Indirect bounds from EW physics

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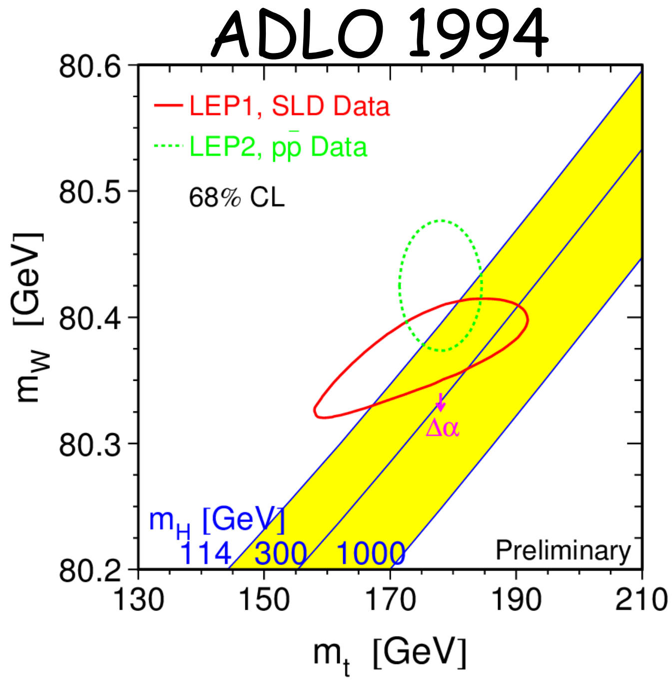
- EWPO: SM & NP fit
- Higgs couplings in EFT
- The dim-6 effective Lagrangian
- Future prospects

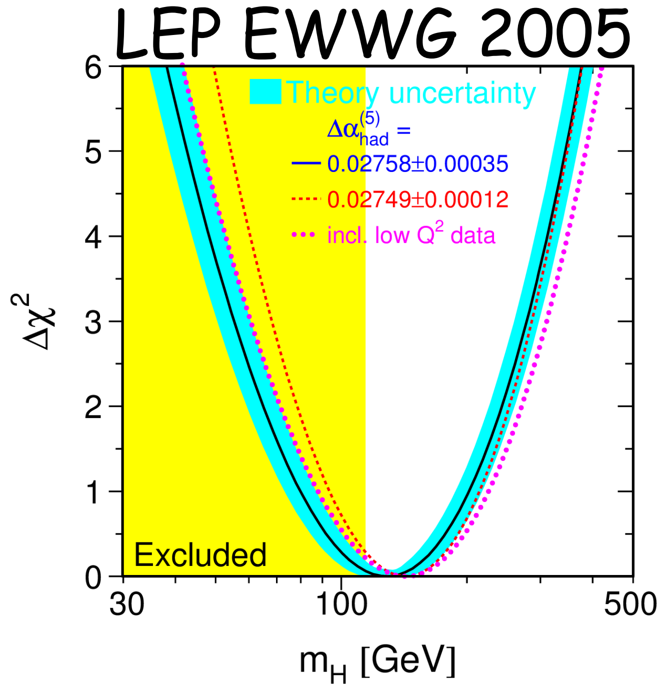
based on work done with:
J. de Blas, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini & the HEP*fit* crew
JHEP 08 (2013) 106, 12 (2016) 135
+ update in preparation

special thanks to Jorge & Luca

HEFT 2017
22-24 May 2017
Lumley Castle

EWPO & SM FIT





Spontaneous breaking of $SU(2)_L \otimes U(1)_Y$ via Higgs doublet vev & renormalizability imply:

1) tree-level relations in EW sector

2) calculable loop corrections

$\Rightarrow$ EWPO are potentially very sensitive to the NP scale

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

actual NP scale sensitivity depends on the experimental precision and SM theoretical uncertainty

EW fits

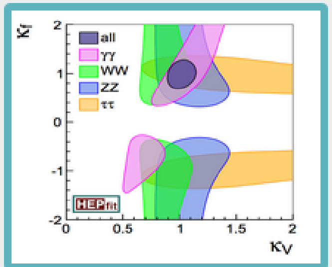
- choose the SM input parameters: G_F, α, M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}^{(5)}$
- use latest experimental data and state-of-the-art computation of EWPO
- parametrize possible NP effects: modified couplings, additional loop contributions, D=6 operators
- perform a fit to experimental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

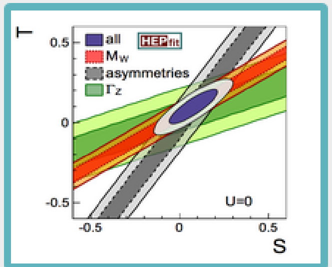
webpage with docs & releases: http://hepfit.roma1.infn.it
developer repository: https://github.com/silvest/HEPfit

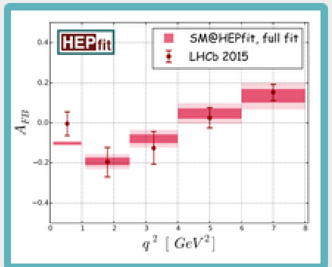
HEPfit

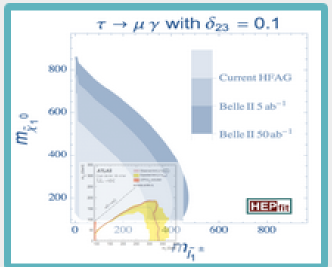
home developers samples documentation

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.

Open source, community-developed C++ code

	Ref.	Measurement	Posterior	Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	[10]	0.1179 ± 0.0012	PDG .1180 ± 0.0011	0.1185 ± 0.0028	-0.2	
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$	[13]	0.02750 ± 0.00033	Burkhardt et al 025	0.02743 ± 0.00038	0.04	
M_Z [GeV]	[14]	91.1875 ± 0.0021	LEP 1.1879 ± 0.0020	91.199 ± 0.011	[illegible]	
m_t [GeV]	[15]	173.34 ± 0.76	TeV + LHC ± 0.73	176.6 ± 2.5	-1.3	
m_H [GeV]	[16]	125.09 ± 0.24	LHC 125.09 ± 0.24	102.8 ± 26.3	0.8	
M_W [GeV]	[17]	80.385 ± 0.015	TeV + LEP2 0.0061	80.3604 ± 0.0066	1.5	
Γ_W [GeV]	[18]	2.085 ± 0.042	TeV + LEP2 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	LEP .231464 ± 0.000087	0.231435 ± 0.000090	0.8	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	[14]	0.1465 ± 0.0033	LEP .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	LEP 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	LEP + SLD ± 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	CDF		2.1	
$\sin^2\theta_{\rm eff}^{\mu\mu}$	[20]	0.2315 ± 0.0010	CDF		0.07	
$\sin^2\theta_{\rm eff}^{ee}$	[21]	0.23146 ± 0.00047	D0 0.231464 ± 0.000087	0.231435 ± 0.000090	0.1	
$\sin^2\theta_{\rm eff}^{ee,\mu\mu}$	[22]	0.2308 ± 0.0012	ATLAS		-0.5	
$\sin^2\theta_{\rm eff}^{\mu\mu}$	[23]	0.2287 ± 0.0032	CMS		-0.8	
$\sin^2\theta_{\rm eff}^{\mu\mu}$	[24]	0.2314 ± 0.0011	LHCb		-0.1	

Input parameters

preliminary

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Result of the global fit

Result of the fit not using the corresponding measurement

preliminary

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Difference between measurement and prediction in units of σ, taking all correlations into account

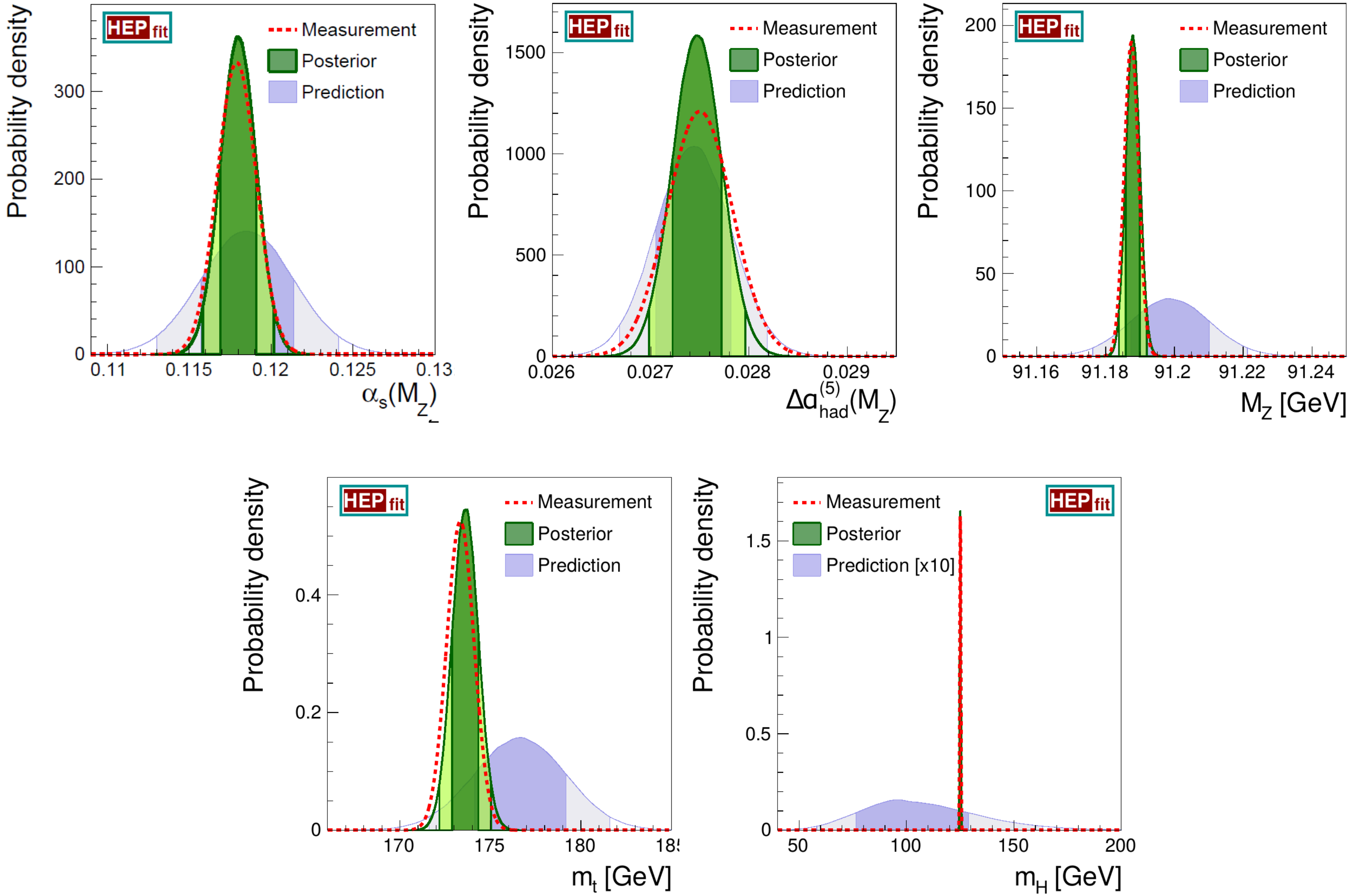
Difference between measurement and prediction in units of σ, neglecting correlations

Correlated Observables

preliminary

	Prediction	α_s	$\Delta\alpha_{\rm had}^{(5)}$	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
$\sin^2\theta_{\rm eff}^{\rm lept}$	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)

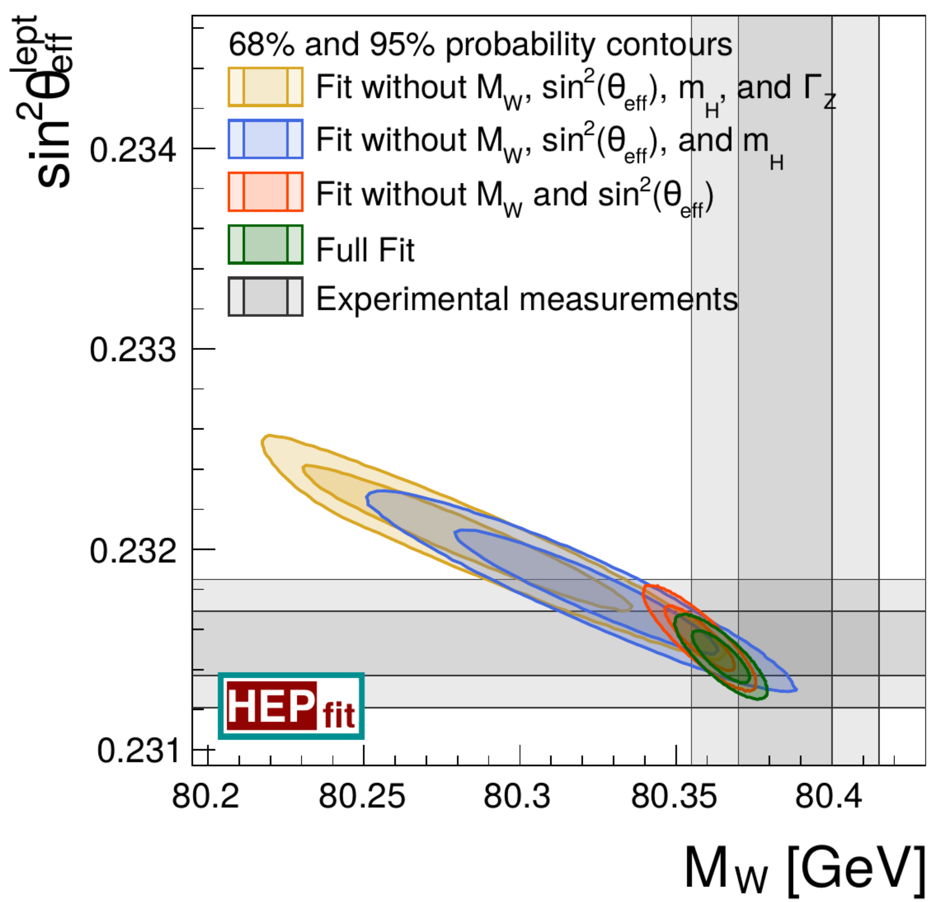


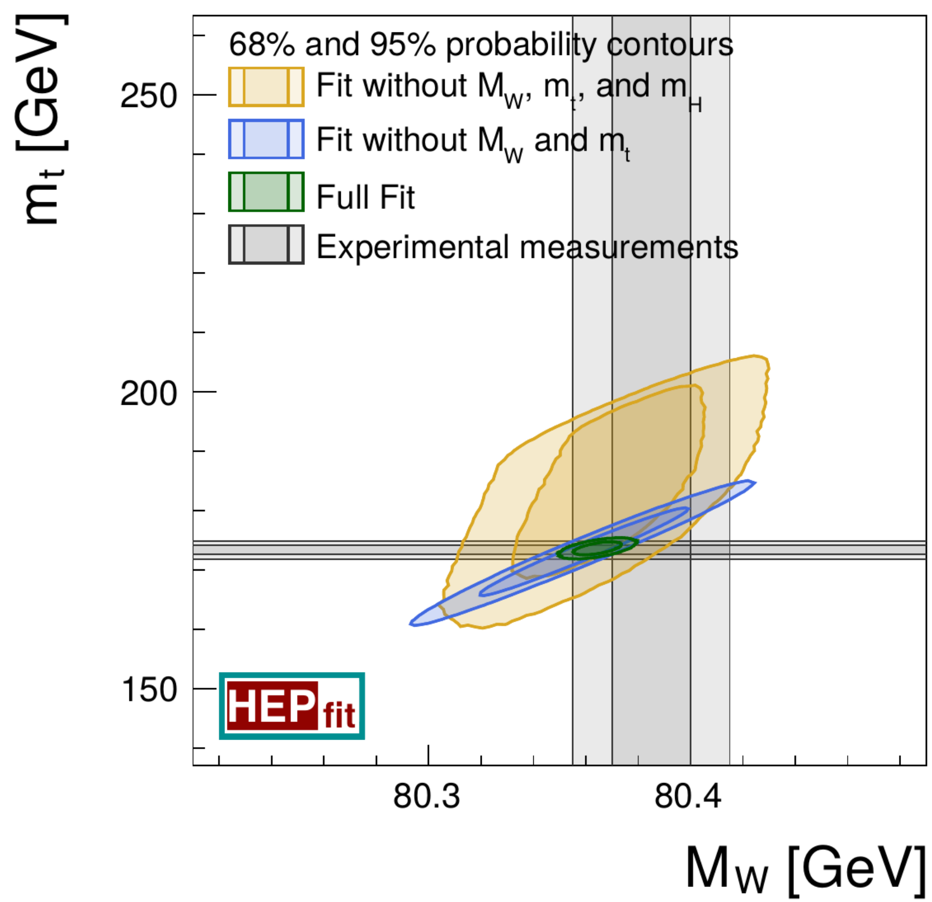
Excellent agreement between full, direct and indirect determinations of input parameters

preliminary

Impact of m_H, m_t, M_W, $\sin^2\theta$ & Γ_Z

preliminary



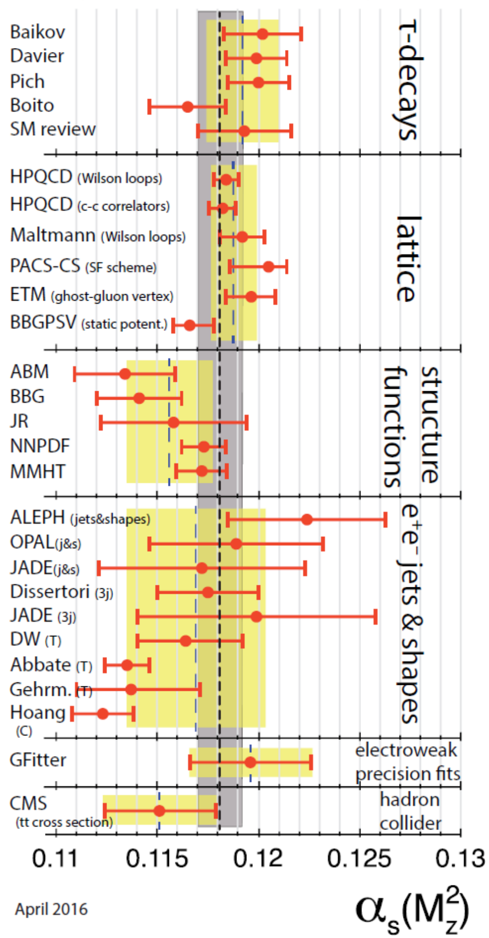


Recent changes

- **Strong coup. constant**

$$\alpha_S(M_Z) = 0.1180 \pm 0.0010$$

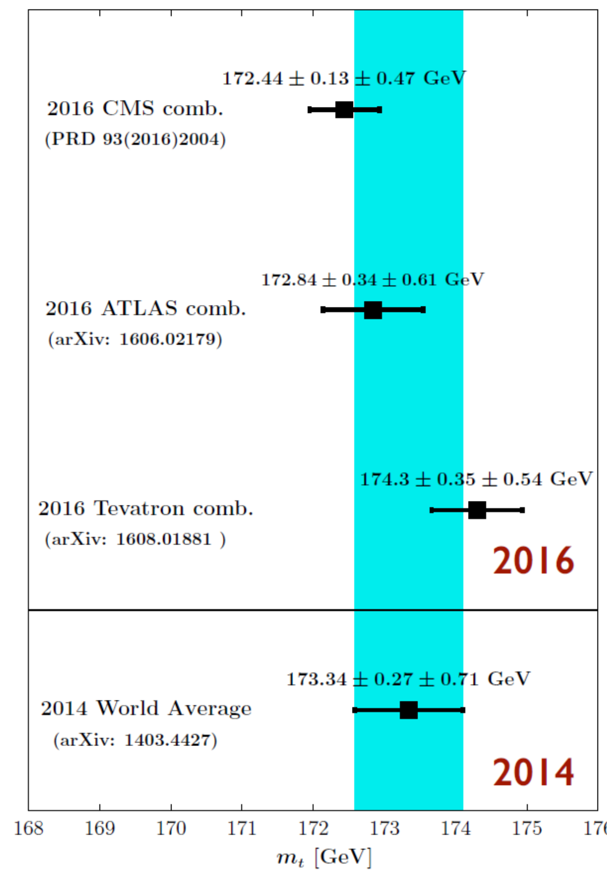
2016 PDG world average
(Excl. EW fit results)



- **Top quark mass**

$$m_t = 173.34 \pm 0.76 \text{ GeV}$$

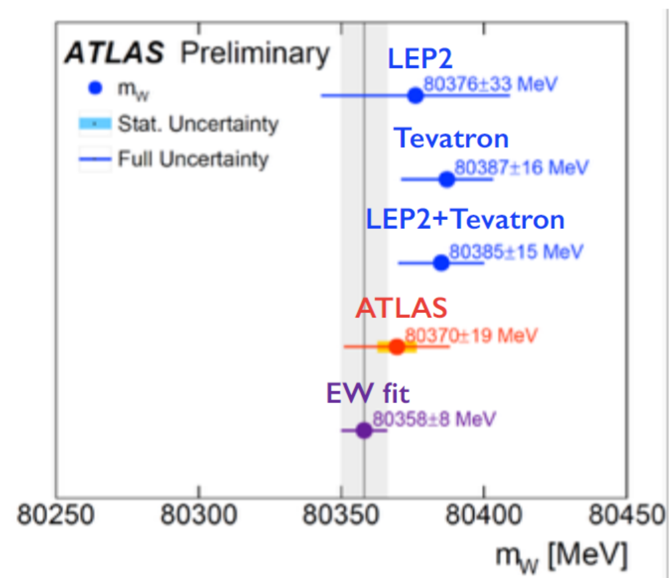
Current world average (2014)



- **W mass**

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

First LHC meas. of M_W

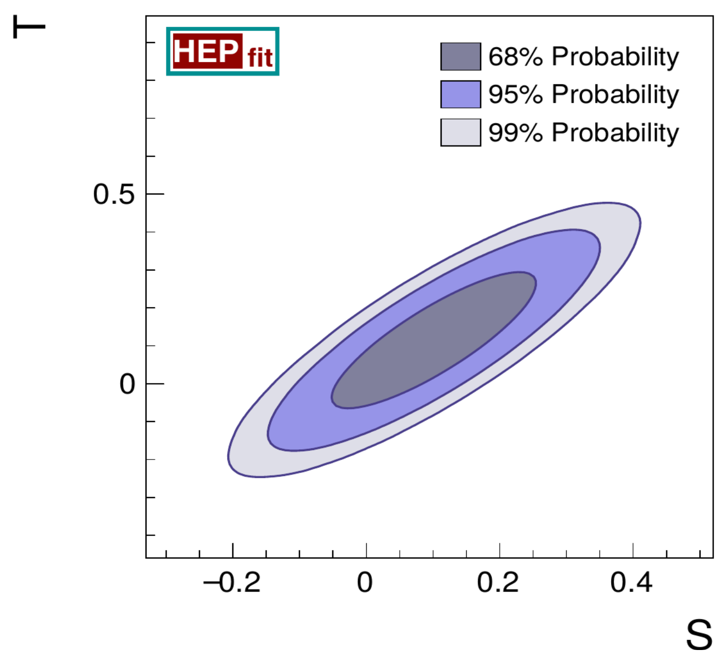


minor effect on the results of the fit

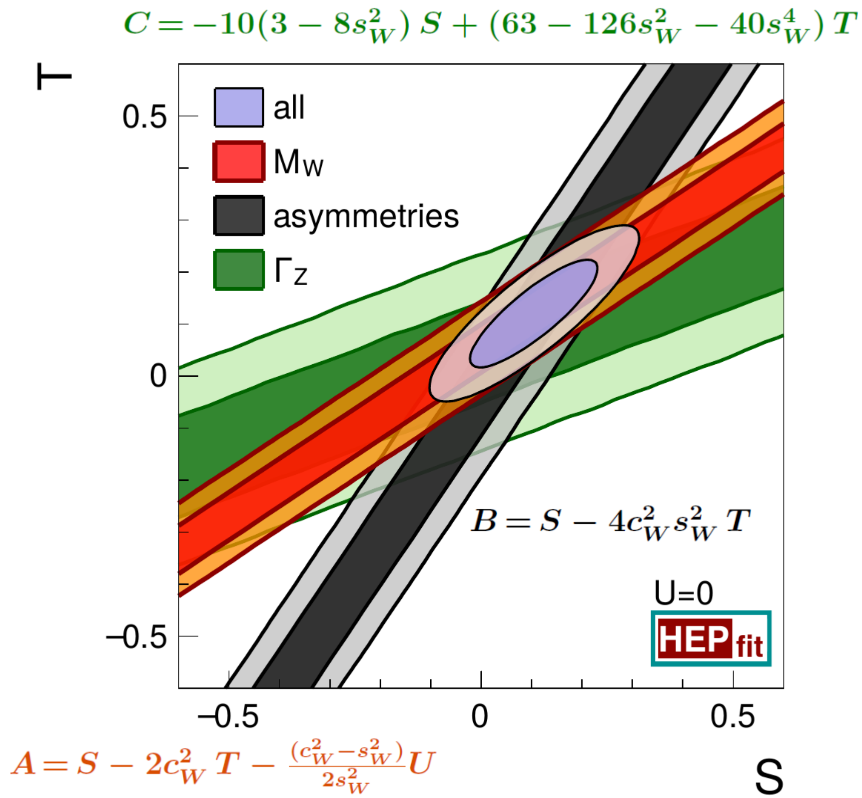
EWPO beyond the SM

Oblique corrections: NP in gauge boson vacuum polarizations

S,T,U or $\delta\varepsilon_{1,2,3,b}$



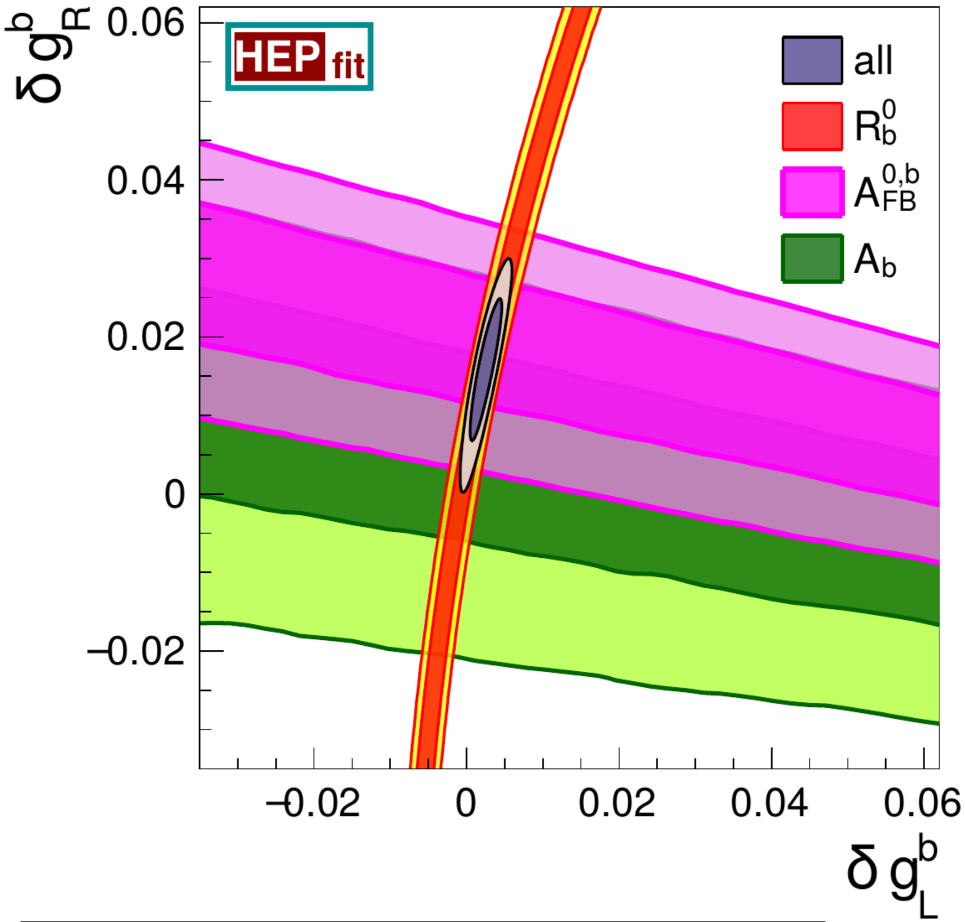
	Result	Correlation Matrix		
S	0.09 ± 0.10	1.00		
T	0.10 ± 0.12	0.86	1.00	
U	0.01 ± 0.09	-0.54	-0.81	1.00

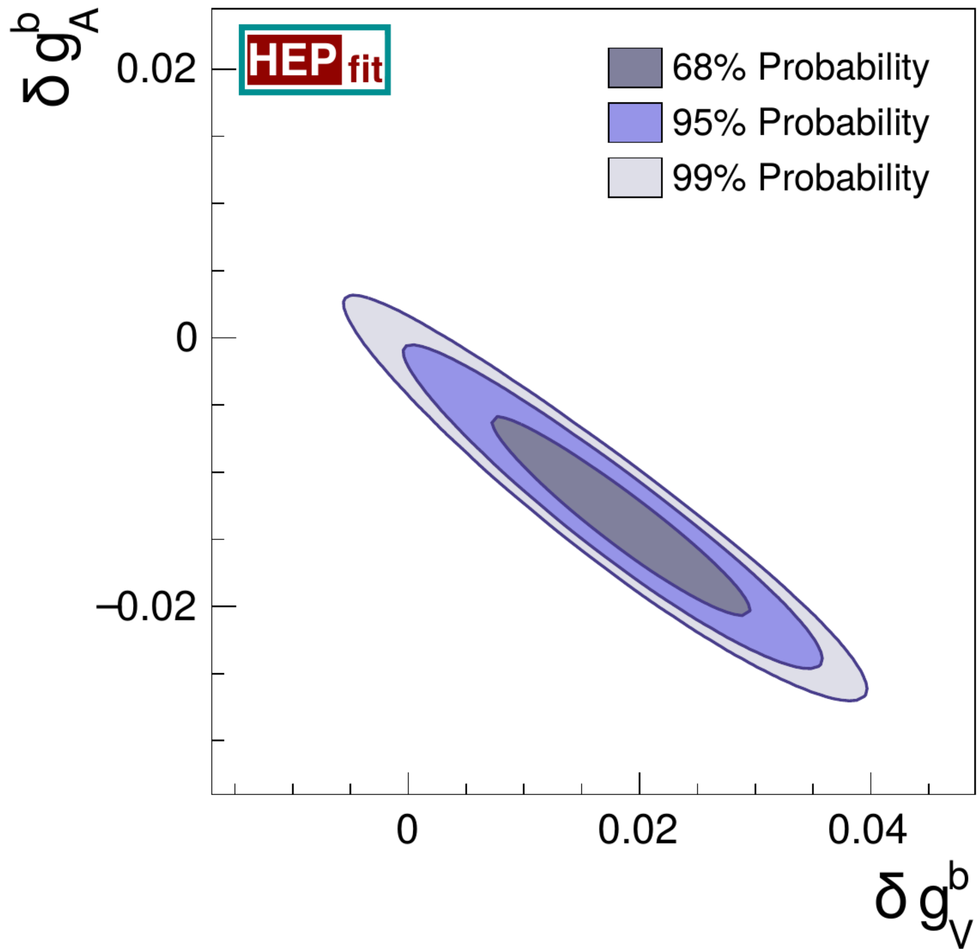


	Result	Correlation Matrix	
S	0.10 ± 0.08	1.00	
T	0.12 ± 0.07	0.86	1.00

	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 physics: signal strenghts

Theoretical predictions:

$$\mu = \sum_i w_i r_i \qquad r_i = \frac{[\sigma \times BR]_i}{[\sigma_{\rm SM} \times BR_{\rm SM}]_i} \qquad w_i = \frac{\epsilon_i [\sigma_{\rm SM} \times BR_{SM}]_i}{\sum_j \epsilon_j [\sigma_{\rm SM} \times BR_{SM}]_j}$$

Bechtle et al.

- σ's from LHC H cross section WG and BR's from Contino et al (14)
- no theoretical uncertainties attached to σ's and BR's
- SM efficiencies and K factors used

an example: ATLAS $h\gamma\gamma$ data card

```
###################
# arXiv 1408.7084
###################
# Name Definition weights mu -err_mu +err_mu
# weights are given as |ggH fraction, ttH fraction, VBF fraction, WH fraction,
ZH fraction|
###################
CATEGORIES ggH ttH VBF WH ZH
MEASUREMENT CentralLowpT |0.923 0.001 0.04 0.015 0.01| 0.624 -0.398 0.425
MEASUREMENT CentralHighpT |0.733 0.013 0.157 0.055 0.034| 1.619 -0.831 1.003
MEASUREMENT ForwLowpT |0.917 0.001 0.041 0.019 0.012| 2.034 -0.526 0.57
MEASUREMENT ForHighpT |0.719 0.009 0.162 0.064 0.039| 1.729 -1.18 1.343
MEASUREMENT VBFloose |0.419 0.001 0.565 0.006 0.004| 1.327 -0.773 0.915
MEASUREMENT VBFtight |0.19 0.01 0.805 0.002 0.001| 0.682 -0.508 0.667
MEASUREMENT VHhad |0.459 0.013 0.032 0.303 0.188| 0.227 -1.388 1.674
MEASUREMENT VHETmiss |0.023 0.095 0.003 0.369 0.51| 3.51 -2.417 3.304
MEASUREMENT VHl |0.005 0.033 0.002 0.898 0.063| 0.408 -1.056 1.427
MEASUREMENT ttHhad |0.073 0.841 0.01 0.007 0.013| -0.842 -1.25 3.229
MEASUREMENT ttHlept |0.01 0.803 0.002 0.081 0.023| 2.423 -2.068 3.212
###################
```

Experimental constraints:

$h\gamma\gamma$: 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)

+ updates from Moriond '17 to be included

Higgs coupling analysis

In extensions of the SM for which:

Giudice et al.; Barbieri et al.; Contino et al.; Azatov et al.

- there is only one Higgs boson h below the cutoff $\Lambda = 4\pi v/\sqrt{|1-\kappa_v^2|}$
- there is an approximate custodial symmetry
- corrections are flavour diagonal and universal

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

- κ_V rescales the hVV couplings (=1 in SM)

  → oblique corrections:

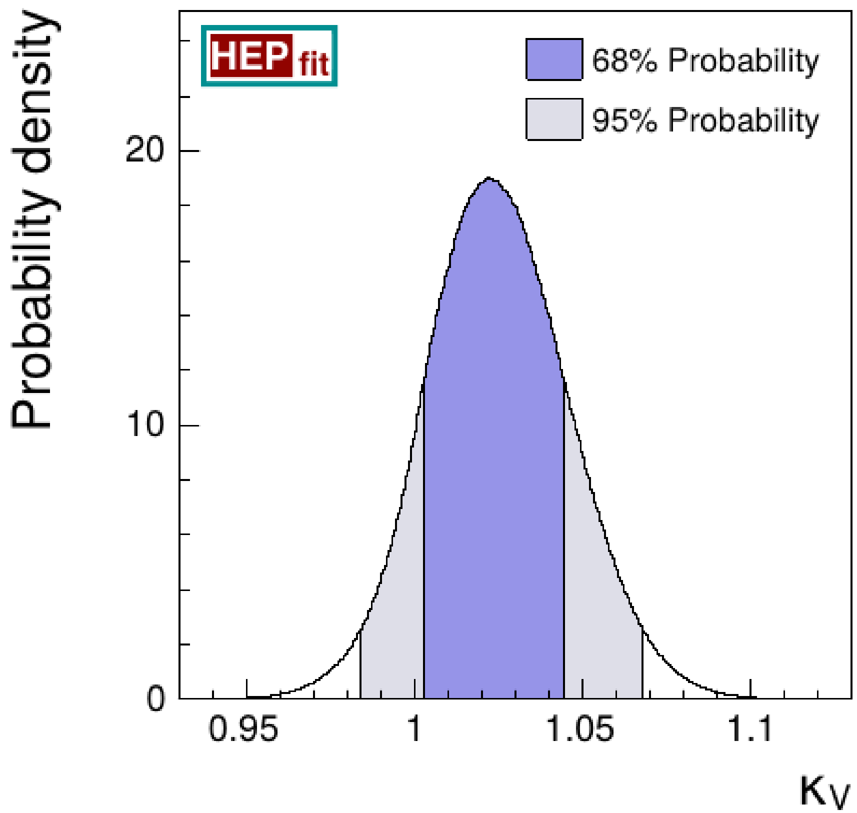
- κ_f rescales the hff couplings (=1 in SM)

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

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

Barbieri et al., PRD 76 (2007) 115008

EWPO constraints on κ_V and Λ *preliminary*



EWPO

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

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

Λ > 13 TeV for κ_V < 1

> 9 TeV for κ_V > 1

@95% prob.

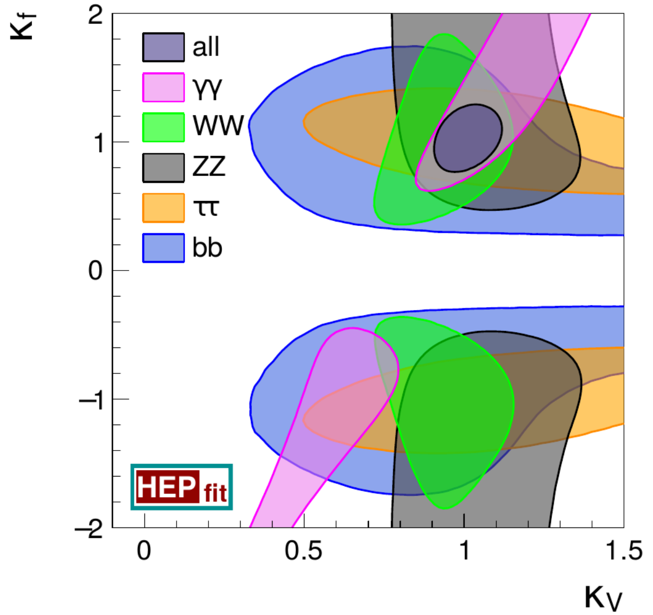
Implication for composite Higgs models (k_v < 1):

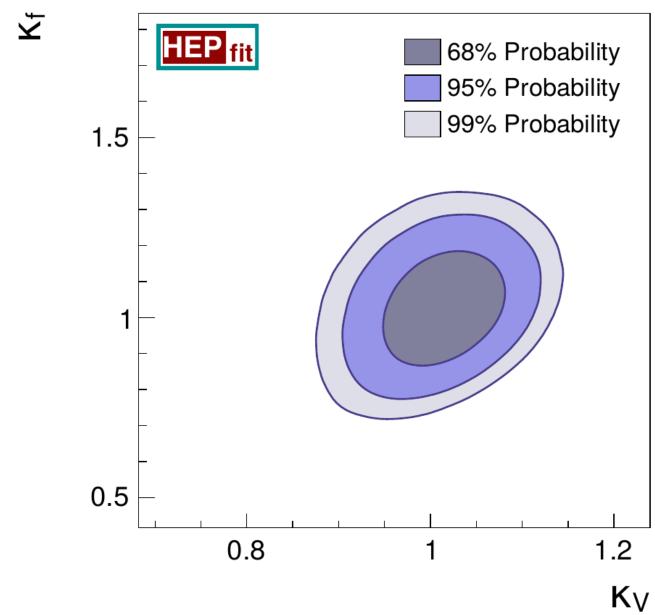
additional contributions to oblique corrections are needed to comply with the EWPO constraints

Grojean et al.; Azatov et al.; Pich et al.

Fit to κ_V and κ_f

preliminary



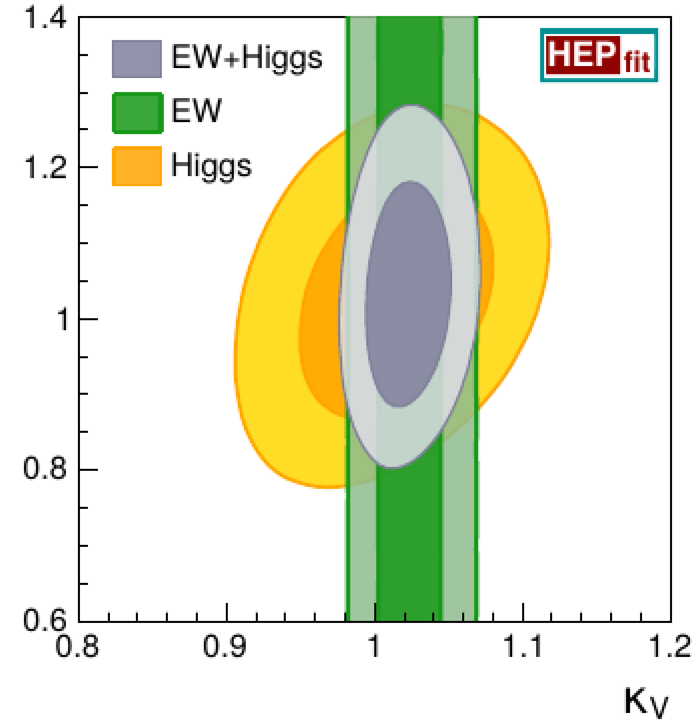


Higgs data only

	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

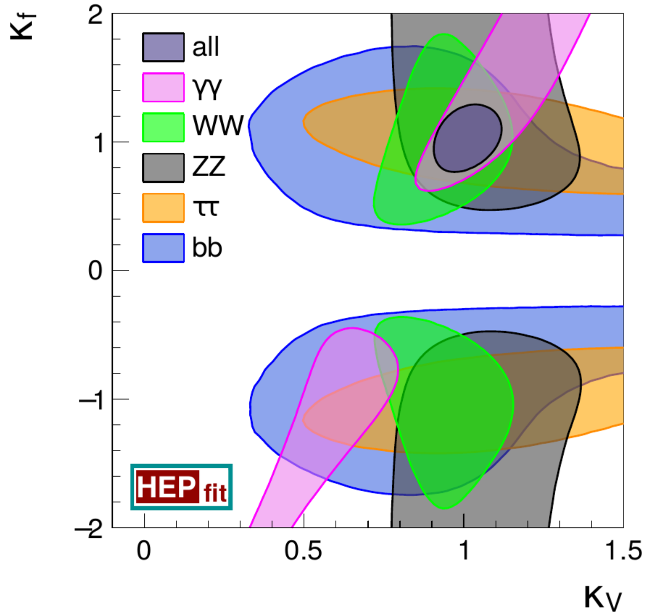
Higgs + EWPO

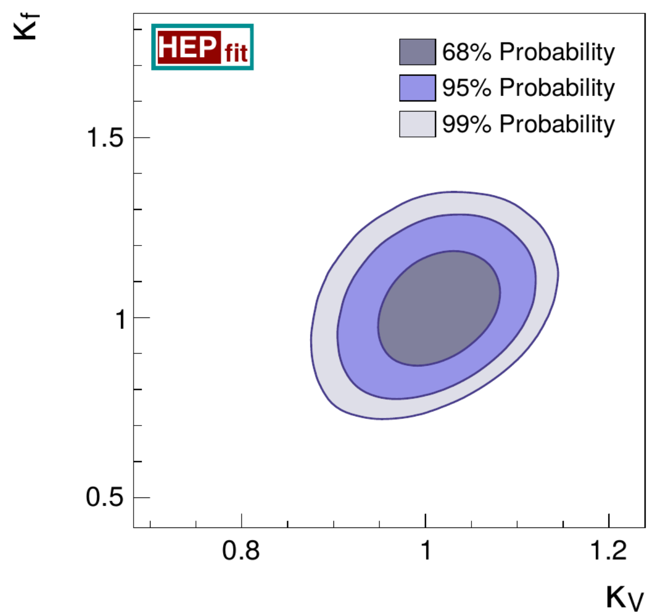
	Result	95% Prob.	Correlation Matrix	
κ_V	1.02 ± 0.02	$[0.99, 1.06]$	1.00	
κ_f	1.03 ± 0.10	$[0.85, 1.23]$	0.14	1.00



Fit to κ_V and κ_f

preliminary





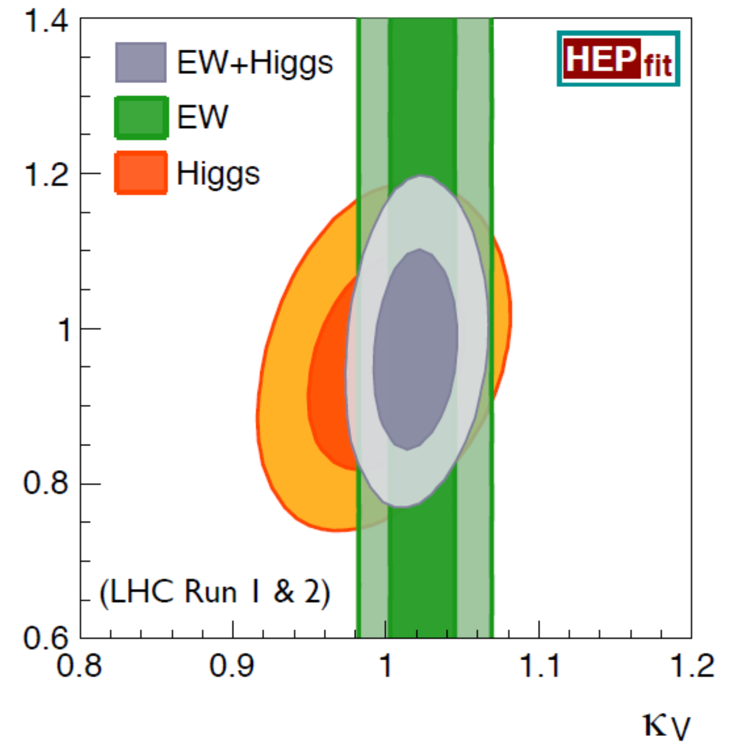
Higgs data only

	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

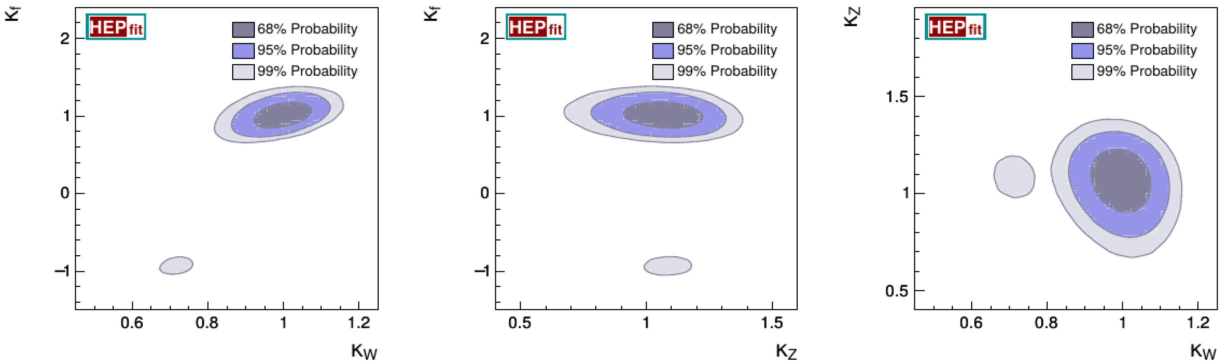
	Fit result	95% Prob.	Correlations	
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00	
κ_f	0.98 ± 0.08	[0.81, 1.14]	0.18	1.00

+ LHC Run 2 data



Testing the assumptions

- Custodial symmetry ($\kappa_V \to \kappa_W, \kappa_Z$)



Higgs

	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

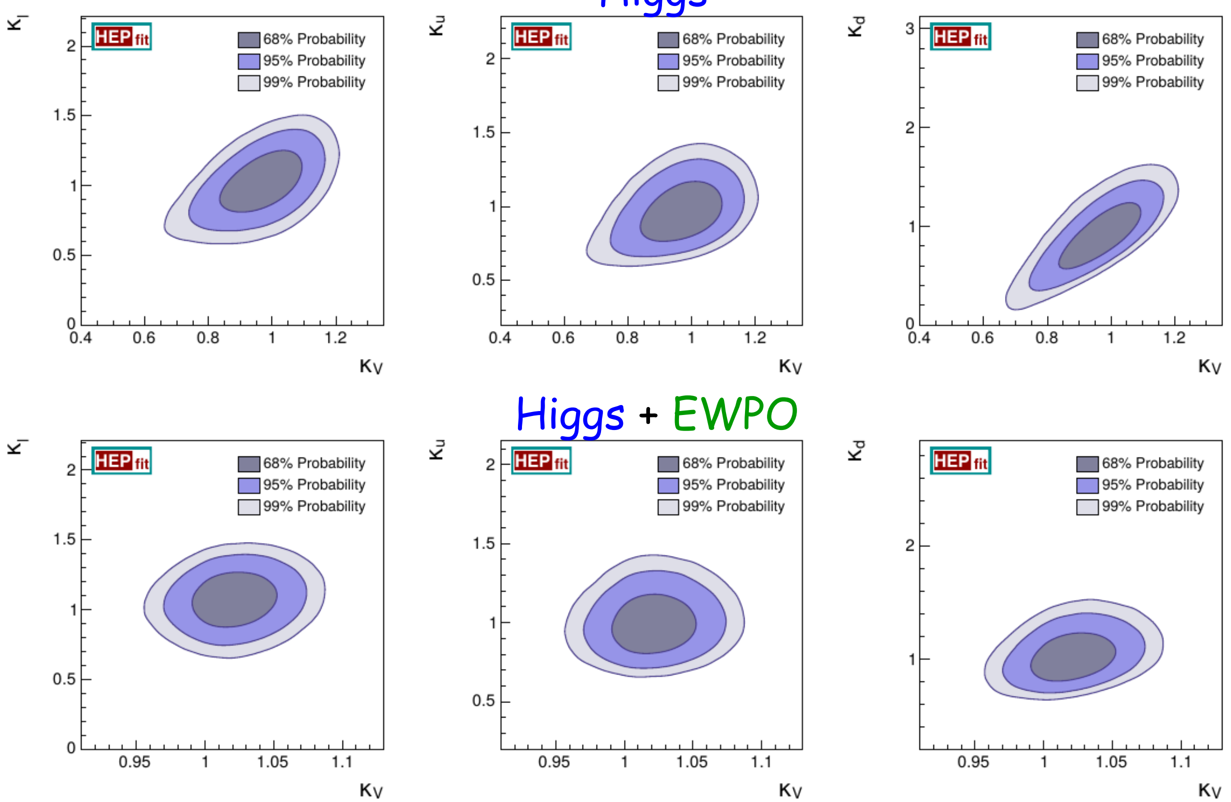
- Flavour universality ($\kappa_f \to \kappa_l, \kappa_u, \kappa_d$)

Higgs

	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



SMEFT & the NP scale

SU(2)xU(1)-invariant EFT with dim-6 NP operators:

Buchmuller & Wyler; Grzadkowski et al; Aguilar-Saavedra; del Aguila et al; Barbieri & Strumia; del Aguila & de Blas; Contino et al; Alonso et al

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- The full operator basis: 2499 operators
- Considering only flavour-diagonal and family-universal contributions: 59 operators
- Including only CP-even terms with at least one Higgs field: 27 operators
- Contributing to the observables
  - EWPO + Higgs: 17 operators
  - EWPO: 10 operators

Operator basis

Grzadkowski et al

bosonic

$$\mathcal{O}_{HG} = (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H) W^I_{\mu\nu} W^{I\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$
$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$

- corrections to hVV production & decays
- oblique corrections
- corrections to WWZ, WWγ

single-fermionic-current

$$\mathcal{O}^{(1)}_{HL} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{L} \gamma^\mu L)$$
$$\mathcal{O}^{(3)}_{HL} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{L} \tau^I \gamma^\mu L)$$
$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e}_R \gamma^\mu e_R)$$
$$\mathcal{O}^{(1)}_{HQ} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{Q} \gamma^\mu Q)$$
$$\mathcal{O}^{(3)}_{HQ} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{Q} \tau^I \gamma^\mu Q)$$
$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u}_R \gamma^\mu u_R)$$
$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d}_R \gamma^\mu d_R)$$

- corrections to hff
- corrections to Vff

single-fermionic-scalar

$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}\, e_R H)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\, u_R \widetilde{H})$$
$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}\, d_R H)$$

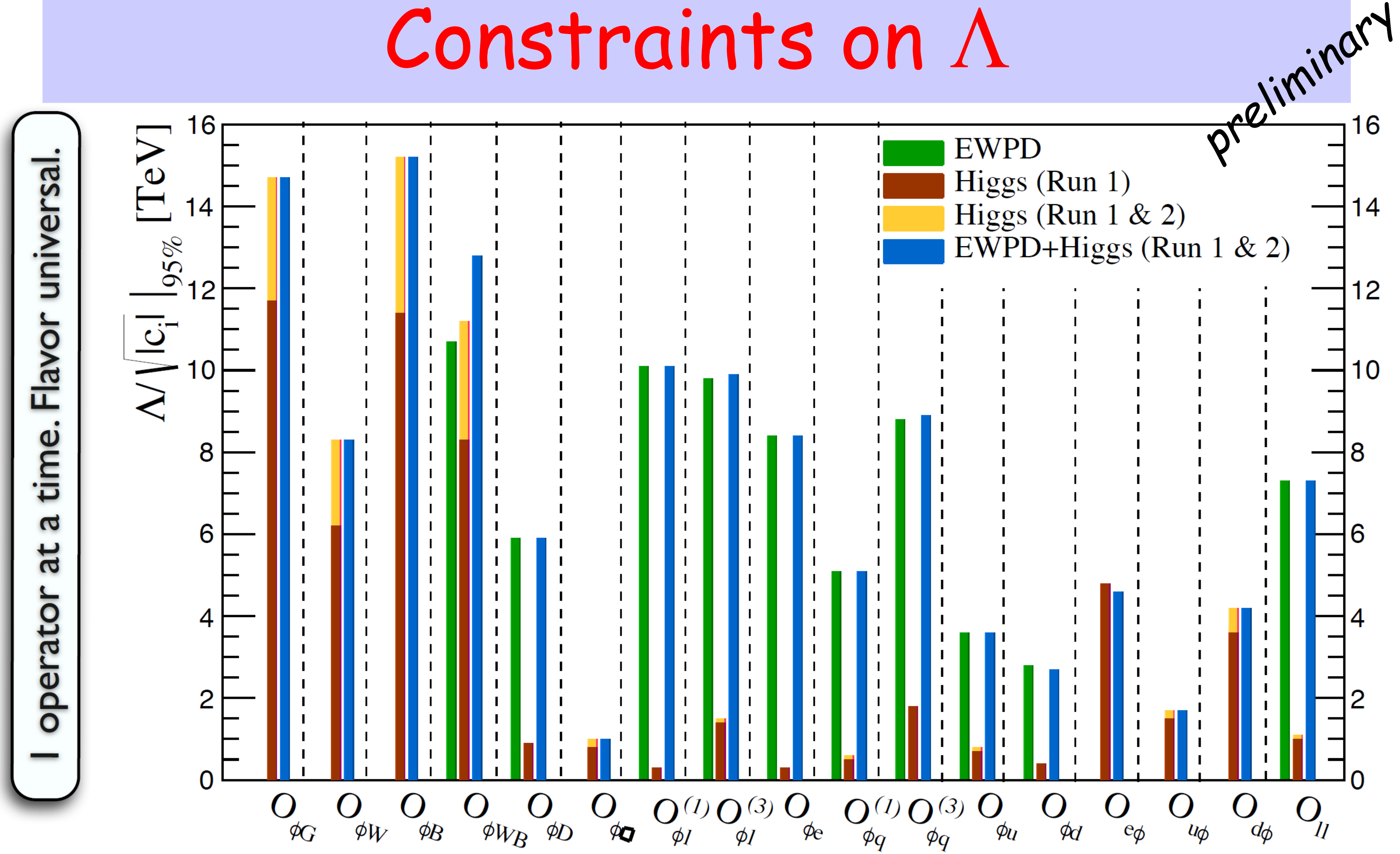
- corrections to Y's & hff

four-fermion

$$\mathcal{O}^{pqrs}_{LL} = (\overline{L}^p \gamma_\mu L^q)(\overline{L}^r \gamma^\mu L^s)$$

- G_F extraction from μ decay

Constraints on Λ



NP scale for $|C_i|$ = 1 in the multi-TeV region,
EWPO still more constraining than Higgs data

courtesy of J. de Blas

Future Prospects: EWPO

	Current Data	HL-LHC	ILC	FCCee	(Run)	CepC
$\alpha_s(M_Z)$	0.1179±0.0012					
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	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_h^0 [nb]	41.540±0.037			±0.025	(FCCee-Z)	
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.2324±0.0012			±0.0001	(FCCee-Z)	±0.000023
$P_\tau^{\rm pol}$	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])	
$A_{\rm FB}^{0,\ell}$	0.0171±0.0010			±0.0001	(FCCee-Z)	±0.0010
$A_{\rm FB}^{0,c}$	0.0707±0.0035			±0.0003	(FCCee-Z)	
$A_{\rm FB}^{0,b}$	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

Future Prospects: Higgs & theory

	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%	0.57%
$H \to c\bar{c}$			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

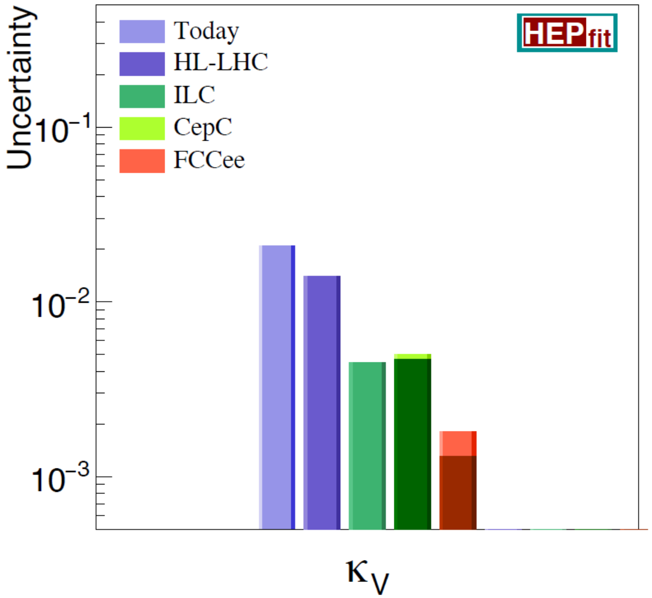
Freitas et al., 1307.3962; Freitas, 1406.6980, 1604.00406

P. Janot, 1512.05544

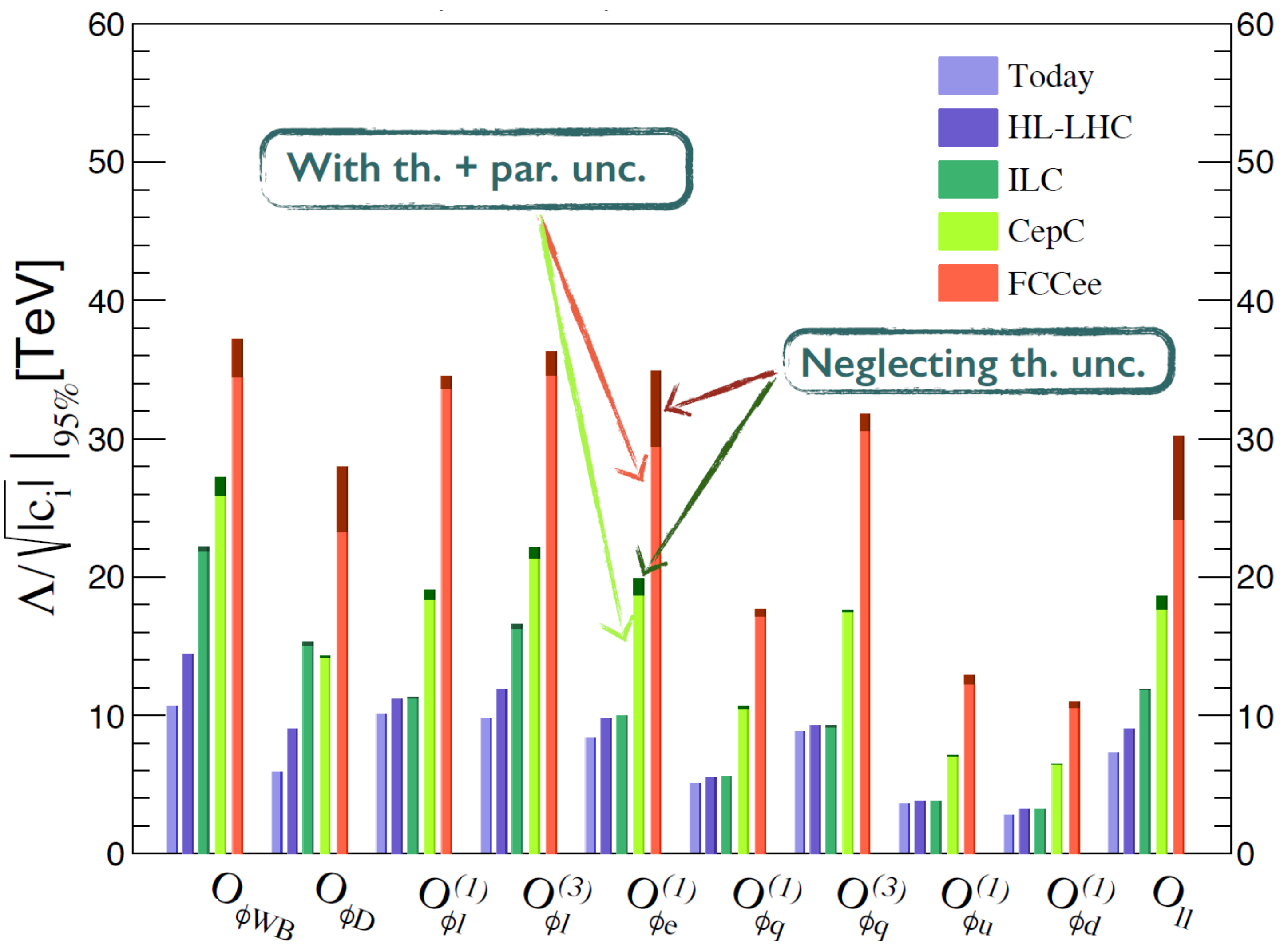
$\delta\alpha_s(M_Z) = 2\times10^{-4}$ (LQCD), $\delta\Delta\alpha^{(5)}_{\rm had} = 5\times10^{-5}$ (R) $[\delta\alpha(M_Z)=3\times10^{-5}\,(A_{FB}^{\mu\mu})]$

Future Prospects: NP analyses

preliminary



EWPO only

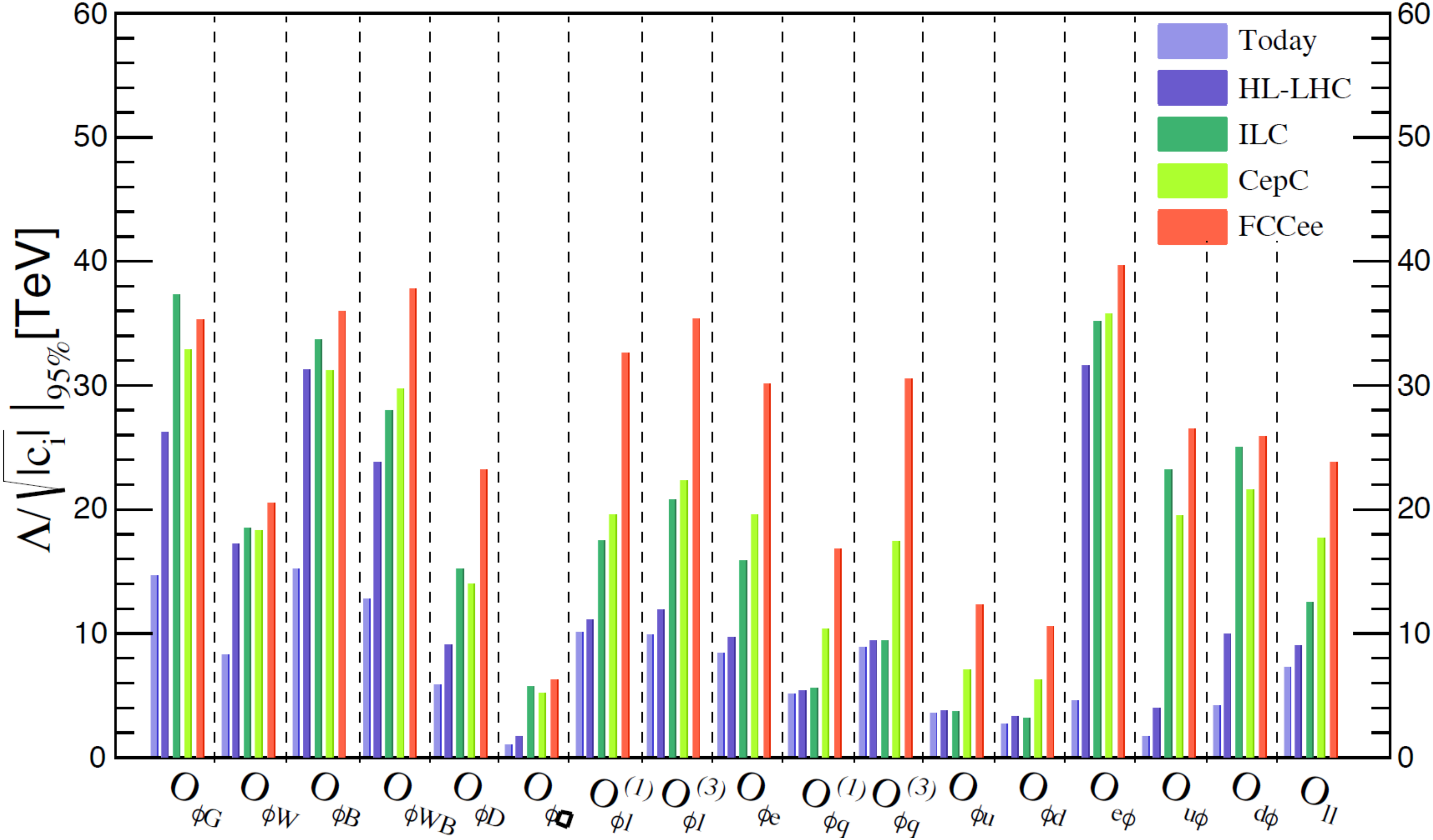


$\delta\kappa_v \rightarrow \delta\kappa_v / 10$

$\Lambda \rightarrow \Lambda \times 4$

Future Prospects: Λ from EWPO & μ_i

1 operator at a time. Flavor universal.



Conclusions & Outlook

EW fit is more important than ever: SM is complete, EWPO and Higgs data are complementary.
Agreement with 2-loop SM → strong contraints on NP (Λ > ~10 TeV for $|C_i|=1$)

Future e^+e^- experimental programs would substantially improve the NP sensitivity of the fit: ≥ 10x reduction of the uncertainty on S,T,U, and the Higgs couplings, ~4x improvement on the sensitivity to the NP scale

Reducing the parametric & theoretical uncertainties at the level required by future experiments is the challenge for the forthcoming years

BACKUP SLIDES

EWPO: M_W, Γ_W and 13 Z-pole observables

(LEP2/Tevatron) (LEP/SLD)

Pseudo-observables can be written in terms of Δr and effective Zff couplings

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

LEP EWWG; ZFITTER;
Chetyrkin et al; Baikov et al;
Czarnecki & Kühn;
Harlander et al; Bardin et al

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

$$\rho_Z^f = \left(\frac{g_A^f}{I_3^f}\right)^2$$

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

$$s_W^2 = 1 - \frac{M_W^2}{M_Z^2}$$ on-shell scheme

$$A_{\rm LR}^{0,f} = \mathcal{A}_f = \frac{2\,\mathrm{Re}\left(g_V^f/g_A^f\right)}{1+\left[\mathrm{Re}\left(g_V^f/g_A^f\right)\right]^2}$$

$$A_{\rm FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad (f=\ell,c,b)$$

$$P_\tau^{\rm pol} = \mathcal{A}_\tau$$

$$\sin^2\theta_{\rm eff}^{\rm lept} = \mathrm{Re}(\kappa_Z^\ell)s_W^2$$

$$\Gamma_f = \Gamma(Z\to f\bar{f}) \propto |\rho_Z^f|\left[\left|\frac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right] \Rightarrow \Gamma_Z,\ \sigma_h^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_h}{\Gamma_Z^2},\ R_\ell^0 = \frac{\Gamma_h}{\Gamma_\ell},\ R_{c,b}^0 = \frac{\Gamma_{c,b}}{\Gamma_h}$$

The 7 SM Input Parameters

- G_μ=1.1663787 10^{-5} GeV^{-2}, α=1/137.035999074 (PDG)
- M_Z = 91.1875 ± 0.0021 GeV (LEP)
- m_h=(125.09±0.24) GeV (ATLAS+CMS, 1503.07589)
- $\alpha_s(M_Z^2)$=0.1185±0.0005 (PDG excluding EWPO)
- $\Delta\alpha^5_{had}(M_Z^2)$ = 0.02750±0.00033 (Burkhardt & Pietrzyk; see also Davier et al, Hagiwara et al, Jegerlehner)
- m_t = 173.34 ± 0.76 GeV (TeVatron+LHC, 1403.4427)
  newer results from ATLAS (m_t = 172.99 ± 0.91 GeV), CMS (m_t = 172.38 ± 0.66 GeV) & TeVatron (m_t = 174.34 ± 0.63 GeV) have not been included yet

EW PRECISION OBSERVABLES IN THE SM

- Theory status:
  - 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
  - M_W : Full EW 2-loop + leading 3-loop & some 4-loop
    M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Phys. Rev D69 (2004) 053006
  - $\sin^2\theta^f_{\rm Eff}$ (light ferm): Full EW 2-loop + leading higher order
    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
  - 2014 Γ^f_Z : Full fermionic EW 2-loop
    A. Freitas, JHEP 1404 (2014) 070
  - 2016 $\sin^2\theta^b_{\rm Eff}$: First calculation of 2-loop bosonic corrections
    I. Dubovyk, A. Freitas, J. Gluza, T. Riemann, J. Usovitsch, arXiv: 1607.08375

- Experimental vs Theoretical uncertainties:

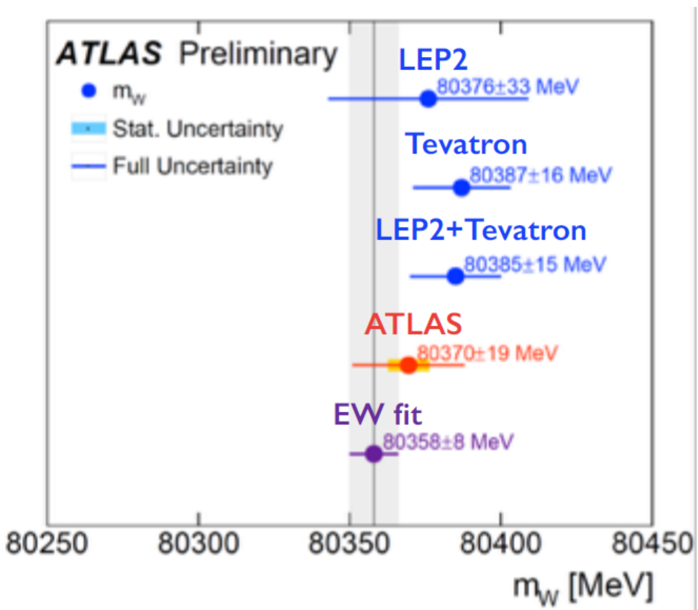
	M_W	Γ_Z	$\sigma^0_{\rm had}$	R_b	$\sin^2\theta^\ell_{\rm eff}$
Exp. error	15 MeV	2.3 MeV	37 pb	6.6×10^{-4}	1.6×10^{-4}
Theory error	4 MeV	0.5 MeV	6 pb	1.5×10^{-4}	0.5×10^{-4}

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

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

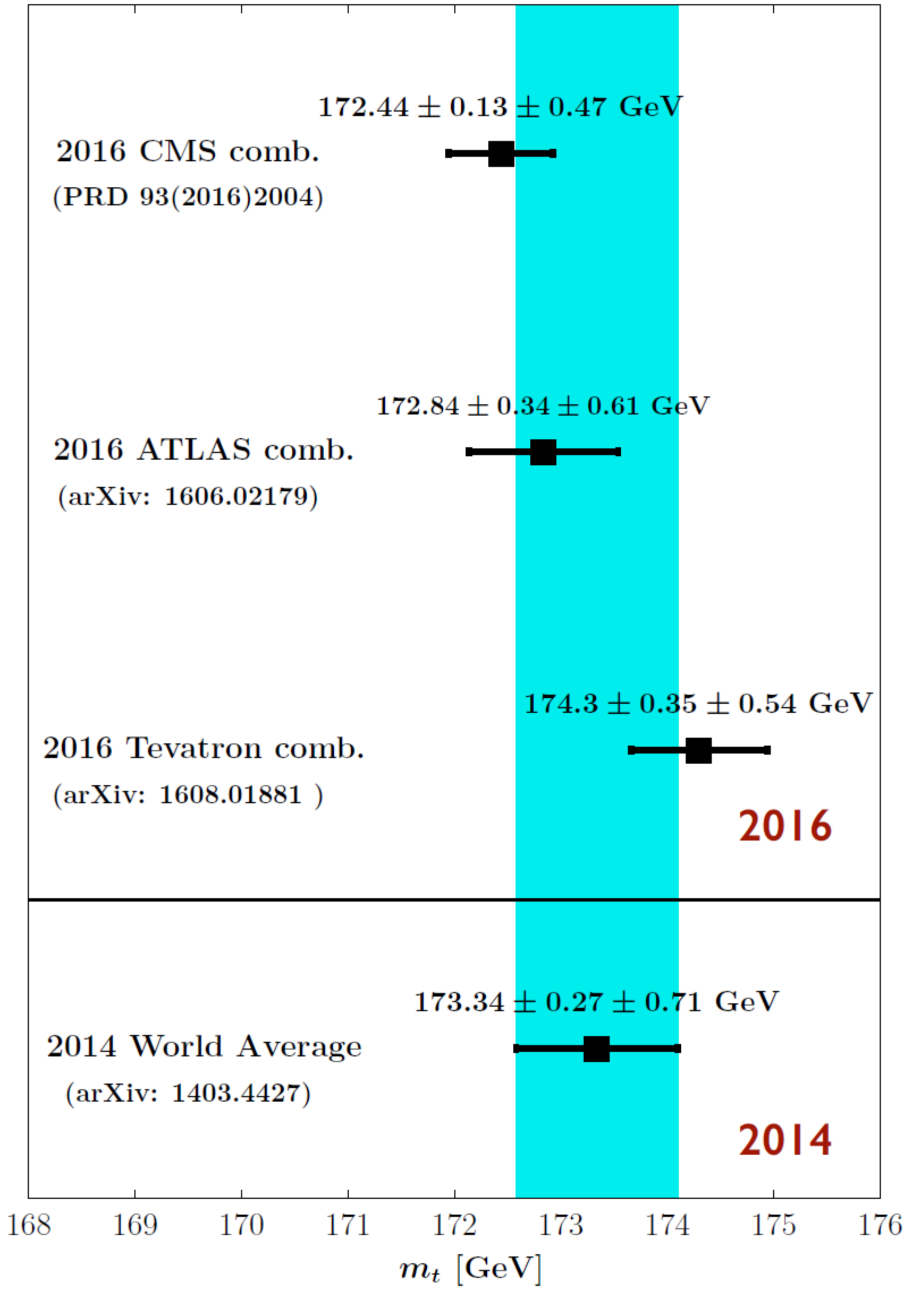
$$M_W^{\text{ATLAS}} = 80.370 \pm 0.019 \text{ GeV}$$

First LHC meas. of M_W



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

- Top mass and Higgs mass prediction:



$\rightarrow \quad M_H = 95 \pm 24 \text{ GeV} \quad (1.25\,\sigma)$

$\rightarrow \quad M_H = 99 \pm 25 \text{ GeV} \quad (1.04\,\sigma)$

$\rightarrow \quad M_H = 112 \pm 28 \text{ GeV} \quad (0.47\,\sigma)$

1. oblique NP: S, T, U

Assume that the dominant NP contributions come through the gauge boson self-energies

Kennedy & Lynn (89);
Peskin & Takeuchi (90,92)

$$S = -16\pi\Pi'_{30}(0) = 16\pi\left[\Pi_{33}^{\mathrm{NP}\prime}(0) - \Pi_{3Q}^{\mathrm{NP}\prime}(0)\right]$$

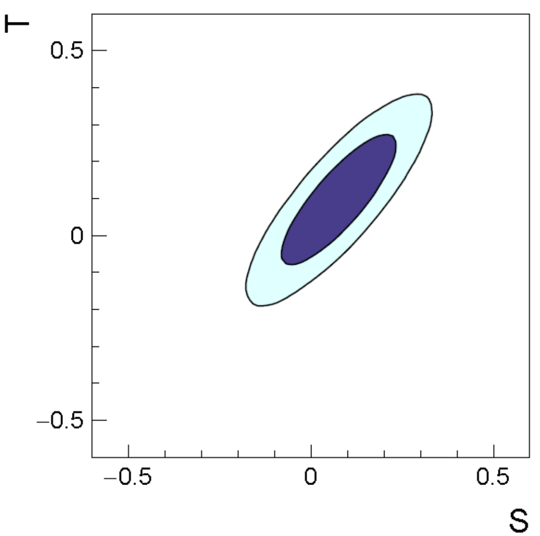
$$T = \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi_{11}^{\mathrm{NP}}(0) - \Pi_{33}^{\mathrm{NP}}(0)\right]$$

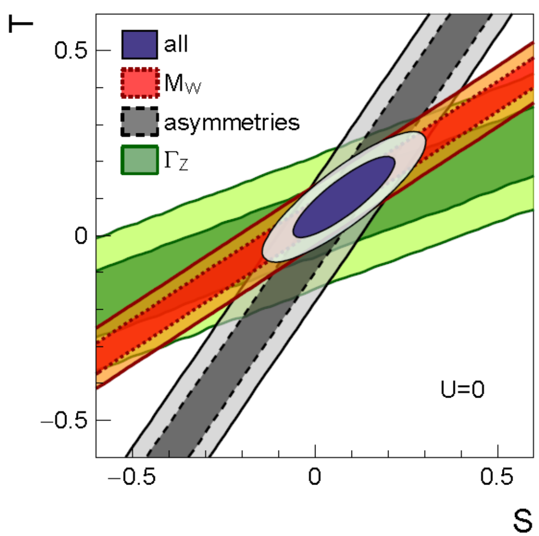
$$U = 16\pi\left[\Pi_{11}^{\mathrm{NP}\prime}(0) - \Pi_{33}^{\mathrm{NP}\prime}(0)\right]$$

$$\delta M_W,\ \delta\Gamma_W \propto -S + 2c_W^2\, T + \frac{(c_W^2 - s_W^2)\, U}{2s_W^2}$$

$$\delta\Gamma_Z \propto -10(3 - 8s_W^2)\, S + (63 - 126 s_W^2 - 40 s_W^4)\, T$$

$$\text{others} \propto S - 4c_W^2 s_W^2\, T$$





	Fit result	Correlations		
S	0.08 ± 0.10	1.00		
T	0.10 ± 0.12	0.85	1.00	
U	0.01 ± 0.09	−0.48	−0.79	1.00

	Fit result	Correlations	
S	0.08 ± 0.09	1.00	
T	0.10 ± 0.07	0.87	1.00

$U = 0$

see also Gfitter, Erler, ...

Constraints on $\delta\varepsilon_{1,2,3,b}$

$$\epsilon_1 = \Delta\rho'$$

$$\epsilon_2 = c_0^2\Delta\rho' + \frac{s_0^2}{c_0^2 - s_0^2}\Delta r_W - 2s_0^2\Delta\kappa'$$

$$\epsilon_3 = c_0^2\Delta\rho' + (c_0^2 - s_0^2)\Delta\kappa'$$

and ϵ_b

Altarelli et al., 91, 92, 93

$$s_W^2 c_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_\mu M_Z^2(1-\Delta r_W)}$$

$$\sqrt{\mathrm{Re}\,\rho_Z^e} = 1 + \frac{\Delta\rho'}{2}$$

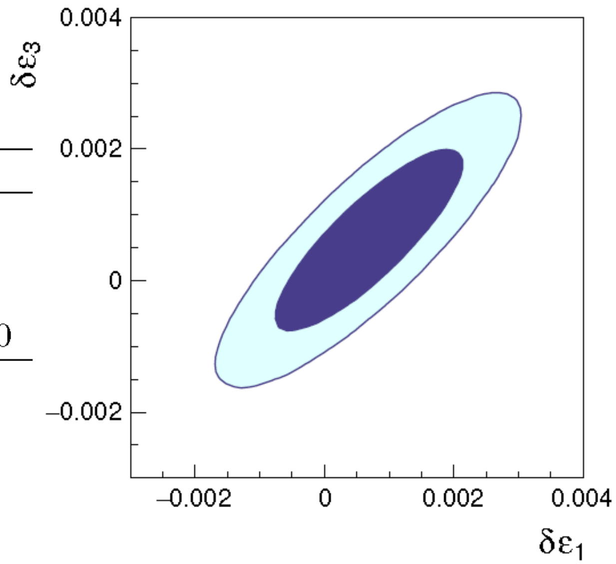
$$\sin^2\theta_{\mathrm{eff}}^e = (1+\Delta\kappa')\,s_0^2$$

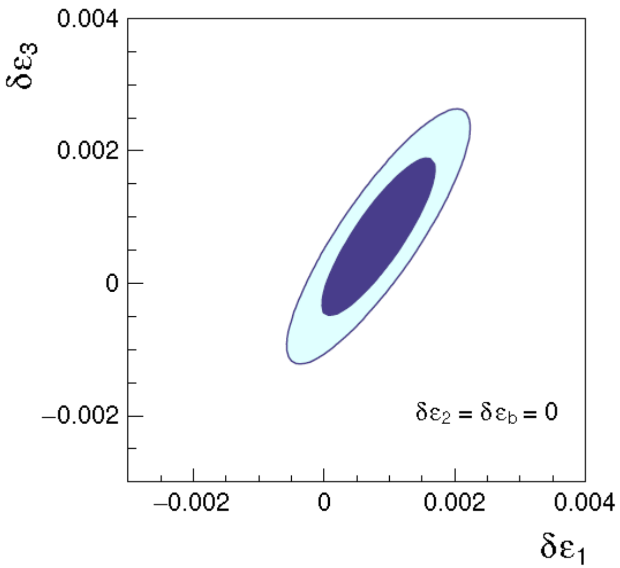
$$\delta\epsilon_i = \epsilon_i - \epsilon_i^{\mathrm{SM}}$$

	Fit result	Correlations			
$\delta\epsilon_1$	0.0007 ± 0.0010	1.00			
$\delta\epsilon_2$	-0.0002 ± 0.0009	0.79	1.00		
$\delta\epsilon_3$	0.0006 ± 0.0009	0.86	0.50	1.00	
$\delta\epsilon_b$	0.0003 ± 0.0013	−0.32	−0.31	−0.21	1.00

$$\delta\epsilon_2 = \delta\epsilon_b = 0$$

	Fit result	Correlations	
$\delta\epsilon_1$	0.0008 ± 0.0006	1.00	
$\delta\epsilon_3$	0.0007 ± 0.0008	0.87	1.00





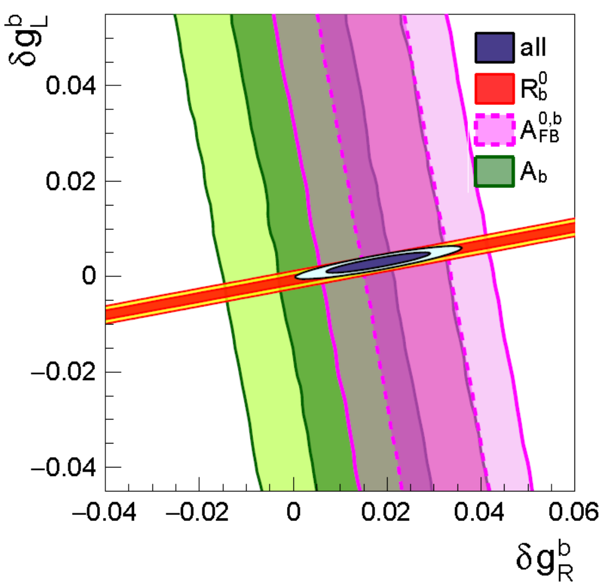
2. constraints on δg_V^b, δg_A^b (δg_R^b, δg_L^b)

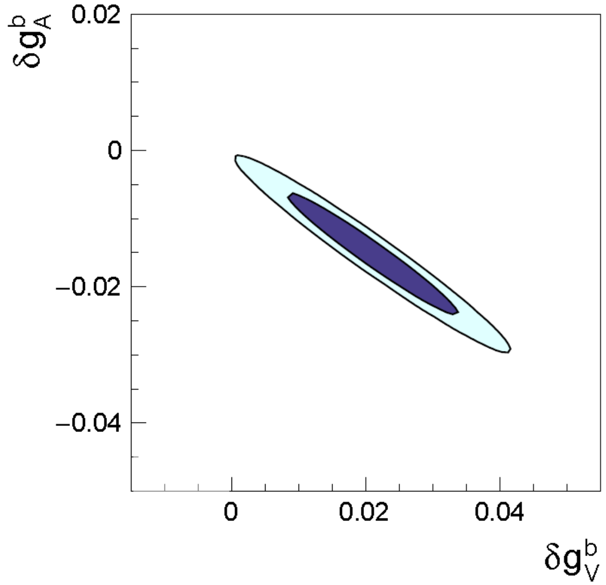
- longstanding pull in $A_{FB}^{0,b}$ may be due to a non-standard Zbb vertex

  Bamert et al. ; Haber&Logan; Choudhury et al. ; Kumar et al. ; Batell, Gori & Wang; ...

$$g_L^b = (g_L^b)_{\rm SM} + \delta g_L^b\,, \quad g_R^b = (g_R^b)_{\rm SM} + \delta g_R^b$$

$$(\delta g_V^b = \delta g_L^b + \delta g_R^b\,, \quad \delta g_A^b = \delta g_L^b - \delta g_R^b)$$





$$\mathcal{A}_{FB}^{0,b} \sim (g_L^b)_{SM}\delta g_R^b - (g_R^b)_{SM}\delta g_L^b$$

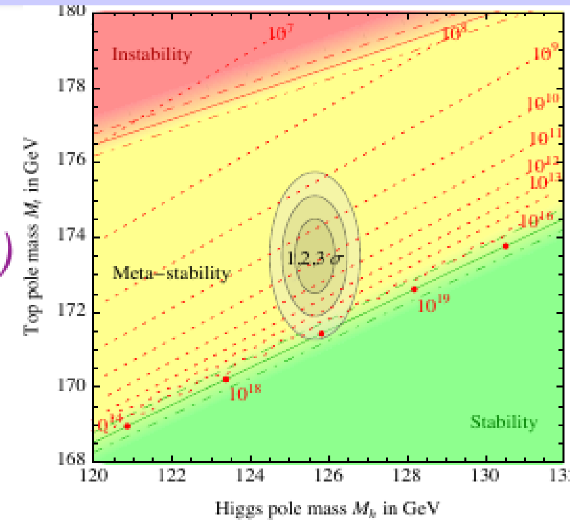
$$R_b^0 \sim (g_L^b)_{SM}\delta g_L^b + (g_R^b)_{SM}\delta g_R^b$$

$$(g_L^b)_{SM} \gg (g_R^b)_{SM}$$

	Fit result	Correlations	
δg_R^b	0.018 ± 0.007	1.00	
δg_L^b	0.0029 ± 0.0014	0.90	1.00
δg_V^b	0.021 ± 0.008	1.00	
δg_A^b	-0.015 ± 0.006	−0.99	1.00

m_t & SM Vacuum Stability

The measurement of the top mass is crucial for testing the stability of the SM vacuum. *Degrassi et al.(12); Buttazzo et al.(13)*



$$m_t^{\rm pole} < 171.53 \pm 0.42 \text{ GeV}$$

Tevatron/LHC pole(?) mass:

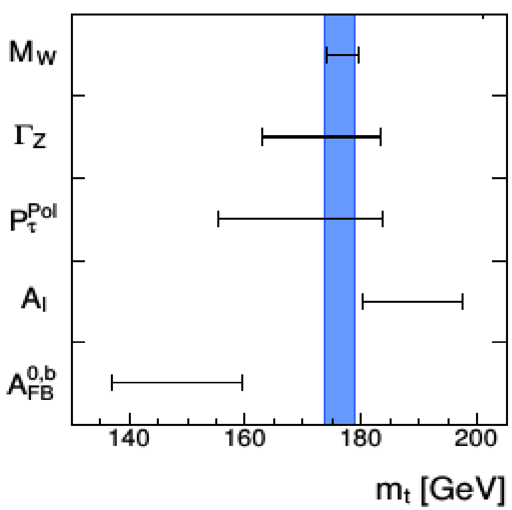
$$173.34 \pm 0.76 \text{ GeV}$$

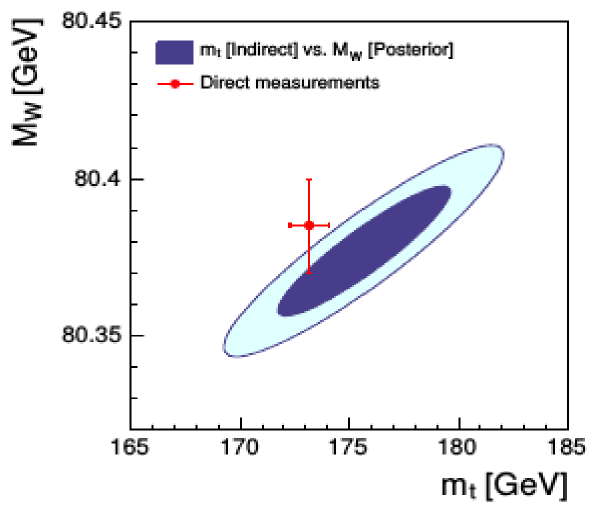
Pole from MSbar: 171.2 ± 2.4 GeV

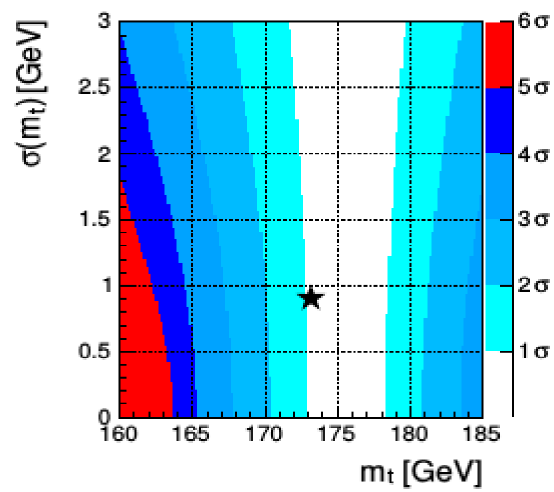
1405.4781

from EW fit:

$$176.6 \pm 2.5 \text{ GeV}$$

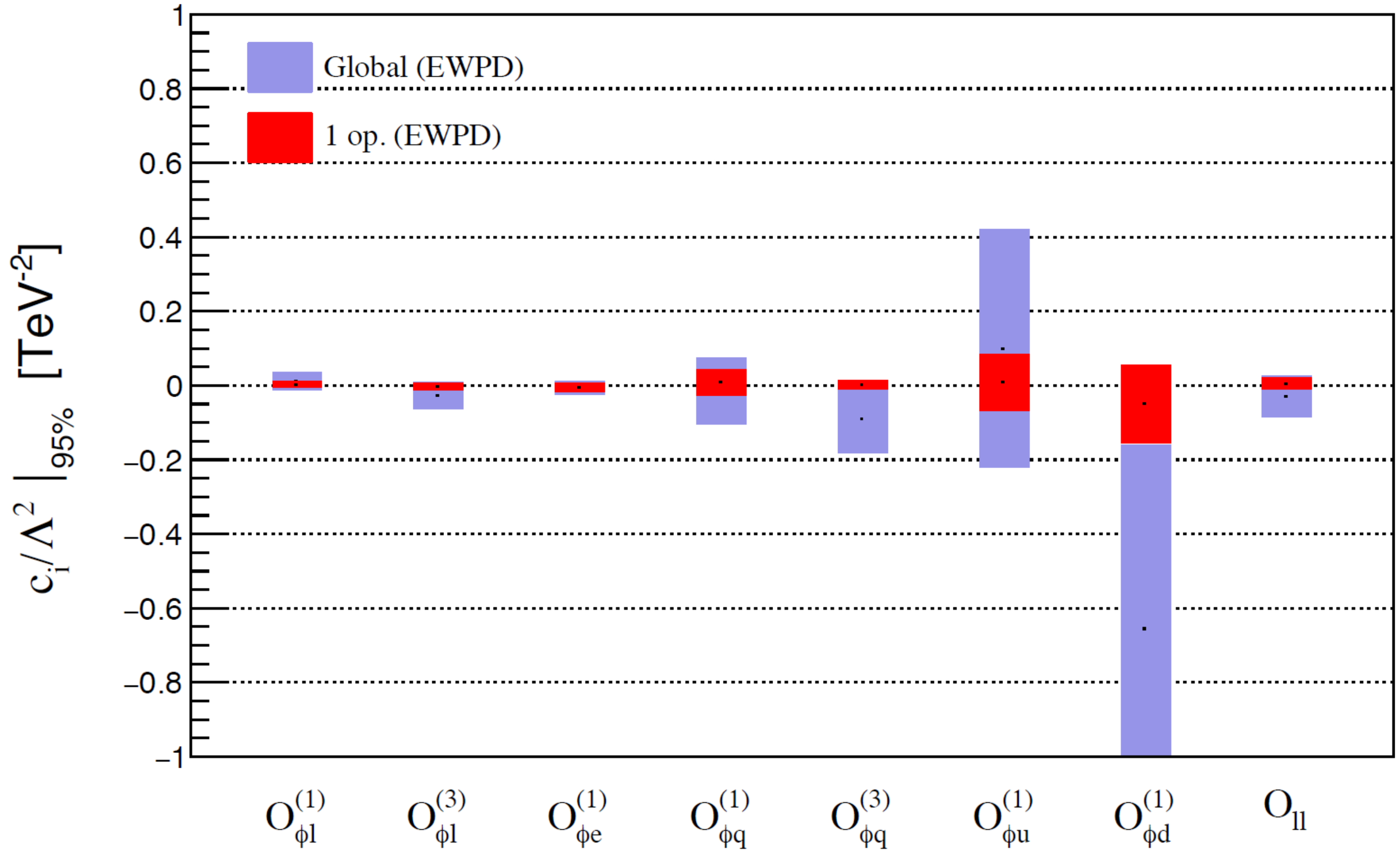






- <u>Dimension six SMEFT (**EWPD**):</u>

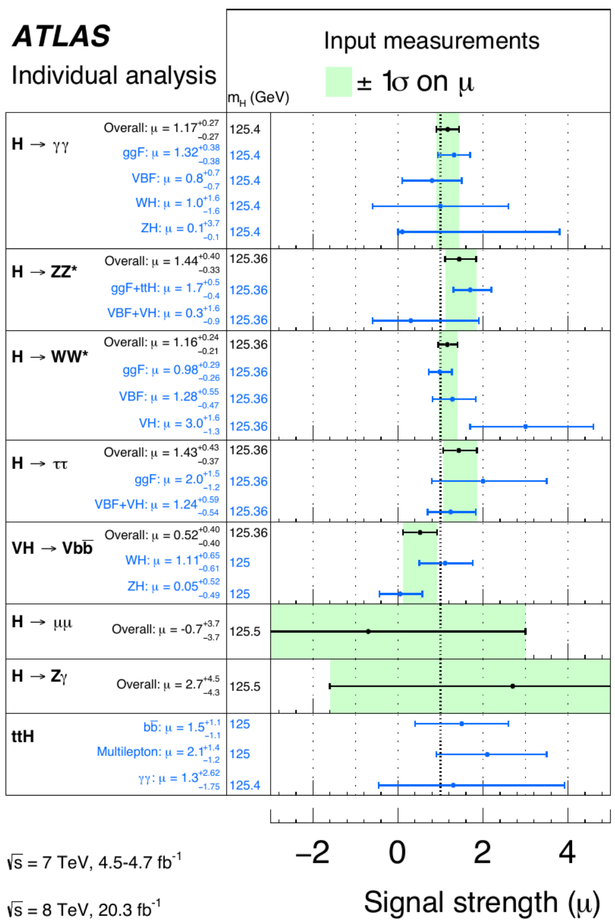
All EW operators at the same time



Large correlations (up to 90%)

Only 8 combinations of dim 6 operators can be constrained. Redefine $\mathcal{O}_{\phi WB}$, $\mathcal{O}_{\phi D}$ away.

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)

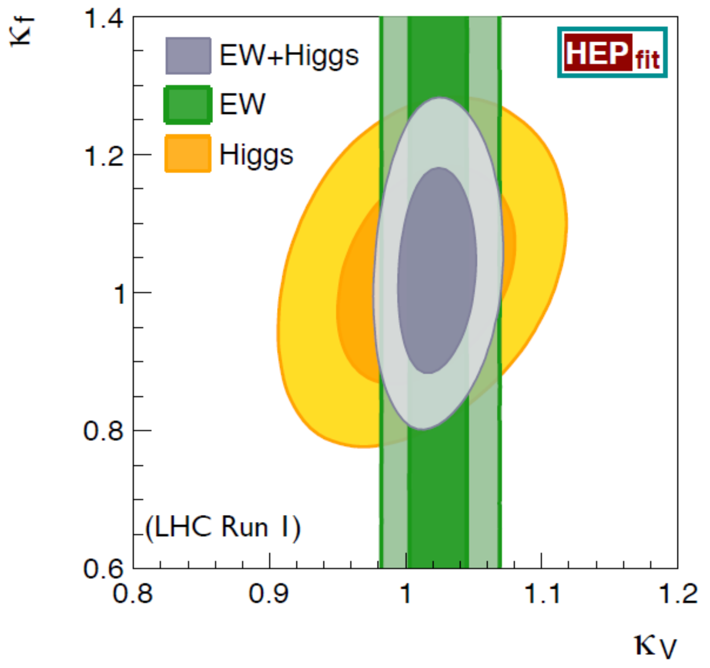
hZZ: ATLAS(1408.5191), CMS(1412.8662)

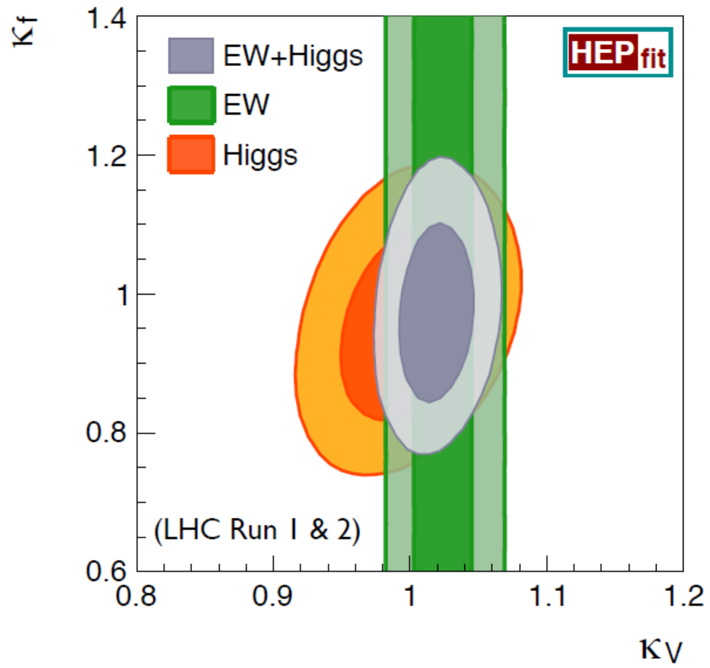
hWW: ATLAS(1412.2641,1506.06641),
CMS(1312.1129)

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

	Fit result	95% Prob.	Correlations	
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

	Fit result	95% Prob.	Correlations	
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00	
κ_f	0.98 ± 0.08	[0.81, 1.14]	0.18	1.00





Constraints on C_i/Λ^2 and Λ

preliminary

Switching on <u>one operator at a time</u>:

bounds on c/Λ^2 [TeV^{-2}] @95% prob.

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

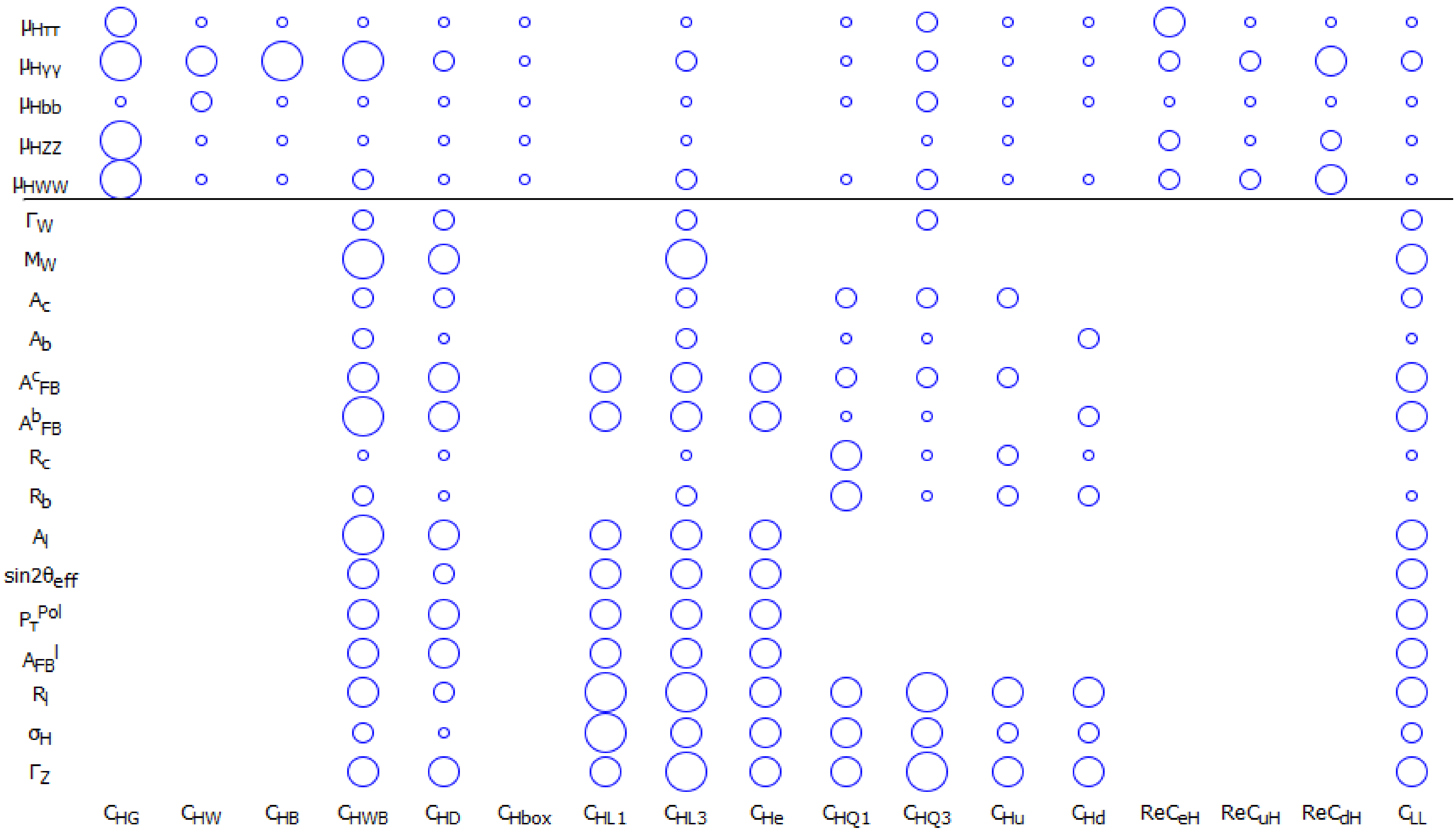
lower bounds on Λ [TeV] @95% prob.

Operator		Only EW $\|C_i\| = 1$	Only Higgs $\|C_i\| = 1$	EW + Higgs $\|C_i\| = 1$
$\mathcal{O}_{HG}$	$(H^\dagger H)\, G^A_{\mu\nu} G^{A\,\mu\nu}$	—	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
$\mathcal{O}_{HD}$	$\left\|H^\dagger D_\mu H\right\|^2$	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
$\mathcal{O}_{He}$	$(H^\dagger i D_\mu H)\, (\overline{e}_R \gamma^\mu e_R)$	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

NP scale for $|C_i| = 1$ in the multi-TeV region,

EWPO more constraining than Higgs data at present

“Correlated” NP contributions

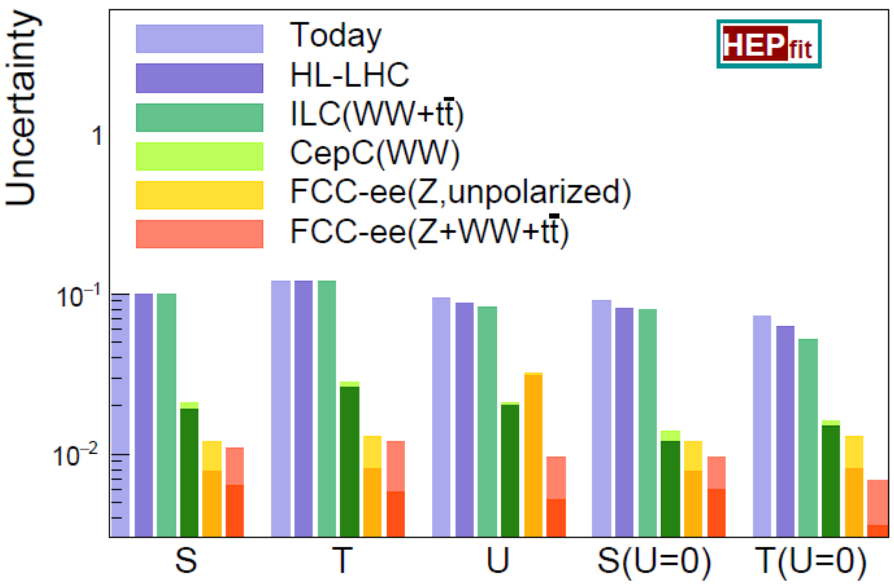


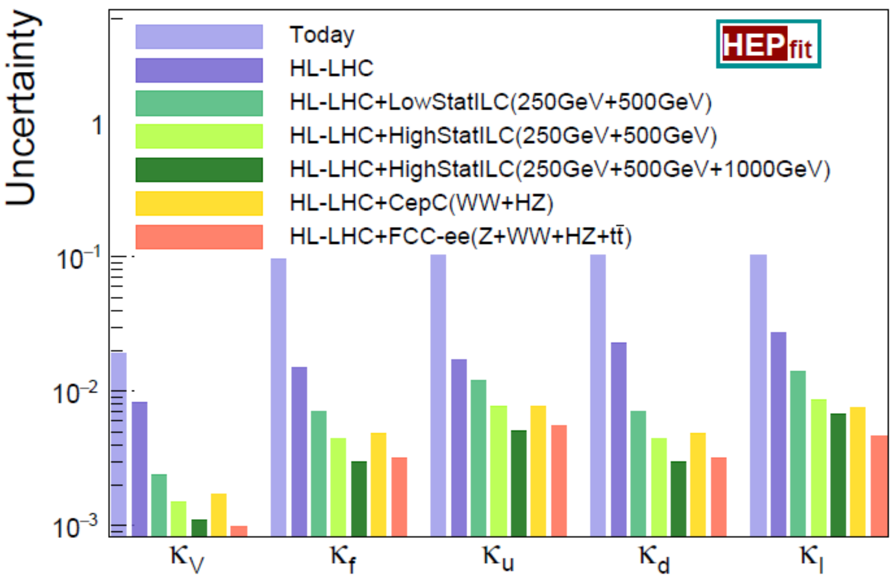
- Physics at the FCC-ee:

FCC-ee run	Z pole	WW threshold	HZ	$t\bar{t}$ 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

- Physics at the CEPC:

CEPC run	Z pole	HZ threshold
$\sqrt{s}$ [GeV]	90	240
$\int \mathcal{L}$ [fb^{-1}]	>150	5×10^3
Events	10^{10}	$>10^6$


Uncertainty
Today
HL-LHC
ILC(WW+tt̄)
CepC(WW)
FCC-ee(Z,unpolarized)
FCC-ee(Z+WW+tt̄)
HEPfit
1
10^{-1}
10^{-2}
S
T
U
S(U=0)
T(U=0)


Uncertainty
Today
HL-LHC
HL-LHC+LowStatILC(250GeV+500GeV)
HL-LHC+HighStatILC(250GeV+500GeV)
HL-LHC+HighStatILC(250GeV+500GeV+1000GeV)
HL-LHC+CepC(WW+HZ)
HL-LHC+FCC-ee(Z+WW+HZ+tt̄)
HEPfit
1
10^{-1}
10^{-2}
10^{-3}
κ_V
κ_f
κ_u
κ_d
κ_l