Current and Future Constraints on Higgs Couplings

– PASCOS, Cleveland, OH –

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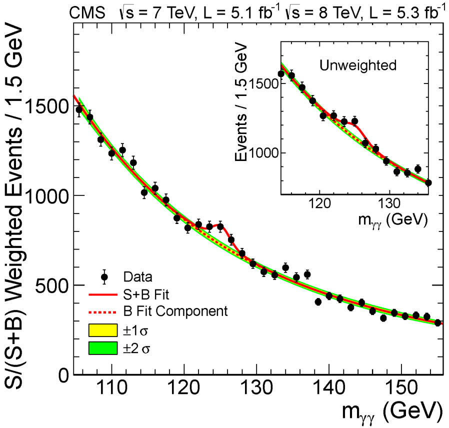
In collaboration with:
Jorge de Blas and Otto Eberhardt, arXiv:1803.00939;
Gerhard Buchalla, Oscar Catà, and Alejandro Celis, arXiv:1504.01707, Phys. Lett. B **750** (2015) 298

Is that the Higgs of the Standard Model?

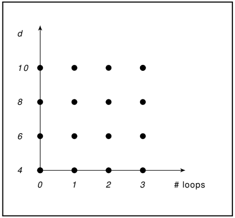


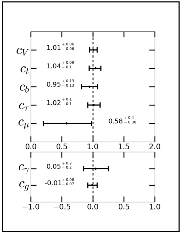
[1207.7235]

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

Current and Future Constraints on Higgs Couplings

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
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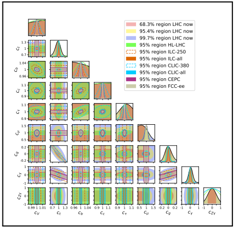
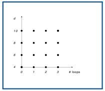




I: The Electroweak Chiral Lagrangian is an EFT.

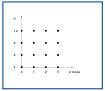
Ingredients:

- 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 [1312.5624]

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

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



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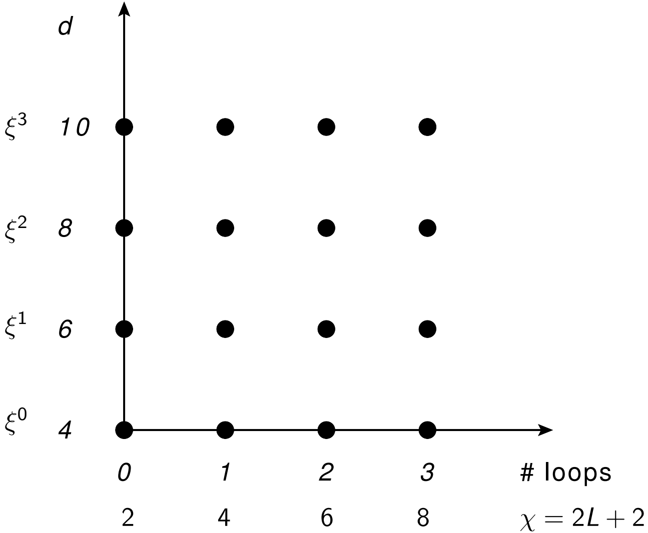
Properties:

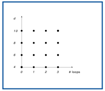
- It has generalized Higgs-couplings compared to the SM.
- There is a hierarchy to the operators that modify the EWPD.

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 power counting.

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





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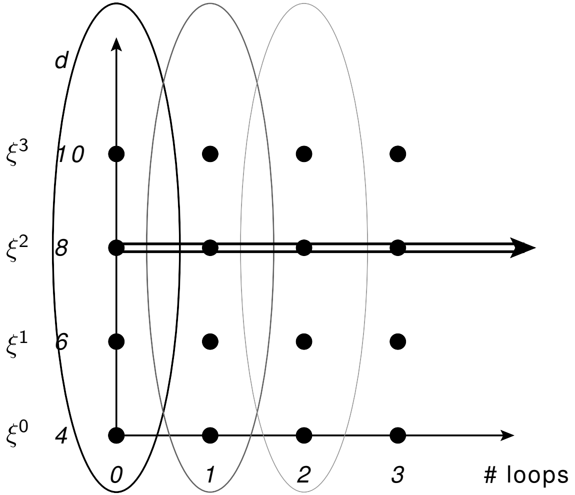

LO	**NLO**	**NNLO**		
2	4	6	8	$\chi = 2L + 2$

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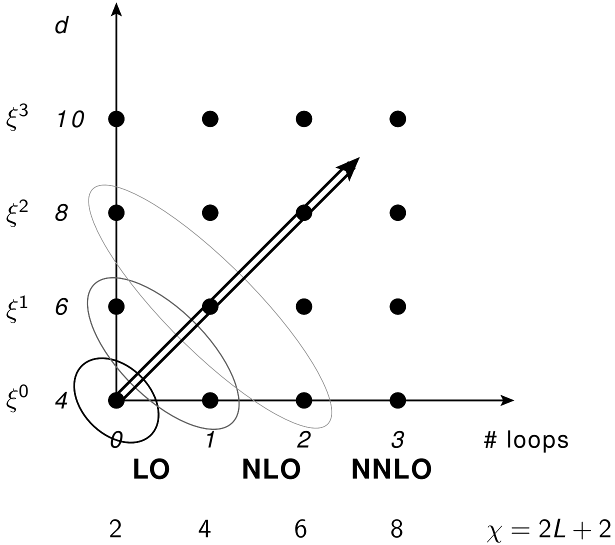
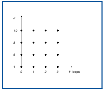
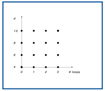




I: Current observables select $\mathcal{L}_{\text{fit}}$ from $\mathcal{L}_{ew\chi h}$.

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

Buchalla/Catà/Celis/CK [1504.01707]



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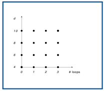

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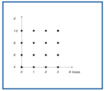

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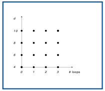

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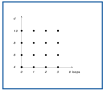

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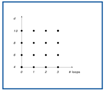

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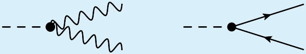
Buchalla/Catà/Celis/CK [1504.01707]

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

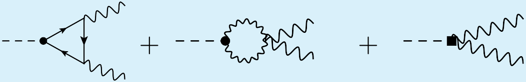
Single h processes:

tree:

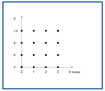


c_V $\quad$ $c_{t,b,\tau,\mu,(c)}$

1-loop:



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



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$$- c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_c y_c \bar{c} c h - c_\tau y_\tau \bar{\tau} \tau h - c_\mu y_\mu \bar{\mu} \mu h$$
$$+ \frac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{e^2}{16\pi^2} c_{Z\gamma} Z_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu} G^{\mu\nu} \rangle \frac{h}{v}$$

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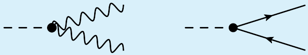

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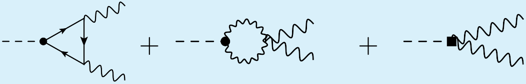

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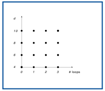

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Buchalla/Catà/Celis/CK [1504.01707]

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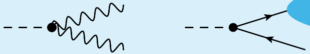
Single h processes:

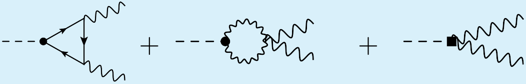
$c_i = \text{SM} + \mathcal{O}(\xi)$

tree:



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

1-loop:



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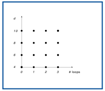
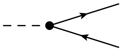


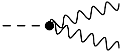
I: There is a relation between the electroweak chiral Lagrangian and the κ framework.

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

tree:

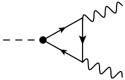


$c_{t,b,\tau}$

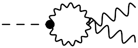


c_V

1-loop:



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



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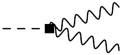
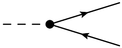


$c_{\gamma\gamma,gg}$

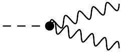
$\kappa_i^2 = \Gamma^i/\Gamma^i_{\mathrm{SM}}, \quad \kappa_i^2 = \sigma^i/\sigma^i_{\mathrm{SM}}$

LHCHXSWG [1209.0040,1307.1347]

tree:



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



κ_V

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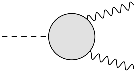
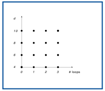


$\kappa_{\gamma,g}$



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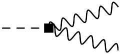
$\mathcal{L}_{ew\chi h}$

tree: $c_{t,b,\tau}$ c_V

1-lo



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

LHCHXSWG [1209.0040,1307.1347]

tree: $\kappa_{t,b,\tau}$ κ_V

$\kappa_{\gamma,g}$

Both have the same number of free parameters:

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

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

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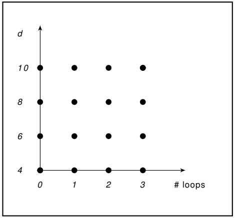

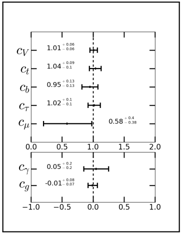

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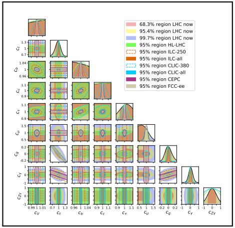
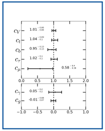


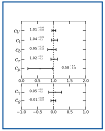


II: We use HEPfit for the Likelihood.

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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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: We use HEPfit for the Likelihood.

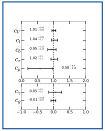
Experimental input: For each decay channel we use the signal strength

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

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

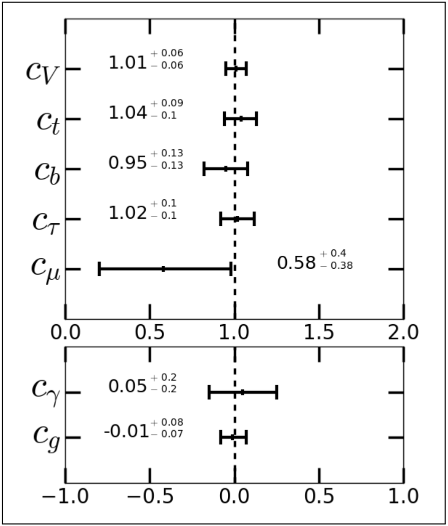
		$b\bar{b}$	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$Z\gamma$	$\mu\mu$
	SM Br	57.5%	21.6%	6.3%	2.7%	2.3‰	1.6‰	0.2‰
ggF8	87.2%	–	AC	AC	AC	AC	AC	AC
ggF13	87.1%	–	AC	C	AC	AC	AC	AC
VBF8	7.2%	–	AC	AC	AC	AC	AC	AC
VBF13	7.4%	C	AC	C	AC	AC	AC	AC
Vh8	5.1%	AC	AC	AC	AC	AC	AC	AC
Vh13	4.4%	AC	AC	C	AC	AC	AC	AC
tth8	0.6%	AC	–	–	AC	AC	AC	AC
tth13	1.0%	AC	AC	AC	AC	AC	AC	AC
Vh2		Tev	Uncertainty of the signal strengths $\mu \pm \Delta\mu$:					
tth2		Tev	$0 < \Delta\mu < 0.5$		$0.5 \leq \Delta\mu < 1.0$		$\Delta\mu > 1.0$	

Table by Otto Eberhardt, HEFT '18, Mainz

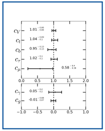


II: The Posterior around the SM solution.

- The likelihood has multiple maxima ($c_i \to -c_i$ 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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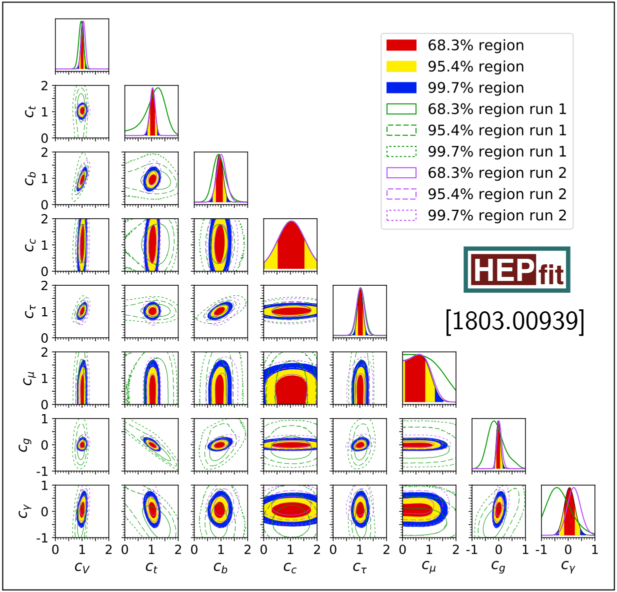
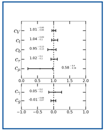




II: We connect to the κ-framework.

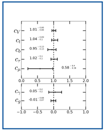
$$\kappa_i^2 = \Gamma^i/\Gamma^i_{\text{SM}}, \quad \kappa_i^2 = \sigma^i/\sigma^i_{\text{SM}}$$

LHCHXSWG [1209.0040,1307.1347]

Assuming vanishing imaginary parts, we find a linear transformation $c_i(\kappa_j)$.

$\Rightarrow$ To properly translate the uncertainties, we need the correlations.

Parameter	Fit result	Parameter	Fit result	Result translated from κ (ignoring κ correlations)
κ_V	1.00 ± 0.06	c_V	1.00 ± 0.06	1.00 ± 0.06
κ_t	$1.04^{+0.09}_{-0.10}$	c_t	1.03 ± 0.09	1.04 ± 0.10
κ_b	0.94 ± 0.13	c_b	0.94 ± 0.13	0.94 ± 0.13
κ_ℓ	1.00 ± 0.10	c_τ	1.01 ± 0.10	1.00 ± 0.10
κ_g	$1.02^{+0.08}_{-0.07}$	c_g	$-0.01^{+0.08}_{-0.07}$	-0.02 ± 0.10
κ_γ	0.97 ± 0.07	c_γ	0.05 ± 0.20	0.06 ± 0.35



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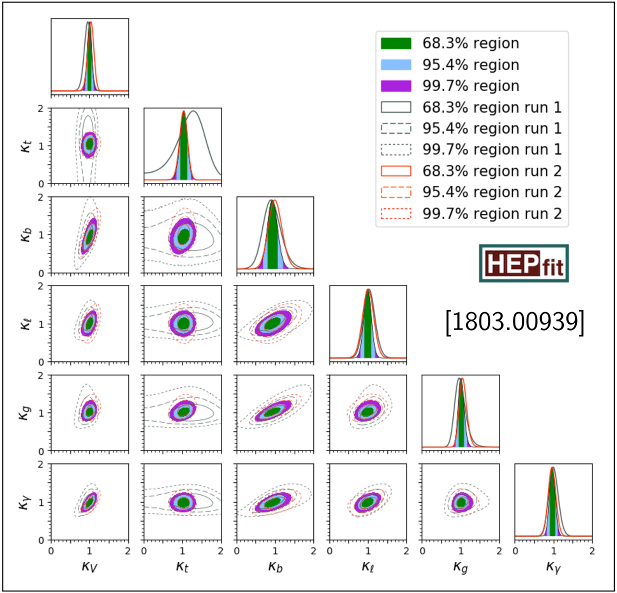
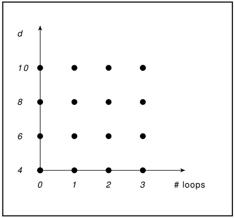
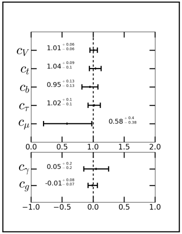


Current and Future Constraints on Higgs Couplings

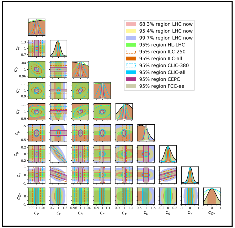
Part I: The Electroweak Chiral Lagrangian
[1307.5017,1412.6356,1504.01707]

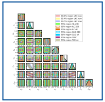




Part II: The Fit to Current Data
[1803.00939]

Part III: Future Prospects
[1803.00939]



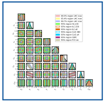


III: Several different future colliders are proposed.

Collider	HL-LHC	ILC 250	ILC all	CLIC 380	CLIC all	CEPC	FCC-ee
L [ab^{-1}]	3	1.2	5.3	0.5	4	5	12.6
$\sqrt{s}$ [TeV]	14	0.25	0.25 0.5 1.0	0.38	0.38 1.4 3.0	0.25	0.24 0.35

Procedure:

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



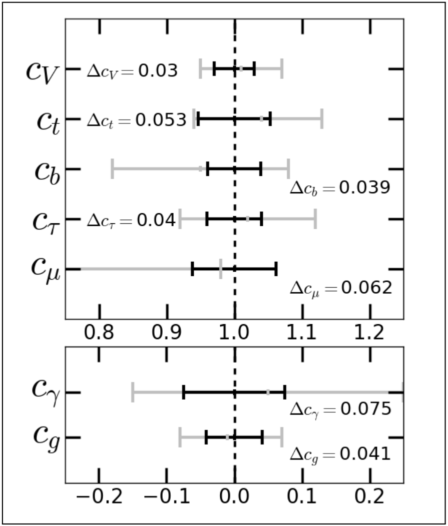
III: The uncertainties at the HL-LHC are $\mathcal{O}(5\%)$.

Improvements:

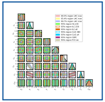
- c_V, c_t, c_τ, and c_g gain a factor of 2.
- c_b, and c_γ gain a factor of 3.
- c_μ gains a factor of 6.

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

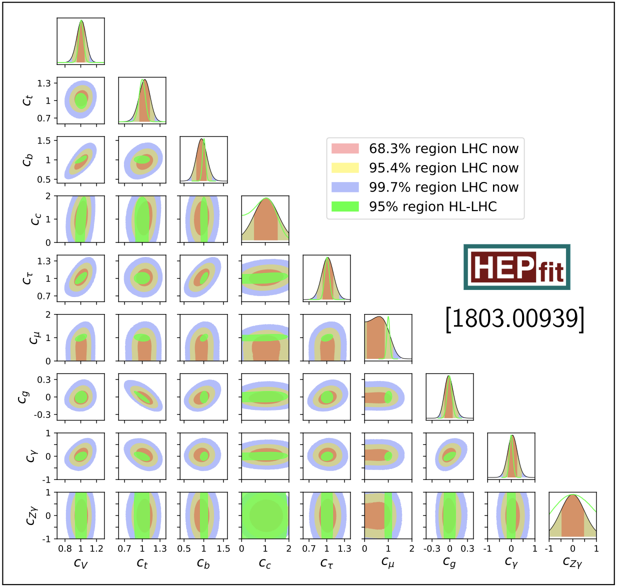
Loop corrections will start to become important at this level.

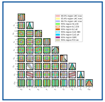


de Blas/Eberhardt/CK [1803.00939]

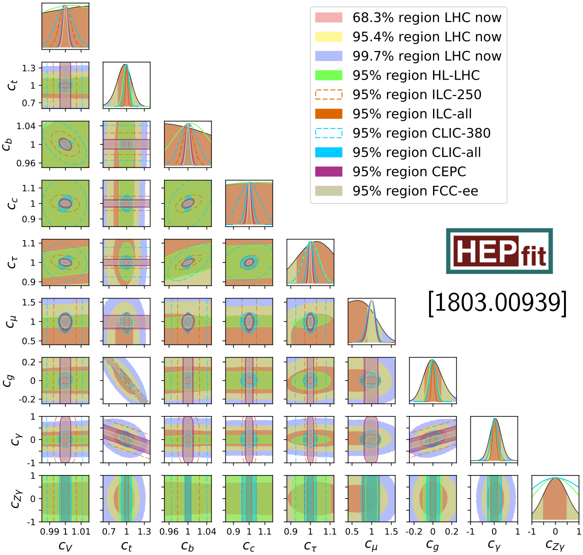


III: The Posterior of the HL-LHC projection.





III: The future collider projection.



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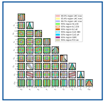

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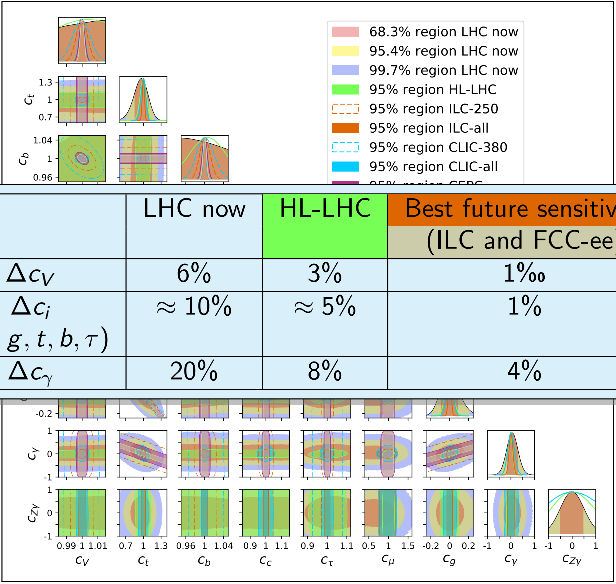
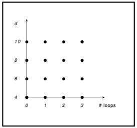


	LHC now	HL-LHC	Best future sensitivity (ILC and FCC-ee)
Δc_V	6%	3%	1‰
Δc_i $(i = g, t, b, \tau)$	$\approx$ 10%	$\approx$ 5%	1%
Δc_γ	20%	8%	4%

Summary

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



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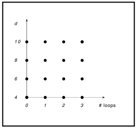
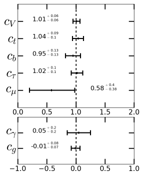


The fit to current LHC data gives an uncertainty of $\mathcal{O}(10\%)$.

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

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

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



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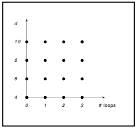

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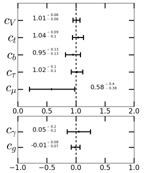


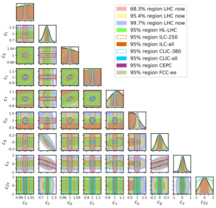
The projection to HL-LHC gives an uncertainty of $\mathcal{O}(5\%)$.

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

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

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

Other future colliders might constrain some of them to ‰.



Backup

The construction of the electroweak chiral Lagrangian

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

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

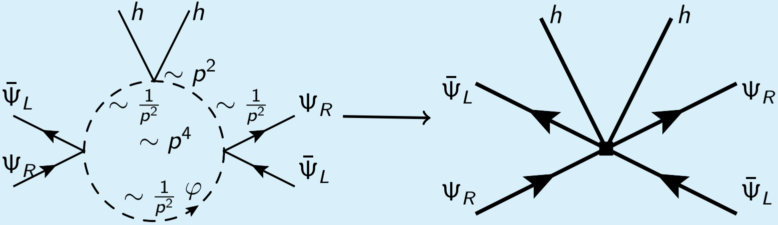
⇒ The basis of NLO-operators is at least given by the counterterms of the one loop divergences.

- 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.

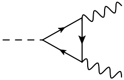
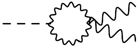
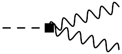
Buchalla/Catà/Celis/Knecht/CK [1710.06412]; Abbott ['82 Acta Phys. Polon. B]; Neufeld/Gasser/Ecker [hep-ph/9806436]; Alonso/Kanshin/Saa [1710.06848]

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

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

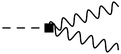
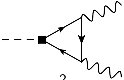
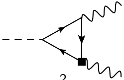
example: $h \to Z\gamma$

LO:

 $+$  $+$  $+ \ldots$

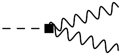
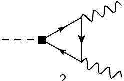
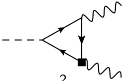
SM $+$ SM $+$ $\mathcal{O}(\frac{v^2}{\Lambda^2})$

LO $+$ NLO:

 $+$  $+$  $+ \ldots$

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]:

 $+$  $+$  $+ \ldots$

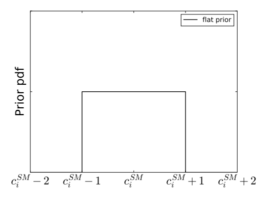
SM $+ \mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$ $+$ $\mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$ $+$ $\mathcal{O}(\frac{v^2}{16\pi^2\Lambda^2})$

The Prior reflects our initial knowledge.

We expect the size of the parameters to be

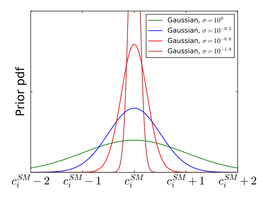
$$c_i = \mathrm{SM} + \mathcal{O}(\xi)$$

Flat prior



- ✓ Gives Likelihood
- × All values have same weight
- × Hard cutoff

Gaussian prior



- ✓ Reflects knowledge best

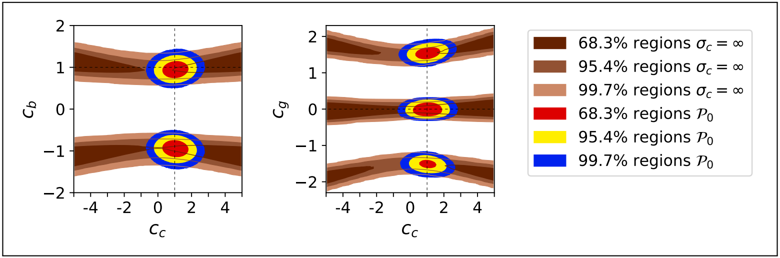
  Jaynes ['57 Phys. Rev.]
- × Which is the right width?

The result should be independent of the particular prior implementation!

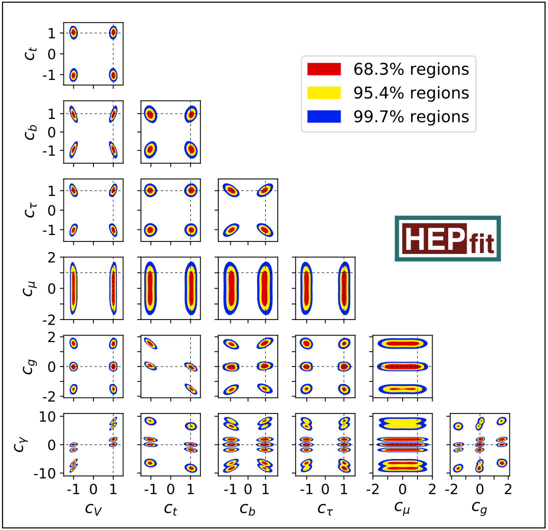
⇒ Study Prior dependence   Wesolowski/Klco/Furnstahl/Phillips/Thapaliya [1511.03618]

Completely Flat Prior — Overfitting.

- There is no measurement that strongly constraints c_c.
  Current limit: $\mu_{h\to cc} < 110$ ATLAS [1802.04329]
- Fitting it with a large, flat prior leads to **overfitting**.
- Large c_c decreases the $\text{Br}(h \to Y)$, $(Y \neq \bar{c}c)$
  all c_i compensate in production, the SM seems fine-tuned.

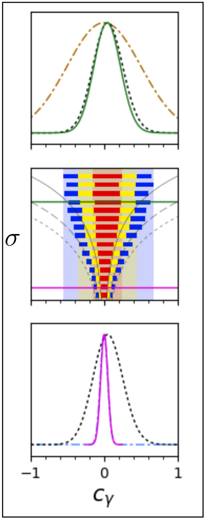


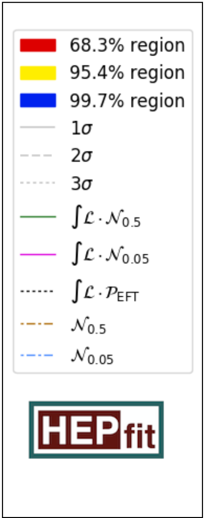
Flat Prior — the pure Likelihood.



$$\text{all priors flat, except } \pi(c_{c,Z\gamma}) \sim \exp\left[-\frac{(c_{c,Z\gamma}-c_{c,Z\gamma}^{\text{SM}})^2}{2\,(0.5)^2}\right].$$

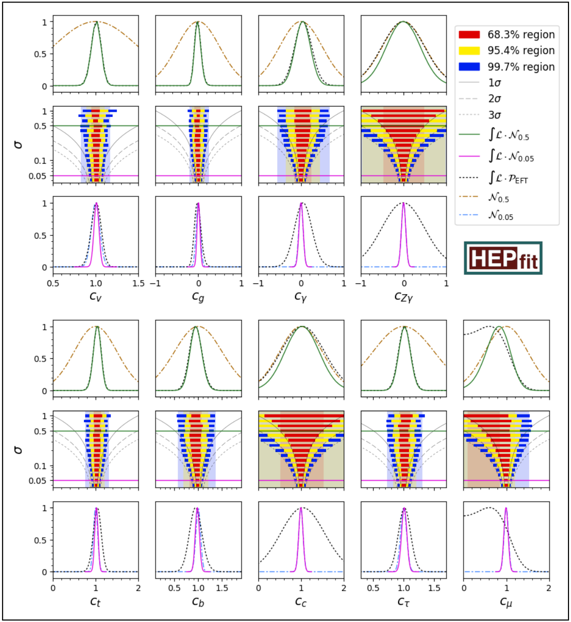
We study the prior dependence.





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.

We study the prior dependence.



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

$\to$ 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:

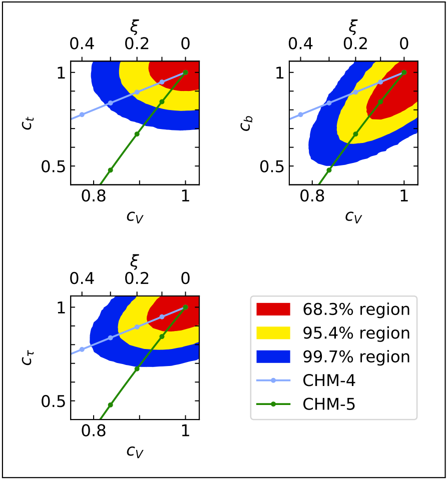
$$\mathcal{L}_{\text{kin}} = \frac{1}{2}\partial_\mu |h| \partial^\mu |h| + \frac{f^2}{4}\langle D_\mu U D^\mu U^\dagger \rangle (\sin|h|/f)^2$$

The Minimal Composite Higgs Model

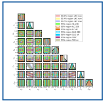
Agashe *et al.* [hep-ph/0412089], Contino *et al.* [hep-ph/0612048]

In the coset $SO(5)/SO(4)$: $\xi = \frac{v^2}{f^2}$

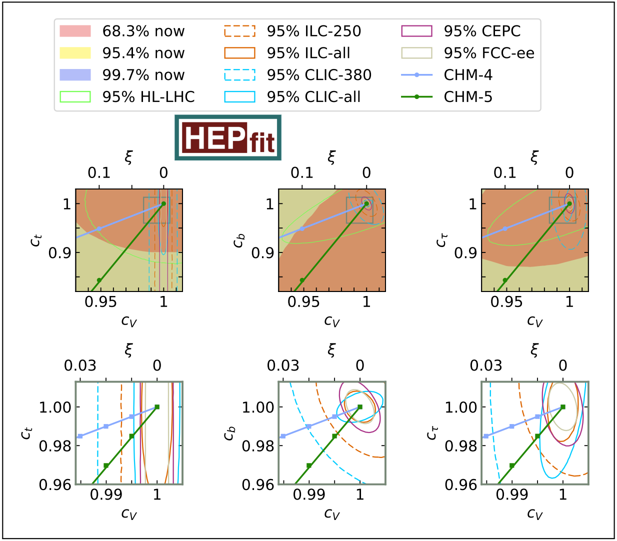
- $c_V = \sqrt{1-\xi}$
  universal
- $c_\psi^{(4)} = \sqrt{1-\xi}$ or $c_\psi^{(5)} = \frac{1-2\xi}{\sqrt{1-\xi}}$
  representation dependent
- **4** : $\xi < 0.22, \quad f > 530$ GeV
  5 : $\xi < 0.12, \quad f > 710$ GeV



de Blas/Eberhardt/CK [1803.00939]



III: Future Prospects for the Minimal Composite Higgs model.



[1803.00939]

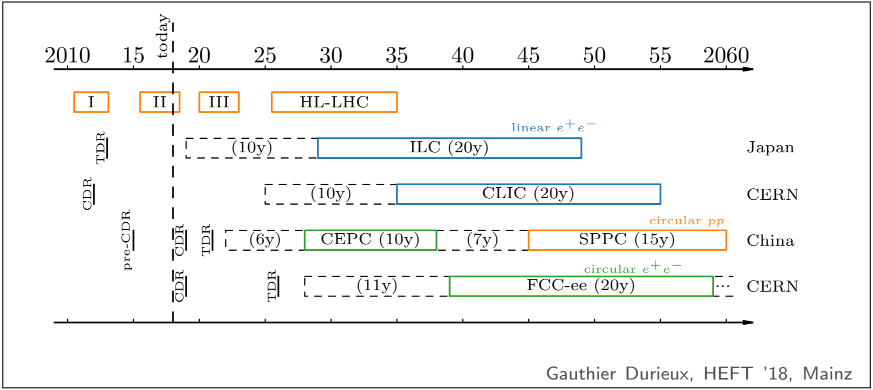
- flat priors
- $c_V = \sqrt{1-\xi}$
- $c_\psi^{(4)} = \sqrt{1-\xi}$

or

$$c_\psi^{(5)} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

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

The Projection to Future Colliders



The Projection to Future Colliders

Collider	LHC now	HL-LHC	ILC 250	ILC all	CLIC 380	CLIC all	CEPC	FCC-ee
L [ab^{-1}]	0.06	3	1.2	5.3	0.5	4	5	12.6
c_V	60	30	3.0 (3.5)	1.2 (1.2)	4.4 (5.6)	1.6 (1.8)	1.6 (1.7)	1.1 (1.1)
c_t	100	53	52 (–)	17 (19)	53 (–)	32 (40)	52 (–)	51 (–)
c_b	130	39	8.5 (11)	3.1 (3.2)	11 (19)	3.0 (3.2)	5.0 (5.5)	3.3 (3.5)
c_c	–	–	21 (23)	8.4 (8.5)	63 (67)	22 (22)	12 (13)	6.9 (7.0)
c_τ	100	40	12 (15)	6.9 (7.2)	22 (38)	13 (15)	7.7 (8.2)	4.8 (4.9)
c_μ	400	62	53 (–)	46 (100)	53 (–)	47 (110)	45 (88)	41 (66)
c_g	80	41	40 (–)	14 (15)	40 (–)	25 (32)	40 (–)	39 (–)
c_γ	200	75	63 (–)	41 (79)	66 (–)	49 (140)	59 (–)	54 (–)
$c_{Z\gamma}$	–	950	900 (–)	530 (–)	900 (–)	760 (1000)	920 (–)	920 (–)
	Sensitivity/uncertainty [$\times 10^{-3}$]							