Title: The electroweak chiral Lagrangian with a light Higgs â€“ systematics & application

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Abstract: <p>I consider the Standard Model as an effective field theory (EFT) at the electroweak scale v. At the scale $f\geq v$ I assume a new, strong interaction that breaks the electroweak symmetry dynamically. The Higgs boson arises as a composite pseudo-Nambu-Goldstone boson in these scenarios and is therefore naturally light $(m_{h}\sim v)$. Based on these assumptions and the value of $\xi=v^{2}/f^{2}$, I explain the systematics that governs the effective expansion:\\</p>

<p>For $\xi=\mathcal{O}(1)$ the effective theory is given by a loop expansion, equivalent to an expansion in chiral dimensions (similar to chiral perturbation theory). I will briefly discuss the operators that arise at next-to-leading order ($\mathcal{O}(f^{2} / \Lambda^{2})\simeq \mathcal{O}(1/16\pi^{2})$). On the other hand, in the decoupling limit where $\xi\rightarrow 0$, an expansion in canonical dimension is recovered. The case where ξ is small but non-zero is of phenomenological interest. It leads to a double expansion in ξ and $1/16\pi^{2}$, which captures the expected corrections of a strongly-interacting light Higgs to the Standard Model in a systematic way. \\</p>

<p>Further, I will apply the leading order chiral Lagrangian to current LHC Higgs data. I will show that this gives a QFT justification of the κ-framework, which is currently used as phenomenological signal-strength parametrization by the experiments at the LHC. I will also present a fit of the leading order chiral Lagrangian to the LHC Higgs data.</p>

<p> </p>

The electroweak chiral Lagrangian with a light Higgs

– systematics & application –

Claudius Krause

Ludwig-Maximilians-Universität München

November 13, 2015

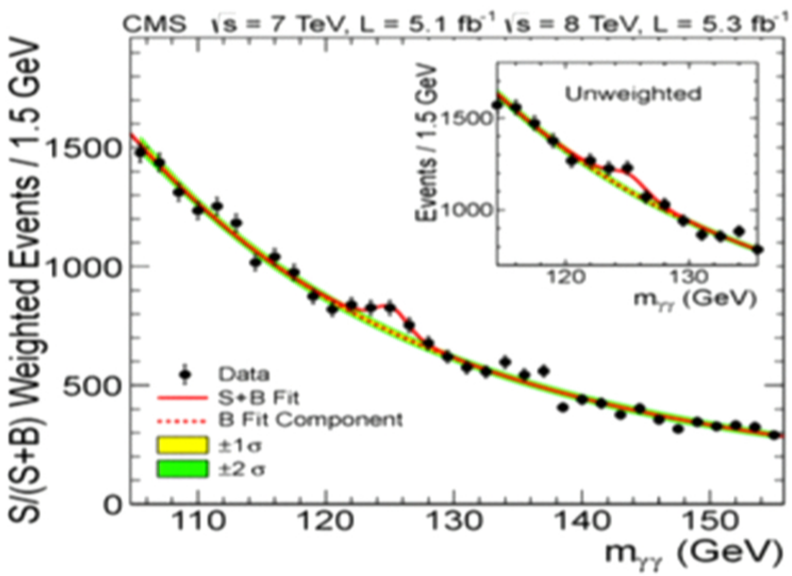
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

DFG

ARNOLD SOMMERFELD CENTER FOR THEORETICAL PHYSICS

In collaboration with G. Buchalla, O. Catà and 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 ∼ 10%

Is it the/a Higgs or something else?

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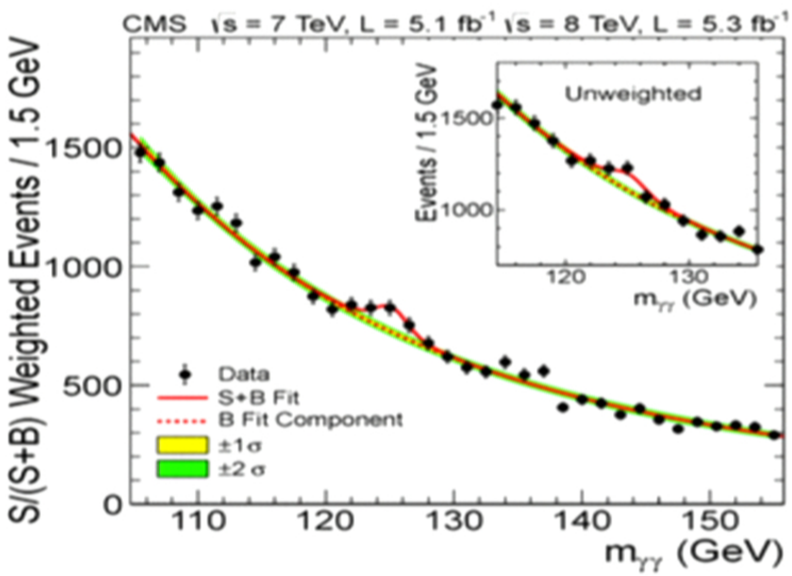

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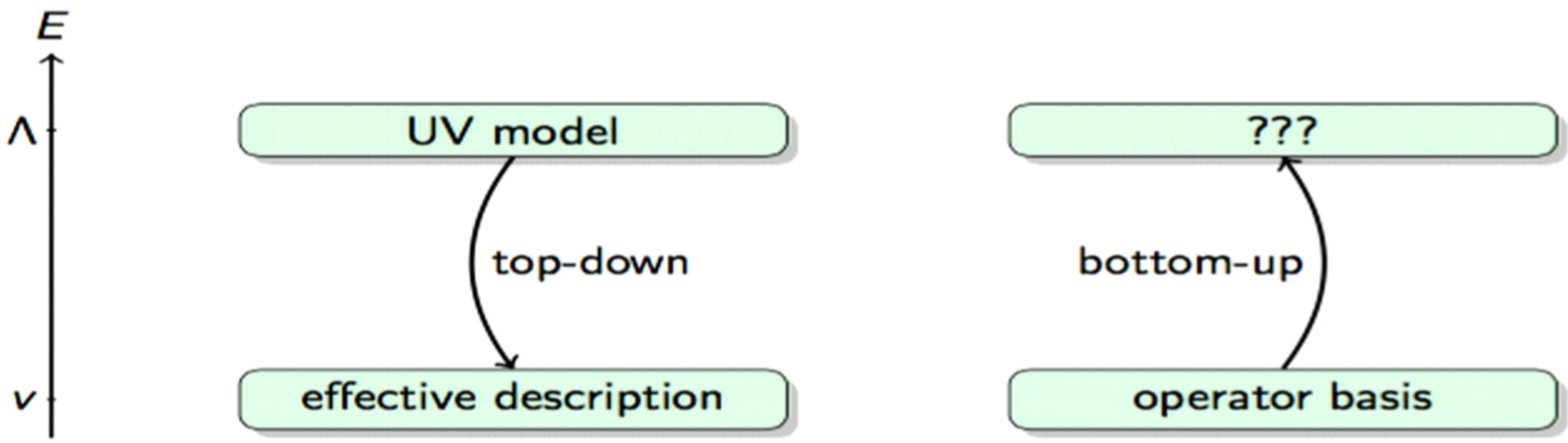

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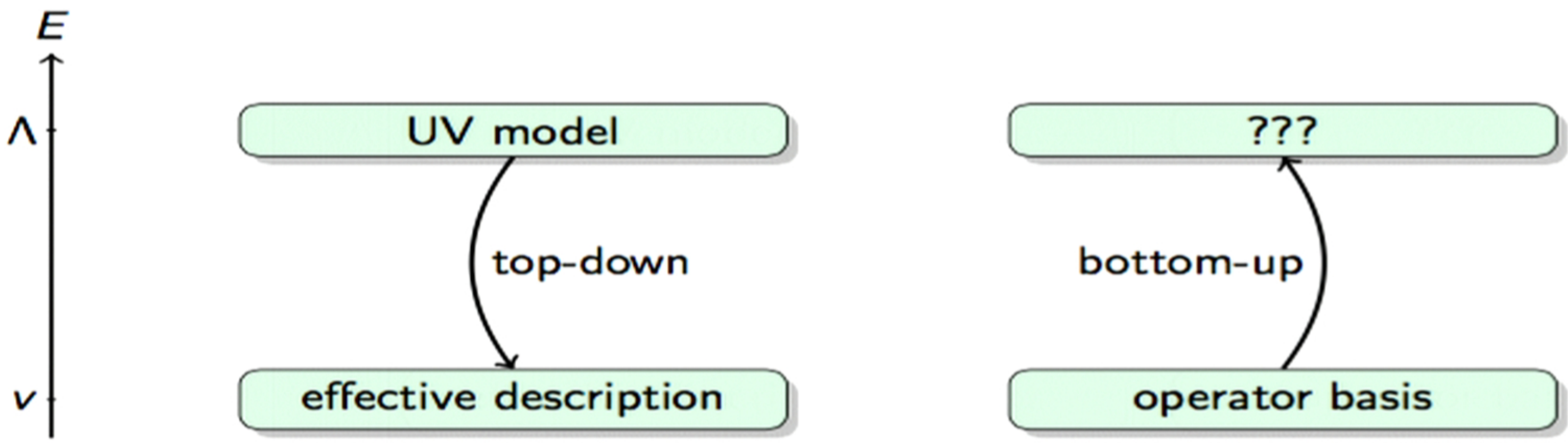
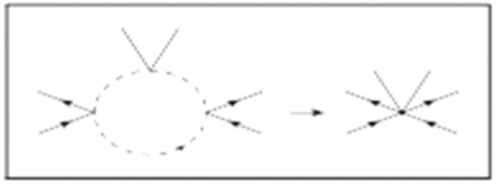


For a model-independent analysis we use the bottom-up approach.

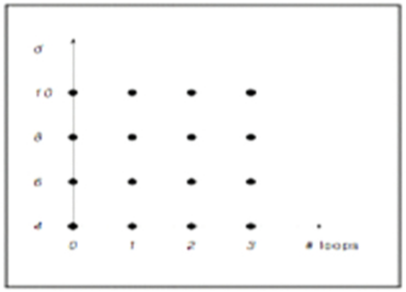
We need:

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

The electroweak chiral Lagrangian with a light Higgs

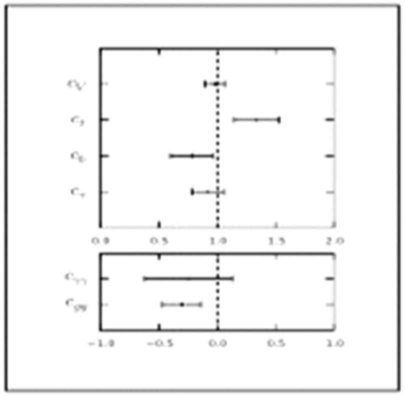


Part 1 – Building the EFT
[1307.5017,1312.5624]



Part 2 – Relation to the linear EFT
[1412.6356]

Part 3 – Application to data
[1504.01707,1511.00988]



1. Building the EFT

Ingredients:

- Particles: all SM particles + 3 Goldstone bosons for the $W^{\pm}/Z$ masses
- Symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$, B, L at LO: CP and custodial sym.
- Power counting: depends on realization of the symmetry:

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- Power counting: depends on realization of the symmetry:

linear realization:

- scalar h and Goldstones form Higgs-doublet ϕ
- NLO is given by dimension 6
  Buchmüller/Wyler ['86 Nucl. Phys. B], Grzadkowski et al. [1008.4884]
  $\rightarrow$ more in Part 2.

$\rightarrow$ not the most general ansatz

nonlinear realization:

- include h as scalar singlet
- NLO will be discussed now

$\rightarrow$ more general ansatz

1. The nonlinear realization

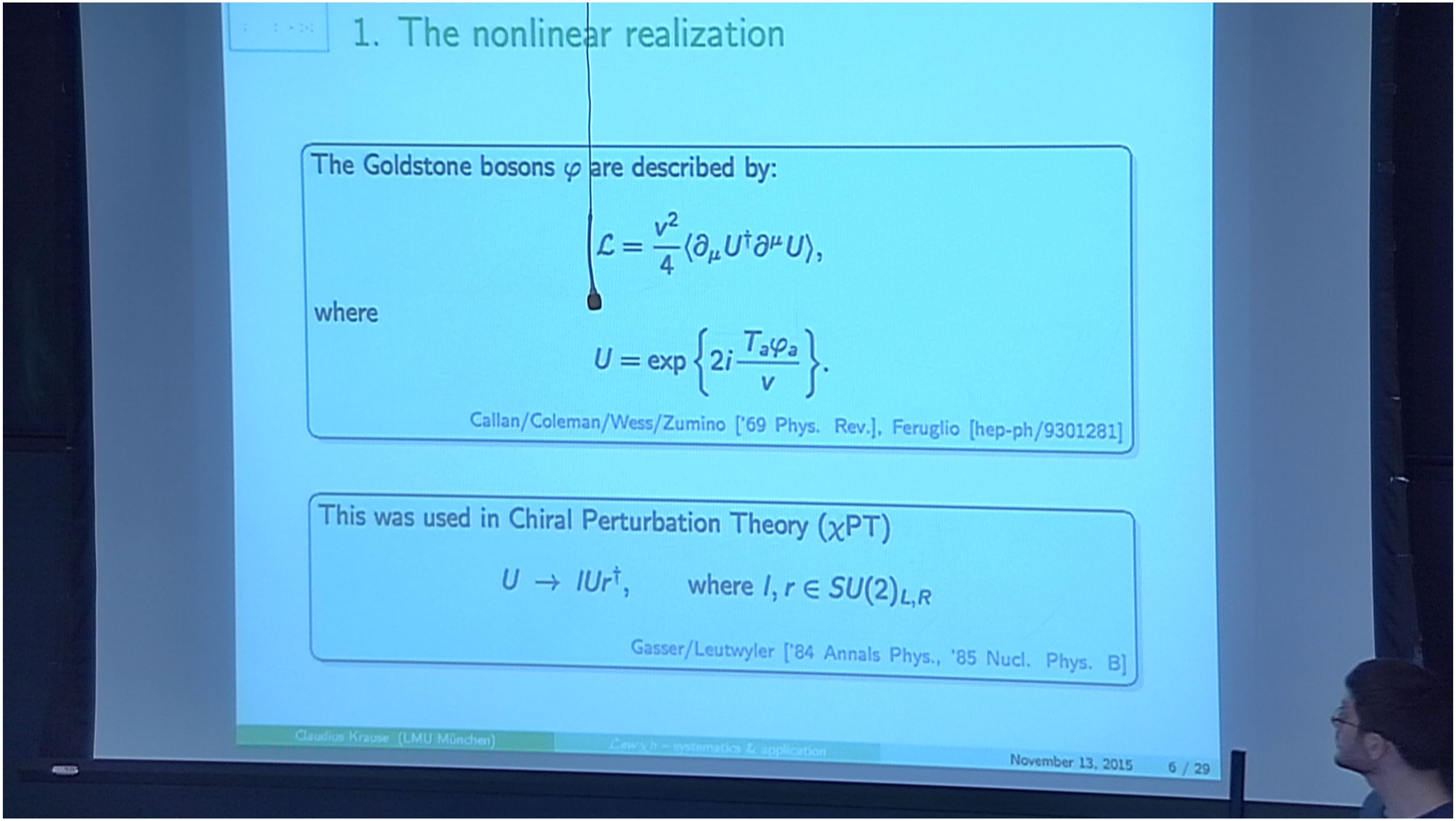
The Goldstone bosons φ are described by:

$$\mathcal{L} = \frac{v^2}{4}\langle \partial_\mu U^\dagger \partial^\mu U \rangle,$$

where

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

Callan/Coleman/Wess/Zumino ['69 Phys. Rev.], Feruglio [hep-ph/9301281]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This was used in Chiral Perturbation Theory (χPT)
$$U \rightarrow lUr^\dagger, \qquad \text{where } l, r \in SU(2)_{L,R}$$
Gasser/Leutwyler ['84 Annals Phys., '85 Nucl. Phys. B]
Claudius Krause (LMU München)
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1. Effective Lagrangian at leading order

assumptions

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], ...

- A new strong sector is generating the 3 Goldstones of EWSB and the h.
- The scale of the new dynamics is given by f.
- The transverse gauge bosons and the fermions of the SM are weakly coupled.
- The pattern of symmetry breaking is $SU(2)_L \times SU(2)_R \to SU(2)_{V=L+R}$

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$$\mathcal{L}_{\text{LO}} = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mathcal{V}(h) + \frac{v^2}{4}\langle(D_\mu U)(D^\mu U^\dagger)\rangle\ (1 + F_U(h))$$
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- $\mathcal{L}_{\mathrm{LO}}$ is not renormalizable in the traditional sense.
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Claudius Krause (LMU München) $\mathcal{L}ew\chi h$ – systematics & application

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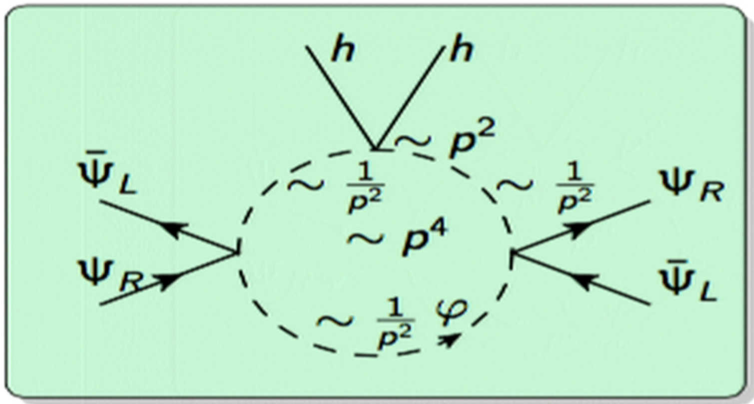

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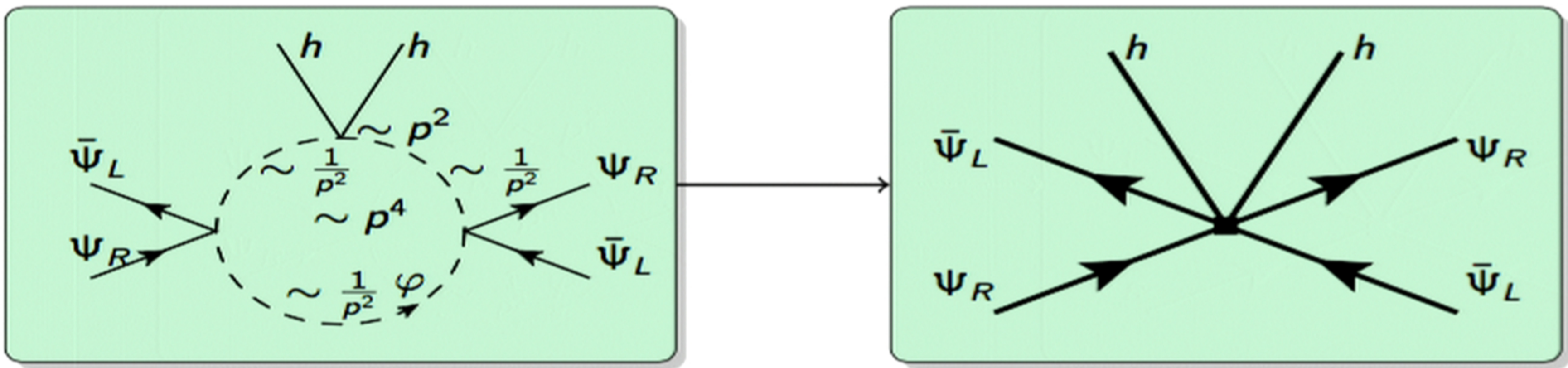

1. Power counting

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

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

This is equiva…

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

$$[\text{bosons}]_\chi = 0,$$
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This is equivalent to a counting of chiral dimensions:

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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.* $F_{\mu\nu}F^{\mu\nu}$.

1. Application of chiral dimensions

- Classify the NLO ($\chi = 4$) operators
- Control the explicit breaking of symmetries (*e.g.* custodial or CP): If they are broken by weak perturbations (like gauge or Yukawa), their spurions come with chiral dimensions as well.
- Gain additional informations about dimension 6 operators: $[g^3 \langle W_\mu^\nu W_\nu^\rho W_\rho^\mu \rangle]_\chi = 6 \rightarrow$ arises at 2 loops
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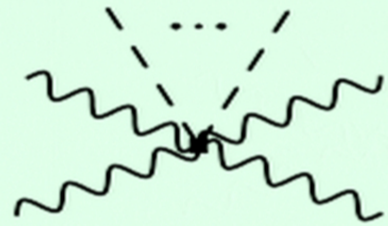
1. Examples for NLO operators without fermions

$g^2 U D^2 h$

$$\mathcal{O}_T = (g' v)^2 \langle U T_3 D_\mu U^\dagger \rangle^2 \mathcal{F},$$

$\sum$: 1 operator

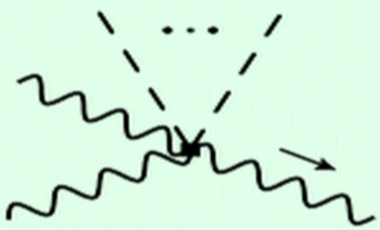
$U D^4 h$



$$\mathcal{O}_{D0,1} = \langle D_\mu U D^\mu U^\dagger \rangle^2 \mathcal{F},$$

$\sum$: 15 operators

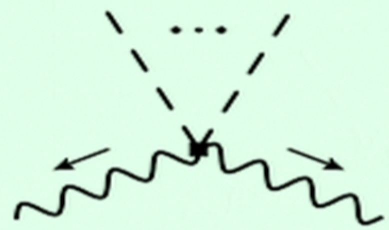
$g U X D^2 h$



$$\mathcal{O}_{XUD1} = g' \langle T_3 D_\mu U^\dagger D_\nu U \rangle B^{\mu\nu} \widetilde{\mathcal{F}},$$

$\sum$: 8 operators

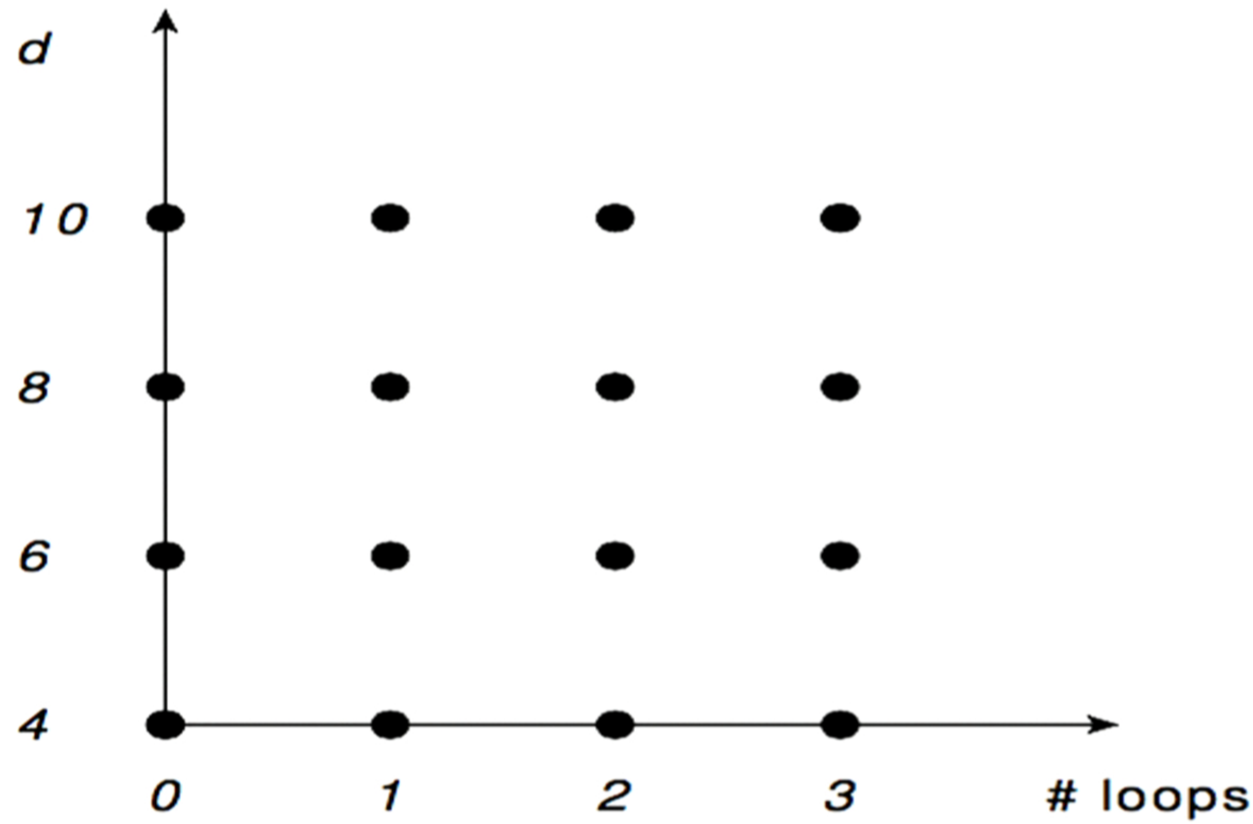
$g^2 U X^2 h$



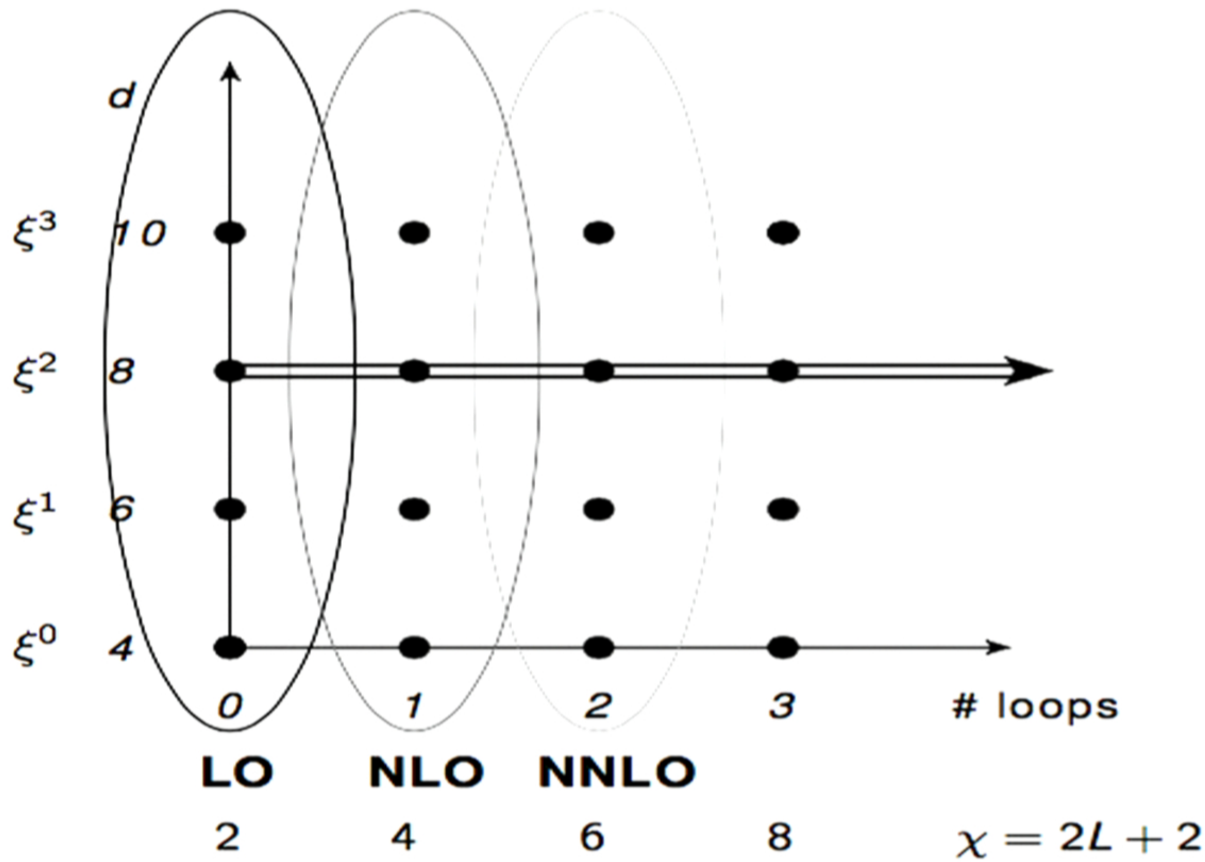
$$\mathcal{O}_{XU1} = g'^2 B_{\mu\nu} B^{\mu\nu} \widetilde{\mathcal{F}},$$

$\sum$: 10 operators

2. A graphical way to see the expansion.



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



2. In the linear EFT, the expansion parameter is $\left(\frac{v}{\Lambda}\right)$.

Assumptions:

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- dim 5: 1 operator (violating L) Weinberg ['79 Phys. Rev. Lett.]
- dim 6: 59 operators (conserving B)
  4 operators (violating B)
  Buchmüller, Wyler ['86 Nucl. Phys. B]; Grzadkowski et al. [1008.4884]
- dim 7: 20 operators (all violating L, some B) Lehman [1410.4193]
- dim 8: 489 operators (conserving B)
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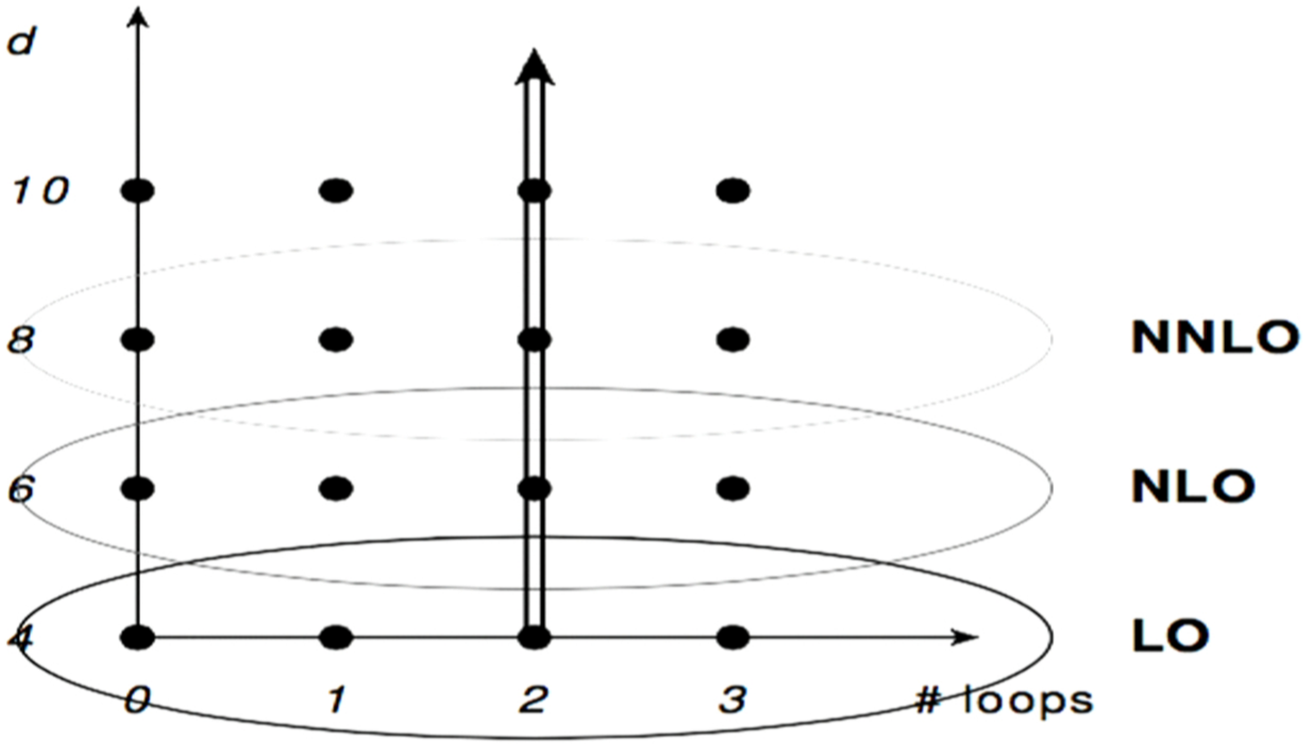

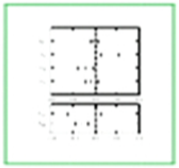

3. Current observables select $\mathcal{L}_{\text{fit}}$ from $\mathcal{L}_{ew\chi h}$.

$$\mathcal{L}_{ew\chi h} = \mathcal{L}_{\text{kin}}^{h,\Psi,\text{gauge}} + \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \; (1 + F_U(h)) - \mathcal{V}(h)$$
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We focus on current observables and phenomenology requires $f > v$, *i.e.* $\xi = v^2/f^2 < 1$.

Single h processes

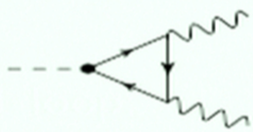
tree:

c_V

$c_{t,b,\tau}$

(3^{rd} generation only)

1-loop:



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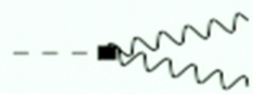

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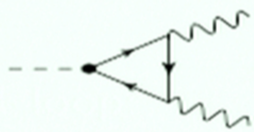

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(gg and $\gamma\gamma$ only)

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

$$\mathcal{L}_{\text{fit}} = 2c_V \left(m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(\tfrac{h}{v}\right) - c_t y_t \bar{t} t h - c_b y_b \bar{b} b h - c_\tau y_\tau \bar{\tau} \tau h + \tfrac{e^2}{16\pi^2} c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} \tfrac{h}{v} + \tfrac{g_s^2}{16\pi^2} c_{gg} \langle G_{\mu\nu} G^{\mu\nu} \rangle \tfrac{h}{v}$$

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

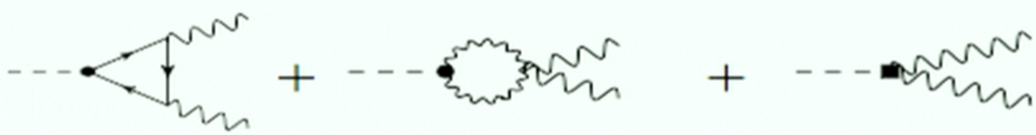
Single h processes

tree:

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

(3rd generation only)

1-loop:



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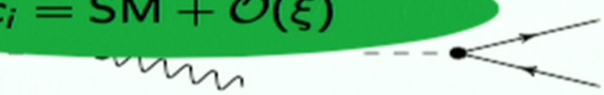
$c_i = \text{SM} + \mathcal{O}(\xi)$

Single h processes

tree:



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(3[rd] generation only)

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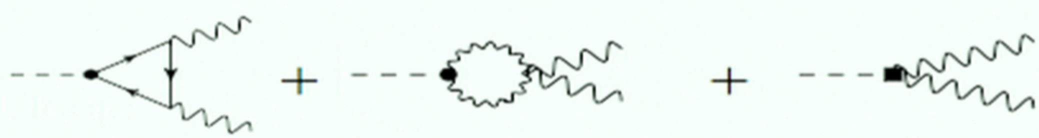


$c_{t,b,\tau}$ $\quad$ c_V $\quad$ $c_{\gamma\gamma,gg}$

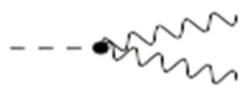
(gg and $\gamma\gamma$ only)

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

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

tree:

$c_{t,b,\tau}$



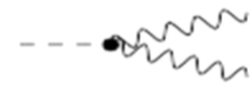
c_V

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

LHCHXSWG [1209.0040,1307.1347]

tree:

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



κ_V

3. 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:

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

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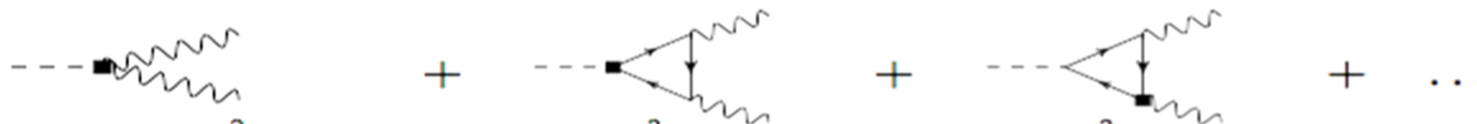
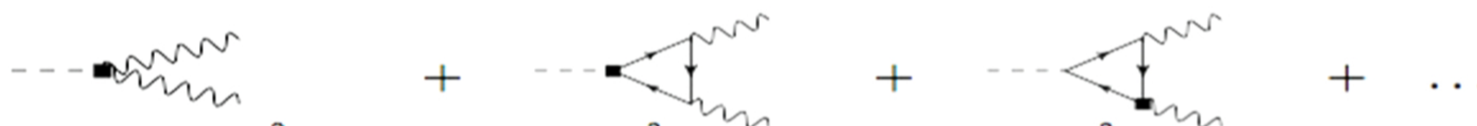
LO + NLO:



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]:



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Between Run-1 and the final stages of the LHC:

κ_V, κ_f

LHCHXSWG [1209.0040,1307.1347]

a, c

Contino[1005.4269]

complexity

time→

small deviations:
full dim-6

Hartmann/Trott [1507.03568],
Ghezzi *et al.* [1505.03706]

larger deviations
in Higgs-sector:
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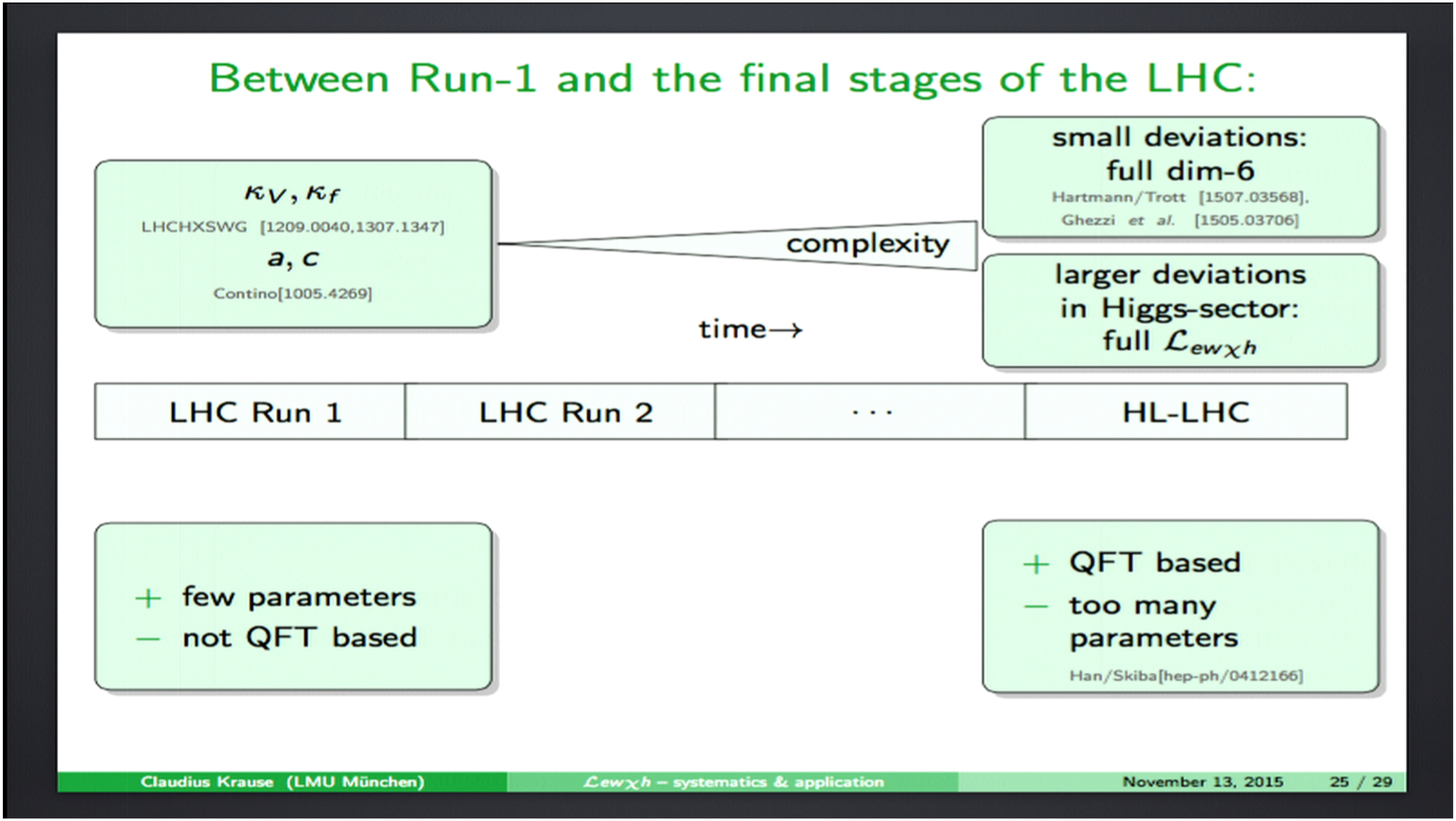
LHC Run 1	LHC Run 2	...	HL-LHC



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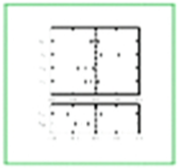
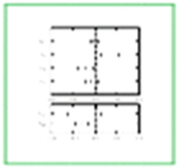
LHC Run 1
LHC Run 2
· · ·
HL-LHC
+ few parameters
− not QFT based
+ QFT based
− too many parameters
Han/Skiba[hep-ph/0412166]
Claudius Krause (LMU München)
$\mathcal{L}_{ew\chi h}$ – systematics & application
November 13, 2015
25 / 29



3. We performed a Bayesian fit to LHC 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

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

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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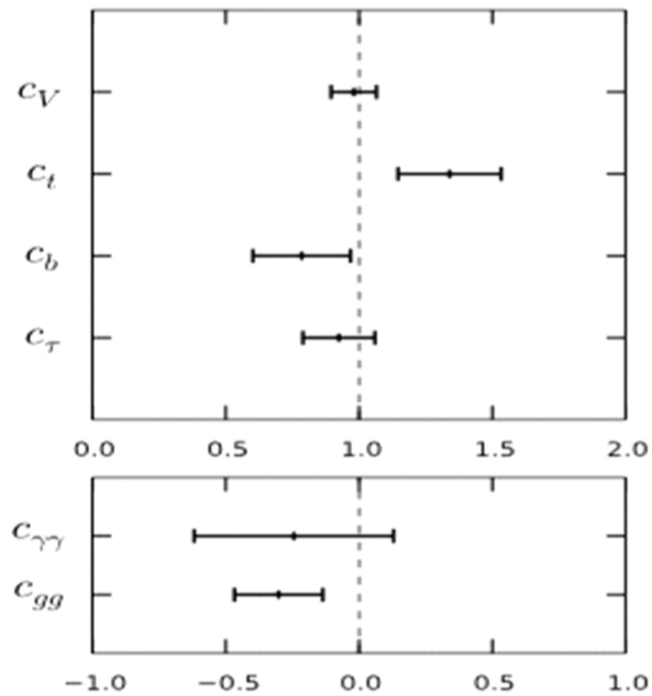
Results:

$$\begin{pmatrix} c_V \\ c_t \\ c_b \\ c_\tau \\ c_{\gamma\gamma} \\ c_{gg} \end{pmatrix} = \begin{pmatrix} 0.98 & \pm & 0.08 \\ 1.37 & \pm & 0.22 \\ 0.83 & \pm & 0.19 \\ 0.95 & \pm & 0.14 \\ -0.41 & \pm & 0.38 \\ -0.31 & \pm & 0.16 \end{pmatrix}$$

$$\rho_{ij} = \frac{\mathrm{cov}(c_i, c_j)}{\sigma_i \sigma_j} =$$

$$\begin{pmatrix} 1.0 & 0.09 & 0.68 & 0.42 & 0.33 & 0.06 \\ . & 1.0 & 0.16 & 0.01 & -0.43 & -0.73 \\ . & . & 1.0 & 0.59 & -0.07 & 0.24 \\ . & . & . & 1.0 & -0.07 & 0.18 \\ . & . & . & . & 1.0 & 0.32 \\ . & . & . & . & . & 1.0 \end{pmatrix}$$



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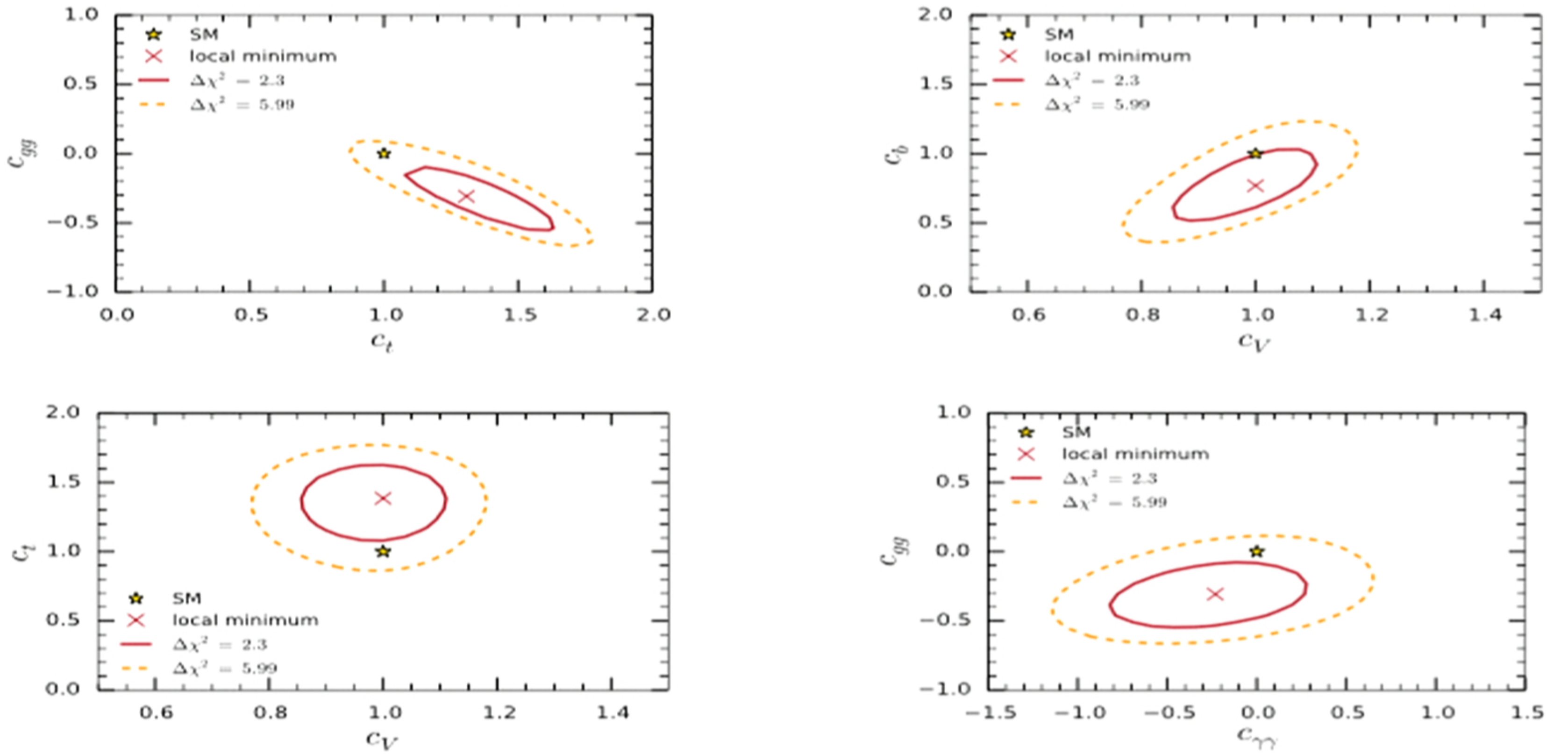

Summary

- I presented the electroweak chiral Lagrangian.
- I discussed the power counting in terms of chiral dimensions.

$$[\varphi]_\chi = [h]_\chi = 0$$
$$[g]_\chi = [y]_\chi = 1$$
$$[\bar{\Psi}\Psi]_\chi = [\partial_\mu]_\chi = 1$$

[1307.5017,1312.5624]

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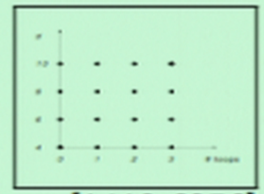

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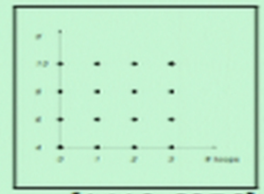

[1412.6356]

- I justified the κ-framework with the chiral Lagrangian.
- I presented a fit to LHC data using the nonlinear EFT.

[1504.01707,1511.00988]