HEPfitting the electroweak chiral Lagrangian

arXiv:1803.00939

in collaboration with Jorge de Blas and Claudius Krause

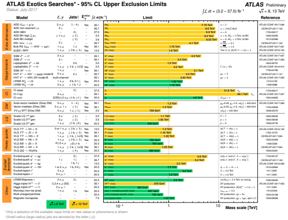
HEFT 2018

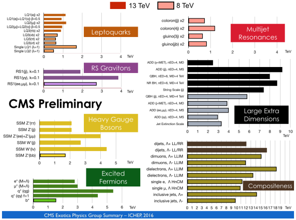
Otto Eberhardt

Instituto de Física Corpuscular

Outline

Introduction





vs.

Vacuum stability

Naturalness

Origin of masses

Baryogenesis

$(g-2)_\mu$

Dark matter

Neutrino masses

General approaches to BSM physics

SMEFT

h in a doublet

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

Expansion in dimensions

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

h and φ_a are independent

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

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

The electroweak chiral Lagrangian

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

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

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

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

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

HEPfit

What?

Why?

Where?

Who?

When?

HEPfit

What?	High energy physics observables	
Why?	in the SM and beyond	
Where?	featuring	Flavour observables, Electroweak precision observables and Higgs observables
Who?		
When?		

HEPfit

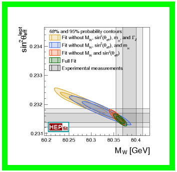
What? Stand-alone library or global fits for

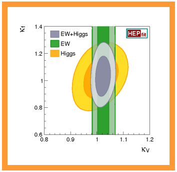
Why? SM EFT 2HDM MSSM …

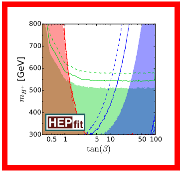
Where?

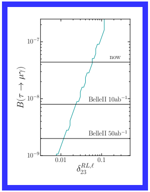
Who?

When?









HEPfit

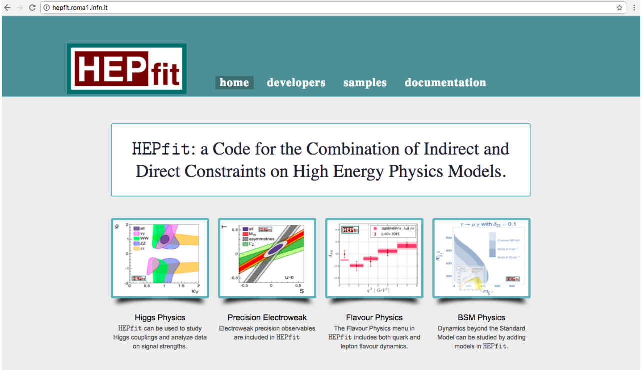
What?

Why?

Where?

Who?

When?



http://hepfit.roma1.infn.it

HEPfit

What?

Why?

Where?

Who?

When?

HEPfit was already used for:

JHEP 1611 (2016) 026

JHEP 1612 (2016) 135

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

JHEP 1801 (2018) 108

arXiv:1711.02095

arXiv:1803.00939

+ many proceedings

HEPfit

- What?
- Why?
- Where?
- **Who?**
- When?

Shehu AbdusSalam (U Tehran)	Otto Eberhardt (IFIC València)	Ana Peñuelas (IFIC València)
Jorge de Blas (INFN Padova)	Marco Fedele (U Paris-Sud)	Maurizio Pierini (CERN)
Debtosh Chowdhury (EP Paris)	Enrico Franco (INFN Rome)	Laura Reina (Florida State)
Marco Ciuchini (INFN Rome)	Giovanni Grilli (U São Paulo)	Luca Silvestrini (INFN Rome)
Giovanna Cottin (NTU Taipei)	Satoshi Mishima (KEK)	Mauro Valli (INFN Rome)
António Coutinho (INFN Rome)	Ayan Paul (HU Berlin)	Norimi Yokozaki (Tohoku U)

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

IFIC INSTITUT DE FISICA CORPUSCULAR

HEPfit

What?

Why?

Where?

Who?

When?

How much?

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

Current inputs

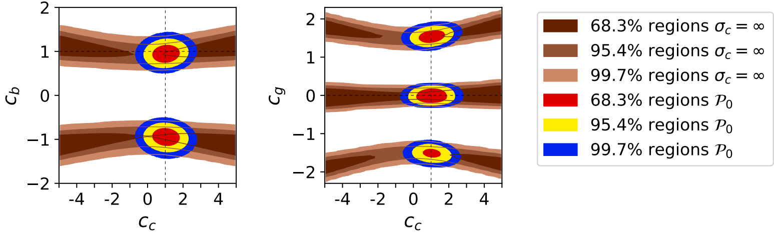
		$b\bar{b}$	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$Z\gamma$	$\mu\mu$
	SM Br	57.5%	21.6%	6.3%	2.7%	2.3‰	1.6‰	0.2‰
ggF8	87.2%	–	AC	AC	AC	AC	AC	AC
ggF13	87.1%	–	AC	C	AC	AC	AC	AC
VBF8	7.2%	–	AC	AC	AC	AC	AC	AC
VBF13	7.4%	C	AC	C	AC	AC	AC	AC
Vh8	5.1%	AC	AC	AC	AC	AC	AC	AC
Vh13	4.4%	AC	AC	C	AC	AC	AC	AC
tth8	0.6%	AC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

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

$0 < \sigma < 0.5$	$0.5 \leq \sigma < 1.0$	$\sigma > 1.0$

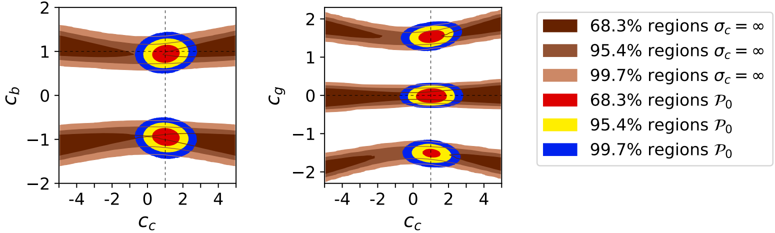
Flat vs. Gaussian priors

All priors flat vs. natural solutions:



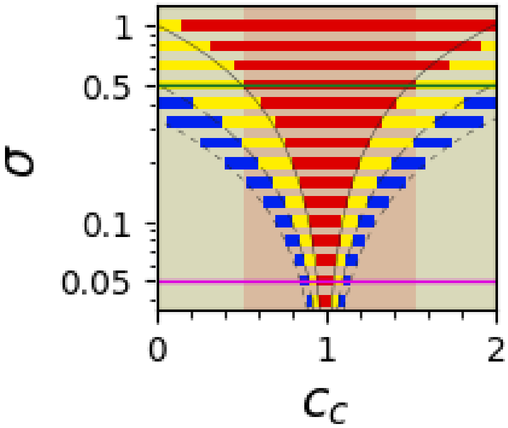
Flat vs. Gaussian priors

All priors flat vs. natural solutions:



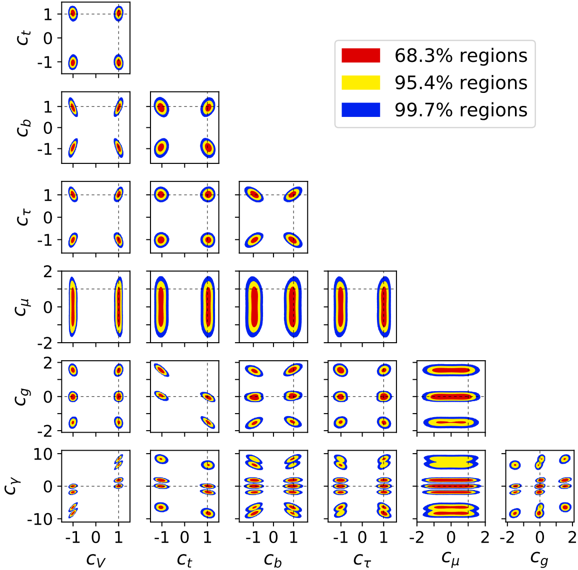
Which Gaussians to avoid overfitting?

Flat vs. Gaussian priors



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

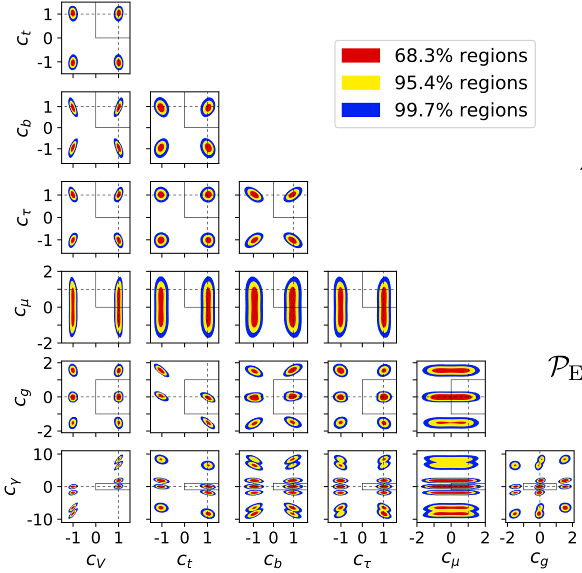
All solutions



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

$$\mathcal{P}_0 \begin{cases} \text{Flat in } & c_{\psi,V} \in [-2,2] \\ & c_g \in [-3,3] \\ & c_\gamma \in [-12,12] \end{cases}$$

All solutions

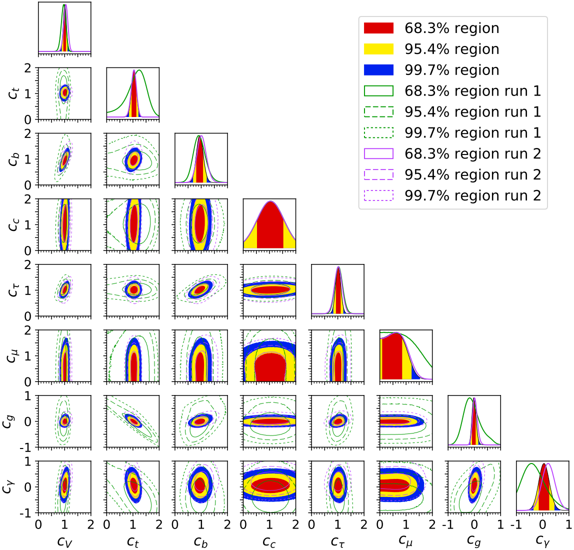


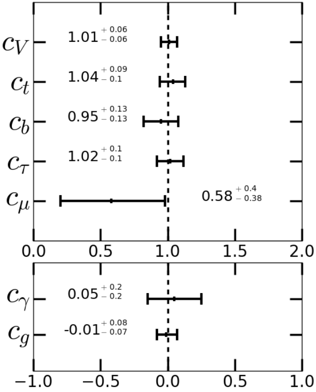
Gaussian for c_c, $c_{Z\gamma}$ with $\sigma_{c,Z\gamma} = 0.5$

$$\mathcal{P}_0 \begin{cases} \text{Flat in } & c_{\psi,V} \in [-2,2] \\ & c_g \in [-3,3] \\ & c_\gamma \in [-12,12] \end{cases}$$

$$\mathcal{P}_{\rm EFT} \begin{cases} \text{Flat in } & c_{\psi,V} \in [0,2] \\ & c_g \in [-1,1] \\ & c_\gamma \in [-1,1] \\ & c_t + c_g > 0 \end{cases}$$

Current status of the Higgs fits – posteriors





Current status of the minimal composite Higgs models

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

In the coset SO(5)/SO(4):

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

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

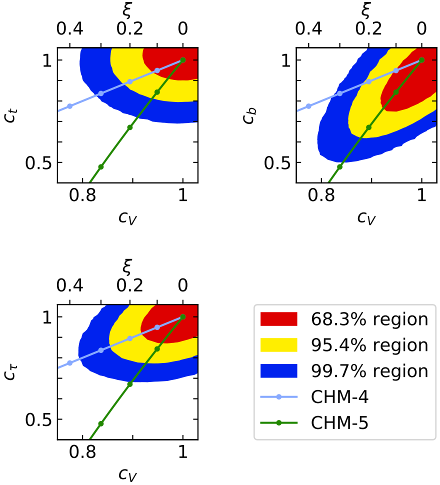
Current status of the minimal composite Higgs models

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

In the coset SO(5)/SO(4):

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

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



Current status of the minimal composite Higgs models

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

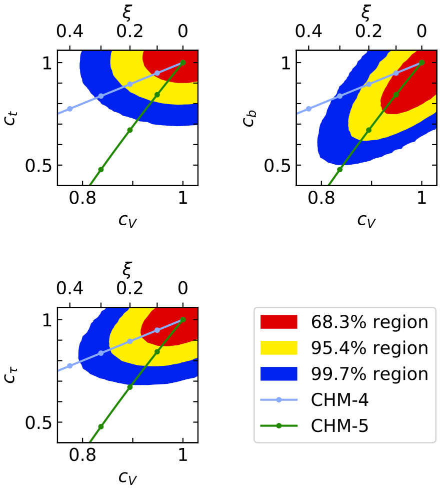
In the coset SO(5)/SO(4):

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

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

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

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

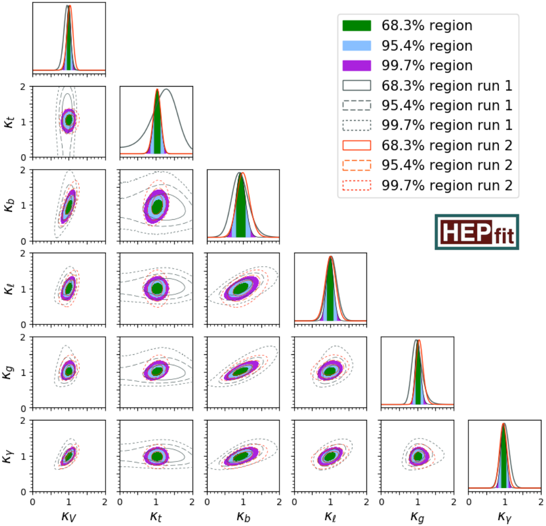


Relation to the κ formalism

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

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

Relation to the κ formalism



Relation to the κ formalism

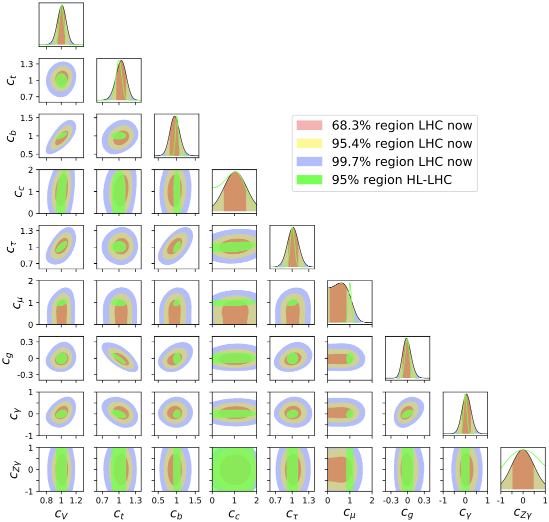
Parameter	Fit result	Parameter	Fit result	Result from κ-fit
κ_V	1.00 ± 0.06	c_V	1.00 ± 0.06	1.00 ± 0.06
κ_t	$1.04^{+0.09}_{-0.10}$	c_t	1.03 ± 0.09	1.04 ± 0.10
κ_b	0.94 ± 0.13	c_b	0.94 ± 0.13	0.94 ± 0.13
κ_ℓ	1.00 ± 0.10	c_τ	1.01 ± 0.10	1.00 ± 0.10
κ_g	$1.02^{+0.08}_{-0.07}$	c_g	$-0.01^{+0.08}_{-0.07}$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

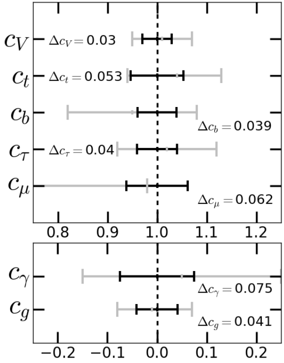
Future scenarios

Collider	HL-LHC	ILC 250	ILC all	CLIC 380	CLIC all	CEPC	FCC-ee
L [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

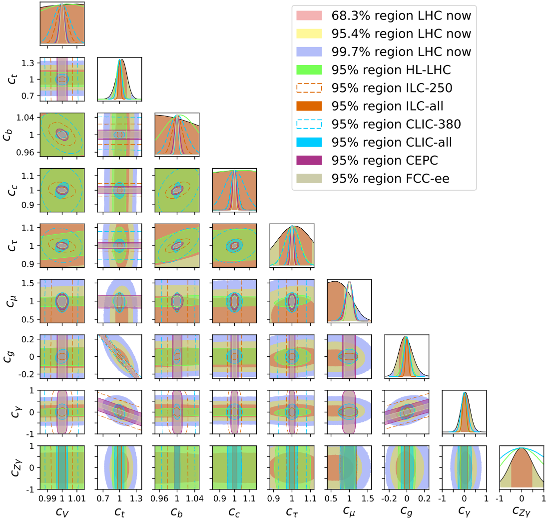
IFIC INSTITUT DE FISICA CORPUSCULAR

Future projections for the HL-LHC

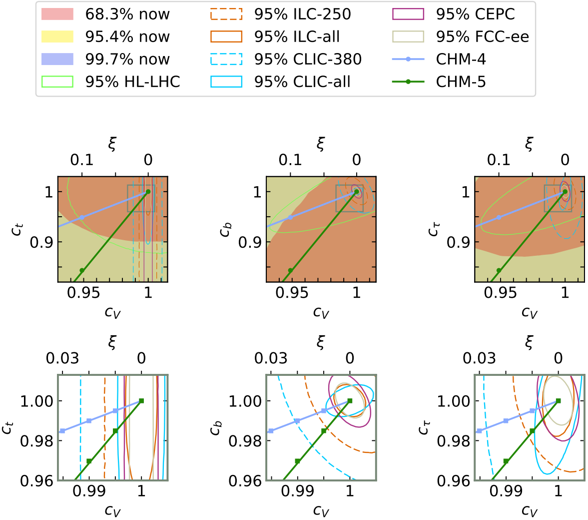




Future projections for ILC, CLIC, CEPC, FCC-ee



Future sensitivity to ξ



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

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