Justifying the κ-framework with the non-linear EFT

– Higgs Effective Field Theory workshop, Chicago 2015 –

Claudius Krause

Ludwig-Maximilians-Universität München

November 4th - 6th, 2015

In collaboration with G. Buchalla, O. Catà and A. Celis

Between Run-1 and the final stages of the LHC:

κ_V, κ_f

LHCHXSWG [1209.0040,1307.1347]

a, c

Contino[1005.4269]

complexity

time→

small deviations:
full dim-6

Hartmann/Trott [1507.03568],
Ghezzi *et al.* [1505.03706]

larger deviations
in Higgs-sector:
full $\mathcal{L}_{ew\chi h}$

LHC Run 1	LHC Run 2	···	HL-LHC

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+ few parameters
− not QFT based

+ QFT based
− too many parameters

Han/Skiba[hep-ph/0412166]

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LO analysis of the $\mathcal{L}_{ew\chi h}$

+ QFT based
+ few parameters

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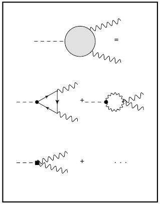
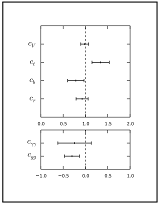
− too many parameters

Han/Skiba[hep-ph/0412166]

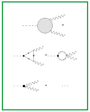
We use the electroweak chiral Lagrangian to analyze LHC data.

Part 1 – from $\mathcal{L}_{ew\chi h}$ to $\mathcal{L}_{\text{fit}}$ & the κ's
[1504.01707]





Part 2 – Fit to LHC Data
[1511.00988]

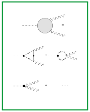


1. The electroweak chiral Lagrangian $\mathcal{L}_{ew\chi h}$

assumptions

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], ...

- A new strong sector is generating the 3 Goldstones of EWSB and the h.
- The scale of the new dynamics is given by f.
- The transverse gauge bosons and the fermions of the SM are weakly coupled.
- The pattern of symmetry breaking is $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{V=L+R}$



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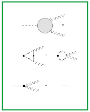
power counting

Weinberg [Physica A96 '79]; Nyffeler/Schenk [hep-ph/9907294]; Buchalla, Catà, CK [1312.5624]

- The EFT is organized as an expansion in loops.
- This is equivalent to a counting of chiral dimensions:

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

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



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power counting

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- The EFT is organized as a...
- This is equivalent to a cou...

Example:

$$[gg' B_{\mu\nu} \langle U T_3 U^\dagger W^{\mu\nu} \rangle \, \mathcal{F}\left(\tfrac{h}{v}\right)]_\chi = 4$$
$$\rightarrow L = 1$$

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

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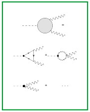
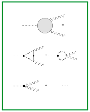


1. Current observables select $\mathcal{L}_{\text{fit}}$ from $\mathcal{L}_{ew\chi h}$.

$$\begin{aligned}\mathcal{L}_{ew\chi h} =& \mathcal{L}_{\text{kin}}^{h,\Psi,\text{gauge}} + \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \; (1+F_U(h)) - \mathcal{V}(h) \\ & - v\left(\bar{\Psi}_f Y_{j,f} U \Psi_f + \text{h.c.}\right) \; \left(\frac{h}{v}\right)^j + \mathcal{L}_{\text{NLO}}\end{aligned}$$

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



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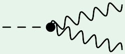
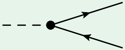
Single h processes

tree:



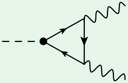
c_V



$c_{t,b,\tau}$

(3^{rd} generation only)

1-loop:

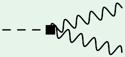


$c_{t,b,\tau}$

+

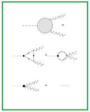
c_V

+



$c_{\gamma\gamma,gg}$

(gg and $\gamma\gamma$ only)



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

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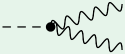

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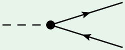

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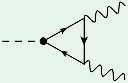
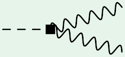


$c_{t,b,\tau}$

$+$

c_V

$+$



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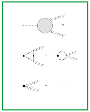

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$c_i = \text{SM} + \mathcal{O}(\xi)$

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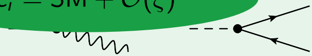

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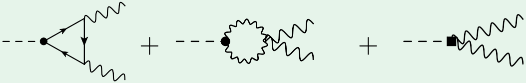

$c_{t,b,\tau}$ c_V $c_{\gamma\gamma,gg}$

(gg and $\gamma\gamma$ only)

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

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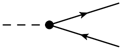

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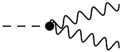

c_V

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

LHCHXSWG [1209.0040,1307.1347]

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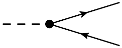
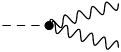
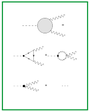


$\kappa_{t,b,\tau}$



κ_V



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Electroweak chiral Lagrangian

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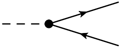
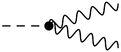
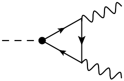


$c_{t,b,\tau}$



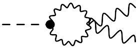
c_V

1-loop:



$c_{t,b,\tau}$

$+$



c_V

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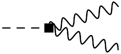
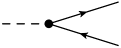


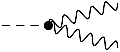
$c_{\gamma\gamma,gg}$

κ framework

tree:

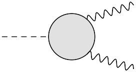


$\kappa_{t,b,\tau}$

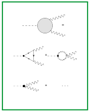


κ_V

1-loop:



$\kappa_{\gamma,g}$



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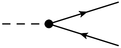
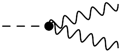


$c_{t,b,\tau}$



c_V

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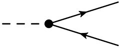
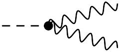


$\kappa_{t,b,\tau}$

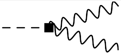


κ_V

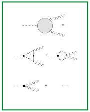
Both have the same number of free parameters:

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

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



$c_{\gamma\gamma,gg}$

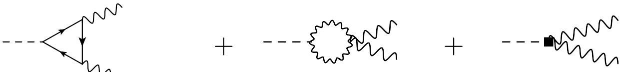


1. The κ framework cannot be recovered as a limit of the SMEFT (dim 6).

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

example: $h \to Z\gamma$

LO:



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

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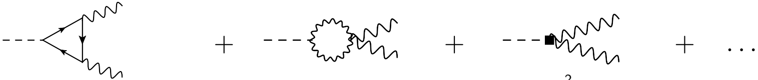
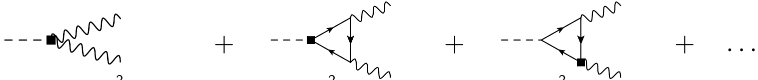
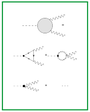


SM $+$ SM $+$ $\mathcal{O}(\frac{v^2}{\Lambda^2})$

LO + NLO:



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



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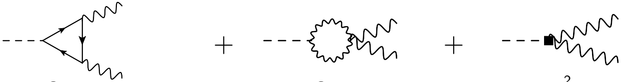
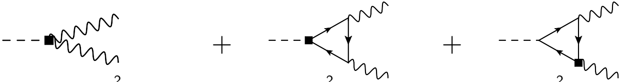
example: $h \to Z\gamma$

LO:



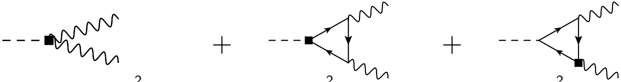
$\text{SM} + \text{SM} + \mathcal{O}(\frac{v^2}{\Lambda^2}) + \ldots$

LO + NLO:



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

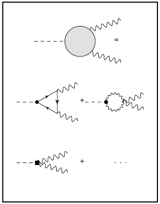
Additional assumption of weakly coupled UV Einhorn/Wudka[1307.0478]:

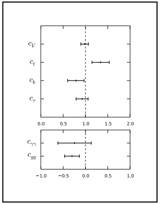


$\text{SM} + \mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2}) + \mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2}) + \mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2}) + \ldots$

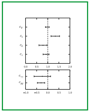
We use the electroweak chiral Lagrangian to analyze LHC data.

Part 1 – from $\mathcal{L}_{ew\chi h}$ to $\mathcal{L}_{\text{fit}}$ & the κ's
[1504.01707]





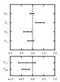
Part 2 – Fit to LHC Data
[1511.00988]



2. We performed a Bayesian fit to LHC data.

Bayes Theorem:

(**posterior pdf** probability of the parameters, given data) = **prior** × (**Likelihood** probability of data, given the parameters)



2. We performed a Bayesian fit to LHC data.

Bayes Theorem:

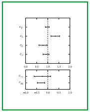
$$\left(\begin{array}{c}\textbf{posterior pdf}\\ \text{probability of the}\\ \text{parameters, given data}\end{array}\right) = \textbf{prior} \times \left(\begin{array}{c}\textbf{Likelihood}\\ \text{probability of data,}\\ \text{given the parameters}\end{array}\right)$$

flat prior in

- $c_V \in [0.5, 1.5]$
- $c_{f=t,b,\tau} \in [0, 2]$
- $c_{\gamma\gamma} \in [-1.5, 1.5]$
- $c_{gg} \in [-1, 1]$

Likelihood

- given by the code `Lilith`
  Bernon/Dumont[1502.04138]
- using `DB 15.09`
  [ATLAS-CONF-2015-044, CMS-PAS-HIG- 15-002]



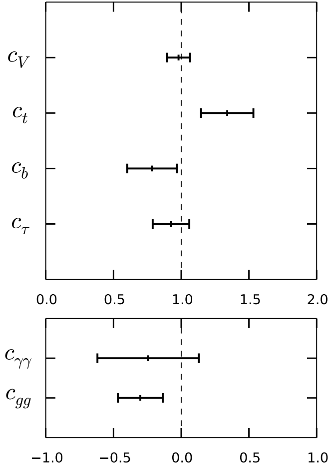
2. We performed a Bayesian fit to LHC data.

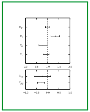
Results:

$$\begin{pmatrix} c_V \\ c_t \\ c_b \\ c_\tau \\ c_{\gamma\gamma} \\ c_{gg} \end{pmatrix} = \begin{pmatrix} 0.98 & \pm & 0.08 \\ 1.37 & \pm & 0.22 \\ 0.83 & \pm & 0.19 \\ 0.95 & \pm & 0.14 \\ -0.41 & \pm & 0.38 \\ -0.31 & \pm & 0.16 \end{pmatrix}$$

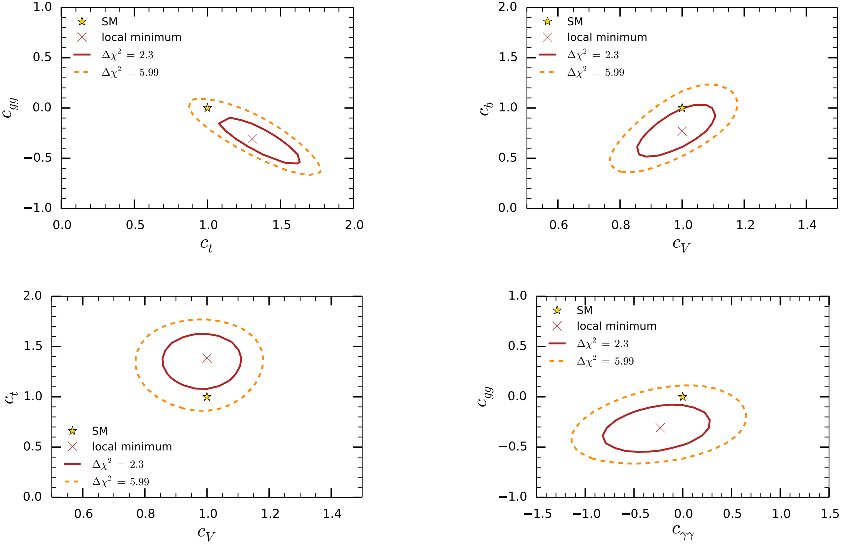
$$\rho_{ij} = \frac{\mathrm{cov}(c_i, c_j)}{\sigma_i \sigma_j} =$$

$$\begin{pmatrix} 1.0 & 0.09 & 0.68 & 0.42 & 0.33 & 0.06 \\ . & 1.0 & 0.16 & 0.01 & -0.43 & -0.73 \\ . & . & 1.0 & 0.59 & -0.07 & 0.24 \\ . & . & . & 1.0 & -0.07 & 0.18 \\ . & . & . & . & 1.0 & 0.32 \\ . & . & . & . & . & 1.0 \end{pmatrix}$$





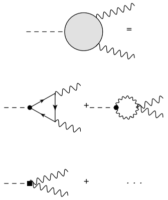
2. We performed a Bayesian fit to LHC data.



Conclusions

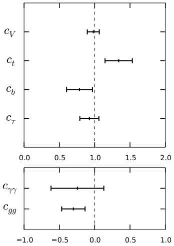
1. The electroweak chiral Lagrangian analysis at leading order [1504.01707]
    - justifies the κ framework
    - is suitable for current LHC analyses, since it is based on EFT and has rel. few parameters.

   This is in contrast to the dim-6 analysis, where new physics effects arise at NLO.



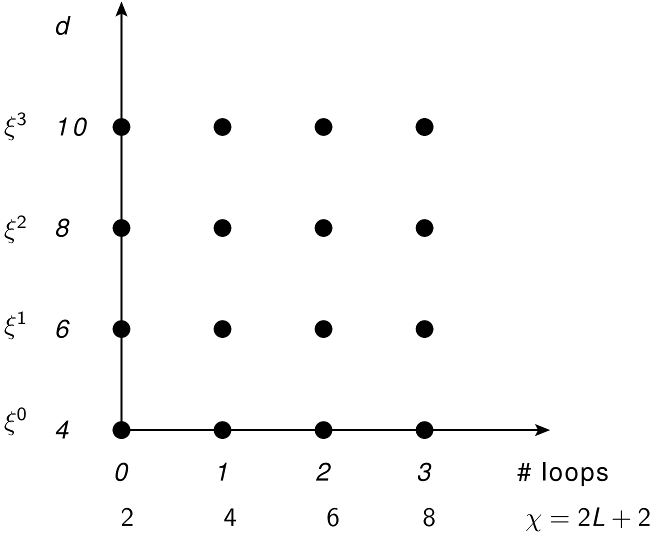
2. We fitted the set $\{c_V, c_t, c_b, c_\tau, c_{\gamma\gamma}, c_{gg}\}$ to LHC data: [1511.00988]

$$\begin{pmatrix} c_V \\ c_t \\ c_b \\ c_\tau \\ c_{\gamma\gamma} \\ c_{gg} \end{pmatrix} = \begin{pmatrix} 0.98 & \pm & 0.08 \\ 1.37 & \pm & 0.22 \\ 0.83 & \pm & 0.19 \\ 0.95 & \pm & 0.14 \\ -0.41 & \pm & 0.38 \\ -0.31 & \pm & 0.16 \end{pmatrix}$$

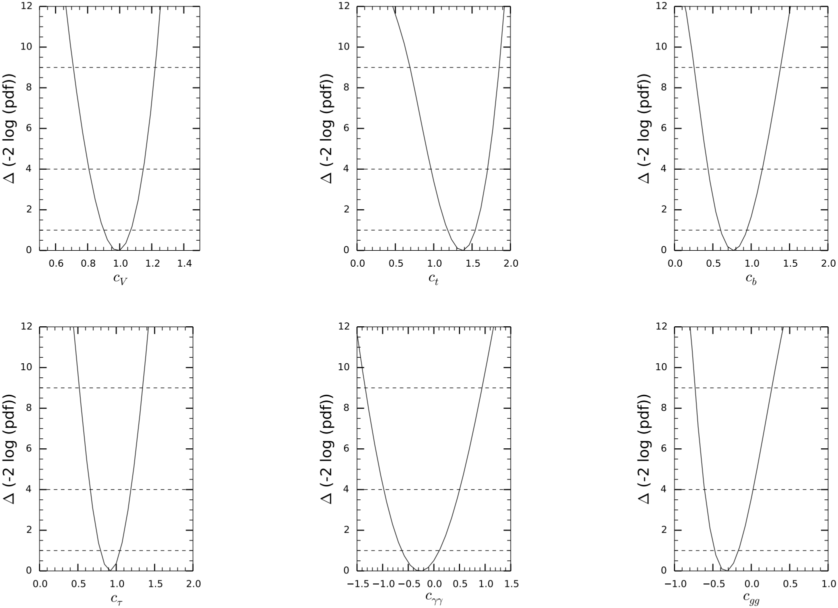


Backup

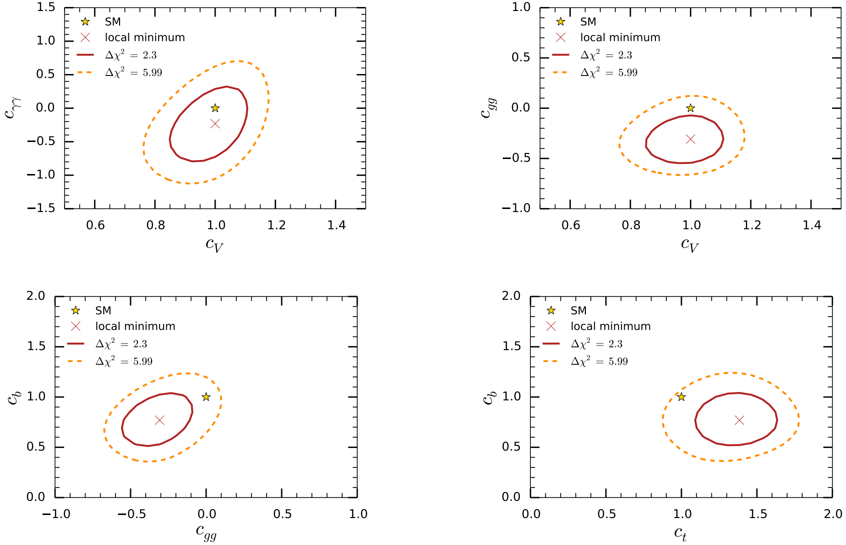
The difference between expansions in canonical and chiral dimensions:



$\Delta\chi^2$ for the one-dimensional marginalized pdf:



Further 2-dim plots



Further 2-dim plots