Snowmass 2021 Letter of Intent:
Higgs Coupling Measurements and Model-Independent Bounds on the Scale of New Physics

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The experimental study of the Higgs boson discovered in 2012 is a clear priority of the high-energy frontier. The currently observed properties of the Higgs particle are beautifully compatible with those of the minimal Standard Model (SM) Higgs boson. However, experimental constraints on the couplings of the Higgs boson to itself and to other SM particles will improve dramatically at the High-Luminosity Large Hadron Collider (HL-LHC) and other future colliders. If the SM is assumed to be correct, these couplings are predicted at the percent level by other measurements, so the measurement of these couplings can be viewed as a search for physics beyond the SM that is complementary to direct searches.

In this Letter, we highlight the fact that any deviation of the Higgs couplings from SM predictions not only implies new physics beyond the SM, but also gives a model-independent upper bound on the scale of the new physics from unitarity considerations. The reason is that the SM is the unique UV-complete theory with the experimentally observed particle content, and so any experimental measurement that cannot be accommodated within the SM implies either new light degrees of freedom, or the breakdown of the theory at high energies, manifested in a loss of tree-level unitarity. Unitarity arguments applied to the Higgs sector of the SM in the 1970s were instrumental in motivating and guiding the LHC, which indeed discovered the Higgs boson in the predicted energy range. We propose that the same considerations applied to Higgs coupling measurements can help motivate and guide future high-energy collider experiments.

Below we give some examples of model-independent bounds on new physics from Higgs coupling measurements. The results are based on Ref. [1] and a forthcoming paper by the authors of this Letter, and we refer to these for details of the method and calculations. Here we confine ourselves to summarizing the main ideas and giving some example results.

We consider the situation where one or more measurements of Higgs couplings have given results incompatible with SM predictions, but no new physics has been found in direct searches. In this case, the most natural interpretation is that the observed deviation is due to new physics at high energies. At low energies the deviations can be parameterized by the following effective Lagrangian:

$$\begin{aligned}
\mathcal{L} = \mathcal{L}_{\text{SM}} &- \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \cdots \\
&+ \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu+} W_\mu^- + \delta_{Z2} \frac{m_Z^2}{2v^2} h^2 Z^\mu Z_\mu + \delta_{W2} \frac{m_W^2}{v} h^2 W^{\mu+} W_\mu^- \\
&+ \sum_{n=3}^{\infty} \left[\frac{c_{Zn}}{n!} \frac{m_Z^2}{v^n} h^n Z^\mu Z_\mu + \frac{c_{Wn}}{n!} \frac{2m_W^2}{v^n} h^n W^{\mu+} W_\mu^- \right] + \cdots \\
&- \delta_{t1} \frac{m_t}{v} h \bar{t} t - \sum_{n=2}^{\infty} \frac{c_{tn}}{n!} \frac{m_t}{v^n} h^n \bar{t} t + \cdots
\end{aligned} \tag{1}$$

Here $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian, h is the real scalar that parameterizes the physical Higgs boson (with $\langle h \rangle = 0$), Z_μ, $W_\mu^\pm$ are the SM gauge fields, and t is the top quark field. The δ parameters represent fractional deviations from SM predictions, for example,

$$\delta_3 = \frac{g_{hhh} - g_{hhh}^{(\text{SM})}}{g_{hhh}^{(\text{SM})}}, \qquad \delta_{Z1} = \frac{g_{hZZ} - g_{hZZ}^{(\text{SM})}}{g_{hZZ}^{(\text{SM})}}, \tag{2}$$

while the c_n are couplings that are not present in the SM.[1] A nonzero value of any of the δ or c couplings implies that the theory violates unitarity at high energies. The reason is that unitarity of the SM at high energies is guaranteed by cancelations among different diagrams enforced by SM relations between different couplings. Any deviation from the SM will destroy these cancelations and lead to unitarity violation at high energies. The relevant amplitudes are those involving longitudinally polarized gauge bosons, Higgs bosons, and third-generation quarks.

For example, Fig. 1 gives the upper bound on the scale of new physics E_{max} as a function of the observed value of the Higgs cubic coupling. The blue band gives an estimate of the uncertainty of the 'model independent' prediction for E_{max} that is independent of the infinitely many unmeasured couplings in Eq. (1), while the orange line bounds the 'optimal bound' that is obtained by marginalizing over the unobserved couplings. Note that a deviation that can be observed at the HL-LHC would indicate a scale of new physics below 10 TeV, a scale that can be plausibly explored by future colliders.

Similarly, Fig. 2 gives the bound on E_{max} arising from a measured deviation in the hZZ and hWW couplings, and Fig. 3 gives the bound on E_{max} arising from a measured deviation on the $h\bar{t}t$ coupling. In both cases, we see that current measurements allow for deviations that imply a value for E_{max} in the range 1–10 TeV. Measurements of these couplings at the HL-LHC can therefore point to a scale of new physics that can be explored at future colliders.

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[1] Note that the δ parameters are precisely equivalent to the 'κ parameters' used to report LHC measurements of Higgs couplings [2].

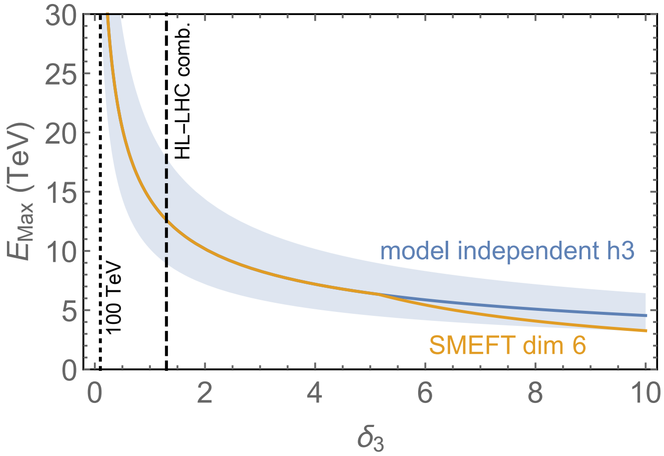

Fig. 1. The unitarity bound as a function of the deviation in the h^3 coupling. The optimal bound lies between the model independent and SMEFT estimates. The band around the model-independent scale results from varying the unitarity bound to $\frac{1}{2} \leq |\hat{\mathcal{M}}| \leq 2$. For comparison, we show projected 95% C.L. limits on δ_3 from a combination at HL-LHC and a 100 TeV pp collider from [3].

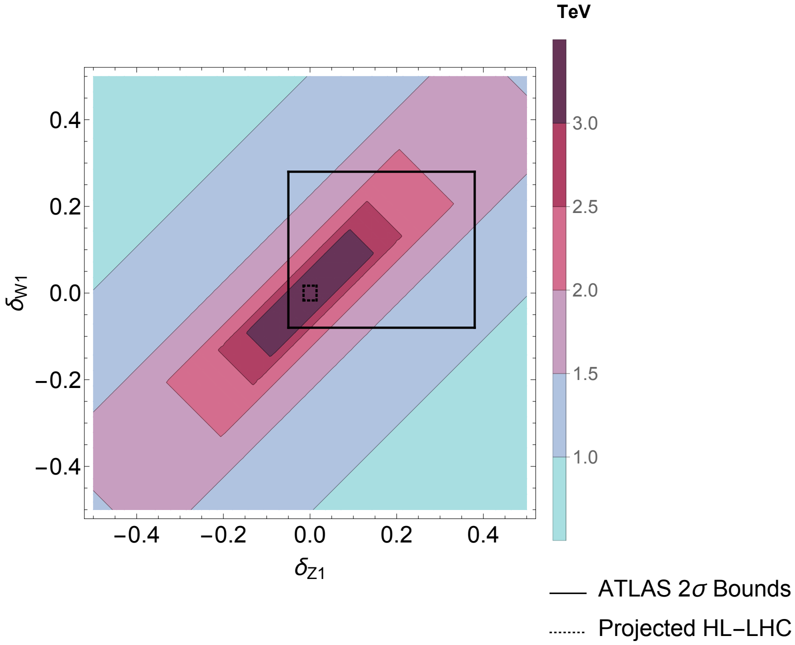

Fig. 2. The unitarity-violating scale that depends on δ_{Z1} and δ_{W1} assuming that custodial symmetry is not preserved. The solid black line represents the current ATLAS constraints while the dotted black line gives the HL-LHC projections [4].

To summarize, unitarity bounds provide a model-independent quantitative relationship between precision of Higgs coupling measurements and the scale of new physics. Using these

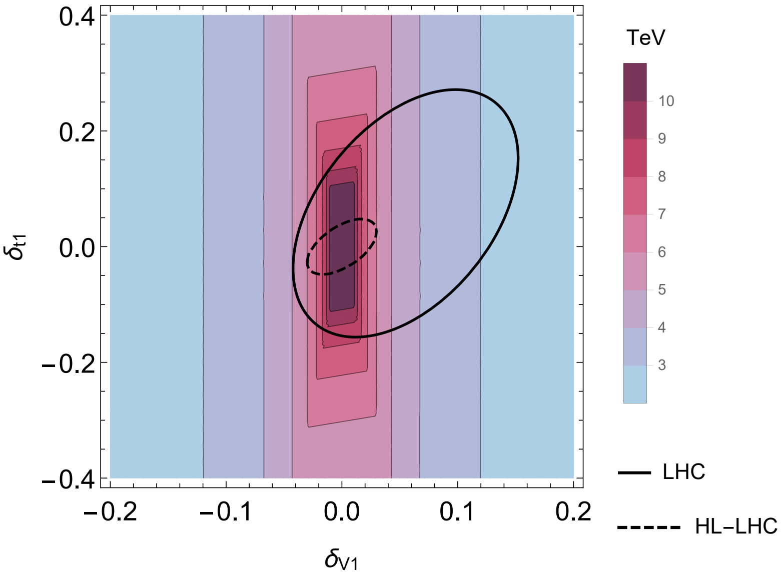

Fig. 3. Unitarity violating scales given values of δ_{t1} and δ_{V1}. The solid line represents the 95% C.L. at the LHC [5] and the dashed line is the HL-LHC projection [6].

bounds one can see that increased precision in coupling measurements translates directly into probing higher energy scales. We would be interested in partnering with other researchers making projections for these measurements to present them in this way.

References

[1] S. Chang and M. A. Luty, "The Higgs Trilinear Coupling and the Scale of New Physics," *JHEP* **20** (2020) 140, `arXiv:1902.05556 [hep-ph]`.

[2] **LHC Higgs Cross Section Working Group** Collaboration, A. David, A. Denner, M. Duehrssen, M. Grazzini, C. Grojean, G. Passarino, M. Schumacher, M. Spira, G. Weiglein, and M. Zanetti, "LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle," `arXiv:1209.0040 [hep-ph]`.

[3] M. Cepeda *et al.*, *Report from Working Group 2: Higgs Physics at the HL-LHC and HE-LHC*, vol. 7, pp. 221–584. 12, 2019. `arXiv:1902.00134 [hep-ph]`.

[4] **Particle Data Group** Collaboration, M. Tanabashi *et al.*, "Review of Particle Physics - Status of Higgs Boson Physics," *Phys. Rev. D* **98** no. 3, (2019) 030001.

[5] **ATLAS** Collaboration, G. A. et al, "Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$

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[6] **ATLAS** Collaboration, "Projections for measurements of Higgs boson cross sections, branching ratios, coupling parameters and mass with the ATLAS detector at the HL-LHC,". `https://cds.cern.ch/record/2652762`.