New physics interpretations for nonstandard values of $h \to Z\gamma$

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Current measurements of the $h \to Z\gamma$ signal strength invite us to speculate about possible new physics interactions that exclusively affect $\mu_{Z\gamma}$ without altering the other signal strengths. Additional consideration of tree unitarity enables us to correlate the nonstandard values of $\mu_{Z\gamma}$ with an upper limit on the scale of new physics. We find that even when $\mu_{Z\gamma}$ deviates from the Standard Model value by only 20%, the scale of new physics should be well within the reach of the LHC.

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The loop-induced decay modes of the Higgs boson (h) have been impactful in many different aspects of Higgs physics. In particular, the decay $h \to \gamma\gamma$ played a pivotal role in the discovery of the Higgs boson [1,2]. Such loop-induced Higgs couplings have also proven useful in sensing the presence of new physics beyond the Standard Model (BSM) through new loop contributions arising from additional nonstandard particles [3]. This is essentially how the sequential fermionic fourth-generation models fell out of favor [4–6]. These loop-induced Higgs couplings can also provide important insights into the constructional aspects of the scalar extensions of the SM. Measurements of these couplings can severely restrict the fraction of nonstandard masses that can be attributed to the electroweak vacuum expectation value, [3,7] thereby providing nontrivial information about the mechanism of electroweak symmetry breaking.

The preliminary measurement of the $h \to Z\gamma$ signal strength has opened up new avenues to investigate the nature of new physics that may lie beyond the SM. The currently measured value stands at [8–10]

$$\mu_{Z\gamma} = 2.2 \pm 0.7, \tag{1}$$

which, although not statistically significant yet, may be indicative of an enhancement compared to the corresponding SM expectation [11], $\mu_{Z\gamma} = 1$. This poses the rather curious question that, if the measurement of $\mu_{Z\gamma}$ settles to a nonstandard value while $\mu_{\gamma\gamma}$ is consistent with the SM expectation, what kind of new physics would be required to reconcile such an observation? Given the current value of $\mu_{Z\gamma}$, such a possibility might not be far off and, from a theoretical standpoint, we must prepare ourselves to accommodate such an outcome.

It is important to realize that, in the usual BSM scenarios, the new physics contributions affect $\mu_{\gamma\gamma}$ and $\mu_{Z\gamma}$ in a correlated manner [12,13]. However, if we are to keep $\mu_{\gamma\gamma}$ intact at its SM value, we must seek new interactions that exclusively contribute to $\mu_{Z\gamma}$ without altering $\mu_{\gamma\gamma}$. A little contemplation reveals that "off-diagonal" couplings of the Higgs and the Z boson would achieve this goal without much hardship. To illustrate this prescription, let us assume that there exist new charged scalars with couplings parametrized in the following manner[1]:

$$\begin{aligned}\mathscr{L}_S^{\rm int} = {}& \lambda_{hs_is_j} M_W h S_i^{+Q} S_j^{-Q} + i g_{zs_is_j} Z^\mu \{ (\partial_\mu S_i^{+Q}) S_j^{-Q} \\ & - (\partial_\mu S_j^{-Q}) S_i^{+Q} \} + eQ g_{zs_is_j} A^\mu Z_\mu S_i^{+Q} S_j^{-Q} \\ & + g_{zzs_is_j} Z^\mu Z_\mu S_i^{+Q} S_j^{-Q} + \text{H.c.},\end{aligned} \tag{2}$$

where M_W is the W-boson mass, e is the electromagnetic coupling constant, and S_i^{+Q} denotes the ith charged scalar with electric charge $+Q$. Note that the correlation between the trilinear and quartic couplings should follow from the

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[1]A similar exercise can also be done assuming the presence of extra charged fermions or vector bosons possessing analogous off-diagonal couplings.

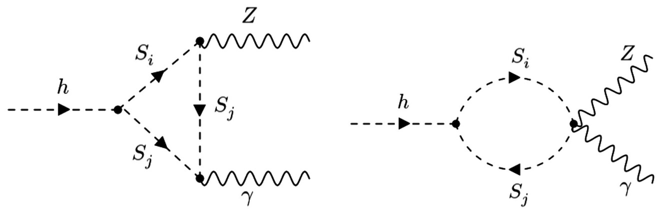

FIG. 1. Representative Feynman diagrams that give additional contributions to $\mu_{Z\gamma}$ exclusively.

underlying gauge theory.[2] In Eq. (2), we also assume that the off-diagonal couplings corresponding to $i \neq j$ are overwhelmingly dominant over the diagonal couplings corresponding to $i = j$, except for the quartic couplings of the form $ZZSS$. Under these assumptions, only $h \to Z\gamma$ will pick up additional contributions through the Feynman diagrams shown in Fig. 1. These diagrams, quite obviously, cannot contribute to $h \to \gamma\gamma$ as the photon, in its tree-level couplings, does not change particle species. The uncommon interactions of Eq. (2) will become quintessential if $\mu_{Z\gamma}$ settles to a nonstandard value while the other signal strengths are compatible with the SM. The strengths of the couplings required for accommodating nonstandard values $\mu_{Z\gamma}$ are presented in Fig. 2.[3] As can be observed from the figure, the quantity $g_{zs_1s_2}\lambda_{hs_1s_2}/m_C^2$ can be almost pinned down uniquely as a function of $\mu_{Z\gamma}$, $\frac{f(\mu_{Z\gamma})}{M_W^2}$, in the limit $m_{C1} = m_{C2} = m_C$, where m_{Ci} denotes the mass of the ith charged scalar. In this spirit, we may approximately write

$$\frac{\lambda_{hs_1s_2} g_{zs_1s_2}}{m_C^2} \approx \frac{f(\mu_{Z\gamma})}{M_W^2}, \tag{3}$$

with the understanding that $f(\mu_{Z\gamma}) = 0$ for $\mu_{Z\gamma} = 1$, as can be confirmed using Fig. 2. For a particular value of $\mu_{Z\gamma}$, the thickness of the black plot arises because m_C is scanned from relatively low values, within the range $100\ \text{GeV} < m_C < 1\ \text{TeV}$. The thickness of the plot, for practical purposes, becomes negligible once we go beyond $m_C \gtrsim 250$ GeV, as can be seen from the thin red (dark gray) overlaid region, and in this case the equality in Eq. (3) becomes more robust.

Now that the essential strategy to accommodate a nonstandard $\mu_{Z\gamma}$ has been laid out, it might be reasonable to ask whether the couplings of Eq. (2) have any additional

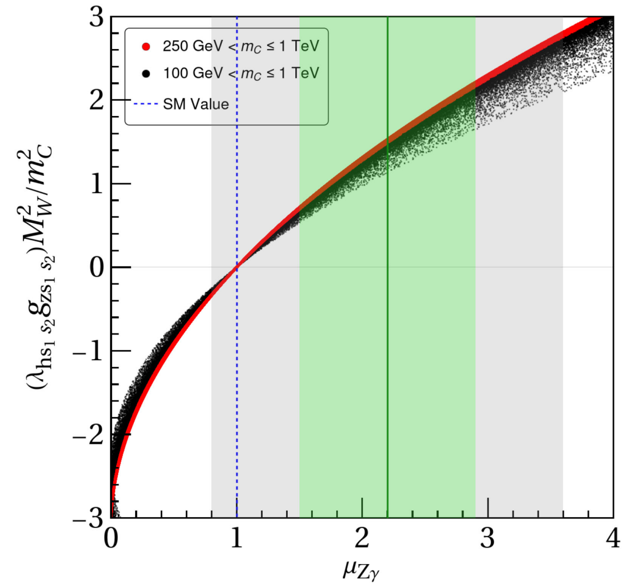

FIG. 2. Required values of $f(\mu_{Z\gamma})$ [defined in Eq. (3)] as a function of $\mu_{Z\gamma}$. The common charged scalar mass ($m_{C_1} = m_{C_2} = m_C$) has been scanned within the range [100 GeV, 1 TeV] for the black region and within [250 GeV, 1 TeV] for the thin red (dark gray) region. The dark-green solid vertical line marks the currently measured central value of $\mu_{Z\gamma}$ and the light-green (darker gray shade) and gray (lighter gray shade) vertical bands around it correspond to the 1σ and 2σ ranges, respectively. The dashed blue vertical line denotes the SM value of $\mu_{Z\gamma}$. In making this plot the unitarity conditions of Eqs. (8) and (10) have been satisfied.

observable consequences that can potentially falsify such a scenario. A related study will be to investigate whether the couplings of Eq. (2) can arise from a more complete gauge-theoretical framework. It is well known that the off-diagonal charged scalar couplings can emerge whenever the physical charged scalars are derived from an admixture of two different $SU(2)_L \times U(1)_Y$ multiplets. The Zee-type [15] scalar potential constitutes a good example of such a scenario. For the Zee-type setup, dominant off-diagonal couplings overpowering the diagonal couplings can be achieved when the two charged scalars mix maximally [16].[4]

However, instead of channeling our efforts to construct a specific model, we can follow a bottom-up method by exploring the high-energy unitarity behaviors of the tree-level scattering amplitudes [19] involving the couplings

[2] A connection between $g_{zs_is_j}$ and $g_{zzs_is_j}$ is established in Appendix A.

[3] The general expression for the $h \to Z\gamma$ amplitude may be found in Ref. [14]. Although for simplicity we chose $Q = 1$, for the general case the quantity on the vertical axis of Fig. 2 will be scaled by a factor of Q. Additionally, in the rest of the text we choose to focus on the scenario with only two species of charged scalars.

[4] Even in the presence of diagonal couplings, one may try to keep $\mu_{\gamma\gamma}$ in the neighborhood of unity by adjusting $\mathcal{A}_{\gamma\gamma}^{\rm NP} = -2\mathcal{A}_{\gamma\gamma}^{\rm SM}$ in the $h \to \gamma\gamma$ amplitude. An example of this with fermionic couplings can be found in a recent work [17]. A similar effort within the ambit of left-right symmetry [18] leads to modifications of $\mu_{Z\gamma}$ and $\mu_{\gamma\gamma}$ in a correlated manner, resulting in a limitation to the possible enhancement in $\mu_{Z\gamma}$.

of Eq. (2).[5] Such an analysis is known to reveal the compatibility of the set of couplings in Eq. (2) with a UV-complete gauge theory [22,23]. If the interactions in Eq. (2) necessitate additional dynamics accompanying them, the scattering amplitudes are expected to possess undesirable energy growths, which will lead to a violation of tree unitarity [24] at high energies. The energy scale at which unitarity is violated can be interpreted as the maximum energy scale before which the effects of new physics must set in to restore unitarity. Such an exercise provides an alternative strategy to discover the need for additional effects that should be accompanied by an enhanced $\mu_{Z\gamma}$. As we show in Appendix B, the inclusion of a proper quartic interaction of the form $ZZSS$ will neutralize the bad high-energy behaviors.

To demonstrate this explicitly, we now concentrate on the impact of the $ZZSS$ quartic couplings in Eq. (2), namely,

$$\mathscr{L}^{\rm int}_{ZZSS} = g_{zzs_is_j} Z^\mu Z_\mu S_i^{+Q} S_j^{-Q} + \text{H.c.} \tag{4}$$

As mentioned earlier, these couplings will be required to complement the underlying gauge structure. As we show in Appendix A, even in the limit when the rest of the couplings of Eq. (2) are purely off diagonal, the quartic interactions of Eq. (4) should be diagonal with a specific relation between $g_{zzs_is_j}$ and $g_{zs_is_j}$.[6] With this information, we can now proceed to calculate the amplitude for the process $Z_LZ_L \to S_1^+S_1^-$, where the subscript L represents longitudinal polarization. In the high-energy limit, $E_{\rm CM} \gg M$, meaning that the center-of-mass (CM) energy is much larger than all of the masses in our current theory, we obtain

$$\mathcal{M}_{Z_LZ_L\to S_1^+S_1^-} \approx \frac{2g^2_{zs_1s_2}}{M_Z^2}(m^2_{C_1} - m^2_{C_2}) + \mathcal{O}\left(\frac{M^2}{E^2_{\rm CM}}\right). \tag{5}$$

Thus, it is clear that the splitting between the two charged scalar masses is constrained from unitarity as

$$\left|\frac{2g^2_{zs_1s_2}}{M_Z^2}(m^2_{C_1} - m^2_{C_2})\right| < 16\pi. \tag{6}$$

Therefore, our simplified assumption of $m_{C_1} = m_{C_2} = m_C$ is manifestly consistent with the unitarity requirements irrespective of the magnitude of $g_{zs_1s_2}$. Next, we consider the process $Z_LZ_L \to S_1^+S_2^-$. In the high-energy limit, the amplitude is found to be

$$\mathcal{M}_{Z_LZ_L\to S_1^+S_2^-} \approx -\frac{g}{2}\lambda_{hs_1s_2} + \mathcal{O}\left(\frac{M^2}{E^2_{\rm CM}}\right), \tag{7}$$

where g is the $SU(2)_L$ gauge coupling. This puts an upper limit on $\lambda_{hs_1s_2}$ as follows:

$$\left|\frac{g}{2}\lambda_{hs_1s_2}\right| < 16\pi. \tag{8}$$

Finally, we note that a direct upper bound on the charged scalar masses can be placed by considering the scattering process $Z_LS_1^+ \to hS_1^+$. In the high-energy limit, the tree-level amplitude can be written as

$$\mathcal{M}_{Z_LS_1^+\to hS_1^+} \approx -g_{zs_1s_2}\lambda_{hs_1s_2}\frac{M_W}{M_Z} + \mathcal{O}\left(\frac{M^2}{E^2_{\rm CM}}\right). \tag{9}$$

Therefore, the unitarity constraint should imply

$$|g_{zs_1s_2}\lambda_{hs_1s_2}|\frac{M_W}{M_Z} < 16\pi. \tag{10}$$

This is where the experimental determination of $\mu_{Z\gamma}$ becomes relevant. A nonstandard value of $\mu_{Z\gamma}$ exclusively will necessitate such couplings, whose strength can be estimated using Eq. (3) as follows:

$$\lambda_{hs_1s_2}g_{zs_1s_2} = \frac{f(\mu_{Z\gamma})m_C^2}{M_W^2}. \tag{11}$$

Plugging this into Eq. (10), we may infer that

$$m_C < \sqrt{16\pi\frac{M_ZM_W}{|f(\mu_{Z\gamma})|}}. \tag{12}$$

It should be noted that, as $f(\mu_{Z\gamma} = 1) = 0$, the upper limit on m_C can be infinitely large for $\mu_{Z\gamma} = 1$, implying that the new physics effects can be safely decoupled in the SM limit, as expected. However, a more intriguing thing to note will be the fact that any deviation of $\mu_{Z\gamma}$ from the SM value will mandate the intervention of new physics. To quantify the required proximity of the new-physics scale, we plot the right-hand side of Eq. (12) as the red (black) region in Fig. 3, where the value of the function $f(\mu_{Z\gamma})$ is mapped from Fig. 2. From Fig. 3, we can see that new-physics effects in the sub-TeV regime will be imminent even when $\mu_{Z\gamma}$ deviates from unity by only 20%. In fact, the current central value of $\mu_{Z\gamma} = 2.2$ (marked by the dark-green vertical solid line) decrees the common charged scalar mass

[5] Our approach in this regard is different from previous studies. For example, the unitarity bounds considered in Ref. [20] arise mostly from modifications in the tree-level couplings of the Higgs boson with the SM particles. Of course, it is well known that the unitarity of the theory will be compromised if such couplings in the SM are tinkered with [21]. We, on the other hand, do not touch any of the tree-level SM couplings and the new physics interactions we introduce do not even affect $\mu_{\gamma\gamma}$.

[6] For off-diagonal couplings in Eq. (2) and diagonal couplings in Eq. (4), there will be no additional loop-induced effects for the hZZ vertex as well [25] as long as we work with only two flavors of charged scalars.

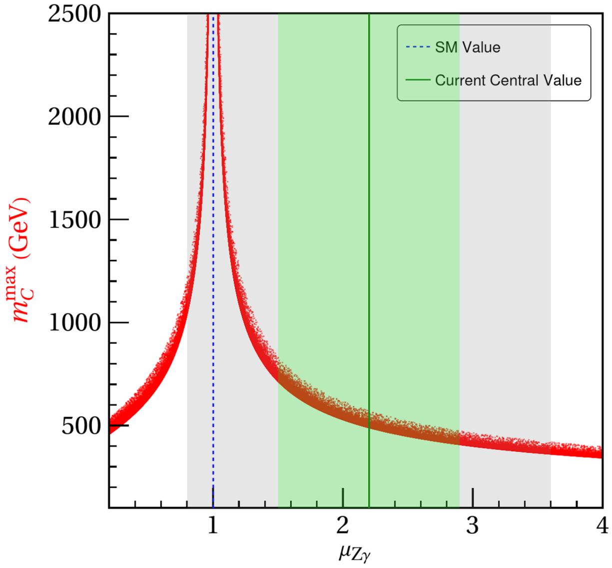

FIG. 3. The upper limits in Eq. (12) plotted against $\mu_{Z\gamma}$ shown by the red (black) region respectively. The dark-green solid vertical line marks the currently measured central value of $\mu_{Z\gamma}$ and the light-green (darker gray shade) and gray (lighter gray shade) vertical bands around it correspond to the 1σ and 2σ ranges respectively. The dashed blue vertical line denotes the SM value of $\mu_{Z\gamma}$.

to be below 500 GeV, which should be well within the reach of the LHC.

To summarize, recent experimental data on $\mu_{Z\gamma}$ instigates us to contemplate the possibility of having all of the Higgs signal strengths in excellent agreement with the corresponding SM expectations, except for $\mu_{Z\gamma}$ which deviates substantially from its SM value. Our current article can be considered as a theoretical preparation for such an eventuality in a bottom-up manner. We provided a general template for the new physics interactions that will exclusively affect $h \to Z\gamma$. We particularized our strategy with new charged scalars endowed with dominant off-diagonal couplings with the Higgs and Z bosons, as exemplified through Eq. (2). However, as we have explicitly shown, such interactions do not compromise unitarity at high energies, indicating compatibility with spontaneously broken gauge theories. The unitarity constraints have been used to place upper bounds on the magnitudes of the new couplings. We then translated them into an upper bound on the common charged scalar mass, which can be as low as 500 GeV for the current central value of $\mu_{Z\gamma}$. This means that, if the current nonstandard value of $\mu_{Z\gamma}$ becomes statistically significant as more data accumulates, the discovery of new-physics effects at the LHC should be just around the corner. The charged scalars, owing to their couplings with the photon, can be pair produced by the Drell-Yan mechanism [26,27]. The subsequent decay modes of these charged scalars will, of course, depend on the finer details of the BSM scenario from which they arise. Even if the charged scalars are stable, they can be probed in the ongoing searches for long-lived charged particles [28,29]. This anticipatory experimental scenario may be compared with the status of the LHC in the pre-Higgs-discovery era, as a win-win machine in the sense that the LHC should either observe the Higgs boson or something equivalent, or a violation of unitarity at high energies. In a similar spirit, the LHC can again act as a win-win experiment for BSM searches if $\mu_{Z\gamma}$ eventually settles towards a nonstandard value. That would definitely be an exciting future to look forward to.

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APPENDIX A: THEORETICAL CONDITIONS FOR OFF-DIAGONAL Z-BOSON COUPLINGS

Let H_1^{+Q} and H_2^{+Q} be two (unphysical) charged scalars originating from two different $SU(2)_L$ multiplets and therefore having well-defined T_3 eigenvalues denoted by $T_3^{(1)}$ and $T_3^{(2)}$, respectively. Thus, their interactions with the Z boson may be parametrized as

$$\begin{aligned}\mathscr{L}_H^Z = {}& iR_{z_1}\{(\partial_\mu H_1^{+Q})H_1^{-Q} - (\partial_\mu H_1^{-Q})H_1^{+Q}\}Z^\mu \\ & + R_{z_1}^2(H_1^{+Q}H_1^{-Q})(Z^\mu Z_\mu) + iR_{z_2}\{(\partial_\mu H_2^{+Q})H_2^{-Q} \\ & - (\partial_\mu H_2^{-Q})H_2^{+Q}\}Z^\mu + R_{z_2}^2(H_2^{+Q}H_2^{-Q})(Z^\mu Z_\mu), \quad (A1)\end{aligned}$$

where

$$R_{z_i} = \frac{g}{c_w}\left(T_3^{(i)} - Qs_w^2\right), \quad i = 1, 2. \quad (A2)$$

Here g denotes the $SU(2)_L$ gauge coupling, and s_w and c_w are the sine and cosine of the weak mixing angle, respectively. The physical charged scalars, S_1^{+Q} and S_2^{+Q}, should be obtained by the following rotation:

$$\begin{pmatrix} H_1^{+Q} \\ H_2^{+Q} \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix}\begin{pmatrix} S_1^{+Q} \\ S_2^{+Q} \end{pmatrix}. \quad (A3)$$

Substituting Eq. (A3) into Eq. (A1), we find

$$\begin{aligned}\mathscr{L}_S^Z = &\, iR_{z_1}\big[\cos^2\zeta\{(\partial_\mu S_1^{+Q})S_1^{-Q} - (\partial_\mu S_1^{-Q})S_1^{+Q}\} + \sin^2\zeta\{(\partial_\mu S_2^{+Q})S_2^{-Q} - (\partial_\mu S_2^{-Q})S_2^{+Q}\} \\ &+ \sin\zeta\cos\zeta\{(\partial_\mu S_1^{+Q})S_2^{-Q} - (\partial_\mu S_1^{-Q})S_2^{+Q} + (\partial_\mu S_2^{+Q})S_1^{-Q} - (\partial_\mu S_2^{-Q})S_1^{+Q}\}\big]Z^\mu \\ &+ R_{z_1}^2\big[\cos^2\zeta S_1^{+Q}S_1^{-Q} + \sin^2\zeta S_2^{+Q}S_2^{-Q} + \cos\zeta\sin\zeta\{S_1^{+Q}S_2^{-Q} + S_2^{+Q}S_1^{-Q}\}\big](Z^\mu Z_\mu) \\ &+ iR_{z_2}\big[\sin^2\zeta\{(\partial_\mu S_1^{+Q})S_1^{-Q} - (\partial_\mu S_1^{-Q})S_1^{+Q}\} + \cos^2\zeta\{(\partial_\mu S_2^{+Q})S_2^{-Q} - (\partial_\mu S_2^{-Q})S_2^{+Q}\} \\ &- \sin\zeta\cos\zeta\{(\partial_\mu S_1^{+Q})S_2^{-Q} - (\partial_\mu S_1^{-Q})S_2^{+Q} + (\partial_\mu S_2^{+Q})S_1^{-Q} - (\partial_\mu S_2^{-Q})S_1^{+Q}\}\big]Z^\mu \\ &+ R_{z_2}^2\big[\sin^2\zeta S_1^{+Q}S_1^{-Q} + \cos^2\zeta S_2^{+Q}S_2^{-Q} - \cos\zeta\sin\zeta\{S_1^{+Q}S_2^{-Q} + S_2^{+Q}S_1^{-Q}\}\big](Z^\mu Z_\mu), \end{aligned} \tag{A4}$$

such that the diagonal couplings are given by

$$\begin{aligned} g_{zs_1s_1} &= \cos^2\zeta R_{z_1} + \sin^2\zeta R_{z_2} = R_{z_1} - \sin^2\zeta(R_{z_1} - R_{z_2}), \\ g_{zzs_1s_1} &= \cos^2\zeta R_{z_1}^2 + \sin^2\zeta R_{z_2}^2, \\ g_{zs_2s_2} &= \sin^2\zeta R_{z_1} + \cos^2\zeta R_{z_2} = \sin^2\zeta(R_{z_1} - R_{z_2}) + R_{z_2}, \\ g_{zzs_2s_2} &= \sin^2\zeta R_{z_1}^2 + \cos^2\zeta R_{z_2}^2, \end{aligned} \tag{A5}$$

and the off-diagonal couplings are given by

$$\begin{aligned} g_{zs_1s_2} &= \frac{1}{2}\left(R_{z_1} - R_{z_2}\right)\sin 2\zeta, \\ g_{zzs_1s_2} &= \frac{1}{2}\left(R_{z_1}^2 - R_{z_2}^2\right)\sin 2\zeta = g_{zs_1s_2}\left(R_{z_1} + R_{z_2}\right). \end{aligned} \tag{A6}$$

Both trilinear diagonal couplings, $g_{zs_1s_1}$ and $g_{zs_2s_2}$, will vanish simultaneously if the following conditions are satisfied:

$$R_{z_1} = -R_{z_2}, \qquad \Rightarrow T_3^{(1)} + T_3^{(2)} = 2Qs_w^2, \tag{A7a}$$

$$\text{and} \quad \sin\zeta = \frac{1}{\sqrt{2}}. \tag{A7b}$$

Under these conditions, the remaining couplings take the forms

$$g_{zzs_1s_2} = 0, \tag{A8a}$$

$$g_{zs_1s_2} = R_{z_1}, \tag{A8b}$$

$$g_{zzs_1s_1} = R_{z_1}^2 = g_{zs_1s_2}^2, \tag{A8c}$$

$$g_{zzs_2s_2} = R_{z_1}^2 = g_{zs_1s_2}^2. \tag{A8d}$$

Because of the numerical value [30] of $s_w^2 \approx 0.23$, Eq. (A7a) can be approximately satisfied when two singly charged scalars ($Q = 1$) arise from a mixing between an $SU(2)_L$ singlet ($T_3^{(1)} = 0$) and an $SU(2)_L$ doublet ($T_3^{(2)} = 1/2$). The Zee-type model [15] constitutes a prototypical example of such a scenario. We have verified the existence of allowed points in the parameter space of such a model [16], which conform to maximal mixing as in Eq. (A7b)[7] and lead to very suppressed trilinear diagonal couplings with the Higgs and Z bosons as compared with the corresponding off-diagonal couplings. Furthermore, the Zee-type model admits an "alignment limit" which ensures that the lightest CP-even scalar mimics an SM-like Higgs boson. Therefore, one can achieve the SM-like hXX couplings (where X denotes a massive SM particle) by staying in the proximity of the "alignment limit" while independently realizing the maximal mixing ($\zeta \approx 45°$) between the charged scalars by adjusting the parameters in the scalar potential.

APPENDIX B: EXPLICIT CALCULATIONS OF THE SCATTERING AMPLITUDES

In this appendix, we show the explicit calculations of the scattering amplitudes discussed in the main text. First, we consider the process

$$Z_L(p_1) + Z_L(p_2) \to S_1^+(k_1) + S_1^-(k_2). \tag{B1}$$

The Feynman diagrams are shown in Fig. 4. The vertex factor for the interaction $Z_\mu S_1^+(p)S_2^-(p')$ is written as $ig_{zs_1s_2}(p-p')_\mu$, where p and p' are the momenta of the incoming charged scalars. Considering the momentum assignment of the initial- and final-state particles as in Eq. (B1), we can write

$$p_1 + p_2 = k_1 + k_2. \tag{B2}$$

Now, the Feynman amplitude for the t-channel diagram is given by

$$\begin{aligned} i\mathcal{M}_t = &\,(ig_{zs_1s_2})^2[-(p_1-k_1)+k_1]_\mu \frac{i}{t-m_{C_2}^2} \\ &\times[-k_2-(p_1-k_1)]_\nu \epsilon^\mu(p_1)\epsilon^\nu(p_2) \\ = &\,\frac{ig_{zs_1s_2}^2}{t-m_{C_2}^2}(p_1-2k_1)_\mu\epsilon^\mu(p_1)(p_2-2k_2)_\nu\epsilon^\nu(p_2), \end{aligned} \tag{B3}$$

[7] The angle ζ corresponds to γ in the Zee-type model [15].

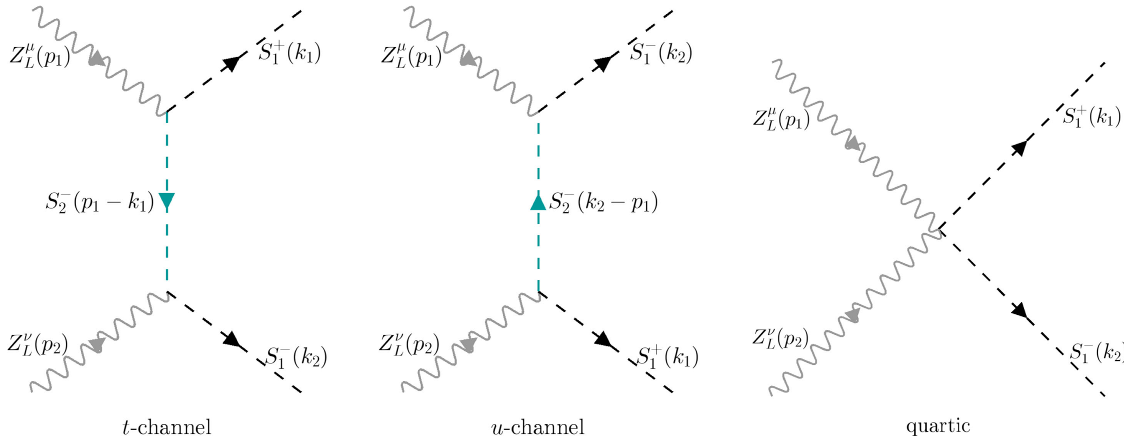

FIG. 4. Feynman diagrams for $Z_L Z_L \to S_1^+ S_1^-$.

where we used Eq. (B2) in the last step. In a similar manner, we write down the matrix element for the u-channel diagram as

$$\begin{aligned} i\mathcal{M}_u &= (ig_{zs_1s_2})^2[-k_2-(k_2-p_1)]_\mu \frac{i}{u-m_{C_2}^2} \\ &\quad \times [k_1-(k_2-p_1)]_\nu \epsilon^\mu(p_1)\epsilon^\nu(p_2) \\ &= \frac{ig_{zs_1s_2}^2}{u-m_{C_2}^2}(p_1-2k_2)_\mu \epsilon^\mu(p_1)(p_2-2k_1)_\nu \epsilon^\nu(p_2). \end{aligned} \tag{B4}$$

Next, we express the longitudinal polarization vector for the Z boson as $\epsilon_L^\mu(p) \equiv \epsilon^\mu(p)/M_Z$ with the understanding that $\epsilon^\mu(p)\epsilon_\mu(p) = -M_Z^2$ and $p_\mu \epsilon^\mu(p) = 0$. The kinematics for the process in the CM frame is schematically depicted in fig. 5. Following this, we may write

$$k_1 \cdot \epsilon_L(p_1) = \frac{E}{M_Z}(p - k\cos\theta) = k_2 \cdot \epsilon_L(p_2), \tag{B5a}$$

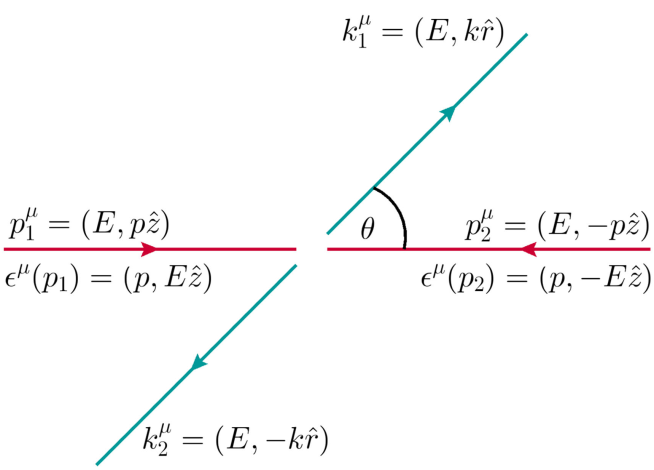

FIG. 5. Kinematics in the CM frame for the process in Eq. (B1).

$$k_2 \cdot \epsilon_L(p_1) = \frac{E}{M_Z}(p + k\cos\theta) = k_1 \cdot \epsilon_L(p_2). \tag{B5b}$$

Using the relations given in Eq. (B5), we now rewrite the matrix elements as

$$\mathcal{M}_t = 4g_{zs_1s_2}^2 \frac{E^2}{M_Z^2} \frac{(p-k\cos\theta)^2}{t-m_{C_2}^2}, \tag{B6a}$$

$$\mathcal{M}_u = 4g_{zs_1s_2}^2 \frac{E^2}{M_Z^2} \frac{(p+k\cos\theta)^2}{u-m_{C_2}^2}. \tag{B6b}$$

Now, using $t = (p_1-k_1)^2$ and $u = (p_2-k_1)^2$ in combination with Eq. (B2), we can show that

$$(p - k\cos\theta) = \frac{\Delta m^2 - t}{2p}, \tag{B7a}$$

$$(p + k\cos\theta) = \frac{\Delta m^2 - u}{2p}, \tag{B7b}$$

where we have defined $\Delta m^2 = m_{C_1}^2 - M_Z^2$. Thus, substituting Eq. (B7) into Eqs. (B6), we find

$$\mathcal{M}_t = \frac{g_{zs_1s_2}^2 E^2}{p^2 M_Z^2}(\Delta m^2 - t)^2 \frac{1}{t}\left(1 - \frac{m_{C_2}^2}{t}\right)^{-1}, \tag{B8a}$$

$$\Rightarrow \mathcal{M}_t \simeq \frac{g_{zs_1s_2}^2 E^2}{p^2 M_Z^2}\left(t - 2\Delta m^2 + m_{C_2}^2\right), \tag{B8b}$$

$$\text{and, similarly } \mathcal{M}_u \simeq \frac{g_{zs_1s_2}^2 E^2}{p^2 M_Z^2}\left(u - 2\Delta m^2 + m_{C_2}^2\right), \tag{B8c}$$

where we have neglected the terms $\mathcal{O}(M^2/E^2)$ in the high-energy limit. Furthermore, using the identity

$$\frac{E^2}{p^2} = E^2\left(E^2 - M_Z^2\right)^{-1} \simeq \left(1 + \frac{M_Z^2}{E^2}\right), \tag{B9}$$

we reduce the above amplitudes to

$$\mathcal{M}_t = \frac{g_{zs_1s_2}^2}{M_Z^2}t + g_{zs_1s_2}^2\left[\frac{t}{E^2} - \frac{\Lambda^2}{M_Z^2}\right] + \mathcal{O}\left(\frac{M^2}{E^2}\right), \tag{B10a}$$

and $$\mathcal{M}_u = \frac{g_{zs_1s_2}^2}{M_Z^2}u + g_{zs_1s_2}^2\left[\frac{u}{E^2} - \frac{\Lambda^2}{M_Z^2}\right] + \mathcal{O}\left(\frac{M^2}{E^2}\right), \tag{B10b}$$

where we defined $\Lambda^2 = (2\Delta m^2 - m_{C_2}^2)$. Next, the Feynman amplitude for the quartic diagram is

$$i\mathcal{M}_Q = 2i(g_{zs_1s_2})^2\epsilon_L^\mu(p_1)\epsilon_{\mu L}(p_2). \tag{B11}$$

Replacing the longitudinal polarization vector for the Z boson as $\epsilon_L^\mu(p) \equiv \epsilon^\mu(p)/M_Z$, we get

$$\epsilon_L(p_1)\cdot\epsilon_L(p_2) = \frac{1}{M_Z^2}\epsilon(p_1)\cdot\epsilon(p_2) = \left(\frac{2E^2}{M_Z^2} - 1\right). \tag{B12}$$

Thus, the total amplitude will be given by

$$\begin{aligned}\mathcal{M}_{Z_LZ_L\to S_1^+S_1^-} &= \left(\mathcal{M}_t + \mathcal{M}_u + \mathcal{M}_Q\right)\\ &= \frac{g_{zs_1s_2}^2}{M_Z^2}(t+u) + g_{zs_1s_2}^2\left[\frac{(t+u)}{E^2} - \frac{2\Lambda^2}{M_Z^2}\right]\\ &\quad + 2g_{zs_1s_2}^2\left(\frac{2E^2}{M_Z^2} - 1\right) + \mathcal{O}\left(\frac{M^2}{E^2}\right). \end{aligned}\tag{B13}$$

Substituting $t + u = 2(M_Z^2 + m_{C_1}^2) - 4E^2$, we obtain

$$\begin{aligned}\mathcal{M}_{Z_LZ_L\to S_1^+S_1^-} &= -\frac{4g_{zs_1s_2}^2}{M_Z^2}E^2 + \frac{g_{zs_1s_2}^2}{M_Z^2}\\ &\quad \times\left[2\left(M_Z^2 + m_{C_1}^2\right) - 2\Lambda^2 - 4M_Z^2\right]\\ &\quad + 2g_{zs_1s_2}^2\left(\frac{2E^2}{M_Z^2} - 1\right) + \mathcal{O}\left(\frac{M^2}{E^2}\right).\end{aligned}\tag{B14a}$$

Now we can use the definition of Λ to write

$$\begin{aligned}\Rightarrow \mathcal{M}_{Z_LZ_L\to S_1^+S_1^-} &\approx -\frac{4g_{zs_1s_2}^2}{M_Z^2}E^2 + \frac{2g_{zs_1s_2}^2}{M_Z^2}\\ &\quad\times\left[M_Z^2 + (m_{C_1}^2 - m_{C_2}^2)\right]\\ &\quad + 2g_{zs_1s_2}^2\left(\frac{2E^2}{M_Z^2} - 1\right),\end{aligned}\tag{B14b}$$

$$\Rightarrow \mathcal{M}_{Z_LZ_L\to S_1^+S_1^-} \approx \frac{2g_{zs_1s_2}^2}{M_Z^2}\left(m_{C_1}^2 - m_{C_2}^2\right). \tag{B14c}$$

It is quite interesting to note that the energy growths of $\mathcal{O}(E^2)$ arising from the t- and u-channel diagrams are exactly canceled by the quartic diagram, as is expected in spontaneously broken gauge theories.

Next, we consider the process

$$Z_L(p_1) + Z_L(p_2) \to S_1^+(k_1) + S_2^-(k_2). \tag{B15}$$

Since we are assuming the presence of off-diagonal couplings only, with the Higgs and Z bosons, the above process can only proceed via the s-channel Higgs exchange. The corresponding amplitude is given by

$$\begin{aligned}i\mathcal{M}_{Z_LZ_L\to S_1^+S_2^-} &= \left(\frac{igM_Z}{c_w}\right)\frac{i}{s - m_h^2}(i\lambda_{hs_1s_2}M_W)\\ &\quad\times\epsilon_L^\mu(p_1)\epsilon_{L\mu}(p_2)\end{aligned}\tag{B16a}$$

$$\Rightarrow \mathcal{M}_{Z_LZ_L\to S_1^+S_2^-} = (-gM_Z^2\lambda_{hs_1s_2})\frac{1}{s - m_h^2}\frac{(p^2 + E^2)}{M_Z^2}, \tag{B16b}$$

where we used $p_1^\mu = (E, p\hat{z})$ and $p_2^\mu = (E, -p\hat{z})$ in the CM frame. Furthermore, using $p^2 + E^2 = s/2 - M_Z^2$, we get

$$\mathcal{M}_{Z_LZ_L\to S_1^+S_2^-} \approx -\frac{1}{2}g\lambda_{hs_1s_2} + \mathcal{O}\left(\frac{M^2}{E^2}\right). \tag{B17}$$

Finally, we consider the process

$$Z_L(p_1) + S_1^+(p_2) \to h(k_1) + S_1^+(k_2). \tag{B18}$$

The Feynman diagram along with the kinematics in the CM frame are depicted in Fig. 6. The amplitude for the process may be written as

$$\begin{aligned}i\mathcal{M}_{Z_LS_1^+\to hS_1^+} &= ig_{zs_1s_2}\{p_2 + (p_1 + p_2)\}_\mu\frac{i}{s - m_{C_2}^2}\\ &\quad\times(i\lambda_{hs_1s_2}M_W)\epsilon_L^\mu(p_1)\end{aligned}\tag{B19a}$$

$$\Rightarrow \mathcal{M}_{Z_LS_1^+\to hS_1^+} = -g_{zs_1s_2}\lambda_{hs_1s_2}\frac{M_W}{M_Z}\frac{1}{s - m_{C_2}^2}(2p_2\cdot\epsilon(p_1)). \tag{B19b}$$

Now, following the kinematics in Fig. 6, we have the following relations:

$$p_2\cdot\epsilon(p_1) = (E_+p + E_zp) = p(E_+ + E_z) \equiv p\sqrt{s}, \tag{B20a}$$

$$\text{and}\quad p^2 = E_z^2 - M_Z^2 = E_+^2 - m_{C_1}^2 \tag{B20b}$$

$$\Rightarrow M_Z^2 - m_{C_1}^2 = E_z^2 - E_+^2 \tag{B20c}$$

$$\Rightarrow (E_z - E_+) = \frac{M_Z^2 - m_{C_1}^2}{\sqrt{s}}. \tag{B20d}$$

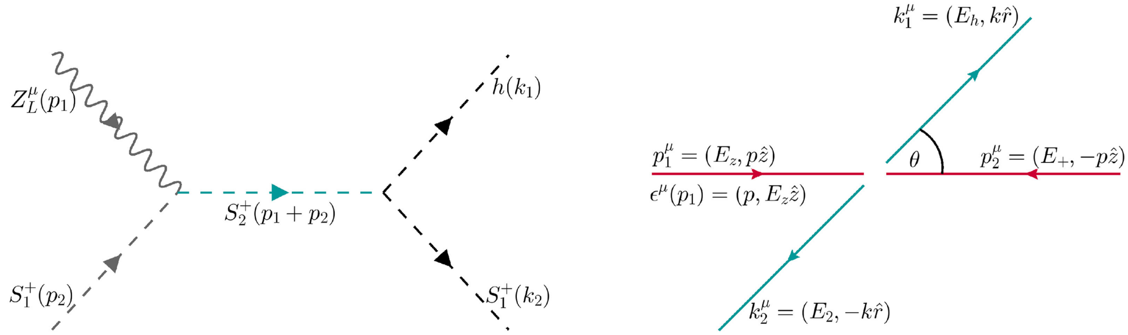

FIG. 6. Feynman diagram for the process appearing in Eq. (B18) and the corresponding kinematics in the CM frame.

Alternatively, one can also write

$$2p^2 = E_z^2 + E_+^2 - \left(M_Z^2 + m_{C_1}^2\right)$$
$$= \frac{1}{2}[(E_+ + E_z)^2 + (E_+ - E_z)^2] - \left(M_Z^2 + m_{C_1}^2\right)$$
$$= \frac{1}{2}\left[s + \frac{(M_Z^2 - m_{C_1}^2)^2}{s} - 2\left(M_Z^2 + m_{C_1}^2\right)\right] \tag{B21a}$$

$$\Rightarrow p^2 = \frac{1}{4}\left[s + \frac{(M_Z^2 - m_{C_1}^2)^2}{s} - 2(M_Z^2 + m_{C_1}^2)\right] \tag{B21b}$$

$$\Rightarrow p = \frac{\sqrt{s}}{2}\left[1 - 2\frac{(M_Z^2 + m_{C_1}^2)}{s} + \frac{(M_Z^2 - m_{C_1}^2)^2}{s^2}\right]^{\frac{1}{2}}, \tag{B21c}$$

$$p \approx \frac{\sqrt{s}}{2}\left[1 - \frac{(M_Z^2 + m_{C_1}^2)}{s} + \mathcal{O}\left(\frac{M^4}{s^2}\right)\right]. \tag{B21d}$$

Thus, one may write

$$p_2 \cdot \epsilon(p_1) = \frac{s}{2}\left[1 - \frac{(M_Z^2 + m_{C_1}^2)}{s} + \mathcal{O}\left(\frac{M^4}{s^2}\right)\right]. \tag{B22}$$

Using this in Eq. (B19b), the final expression for the amplitude, in the high-energy limit, can be written as

$$\mathcal{M}_{Z_L S_1^+ \to h S_1^+} \approx -g_{zs_1s_2}\lambda_{hs_1s_2}\frac{M_W}{M_Z} + \mathcal{O}\left(\frac{M^2}{s}\right). \tag{B23}$$

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