$	$\pm 0.0005$
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	$0.23148 \pm 0.00012$	$\pm 0.00000$	$\pm 0.00012$	$\pm 0.00002$	$\pm 0.00002$
$P_\tau^{\text{pol}} = \mathcal{A}_\ell$	$0.14731 \pm 0.00093$	$\pm 0.00003$	$\pm 0.00091$	$\pm 0.00012$	$\pm 0.00019$
$\mathcal{A}_c$	$0.66802 \pm 0.00041$	$\pm 0.00001$	$\pm 0.00040$	$\pm 0.00005$	$\pm 0.00008$
$\mathcal{A}_b$	$0.934643 \pm 0.000075$	$\pm 0.000001$	$\pm 0.000075$	$\pm 0.000010$	$\pm 0.000005$
$A_{\text{FB}}^{0,\ell}$	$0.01627 \pm 0.00021$	$\pm 0.00001$	$\pm 0.00020$	$\pm 0.00003$	$\pm 0.00004$
$A_{\text{FB}}^{0,c}$	$0.07381 \pm 0.00052$	$\pm 0.00002$	$\pm 0.00050$	$\pm 0.00007$	$\pm 0.00010$
$A_{\text{FB}}^{0,b}$	$0.10326 \pm 0.00067$	$\pm 0.00002$	$\pm 0.00065$	$\pm 0.00008$	$\pm 0.00013$
$R_\ell^0$	$20.7478 \pm 0.0065$	$\pm 0.0062$	$\pm 0.0020$	$\pm 0.0003$	$\pm 0.0003$
$R_c^0$	$0.172222 \pm 0.000022$	$\pm 0.000019$	$\pm 0.000007$	$\pm 0.000001$	$\pm 0.000009$
$R_b^0$	$0.215800 \pm 0.000029$	$\pm 0.000011$	$\pm 0.000004$	$\pm 0.000000$	$\pm 0.000026$

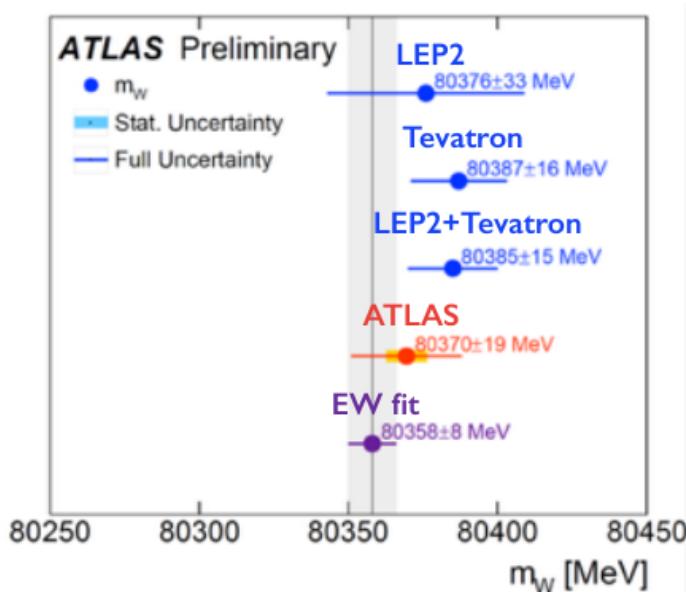
Parametric error budget for theoretical predictions (no fit)

# IMPACT OF ATLAS MEASUREMENT OF $W$ MASS

- $W$  mass combination:  $M_W = 80.379 \pm 0.012 \text{ GeV}$
- Minor effect on the global SM EW fit

$$M_W^{\text{ATLAS}} = 80.370 \pm 0.019 \text{ GeV}$$

First LHC meas. of  $M_W$



	Posterior	Posterior
$\alpha_s(M_Z)$	$0.1181 \pm 0.0009$	$0.1180 \pm 0.0009$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z)$	$0.02740 \pm 0.00025$	$0.02740 \pm 0.00024$
$M_Z$ [GeV]	$91.1879 \pm 0.0021$	$91.1879 \pm 0.0021$
$m_t$ [GeV]	$173.62 \pm 0.73$	$173.64 \pm 0.72$
$m_H$ [GeV]	$125.09 \pm 0.24$	$125.09 \pm 0.24$
$M_W$ [GeV]	$80.366 \pm 0.006$	$80.366 \pm 0.006$
$\Gamma_W$ [GeV]	$2.0889 \pm 0.0006$	$2.0889 \pm 0.0006$
$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	$0.231440 \pm 0.000086$	$0.231437 \pm 0.000083$
$P_\tau^{\text{pol}} = \mathcal{A}_\ell$	$0.14767 \pm 0.00067$	$0.14769 \pm 0.00065$
$\Gamma_Z$ [GeV]	$2.4943 \pm 0.0006$	$2.4943 \pm 0.0006$
$\sigma_h^0$ [nb]	$41.490 \pm 0.005$	$41.490 \pm 0.005$
$R_\ell^0$	$20.749 \pm 0.006$	$20.749 \pm 0.006$
$A_{\text{FB}}^{0,\ell}$	$0.01635 \pm 0.00015$	$0.01636 \pm 0.00015$
$\mathcal{A}_\ell$ (SLD)	$0.14767 \pm 0.00067$	$0.14769 \pm 0.00065$
$\mathcal{A}_c$	$0.6682 \pm 0.0003$	$0.6682 \pm 0.0003$
$\mathcal{A}_b$	$0.93479 \pm 0.00006$	$0.93480 \pm 0.00005$
$A_{\text{FB}}^{0,c}$	$0.07400 \pm 0.00037$	$0.07401 \pm 0.00036$
$A_{\text{FB}}^{0,b}$	$0.10353 \pm 0.00048$	$0.10354 \pm 0.00046$
$R_c^0$	$0.17223 \pm 0.00002$	$0.17223 \pm 0.00002$
$R_b^0$	$0.21579 \pm 0.00003$	$0.21579 \pm 0.00003$
$M_W$ LEP2+Tevatron		$M_W$ LEP2+Tevatron+ATLAS

# Future Prospects: EWPO

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

# Future Prospects: Higgs + Th

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

Observable	Current	Future	Current	ILC	FCC-ee	CepC	[Freitas et al., <a href="#">1307.3962</a> ; A. Freitas, <a href="#">1406.6980</a> , <a href="#">1604.00406</a> ]
	Th. Error	Th. Error	Exp. Error				
$M_W$ [MeV]	4	1	15	3 – 4	1	3	
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$ [ $10^{-5}$ ]	4.5	1.5	16	1	0.6	2.3	
$\Gamma_Z$ [MeV]	0.5	0.2	2.3	0.8	0.1	0.5	
$R_b^0$ [ $10^{-5}$ ]	15	10	66	14	6	17	

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

# EWPO AT FUTURE COLLIDERS: SM UNCERTAINTIES

- Current SM parametric uncertainties dominated by  $\alpha_S$  &  $\alpha_{\text{QED}}$  at  $M_Z$
- Future determinations of SM input parameters ( $\alpha_S$  &  $\alpha_{\text{QED}}$  at  $M_Z$ ):
  - Strong coupling constant:
    - Lattice projection:  $\delta\alpha_S(M_Z^2) \approx 0.0002$
  - Electromagnetic constant:
    - BES III & VEPP-2000  $\delta(\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)) \approx 0.00005$
    - FCC-ee P. Janot, JHEP 1602 (2016) 053

Measure  $A_{FB}^{\mu\mu}$  just below and just above the  $Z$  pole  
→ Direct determination of  $\alpha_{\text{QED}}(M_Z^2)$

With a 1-year running period at 87.9/94.3 GeV (85 ab<sup>-1</sup>):

$$\frac{\delta\alpha_{\text{QED}}^{-1}(M_Z^2)}{\alpha_{\text{QED}}^{-1}(M_Z^2)} \sim 3 \times 10^{-5}$$

(Comparable to  $\delta(\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)) \approx 0.00003$  )

# EWPO AT FUTURE COLLIDERS: SM UNCERTAINTIES

- Experimental vs Parametric Uncertainties at the FCCee:

	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
$\delta M_W$ [MeV]	$\pm 15$	$\pm 8$	$\pm 1$	$\pm 0.6/\pm 1$	$\pm 1$
$\delta \Gamma_Z$ [MeV]	$\pm 2.3$	$\pm 0.73$	$\pm 0.1$	$\pm 0.1$	$\pm 0.2$
$\delta \mathcal{A}_\ell [\times 10^{-5}]$	$\pm 210$	$\pm 93$	$\pm 2.1$	$\pm 8/\pm 14$	$\pm 11.8$
$\delta R_b^0 [\times 10^{-5}]$	$\pm 66$	$\pm 3$	$\pm 6$	$\pm 0.3$	$\pm 10$

	$\alpha_s$	$\alpha_{\text{QED}}/\Delta\alpha_{\text{had}}^{(5)}$	$M_Z$	$m_t$	Total	FCCee
$\delta M_W$ [MeV]	$\pm 0.14$	$\pm 0.53/\pm 0.92$	$\pm 0.1$	$\pm 0.3$	$\pm 0.64/\pm 0.98$	$\pm 1$
$\delta \Gamma_Z$ [MeV]	$\pm 0.099$	$\pm 0.03/\pm 0.05$	$\pm 0.01$	$\pm 0.01$	$\pm 0.1/\pm 0.11$	$\pm 0.1$
$\delta \mathcal{A}_\ell [\times 10^{-5}]$	$\pm 0.54$	$\pm 8/\pm 14$	$\pm 0.56$	$\pm 1.2$	$\pm 8.1/\pm 14$	$\pm 2.1$
$\delta R_b^0 [\times 10^{-5}]$	$\pm 0.22$	$\pm 0.04/\pm 0.07$	$\pm 0.003$	$\pm 0.17$	$\pm 0.28/\pm 0.29$	$\pm 6$

Even with future improvements  
 SM par. + th. unc.  $\gtrsim$  exp. errors

# Data from Run II

- $h \rightarrow b\bar{b}$ : ATLAS-CONF-2016-091, ATLAS-CONF-2016-080, CMS-PAS-HIG-16-003, CMS-PAS-HIG-16-038
- $h \rightarrow \gamma\gamma$ : ATLAS-CONF-2016-081, CMS-PAS-HIG-16-040
- $h \rightarrow \tau\bar{\tau}$ : CMS-PAS-HIG-16-043, CMS-PAS-HIG-17-003
- $h \rightarrow W^+W^-$ : ATLAS-CONF-2016-112
- $h \rightarrow ZZ$ : ATLAS-CONF-2016-081, CMS-PAS-HIG-16-041
- $h \rightarrow \mu\bar{\mu}$ : arXiv:1705.04582

# EW fit - all ops

Operator	Fit result		Correlations							
	$\frac{C_i}{\Lambda^2}$	[TeV $^{-2}$ ]								
$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{l}_L \gamma^\mu l_L)$	$0.012 \pm 0.012$	1							
$\mathcal{O}_{\phi l}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu^a \phi) (\bar{l}_L \gamma^\mu \sigma_a l_L)$	$-0.027 \pm 0.018$	-0.47	1						
$\mathcal{O}_{\phi e}^{(1)}$	$(\phi^\dagger i D_\mu \phi) (\bar{e}_R \gamma^\mu e_R)$	$-0.006 \pm 0.010$	0.45	0.30	1					
$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{q}_L \gamma^\mu q_L)$	$-0.017 \pm 0.045$	-0.04	-0.03	-0.11	1				
$\mathcal{O}_{\phi q}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu^a \phi) (\bar{q}_L \gamma^\mu \sigma_a q_L)$	$-0.095 \pm 0.048$	0.06	0.09	-0.05	-0.39	1			
$\mathcal{O}_{\phi u}^{(1)}$	$(\phi^\dagger i D_\mu \phi) (\bar{u}_R \gamma^\mu u_R)$	$0.100 \pm 0.160$	0.02	0.00	0.04	0.62	-0.78	1		
$\mathcal{O}_{\phi d}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{d}_R \gamma^\mu d_R)$	$-0.670 \pm 0.260$	-0.09	-0.06	-0.26	0.35	0.61	-0.12	1	
$\mathcal{O}_{ll}$	$(\bar{l} \gamma_\mu l)(\bar{l} \gamma^\mu l)$	$-0.028 \pm 0.029$	-0.75	0.86	0.03	-0.03	-0.04	0.01	-0.08	1