Dark Sector and Dark Matter model searches from exotic Z decays at future electron positron colliders, High-Luminosity LHC, and future hadron colliders

Jia Liu,[1,*] Lian-Tao Wang,[2,3,†] and Xiao-Ping Wang[4,‡]

[1] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[3] *Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[4] *School of Physics, Beihang University, Beijing 100083, China*

Thematic Areas: EF09, EF10

I. INTRODUCTION

Searching for dark sector particles, including dark matter (DM) itself and other associated states, is a central goal of many experimental programs around the world. There are many dark sector models can give rise to exotic Z decay modes, many of which also contain missing energy in the final states. Recently, there have been a couple of proposals for future Z-factories based on circular e^+e^- colliders, including FCC-ee [1] and CEPC [2, 3], which are considering both Giga-Z (10^9 of Zs) and Tera-Z (10^{12} of Zs) options. The Large Electron Positron collider has already searched for exotic Z decays into light Higgs [4, 5], two light Higgs in MSSM [6], photon and missing energy [7–9] and three photons [10]. There have been previous work on constraining dark sector related new physics from Z properties at future e^+e^- colliders, including dark photon [11, 12], sterile neutrino model [13, 14], Z invisible width e.g. [15], rare SM Z decays [16–20], light CP-odd Higgs bosons and supersymmetric models [21–25], . Recently, this topic has been addressed for some specific models [26–30].

II. PREVIOUS WORK

We have comprehensively studied dark sector models and also model independent exotic Z decay channels at future e^+e^- colliders with Giga Z and Tera Z options [31]. Four general categories of dark sector models: Higgs portal dark matter, vector portal dark matter, inelastic dark matter and axionlike particles have been studied in the [31]. In addition, focusing on channels motivated by the dark sector models, we carried out a model independent study of the sensitivities of Z-factories in probing exotic decays and compare it with the reach of high luminosity LHC. We classify final states of the exotic decays with the number of resonances, and possible topologies it could have. We make projections on the sensitivity of the branching ratio of exotic Z decay at future Z-factory. The summary plot for those channels is given in Fig. 1.

A Z-factory generally provides a clean environment for decay modes which can be overwhelmed by large background at hadron colliders. Another advantage of searching for such exotic Z decay at future e+e colliders is the ability of reconstructing the full missing 4-momentum, while we can only reconstruct missing transverse momentum at hadron colliders. We have carefully made estimates of the reach of the High Luminosity LHC on the exotic Z decay modes. Given that the channels chosen in [31] contains missing energy in the final states, the future Z-factory has a better reach than the HL-LHC. The decay products from exotic Z decays are usually quite soft for LHC, thus it is hard to beat the large QCD backgrounds even consider additional energetic initial state radiation. It demonstrate that future Z-factories can provide its unique and leading sensitivity, and highlight the complementarity with other experiments, including the indirect and direct dark matter search limits, and the existing collider limits.

*Electronic address: jialiu@pku.edu.cn
†Electronic address: liantaow@uchicago.edu
‡Electronic address: hcwangxiaoping@163.com

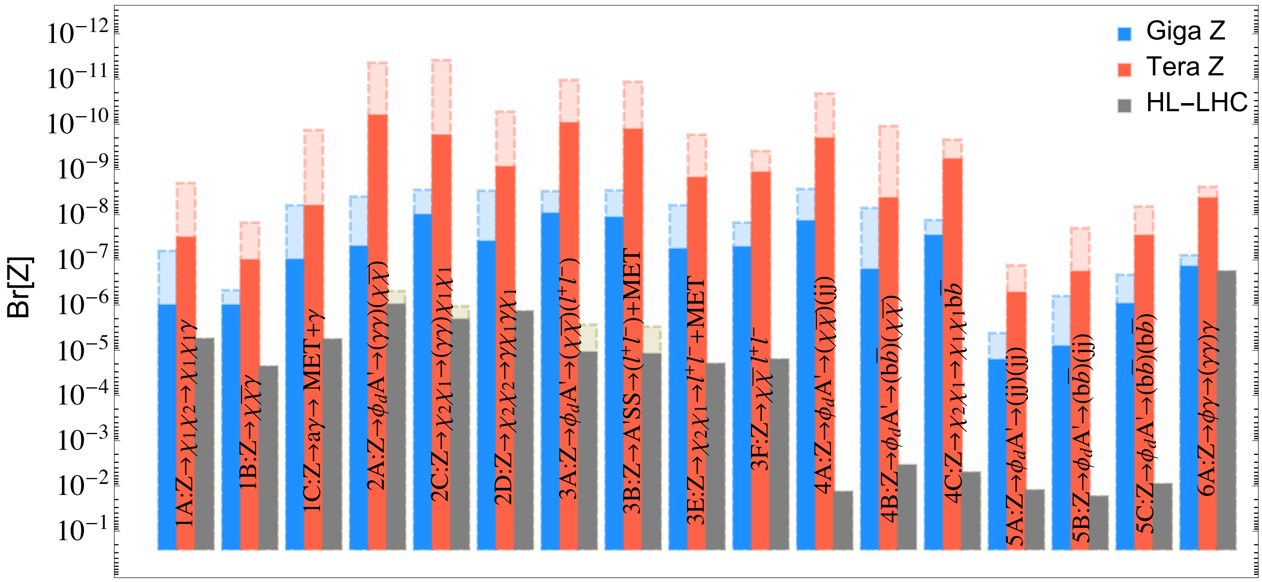

FIG. 1: The sensitivity reach for BR for various exotic Z decay topologies at the future Z-factory (Giga Z and Tera Z) and the HL-LHC at 13 TeV with $\mathcal{L} = 3$ ab^{-1}. The BR sensitivity generally depends on model parameter, for example mediator mass and dark matter mass. The dark color region with solid line as boundary indicates the worst reach for the topology, while the lighter region with dashed line indicates the best reach.

III. FUTURE PROPOSAL

However, there is still one channel HL-LHC has a comparable sensitivity comparing with future Z-Factory, which is $Z \to (\gamma\gamma)\gamma$ where the two photons in the bracket is from a resonance. Moreover, given the inclusive cross-section of Z at LHC [32], the HL-LHC can have about 1.7×10^{11} number of Z boson collected. Therefore, for the fully visible final states with multiple leptons and photons in the final states, the LHC can potentially suppress the QCD backgrounds and have the same discrimination power with Z-factory. Hence, in the near future, HL-LHC can be very attractive and provide complementary probes in such channels. Moreover, future hadron colliders such as the FCC-hh [33] and SppC [34, 35] will explore much further into this direction. For the Snowmass 21 studies, we plan to make detailed projections for the search of exotic Z decays at the HL-LHC and future hadron colliders, and explore the complementarity between the hadron and lepton colliders.

---

[1] **FCC** Collaboration, A. Abada et al., *FCC-ee: The Lepton Collider*, *Eur. Phys. J. ST* **228** (2019), no. 2 261–623.

[2] **CEPC Study Group** Collaboration, *CEPC Conceptual Design Report: Volume 1 - Accelerator*, `arXiv:1809.00285`.

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

[4] **L3** Collaboration, M. Acciarri et al., *Search for neutral Higgs boson production through the process e+ e- → Z* H0*, *Phys. Lett.* **B385** (1996) 454–470.

[5] X. Guo, T. Feng, S. Zhao, H.-W. Ke, and X.-Q. Li, *Constraining parameter space of the little Higgs model using data from tera-Z factory and ILC*, *Chin. Phys.* **C39** (2015), no. 2 023103, [`arXiv:1302.0485`].

[6] **DELPHI, OPAL, ALEPH, LEP Working Group for Higgs Boson Searches, L3** Collaboration, S. Schael et al., *Search for neutral MSSM Higgs bosons at LEP*, *Eur. Phys. J.* **C47** (2006) 547–587, [`hep-ex/0602042`].

[7] **L3** Collaboration, M. Acciarri et al., *Search for new physics in energetic single photon production in e^+e^- annihilation at the Z resonance*, *Phys. Lett.* **B412** (1997) 201–209.

[8] **OPAL** Collaboration, R. Akers et al., *Measurement of single photon production in e+ e- collisions near the Z0 resonance*, *Z. Phys.* **C65** (1995) 47–66.

[9] **L3** Collaboration, M. Acciarri et al., *Single and multiphoton events with missing energy in e^+e^- collisions at $\sqrt{S}$ - 189-GeV*, *Phys. Lett.* **B470** (1999) 268–280, [`hep-ex/9910009`].

[10] **L3** Collaboration, M. Acciarri et al., *Search for anomalous Z –¿ gamma gamma gamma events at LEP*, *Phys. Lett.* **B345** (1995) 609–616.
[11] A. Hook, E. Izaguirre, and J. G. Wacker, *Model Independent Bounds on Kinetic Mixing*, *Adv. High Energy Phys.* **2011** (2011) 859762, [arXiv:1006.0973].
[12] D. Curtin, R. Essig, S. Gori, and J. Shelton, *Illuminating Dark Photons with High-Energy Colliders*, *JHEP* **02** (2015) 157, [arXiv:1412.0018].
[13] **FCC-ee study Team** Collaboration, A. Blondel, E. Graverini, N. Serra, and M. Shaposhnikov, *Search for Heavy Right Handed Neutrinos at the FCC-ee*, *Nucl. Part. Phys. Proc.* **273-275** (2016) 1883–1890, [arXiv:1411.5230].
[14] A. Abada, V. De Romeri, S. Monteil, J. Orloff, and A. M. Teixeira, *Indirect searches for sterile neutrinos at a high-luminosity Z-factory*, *JHEP* **04** (2015) 051, [arXiv:1412.6322].
[15] M. Carena, A. de Gouvea, A. Freitas, and M. Schmitt, *Invisible Z boson decays at e+ e- colliders*, *Phys. Rev.* **D68** (2003) 113007, [hep-ph/0308053].
[16] H.-W. Ke and X.-Q. Li, *Search for B(c)(ns) via the B(c)(ns) —¿ B(c)(ms) pi+ pi- transition at LHCb and Z(0) factory*, *Sci. China Phys. Mech. Astron.* **53** (2010) 2019–2024, [arXiv:0910.1158].
[17] Y. Jin, Z. Si, Q. Xie, and T. Yao, *An Investigation of Hadronization Mechanism at Z^0 Factory*, *Sci. China Phys. Mech. Astron.* **53** (2010) 1998–2004, [arXiv:1003.1427].
[18] T.-C. Huang and F. Petriello, *Rare exclusive decays of the Z-boson revisited*, *Phys. Rev.* **D92** (2015), no. 1 014007, [arXiv:1411.5924].
[19] Q.-J. Xu and C.-H. Chang, *Suggestion for measuring the weak dipole moment of τ lepton at Z factory*, *Phys. Rev.* **D91** (2015), no. 1 013011, [arXiv:1410.1774].
[20] G. Durieux, Y. Grossman, M. K?nig, E. Kuflik, and S. Ray, *Rare Z Decays and Neutrino Flavor Universality*, *Phys. Rev.* **D93** (2016), no. 9 093005, [arXiv:1512.03071].
[21] J. Cao, Z. Heng, and J. M. Yang, *Rare Z-decay into light CP-odd Higgs bosons: a comparative study in different new physics models*, *JHEP* **11** (2010) 110, [arXiv:1007.1918].
[22] L. Wang and X.-F. Han, *Rare Z-decay into light pseudoscalar bosons in the simplest little Higgs model*, *Nucl. Phys.* **B853** (2011) 625–634, [arXiv:1101.0412].
[23] F. Domingo and T. Lenz, *W mass and Leptonic Z-decays in the NMSSM*, *JHEP* **07** (2011) 101, [arXiv:1101.4758].
[24] L. Wang and X.-F. Han, *Light Higgs decay modes of Z-boson in the left-right twin Higgs model*, *Nucl. Phys.* **B850** (2011) 233–241.
[25] P. Ghosh, D. E. Lpez-Fogliani, V. A. Mitsou, C. Muoz, and R. Ruiz de Austri, *Hunting physics beyond the standard model with unusual $W^\pm$ and Z decays*, *Phys. Rev.* **D91** (2015), no. 3 035020, [arXiv:1403.3675].
[26] T. Flacke, C. Frugiuele, E. Fuchs, R. S. Gupta, and G. Perez, *Phenomenology of relaxion-Higgs mixing*, *JHEP* **06** (2017) 050, [arXiv:1610.02025].
[27] N. Blinov, E. Izaguirre, and B. Shuve, *Rare Z Boson Decays to a Hidden Sector*, arXiv:1710.07635.
[28] Y. Gao and M. Jin, *Z-pole test of effective dark matter diboson interactions at the CEPC*, arXiv:1712.02140.
[29] Z.-H. Yu, X.-J. Bi, Q.-S. Yan, and P.-F. Yin, *Dark matter searches in the mono-Z channel at high energy e^+e^- colliders*, *Phys. Rev.* **D90** (2014), no. 5 055010, [arXiv:1404.6990].
[30] M. Fabbrichesi, E. Gabrielli, and B. Mele, *Z boson decay into light and darkness*, arXiv:1712.05412.
[31] J. Liu, L.-T. Wang, X.-P. Wang, and W. Xue, *Exposing the dark sector with future Z factories*, *Phys. Rev.* **D97** (2018), no. 9 095044, [arXiv:1712.07237].
[32] **ATLAS** Collaboration, G. Aad et al., *Measurement of $W^\pm$ and Z-boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Lett. B* **759** (2016) 601–621, [arXiv:1603.09222].
[33] **FCC** Collaboration, A. Abada et al., *FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3*, *Eur. Phys. J. ST* **228** (2019), no. 4 755–1107.
[34] M. Ahmad et al., *CEPC-SPPC Preliminary Conceptual Design Report. 1. Physics and Detector*, .
[35] *CEPC-SPPC Preliminary Conceptual Design Report. 2. Accelerator*, .