Resolving electron and muon $g - 2$ within the 2HDM

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Recent precise measurement of the electron anomalous magnetic moment (AMM) adds to the longstanding tension of the muon AMM and together strongly point towards physics beyond the Standard Model (BSM). In this work, we propose a solution to both anomalies in an economical fashion via a light scalar that emerges from a second Higgs doublet and resides in the $O(10)$-MeV mass range yielding the right sizes and signs for these deviations due to one-loop and two-loop dominance for the muon and the electron, respectively. A scalar of this type is subject to a number of various experimental constraints, however, as we show, it can remain sufficiently light by evading all experimental bounds and has the great potential to be discovered in the near-future low-energy experiments. The analysis provided here is equally applicable to any BSM scenario for which a light scalar is allowed to have sizable flavor-diagonal couplings to the charged leptons. In addition to the light scalar, our theory predicts the existence of a nearly degenerate charged scalar and a pseudoscalar, which have masses of the order of the electroweak scale. We analyze possible ways to probe new-physics signals at colliders and find that this scenario can be tested at the LHC by looking at the novel process $pp \rightarrow H^\pm H^\pm jj \rightarrow l^\pm l^\pm jj + E_T$ via same-sign pair production of charged Higgs bosons.

I. INTRODUCTION

For a charged elementary particle with half-integer intrinsic spin, the Landé g-factor at the tree-level has the value $g = 2$. Any departure from this is called the anomalous magnetic moment (AMM) defined by $a = (g - 2)/2$. The first radiative correction to this value at the one-loop level was performed by Schwinger [1]. Our current best understanding of physics at the fundamental scale is precisely described by the Standard Model (SM) and, within this theory, contribution to $a_{SM}$ arises from loops containing Quantum Electrodynamics (QED) corrections, hadronic (QCD) processes, and electro-weak (EW) pieces. For the electron and the muon, the QED contributions [1–18] to the AMMs, which are the most dominant corrections, have been computed up to 5-loop order [19–21]. Furthermore, within the SM the accurately computed corrections from QCD [22–43] and EW [44–49] interactions can be important due to the current experimental precision.

Since the electron and the muon AMMs $a_{e,\mu}$ can be measured with great precision in the experiments, and simultaneously can be computed with outstanding accuracy within the SM, these two quantities are the most crucial observables in particle physics. A slight deviation of these measured quantities from the SM values will be a direct indication of physics beyond the SM (BSM). Hence, any BSM particle that couples to a lepton ($\ell = e$ and/or $\mu$), either directly or indirectly, and contributes to its AMM $a_\ell$ can be probed in the experiments.

In the muon sector, there has been a longstanding tension between the theoretical prediction and the value measured at the Brookhaven National Laboratory [50], corresponding to a deviation:

$$\Delta a_\mu = (2.74 \pm 0.73) \times 10^{-9}. \quad (1)$$

Since their first measurement of $\Delta a_\mu$ [51], the discrepancy has been slowly growing due to the reduction of both theoretical and experimental uncertainties and has gained a lot of attention to the theory community over the last almost two decades; for reviews see e.g. Refs. [52, 53]. In the near future, Fermilab’s E989 Muon $g - 2$ experiment [54] that has the precision a factor of four times better than the previous experimental measurements, is likely to publish their first result, which makes the scenario even more exciting. Additionally, the future J-PARC experiment [55] developed by the E34 collaboration also aims to measure muon AMM with similar precision. Moreover, the objective of the recently proposed MUonE experiment [56] at CERN is to determine the hadronic contribution to muon AMM with a precision smaller than the theoretical uncertainty originating from leading-order QCD processes. For discussions on possible new-physics (NP) effects on the measurements of the MUonE experiment, see Refs. [57, 58].

On the other hand, just recently an improved measurement [59] of the fine-structure constant $\alpha$ using Caesium atom points toward a deviation in the electron AMM from theoretical prediction as well:

$$\Delta a_e = -(8.7 \pm 3.6) \times 10^{-13}. \quad (2)$$

Eq. (2) corresponds to a negative $\sim 2.4\sigma$ discrepancy for the electron, whereas Eq. (1) for the muon signifies a positive $\sim 3.7\sigma$ deviation from the SM predictions. These tantalizing disparities could play a significant role in finding clues of NP BSM. Note however that having opposite signs of these two anomalies, along with the fact that the mass ratio of the muon to the electron is $\sim O(100)$, makes it more difficult to explain them simultaneously within a common BSM origin.

In the literature, a few different mechanisms are proposed to take into account these deviations, e.g., by in-
introducing scalar degrees of freedom [60–67], in the supersymmetric context [68–71], utilizing vector-like fermions [72–74], in models with gauge-extensions [75–77], and considering non-local QED effects [78]. Whereas most of the constructions are effective theories or require the presence of additional fermionic states, in this work, we propose a simple ultraviolet (UV) complete model without extending the gauge sector of the SM and without introducing BSM fermionic states. In our framework, the observed disparities of the lepton AMMs given in Eqs. (1)-(2) have a common origin, and proper explanation of both these anomalies relies on the existence of a new light scalar degree of freedom that resides in the $O(10)$-MeV to $O(1)$-GeV mass range. NP around this low-energy regime is very interesting and has the potential to be probed in the ongoing, as well as in the upcoming experiments. As we will show, such a light scalar, even though subject to a number of various experimental constraints, can simultaneously incorporate the deviations observed in the muon and the electron AMMs.

Our UV-complete theory is the well-motivated two-Higgs-doublet-model (2HDM) [79, 80], which is one of the simplest extensions of the SM. A variety of theories beyond the SM naturally contain a second Higgs doublet, such as supersymmetric theories [81], axion models to solve the strong CP-problem [82, 83], left-right symmetric models [84], and more. In this theory, in addition to the SM Higgs $h$, there exist one CP-even $H$, one CP-odd $A$, and a charged $H^+$ physical scalars. We show that the new CP-even state can remain significantly light ($m_H \ll m_h, m_A, m_{H^+}$) evading all experimental constraints and contribute to both $\alpha_u$ and $\alpha_e$ to the right amounts. Even though the corrections to each of the AMMs arise from $H$ mediated one-loop and two-loop processes, a positive one-loop quantum correction dominates for the muon AMM, whereas the required contribution to the electron AMM originates primarily from a two-loop diagram that has a sign ambiguity. For elaborated discussions on loop-mediated contributions to lepton AMMs via scalars see e.g. Refs. [85, 86]. For explanations of only the muon $g-2$ within the 2HDM see e.g. Refs. [87–110]. It should be stressed that the analysis provided in this work is equally applicable to any BSM scenario for which the effective theory consists of a light CP-even state [111] having sizable flavor-diagonal couplings to charged leptons and negligible mixing with the SM Higgs.

In the next section we introduce the proposed model, then in Sec. III we summarize experimental constraints relevant to our study and present detailed results, and finally, we conclude in Sec. IV.

II. MODEL

Scalar sector:— In our proposed model, the SM containing a Higgs doublet $\Phi_1$ is extended by a second Higgs doublet $\Phi_2$, each carrying hypercharge=1/2. Both the Higgs doublets can acquire vacuum expectation values (VEVs) $(\Phi_1) = v_1$, such that $v_1^2 = (246 \text{ GeV})^2$. This introduces a parameter in the theory defined as: $\tan \beta = v_2/v_1$. However, one can choose a particularly convenient rotated basis in which only one neutral Higgs has a nonzero vacuum expectation value. The most general scalar potential of 2HDM written in this so-called Higgs-basis is given by [80, 112–114]:

$$ V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - \{m_{12} H_1^\dagger H_2 + \text{h.c.}\} $$

$$ + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) $$

$$ + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{ \frac{\lambda_5}{2} (H_1^\dagger H_2)^2 + \text{h.c.} \right\} $$

$$ + \left\{ [\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\}. \quad (3) $$

Here $m_1^2$, and $\lambda_{5,6,7}$ can be complex in general, whereas the rest of the parameters are real. We work in the CP-conserving limit and take all the parameters to be real. The Higgs-basis and the original basis are related by the following transformations:

$$ H_1 = \cos \beta \Phi_1 + \sin \beta \Phi_2, \quad (4) $$

$$ H_2 = -\sin \beta \Phi_1 + \cos \beta \Phi_2. \quad (5) $$

Note that in this basis, only $H_1$ has non-zero VEV [114], and these fields can be parametrized as:

$$ H_1 = \left( \frac{G^+}{\sqrt{2}} \right), \quad H_2 = \left( \frac{H^+}{h^0+i A^0} \right). \quad (6) $$

Here $G^+$ and $G^0$ are the Goldstone bosons eaten up by the gauge bosons after the EW symmetry is broken. The mixing between the two CP-even scalars contained in these two doublets is parametrized by $\sin(\alpha - \beta) \propto \lambda_6$ [114] and we work in the alignment limit [80, 115], where $\sin(\alpha - \beta) \sim 0$. In this $\alpha \approx \beta$ limit, $H_1^0 \approx h$ is the SM Higgs and almost decouples from the other CP-even state $H_2^0 \approx H$. Then the masses of all the physical scalars in this theory are given by [114]:

$$ m_h^2 = \lambda_1 v_1^2, \quad m_H^2 = m_{12}^2 + \frac{v_2^2}{2} (\lambda_3 + \lambda_4 + \lambda_5), \quad (7) $$

$$ m_A^2 = m_{22}^2 - v_2^2 \lambda_5, \quad m_{H^\pm}^2 = m_H^2 - \frac{v_2^2}{2} (\lambda_4 + \lambda_5). \quad (8) $$

As aforementioned, we are interested in the scenario with a mass hierarchy of the form: $m_H^2 \ll m_{H^\pm}^2, m_A^2$. With this choice, the EW precision measurements put restrictions on the mass splitting between $H^+$ and $A^0$
states, hence, for simplicity, we take them to be degenerate, $m_{H^±} = m_{A^0}$. This demands, $λ_4 = λ_5 (= λ)$, and consequently one finds: $m_{H^±}^2 = m_A^2 = -v^2λ$ (here we have neglected the small mass of $H$ scalar). From this, it is evident that masses of the heavy scalars $H^+$ and $A$ cannot be made arbitrarily large. Perturbatively of the couplings $|λ| ≲ 2$ (or $1/4π$) provides an upper bound on the mass of the heavy states $m_{H^±} = m_A ≲ 350$ (or 460) GeV, as long as $m_H ≈ 0$.

On the other hand, a lower bound on the charged Higgs mass utilizing LEP constraints in our scenario is found to be $m_{H^±} ≥ 110$ GeV as will be discussed later in the text. For the simplicity of our analysis, we fix its mass to be 110 GeV for the rest of this work that corresponds to the case $Δm ≡ m_H - m_{H^±} = -110$ GeV. This bound can be then translated to $λ = Δm^2/v^2 = -0.199$, which essentially remains the same for a wide range of mass 0 GeV $≤ m_H$ $≤ 1$ GeV, but can be significantly different in the larger mass region.

Yukawa sector:— The Yukawa coupling of this theory is given by [80, 112, 113]:

\[-L_Y \supset \sqrt{2}(Y^{(1)}_{ℓ,i,j} \Phi_1 + Y^{(2)}_{ℓ,i,j} \Phi_2)k_{Li}k_{Rj} + h.c.\]  

(9)

Here for quarks $k_L = Q_L, k_R = u_R, d_R$, for leptons $k_L = L_L, k_R = ℓ_R$, and in the up-quark sector $Φ → iτ_2Φ^*$ must be made. In the Higgs-basis the Lagrangian has the same form as that of Eq. (9) with the replacements: $Φ_i → H_i$, and \{$Y^{(1)}_{ℓ,i,j}, Y^{(2)}_{ℓ,i,j}$\} → \{$Y_{ℓ,i,j}, Y_{ℓ,i,j}$\}, where we have defined: $Y_{ℓ,i,j} = Y^{(1)}_{ℓ,i,j} \cos β + Y^{(2)}_{ℓ,i,j} \sin β$ and $Y_{ℓ,i,j} = -Y^{(1)}_{ℓ,i,j} \sin β + Y^{(2)}_{ℓ,i,j} \cos β$. Note that $Y_{ℓ,i,j}$ and $Y_{ℓ,i,j}$ are independent $3 \times 3$ Yukawa coupling matrices. Since in the Higgs-basis only $H_3$ acquires a VEV, the masses of the fermions are entirely coming from $Y_{ℓ,i,j}$ Yukawa couplings that follow the relations $Y_{ℓ,i,j} = \sqrt{2}M_{ℓ,i,j}$, whereas $Y_{ℓ,i,j}$ are free parameters. We work in a basis, where the mass matrices are real and diagonal. In this chosen basis, the second set of Yukawa coupling matrices, $Y_{ℓ,i,j}$ are in general arbitrary non-diagonal matrices and we denote these rotated matrices by $Y_{ℓ,i,j}$. However, $Y_{ℓ,i,j}$ are subject to stringent phenomenological constraints, since they mediate dangerous flavor violating processes. In the quark sector, even if one starts with diagonal $Y_{ℓ,i,j}$, off-diagonal entries reappear in $Y_{ℓ,i,j}$ matrices due to non-vanishing CKM entries. This is why we assume $Y_{u,d} \ll 1$, and focus only on the lepton sector. Following the above discussions, the Yukawa interactions of the leptons with the physical scalars are then given by:

\[-L_Y \supset \left[ Y^{H^0}_{ℓ,i,j} H^0 + i Y^{A^0}_{ℓ,i,j} A^0 \right] \bar{L}_i \ell_Rj + h.c.\]  

(10)

here, $Y^{H^0}_{ℓ,i,j} = Y^{A^0}_{ℓ,i,j} = Y^{H^+}_{ℓ,i,j} = Y_{ℓ,i,j}$. For this lepton Yukawa matrix, we assume a texture of the form: $Y_{ℓ} = \text{diag}(y_ε, y_µ, y_τ)$, where, couplings $y_ε$ are uncorrelated to the masses of the leptons and we take them to be real. This choice of Yukawa texture is taken purely due to phenomenological considerations to avoid dangerous flavor violating processes.

Lepton anomalous magnetic moments:— Now we compute all possible BSM contributions to lepton AMMs within our framework. We first derive the one-loop contributions as shown in Fig. 1 (diagram on the left) arising from the charged, CP-even, and CP-odd scalars which are given by [116]:

\[\Delta α^{H^+}_{ℓ,ε} = \frac{-Q_H(ε Y^{H^+}_{ℓ,ε})^2}{4π^2} F_{H^+}[z_{H^+}],\]  

(11)

\[\Delta α^{φ^0}_{ℓ,ε} = \frac{-1}{8π^2} \sum_{f} \sum_{φ^0} Q_f \left( Y^{φ^0}_{ℓ,ε} \right)^2 F_{φ^0}[z_{φ^0} z_{φ^0}],\]  

(12)
In the future, the electron and the muon deviations of both the electron and the muon AMMs. Compared to the EW scale can naturally explain the observed deviations from the second Higgs doublet remains sufficiently over the lighter compared to its partners. In our scenario, a mass splitting of this type is essential for concurrent explanation of $\Delta a_\mu$ and $\Delta a_e$. As will be apparent from the detailed analysis performed in the next section, the experimentally allowed mass window is $O(10)$-MeV to $O(1)$-GeV for the light scalar. In this scheme, only the contribution of the light state to the lepton AMMs is significant, since our case corresponds to $m_{H^+} = m_A \gg m_H$. Here we investigate the viability of attaining right sizes and signs for both the deviations observed in $g_\mu - 2$ and $g_e - 2$ measurements via CP-even scalar $H$. For completeness we have also included the contributions from $H^+$ and $A$ that can provide sizable corrections at the higher mass regime. To get an understanding of the relative magnitudes, in Fig. 2, we show both the one-loop (dotted line) and the two-loop (dashed line) contributions to AMMs for two different values of the Yukawa couplings as a function of its mass $m_H$. In this work, we take a fixed value of the tau Yukawa coupling $y_\tau \approx 10^{-1}$, which is allowed by the experiment data to be discussed later in the text. The solid lines correspond to overall contributions to $|\Delta a_{\mu,e}|$, and the horizontal gray bands indicate the experimental measurements within their $2\sigma$ values. From Fig. 2, one finds that within the mass range under consideration, the positive one-loop contribution is the primary source of $\Delta a_\mu$, whereas the two-loop correction with a negative sign must dominate over the positive one-loop correction to $\Delta a_e$, to properly take into account the observed data given in Eqs. (1)-(2).

III. EXPERIMENTAL CONSTRAINTS AND FUTURE PROSPECTS

As demonstrated above, a relatively light scalar compared to the EW scale can naturally explain the observed deviations of both the electron and the muon AMMs. However, a light scalar of mass $m_H \ll \text{TeV}$, having siz-
experiments \cite{119-121} can probe light scalars that have coupling with the electrons. In these experiments light scalars can be produced via Bremsstrahlung-like processes: $e + N \rightarrow e + N + H$. For a scalar of mass $m_H < 2m_e$, after traveling macroscopic distances, it would decay back to electron pairs. The lack of such events at the electron beam-dump experiments provide stringent constraints \cite{122,123} on the mass of the light scalar and its corresponding couplings to the electrons, which is depicted in the brown-shaded exclusion region in Fig. 5.

Another low-energy fixed-target experiment, HPS at the JLab \cite{124} is designed to search for heavy-photons. Displaced decays of scalars that are produced via their couplings to electrons can be detected in this experiment within a few cm from the target \cite{123}. The HPS projection for a light scalar that couples to the electron is plotted as a dashed-purple line in Fig. 5.

**Dark Photon searches:** There are several experiments that search for the presence of dark-photons and their null observations can be translated to provide stringent constraints on the allowed parameter space of light scalars. KLOE collaboration \cite{125} searches for the dark-photons $A_d$ through the process: $e^+ e^- \rightarrow \gamma A_d$, with $A_d \rightarrow e^+ e^-$. The lack of such signals at this experiment can be used to set constraints on the light scalars \cite{126} that have coupling with the electrons, which is indicated by cyan-shaded region in Fig. 5.

Through a similar process, the BaBar collaboration \cite{127} also searches for the dark-photons with $A_d \rightarrow \ell^+ \ell^-$. By recasting the results from BaBar, Ref. \cite{128} provides exclusion regions in the light scalar mass and Yukawa coupling plane, which is depicted by a light-black shaded region in Fig. 5. The dashed black line below this region represents the projected sensitivity from the Belle-II experiment \cite{129,130} for a similar process \cite{123}. For a scalar mass $m_H > 200$ MeV the dark-boson searches at the BaBar \cite{131} can be used to impose limits on $H \mu^+ \mu^-$ coupling via $e^+ e^- \rightarrow \mu^+ \mu^- H$ process \cite{123,122}. We recast this result for our scenario, which is shown as light brown shaded region in Fig. 5. The corresponding projected sensitivity from Belle-II experiment \cite{123,130} is also presented by a dashed brown line.

**Rare Z-decay constraints:** Exotic $Z$ decay of the type $Z \rightarrow 4 \mu$ has been searched by both the ATLAS \cite{133} and the CMS \cite{134} collaborations at the LHC with 7 TeV, as well as 8 TeV data. The LHC results have been interpreted as constraints on the process $Z \rightarrow \mu^+ \mu^- H$, with $H \rightarrow \mu^+ \mu^-$ by Ref. \cite{122}. We recast the LHC results for our model, which is plotted as a light red region in Fig. 5.

**LEP and LHC constraints:** Here, we discuss the existing collider constraints on the neutral and charged scalars relevant for our set-up. Collisions of electron-positron at center-of-mass energies above the $Z$-boson mass are carried-out at LEP experiment \cite{135}, which impose stringent constraints on contact interactions involving $e^+ e^- \rightarrow f\bar{f}$ processes. If a neutral scalar $(\phi^0 = H, A)$ is heavy enough, integrating it out leads to a $d = 6$ effective operator to describe the associated contact interactions. LEP constraints are then directly translated into the lower bounds on the mass of the scalar for a given Yukawa coupling. The most constraining process is the one with electrons in the final states and the associated bound is found to be $m_{\phi^0}/|y_\ell| > 1.99$ TeV \cite{136}. However, if the neutral scalar is light, the aforementioned bound is no longer applicable. To properly incorporate such a scenario, we implement our model file in FeynRules package \cite{137} and compute the cross-section of the process $e^+ e^- \rightarrow f\bar{f}$ using MadGraph5 event generator \cite{138}. The generated data set is then compared with the measured cross-sections \cite{135,139} to find the limits on the mass $m_{\phi^0}$ as a function of its Yukawa couplings. The obtained LEP bounds for our model is then projected in Fig. 5 in blue-shaded region. As far as the LHC bounds, most of the searches for heavy neutral scalars are done in the context of either MSSM or generic 2HDM, which are not directly applicable in our scenario since, $\phi^0$ has negligible couplings to quarks, and therefore, cannot be produced via gluon fusion. However, LHC bounds on neutral scalars come out to be weaker than the LEP bounds as discussed above due to its leptophilic nature.

Even though the charged scalars, $H^{\pm}$ do not couple to the quarks, they can still be pair-produced through $s$-channel Drell-Yan process mediated by $Z$ or $\gamma$ at LEP. In our model, each charged scalar produced, will then decay into $\ell + \nu_{\ell}$. These leptonic final states exactly mimic slepton searches in supersymmetric models, and we use the associated LEP limits and recast these results for our scenario, which provides a lower bound for its mass $m_{\pm} \geq 110$ GeV. The collider constraints of this type of leptophilic charged scalars are analyzed and discussed in detail in Ref. \cite{136}. At the LHC, the charged scalars can also be pair produced via Drell-Yan process followed by leptonic decays $H^{\pm} \rightarrow \ell \nu_{\ell}$. Such a leptophilic-like charged scalar will be constrained from the LHC searches by processes involving the left-handed selectrons/smuons/staus \cite{140-142} $pp \rightarrow \tilde{\ell}^*_{L,R} \tilde{\tau}_L \rightarrow \ell^*_{L,R}X^0\ell^*_{L,R}X^0$, which will mimic the similar final states $\ell^+\nu_{\ell}\ell^-\nu_{\ell}$ from $H^+H^-$ decays in the massless neutralino limit. We adapt the $\sqrt{s} = 13$ TeV CMS selectron search \cite{142} limit and the current limits \cite{140} on stau searches, and translate into a bound on the charged scalar mass. It is quite evident that the LHC limits can be evaded by going to larger $BR_{\tau\nu} \gtrsim 0.4$, which is achieved in our scenario by choosing an appropriate Yukawa coupling $y_{\tau} \sim 0.1$. The LHC searches do not put any stronger bound on the mass of the leptophilic charged scalar due to its tau-philic (mostly) nature. It is quite important to mention that there will not be any significant constraints from Higgs observables since we are considering a scenario with almost no mixing between...
SM Higgs, \( h \) and the other CP-even scalar, \( H \).

**Electroweak precision constraints:** The effects of NP on the self-energies of the gauge bosons are parametrized in terms of oblique parameters \( S, T, \) and \( U \). From the EW precision data, these parameters impose strong constraints on any NP beyond the SM and have been calculated at the one-loop level for general multi-Higgs-doublet models in Refs. [114, 143–145]. In the alignment limit, the \( T \) parameter in the 2HDM can be expressed as:

\[
T = \frac{1}{16\pi^2} \frac{1}{M_W^2} \left\{ F(m_{H^+}^2, m_{h}^2) + F(m_{H^+}^2, m_{A}^2) - F(m_{H^0}^2, m_{A}^2) \right\},
\]

(19)

where the symmetric function \( F \) is given by

\[
F(m_1^2, m_2^2) = \frac{1}{2} (m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \left( \frac{m_1^2}{m_2^2} \right).
\]

(20)

By analyzing these additional contributions, we find that the bound on the \( T \) parameter imposes strong restrictions on the mass splittings among the scalars in our scenario. As discussed above, in this work we set \( m_{H^\pm} = 110 \text{ GeV} \), which is consistent with the aforementioned LEP precision data. We then turn on the mass splitting between charged scalar and the CP-even neutral scalar \( H \) as well as between the charged scalar and the CP-odd neutral scalar \( A \). Now, we investigate the maximum possible mass splittings allowed by the \( T \) parameter constraints. The corresponding region plot is shown in Fig. 3. The yellow and green shaded regions indicate the \( 1\sigma \) and \( 2\sigma \) exclusion regions from the \( T \) parameter constraint, respectively. From this figure it is apparent that our scenario: \( m_H^2 < m_{H^+}^2 = m_A^2 \sim 110 \text{ GeV} \) is well consistent with the EW precision constraints.

**Future implications at collider:** Here we discuss the testability of the proposed scenario in the upcoming experiments. As we discussed earlier, explanations of the experimental data of \( \Delta a_{\mu, e} \) solely depend on the existence of a light CP-even scalar. This scenario can be tested at the LHC by looking at the novel process \( pp \to H^\pm jj \to \tau^\pm \tau^\pm jj + E_T \), and the corresponding representative Feynman diagram is presented in Fig. 4. It is interesting to note that if the mass splitting between the CP-even and CP-odd neutral scalars is turned off, then the amplitude for this process will be exactly zero. Correspondingly, our scenario will fail to explain the lepton AMMs, since a large mass splitting is essential to properly incorporate \( \Delta a_{\mu, e} \) data as discussed above. Hence, observed deviations in the lepton AMMs are directly correlated with the signal \( pp \to \tau^\pm \tau^\pm jj + E_T \) in our set-up. Due to this complementarity, this particular explanation of the electron and the muon \( g - 2 \) within the 2HDM can be tested by this novel same sign charge lepton process. This same-sign charged lepton signature via vector-boson fusion process at the LHC has been studied extensively in Ref. [146], although in a different context. We recast this analysis for our case and obtain the projected sensitivity for the signal \( pp \to H^\pm H^\pm jj \to \tau^\pm \tau^\pm jj + E_T \) at the LHC for centre of mass energy 14 TeV with integrated luminosity \( \mathcal{L} = 3 \text{ ab}^{-1} \) and also for the centre of mass energy 27 TeV with integrated luminosity \( \mathcal{L} = 15 \text{ ab}^{-1} \). We find that a charged scalar of mass 282 GeV (630 GeV) can be probed at the 14 TeV (27 TeV) LHC with integrated luminosity \( \mathcal{L} = 3 \text{ ab}^{-1} (\mathcal{L} = 15 \text{ ab}^{-1}) \) while there is 110 GeV mass splitting between CP-even \( (H) \) and CP-odd \( (A) \) scalar. These projected sensitivities are shown in Fig. 5 by black dashed lines. Another interesting collider
The green (red) and yellow (pink) regions represent the experimental 1σ and 2σ bands for the electron (muon) AMM $\Delta a_e$ ($\Delta a_\mu$). The color shaded regions with solid boundary denote the excluded parameter space by current experiments: brown region from the electron beam-dump experiments [119–121]; cyan and light black regions from the dark-photon searches through $e^+e^-\rightarrow \gamma H$ process at KLOE [125] and BaBar [127] respectively; light brown region from the $e^+e^-\rightarrow \mu^+\mu^- H$ searches at BaBar [131]; blue shaded region from LEP [135]; light red region from CMS [134]. In this plot, we also present the projected sensitivities from several proposed experiments: heavy-photon searches (HPS) from JLab experiment (dashed purple line) [124]; dark-photon searches through $e^+e^-\rightarrow \gamma H$ process and $e^+e^-\rightarrow \mu^+\mu^- H$ process from Belle-II (dashed black and dashed light brown lines respectively) [129, 130]. The projected sensitivities for the signal $p p \rightarrow H^+H^-jj \rightarrow \tau^+\tau^-jj+E_T$ at the LHC for centre of mass energy 14 TeV with integrated luminosity $L=3$ ab$^{-1}$ and also for the centre of mass energy 27 TeV with integrated luminosity $L=15$ ab$^{-1}$ are shown by black dashed vertical lines.

Prospect that we briefly mention here is the decay of the SM Higgs into a pair of light scalars. As can be seen from Fig. 5 that the light scalar of mass $\sim O(200)$ MeV, which is experimentally allowed can incorporate the deviations in the lepton AMMs. A light scalar around this mass region is particularly interesting since, the pair produced light scalars from the decay of the SM Higgs, will further decay into two electrons or two muons. The process $p p \rightarrow h \rightarrow HH \rightarrow \mu^+\mu^-\mu^+\mu^-$, which is consistent with current experimental observations, however, this can be tested in future experiments, such as, HL-LHC and/or FCC-hh. The associated detailed collider studies are beyond the scope of this paper and are left for future work.

Synopsis: All the aforementioned current experimental constraints applicable to our model, along with the future sensitivities are summarized in Fig. 5. On top of that, we have also plotted the experimentally measured values of AMMs of the electron and muon within 2σ allowed range that arise from all the BSM degrees of freedom within this scenario. It is evident from this summary plot that despite numerous tight constraints, the CP-even scalar $H$ can remain light and live in the $O(10)$-MeV to $O(1)$-GeV mass range, and contribute to both $\Delta a_{e,\mu}$ with correct magnitudes and signs. In the lower mass regime $m_H < O(10)$ MeV, it is incapable of explaining observed values of $\Delta a_e$ and $\Delta a_\mu$ simultaneously regardless of other experimental constraints. On the contrary, in the opposite side of the parameter space, i.e., for $m_H > O(1)$ GeV, even though a concurrent explanation of both $\Delta a_e$ and $\Delta a_\mu$ is possible, however, various experimental constraints kill this portion of the parameter space.

**IV. CONCLUSION**

Motivated by the recent precise measurement of the electron AMM $a_e$, which shows a significant deviation from the SM prediction, together with the intriguing deviation observed in the muon AMM $a_\mu$, we have proposed a novel scenario consisting of a light neutral scalar $H$ that is behind the origin of both these anomalies. By properly
taking into account theoretical and all existing experimental constraints, we have shown that a wide range of parameter space $O(10) \text{ MeV} \leq m_H \leq O(1) \text{ GeV}$ is still allowed, which provides correct sizes and signs for both the $a_e$ and $a_\mu$. This is a highly non-trivial task since the light scalar is required to have sizeable couplings to all the SM charged leptons, and consequently is under severe experimental constraints. We have demonstrated how such a light CP-even scalar naturally arises from general 2HDM and serves the required purpose. Our model predicts that the light scalar $H$ must be accompanied by nearly degenerate charged scalar $H^\pm$ and a pseudoscalar $A$ that have masses of the order of the EW symmetry breaking scale. As we have shown by detailed analysis, the currently allowed parameter space can be probed entirely in the upcoming experiments, which will either discover NP or completely rule out our scenario. A complementarity test of this scenario at the LHC by seeking the novel process $pp \rightarrow H^\pm H^\pm jj \rightarrow l^\pm l^\pm jj + E_T$ via same-sign pair production of charged Higgs bosons is also discussed.

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[1] J. S. Schwinger, “On Quantum electrodynamics and the magnetic moment of the electron,” Phys. Rev. **73** (1948) 416–417.
[2] C. M. Sommerfeld, “Magnetic Dipole Moment of the Electron,” Phys. Rev. **107** (1957) 328–329.
[3] A. Petermann, “Fourth order magnetic moment of the electron,” Helv. Phys. Acta **30** (1957) 407–408.
[4] T. Kinoshita and W. B. Lindquist, “Eighth Order Anomalous Magnetic Moment of the electron,” Phys. Rev. Lett. **47** (1981) 1573.
[5] T. Kinoshita, B. Nizic, and Y. Okamoto, “Eighth order QED contribution to the anomalous magnetic moment of the muon,” Phys. Rev. **D41** (1990) 593–610.
[6] S. Laporta and E. Remiddi, “The Analytical value of the electron (g-2) at order alpha**3 in QED,” Phys. Lett. **B379** (1996) 283–291, arXiv:hep-ph/9602417 [hep-ph].
[7] G. Degrassi and G. F. Giudice, “QED logarithms in the electroweak corrections to the muon anomalous magnetic moment,” Phys. Rev. **D58** (1998) 053007, arXiv:hep-ph/9803384 [hep-ph].
[8] T. Kinoshita and M. Nio, “Improved alpha**4 term of the muon anomalous magnetic moment,” Phys. Rev. **D70** (2004) 113001, arXiv:hep-ph/0402206 [hep-ph].
[9] T. Kinoshita and M. Nio, “The Tenth-order QED contribution to the lepton g-2: Evaluation of dominant alpha**5 terms of muon g-2,” Phys. Rev. **D73** (2006) 053007, arXiv:hep-ph/0512330 [hep-ph].
[10] M. Passera, “Precise mass-dependent QED contributions to leptonic g-2 at order alpha**2 and alpha**3,” Phys. Rev. **D75** (2007) 013002, arXiv:hep-ph/0608174 [hep-ph].
[11] A. L. Kataev, “Reconsidered estimates of the tenth order QED contributions to the muon anomaly,” Phys. Rev. **D74** (2006) 073011, arXiv:hep-ph/0608120 [hep-ph].
[12] T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, “Revised value of the eighth-order QED contribution to the anomalous magnetic moment of the electron,” Phys. Rev. **D77** (2008) 053012, arXiv:0712.2607 [hep-ph].
[13] T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, “Tenth-Order QED Contribution to the Electron g-2 and an Improved Value of the Fine Structure Constant,” Phys. Rev. Lett. **109** (2012) 111807, arXiv:1205.5368 [hep-ph].
[14] T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, “Complete Tenth-Order QED Contribution to the Muon g-2,” Phys. Rev. Lett. **109** (2012) 111808, arXiv:1205.5370 [hep-ph].
[15] S. Laporta, “High-precision calculation of the 4-loop contribution to the electron g-2 in QED,” Phys. Lett. **B772** (2017) 232–238, arXiv:1704.06996 [hep-ph].
[16] T. Aoyama, T. Kinoshita, and M. Nio, “Revised and Improved Value of the QED Tenth-Order Electron Anomalous Magnetic Moment,” Phys. Rev. **D97** no. 3, (2018) 036001, arXiv:1712.06060 [hep-ph].
[17] S. Volkov, “New method of computing the contributions of graphs without lepton loops to the electron anomalous magnetic moment in QED,” Phys. Rev. **D96** no. 9, (2017) 096018, arXiv:1705.05800 [hep-ph].
[18] S. Volkov, “Numerical calculation of high-order QED contributions to the electron anomalous magnetic moment,” Phys. Rev. **D98** no. 7, (2018) 076018, arXiv:1807.05281 [hep-ph].
[19] Particle Data Group Collaboration, M. Tanabashi et al., “Review of Particle Physics,” Phys. Rev. **D98** no. 3, (2018) 030001.
[20] P. J. Mohr and B. N. Taylor, “CODATA Recommended Values of the Fundamental Physical Constants: 1998,” Rev. Mod. Phys. **72** (2000) 351–495.
[21] A. Czarnecki and W. J. Marciano, “Lepton anomalous magnetic moments: A Theory update,” Nucl. Phys. Proc. Suppl. **76** (1999) 245–252, arXiv:hep-ph/9810512 [hep-ph].
[22] F. Jegerlehner, “Hadronic Contributions to Electroweak Parameter Shifts: A Detailed Analysis,” Z. Phys. **C32** (1986) 195.
[23] B. W. Lynn, G. Penso, and C. Verzegnassi, “STRONG INTERACTION CONTRIBUTIONS TO ONE LOOP LEPTONIC PROCESS,” Phys. Rev. **D35** (1987) 42.
[24] M. L. Swartz, “Reevaluation of the hadronic contribution to $\alpha(M(Z)^2)$,” Submitted to: Phys. Rev. D (1994), arXiv:hep-ph/9411353 [hep-ph].
[25] A. D. Martin and D. Zeppenfeld, “A Determination of the QED coupling at the Z pole,” Phys. Lett. **B345** (1995) 558–563, arXiv:hep-ph/9411377 [hep-ph].
[26] S. Eidelman and F. Jegerlehner, “Hadronic contributions to g-2 of the leptons and to the effective fine structure constant alpha (M(z)**2),” Z. Phys.
[hep-ex].

[57] P. S. B. Dev, W. Rodejohann, X.-J. Xu, and Y. Zhang, “MUonE sensitivity to new physics explanations of the muon anomalous magnetic moment,” arXiv:2002.04822 [hep-ph].

[58] A. Masiero, P. Paradisi, and M. Passera, “New physics at the MUonE experiment at CERN,” arXiv:2002.05418 [hep-ph].

[59] R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Mueller, “Measurement of the fine-structure constant as a test of the Standard Model,” Science 360 (2018) 191, arXiv:1812.04130 [physics.atom-ph].

[60] H. Davoudiasl and W. J. Marciano, “Tale of two anomalies,” Phys. Rev. D98 no. 7, (2018) 075011, arXiv:1806.10252 [hep-ph].

[61] J. Liu, C. E. M. Wagner, and X.-P. Wang, “A light complex scalar for the electron and muon anomalous magnetic moments,” JHEP 03 (2019) 008, arXiv:1810.11028 [hep-ph].

[62] X.-F. Han, T. Li, L. Wang, and Y. Zhang, “Simple interpretations of lepton anomalies in the lepton-specific inert two-Higgs-doublet model,” Phys. Rev. D99 no. 9, (2019) 095034, arXiv:1812.02449 [hep-ph].

[63] A. Thamm, “Axion-like particles, lepton-flavor violation and a new explanation of a_e, a_µ,” arXiv:2002.10230 [hep-ph].

[64] C. Cornella, P. Paradisi, and O. Sumensari, “Hunting for ALPs with Lepton Flavor Violation,” arXiv:1911.06279 [hep-ph].

[65] M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, “Axion-like particles, lepton-flavor violation and a new explanation of a_e, a_µ,” arXiv:1908.00008 [hep-ph].

[66] C. Cornella, P. Paradisi, and O. Sumensari, “Hunting for ALPs with Lepton Flavor Violation,” arXiv:1911.06279 [hep-ph].

[67] M. Endo, S. Iguro, and T. Kitahara, “Probing eµ flavor-violating ALP at Belle II,” arXiv:2002.05948 [hep-ph].

[68] M. Endo, S. Iguro, and T. Kitahara, “Probing eµ flavor-violating ALP at Belle II,” arXiv:2002.05948 [hep-ph].

[69] M. Endo and W. Yin, “Explaining electron and muon g-2 anomaly in SU(5) without lepton-flavor mixings,” JHEP 08 (2019) 122, arXiv:1906.08768 [hep-ph].

[70] B. Dutta and Y. Mimura, “Electron g-2 with flavor violation in MSSM,” Phys. Lett. B790 (2019) 563–567, arXiv:1811.10209 [hep-ph].

[71] B. Dutta and Y. Mimura, “Electron g-2 with flavor violation in MSSM,” Phys. Lett. B790 (2019) 563–567, arXiv:1811.10209 [hep-ph].

[72] G. Hiller, C. Hormigos-Feliu, D. F. Litim, and T. Steudtner, “Anomalous magnetic moments from asymptotic safety,” arXiv:1910.14062 [hep-ph].

[73] A. Crivellin and M. Hoferichter, “Combined explanations of (g − 2)µ, (g − 2)µ, and implications for a large muon EDM,” in 33rd Rencontres de Physique de La Vallée d’Aoste (LaThuile 2019) La Thuile, Aosta, Italy, March 10-16, 2019. 2019, arXiv:1905.03789 [hep-ph].

[74] A. Crivellin, M. Hoferichter, and P. Schmidt-Wellenburg, “Combined explanations of (g − 2)µ,e and implications for a large muon EDM,” Phys. Rev. D98 no. 11, (2018) 113002, arXiv:1807.11484 [hep-ph].

[75] M. Abdullah, B. Dutta, S. Ghosh, and T. Li, “(g − 2)µ,e and the ANITA anomalous events in a three-loop neutrino mass model,” Phys. Rev. D100 no. 11, (2019) 115006, arXiv:1907.08109 [hep-ph].

[76] A. E. Cárcamo Hernández, Y. H. Velásquez, S. Kovalenko, H. N. Long, N. A. Pérez-Julve, and V. V. Vien, “Fermion masses and mixings and g-2 anomalies in a low scale 3-3-1 model,” arXiv:2002.07347 [hep-ph].

[77] A. E. Cárcamo Hernández, S. F. King, H. Lee, and S. J. Rowley, “Is it possible to explain the muon electron and g − 2 in a Z′ model?,” arXiv:1910.10734 [hep-ph].

[78] F. He and P. Wang, “Pauli form factors of electron and muon in nonlocal quantum electrodynamics,” arXiv:1901.00271 [hep-ph].

[79] T. D. Lee, “A Theory of Spontaneous T Violation,” Phys. Rev. D8 (1973) 1226–1239, [516(1973)].

[80] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, “Theory and phenomenology of two-Higgs-doublet models,” Phys. Rept. 516 (2012) 1–102, arXiv:1106.0034 [hep-ph].

[81] H. E. Haber and G. L. Kane, “The Search for Supersymmetry: Probing Physics Beyond the Standard Model,” Phys. Rept. 117 (1985) 75–263.

[82] R. D. Peccei and H. R. Quinn, “CP Conservation in the Presence of Instantons,” Phys. Rev. Lett. 38 (1977) 1440–1443, [328(1977)].

[83] J. E. Kim, “Light Pseudoscalars, Particle Physics and Cosmology,” Phys. Rept. 150 (1987) 1–177.

[84] G. Senjanovic and R. N. Mohapatra, “Exact Left-Right Symmetry and Spontaneous Violation of Parity,” Phys. Rev. D12 (1975) 1502.

[85] G. F. Giudice, P. Paradisi, and M. Passera, “Testing new physics with the electron g-2,” JHEP 11 (2012) 113, arXiv:1208.6583 [hep-ph].

[86] W. J. Marciano, A. Masiero, P. Paradisi, and M. Passera, “Contributions of axionlike particles to lepton dipole moments,” Phys. Rev. D94 no. 11, (2016) 115033, arXiv:1607.01022 [hep-ph].

[87] H. E. Haber, G. L. Kane, and T. Sterling, “The Fermion Mass Scale and Possible Effects of Higgs Bosons on Experimental Observables,” Nucl. Phys. B161 (1979) 493–532.

[88] M. Krawczyk and J. Zochowski, “Constraining 2HDM by present and future muon (g-2) data,” Phys. Rev. D55 (1997) 6968–6974, arXiv:hep-ph/9608321 [hep-ph].

[89] S. Nie and M. Sher, “The Anomalous magnetic moment of the muon and Higgs mediated flavor changing neutral currents,” Phys. Rev. D58 (1998) 097701, arXiv:hep-ph/9805376 [hep-ph].

[90] A. Dedes and H. E. Haber, “Can the Higgs sector contribute significantly to the muon anomalous magnetic moment?,” JHEP 05 (2001) 006, arXiv:hep-ph/0102297 [hep-ph].

[91] E. O. Iltan and H. Sundu, “Anomalous magnetic moment of muon in the general two Higgs doublet model,” Acta Phys. Slov. 53 (2003) 17, arXiv:hep-ph/0103105 [hep-ph].

[92] M. Krawczyk, “The New (g-2) for muon measurement and limits on the light Higgs bosons in 2HDM (II),” [hep-ph].
arXiv:hep-ph/0103223 [hep-ph].

[93] Y.-L. Wu and Y.-F. Zhou, “Muon anomalous magnetic moment in the standard model with two Higgs doublets,” *Phys. Rev.* **D64** (2001) 115018, arXiv:hep-ph/0104056 [hep-ph].

[94] J. F. Gunion, “A Light CP-odd Higgs boson and the muon anomalous magnetic moment,” *JHEP* **08** (2009) 032, arXiv:0808.2509 [hep-ph].

[95] A. Broggio, E. J. Chun, M. Passera, K. M. Patel, and S. K. Vempati, “Limiting two-Higgs-doublet models,” *JHEP* **11** (2014) 058, arXiv:1409.3199 [hep-ph].

[96] E. J. Chun and J. Kim, “Leptonic Precision Test of Leptophilic Two-Higgs-Doublet Model,” *JHEP* **07** (2016) 110, arXiv:1605.06298 [hep-ph].

[97] L. Wang and X.-F. Han, “A light pseudoscalar of 2HDM confronted with muon g-2 and experimental constraints,” *JHEP* **05** (2015) 039, arXiv:1412.4874 [hep-ph].

[98] T. Abe, R. Sato, and K. Yagyu, “Lepton-specific two Higgs doublet model as a solution of muon g - 2 anomaly,” *JHEP* **07** (2015) 064, arXiv:1504.07059 [hep-ph].

[99] E. J. Chun, J. Heeck, and P. Stoffer, “A perturbed lepton-specific two-Higgs-doublet model facing experimental hints for physics beyond the Standard Model,” *Phys. Rev. Lett.* **116** no. 8, (2016) 081801, arXiv:1507.07567 [hep-ph].

[100] E. J. Chun, Z. Kang, M. Takeuchi, and Y.-L. S. Tsai, “LHC τ-rich tests of lepton-specific 2HDM for (g - 2)μ,” *JHEP* **11** (2015) 009, arXiv:1507.08067 [hep-ph].

[101] T. Han, S. K. Kang, and J. Sayre, “Muon g - 2 in the aligned two Higgs doublet model,” *JHEP* **02** (2016) 097, arXiv:1511.05162 [hep-ph].

[102] V. Ilisie, “New Barr-Zee contributions to (g - 2)μ in two-Higgs-doublet models,” *JHEP* **04** (2015) 077, arXiv:1502.04199 [hep-ph].

[103] A. Cherchiglia, P. Kneschke, D. Stöckinger, and H. Stöckinger-Kim, “The muon magnetic moment in the 2HDM: complete two-loop result,” *JHEP* **01** (2017) 007, arXiv:1607.06292 [hep-ph].

[104] T. Abe, R. Sato, and K. Yagyu, “Muon specific two-Higgs-doublet model,” *JHEP* **07** (2017) 012, arXiv:1705.01469 [hep-ph].

[105] A. Cherchiglia, D. Stöckinger, and H. Stöckinger-Kim, “Muon g-2 in the 2HDM: maximum results and detailed phenomenology,” *Phys. Rev.* **D98** (2018) 035001, arXiv:1711.11567 [hep-ph].

[106] V. Keus, N. Koivunen, and K. Tuominen, “Singlet scalar and 2HDM extensions of the Standard Model: CP-violation and constraints from (g - 2)μ and eEDM,” *JHEP* **09** (2018) 059, arXiv:1712.09613 [hep-ph].

[107] S.-P. Li, X.-Q. Li, and Y.-D. Yang, “Muon g - 2 in a U(1)-symmetric Two-Higgs-Doublet Model,” *Phys. Rev.* **D99** no. 3, (2019) 035010, arXiv:1808.02424 [hep-ph].

[108] L. Wang, J. M. Yang, M. Zhang, and Y. Zhang, “Revisiting lepton-specific 2HDM in light of muon g - 2 anomaly,” *Phys. Lett.* **B788** (2019) 519–529, arXiv:1809.05857 [hep-ph].

[109] E. J. Chun, J. Kim, and T. Mondal, “Electron EDM and Muon anomalous magnetic moment in Two-Higgs-Doublet Models,” *JHEP* **12** (2019) 068, arXiv:1906.00612 [hep-ph].

[110] S. Iguro, Y. Omura, and M. Takeuchi, “Testing the 2HDM explanation of the muon g - 2 anomaly at the LHC,” *JHEP* **11** (2019) 130, arXiv:1907.09845 [hep-ph].

[111] E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, “Neutrino Masses and Mixings Dynamically Generated by a Light Dark Sector,” *Phys. Lett.* **B791** (2019) 210–214, arXiv:1808.02500 [hep-ph].

[112] Y. L. Wu and L. Wolfenstein, “Sources of CP violation in the two Higgs doublet model,” *Phys. Rev. Lett.* **73** (1994) 1762–1764, arXiv:hep-ph/9409421 [hep-ph].

[113] S. Davidson and H. E. Haber, “Basis-independent methods for the two-Higgs-doublet model,” *Phys. Rev.* **D72** (2005) 055004, arXiv:hep-ph/0504050 [hep-ph]. [Erratum: Phys. Rev.D72.099902(2005)].

[114] K. S. Babu and S. Jana, “Enhanced Di-Higgs Production in the Two Higgs Doublet Model,” *JHEP* **02** (2019) 193, arXiv:1812.11943 [hep-ph].

[115] J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang, and S. Kraml, “Scrutinizing the alignment limit in two-Higgs-doublet models: mh = 125 GeV,” *Phys. Rev.* **D92** no. 7, (2015) 075004, arXiv:1507.00933 [hep-ph].

[116] J. P. Leveille, “The Second Order Weak Correction to (G-2) of the Muon in Arbitrary Gauge Models,” *Nucl. Phys.* **B137** (1978) 63–76.

[117] J. D. Bjorken and S. Weinberg, “A Mechanism for Nonconservation of Muon Number,” *Phys. Rev. Lett.* **38** (1977) 622.

[118] S. M. Barr and A. Zee, “Electric Dipole Moment of the Electron and of the Neutron,” *Phys. Rev. Lett.* **65** (1990) 21–24. [Erratum: Phys. Rev. Lett.65.2920(1990)].

[119] J. D. Bjorken, S. Ecklund, W. R. Nelson, A. Abashian, C. Church, B. Lu, L. W. Mo, T. A. Nunamaker, and P. Rassmann, “Search for Neutral Metastable Penetrating Particles Produced in the SLAC Beam Dump,” *Phys. Rev.* **D38** (1988) 3375.

[120] E. M. Riordan et al., “A Search for Short Lived Axions in an Electron Beam Dump Experiment,” *Phys. Rev. Lett.* **59** (1987) 755.

[121] M. Davier and H. Nguyen Ngoc, “An Unambiguous Search for a Light Higgs Boson,” *Phys. Lett.* **B229** (1989) 150–155.

[122] Y.-S. Liu, D. McKeen, and G. A. Miller, “Electrophobic Scalar Boson and Muonic Puzzles,” *Phys. Rev. Lett.* **117** no. 10, (2016) 101801, arXiv:1605.04612 [hep-ph].

[123] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, “Muon anomalous magnetic moment through the leptonic Higgs portal,” *Phys. Rev.* **D95** no. 7, (2017) 075003, arXiv:1606.04943 [hep-ph].

[124] M. Battaglieri et al., “The Heavy Photon Search Test Detector,” *Nucl. Instrum. Meth.* **A777** (2015) 91–101, arXiv:1406.6115 [physics.ins-det].

[125] A. Anastasi et al., “Limit on the production of a low-mass vector boson in e + e − → γγ, U → e + e −“ with the KLOE experiment,” *Phys. Lett.* **B750** (2015) 633–637, arXiv:1509.00740 [hep-ex].

[126] D. S. M. Alves and N. Weiner, “A viable QCD axion in the MeV mass range,” *JHEP* **07** (2018) 092, arXiv:1710.03764 [hep-ph].
[127] BaBar Collaboration, J. P. Lees et al., “Search for a Dark Photon in e+e− Collisions at BaBar,” Phys. Rev. Lett. 113 no. 20, (2014) 201801, arXiv:1406.2980 [hep-ex].

[128] S. Knapen, T. Lin, and K. M. Zurek, “Light Dark Matter: Models and Constraints,” Phys. Rev. D96 no. 11, (2017) 115021, arXiv:1709.07882 [hep-ph].

[129] Belle-II Collaboration, T. Abe et al., “Belle II Technical Design Report,” arXiv:1011.0352 [physics.ins-det].

[130] Belle-II Collaboration, W. Altmannshofer et al., “The Belle II Physics Book,” arXiv:1709.07882 [hep-ph].

[131] N. D. Christensen and C. Duhr, “FeynRules - Feynman rules made easy,” Comput. Phys. Commun. 180 (2009) 1614–1641, arXiv:0806.4194 [hep-ph].

[132] 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].

[133] CMS Collaboration, A. M. Sirunyan et al., “Search for supersymmetry in events with a τ lepton pair and missing transverse momentum in proton-proton collisions at √s = 13 TeV,” JHEP 11 (2018) 151, arXiv:1807.02048 [hep-ex].

[134] ATLAS Collaboration, G. Abbiendi et al., “Tests of the standard model and constraints on new physics from measurements of fermion pair production at 189-GeV to 209-GeV at LEP,” Eur. Phys. J. C33 (2004) 173–212, arXiv:hep-ex/0309053 [hep-ex].

[135] CMS Collaboration, A. M. Sirunyan et al., “Search for supersymmetric partners of electrons and muons in proton-proton collisions at √s = 8 TeV with the ATLAS detector,” JHEP 10 (2014) 096, arXiv:1407.0350 [hep-ex].

[136] CMS Collaboration, A. M. Sirunyan et al., “Search for supersymmetric partners of electrons and muons in proton-proton collisions at √s = 13 TeV,” Phys. Lett. B790 (2019) 140–166, arXiv:1806.05264 [hep-ex].

[137] G. Funk, D. O’Neil, and R. M. Winters, “What the Oblique Parameters S, T, and U and Their Extensions Reveal About the 2HDM: A Numerical Analysis,” Int. J. Mod. Phys. A27 (2012) 1250021, arXiv:1101.3812 [hep-ph].

[138] W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, “A Precision constraint on multi-Higgs-doublet models,” J. Phys. G35 (2008) 075001, arXiv:0711.4022 [hep-ph].

[139] W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, “The Oblique parameters in multi-Higgs-doublet models,” Nucl. Phys. B801 (2008) 81–96, arXiv:0802.4353 [hep-ph].

[140] M. Aiko, S. Kanemura, and K. Mawatari, “Exploring the global symmetry structure of the Higgs potential via same-sign pair production of charged Higgs bosons,” Phys. Lett. B797 (2019) 134854, arXiv:1906.09101 [hep-ph].