Higgs Couplings and the Scale of New Physics

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S. Chang, ML, JHEP 2020, 140 (2020)
F. Abu-Ajamieh, S. Chang, M. Chen, ML, arXiv:2009.11293

Introduction

Why measure Higgs couplings?

$$\kappa_X = \frac{g_{hX}}{g_{hX}^{(\mathrm{SM})}}$$

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Higgs couplings *already* known to $\sim 1\%$ within SM…

Measuring Higgs couplings is a search for physics beyond the Standard Model

Introduction

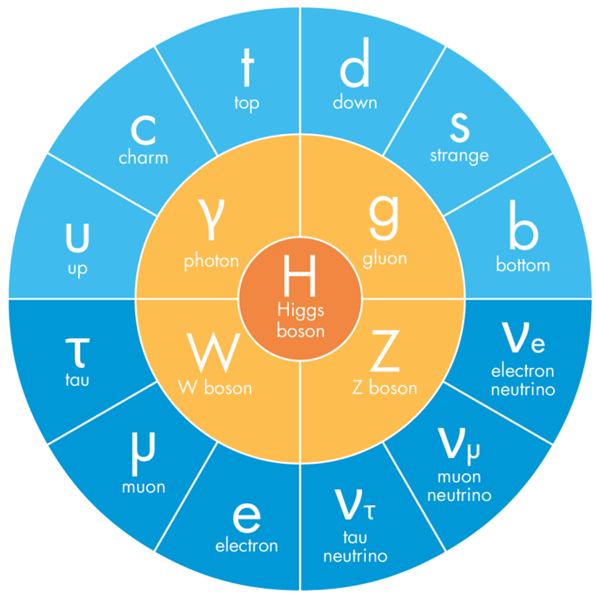
What kind of new physics?

- Low scale: LHC direct searches
- High scale: target for future colliders?

This work: *model-independent* implications of Higgs coupling measurements for new physics at high energies

Introduction

SM = unique UV-complete theory with observed spectrum of elementary particles



$\kappa_X \neq 1:$

⇒ scattering amplitudes are harder at high energies than allowed by unitarity

⇒ model-independent upper bound on scale of new physics

Introduction

Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass

Benjamin W. Lee, C. Quigg,* and H. B. Thacker
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 28 February 1977)

It is shown that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$ partial-wave unitarity is not respected by the tree diagrams for two-body reactions of gauge bosons, and the weak interactions must become strong.

History repeats itself?

Let's hope so!

Outline

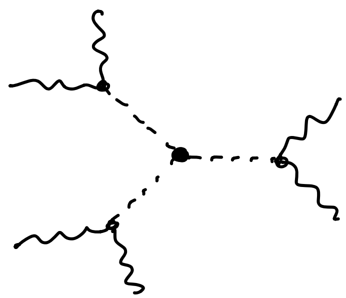
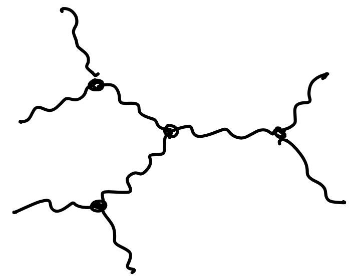
- Unitarity bounds from BSM physics
- Parameterizing new physics
  - Equivalence theorem
  - Model independence

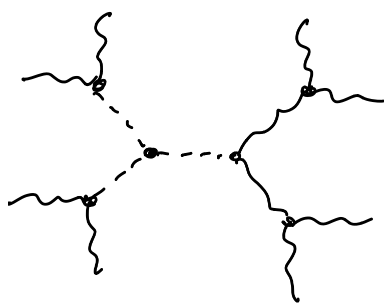
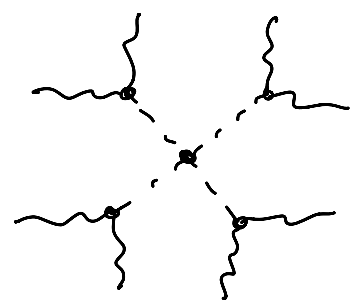
  } h^3 coupling
- Results for general Higgs couplings
  - Scale of new physics
  - SMEFT without SMEFT

Unitarity Bounds

Example: Higgs cubic coupling: $g_{h^3} = (1 + \delta_3)\dfrac{m_h^2}{2v}$

Generalized partial wave amplitudes:

$\hat{\mathcal{M}}(V_L^3 \to V_L^3) =$  $+$  $+ \cdots \sim \delta_3 \dfrac{E^2}{v^2}$

$\hat{\mathcal{M}}(V_L^4 \to V_L^4) =$  $+$  $+ \cdots \sim (\delta_3 + \delta_4)\dfrac{E^4}{v^4}$

$\delta_3 \neq 0$ ruins SM cancelations that ensure good UV behavior

⇒ model-independent unitarity bound
on scale of new physics

“Model Independent?”

- Marginalize over infinitely many unmeasured couplings
  e.g. $h^4, h^5, \ldots$

- Bound on scale of new physics depends directly on experimentally measured couplings

- No power counting/EFT truncation

Parameterizing New Physics

High scale new physics ⇒ new local couplings

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n$$
$$+ \sum_{n=2}^{\infty} c_{3,n} \frac{m_h^2}{v^{2n+1}} h(\partial_{\mu_1} \cdots \partial_{\mu_n} h)^2 + \cdots$$

- Allow all possible couplings with no power counting
- Integration by parts + field redefinitions used to define basis where derivatives count powers of energy (equations of motion ⇒ $\Box h = -m_h^2 h$)

Equivalence Theorem

Leading high-energy behavior of V_L scattering amplitudes is given by scattering amplitudes of “eaten” NGBs.

Dependence on NGB fields determined by gauge invariance:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v + h + i G^0 \end{pmatrix}$$

$$X = \sqrt{2 H^\dagger H} - v = h + \frac{1}{2v} \vec{G}^2 + \frac{1}{2v^3} h \vec{G}^2 + \cdots$$

Note: we are expanding around $h = 0$, not $H = 0$

Model Independence

$$X^3 \sim h^3 + \vec{G}^2(h^2 + h^3 + \cdots) + \vec{G}^4(h + h^2 + \cdots) + \vec{G}^6(1 + h + \cdots)$$
$$+ \vec{G}^8(1 + h + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots ,$$

$$X^4 \sim h^4 + \vec{G}^2(h^3 + h^4 + \cdots) + \vec{G}^4(h^2 + h^3 + \cdots) + \vec{G}^6(h + h^2 + \cdots)$$
$$+ \vec{G}^8(1 + h + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots ,$$

$$X^5 \sim h^5 + \vec{G}^2(h^4 + h^5 + \cdots) + \vec{G}^4(h^3 + h^4 + \cdots) + \vec{G}^6(h^2 + h^3 + \cdots)$$
$$+ \vec{G}^8(h + h^2 + \cdots) + \vec{G}^{10}(1 + h + \cdots) + \cdots .$$

The circled terms can only come from δ_3

Scale of New Physics

$$W_L^+ W_L^- \to W_L^+ W_L^- h: \qquad E_{\rm max} = \frac{9.4\ \text{TeV}}{|\delta_3/7.5|}$$

$$W_L^+ W_L^+ W_L^- \to W_L^+ W_L^+ W_L^-: \qquad E_{\rm max} = \frac{5.2\ \text{TeV}}{|\delta_3/7.5|^{1/2}}$$

Normalized to 95% CL ATLAS/CMS bound

- Current constraints still allow nearby new physics
- An observation of a deviation from the SM implies an upper bound on the scale of new physics

  ⇒ "no lose theorem" for a future collider

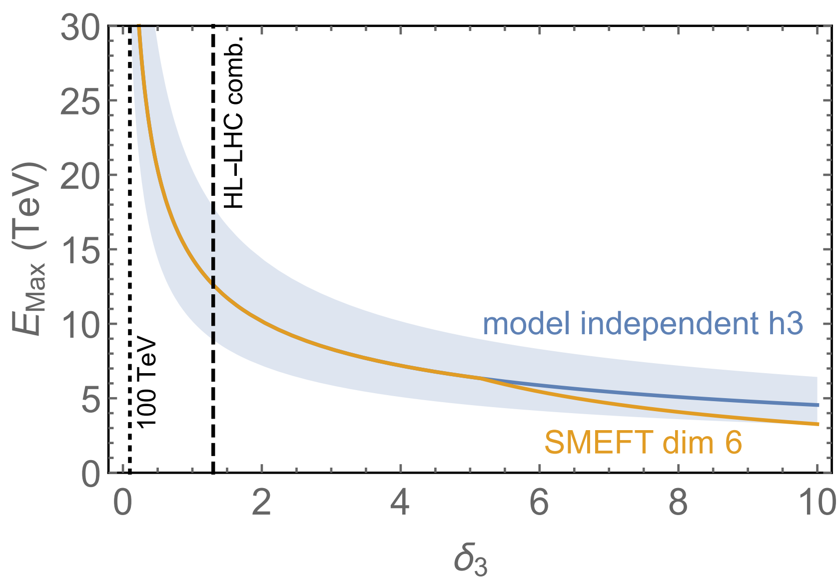
More on Model Independence

- Higher derivative terms give parametrically lower $E_{\max}$

$$\Delta\mathcal{L}_{\text{eff}} = \frac{c_{3,n} m_h^2}{v^{2n+1}} h(\partial^n h)^2 \quad \Rightarrow \quad \kappa_h - 1 \sim c_{3,n} \left(\frac{m_h}{v}\right)^{2n}$$

$$E_{\max} \sim m_h \left| \frac{m_h^4}{v^4}(\kappa_h - 1) \right|^{-1/(2n+2)} \ll v \left| \frac{m_h^2}{v^2}(\kappa_h - 1) \right|^{-1/2} .$$

- Marginalizing over infinitely many unmeasured couplings does not improve bound

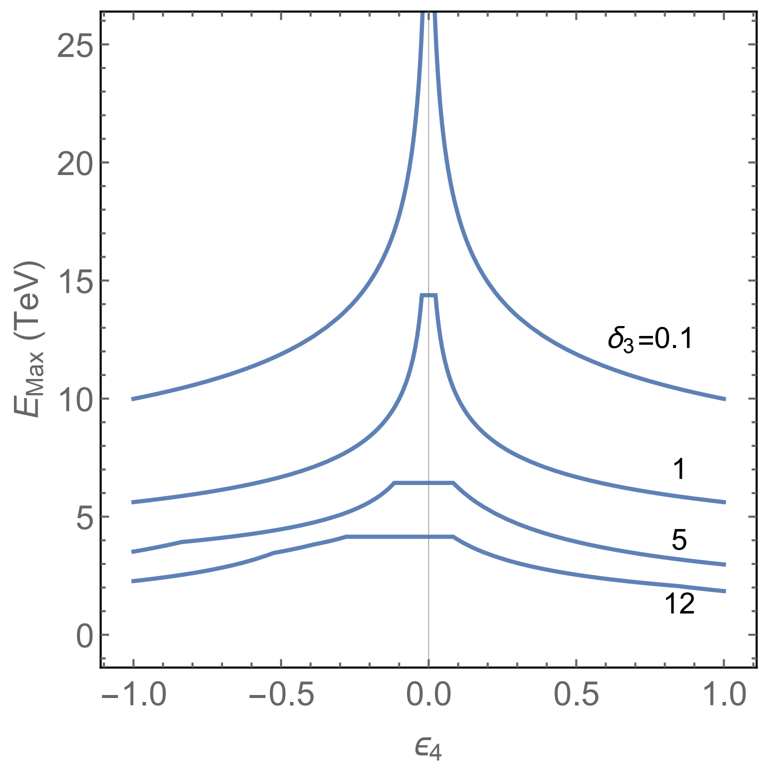


SMEFT without SMEFT

If $E_{\max} \gg \mathrm{TeV}$ we expect SMEFT to be a good description.

Dimension 6 SMEFT: $\delta_4 = 6\delta_3$

$$\epsilon_4 = \frac{\delta_4 - \delta_4^{\dim 6}}{\delta_4}$$



Unitarity alone implies a quantitative bound on error of dimension 6 SMEFT

Other Higgs Couplings