Snowmass 2021 White Paper: Higgs Coupling Sensitivities and Model-Independent Bounds on the Scale of New Physics

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Abstract

In this Snowmass white paper, we describe how unitarity bounds can convert sensitivities for Higgs couplings at future colliders into sensitivities to the scale of new physics. This gives a model-independent consequence of improving these sensitivities and illustrate the impact they would have on constraining new physics. Drawing upon past successful applications of unitarity as a guide for future colliders (e.g. the Higgs mass bound and discovering it at the LHC), we hope this data will be useful in the planning for next generation colliders. The experimental study of the Higgs boson, in particular its couplings to Standard Model particles, is a crucial priority of the high-energy frontier. Unlike all other known elementary particles, the Higgs boson has no quantum numbers that distinguish it from the vacuum, and plays a fundamental role in the breaking of electroweak symmetry and the origin of the mass of elementary particles. Precise studies of the Higgs boson are critical for further progress in elementary particle physics, and this is one of the main motivations for next generation of high-energy colliders.

In this Snowmass white paper, we focus on measurements of Higgs boson couplings to Standard Model particles, specifically W, Z, γ , g, t, b, μ , τ , and the Higgs itself. Comparisons of the sensitivity of future colliders for these measurements is an important input in comparing different proposals for future colliders. For example, Table 1 contains such a comparison, using numbers from the Higgs@FutureColliders study for the European Strategy Report [1], as well as muon collider sensitivities from [2–5].

Within the Standard Model, all Higgs couplings are predicted at high precision because they are related to other well-measured quantities. Therefore, in addition to being a crucial check of the Standard Model, measurements of these couplings constitute a search for physics beyond the Standard Model: any observed deviation from the Standard Model prediction for these couplings is an unambiguous sign of new physics. The most natural interpretation of such a deviation (assuming that no other new particles have been discovered) is that the deviation is due to new particles and interactions that are too heavy to be probed in current experiments. In this scenario, perturbative unitarity is violated at high energies. This is because perturbative unitarity in the Standard Model results from the cancelation of energy-growing behavior in different amplitudes, and these cancelations are spoiled when couplings deviate from their Standard Model values.

For example, the right diagram of Fig. 1 shows a contribution to a $ZZ \rightarrow ZZZZ$ amplitude that involves the Higgs self-coupling h^3 . This diagram by itself violates perturbative unitarity at high energies, but in the Standard Model the leading high-energy behavior of this diagram is canceled by additional diagrams such as those shown in the left diagram of Fig. 1, which do not depend on the Higgs cubic coupling. For this reason, any deviation in the h^3 coupling compared to the canceling diagrams leads to violation of perturbative unitarity at high energies. In Refs. [6–10] the leading high-energy behavior of these amplitudes were computed using equivalence principle techniques, and unitarity bounds were presented for various Higgs couplings.

In this way, the sensitivity of Higgs coupling measurements can be directly translated to a a sensitivity to the scale Λ of new physics that can give rise to deviations from the Standard Model prediction. We emphasize that this connection is completely model-independent, since it only uses the measured values of couplings and the assumed absence of new physics below Λ to determine the scale of unitarity violation. In particular, any observed deviation in the couplings gives an upper bound on the scale of new physics. In many cases, this is a

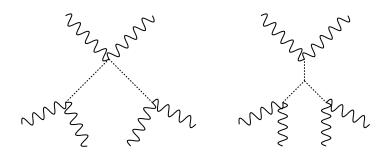


Fig. 1. Feynman diagrams for $ZZ \rightarrow ZZZZ$ in unitary gauge.

scale that can be explored in future collider experiments.

We present the bounds on the scale Λ of new physics arising from Higgs coupling measurements at various future colliders in Table 1. A graphical depiction of these numbers can be seen in Figure 2. For the deviations considered here, the unitarity bounds from the h coupling to X scale as $\Lambda_X \propto (\delta \kappa_X)^{-1/2}$, so increasing sensitivity by a factor of 4 gives a factor of 2 improvement on the bound of new physics. The numerical values involve the scale where couplings become strong, and is therefore subject to theoretical uncertainties, which can be estimated by varying the unitarity bound on the amplitude (see [8–10]). For example, varying the bound on the amplitude by a factor of 4 would change the unitarity bound by a factor of 2. Despite these uncertainties, they provide a critical model-independent estimate of the scale of new physics that can motivate future experiments, just as the unitarity bounds on the Higgs boson mass motivated the design of the Large Hadron Collider, which ultimately discovered the Higgs boson well below the unitarity bound. To conclude, the model-independent bound on the scale of new physics probed by these measurements gives a physical interpretation of the sensitivity of these measurements that is complementary to the comparison with specific models.

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References

 J. de Blas *et al.*, "Higgs Boson Studies at Future Particle Colliders," *JHEP* 01 (2020) 139, arXiv:1905.03764 [hep-ph].

Coupling (2σ)	HL-LHC	LHeC	HE-I	LHC		ILC			CLIC	2	CEPC	FCO	C-ee	FCC]	Muon
Unitarity Bound			S2	S2'	250	500	1000	380	1500	3000		240	365	ee/eh/hh	10	10 TeV+
															TeV	$125~{\rm GeV}$
$2\delta\kappa_V$ [%]	3.0	1.5	2.6	1.8	0.58	0.46	0.44	1.0	0.32	0.22	0.28	0.40	0.34	0.24	0.26	0.24
$\Lambda_V (\text{TeV})$	6.0	9	6.4	7.7	14	15	16	10	18	22	20	16	18	21	20	21
$2\delta\kappa_g \ [\%]$	4.6	7.2	3.8	2.4	4.6	1.94	1.32	5.0	2.6	1.8	3.0	3.4	2.0	0.98	1.34	1.31
$\Lambda_g \ (\text{TeV})$	51	41	56	70	51	78	95	49	68	81	63	59	77	110	94	95
$2\delta\kappa_{\gamma}$ [%]	3.8	15.2	3.2	2.4	13.4	6.8	3.8	196	10	4.4	7.4	9.4	7.8	0.58	2.2	2.13
$\Lambda_{\gamma} (\text{TeV})$	120	61	130	150	65	92	120	17	76	110	88	78	86	310	160	160
$2\delta\kappa_{Z\gamma}$ [%]	20	—	11.4	7.6	198	172	170	240	30	13.8	16.4	162	150	1.38	20	20
$\Lambda_{Z\gamma}$ (TeV)	34	_	45	55	11	12	12	10	28	41	37	12	12	130	34	34
$2\delta\kappa_t$ [%]	6.6	—	5.6	3.4	_	13.8	3.2	_	—	5.4	_	_	—	2.0	104	4.2
$\Lambda_t \ (\text{TeV})$	13	—	14	18	_	9	19	-	—	14	-	-	—	24	3	16
$2\delta\kappa_b$ [%]	7.2	4.2	6.4	4.6	3.6	1.16	0.96	3.8	0.92	0.74	2.4	2.6	1.34	0.86	0.54	0.48
$\Lambda_b \ ({\rm TeV})$	80	100	85	100	110	200	220	110	220	250	140	130	180	230	290	310
$2\delta\kappa_{\mu}$ [%]	9.2	—	5.0	3.4	30	18.8	12.4	640	26	11.6	17.8	20	17.8	0.82	3.6	0.19
$\Lambda_{\mu} (\text{TeV})$	590	—	800	970	320	410	510	70	350	520	420	400	420	2000	540	2400
$2\delta\kappa_{\tau}$ [%]	3.8	6.6	3.0	2.2	3.8	1.40	1.14	6.0	2.6	1.76	2.6	2.8	1.46	0.88	0.47	0.47
Λ_{τ} (TeV)	220	170	250	290	220	370	410	180	270	330	270	260	360	460	360	360
$2\delta\kappa_h$ [%]	94	—	40	40	58	54	20	92	72	22	34	38	38	10	7.4	7.4
$\Lambda_h (\text{TeV})$	15	_	23	23	19	19	32	15	17	30	25	23	23	45	52	52

Table 1. Approximate 2σ sensitivities for Higgs couplings obtained by doubling the 1σ sensitivities reported in the Higgs@FutureColliders study [1]. The muon collider numbers use numbers from [2–5]. The sensitivities are obtained under the assumption that there are no additional light states that the Higgs decays into ('kappa-0 scenario'). For $\delta\kappa_V$ we use the smaller of $\delta\kappa_W$ and $\delta\kappa_Z$, while for $\delta\kappa_h$ we use the best sensitivity reported for single or di-Higgs production. Below each sensitivity line, we list the unitarity bound for a Higgs coupling bound, Λ_X , assuming $\kappa_X = 1 + 2\delta\kappa_X$. Due to theoretical uncertainties on the unitarity bound, we present the bounds to two significant digits.

- [2] J. de Blas, J. Gu, and Z. Liu, "Higgs Precision at a 125 GeV Muon Collider," arXiv:2203.04324 [hep-ph].
- [3] M. Forslund and P. Meade, "High Precision Higgs from High Energy Muon Colliders," arXiv:2203.09425 [hep-ph].
- [4] J. De Blas et al., "The physics case of a 3 TeV muon collider stage," in 2022 Snowmass Summer Study. 3, 2022. arXiv:2203.07261 [hep-ph].
- [5] P. Meade. Private communication, Mar., 2022.
- [6] 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].
- [7] A. Falkowski and R. Rattazzi, "Which EFT," JHEP 10 (2019) 255, arXiv:1902.05936 [hep-ph].
- [8] F. Abu-Ajamieh, S. Chang, M. Chen, and M. A. Luty, "Higgs coupling measurements and the scale of new physics," *JHEP* 07 (2021) 056, arXiv:2009.11293 [hep-ph].
- [9] F. Abu-Ajamieh, "The Scale of New Physics from the Higgs Couplings to $\gamma\gamma$ and γZ ," arXiv:2112.13529 [hep-ph].
- [10] F. Abu-Ajamieh, "The Scale of New Physics from the Higgs Couplings to gg," arXiv:2203.07410 [hep-ph].

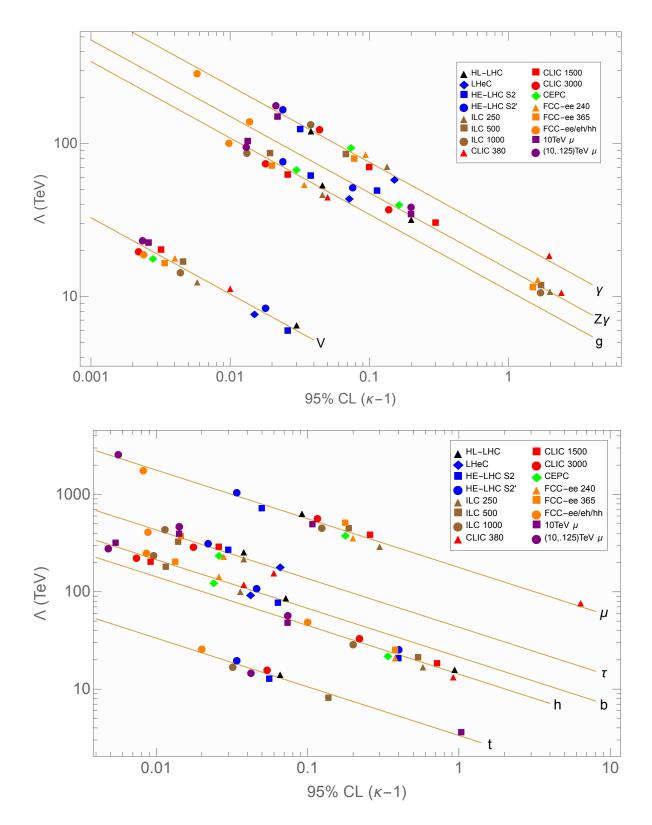


Fig. 2. Figures for the data in Table 1. The lines represent the theoretical relation between the precision on $\kappa - 1$ and the scale of new physics. All data points should be on the line, but are arbitrarily displaced up and down for visual clarity.