A Bayesian Fit to Higgs Data Using HEPfit and the Electroweak Chiral Lagrangian

– Higgs Couplings 2017, Heidelberg –

Claudius Krause

Instituto de Física Corpuscular Valencia,
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November 8, 2017

VNIVERSITAT D VALÈNCIA

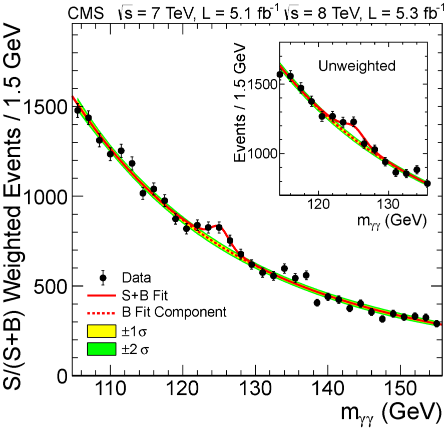
IFIC INSTITUT DE FÍSICA CORPUSCULAR

EXCELENCIA SEVERO OCHOA

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

In collaboration with: Jorge de Blas and Otto Eberhardt
— preliminary results —

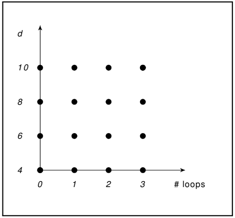
Is that the Higgs of the Standard Model?



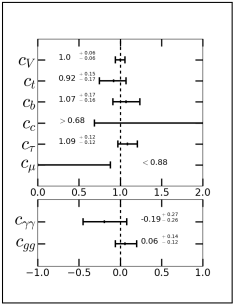
[1207.7235]

⇒ For a model-independent analysis we use a bottom-up Effective Field Theory.

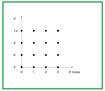
A Bayesian Fit to Higgs Data Using HEPfit and the Electroweak Chiral Lagrangian



Part I: The Electroweak Chiral Lagrangian
[1307.5017,1412.6356,1504.01707]



Part II: The Bayesian Fit
[in preparation]



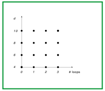
I: The Electroweak Chiral Lagrangian is an EFT.

Ingredients:

- Particles: all SM particles, but we do not assume a relation between the GB and the Higgs
- Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$, B, L at LO: flavor and custodial symmetry
- Power counting: in terms of chiral dimensions

$$2L + 2 = [\text{couplings}]_\chi + [\text{derivatives}]_\chi + [\text{fields}]_\chi$$

$$[\text{bosons}]_\chi = 0,$$
$$[\text{fermion bilinears}]_\chi = [\text{derivatives}]_\chi = [\text{weak couplings}]_\chi = 1$$



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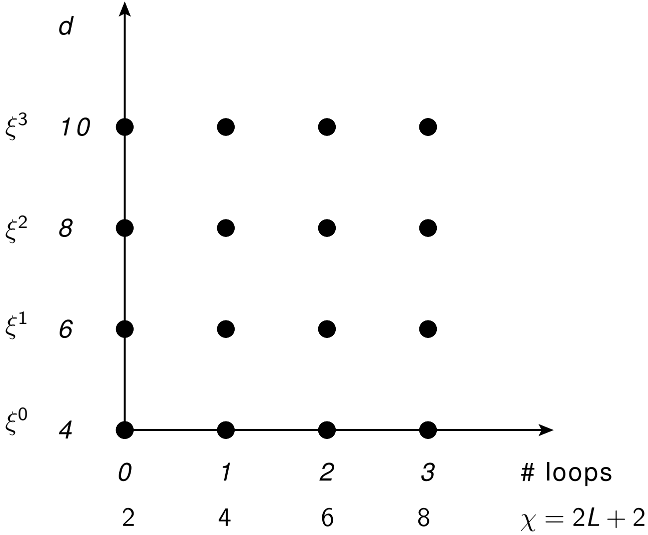
Properties:

- It has generalized Higgs-couplings compared to the SM.
- There is a hierarchy to the operators that modify the EWPD.
- It is related to the κ-formalism at LO.

Feruglio[hep-ph/9301281], Bagger *et al.*[hep-ph/9306256], Chivukula *et al.*[hep-ph/9312317], Wang/Wang[hep-ph/0605104], Grinstein/Trott[0704.1505], Contino[1005.4269], Alonso *et al.*[1212.3305]

I: A graphical way to see the relation of SMEFT *vs.* ew$\chi\mathcal{L}$

$\xi = \frac{v^2}{f^2}$



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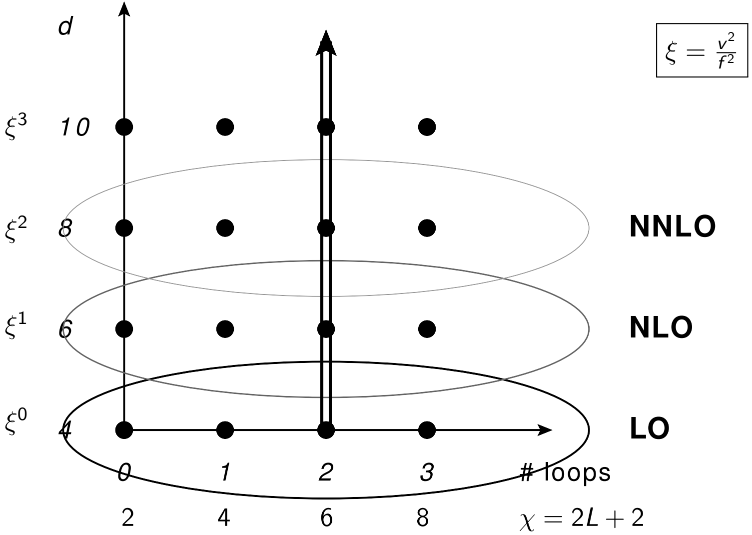

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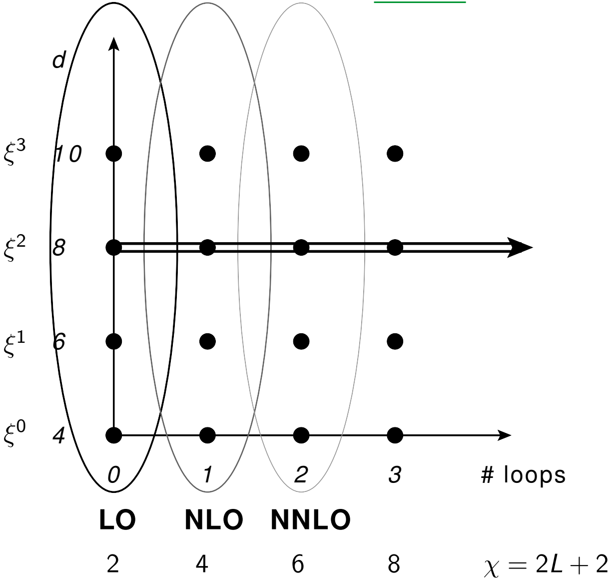

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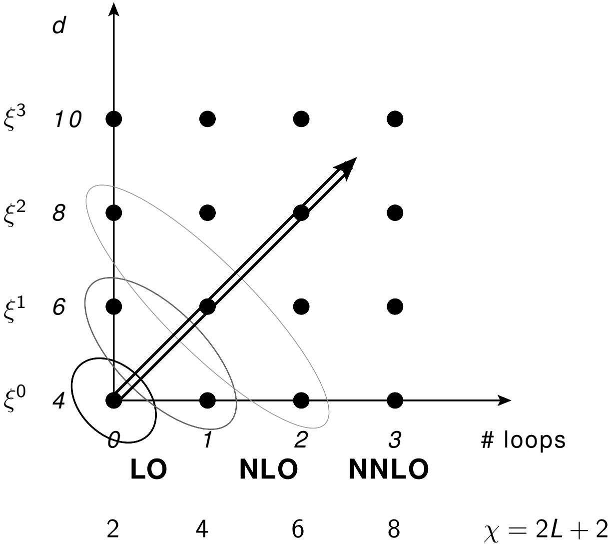
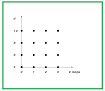
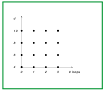




I: Current observables select $\mathcal{L}_{\text{fit}}$ from $\mathcal{L}_{ew\chi h}$.

$$\mathcal{L}_{ew\chi h} = \mathcal{L}_{\text{kin}}^{h,\Psi,\text{gauge}} + \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \ (1 + F_U(h)) - \mathcal{V}(h) \\ - (v\,\bar{\Psi}_f U\, Y_f(h)\Psi_f + \text{h.c.}) + \mathcal{L}_{\text{NLO}}$$

We focus on current observables and require $f > v$, *i.e.* $\xi = v^2/f^2 < 1$.



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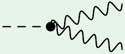
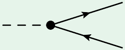
Single h processes

tree:

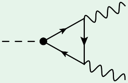


c_V



$c_{t,b,\tau,\mu,(c)}$

1-loop:



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$+$

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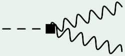

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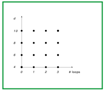

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$$\begin{aligned}\mathcal{L}_{\text{fit}} =& 2c_V \left(m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(\tfrac{h}{v}\right)\\ &- c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_c y_c \bar{c} c h - c_\tau y_\tau \bar{\tau}\tau h - c_\mu y_\mu \bar{\mu}\mu h\\ &+ \tfrac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \tfrac{h}{v} + \tfrac{e^2}{16\pi^2} c_{Z\gamma} Z_{\mu\nu} F^{\mu\nu} \tfrac{h}{v} + \tfrac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu} G^{\mu\nu}\rangle \tfrac{h}{v}\end{aligned}$$

Buchalla/Catà/Celis/CK [1504.01707]

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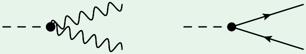

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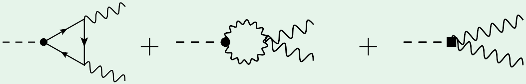

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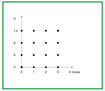

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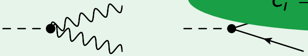

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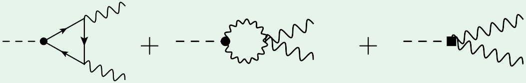

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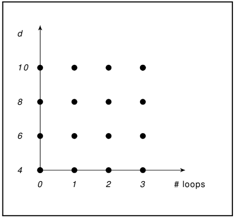

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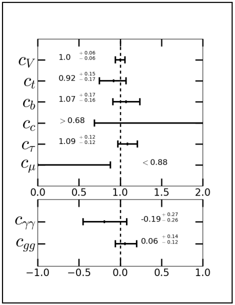
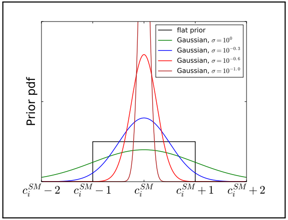


Part II: The Bayesian Fit
[in preparation]

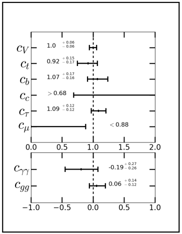
II. Posterior = Prior × Likelihood

Part II.1: The Likelihood



Part II.2: The Prior

Part II.3: The Posterior



II.1: We use HEPfit for the Likelihood.

HEPfit: ⇒ http://hepfit.roma1.infn.it/

A Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models. The HEPfit Collaboration [in preparation]

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HEPfit: ⇒ http://hepfit.roma1.infn.it/
A Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.
The HEPfit Collaboration [in preparation]

It is:

- an open source fitter:
  available at https://github.com/silvest/HEPfit
- flexible:
  add your favorite model or observable
- a stand-alone code with few dependencies:
  ROOT, GSL, BOOST, (BAT)
- fast (& optional):
  using the MCMC implementation of the Bayesian Analysis Toolkit (BAT)

Caldwell/Kollar/Kroninger [0808.2552]

II.1: We use HEPfit for the Likelihood.

Experimental input: For each decay channel we use the signal strength

$$\mu(Y) = \sum_X \text{eff}(X,Y) \frac{\sigma(X)\cdot \text{Br }(h\to Y)}{(\sigma(X)\cdot \text{Br }(h\to Y))_{\text{SM}}}$$

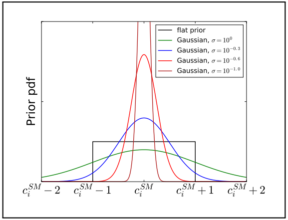
- If available, per experimental production category.
- Otherwise, per production mechanism.

Used datasets:

Final state	CDF	DØ	ATLAS 8 TeV	ATLAS 13 TeV	CMS 8 TeV	CMS 13 TeV
$H\to\gamma\gamma$	–	–	✓	✓	✓	✓
$H\to ZZ^*$	–	–	✓	✓	✓	✓
$H\to WW^*$	–	–	✓	✓	✓	✓
$H\to b\bar{b}$	✓	✓	✓	✓	✓	✓
$H\to\tau^+\tau^-$	–	–	✓	–	✓	✓
$H\to\mu^+\mu^-$	–	–	✓	✓	–	–
$H\to Z\gamma$	–	–	✓	✓	✓	–

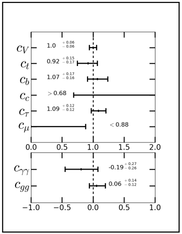
II. Posterior = Prior × Likelihood

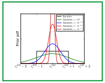
Part II.1: The Likelihood



Part II.2: The Prior

Part II.3: The Posterior



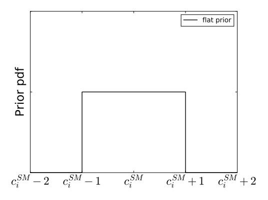


II.2: The Prior reflects our initial knowledge.

We expect the size of the parameters to be

$$c_i = \mathrm{SM} + \mathcal{O}(\xi)$$

Flat prior

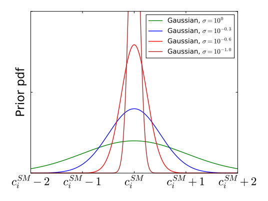


✓ Gives Likelihood

× All values have same weight

× Hard cutoff

Gaussian prior



✓ Reflects knowledge best

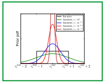
Jaynes ['57 Phys. Rev.]

× Which is the right width?

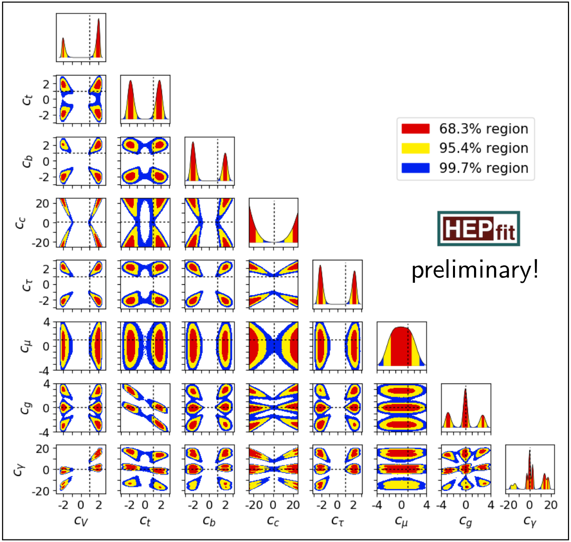
The result should be independent of the particular prior implementation!

⇒ Study Prior dependence

Wesolowski/Klco/Furnstahl/Phillips/Thapaliya [1511.03618]

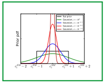


II.2: Flat Prior — the pure Likelihood.

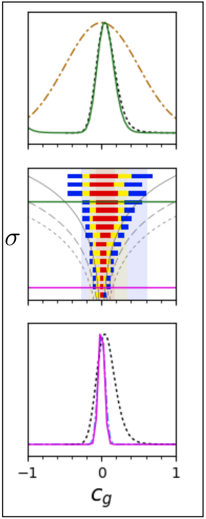


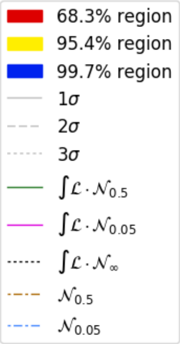
Some of these solutions are unnatural and overfitted.

Wesolowski/Klco/Furnstahl/Phillips/Thapaliya [1511.03618]



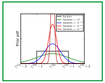
II.2: We study the prior dependence.





preliminary!

We scan different widths: $\sigma = 10^{a}$ with $a \in \{0, -0.1, \ldots, -1.4\}$.
$\sigma = 10^{-0.3} \approx 0.5$ gives same error bars as the flat prior.



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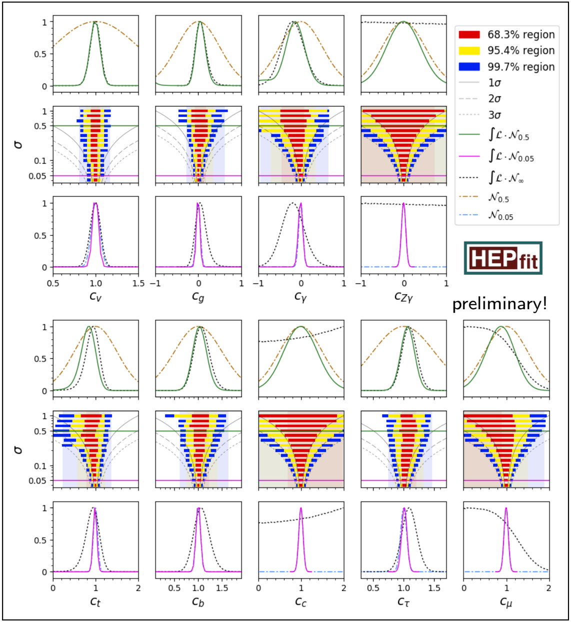
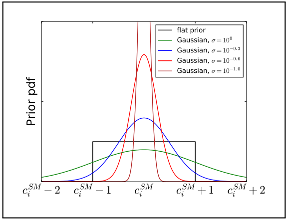


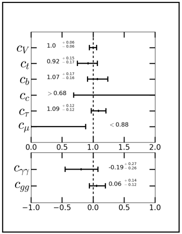
II. Posterior = Prior × Likelihood

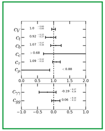
Part II.1: The Likelihood

Part II.2: The Prior



Part II.3: The Posterior



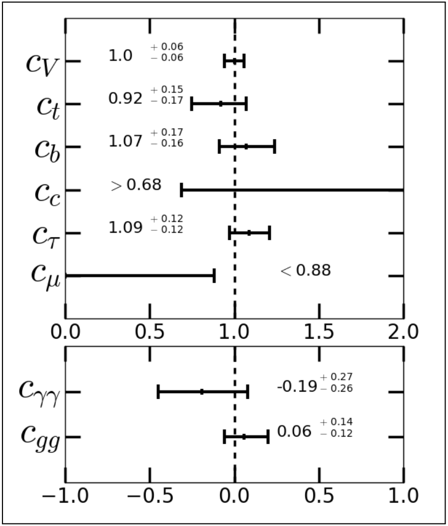


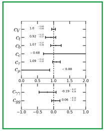
II.3: The Posterior.

Gaussian Prior $\sigma = 10^{-0.3}$:

- Consistent with SM, but $\mathcal{O}(10\%)$ deviations still possible
- $c_{Z\gamma}, c_c$ and c_μ not constrained beyond prior:
- c_μ only upper bound
- $c_c \neq 0$ preferred
- Disconnected solutions disfavored, as anticipated

preliminary!





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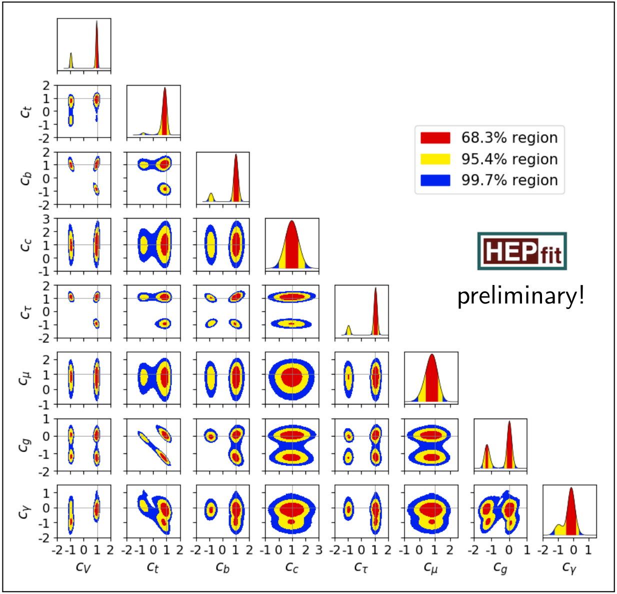

Summary

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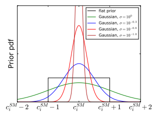

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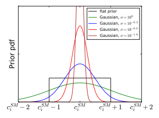
We studied in detail the prior dependence of the result.

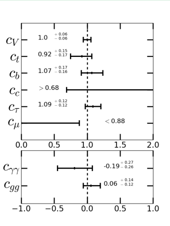


For a Gaussian prior with $\sigma \approx 0.5$, we find:

$$c_V = 1.00 \pm 0.06 \quad c_t = 0.92^{+0.15}_{-0.17} \quad c_b = 1.07^{+0.17}_{-0.16}$$

$$c_\tau = 1.09 \pm 0.12 \quad c_g = 0.06^{+0.14}_{-0.12} \quad c_\gamma = -0.19^{+0.27}_{-0.26}$$

$$(c_\mu < 0.88 \,@\, 68\% \quad c_c > 0.68 \,@\, 68\%)$$



Backup

The construction of the electroweak chiral Lagrangian

$$\mathcal{L}_{\mathrm{LO}} = \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \; (1 + F_U(h)) + \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mathcal{V}(h)$$
$$+ i\bar{\Psi}_f \not{D}\Psi_f - (v\,\bar{\Psi}_f U\, Y_f(h)\Psi_f + \mathrm{h.c.})$$
$$- \frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

- $\mathcal{L}_{\mathrm{LO}}$ is not renormalizable in the traditional sense, but it is renormalizable in the modern sense — order by order in an EFT:
- The LO counterterms are included at NLO.

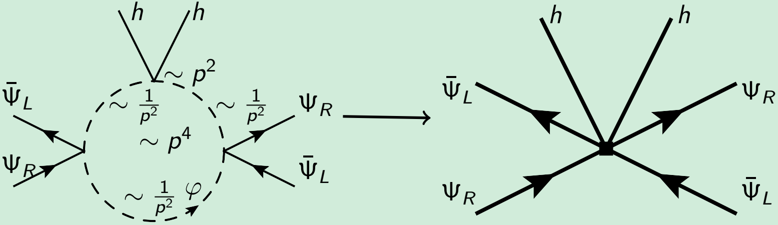
⇒ The basis of NLO-operators is at least given by the counterterms of the one loop divergences.

- We identify $\frac{f^2}{\Lambda^2} \simeq \frac{1}{16\pi^2}$.
- There is an additional ratio of scales: $\xi = \frac{v^2}{f^2}$

The Power counting is based on a loop expansion.

How can we identify the necessary counterterms?

1) Using the superficial degree of divergence:



$$\mathcal{D} \sim p^{2L+2-X-\frac{1}{2}(F_L+F_R)-N_w} \left(\frac{\varphi}{v}\right)^B \left(\frac{h}{v}\right)^H \bar{\Psi}_L^{F_L^1} \Psi_L^{F_L^2} \bar{\Psi}_R^{F_R^1} \Psi_R^{F_R^2} \left(\frac{\mathcal{X}_{\mu\nu}}{v}\right)^X$$

2) Computing all divergent one-loop terms:

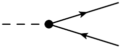
Using the Background-Field method and the super-heat-kernel expansion, we recently obtained the result.

Buchalla/Catà/Celis/Knecht/CK [1710.06412]; Abbott ['82 Acta Phys. Polon. B]; Neufeld/Gasser/Ecker [hep-ph/9806436]; Alonso/Kanshin/Saa [1710.06848]

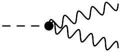
There is a relation between the electroweak chiral Lagrangian and the κ framework.

$\mathcal{L}_{ew\chi h}$

tree:

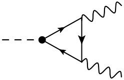


$c_{t,b,\tau}$

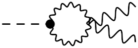


c_V

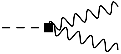
1-loop:



$c_{t,b,\tau}$ $+$



c_V $+$

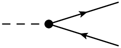


$c_{\gamma\gamma,gg}$

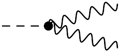
$\kappa_i^2 = \Gamma^i/\Gamma^i_{\text{SM}}, \quad \kappa_i^2 = \sigma^i/\sigma^i_{\text{SM}}$

LHCHXSWG [1209.0040,1307.1347]

tree:

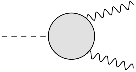


$\kappa_{t,b,\tau}$



κ_V

1-loop:

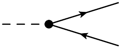


$\kappa_{\gamma,g}$

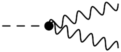
There is a relation between the electroweak chiral Lagrangian and the κ framework.

$\mathcal{L}_{ew\chi h}$

tree:



$c_{t,b,\tau}$

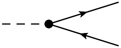


c_V

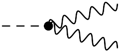
$\kappa_i^2 = \Gamma^i/\Gamma^i_{\mathrm{SM}}, \quad \kappa_i^2 = \sigma^i/\sigma^i_{\mathrm{SM}}$

LHCHXSWG [1209.0040,1307.1347]

tree:



$\kappa_{t,b,\tau}$

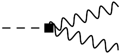


κ_V

Both have the same number of free parameters:

$$\{c_V, c_{t,b,\tau}, c_{\gamma\gamma}, c_{gg}\} \quad vs. \quad \{\kappa_V, \kappa_{t,b,\tau}, \kappa_\gamma, \kappa_g\}$$

$\Rightarrow$ κ's are QFT consistent and with small modifications directly interpretable within an EFT!



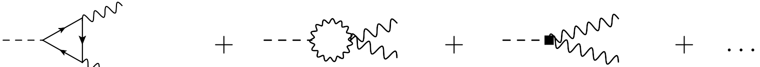
$c_{\gamma\gamma,gg}$

The κ framework cannot be recovered as a limit of the SMEFT (dim 6).

Full dimension 6 Grzadkowski *et al.* [1008.4884]:

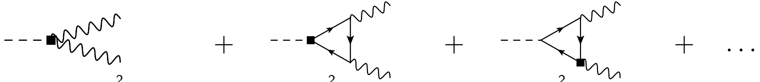
example: $h \to Z\gamma$

LO:



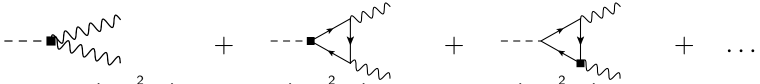
SM $+$ SM $+$ $\mathcal{O}(\frac{v^2}{\Lambda^2})$

LO + NLO:



SM $+ \mathcal{O}(\frac{v^2}{\Lambda^2})$ $+$ $\mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$ $+$ $\mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$

Additional assumption of weakly coupled UV Einhorn/Wudka[1307.0478]:



SM $+ \mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$ $+$ $\mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$ $+$ $\mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$

The Minimal Composite Higgs Model

Agashe *et al.* [hep-ph/0412089], Contino *et al.* [hep-ph/0612048]

- global symmetry spontaneoulsy broken at scale f: $SO(5) \to SO(4)$
- $SU(2)_L \times U(1)_Y \subset SO(4)$ is gauged

$\rightarrow$ massive $W^{\pm}/Z$, light h

$$\mathcal{L}_{\text{kin}} = \frac{f^2}{2}(D_\mu \Sigma)^T (D^\mu \Sigma),$$

where

$$\Sigma = \frac{\sin|h|/f}{|h|} \begin{pmatrix} h_a \\ \cot|h|/f \end{pmatrix},$$

$$|h| = \sqrt{h_a h_a}, \; a = 1, 2, 3, 4$$

With $|h|U \equiv \begin{pmatrix} h_4 + ih_3 & h_2 + ih_1 \\ -(h_2 - ih_1) & h_4 - ih_3 \end{pmatrix} = (\widetilde{\phi}, \phi)$ we find:

$$\mathcal{L}_{\text{kin}} = \frac{1}{2}\partial_\mu |h| \partial^\mu |h| + \frac{f^2}{4}\langle D_\mu U D^\mu U^\dagger \rangle (\sin|h|/f)^2$$