Overview of the Snowmass SMEFT fit results

First ECFA workshop on e^+e^- Higgs/EW/Top Factories

Hamburg, 5th October 2022

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More details in [2206.08326]

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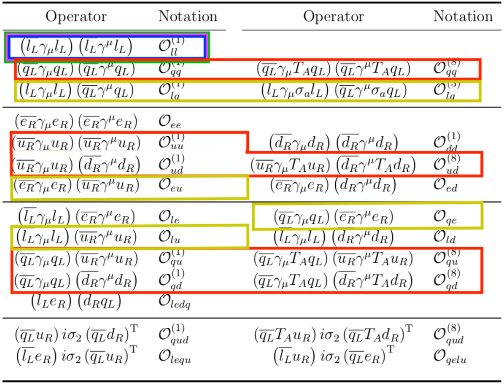
Introduction

- The SM although being extremely successful does not provide a completely satisfactory description of Nature
- Given the immense number of possibilities of extending the SM, it is specially interesting to analyse the NP in a "model agnostic" way
- The SMEFT provides such a framework although constraining all the operators already at d6 at the same time is not currently possible
- The current available data and the data coming from possible future colliders will be used
- In this work we will show the results of fits on different sectors of the SMEFT
    1. Fit on electroweak and higgs sector
    2. Fit on electroweak sector and 4-fermion operators
    3. Fit on bosonic CPV operators
    4. Fit on on top-quark sector

Higgs + EW fit including helicity conserving 4-fermion operators (M. Peskin's talk): Fixing the SMEFT Lagrangian with data from e^+e^- Higgs factories

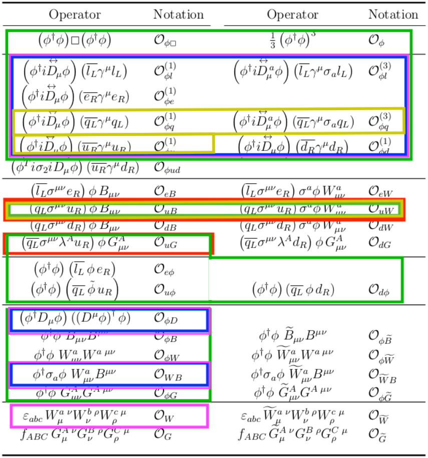
SMEFT operators in the Warsow basis



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

CP-even dim 6 ops. interfering with SM

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



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

Slide from J. de Blas at Seattle Snowmass Summer Study

Future Facilities Considered

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}

Comparison with European Strategy Update (ESU)

- All the data from the ESU has been updated
- In the diboson channels a new parameterisation including all relevant SMEFT coefficients has been used [Grojean, Montull, Riembau, 1810.05149] [de Blas, Durieux, Grojean, Gu, Paul, 1907.04311]
- The impact of building a future muon collider has been studied
- A new comprehensive fit is performed focusing on 4-fermion interactions at future colliders
- The impact of the future lepton colliders in constraining the bosonic CPV operators has been studied
- Top-quark sector is studied in a dedicated fit

Fits on electroweak and Higgs sector

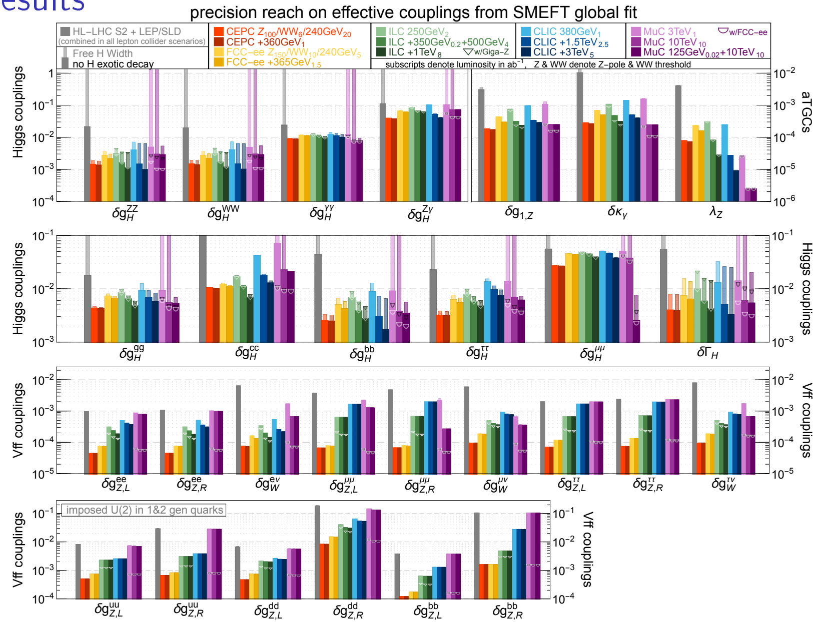
Observables included

- **Higgs rates:** The results from future colliders have been combined with HL-LHC
- **Electroweak precision observables:** Current measurements have been combined with future colliders
- **Diboson measurements:** Optimal observables analysis for lepton colliders. HL-LHC obtained from [Grojean, Montull, Riembau, 1810.05149]
- **High energy muon collider measurements:** Only the process $\gamma\gamma \to W^+W^-$ for the measurements of the W branching fraction has been included

Assumptions

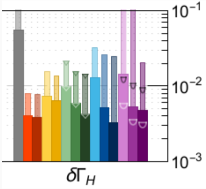
- The effect of 4-fermion operators is mostly negligible in the observables included here (except the 4-lepton operator affecting G_F) and will only be considered in a different fit
- For this sector CP-conservation in the NP effects is also assumed
- The effects of the dipole operators will be considered only in the fit of the top-quark sector
- A $U(2)$ symmetry is imposed in the first two generations quarks for the gauge couplings → Working in relaxing this assumption! [Bresó-Pla, Falkowski, González-Alonso, 2103.12074]
- 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

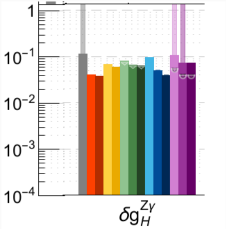

precision reach on effective couplings from SMEFT global fit
▨ HL−LHC S2 + LEP/SLD
(combined in all lepton collider scenarios)
Free H Width
no H exotic decay
CEPC Z_{100}/WW_6/$240GeV_{20}$
CEPC $+360GeV_1$
FCC−ee Z_{150}/WW_{10}/$240GeV_5$
FCC−ee $+365GeV_{1.5}$
ILC $250GeV_2$
ILC $+350GeV_{0.2}$+$500GeV_4$
ILC $+1TeV_8$
▽w/Giga−Z
CLIC $380GeV_1$
CLIC $+1.5TeV_{2.5}$
CLIC $+3TeV_5$
MuC $3TeV_1$
MuC $10TeV_{10}$
MuC $125GeV_{0.02}$+$10TeV_{10}$
w/FCC−ee
subscripts denote luminosity in ab^{-1}, Z & WW denote Z−pole & WW threshold
Higgs couplings
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
δg_H^{ZZ}
δg_H^{WW}
$\delta g_H^{\gamma\gamma}$
$\delta g_H^{Z\gamma}$
$\delta g_{1,Z}$
$\delta \kappa_\gamma$
λ_Z
aTGCs
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Higgs couplings
10^{-1}
10^{-2}
10^{-3}
δg_H^{gg}
δg_H^{cc}
δg_H^{bb}
$\delta g_H^{\tau\tau}$
$\delta g_H^{\mu\mu}$
$\delta \Gamma_H$
Higgs couplings
10^{-1}
10^{-2}
10^{-3}
Vff couplings
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\delta g_{Z,L}^{ee}$
$\delta g_{Z,R}^{ee}$
$\delta g_W^{e\nu}$
$\delta g_{Z,L}^{\mu\mu}$
$\delta g_{Z,R}^{\mu\mu}$
$\delta g_W^{\mu\nu}$
$\delta g_{Z,L}^{\tau\tau}$
$\delta g_{Z,R}^{\tau\tau}$
$\delta g_W^{\tau\nu}$
Vff couplings
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Vff couplings
imposed U(2) in 1&2 gen quarks
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\delta g_{Z,L}^{uu}$
$\delta g_{Z,R}^{uu}$
$\delta g_{Z,L}^{dd}$
$\delta g_{Z,R}^{dd}$
$\delta g_{Z,L}^{bb}$
$\delta g_{Z,R}^{bb}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Vff couplings

Results: Highlights

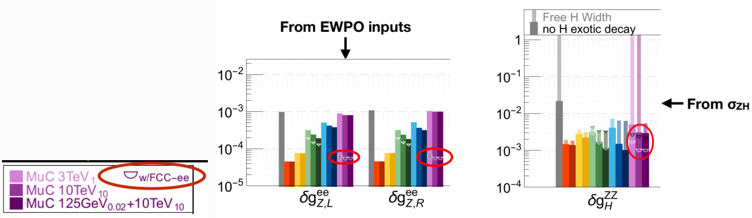
A low energy run accessing $e^+e^- \to HZ$ becomes highly relevant to measure Γ_H



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

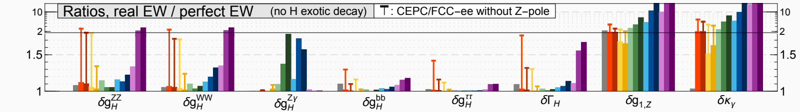


There is an excellent complementarity between e^+e^- and $\mu^+\mu^-$ colliders

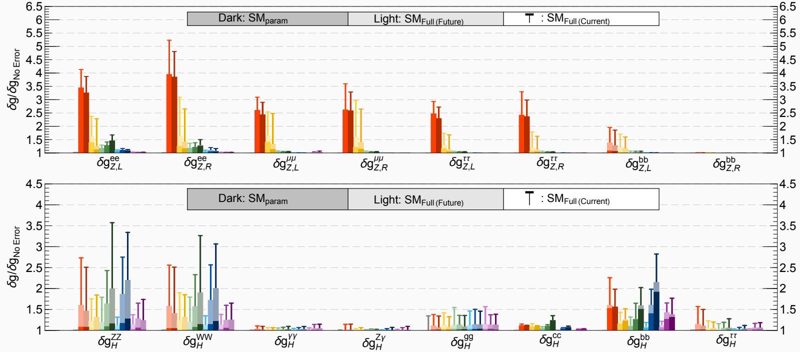


Results: Impact of uncertainties

Impact of EW uncertainties in Higgs and aTG couplings



Impact of theoretical uncertainties in the fit



Fits on electroweak sector and 4-fermion operators

Observables included

- **Z- and W-pole observables:** Sensitive to the electroweak vertex corrections.
  1. Z-pole observables from LEP-1, A_s from SLD, and R_{uc}
  2. W-pole, LEP-2 data for leptonic branching ratios, R_{Wc}, and R_σ

- **High-energy observables for 4-fermion operators:** LEP-2 data included. Production cross section and A_{FB} for $\mu^+\mu^-$, $\tau^+\tau^-$ and quark final states and, in addition, differential cross section for e^+e^- final state.

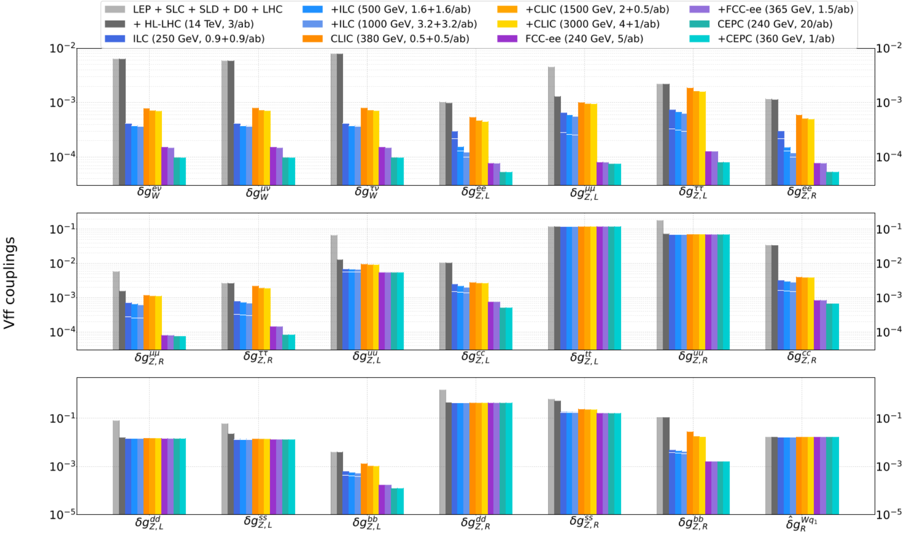
- **Low-energy precision observables:** To include these observables a matching with the LEFT must be done with the appropriate running, which is specially relevant for $2\ell 2q$ type operators

Full list of observables in the backup slides

Assumptions

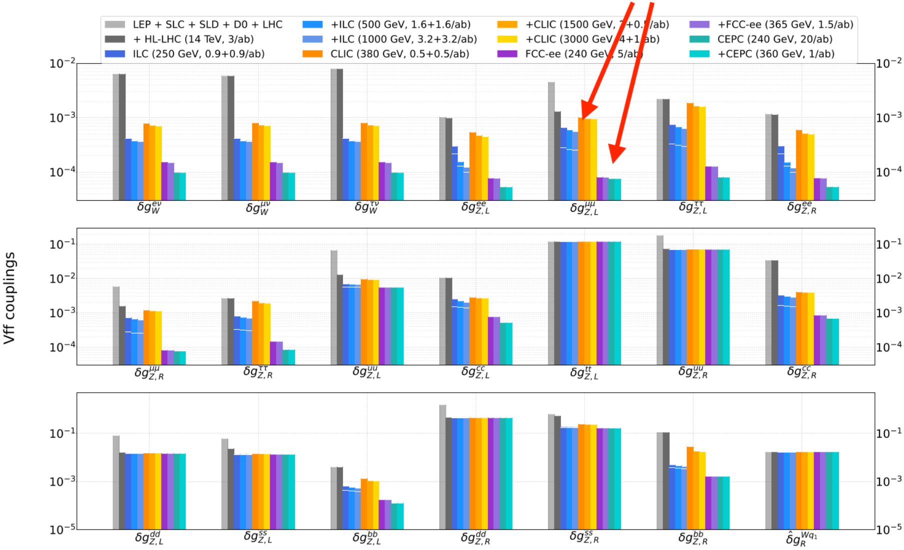
- No flavour symmetries imposed in the EW part (contrary as before)
- Only considered flavour conserving 4-fermion operators
- It is not possible to completely close the fit and several flat directions emerge:
  1. **Flat[top]**: Since LEP was run below the top-pair threshold a flat direction in the third family of $2\ell 2q$ type operators appears
  2. **Flat[strange]**($\times 3$): The σ and A_{FB} is available for $c\bar{c}$ but not for $s\bar{s}$ generating flat directions in the second family of $2\ell 2q$
  3. **Flat[parity]**($\times 5$): The $(e\gamma_\mu\gamma_5 e)(q_1\gamma_\mu\gamma_5 q_1)$ and $(\nu_L\gamma_\mu\nu_L)(q_1\gamma_\mu\gamma_5 q_1)$ operators remain unconstrained at the low-energy parity-violating scattering experiments or LEP
  4. **Flat[SPS]**: The muon scattering off the Carbon target at CERN SPS is insufficient to disentangle the contributions from $\mathscr{O}_{eq,eu,ed}$
  5. **Flat[trident]**: The trident process is the only low-energy channel sensitive to the four-muon operators $\mathscr{O}_{\ell\ell,\ell e}$
  6. **Flat[flavour]**: The $\pi_{\mu 2}$ decay rate only provides one constraint on $\varepsilon_P^{d\mu}$ (which depends on $\mathscr{O}_{ledq}$ and $\mathscr{O}_{lequ}$) from the flavor observable R_π

Results for Vff couplings



Results for Vff couplings

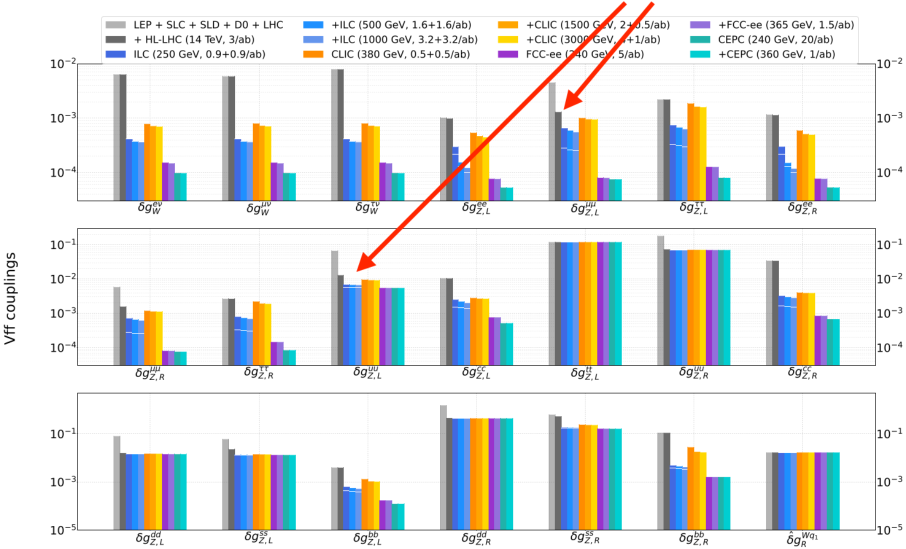
Luminosity wins (through radiative return)



Slide from Y. Du at Seattle Snowmass Summer Study

Results for Vff couplings

D0 + A_{FB} at the (HL-)LHC relaxes the U2 assumption & improve the fit



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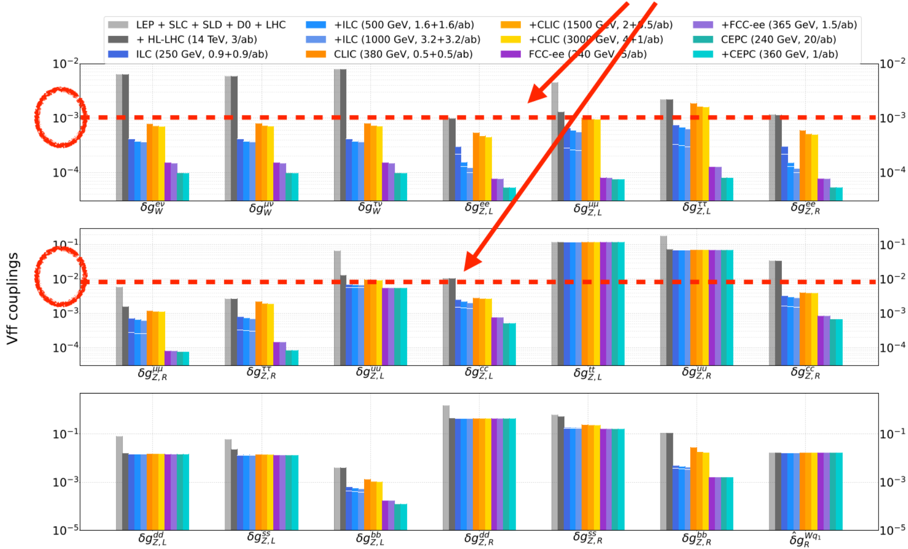
Results for Vff couplings

$\mathcal{O}(10)$ weaker: Limited by the missing projections of R_{uc}, A_{FB}^{ss}, σ^{ss}



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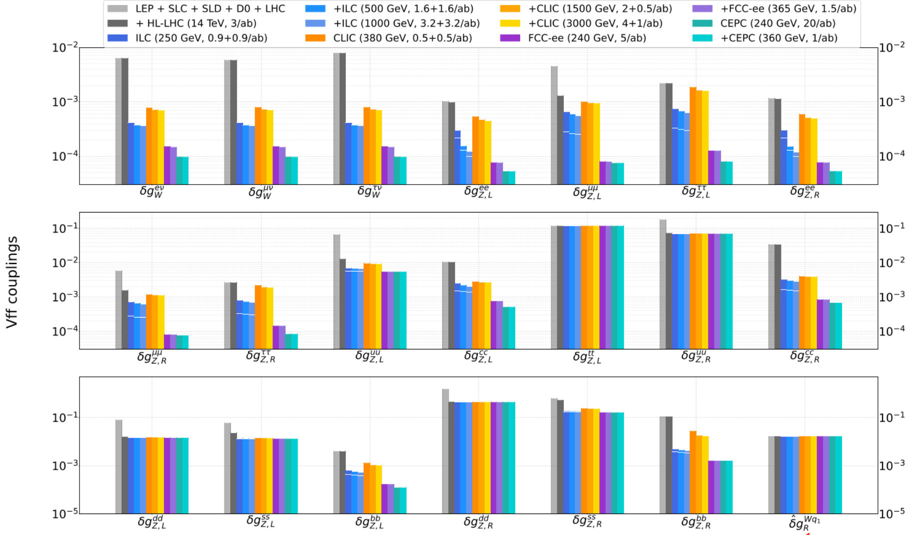
Results for Vff couplings



CKM unitarity test

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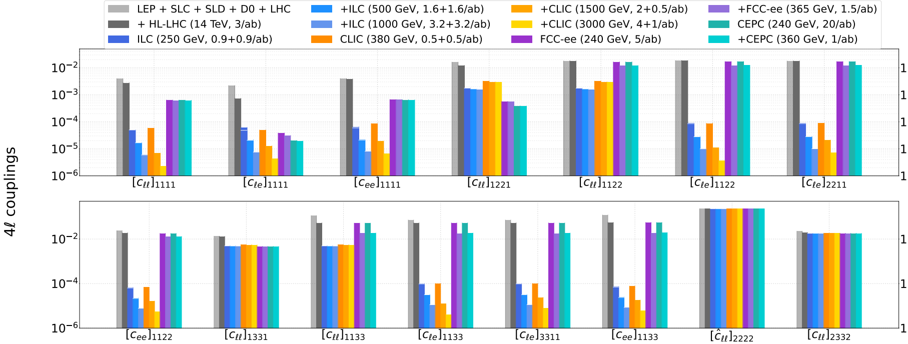
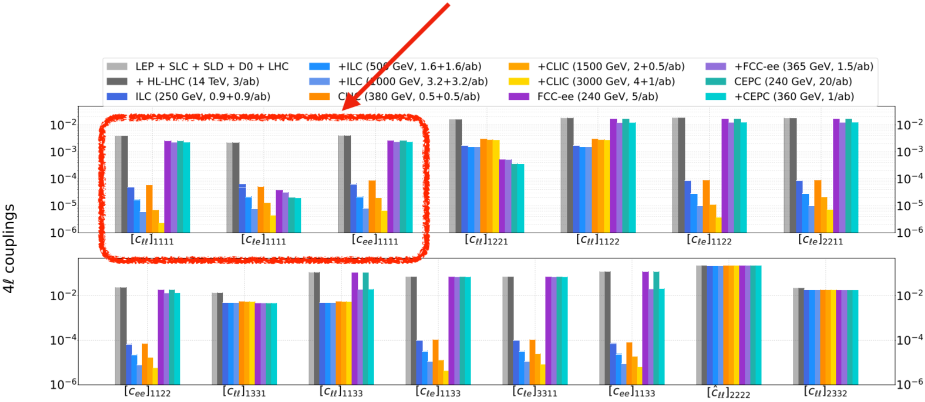
Results for 4ℓ couplings



Results for 4ℓ couplings

Beam polarization is the key in beating the (HL-)LHC and also circular colliders



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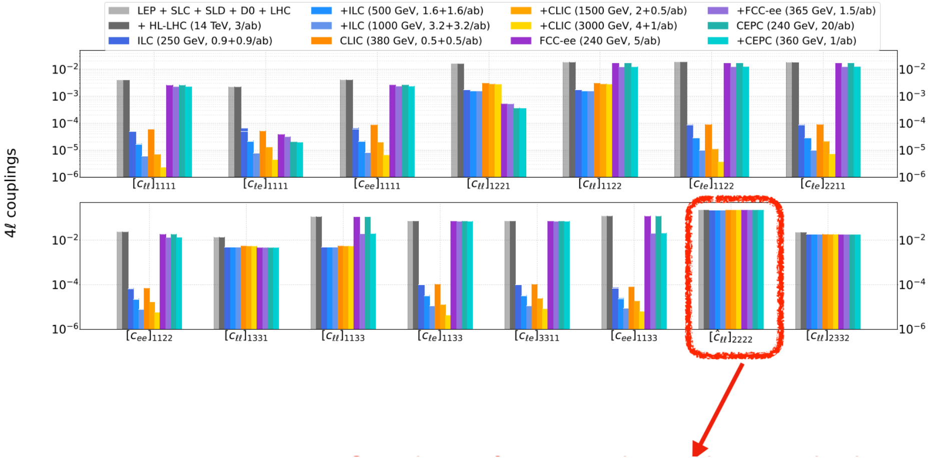
Results for 4ℓ couplings



One input from neutrino trident production at CCFR. Muon colliders/FASERν could play the role of lifting this flat direction

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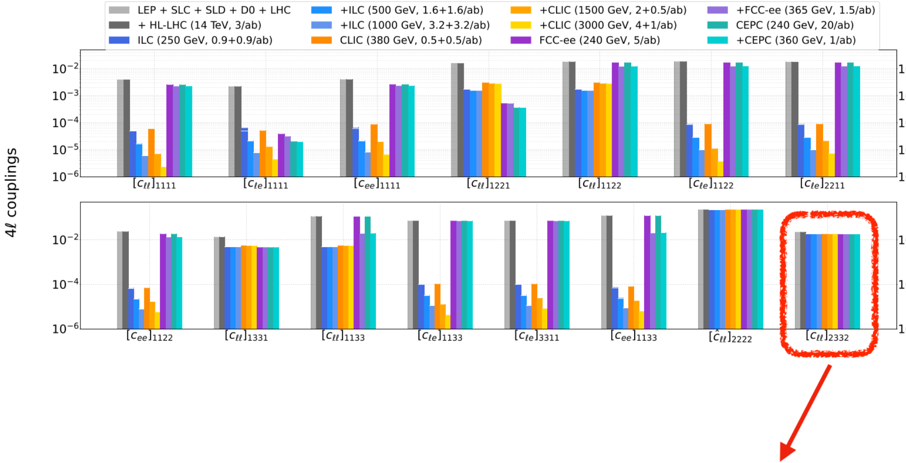
Results for 4ℓ couplings



Limited by leptonic τ decay, but is the only one sensitive to this operator. A muon collider also helps

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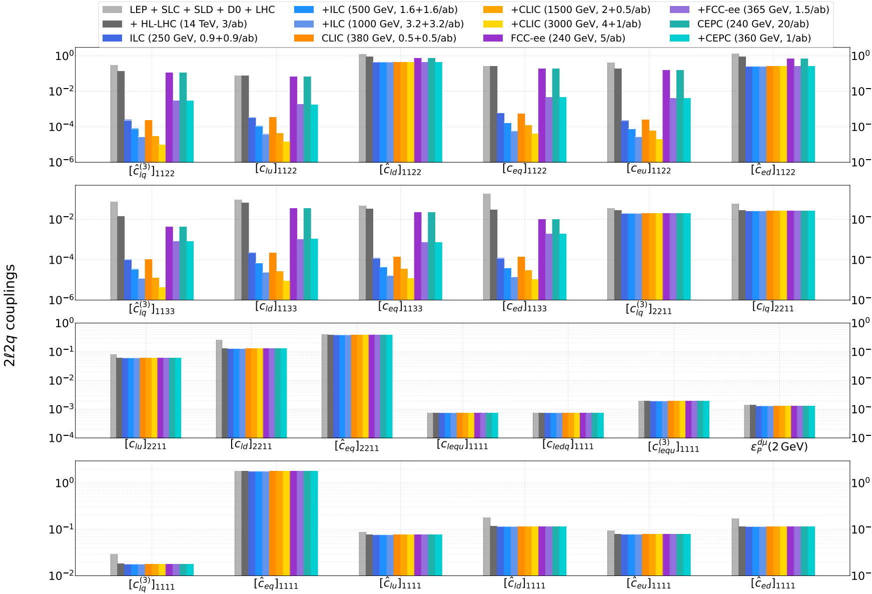
Results for $2\ell2q$ couplings



Fits on bosonic CPV operators

Operators and observables

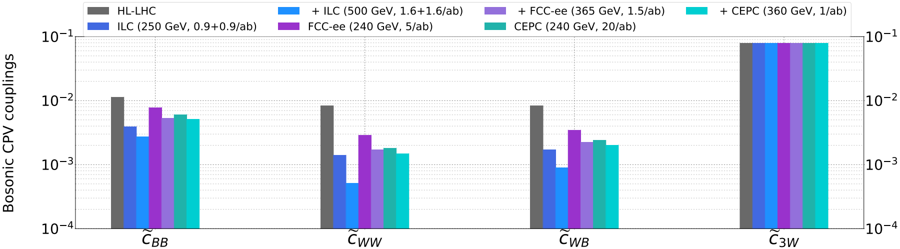
$$\mathcal{O}_{\widetilde{G}} = f^{ABC}\widetilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho} \qquad \mathcal{O}_{\varphi\widetilde{G}} = \varphi^\dagger\varphi\widetilde{G}^{A}_{\mu\nu}G^{A\mu\nu} \qquad \mathcal{O}_{\varphi\widetilde{W}} = \varphi^\dagger\varphi\widetilde{W}^{I}_{\mu\nu}W^{I\mu\nu}$$

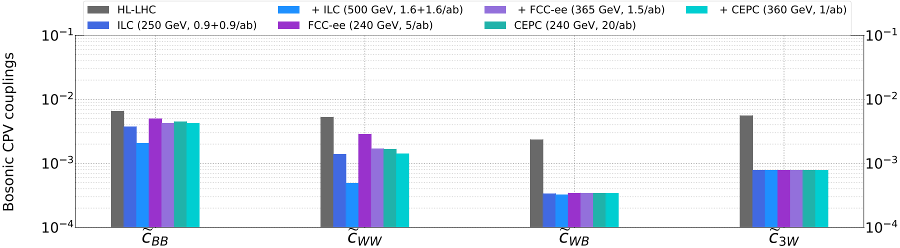
$$\mathcal{O}_{\varphi\widetilde{B}} = \varphi^\dagger\varphi\widetilde{B}_{\mu\nu}B^{\mu\nu} \qquad \mathcal{O}_{\varphi\widetilde{W}B} = \varphi^\dagger\tau^I\varphi\widetilde{W}^{I}_{\mu\nu}B^{\mu\nu} \qquad \mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$$

- $\mathcal{O}_{\widetilde{G}}$ and $\mathcal{O}_{\varphi\widetilde{G}}$ will not be included in the fit → strongly constraint from neutron and diamagnetic atoms EDMs
- The OPAL measurements of $e^+e^- \to W^+W^-$ constrains the aTGCs $\mathcal{O}_{\varphi\widetilde{W}B}$ and $\mathcal{O}_{\widetilde{W}}$ → Although weak are essential to lift flat directions
- Stringent bounds can be obtained from the angular distribution of $h \to 4\ell$
- In future lepton colliders important constraints (on $\mathcal{O}_{\varphi\widetilde{W}}$, $\mathcal{O}_{\varphi\widetilde{B}}$ and $\mathcal{O}_{\varphi\widetilde{W}B}$) are obtained from the angular asymmetries $A^{(1)}_{\phi}$ and $A^{(2)}_{\phi}$ on $e^+e^- \to ZH$ production

Results

The bottom plot comes from assuming that the OPAL precision on aTGCs is improved by a factor of 10 (100) for HL-LHC (future colliders)

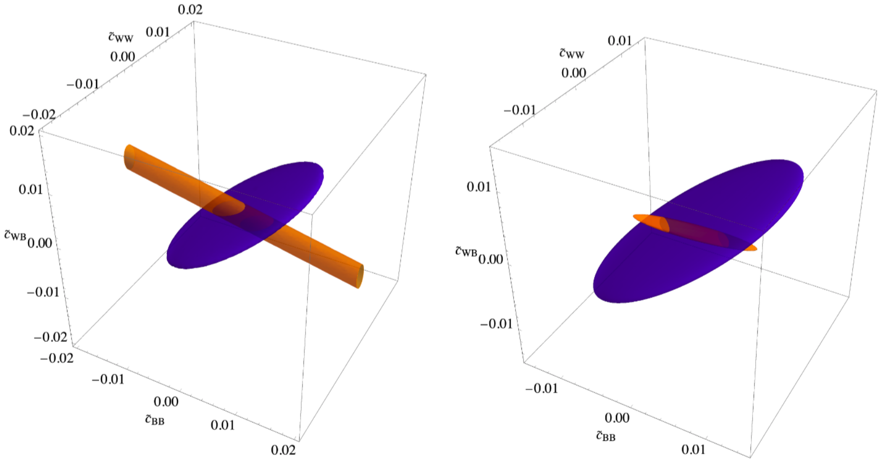




Results: Complementarity HL-LHC/Future e^+e^-

Blue → HL-LHC // Orange → ILC250

Left→ current fit // Right → Assuming OPAL precision on aTGCs is improved by a factor of 10 (100) for HL-LHC (future colliders)



Fits on top-quark sector

All the details in [2205.02140] and my previous talk:
Prospects for the measurement of top-quark couplings

Observables

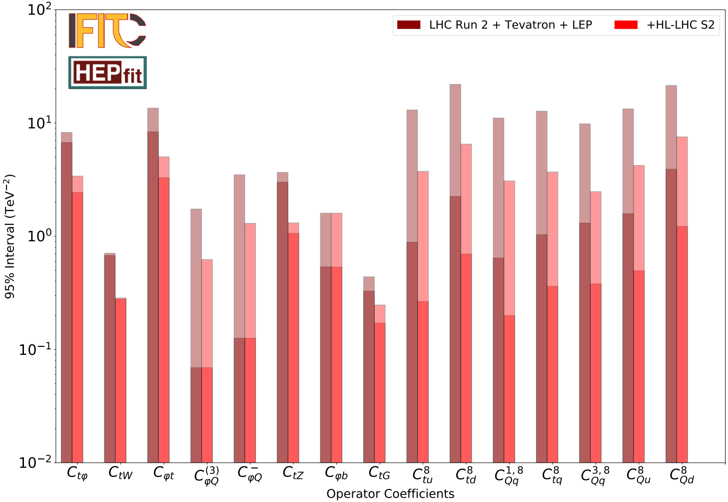
- Pair production of top quarks and in association with SM bosons at LHC
- Single top-quark production at LHC and Tevatron
- Single top-quark production in association with electroweak bosons at LHC
- W boson helicity fractions from top-quark decay at LHC
- R_b and A_{FBLR}^{bb} at LEP and future lepton colliders
- Optimal observables that maximally exploit the information in the fully differential $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ distribution at future lepton colliders [G. Durieux, M. Perelló, M. Vos, C. Zhang 1807.02121]
- Inclusive cross section of $e^+e^- \to t\bar{t}H$ at future lepton colliders

Assumptions

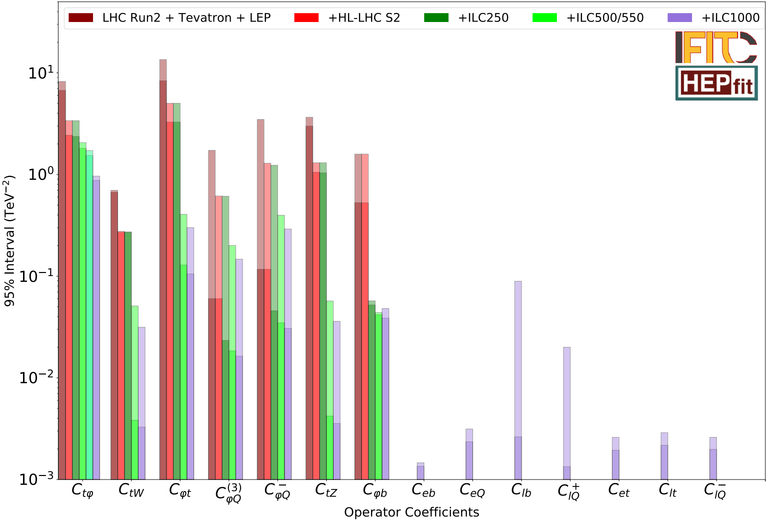
- We will only consider here the operators that affect the top quark and those that affect the bottom quark and enter in the same processes
- CP-conservation in the NP effects is assumed for this part of the fit
- A $U(2)$ symmetry is imposed for the first two generations of quarks
- We will only consider the linear terms of the dimension six operators
- The results will be presented in terms of the Wilson coefficients of the SMEFT

Results at HL-LHC

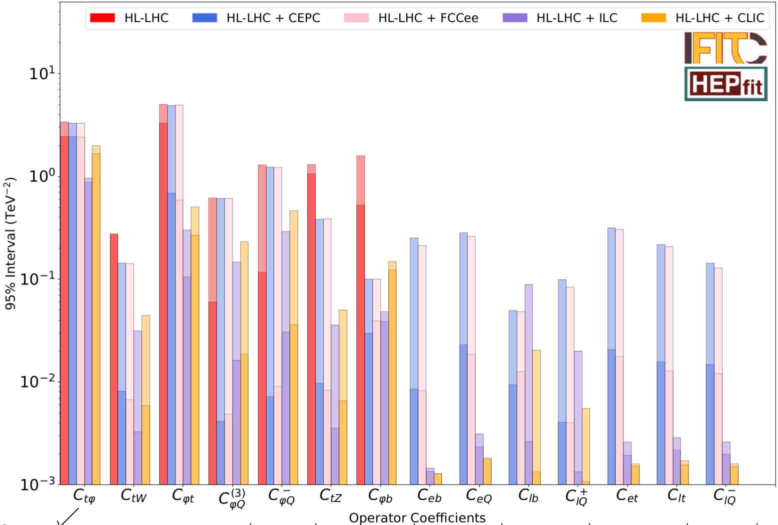
Shadowed (solid) bars →marginalised from global (individual) fit



Results at different energies of a future lepton collider



Results at future lepton colliders



$$\delta y_t = -\frac{C_{t\varphi}}{2}\frac{v^2}{\Lambda^2}$$

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	6.12	2.53	1.57	1.30	0.739	1.48
	Indiv. fit	5.08	1.85	1.41	1.17	0.705	1.26

Summary

- We performed a few global SMEFT fits with a well defined subset of dimension-6 operators in the Warsaw basis
- 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.
- The 4-fermion interactions the reaches are significantly better at linear e^+e^- than circular
- There are important synergies with low-energy measurements without which certain degeneracies can not be lift
- The degeneracies in *eett* contact interactions can not be lift without running at two different energies well above *tt*-threshold
- Many top-quark measurements at (HL-)LHC are helpful in the global fit for improving the precision of top-quark EW couplings

Thanks for your attention!

and special thanks to the other members of the team!

Back up

Effective couplings

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

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

- Electroweak effective couplings

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

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

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

Z-(W-)pole obs. used in the EW + 4-fermion fit

Observable	Experimental value	SM prediction
Γ_Z [GeV]	2.4952 ± 0.0023	2.4950
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037	41.484
R_e	20.804 ± 0.050	20.743
R_μ	20.785 ± 0.033	20.743
R_τ	20.764 ± 0.045	20.743
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025	0.0163
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013	0.0163
$A_{\rm FB}^{0,\tau}$	0.0188 ± 0.0017	0.0163
R_b	0.21629 ± 0.00066	0.21578
R_c	0.1721 ± 0.0030	0.17226
$A_b^{\rm FB}$	0.0992 ± 0.0016	0.1032
$A_c^{\rm FB}$	0.0707 ± 0.0035	0.0738
A_e	0.1516 ± 0.0021	0.1472
A_μ	0.142 ± 0.015	0.1472
A_τ	0.136 ± 0.015	0.1472
A_e	0.1498 ± 0.0049	0.1472
A_τ	0.1439 ± 0.0043	0.1472
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_s	0.895 ± 0.091	0.935
R_{uc}	0.166 ± 0.009	0.1724
m_W [GeV]	80.385 ± 0.015	80.364
Γ_W [GeV]	2.085 ± 0.042	2.091
${\rm Br}(W \to e\nu)$	0.1071 ± 0.0016	0.1083
${\rm Br}(W \to \mu\nu)$	0.1063 ± 0.0015	0.1083
${\rm Br}(W \to \tau\nu)$	0.1138 ± 0.0021	0.1083
R_{Wc}	0.49 ± 0.04	0.50
R_σ	0.998 ± 0.041	1.000

High-energy 4-fermion obs. used in the EW + 4-fermion fit

Observable	Experimental value
$\sigma(\mu^+\mu^-)$	$f(s)$
$\sigma(\tau^+\tau^-)$	$f(s)$
$\sum_{q\neq t} \sigma(q\bar{q})$	$f(s)$
$\sigma(b\bar{b})$	$f(s)$
$\sigma(c\bar{c})$	$f(s)$
$\frac{\sigma_{\text{FB}}(b\bar{b})}{\sum_{q\neq t} \sigma(q\bar{q})}$	$f(s)$
$\frac{\sigma_{\text{FB}}(c\bar{c})}{\sum_{q\neq t} \sigma(q\bar{q})}$	$f(s)$
$A_{\text{FB}}(\mu^+\mu^-)$	$f(s)$
$A_{\text{FB}}(\tau^+\tau^-)$	$f(s)$
$\frac{d\sigma}{d\cos\theta}(\text{Bhabha})$	$f(s,\cos\theta)$

Low-energy 4-fermion obs. used in the EW + 4-fermion fit

Process	Observable	Experimental value	Ref.	SM prediction
$\overset{(-)}{\nu}_\mu - e^-$ scattering	$g_{LV}^{\nu_\mu e}$ $g_{LA}^{\nu_\mu e}$	-0.035 ± 0.017 -0.503 ± 0.017	CHARM-II	-0.0396 -0.5064
τ decay	$\frac{G_{\tau e}^2}{G_F^2}$ $\frac{G_{\tau\mu}^2}{G_F^2}$	1.0029 ± 0.0046 0.981 ± 0.018	PDG2014	1
Neutrino scattering	R_{ν_μ} $R_{\bar{\nu}_\mu}$	0.3093 ± 0.0031 0.390 ± 0.014	CHARM ($r = 0.456$)	0.3156 0.370
	R_{ν_μ} $R_{\bar{\nu}_\mu}$	0.3072 ± 0.0033 0.382 ± 0.016	CDHS ($r = 0.393$)	0.3091 0.380
	κ	0.5820 ± 0.0041	CCFR	0.5830
	$R_{\nu_e \bar{\nu}_e}$	$0.406^{+0.145}_{-0.135}$	CHARM	0.33
Parity-violating scattering	$(s_w^2)^{\text{Møller}}$	0.2397 ± 0.0013	SLAC-E158	0.2381 ± 0.0006
	$Q_W^{\text{Cs}}(55,78)$	-72.62 ± 0.43	PDG2016	-73.25 ± 0.02
	$Q_W^{\text{p}}(1,0)$	0.064 ± 0.012	QWEAK	0.0708 ± 0.0003
	A_1 A_2	$(-91.1 \pm 4.3) \times 10^{-6}$ $(-160.8 \pm 7.1) \times 10^{-6}$	PVDIS	$(-87.7 \pm 0.7) \times 10^{-6}$ $(-158.9 \pm 1.0) \times 10^{-6}$
	$g_{VA}^{eu} - g_{VA}^{ed}$	-0.042 ± 0.057 -0.12 ± 0.074	SAMPLE ($\sqrt{Q^2} = 200\,\text{MeV}$) SAMPLE ($\sqrt{Q^2} = 125\,\text{MeV}$)	-0.0360 0.0265
	b_{SPS}	$-(1.47 \pm 0.42) \times 10^{-4}\,\text{GeV}^{-2}$ $-(1.74 \pm 0.81) \times 10^{-4}\,\text{GeV}^{-2}$	SPS ($\lambda = 0.81$) SPS ($\lambda = 0.66$)	$-1.56 \times 10^{-4}\,\text{GeV}^{-2}$ $-1.57 \times 10^{-4}\,\text{GeV}^{-2}$
τ polarization	$\mathscr{P}_\tau$ $\mathscr{A}_\mathscr{P}$	0.012 ± 0.058 0.029 ± 0.057	VENUS	0.028 0.021
Neutrino trident production	$\frac{\sigma}{\sigma^{\text{SM}}}(\nu_\mu \gamma^* \to \nu_\mu \mu^+ \mu^-)$	0.82 ± 0.28	CCFR	1
$d_I \to u_J \ell \bar{\nu}_\ell (\gamma)$	$\varepsilon_{L,R,S,P,T}^{de_J}$	See text		0
$e^+e^- \to f\bar{f}$	δA_{LR}^e δA_{LR}^μ δA_{LR}^τ δA_{LR}^c δA_{LR}^b	2.0% 1.5% 2.4% 0.5% 0.4%	SuperKEKB	0.00015 -0.0006 -0.0006 -0.005 -0.020

Wilson coefficients for the 4-fermion operators

$2\ell 2q$ operators $(p,r=1,2,3)$	4ℓ operators $(p<r=1,2,3)$
Chirality conserving	Two flavors
$[\mathcal{O}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell\ell}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_r \bar{\sigma}^\mu \ell_r)$
$[O^{(3)}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \sigma^i \ell_p)(\bar{q}_r \bar{\sigma}^\mu \sigma^i q_r)$	$[\mathcal{O}_{\ell\ell}]_{prrp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_r)(\bar{\ell}_r \bar{\sigma}^\mu \ell_p)$
$[\mathcal{O}_{\ell u}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(u^c_r \sigma^\mu \bar{u}^c_r)$	$[\mathcal{O}_{\ell e}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e^c_r \sigma^\mu \bar{e}^c_r)$
$[\mathcal{O}_{\ell d}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(d^c_r \sigma^\mu \bar{d}^c_r)$	$[\mathcal{O}_{\ell e}]_{rrpp} = (\bar{\ell}_r \bar{\sigma}_\mu \ell_r)(e^c_p \sigma^\mu \bar{e}^c_p)$
$[\mathcal{O}_{eq}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell e}]_{prrp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_r)(e^c_r \sigma^\mu \bar{e}^c_p)$
$[\mathcal{O}_{eu}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(u^c_r \sigma^\mu \bar{u}^c_r)$	$[\mathcal{O}_{ee}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(e^c_r \sigma^\mu \bar{e}^c_r)$
$[\mathcal{O}_{ed}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(d^c_r \sigma^\mu \bar{d}^c_r)$	
Chirality violating	One flavor
$[\mathcal{O}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{e}^c_p)\varepsilon_{jk}(\bar{q}^k_r \bar{u}^c_r)$	$[\mathcal{O}_{\ell\ell}]_{pppp} = \frac{1}{2}(\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_p \bar{\sigma}^\mu \ell_p)$
$[O^{(3)}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{\sigma}_{\mu\nu} \bar{e}^c_p)\varepsilon_{jk}(\bar{q}^k_r \bar{\sigma}_{\mu\nu} \bar{u}^c_r)$	$[\mathcal{O}_{\ell e}]_{pppp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e^c_p \sigma^\mu \bar{e}^c_p)$
$[\mathcal{O}_{\ell edq}]_{pprr} = (\bar{\ell}^j_p \bar{e}^c_p)(d^c_r q^j_r)$	$[\mathcal{O}_{ee}]_{pppp} = \frac{1}{2}(e^c_p \sigma_\mu \bar{e}^c_p)(e^c_p \sigma^\mu \bar{e}^c_p)$

Flat directions in 4-fermion operators

Flat[top]:

$$\left[\hat{c}^{(3)}_{\ell q}\right]_{1133} = \left[c^{(3)}_{\ell q}\right]_{1133} + \left[c_{\ell q}\right]_{1133}$$

Flat[strange]:

$$\left[\hat{c}^{(3)}_{\ell q}\right]_{1122} = \left[c^{(3)}_{\ell q}\right]_{1122} - \left[c_{\ell q}\right]_{1122} ,$$

$$[\hat{c}_{\ell d}]_{1122} = [c_{\ell d}]_{1122} + \left(5 - \frac{3g^2}{g'^2}\right)\left[c_{\ell q}\right]_{1122} - [\hat{c}_{eq}]_{1111} ,$$

$$[\hat{c}_{ed}]_{1122} = [c_{ed}]_{1122} - \left(3 - \frac{3g^2}{g'^2}\right)\left[c_{\ell q}\right]_{1122} - [\hat{c}_{eq}]_{1111}$$

Flat[parity]:

$$[\hat{c}_{eq}]_{1111} = [c_{eq}]_{1111} + \left[c_{\ell q}\right]_{1111} ,$$

$$[\hat{c}_{\ell u}]_{1111} = [c_{\ell u}]_{1111} + \left[c_{\ell q}\right]_{1111} - [\hat{c}_{eq}]_{1111} ,$$

$$[\hat{c}_{\ell d}]_{1111} = [c_{\ell d}]_{1111} + \left[c_{\ell q}\right]_{1111} - [\hat{c}_{eq}]_{1111} ,$$

$$[\hat{c}_{eu}]_{1111} = [c_{eu}]_{1111} - \left[c_{\ell q}\right]_{1111} ,$$

$$[\hat{c}_{ed}]_{1111} = [c_{ed}]_{1111} - \left[c_{\ell q}\right]_{1111}$$

Flat directions in 4-fermion operators

Flat[SPS]:

$$[\hat{c}_{eq}]_{2211} = [c_{eq}]_{2211} + [c_{ed}]_{2211} - 2\,[c_{eu}]_{2211}$$

Flat[trident]:

$$[\hat{c}_{\ell\ell}]_{2222} = [c_{\ell\ell}]_{2222} + \frac{2g'^2}{g^2+3g'^2}\,[c_{\ell e}]_{2222}$$

Flat[flavor]:

$$\varepsilon_P^{d\mu}[2\,\mathrm{GeV}] = 0.86\left[c_{ledq}\right]_{2211} - 0.86\left[c_{lequ}\right]_{2211} + 0.012\left[c_{ledq}^{(3)}\right]_{2211}$$