Recent results from electroweak fits

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HEPfit COLLABORATION

European Research Council
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INFN Istituto Nazionale di Fisica Nucleare

- Electroweak Precision Data:
  - Very precise measurements of the W & Z boson properties taken at $e^+ e^-$ colliders

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$

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

$$M_W,\ \Gamma_W$$

W obs. (LEP2) 0.02-O(1)%

  - From Hadron colliders (Tevatron & LHC):

$M_W,\ \Gamma_W$	m_t	M_H
0.02-O(1)%	0.4%	0.2%

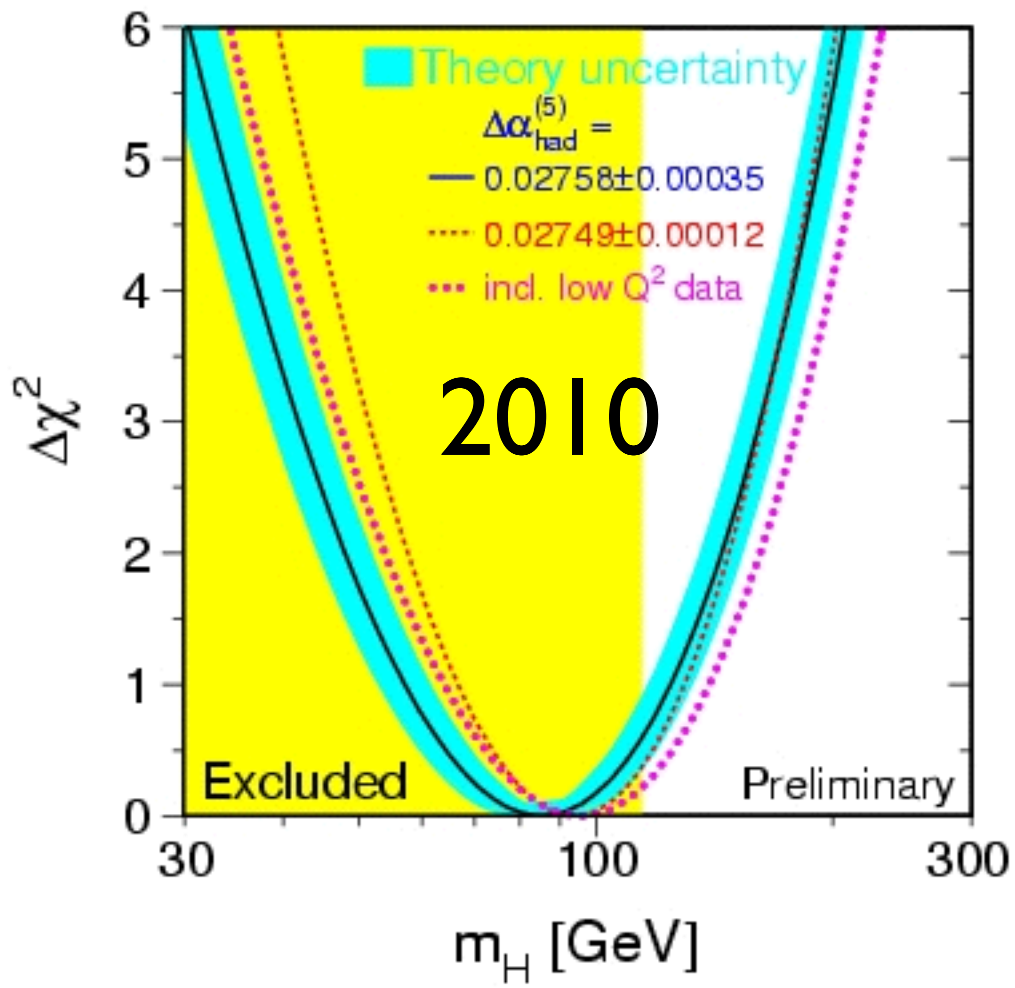
Precision in many cases of the order of 1 ‰

- Precision is such that can test the SM predictions to the level of radiative corrections:
  - Tested validity of the SM description of EW interactions
  - Sensitive to all SM particle masses via loop corrections:

Before Higgs discovery:

- Indirect evidence of a light Higgs

- Interplay SM-NP in EWPO



- Precision is such that can test the SM predictions to the level of radiative corrections:
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After Higgs discovery:

- All inputs of the SM are known

- Observables can be fully predicted in the SM

- Strong (unambiguous) constraints on NP modifying the EW sector (e.g. solutions to the hierarchy problem)

Electroweak precision observables: Experimental and Theory status

- Input parameters: $\{G_\mu,\ \alpha_{\rm em}\}$ (Fixed)

$$\left\{m_h,\ m_t,\ M_Z,\ \alpha_s(M_Z^2),\ \Delta\alpha_{\rm had}^{(5)}(M_Z^2)\right\}$$ (Floating)

- W mass parametrized in terms of Δr

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

- Z-pole observables parametrized in terms of effective Zff couplings

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

$$\rho_Z^f = \left(\frac{g_A^f}{I_3^f}\right)^2 \qquad \kappa_Z^f = \frac{1}{4|Q_f|s_W^2}\left(1-\frac{g_V^f}{g_A^f}\right) \qquad s_W^2 = 1-\frac{M_W^2}{M_Z^2}$$

On-shell ren. scheme

- Z-pole observables parametrized in terms of Effective Zff couplings (plus additional QED/QCD corrections [radiators, FSI])

Left-Right and Forward-Backward Asymmetries

$$A_{L,R}^{0,f} = A_f = \frac{2\mathrm{Re}\left\{\frac{g_V^f}{g_A^f}\right\}}{1+\mathrm{Re}\left\{\frac{g_V^f}{g_A^f}\right\}^2} \qquad A_{FB}^{0,f} = \frac{3}{4}A_e A_f \qquad (f = \ell, c, b)$$

Effective electroweak mixing angle

$$\sin^2\theta_{\mathrm{Eff}}^{\mathrm{lept}} = \mathrm{Re}\left\{\kappa_Z^\ell\right\} s_W^2$$

Decay widths (and ratios), hadronic cross section

$$\Gamma_f \propto \left|\rho_Z^f\right| \left[\left|\frac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right] + \Delta_{\mathrm{EW/QCD}}$$

$$\Gamma_Z,\ \sigma_h^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_h}{\Gamma_Z^2},\ \ R_\ell^0 = \frac{\Gamma_h}{\Gamma_\ell},\ \ R_{c,b}^0 = \frac{\Gamma_{c,b}}{\Gamma_h}$$

EW precision observables: Exp. inputs

- Strong coupling constant:

$$\alpha_S(M_Z) = 0.1179 \pm 0.0012$$

New PDG world average

(Excl. EW fit results)

$$\left(\alpha_S(M_Z)|_{2014} = 0.1185 \pm 0.0005 \right)$$

Previous PDG average

- Result dominated by Lattice results:
  - PDG (unweighted) average:

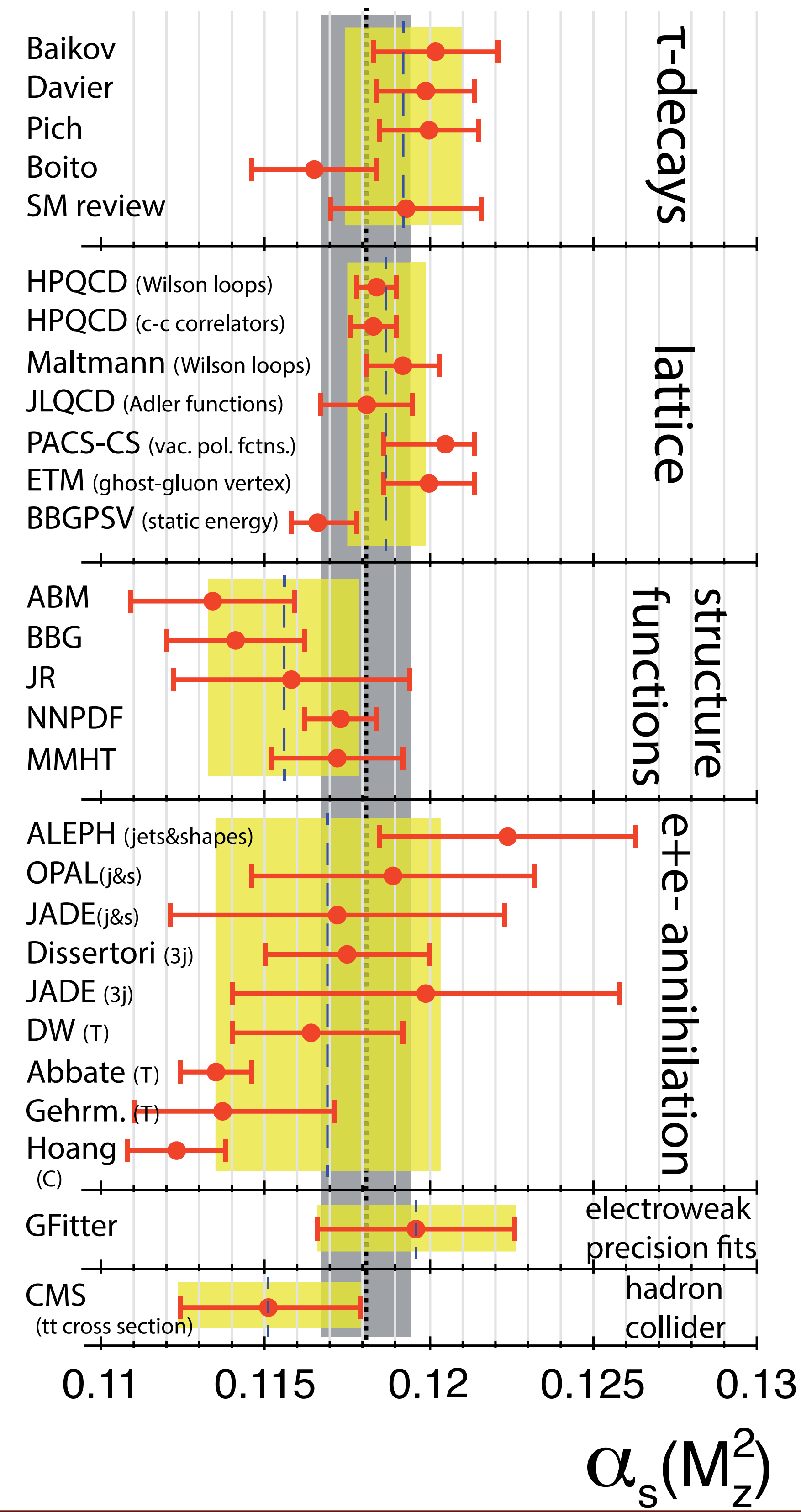
$$\alpha_S(M_Z)|^{\rm PDG}_{\rm Lattice} = 0.1187 \pm 0.0012$$

  - Consistent with FLAG average:

$$\alpha_S(M_Z)|^{\rm FLAG}_{\rm Lattice} = 0.1182 \pm 0.0012$$

S. Aoki et al., arXiv: 1607.00299 [hep-lat]

S. Bethke, G. Dissertori, G.P. Salam, PDG Review QCD 2015

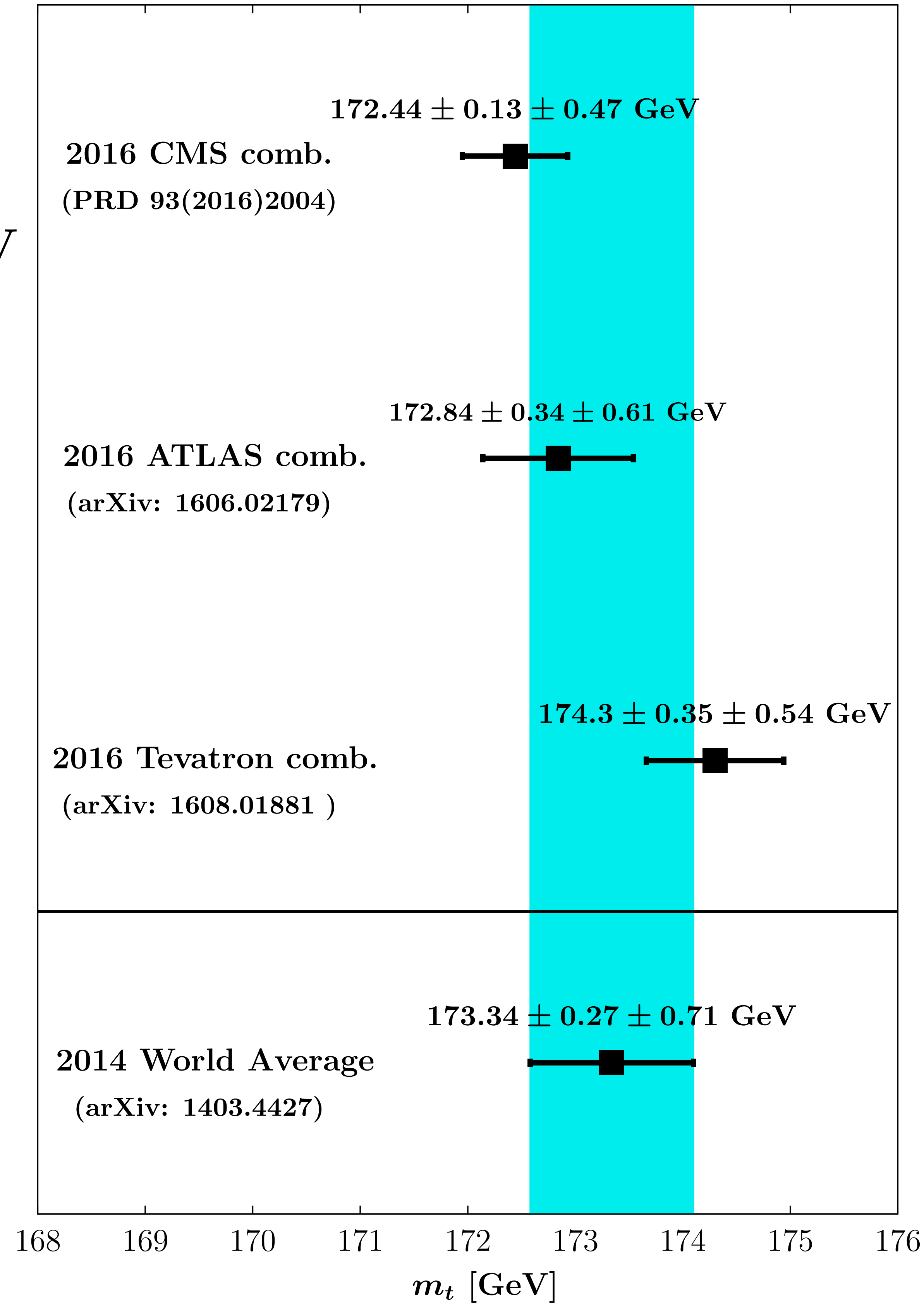


- Top quark mass:

$$m_t = 173.34 \pm 0.27\ (\text{stat.}) \pm 0.71\ (\text{sys.})\ \text{GeV}$$

Current world average (2014)

- **New** individual combinations from CDF, D0, ATLAS and CMS:
  - All more precise than current world average



- <u>EWPO at Hadron colliders: Effective weak mixing angle (and M_W)</u>
- Tevatron and LHC meas. of $\sin^2\theta_{\rm Eff}^{\rm lept}$ from asymmetries in the dilepton channel
  - Precision still below the one of the LEP/SLD result
  - Tevatron <u>indirect</u> M_W determination

$$M_W(\mathrm{ind.}) = 80.351 \pm 0.018~\mathrm{GeV}$$

- Waiting for Tevatron updates on the <u>direct</u> M_W measurements…
- Also ongoing effort at the LHC to obtain <u>direct</u> M_W measurement

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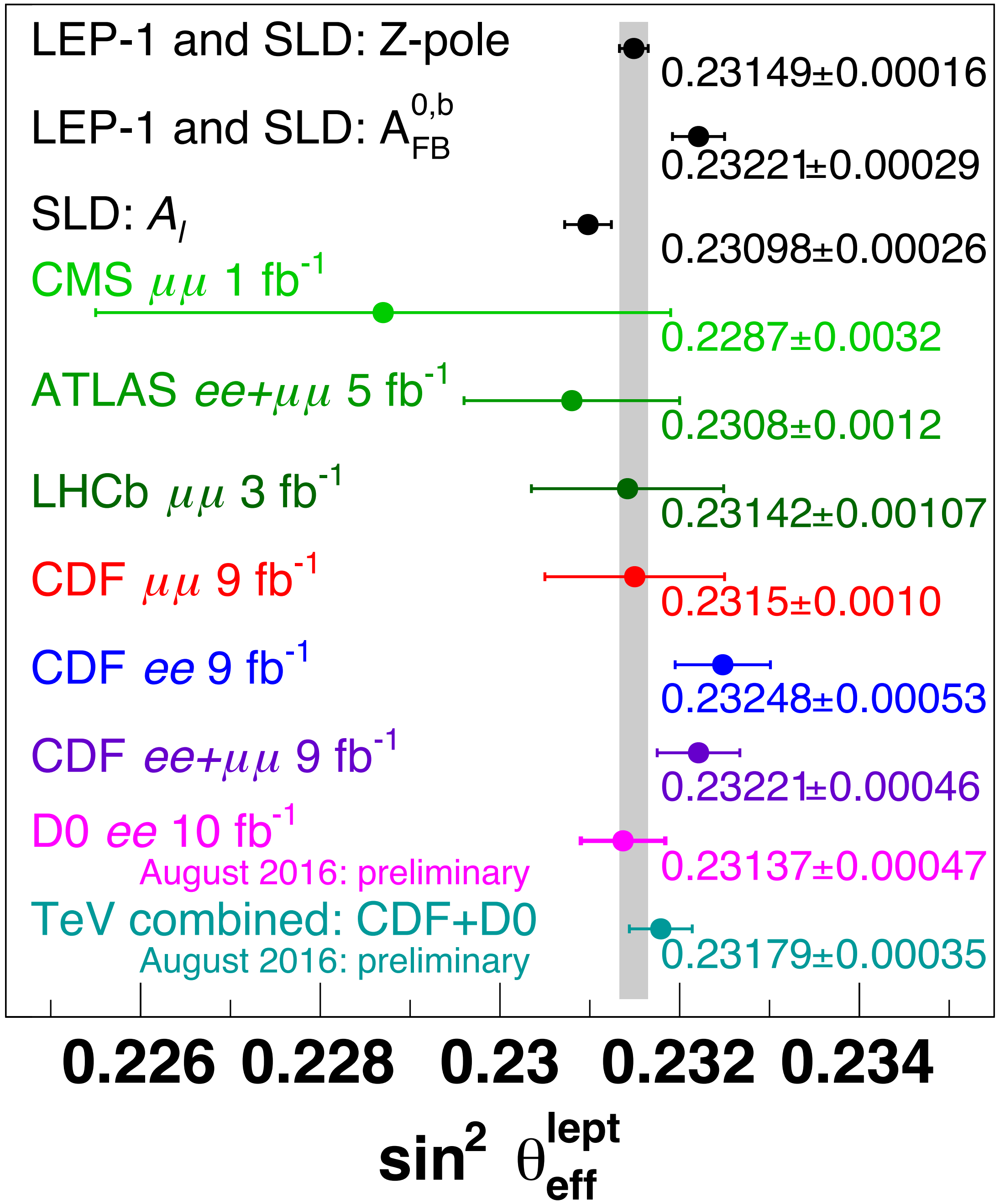


See also R. Hirosky talk on Aug 31

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 **NEW**
    I. Dubovyk, A. Freitas, J. Gluza, T. Riemann, J. Usovitsch, arXiv: 1607.08375

- Experimental vs Theoretical uncertainties:

	$M_{\rm W}$	$\Gamma_{\rm Z}$	$\sigma^0_{\rm had}$	$R_{\rm b}$	$\sin^2\theta^\ell_{\rm eff}$
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}

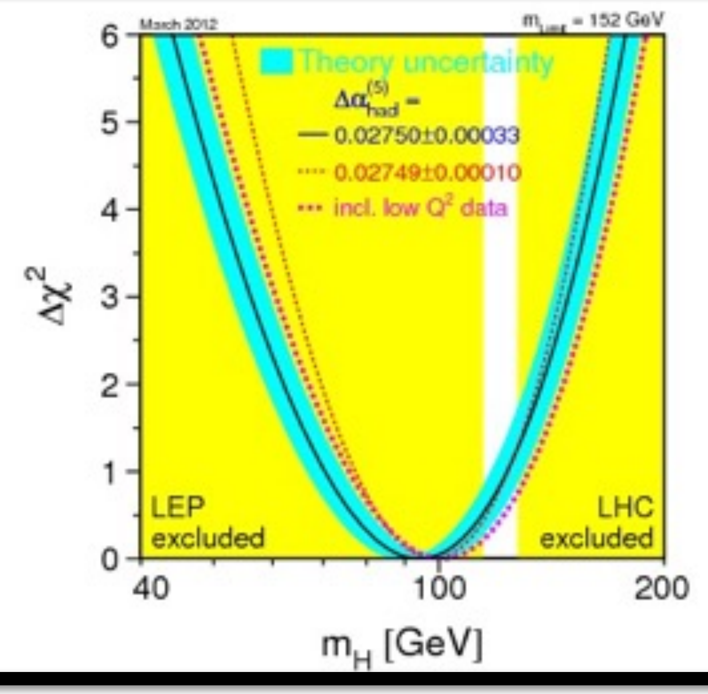
A. Freitas, **PoS(LL2014)050** [arXiv: 1406.6980]

- Several groups/codes for the EWPD fit:

LEP EWWG USING ZFITTER

v6.42: A. Arbuzov et al. , Comput. Phys. Commun. 174 (2006)
A. Akhundov et al. (arXiv: 1302.1395 [hep-ph])

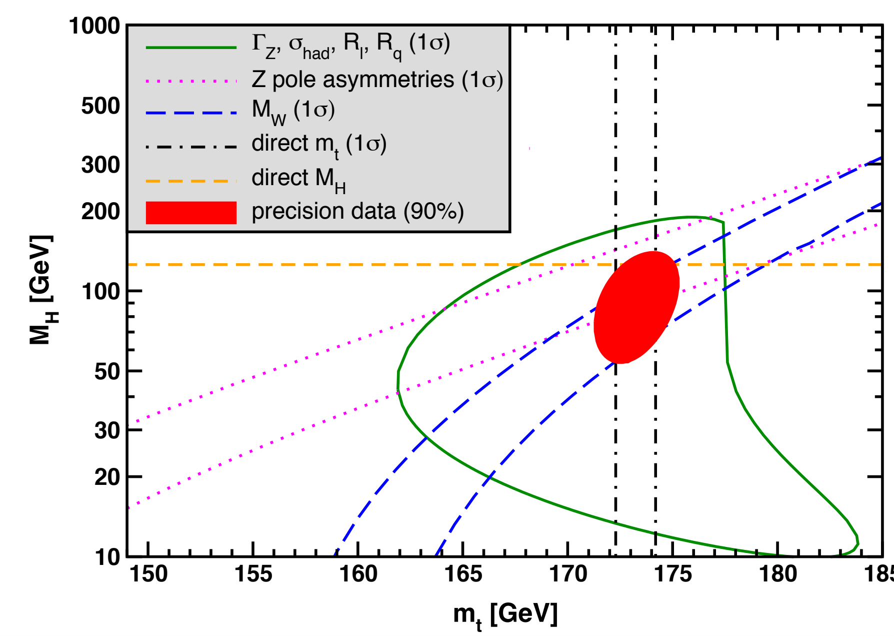
- On-shell ren.
- Frequentist stat. analysis



PDG USING GAPP

Global Analysis of Particle Properties
J. Erler (arXiv: hep-ph/0005084)

- $\overline{\text{MS}}$ ren.
- Frequentist stat. analysis

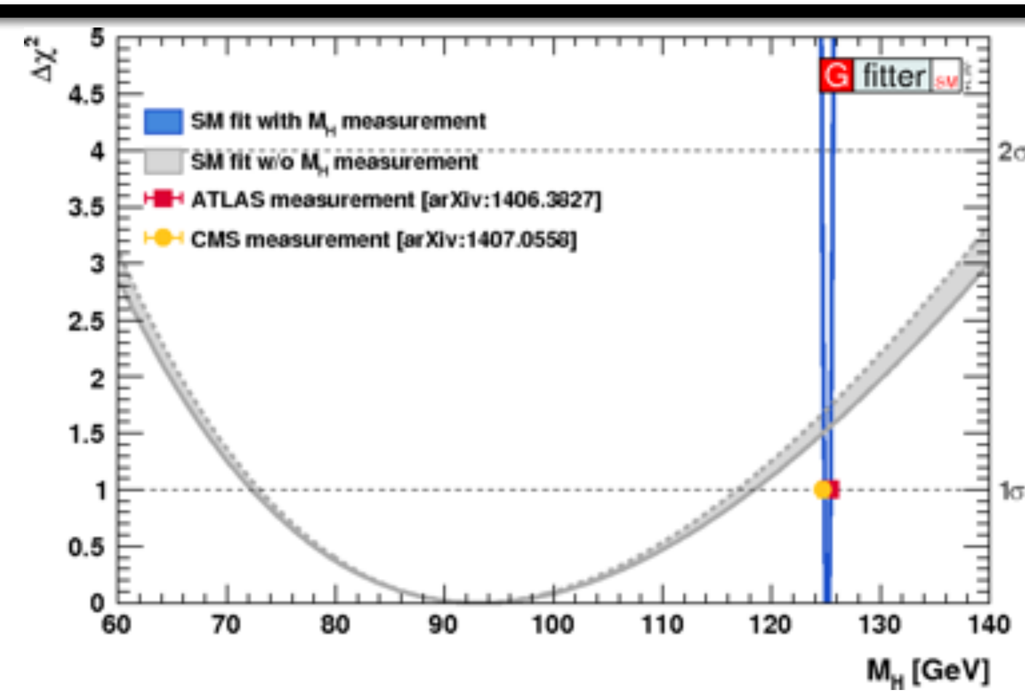


- Several groups/codes for the EWPD fit:

Gfitter

M. Baak et al. , Eur. Rhys. J. C 74, 3046 (2014)

- On-shell ren.
- Frequentist stat. analysis



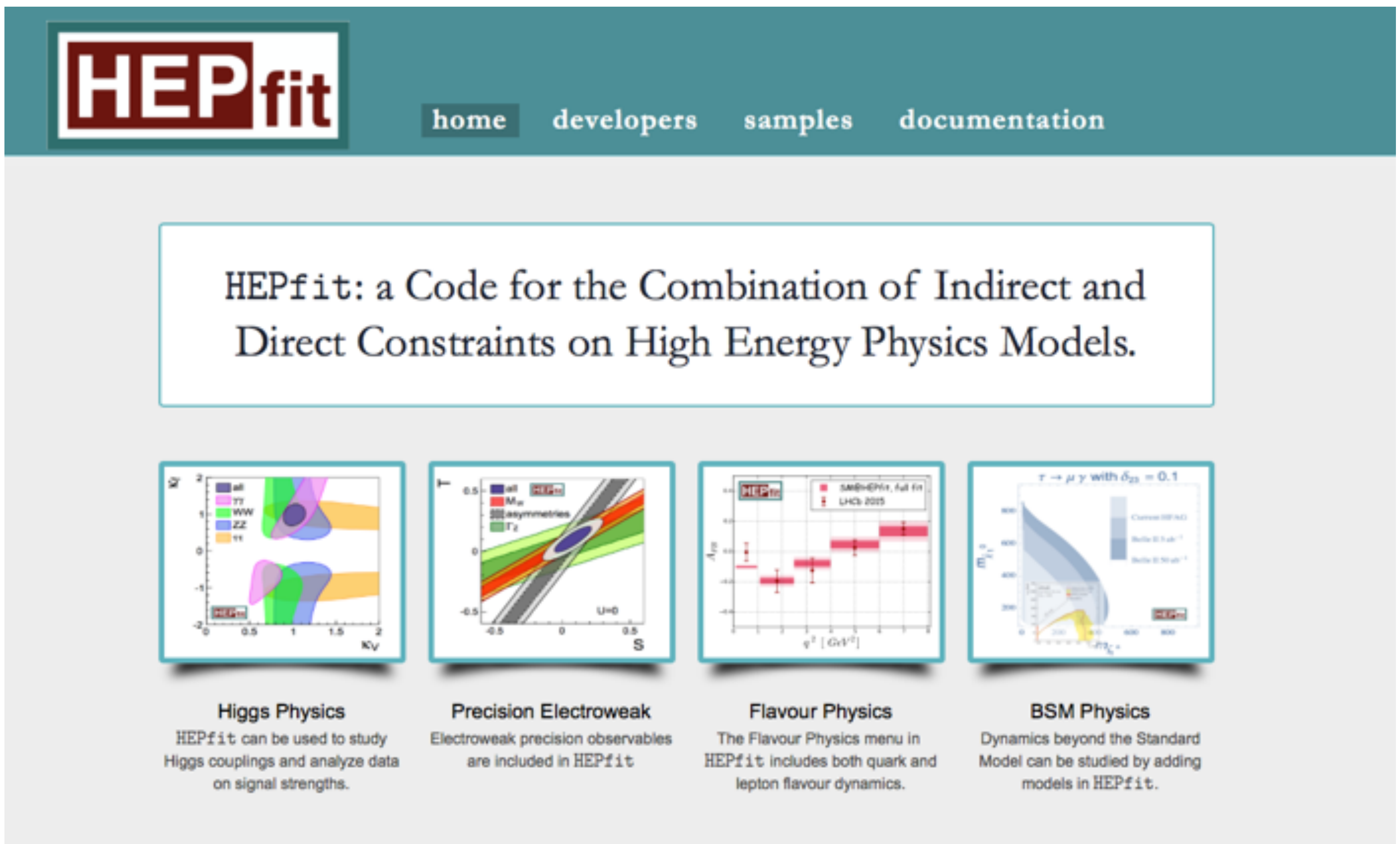
In this talk I will focus mostly on the results obtained with the HEPfit code

- On-shell ren.
- Bayesian stat. analysis

Mainly from:
M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina & L. Silvestrini
arXiv: 1608.01509 [hep-ph]

The HEPfit code

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on github) https://github.com/silvest/HEPfit
- Webpage: http://hepfit.roma1.infn.it



Electroweak precision observables: The Standard Model fit

The SM fit to EWPD

	Measurement	Posterior	Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	0.1179±0.0012	0.1180±0.0011	0.1185±0.0028	-0.2	
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02750±0.00033	0.02747±0.00025	0.02743±0.00038	0.04	
M_Z [GeV]	91.1875±0.0021	91.1879±0.0020	91.199±0.011	-1.0	
m_t [GeV]	173.34±0.76	173.61±0.73	176.6±2.5	-1.3	
m_H [GeV]	125.09±0.24	125.09±0.24	102.8±26.3	0.8	
M_W [GeV]	80.385±0.015	80.3644±0.0061	80.3604±0.0066	1.5	
Γ_W [GeV]	2.085±0.042	2.08872±0.00064	2.08873±0.00064	-0.2	
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324±0.0012	0.231464±0.000087	0.231435±0.000090	0.8	
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	0.1465±0.0033	0.14748±0.00068	0.14752±0.00069	-0.4	
Γ_Z [GeV]	2.4952±0.0023	2.49420±0.00063	2.49405±0.00068	0.5	
σ^0_h [nb]	41.540±0.037	41.4903±0.0058	41.4912±0.0062	1.3	0.7
R^0_ℓ	20.767±0.025	20.7485±0.0070	20.7472±0.0076	0.8	
$A^{0,\ell}_{\rm FB}$	0.0171±0.0010	0.01631±0.00015	0.01628±0.00015	0.8	
$\mathcal{A}_\ell$ (SLD)	0.1513±0.0021	0.14748±0.00068	0.14765±0.00076	1.7	
$\mathcal{A}_c$	0.670±0.027	0.66810±0.00030	0.66817±0.00033	0.02	
$\mathcal{A}_b$	0.923±0.020	0.934650±0.000058	0.934663±0.000064	-0.6	
$A^{0,c}_{\rm FB}$	0.0707±0.0035	0.07390±0.00037	0.07399±0.00042	-0.9	1.5
$A^{0,b}_{\rm FB}$	0.0992±0.0016	0.10338±0.00048	0.10350±0.00054	-2.6	
R^0_c	0.1721±0.0030	0.172228±0.000023	0.172229±0.000023	-0.05	
R^0_b	0.21629±0.00066	0.215790±0.000028	0.215788±0.000028	0.7	
$\sin^2\theta^{ee}_{\rm eff}$ (CDF)	0.23248±0.00052			2.1	
$\sin^2\theta^{\mu\mu}_{\rm eff}$ (CDF)	0.2315±0.0010			0.07	
$\sin^2\theta^{ee}_{\rm eff}$ (D0)	0.23146±0.00047	0.231464±0.000087	0.231435±0.000090	0.1	
$\sin^2\theta^{ee,\mu\mu}_{\rm eff}$ (ATLAS)	0.2308±0.0012			-0.5	
$\sin^2\theta^{\mu\mu}_{\rm eff}$ (CMS)	0.2287±0.0032			-0.8	
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New: 2016 world average

LHC & Tevatron measurements of the eff. weak mixing angle

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$\sin^2\theta_{\rm eff}^{\mu\mu}$ (CMS)	0.2287±0.0032			-0.8	
$\sin^2\theta_{\rm eff}^{\mu\mu}$ (LHCb)	0.2314±0.0011			-0.1	

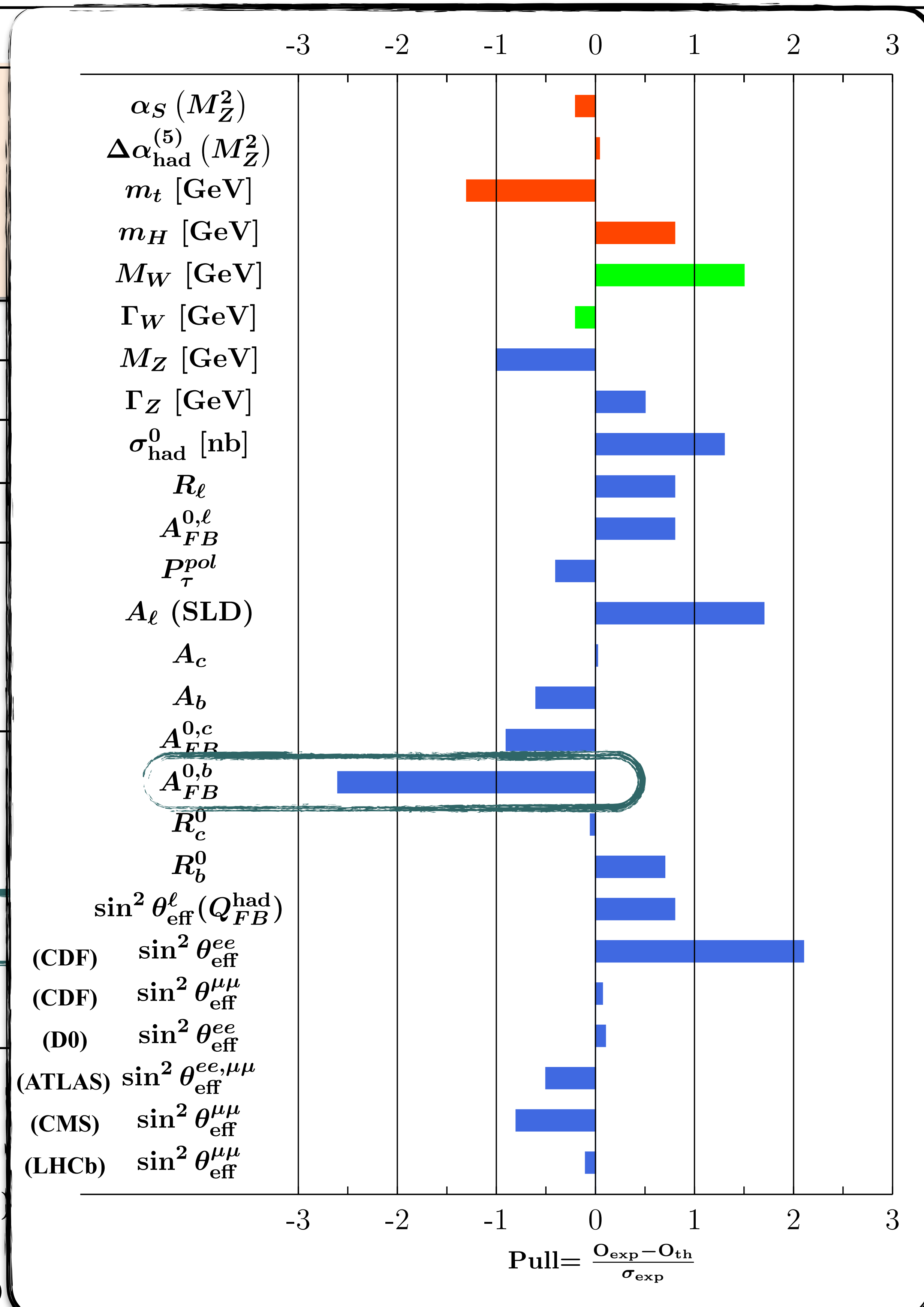
The SM fit to EWPD

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

Only 1 significant discrepancy

The SM fit to EWPD

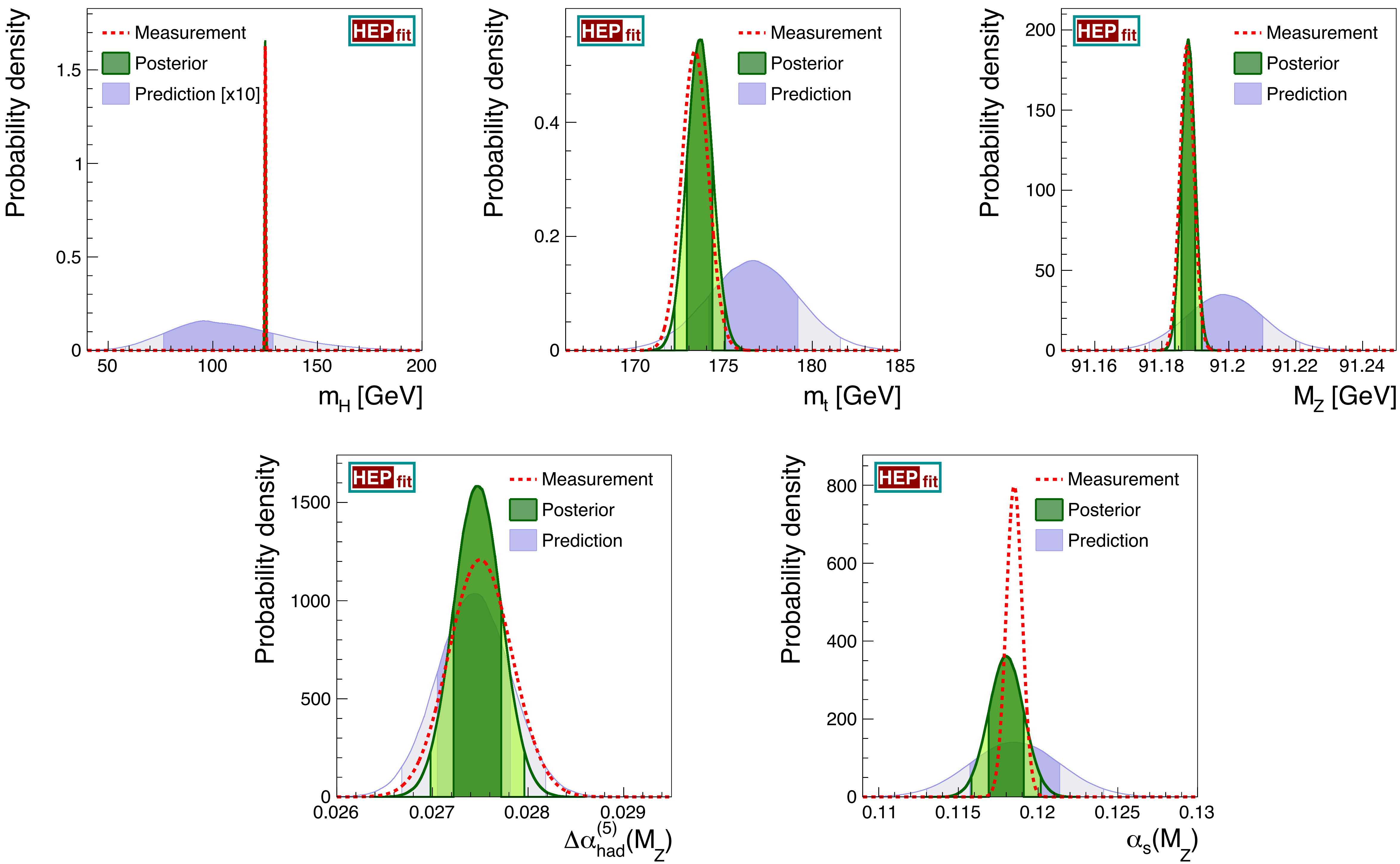
		1D Pull	nD Pull
$\alpha_s(M_Z)$	28	-0.2	
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$	038	0.04	
M_Z [GeV]	1	-1.0	
m_t [GeV]		-1.3	
m_H [GeV]		0.8	
M_W [GeV]	066	1.5	
Γ_W [GeV]	064	-0.2	
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0090	0.8	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	069	-0.4	
Γ_Z [GeV]	068	0.5	
σ_h^0 [nb]	62	1.3	0.7
R_ℓ^0	76	0.8	
$A_{\rm FB}^{0,\ell}$	015	0.8	
$\mathcal{A}_\ell$ (SLD)	076	1.7	
$\mathcal{A}_c$	033	0.02	
$\mathcal{A}_b$	0064	-0.6	
$A_{\rm FB}^{0,c}$	042	-0.9	1.5
$A_{\rm FB}^{0,b}$	054	-2.6	
R_c^0	0023	-0.05	
R_b^0	0028	0.7	
$\sin^2\theta_{\rm eff}^{ee}$ (CDF)		2.1	
$\sin^2\theta_{\rm eff}^{\mu\mu}$ (CDF)		0.07	
$\sin^2\theta_{\rm eff}^{ee}$ (D0)		0.1	
$\sin^2\theta_{\rm eff}^{ee,\mu\mu}$ (ATLAS)	0090	-0.5	
$\sin^2\theta_{\rm eff}^{\mu\mu}$ (CMS)		-0.8	
$\sin^2\theta_{\rm eff}^{\mu\mu}$ (LHCb)		-0.1	



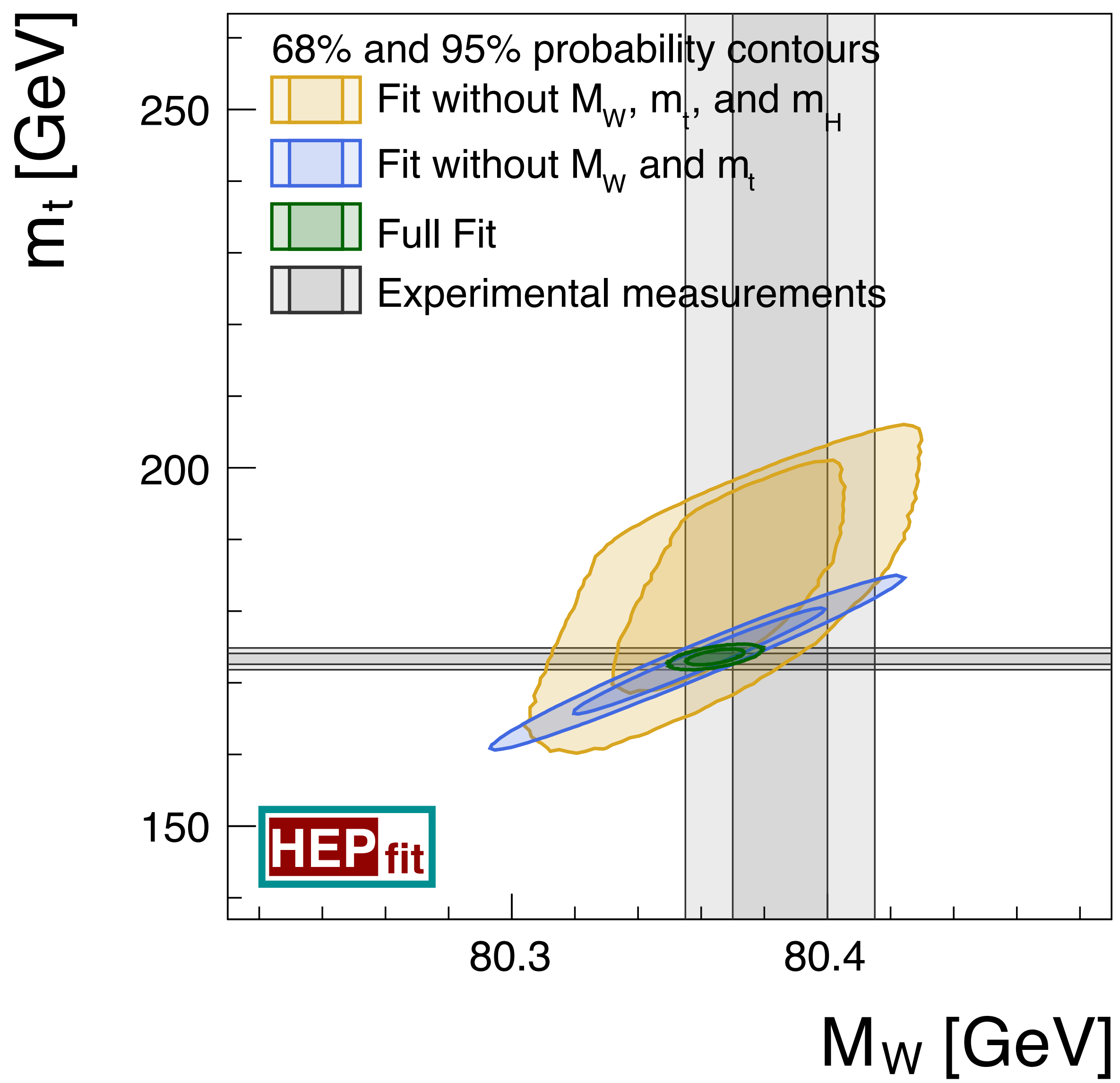
Only 1 significant discrepancy

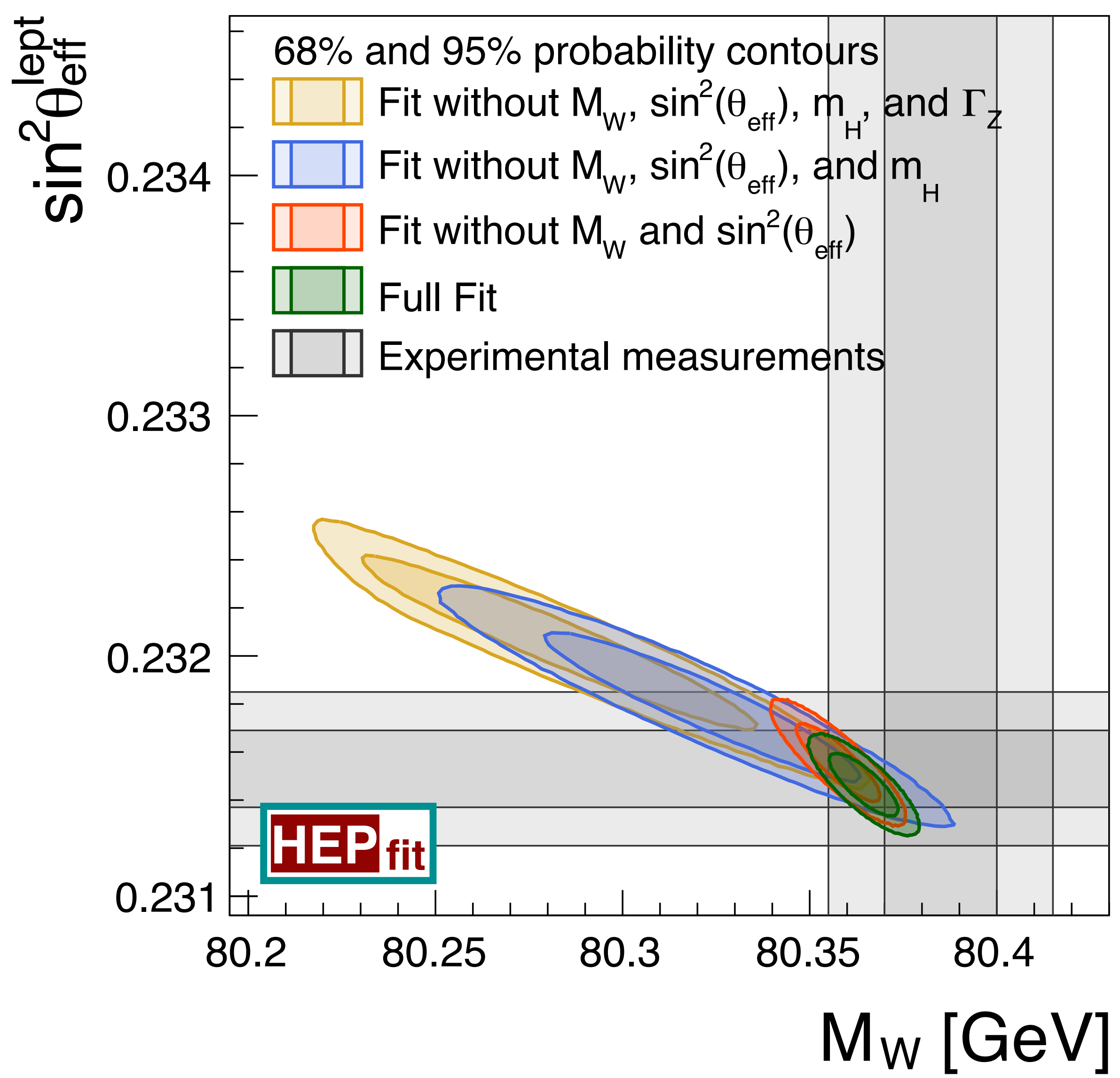
The SM fit to EWPD

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



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





$$10 \text{ GeV} \leq M_H \leq 1000 \text{ GeV}$$

Electroweak precision constraints on new physics

J.B., M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina & L. Silvestrini
arXiv: 1608.01509 [hep-ph]
+ In Preparation

EWPD limits on NP: S, T, U

- Oblique Parameters: New Physics contributing to gauge boson self-energies. EWPD depends only on 3 parameters

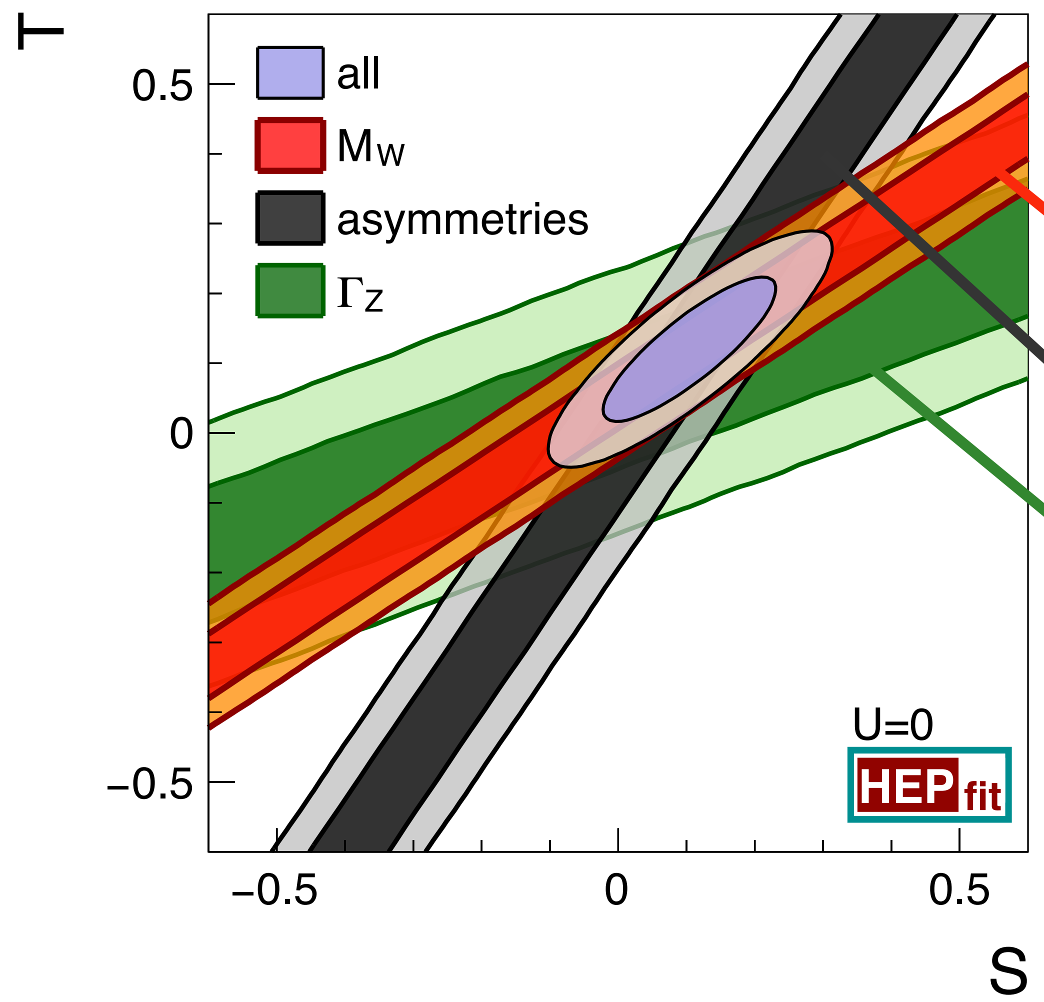
M.E. Peskin, T. Takeuchi, Phys. Rev. D46 (1992) 381-409

$$\alpha S = 4e^2 \left[\Pi_{33}^{\mathrm{NP}\,\prime}(0) - \Pi_{3Q}^{\mathrm{NP}\,\prime}(0) \right]$$
$$\alpha T = \frac{e^2}{s_W^2 c_W^2 M_Z^2} \left[\Pi_{11}^{\mathrm{NP}}(0) - \Pi_{33}^{\mathrm{NP}}(0) \right]$$
$$\alpha U = 4e^2 \left[\Pi_{11}^{\mathrm{NP}\,\prime}(0) - \Pi_{33}^{\mathrm{NP}\,\prime}(0) \right]$$

- In models where EWSB is realized linearly, U is expected to be << S,T

dim 8 (for U) dim 6 (for S,T)

- Oblique Parameters(*S, T [U=0]*):



EWPO depend on STU via

$$A = S - 2c_W^2\, T - \frac{(c_W^2 - s_W^2)}{2s_W^2} U$$

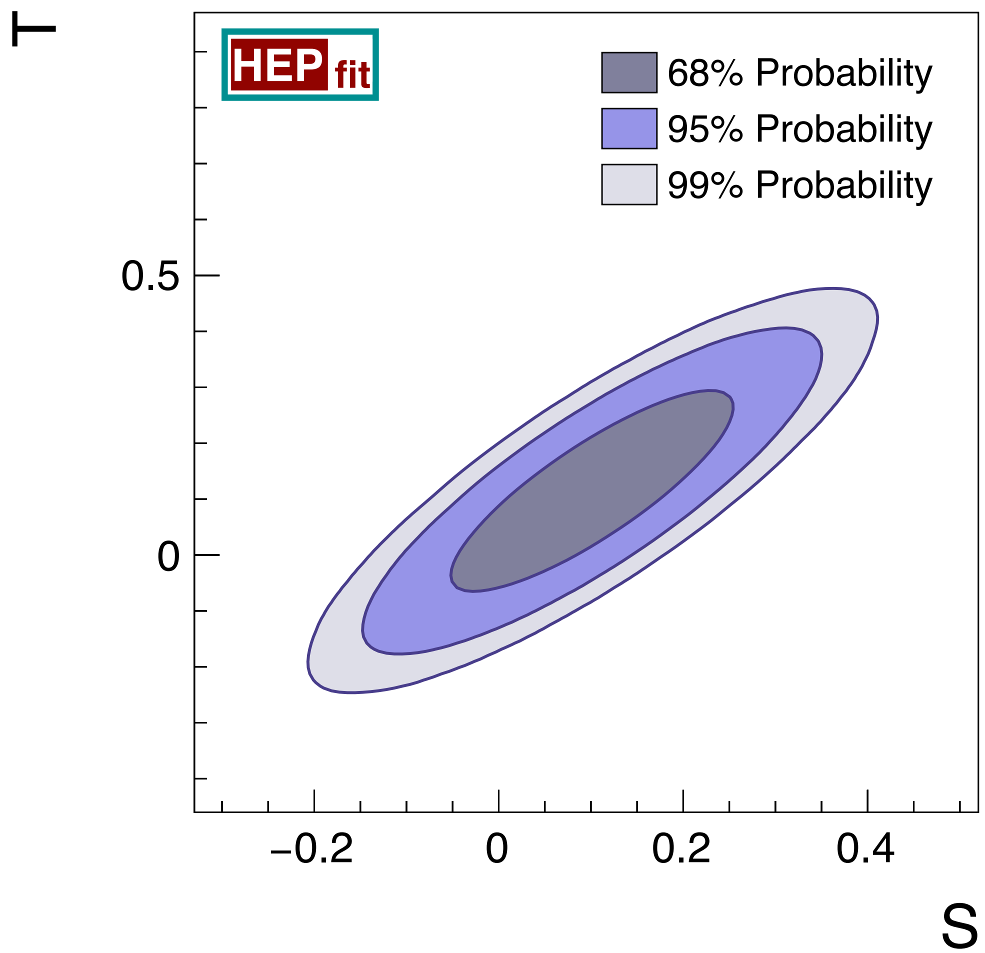
$$B = S - 4c_W^2 s_W^2\, T$$

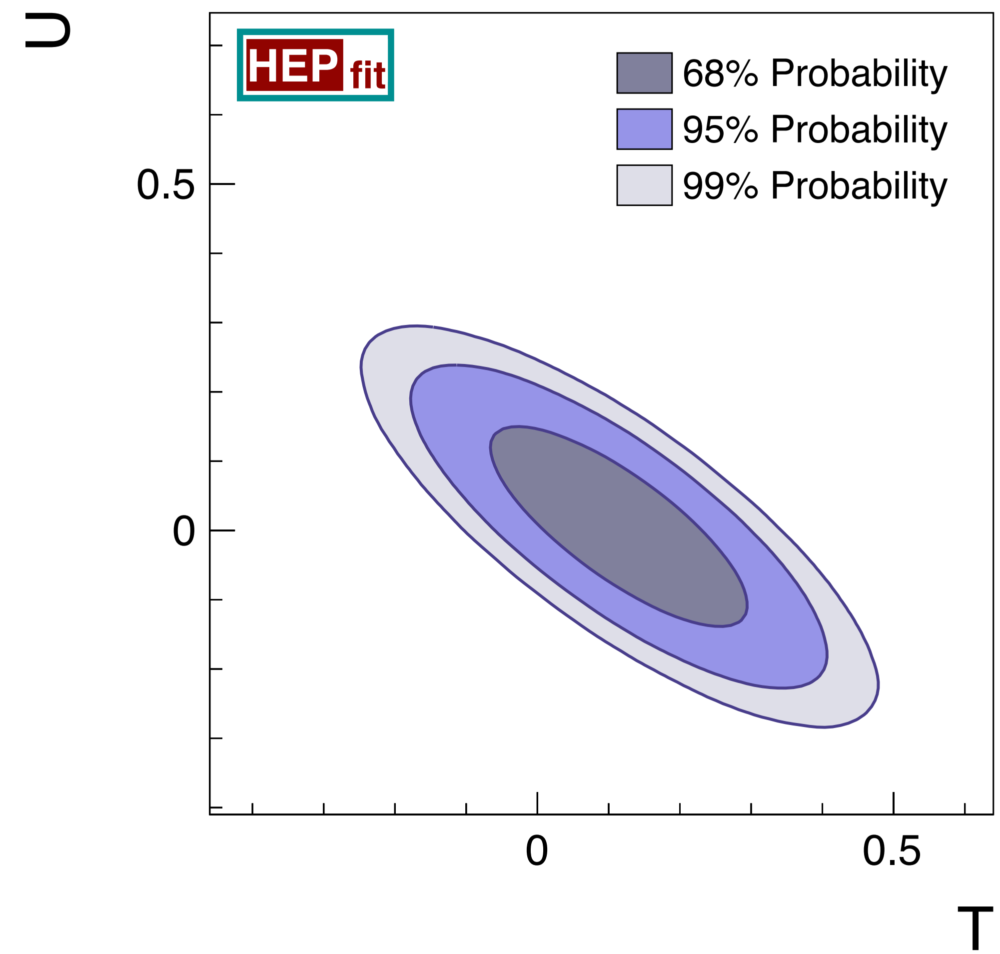
$$C = -10(3 - 8s_W^2)\, S + (63 - 126s_W^2 - 40s_W^4)\, T$$

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

EWPD limits on NP: S, T, U

- Oblique Parameters (S, T, U):





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

EWPD limits on NP: Modified Higgs couplings

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

Rescaled hVV couplings

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

Rescaled hff couplings

- EWPO: One-loop contribution to S & T

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

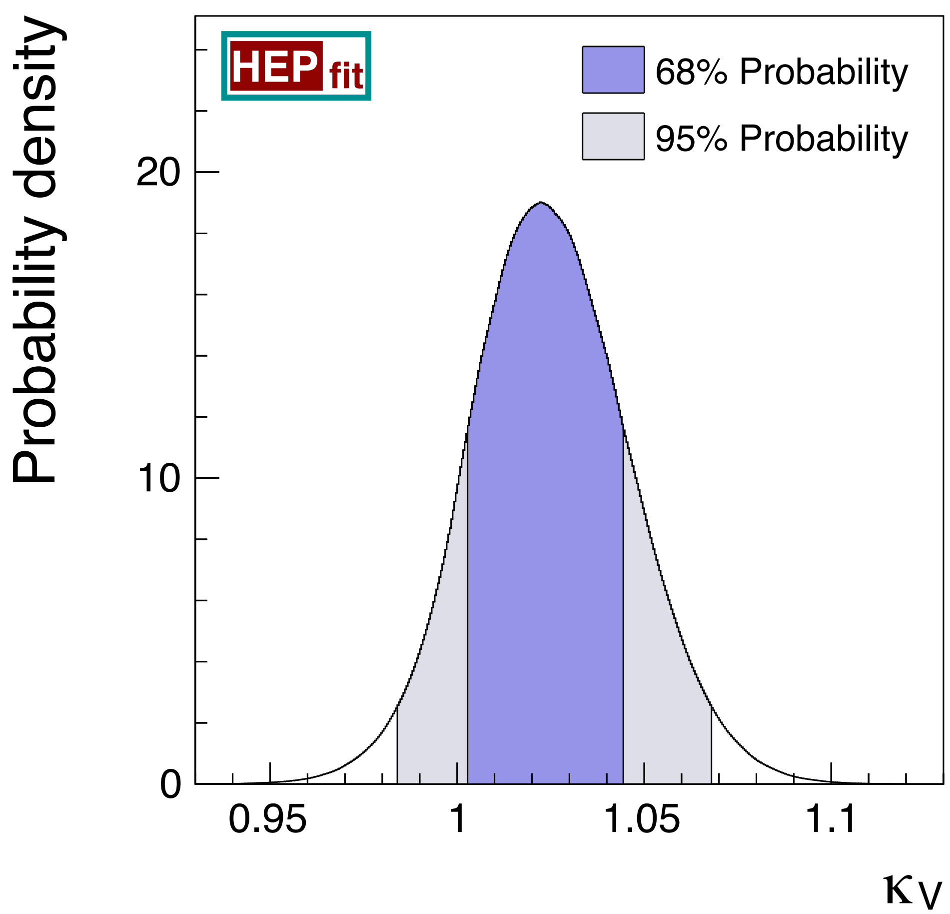
$$\Lambda = \frac{4\pi v}{\sqrt{\left|1-\kappa_V^2\right|}}$$

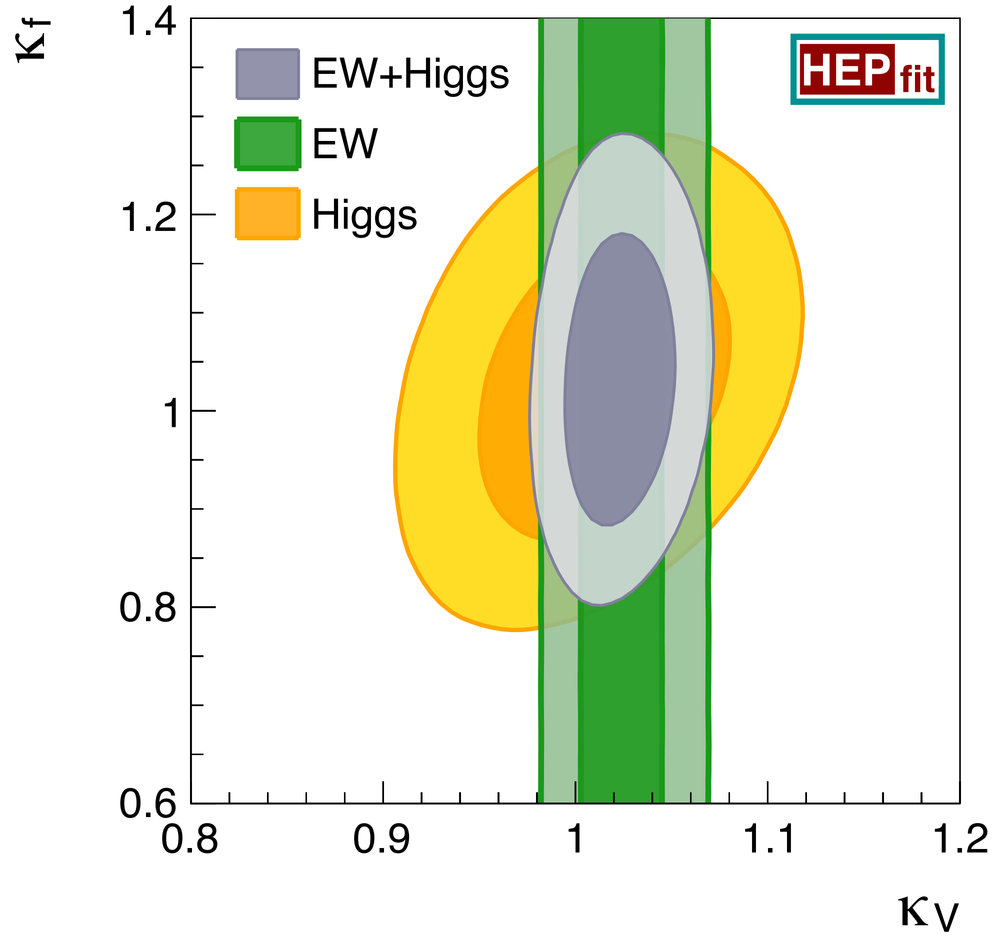
Cut-off of the Higgs Eff. Lag.

- Modified Higgs couplings (κ_V):

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

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





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

EWPD bounds (κ_V) stronger than Higgs limits (LHC run 1)

EWPD limits on NP: Dim 6 SMEFT

- The SM Effective Theory:

$$\mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

  - General parametrization compatible with assumptions
  - Provides ordering principle (power counting)
  - Provides (Lorentz & Gauge invariance) correlations between different types of observables

- SMEFT basis:
  - Dimension 5: 1 operator — S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566
  - Dimension 6: 59 operators — W. Buchmüller, D. Wyler, Nucl. Phys. B268 (1986) 621; C. Arzt, M.B. Einhorn, J. Wudka, Nucl. Phys. B433 (1995) 41; B.Grzadkowski, M.Iskrynski, M.Misiak, J.Rosiek, JHEP 1010 (2010) 085

We use the GIMR/Warsaw basis

- EWPO sensitive to:
  - Oblique corrections

$$\mathcal{O}_{HD} = \left|H^\dagger iD_\mu H\right|^2 \qquad \mathcal{O}_{HWB} = (H^\dagger \sigma_a H) W^a_{\mu\nu} B^{\mu\nu}$$

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

  - Corrections to EW *Vff* couplings

$$\mathcal{O}^{(1)}_{Hf} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{f}\gamma^\mu f) \qquad \mathcal{O}^{(3)}_{Hf} = (H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{f}\gamma^\mu \sigma_a f)$$

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

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

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

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

EWPD limits on dim 6 interactions

1 operator at a time. Flavor universal.

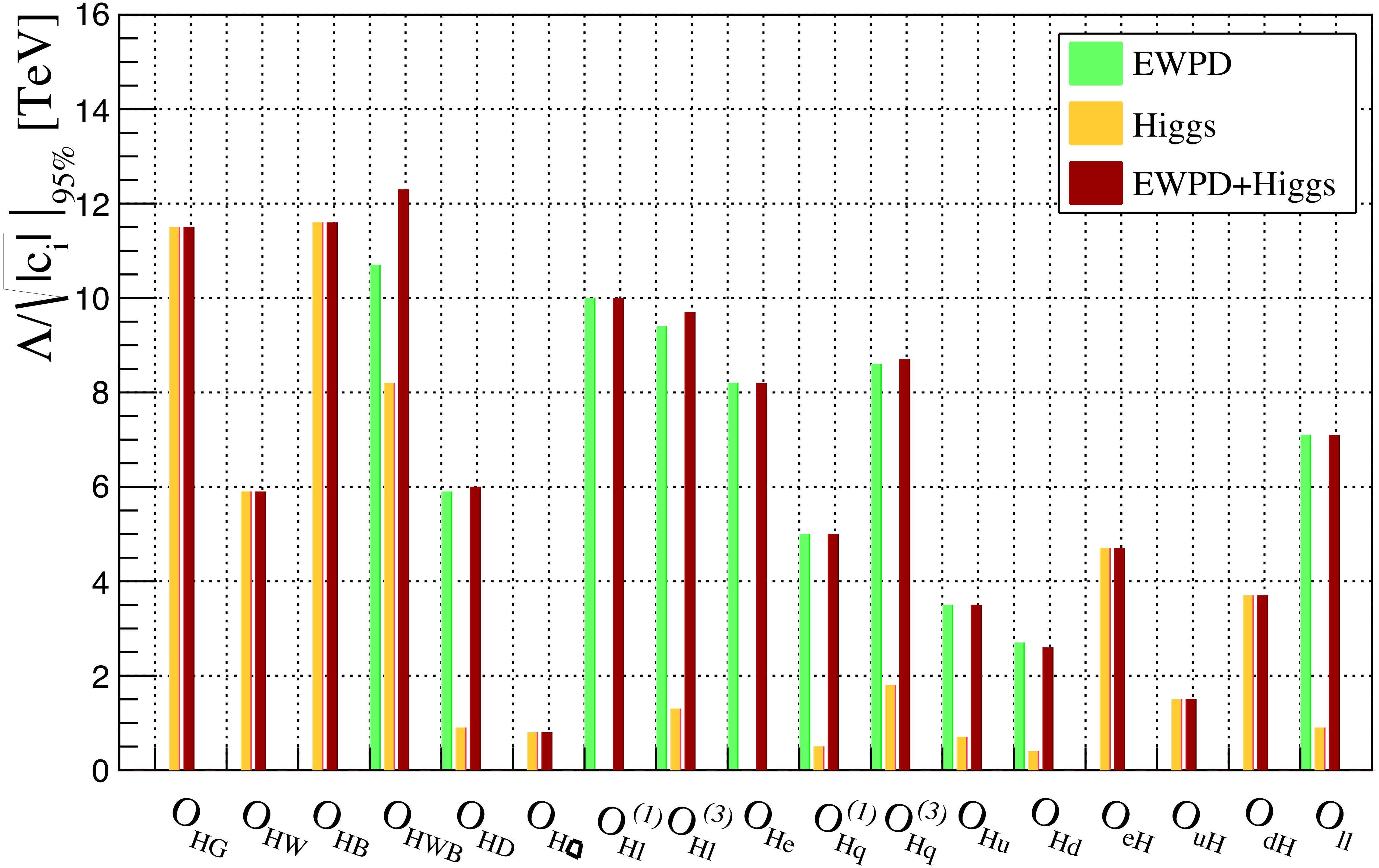
	Operator	95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	Λ [TeV] $C_i = 1$	$C_i = -1$	$C_i = \pm 1$
$\mathcal{O}_{HWB}$	$(H^\dagger \sigma_a H)\, W^a_{\mu\nu} B^{\mu\nu}$	[−0.010, 0.004]	14 (22.4%)	10 (77.6%)	11
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H \right\rvert^2$	[−0.032, 0.006]	9.4 (7.3%)	5.9 (92.7%)	5.9
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\,(\overline{l_L}\gamma^\mu l_L)$	[−0.006, 0.011]	9.8 (75.6%)	12 (24.4%)	10
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)\,(\overline{l_L}\gamma^\mu \sigma_a l_L)$	[−0.013, 0.006]	12 (21.5%)	9.3 (78.5%)	9.4
$\mathcal{O}_{He}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\,(\overline{e_R}\gamma^\mu e_R)$	[−0.017, 0.006]	11 (16.8%)	8.2 (83.2%)	8.2
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\,(\overline{q_L}\gamma^\mu q_L)$	[−0.025, 0.046]	4.9 (70.9%)	5.9 (29.1%)	5.0
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)\,(\overline{q_L}\gamma^\mu \sigma_a q_L)$	[−0.011, 0.016]	8.3 (63.4%)	9.4 (36.6%)	8.6
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\,(\overline{u_R}\gamma^\mu u_R)$	[−0.069, 0.088]	3.4 (59.0%)	3.8 (41.0%)	3.5
$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)\,(\overline{d_R}\gamma^\mu d_R)$	[−0.159, 0.058]	3.7 (17.6%)	2.6 (82.4%)	2.7
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	[−0.010, 0.023]	7.0 (79.1%)	9.1 (20.9%)	7.1

Assuming $C_i \sim 1$ ⇒ EWPD bounds on NP scale > 3-12 TeV

EWPD limits on dim 6 interactions

1 operator at a time. Flavor universal.

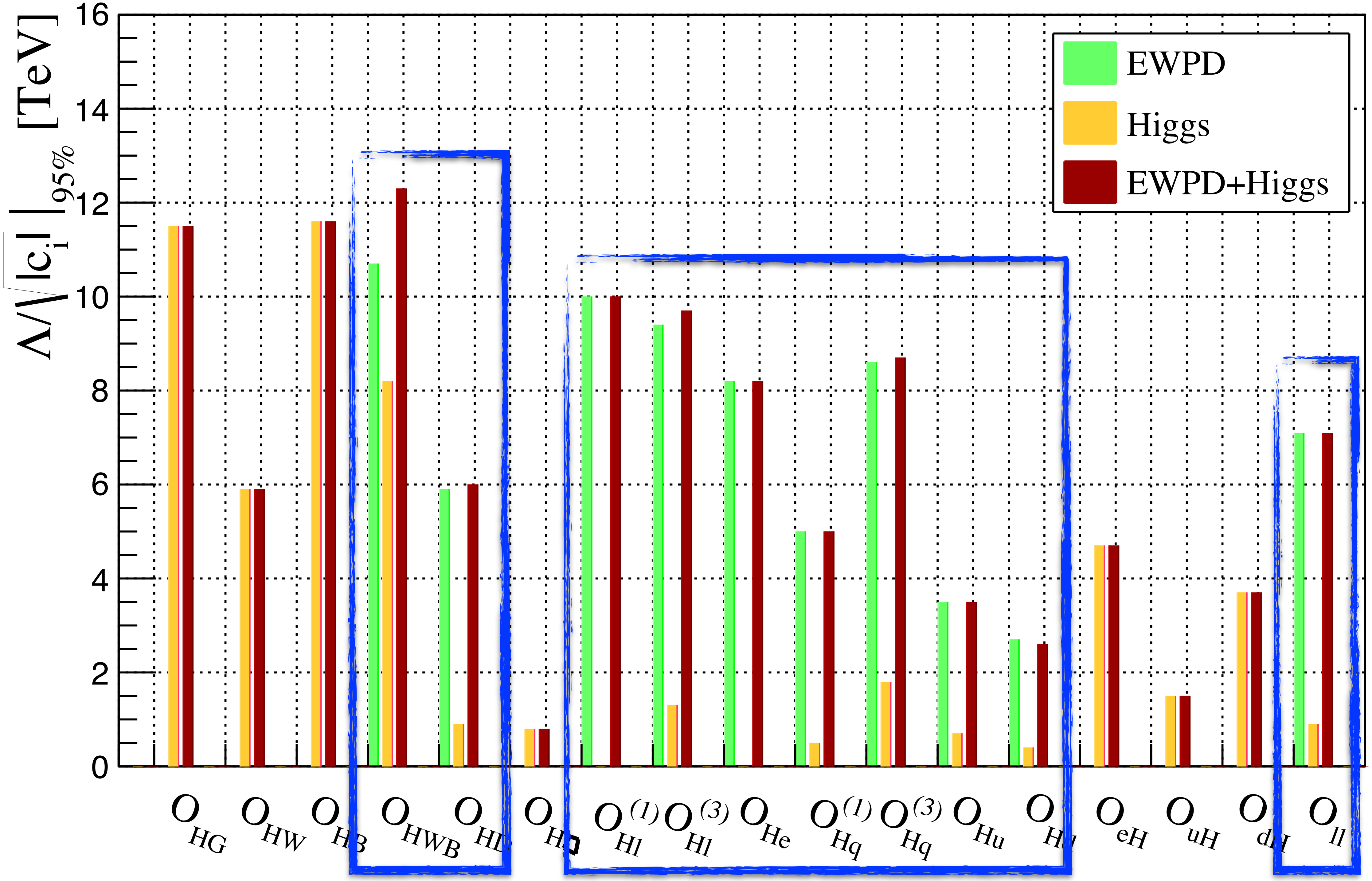
Comparison EWPD and Higgs bounds



EWPD limits on dim 6 interactions

1 operator at a time. Flavor universal.

Comparison EWPD and Higgs bounds



EWPD bounds stronger than Higgs limits (LHC run 1)

EWPD limits on dim 6 interactions

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	$[-0.012, 0.036]$	$[-0.006, 0.011]$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	$[-0.064, 0.009]$	$[-0.013, 0.006]$
$\mathcal{O}_{He}$	$(H^\dagger i D_\mu H)(\overline{e_R}\gamma^\mu e_R)$	$[-0.026, 0.014]$	$[-0.017, 0.006]$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	$[-0.106, 0.070]$	$[-0.025, 0.046]$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.189, -0.001]$	$[-0.011, 0.016]$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	$[-0.220, 0.420]$	$[-0.069, 0.088]$
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.18, -0.150]$	$[-0.159, 0.058]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.084, 0.030]$	$[-0.010, 0.023]$

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. "Remove" $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EWPD limits on dim 6 interactions

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]
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$\mathcal{O}_{He}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$	$[-0.026, 0.014]$	$[-0.017, 0.006]$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	$[-0.106, 0.070]$	$[-0.025, 0.046]$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.189, -0.001]$	$[-0.011, 0.016]$
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$\mathcal{O}_{Hd}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.18, -0.150]$	$[-0.159, 0.058]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.084, 0.030]$	$[-0.010, 0.023]$

~30-50% correlations

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. "Remove" $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EWPD limits on dim 6 interactions

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	$[-0.012, 0.036]$	$[-0.006, 0.011]$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	$[-0.064, 0.009]$	$[-0.013, 0.006]$
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$	$[-0.026, 0.014]$	$[-0.017, 0.006]$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	$[-0.106, 0.070]$	$[-0.025, 0.046]$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.189, -0.001]$	$[-0.011, 0.016]$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	$[-0.220, 0.420]$	$[-0.069, 0.088]$
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.18, -0.150]$	$[-0.159, 0.058]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.084, 0.030]$	$[-0.010, 0.023]$

~80-90% correlations

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. "Remove" $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EWPD limits on dim 6 interactions

All EW operator at the same time

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{l_L}\gamma^\mu l_L)$	$[-0.012, 0.036]$	$[-0.006, 0.011]$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$	$[-0.064, 0.009]$	$[-0.013, 0.006]$
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$	$[-0.026, 0.014]$	$[-0.017, 0.006]$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$	$[-0.106, 0.070]$	$[-0.025, 0.046]$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.189, -0.001]$	$[-0.011, 0.016]$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$	$[-0.220, 0.420]$	$[-0.069, 0.088]$
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$	$[-1.18, -0.150]$	$[-0.159, 0.058]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.084, 0.030]$	$[-0.010, 0.023]$

~10-80% correlations

1 operator at a time

Only 8 combinations of dim6 operators can be constrained. "Remove" $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$.

EWPD LIMITS ON DIM 6 INTERACTIONS

- Many other ops. can contribute at the loop level... The high precision of EWPD can compensate the loop suppression and set significant constraints.

- We use the full set of RGE for the dim 6 Eff. Lagrangian to classify those interactions that can have large (log-enhanced) contributions to EWPD

E. Jenkins, A. Manohar, M. Trott, JHEP 1310 (2013) 087; JHEP 1401 (2014) 035
R. Alonso, E. Jenkins, A. Manohar, M. Trott, JHEP 1404 (2014) 159

- Large effects ~ y_t ⇒ Top quark interactions, e.g.

$$\mathcal{O}_{\phi u}^{(1)} = (\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\overline{u_R^3}\gamma^\mu u_R^3) \qquad \mathcal{O}_{qq}^{(1)} = \frac{1}{2}(\overline{q_L^3}\gamma_\mu q_L^3)(\overline{q_L^3}\gamma^\mu q_L^3) \qquad \ldots$$

$$\mathcal{O}_{lq}^{(1)} = (\overline{l_L}\gamma_\mu l_L)(\overline{q_L^3}\gamma^\mu q_L^3) \qquad \mathcal{O}_{uB} = (\overline{q_L^3}\sigma^{\mu\nu} u_R^3)\tilde{\phi} B_{\mu\nu}$$

- Work in the leading log approximation for the RGE

$$\frac{dC_i}{d\log\mu} = \frac{1}{16\pi^2}\gamma_i^j C_j \Longrightarrow C_i(\mu) \approx \left(\delta_i^j + \frac{1}{16\pi^2}\gamma_i^j(\Lambda)\log\frac{\mu}{\Lambda}\right) C_j(\Lambda) \qquad \left(C_i \equiv \frac{\alpha_i}{\Lambda^2}\right)$$

EWPD bounds will depend on $\frac{\alpha_i}{\Lambda^2}\log\frac{M_Z}{\Lambda}$

J. B., M. Chala, J. Santiago, JHEP 1509 (2015) 189 (arXiv: 1507.00757 [hep-ph])

- EWPD constraints on electron-top contact interactions

Operator		95% prob. interval $\frac{\alpha_i}{\Lambda^2}\log\frac{M_Z}{\Lambda}$ $[\mathrm{TeV}^{-2}]$	α_i $(\Lambda = 1\ \mathrm{TeV})$	95% prob. lower bound Λ [TeV] $(\alpha_i = +1)$	$(\alpha_i = -1)$
$(\mathcal{O}_{lq}^{(1)})_{eett}$	$(\overline{l_L^1}\gamma_\mu l_L^1)(\overline{q_L^3}\gamma^\mu q_L^3)$	$[-0.15, 0.38]$	$[-0.16, 0.06]$	4.4	3.2
$(\mathcal{O}_{lq}^{(3)})_{eett}$	$(\overline{l_L^1}\gamma_\mu\sigma_a l_L^1)(\overline{q_L^3}\gamma^\mu\sigma_a q_L^3)$	$[-0.26, 0.36]$	$[-0.15, 0.11]$	3.7	3.3
$(\mathcal{O}_{eu})_{eett}$	$(\overline{e_R^1}\gamma_\mu e_R^1)(\overline{u_R^3}\gamma^\mu u_R^3)$	$[-0.21, 0.44]$	$[-0.18, 0.09]$	3.8	2.9
$(\mathcal{O}_{lu})_{eett}$	$(\overline{l_L^1}\gamma_\mu l_L^1)(\overline{u_R^3}\gamma^\mu u_R^3)$	$[-0.40, 0.16]$	$[-0.07, 0.17]$	3.1	4.3
$(\mathcal{O}_{qe})_{ttee}$	$(\overline{q_L^3}\gamma_\mu q_L^3)(\overline{e_R^1}\gamma^\mu e_R^1)$	$[-0.42, 0.20]$	$[-0.08, 0.18]$	3	3.9

- Only three approximate combinations can be constrained

$$\frac{d(C_{\phi l}^{(1)})_{ij}}{d\log\mu} = \frac{N_c}{8\pi^2}\left\{\left(Y_u^\dagger Y_u\right)_{lk}\left(C_{lq}^{(1)}\right)_{ijkl} - \left(Y_u Y_u^\dagger\right)_{lk}\left(C_{lu}\right)_{ijkl}\right\} + \dots$$

$$\frac{d(C_{\phi e}^{(1)})_{ij}}{d\log\mu} = \frac{N_c}{8\pi^2}\left\{\left(Y_u^\dagger Y_u\right)_{lk}\left(C_{qe}\right)_{klij} - \left(Y_u Y_u^\dagger\right)_{lk}\left(C_{eu}\right)_{ijkl}\right\} + \dots$$

$$\left(C_i \equiv \frac{\alpha_i}{\Lambda^2}\right)$$

J. B., M. Chala, J. Santiago, JHEP 1509 (2015) 189 (arXiv: 1507.00757 [hep-ph])

EWPD LIMITS ON DIM 6 INTERACTIONS

- EWPD constraints on Top & Top-Bottom contact interactions

		95% prob. interval		95% prob. lower bound	
		$\frac{\alpha_i}{\Lambda^2}\log\frac{M_Z}{\Lambda}$	α_i	Λ [TeV]	
Operator		$[\text{TeV}^{-2}]$	$(\Lambda = 1\ \text{TeV})$	$(\alpha_i = +1)$	$(\alpha_i = -1)$
$(\mathcal{O}_{qq}^{(1)})_{tttt}$	$\frac{1}{2}(\overline{q_L^3}\gamma_\mu q_L^3)(\overline{q_L^3}\gamma^\mu q_L^3)$	$[-0.55, 1.38]$	$[-0.58, 0.23]$	2.1	1.5
$(\mathcal{O}_{ud}^{(1)})_{ttbb}$	$(\overline{u_R^3}\gamma_\mu u_R^3)(\overline{d_R^3}\gamma^\mu d_R^3)$	$[0.25, 10.9]$	$[-4.6, -0.10]$	0.89	0.37
$(\mathcal{O}_{qu}^{(1)})_{tttt}$	$(\overline{q_L^3}\gamma_\mu q_L^3)(\overline{u_R^3}\gamma^\mu u_R^3)$	$[-1.47, 0.59]$	$[-0.25, 0.62]$	1.4	2
$(\mathcal{O}_{qd}^{(1)})_{ttbb}$	$\overline{q_L^3}\gamma_\mu q_L^3)(\overline{d_R^3}\gamma^\mu d_R^3)$	$[-9.7, -0.07]$	$[0.03, 4.06]$	0.41	0.95

- Very difficult to constrain at the LHC (current LHC bound ~ 390 GeV)

ATLAS, arXiv: 1505.04306 [hep-ex]

- Only two independent combinations

$$\frac{d(C_{\phi q}^{(1)}+C_{\phi q}^{(3)})_{ij}}{d\log\mu} = \frac{N_c}{16\pi^2}\left\{(Y_u^\dagger Y_u)_{lk}\left(\left(C_{qq}^{(1)}\right)_{ijkl} + \left(C_{qq}^{(1)}\right)_{klij}\right) - 2\,(Y_u Y_u^\dagger)_{lk}\left(C_{qu}^{(1)}\right)_{ijkl}\right\} + \ldots$$

$$\frac{d(C_{\phi d}^{(1)})_{ij}}{d\log\mu} = \frac{N_c}{8\pi^2}\,(Y_u^\dagger Y_u)_{lk}\left(\left(C_{qd}^{(1)}\right)_{klij} - \left(C_{ud}^{(1)}\right)_{klij}\right) + \ldots$$

J. B., M. Chala, J. Santiago, JHEP 1509 (2015) 189 (arXiv: 1507.00757 [hep-ph])

EWPD limits on dim 6 interactions

- EWPD constraints on Top dipole interactions

		95% prob. interval $\frac{\alpha_i}{\Lambda^2}\log\frac{M_Z}{\Lambda}$	95% prob. interval α_i	95% prob. lower bound Λ [TeV]	
	Operator	$[\mathrm{TeV}^{-2}]$	$(\Lambda = 1\ \mathrm{TeV})$	$(\alpha_i=+1)$	$(\alpha_i=-1)$
$(\mathcal{O}_{uB})_{tt}$	$(\overline{q_L^3}\sigma^{\mu\nu}u_R^3)\tilde{\phi}B_{\mu\nu}$	$[-0.35, 0.10]$	$[-0.04, 0.15]$	3.4	5.1
$(\mathcal{O}_{uW})_{tt}$	$(\overline{q_L^3}\sigma^{\mu\nu}\sigma_a u_R^3)\tilde{\phi}W^a_{\mu\nu}$	$[-0.39, 0.11]$	$[-0.05, 0.17]$	3.2	4.7

- Both come from the contribution in the running to the "*S*" operator:

$$\frac{dC_{WB}}{d\log\mu} = -\frac{N_c}{8\pi^2}\left\{g_2 \mathrm{Re}\left\{(C_{uB})_{ij}(Y_u)_{ji}\right\} + 2g_1(\mathrm{y}_q+\mathrm{y}_u)\mathrm{Re}\left\{(C_{uW})_{ij}(Y_u)_{ji}\right\}\right\} + \ldots$$

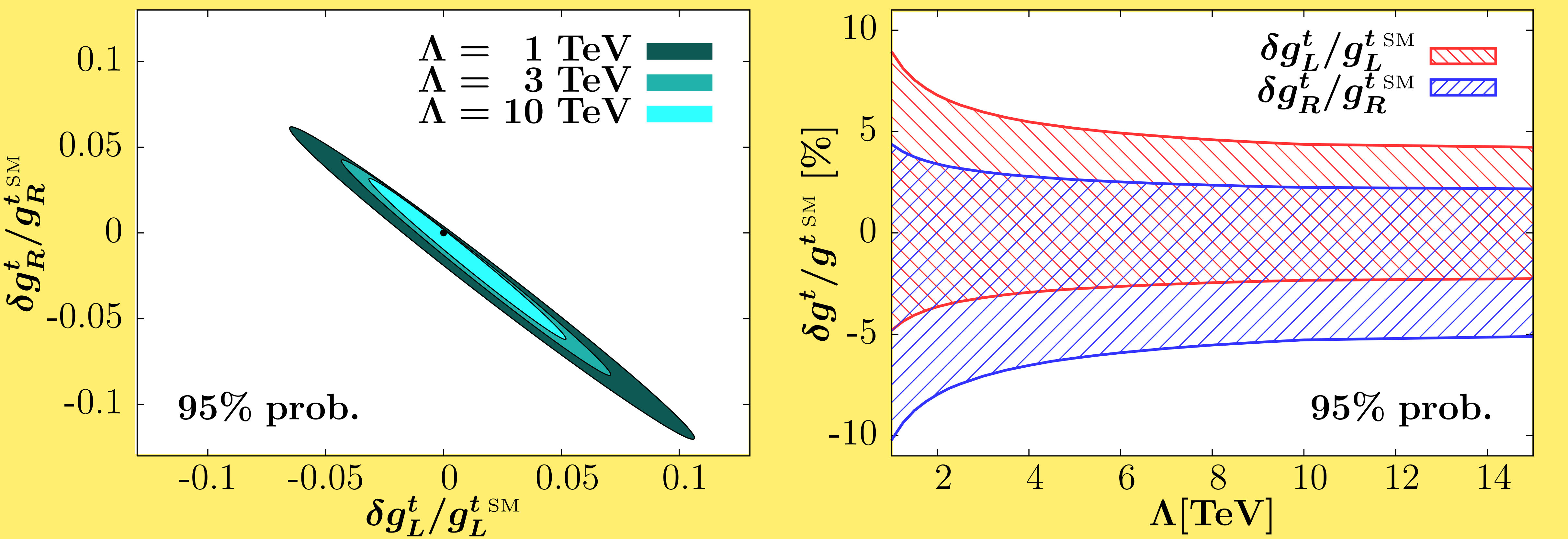
J. B., M. Chala, J. Santiago, JHEP 1509 (2015) 189 (arXiv: 1507.00757 [hep-ph])

- EWPD constraints on electroweak Top couplings

$$\delta g_L^t = -\frac{1}{2}\left(V\left(\alpha_{\phi q}^{(1)} - \alpha_{\phi q}^{(3)}\right)V^\dagger\right)_{tt}\frac{v^2}{\Lambda^2} = -\alpha_{\phi q}^{(t)}\frac{v^2}{\Lambda^2}, \qquad \delta g_R^t = -\frac{1}{2}\left(\alpha_{\phi u}^{(1)}\right)_{tt}\frac{v^2}{\Lambda^2}$$

$$\frac{\delta g_L^t}{g_L^{t\ \mathrm{SM}}} \in [-0.048, 0.089], \qquad \frac{\delta g_R^t}{g_R^{t\ \mathrm{SM}}} \in [-0.102, 0.044] \qquad (\Lambda = 1\ \mathrm{TeV})$$

$$\left(\alpha_{\phi q}^{(t)} \in [-0.52, 0.28], \qquad (\alpha_{\phi u}^{(1)})_{tt} \in [-0.50, 0.21]\right)$$



Electroweak precision observables at future colliders

J.B., M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina & L. Silvestrini
arXiv: 1608.01509 [hep-ph]
+ In Preparation

EWPO at Future colliders

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

	Z pole	WW threshold	HZ threshold	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}(ab^{-1}/year)$	86	15	3.5	1.0	1.0
Years of run	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	6×10^7	2×10^6	2×10^5	7.5×10^4

Each run improves the precision of different sectors of EWPO and/or Higgs observables

- Physics at the ILC: Optimized for a precise determination of Higgs properties. Operation at 250, 350, 500 (and 1000?) GeV

- Physics at the CEPC: designed as a Z and H factory (Z-pole and HZ runs)

- Expected sensitivities to EWPO

	Current Data	HL-LHC	ILC	FCCee	(Run)	CEPC
$\alpha_s(M_Z^2)$	0.1179±0.0012					
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	0.02750±0.00033					
M_Z[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)	±0.037
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	0.2324±0.0012			±0.0001	(FCCee-Z)	±0.000023
P_τ^{pol}	0.1465±0.0033			±0.0002	(FCCee-Z)	
A_ℓ	0.1513±0.0021			±0.000021	(FCCee-Z [pol])	
A_c	0.670±0.027			±0.01	(FCCee-Z [pol])	
A_b	0.923±0.020			±0.007	(FCCee-Z [pol])	
$A_{\text{FB}}^{0,\ell}$	0.0171±0.0010			±0.0001	(FCCee-Z)	±0.0010
$A_{\text{FB}}^{0,c}$	0.0707±0.0035			±0.0003	(FCCee-Z)	
$A_{\text{FB}}^{0,b}$	0.0992±0.0016			±0.0001	(FCCee-Z)	±0.00014
R_ℓ^0	20.767±0.025			±0.001	(FCCee-Z)	±0.007
R_c^0	0.1721±0.0030			±0.0003	(FCCee-Z)	
R_b^0	0.21629±0.00066			±0.00006	(FCCee-Z)	±0.00018

$\gtrsim O(10)$ improv.

- Experimental vs Theoretical uncertainties:

Present

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	4.5	16
Γ_Z [MeV]	0.5	2.3
R_b $[10^{-5}]$	15	66

Future

Quantity	ILC	FCC-ee	CEPC	Projected theory error
M_W [MeV]	3–4	1	3	1
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	1	0.6	2.3	1.5
Γ_Z [MeV]	0.8	0.1	0.5	0.2
R_b $[10^{-5}]$	14	6	17	5–10

A. Freitas, arXiv: 1604.00406

EWPO at Future colliders

- Experimental vs Theoretical uncertainties:

Present

Quantity	Theory error	Exp. error
M_W [MeV]	4	15
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	4.5	16
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Future

Quantity	ILC	FCC-ee	CEPC	Projected theory error
M_W [MeV]	3–4	1	3	1
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	1	0.6	2.3	1.5
Γ_Z [MeV]	0.8	0.1	0.5	0.2
R_b [10^{-5}]	14	6	17	5–10

A. Freitas, arXiv: 1604.00406

Theoretical effort necessary to achieve future experimental precision

EWPO at Future colliders: sensitivity to NP

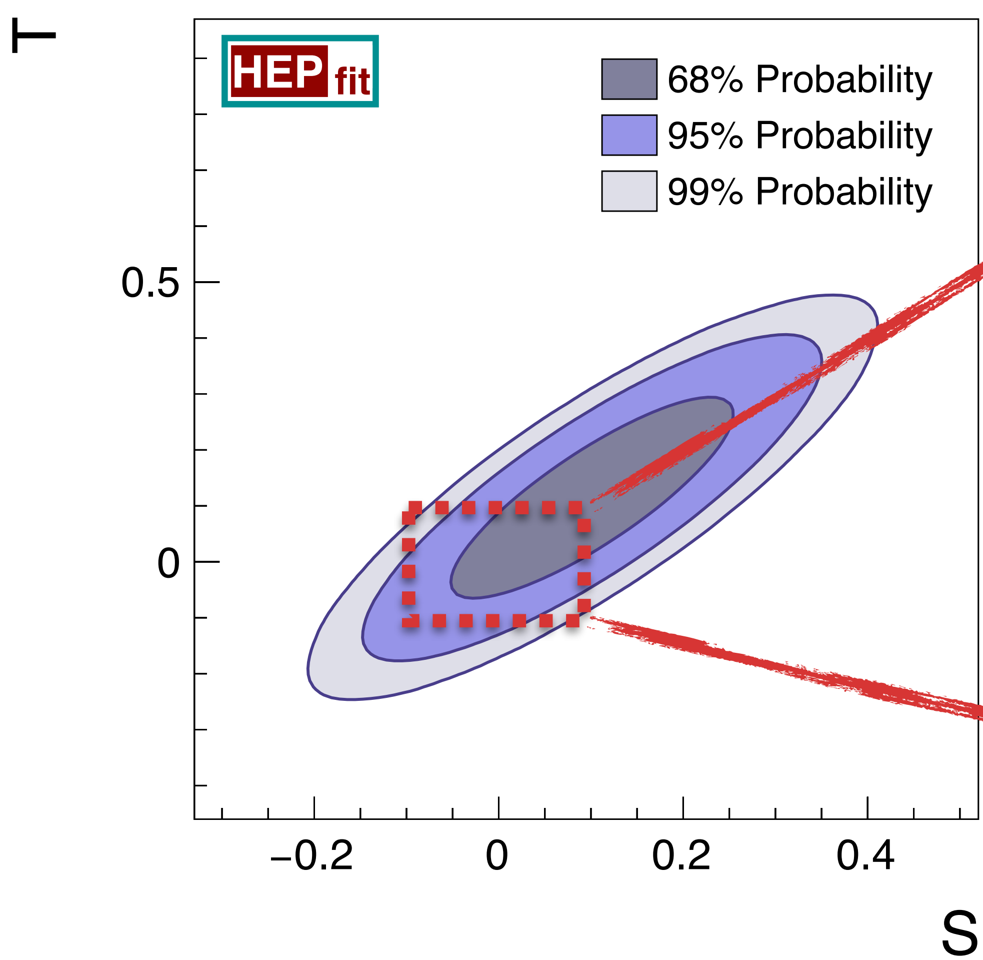
- General strategy for the calculation of future sensitivities:
  - Assume theoretical uncertainties will be reduced as needed to reach future experimental precision

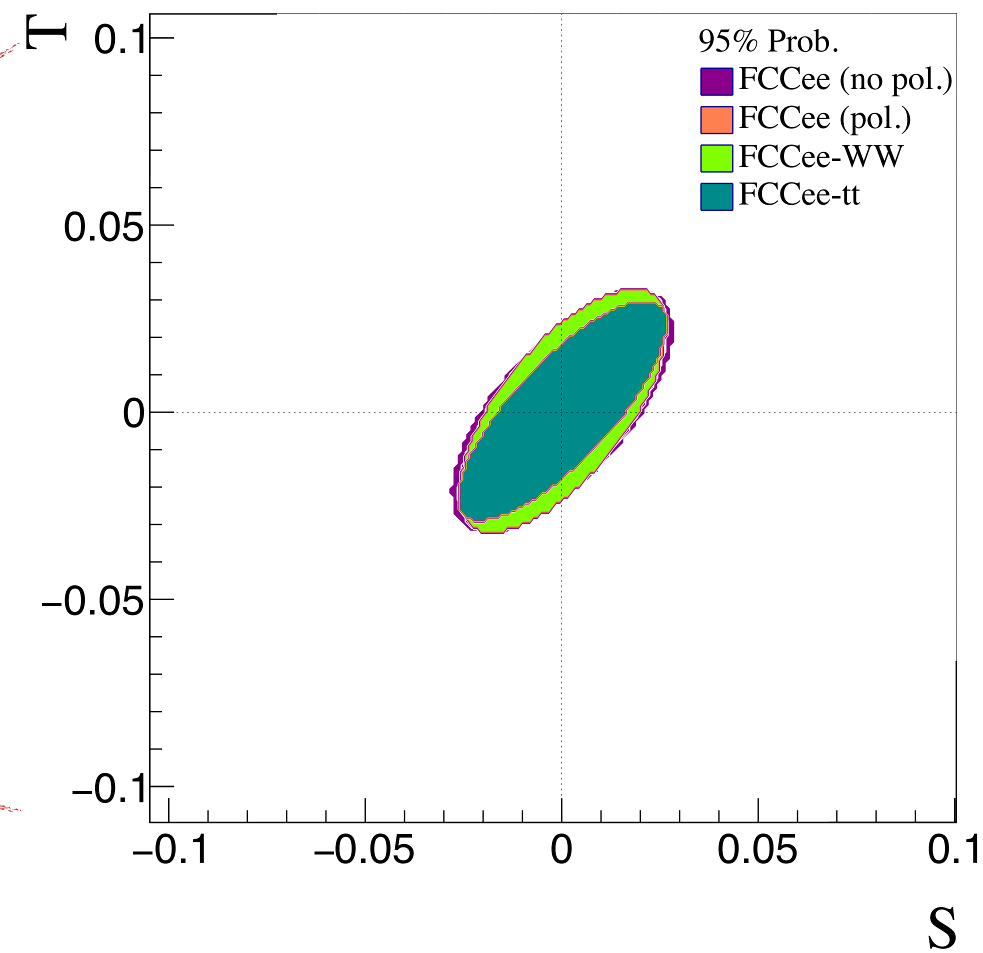
(Also use the future expected uncertainties $\delta(\Delta\alpha_{\rm had}^{(5)}(M_Z^2)) \approx 0.00005$)
$\delta\alpha_s(M_Z^2) \approx 0.0002$

  - Use SM best-fit results as central values for future data. Limits provide future sensitivity to New Physics.

- Will use the FCCee as a reference to illustrate the sensitivity to NP at future colliders

- Oblique Parameters (S, T, U): **Present vs. Future**



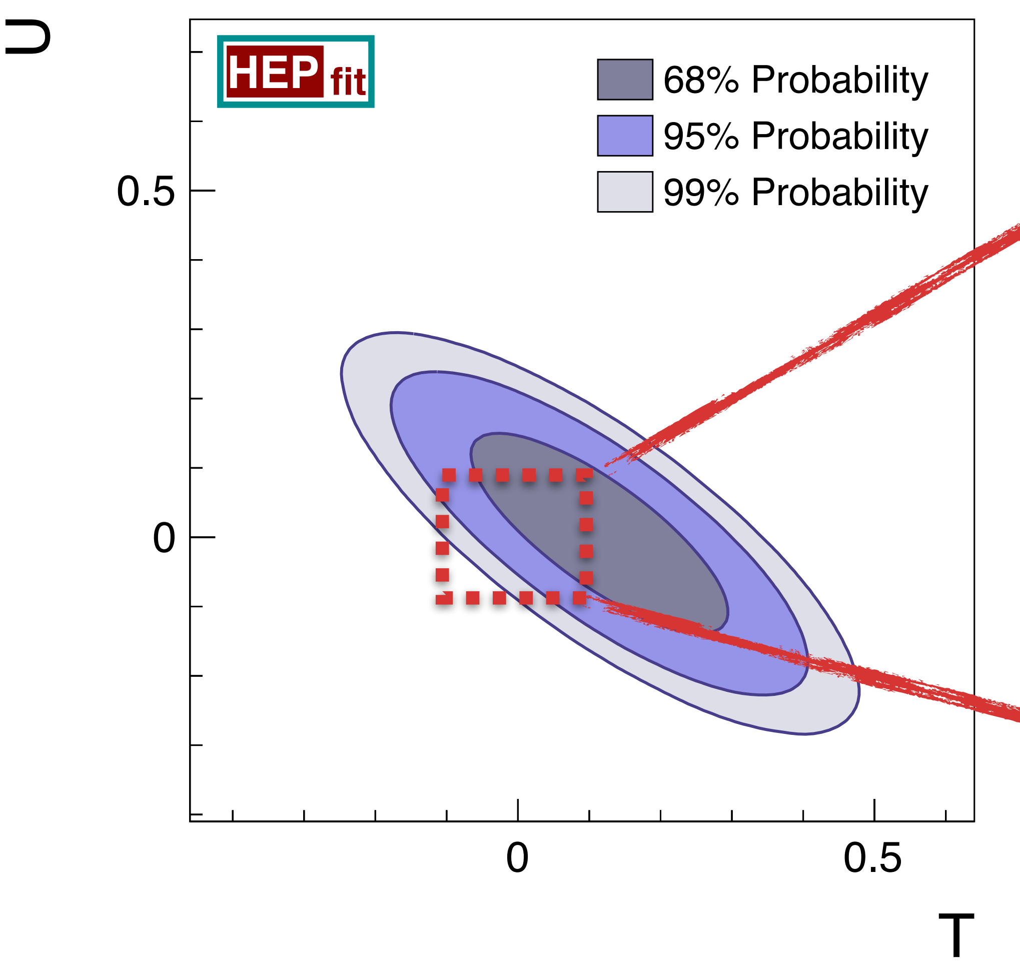


	Fit result	Correlations		
S	0.09 ± 0.10	1.00		
T	0.10 ± 0.12	0.86	1.00	
U	0.01 ± 0.09	-0.54	-0.81	1.00

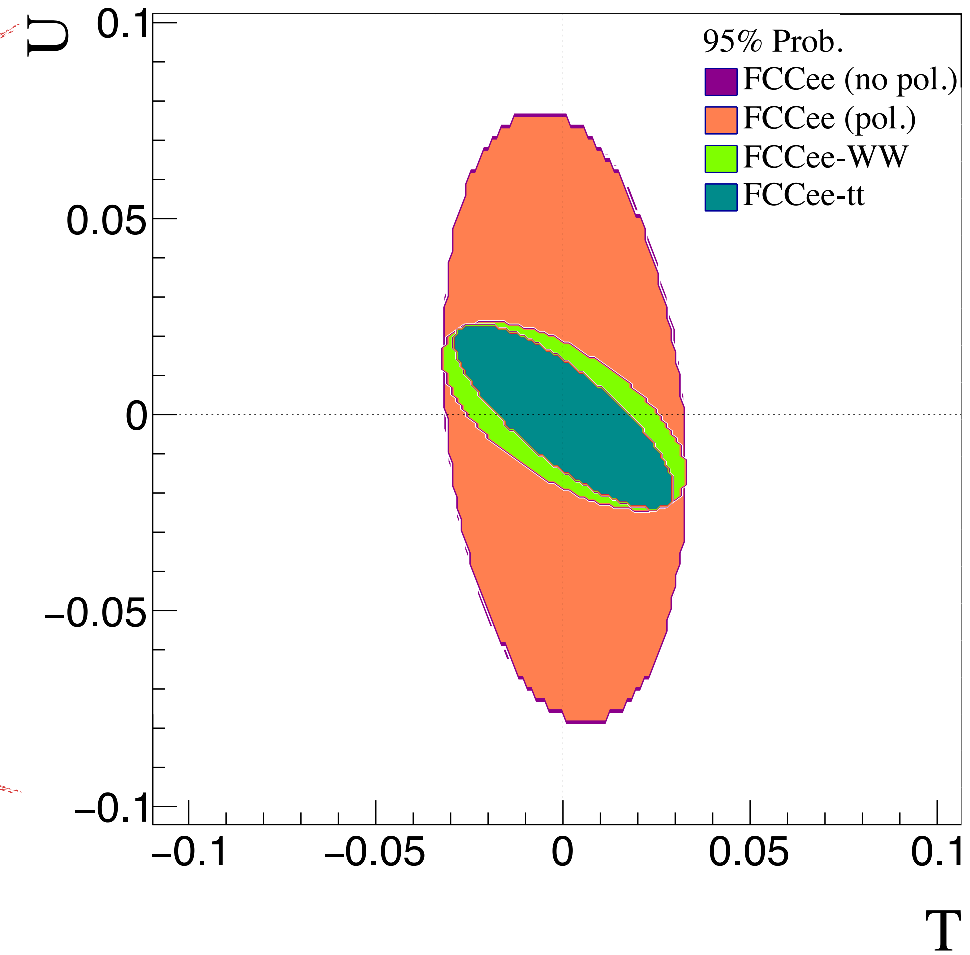
FCCee

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

- Oblique Parameters (S, T, U): **Present vs. Future**



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



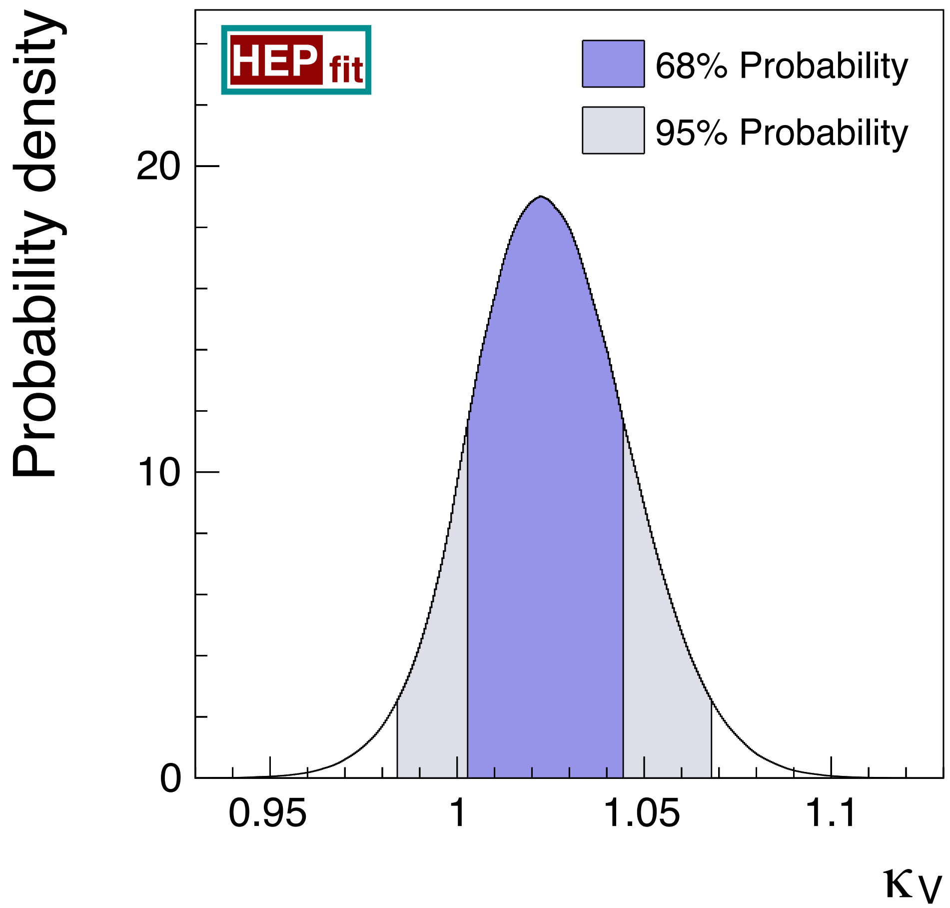
FCCee

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

Major improvement on U at FCCee-WW

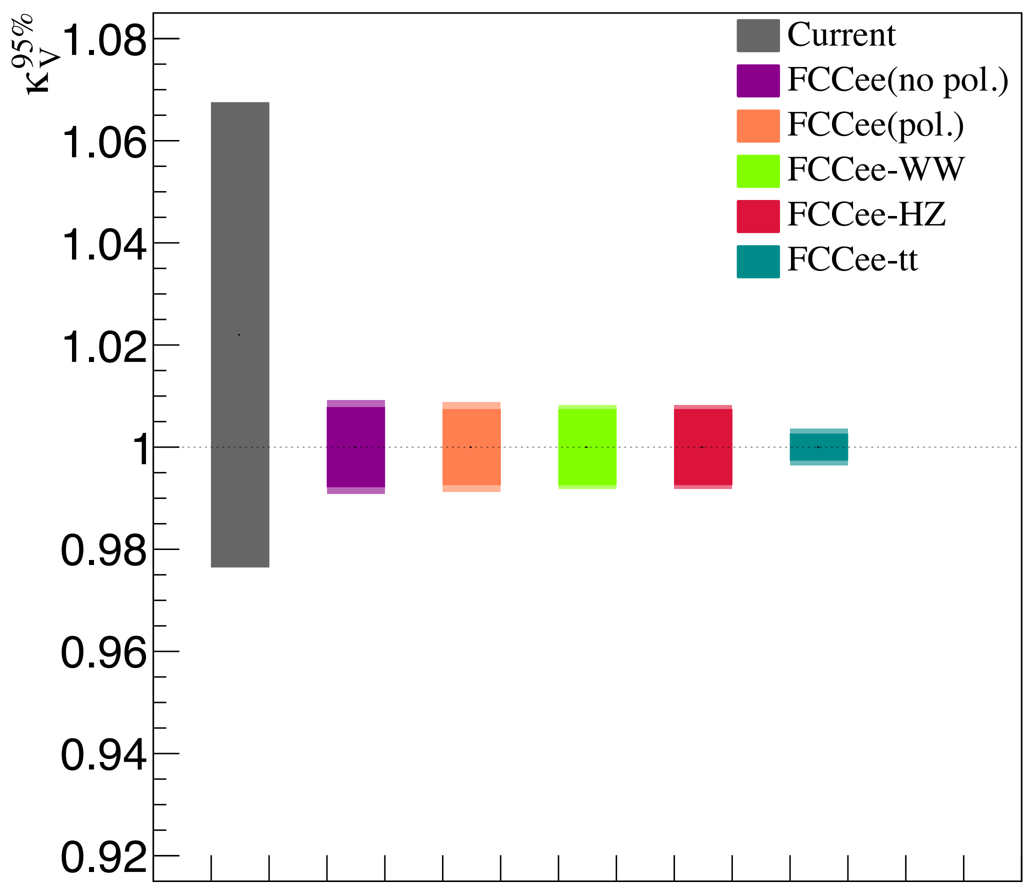
- Modified Higgs couplings (κ_V): **Present vs. Future**

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



Implications for composite Higgs (κ_V<1):

Extra contrib. to S, T required to agree with EWPD fit



FCCee

$\Delta\kappa_V \sim 0.002$

EWPO at Future colliders: sensitivity to NP

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

	Current	HL-LHC	ILC		FCCee								CEPC	
					Z (no pol)		Z (pol)		WW		$t\bar{t}$			
ΔS $[\times 10^{-3}]$	100	99	99	99	12	7.8	11	6.4	11	6.4	11	6.3	21	19
ΔT $[\times 10^{-3}]$	120	120	120	120	13	8.1	13	7.9	13	7.9	12	5.8	28	26
ΔU $[\times 10^{-3}]$	95	87	83	82	32	31	32	31	9.8	5.4	9.6	5.2	21	20
ΔS $[\times 10^{-3}]$	91	81	79	79	12	7.8	11	6.4	9.5	6.1	9.5	6	14	12
ΔT $[\times 10^{-3}]$	72	63	52	52	13	8.1	13	7.9	10	7.4	6.8	3.6	16	15
$(U=0)$														
$\Delta\varepsilon_1^{\mathrm{NP}}$ $[\times 10^{-5}]$	96	96	96	95	11	7.3	11	7.2	11	7.2	9.5	4.7	25	23
$\Delta\varepsilon_2^{\mathrm{NP}}$ $[\times 10^{-5}]$	86	81	77	76	29	28	28	28	8.6	4.8	8.5	4.7	21	19
$\Delta\varepsilon_3^{\mathrm{NP}}$ $[\times 10^{-5}]$	91	87	88	87	9.9	6.6	9.3	5.5	9.2	5.5	9.3	5.5	20	18
$\Delta\varepsilon_b^{\mathrm{NP}}$ $[\times 10^{-5}]$	130	130	130	130	15	12	15	12	15	12	14	11	41	37
$\Delta\delta g_L^b$ $[\times 10^{-4}]$	14	14	14	14	1.5	1.3	1.2	1.1	1.2	1.1	1.2	1.1	2.4	2.2
$\Delta\delta g_R^b$ $[\times 10^{-4}]$	72	70	70	70	7.1	6.6	5.3	5.3	5.3	5.3	5.3	5.3	8.9	8.6
$\Delta\kappa_V$ $[\times 10^{-3}]$	22	14	4.5	4.4	4.6	3.9	4.4	3.7	4.1	3.7	1.8	1.3	5	4.7

[shaded box] Including future theory errors

[empty box] Assuming subdominant theory errors

J.B., M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina & L. Silvestrini, arXiv: 1608.01509 [hep-ph]

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

	Current	HL-LHC	ILC		FCCee								CEPC	
					Z (no pol)		Z (pol)		WW		$t\bar{t}$			
ΔS $[\times 10^{-3}]$	100	99	99	99	12	7.8	11	6.4	11	6.4	11	6.3	21	19
ΔT $[\times 10^{-3}]$	120	120	120	120	13	8.1	13	7.9	13	7.9	12	5.8	28	26
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$\Delta\varepsilon_b^{\mathrm{NP}}$ $[\times 10^{-5}]$	130	130	130	130	15	12	15	12	15	12	14	11	41	37
$\Delta\delta g_L^b$ $[\times 10^{-4}]$	14	14	14	14	1.5	1.3	1.2	1.1	1.2	1.1	1.2	1.1	2.4	2.2
$\Delta\delta g_R^b$ $[\times 10^{-4}]$	72	70	70	70	7.1	6.6	5.3	5.3	5.3	5.3	5.3	5.3	8.9	8.6
$\Delta\kappa_V$ $[\times 10^{-3}]$	22	14	4.5	4.4	4.6	3.9	4.4	3.7	4.1	3.7	1.8	1.3	5	4.7

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

Including future theory errors (grey-shaded cells)

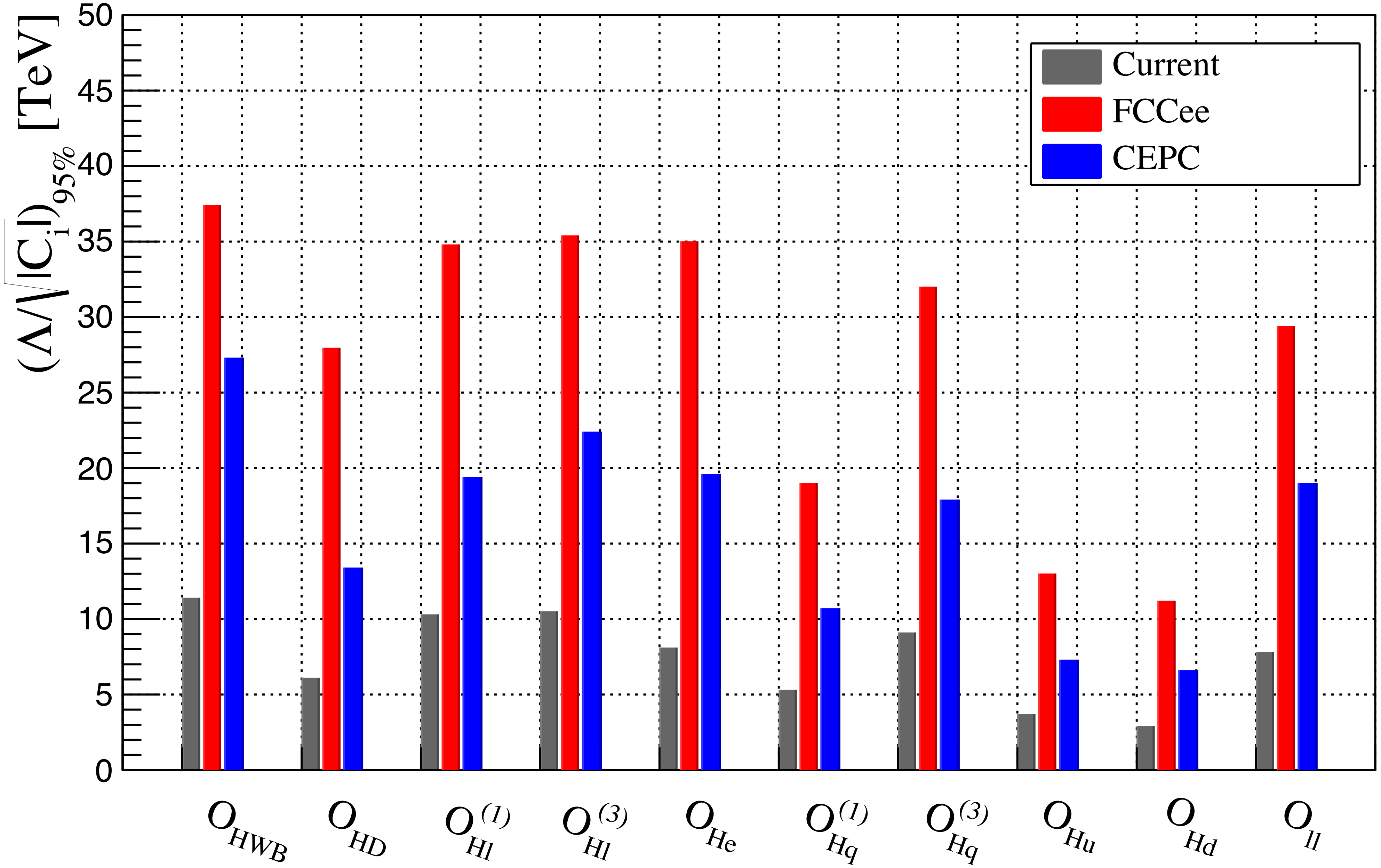
Assuming subdominant theory errors

J.B., M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina & L. Silvestrini, arXiv: 1608.01509 [hep-ph]

Preliminary

- Dimension six SMEFT: **Present vs. Future**

1 operator at a time. Flavor universal.



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

- Current EWPD fit shows good agreement with the SM predictions at the 2-loop level

  ⇒ Strong constraints on NP at the TeV scale

  (Guide and complement the information from LHC direct searches)

- Future e^+e^- colliders would strengthen the constraining/discriminating power of the EWPD fit. Significant **improvement in theoretical calculations is required** to match future exp. precision of EWPO.

- Projected sensitivities to NP (EWPO at FCCee):

	Expected sensitivity	Improvement
$S,\ T,\ U$	$\Delta S,\ \Delta T,\ \Delta U \sim 5\text{-}10 \cdot 10^{-3}$	10-20x
κ_V	$\Delta\kappa_V \sim 0.001\text{-}0.002$	10-20x
$\mathcal{L}^{d=6}_{\mathrm{SMEFT}}$	$\Lambda_{NP}\|_{\|C_i\|=1} \gtrsim 5\text{-}40$ TeV	$\sim$ 4x

Backup

The SM fit to EWPD

- Parametric uncertainties

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

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

	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

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

The SM fit to EWPD

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

PDG average (Excluding EW fit determination)

	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

($\delta\alpha_s(M_Z^2) \approx 0.0002$ future lattice projection)