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Correlating $h \rightarrow \mu^+ \mu^-$ to the Anomalous Magnetic Moment of the Muon via Leptoquarks

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Recently, both ATLAS and CMS measured the decay $h \rightarrow \mu^+ \mu^-$, finding a signal strength with respect to the standard model expectation of 1.2 ± 0.6 and $1.19_{-0.39-0.16}^{+0.41+0.17}$, respectively. This provides, for the first time, evidence that the standard model Higgs couples to second generation fermions. This measurement is particularly interesting in the context of the intriguing hints for lepton flavor universality violation, accumulated within recent years, as new physics explanations could also be tested in the $h \rightarrow \mu^+ \mu^-$ decay mode. Leptoquarks are prime candidates to account for the flavor anomalies. In particular, they can provide the necessary chiral enhancement (by a factor m_t/m_μ) to address a_μ with tera-electron-volt scale new physics. In this Letter we point out that such explanations of a_μ also lead to enhanced effects in $h \rightarrow \mu^+ \mu^-$ and we examine the correlations between $h \rightarrow \mu^+ \mu^-$ and a_μ within leptoquark models. We find that the effect in the branching ratio of $h \rightarrow \mu^+ \mu^-$ ranges from several percent up to a factor of 3, if one aims at accounting for a_μ at the 2σ level. Hence, the new ATLAS and CMS Collaboration measurements already provide important constraints on the parameter space, rule out specific a_μ explanations, and will be very important to test the flavor anomalies in the future.

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Introduction.—The Large Hadron Collider (LHC) at CERN confirmed the predictions of the standard model (SM) of particle physics by discovering the Brout-Englert-Higgs boson [1,2] in 2012. However, until now, high energy searches did not discover any particles beyond the ones present in the SM. Therefore, great hopes of finding new physics (NP) rest on low energy precision physics where flavor experiments have accumulated intriguing hints for physics beyond the SM within the recent years, most prominently in $b \rightarrow s\ell^+\ell^-$ data [3–5], $b \rightarrow c\tau\nu$ transitions [6–8], and the anomalous magnetic moment (AMM) of the muon [$a_\mu = (g-2)_\mu/2$] [9–11]. Interestingly, these hints for NP fall into a common pattern: they can be considered as

signs of lepton flavor universality violation (LFUV) [12], which is respected by the SM gauge interactions and is only broken by the Higgs Yukawa couplings.

Among these anomalies, a_μ , which displays a 4.2σ deviation from the SM prediction [15], is most closely related to Higgs interactions as it is a chirality changing observable. I.e., it involves a chirality flip and therefore a violation of $SU(2)_L$ is required to obtain a nonzero contribution. Furthermore, the required NP effect to explain a_μ is of the order of the electroweak (EW) SM contribution and tera-electron-volt scale solutions need an enhancement mechanism, called chiral enhancement, to be able to account for the deviation (see, e.g., Ref. [16] for a recent discussion). Obviously, also $h \rightarrow \mu^+ \mu^-$ is a chirality changing process and any enhanced effect in a_μ should also result in an enhanced effect [17]. Recently, both ATLAS and CMS Collaborations measured $h \rightarrow \mu^+ \mu^-$, finding a signal strength with respect to the SM expectation of 1.2 ± 0.6 [23] and $1.19_{-0.39-0.16}^{+0.41+0.17}$ [24], respectively.

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TABLE I. Scalar LQ representations together with their couplings to quarks and leptons, generating the desired m_t/m_μ -enhanced effect in the AMM of the muon. Here, \mathcal{G}_{SM} refers to the SM gauge group $\text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y$, L (Q) is the lepton (quark) $\text{SU}(2)_L$ doublet, u (ℓ) the up-type quark (lepton) singlet and c refers to charge conjugation. Furthermore, j and f are flavor indices and τ_k the Pauli matrices.

	\mathcal{G}_{SM}	$\mathcal{L}_{q\ell}$
S_1	$(3, 1, -\frac{2}{3})$	$(\lambda_{fj}^R \bar{u}_f^c \ell_j + \lambda_{fj}^L \bar{Q}_f^c i\tau_2 L_j) S_1^\dagger + \text{H.c.}$
S_2	$(3, 2, \frac{7}{3})$	$\gamma_{fj}^{RL} \bar{u}_f S_2^\dagger i\tau_2 L_j + \gamma_{fj}^{LR} \bar{Q}_f \ell_j S_2 + \text{H.c.}$
S_3	$(3, 3, -\frac{2}{3})$	$\kappa_{fj} \bar{Q}_f^c i\tau_2 (\tau \cdot S_3)^\dagger L_j + \text{H.c.}$

The mechanism of chiral enhancement, necessary to explain a_μ , has been well studied (see Ref. [16] for a recent account). Here, leptoquarks (LQs) are particularly interesting since they can give rise to an enhancement factor of $m_t/m_\mu \approx 1700$ [16,25–48], allowing for a tera-electron-volt scale explanation with perturbative couplings that are not in conflict with direct LHC searches. In fact, there are only two LQs, out of the ten possible representations [49], that can yield this enhancement: the scalar LQ $\text{SU}(2)_L$ singlet (S_1) and the scalar LQ $\text{SU}(2)_L$ doublet (S_2) with hypercharge $-2/3$ and $-7/3$, respectively. In addition, there is the possibility that S_1 mixes with the $\text{SU}(2)_L$ triplet LQ S_3 , where S_1 only couples to right-handed fermions [43].

Furthermore, LQs are also well motivated by the hints for LFUV in semileptonic B decays, both in $b \rightarrow s\mu^+\mu^-$ [3–5] and $b \rightarrow c\tau\nu$ data [6–8], which deviate from the SM with up to $\approx 6\sigma$ [50–53] and $\approx 3\sigma$ [54–58], respectively. Here, possible solutions include again S_1 [28,29,40,59–75], S_2 [30,61,76–83], and S_3 [67,84–90], where S_1 and S_3 together can provide a common explanation of the B anomalies and the AMM of the muon [39,44,67,91,92]. We take this as a motivation to study these correlations for the LQs which can generate m_t/m_μ -enhanced effects by considering three scenarios: (1) S_1 only, (2) S_2 only, (3) $S_1 + S_3$, where S_1 only couples to right-handed fermions. Note that these are the only scenarios which can give rise to the desired m_t/m_μ -enhanced effect.

Setup and Observables.—The most precise measurements of the anomalous magnetic moment (AMM) of the muon [$a_\mu = (g-2)_\mu/2$] has been achieved by the E821 experiment at Brookhaven [9,10] and recently by the g-2 experiment at Fermilab [11], which differs from the SM prediction by

$$\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}, \quad (1)$$

corresponding to a 4.2σ deviation [15,93]. Therefore, it is very interesting to investigate if and how this discrepancy can be explained by physics beyond the SM.

As we motivated in the introduction, we will focus on the three scalar LQs S_1 , S_2 , and S_3 for explaining a_μ . These representations couple to fermions as given in Table I [94]. Since we are in the following only interested in muon couplings to third generation quarks, we define $\lambda_R \equiv \lambda_{32}^R$, $\lambda_L \equiv \lambda_{32}^L$, $\gamma_{LR} \equiv \gamma_{32}^{LR}$, $\gamma_{RL} \equiv \gamma_{32}^{RL}$, $\kappa = \kappa_{32}$.

In addition to the gauge interactions, which are determined by the representation under the SM gauge group, LQ can couple to the SM Higgs [121]

$$\begin{aligned} \mathcal{L}_H = & Y_{13} S_1^\dagger [H^\dagger (\tau S_3) H] + \text{H.c.} \\ & - Y_{22} (H i\tau_2 S_2)^\dagger (H i\tau_2 S_2) - \sum_{k=1}^3 (m_k^2 + Y_k H^\dagger H) S_k^\dagger S_k. \end{aligned} \quad (2)$$

Here, m_k^2 are the $\text{SU}(2)_L$ invariant bilinear masses of the LQs. After $\text{SU}(2)_L$ breaking, the term Y_{13} generates off-diagonal elements in the LQ mass matrices and one has to diagonalize them through unitary transformations in order to arrive at the physical basis. Therefore, nonzero values of Y_{13} are necessary to generate m_t/m_μ -enhanced effects in scenario 3. Y_1 and $Y_{2,22}$ are phenomenologically relevant for $h \rightarrow \mu^+\mu^-$ in scenarios 1 and 2, respectively, but not necessary for an m_t/m_μ enhancement.

Now we can calculate the effects in a_μ and $h \rightarrow \mu^+\mu^-$ [122] for which sample diagrams are shown in Fig. 1. In both cases we have on-shell kinematics. For a_μ the self-energies can simply be taken into account via the Lehmann-Symanzik-Zimmermann formalism and no renormalization is necessary. This is, however, required for $h \rightarrow \mu^+\mu^-$ in order to express the result in terms of the physical muon mass. Here, the effective Yukawa coupling, which enters $h \rightarrow \mu^+\mu^-$, is given by

$$Y_\mu^{\text{eff}} = \frac{m_\mu - \Sigma_{\mu\mu}^{LR}}{v} + \Lambda_{\mu\mu}^{LR}, \quad (3)$$

where $\Lambda_{\mu\mu}^{LR}$ is the genuine vertex correction shown in Fig. 1 and $\Sigma_{\mu\mu}^{LR}$ is the chirality changing part of the muon self-energy. In these conventions $-i\Sigma_{\mu\mu}^{LR} P_R$ equals the expression of the Feynman diagram for the self-energy. Note that Y_μ^{eff} is finite without introducing a counterterm. For a_μ we expand in the muon mass and external momenta up to the first nonvanishing order, while in $h \rightarrow \mu^+\mu^-$ external momenta can be set to zero from the outset but we expand in $m_h^2/m_{1,2,3}^2$. The resulting amplitudes can be further simplified by expanding the LQ mixing matrices and mass eigenvalues in $v^2/m_{1,2,3}^2$ and the loop functions in m_h^2/m_t^2 , which gives a very precise numerical approximation, resulting in

$$\frac{\text{Br}[h \rightarrow \mu^+\mu^-]}{\text{Br}[h \rightarrow \mu^+\mu^-]_{\text{SM}}} \approx \left| 1 + \frac{m_t}{m_\mu} \frac{N_c}{8\pi^2} \left\{ \frac{\lambda_R^* \lambda_L}{m_t^2} \left[\frac{m_t^2}{8} \mathcal{J} \left(\frac{m_h^2}{m_t^2}, \frac{m_t^2}{m_1^2} \right) + v^2 Y_1 \right] + v^2 \lambda_R^* \kappa Y_{13} \frac{\log(m_3^2/m_1^2)}{m_3^2 - m_1^2} \right. \right. \right. \\ \left. \left. \left. + \frac{\gamma_{LR}^* \gamma_{RL}}{m_2^2} \left[\frac{m_t^2}{8} \mathcal{J} \left(\frac{m_h^2}{m_t^2}, \frac{m_t^2}{m_2^2} \right) + v^2 (Y_2 + Y_{22}) \right] \right\} \right|^2, \quad (4)$$

$$\delta a_\mu \approx \frac{m_\mu}{4\pi^2} \frac{N_c m_t}{12} \text{Re} \left\{ \frac{\gamma_{LR} \gamma_{RL}^*}{m_2^2} \mathcal{E}_1 \left(\frac{m_t^2}{m_2^2} \right) - \frac{\lambda_R}{m_1^2} \left[\lambda_L^* \mathcal{E}_2 \left(\frac{m_t^2}{m_1^2} \right) + \kappa Y_{13} \frac{v^2}{m_3^2} \mathcal{E}_3 \left(\frac{m_1^2}{m_3^2}, \frac{m_1^2}{m_3^2} \right) \right] \right\}, \quad (5)$$

with the loop functions given by

$$\mathcal{J}(x, y) = 2(x-4) \log(y) - 8 + \frac{13}{3}x, \quad (6)$$

$$\begin{aligned} \mathcal{E}_1(x) &= 1 + 4 \log(x), & \mathcal{E}_2(x) &= 7 + 4 \log(x), \\ \mathcal{E}_3(x, y) &= \mathcal{E}_2(y) + \frac{4 \log(x)}{x-1}. \end{aligned} \quad (7)$$

We only considered the m_t -enhanced effects and neglected small CKM rotations, which in principle appear after EW symmetry breaking. As anticipated, in Eq. (5) one can see that scenario 3 only contributes if Y_{13} is nonzero. Furthermore, since in this scenario a_μ has a relative suppression of $v^2/m_{1,3}^2$ with respect to $h \rightarrow \mu^+\mu^-$, one expects here the largest effects in Higgs decays. In principle also Y_1 , Y_2 , and Y_{22} enter in Eq. (5). However, their effect is subleading as it is suppressed by $v^2/m_{1,2}^2$.

Effective field theory: In the SM effective field theory (SMEFT), which is realized above the EW breaking scale

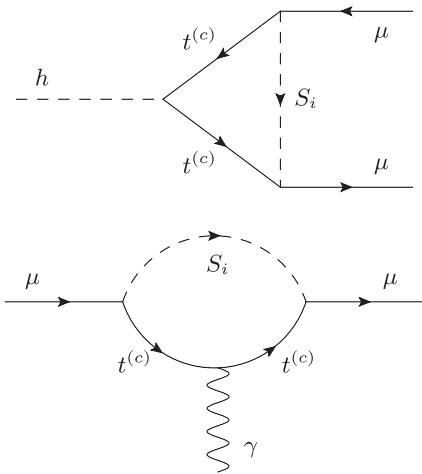


FIG. 1. Sample Feynman diagrams which contribute to $h \rightarrow \mu^+\mu^-$ (top) and the AMM of the muon (bottom). In addition, we have to include the diagrams where the Higgs and photon couple to the LQ, as well as self-energy diagrams.

and therefore explicitly $SU(2)_L$ invariant, there are only two chirality flipping four-fermion operators [126] which can give rise to m_t -enhanced effects in a_μ and $h \rightarrow \mu^+\mu^-$ via renormalization group evolution (RGE) effects:

$$\begin{aligned} Q_{\ell\text{equ}}^{(1)} &= (\bar{\ell}_2^a e_2) \varepsilon_{ab} (\bar{q}_3^b u_3), \\ Q_{\ell\text{equ}}^{(3)} &= (\bar{\ell}_2^a \sigma_{\mu\nu} e_2) \varepsilon_{ab} (\bar{q}_3^b \sigma^{\mu\nu} u_3). \end{aligned} \quad (8)$$

Importantly, while both operators mix at order $\alpha_{(s)}$ with each other, only the second operator mixes (directly) into the magnetic operator [127–129]

$$\begin{aligned} Q_{eB} &= \bar{\ell}_2 \sigma^{\mu\nu} e_2 H B_{\mu\nu}, \\ Q_{eW} &= \bar{\ell}_2 \sigma^{\mu\nu} e_2 \tau^I H W_{\mu\nu}^I, \end{aligned} \quad (9)$$

giving rise to the AMM of the muon after EW symmetry breaking [130]. Furthermore, as $Q_{\ell\text{equ}}^{(1)}$ mixes into $Q_{e\varphi} = H^\dagger H \bar{\ell}_2 e_2 H$ (generating modified Higgs couplings to muons) it is clear that a UV complete (or at least simplified) model is necessary to correlate a_μ to $h \rightarrow \mu^+\mu^-$.

The EFT approach is beneficial in our LQ setup since it allows for the inclusion of RGE effects, as recently done in Ref. [132]. In a first step, the LQ model is matched on the SMEFT (at the LQ scale), giving tree-level effects in $C_{\ell\text{equ}}^{(1,3)}$ [133] and a loop effect in Q_{eB} and Q_{eW} [134]. Then the SMEFT is used to evolve the Wilson coefficients of these operators to the weak scale where the EW gauge bosons, the Higgs and the top quark are integrated out [135–137]. Next, the magnetic operator of the muon is evolved to the muon scale [138,139] where the AMM is measured. Reference [132] finds a reduction of a_μ by $\approx 20\% - 30\%$ compared to the leading order estimate of LQ masses between 1–10 TeV. Furthermore, as $C_{\ell\text{equ}}^{(1)}$ is enhanced by $\approx 5\% - 10\%$ by the running from the LQ scale to the EW scale [140], this leads to an important enhancement of 50%–70% of the prediction for $\text{Br}[h \rightarrow \mu^+\mu^-]$ with respect to the leading order calculation. To be conservative, we will use 50% in our following phenomenological analysis.

Phenomenology.—Let us now study the correlations between a_μ and $h \rightarrow \mu^+\mu^-$ in our three scenarios with m_t -enhanced contributions. First, we consider scenarios 1 and 2 where S_1 and S_2 give separately rise to m_t -enhanced effects in a_μ and $h \rightarrow \mu^+\mu^-$. Since both processes involve the same product of couplings to SM fermions, the correlation depends only weakly via a logarithm on $m_t^2/m_{1,2}^2$. However, there is a dependence on Y_1 and $Y_{22} + Y_2$ which breaks the direct correlation but cannot change the sign of the effect for order one couplings. This can be seen in Fig. 2, where the correlations are depicted for $m_{1,2} = 1.5$ TeV, respecting LHC bounds [141–143]. The predicted effect is not large enough such that the current ATLAS and CMS Collaboration measurements are sensitive to it. However, note that it is still sizable due to the m_t enhancement and therefore detectable at future colliders where the ILC [144], the HL-LHC [145], the FCC- ee [146], CEPC [147] or the FCC- hh [148] aim at a precision of approximately 10%, 8%, 6%, and below 1%, respectively. Furthermore, the effect in $\text{Br}[h \rightarrow \mu^+\mu^-]$ in scenario 1 is necessarily constructive while in scenario 2 it is destructive, such that in the future a LQ explanation of a_μ by S_1 could be clearly distinguished from the one involving S_2 .

In scenario 3, where S_1 only couples to right-handed fermions, the effect in $\text{Br}[h \rightarrow \mu^+\mu^-]$ is even more pronounced due to the relative suppression of the contribution to a_μ by $v^2/m_{1,3}^2$, see Eq. (5). Furthermore, in this case the correlation between a_μ and $h \rightarrow \mu^+\mu^-$ depends to a good approximation only on the ratio m_1/m_3 . As the effect is symmetric in m_1 and m_3 we fix one mass to 1.5 TeV and

obtain the band shown in Fig. 3 by varying the other mass between 1.5 and 3 TeV. The effect in $h \rightarrow \mu^+\mu^-$ within the preferred region for a_μ is necessarily constructive and large enough that an explanation of the central value of a_μ is already disfavored by the ATLAS and CMS Collaboration measurements of $h \rightarrow \mu^+\mu^-$. Clearly, with more data the LHC will be able to support (disprove) this scenario if it finds a (no) significant enhancement of the $h \rightarrow \mu^+\mu^-$ decay, assuming δa_μ is confirmed. This scenario also leads to sizable effects in $Z\mu\mu$ [43] which are compatible with LEP Electroweak Working Group data [149], but could be observed at the ILC [144], CLIC [150] or the FCC- ee [146].

Conclusions.—LQs are prime candidates for an explanation of the intriguing hints of LFUV. As LFUV within the SM only originates from the Higgs, chirality changing observables as the AMM of the muon and, of course, $h \rightarrow \mu^+\mu^-$ are especially interesting. In particular, there are three possible LQ scenarios which can address the discrepancy in the AMM of the muon by an m_t/m_μ enhancement. This also leads to enhanced corrections in $h \rightarrow \mu^+\mu^-$, which involve the same coupling structure as the a_μ contribution. This leads to interesting correlations between a_μ and $h \rightarrow \mu^+\mu^-$, which we study in light of the recent ATLAS and CMS Collaboration measurements.

We find that scenario 3, in which S_1 only couples to right-handed fermions and mixes after EW symmetry breaking with S_3 , predicts large constructive effects in $h \rightarrow \mu^+\mu^-$ such that the current ATLAS and CMS Collaboration measurements are already excluding part of the parameter space. In case δa_μ is solely explained by S_1 or S_2 the effect in $\text{Br}[h \rightarrow \mu^+\mu^-]$ is of the order of several percent and

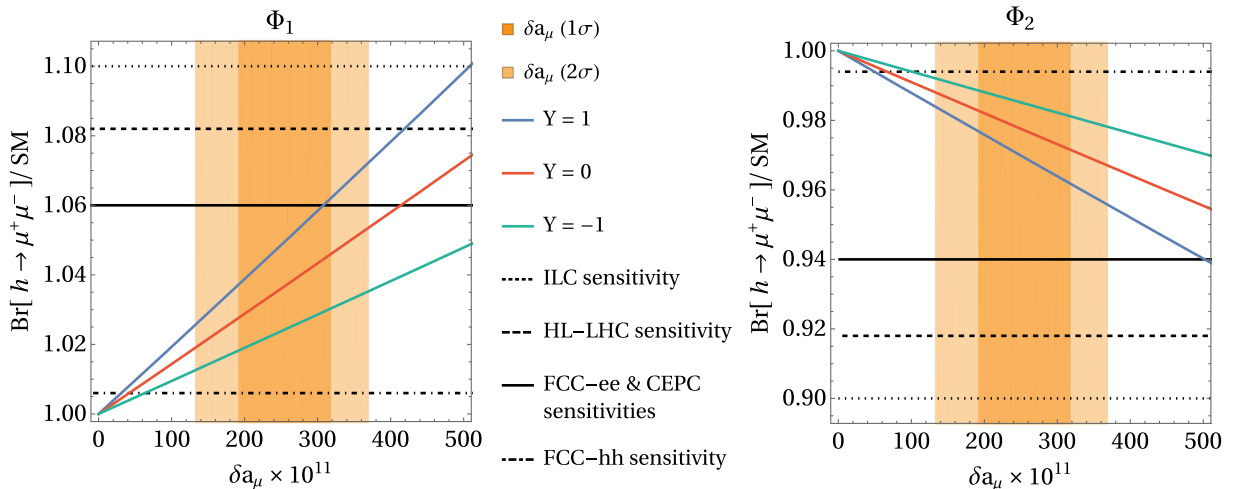


FIG. 2. Correlations between the $\text{Br}[h \rightarrow \mu^+\mu^-]$, normalized to its SM value, and the NP contribution in the AMM of the muon δa_μ for scenario 1 (left) and scenario 2 (right) with $m_{1,2} = 1.5$ TeV. The predictions for different values of the LQ couplings to the Higgs are shown, where for scenario 1, $Y = Y_1$ while in scenario 2, $Y = Y_2 + Y_{22}$. Even though the current ATLAS and CMS Collaboration results are not yet constraining for these models, sizable effects are predicted, which can be tested at future colliders. Furthermore, scenario 1 yields a constructive effect in $h \rightarrow \mu^+\mu^-$ while the one in scenario 2 is destructive such that they can be clearly distinguished with increasing experimental precision.

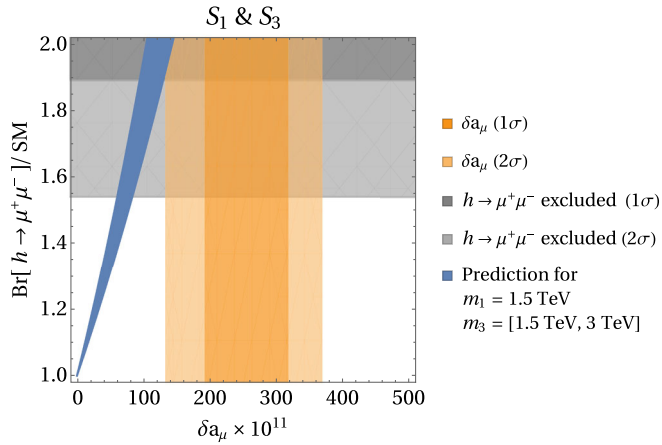


FIG. 3. Correlations between the NP contribution to the AMM of the muon (δa_μ) and $\text{Br}[h \rightarrow \mu^+\mu^-]$, normalized to its SM value in scenario 3. This correlation depends to a good approximation only on the ratio m_1/m_3 . As the effect is symmetric in m_1 and m_3 , we fix one mass to 1.5 TeV and obtain the dark-blue band by varying the other mass between 1.5 TeV and 3 TeV. The effect in $h \rightarrow \mu^+\mu^-$ within the preferred region for a_μ is necessarily constructive and so large that an explanation is already constrained by the ATLAS and CMS Collaboration measurements of $h \rightarrow \mu^+\mu^-$.

therefore detectable at future colliders, in particular at the FCC- hh . Furthermore, while the S_1 scenario predicts constructive interference in $h \rightarrow \mu^+\mu^-$ for the currently preferred range of a_μ , the S_2 scenario predicts destructive interference such that they can be clearly distinguished in the future.

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