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Three slides on triple Higgs couplings

LHCHXSWG HH subgroup meeting, 12 December 2016

Based on work in progress with Riccardo Rattazzi

Higgs boson in SM or SM EFT

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \cdots \\ v + h + \ldots \end{pmatrix}$$

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 + \left(\frac{y_{ij}}{\sqrt{2}} H \bar{\psi}_i \psi_j + \text{h.c.} \right) + \ldots$$ (no Higgs)

Couplings to EW gauge bosons

$$\left(\frac{h}{v} + \frac{h^2}{2v^2} \right) (2 m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu)$$

Ensures unitarity of VV->hh scattering

Ensures unitarity of VV->VV scattering

Self-Couplings

$$-\frac{m_h^2}{2v} h^3 - \frac{m_h^2}{8v^2} h^4$$

What are self-couplings for?

Couplings to fermions

$$-\frac{h}{v} \sum_f m_f \bar{f} f$$

Ensures unitarity of VV->ff scattering

It is clear what goes wrong when self-couplings are modified in framework of SM EFT where SM Lagrangian is extended by higher-dimensional operators. New scale M suppressing D>4 operators sets maximum validity range Λ of SM EFT

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{(H^\dagger H)^3}{M^2}$$

$$\mathcal{L} \supset -\frac{m_h^2}{2v} (1 + \delta\lambda_3) h^3 - \frac{m_h^2}{8v^2} (1 + \delta\lambda_4) h^4 - \frac{\lambda_5}{v} h^5 - \frac{\lambda_6}{v^2} h^6$$

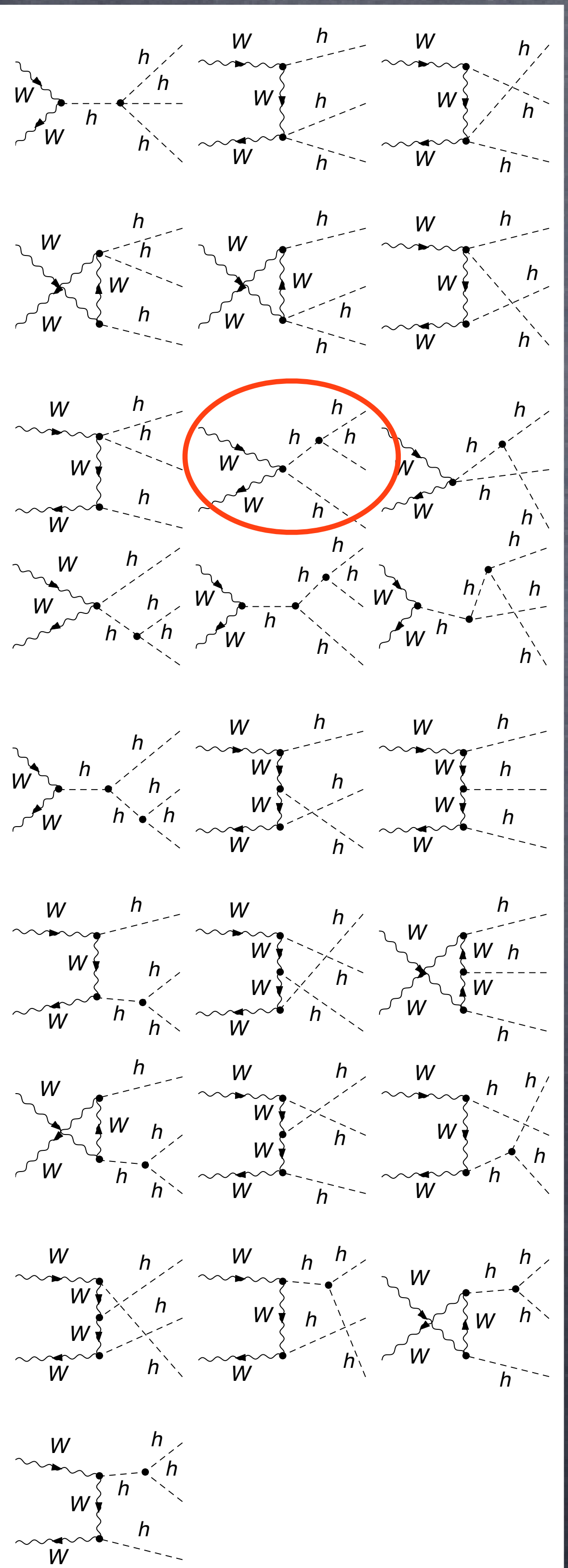
$$\delta\lambda_3 = \frac{2v^4}{m_h^2 M^2} \quad \delta\lambda_4 = \frac{12 v^4}{m_h^2 M^2} \quad \lambda_5 = \frac{3v^2}{4M^2} \quad \lambda_6 = \frac{v^2}{8M^2}$$

$$\Lambda \lesssim 4\pi M = \frac{4\pi v}{\sqrt{|\delta\lambda_3|}} \frac{\sqrt{2} v}{m_h}$$

E.g. hh→hhh or $V_L V_L$→hhh scattering loses perturbative unitarity at scale Λ

h^3-deformed SM

Here I address a different question: what goes wrong in a theory where only triple Higgs coupling is deformed away from SM and no other interactions are affected (in particular, there's no h^5 or h^6 terms in the Lagrangian)



Answer: multibody $V_L V_L \to (n \times h)(m \times V_L)$ (and crossed) scattering with n+m>2 loses perturbative unitarity around the scale $\Lambda \sim 4\pi v \sim 3$ TeV

Consider $V_L V_L \to hhh$ which depends on triple and other Higgs couplings. Diagrams with one triple Higgs vertex contribute

$$\mathcal{M} \sim \frac{m_W^2}{v^2} \frac{m_h^2}{v} (1 + \delta\lambda_3) \left(\frac{\sqrt{s}}{m_W} \right)^2 \frac{1}{s - m_h^2} + \dots$$

hhWW vertex — Triple Higgs vertex — Longitudinal polarization — Propagator

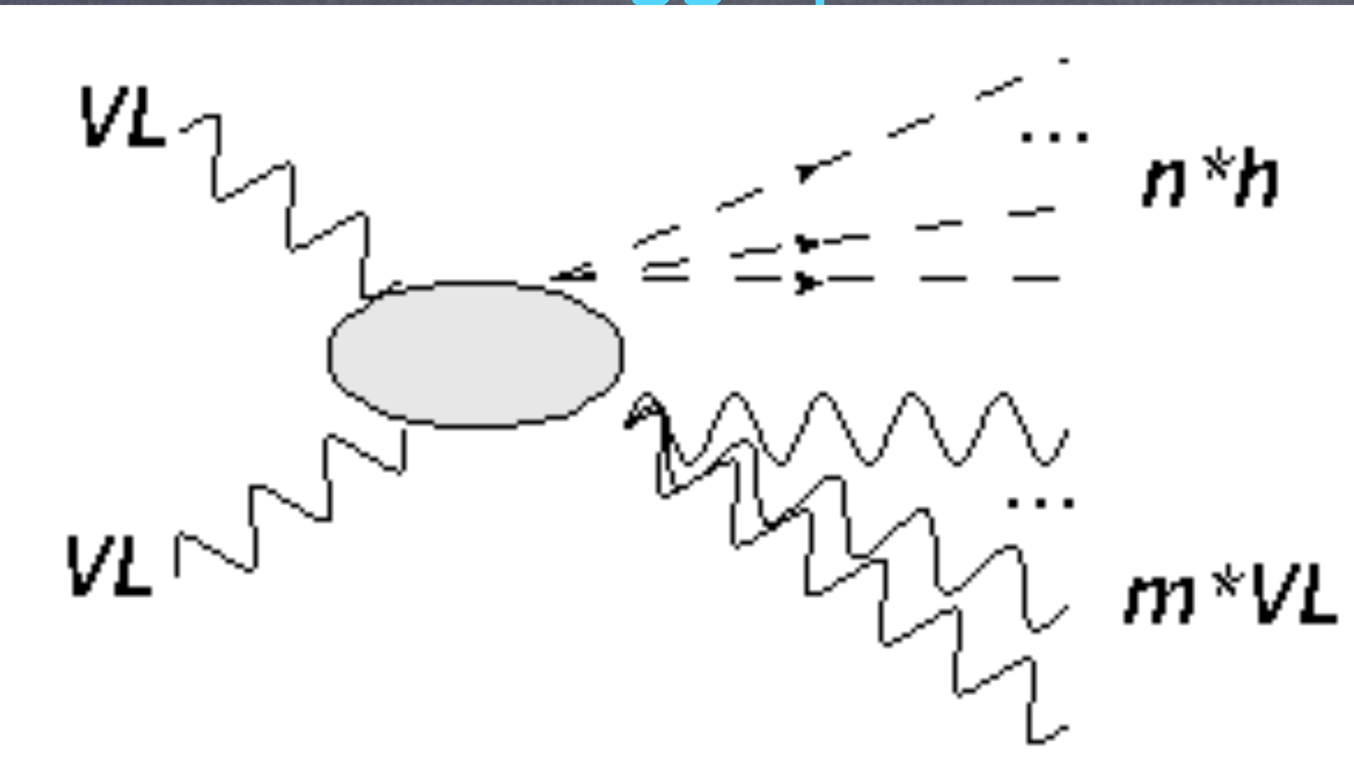
In SM, various contributions that go like E^0 cancel against each other so that full amplitude behaves as 1/E at high energy, consistently with perturbative unitarity

However, as soon as δλ3≠0, cancellation is no longer happening, and then tree level $V_L V_L \to hhh$ cross section explodes at high energies

Perturbative unitarity of $V_L V_L \to hhh$ is lost at scale

$$\Lambda \sim \frac{4\pi v}{|\delta\lambda_3|}$$

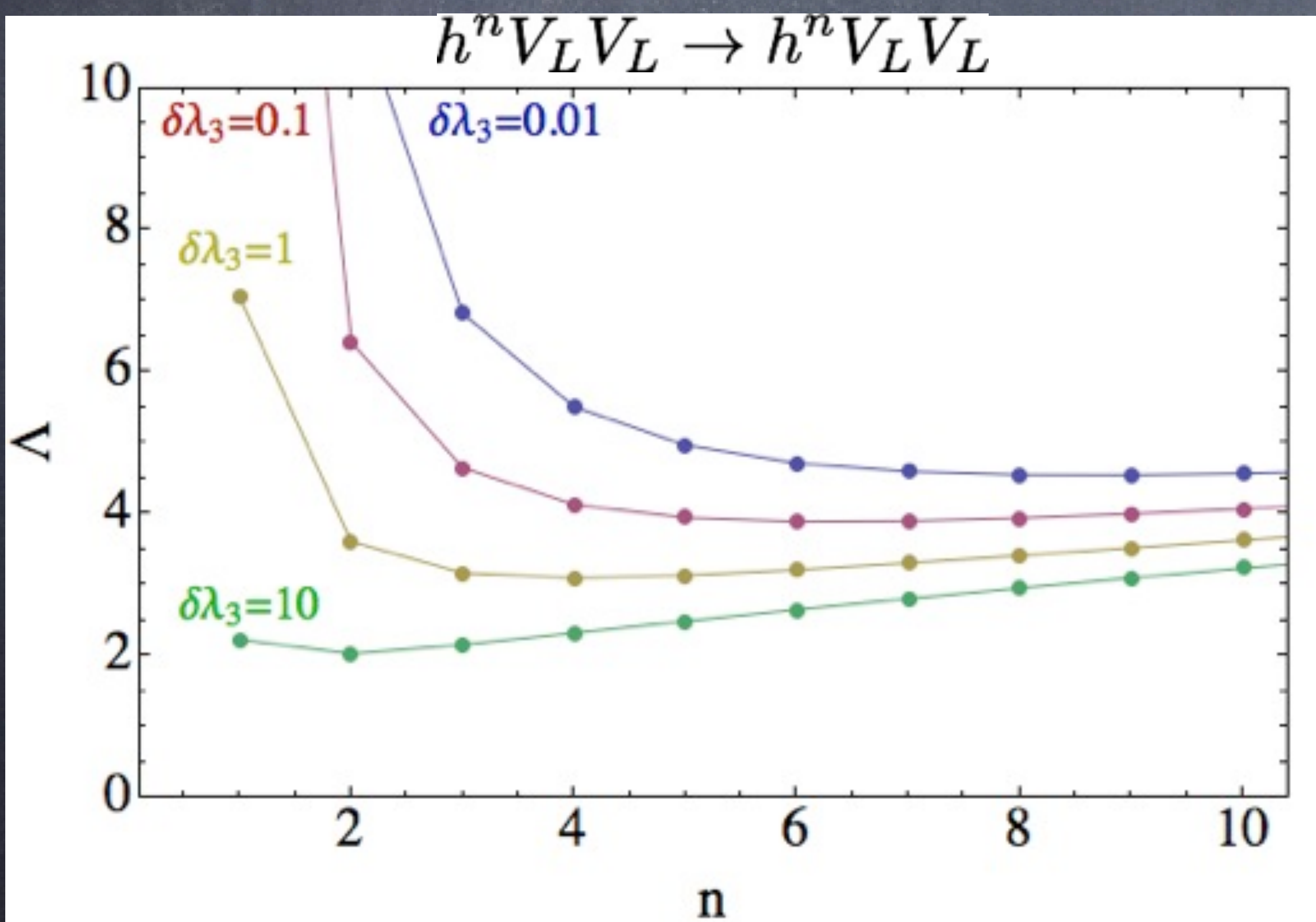
multi-Higgs production in h^3-deformed SM



For small δλ3, stronger bound on Λ may be obtained by demanding perturbative unitarity of multi-h and multi-VL scattering. E.g. for m=0:

$$\mathcal{M}(V_L V_L \to h^n) \sim \frac{n! m_h^2}{v^n} \delta\lambda_3$$

$$\Lambda \lesssim \frac{4\pi v \sqrt{(n-2)!}}{|\delta\lambda_3|^{\frac{1}{n-2}}}$$



So far, best limits from

(error in SM EFT column in previous version of slides corrected thanks to Fabio and Christophe)

$h^n V_L V_L \to h^n V_L V_L$

$\lvert\delta\lambda_3\rvert$	Λ [TeV]	n_{best}	Λ_{SMEFT} [TeV]
0.01	4.5	9	160
0.1	3.9	6	50
1	3.1	4	16
10	2.0	2	5.0
20	1.6	1	2.8
40	1.1	1	1.4

For small |δλ3|, cutoff approximately

$$\Lambda \sim 2\pi v \sqrt{|\log|\delta\lambda_3||}$$

in practice, never parametrically above 4πv

Summary

- The h^3-deformed SM (the theory with the SM field content and interactions except for the triple Higgs boson coupling deformed away from the SM value) is similar to Higgsless theories in that it loses perturbative unitarity around the scale $4\pi v$, even if the deformation is small. Same conclusions if the quartic Higgs coupling is deformed

- Such set-up does not belong to the SM EFT class, and is not an effective theory obtained by integrating out heavy BSM particles. In fact, it corresponds to an effective theory where masses of integrated-out particles vanish in the limit of no electroweak symmetry breaking

- For precision studies of small and moderate deformations of the cubic Higgs couplings deformations, it is safer to use the regular SM EFT framework, as it allows one to control the validity range. If the deformations are large, $\delta\lambda 3>10$, it is not completely clear if the new degrees of freedom, which necessarily have to appear near 1 TeV scale, would not always introduce comparable corrections to the precision observables

- Similar discussion applies for other Higgs couplings deformations that are not described by SM EFT