

HEPfitting the electroweak chiral Lagrangian

arXiv:1803.00939

in collaboration with Jorge de Blas and Claudius Krause

HEFT 2018

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Outline

Introduction

The electroweak chiral Lagrangian

HEPfit

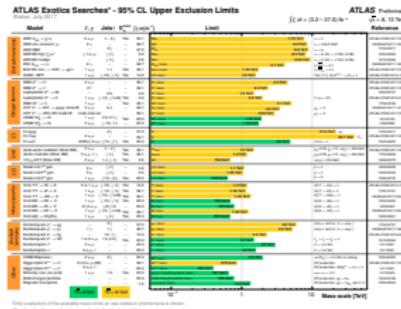
Higgs fits – Current status

Higgs fits – Future projections

Summary



Introduction



Vacuum stability

Naturalness

Origin of masses

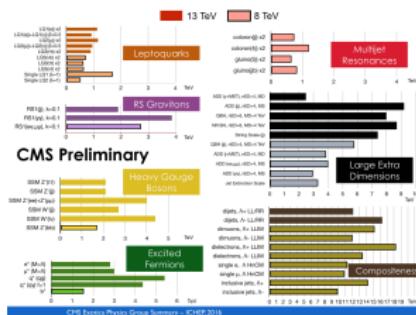
Baryogenesis

$(g - 2)_\mu$

Dark matter

Neutrino masses

VS.



General approaches to BSM physics

SMEFT

h in a doublet

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \sum_i c_i \mathcal{O}_i$$

Expansion in dimensions

Electroweak chiral Lagrangian (ew $\chi\mathcal{L}$)

h and φ_a are independent

$$\mathcal{L} \neq \mathcal{L}_{\text{SM}} @ \text{LO}$$

Expansion in chiral dimensions
and $\xi = v^2/f^2$



The electroweak chiral Lagrangian

$$\begin{aligned}
 \mathcal{L}_{\text{LO}} = & -\frac{1}{2} \langle G_{\mu\nu} G^{\mu\nu} \rangle - \frac{1}{2} \langle W_{\mu\nu} W^{\mu\nu} \rangle - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
 & + i\bar{q}_L \not{D} q_L + i\bar{\ell}_L \not{D} \ell_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{e}_R \not{D} e_R \\
 & + \frac{v^2}{4} \langle D_\mu U^\dagger D^\mu U \rangle (1 + F_U(h)) + \frac{1}{2} \partial_\mu h \partial^\mu h - V(h) \\
 & - \frac{v}{\sqrt{2}} [\bar{q}_L Y_u(h) UP_+ q_R + \bar{q}_L Y_d(h) UP_- q_R + \bar{\ell}_L Y_e(h) UP_- \ell_R + \text{h.c.}] \\
 U = & \exp(2i\varphi_a T^a/v) \\
 P_\pm = & \frac{1}{2} \pm T^3
 \end{aligned}$$

Polynomials $V(h)$, $F_U(h)$, $Y_\psi(h)$ can be of any order in h , but focus on one h here.

The Higgs electroweak chiral Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{fit}} = & 2\textcolor{red}{c_V} (m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} m_Z^2 Z_\mu Z^\mu) \frac{h}{v} \\ & - \textcolor{red}{c_t} m_t \bar{t} t \frac{h}{v} - \textcolor{red}{c_b} m_b \bar{b} b \frac{h}{v} - \textcolor{red}{c_\tau} m_\tau \bar{\tau} \tau \frac{h}{v} - \textcolor{red}{c_c} m_c \bar{c} c \frac{h}{v} - \textcolor{red}{c_\mu} m_\mu \bar{\mu} \mu \frac{h}{v} \\ & + \frac{e^2}{16\pi^2} \textcolor{red}{c_\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{e^2}{16\pi^2} \textcolor{red}{c_{Z\gamma}} Z_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} \textcolor{red}{c_g} \langle G_{\mu\nu} G^{\mu\nu} \rangle \frac{h}{v}, \end{aligned}$$

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

$$c_i^{\text{SM}} = \begin{cases} 1 & \text{for } i = V, t, b, \tau, c, \mu \\ 0 & \text{for } i = g, \gamma, Z\gamma. \end{cases}$$

HEPfit

What?

Why?

Where?

Who?



When?



HEPfit

What?

High energy physics observables

Why?

in the SM and beyond

Where?

featuring Flavour observables,

Who?

Electroweak precision observables and
Higgs observables

When?



HEPfit

What?

Stand-alone library or global fits for

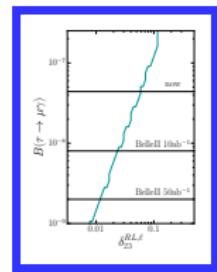
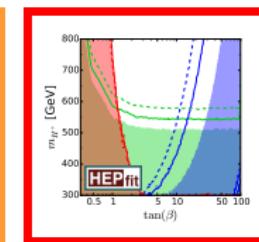
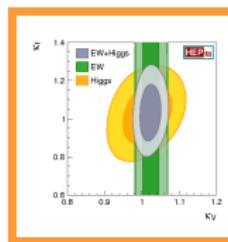
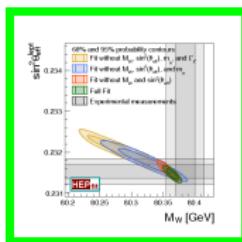
Why?



Where?

Who?

When?



HEPfit

What?

Why?

Where?

Who?

When?

The screenshot shows the official website for HEPfit at hepfit.roma1.infn.it. The header features the HEPfit logo in red and white. Below the logo is a navigation menu with links to 'home', 'developers', 'samples', and 'documentation'. A central box contains the text: 'HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.' Below this text are four sub-sections with plots and descriptions:

- Higgs Physics**: A plot showing signal strengths $\hat{\sigma}/\sigma_0$ versus mass m_H in GeV. Text below states: "HEPfit can be used to study Higgs couplings and analyze data on signal strengths."
- Precision Electroweak**: A plot showing electroweak precision observables versus mass m_H in GeV. Text below states: "Electroweak precision observables are included in HEPfit."
- Flavour Physics**: A plot showing $\tau \rightarrow \mu \gamma$ with $\delta_{23} = 0.1$ versus s^2_W in cm $^{-2}$. Text below states: "The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics."
- BSM Physics**: A plot showing constraints on BSM models versus mass m_H in GeV. Text below states: "Dynamics beyond the Standard Model can be studied by adding models in HEPfit."

<http://hepfit.roma1.infn.it>



HEPfit

What?

HEPfit was already used for:

Why?

JHEP 1611 (2016) 026

Where?

JHEP 1612 (2016) 135

Who?

Eur.Phys.J. C77 (2017) no.10, 688

When?

JHEP 1801 (2018) 108

arXiv:1711.02095

arXiv:1803.00939

+ many proceedings



HEPfit

What?

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(HU Berlin)

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HEPfit

What?

Why?

Already now: development version

Where?

<https://github.com/silvest/HEPfit>

Who?

Autumn 2018: first fully documented release

When?

<http://hepfit.roma1.infn.it>



HEPfit

What?

Why?

It's free and it's open-source!

Where?

Who?

When?

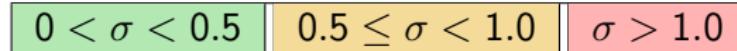
How much?



Current inputs

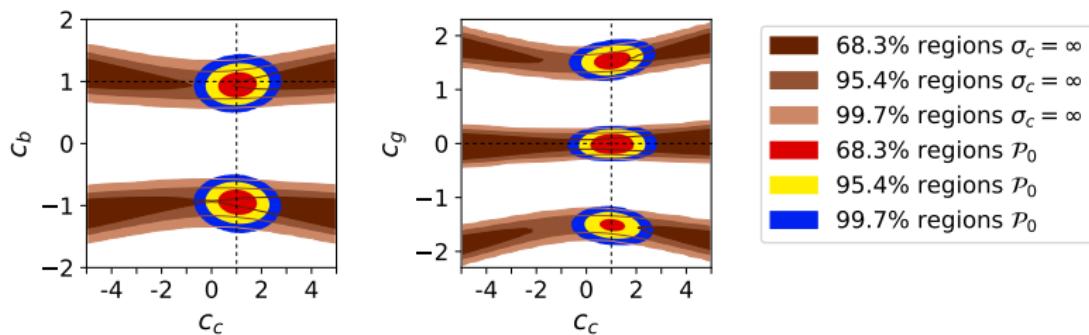
	$b\bar{b}$	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$Z\gamma$	$\mu\mu$
SM Br	57.5%	21.6%	6.3%	2.7%	2.3%	1.6%	0.2%
ggF8	87.2%	—	AC	AC	AC	AC	AC
ggF13	87.1%	—	AC	C	AC	AC	AC
VBF8	7.2%	—	AC	AC	AC	AC	AC
VBF13	7.4%	C	AC	C	AC	AC	AC
Vh8	5.1%	AC	AC	AC	AC	AC	AC
Vh13	4.4%	AC	AC	C	AC	AC	AC
tth8	0.6%	AC	—	—	AC	AC	AC
tth13	1.0%	AC	AC	AC	AC	AC	AC
Vh2	Tev						
tth2	Tev						

Uncertainty of the signal strengths $\mu \pm \sigma$:



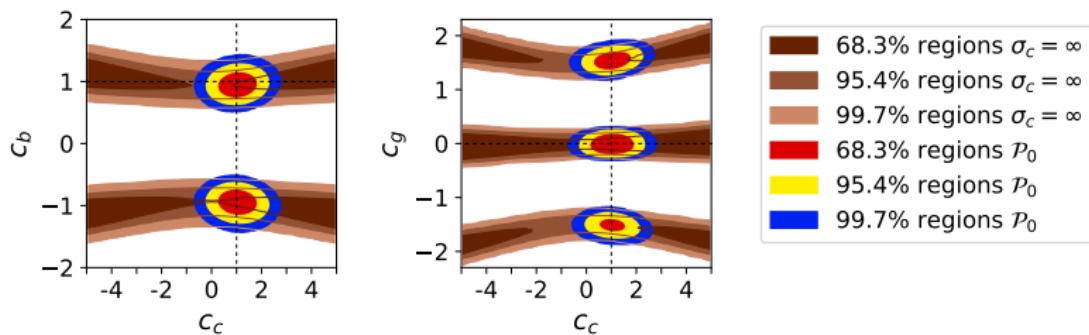
Flat vs. Gaussian priors

All priors flat vs. natural solutions:



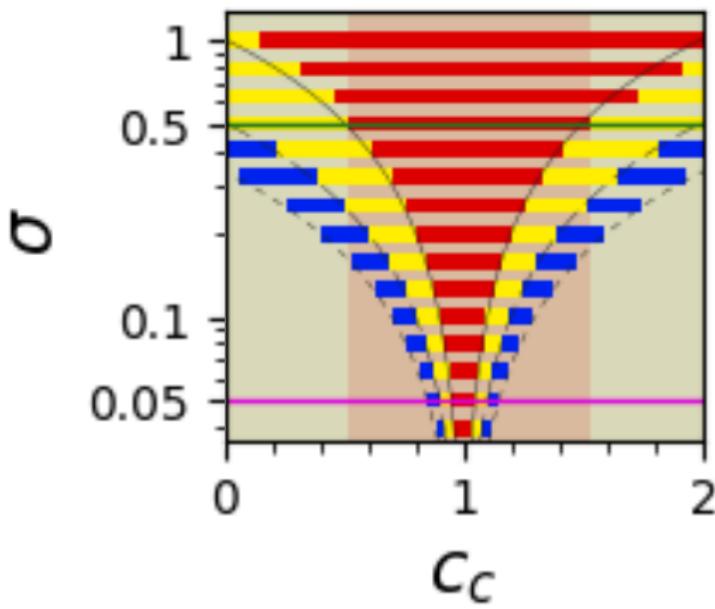
Flat vs. Gaussian priors

All priors flat vs. natural solutions:



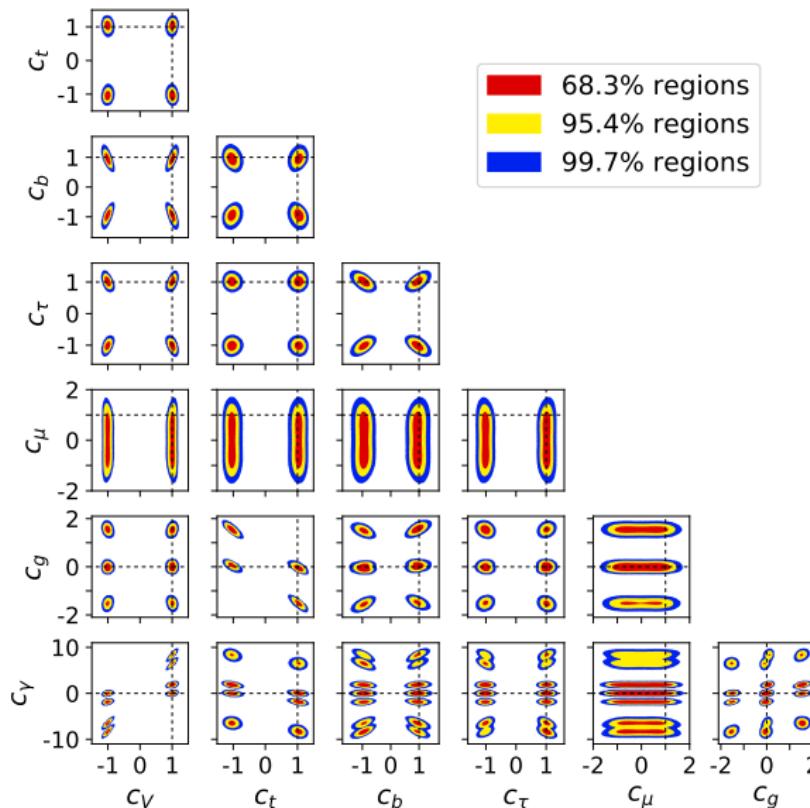
Which Gaussians to avoid overfitting?

Flat vs. Gaussian priors



Choose a Gaussian
 \Rightarrow with $\sigma = 0.5$
 for c_c and $c_{Z\gamma}$

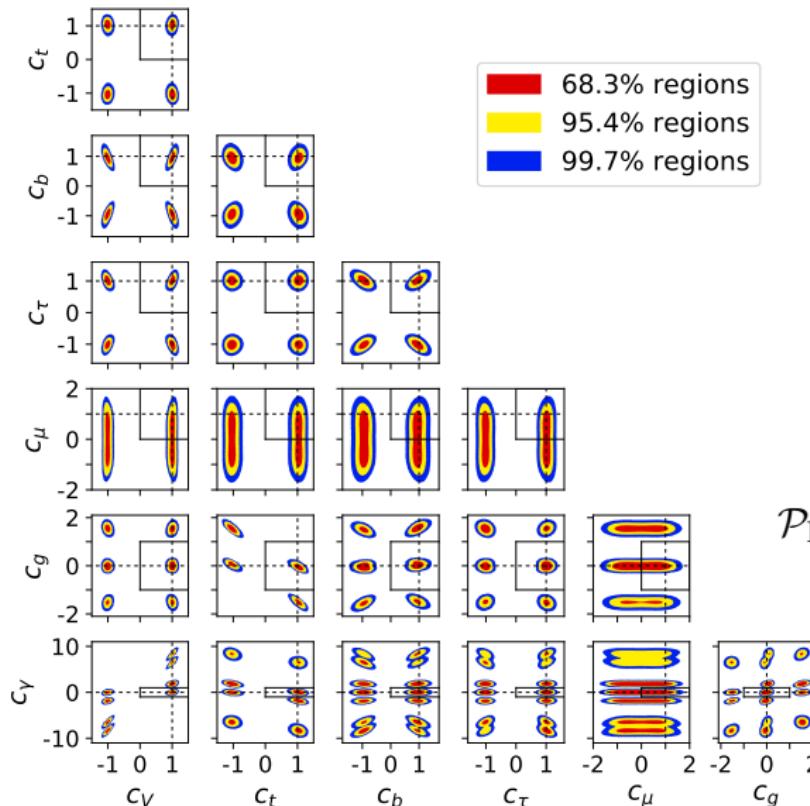
All solutions



Gaussian for $c_c, c_{Z\gamma}$
with $\sigma_{c,Z\gamma} = 0.5$

$$\mathcal{P}_0 \left\{ \begin{array}{l} \text{Flat in } c_{\psi,v} \in [-2, 2] \\ c_g \in [-3, 3] \\ c_\gamma \in [-12, 12] \end{array} \right.$$

All solutions

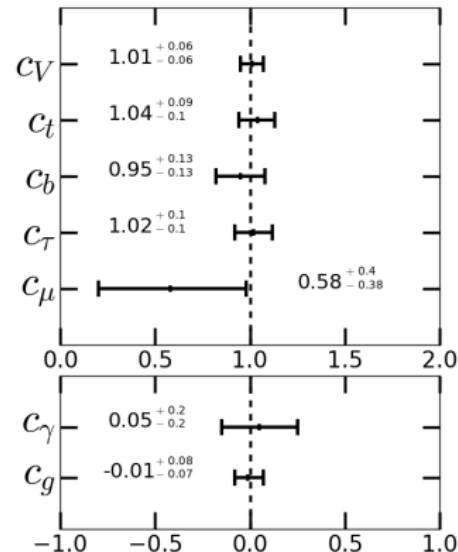
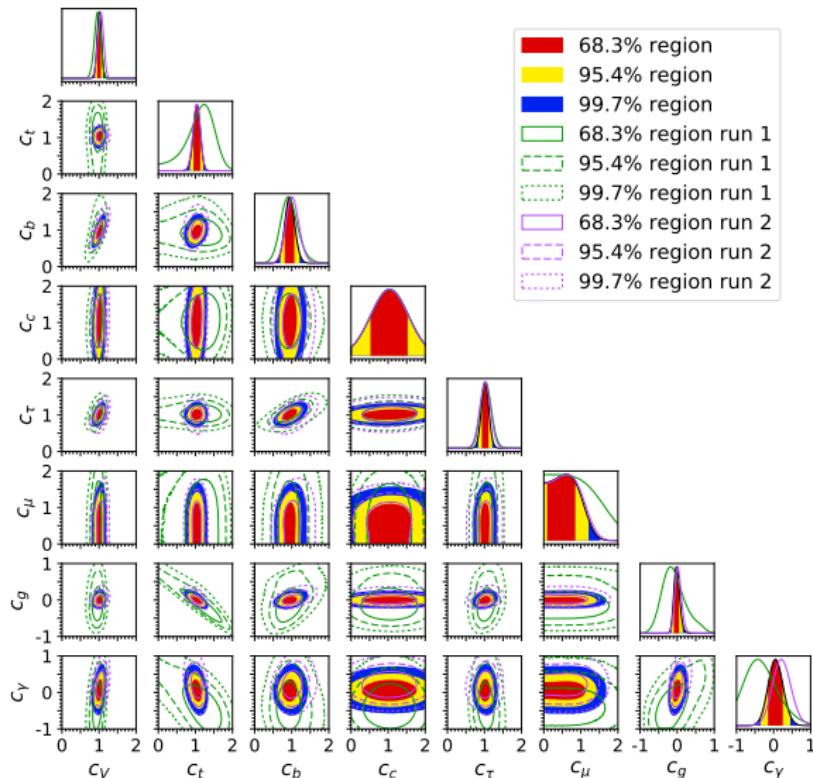


Gaussian for $c_c, c_{Z\gamma}$
with $\sigma_{c,Z\gamma} = 0.5$

$$\mathcal{P}_0 \left\{ \begin{array}{l} \text{Flat in } c_{\psi,V} \in [-2, 2] \\ c_g \in [-3, 3] \\ c_\gamma \in [-12, 12] \end{array} \right.$$

$$\mathcal{P}_{\text{EFT}} \left\{ \begin{array}{l} \text{Flat in } c_{\psi,V} \in [0, 2] \\ c_g \in [-1, 1] \\ c_\gamma \in [-1, 1] \\ c_t + c_g > 0 \end{array} \right.$$

Current status of the Higgs fits – posteriors



Current status of the minimal composite Higgs models

$$\xi = v^2/f^2$$

In the coset $\text{SO}(5)/\text{SO}(4)$:

$$c_V = \sqrt{1 - \xi}$$

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

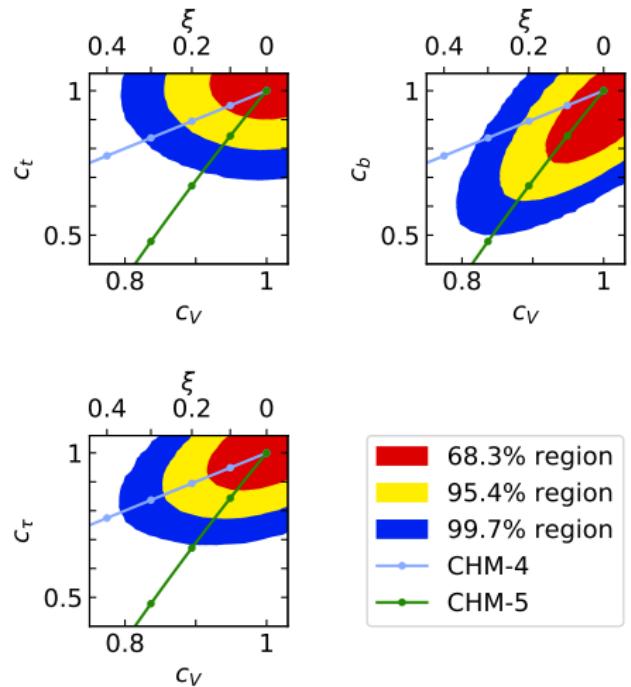
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Current status of the minimal composite Higgs models

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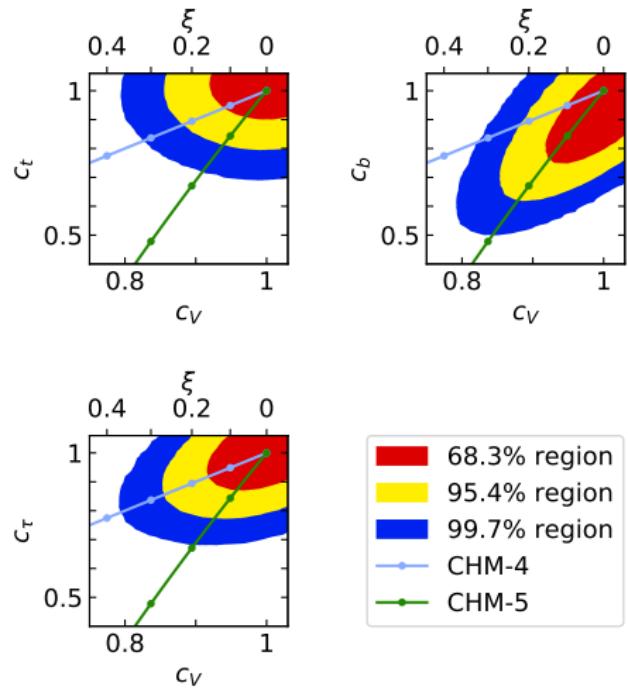
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4: $\xi < 0.22$, $f > 530$ GeV

5: $\xi < 0.12$, $f > 710$ GeV



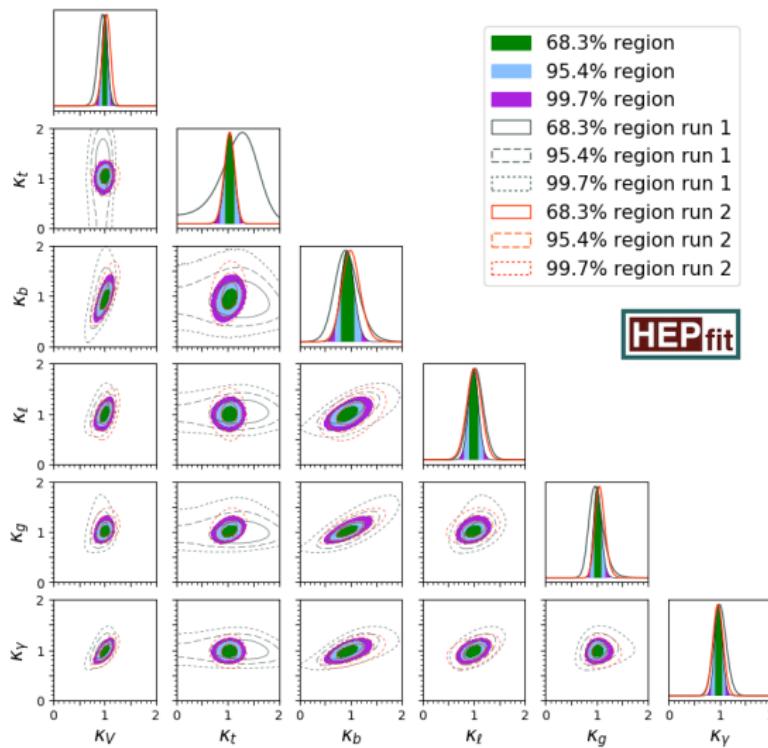
- 68.3% region
- 95.4% region
- 99.7% region
- CHM-4
- CHM-5

Relation to the κ formalism

$$\kappa_X^2 = \frac{\sigma(X \rightarrow h)}{\sigma(X \rightarrow h)_{\text{SM}}}, \quad \kappa_Y^2 = \frac{\Gamma(h \rightarrow Y)}{\Gamma(h \rightarrow Y)_{\text{SM}}}, \quad \kappa_i = |f_i(c_j)| \equiv \frac{|\mathcal{A}_i(c_j)|}{|\mathcal{A}_i(c_j^{\text{SM}})|}$$

$$\begin{pmatrix} c_V \\ c_t \\ c_b \\ c_\tau \\ c_g \\ c_\gamma \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -0.76 & 0.04 & 0 & 0.72 & 0 \\ 4.15 & -0.88 & 0.012 & 0.012 & 0 & -3.29 \end{pmatrix} \cdot \begin{pmatrix} \kappa_V \\ \kappa_t \\ \kappa_b \\ \kappa_\ell \\ \kappa_g \\ \kappa_\gamma \end{pmatrix}.$$

Relation to the κ formalism



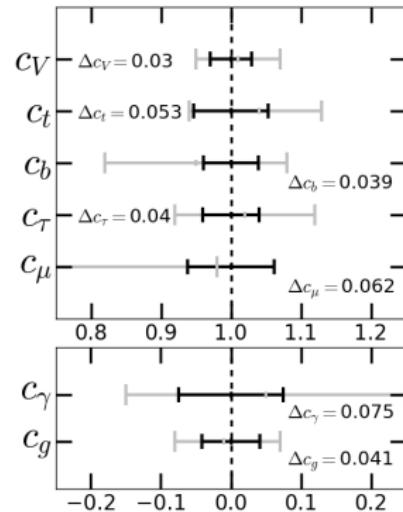
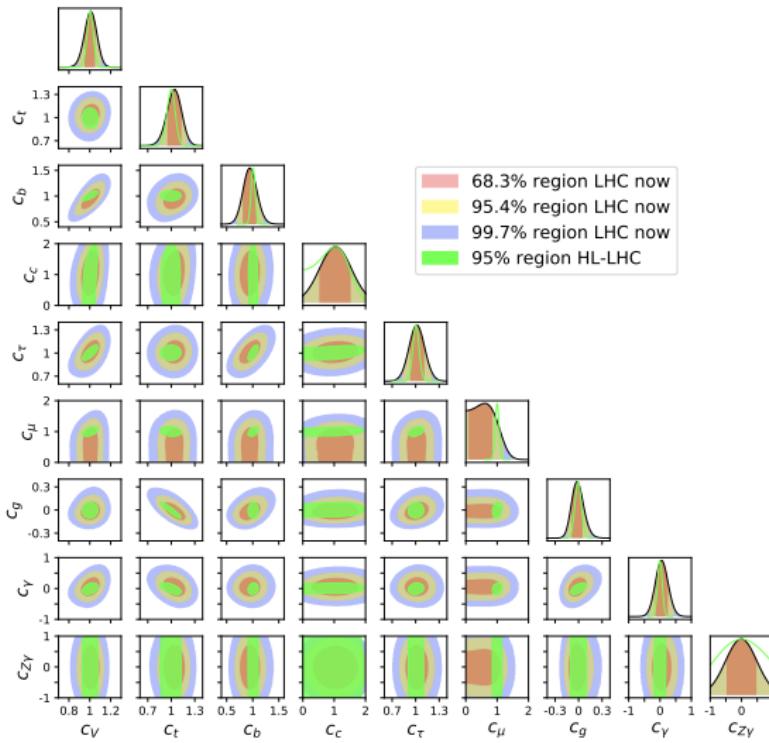
Relation to the κ formalism

Para-meter	Fit result	Para-meter	Fit result	Result from κ -fit
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

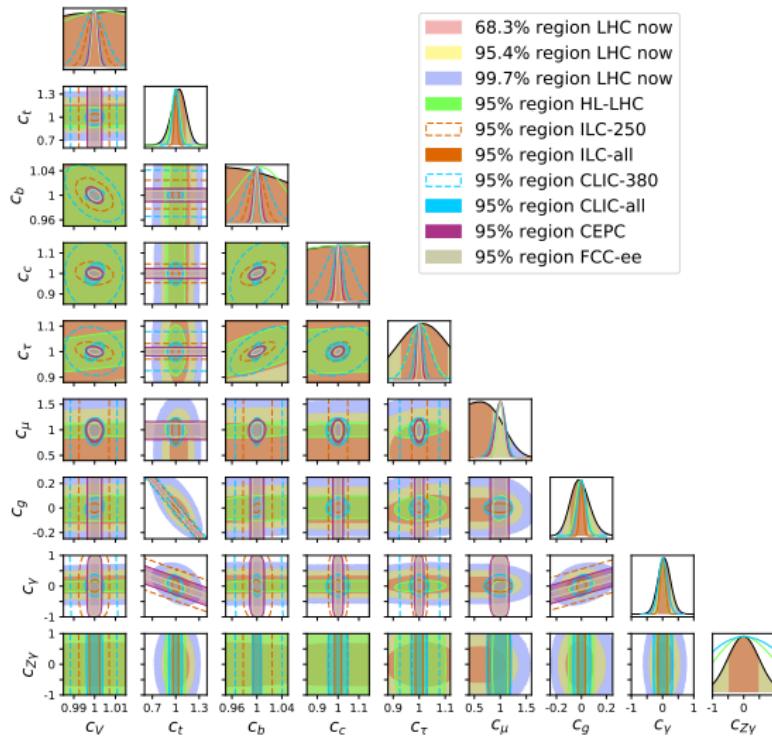
Future scenarios

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

Future projections for the HL-LHC

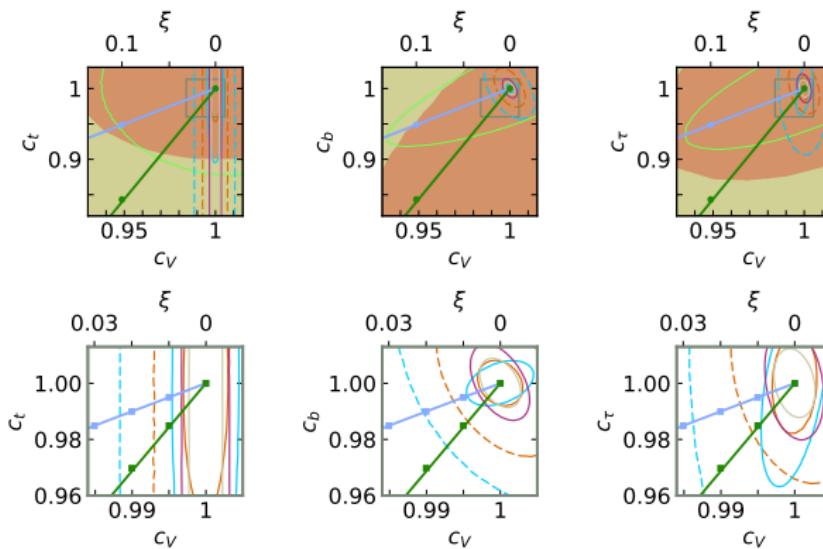


Future projections for ILC, CLIC, CEPC, FCC-ee



Future sensitivity to ξ

68.3% now	95% ILC-250	95% CEPC
95.4% now	95% ILC-all	95% FCC-ee
99.7% now	95% CLIC-380	CHM-4
95% HL-LHC	95% CLIC-all	CHM-5



ξ down to 0.003
and f up to 4 TeV
can be probed.

Summary

Fit to the electroweak chiral Lagrangian:

No sign for New Physics in the signal strengths.

	LHC now	HL-LHC	Best future sensitivity (ILC and FCC-ee)
Δc_V	6%	3%	1%
Δc_X ($X = g, t, b, \tau$)	$\approx 10\%$	$\approx 5\%$	1%
Δc_γ	20%	8%	4%
f [TeV]	> 0.5	> 0.8	> 4

Back-up



Correlations in the current $\text{ew}\chi\mathcal{L}$ fit:

	c_V	c_t	c_b	c_c	c_τ	c_μ	c_g	c_γ	$c_{Z\gamma}$
c_V	1	0.12	0.71	0.25	0.49	0.09	0.14	0.32	0
c_t	0.12	1	0.25	0.16	0.05	0.01	-0.68	-0.31	0
c_b	0.71	0.25	1	0.09	0.56	0.07	0.36	0.03	0
c_c	0.25	0.16	0.09	1	0.14	0.02	0.04	0.03	0
c_τ	0.49	0.05	0.56	0.14	1	0.06	0.25	0.01	0
c_μ	0.09	0.01	0.07	0.02	0.06	1	0	0	0
c_g	0.14	-0.68	0.36	0.04	0.25	0	1	0.33	0
c_γ	0.32	-0.31	0.03	0.03	0.01	0	0.33	1	0
$c_{Z\gamma}$	0	0	0	0	0	0	0	0	1

Correlations in the current κ_i fit:

	κ_V	κ_t	κ_b	κ_ℓ	κ_g	κ_γ
κ_V	1	0.13	0.73	0.49	0.26	0.68
κ_t	0.13	1	0.27	0.06	0.33	0.05
κ_b	0.73	0.27	1	0.56	0.74	0.60
κ_ℓ	0.49	0.06	0.56	1	0.33	0.47
κ_g	0.26	0.33	0.74	0.33	1	0.11
κ_γ	0.68	0.05	0.60	0.47	0.11	1

Model	Collider	LHC now	HL-LHC	ILC 250	ILC all
	$L [ab^{-1}]$	0.06	3	1.2	5.3
CHM-4	$\xi [\times 10^{-3}]$	220	100	13	5.4
	$f [GeV]$	530	770	2200	3300
CHM-5	$\xi [\times 10^{-3}]$	120	42	8.9	3.6
	$f [GeV]$	710	1200	2600	4100

Model	Collider	CLIC 380	CLIC all	CEPC	FCC-ee
	$L [ab^{-1}]$	0.5	4	5	12.6
CHM-4	$\xi [\times 10^{-3}]$	21	9.2	6.2	4.8
	$f [GeV]$	1700	2500	3300	3500
CHM-5	$\xi [\times 10^{-3}]$	15	5.2	4.7	3.2
	$f [GeV]$	2000	3400	3600	4300