LHC Future Prospects of the 750 GeV Resonance

Ryosuke Sato$^1$ and Kohsaku Tobioka$^{1,2}$

$^1$Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel

$^2$Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel

A quantitative discussion on the future prospects of the 750 GeV resonance at the LHC experiment is given using a simple effective field theory analysis. The relative size of two effective operators relevant to diphoton decays can be probed by ratios of diboson signals in a robust way. We obtain the future sensitivities of $Z\gamma$, $ZZ$ and $WW$ resonance searches at the high luminosity LHC, rescaling from the current sensitivities at $\sqrt{s} = 13$ TeV. Then, we show that a large fraction of parameter space in the effective field theory will be covered with 300 fb$^{-1}$ and almost the whole parameter space will be tested with 3000 fb$^{-1}$. This discussion is independent of production processes, other decay modes and total decay width.

I. INTRODUCTION

Recently, the LHC experiment reported an event excess in diphoton invariant mass distribution near 750 GeV [1–4]. This event excess triggered significant theoretical interest and hundreds of papers have appeared. One of the plausible candidates to explain this excess is a heavy pion associated with new strong dynamics [5, 6] (see also Refs. [7–16]). This model naturally explains the relatively large cross section of the diphoton signal, because of electroweak gauge invariance [19]. Moreover, it is worth noting that such a model predicts other resonances at the TeV scale, e.g., a color-octet pion as discussed in Ref. [17]. Although the effective Lagrangian tells us that we can expect a $WW$, $Z\gamma$, $ZZ$ and $WW$ resonance searches at the high luminosity LHC, rescaling from the current sensitivities at $\sqrt{s} = 13$ TeV. Then, we show that a large fraction of parameter space in the effective field theory will be covered with 300 fb$^{-1}$ and almost the whole parameter space will be tested with 3000 fb$^{-1}$. This discussion is independent of production processes, other decay modes and total decay width.

UV theory behind the 750 GeV resonance. For example, in the case of the heavy pion models, the charge of the “new quarks” can be extracted from the ratio of signal strengths. This information will be useful for the discrimination of the various models. Here we discuss the high luminosity LHC with $\sqrt{s} = 14$ TeV because parton luminosities ($gg, q\bar{q}$) at 750 GeV are changed by only up to 25% [31].

II. ANALYSIS

For concreteness, we assume that the 750 GeV diphoton resonance is explained by a CP odd scalar boson $\phi$. The effective interaction of $\phi$ with electroweak gauge bosons is

$$\mathcal{L}_{\text{eff}} = \frac{k_Y}{m_\phi} \frac{\alpha_Y}{4\pi} \phi B_{\mu\nu} \bar{B}^{\mu\nu} + \frac{k_L}{m_\phi} \frac{\alpha_2}{4\pi} \phi W_{\mu\nu} \bar{W}^{\mu\nu},$$

(1)

where $k_L$ and $k_Y$ are determined by the UV theory. As we mentioned in the introduction, this is an effective theory of various models. If we consider a CP-even scalar, the effective interactions are changed to $\phi B_{\mu\nu} B^{\mu\nu}$ and $\phi W_{\mu\nu} W^{\mu\nu}$ and the following discussion is same in the limit of $m_\phi \gg m_{Z,W}$ assuming no mixing with the Higgs boson. By using the above effective interaction, the partial widths of $\phi$ decaying into a pair of electroweak gauge

---

$^1$ A recent trigger level analysis of dijet resonance search gives an upper bound of $\sim 3$ pb on 750 GeV resonance if we take 40 % acceptance [30]. Although we do not discuss dijet search, this could be important in some models.
bosons are given as

\[ \Gamma(\phi \rightarrow \gamma\gamma) = \frac{\alpha^2(k_Y + k_L)^2 m_\phi}{64\pi^3}, \quad (2) \]

\[ \Gamma(\phi \rightarrow Z\gamma) = \frac{\alpha^2(k_Y t_W^2 - k_L t_W^{-2})^2 m_\phi}{32\pi^3} \left(1 - \frac{m_Z^2}{m_\phi^2}\right)^3, \quad (3) \]

\[ \Gamma(\phi \rightarrow ZZ) = \frac{\alpha^2(k_Y t_W^2 + k_L t_W^{-2})^2 m_\phi}{64\pi^3} \left(1 - \frac{m_Z^2}{m_\phi^2}\right)^{3/2}, \quad (4) \]

\[ \Gamma(\phi \rightarrow W^+W^-) = \frac{\alpha^2 k_Y^2 s_W^4 m_\phi}{32\pi^3} \left(1 - \frac{4m_W^2}{m_\phi^2}\right)^{3/2}, \quad (5) \]

where \( s_W = \sin \theta_W \) and \( t_W = \tan \theta_W \) with the Weinberg angle \( \theta_W \).

Although there are four possible observables of \( \sigma \cdot \text{Br} \) in the electroweak gauge boson final states against two parameters, a robust measurement is possible only for a relative size of the two parameters \( k_Y/k_L \) (see Refs. [13, 19] for related works). Therefore, we parametrize the coefficients as [15]

\[ k_Y = k \cos \theta, \quad k_L = k \sin \theta. \quad (6) \]

By taking ratios of the signal strengths, we obtain functions depending only on \( \theta \) and \( \theta_W \),

\[ \frac{\sigma \cdot \text{Br}_{Z\gamma}}{\sigma \cdot \text{Br}_{\gamma\gamma}} = \frac{2(t_W \cos \theta - t_W^{-1} \sin \theta)^2}{(\cos \theta + \sin \theta)^2} \left(1 - \frac{m_Z^2}{m_\phi^2}\right)^3, \quad (7) \]

\[ \frac{\sigma \cdot \text{Br}_{ZZ}}{\sigma \cdot \text{Br}_{\gamma\gamma}} = \frac{(t_W^2 \cos \theta + t_W^{-2} \sin \theta)^2}{(\cos \theta + \sin \theta)^2} \left(1 - \frac{4m_Z^2}{m_\phi^2}\right)^{3/2}, \quad (8) \]

\[ \frac{\sigma \cdot \text{Br}_{WW}}{\sigma \cdot \text{Br}_{\gamma\gamma}} = \frac{2s_W^4 \sin^2 \theta}{(\cos \theta + \sin \theta)^2} \left(1 - \frac{4m_W^2}{m_\phi^2}\right)^{3/2}. \quad (9) \]

We, therefore, study diboson (ZZ, Z\gamma, WW) final states with respect to \( \theta \) and \( \sigma \cdot \text{Br}_{\gamma\gamma} \). The discussion is independent of other decay modes, total decay width, and production processes (therefore independent of QCD uncertainties associated with the productions from quarks and gluons). In order to see the above statement more explicitly, it is shown in Fig. 1 that the LHC bounds on diboson resonances at 750 GeV are given by the angle \( \theta \) and are insensitive to \( k \) if we take a fixed value of \( \sigma \cdot \text{Br}_{\gamma\gamma} \).

For the LHC future prospects, based on the current bounds of 3.2 fb\(^{-1}\), we obtain future sensitivities in Table I using Gaussian probability distribution. We assume a narrow width of the resonance here. In a case of large width the bounds and sensitivities become weaker by up to 50% because backgrounds in the wider mass range will be relevant (c.f., a difference between narrow width approximation (NWA) and large width approximation (LWA) in Ref. [27]). For the estimation of the future sensitivities of the ZZ and WW resonances at \( \sqrt{s} = 13 \) TeV, we used the \( \ell \ell \nu \nu \) [26] and \( \ell \ell q \bar{q} \) [27] final states, respectively. For ZZ mode, a search in \( \ell \ell q \bar{q} \) final state [28] is not included and a search in \( 4\ell \) final state is not reported yet. For Z\gamma mode, we adopted ATLAS result [25] and CMS reported a similar result [29]. In Fig. 1 we show current bound, expected cross section, and future prospects for each diboson resonance search in \( (\sigma \cdot \text{Br}_{\gamma\gamma}) \cdot \theta \) plane. At angle of \( \theta \approx 3\pi/4 \), the cross sections are enhanced because of cancellation in the diboson channel as in Eqs. (7, 8, 9). This is also seen in Fig. 1. On the other hand, there are angles where each diboson channel is cancelled. Eqs. (7, 8, 9) tell that the signals vanish at

\[ \theta = \begin{cases} \arctan t_W^2 \approx 0.09\pi & \text{for } Z\gamma \\ -\arctan t_W^4 + \pi \approx 0.97\pi & \text{for } ZZ \\ 0 & \text{for } WW \end{cases} \quad (10) \]

The angles \( \theta \) and \( \theta + \pi \) in the present effective Lagrangian are physically equivalent, and we can see the cancellation angles are rather close to each other due to the small Weinberg angle. Thus we need large luminosity to cover the region near \( \theta \approx 0, \pi \).

The combined plots are presented in Fig. 3. We also include the 2\( \sigma \) allowed range of diphoton rate assuming
In a GUT motivated heavy pion model [5], we can take the simplest heavy pion model with SU(2) \( \times SU(2) \times U(1) \). If we cancel a factor of 3 improvement is achieved in each channel.

Finally, we apply the results to specific models. If we take the simplest heavy pion model with SU(2) \( \times SU(2) \times U(1) \), \( \phi \) does not have \( W_\mu W^{\mu} \) and then \( \theta = 0 \). In this case, Fig. 3 shows \( Z\gamma \) resonance searches will be important for the future. Other interesting examples are GUT motivated models. In a GUT motivated heavy pion model [5], \( \phi \) is a SM

\[ \text{narrow width} \quad \sigma \cdot \text{Br}(\phi \rightarrow \gamma \gamma) \lesssim 8.5 \text{ fb} \quad \text{(ATLAS, 3.2 fb}^{-1}) \]

\[ 0.6 \lesssim \sigma \cdot \text{Br}(\phi \rightarrow \gamma \gamma) \lesssim 9 \text{ fb} \quad \text{(CMS, 3.3 fb}^{-1}) \]
singlet in an adjoint multiplet of $SU(5)_{GUT}$. The GUT relation predicts $\theta = \arctan 9/5 \approx 0.34\pi$, and Fig. 3 shows $WW$ and $Z\gamma$ resonance searches will be important with 300 fb$^{-1}$ and $ZZ$ resonance search will be relevant if $\sigma \cdot Br_{\gamma\gamma} \gtrsim 4$ fb. If $\phi$ is a singlet of $SU(5)_{GUT}$, the GUT relation predicts $\theta = \arctan 3/5 \approx 0.17\pi$ [15], and Fig. 3 shows $WW$ resonance search will be important with 300 fb$^{-1}$ and also $ZZ$ resonance search will be relevant with 3000 fb$^{-1}$. The ratio of the signal strength is important information for the discrimination of the various models.

III. CONCLUSION

In this paper, we discussed the LHC future prospects of the 750 GeV diphoton resonance. As pointed out in Refs. [15]–[19], the ratio of the signal strengths between different final states can be discussed by using the coefficient of the effective interactions. Our analysis is based on $\sqrt{s} = 13$ TeV, but the results can be applied to those at $\sqrt{s} = 14$ TeV. We found, at the high luminosity LHC, a large fraction of the parameter space in the effective theory will be covered with 300 fb$^{-1}$ and almost the whole parameter space will be tested with 3000 fb$^{-1}$. In particular, in the case with only $\phi B_{\mu\nu}B^{\mu\nu} (\theta = 0)$ as in the simplest heavy pion model, $Z\gamma$ resonance searches will have good sensitivity. Also, in the GUT motivated case ($\theta = \arctan 9/5 \approx 0.34\pi$), $WW$ and $Z\gamma$ resonance searches will have good sensitivity and also $ZZ$ resonance search will be relevant with 300 fb$^{-1}$.

ACKNOWLEDGEMENTS

We thank Elina Fuchs for useful discussions in the early stage of this work. We also thank Yevgeny Kats and Lorenzo Ubaldi for careful reading and helpful comments on the manuscript.

[1] ATLAS Collaboration, “Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of p p collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,” Tech. Rep. ATLAS-CONF-2015-081, CERN, Geneva, Dec, 2015.
[2] CMS Collaboration, “Search for new physics in high mass diphoton events in proton-proton collisions at 13 TeV,” Tech. Rep. CMS-PAS-EXO-15-004, CERN, Geneva, Dec, 2015.
[3] “Search for resonances in diphoton events with the ATLAS detector at $\sqrt{s} = 13$ TeV,” Tech. Rep. ATLAS-CONF-2016-018, CERN, Geneva, Mar, 2016.
[4] CMS Collaboration, “Search for new physics in high mass diphoton events in 3.3 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV and combined interpretation of searches at 8 TeV and 13 TeV,” Tech. Rep. CMS-PAS-EXO-16-018, CERN, Geneva, 2016.
[5] K. Harigaya and Y. Nomura, “Composite Models for the 750 GeV Diphoton Excess,” Phys. Lett. B754 (2016) 151–156 arXiv:1512.04850 [hep-ph].
[6] Y. Nakai, R. Sato, and K. Tobioka, “Footprints of New Strong Dynamics via Anomaly and the 750 GeV Diphoton,” Phys. Rev. Lett. 116 no. 15, (2016) 151802 arXiv:1512.04924 [hep-ph].
[7] R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia, and R. Torre, “What is the $\gamma\gamma$ resonance at 750 GeV?,” JHEP 03 (2016) 144 arXiv:1512.04933 [hep-ph].
[8] M. Low, A. Tesi, and L-T. Wang, “A pseudoscalar decaying to photon pairs in the early LHC Run 2 data,” JHEP 03 (2016) 108 arXiv:1512.05328 [hep-ph].
[9] B. Bellazzini, R. Franceschini, F. Sala, and J. Serra, “Goldsteins in Diphotons,” JHEP 04 (2016) 072 arXiv:1512.05330 [hep-ph].
[10] S. Matsuzaki and K. Yamawaki, “750 GeV Diphoton Signal from One-Family Walking Technipion,” arXiv:1512.05564 [hep-ph].
[11] J. M. No, V. Sanz, and J. Setford, “See-Saw Composite Higgses at the LHC: Linking Naturalness to the 750 GeV Di-Photon Resonance,” arXiv:1512.05700 [hep-ph].
[12] L. Bian, N. Chen, D. Liu, and J. Shu, “A hidden confining world on the 750 GeV diphoton excess,” arXiv:1512.05759 [hep-ph].
[13] Y. Bai, J. Berger, and R. Lu, “750 GeV dark pion: Cousin of a dark G-parity odd WIMP,” Phys. Rev. D93 no. 7, (2016) 076009 arXiv:1512.05779 [hep-ph].
[14] A. Belyaev, G. CacciaPaglia, H. Cai, T. Flacke, A. Parolini, and H. Seródio, “Singlets in Composite Higgs Models in light of the LHC di-photon searches,” arXiv:1512.07242 [hep-ph].
[15] N. Craig, P. Draper, C. Kille, and S. Thomas, “Shedding Light on Diphoton Resonances,” arXiv:1512.07733 [hep-ph].
[16] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, “Toward a coherent solution of diphoton and flavor anomalies,” arXiv:1604.03940 [hep-ph].
[17] Y. Bai, V. Barger, and J. Berger, “Color-octet Companions of a 750 GeV Heavy Pion,” arXiv:1604.07835 [hep-ph].
[18] R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, F. Riva, A. Strumia, and R. Torre, “Digamma, what next?,” arXiv:1604.06446 [hep-ph].
[19] I. Low and J. Lykken, “Implications of Gauge Invariance on a Heavy Diphoton Resonance,” arXiv:1512.09089 [hep-ph].
[20] S. Fichet, G. von Gersdorff, and C. Royon, “Measuring the diphoton coupling of a 750 GeV resonance,” arXiv:1601.01712 [hep-ph].
[21] K. Howe, S. Knapen, and D. J. Robinson, “Diphotons from an Electroweak Triplet-Singlet,” arXiv:1603.08932 [hep-ph].
[22] M. Chala, C. Grojean, M. Riembau, and T. Vantalon, “Deciphering the CP nature of the 750 GeV resonance,” arXiv:1604.02029 [hep-ph]

[23] A. Djouadi, J. Ellis, R. Godbole, and J. Quevillon, “Future Collider Signatures of the Possible 750 GeV State,” JHEP 03 (2016) 205 arXiv:1601.03696 [hep-ph]

[24] H. Ito and T. Moroi, “Production and Decay of Di-photon Resonance at Future e⁺e⁻ Colliders,” arXiv:1604.04076 [hep-ph]

[25] ATLAS Collaboration, “Search for heavy resonances decaying to a Z boson and a photon in pp collisions at √s = 13 TeV with the ATLAS detector,” Tech. Rep. ATLAS-CONF-2016-010, CERN, Geneva, Mar, 2016.

[26] ATLAS Collaboration, “Search for high-mass resonances decaying into a Z boson pair in the ℓℓτν final state in pp collisions at √s = 13 TeV with the ATLAS detector,” Tech. Rep. ATLAS-CONF-2016-012, 2016.

[27] ATLAS Collaboration, “Search for a high-mass Higgs boson decaying to a pair of W bosons in pp collisions at √s=13 TeV with the ATLAS detector,” Tech. Rep. ATLAS-CONF-2016-021, 2016.

[28] ATLAS Collaboration, “Search for diboson resonances in the ℓνq̅q final state in pp collisions at √s = 13 TeV with the ATLAS detector,” Tech. Rep. ATLAS-CONF-2015-071, CERN, Geneva, Dec, 2015.

[29] CMS Collaboration Collaboration, “Search for high-mass resonances in Zγ → e⁺e⁻γ/µ⁺µ⁻γ final states in proton-proton collisions at √s = 13 TeV,” Tech. Rep. CMS-PAS-EXO-16-019, CERN, Geneva, 2016.

[30] ATLAS Collaboration, “Search for light dijet resonances with the ATLAS detector using a Trigger-Level Analysis in LHC pp collisions at √s = 13 TeV,” Tech. Rep. ATLAS-CONF-2016-030, 2016.

[31] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Parton distributions for the LHC,” Eur. Phys. J. C63 (2009) 189–285 arXiv:0901.0002 [hep-ph]