	$\lambda_{\rm 2HDM}/\lambda_{\rm SM}$
hVV	$\sin(\beta-\alpha)$
$hQ\bar{u}$	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$
$hQ\bar{d}$	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$
$hL\bar{e}$	$\sin(\beta-\alpha)-\tan\beta\cos(\beta-\alpha)$
HVV	$\cos(\beta-\alpha)$
$HQ\bar{u}$	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$
$HQ\bar{d}$	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$
$HL\bar{e}$	$\cos(\beta-\alpha)+\tan\beta\sin(\beta-\alpha)$

TABLE I: Tree level couplings for CP even eigenstates h and H in a Type III 2HDM normalized to their values in the SM. For large $\tan\beta \gg 1$ in the alignment limit where $\sin(\beta-\alpha)\to 1$, h recovers the SM like couplings and H becomes lepophilic with mass proportional Yukawa couplings.

Appendix A: Realization in a Two Higgs Doublet Model

The mass weighted couplings in our scenario can arise in a type-III two Higgs (2HDM) doublet model with an additional CP even scalar singlet φ that mixes with the SM-like h and heavy Higgs state H. In this realization of a 2HDM, before electroweak symmetry breaking, the Yukawa interactions can be written

$$\mathcal{L} \supset \lambda_u H_1 Q\bar{u} + \lambda_d H_1^\dagger Q\bar{d} + \lambda_\ell H_2 L\bar{e}\ , \tag{A1}$$

where $H_{1,2}$ are electroweak doublets with quantum numbers $2_{\pm 1/2}$ under $SU(2)_L\times U(1)_Y$, so H_1 gives mass to the quarks and H_2 gives mass to charged leptons. Here we use two-component Weyl fermion notation for the quark and lepton fields, where Q, L are electroweak doublets and $\bar{u}, \bar{d}, \bar{e}$ are $SU(2)_L$ singlet Dirac partners for the up-type, down-type, and charged lepton fields, respectively.

Following the conventions in Ref. [1], after electroweak symmetry breaking, the vacuum expectation values are $\langle H_i\rangle = v_i$. We define the ratio $\tan\beta \equiv v_2/v_1$ and diagonalize the CP even mass eigenstates with the rotation matrix

$$\begin{pmatrix}\sqrt{2}\,\mathrm{Re}(H_1)-v_1\\ \sqrt{2}\,\mathrm{Re}(H_2)-v_2\end{pmatrix} = \begin{pmatrix}\cos\alpha & \sin\alpha\\ -\sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}h\\ H\end{pmatrix}, \tag{A2}$$

where h is the SM-like Higgs mass eigenstate and H is the heavy CP-even state. In the mass eigenbasis, the h, H couplings to fermions and electroweak gauge bosons (denoted by V) are given in Table I

To realize our scenario at low energy, we add a singlet scalar φ and introduce super-renormalizable Higgs-portal couplings

$$V(H_1,H_2,\varphi) = \varphi\left(\mu_{11}H_1^\dagger H_1 + \mu_{12}H_1H_2 + \mu_{12}^* H_2^\dagger H_1^\dagger + \mu_{22}H_2^\dagger H_2\right)\ , \tag{A3}$$

where $\mu_{ij} \ll v_h$ are dimensionful mixing parameters. Writing this expression in terms of mass eigenstates in the electroweak breaking vacuum, we have

$$\mathrm{Re}(H_1) = \frac{h\cos\alpha + H\sin\alpha + v_1}{\sqrt{2}}\quad,\quad \mathrm{Re}(H_2) = \frac{-h\sin\alpha + H\cos\alpha + v_2}{\sqrt{2}}\ , \tag{A4}$$

so the mixed potential involving S becomes

$$\begin{aligned} V(h,H,\varphi) \ =\ \frac{\varphi}{2}\Big[&\mu_{11}\left(h\cos\alpha + H\sin\alpha + v_1\right)^2 + 2\mathrm{Re}(\mu_{12})\left(h\cos\alpha+H\sin\alpha+v_1\right)\left(-h\sin\alpha + H\cos\alpha + v_2\right)\\ &+\mu_{22}\left(-h\sin\alpha + H\cos\alpha + v_2\right)^2\Big]\ , \end{aligned} \tag{A5}$$

and the mass-squared mixing coefficients for φ-H and φ-h mixing can respectively be extracted via

$$\begin{aligned} \mu_{\varphi H} &\equiv \frac{\partial^2 V}{\partial\varphi\partial H}\bigg|_{h,H,\varphi=0} = \sin\alpha(v_1\mu_{11}+v_2\mu_{12}) + \cos\alpha(v_1\mu_{12}+v_2\mu_{22})\\ \mu_{\varphi h} &\equiv \frac{\partial^2 V}{\partial\varphi\partial h}\bigg|_{h,H,\varphi=0} = \cos\alpha(v_1\mu_{11}+v_2\mu_{12}) - \sin\alpha(v_1\mu_{12}+v_2\mu_{22}) \end{aligned} \tag{A6}$$

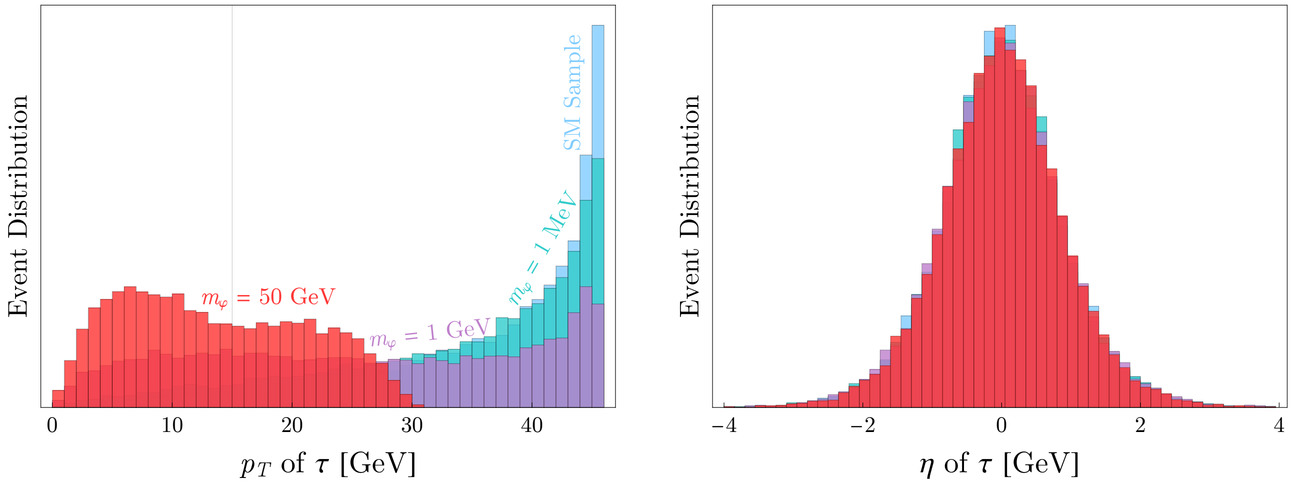

FIG. 1: The truth-level p_T and η distributions of the τ particles produced from Z decays as a function of the φ mass.

For parameter choices that satisfy $\mu_{\varphi h} \ll \mu_{\varphi H} \ll v_h$ in the $\tan\beta \gg 1$ limits, φ will mix predominantly with the H state whose couplings are leptophilic and proportional to charged lepton masses. Diagonalizing this additional mixing between φ-H thus yields the $\varphi\bar{\ell}\ell$ interactions. Note that, as in the case of one SM Higgs doublet, a additional singlet scalar can mix through the super-renormalizable portal wihtout acquiring a vacuum expectation value provided that a suitably chosen linear S term is included in the potential (see [2] for a discussion).

Appendix B: $Z \to \ell^+\ell^-\varphi$ decays

The amplitude for radiative φ production in $Z \to \ell^+(p_1)\ell^-(p_2)\varphi(p_3)$ decays can be written

$$\mathcal{M} = \frac{g_\tau m_Z}{v_h}\bar{u}(p_1)\left[\frac{(\not{p}_1+\not{p}_3)+m_\tau}{m_{13}^2-m_\ell^2}\gamma^\mu(g_V+g_A\gamma^5)+\gamma^\mu(g_V+g_A\gamma^5)\frac{(\not{p}_2+\not{p}_3)+m_\tau}{m_{12}^2-m_\ell^2}\right]v(p_2), \tag{B1}$$

where p_i are the final state momenta with $m_{ij}^2 \equiv (p_i+p_j)^2$, $v_h = 246$ GeV is the SM Higgs vacuum expectation value, and $g_{V,A}$ are respectively the tau vector and axial-vector charges, which satisfy

$$g_V = -\frac{1}{2}(1-4\sin^2\theta_W) \quad , \quad g_A = -\frac{1}{2} \ . \tag{B2}$$

The partial width can be written

$$\Gamma(Z\to \ell^+\ell^-\varphi) = \frac{1}{256\pi^3 m_Z^3}\int dm_{12}^2\int dm_{23}^2\,\overline{|\mathcal{M}|^2} \ , \tag{B3}$$

where the m_{12}^2 integration limits satisfy $(m_{12}^2)_{\rm min} = 4m_\ell^2$, $(m_{12}^2)_{\rm max} = (m_Z - m_\varphi)^2$, and the m_{23}^2 limits are

$$(m_{23}^2)^{\rm max}_{\rm min} = (E_2^*+E_3^*)^2 - \left(\sqrt{E_2^{*2}-m_\ell^2} \mp \sqrt{E_3^{*2}-m_\varphi^2}\right)^2, \tag{B4}$$

and we have defined

$$E_2^* = \frac{m_{12}}{2} \ , \ E_3^* = \frac{m_Z^2-m_{12}^2-m_\varphi^2}{2m_{12}} \ . \tag{B5}$$

Appendix C: Estimates on Acceptance Efficiency for $Z \to \tau\tau\varphi$

Sinceτdecays are too complex to simply reconstruct the Z peak, as a proxy for the much more involved analysis we perform truth-level cuts on taus from `MadGraph`-simulated events [3] to estimate the number of new physics events that would resemble SM events close enough to be included in the decay width measurement. As done in LEP and LHC [4, 5] analyses, we put a cut on the transverse momentum of taus $p_T > 15$ GeV and on the total energy squared s' of the $\tau\tau$ system to be $s' > 4m_\tau^2$. While a more rigorous study would include evaluating the cuts of individual τ decay channels specifically and simulating the full τ decay, comparing truth-level τ information with and without the ϕ production gives us an order-of-magnitude understanding of how many new-physics events can be mistaken for SM events.

We show the τ distributions in p_T and η in Figure 1. Note that as the mass of the φ is increased to $\mathcal{O}(m_Z \gtrsim 10$ GeV), the p_T of the taus is dramatically affected and most of the new physics events will be rejected. However, the η distribution of the taus is largely unchanging.

[1] N. Craig, J. Galloway, and S. Thomas, "Searching for Signs of the Second Higgs Doublet," arXiv:1305.2424 [hep-ph].

[2] B. Batell, D. McKeen, and M. Pospelov, "Singlet Neighbors of the Higgs Boson," *JHEP* **10** (2012) 104, arXiv:1207.6252 [hep-ph].

[3] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations," *JHEP* **07** (2014) 079, arXiv:1405.0301 [hep-ph].

[4] **ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group** Collaboration, S. Schael *et al.*, "Precision electroweak measurements on the Z resonance," *Phys. Rept.* **427** (2006) 257–454, arXiv:hep-ex/0509008.

[5] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Measurement of the $Z\gamma^* \to \tau\tau$ cross section in pp collisions at $\sqrt{s} = 13$ TeV and validation of τ lepton analysis techniques," *Eur. Phys. J. C* **78** no. 9, (2018) 708, arXiv:1801.03535 [hep-ex].