Higgs Couplings
à la HXSWG

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Outline

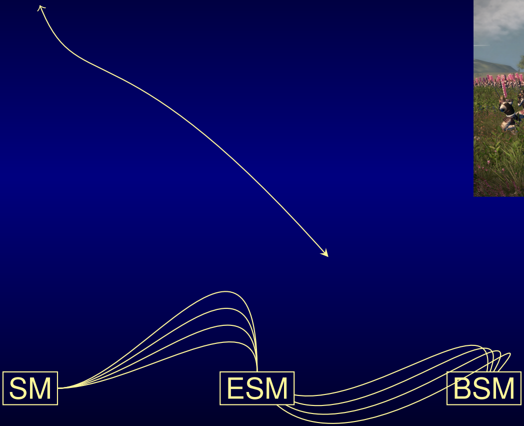
Higgs couplings à la HXSWG

recipe by A. Tinoco Mendes

- generic Intro side dish
- generic BSM directions flavouring
- if any discrepancy, dissecting it
- how it may go away adding some zing to the dish
- a final touch

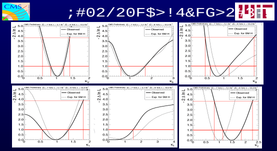
Outline

Let's consider the following path



Status HCP 2012

- Uncertainties of coupling parameters $\approx \mathbf{20-30\%}$
- No significant deviations from the SM couplings are observed (well within $\mathbf{2}\,\sigma$). **N.B.** $\mathbf{20\%}$ deviation $\equiv \Lambda \approx 5\ TeV$.
- Too early to draw any conclusion? Data-driven Theory!



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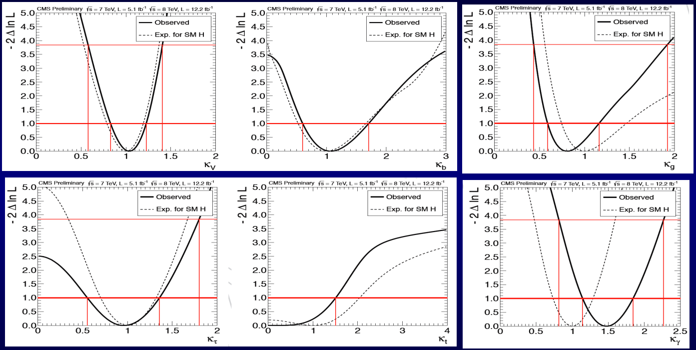

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Theory Choice

Inference to Best Explanation

Richter's IBE Criteria (Physics Today, October 2006)

- Most of what currently passes as the most advanced theory looks to be more theological speculation, the development of models with no testable consequences, than it is the development of practical knowledge, the development of models with testable and falsifiable consequences.

Nature Choice? Rashomon effect?

- **H**(**125**.**9**) it is more SM-like than at ICHEP except for $\gamma\gamma$ where it is exactly what it was in ICHEP.
- Chris Parkes told BBC News: "**Supersymmetry may not be dead but these latest results have certainly put it into hospital.**"
- John Ellis said "**it was actually expected in (some) supersymmetric models. I certainly won't lose any sleep over the result.**"
- If new physics exists, then it is hiding very well behind the Standard Model.

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Mission (impossible)

- **Higgs precision physics** must addresse the incredible goal of making **BSM $\equiv$ SM** examining emerging algorithms to circumvent limited technology

(for results $\rightarrow$ rest of the workshop Rauch, $\cdots$, Grojean time-ordered)

Example

let's pick up one particular example: the *fermiophobic Higgs model* studied in present **LHC** analyses. Field-theoretically no consistent model of such kind exists, i.e. current analyses can only be viewed as purely phenomenological studies rather than putting constraints on solid models.

Key formula arXiv:1209.5538

A. David, A. Denner, M. Duehrssen, M. Grazzini, C. Grojean, G. P., M. Schumacher, M. Spira, G. Weiglein, M. Zanetti

The width of the assumed Higgs boson near 125 *GeV* is neglected ($5-10\%$ accuracy for single channels), i.e. the zero-width approximation for this state is used. Hence

$$(\sigma \cdot \mathrm{BR})(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

Taking the process $\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$ as an example, one would use as cross section:

$$(\sigma \cdot \mathrm{BR})(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

Scaling of the VBF cross section

κ^2_{VBF} refers to the functional dependence of the VBF cross section on the scale factors κ^2_{W} and κ^2_{Z}:

$$\kappa^2_{\mathrm{VBF}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}}) = \frac{\kappa^2_{\mathrm{W}} \cdot \sigma_{\mathrm{W}F}(m_{\mathrm{H}}) + \kappa^2_{\mathrm{Z}} \cdot \sigma_{\mathrm{Z}F}(m_{\mathrm{H}})}{\sigma_{\mathrm{W}F}(m_{\mathrm{H}}) + \sigma_{\mathrm{Z}F}(m_{\mathrm{H}})}$$

Gluon fusion

As **NLO QCD** corrections factorize with the scaling of the electroweak couplings with κ_t and κ_b, the function $\kappa_g^2(\kappa_b, \kappa_t, \mathbf{m}_H)$ can be calculated in **NLO QCD**:

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

Here, σ_{ggH}^{tt}, σ_{ggH}^{bb} and σ_{ggH}^{tb} denote the square of the top-quark, of the bottom-quark contribution and the top-bottom interference, respectively.

Partial width scaling

Treat the scale factor for Γ_{gg} as a second order polynomial in κ_b and κ_t

How to interpret κ_X?

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}(m_H)} = \frac{\kappa_t^2 \cdot \Gamma_{gg}^{tt}(m_H) + \kappa_b^2 \cdot \Gamma_{gg}^{bb}(m_H) + \kappa_t \kappa_b \cdot \Gamma_{gg}^{tb}(m_H)}{\Gamma_{gg}^{tt}(m_H) + \Gamma_{gg}^{bb}(m_H) + \Gamma_{gg}^{tb}(m_H)}$$

κ_γ^2 refers to the scale factor for the loop-induced $\mathrm{H} \rightarrow \gamma\gamma$ decay. Also for the $\mathrm{H} \rightarrow \gamma\gamma$ decay **NLO QCD** corrections exist. This allows to treat the scale factor for the $\gamma\gamma$ partial width as a second order polynomial in κ_b, κ_t, κ_τ, and κ_W:

$$\kappa_\gamma^2(\kappa_\mathrm{b}, \kappa_\mathrm{t}, \kappa_\tau, \kappa_\mathrm{W}, m_\mathrm{H}) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_\mathrm{H})}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_\mathrm{H})}$$

where the pairs (i,j) are $\mathrm{bb}, \mathrm{tt}, \tau\tau, \mathrm{WW}, \mathrm{bt}, \mathrm{b}\tau, \mathrm{bW}, \mathrm{t}\tau, \mathrm{tW}, \tau\mathrm{W}$.
The $\Gamma_{\gamma\gamma}^{ii} \Leftrightarrow \{\kappa_\mathbf{i} = \mathbf{1}, \kappa_\mathbf{j} = \mathbf{0}, (\mathbf{j} \neq \mathbf{i})\}$.
The cross-terms $\Gamma_{\gamma\gamma}^{ij}, (i \neq j) \Leftrightarrow \{\kappa_\mathbf{i} = \kappa_\mathbf{j} = \mathbf{1}, \kappa_\mathbf{l} = \mathbf{0}, (\mathbf{l} \neq \mathbf{i}, \mathbf{j})\}$, subtracting $\Gamma_{\gamma\gamma}^{ii}$ and $\Gamma_{\gamma\gamma}^{jj}$.

The total width Γ_{H} is the sum of all Higgs partial decay widths. Under the assumption that no additional **BSM** Higgs decay modes (into either invisible or undetectable final states) contribute to the total width, Γ_{H} = the sum of the scaled partial Higgs decay widths to **SM** particles, $\rightsquigarrow$ a total scale factor κ_{H}^2 compared to the **SM** total width $\Gamma_{\mathrm{H}}^{\mathrm{SM}}$:

$$\kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}}) = \sum_{\substack{j=\mathrm{WW}^{(*)},\mathrm{ZZ}^{(*)},\mathrm{b\bar{b}},\tau^-\tau^+,\\ \gamma\gamma,\mathrm{Z}\gamma,\mathrm{gg},\mathrm{t\bar{t}},\mathrm{c\bar{c}},\mathrm{s\bar{s}},\mu^-\mu^+}} \frac{\Gamma_j(\kappa_i, m_{\mathrm{H}})}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}(m_{\mathrm{H}})}$$

Common scale factor

Free parameter: $\kappa (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_W = \kappa_Z)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^- \tau^+$
ggH $t\bar{t}H$ VBF WH ZH			κ^2		

The simplest possible benchmark parametrization where a single scale factor applies to all production and decay modes. Cannot be realized within ESM.

Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_W = \kappa_Z)$, $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

Boson and fermion scaling without assumptions on the total width

Free parameters: $\kappa_{VV} (= \kappa_V \cdot \kappa_V / \kappa_H)$, $\lambda_{fV} (= \kappa_f / \kappa_V)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2$		$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \lambda_{fV}^2$	
VBF WH ZH	$\kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	κ_{VV}^2		$\kappa_{VV}^2 \cdot \lambda_{fV}^2$	

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$	

Boson and fermion scaling without assumptions on the to

Free parameters: $\kappa_{VV} (= \kappa_V \cdot \kappa_V / \kappa_H)$, λ_{fV} (

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to$
ggH $t\bar{t}H$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2$	
VBF WH ZH	$\kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	κ_{VV}^2	

Probing up-type and down-type fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_Z = \kappa_W)$, $\lambda_{du} (= \kappa_d / \kappa_u)$, $\kappa_u (= \kappa_t)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	
$t\bar{t}H$	$\frac{\kappa_u^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_u^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_u^2\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	

Probing up-type and down-type fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{uu} (= \kappa_u \cdot \kappa_u / \kappa_H)$, $\lambda_{du} (= \kappa_d / \kappa_u)$, $\lambda_{Vu} (= \kappa_V / \kappa_u)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{du}^2$	
$t\bar{t}H$	$\kappa_{uu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\cdot\lambda_{du}^2$	
VBF WH ZH	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{du}^2$	

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	H
ggH	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u}{\kappa_H^2(\kappa_i)}$	
$t\bar{t}H$	$\frac{\kappa_u^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_u^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$	

Probing up-type and down-type fermion symmetry without as

Free parameters: $\kappa_{uu}(=\kappa_u\cdot\kappa_u/\kappa_H)$, $\lambda_{du}(=\kappa_d$

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	H
ggH	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)$	
$t\bar{t}H$	$\kappa_{uu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\cdot\lambda_{Vu}^2$	
VBF WH ZH	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda$	

68% CL HCP 2012

$$\kappa_g^2\, \sigma_{SM}(gg \to H)\, \frac{\kappa_\gamma^2}{\kappa_H^2}\, BR_{SM}(H \to \gamma\gamma)$$

$$\kappa_F \in [-1.0, -0.7] \cup [0.7, 1.3]$$

$$\kappa_V \in [0.9, 1.0] \cup [1.1, 1.3]$$

$$\frac{\kappa_W}{\kappa_Z} = 1.07^{+0.35}_{-0.27} \mapsto$$ $SU(2)_C$

$$\kappa_\gamma = 1.2^{+0.3}_{-0.2} \quad \kappa_g = 1.1^{+0.2}_{-0.3} \mapsto$$ new colored states

95% CL HCP 2012

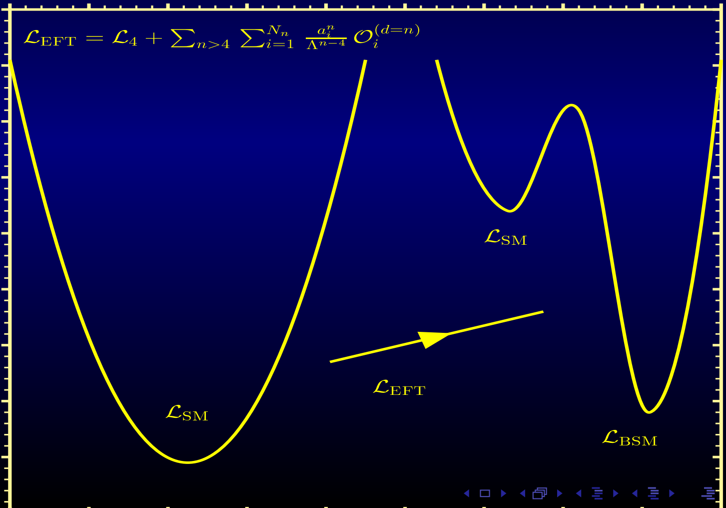
Good fit to individual couplings (still limited precision)

$$\frac{\kappa_W}{\kappa_Z} \in \left[0.57\,,\,1.65\right] \mapsto \boxed{SU(2)_C}$$

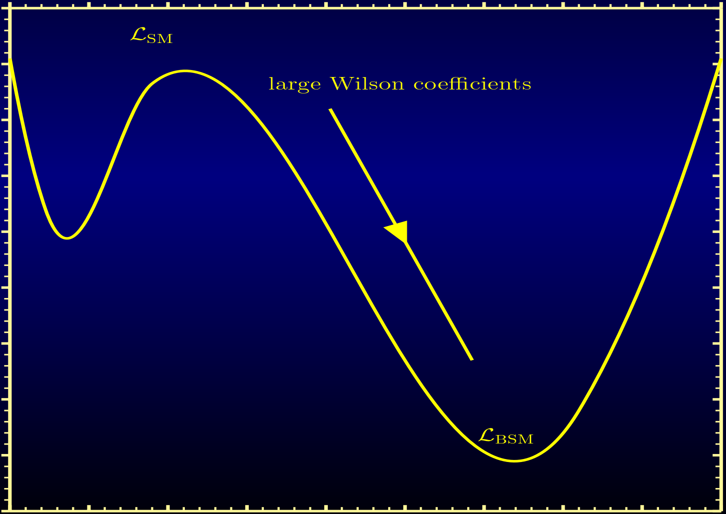
$$\kappa_g \in \left[0.55\,,\,1.07\right] \quad \kappa_\gamma \in \left[0.98\,,\,1.92\right] \mapsto \boxed{\text{new colored states}}$$

Space of Lagrangians (arXiv:1202.3144, arXiv:1202.3415, arXiv:1202.3697)

Wilson coefficients in $\mathscr{L}_{\rm ESM}$ are assumed to be small enough that they can be treated at leading order.



But $\rightsquigarrow$ model-dependent (non-decoupling, new light degrees of freedom . . .) . ($\cdots$ *not favored by the data*)



Strategy

- measure κ

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}(m_H)} = \frac{\kappa_t^2 \cdot \Gamma_{gg}^{tt}(m_H) + \kappa_b^2 \cdot \Gamma_{gg}^{bb}(m_H) + \kappa_t \kappa_b \cdot \Gamma_{gg}^{tb}(m_H)}{\Gamma_{gg}^{tt}(m_H) + \Gamma_{gg}^{bb}(m_H) + \Gamma_{gg}^{tb}(m_H)}$$

- find $\mathcal{O}_i \Leftrightarrow \kappa_x$ (epistemological stop, true ESM believers stop here)

$$\mathcal{L}_{ESM} = \mathcal{L}_{SM} + \sum_{n>4} \sum_{i=1}^{N_n} \frac{a_i^n}{\Lambda^{n-4}} \mathcal{O}_i^{(d=n)}$$

- find $\{\mathcal{L}_{BSM}\}$ that produces $\mathcal{O}_i$

Theoretical uncertainties

- Such uncertainties will directly affect the determination of the κ_X. When one or more of the κ_X differ from **1**, **THU** from missing **NLO**(**NNLO**) contributions will be larger than what estimated so far.
- Without a consistent **EW NLO** calculation for deviations from the **SM** , **EW** corrections and their **THU** are naively scaled together. In **SM THU** is
  - $\sim$ **5**% in $gg \to H$
  - $\sim$ **2**% in $H \to \gamma\gamma$
- Crucial approximations are:
  - missing off-shell effects and **ZWA** (**5**–**10**%)
  - missing **S**/**I** effects (**10**% for $H \to e^+e^-e^+e^-$ at **125 GeV**).

NLO: QCD and EW

- The treatment of **EW** corrections becomes easily inconsistent because they will be rescaled in the same way as all tree-level contributions and **QCD** corrections.
- A first-step treatment would be to include the **QCD** corrections into the rescaling, since they factorise in all cases, but to omit the **EW** ones.
- A better choice is to set up a strategy for most of the near-future **LHC** analyses. This strategy has to be as consistent as possible - in particular in the context of higher-dimensional operators.

Open problems: arXiv:1209.5538

Mathematical consistency must have a preeminent role with observational consistency

- From the Lagrangian to the S-matrix
- Nature of $\mathbf{d} = \mathbf{6}$ operators, tree versus loop
- Implementation:
  - Insertion of $\mathbf{d} = \mathbf{6}$ operators in loops
  - Effective theory and renormalization
- Decoupling
- Mixing
- Perturbative unitarity

Nobody ever used the Effective-Fermi-Theory to study the Z-pole, at most the muon-decay.

Improved Buchmüller - Wyler basis

1. Use the minimal bases of $\mathscr{O}_i$, apart from those that are irrelevant for Higgs processes. This is a minimal set after the use of **EOM**.
2. The operators can be organized in a subset that result from **tree-level** exchange and those that result from **loops** of heavy degrees of freedom.
3. Further split the operators in those that respect CP and those that violate CP.
4. The absence of **FCNC** puts requirements on the coupling matrices of the operators $\mapsto$ **29** free coupling parameters. Of course the analysis could be done on subsets.

Operators

- Note that the **L**-operators are usually not included in the analysis. The accuracy at which results for amplitudes will be presented is given by **LO SM** (the first order in perturbation theory where the amplitude receives a contribution), **NLO SM, LO+NLO ESM**.

- One example of **L**-operator is given by the contributions from heavy colored scalar fields transforming in a $(\mathbf{C}, \mathbf{T}, \mathbf{Y})$ representation of $\mathbf{SU}(\mathbf{3}) \otimes \mathbf{SU}(\mathbf{2}) \otimes \mathbf{U}(\mathbf{1})$, e.g. the $(\mathbf{8}, \mathbf{2}, \mathbf{1}/\mathbf{2})$ representation.

$$\mathrm{K} = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathrm{H} + 2\frac{M}{g} + i\phi^0 \\ \sqrt{2}\, i\phi^- \end{pmatrix}$$

$\mathrm{H} =$ custodial singlet in $(2_\mathrm{L} \otimes 2_\mathrm{R}) = 1 \oplus 3$.

Table: A selection of relevant $d = 6$ operators

$\mathcal{O}_\mathrm{K} = -\frac{g^3}{3}\left(\mathrm{K}^\dagger\mathrm{K}\right)^3$	$\mathcal{O}_{\partial\mathrm{K}} = \frac{g^2}{2}\,\partial_\mu\left(\mathrm{K}^\dagger\mathrm{K}\right)\partial_\mu\left(\mathrm{K}^\dagger\mathrm{K}\right)$
$\mathcal{O}^1_\mathrm{K} = g^2\left(\mathrm{K}^\dagger\mathrm{K}\right)\left(D_\mu\mathrm{K}\right)^\dagger D_\mu\mathrm{K}$	$\mathcal{O}^3_\mathrm{K} = g^2\left(\mathrm{K}^\dagger D_\mu\mathrm{K}\right)\left[\left(D_\mu\mathrm{K}\right)^\dagger\mathrm{K}\right]$
$\mathcal{O}^4_\mathrm{K} = i g^2\left(D_\mu\mathrm{K}\right)^\dagger\tau_a D_\mu\mathrm{K}\,F^a_{\mu\nu}$	$\mathcal{O}^5_\mathrm{K} = i g^2\left(D_\mu\mathrm{K}\right)^\dagger D_\mu\mathrm{K}\,F^0_{\mu\nu}$
$\mathcal{O}^1_\mathrm{V} = g\left(\mathrm{K}^\dagger\mathrm{K} - v^2\right)F^a_{\mu\nu}F^a_{\mu\nu}$	$\mathcal{O}^2_\mathrm{V} = g\left(\mathrm{K}^\dagger\mathrm{K} - v^2\right)F^0_{\mu\nu}F^0_{\mu\nu}$
$\mathcal{O}^3_\mathrm{V} = g\,\mathrm{K}^\dagger\tau_a\mathrm{K}\,F^a_{\mu\nu}F^0_{\mu\nu}$	$\mathcal{O}^1_\mathrm{eV} = g\left(\mathrm{K}^\dagger\mathrm{K} - v^2\right)\mathrm{F}^a_{\mu\nu}\mathrm{F}^a_{\mu\nu}$
$\mathcal{O}^2_\mathrm{eV} = g\left(\mathrm{K}^\dagger\mathrm{K} - v^2\right)\mathrm{F}^0_{\mu\nu}\mathrm{F}^a_{\mu\nu}$	$\mathcal{O}^3_\mathrm{eV} = g\,\mathrm{K}^\dagger\tau_a\mathrm{K}\,\mathrm{F}^a_{\mu\nu}F^0_{\mu\nu}$
$\mathcal{O}_\mathrm{g} = g\left(\mathrm{K}^\dagger\mathrm{K} - v^2\right)G^a_{\mu\nu}G^a_{\mu\nu}$	$\mathcal{O}^1_\mathrm{f} = g^2\left(\mathrm{K}^\dagger\mathrm{K} - v^2\right)\overline{\psi}_\mathrm{L}\,\mathrm{K}\,\mathrm{t}_\mathrm{R} + \mathrm{h.\,c.}$
$\mathcal{O}^2_\mathrm{f} = g^2\left(\mathrm{K}^\dagger\mathrm{K} - v^2\right)\overline{\psi}_\mathrm{L}\,\mathrm{K}^c\,\mathrm{b}_\mathrm{R} + \mathrm{h.\,c.}$	$\mathcal{O}^3_\mathrm{f} = \overline{\psi}_\mathrm{L}\,D_\mu\,\mathrm{t}_\mathrm{R}\,D_\mu\,\mathrm{K} + \mathrm{h.\,c.}$
$\mathcal{O}^4_\mathrm{f} = \overline{\psi}_\mathrm{L}\,D_\mu\,\mathrm{b}_\mathrm{R}\,D_\mu\,\mathrm{K}^c + \mathrm{h.\,c.}$	

Return

UV and Effective NLO Approximation

- What is needed is a preliminar study of the insertion of $\mathbf{d} = \mathbf{6}$ operators in **SM** loop diagrams, analyzing their UV effect on all relevant processes. This defines the **ENLOA**
  - operators altering the UV power-counting of a **SM** diagram and
  - operators that do not change the UV power-counting.
- A set of **SM** diagrams is UV-scalable w.r.t. a combination of $\mathbf{d} = \mathbf{6}$ operators if their sum is UV finite and all diagrams in the set are scaled by the same combination of $\mathbf{d} = \mathbf{6}$ operators.

ESM /UCSM and renormalization

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{2}\,\partial_\mu S\,\partial_\mu S - \frac{1}{2}\,M_{\rm S}^2\,S^2 + \mu_{\rm S}\,{\rm K}^\dagger\,{\rm K}\,S$$

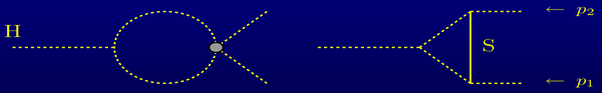
$$\mathscr{L}_{\rm int} = \frac{1}{2}\,\mu_{\rm S}\left({\rm H}^2 + \phi^0\phi^0 + 2\,\phi^+\phi^-\right)\,S$$

In the limit $\mathbf{M}_{\rm S} \to \infty$ we have

$$\mathscr{L} \to \mathscr{L}_{\rm SM}^{\rm LO} + \frac{\mu_{\rm S}^2}{M_{\rm S}^2}\,\left({\rm K}^\dagger{\rm K}\right)^2 + \frac{\mu_{\rm S}^2}{M_{\rm S}^4}\,\mathscr{O}_{\partial{\rm K}}$$

The **d** $=$ **4** operator can be absorbed through a parameter redefinition, and we are left with a contribution to the **d** $=$ **6** operator $\mathscr{O}_{\partial \mathrm{K}}$.

The three-point function H^3 with the insertion of the $\mathscr{O}_{\partial \mathrm{K}}$ operator (left) and the same contribution in the full Lagrangian.



N.B. $\overline{\text{parameters}} \rightsquigarrow$ **SM-like kinetic and mass terms**

$$I^{\rm DR}_{\rm eff} = \frac{3}{4}\, g\, \frac{\overline{\rm M}^{\,2}_{\rm H}}{\overline{\rm M}\Lambda^2} \left[\left(\frac{1}{2}\, s - 3\, \overline{\rm M}^{\,2}_{\rm H} \right) \left(\frac{1}{\bar{\varepsilon}} - \ln \frac{s}{\mu^2_{\rm R}} \right) + \quad \text{finite part} \right]$$

After subtracting the UV pole we can say that the insertion of a $\mathbf{d} = \mathbf{6}(\mathbf{8})$ operator produces a result

$$I^{\rm ren}_{d=6} \sim \frac{\overline{\rm M}^{\,2}_{\rm H}}{\Lambda^2} \ln \mu_{\rm R} \qquad I^{\rm ren}_{d=8} \sim \frac{\overline{\rm M}^{\,4}_{\rm H}}{\Lambda^4} \ln \mu_{\rm R}$$

Note that, with cutoff regularization, both integrals would be of $\mathscr{O}(\mathbf{1})$.

Working (for simplicity) with $\overline{\mathrm{M}}_{\mathrm{H}}^2 \ll s \ll M_{\mathrm{S}}^2$ we obtain

$$I_{\text{full}} = \frac{3}{2} g \frac{\overline{\mathrm{M}}_{\mathrm{H}}^2 \mu_{\mathrm{S}}^2}{\overline{\mathrm{M}} s} \left[\zeta(2) - \mathrm{Li}_2 \left(1 + \frac{s + i0}{M_{\mathrm{S}}^2} \right) \right]$$

We can identify $\Lambda = \mathbf{M}_{\mathrm{S}}^{\mathbf{2}} / \mu_{\mathrm{S}}$, expand in $\mathbf{s}/\mathbf{M}_{\mathrm{S}}^{\mathbf{2}}$, and obtain

$$I_{\text{full}} = -\frac{3}{2} g \frac{\overline{\mathrm{M}}_{\mathrm{H}}^2 \mu_{\mathrm{S}}^2}{\overline{\mathrm{M}} M_{\mathrm{S}}^2} \left[1 - \frac{1}{4} \frac{s}{M_{\mathrm{S}}^2} - \left(1 - \frac{1}{2} \frac{s}{M_{\mathrm{S}}^2} \right) \ln \frac{-s - i0}{M_{\mathrm{S}}^2} + \mathscr{O}\left(\frac{s^2}{M_{\mathrm{S}}^4} \right) \right]$$

The first term in $\mathbf{I}_{\text{full}}$ reproduces the $\mathbf{d} = \mathbf{4}$ operator while the second term corresponds to the $\mathbf{d} = \mathbf{6}$, $\mathscr{O}_{\partial \mathrm{K}}$ operator. There is no UV divergence in $\mathbf{I}_{\text{full}}$ and the logarithm is uniquely fixed.

List

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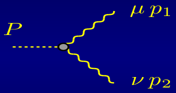
▸ List

Higgs-like couplings

$$T^{\mu\nu} = p_2^\mu p_1^\nu - p_1 \cdot p_2 \, \delta^{\mu\nu} \qquad P^{\mu\nu} = p_1^\mu p_1^\nu + 2 p_1^\nu p_2^\mu + p_2^\mu p_2^\nu$$

$$E^{\mu\nu} = \varepsilon^{\alpha\beta\mu\nu} p_{1\alpha} p_{2\beta}$$



HAA

$$8 \frac{\overline{\mathrm{M}}}{\Lambda^2} \left(\hat{s}_\theta^2 \, a_{\mathrm{V}}^1 + \hat{c}_\theta^2 \, a_{\mathrm{V}}^2 + g \, \hat{c}_\theta \, \hat{s}_\theta \, a_{\mathrm{V}}^3 \right) T^{\mu\nu}$$

$$+ \quad 16 \frac{\overline{\mathrm{M}}}{\Lambda^2} \left(\hat{s}_\theta^2 \, a_{\mathrm{eV}}^1 + \hat{c}_\theta^2 \, a_{\mathrm{eV}}^2 + g \, \hat{c}_\theta \, \hat{s}_\theta \, a_{\mathrm{eV}}^3 \right) E^{\mu\nu}$$

$\mathcal{O}_i \Leftrightarrow \kappa_x$

For $\mathrm{H} \to \gamma\gamma$ the **SM** amplitude reads

$$\mathcal{M}_{\mathrm{SM}} = F_{\mathrm{SM}} \left(\delta^{\mu\nu} + 2\, \frac{p_1^{\nu} p_2^{\mu}}{\overline{\mathrm{M}}_{\mathrm{H}}^{2}} \right) e_{\mu}(p_1)\, e_{\nu}(p_2)$$

$$\boxed{F_{\mathrm{SM}}} = -g\,\overline{\mathrm{M}}\, F^{\mathrm{W}}_{\mathrm{SM}} - \frac{1}{2}\, g\, \frac{M_{\mathrm{t}}^2}{\overline{\mathrm{M}}}\, F^{\mathrm{t}}_{\mathrm{SM}} - \frac{1}{2}\, g\, \frac{M_{\mathrm{b}}^2}{\overline{\mathrm{M}}}\, F^{\mathrm{b}}_{\mathrm{SM}}$$

$$F^{\mathrm{W}}_{\mathrm{SM}} = 6 + \frac{\overline{\mathrm{M}}_{\mathrm{H}}^{2}}{\overline{\mathrm{M}}^{2}} + 6\left(\overline{\mathrm{M}}_{\mathrm{H}}^{2} - 2\,\overline{\mathrm{M}}^{2}\right) C_0\left(-\overline{\mathrm{M}}_{\mathrm{H}}^{2}, 0, 0; \overline{\mathrm{M}}, \overline{\mathrm{M}}, \overline{\mathrm{M}}\right)$$

$$F^{\mathrm{t}}_{\mathrm{SM}} = -8 - 4\left(\overline{\mathrm{M}}_{\mathrm{H}}^{2} - 4\, M_{\mathrm{t}}^2\right) C_0\left(-\overline{\mathrm{M}}_{\mathrm{H}}^{2}, 0, 0; M_{\mathrm{t}}, M_{\mathrm{t}}, M_{\mathrm{t}}\right)$$

$H \to \gamma\gamma$

$$\mathcal{M}_{H\to\gamma\gamma} = \left(4\sqrt{2}\,G_F\right)^{1/2}\Big\{-\frac{\alpha}{\pi}\Big[\kappa_W^{\gamma\gamma}\,F_{SM}^{W} + 3\,Q_t^2\,\kappa_t^{\gamma\gamma}\,F_{SM}^{t} + 3\,Q_b^2\,\kappa_b^{\gamma\gamma}\,F_{SM}^{b}\Big] + \boxed{\kappa_{loop}^{\gamma\gamma}}\Big\}$$

$$\kappa_{loop}^{\gamma\gamma} = \frac{g_6}{\sqrt{2}}\,\overline{M}_H^2\left(\hat{s}_\theta^2\,A_V^1 + \hat{c}_\theta^2\,A_V^2 + \hat{c}_\theta\,\hat{s}_\theta\,A_V^3\right)$$

$$g_6 = \frac{1}{G_F\,\Lambda^2} = 0.085736\left(\frac{TeV}{\Lambda}\right)^2$$

$\kappa^{\gamma\gamma}$ (ENLOA only)

for the W-loop

$$\kappa_{\mathrm{W}}^{\gamma\gamma} = \frac{1}{4}\,\overline{\mathrm{M}}^{\,2}\left\{1 + \frac{g_6}{4\sqrt{2}}\left[8\,A_{\mathrm{V}}^{3}\,\hat{c}_\theta\left(\hat{s}_\theta + \frac{1}{\hat{s}_\theta}\right) + A_{\mathrm{K}}^{0}\right]\right\}$$

for the quark loops

$$\kappa_{\mathrm{t}}^{\gamma\gamma} = \frac{1}{8}\,M_{\mathrm{t}}^{2}\left\{1 + \frac{g_6}{4\sqrt{2}}\left[8\,A_{\mathrm{V}}^{3}\,\hat{c}_\theta\left(\hat{s}_\theta + \frac{1}{\hat{s}_\theta}\right) + A_{\mathrm{K}}^{0} - A_{\mathrm{f}}^{1}\right]\right\}$$

$$\kappa_{\mathrm{b}}^{\gamma\gamma} = \frac{1}{8}\,M_{\mathrm{b}}^{2}\left\{1 + \frac{g_6}{4\sqrt{2}}\left[8\,A_{\mathrm{V}}^{3}\,\hat{c}_\theta\left(\hat{s}_\theta + \frac{1}{\hat{s}_\theta}\right) + A_{\mathrm{K}}^{0} - A_{\mathrm{f}}^{2}\right]\right\}$$

$\mathrm{H} \to \bar{\mathrm{b}}\mathrm{b}$

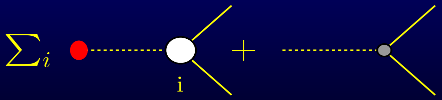
$$\mathcal{M}_{\mathrm{H}\to\bar{\mathrm{b}}\mathrm{b}} = \left(4\sqrt{2}\,G_{\mathrm{F}}\right)^{1/2} M_{\mathrm{b}}\,\bar{u}(p_2)\,v(p_1)\left\{\frac{G_{\mathrm{F}}\,\overline{\mathrm{M}}^{\,2}}{\pi^2}\,\kappa^{\bar{\mathrm{b}}\mathrm{b}}\,F^{\mathrm{SM}}_{\mathrm{H}\to\bar{\mathrm{b}}\mathrm{b}} + \kappa^{\bar{\mathrm{b}}\mathrm{b}}_{\mathrm{loop}}\right\}$$

$$\kappa^{\bar{\mathrm{b}}\mathrm{b}}_{\mathrm{loop}} = \frac{g_6}{128\sqrt{2}}\left[\frac{\overline{\mathrm{M}}^{\,2}_{\mathrm{H}}}{\overline{\mathrm{M}}^{\,2}}\,A^4_{\mathrm{f}} - 16\left(A^3_{\mathrm{K}} + 2\,A_{\partial\mathrm{K}} + A^2_{\mathrm{f}}\right)\right]\Big\}$$

$$\kappa^{\bar{\mathrm{b}}\mathrm{b}} = \frac{1}{2\sqrt{2}}\left[1 + \frac{g_6}{4\sqrt{2}}\left(A^1_{\mathrm{K}} + A^3_{\mathrm{K}} + 6\,A_{\partial\mathrm{K}}\right)\right]$$

ENLOA

Amplitude for a two-body decay of the Higgs boson (dash line) including **LO+NLO SM** contributions with a sum over all one-loop diagrams (i); **SM** diagrams are eventually multiplied by an admissible scaling from $\mathbf{d} = \mathbf{6}$ operators (red circle); the grey circle represents a contact term (including L-operators).



Score

UV completion of the SM (UCSM) versus ESM

Bottom-up or top-down approach to **ESM** ?

- How many facts the theory explains: it is a draw
- Having the fewer auxiliary hypothesis: **SM** $\longrightarrow$ **UCSM** superior
- Analogy: **SM** should be augmented by all possible terms consistent with symmetries $\longrightarrow$ **ESM**

The regulative ideal of an ultimate theory remains a powerful aesthetic ingredient

Decoupling and $SU(2)_C$

- Heavy degrees of freedom $\hookrightarrow \mathrm{H} \rightarrow \gamma\gamma$: to be fully general one has to consider effects due to heavy fermions $\in \mathbf{R_f}$ and heavy scalars $\in \mathbf{R_s}$ of $\mathbf{SU(3)}$. Colored scalars disappear from the low energy physics as their mass increases . However, the same is not true for fermions.

- Renormalization: whenever $\rho_{\mathrm{LO}} \neq 1$, quadratic power-like contribution to $\Delta\rho$ are absorbed by renormalization of the new parameters of the model $\leadsto \rho$ is not a measure of the custodial symmetry breaking. Alternatively one could examine models containing $\mathbf{SU(2)}_{\mathrm{L}} \otimes \mathbf{SU(2)}_{\mathrm{R}}$ multiplets.

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  Alternatively one could examine models containing $\mathbf{SU(2)_L} \otimes \mathbf{SU(2)_R}$ multiplets.

Conclusions?

Data-driven Theory?
or

If you’re looking for your lost keys, failing to find them in the kitchen is not evidence against their being somewhere else in the house

Conclusions?

- Higgs-landscape: asking the right questions takes as much skill as giving the right answers
- A conclusion is the place where you got tired of thinking (Arthur Bloch)
- I am turned into a sort of machine for observing facts and grinding out conclusions (Charles Darwin)
- El sueño de la razõn produce monstruos (Francisco Goya)

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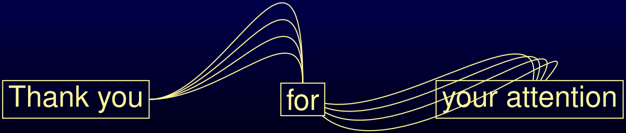
ご清聴ありがとうございました



ENLOA

In the one-loop (bosonic) amplitude for $H \to \gamma\gamma$ there are three different contribution

- a W-loop
- a charged ϕ-loop and
- a mixed $W - \phi$ loop

It is straightforward to show that the **SM** one-loop, bosonic, amplitude for $H \to \gamma\gamma$ with on-shell Higgs line is UV-scalable w.r.t. the combination

$$C_{bos} = \frac{\overline{M}^2}{\Lambda^2}\left(a^3_K - 2\,a^1_K + 2\,a_{\partial K}\right)$$

which could be admissible.

However, in the one-loop amplitude we also have FP-ghost loops Therefore the bosonic component is only UV-scalable w.r.t. the combination

$$C^1_{\text{bos}} = \frac{\overline{\mathrm{M}}^{\,2}}{\Lambda^2}\left(a^3_{\mathrm{K}} + 2\, a_{\partial\mathrm{K}}\right)$$

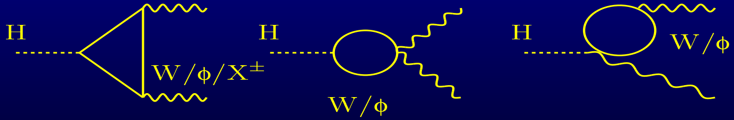
Similarly, we consider the $\gamma\mathrm{WW}$, $\gamma\mathrm{W}\phi$, $\gamma\phi\phi$ and $\gamma \overline{\mathrm{X}}^{\pm}\mathrm{X}^{\pm}$ vertices, which also appear in the one-loop bosonic amplitude for $\mathrm{H} \to \gamma\gamma$, and conclude that the latter is UV-scalable w.r.t. the combination

$$C^2_{\text{bos}} = \frac{\overline{\mathrm{M}}^{\,2}}{\Lambda^2}\,\frac{\hat{c}_\theta}{\hat{s}^2_\theta}\left(4\,\hat{s}_\theta\, a^3_{\mathrm{V}} + \hat{c}_\theta\, a^3_{\mathrm{K}}\right)$$

which is also admissible. Obviously, the wave-function factors are also admissible.

To be more precise, the one-loop bosonic amplitude for $\mathrm{H} \to \gamma\gamma$ is made of three different families of diagrams

The three families of diagrams contributing to the bosonic amplitude for $\mathrm{H} \to \gamma\gamma$; W/ϕ denotes a W-line or a ϕ-line. $\mathrm{X}^{\pm}$ denotes a FP-ghost line.



- We find that the $\gamma\gamma WW$, $\gamma\gamma W\phi$ and $\gamma\gamma\phi\phi$ vertices are all UV-scalable w.r.t. $2\,\mathbf{C}^2_{\text{bos}}$.
- Furthermore, the vertex $\gamma HW\phi$ is UV-scalable w.r.t. $\mathbf{C}^1_{\text{bos}} + \mathbf{C}^2_{\text{bos}}$.

The underlying algebra is such that

- the quadrilinear vertex with two γs is equivalent to the square of the trilinear vertex with one γ (to $\mathcal{O}\left(1/\Lambda^2\right)$) and
- the quadrilinear vertex with one H is equivalent (to the same order) to the product of the two trilinear vertices, with a γ and with a H

As a consequence, there is a non-trivial scaling factor which is admissible, not spoiling the UV behavior.