Higgs Global Fits

Higgs Hunting 2023

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Mainly based on [Jorge de Blas, Yong Du, Christophe Grojean, Jiayin Gu, VM, Michael E. Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou, arXiv:2206.08326]

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Introduction

- Besides the success of the SM, it does not provide a completely satisfactory description of Nature
- The discovery of the Higgs boson more than 10 years ago opened a new window to study new physics
- A huge effort have been developed in studying its properties providing considerable amounts of data
- Combining all the data in one framework is may be crucial to discover new physics
- To perform these studies becomes interesting to employ a "model agnostic" framework, enabling the simultaneous exploration of numerous new physics extensions
- The absence of direct evidences of additional particles at the LHC suggest the existence of an energy gap between the NP and the LHC energy range
- The SMEFT becomes a good framework given the current measurements

Theoretical Framework

- The SM is treated as an EFT

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathscr{O}\left(\Lambda^{-4}\right)$$

- The Wilson coefficients can be interpreted in terms of NP mediators
- The Lagrangian is expanded up to D6
- The amplitudes include the Λ^{-2} terms from the interference between the SM and D6
- Sometimes the Λ^{-4} operators arising from squaring the D6 are also included
- The double insertions of D6 and the effects of D8 operators, contributing to the same Λ^{-4} order, are usually omitted

$$\sigma = \sigma_{\text{SM}} + \underbrace{\frac{1}{\Lambda^2}\sum C_i O_i}_{\text{SM } \times \text{D6}} + \underbrace{\left(\frac{1}{\Lambda^2}\sum C_i O_i\right)\left(\frac{1}{\Lambda^2}\sum C_j O_j\right)}_{\text{D6}\times\text{D6}} + \underbrace{O(1/\Lambda^4)}_{\text{SM } \times \text{D8}}$$

Global fits strategy

- The total number of parameters in the SMEFT prohibits conducting a comprehensive global fit of all the WC even at dimension six
- Usually CP-conservation is assumed besides invoking some flavour symmetry in order to reduce the degrees of freedom
- The most common assumptions are flavour universality for the light quarks $U(2)_q \otimes U(2)_u \otimes U(2)_d$ or even leaving only the top-quark aside $U(2)_q \otimes U(2)_u \otimes U(3)_d$
- We can also divide the fit in the electroweak, the Higgs, and the top-quark sectors
- To fit the Higgs sector, the EW part must also be considered since those operators generate relevant contributions to the Higgs sector
- The top-quark sector is more independent but huge efforts have been done in the community to fit all three sectors at the same time

Global fits works

- Several theory groups have performed global fits on the SMEFT (among others we highlight)
  - `Fitmaker` [2012.02779] (look at Maeve Madigan's talk on Wedneday!)
  - `SMEFiT` [2105.00006] (look at Luca Mantani's talk at Higgs Hunting 2021 link)
  - `HEPfit` [2206.08326] : Last efforts have been done in future colliders, we will see some results later. We are working on a fit using current data in collaboration with Jorge de Blas, Angelica Goncalves, Laura Reina and Luca Silvestrini.

- `HEPfit` [1910.14012] link:
  - Flexible open-source C++ code
  - Based on BAT (bayesian statistical framework)
  - Markov Chain Monte Carlo procedure
  - Useful for SM, new physics models or EFTs
  - Versatile enough to include flavour, electroweak and Higgs observables

SMEFT operators in the Warsow basis

Operator	Notation	Operator	Notation
$(\bar{l}_L\gamma_\mu l_L)(\bar{l}_L\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\bar{q}_L\gamma_\mu q_L)(\bar{q}_L\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_L\gamma_\mu T_A q_L)(\bar{q}_L\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\bar{l}_L\gamma_\mu l_L)(\bar{q}_L\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_L\gamma_\mu \sigma_a l_L)(\bar{q}_L\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\bar{u}_R\gamma_\mu u_R)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\bar{d}_R\gamma_\mu d_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\bar{u}_R\gamma_\mu u_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_R\gamma_\mu T_A u_R)(\bar{d}_R\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\bar{l}_L\gamma_\mu l_L)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\bar{q}_L\gamma_\mu q_L)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\bar{l}_L\gamma_\mu l_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\bar{l}_L\gamma_\mu l_L)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\bar{q}_L\gamma_\mu q_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_L\gamma_\mu T_A q_L)(\bar{u}_R\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\bar{q}_L\gamma_\mu q_L)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_L\gamma_\mu T_A q_L)(\bar{d}_R\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\bar{l}_L e_R)(\bar{d}_R q_L)$	$\mathcal{O}_{ledq}$		
$(\bar{q}_L u_R)\, i\sigma_2\, (\bar{q}_L d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\bar{q}_L T_A u_R)\, i\sigma_2\, (\bar{q}_L T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\bar{l}_L e_R)\, i\sigma_2\, (\bar{q}_L u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\bar{l}_L u_R)\, i\sigma_2\, (\bar{q}_L e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}_L\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{l}_L\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_L\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}_L\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)(\bar{u}_R\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\bar{l}_L\sigma^{\mu\nu}e_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_L\sigma^{\mu\nu}e_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
$(\bar{q}_L\sigma^{\mu\nu}u_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_L\sigma^{\mu\nu}u_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
$(\bar{q}_L\sigma^{\mu\nu}d_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_L\sigma^{\mu\nu}d_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
$(\bar{q}_L\sigma^{\mu\nu}\lambda^A u_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_L\sigma^{\mu\nu}\lambda^A d_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)(\bar{l}_L\,\phi\, e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)(\bar{q}_L\,\tilde{\phi}\, u_R)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\bar{q}_L\,\phi\, d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\, W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\, \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\, W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\, \widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\, G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\, \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\, W^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_{W}$	$\varepsilon_{abc}\, \widetilde{W}^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\, G^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_{G}$	$f_{ABC}\, \widetilde{G}^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{G}}$

CP-even dim 6 ops. interfering with SM

EWPO **EW diboson** **Higgs** **Top (Had. Coll., Lept. Coll.)**

Slide from J. de Blas at Seattle Snowmass Summer Study

Effective couplings

- For the Higgs and EW fit the results are shown in terms of effective couplings

- Higgs effective couplings:

$$ {g_{HX}^{\rm eff}}^2 \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\rm SM}} $$

- Electroweak effective couplings

$$ \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}(|g_{Zee,L}^{\rm eff}|^2 + |g_{Zee,R}^{\rm eff}|^2), \quad A_e = \frac{|g_{Zee,L}^{\rm eff}|^2 - |g_{Zee,R}^{\rm eff}|^2}{|g_{Zee,L}^{\rm eff}|^2 + |g_{Zee,R}^{\rm eff}|^2} $$

- To further connect with diboson processes the following aTGC are also used

$$ \delta g_{1,Z}, \quad \delta\kappa_\gamma, \quad \lambda_Z $$

Observables for Higgs + EW fits: current data sets

- **Electroweak Precision Measurements:** Pseudo-observables measured on the Z resonance by LEP and SLD and W-boson measurements from Tevatron and LHC $\{m_Z, \Gamma_Z, A_f, R_f, m_W, \Gamma_W\}$

- **Higgs Measurements:** Inclusive $\sigma \cdot Br$ ratios, differential distributions and STXS

- **Diboson Measurements:** *WW* diboson production cross-section inherited from LEP. *WW* and *WZ* differential cross-section measurements at LHC

What do we expect for the future?

Machine	**Pol. (e^-, e^+)**	**Energy**	**Luminosity**
HL-LHC	Unpolarised	14 TeV	3 ab^{-1}
ILC	($\mp$80%, $\pm$30%)	250 GeV	2 ab^{-1}
		350 GeV	0.2 ab^{-1}
		500 GeV	4 ab^{-1}
	($\mp$80%, $\pm$20%)	1 TeV	8 ab^{-1}
CLIC	($\pm$80%, 0%)	380 GeV	1 ab^{-1}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC-*ee*	Unpolarised	Z-pole	150 ab^{-1}
		$2m_W$	10 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		365 GeV	1.5 ab^{-1}
CEPC	Unpolarised	Z-pole	100 ab^{-1}
		$2m_W$	6 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}
MuC	Unpolarised	125 GeV	0.02 ab^{-1}
		3 TeV	3 ab^{-1}
		10 TeV	10 ab^{-1}

Observables for Higgs + EW fits: future data sets

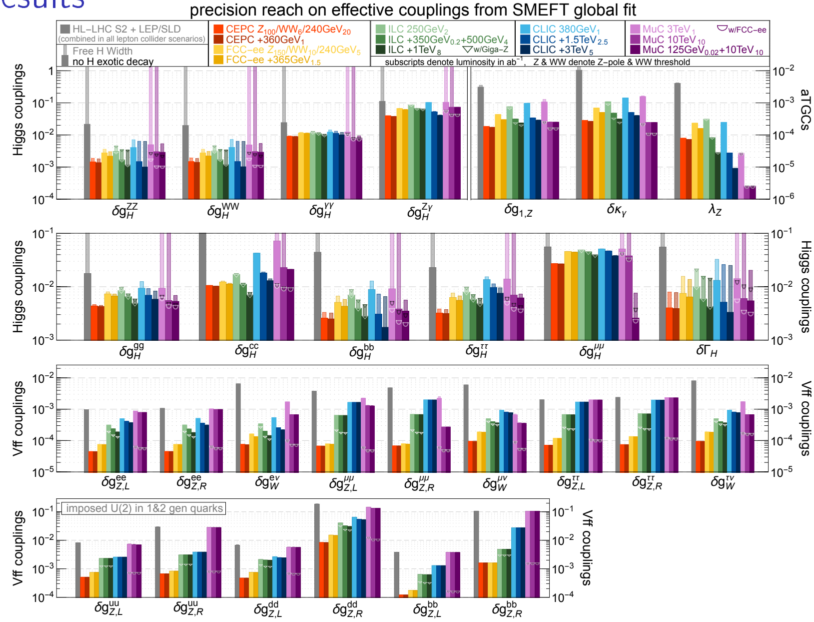
- **Higgs rates:**
  - $\sigma \cdot Br$ ratios for numerous production and decay channels (where HL-LHC have been combined with future lepton colliders)
  - Inclusive production cross section measurement for $e^+e^- \to ZH$ at future lepton colliders

- **Electroweak precision observables:** Current measurements have been combined with future colliders (dedicated Z-pole run and radiative return at 250 and 380 GeV)

- **Diboson measurements:**
  - For HL-LHC we use the results from [Grojean, Montull, Riembau, 1810.05149]
  - Optimal observables analysis for lepton colliders for $e^+e^- \to W^+W^-$

- **High energy muon collider measurements:** Only the process $\gamma\gamma \to W^+W^-$ for the measurements of the W branching fraction has been included

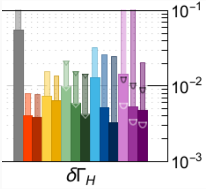
Results



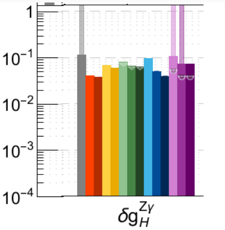
precision reach on effective couplings from SMEFT global fit
HL−LHC S2 + LEP/SLD
(combined in all lepton collider scenarios)
Free H Width
no H exotic decay
CEPC Z100/WW6/240GeV20
CEPC +360GeV1
FCC−ee Z150/WW10/240GeV5
FCC−ee +365GeV1.5
ILC 250GeV2
ILC +350GeV0.2+500GeV4
ILC +1TeV8
w/Giga−Z
CLIC 380GeV1
CLIC +1.5TeV2.5
CLIC +3TeV5
MuC 3TeV1
MuC 10TeV10
MuC 125GeV0.02+10TeV10
w/FCC−ee
subscripts denote luminosity in ab−1, Z & WW denote Z−pole & WW threshold
Higgs couplings
aTGCs
Vff couplings
imposed U(2) in 1&2 gen quarks

Results: Highlights

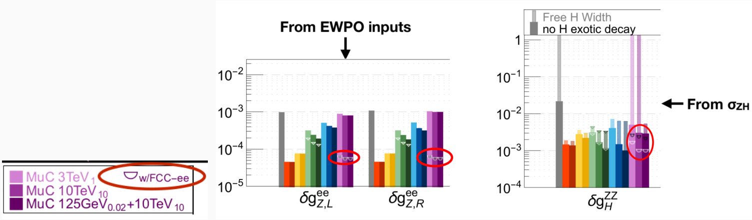
A low energy run accessing $e^+e^- \to HZ$ becomes highly relevant to measure Γ_H



HL-LHC dominates the constraints on rare decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)



There is an excellent complementarity between e^+e^- and $\mu^+\mu^-$ colliders



Summary

- Future lepton colliders can advance significantly our understanding of the properties of various SM particles
- Future e^+e^--machines improve the precision of Higgs measurements (a factor of 2-10) and can test Γ_H as a free parameter
- Muon colliders can offer comparable precision in the cases where, either Γ_H is fixed or the 125 GeV run is combined
- Electroweak effective couplings for W and Z can be improved by a few orders of magnitude at future e^+e^- colliders over what we know of today
- There are important synergies between EWPOs and direct Higgs obs.

Thanks for your attention!

Back up

Effective Lagrangian in the mass eigenstate basis

- **Higgs couplings to vector bosons:**

$$\Delta\mathscr{L}_6^{\mathrm{hVV}} = \frac{h}{v}\left[2\delta c_W\, m_W^2 W_\mu^+ W^{-\mu} + \delta c_Z\, m_Z^2 Z_\mu Z^\mu + c_{WW}\,\frac{g^2}{2} W_{\mu\nu}^+ W^{-\mu\nu}\right.$$

$$+ c_{W\Box}\, g^2 \left(W^{-\mu}\partial^\nu W_{\mu\nu}^+ + \mathrm{h.c.}\right) + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^A G^{A\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}A^{\mu\nu}$$

$$+ c_{Z\gamma}\frac{e\sqrt{g^2+g'^{\,2}}}{2} Z_{\mu\nu}A^{\mu\nu} + c_{ZZ}\,\frac{g^2+g'^{\,2}}{4} Z_{\mu\nu}Z^{\mu\nu}$$

$$\left. + c_{Z\Box}\, g^2 Z^\mu \partial^\nu Z_{\mu\nu} + c_{\gamma\Box}\, g g' Z^\mu \partial^\nu A_{\mu\nu}\right]$$

- **Trilinear Gauge Couplings:**

$$\Delta\mathscr{L}^{\mathrm{aTGC}} = ie\delta\kappa_\gamma A^{\mu\nu} W_\mu^+ W_\nu^- + ig\cos\theta_w\left[\delta g_{1,Z}\left(W_{\mu\nu}^+ W^{-\mu} - W_{\mu\nu}^- W^{+\mu}\right)Z^\nu\right.$$

$$\left. + \left(\delta g_{1,Z} - \frac{g'^{\,2}}{g^2}\delta\kappa_\gamma\right) Z^{\mu\nu} W_\mu^+ W_\nu^-\right] + \frac{ig\lambda_Z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu} W_\nu^{-\rho} A_\rho^\mu + \cos\theta_w W_\mu^{+\nu} W_\nu^{-\rho} Z_\rho^\mu\right)$$

- **Only 7 d.o.f.**

Effective Lagrangian in the mass eigenstate basis

- **Yukawa couplings:**

$$\Delta\mathscr{L}_6^{\rm hff} = -\frac{h}{v}\sum_{f\in u,d,e}\hat{\delta}y_f\, m_f \bar{f} f + \text{h.c.},$$

usually NP at Yukawas assumed to be diagonal

- **Vector couplings to fermions:**

$$\Delta\mathscr{L}_6^{\rm Vff,hVff} = \frac{g}{\sqrt{2}}\left(1+2\frac{h}{v}\right)W_\mu^+\left(\hat{\Delta}g_W^\ell \bar{\nu}_L\gamma^\mu e_L + \hat{\Delta}g_{W,L}^q \bar{u}_L\gamma^\mu d_L + \hat{\Delta}g_{W,R}^q \bar{u}_R\gamma^\mu d_R + \text{h.c.}\right)$$
$$+\sqrt{g^2+g'^{\,2}}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}\hat{\Delta}g_{Z,L}^f \bar{f}_L\gamma^\mu f_L + \sum_{f=u,d,e}\hat{\Delta}g_{Z,R}^f \bar{f}_R\gamma^\mu f_R\right]$$

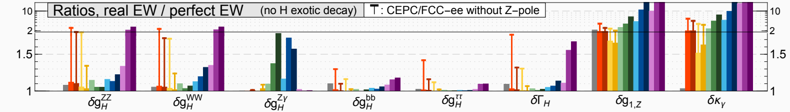
Not all terms are independent. Furthermore, usually the couplings are assumed to be diagonal and a $U(2)$ symmetry is imposed for the first two quark generations

Assumptions

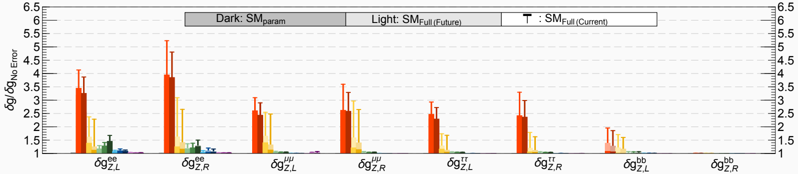
- The effect of 4-fermion operators is mostly negligible in the observables included here (except the 4-lepton operator affecting G_F)
- CP-conservation in the NP effects is also assumed
- The effects of the dipole operators will be neglected
- A $U(2)$ symmetry is imposed in the first two generations quarks for the gauge couplings
- Higgs couplings are assumed to be diagonal but independent for different fermion families
- Two scenarios for the Higgs decay are shown:
  1. The Higgs is assumed to decay only to SM particles
  2. The Higgs width is considered as a free parameter

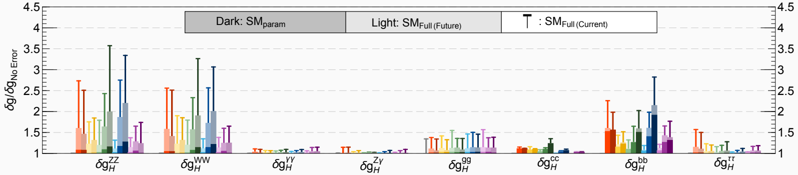
Results: Impact of uncertainties

Impact of EW uncertainties in Higgs and aTG couplings



Impact of theoretical uncertainties in the fit





Results: what about top-quark Yukawa (from top-quark sector fit)?

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.20	3.70	2.82	2.34	1.41	2.56

- Since the sensitivity at ILC500 is worse than in HL-LHC there is no a huge improvement for the individual constraint
- For the global fit the improvement is relevant even for ILC500, thanks to constraining the Yukawa from an additional observable
- Increasing the energy by 50 GeV provides an important improvement in the constraints thanks to the growth in the cross section
- Similar results are found for CLIC
- A reduction higher than a factor of 3 on the uncertainty would be obtain at the final stage of ILC w.r.t. the HL-LHC