Global SMEFT limits on future accelerators.

Master Thesis

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Motivation

- Nowadays the Standart Model is in good agreement with experimental data, but we know there must be something else
  - Dark matter composition, matter-antimatter asymmetry origin, neutrino masses origin.
  - Hierarchy problem, the existence of 3 families.
- Furthermore, we have not seen any not predicted particle for decades. In this regard, Effective Field theory seems perfect for parametricing our ignorance.

⬇

$$\mathcal{L}_{\text{EFT}} = \sum_{n=0}^{\infty} \sum_{i=1}^{N_n} \sum_{l=0}^{\infty} \frac{\hbar^l c^{(n,i,l)}}{\Lambda^n} \mathcal{Q}_i(\phi)$$

Future circular collider (FCC) project

- Clean environment for Higgstralung $e^+e^- \to HZ$

- We have worked on the Standard Model Effective Field Theory (SMEFT)

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_Q \tag{1}$$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \dots, \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_i^{(d)}$$

- Specifically we have worked at dimension 6 on the Warsaw basis, the first non redundant basis of the SMEFT.
- We chose to work on the $\{\alpha_{EW},\ m_Z,\ G_F\}$ input scheme, from which we derived numeric expression for the EW coefficients $\{g_1, g_2, v\}$.

I analytically computed corrections to Lagrangian couplings after EWSB and their corresponding Feynman rules (cross-checked with literature) for the following groups:

- Precision observables on the Z pole

$$\{\Gamma_Z,\ \sigma_{had},\ R_e,\ R_\mu,\ R_\tau,\ R_b,\ R_c,\ A_{FB}^e,\ A_{FB}^\mu,\ A_{FB}^\tau,\ A_{FB}^b,\ A_{FB}^c,\ A_e,\ A_\mu,\ A_\tau,\ A_b,\ A_c\}$$

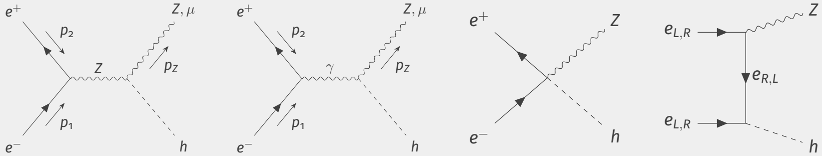
- Precision observables of the W

$$\{m_W,\ \Gamma_W,\ BR_W^{l1},\ BR_W^{l2},\ BR_W^{l3},\ BR_W^{\text{had}}\}$$

- Higgs observables

$$\{\sigma_{eeZh},\ \sigma_{eeZh}^{bb},\ \sigma_{eeZh}^{cc},\ \sigma_{eeZh}^{\tau\tau},\ \sigma_{eeZh}^{\mu\mu},\ \sigma_{eeZh}^{gg},\ \sigma_{eeZh}^{WW},\ \sigma_{eeZh}^{ZZ},\ \sigma_{eeZh}^{Z\gamma},\ \sigma_{eeZh}^{\gamma\gamma}\}$$

All Higgs observables studied began with the production of a Zh, trough $e^+e^- \to Zh$



The Higgs boson will rapidly decay, and we will detect its decay products. But we had the conditions to apply the narrow width approximation, under which

$$\sigma_{tot} = \sigma_{eeZh} \times \text{BR}(h \to \text{fianl state})$$

- **Analitically:** ff, WW, ZZ
- **Using MG5 alongside SMEFTsim:** $Z\gamma$ and ZZ
- **Literature:** $\gamma\gamma$ and gg

To perform the fit between theorital prediction and experimental observables we have used the least squares method. Where we minimiced:

$$\chi^2(\theta) = \sum_{i,j=1}^{N} (y_i - \lambda_i(\theta)) \left(V^{-1}\right)_{ij} \left(y_j - \lambda_j(\theta)\right)$$

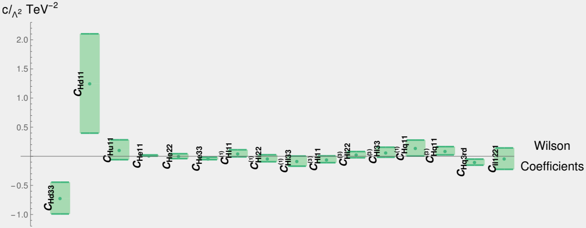
A n-dimensional confidence interval $[\boldsymbol{a}, \boldsymbol{b}]$ for n parameters $\boldsymbol{\theta} = (\theta_1, \ldots, \theta_n)$ its build so if we repeat N times the experimental measurements and the interval calculus, this will contain simultaneously $(1-\gamma)N$ times the true value for all θ_i parameters [**?**].

$$Q(\hat{\boldsymbol{\theta}}, \boldsymbol{\theta}) = \chi^2(\boldsymbol{\theta}) - \chi^2_{min}$$

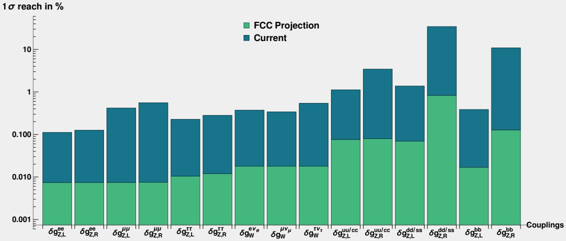
$1-\gamma$	Q_γ				
	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$
0.683	1.00	2.30	3.53	4.72	5.89
0.90	2.71	4.61	6.25	7.78	9.24
0.95	3.84	5.99	7.82	9.49	11.1
0.99	6.63	9.21	11.3	13.3	15.1

Results

- Actual data central value and uncertainties:

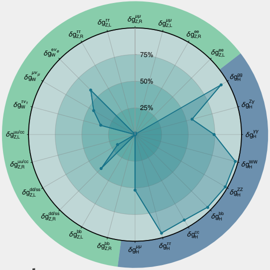


- FCC-ee program relative improvement:



Higgs sector analysis

- We also introduced diBoson data, $e^+e^- \to W^+W^-$, highly complementary to Higgs data.



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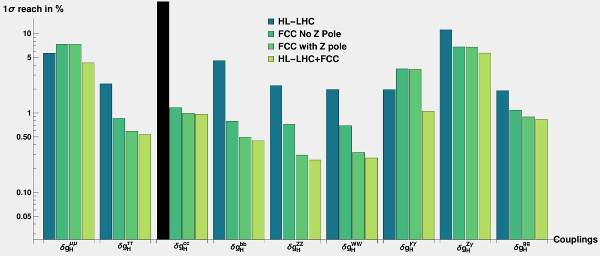

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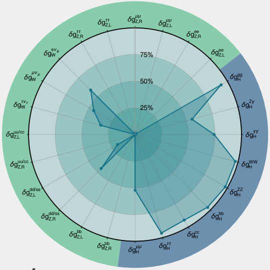

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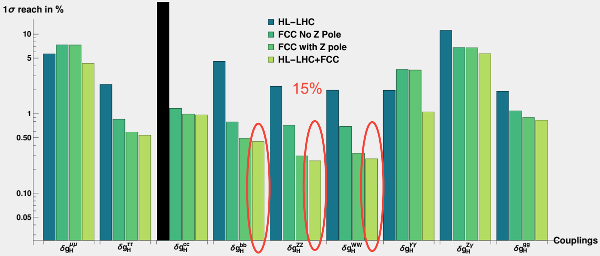

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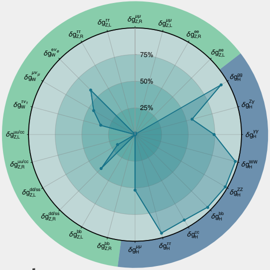

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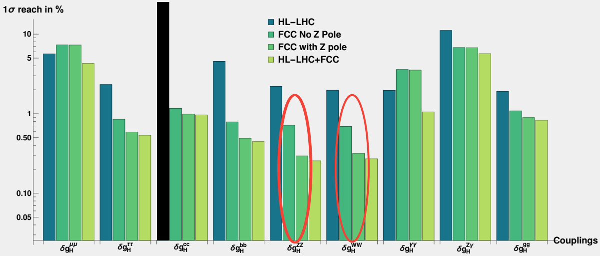

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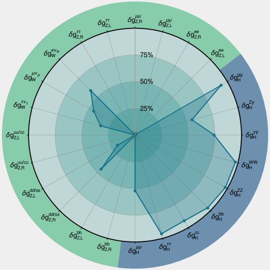

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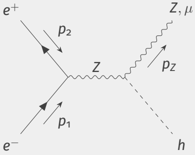
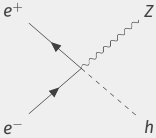
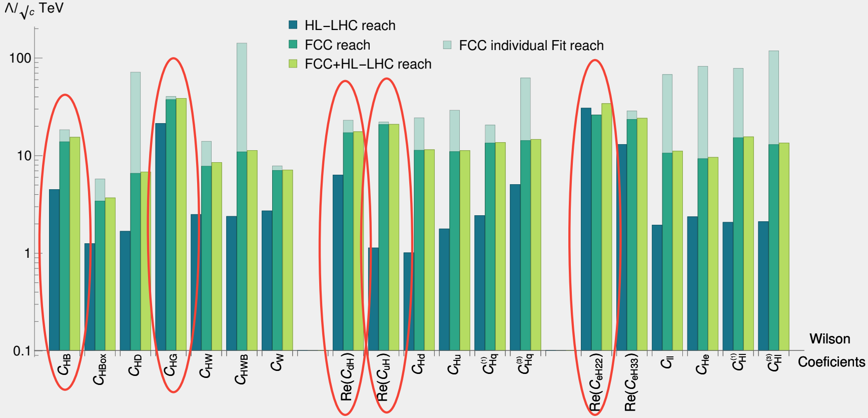


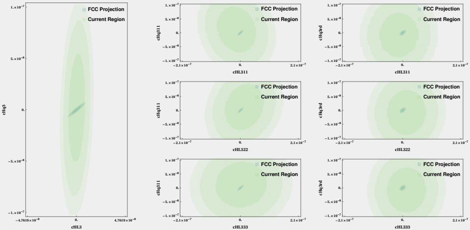


Limits on new physics scale

In an analysis of effective theories we only have access to the interaction scale, c_i/Λ^2. Even so, under the assumption of natural Wilson coefficients $c_i \approx 1$, we have been able to estimate the reach in the determination of the scale of new physics.



- Correlation between quarks and leptons sector of 93% for $C_{Hl}^{(3)}$ and $C_{Hq}^{(3)}$:



- Correlation of 80% between $C_{Hl}^{(3)}$ y C_{ll}, due to the great experimental precision in G_F.
- Significant correlations of C_{HWB} and C_{HD} with operators $C_{Hf}^{(1)}$ and $C_{Hf}^{(3)}$.

Thanks for your time.

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Narrow width aproximation conditions:

- A narrow resonance peak $\Gamma_H \ll m_H$,
- Higgs decay is kinematically allowed $m_{\text{final-state}} \ll m_H$,
- The process energy $\sqrt{s}$ is enough to ignore border effects near the resonance pole $\sqrt{s} \gg m_H + m_Z + m_{\text{final-state}}$,
- Loop effects on the propagator are small, i.e., The resonance propagator can be split from the matrix element.
- There is not a huge interference with non-resonant processes.

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Expressions for the electroweak precision observables:

$$A_f = \frac{\bar{g}_{Lf}^2 - \bar{g}_{Rf}^2}{\bar{g}_{Lf}^2 + \bar{g}_{Rf}^2} \qquad y \qquad A_{FB}^f = \frac{3}{4} A_e A_f \ . \tag{2}$$

$$R_l \equiv \frac{\Gamma_{had}}{\Gamma_{ll}} \qquad y \qquad R_q \equiv \frac{\Gamma_{qq}}{\Gamma_{had}} \quad . \tag{3}$$

$$d\Gamma = \frac{1}{32\pi^2} |\mathcal{M}|^2 \frac{|\vec{p}_{final}|}{m_{inicial}^2} d\Omega. \tag{4}$$

$$\mathcal{L}_{\mathrm{GF}} \supset -\frac{4G_F}{\sqrt{2}} \left(\overline{\nu}_\mu \gamma^\mu P_L \mu\right) \left(\overline{e} \gamma_\mu P_L \nu_e\right) .$$

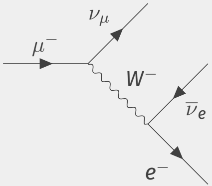

Figure: Diagram of contributing to the β decay in the SM.

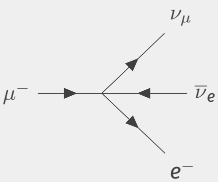

Figure: Diagram contributing to the β decay in the Fermi Theory.

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Not only the first diagram receives corrections in the SMEFT through the coupling of the W to the fermions, but also the second one is present.

α_{EW} will also receive corrections, taking what in the SM is a set of 3 equations with 3 unknowns to 6 unknowns. [**?**].

$$\overline{g}_i = \hat{g}_i + \delta g_i$$

$$\mathcal{O}_n = F_n^{(0)}(g) + \frac{1}{\Lambda^2} F_n^{(2)}(g, C) \qquad \hat{\mathcal{O}}_n = F_n^{(0)}(g)$$

$$g_i = K_i^{(0)}(\mathcal{O}) + \frac{1}{\Lambda^2} K_i^{(2)}(\mathcal{O}, C) \qquad \hat{g}_i = K_i^{(0)}(\mathcal{O})$$

$$\delta\mathcal{O}_n \equiv F_n^{(2)}\left(K^{(2)}(\mathcal{O})\right) \implies K_i^{(2)} = -\left(\mathcal{J}^{-1}\right)_{in} F_n^{(2)}$$

Fits

- Electroweak fits: **CurrentEWFitNoSMCV**, **CurrentEWFitSMCV**, **FCCEWFit**

$$\{\hat{C}_{Hd11},\ \hat{C}_{Hd33},\ \hat{C}_{Hu11},\ \hat{C}_{He11},\ \hat{C}_{He22},\ \hat{C}_{He33},\ \hat{C}^{(1)}_{Hl11},\ \hat{C}^{(1)}_{Hl22},$$
$$\hat{C}^{(1)}_{Hl33},\ \hat{C}^{(3)}_{Hl11},\ \hat{C}^{(3)}_{Hl22},\ \hat{C}^{(3)}_{Hl33},\ \hat{C}^{(1)}_{Hq11},\ \hat{C}^{(3)}_{Hq11},\ \hat{C}_{Hq3rd}, C_{ll1221}\}$$

- Higgs and Electroweak Fits:
  - **FCCHiggsFitDiBoson** or **FCCHiggsFitNoDiBoson**
  - **FCCHiggsFitZPole** or **FCCHiggsFitNoZPole**
  - **FCCHiggsFitHLLHC** or **FCCHiggsFitNoHLLHC**

$$\{C_{Hd11},\ C_{Hd33},\ C_{Hu11},\ C_{He11},\ C_{He22},\ C_{He33},\ C^{(1)}_{Hl11},\ C^{(1)}_{Hl22},\ C^{(1)}_{Hl33},$$
$$C^{(3)}_{Hl11},\ C^{(3)}_{Hl22},\ C^{(3)}_{Hl33},\ C^{(1)}_{Hq11},\ C^{(3)}_{Hq11},\ \hat{C}_{Hq3rd},\ \mathrm{Re}\left[C_{dH33}\right],\ \mathrm{Re}\left[C_{uH22}\right],$$
$$\mathrm{Re}\left[C_{eH22}\right],\ \mathrm{Re}\left[C_{eH33}\right],\ C_{HB},\ C_{HW},\ C_{HWB},\ C_{H\Box},\ \hat{C}_{HG},\ C_{HD},\ C_{ll1221}\}$$

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Working with the presented observables, and on the Warsaw basis, there are different flat directions.

- Flat directions between the first and second family

$$C^{(1)}_{Hq22} = C^{(1)}_{Hq11}, \quad C^{(3)}_{Hq22} = C^{(3)}_{Hq11}, \quad C_{Hu22} = C_{Hu11}, \quad C_{Hd22} = C_{Hd11}$$

- Flat directions of electroweak fit on the Warsaw basis [?, ?]

$$\hat{C}^{(1)}_{Hf} = C^{(1)}_{Hf} - \frac{Y_f}{2} C_{HD}, \quad f = l, q, e, u, d,$$
$$\hat{C}^{(3)}_{Hf} = C^{(3)}_{Hf} + \frac{c_w^2}{4 s_w^2} C_{HD} + \frac{c_w}{s_w} C_{HWB}, \quad f = l, q$$

- Flat directions of the third family

$$\hat{C}_{Hq3rd} = C^{(1)}_{Hq33} + C^{(3)}_{Hq33}, \qquad \hat{C}_{HG} = C_{HG} - \frac{2}{790} \mathrm{Re}\left[C_{uH33}\right]$$