Higgs Effective Field Theories

– IMPRS Young Scientist Workshop –

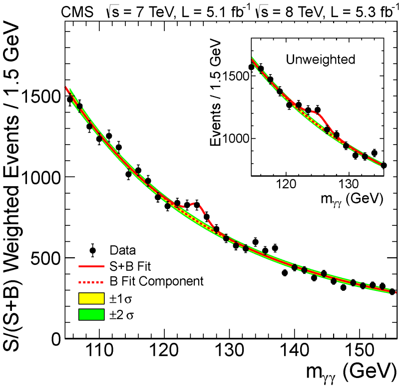
Claudius Krause

Ludwig-Maximilians-Universität München

June 8, 2016

In Collaboration with G. Buchalla, O. Catà und A. Celis

A Higgs-like particle was found at the LHC.

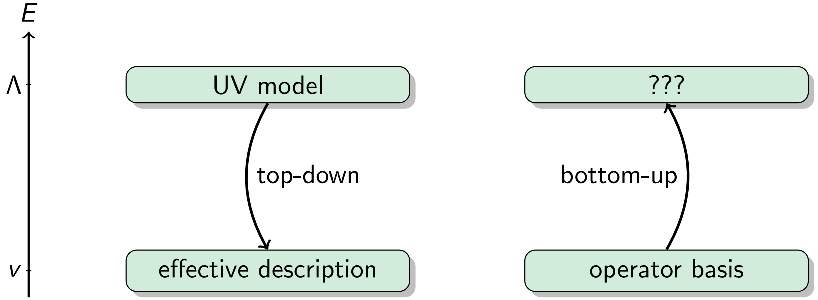


[1207.7235]

- Standard Model is confirmed to good accuracy
- Scalar particle found by CMS [1207.7235] and ATLAS [1207.7214]
- Experimental precision of Higgs-couplings is $\sim 10\%$

Is it the/a Higgs or something else?

EFTs provide a model-independent answer.



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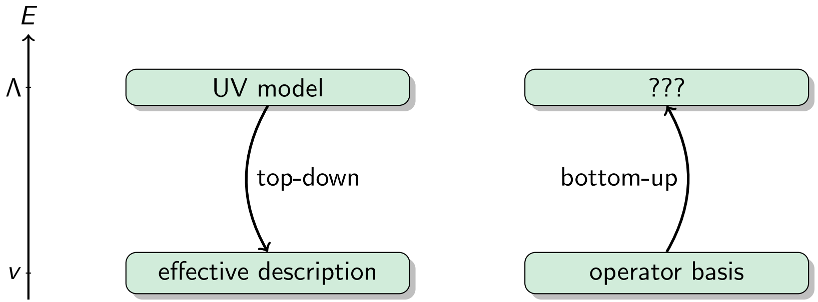
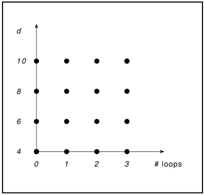


For a model-independent analysis, we use the bottom-up approach.

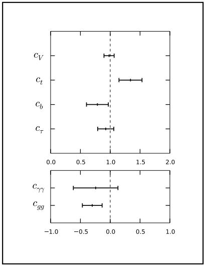
We need:

- All low-energy particles
- Symmetries and patterns of symmetry breaking
- A consistent power counting

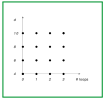
First, we focus on the power counting.



Part 1 – power counting
[1307.5017,1312.5624,1412.6356]



Part 2 – Fit to LHC Higgs data
[1504.01707,1511.00988]



1. There are 2 types of EFTs, decoupling and non-decoupling.

i) The new physics decouples from the SM:

- The leading order is the SM, the Higgs is part of an $SU(2)_L$ doublet.
- Heavy particles are not connected to the SM particles by large mixing or symmetries.
- The scale of new physics is at $\Lambda \gg v$.
- The expansion is given by canonical (energy) dimensions, the expansion parameter is v/Λ.

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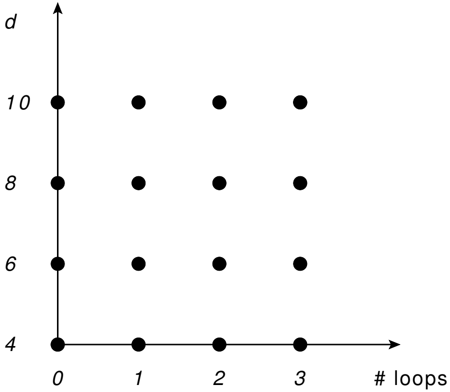

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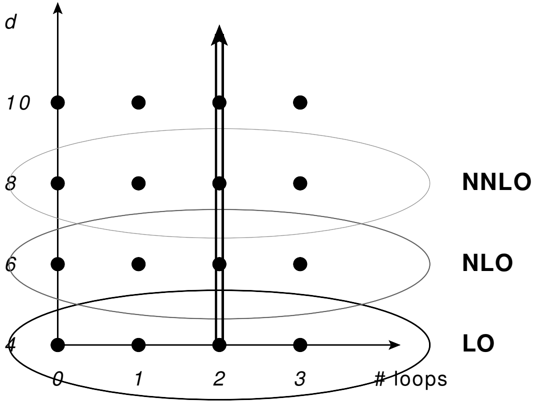
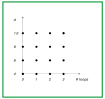


Relevant for Higgs physics: dimension 6, of order $\mathcal{O}(\frac{v^2}{\Lambda^2})$

Buchmüller, Wyler ['86 Nucl. Phys. B]; Grzadkowski et al. [1008.4884]



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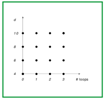
ii) The new physics is non-decoupling:

- Heavy particles are connected to the SM particles by large mixing or symmetries.
- h and the 3 Goldstones of EWSB come from a strongly coupled sector at $f \gtrsim v$.
- The remaining particles of the SM are weakly coupled.



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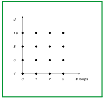
Leading order is more general than the SM.

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], ...

$$\mathcal{L}_{\text{LO}} = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mathcal{V}\left(\frac{h}{v}\right) + \frac{v^2}{4}\,\text{Tr}\left(D_\mu U D^\mu U^\dagger\right)\left(1 + F_U\left(\frac{h}{v}\right)\right)$$

$$+ \mathcal{L}_{\text{gauge}} + \mathcal{L}_\Psi + \mathcal{L}_{\text{Yukawa}}\left(\frac{h}{v}\right)$$

$$U = \exp\left\{2i\,\frac{T_a \varphi_a}{v}\right\}$$

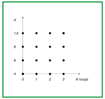


1. There are 2 types of EFTs, decoupling and non-decoupling.

- $\mathcal{L}_{\text{LO}}$ is not renormalizable in the traditional sense, but in the modern sense – order by order in an effective expansion:

- The LO counterterms are included at NLO.

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



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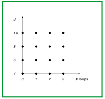
- We identify $\frac{f^2}{\Lambda^2} \simeq \frac{1}{16\pi^2}, \qquad \Lambda \simeq 4\pi f.$

- The scale of new physics $f \sim v, \qquad \xi = \frac{v^2}{f^2} \approx 1$



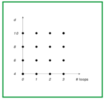
1. There are 2 types of EFTs, decoupling and non-decoupling.

$\rightarrow$ With the use of topological identities we find all classes of one loop operators.

This is equivalent to a counting of chiral dimensions:

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

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



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

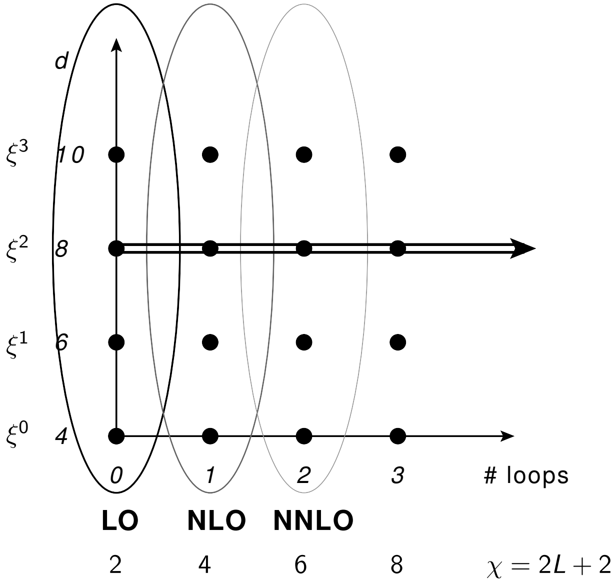
This is equivalent to a c

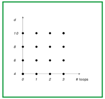
$$2L + 2 = \quad [\text{all couplings}]_\chi + [\text{all derivatives}]_\chi + [\text{all fields}]_\chi$$

$$[\text{bosons}]_\chi = 0,$$

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

1. At each order, all powers of $\xi = \frac{v^2}{f^2}$ are summed.





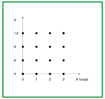
1. In a realistic scenario, we have a double expansion.

Assume now:

h is generated by a strong sector at scale $f \gg v$

$\rightarrow$ We get a double expansion in

$$\frac{f^2}{\Lambda^2} \simeq \frac{1}{16\pi^2} \qquad \& \qquad \xi = \frac{v^2}{f^2}$$



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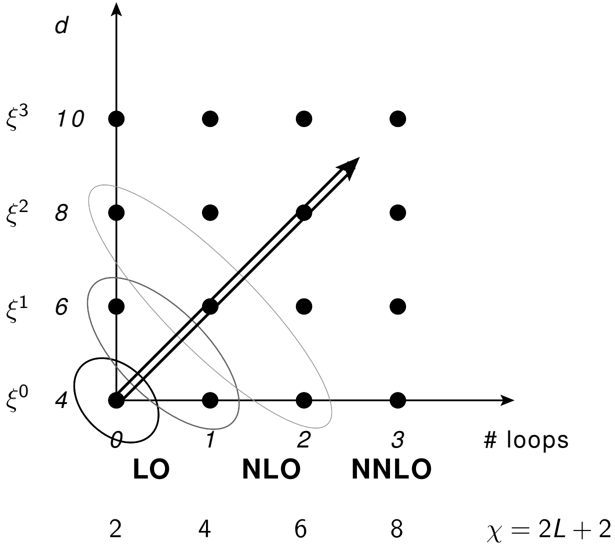
Corrections in the Higgs sector start at $\mathcal{O}(\xi)$,

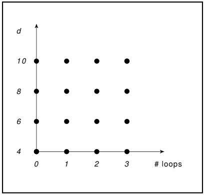
corrections to electroweak observables at $\mathcal{O}(\xi/16\pi^2)$

$\Rightarrow$ This expansion tests primarily the Standard Models Higgs hypothesis.

1. The “angle” depends on ξ.



The application of the EFT in LHC Higgs data analysis.



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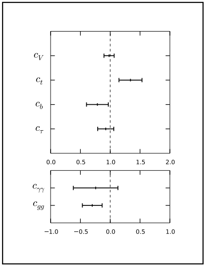

Part 2 – Fit to LHC Higgs data
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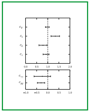
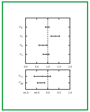


2. Currently available LHC Higgs data.

Signal strength: $\mu = \frac{\sigma(\text{prod.}) \times \mathrm{Br}(\text{dec.})}{\sigma(\text{prod.})_{\text{SM}} \times \mathrm{Br}(\text{dec.})_{\text{SM}}}$



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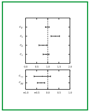
Higgs production

- Gluon fusion
- Associated production with $W^{\pm}/Z$
- Vector boson fusion
- Associated production with $t\bar{t}$

Higgs decay

- $b\bar{b}$
- $\tau^{+}\tau^{-}$
- $W^{+}W^{-}$
- ZZ
- $\gamma\gamma$



2. A consistent fit in this expansion has 6 free parameters.

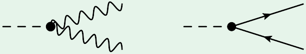
$$\mathcal{L}_{\text{Int}} = 2c_V \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \frac{h}{v} - c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_\tau y_\tau \bar{\tau} \tau h$$

$$+ \frac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} c_{gg} \, \text{Tr}\left(G_{\mu\nu} G^{\mu\nu} \right) \frac{h}{v}$$

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

Single h processes

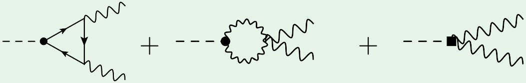
tree:



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

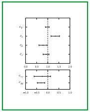
(3rd generation only)

1-loop:



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

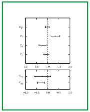
(gg and $\gamma\gamma$ only)



2. We performed a Bayesian fit to LHC Higgs data.

Bayes Theorem:

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



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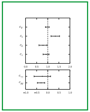
flat prior in

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

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

Likelihood

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



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$$+ \frac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} c_{gg} \, \text{Tr}\left(G_{\mu\nu} G^{\mu\nu} \right) \frac{h}{v} \qquad \boxed{c_i = \text{SM} + \mathcal{O}(\xi)}$$

Best fit:

$$\begin{pmatrix} c_V & = 0.98 \pm 0.09 \\ c_t & = 1.34 \pm 0.19 \\ c_b & = 0.79 \pm 0.18 \\ c_\tau & = 0.92 \pm 0.14 \\ c_{\gamma\gamma} & = -0.24 \pm 0.37 \\ c_{gg} & = -0.30 \pm 0.16 \end{pmatrix}$$

Correlation matrix:

$$\rho_{ij} = \begin{pmatrix} 1.0 & 0.01 & 0.67 & 0.37 & 0.41 & 0.1 \\ . & 1.0 & 0.02 & -0.04 & -0.36 & -0.84 \\ . & . & 1.0 & 0.58 & 0.02 & 0.37 \\ . & . & . & 1.0 & -0.05 & 0.26 \\ . & . & . & . & 1.0 & 0.31 \\ . & . & . & . & . & 1.0 \end{pmatrix}$$

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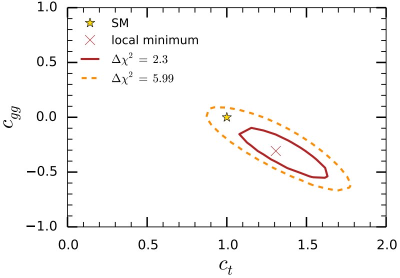
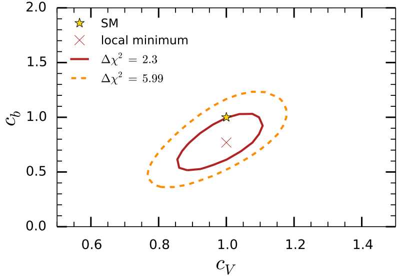
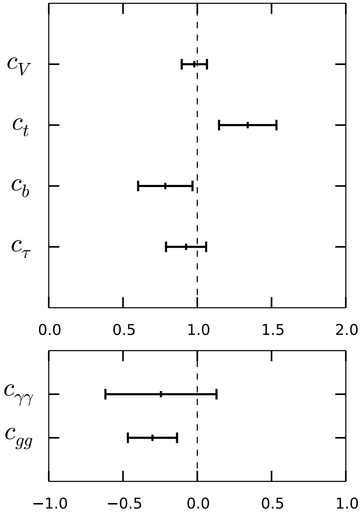
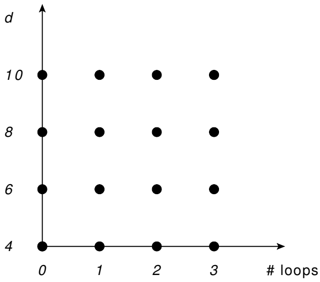






Summary

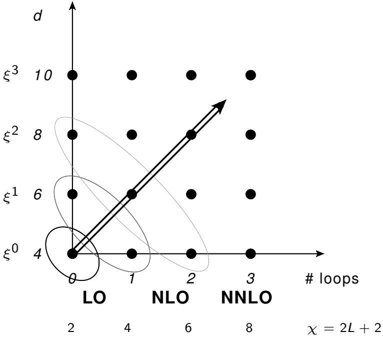
- The power counting depends on the (non-)decoupling nature of the new physics.



Summary

- The power counting depends on the (non-)decoupling nature of the new physics.

- Phenomenologically interesting is a double expansion in $\frac{f^2}{\Lambda^2} \simeq \frac{1}{16\pi^2}$ & $\xi = \frac{v^2}{f^2}$.



Summary

- The power counting depends on the (non-)decoupling nature of the new physics.
- Phenomenologically interesting is a double expansion in $\frac{f^2}{\Lambda^2} \simeq \frac{1}{16\pi^2}$ & $\xi = \frac{v^2}{f^2}$.
- The leading terms in the chiral expansion lead to a Lagrangian that is suitable for fitting LHC Higgs data. It has only 6 free parameters.

Best fit:

$$\begin{pmatrix} c_V & = 0.98 \pm 0.09 \\ c_t & = 1.34 \pm 0.19 \\ c_b & = 0.79 \pm 0.18 \\ c_\tau & = 0.92 \pm 0.14 \\ c_{\gamma\gamma} & = -0.24 \pm 0.37 \\ c_{gg} & = -0.30 \pm 0.16 \end{pmatrix}$$

$\Rightarrow$ The Standard Model Higgs hypothesis can be tested effectively. A systematic expansion of this analysis is – via the EFT – straightforward.

Backup

$\mathcal{L}_{\text{LO}}$, power counting and NDA

$$\mathcal{L}_{\text{LO}} = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mathcal{V}\left(\tfrac{h}{v}\right) + \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \; a_n\left(\tfrac{h}{v}\right)^n + i\bar{\Psi}_f \not{D}\Psi_f$$
$$- v\left(\bar{\Psi}_f Y_{j,f} U \Psi_f + \text{h.c.}\right)\; \left(\tfrac{h}{v}\right)^j - \frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

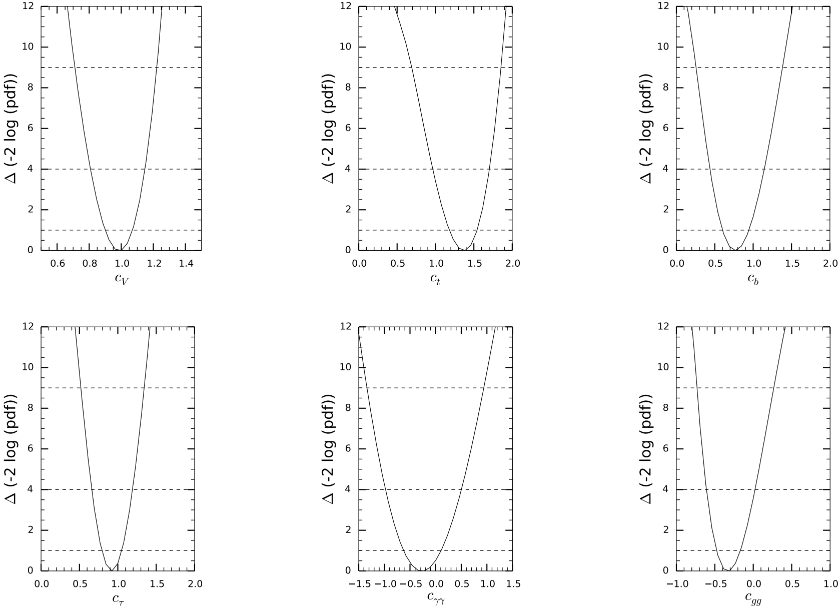
$$\mathcal{D} \sim p^{2L+2-X-\frac{1}{2}(F_L+F_R)-N_V}\; \left(\frac{\varphi}{v}\right)^B \left(\frac{h}{v}\right)^H \bar{\Psi}_L^{F_L^1}\; \Psi_L^{F_L^2}\; \bar{\Psi}_R^{F_R^1}\; \Psi_R^{F_R^2} \left(\frac{\mathcal{X}_{\mu\nu}}{v}\right)^X$$

Naive dimensional analysis - NDA:

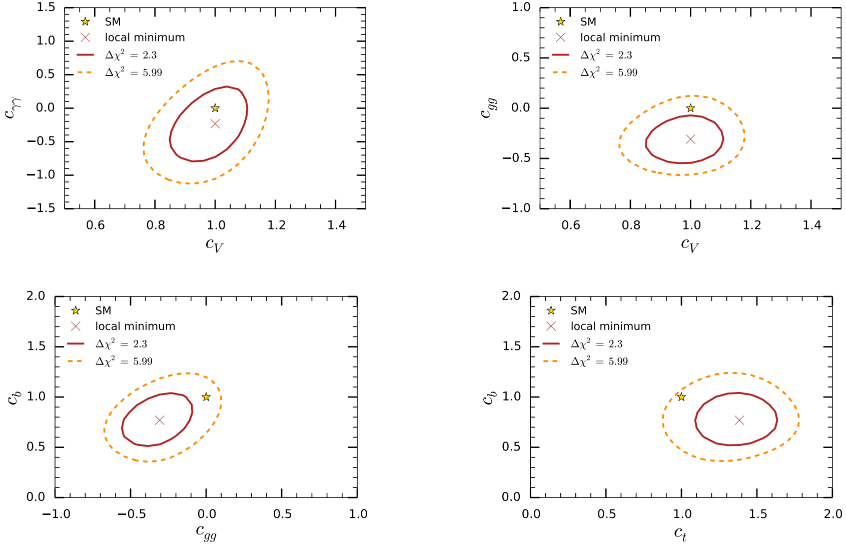
Georgi, Manohar ['84 Nucl. Phys. B]; Georgi [hep-ph/9207278]

- Overall factor $f^2\Lambda^2$, f^{-1} for each strongly interacting field, Λ^{-1} to reach dimension 4
- Is consistent with our counting only if internal gauge lines and Yukawa interactions are neglected.
- Gives wrong scaling in some cases, *e.g.* $F_{\mu\nu}F^{\mu\nu}$.

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



Further 2-dim plots



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