Foundations of HEFT

An Excerpt

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LHC HXSWG, 13 November 2013
LM virtual meeting

Memo:
Skip
meetings

Main Theorem:
HEFT is a realization of $\boldsymbol{\kappa}$-language

Definition:
$\boldsymbol{\kappa}$-language
is BSM
MI approach

Chapter IV
Renorm.
dim. reg. QFT
role of $\boldsymbol{\Lambda}$
top? - down

Strategy: How to interpret κ_X?

① *measure* $\boldsymbol{\kappa}$

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

② find $\mathcal{O}_i \Leftrightarrow \kappa_x$ (epistemological stop, true ESM believers stop here)

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

③ find $\{\mathcal{L}_{BSM}\}$ that produces $\mathcal{O}_i$

Chapter II
Nature of $\mathcal{O}^{\mathbf{d}}$
Chapter III
Ontology of
HEFT

Corollary:
$\boldsymbol{\kappa}$-language
requires insertion
of $\mathcal{O}^{\mathbf{d}}$ operators
in SM loops

with the physical mass parameters

$$
\begin{aligned}
M_\mathrm{W}^2 &= \frac{1}{4}g^2v^2\left[1+2\frac{v^2}{\Lambda^2}\alpha_{\Phi\mathrm{W}}\right],\\
M_\mathrm{Z}^2 &= \frac{1}{4}(g^2+g'^2)v^2\left[1+\frac{v^2}{2\Lambda^2}\left(4\alpha_{\mathrm{ZZ}}+\alpha_{\Phi D}\right)\right],\\
M_\mathrm{H}^2 &= \lambda v^2\left[1+\frac{v^2}{2\Lambda^2}\left(4\alpha_{\Phi\Box}-\frac{6}{\lambda}\alpha_\Phi-\alpha_{\Phi D}\right)\right],\\
m_\mathrm{f} &= \frac{1}{\sqrt{2}}U^{\hat{\mathrm{f}}}\Gamma_\mathrm{f}U^{\mathrm{f},\dagger}v\left[1-\frac{1}{2}\frac{v^2}{\Lambda^2}\alpha_{\mathrm{f}\phi}\right].
\end{aligned}
\tag{151}
$$

In (150) we have used the usual 't Hooft–Feynman gauge-fixing term

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\mathcal{L}_\mathrm{fix} = -C_+C_- - \frac{1}{2}(C_\mathrm{Z})^2 - \frac{1}{2}(C_\mathrm{A})^2 - \frac{1}{2}C_G^AC_G^A \tag{152}
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with

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C_G^A = \partial_\mu G^{A\mu}, \qquad C_\mathrm{A} = \partial_\mu \mathrm{A}^\mu, \qquad C_\mathrm{Z} = \partial_\mu \mathrm{Z}^\mu + M_\mathrm{Z}\phi^0, \qquad C_\pm = \partial_\mu \mathrm{W}^{\pm\mu} \pm \mathrm{i}M_\mathrm{W}\phi^\pm \tag{153}
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in terms of the physical fields and parameters, which gives rise to the same propagators as in the SM.

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The parameters of the SM Lagrangian g, g', λ, m^2, and Γ_f keep their meaning in the presence of dimension-6 operators.

10.4.2 Higgs vertices

Here we list the most important Feynman rules for vertices involving exactly one physical Higgs boson. These are given in terms of the above-defined physical fields and parameters. In the coefficients of dimension-6 couplings we replaced v^2 by the Fermi constant via $v^2 = 1/(\sqrt{2}G_F)$.

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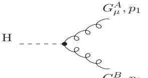

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= \mathrm{i}\frac{2g}{M_\mathrm{W}}\frac{1}{\sqrt{2}G_F\Lambda^2}\left[\alpha_{GG}(p_{2\mu}p_{1\nu}-p_1p_2g_{\mu\nu}) + \alpha_{G\tilde{G}}\varepsilon_{\mu\nu\rho\sigma}p_1^\rho p_2^\sigma\right]\delta^{AB},
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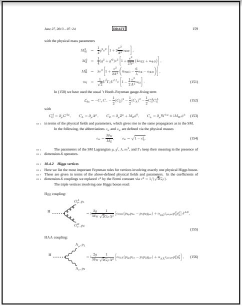

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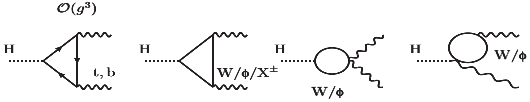


Figure 1: The three families of diagrams contributing to the amplitude for H $\rightarrow \gamma\gamma$; W/ϕ denotes a W-line or a ϕ-line. $X^{\pm}$ denotes a FP-ghost line

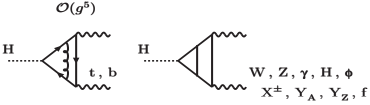
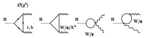


Figure 2: Example of two-loop diagrams contributing to the amplitude for H $\rightarrow \gamma\gamma$

HEFT



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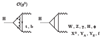

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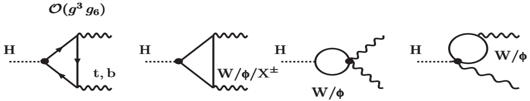

Figure 3: Example of one-loop SM diagrams with $\mathcal{O}$-insertions, contributing to the amplitude for $H \to \gamma\gamma$

$\searrow$ κ_f , A_{NF} $\searrow$ κ_W , A_{NF}

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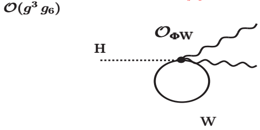

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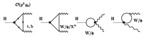

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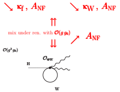

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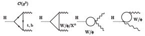

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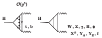

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Glimpsing at the headlines of the **complete** calculation for
☛ $\mathbf{H \to \gamma\gamma}$

- **SM** loops, dressed with admissible operators
- **New 33** loop-diagrams + **Counter-terms**
- at $\mathcal{O}(g^3, g^3\, g_6)$, with $g_6 = 1/\sqrt{2}\, G_F\, \Lambda^2$ ✎

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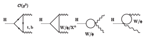

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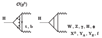

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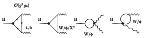

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↘ κ_f, $A_{\rm NF}$ ↘ κ_W, $A_{\rm NF}$

⇈

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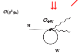
⇊



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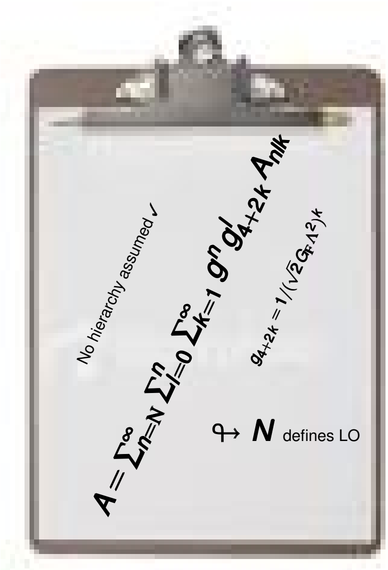
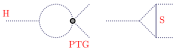


✍**PTG**: T - generated in at least one extension of SM

Note that for $\Lambda \approx 5$ TeV we have

$$1/(\sqrt{2} G_F \Lambda^2) \approx g^2/(4\pi),$$

i.e. ⤀ the contributions of $d = 6$ operators are ≊ loop effects.
⤀ ⤀ For higher scales, loop contributions tend to be more important (⪰)



PTG - operators versus LG - operators, cf. Einhorn, Wudka, . . .

✍ It can be argued that (at LO) the basis operator should be chosen from among the **PTG operators**

✍ take $\mathcal{O}^6_{\rm LG}$, contract two lines, is ren of some $\mathcal{O}^4$

a SM vertex with $\mathcal{O}^6_{\rm PTG}$ required . . . same order

$1/\Lambda$ expansion → power-counting ✓

LG → low-energy analytic structure ✗

PROPOSITION: There are two ways of formulating HEFT

a) mass-dependent scheme(s) or **Wilsonian** HEFT

b) mass-independent scheme(s) or **Continuum** HEFT (CHEFT)

- only a) is conceptually consistent with the image of an EFT as a low-energy approximation to a high-energy theory
- however, inclusion of NLO corrections is only meaningful in b) since we cannot regularize with a cutoff and NLO requires regularization
  - There is an additional problem, CHEFT requires evolving our theory to lower scales until we get below the “heavy-mass" scale where we use $\mathscr{L} = \mathscr{L}_{SM} + d\mathscr{L}$, $d\mathscr{L}$ encoding matching corrections at the boundary. Therefore, CHEFT does not integrate out heavy degrees of freedom but removes them compensating for by an appropriate matching calculation

Not quite the same as it is usually discussed (no theory approaching the boundary from above ...) cf. low-energy SM, weak effects on $g-2$ etc.

✍ $\dim \phi = d/2 - 1$

$\dim \mathcal{O}^d = N_\phi \dim \phi + N_{der}$

For $d \geq 3$ there is a finite number of relevant + marginal operators

For $d \geq 1$ there is a finite number of irrelevant operators

Sounds good for finite dependence on high-energy theory

✍ This assumes that high-energy theory is weakly coupled

✍ Dimensional arguments work for LO HEFT

✍ In NLO HEFT scaling may break down, implying appeal to a particular renormalization scheme

Ren. group should only be applied to EFTs that are nearly massless

Decoupling theorem fails for CHEFT, but, arguably this does not prevent them from supporting a well defined scheme, but decoupling must be inserted in the form of matching calculations (which we don't have ...)

✍ Match Feynman diagrams ∈ HEFT with corresponding **1**(light)**PI** diagrams ∈ high-energy theory (and discover that Taylor-expanding is not always a good idea)

Having said that ... no space left for annotations

Renormalization

FP-sector: handle with care

✓ Make finite all Green's functions

Schemes: remember β_{QED} in large m_e -limit

$$g = g_{\rm ren}\left[1 + \frac{g^2_{\rm ren}}{16\,\pi^2}\left(dZ_g + g_6\,dZ_g^{(6)}\right)\frac{1}{\bar{\varepsilon}}\right]$$

✓ Don't forget background

$$M_{\rm W} = M^{\rm ren}_{\rm W}\left[1 + \frac{1}{2}\,\frac{g^2_{\rm ren}}{16\,\pi^2}\left(dZ_{M_{\rm W}} + g_6\,dZ^{(6)}_{M_{\rm W}}\right)\frac{1}{\bar{\varepsilon}}\right]$$

etc.

Oops! ... $4f\,\mathcal{O}$ needed for $\mathbf{H} \to b\bar{b}$

Wilson coefficients $\quad\rightarrow\quad W_i$

$$\frac{1}{\bar{\varepsilon}} = \frac{2}{\varepsilon} - \gamma - \ln\pi + \ln\mu_R$$

$\mathbf{H} \to \gamma\gamma$ not finite

$$W_i = \sum_j Z^{\rm wc}_{ij}\,W^{\rm ren}_j$$

$$Z^{\rm wc}_{ij} = \delta_{ij} + \frac{g^2_{\rm ren}}{16\,\pi^2}\,dZ^{\rm wc}_{ij}\,\frac{1}{\bar{\varepsilon}}$$

Appendix C. Dimension-Six Basis Operators for the SM[22].

X^3 (LG)		φ^6 and $\varphi^4 D^2$ (PTG)		$\psi^2\varphi^3$ (PTG)	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$ (LG)		$\psi^2 X\varphi$ (LG)		$\psi^2\varphi^2 D$ (PTG)	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

Table C.1: Dimension-six operators other than the four-fermion ones.

[22] These tables are taken from [5], by permission of the authors.

Effective Lagrangians cannot be blithely used without acknowledging implications of their choice
ex: non gauge-invariant, intended to be used in U-gauge
ex: $\mathbf{H} \to \mathbf{W}\mathbf{W}^*$ is virtual $\mathbf{W}$ + something else, depending on the operator basis

Murphy's law of Higgs Physics

- *Although skipping foundations is not specifically recommended*
- *Foundations without tools Is Worth Nothing*
- (*Tools without foundations have no scientific basis*)
- *Construction of HEFT follows Hofstadter's Law: It always takes longer than you expect, even when you take into account Hofstadter's Law (also check Hanlon's razor)*