Precision Higgs Couplings in Neutral Naturalness Models

Lucien Heurtier[a] , **Hao-Lin Li**[b] , **Huayang Song**[a] , **Shufang Su**[a] , **Wei Su**[c] , **Jiang-Hao Yu**[b,d,e]

[a]*Department of Physics, University of Arizona, Tucson, AZ 85721, USA*
[b]*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P. R. China*
[c]*ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics,University of Adelaide, South Australia 5005, Australia*
[d]*School of Physical Sciences, University of Chinese Academy of Sciences, No.19A Yuquan Road, Beijing 100049, P.R. China*
[e]*School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China*

E-mail: heurtier@arizona.edu, lihaolin@itp.ac.cn

ABSTRACT: The puzzle of little hierarchy problem remains unsolved after the discovery of the Standard Model (SM)-like light Higgs with no evidence for new particles observed. The neutral naturalness models where the top partner is not charged under the SM $\mathrm{SU}(3)$ color gauge group are proposed to reduce the fine-tuning level in this situation. The Higgs sector in neutral naturalness models provides a portal to the hidden sectors, and thus measurements of Higgs couplings at current and future colliders play a central role in constraining the parameter space of the model. Since the scale of the new physics may be high, the precision study of the Higgs properties provides a indirect probe of these models. Therefore the theoretical framework for the precision calculation of various Higgs couplings and estimation of the relevant theoretical uncertainties should be established.

STATE OF THE ART. After the last run of the Large Hadron Collider (LHC), the lack of evidence for the existence of coloured superpartners at a *natural* energy scale has triggered more and more interest for alternative theories to supersymmetry such as neutral-naturalness models [1–16] in which top partners do not carry any SM Quantum Chromodynamics (QCD) color. In particular, in models such as the twin Higgs [3], minimal neutral naturalness [15], brother/trigeometric Higgs [10, 11], the SM Higgs boson is identified as a pseudo Nambu-Goldstone Boson (pNGB) from a spontaneous global symmetry breaking, and the corresponding top partner that help to solve the little hierarchy problem carries a hidden QCD charges. Therefore, the conventional smoking-gun signature of a top partner at the LHC does not apply to this type of models. On the other hand, the hidden QCD sector interacts with the visible sector via the exchange of the Higgs boson, therefore neutral naturalness models generically stand as prototypes of a Higgs portal to new physics.

As a result, three important effects can be used to probe the parameter space in such models. First, there will be modifications of the Higgs couplings to the SM particles that mainly originate from the pseudo-Goldstone nature of the Higgs boson, which can be universally parameterized by the ratio v/f characterizing the misalignment between the electroweak scale v and the spontaneous global symmetry breaking scale f [17, 18]. Measuring the deviation of the Higgs couplings from their SM values precisely provides an indirect probe of the new physics scale f. Second, depending on the ultra-violet (UV) dynamics, there could exist a radial mode from the spontaneous global symmetry breaking, identified as a heavy scalar boson. The presence of such a heavy-scalar boson at a scale of order $\mathcal{O}(\mathrm{TeV})$ could be tested at current and future particle colliders [19, 20]. Third, after the electroweak symmetry breaking (EWSB), the mixing between this heavy scalar and the SM Higgs boson also induces interactions between the SM Higgs boson and the mirror sector particles, such as, mirror bottom, mirror glue-balls, etc. This will open several channels of the Higgs invisible decay, which can also be probed at the future Higgs precision measurement experiments, including the Future Circular Collider (FCC-ee) [21–25] at CERN, Circular Electron Positron Collider (CEPC) [26, 27] in China, as well as the International Linear Collider (ILC) [28–30] in Japan.

The precision study of the Higgs potential in the Composite Twin Higgs Model has been studied in Ref. [31, 32] in which the authors have calculated the renormalization group equation for the Higgs potential and have shown that a significant fraction of the Higgs mass actually comes from the running of the effective potential from the UV scale down to the electroweak scale, which leads to a large theoretical uncertainty on the predicted Higgs mass. A similar method has been applied to study neutral-naturalness models that are weakly coupled in the UV, such as the twin Higgs model [3], minimal neutral naturalness models [15], brother/trigonometric Higgs [10, 11]. Using an effective field theory description of the Higgs sector in generic classes of neutral-naturalness models, the authors of Ref. [33] performed a global fit using the current LHC Run-II as well as the future HL-LHC and CEPC and showed that future Higgs factories are able to set strong constraints on such models.

Proposal We propose to construct a more fundamental framework in order to analyze the corrections to the Higgs potential that can arise at the electroweak scale from the UV physics present in models addressing the hierarchy problem beyond supersymmetric models. In particular, in both Ref. [31, 32] and Ref. [33], the renormalization group equation of the Higgs potential are derived at the one-loop order. A higher-order calculation may be beneficial in order to reduce the theoretical uncertainties on the predicted value of the Higgs mass at low energy which is inherent to such models. In addition, in order to set meaningful constraints on such models in the future, a systematic method to estimate the theoretical uncertainties on the observable such as Higgs mass should also be investigated, as they in principle go into the Higgs global fit. The increasing precision of the calculation helps to probe a series of neutral naturalness models.

More generically, we believe that precision measurement of the Higgs sector will help constraining any BSM scenario involving the presence of heavy states interacting with the Higgs boson, and we aim to generalize the study of Ref. [33] to various BSM microscopic theories.

References

[1] N. Craig, A. Katz, M. Strassler, and R. Sundrum, *Naturalness in the Dark at the LHC*, *JHEP* **07** (2015) 105, [arXiv:1501.05310].

[2] N. Craig, S. Knapen, and P. Longhi, *Neutral Naturalness from Orbifold Higgs Models*, *Phys. Rev. Lett.* **114** (2015), no. 6 061803, [arXiv:1410.6808].

[3] Z. Chacko, H.-S. Goh, and R. Harnik, *The Twin Higgs: Natural electroweak breaking from mirror symmetry*, *Phys. Rev. Lett.* **96** (2006) 231802, [hep-ph/0506256].

[4] G. Burdman, Z. Chacko, H.-S. Goh, and R. Harnik, *Folded supersymmetry and the LEP paradox*, *JHEP* **02** (2007) 009, [hep-ph/0609152].

[5] D. Poland and J. Thaler, *The Dark Top*, *JHEP* **11** (2008) 083, [arXiv:0808.1290].

[6] H. Cai, H.-C. Cheng, and J. Terning, *A Quirky Little Higgs Model*, *JHEP* **05** (2009) 045, [arXiv:0812.0843].

[7] M. Geller and O. Telem, *Holographic Twin Higgs Model*, *Phys. Rev. Lett.* **114** (2015) 191801, [arXiv:1411.2974].

[8] R. Barbieri, D. Greco, R. Rattazzi, and A. Wulzer, *The Composite Twin Higgs scenario*, *JHEP* **08** (2015) 161, [arXiv:1501.07803].

[9] M. Low, A. Tesi, and L.-T. Wang, *Twin Higgs mechanism and a composite Higgs boson*, *Phys. Rev.* **D91** (2015) 095012, [arXiv:1501.07890].

[10] J. Serra and R. Torre, *Neutral naturalness from the brother-Higgs model*, *Phys. Rev.* **D97** (2018), no. 3 035017, [arXiv:1709.05399].

[11] C. Csáki, T. Ma, and J. Shu, *Trigonometric Parity for Composite Higgs Models*, *Phys. Rev. Lett.* **121** (2018), no. 23 231801, [arXiv:1709.08636].

[12] B. M. Dillon, *Neutral-naturalness from a holographic SO(6)/SO(5) composite Higgs model*, arXiv:1806.10702.

[13] T. Cohen, N. Craig, G. F. Giudice, and M. Mccullough, *The Hyperbolic Higgs*, *JHEP* **05** (2018) 091, [arXiv:1803.03647].

[14] H.-C. Cheng, L. Li, E. Salvioni, and C. B. Verhaaren, *Singlet Scalar Top Partners from Accidental Supersymmetry*, *JHEP* **05** (2018) 057, [arXiv:1803.03651].

[15] L.-X. Xu, J.-H. Yu, and S.-H. Zhu, *Minimal Neutral Naturalness Model*, *Phys. Rev. D* **101** (2020), no. 9 095014, [arXiv:1810.01882].

[16] A. Ahmed, S. Najjari, and C. B. Verhaaren, *A Minimal Model for Neutral Naturalness and pseudo-Nambu-Goldstone Dark Matter*, *JHEP* **06** (2020) 007, [arXiv:2003.08947].

[17] R. Alonso, E. E. Jenkins, and A. V. Manohar, *Sigma Models with Negative Curvature*, *Phys. Lett. B* **756** (2016) 358–364, [arXiv:1602.00706].

[18] R. Alonso, E. E. Jenkins, and A. V. Manohar, *Geometry of the Scalar Sector*, *JHEP* **08** (2016) 101, [arXiv:1605.03602].

[19] Z. Chacko, C. Kilic, S. Najjari, and C. B. Verhaaren, *Testing the Scalar Sector of the Twin Higgs Model at Colliders*, *Phys. Rev.* **D97** (2018), no. 5 055031, [arXiv:1711.05300].

[20] A. Ahmed, *Heavy Higgs of the Twin Higgs Models*, *JHEP* **02** (2018) 048, [arXiv:1711.03107].

[21] **TLEP Design Study Working Group** Collaboration, M. Bicer et al., *First Look at the Physics Case of TLEP*, *JHEP* **01** (2014) 164, [arXiv:1308.6176].

[22] "The FCC-ee design study." http://tlep.web.cern.ch/content/fcc-ee-tlep.

[23] M. Benedikt and F. Zimmermann, "Future Circular Collider Study, Status and Progress." https://indico.cern.ch/event/550509/contributions/2413230/attachments/1396002/2128079/170116-MBE-FCC-Study-Status_ap.pdf, 2017.

[24] **FCC** Collaboration, A. Abada et al., *FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2*, *Eur. Phys. J. ST* **228** (2019), no. 2 261–623.

[25] **FCC** Collaboration, A. Abada et al., *FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1*, *Eur. Phys. J. C* **79** (2019), no. 6 474.

[26] CEPC-SPPC Study Group, "CEPC-SPPC Preliminary Conceptual Design Report. 1. Physics and Detector." http://cepc.ihep.ac.cn/preCDR/volume.html, 2015.

[27] **CEPC Study Group** Collaboration, M. Dong et al., *CEPC Conceptual Design Report: Volume 2 - Physics & Detector*, arXiv:1811.10545.

[28] H. Baer, T. Barklow, K. Fujii, Y. Gao, A. Hoang, S. Kanemura, J. List, H. E. Logan, A. Nomerotski, M. Perelstein, et al., *The International Linear Collider Technical Design Report - Volume 2: Physics*, arXiv:1306.6352.

[29] P. Bambade et al., *The International Linear Collider: A Global Project*, arXiv:1903.01629.

[30] **LCC Physics Working Group** Collaboration, K. Fujii et al., *Tests of the Standard Model at the International Linear Collider*, arXiv:1908.11299.

[31] D. Greco and K. Mimouni, *The RG-improved Twin Higgs effective potential at NNLL*, *JHEP* **11** (2016) 108, [arXiv:1609.05922].

[32] R. Contino, D. Greco, R. Mahbubani, R. Rattazzi, and R. Torre, *Precision Tests and Fine Tuning in Twin Higgs Models*, *Phys. Rev.* **D96** (2017), no. 9 095036, [arXiv:1702.00797].

[33] L. Heurtier, H.-L. Li, H. Song, S. Su, W. Su, and J.-H. Yu, *Precision Higgs Couplings in Neutral Naturalness Models: an Effective Field Theory Approach*, arXiv:2007.15021.