Current status of electroweak precision constraints

Satoshi Mishima (KEK)

Kyoto Univ. May 24, 2017

in collaboration with J. de Blas, M. Ciuchini, E. Franco, M. Pierini, L. Reina & L. Silvestrini

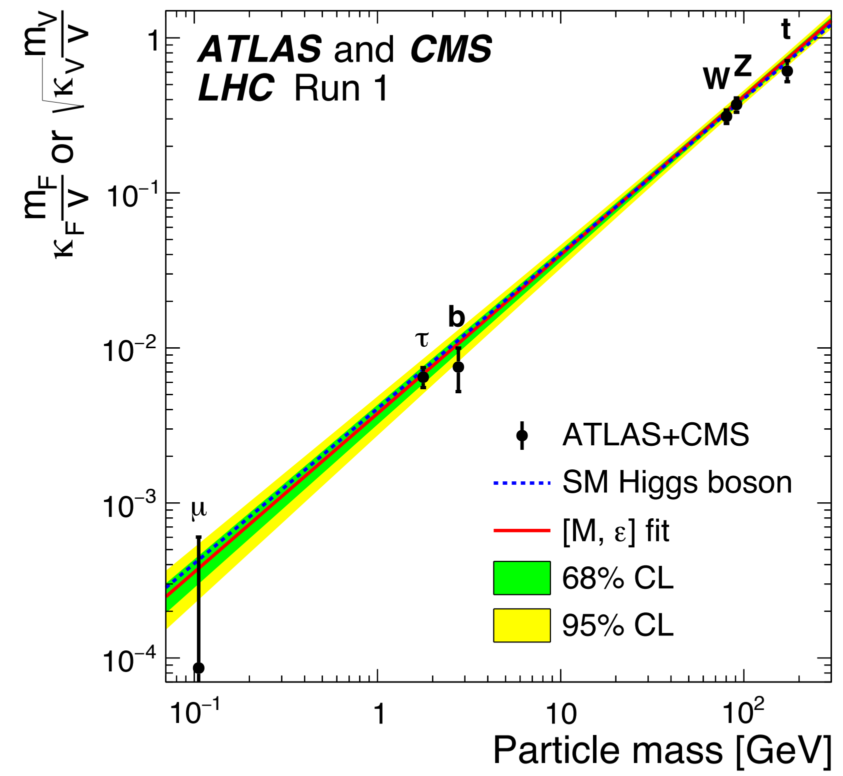
- *JHEP 1612 (2016) 135 [arXiv:1608.01509]*
- *PoS ICHEP2016 (2017) 690 [arXiv:1611.05354]*

+ in preparation

1. Introduction

- In 2012, a Higgs boson was discovered at the LHC.

1606.02266



- It looks very much like the SM Higgs!

$$m_H \approx 125 \text{ GeV}$$

$$J^P = 0^+$$

- However the SM is not satisfactory:

finite neutrino masses, origins of the gauge and flavor structures, cosmological problems (dark matter, baryon asymmetry, inflation, dark energy), quantum gravity, naturalness, …

$$\kappa_{F,i} = \frac{v \cdot m_{F,i}^{\epsilon}}{M^{1+\epsilon}}$$

$$\kappa_{V,i} = \frac{v \cdot m_{V,i}^{2\epsilon}}{M^{1+2\epsilon}}$$

- But, no NP particle has been found so far at the LHC!

Naturalness?

- Naturalness has been a guideline to the scale of new physics (NP) beyond the SM over the last three decades.

't Hooft (79)

Naturalness suggests the existence of NP at TeV scale or below, but no new particle has been observed so far.

⇓

The naturalness argument is facing a puzzling situation!

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NP scale?

The NP scale might be higher than the TeV scale, against the naturalness argument.

Indirect searches for NP through the virtual effects of new particles can explore above TeV scale.

NP searches

Direct searches
high-energy frontier
ATLAS, CMS

Indirect searches
high-intensity frontier
LHCb, Belle II, …

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Indirect searches for NP

- Indirect searches are as relevant as ever after the LHC 7-8 TeV run.

- Historically, indirect hints to unobserved heavy particles were obtained from low-energy experiments:

  the existence of charm quark from kaon decays,
  the heavy top mass from B-Bbar oscillation,
  the Higgs mass from the EW precision fit, …

- It is important to investigate the interplay of direct and indirect searches in the light of experimental data available currently and in the forthcoming years:

  ATLAS/CMS/LHCb at LHC, Belle II (phase-3: 2018/12-),
  other flavor factories

Current work

- We revisit the global fit to EW precision observables (EWPO).

  - a fit in the SM
  - model-independent constraints on several general NP scenarios

- We present a future projection of the fit, and compare the constraining power of proposed experiments.

- Numerical results are obtained with the HEPfit code.

Outline

2. HEPfit
3. EW precision fit in the SM
4. EW precision constraints on NP
5. Expected sensitivities at future colliders
6. Summary

2. HEPfit

HEPfit

- ***HEPfit*** is a framework for calculating various observables (EWPO, Higgs, flavor…) in the SM and in its extensions and for constraining their parameter space with a global fit.

- The real effort of this project started about six years ago, when I was in Rome.

HEPfit codes

- ***HEPfit*** is written in C++, supporting MPI parallelization.
- Dependencies: ROOT, GSL, Boost header files
  Bayesian Analysis Toolkit (BAT) ← *optional*
  Beaujean, Caldwell, Greenwald, Kollar & Kroninger
- ***HEPfit*** will be made available to the public under GPL.
  http://hepfit.roma1.infn.it
  HEPfit ver.1.0 will be released soon(?).
- Working developer versions, requiring ***NetBeans IDE***, are always available through ***github***.
  https://github.com/silvest/HEPfit

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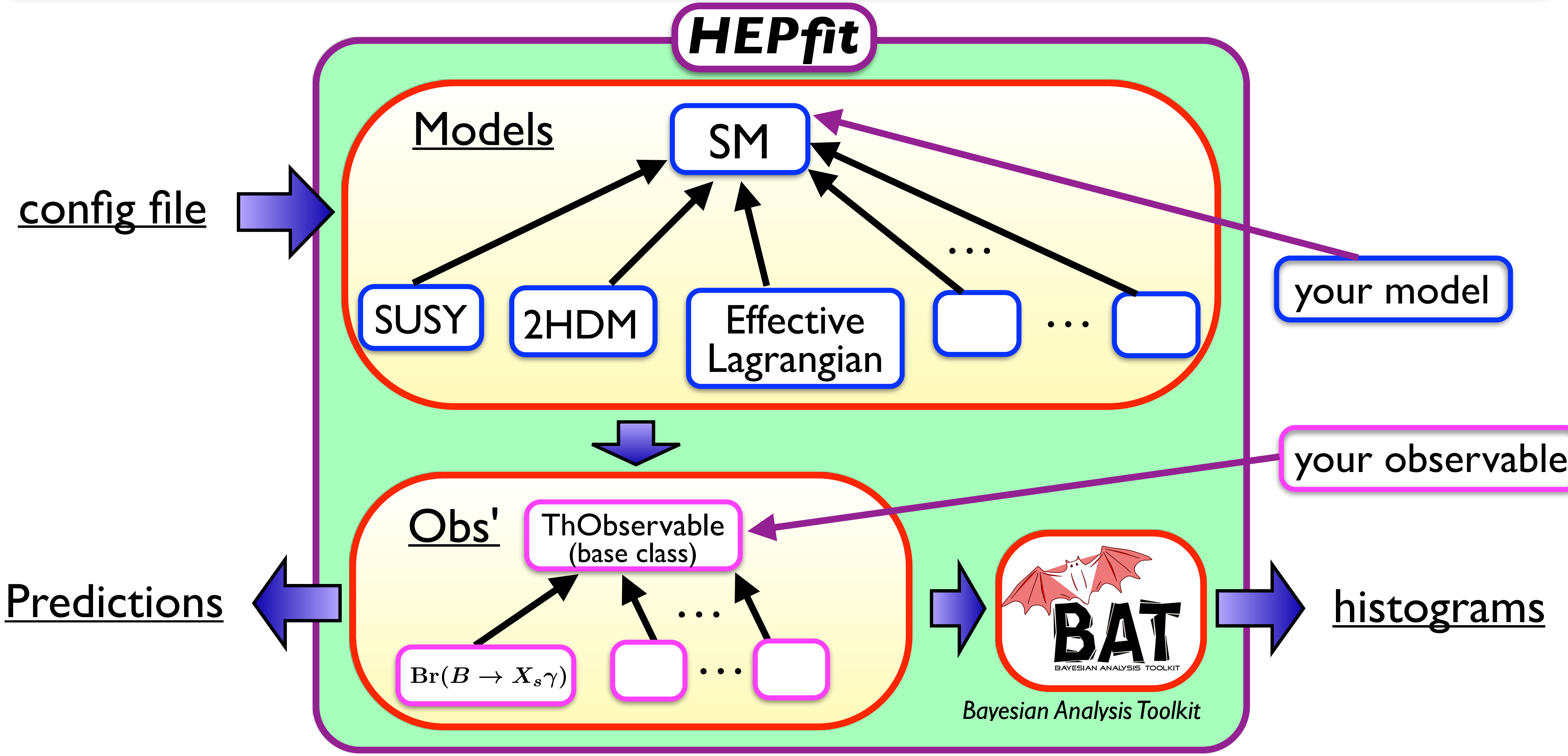
HEPfit



- a stand-alone program to perform a Bayesian statistical analysis.
- alternatively, a library to compute observables in a given model. (*libHEPfit.a* and *HEPfit.h*)
- add user's favorite models and observables as external modules.

Models

HEPfit

- Each ***model*** class contains the definitions of parameters, effective couplings, RGEs, etc.

  - Standard Model

  - MSSM (SLHA2 compatible, in progress)

    (*FeynHiggs* is used to compute Higgs masses, etc.)

  - Two-Higgs-doublet models

  - Some NP extensions for model-independent studies of EW and Higgs

    dim-6 operators, oblique parameters, etc.

Observables

- ***Observables*** are computed from the parameters, the effective couplings and so on that are defined in each model class.

  - EW precision observables

$$M_W,\ \Gamma_W,\ \Gamma_Z,\ \sigma_h^0,\ \sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had}),\ P_\tau^{\rm pol},\ \mathcal{A}_f,\ A_{\rm FB}^{0,f},\ R_f^0$$
$$\text{for}\ \ f=\ell,c,b$$

  - Higgs-boson signal strengths

$$H\to\gamma\gamma,\ ZZ,\ WW,\ \tau^+\tau^-,\ b\bar{b}\quad \text{for different categories}$$

  - LEP2 two-fermion processes (in progress/testing)

$$\sigma\ \text{and}\ A_{\rm FB}\quad \text{for}\ e^+e^-\to e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ c\bar{c},\ b\bar{b}$$

  - Flavor observables ➡ next slide

Examples of flavor observables

HEPfit

- UT-analysis observables: (tested against UTfit)

  CKM sides and angles, $\Delta F = 2$ amplitudes, $B \to \tau\nu$

- Rare decays:

  $B \to K^*\gamma\,,\ B \to K\ell^+\ell^-\,,\ B \to K^*\ell^+\ell^-$ NNLL

  $B \to X_s\gamma\,,\ B \to X_s\ell^+\ell^-$ NNLO+EW

  $B_{s,d} \to \mu^+\mu^-$ NLO(NNLO)+NLO-EW

  $K \to \pi\nu\bar{\nu}\,,\ K \to \mu^+\mu^-$ (in progress)

  $\tau \to \mu\gamma,\ \tau \to e\gamma,\ \mu \to e\gamma$

  $\tau \to 3\ell,\ \mu \to 3e$

- Non-leptonic decays:

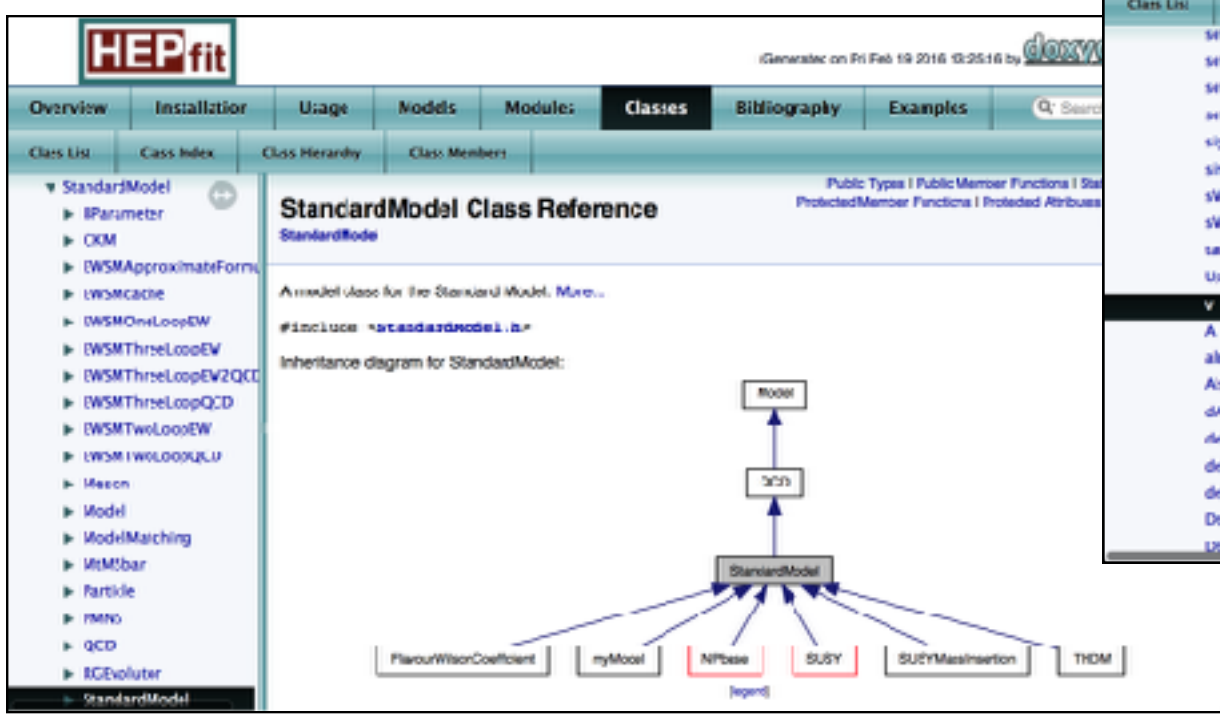
  $B \to PP,\ PV\,,\quad \epsilon'/\epsilon$ (in progress)

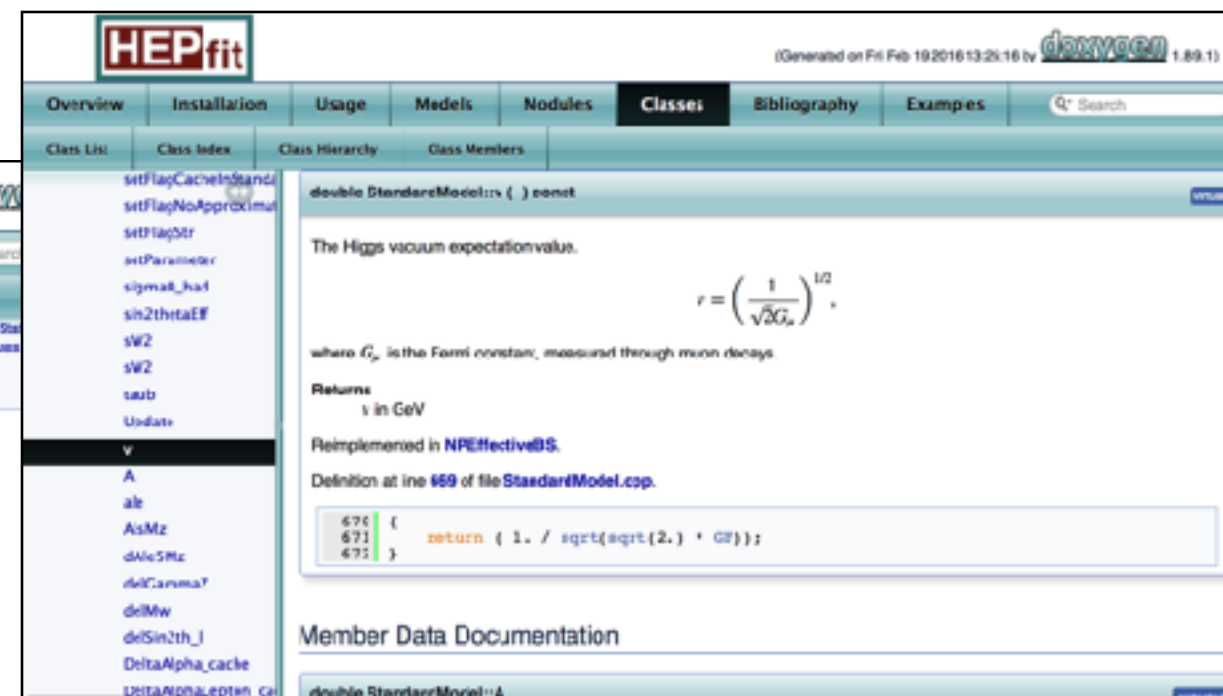
Observable	SM	THDM	SUSY	Dim-6
Flavour:				
$\mathcal{B}(B_s \to \mu^+\mu^-)$	✓	✓	×	×
$\mathcal{B}(\bar{B} \to X_s\gamma)$	✓	✓	×	×
$\mathcal{B}(\tau \to \mu\gamma, 3\mu)$	–	–	✓	×
(...)				
Higgs:				
μ's	✓	✓	×	✓
Direct searches	–	✓	×	–
Electroweak precision observables:				
STU	✓	✓	×	✓
(...)				

Public release

- We are going to release ***HEPfit*** to the public with
  - EWPO/Higgs + flavor [CMK fit, radiative, (semi-)leptonic];
  - a cross-platform build system with ***CMake***;
  - detailed documentation (paper, doxygen);
  - example codes.

in progress!





- Current version: RC1 (Release Candidate 1)

Publications (EW precision fit)

HEPfit

- *M. Ciuchini, E. Franco, **S.M.**, L. Silvestrini, JHEP08 (2013) 106 [arXiv:1306.4644]*
- *M. Ciuchini, E. Franco, **S.M.**, L. Silvestrini, EPJ Web Conf. 60 (2013) 08004* LHCP2013
- *J. de Blas, M. Ciuchini, E. Franco, D. Ghosh, **S.M.**, M. Pierini, L. Reina, L. Silvestrini, Nucl.Part.Phys.Proc. 273-275 (2016) 834 [arXiv:1410.4204]* ICHEP2014
- *M. Ciuchini, E. Franco, **S.M.**, M. Pierini, L. Reina, L. Silvestrini, Nucl.Part.Phys.Proc. 273-275 (2016) 2219 [arXiv:1410.6940]* ICHEP2014
- *J. de Blas, M. Ciuchini, E. Franco, D. Ghosh, **S.M.**, M. Pierini, L. Reina, L. Silvestrini, PoS EPS-HEP2015 (2015) 187* EPS-HEP2015
- *J. de Blas, M. Ciuchini, E. Franco, D. Ghosh, **S.M.**, M. Pierini, L. Reina, L. Silvestrini, PoS LeptonPhoton2015 (2016) 013* Lepton-Photon2015
- *J. de Blas, M. Ciuchini, E. Franco, **S.M.**, M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]*
- *J. de Blas, M. Ciuchini, E. Franco, **S.M.**, M. Pierini, L. Reina, L. Silvestrini, PoS ICHEP2016 (2017) 690 [arXiv:1611.05354]* ICHEP2016

HEPfit developers & contributors

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3. EW precision fit in the SM

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EW precision fit

- Electroweak precision observables (EWPO) offer a very powerful handle on the mechanism of EWSB and allow us to strongly constrain NP models relevant to solve the naturalness (hierarchy) problem.
- Recent qualitative change: Higgs mass measurements

  ⇨ No free SM parameter in the fit

- The precise measurements of the W and top masses at the Tevatron/LHC improve the power of the fit.
- Theoretical calculations of higher-order corrections in the SM have been improved in recent years.
- Precision is such that SM predictions can be tested to the level of radiative corrections.

EW precision observables (EWPO)

M_W, Γ_W and 13 Z-pole observables

(LEP2/Tevatron) (LEP/SLD)

- Z-pole ob's are given in terms of effective couplings:

$$\mathcal{L} = \frac{e}{2 s_W c_W} Z_\mu \bar{f} \left(g_V^f \gamma_\mu - g_A^f \gamma_\mu \gamma_5 \right) f$$

$$A_{\rm LR}^{0,f} = \mathcal{A}_f = \frac{2\,\mathrm{Re}\left(g_V^f/g_A^f\right)}{1 + \left[\mathrm{Re}\left(g_V^f/g_A^f\right)\right]^2} \qquad A_{\rm FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad (f = \ell, c, b)$$

$$P_\tau^{\rm pol} = \mathcal{A}_\tau \qquad \sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4|Q_\ell|}\left[1 - \mathrm{Re}\left(\frac{g_V^\ell}{g_A^\ell}\right)\right]$$

$\Big\}\ g_V^f/g_A^f$

$$\Gamma_f = \Gamma(Z \to f\bar{f}) \propto \left|g_A^f\right|^2 \left[\left|\frac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right]$$

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

$\Big\}\ g_V^f,\ g_A^f$

Experimental data

- Very precise measurements of the W & Z boson properties at e+ e- colliders:

$$M_Z,\ \Gamma_Z,\ \sigma_h^0,\ \sin^2\theta_{\rm eff}^{\rm lept},\ \mathcal{A}_f,\ A_{\rm FB}^{0,f},\ R_f^0$$

Z-pole obs. (LEP/SLD)

0.002% (M_Z) $\qquad O(0.1\%) - O(1\%)$

$$M_W,\ \Gamma_W$$

W obs. (LEP2)

0.04% $\qquad 2\%$

- Measurements at hadron colliders (Tevatron & LHC):

M_W	m_t	m_h
0.020% (CDF + D0) 0.024% (ATLAS)	0.4%	0.2%

- $G_F,\ \alpha$ are fixed to be constants.

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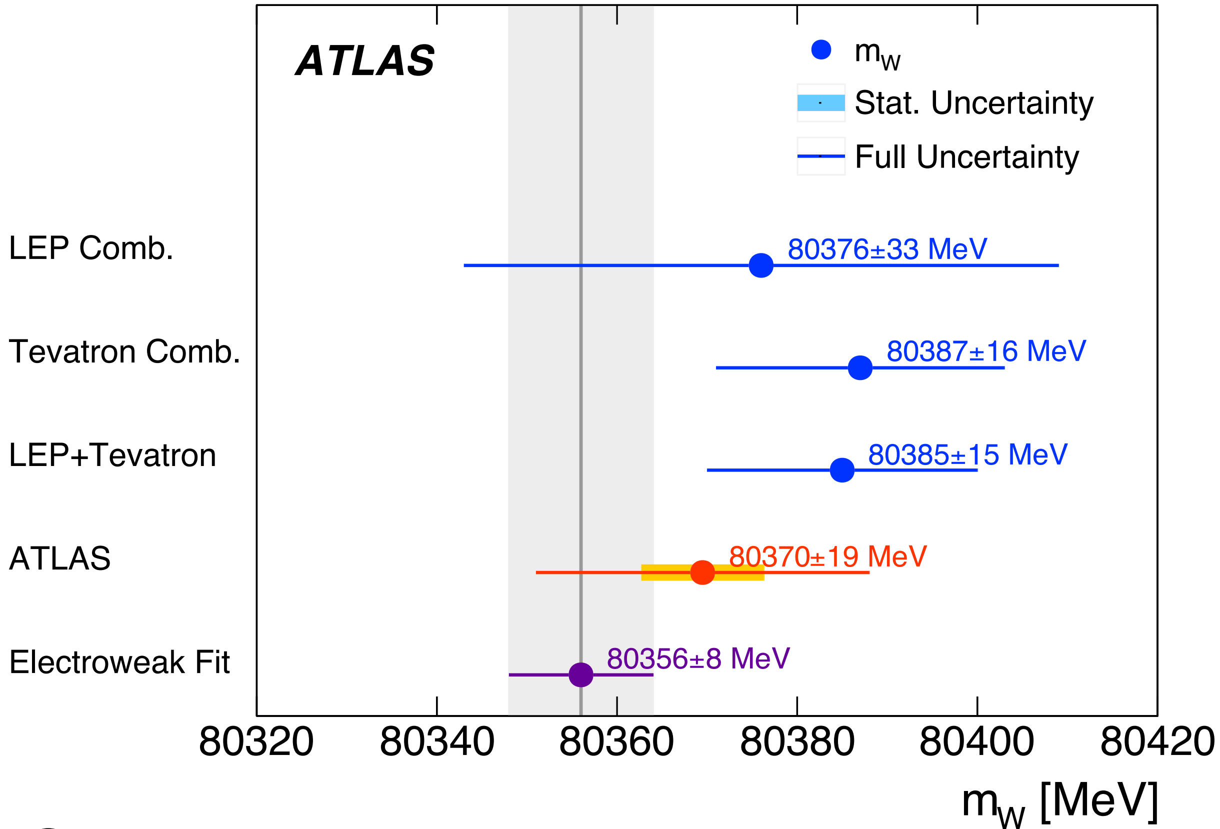
Recent experimental updates

- W mass from LHC:



- Strong coupling:

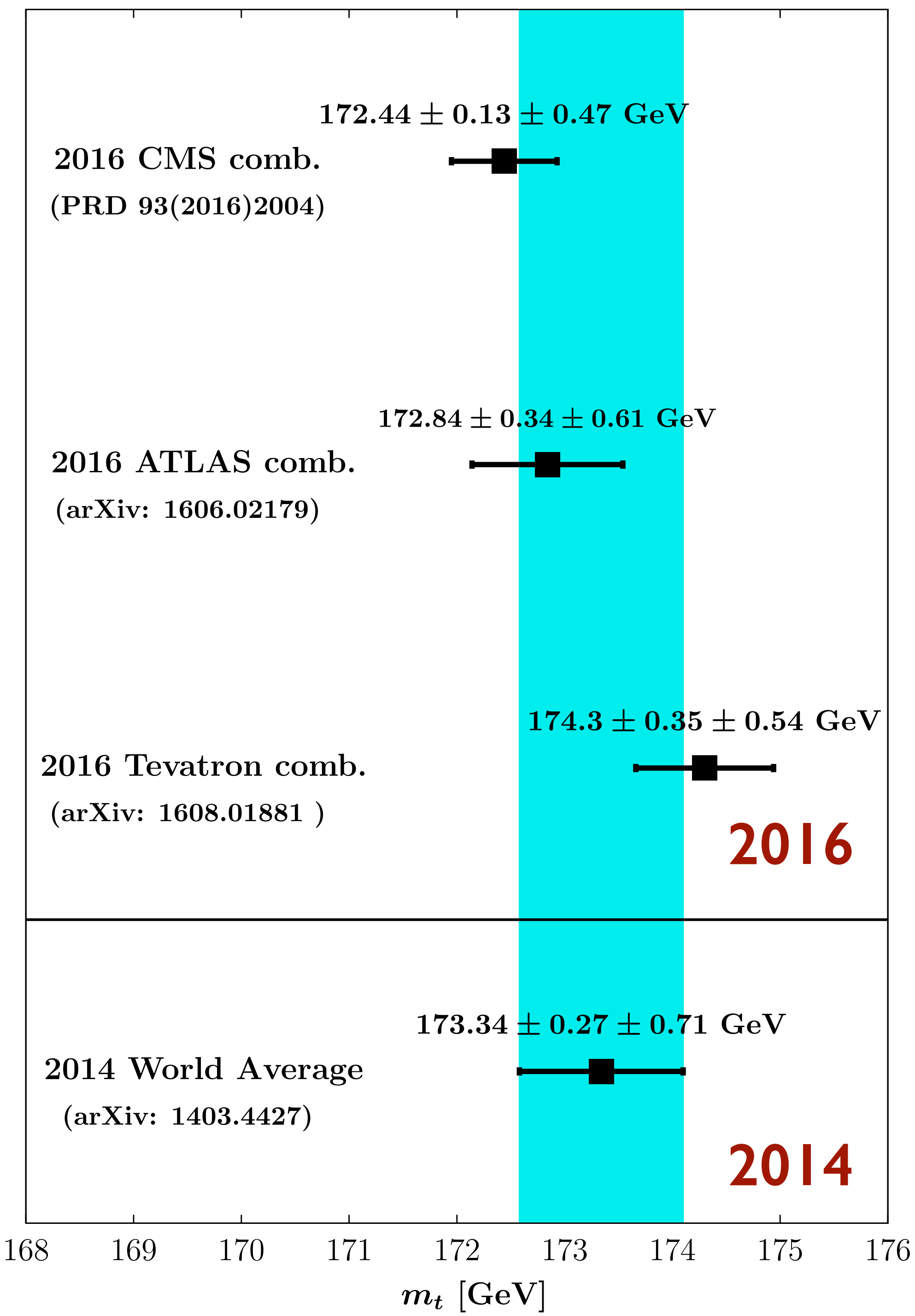
$$\alpha_s(M_Z) = 0.1185 \pm 0.0005$$

previous PDG ave. (w/o EW fit)

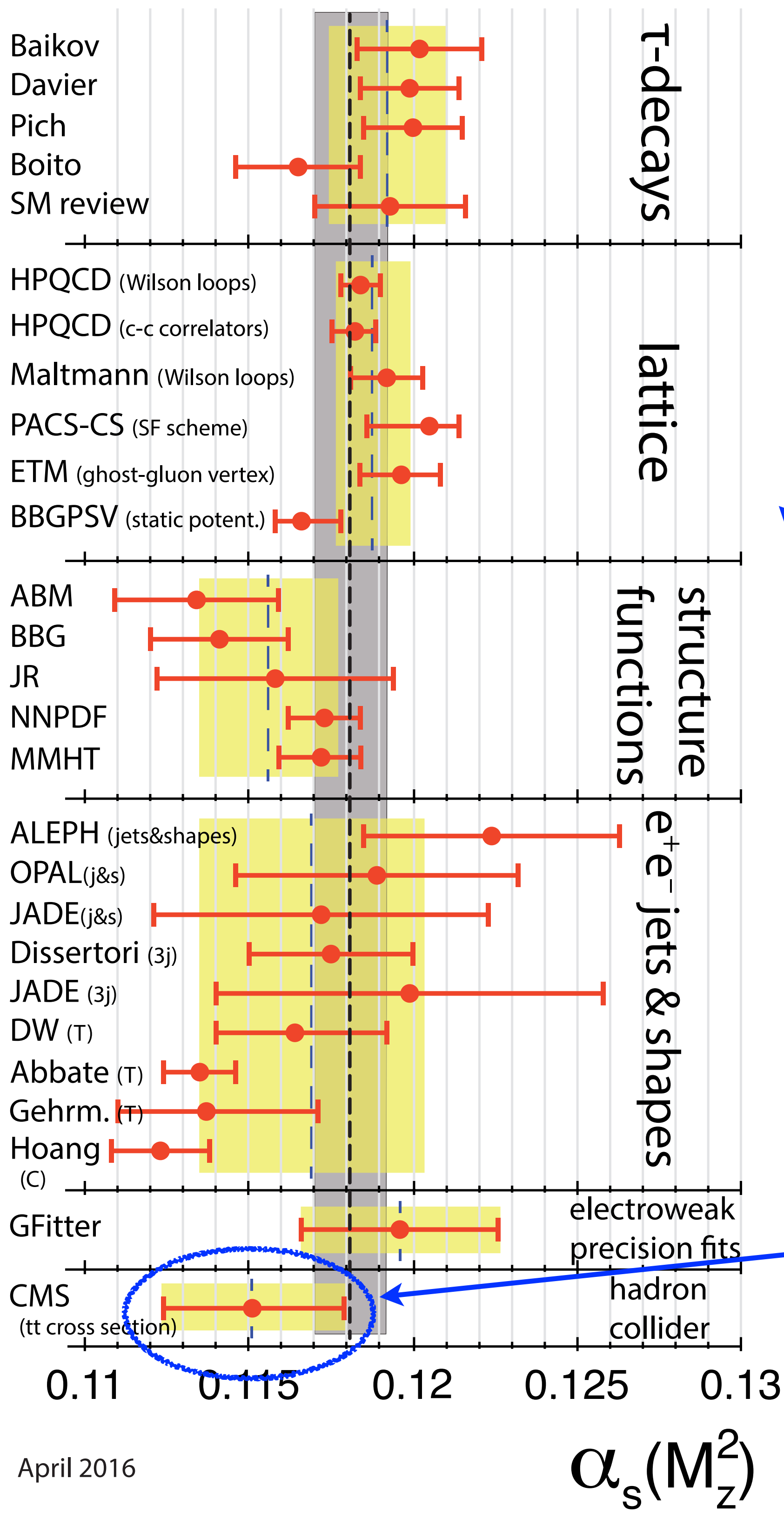
$$\alpha_s(M_Z) = 0.1180 \pm 0.0010$$

PDG2016 (w/o EW fit)

- Top mass:



Strong coupling



$$\alpha_s(M_Z) = 0.1185 \pm 0.0005$$

previous PDG ave. (w/o EW fit)

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

PDG2016 (w/o EW fit)

a more conservative averaging procedure for lattice results

lower value

Theoretical status

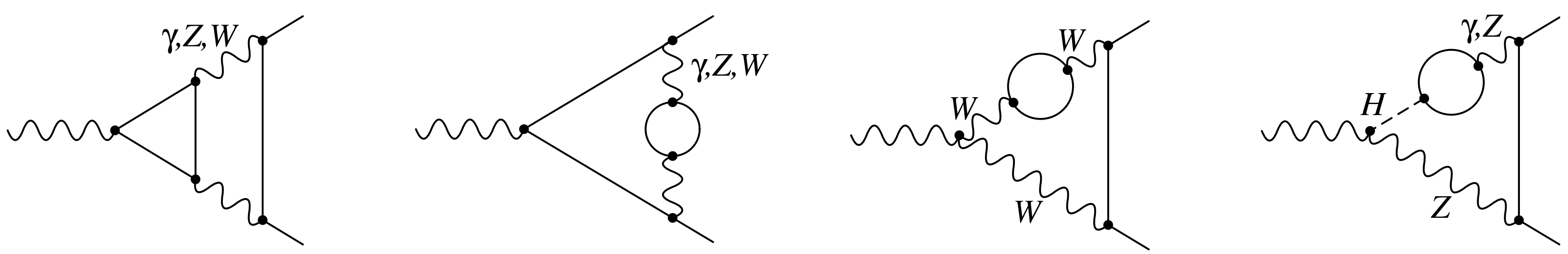
- Mw : full EW 2-loop + leading 3- & 4-loop

  Awramik, Czakon, Freitas & Weiglein (04)

- $\sin^2\theta^f_{\rm eff}$: full EW two-loop (bosonic is missing for f=b) + leading higher-order

  Awramik, Czakon & Freitas (06); Awramik, Czakon, Freitas & Kniehl (09)

- Γ^f_Z : full fermionic EW two-loop *Freitas & Huang (12); Freitas (13); Freitas (14)*



- $\sin^2\theta^b_{\rm eff}$: full bosonic EW two-loop

  Dubovyk, Freitas, Gluza, Riemann & Usovitsch (16)

- on-shell scheme

  See also Sirlin; Marciano&Sirlin; Bardin et al; Djouadi&Verzegnassi; Djouadi; Kniehl; Halzen&Kniehl; Kniehl&Sirlin; Barbieri et al; Fleischer et al; Djouadi&Gambino; Degrassi et al; Avdeev et al; Chetyrkin et al; Freitas et al; Awramik&Czakon; Onishchenko&Veretin; Van der Bij et al; Faisst et al; Awramik et al, and many other works

Exp. vs. Theo. uncertainties

A. Freitas, 1406.6980

	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}

Theory errors from missing higher-order corrections are safely below current experimental errors.

EW precision fits

- Erler et al. (for PDG) *http://www.fisica.unam.mx/erler/GAPPP.html*

  GAPP (Global Analysis of Particle Properties)

  MSbar scheme & frequentist

- Gfitter group

  Gfitter (Generic fitting package) *http://gfitter.desy.de*

  on-shell scheme & frequentist

- Many other groups with ZFITTER *http://zfitter.com*

  on-shell scheme

- Our group *M. Ciuchini, E. Franco, S.M., L. Silvestrini and others …*

  on-shell scheme & Bayesian

SM fit

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

$-2.7\,\sigma$

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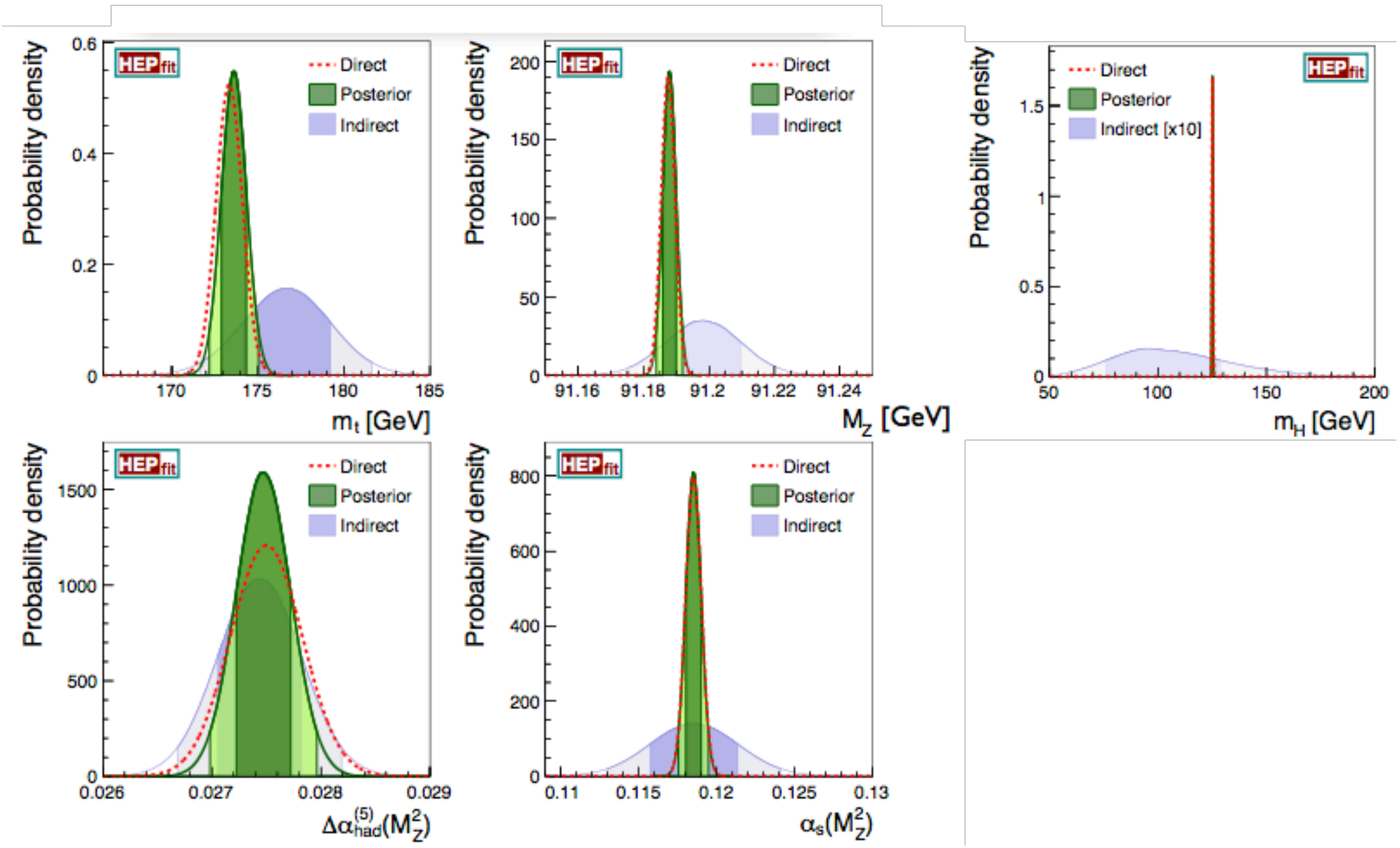
SM input parameters

- Indirect determinations of the SM input parameters from the fit are consistent with the measurements.



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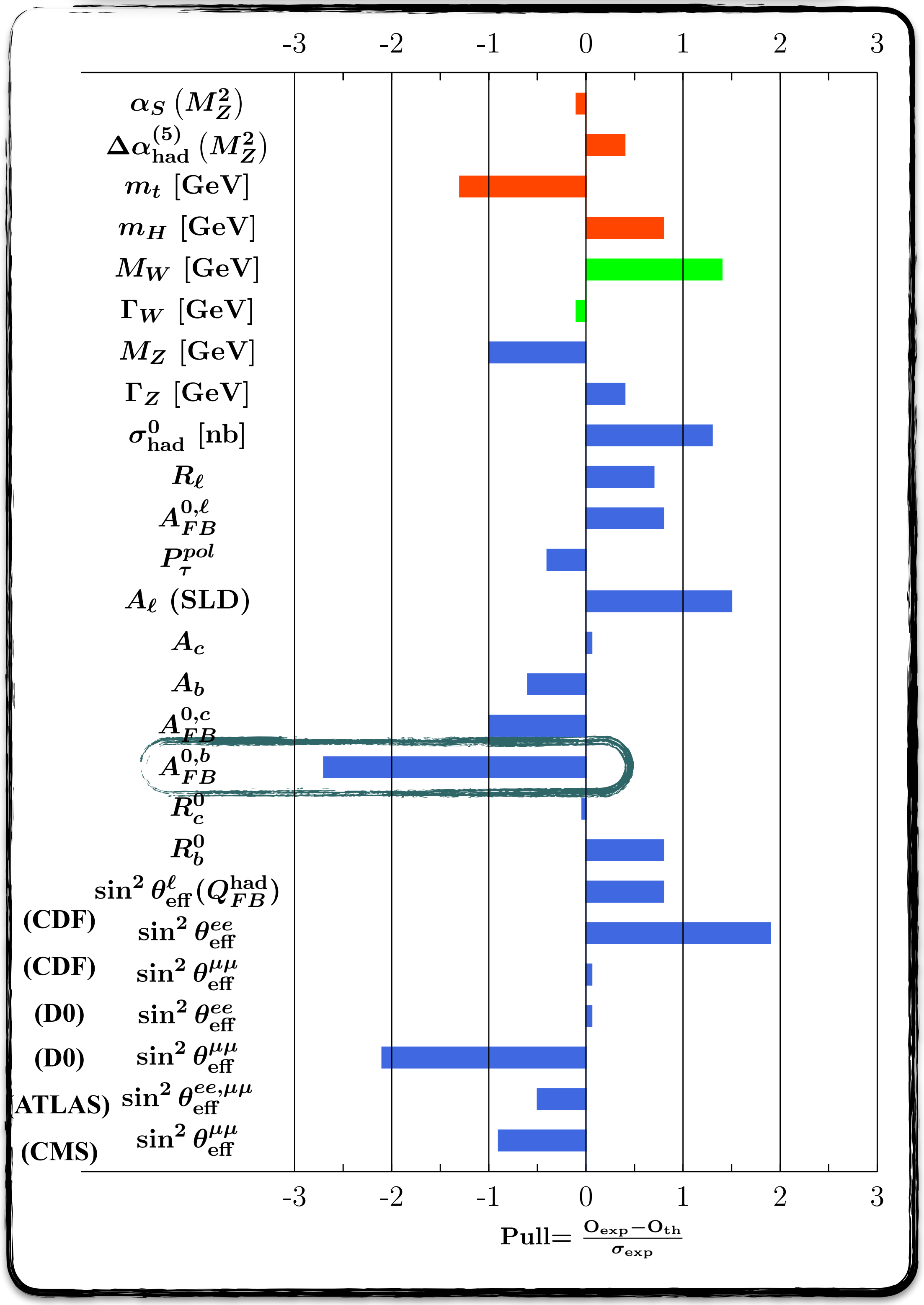
Pulls for the EWPO



The theoretical+parametric uncertainty of the predictions is well below the experimental errors.

only one significant discrepancy!

$-2.7\,\sigma$

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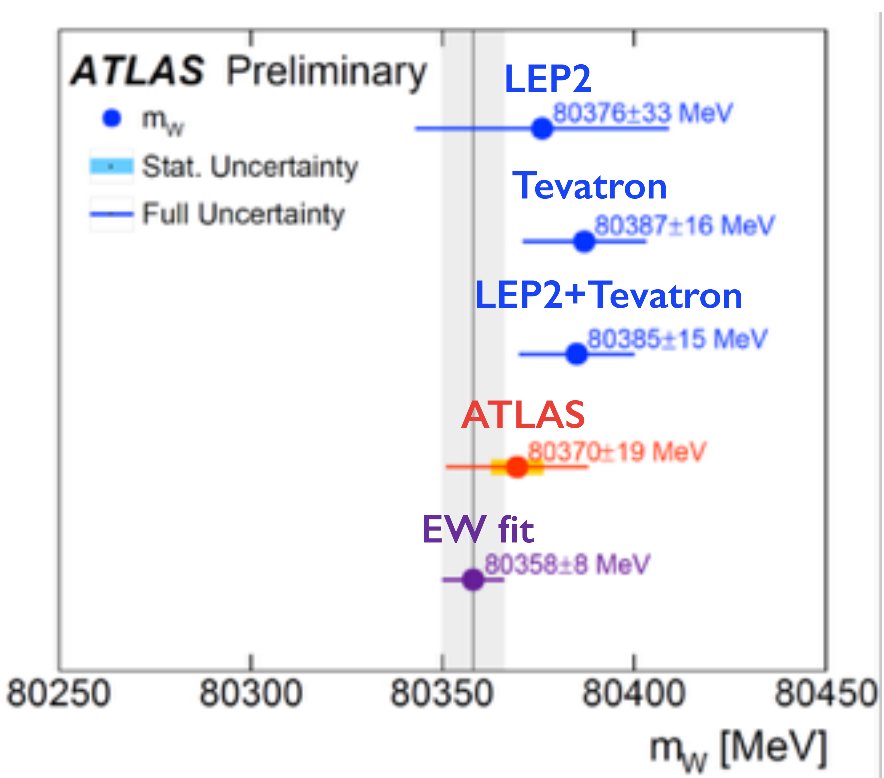
Impact of ATLAS measurement of Mw

$$M_W = 80.385 \pm 0.015\,\text{GeV} \;\Rightarrow\; M_W = 80.379 \pm 0.012\,\text{GeV}$$

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

First LHC meas. of Mw



	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
	Mw LEP2+Tevatron	Mw LEP2+Tevatron+ATLAS

Minor effect!

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4. EW precision constraints on NP

- oblique parameters (S, T, U)
- epsilon parameters
- modified $Zb\bar{b}$ couplings
- Dimension-six operators

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4. EW precision constraints on NP

- ✦ oblique parameters (S, T, U)
- ✦ epsilon parameters
- ✦ modified $Zb\bar{b}$ couplings
- ✦ Dimension-six operators

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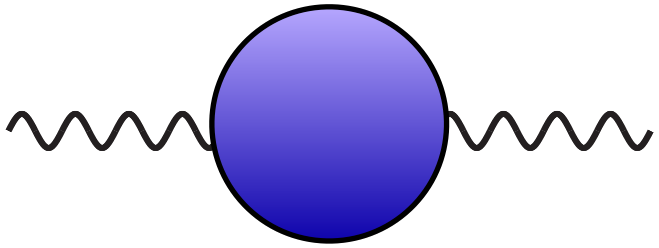
Oblique parameters

- Suppose that dominant NP effects appear in the vacuum polarizations of the gauge bosons:



$$\Pi_{11}(q^2) = \Pi_{11}(0) + q^2\,\Pi'_{11}(0)$$
$$\Pi_{33}(q^2) = \Pi_{33}(0) + q^2\,\Pi'_{33}(0)$$
$$\Pi_{3Q}(q^2) = q^2\,\Pi'_{3Q}(0)\,,$$
$$\Pi_{QQ}(q^2) = q^2\,\Pi'_{QQ}(0)$$

$\Pi'_{XY}(q^2) = d\Pi_{XY}(q^2)/dq^2$ for $q^2 \approx 0$

Three of the above can be fixed by $\alpha,\ M_Z,\ G_F$, and the others are

$$S = -16\pi\Pi'_{30}(0) = 16\pi\left[\Pi^{\mathrm{NP}\,\prime}_{33}(0) - \Pi^{\mathrm{NP}\,\prime}_{3Q}(0)\right]$$
$$T = \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi^{\mathrm{NP}}_{11}(0) - \Pi^{\mathrm{NP}}_{33}(0)\right]$$
$$U = 16\pi\left[\Pi^{\mathrm{NP}\,\prime}_{11}(0) - \Pi^{\mathrm{NP}\,\prime}_{33}(0)\right]$$

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

- When the EW symmetry is realized linearly, U is associated with a dim. 8 operator and thus small.

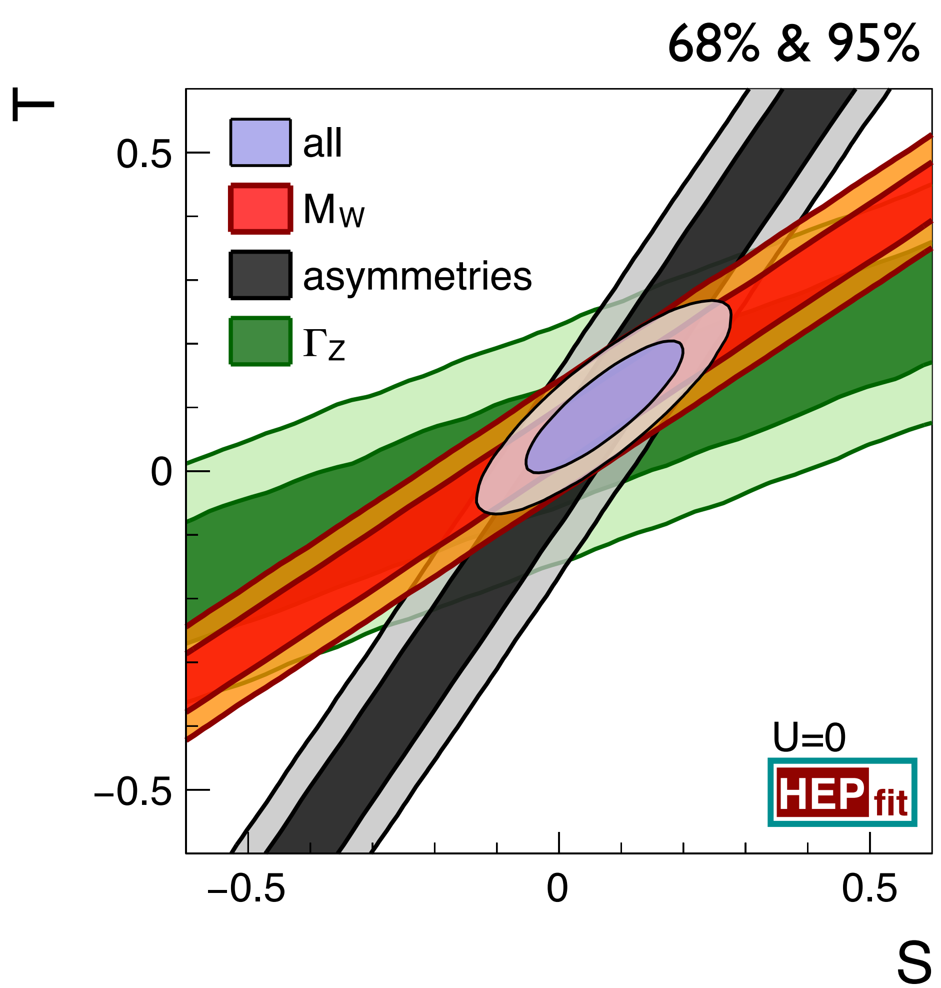
Constraints on the oblique parameters

- EWPO depend on the three combinations:

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

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

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



M_W LEP2+Tevatron

	Fit result	Correlations	
S	0.07 ± 0.08	1.00	
T	0.10 ± 0.07	0.85	1.00

↓

M_W LEP2+Tevatron+ATLAS

	Fit result	Correlations	
S	0.06 ± 0.08	1.00	
T	0.08 ± 0.06	0.86	1.00

Satoshi Mishima (KEK)

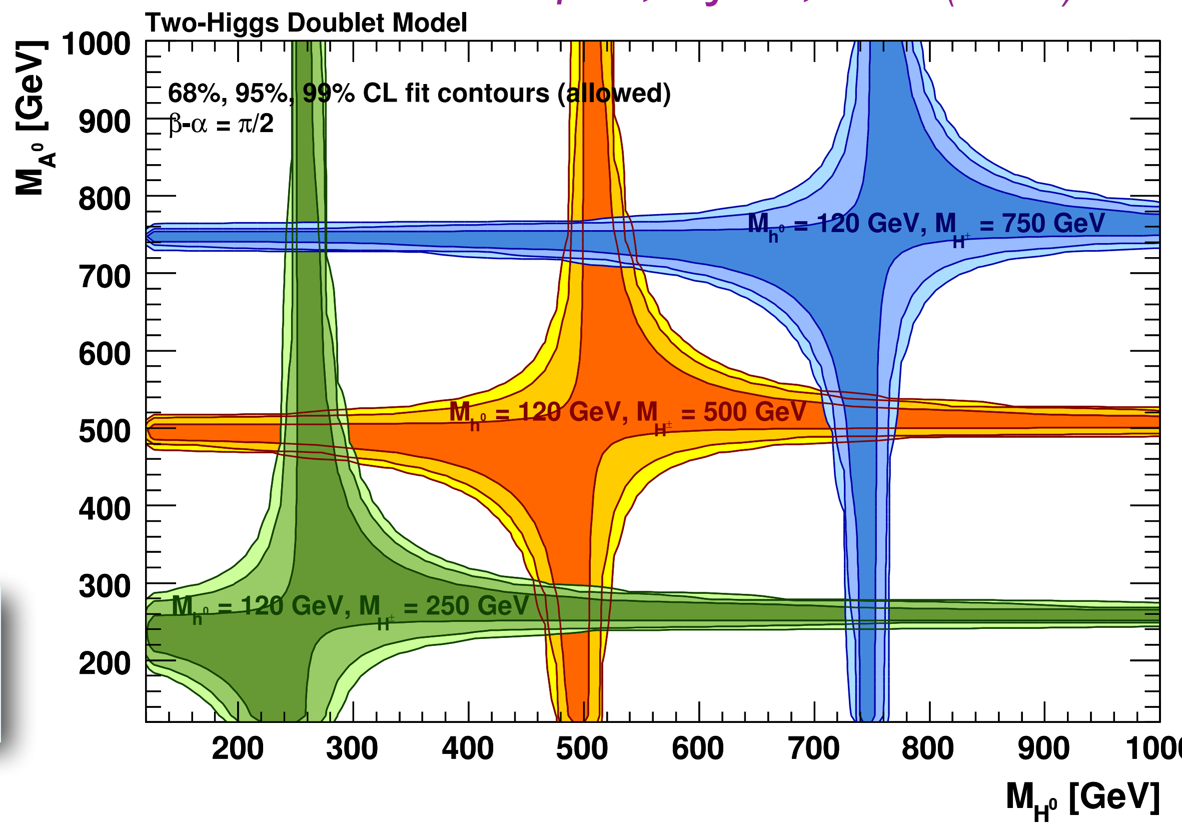
Example 1: Two Higgs doublet models

- 5 physical Higgs bosons: $h, H, A, H^{\pm}$
- 6 parameters: $m_h, m_H, m_A, m_{H^\pm},\ \alpha,\ \tan\beta = v_2/v_1$
- Several models (Type-I, Type-II, …) ⇐ FCNC
- Same S, T and U among the models at one-loop.

$$\kappa_V = \frac{g_{hVV}^{\rm 2HDM}}{g_{hVV}^{\rm SM}} = \sin(\beta-\alpha)$$

$m_H \approx m_{H^\pm}$ or $m_A \approx m_{H^\pm}$

Gfitter, EPJC72, 2003 (2012)



- EWPO alone cannot fix all the parameters.
- See more studies with Higgs and flavor data.

Example 2: EW chiral Lagrangian

- No new state below cutoff + custodial symmetry:

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2\kappa_V \frac{h}{v} + \cdots\right) + \cdots$$

Σ : Goldstone bosons

$\kappa_V = 1$ in the SM

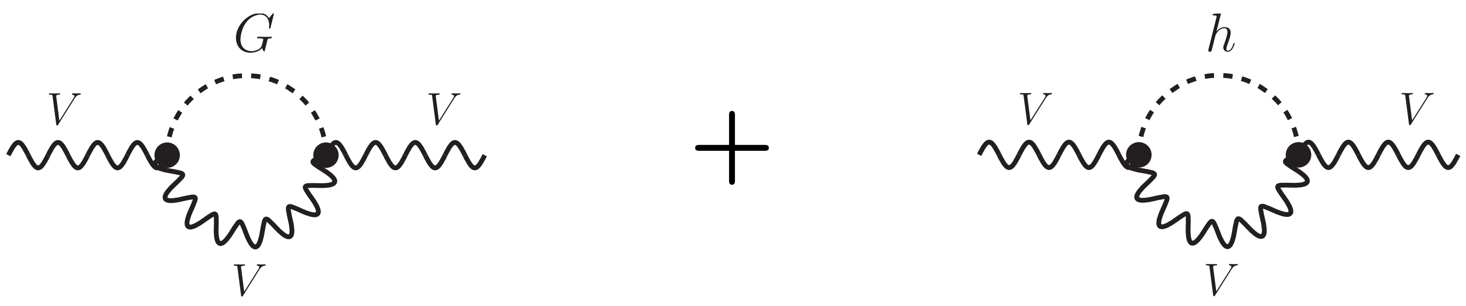
➡ Modified HVV coupling contributes to S and T at one-loop:

Barberi, Bellazzini, Rychkov & Varagnolo (07)

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

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

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

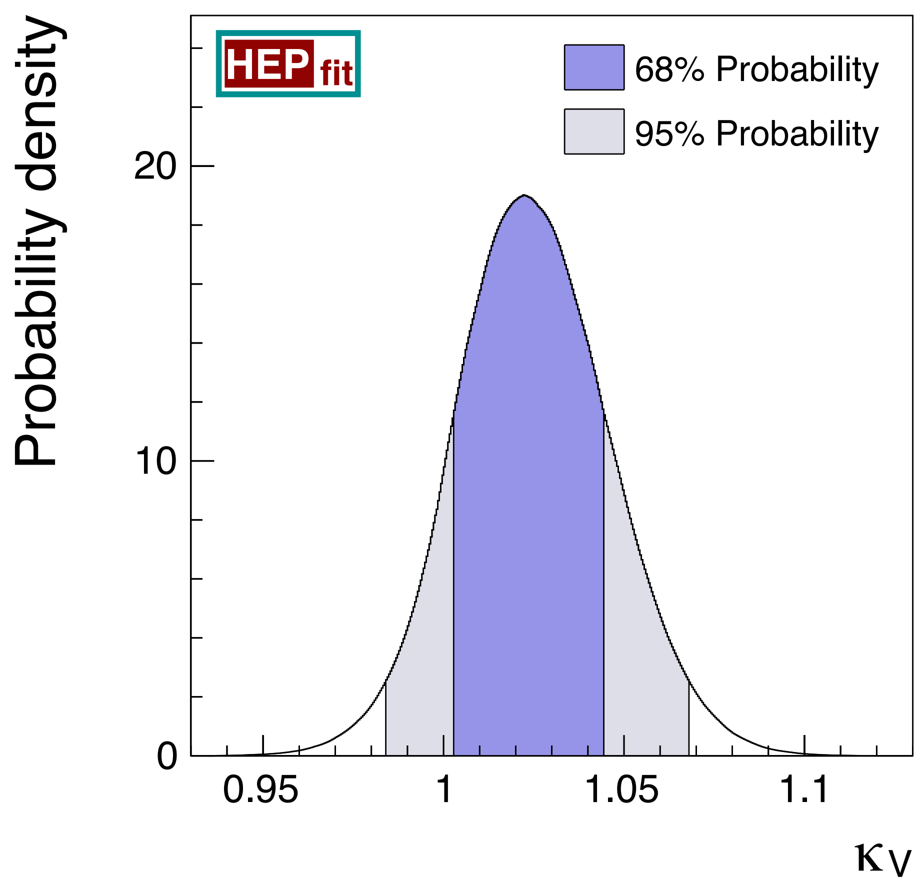


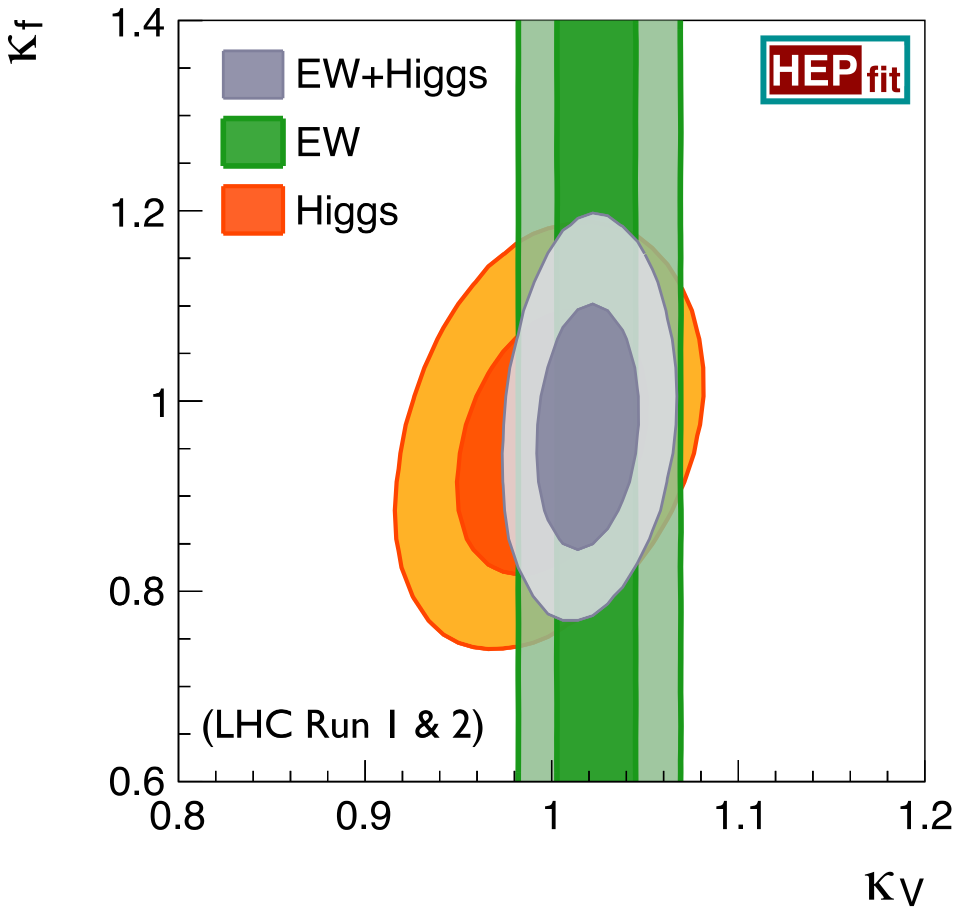
$$\ln(\Lambda^2/M_Z^2) - \kappa_V^2 \ln(\Lambda^2/m_h^2)$$

Example 2: EW chiral Lagrangian

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

	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





- $\kappa_V > 1$ ➡ $W_L W_L$ scattering is dominated by isospin 2 channel

$$1-\kappa_V^2 = \frac{v^2}{6\pi}\int_0^\infty \frac{ds}{s}\left(2\sigma^{\rm tot}_{I=0}(s)+3\sigma^{\rm tot}_{I=1}(s)-5\sigma^{\rm tot}_{I=2}(s)\right)$$

Falkowski, Rychkov & Urbano (12)

- $\Lambda \gtrsim 13\,\mathrm{TeV}$ @ 95% for $\kappa_V < 1$

Example 2': Composite Higgs models

- Composite Higgs models typically generate $\kappa_V < 1$.

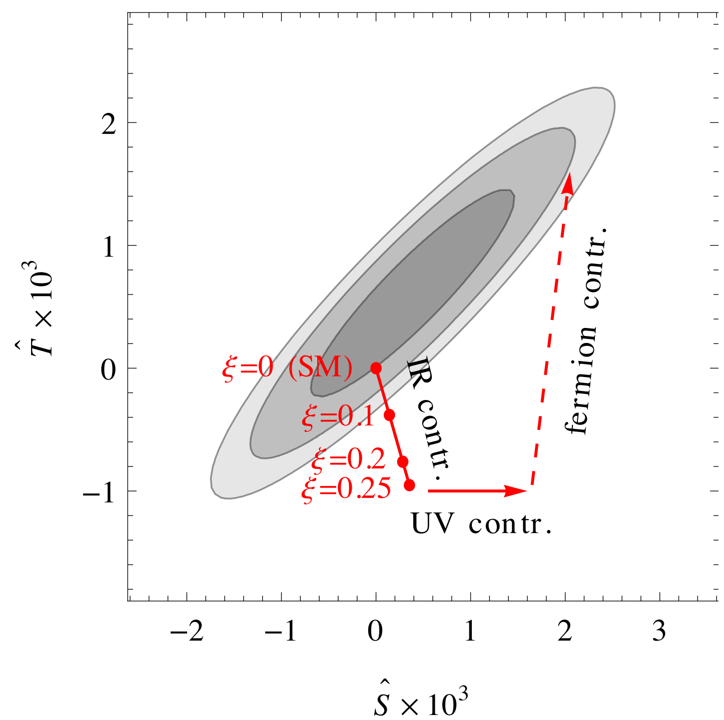
  e.g. Minimal Composite Higgs Models (MCHM) based on SO(5)/SO(4)

  Agashe, Contino & Pomarol (05)

$$\kappa_V = \sqrt{1-\xi} \qquad \xi = \left(\frac{v}{f}\right)^2$$

f : scale of compositeness

- Extra contributions to S and T are required to fix the EW fit under $\kappa_V < 1$.



Grojean et al. (13)

IR contribution

+

UV cont' from heavy vector resonances

+

Fermionic resonances

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4. EW precision constraints on NP

- ✦ oblique parameters (S, T, U)
- ✦ epsilon parameters
- ✦ modified $Zb\bar{b}$ couplings
- ✦ Dimension-six operators

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Epsilon parameters

Altarelli et al. (91,92,93)

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

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

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

and ϵ_b

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

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

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

$$s_0^2\,c_0^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_\mu M_Z^2}$$

- ϵ_i involve the oblique corrections beyond S,T and U.

$$\Pi_{VV'}(q^2) \simeq \Pi_{VV'}(0) + q^2\,\Pi'_{VV'}(0) + \frac{(q^2)^2}{2!}\,\Pi''_{VV'}(0) + \cdots$$

3 parameters

7 parameters

$VV' = \{WW, ZZ, Z\gamma, \gamma\gamma\}$

3 are absorbed in g, g', v

$\Pi_{\gamma\gamma}(0) = \Pi_{Z\gamma}(0) = 0$

- Unlike STU, ϵ_i involve non-oblique vertex corrections.
- Moreover, ϵ_i also involve SM(top/Higgs) contributions.

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

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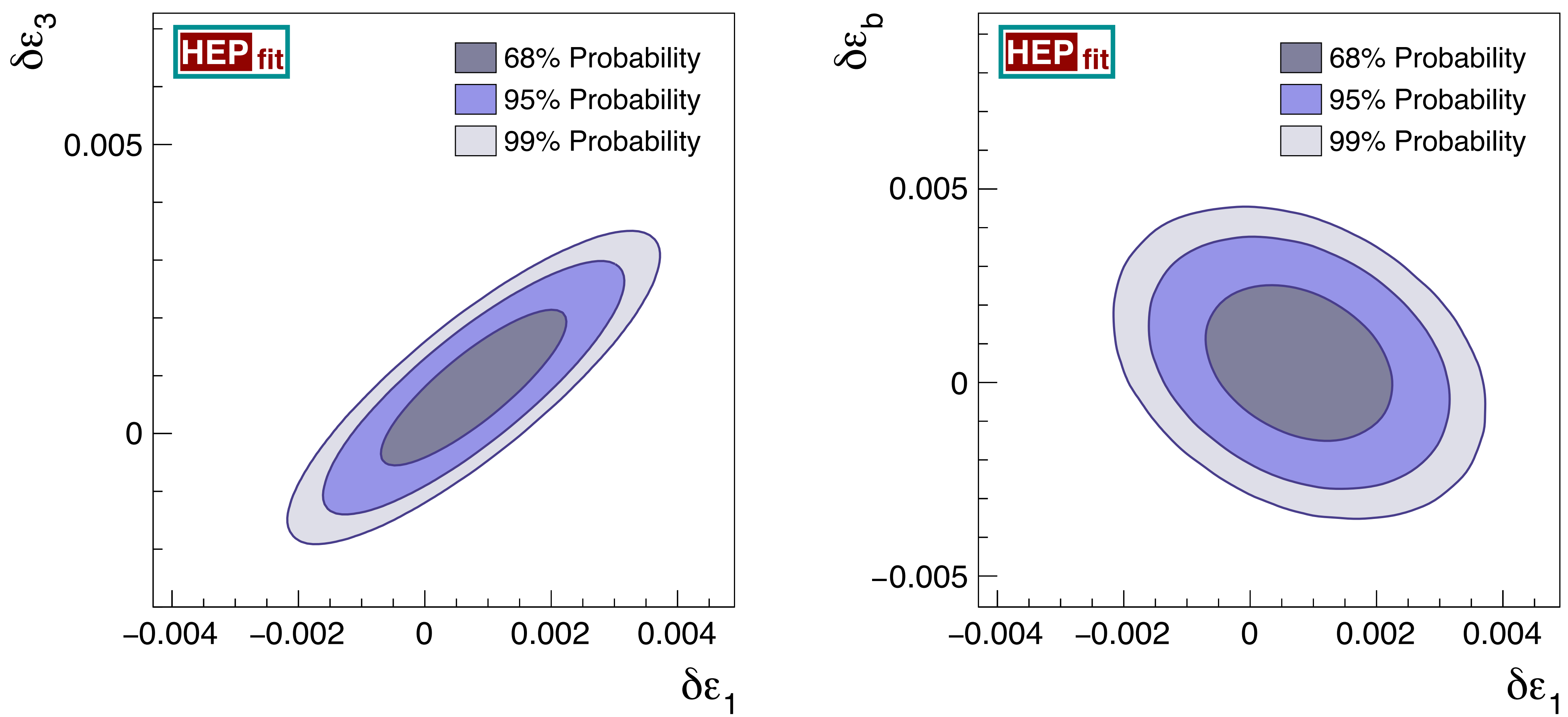
Modified epsilon parameters

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]

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

	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



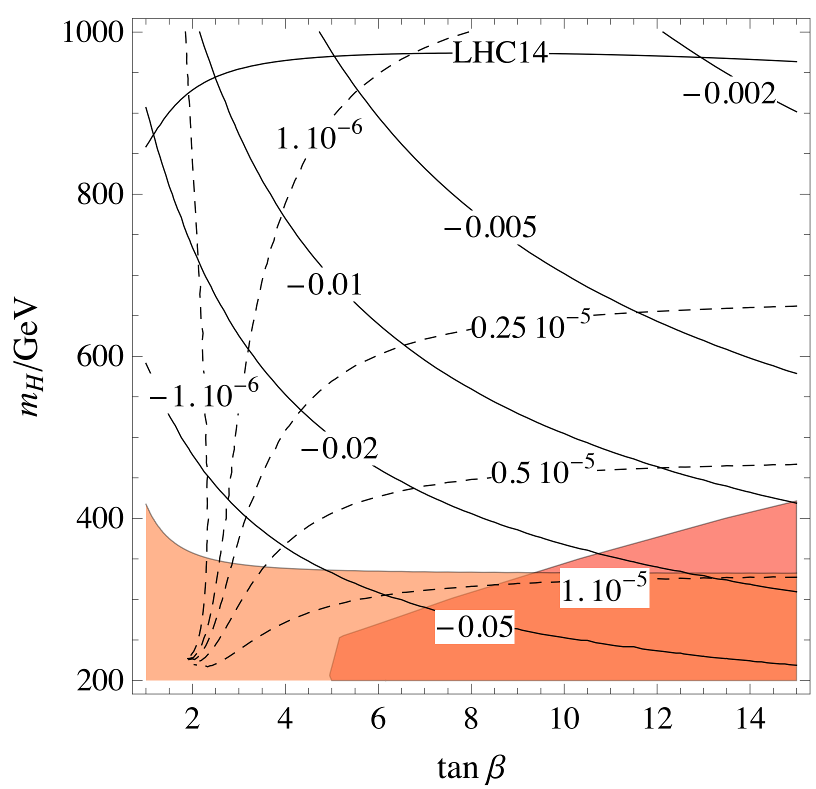
Example: MSSM with decoupled sparticles

R. Barbieri & A. Tesi, PRD89, 055019 (2014)

- All sparticles are assumed to be sufficiently decoupled.
- h_v gets the VEV v, while $h_v^\perp$ is its orthogonal.

$$h = \cos\delta\, h_v - \sin\delta\, h_v^\perp \qquad H = \sin\delta\, h_v + \cos\delta\, h_v^\perp \qquad \delta = \frac{\pi}{2} - \beta + \alpha$$

$$\frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \cos\delta, \qquad \frac{g_{hu\bar{u}}}{g_{hu\bar{u}}^{\rm SM}} = \cos\delta + \frac{\sin\delta}{\tan\beta}, \qquad \frac{g_{hd\bar{d}}}{g_{hd\bar{d}}^{\rm SM}} = \cos\delta - \tan\beta\sin\delta$$



$\delta\epsilon_1$

$\sin\delta$

Current bound: $\delta\epsilon_1 \lesssim 10^{-3}$

⇒ **EWPO are irrelevant.**

Orange: excluded at 95% by the signal strengths of h

Red: excluded at 95% by search for $A, H \to \tau^+\tau^-$

4. EW precision constraints on NP

- ✦ oblique parameters (S, T, U)
- ✦ epsilon parameters
- ✦ modified $Zb\bar{b}$ couplings
- ✦ Dimension-six operators

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NP in Zb$\bar{b}$ couplings

$$\mathcal{L} = \frac{e}{2 s_W c_W} Z_\mu \bar{b} \left(g_V^b \gamma_\mu - g_A^b \gamma_\mu \gamma_5 \right) b$$

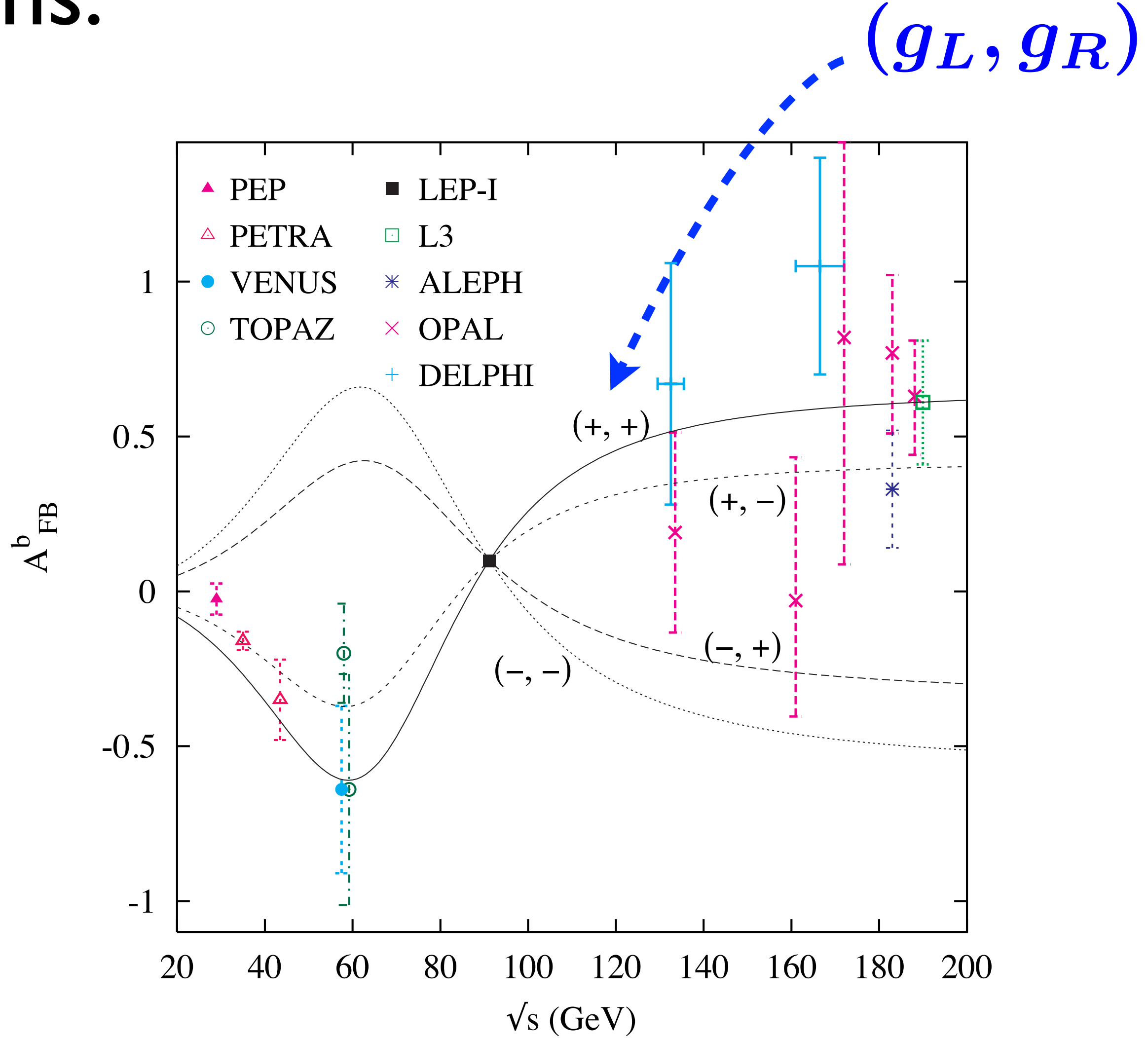
$$g_V^b \to g_V^b + \delta g_V^b \qquad g_A^b \to g_A^b + \delta g_A^b$$

- Z-pole data yield four solutions.

$$A_b \sim \frac{|\delta g_R^b|^2 - |\delta g_L^b|^2}{|\delta g_R^b|^2 + |\delta g_L^b|^2}$$

$$\Gamma_b \sim |\delta g_R^b|^2 + |\delta g_L^b|^2$$

- Two solutions are disfavored by the off Z-pole data for AFBb.



Choudhury et al. (2002)

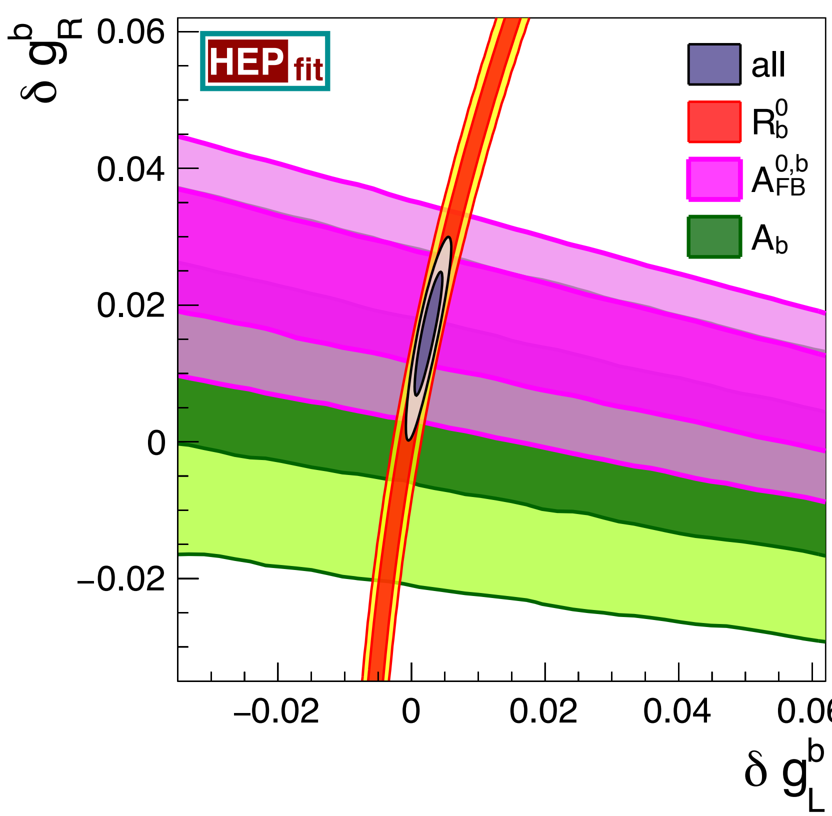
NP in $Zb\bar{b}$ couplings

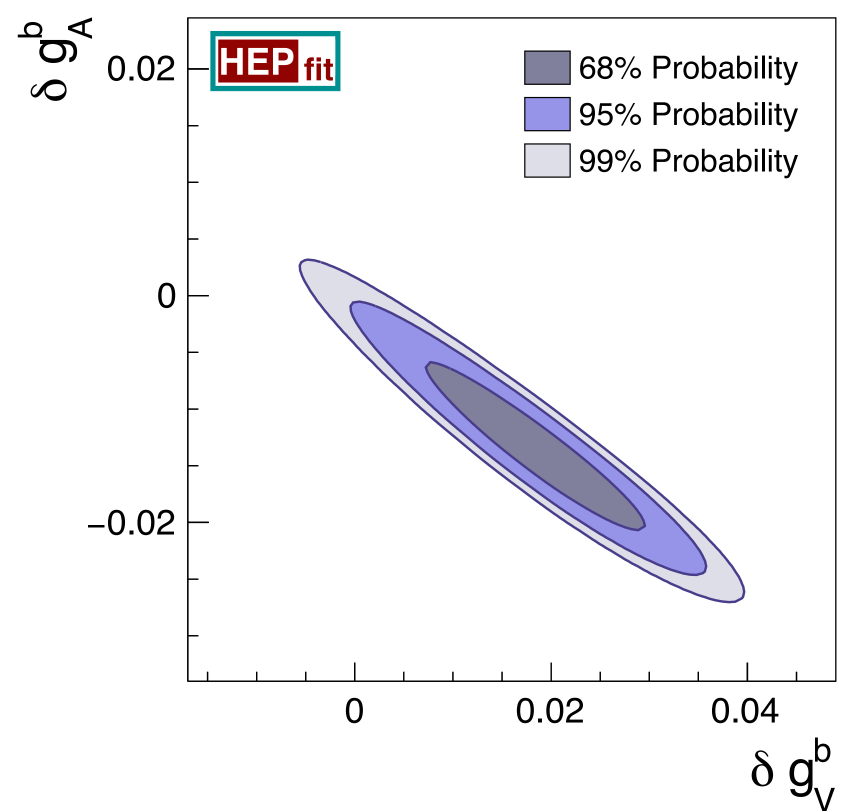
J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]

$$\mathcal{A}_b = \frac{2\,\mathrm{Re}\left(g_V^b/g_A^b\right)}{1+\left[\mathrm{Re}\left(g_V^b/g_A^b\right)\right]^2} \qquad A_{FB}^{0,b} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$$

$$R_b^0 = \frac{\Gamma_b}{\Gamma_h} \quad \text{with} \quad \Gamma_b \propto \left|g_V^b\right|^2 R_V^b + \left|g_A^b\right|^2 R_A^b$$

	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





Deviation from the SM due to $A_{FB}^{0,b}$

NP in $Zb\bar{b}$ couplings + oblique corrections

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]

	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
		$\delta g_R^b = 0$			
S	0.10 ± 0.09	1.00			
T	0.12 ± 0.07	0.85	1.00		
δg_L^b	-0.0001 ± 0.0006	0.07	0.13	1.00	
		$\delta g_L^b = 0$			
S	0.08 ± 0.09	1.00			
T	0.10 ± 0.07	0.86	1.00		
δg_R^b	0.004 ± 0.003	-0.19	-0.21	1.00	

4. EW precision constraints on NP

- oblique parameters (S, T, U)
- epsilon parameters
- modified $Zb\bar{b}$ couplings
- Dimension-six operators

Satoshi Mishima (KEK)

Dim-6 SMEFT

- We have found only a Higgs and no other new particle so far at the LHC.
- Experimental data suggest that the NP scale is well above the EW scale.
- We consider an effective theory built exclusively from the SM fields with the SM gauge symmetries.

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Contributions from higher-dimensional operators are suppressed by powers of the NP scale.

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_j C_j^{(6)} O_j^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

Effective field theory approach

Pros:

- Model-independent
- Correlations among observables are induced by gauge-invariant operators.

  ⇨ *Useful guide to look for NP effects*

- Constraints on the Wilson coefficients will give us clues for constructing the UV theory.

Cons:

- Too many operators in general.
- EFT analyses cannot capture the stronger correlations among operators that may arise in specific NP models.

Dimension-six operators

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_j C_j^{(6)} O_j^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

- Only one dim-5 operator (LH)(LH).
- Dim-6 operators contribute to EW/Higgs physics.

Buchmuller & Wyler, NPB268, 621(1986)

80 op's (for one generation) that respect B/L.

Grzadkowski, Iskrzynski, Misiak & Rosiek, JHEP10, 085 (2010)

59 independent op's

List of dimension-six operators

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{L}eH)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{Q}u\widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{Q}dH)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$(H^\dagger H)\,G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{L}\sigma^{\mu\nu}e)\tau^I HW^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$
$\mathcal{O}_{H\widetilde{G}}$	$(H^\dagger H)\,\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{L}\sigma^{\mu\nu}e)HB_{\mu\nu}$	$\mathcal{O}^{(3)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L)$
$\mathcal{O}_{HW}$	$(H^\dagger H)\,W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{Q}\sigma^{\mu\nu}T^Au)\widetilde{H}\,G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{H\widetilde{W}}$	$(H^\dagger H)\,\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{Q}\sigma^{\mu\nu}u)\tau^I\widetilde{H}\,W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{HB}$	$(H^\dagger H)\,B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{Q}\sigma^{\mu\nu}u)\widetilde{H}\,B_{\mu\nu}$	$\mathcal{O}^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$
$\mathcal{O}_{H\widetilde{B}}$	$(H^\dagger H)\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{Q}\sigma^{\mu\nu}T^Ad)H\,G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{HWB}$	$(H^\dagger\tau^I H)\,W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{Q}\sigma^{\mu\nu}d)\tau^I H\,W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{H\widetilde{W}B}$	$(H^\dagger\tau^I H)\,\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{Q}\sigma^{\mu\nu}d)H\,B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}\gamma^\mu d)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{LL}$	$(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$	$\mathcal{O}_{ee}$	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$	$\mathcal{O}_{Le}$	$(\bar{L}\gamma_\mu L)(\bar{e}\gamma^\mu e)$
$\mathcal{O}^{(1)}_{QQ}$	$(\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{uu}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{Lu}$	$(\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u)$
$\mathcal{O}^{(3)}_{QQ}$	$(\bar{Q}\gamma_\mu\tau^I Q)(\bar{Q}\gamma^\mu\tau^I Q)$	$\mathcal{O}_{dd}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$	$\mathcal{O}_{Ld}$	$(\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$
$\mathcal{O}^{(1)}_{LQ}$	$(\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{eu}$	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{Qe}$	$(\bar{Q}\gamma_\mu Q)(\bar{e}\gamma^\mu e)$
$\mathcal{O}^{(3)}_{LQ}$	$(\bar{L}\gamma_\mu\tau^I L)(\bar{Q}\gamma^\mu\tau^I Q)$	$\mathcal{O}_{ed}$	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$	$\mathcal{O}^{(1)}_{Qu}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$	$\mathcal{O}^{(8)}_{Qu}$	$(\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$	$\mathcal{O}^{(1)}_{Qd}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
				$\mathcal{O}^{(8)}_{Qd}$	$(\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$\mathcal{O}_{LedQ}$	$(\bar{L}^j e)(\bar{d}Q^j)$	$\mathcal{O}_{duQ}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha)^T Cu^\beta\right]\left[(Q^{\gamma j})^T CL^k\right]$		
$\mathcal{O}^{(1)}_{QuQd}$	$(\bar{Q}^j u)\varepsilon_{jk}(\bar{Q}^k d)$	$\mathcal{O}_{QQu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(Q^{\alpha j})^T CQ^{\beta k}\right]\left[(u^\gamma)^T Ce\right]$		
$\mathcal{O}^{(8)}_{QuQd}$	$(\bar{Q}^j T^A u)\varepsilon_{jk}(\bar{Q}^k T^A d)$	$\mathcal{O}^{(1)}_{QQQ}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(Q^{\alpha j})^T CQ^{\beta k}\right]\left[(Q^{\gamma m})^T CL^n\right]$		
$\mathcal{O}^{(1)}_{LeQu}$	$(\bar{L}^j e)\varepsilon_{jk}(\bar{Q}^k u)$	$\mathcal{O}^{(3)}_{QQQ}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(Q^{\alpha j})^T Cq^{\beta k}\right]\left[(Q^{\gamma m})^T CL^n\right]$		
$\mathcal{O}^{(3)}_{LeQu}$	$(\bar{L}^j\sigma_{\mu\nu}e)\varepsilon_{jk}(\bar{Q}^k\sigma^{\mu\nu}u)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha)^T Cu^\beta\right]\left[(u^\gamma)^T Ce\right]$		

Grzadkowski, Iskrzynski, Misiak & Rosiek (10)

- 10 CP-even op's for EWPO.
- To avoid dangerous FCNC, we assume *flavor universality.*

(Alternatively, *MFV* may be assumed.)

- Other choices of the basis are possible.

direct connections to observables

operator mixing in the RG running

See, e.g., Giudice et al. (07); Contino et al. (13)

Indirect and direct contributions

$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$$
$$= \frac{v^2}{4}\left(1+\frac{2h}{v}+\frac{h^2}{v^2}\right)(\partial^\mu h)(\partial_\mu h) + \frac{g^2 v^4}{16 c_W^2} Z^\mu Z_\mu \left(1+\frac{4h}{v}+\frac{6h^2}{v^2}+\frac{4h^3}{v^3}+\frac{h^4}{v^4}\right)$$

- Indirect contribution via input parameters:

$$M_Z^2 = M_{Z,\mathrm{SM}}^2\left(1+\frac{v^2}{2\Lambda^2}C_{HD}\right)$$

⇨ contributes to EW/Higgs observables.

- Direct contribution:

$$\mathcal{L}_{\mathrm{eff}} = \frac{M_Z^2}{v}\left(1+\frac{v^2}{\Lambda^2}C_{HD}\right) Z_\mu Z^\mu h$$

Dim-6 contributions to EWPO

$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$ → *S parameter (W3-B mixing)*

$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$ → *T parameter (Mz)*

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

$$\mathcal{O}^{(3)}_{HL} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{L}\tau^I \gamma^\mu L)$$

$$\mathcal{O}^{(1)}_{HL} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{L}\gamma^\mu L)$$

$$\mathcal{O}^{(3)}_{HQ} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{Q}\tau^I \gamma^\mu Q)$$

$$\mathcal{O}^{(1)}_{HQ} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{Q}\gamma^\mu Q)$$

$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e}_R\gamma^\mu e_R)$$

$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u}_R\gamma^\mu u_R)$$

$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d}_R\gamma^\mu d_R)$$

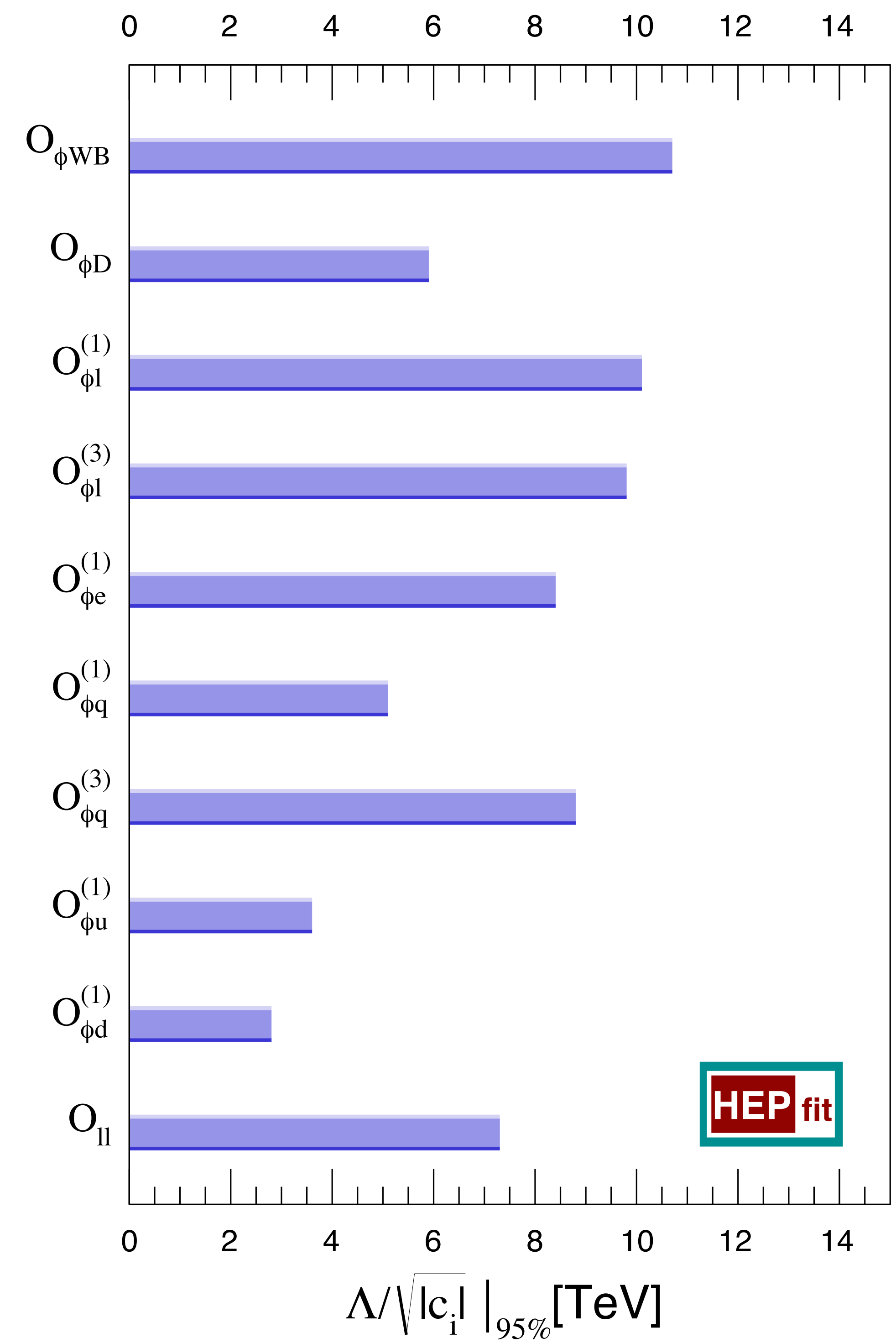
- $\mathcal{O}_{LL}$, $\mathcal{O}^{(3)}_{HL}$ → *Fermi constant*
- $\mathcal{O}^{(3)}_{HL}$, $\mathcal{O}^{(1)}_{HL}$, $\mathcal{O}^{(3)}_{HQ}$, $\mathcal{O}^{(1)}_{HQ}$ → *Left-handed $Zf\bar{f}$*
- $\mathcal{O}_{He}$, $\mathcal{O}_{Hu}$, $\mathcal{O}_{Hd}$ → *Right-handed $Zf\bar{f}$*

- There are two flat directions in the fit. *See, e.g., Han & Skiba (05)*
- switch on one operator at a time

EW constraints on dim-six operators

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, in preparation

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	Λ [TeV] $C_i = \pm 1$
$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \sigma_a \phi)\, W^a_{\mu\nu} B^{\mu\nu}$	$[-0.010,\ 0.004]$	11
$\mathcal{O}_{\phi D}$	$\left\lvert \phi^\dagger D_\mu \phi \right\rvert^2$	$[-0.032,\ 0.006]$	5.9
$\mathcal{O}^{(1)}_{\phi l}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\,(\overline{l_L} \gamma^\mu l_L)$	$[-0.006,\ 0.011]$	10
$\mathcal{O}^{(3)}_{\phi l}$	$(\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)\,(\overline{l_L} \gamma^\mu \sigma_a l_L)$	$[-0.012,\ 0.006]$	9.8
$\mathcal{O}^{(1)}_{\phi e}$	$(\phi^\dagger i D_\mu \phi)\,(\overline{e_R} \gamma^\mu e_R)$	$[-0.016,\ 0.006]$	8.4
$\mathcal{O}^{(1)}_{\phi q}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\,(\overline{q_L} \gamma^\mu q_L)$	$[-0.026,\ 0.044]$	5.1
$\mathcal{O}^{(3)}_{\phi q}$	$(\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)\,(\overline{q_L} \gamma^\mu \sigma_a q_L)$	$[-0.011,\ 0.015]$	8.8
$\mathcal{O}^{(1)}_{\phi u}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\,(\overline{u_R} \gamma^\mu u_R)$	$[-0.067,\ 0.085]$	3.6
$\mathcal{O}^{(1)}_{\phi d}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)\,(\overline{d_R} \gamma^\mu d_R)$	$[-0.154,\ 0.055]$	2.8
$\mathcal{O}_{ll}$	$(\bar{l} \gamma_\mu l)(\bar{l} \gamma^\mu l)$	$[-0.010,\ 0.021]$	7.3



NP scale > 3-10 TeV

EW constraints in a different basis

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, in preparation

- EWPO are sensitive only to 8 combinations of the 10 dim-6 operators in the GIMR/Warsaw basis.

Enter in EWPO	Do not enter in EWPO

$$-\frac{g}{4}\mathcal{O}_{\phi WB}+\frac{g'}{2}\sum_\psi Y_\psi(\mathcal{O}^{(1)}_{\phi\psi})_{ii}+g'\mathcal{O}_{\phi D}=iD^\mu\phi^\dagger D^\nu\phi B_{\mu\nu}+\frac{g'}{4}\mathcal{O}_{\phi B}-\frac{g'}{4}\mathcal{O}_{\phi\Box}$$

$$-\frac{g'}{4}\mathcal{O}_{\phi WB}+\frac{g}{4}\sum_{\psi=q,l}(\mathcal{O}^{(3)}_{\phi\psi})_{ii}=iD^\mu\phi^\dagger\sigma_a D^\nu\phi W^a_{\mu\nu}+\frac{g}{4}\mathcal{O}_{\phi W}$$
$$-\frac{g}{4}\left(3\mathcal{O}_{\phi\Box}-4\mu_\phi^2\left(\phi^\dagger\phi\right)^2+24\lambda_\phi\mathcal{O}_\phi\right)$$
$$-\frac{g}{2}\left(y^e_{ij}\left(\mathcal{O}_{e\phi}\right)_{ij}+y^d_{ij}\left(\mathcal{O}_{d\phi}\right)_{ij}+y^u_{ij}\left(\mathcal{O}_{u\phi}\right)_{ij}+\text{h.c.}\right)$$

Not in the GIMR/Warsaw basis

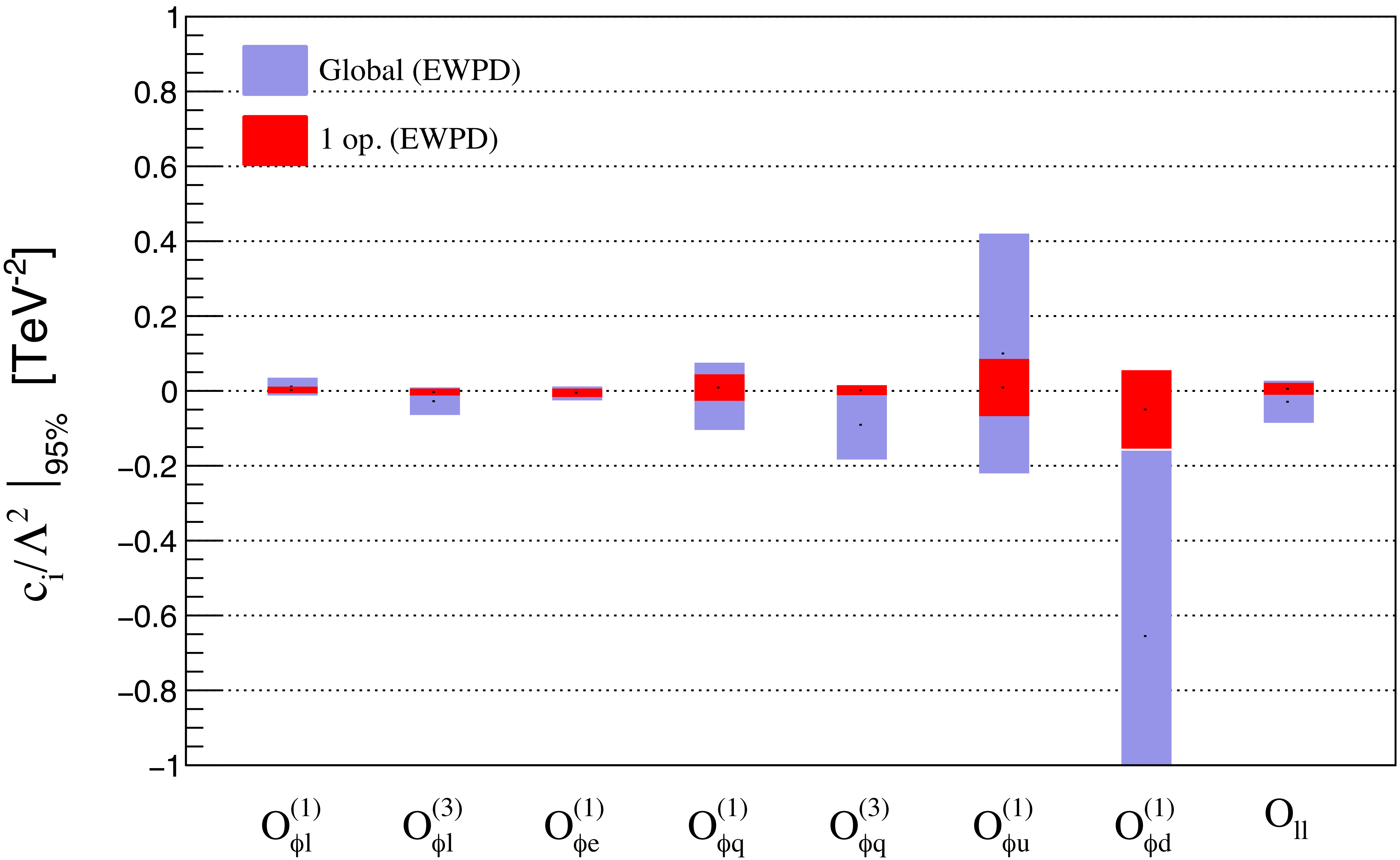
Use field redefinition to replace $\mathcal{O}_{\phi WB}$ and $\mathcal{O}_{\phi D}$ by

$$\mathcal{O}_{D\phi B}=iD^\mu\phi^\dagger D^\nu\phi B_{\mu\nu},\quad \mathcal{O}_{D\phi W}=iD^\mu\phi^\dagger\sigma_a D^\nu\phi W^a_{\mu\nu}$$

⇨ no flat direction in the EW precision fit

EW constraints in a different basis

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, in preparation



Complementary between EWPO & Higgs

$h \to VV$

$$\mathcal{O}_{\phi\Box} = (\phi^\dagger\phi)\,\Box\,(\phi^\dagger\phi)$$
$$\mathcal{O}_{\phi G} = (\phi^\dagger\phi)\,G^A_{\mu\nu}G^{A\,\mu\nu}$$
$$\mathcal{O}_{\phi W} = (\phi^\dagger\phi)\,W^a_{\mu\nu}W^{a\,\mu\nu}$$
$$\mathcal{O}_{\phi B} = (\phi^\dagger\phi)\,B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{\phi WB} = (\phi^\dagger\sigma_a\phi)W^a_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{\phi D} = \left|\phi^\dagger iD_\mu\phi\right|^2$$

$h \to ff$

$$\mathcal{O}_{\phi\Box} = (\phi^\dagger\phi)\,\Box\,(\phi^\dagger\phi)$$
$$\mathcal{O}_{e\phi} = (\phi^\dagger\phi)\,(\overline{l_L}\phi e_R)$$
$$\mathcal{O}_{u\phi} = (\phi^\dagger\phi)\left(\overline{q_L}\tilde{\phi}u_R\right)$$
$$\mathcal{O}_{d\phi} = (\phi^\dagger\phi)\,(\overline{q_L}\phi d_R)$$

Also enter in EWPO & *VV* prod.

Not directly testable with EWPO

$h \to Vff$

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

Indirect

$$\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$
$$\mathcal{O}^{(3)}_{\phi l} = (\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{l}\gamma^\mu\sigma_a l)$$
$$\mathcal{O}_{\phi D} = \left|\phi^\dagger iD_\mu\phi\right|^2$$
$$\mathcal{O}_{\phi WB} = (\phi^\dagger\sigma_a\phi)W^a_{\mu\nu}B^{\mu\nu}$$

Strongly constrained by EWPO
(induce modified *Vff* couplings)

Enter in all EW processes

EW precision data (EWPD) + Higgs data

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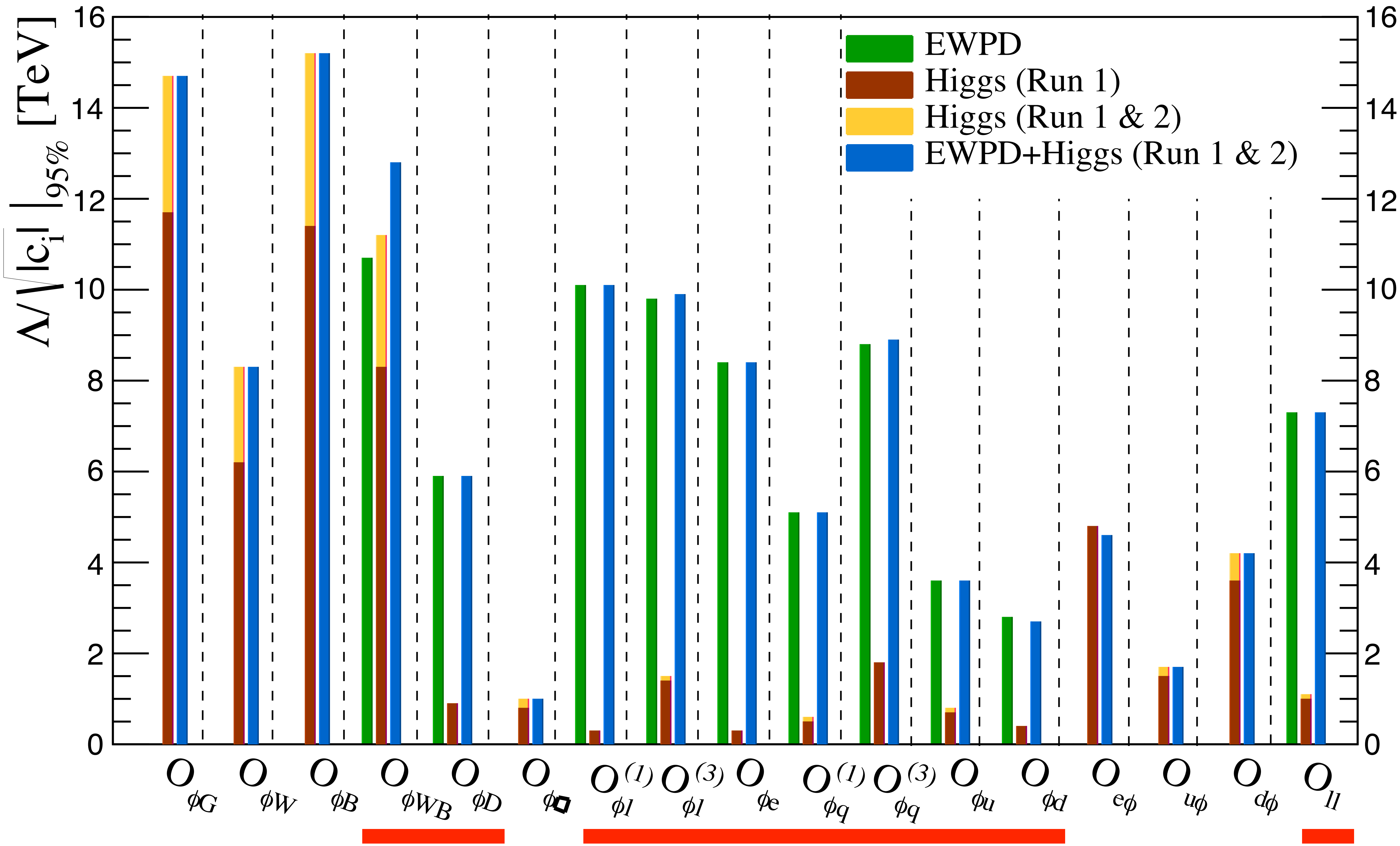


Constraints on EWPO-operators : Higgs << EWPD

5. Expected sensitivities at future colliders

Future colliders

- Future e+e- collider projects: ILC, FCC-ee, CEPC, CLIC, …

  ILC [$\sqrt{s} = 90 - 500\,\mathrm{GeV}$???, ~2028-] *hep-ph/0106315, arXiv:1306.6352*

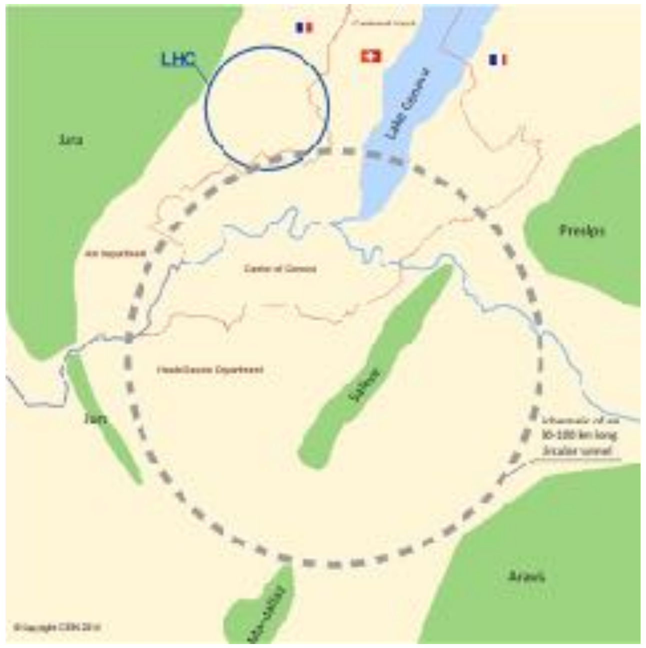
  FCC-ee [$\sqrt{s} = 90 - 400\,\mathrm{GeV}$, ~2035-] *arXiv:1308.6176*

  CEPC [$\sqrt{s} = 90 - 250\,\mathrm{GeV}$, ~2030-] *IHEP-CEPC-DR-2015-01*

  Circumference:
  LHC: 27 km
  FCC: 80-100 km
  CEPC: 50-70 km

- Physics at FCC-ee:

FCCee	Z pole	WW threshold	HZ threshold	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}$ [ab^{-1}/year]	88	15	3.5	1.0	1.0
Years of operation	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	10^8	2×10^6	2.1×10^5	7.5×10^4



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

- Physics at CEPC:

CEPC run	Z pole	HZ threshold
$\sqrt{s}$ [GeV]	90	240
$\int \mathcal{L}$ [fb^{-1}]	>150	5×10^3
Events	10^{11}	$>10^6$

Expected sensitivities to 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)	±0.037
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.2324±0.0012			±0.0001	(FCCee-Z)	±0.000023
$P_\tau^{\rm pol}$	0.1465±0.0033			±0.0002	(FCCee-Z)	
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])	
$A_{\rm FB}^{0,\ell}$	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

O(10) improvement in experimental precision!

Satoshi Mishima (KEK)

Experimental vs. Theoretical uncertainties

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

A. Freitas, arXiv:1604.00406

- Theoretical efforts are necessary to match future experimental precision.
- Assume that $O(\alpha\alpha_s^2)$, fermionic $O(\alpha^2\alpha_s)$ and $O(\alpha^3)$, and leading 4-loop corrections in the rho parameter will become available.

Satoshi Mishima (KEK)

Expected sensitivity to Higgs observables

	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%	0.28%
$H \to c\bar{c}$			8.3%	6.2-13%	3.1%	3.9%	3.5-7.2%	2%	1.2%	2.2%
$H \to gg$			7%	4.1-11%	2.3%	3.3%	2.3-6%	1.4%	1.4%	1.6%
$H \to WW$	$\gtrsim 15\%$	4-11%	6.4%	2.4-9.2%	1.6%	3%	1.3-5.1%	1%	0.9%	1.5%
$H \to \tau\tau$	$\gtrsim 25\%$	5-15%	4.2%	5.4-9%	3.1%	2%	3-5%	2%	0.7%	1.2%
$H \to ZZ$	$\gtrsim 24\%$	4-17%	19%	8.2-25%	4.1%	8.8%	4.6-14%	2.6%	3.1%	4.3%
$H \to \gamma\gamma$	$\gtrsim 20\%$	4-28%	38%	20-38%	7%	16%	13-19%	5.4%	3.0%	9%
$H \to Z\gamma$		10-27%								
$H \to \mu\mu$		14-23%			31%			20%	13%	17%

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

Satoshi Mishima (KEK)

Parametric uncertainties

- $\alpha_s(M_Z)$: lattice QCD projection

$$\delta\alpha_s(M_Z) = \pm 0.0010 \quad \Rightarrow \quad \delta\alpha_s(M_Z) \approx \pm 0.0002$$

- $\Delta\alpha^{(5)}_{\rm had}(M_Z)$: ongoing and future experiments for $\sigma(e^+e^- \to \text{hadrons})$

$$\delta\Delta\alpha^{(5)}_{\rm had}(M_Z) = \pm 0.00033 \quad \Rightarrow \quad \delta\Delta\alpha^{(5)}_{\rm had}(M_Z) \approx \pm 0.00005$$

- m_t : the shape of the $t\bar{t}$ production cross section in a scan around the threshold at future e+e- colliders

$$\delta m_t = \pm 760\,\text{MeV} \quad \Rightarrow \quad \delta m_t \approx \pm 50\,\text{MeV}$$

Strategy

- Assume that the future exp. measurements will be fully compatible with the SM predictions.
- Use SM predictions as central values of inputs:

$$m_H = 125.09 \text{ GeV}, \quad m_t = 173.61 \text{ GeV}, \quad M_Z = 91.1879 \text{ GeV},$$

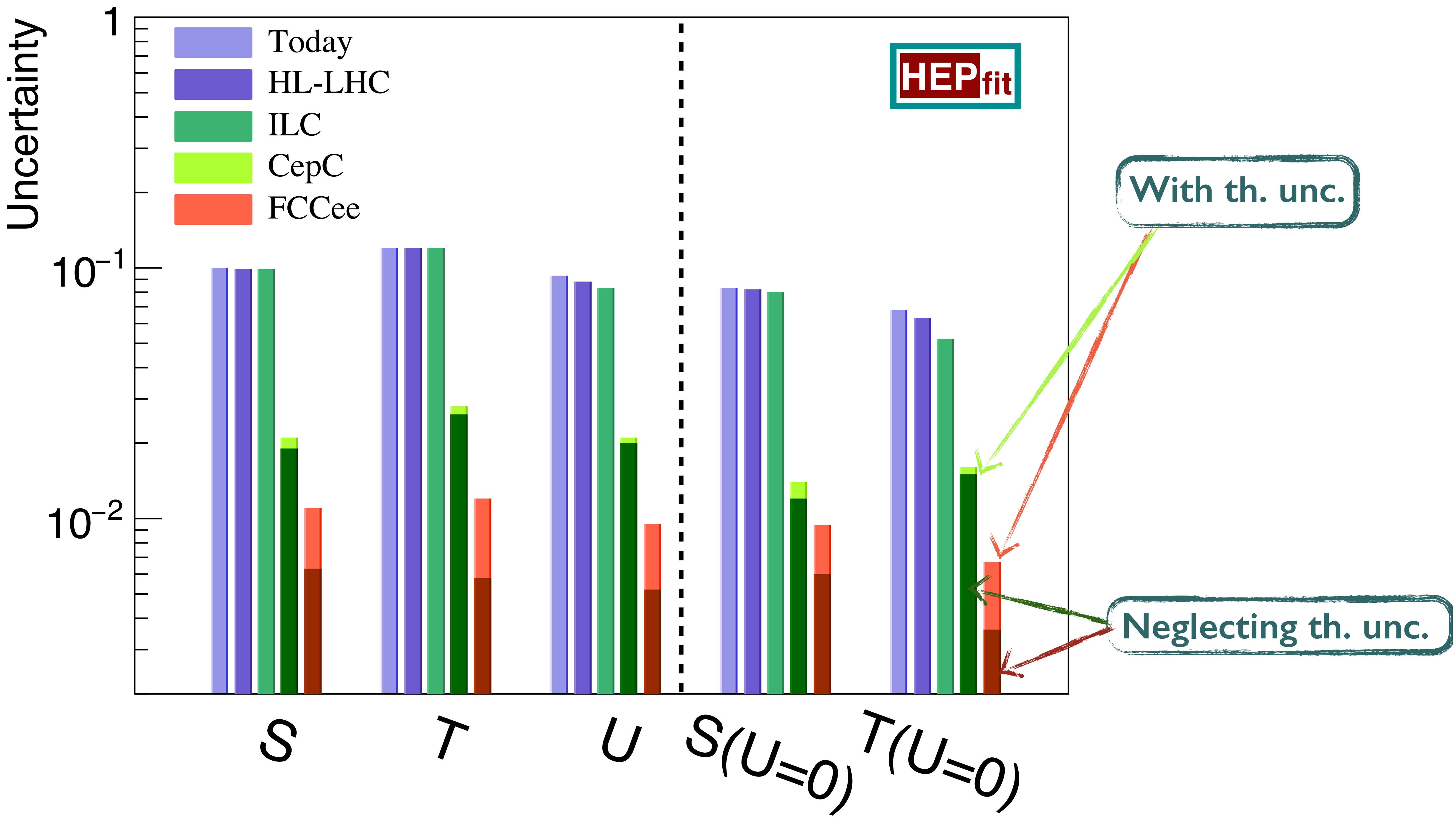
$$\alpha_s(M_Z) = 0.1180 \quad \text{and} \quad \Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02747,$$

➡ Limits provide future sensitivity to NP

- Assume the expected uncertainties explained in the previous slides.
- Consider another scenario, where theoretical uncertainties are subdominant and negligible.

Oblique parameters

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, in preparation



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

NP in $Zb\bar{b}$ couplings

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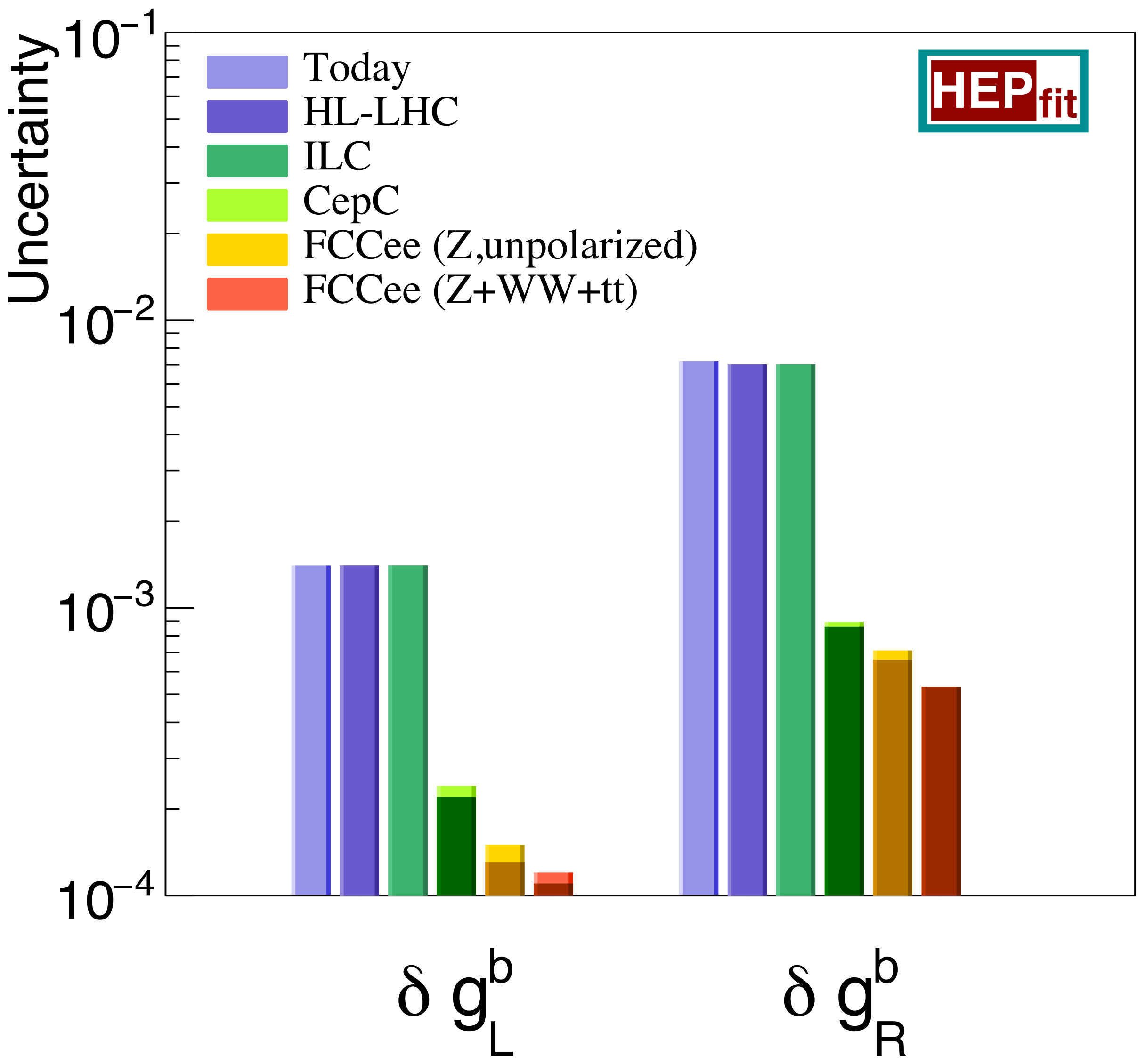

$$\Delta(\delta g_L^b) \sim 0.0001$$
$$\Delta(\delta g_R^b) \sim 0.0005$$

Modified HVV coupling

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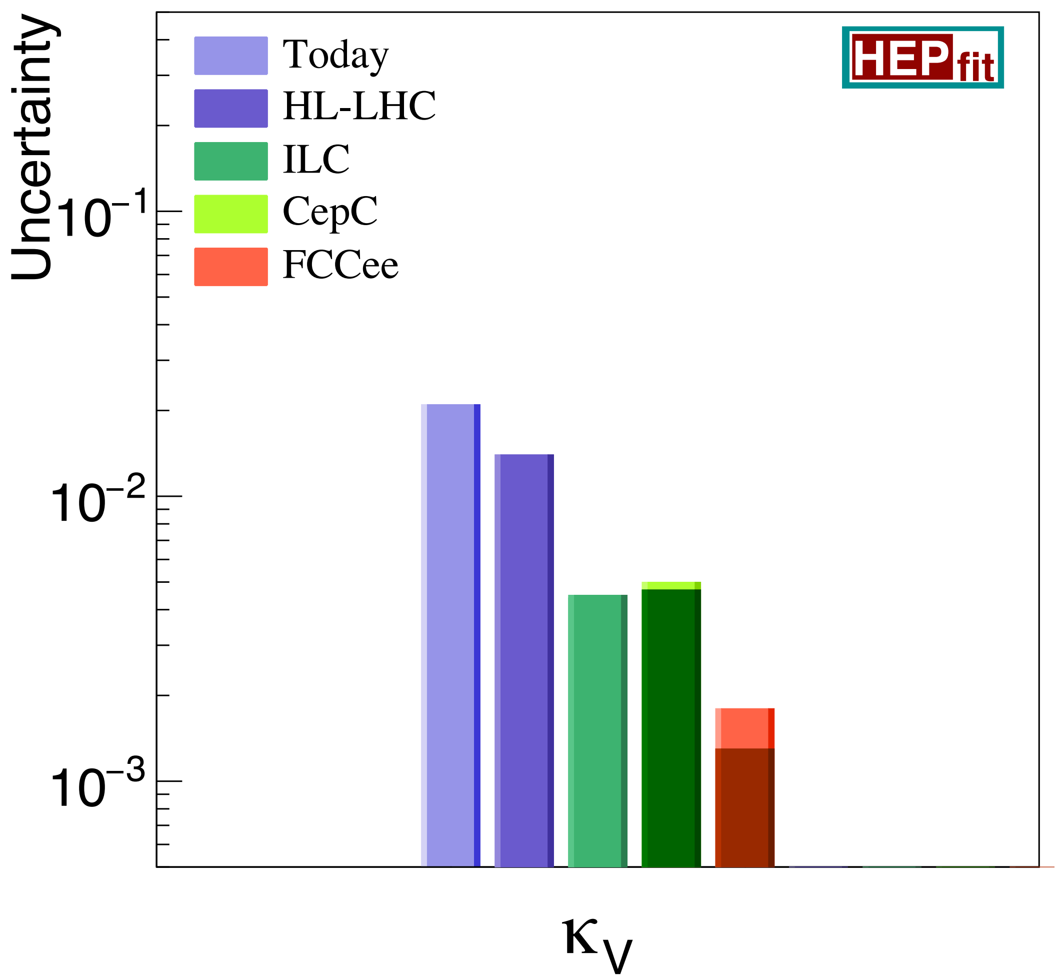
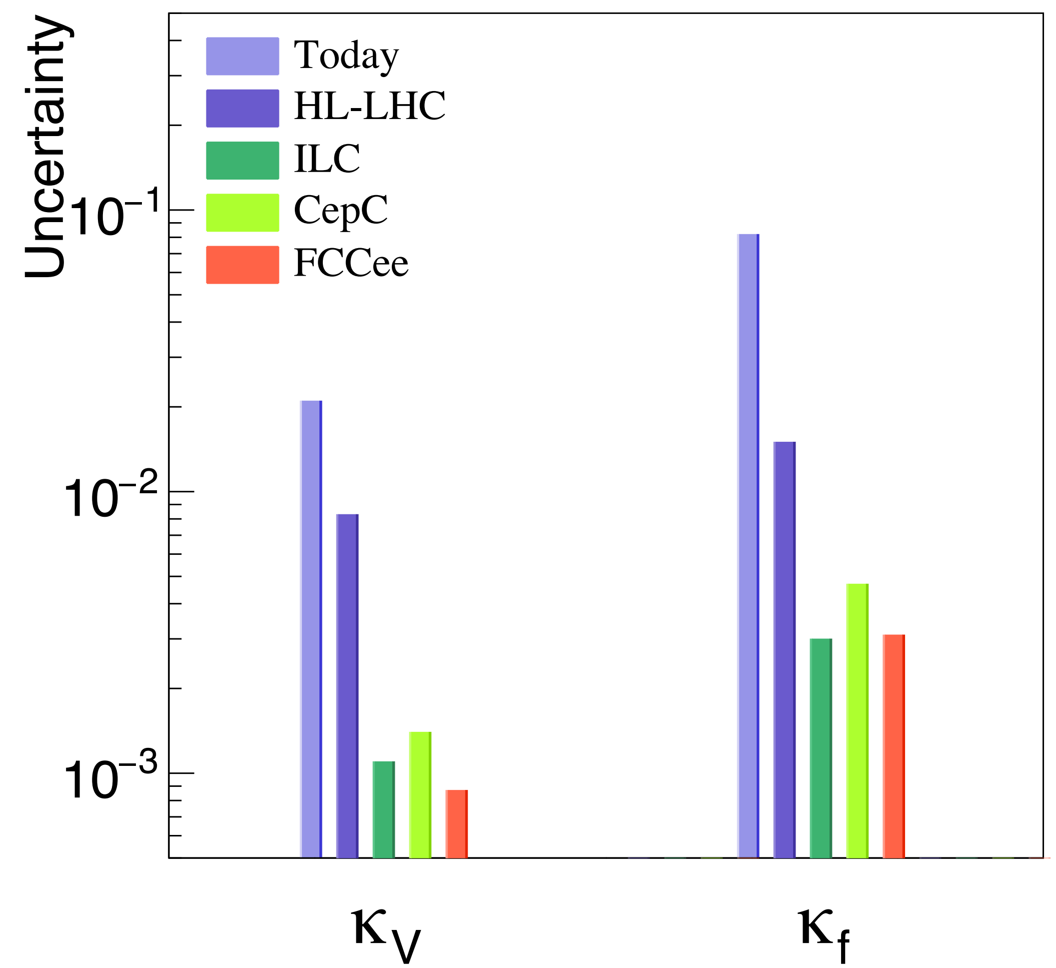




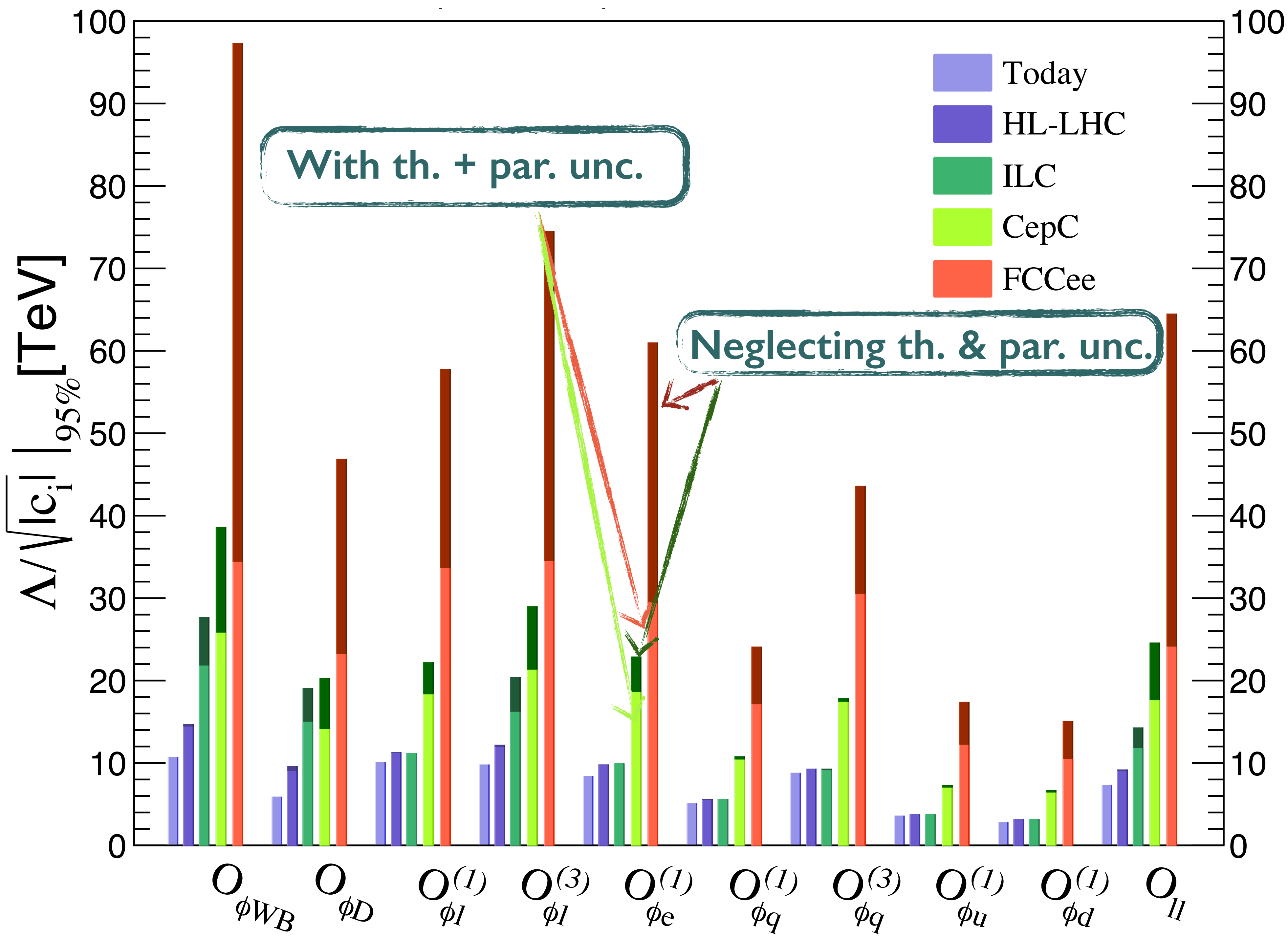
EWPD results

EWPD+Higgs results

$$\Delta\kappa_V \sim \mathbf{0.002}$$

Dimension-six operators (EWPO)

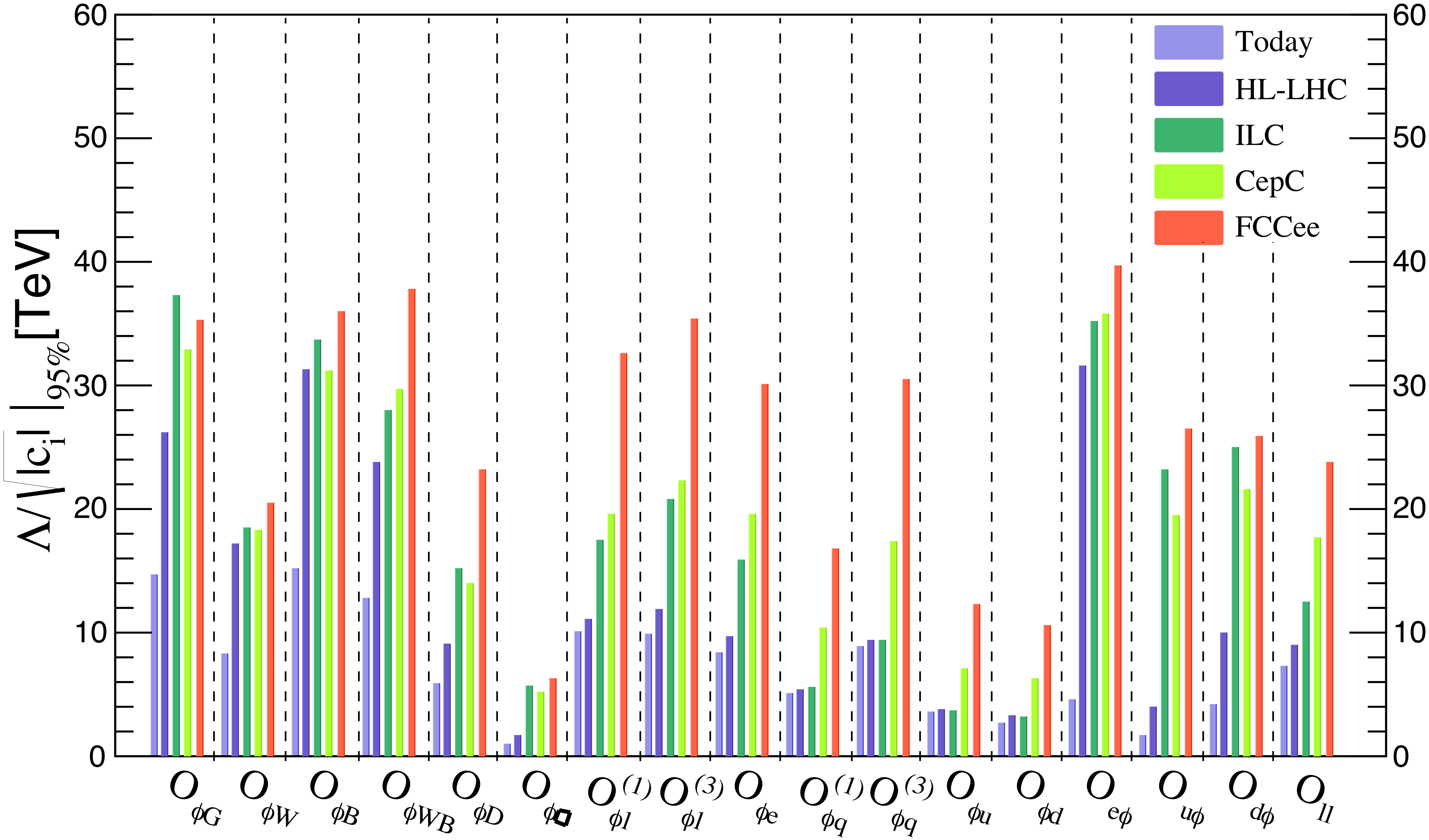
J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, in preparation



NP scale > 5-40 TeV (for Ci=1)

Dimension-six operators (EWPO+Higgs)

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, in preparation



6. Summary

- EW precision measurements offer a very powerful handle to search for NP above the TeV scale.
- We have been developing the ***HEPfit*** package.
- EW precision fit shows a good agreement with the SM predictions at the 2-loop level, and gives strong constraints on NP at the TeV scale.
- Future e+e- colliders would strengthen the power of the EW precision fit.

	Expected sensitivity	Improvement
$S,\ T,\ U$	$\delta S,\ \delta T,\ \delta U \sim 5\text{-}10 \cdot 10^{-3}$	20x
$\delta g_{hVV,hff}\ (\kappa_V,\ \kappa_f)$	$\delta\kappa_V \sim 0.001\text{-}0.002,\ \delta\kappa_f \sim 0.003$	10-20x
$\mathcal{L}_{\mathrm{SMEFT}}^{d=6}$	$\Lambda_{NP}\|_{\|C_i\|=1} \gtrsim 5\text{-}40\ \mathrm{TeV}$	$\sim$ 4x

Satoshi Mishima (KEK)

Backup

Hadronic corrections to the EM coupling

- We adopt a conservative value:

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

measured with inclusive processes.

Burkhardt & Pietrzyk (11)
(see also Davier et al(11); Hagiwara et al(11) ; Jegerlehner(11))

Note: Smaller uncertainty has been obtained if using exclusive processes with pQCD:

$$\delta\left(\Delta\alpha^{(5)}_{\rm had}(M_Z^2)\right) \sim \pm 0.00010$$

but discrepancy has been observed between inclusive and exclusive in low-energy data.

Ambiguity in the top pole mass

- The measurements of the pole mass of the top quark at Tevatron and LHC suffer from ambiguities:

M. Mangano at TOP2013:

"All in all I believe that it is justified to assume that MC mass parameter is interpreted as m_{pole} within the ambiguity intrinsic in the definition of m_{pole}, thus at the level of ~250-500 MeV."

S.O. Moch et al., 1405.4781 (report on the 2014 MITP scientific program):

"The uncertainty on the translation from the MC mass definition to a theoretically well defined short-distance mass definition at a low scale is currently estimated to be of the order of 1 GeV." (There is an additional uncertainty originating from the conversion of the short-distance mass to pole mass.)

S.O. Moch, 1408.6080: $\Delta m_t = {}^{+0.82}_{-0.62}\ \mathrm{GeV}$

Ambiguity in the top pole mass

S.O. Moch, 1408.6080

Nonetheless, the MC mass definition can be translated to a theoretically well-defined short-distance mass definition at a low scale with an uncertainty currently estimated to be of the order of 1 GeV, see [1,40]. This translation uses the fact that multi-observable analyses like in [39] effectively assign a high statistical weight to the invariant mass distribution of the reconstructed boosted top-quarks, because of the large sensitivity of the system on the mass parameter, especially around the peak region.

The top-quark invariant mass distribution can be computed to higher orders in perturbative QCD, cf., Fig. 3, and its peak position can also be described in an effective theory approach based on a factorization [41, 42] into a hard, a soft non-perturbative and a universal jet function. Each of those functions depends in a fully coherent and transparent way on the mass at a particular scale. The reconstructed top object largely corresponds to the jet function which is governed by a short-distance mass $m_t^{\rm MRS}$ at the scale of the top quark width Γ_t, see, e.g., [1,40]. This line of arguments allows one to systematically implement proper short-distance mass schemes for the description of the MC mass in Eq. (5), which can then indeed be converted to the pole mass.

$$\Delta m_{\rm th} =^{+0.32}_{-0.62}\ {\rm GeV}\,(m_t^{\rm MC} \to m_t^{\rm MSR}(3{\rm GeV}))\, +\, 0.50\,{\rm GeV}\,(m_t(m_t) \to m_t^{\rm pole})\,,$$

Direct vs. Indirect

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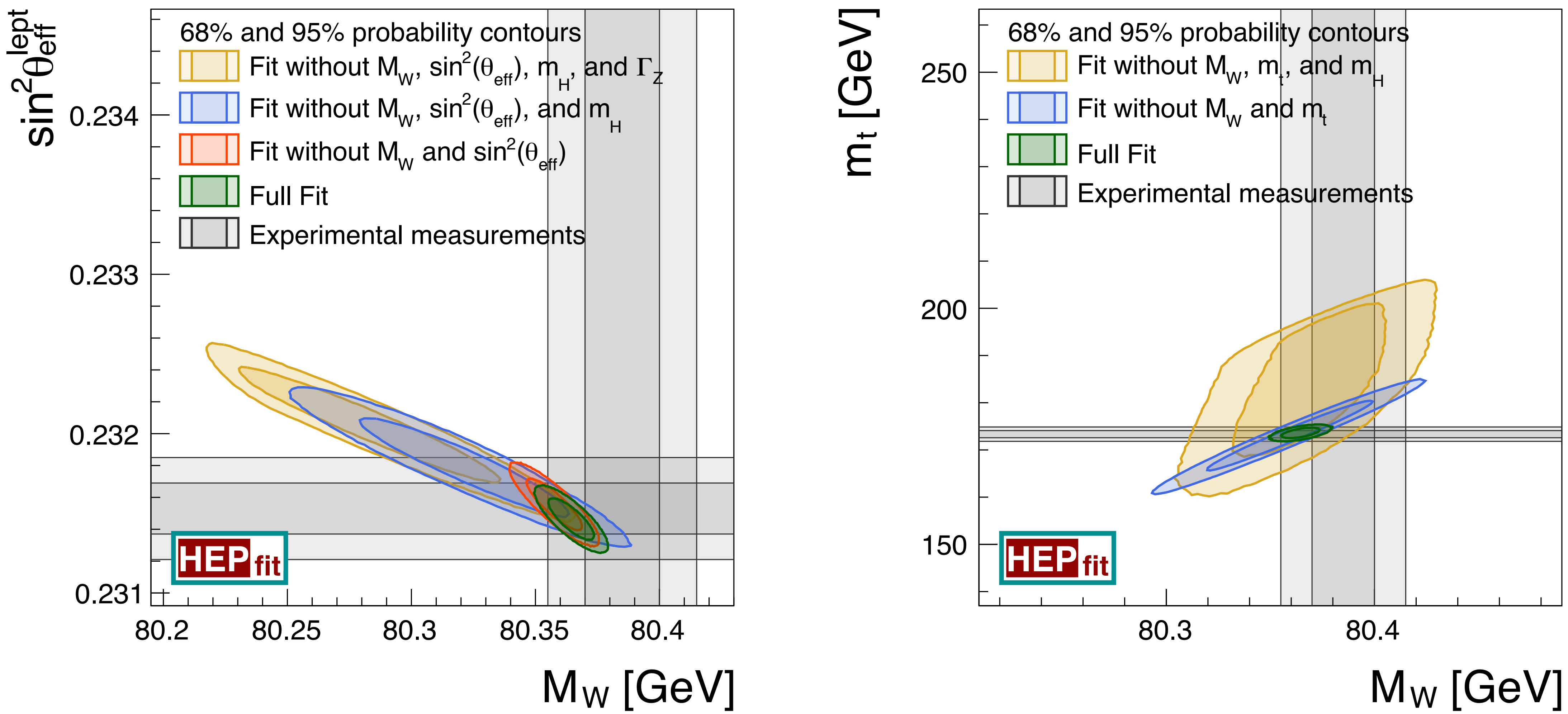


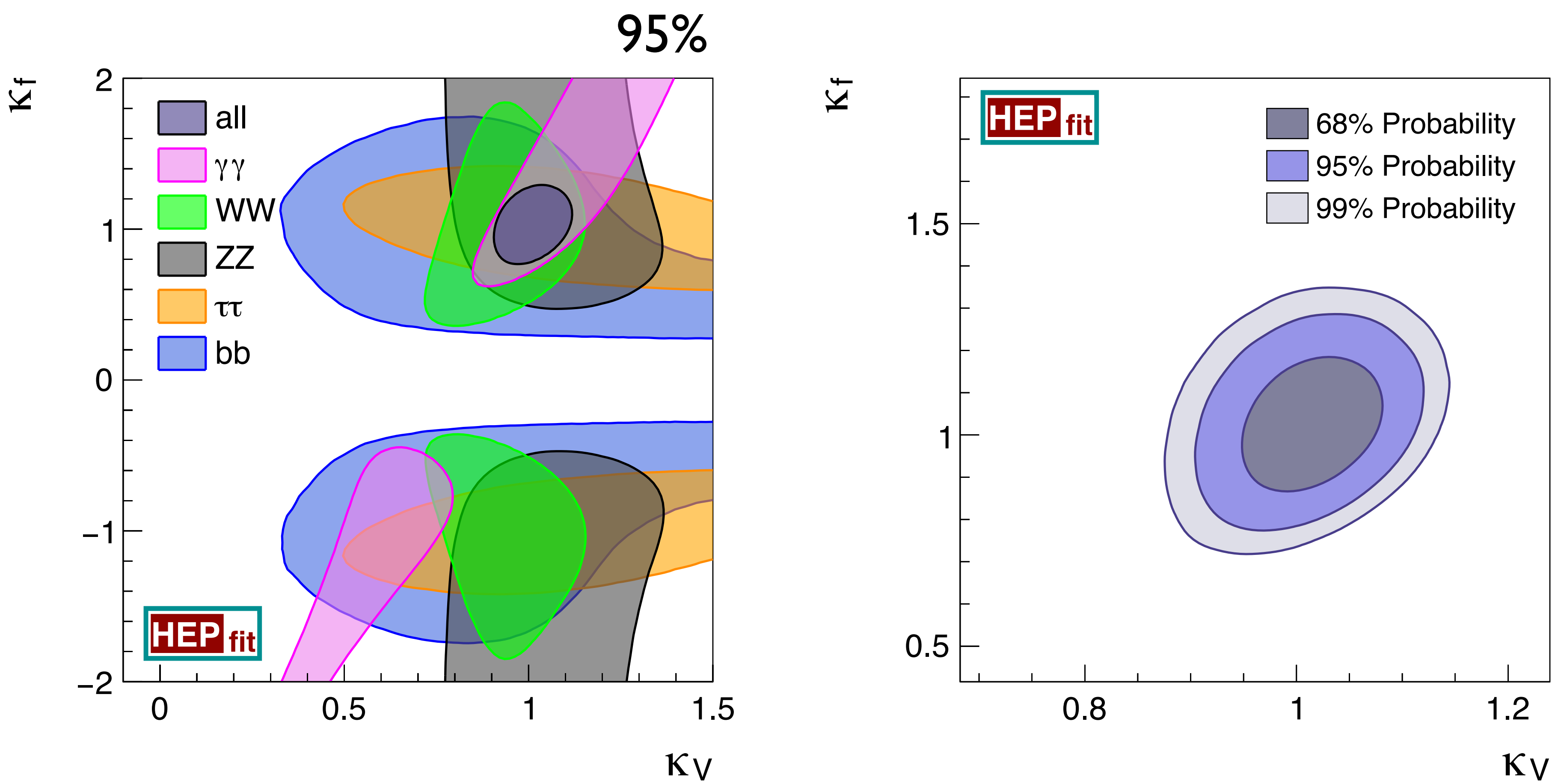
Parametric uncertainties

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]

	Prediction	α_s	$\Delta\alpha^{(5)}_{\rm had}$	M_Z	m_t
M_W [GeV]	80.3618 ± 0.0080	± 0.0008	± 0.0060	± 0.0026	± 0.0046
Γ_W [GeV]	2.08849 ± 0.00079	± 0.00048	± 0.00047	± 0.00021	± 0.00036
Γ_Z [GeV]	2.49403 ± 0.00073	± 0.00059	± 0.00031	± 0.00021	± 0.00017
σ_h^0 [nb]	41.4910 ± 0.0062	± 0.0059	± 0.0005	± 0.0020	± 0.0005
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.23148 ± 0.00012	± 0.00000	± 0.00012	± 0.00002	± 0.00002
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.14731 ± 0.00093	± 0.00003	± 0.00091	± 0.00012	± 0.00019
$\mathcal{A}_c$	0.66802 ± 0.00041	± 0.00001	± 0.00040	± 0.00005	± 0.00008
$\mathcal{A}_b$	0.934643 ± 0.000076	± 0.000003	± 0.000075	± 0.000010	± 0.000005
$A_{\rm FB}^{0,\ell}$	0.01627 ± 0.00021	± 0.00001	± 0.00020	± 0.00003	± 0.00004
$A_{\rm FB}^{0,c}$	0.07381 ± 0.00052	± 0.00002	± 0.00050	± 0.00007	± 0.00010
$A_{\rm FB}^{0,b}$	0.10326 ± 0.00067	± 0.00002	± 0.00065	± 0.00008	± 0.00013
R_ℓ^0	20.7478 ± 0.0077	± 0.0074	± 0.0020	± 0.0003	± 0.0003
R_c^0	0.172222 ± 0.000026	± 0.000023	± 0.000007	± 0.000001	± 0.000009
R_b^0	0.215800 ± 0.000030	± 0.000013	± 0.000004	± 0.000000	± 0.000026

Constraint on Higgs-boson couplings

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]

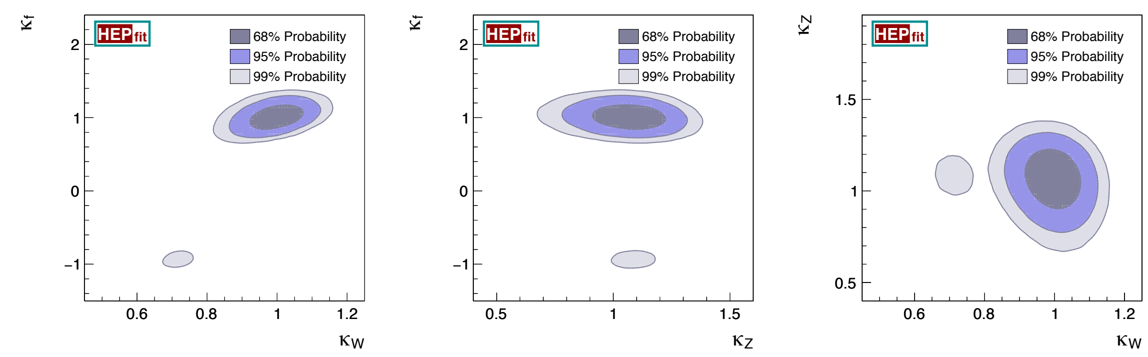


	Result	95% Prob.	Correlation Matrix	
κ_V	1.01 ± 0.04	$[0.93, 1.10]$	1.00	
κ_f	1.03 ± 0.10	$[0.83, 1.23]$	0.31	1.00

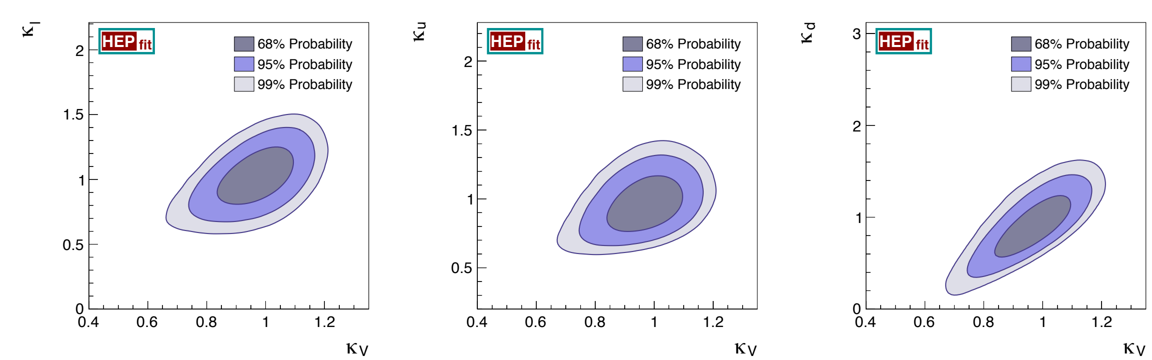
More general cases

J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]

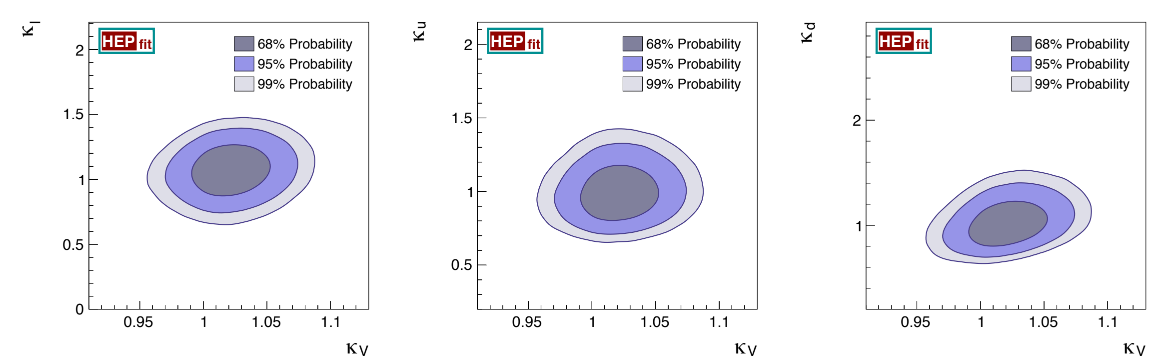
	Result	95% Prob.	Correlation Matrix		
κ_W	1.00 ± 0.05	$[0.89, 1.10]$	1.00		
κ_Z	1.07 ± 0.11	$[0.85, 1.27]$	−0.17	1.00	
κ_f	1.01 ± 0.11	$[0.80, 1.22]$	0.41	−0.14	1.00



	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

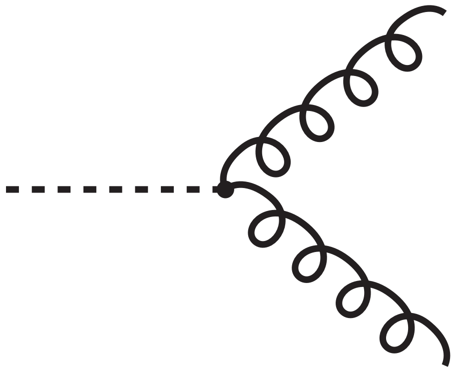


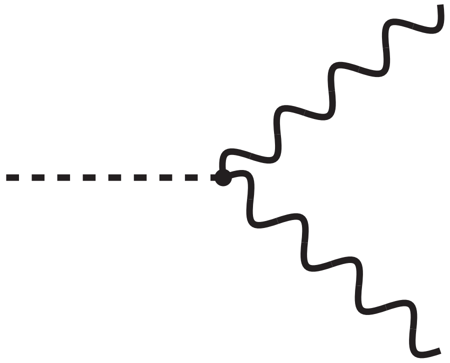
	Result	95% Prob.	Correlation Matrix				
κ_W	0.94 ± 0.10	$[0.73, 1.13]$	1.00				
κ_Z	1.03 ± 0.13	$[0.77, 1.28]$	0.34	1.00			
κ_ℓ	1.02 ± 0.15	$[0.73, 1.33]$	0.55	0.22	1.00		
κ_u	0.95 ± 0.13	$[-0.96, -0.72] \cup [0.68, 1.28]$	0.49	0.04	0.44	1.00	
κ_d	0.91 ± 0.22	$[0.46, 1.36]$	0.81	0.36	0.62	0.78	1.00



Higgs couplings to vector bosons

- Input parameters: G_F , M_Z, M_W (α for EWPO)



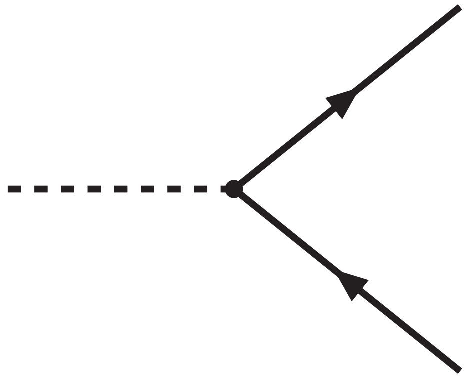


$$\widehat{C}_i = \frac{v^2}{\Lambda^2} C_i$$

$$\delta_{G_F} = \widehat{C}^{(3)11}_{HL} + \widehat{C}^{(3)22}_{HL} - \frac{1}{2}(\widehat{C}^{1221}_{LL} + \widehat{C}^{2112}_{LL})$$

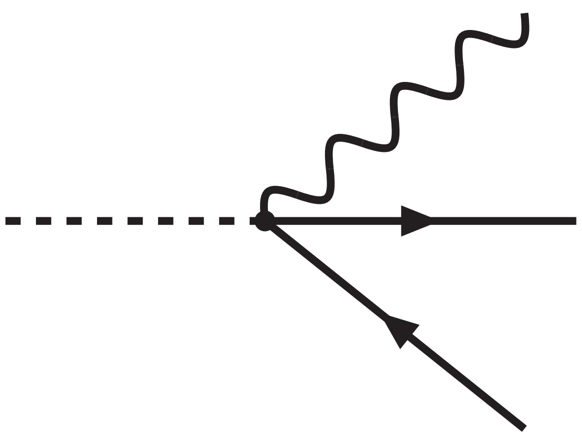
$$\begin{aligned}
\mathcal{L}_{hVV} = & \left(\sqrt{2}\,G_F\right)^{1/2} \widehat{C}_{HG}\, G^A_{\mu\nu} G^{A\mu\nu} h & hgg \\
& + 2\left(\sqrt{2}\,G_F\right)^{1/2} M_W^2 \left(1 - \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F}\right) W^\dagger_\mu W^\mu h & \\
& + 2\left(\sqrt{2}\,G_F\right)^{1/2} \widehat{C}_{HW}\, W^{\mu\nu} W^\dagger_{\mu\nu} h & hWW \\
& + \left(\sqrt{2}\,G_F\right)^{1/2} M_Z^2 \left(1 + \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F}\right) Z_\mu Z^\mu h & \\
& + \left(\sqrt{2}\,G_F\right)^{1/2} \left(c_W^2 \widehat{C}_{HW} + s_W^2 \widehat{C}_{HB} + s_W c_W \widehat{C}_{HWB}\right) Z_{\mu\nu} Z^{\mu\nu} h & hZZ \\
& + \left(\sqrt{2}\,G_F\right)^{1/2} \left[2 s_W c_W \left(\widehat{C}_{HW} - \widehat{C}_{HB}\right) - (c_W^2 - s_W^2)\widehat{C}_{HWB}\right] Z_{\mu\nu} F^{\mu\nu} h & hZ\gamma \\
& + \left(\sqrt{2}\,G_F\right)^{1/2} \left(s_W^2 \widehat{C}_{HW} + c_W^2 \widehat{C}_{HB} - s_W c_W \widehat{C}_{HWB}\right) F_{\mu\nu} F^{\mu\nu} h & h\gamma\gamma
\end{aligned}$$

Higgs couplings to fermions



$h f \bar{f} \qquad f = e, u, d$

$$\mathcal{L}_{hf\bar{f}} = \left[-\left(\sqrt{2}G_F\right)^{1/2} m_f^p \,\delta_{pq} \left(1 - \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F}\right) + \frac{1}{\sqrt{2}}\widehat{C}_{fH}^{\,pq} \right] \bar{f}_L^{\,p} f_R^{\,q} h + \text{h.c.}$$

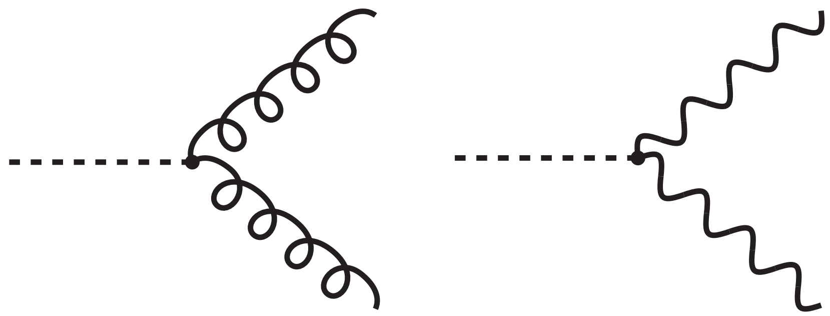


$h V q \bar{q}$

$$\begin{aligned}\mathcal{L}_{hVq\bar{q}} = & -\frac{2M_Z}{v^2}\left(\widehat{C}_{HQ}^{(1)} - \widehat{C}_{HQ}^{(3)}\right) Z_\mu (\overline{u}_L \gamma^\mu u_L) h - \frac{2M_Z}{v^2}\left(\widehat{C}_{HQ}^{(1)} + \widehat{C}_{HQ}^{(3)}\right) Z_\mu (\overline{d}_L \gamma^\mu d_L) h \\ & - \frac{2M_Z}{v^2}\,\widehat{C}_{Hu} Z^\mu (\overline{u}_R \gamma^\mu u_R) h - \frac{2M_Z}{v^2}\,\widehat{C}_{Hd} Z^\mu (\overline{d}_R \gamma^\mu d_R) h \\ & + \left[\frac{2\sqrt{2}M_Z c_W}{v^2}\,\widehat{C}_{HQ}^{(3)} W_\mu^+ (\overline{u}_L \gamma^\mu d_L) h + \frac{\sqrt{2}M_Z c_W}{v^2}\,\widehat{C}_{Hud} W_\mu^+ (\overline{u}_R \gamma^\mu d_R) h + \text{h.c.} \right]\end{aligned}$$

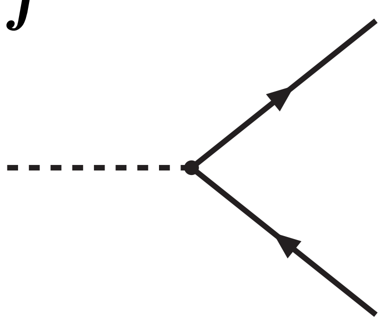
Dim-6 contributions to Higgs physics

hVV



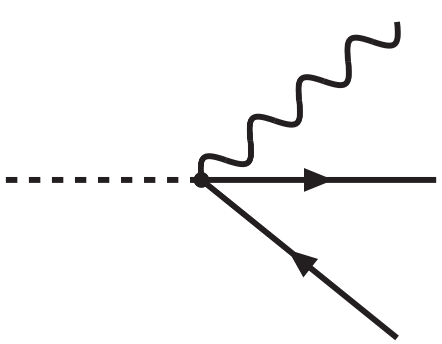
$$
\begin{aligned}
\mathcal{L}_{hVV} = &\left(\sqrt{2}\,G_F\right)^{1/2} \widehat{C}_{HG}\, G^A_{\mu\nu} G^{A\mu\nu} h \\
&+ 2\left(\sqrt{2}\,G_F\right)^{1/2} M_W^2 \left(1 - \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F}\right) W^\dagger_\mu W^\mu h \\
&+ 2\left(\sqrt{2}\,G_F\right)^{1/2} \widehat{C}_{HW}\, W^{\mu\nu} W^\dagger_{\mu\nu} h \\
&+ \left(\sqrt{2}\,G_F\right)^{1/2} M_Z^2 \left(1 + \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F}\right) Z_\mu Z^\mu h \\
&+ \left(\sqrt{2}\,G_F\right)^{1/2} \left(c_W^2 \widehat{C}_{HW} + s_W^2 \widehat{C}_{HB} + s_W c_W \widehat{C}_{HWB}\right) Z_{\mu\nu} Z^{\mu\nu} h \\
&+ \left(\sqrt{2}\,G_F\right)^{1/2} \left[2 s_W c_W \left(\widehat{C}_{HW} - \widehat{C}_{HB}\right) - (c_W^2 - s_W^2)\widehat{C}_{HWB}\right] Z_{\mu\nu} F^{\mu\nu} h \\
&+ \left(\sqrt{2}\,G_F\right)^{1/2} \left(s_W^2 \widehat{C}_{HW} + c_W^2 \widehat{C}_{HB} - s_W c_W \widehat{C}_{HWB}\right) F_{\mu\nu} F^{\mu\nu} h
\end{aligned}
$$

$hf\bar{f}$



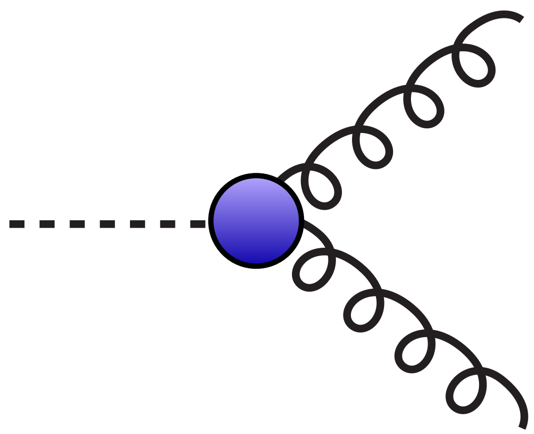
$$
\mathcal{L}_{hf\bar{f}} = \left[- \left(\sqrt{2}G_F\right)^{1/2} m_f^p\, \delta_{pq} \left(1 - \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F}\right) + \frac{1}{\sqrt{2}} \widehat{C}_{fH}^{pq} \right] \bar{f}_L^p f_R^q h + \text{h.c.}
$$

$hVq\bar{q}$



$$
\begin{aligned}
\mathcal{L}_{hVq\bar{q}} = &-\frac{2M_Z}{v^2}\left(\widehat{C}^{(1)}_{HQ} - \widehat{C}^{(3)}_{HQ}\right) Z_\mu (\overline{u}_L\, \gamma^\mu u_L) h - \frac{2M_Z}{v^2}\left(\widehat{C}^{(1)}_{HQ} + \widehat{C}^{(3)}_{HQ}\right) Z_\mu (\overline{d}_L\, \gamma^\mu d_L) h \\
&- \frac{2M_Z}{v^2}\, \widehat{C}_{Hu} Z^\mu (\overline{u}_R \gamma^\mu u_R) h - \frac{2M_Z}{v^2}\, \widehat{C}_{Hd} Z^\mu (\overline{d}_R \gamma^\mu d_R) h \\
&+ \left[\frac{2\sqrt{2} M_Z c_W}{v^2}\, \widehat{C}^{(3)}_{HQ} W^+_\mu (\overline{u}_L\, \gamma^\mu d_L) h + \frac{\sqrt{2} M_Z c_W}{v^2}\, \widehat{C}_{Hud} W^+_\mu (\overline{u}_R \gamma^\mu d_R) h + \text{h.c.} \right]
\end{aligned}
$$

Effective hgg coupling



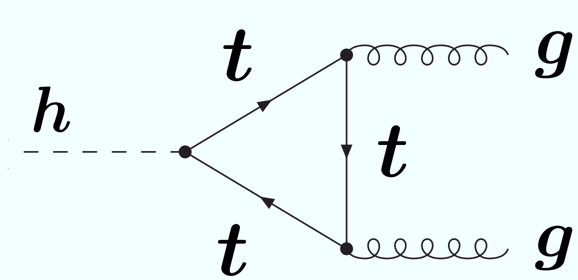
$$\mathcal{O}_{HG} = (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$
$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$
$$\mathcal{O}^{(3)}_{HL} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{L}\, \tau^I \gamma^\mu L)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\, u_R \widetilde{H})$$
$$\mathcal{O}_{LL} = (\overline{L}\gamma_\mu L)(\overline{L}\gamma^\mu L)$$

$$\mathcal{L}_{hgg,\mathrm{eff}} = \left[g^{\mathrm{SM}}_{hgg,\mathrm{eff}} \left(1 - \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F} - \frac{v}{\sqrt{2}m_t}\widehat{C}_{tH} \right) + \frac{1}{v}\widehat{C}_{HG} \right] G^A_{\mu\nu} G^{A\mu\nu} h$$

SM coupling at one-loop

$$g^{\mathrm{SM}}_{hgg,\mathrm{eff}} = \frac{\alpha_s}{16\pi v} A^H_f (4m_t^2/m_h^2)$$

$$A^H_f(\tau) = 2\tau \left[1 + (1-\tau)\arcsin^2 \frac{1}{\sqrt{\tau}} \right]$$



- $hZ\gamma$ and $h\gamma\gamma$ are similar.