

# Current and future constraints on Higgs couplings in the nonlinear Effective Theory

– HL/HE LHC Meeting, Fermilab –

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(previously: IFIC — Instituto de Física Corpuscular, Valencia (CSIC))

April 5, 2018

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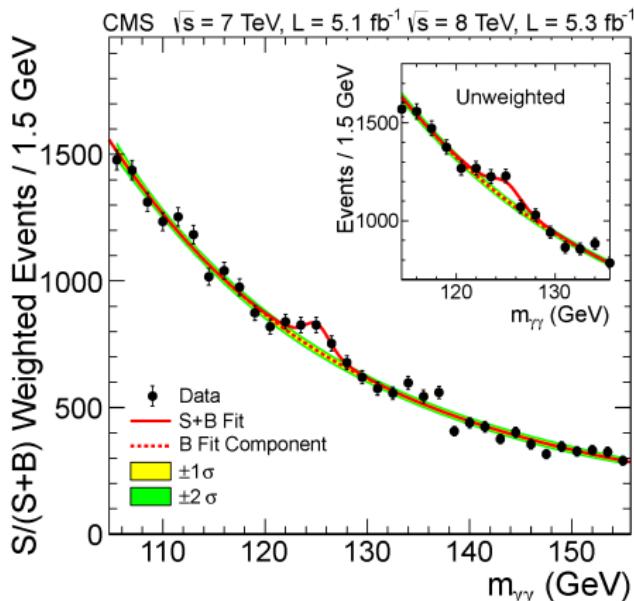


Alexander von Humboldt  
Stiftung/Foundation



In collaboration with: Jorge de Blas and Otto Eberhardt  
arXiv:1803.00939

# Is that the Higgs of the Standard Model?

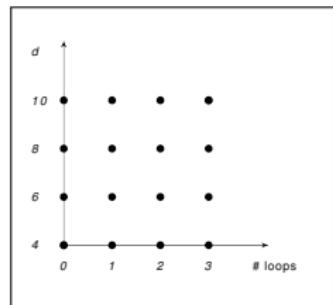
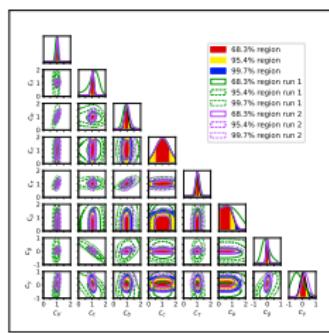


[1207.7235]

⇒ Answers beyond Yes/No are best addressed using a (model-independent) bottom-up Effective Field Theory.

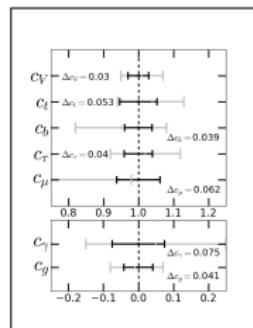
# Current and future constraints on Higgs couplings in the nonlinear Effective Theory

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



## Part II: The Fit to Current Data [1803.00939]

## Part III: Future Prospects [1803.00939]





# 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:  $SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{em}$ ,  $B$ ,  $L$   
at LO: flavor and custodial symmetry
- Power counting: in terms of chiral dimensions

Buchalla/Catà/CK

$$2L + 2 = [\text{couplings}]_\chi + [\text{derivatives}]_\chi + [\text{fields}]_\chi \quad [1312.5624]$$

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



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

Properties:

- It has generalized Higgs-couplings compared to the SM.
- There is a hierarchy to the operators that modify the EWPD.

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

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

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



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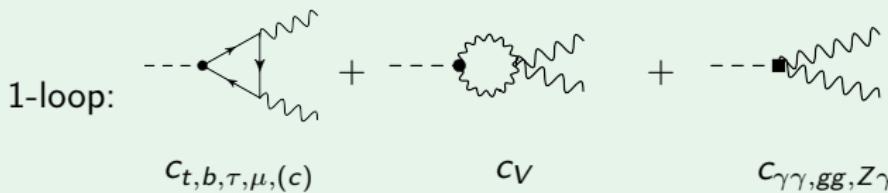
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## Single $h$ processes



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





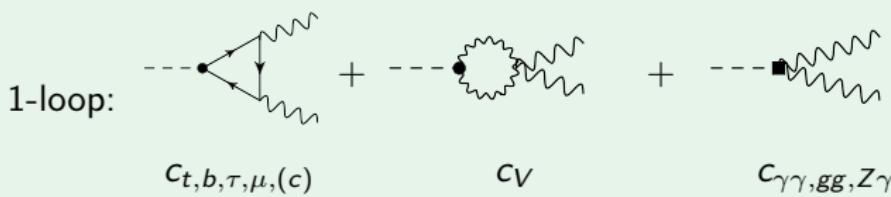
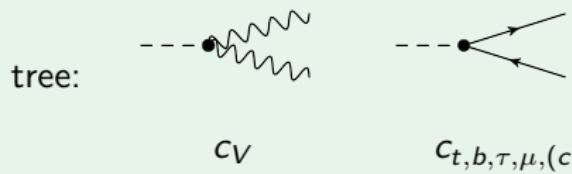
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Buchalla/Catà/Celis/CK [1504.01707]

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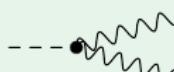
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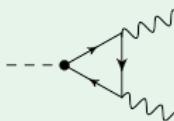
tree:



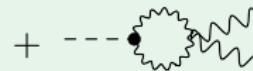
$c_V$

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

1-loop:



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



$c_V$



$c_{\gamma\gamma,gg,Z\gamma}$



# I: There is a relation between the electroweak chiral Lagrangian and the $\kappa$ framework.

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

tree:

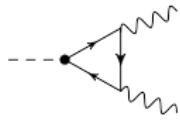
$$c_{t,b,\tau}$$



$$c_V$$

1-loop:

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

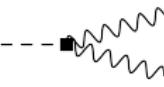


+

$$c_V$$

+

$$c_{\gamma\gamma,gg}$$



$$\kappa_i^2 = \Gamma^i / \Gamma_{SM}^i, \quad \kappa_i^2 = \sigma^i / \sigma_{SM}^i$$

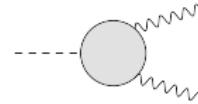
LHCHXSWG [1209.0040, 1307.1347]

tree:

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



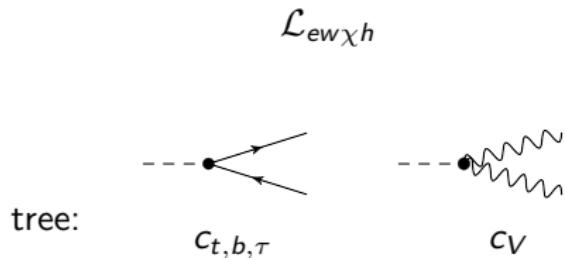
$$\kappa_V$$



$$\kappa_{\gamma,g}$$

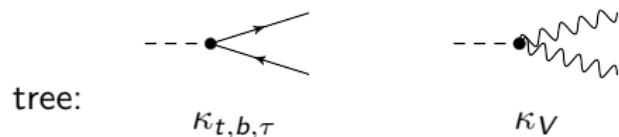


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$$\kappa_i^2 = \Gamma^i / \Gamma_{SM}^i, \quad \kappa_i^2 = \sigma^i / \sigma_{SM}^i$$

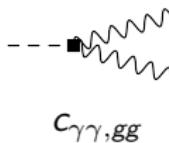
LHCHXSWG [1209.0040, 1307.1347]



Both have the same number of free parameters:

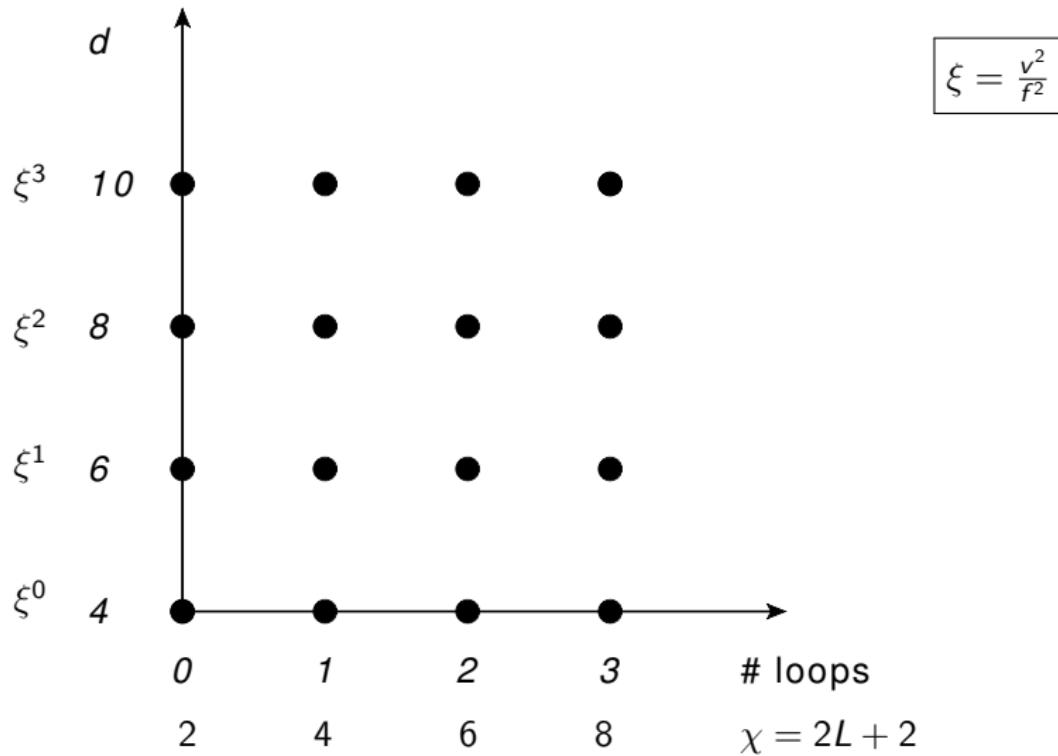
$$\{c_V, c_{t,b,\tau}, c_\gamma, c_g\} \quad vs. \quad \{\kappa_V, \kappa_{t,b,\tau}, \kappa_\gamma, \kappa_g\}$$

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



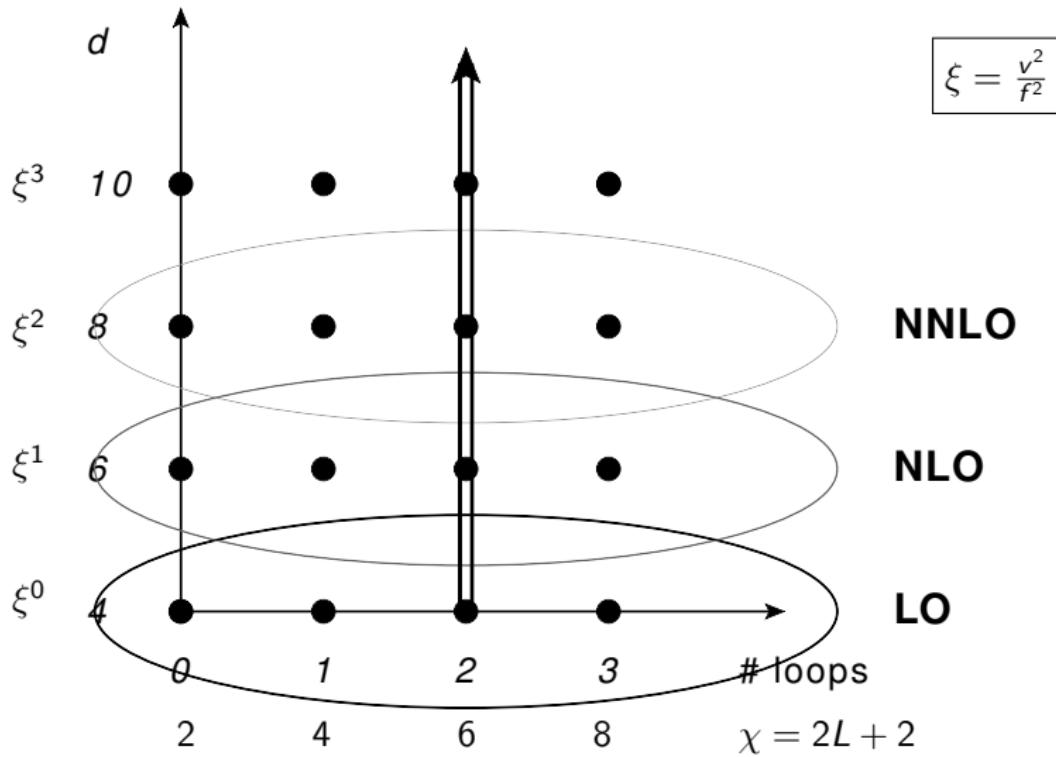


# I: A graphical way to see the relation of SMEFT vs. $\text{ew}\chi\mathcal{L}$



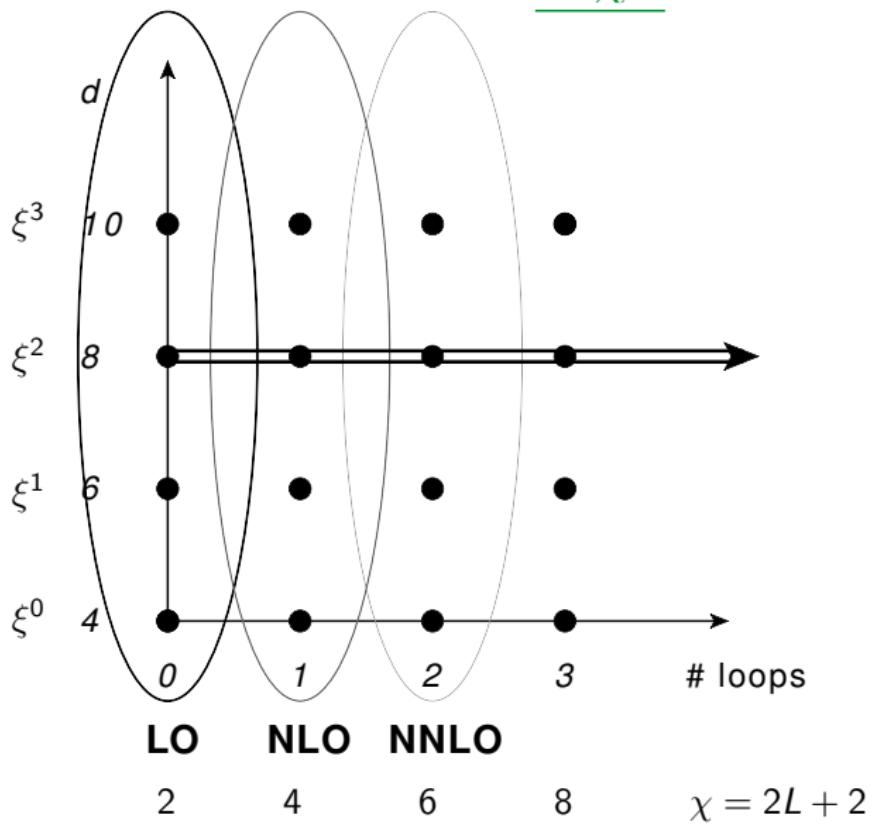


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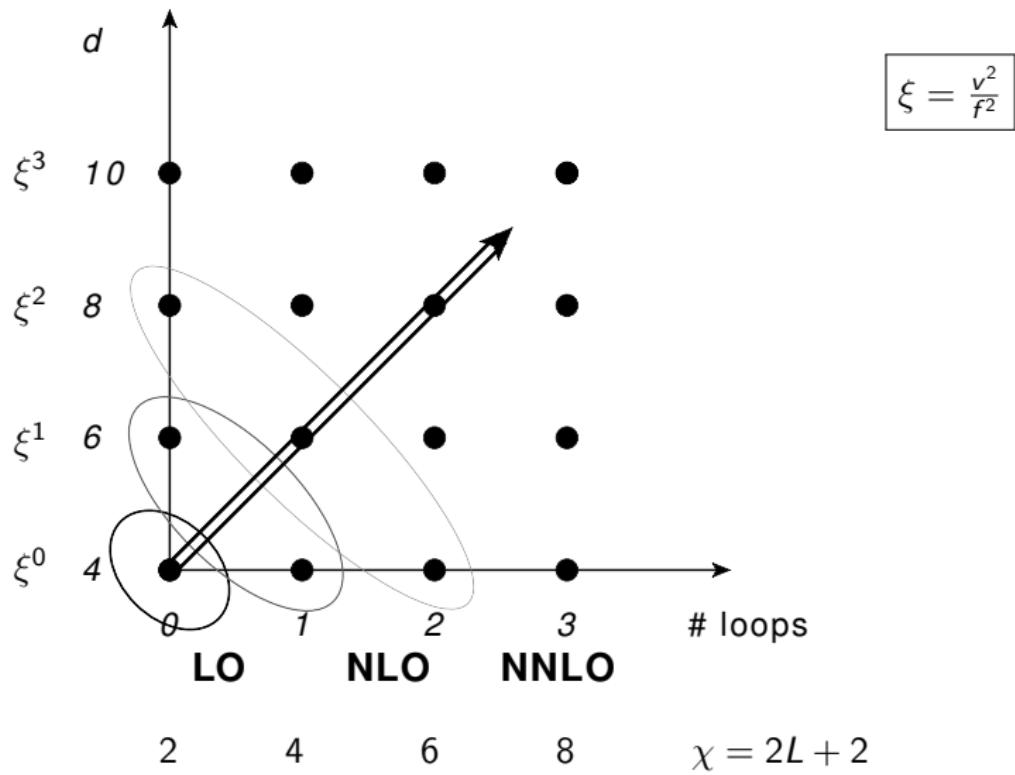
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$$\xi = \frac{v^2}{f^2}$$

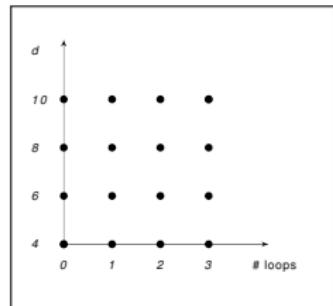
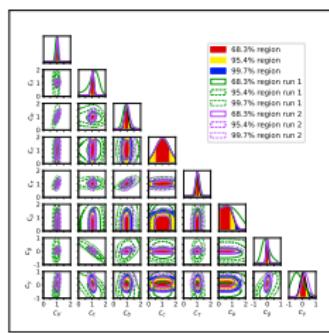


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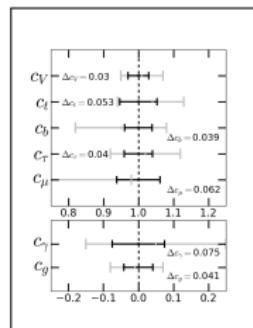


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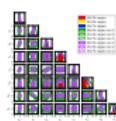
## Part I: The Electroweak Chiral Lagrangian [1307.5017,1412.6356,1504.01707]



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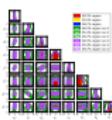
## II: We use HEPfit for the Likelihood.

HEPfit:

$\Rightarrow$  <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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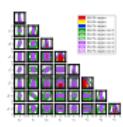
The HEPfit Collaboration [in preparation]

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]



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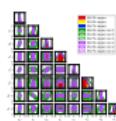
Experimental input: For each decay channel we use the signal strength

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

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

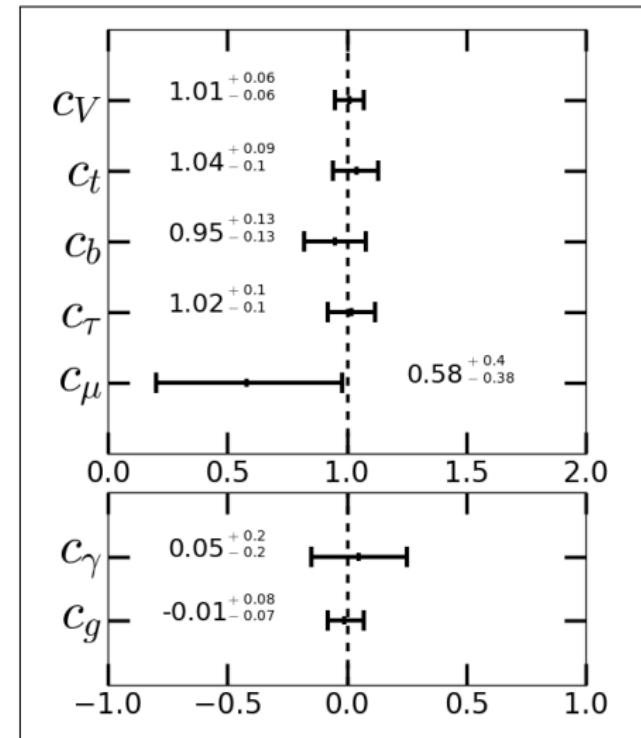
We used all available data up to (& incl.) Moriond 2018:

- $h \rightarrow \bar{b}b$  from CDF & D $\emptyset$
  - ATLAS & CMS run 1, [24–25  $\text{fb}^{-1}$ ]
  - ATLAS & CMS run 2, [36  $\text{fb}^{-1}$ ]
- ⇒ a total of 126 observables

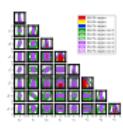


## II: The Posterior around the SM solution.

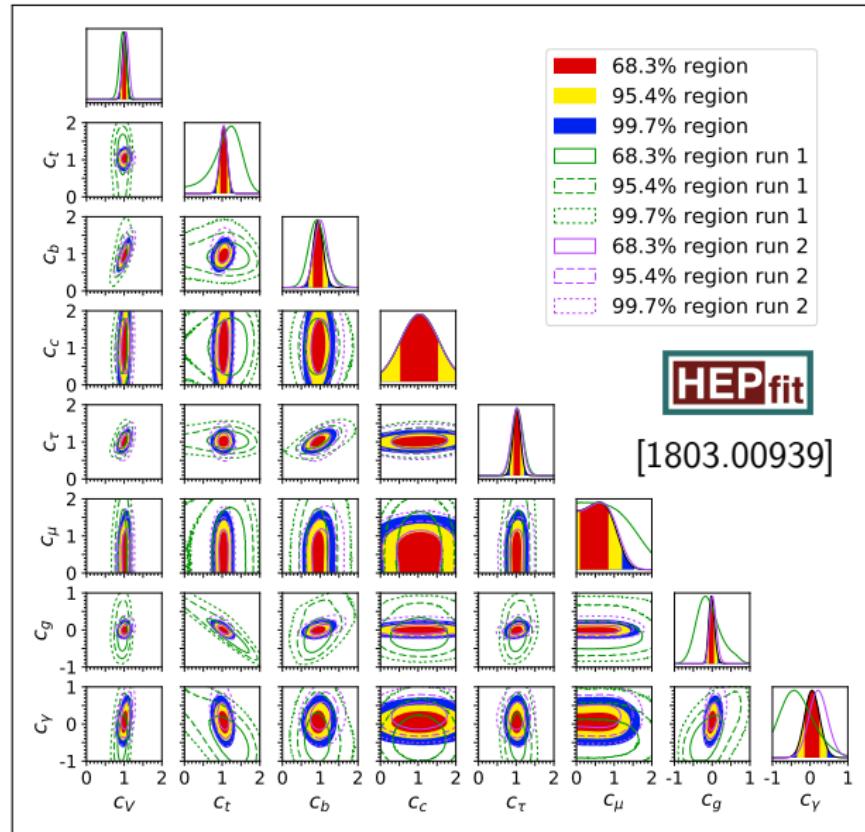
- The likelihood has multiple maxima ( $c_i \rightarrow -c_i$  symmetries).
- We use a prior to select the SM-like solution.
- More details about the choice of priors are in [1803.00939].
- Consistent with SM, but  $\mathcal{O}(10\%)$  deviations still possible.
- $c_{Z\gamma}$  and  $c_c$  are not constrained beyond prior.



de Blas/Eberhardt/CK [1803.00939]

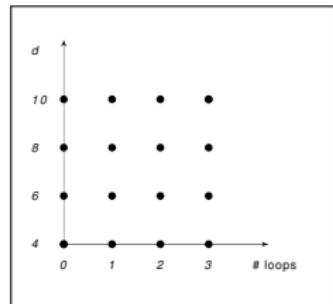
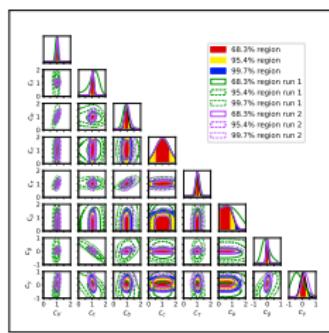


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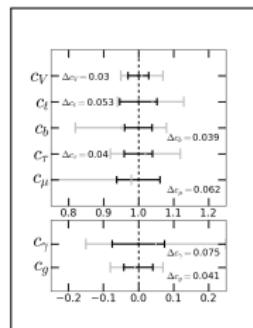


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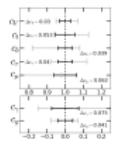
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## Part II: The Fit to Current Data [1803.00939]



## Part III: Future Prospects [1803.00939]



### III: How will the uncertainties evolve?

Experimental input:

- We focus on  $3 \text{ ab}^{-1}$  of the HL-LHC
- We use projections on signal strength uncertainties taken from

ATLAS-PHYS-PUB-2014-016

CMS Snowmass '13

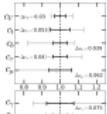
ATLAS-PHYS-PUB-2014-011

[1307.7135]

ATLAS-PHYS-PUB-2013-014

Procedure:

- We assume a Gaussian around the SM, with the exp. uncertainty as width.
- We do not include new channels.  
(even though they might become accessible)
- We use a flat prior for all  $c_i$ .



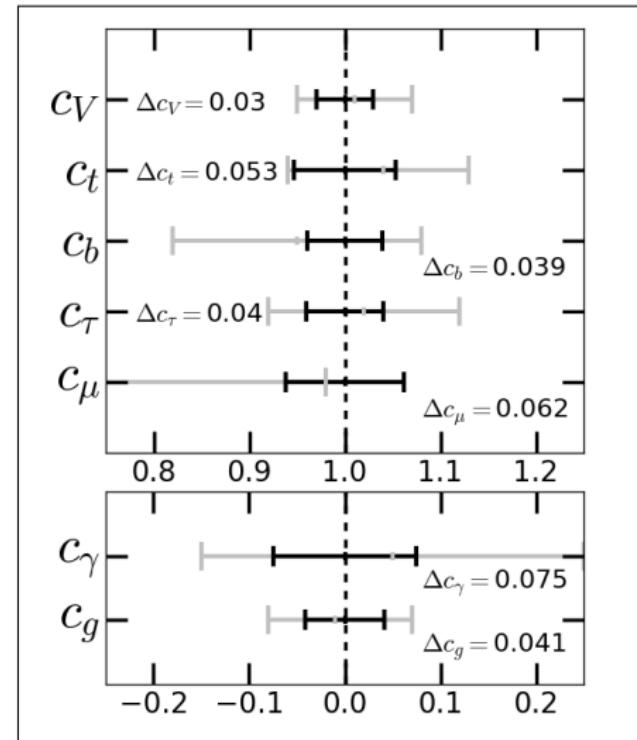
### III: The uncertainties at the HL-LHC are $\mathcal{O}(5\%)$ .

Improvements:

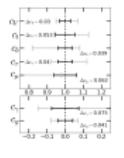
- $c_V$ ,  $c_t$ ,  $c_\tau$ , and  $c_g$  gain a factor of 2.
- $c_b$ , and  $c_\gamma$  gain a factor of 3.
- $c_\mu$  gains a factor of 6.

⇒ The overall uncertainty goes down to  $\mathcal{O}(5\%)$ .

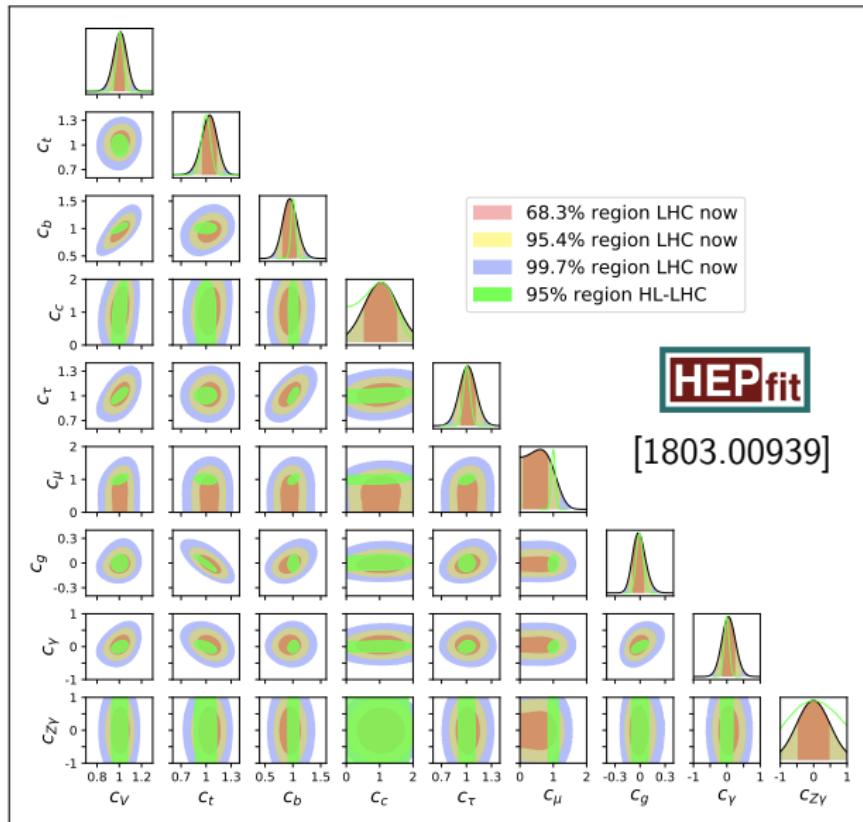
Loop corrections will start to become important at this level.

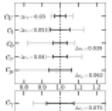


de Blas/Eberhardt/CK [1803.00939]



### III: The Posterior of the HL-LHC projection.





### III: The Minimal Composite Higgs Model

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

- global symmetry spontaneously broken at scale  $f$ :  $SO(5) \rightarrow SO(4)$
- $SU(2)_L \times U(1)_Y \subset SO(4)$  is gauged
- massive  $W^\pm/Z$ , light  $h$

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

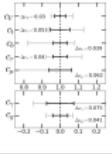
where

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

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

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

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

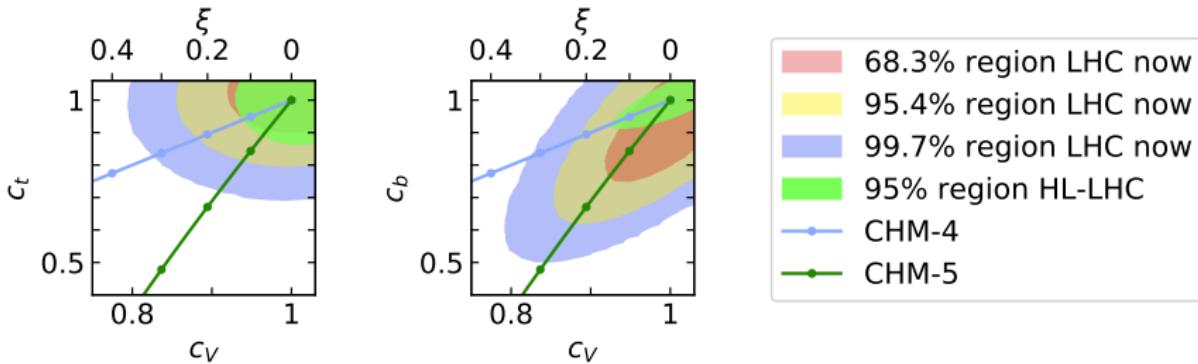


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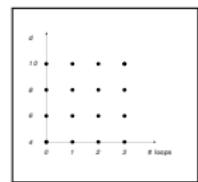
The fermion couplings depend on the representation of the fermion. Minimal choices are **4** and **5**, giving:

$$c_\psi^{(4)} = \sqrt{1 - \xi} \quad \text{and} \quad c_\psi^{(5)} = \frac{1 - 2\xi}{\sqrt{1 - \xi}}.$$



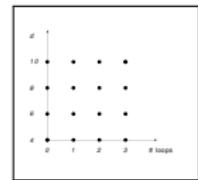
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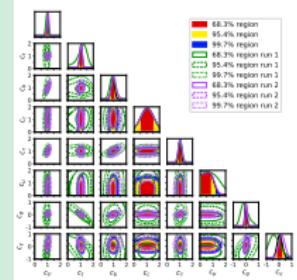


The fit to current LHC data gives an uncertainty of  $\mathcal{O}(10\%)$ .

$$c_V = 1.01 \pm 0.06 \quad c_t = 1.04^{+0.09}_{-0.1} \quad c_b = 0.95 \pm 0.13$$

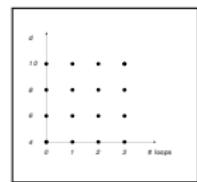
$$c_\tau = 1.02 \pm 0.1 \quad c_\mu = 0.58^{+0.4}_{-0.38}$$

$$c_g = -0.01^{+0.08}_{-0.07} \quad c_\gamma = 0.05 \pm 0.2$$



# Summary

- I introduced the electroweak chiral Lagrangian.
- It is related to the  $\kappa$ -formalism, but more suitable for theorist's interpretations.

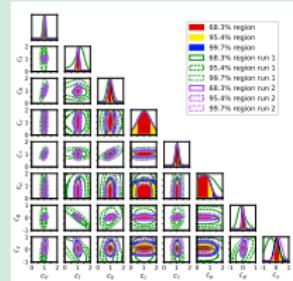


The fit to current LHC data gives an uncertainty of  $\mathcal{O}(10\%)$ .

$$c_V = 1.01 \pm 0.06 \quad c_t = 1.04^{+0.09}_{-0.1} \quad c_b = 0.95 \pm 0.13$$

$$c_\tau = 1.02 \pm 0.1 \quad c_\mu = 0.58^{+0.4}_{-0.38}$$

$$c_g = -0.01^{+0.08}_{-0.07} \quad c_\gamma = 0.05 \pm 0.2$$

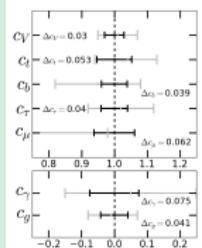


The projection to HL-LHC gives an uncertainty of  $\mathcal{O}(5\%)$ .

$$\Delta c_V = 0.03 \quad \Delta c_t = 0.053 \quad \Delta c_b = 0.039$$

$$\Delta c_\tau = 0.04 \quad \Delta c_\mu = 0.062$$

$$\Delta c_g = 0.041 \quad \Delta c_\gamma = 0.075$$



# Backup

# The construction of the electroweak chiral Lagrangian

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

- $\mathcal{L}_{\text{LO}}$  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.

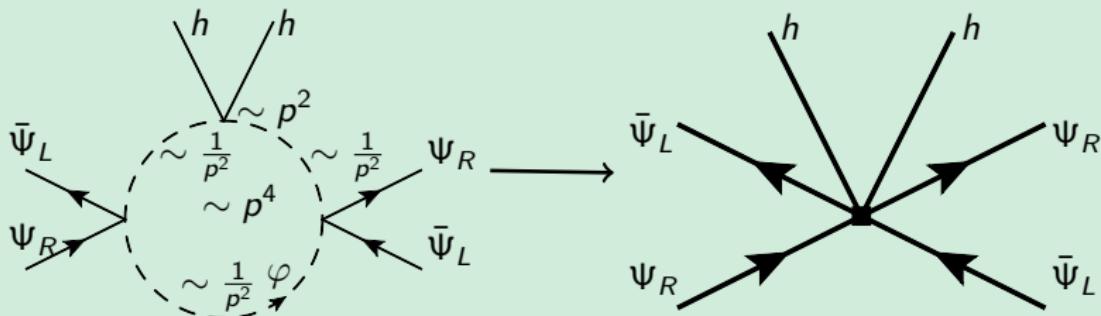


- ⇒ The basis of NLO-operators is at least given by the counterterms of the one loop divergences.
- We identify  $\frac{f^2}{\Lambda^2} \simeq \frac{1}{16\pi^2}$ .
- There is an additional ratio of scales:  $\xi = \frac{v^2}{f^2}$

# The Power counting is based on a loop expansion.

How can we identify the necessary counterterms?

1) Using the superficial degree of divergence:



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

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]

# The $\kappa$ framework cannot be recovered as a limit of the SMEFT (dim 6).

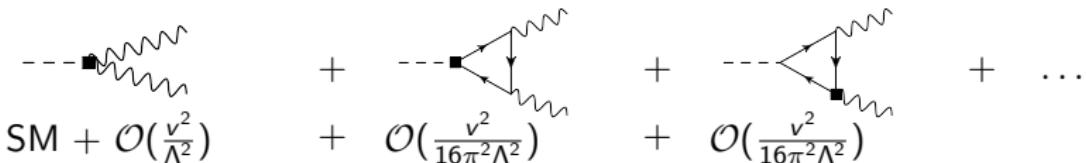
Full dimension 6 Grzadkowski *et al.* [1008.4884]:

example:  $h \rightarrow Z\gamma$

LO:



LO + NLO:



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

