Snowmass2021 - Letter of Interest

New Physics in double-Higgs production at future lepton colliders

EF Topical Groups:

■ (EF01) EW Physics: Higgs Boson properties and couplings
■ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
□ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
■ (TF07) Collider phenomenology
□ (Other)

Contact Information:
Alberto Tonero (Carleton University) [alberto.tonero@gmail.com]
Andres Vasquez Tocora (Université catholique de Louvain and IFT-UNESP) [anfvasquezto@unal.edu.co]
Carlos H. de Lima (Carleton University) [carloshenriquedelima@cmail.ca]

Authors: Carlos H. de Lima, R. Rosenfeld, Alberto Tonero, Andres Vasquez Tocora

Abstract: Double Higgs production at future lepton colliders is a very interesting process which can be used to constrain the presence of New Physics (NP) that couples to the Higgs boson. Due to the unique nature of the Standard Model (SM) Higgs particle, the process $e^+e^- \to hh$ turns out to have a very tiny cross section, of the order of fraction of femtobarns. Therefore, this cross section can be substantially enhanced by contributions coming from physics Beyond the SM (BSM). In this proposal we want to explore this possibility and study the effects of two BSM scenarios where i) NP is heavy and its effects are parametrized by SMEFT operators, whose contribution is enhanced at energies $\sqrt{s} \gg 2m_h$; ii) a new light singlet scalar ϕ couples to the Higgs and it is responsible for a Sommerfeld-like enhancement of the cross section at threshold $\sqrt{s} \sim 2m_h$.

Main: The process $e^+e^- \to hh$ is an interesting one from the theoretical point of view because SM tree level diagrams (see Fig. 1 (a) and (b)) give a negligible contribution to the cross section since they are proportional to m_e/v, where m_e is the electron mass and $v = 246$ GeV is the Higgs vacuum expectation value (VEV). This fact has been recognized long ago and as a consequence the cross section is quite small both in the SM and MSSM extensions[1–3]. The dominant contribution to Higgs pair production in the SM

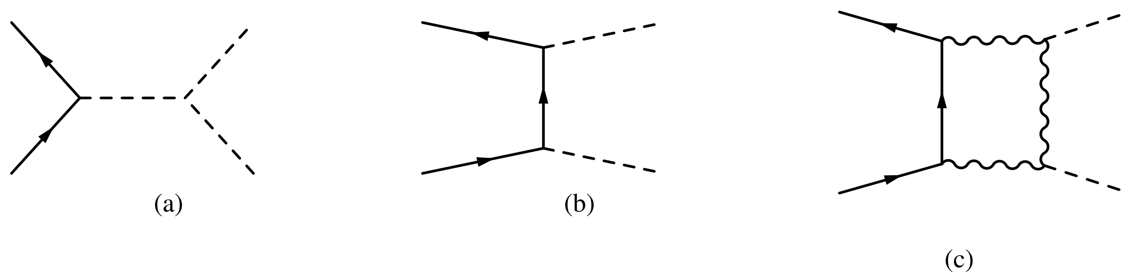

Figure 1: Subset of SM diagrams for $e^+e^- \to hh$: (a) and (b) are subdominant tree level diagrams, while (c) is a dominant one-loop box diagram.

comes from W and Z box diagrams, like the one in Fig. 1 (c). Notice that, contrary to $gg \to hh$, there is no such feature as the cancellation between triangle and box diagrams[4] because the triangle ones vanish in the $m_e = 0$ limit. Moreover, the dependence of the SM cross section on the triple Higgs coupling λ is also negligible because it enters only in diagrams that vanish in the $m_e = 0$ limit. Double Higgs production at e^+e^- colliders in the SM has been shown to have a small cross section of the order of fraction of femtobarns (see Fig. 7 of[5]). However, with large luminosities expected at future e^+e^- colliders, a few hundred events might eventually be collected in the course of a few years, allowing for the experimental study of this final state. In addition, dealing with a process that features a tiny SM cross section in a clean environment represents a *ideal situation* for New Physics (NP) searching, given the fact that the cross section can be substantially enhanced by contributions coming from physics beyond the SM. In this proposal we want to entertain this possibility and study the effects of NP that couples to the Higgs boson in the following BSM scenarios (which are somehow complementary because of the different nature of NP manifestation):

i) NP is heavy and its effects are parametrized by SMEFT operators, whose contribution is enhanced at energies $\sqrt{s} \gg 2m_h$;

ii) a new light singlet scalar ϕ couples to the Higgs and it is responsible for a Sommerfeld-like enhancement[6] of the cross section at threshold ($\sqrt{s} \sim 2m_h$).

i) In the EFT framework[7], the higher dimensional operators modify at perturbative level the SM interaction vertices (and introduce new ones), which in turn affects the cross section of $e^+e^- \to hh$, as shown in [5]. In ref[5] we focused on two operators that are relevant for this process and are characterized by dimensionless Wilson coefficients $c_{e\varphi}$ and c_{et}. By including their contributions to the double Higgs cross section we derived 95% bounds based on several benchmarks for these future colliders under certain assumptions of final decay channels to be reconstructed and the errors. We found that the bounds on $c_{e\varphi}$ typically probe scales of $\mathcal{O}(10$ TeV) while the c_{et} operator is less constrained since it enters only at one-loop level (of course, more stringent limits on c_{et}/Λ^2 of $\mathcal{O}(10^{-3})$ TeV^{-2} can be obtained by studying top quark pair production at future e^+e^- colliders, as shown in[8]).

ii) In the singlet extension of the SM, the exchange of a light scalar boson of mass m_ϕ induces a Yukawa potential $V(r) \sim e^{-m_\phi r}/r$ between the two final-state Higgs particles at threshold, that is responsible for

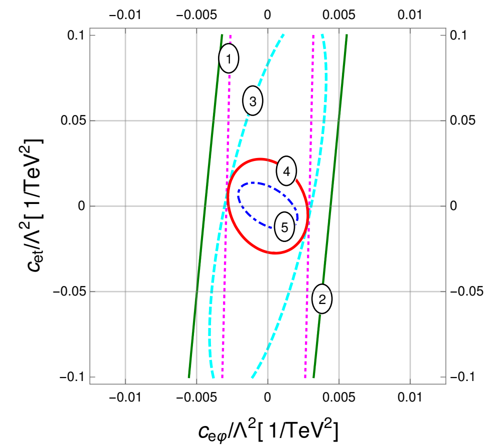

Figure 2: 95% CL exclusion regions in the $(c_{e\varphi}/\Lambda^2, c_{et}/\Lambda^2)$ plane for the different benchmark configurations of energy and luminosity[5].

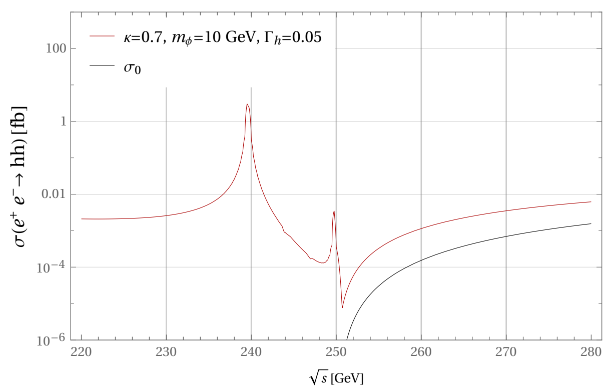

Figure 3: Sommerfeld enhancement in $(e^+e^- \to hh)$ as function of $\sqrt{s}$ (preliminary).

the formation of a non-relativistic di-Higgs bound state. This is a non-perturbative effect which results into a p-wave Sommerfeld-like enhancement of the $e^+e^- \to hh$ cross section, similar to the one investigated in (s)top pair production[9–12]

$$\sigma(e^+e^- \to hh) = \sigma_{\rm SM}(e^+e^- \to hh)R(E)\,, \tag{1}$$

where $R(E)$ is the enhancement factor and $E = \sqrt{s} - 2m_h$. A similar study was made for the $gg \to hh$ at the LHC[13] where, for some values of the model parameters, an overall $\mathcal{O}(10)$ enhancement has been found, after convoluting the $gg \to hh$ cross section with the gluon PDFs of the protons. Lepton colliders are more promising because they allow for a direct exploration of the threshold energy region at $\sqrt{s} \sim 250$ GeV[15] and a bigger enhancement is expected[14] close to threshold, see preliminary plot in Fig 3. The same study can be in principle applied also to the case where the Higgs interacts with a light vector boson. In conclusion, the investigation of the Sommerfeld enhancement in double Higgs production at threshold will allow us to put complementary constraints on the couplings (and masses) of light dark particles that couple to the Higgs boson and this can have important consequences for DM model building[16;17].

References

[1] K. J. F. Gaemers and F. Hoogeveen, "Higgs Boson Pair Production in e^+e^- Reactions," Z. Phys. C **26**, 249 (1984). doi:10.1007/BF01421761

[2] A. Djouadi, V. Driesen and C. Junger, "Loop induced Higgs boson pair production at e+ e- colliders," Phys. Rev. D **54**, 759 (1996) doi:10.1103/PhysRevD.54.759 [arXiv:9602341 [hep-ph]].

[3] J. J. Lopez-Villarejo and J. A. M. Vermaseren, "The Reaction e- e+ $\to$ hh recomputed," Phys. Lett. B **675**, 356 (2009) doi:10.1016/j.physletb.2009.04.022 [arXiv:0812.3750 [hep-ph]].

[4] E. W. N. Glover and J. J. van der Bij, "Higgs Boson Pair Production Via Gluon Fusion," Nucl. Phys. B **309**, 282 (1988); T. Plehn, M. Spira and P. M. Zerwas, "Pair production of neutral Higgs particles in gluon-gluon collisions," Nucl. Phys. B **479**, 46 (1996) Erratum: [Nucl. Phys. B **531**, 655 (1998)] [arXiv:9603205 [hep-ph]].

[5] A. Vasquez, C. Degrande, A. Tonero and R. Rosenfeld, "New physics in double Higgs production at future e^+e^- colliders," JHEP **05**, 020 (2019) doi:10.1007/JHEP05(2019)020 [arXiv:1901.05979 [hep-ph]].

[6] A. Sommerfeld, Annalen Phys. 403 (1931) 257.

[7] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, "Dimension-Six Terms in the Standard Model Lagrangian," JHEP **1010**, 085 (2010) doi:10.1007/JHEP10(2010)085 [arXiv:1008.4884 [hep-ph]].

[8] G. Durieux, M. Perelló, M. Vos and C. Zhang, "Global and optimal probes for the top-quark effective field theory at future lepton colliders," JHEP **1810**, 168 (2018) doi:10.1007/JHEP10(2018)168 [arXiv:1807.02121 [hep-ph]].

[9] M. J. Strassler and M. E. Peskin, "The Heavy top quark threshold: QCD and the Higgs," Phys. Rev. D **43**, 1500-1514 (1991) doi:10.1103/PhysRevD.43.1500

[10] V. S. Fadin and V. A. Khoze, "Production of a pair of $t\bar{t}$ quarks near threshold," Sov. J. Nucl. Phys. **53**, 692-698 (1991)

[11] I. I. Y. Bigi, V. S. Fadin and V. A. Khoze, "Stop near threshold," Nucl. Phys. B **377**, 461-479 (1992) doi:10.1016/0550-3213(92)90297-O

[12] H. Murayama and Y. Sumino, "Axial coupling contribution to toponium resonances," Phys. Rev. D **47**, 82-92 (1993) doi:10.1103/PhysRevD.47.82

[13] A. C. A. Oliveira and R. Rosenfeld, "Hidden sector effects on double higgs production near threshold at the LHC," Phys. Lett. B **702**, 201-204 (2011) doi:10.1016/j.physletb.2011.06.086 [arXiv:1009.4497 [hep-ph]].

[14] C. H. de Lima, R. Rosenfeld, A. Tonero, A. Vasquez, in preparation.

[15] K. Fujii, C. Grojean, M. E. Peskin, T. Barklow, Y. Gao, S. Kanemura, H. Kim, J. List, M. Nojiri, M. Perelstein, R. Poeschl, J. Reuter, F. Simon, T. Tanabe, J. D. Wells, J. Yu, M. Berggren, M. Habermehl, S. Jung, R. Karl, T. Ogawa, J. Tian, J. Brau and H. Murayama, "Physics Case for the 250 GeV Stage of the International Linear Collider," [arXiv:1710.07621 [hep-ex]].

[16] D. O'Connell, M. J. Ramsey-Musolf and M. B. Wise, "Minimal Extension of the Standard Model Scalar Sector," Phys. Rev. D **75**, 037701 (2007) doi:10.1103/PhysRevD.75.037701 [arXiv:hep-ph/0611014 [hep-ph]].

[17] S. Foroughi-Abari and A. Ritz, "LSND Constraints on the Higgs Portal," Phys. Rev. D **102**, no.3, 035015 (2020) doi:10.1103/PhysRevD.102.035015 [arXiv:2004.14515 [hep-ph]].