Multilepton signatures of a hidden sector in rare B decays

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We explore the sensitivity of flavor-changing $b \rightarrow s$ transitions to a (sub-) GeV hidden sector with generic couplings to the standard model through the Higgs, vector, and axion portals. The underlying two-body decays of B mesons, $B \rightarrow X_s \mathcal{S}$, and $B^0 \rightarrow \mathcal{S}\mathcal{S}$, where $\mathcal{S}$ denotes a generic new GeV-scale particle, may significantly enhance the yield of monochromatic lepton pairs in the final state via prompt $\mathcal{S} \rightarrow l\bar{l}$ decays. Existing measurements of the charged lepton spectrum in neutral-current semileptonic B decays provide bounds on the parameters of the light sector that are significantly more stringent than the requirements of naturalness. New search modes, such as $B \rightarrow X_s + n(l\bar{l})$ and $B^0 \rightarrow n(l\bar{l})$ with $n \geq 2$, can provide additional sensitivity to scenarios in which both the Higgs and vector portals are active, and are accessible to (super-) B factories and hadron colliders.

I. INTRODUCTION

The study of B mesons at the B factories, *BABAR* [1] and Belle [2], and the Tevatron experiments [3,4] has significantly advanced the precision with which various standard model (SM) parameters are known, and consequently has placed stringent constraints on models of new physics affecting quark flavor [5]. The prevailing view is that such new physics must reside at or above the electroweak scale, manifesting at low energies in modifications to the Wilson coefficients of effective flavor-changing operators that arise once the heavy degrees of freedom are integrated out. Experimental precision, and the ability to make accurate SM predictions, are thus the controlling factors in probing weak-scale new physics through precision flavor observables.

While new states charged under the SM are generically required to be rather heavy, light (sub-) GeV mass states in a hidden sector, *neutral* under the SM gauge group, can peacefully coexist with the SM, evading precision flavor and electroweak constraints. Such hidden sectors may be weakly coupled to the SM in various ways and are often best probed via experiments at the luminosity frontier. In particular, precision studies of rare SM decays can provide impressive sensitivity to these sectors, opening the possibility for novel decay channels not encountered in the SM itself. Indeed, over the years there have been numerous searches for rare decays of flavored mesons to new light states (see e.g. [6] for a subset of theoretical ideas). As one notable motivation, these hidden sector states can have a significant impact on Higgs decay channels, allowing for a SM-like Higgs with mass well below the conventional LEP bound [7].

In this paper, we revisit the sensitivity of rare flavor-changing decays from the generic standpoint of "portal" operators [8,9], which constitute a systematic way to parametrize the allowed couplings of generic neutral states $\mathcal{S}$

in a hidden sector to the SM in order of increasing canonical operator dimension. In particular, we will be interested in the following set of lowest-dimension portals:

$$
\begin{array}{lll}
H^\dagger H (AS + \lambda S^2) & \text{Higgs portal} & (\text{dim}= 3, 4), \\
\kappa F^Y_{\mu\nu} F'_{\mu\nu} & \text{Vector portal} & (\text{dim}= 4), \\
Y_N \bar{L} H N & \text{Neutrino portal} & (\text{dim}= 4), \\
f_a^{-1} \bar{\psi} \gamma_\mu \gamma_5 \psi \, \partial_\mu a & \text{Axion portal} & (\text{dim}= 5).
\end{array} \tag{1}
$$

Here H is the SM Higgs doublet, $F^Y_{\mu\nu}$ is the hypercharge field strength, L is the left-handed lepton doublet, and ψ is a generic SM fermion, while $\mathcal{S} = S$, N, A'_μ and a denote the fields associated with new light states. The purpose of this study is to analyze the feasibility of searching for light states coupled to the SM via these portals in B meson decays.[1] Specifically, we will concentrate on the manifestations of Higgs, vector, and axion portals in $b \rightarrow s$ transitions with the direct production of one or more exotic states. To be as conservative as possible, we shall not assume any direct flavor-violating operators, which in fact is automatic for the Higgs and vector portals, but requires an extra assumption for the axion portal. Using the resulting flavor-blind portal operators, we calculate the strength of the flavor-changing transitions induced by SM loops.

A primary feature that we will exploit is that the scalar and axion (i.e. axial-vector) portals behave very differently to the conserved vector current portal once dressed by $W - (u, c, t)$ loop corrections. Schematically, this difference can be illustrated as follows:

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[1]Renewed interest in the possibility of light hidden sector states coupled to the SM has emerged from attempts to link certain unexpected features in the multi-GeV scale cosmic electron and positron spectra to the annihilation of galactic dark matter into such light states [10,11].

$$\bar{t}\gamma_\mu t \rightarrow (G_F q^2) \times \bar{b}_L \gamma_\mu s_L;$$
$$\bar{t}\gamma_\mu \gamma_5 t \rightarrow (G_F m_t^2) \times \bar{b}_L \gamma_\mu s_L. \qquad (2)$$

While conservation of the vector current (such as the electric charge or baryon number) requires the dependence on $q^2 \lesssim m_b^2$, the axial current is not conserved and the vertex correction is $\mathcal{O}(m_t^2/q^2)$—enhanced relative to the vector case. Within the SM, scalar or axial-vector currents are associated purely with couplings to the Z boson and the SM Higgs, which cannot be produced in on-shell B decays. Thus, having light states in the spectrum with (pseudo)scalar or axial-vector couplings can enhance the loop-induced two-body decays of the b quark by many orders of magnitude. The enhancement of the loop-induced SM Higgs coupling has been known for some time [12,13]. More recently, it has been exploited in the context of B meson decays to a pair of light dark matter particles through the Higgs portal [14], decays to a singlet scalar mixed with the Higgs [15], and decays to a light pseudo-scalar in the next-to-minimal supersymmetric standard model [16]. Rare Kaon decays to metastable mediators were considered in [17,18].

We will analyze a number of semileptonic and fully leptonic B decay modes opened up by portal couplings, which can serve as a powerful probe of new light states. As often happens in models of this type with intermediate cascade decays, the increased multiplicity of final state leptons implies minimal additional suppression [18–20], thus enhancing signal over background. Specifically, we calculate $B \rightarrow K(K^*)S \rightarrow K(K^*)l\bar{l}$ and $B^0 \rightarrow SS \rightarrow 2(l\bar{l})$ in the minimal extension of the SM by one real scalar S, and $B \rightarrow K(K^*)a \rightarrow K(K^*)l\bar{l}$ in the axion portal model. We will show that the constraints imposed by B physics in the kinematically accessible range where the leptonic decays of S and a occur within the detector are easily the most stringent experimental limits. We also extend our analysis to include the vector portal, and, in particular, the natural combination of Higgs and vector portals, and calculate the branching of $B \rightarrow VK(K^*)$, $B^0 \rightarrow VV$ and $B \rightarrow h'h'$. The final state of two Higgs h' bosons of the extra U(1) group may be dominated by eight leptons. The most important point of our analysis is to show that multilepton signatures of B meson decays, like $B^0 \rightarrow \mu^-\mu^+\mu^-\mu^+$, can be explored using *existing* data sets collected at the B factories and the Tevatron, providing significant new probes of these models with exotic light neutral states.

The remainder of this paper is structured as follows. In Sec. II, we analyze rare B decays in the minimal extension of the SM by a singlet scalar interacting through the Higgs portal, as well as an extension with a pseudoscalar singlet coupled via the axion portal. Section III considers rare B decay modes proceeding via a combination of Higgs and vector portals, and we present our conclusions in Sec. IV.

II. RARE B DECAYS THROUGH THE HIGGS AND AXION PORTALS

The extension of the SM by a singlet scalar has been considered on numerous occasions, e.g. for cosmological applications as a minimal model of dark matter, with stability imposed by symmetry [21,22], or its impact on electroweak baryogenesis or inflation [23]. Novel experimental signatures, including extra decay channels for the SM Higgs boson, were addressed in [7,15,22,24–28].

A generic renormalizable scalar potential that includes S self-interactions and couplings to the SM via the Higgs portal is given by

$$V = \lambda_4 S^4 + \lambda_3 S^3 + m_0^2 S^2 + (AS + \lambda S^2)(H^\dagger H). \qquad (3)$$

Since we are interested only in the low-energy limit of the theory relevant for B decays, we will assume stability of the potential in the S direction and integrate out the Higgs boson to obtain an effective Lagrangian for S (enforcing $\langle S \rangle = 0$ by an appropriate shift of the field),

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \left(\frac{\theta S}{v} + \frac{\lambda S^2}{m_h^2}\right)\mathcal{L}_m - \frac{A'}{6}S^3 + \cdots. \qquad (4)$$

The quantity $\mathcal{L}_m$ comprises the SM mass terms from electroweak symmetry breaking (i.e. $\mathcal{L}_m = m_l \bar{l}l + \cdots$), and the physical mass m_S, mixing angle θ, and self-interaction parameter A' are related to the parameters in (3). The precise nature of these relations ($\theta \simeq Av/m_h^2$ etc.) will not be critical to our analysis. However, the technical naturalness of the model (4) is a valuable criterion to use in setting the characteristic values of θ and A'. In order to shelter a relatively light scalar from large mass corrections induced by electroweak symmetry breaking, we take

$$\theta \lesssim \frac{m_S}{m_h} \sim \mathcal{O}(10^{-2}) \times \left(\frac{m_S}{1 \text{ GeV}}\right),$$
$$A' \lesssim (16\pi^2 m_S^2)^{1/2} \sim \mathcal{O}(10 \text{ GeV}) \times \left(\frac{m_S}{1 \text{ GeV}}\right). \qquad (5)$$

The latter relation follows from the SS loop correction to the mass of the scalar. A larger angle θ and self-interaction parameter A' would require additional tuned cancellations between different contributions to m_S. The possibility of a stronger coupling to the Higgs portal, while keeping S light and avoiding the naturalness constraints, arises in the large $\tan\beta$ two-Higgs doublet extension of the SM [14] and thus also in the MSSM.

We will also explore the axion portal, which avoids corrections to the (sub-) GeV mass of the pseudoscalar via the dimension-five axial-vector couplings of the form,

$$\mathcal{L}_a = \sum_{\text{SM-}\psi} \frac{\partial_\mu a}{f_\psi} \bar{\psi}\gamma_\mu \gamma^5 \psi. \qquad (6)$$

Furthermore, for simplicity, we will neglect the effects of the self-interaction of a, as well as couplings to gauge

bosons, and assume universal couplings of the pseudoscalar to leptons f_l and quarks, f_q. This automatically protects (6) from tree-level flavor-changing neutral currents. While a UV completion is required for (6), we note that in two-Higgs doublet extensions of the SM there also exists the possibility of a renormalizable pseudoscalar portal, e.g. iaH_1H_2, which leads to the mixing of a with the pseudoscalar Higgs boson A.

For both the Higgs and axion portals, on integrating out the W-top loop, we obtain the well-known effective $b - s - h$ and $b - s - a$ vertices,

$$\mathcal{L}_{bs} = \frac{3\sqrt{2}G_F m_t^2 V_{ts}^* V_{tb}}{16\pi^2} \times m_b \bar{s}_L b_R$$
$$\times \left(\frac{\theta S}{v} - i\frac{2}{3}\frac{a}{f_q}\ln(\Lambda_{\mathrm{UV}}^2/m_t^2)\right) + (\text{h.c.}). \quad (7)$$

For the scalar S, the Wilson coefficient in (7) is one-loop exact in the limit $m_b^2/M_W^2 \to 0$, while for the pseudoscalar,[2] we retain only the leading log-divergent term proportional to m_t^2/m_W^2 and for consistency assume at least a small hierarchy between the weak scale and the UV cutoff, $\ln\Lambda_{\mathrm{UV}}/m_t \sim 1$. We have integrated by parts and used the equations of motion for the quark fields in the limit $m_s = 0$ to remove the derivative from the axion field in the interaction (7).

The Lagrangian (7) immediately leads to the inclusive b quark decay width to S and a, but we are more interested in K and K^* final states. The QCD matrix elements involved in $B_{d(u)}$ to $K(K^*)$ transitions have been calculated using light-cone QCD sum rules [30,31], and after a fairly standard calculation, we obtain the following results as functions of m_S and m_a:

$$\mathrm{Br}_{B\to KS} \simeq 4 \times 10^{-7} \times \left(\frac{\theta}{10^{-3}}\right)^2 \mathcal{F}_K^2(m_S)\lambda_{KS}^{1/2},$$

$$\mathrm{Br}_{B\to K^*S} \simeq 5 \times 10^{-7} \times \left(\frac{\theta}{10^{-3}}\right)^2 \mathcal{F}_{K^*}^2(m_S)\lambda_{K^*S}^{3/2},$$

$$\mathrm{Br}_{B\to Ka} \simeq 5 \times 10^{-6} \times \left(\frac{100\,\mathrm{TeV}}{f_q}\ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_t}\right)\right)^2 \mathcal{F}_K^2(m_a)\lambda_{Ka}^{1/2},$$

$$\mathrm{Br}_{B\to K^*a} \simeq 6 \times 10^{-6} \times \left(\frac{100\,\mathrm{TeV}}{f_q}\ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_t}\right)\right)^2 \mathcal{F}_{K^*}^2(m_a)\lambda_{K^*a}^{3/2}.$$
$$(8)$$

The dependence on the unknown mass parameters resides in the phase space factors, $\lambda_{ij} = (1 - m_B^{-2}(m_i + m_j)^2) \times (1 - m_B^{-2}(m_i - m_j)^2)$, and the form factors which we have normalized to their values at zero momentum transfer [31],

$$\mathcal{F}_K(m) = \frac{1}{1 - m^2/(38\,\mathrm{GeV}^2)},$$
$$\mathcal{F}_{K^*}(m) = \frac{3.65}{1 - m^2/(28\,\mathrm{GeV}^2)} - \frac{2.65}{1 - m^2/(37\,\mathrm{GeV}^2)}. \quad (9)$$

The values of the form factors at $q^2 = 0$ used in our calculations are $f_0(0) = 0.33$ and $A_0(0) = 0.37$ [31]. The uncertainty in the form factors is the main source of error for (8), argued to be at the $\mathcal{O}(10\%\text{--}15\%)$ level [30,31].

The results in (8), combined with the subsequent decay of a or S to dilepton pairs close to the interaction point presents an intriguing signal: a monoenergetic lepton pair in association with K or K^*. The branching ratios $\mathrm{Br}_{B\to K\mu\bar{\mu}} = 4.2^{+0.9}_{-0.8} \times 10^{-7}$ and $\mathrm{Br}_{B\to K^*\mu\bar{\mu}} = 1.03^{+0.26}_{-0.23} \times 10^{-6}$ have been measured [32–34] with several hundred decays containing lepton pairs distributed over the entire available q^2 range, while a monoenergetic lepton pair can be efficiently probed at B factories with $\mathcal{O}(10^{-8})$ sensitivity [35]. The hadronic decays of S and a as well as missing energy signatures from decays outside the detector can also be probed, albeit with lesser sensitivity.

With S and a in the intermediate state, the decay widths and branching ratios to leptons are sensitive functions of mass. We follow the standard prescriptions for calculating the total widths of a and S [36–38], and the results can be summarized as follows. When only decays to leptons are kinematically allowed, the leptonic branching is necessarily close to unity,[3] while the partial decay width to a lepton pair is given by

$$\Gamma_{S\to l\bar{l}} = \frac{\theta^2 m_l^2 m_S}{8\pi v^2}\left(1 - \frac{4m_l^2}{m_S^2}\right)^{3/2},$$
$$\Gamma_{a\to l\bar{l}} = \frac{m_l^2 m_a}{8\pi f_l^2}\left(1 - \frac{4m_l^2}{m_a^2}\right)^{1/2}, \quad (10)$$

and is very sensitive to whether the dimuon channel is open. For example, for a 250 MeV mass scalar with mixing angle 10^{-3} the lifetime is $c\tau = 2.7$ cm, and considering a Lorentz boost of $\gamma \sim m_B/(2m_S) \sim 10$, this would correspond to a significantly displaced vertex.

For higher mass scalars, the decay length shrinks while the leptonic branching gets suppressed, especially near the f_0 0^+ resonance [38]. In the region near the resonance, we base our estimate of the branching on a coupled-channel analysis in the framework of chiral perturbation theory, while above the resonance, we use perturbative QCD [36,38]:

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[2]We thank the authors of Ref. [29] for pointing out the presence of a logarithmic UV divergence in this calculation.

[3]Within the axion portal scenario, for certain parameter choices, the decay to $\gamma\gamma$ can be significant and may also be a good search mode.

$$\text{Br}_{S\to\mu\bar{\mu}} \sim \frac{m_\mu^2\beta_\mu^3}{m_\mu^2\beta_\mu^3 + |F_\pi/2m_S|^2\beta_\pi + |F_K/2m_S|^2\beta_K}$$

$$\text{for } m_S \lesssim 1.5 \text{ GeV},$$

$$\text{Br}_{S\to\mu\bar{\mu}} \sim \frac{m_\mu^2}{m_\mu^2 + 3m_s^2 + m_S^2(\alpha_s/\pi)^2(N_f^2/9) + \cdots}$$

$$\text{for } m_S > 1.5 \text{ GeV}, \tag{11}$$

where $\beta_i = (1 - 4m_i^2/m_S^2)^{1/2}$, F_i are the form factors defined in Ref. [38], N_f is the number of heavy quarks, i.e. three below the charm threshold, and the ellipsis in the second line stands for charm and τ contributions once the corresponding thresholds are open. We note that there is at least a 100% uncertainty in this formula above 1 GeV [36].

For the pseudoscalar case, the hadronic width is suppressed by three-pion phase space. In order to estimate the scaling of the branching ratio with f_l and f_q we assume that the decay to hadrons occurs via mixing with the η and η' resonances. Taking a representative value of $m_a = 800$ MeV, the mixing with η' is given by $\theta_{a\eta'} \sim (f_{\eta'}/f_q) \times \sqrt{3}m_a^2/(m_{\eta'}^2 - m_a^2)$, and the hadronic width is approximately $\Gamma_{\text{had}} \sim \theta_{a\eta'}^2\Gamma_{\eta'}$. Using these results, we obtain the following scaling of the leptonic branching fraction:

$$\text{Br}_{a\to\mu\bar{\mu}} \sim \frac{1}{1 + 0.3(f_l/f_q)^2}. \tag{12}$$

It is apparent that the resonant enhancement of the hadronic width can significantly exceed the naive three-pion continuum result.

With these estimates in hand, we can predict the observable signal at (super-) B factories. Having a typical detector design in mind, we require S or a to decay within a transverse distance $l_{\min} = 25$ cm of the beam pipe, and assume $\sim$90% angular acceptance. In practise this amounts to calculating the following angular integral multiplying Eqs. (8):

$$\text{Br}_{S(a)\to\mu\bar{\mu}} \int_{\theta_{\min}}^{\pi-\theta_{\min}} \frac{\sin\theta d\theta}{2} \left(1 - \exp\left[-\frac{l_{\min}\Gamma_{S(a)}}{\gamma_{S(a)}\sin\theta}\right]\right). \tag{13}$$

In the limit of a short decay length, the integral is trivially $\text{Br}_{S(a)\to\mu\bar{\mu}}\cos\theta_{\min}$, and in the opposite limit of a very long decay length it is $(\Gamma_{S(a)\to\mu\bar{\mu}}l_{\min}) \times (\pi/2 - \theta_{\min})\gamma_{S(a)}^{-1}$.

Given that the combined *BABAR*/Belle data set provides sensitivity to the $K\mu\bar{\mu}$ and $K^*\mu\bar{\mu}$ branching with a mono-energetic muon pair at the level of $\mathcal{O}(10^{-8})$, the significant parameter space reach that ensues for the two models is shown in Figs. 1 and 2. For the scalar singlet Higgs portal, Fig. 1 illustrates that the B factories can probe deep within the technically natural region of the $\theta - m_S$ parameter plane [see Eq. (5)], with sensitivity to mixing angles in the 10^{-4}–10^{-3} range. For light scalars with masses below
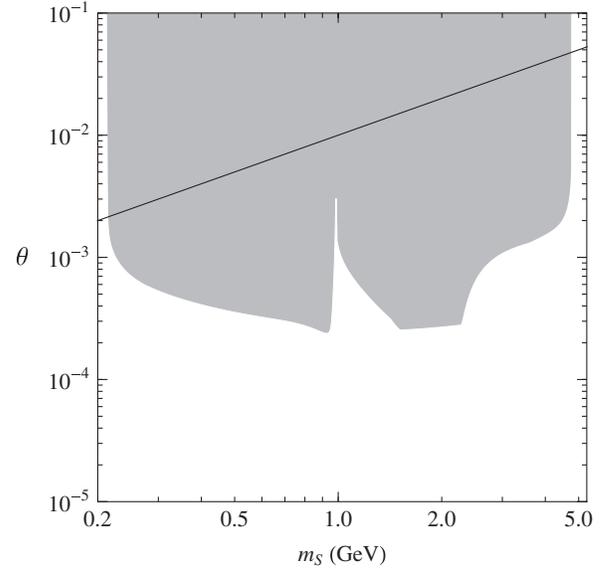
FIG. 1. Sensitivity of the *BABAR*/Belle data set to combined $B \to KS$ and $B \to K^*S$ decays in the dimuon channel. The region below the dashed line is technically natural as discussed in Eq. (5).

the 2π threshold, we see that, although the branching to dimuons approaches 100%, the sensitivity is diminished as the S particle is very narrow and long-lived and thus able to escape the detector. We also observe that the sensitivity is weakened near the f_0 resonance, and for heavy scalars, as in these regions the branching to muons is small. For the axion portal, we present in Fig. 2 the $f_q - f_l$ sensitivity for an 800 MeV pseudoscalar, indicating that the sensitivity to the axion couplings reaches $f_{q,l} \sim 10^3$ TeV. Qualitatively,
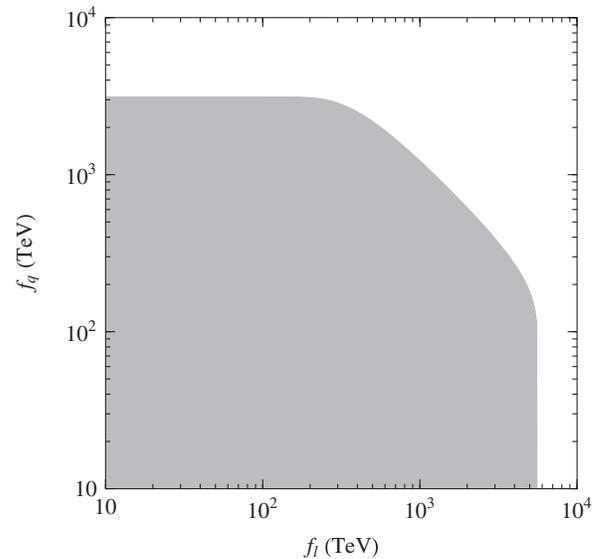
FIG. 2. Sensitivity of the *BABAR*/Belle data set to combined $B \to Ka$ and $B \to K^*a$ decays in the dimuon channel. We have set $\ln\Lambda_{\text{UV}}/m_t \sim 1$.

we see that when f_q is large, sensitivity is lost as the branching of B mesons to pseudoscalars is small, while for large f_l sensitivity is lost as the decays of a are primarily hadronic. Nonetheless, we note that the sensitivity to axion couplings obtained here appears significantly stronger than that of Ref. [29]. We believe that much of this numerical discrepancy can be attributed to the difference in experimental sensitivity to the branching fraction used in the two analyses. In addition, we assume at least a small hierarchy exists between the weak scale and the UV cutoff, whereas Ref. [29] considers the UV-complete two-Higgs doublet model, in which—without this hierarchy—the top-W loop has an additional suppression compared to Eq. (7). Finally, it is also important to emphasize the complementarity of constraints from rare K and B decays. For a weakly interacting (pseudo)scalar particle with a mass below the dimuon threshold and a long lifetime, the $K \to \pi + 1$ mu/E decay (e.g. $K \to \pi \nu \bar{\nu}$) is the most efficient probe [17]. On the other hand, a semileptonic signature of S or a is more efficiently probed via B decays, since the CKM suppression from the top loop is less severe.

There are several other interesting signatures for the Higgs portal scenario in Eq. (7). Consider the decay of B^0 mesons to a pair of scalars. Assuming for simplicity that the A' trilinear vertex dominates, we obtain the following estimate for the branching to an SS pair:

$$\mathrm{Br}_{B_s \to SS} \simeq 4 \times 10^{-3} \times \theta^2 \Big(\frac{A'}{m_B}\Big)^2 \frac{\lambda_{SS}^{1/2}}{(1 - m_S^2/m_B^2)^2}. \quad (14)$$

The suppression of the $2S$ final state relative to KS is due to the fact that the decay amplitude for $2S$ is proportional to the decay constant $f_B \simeq 200$ MeV, while the KS decay amplitude, in the same units, is controlled by $f_0 m_B \sim 2$ GeV. For B_d decays, there is of course an extra CKM suppression by $|V_{td}/V_{ts}|^2$ relative to (14). Nonetheless, the overall rate to muons for 300 MeV scalars can reach $\mathrm{Br}_{B_s \to 4\mu} \sim 10^{-8}$ with a moderate fine-tuning of couplings to allow for a larger A'.

Returning to the decays mediated by $\lambda SSH^\dagger H$, we note that only in the limit $\lambda \gtrsim 10^{-2}$ is the branching for $B_s \to 4\mu$ above the 10^{-8} level. Such values of λ are difficult to reconcile with the large additive renormalization of m_S^2 by λv^2, which would require fine-tuning at the level of 1 part in 10^3 for a 1 GeV scalar. Such a fine-tuning can be avoided in the two-Higgs doublet model with a portal $\lambda_{H_1} H_1^\dagger H_1 S^2$, where λ_{H_1} can naturally be $\mathcal{O}(1)$ if $\tan\beta$ is maximal, $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle \sim 50$. Taking the results of the $b - s - S^2$ transition calculated in [14], with a charged Higgs mass $m_{H^+} = 300$ GeV, we obtain the following estimate for the rate of the $B_s \to 4\mu$ transition:

$$\mathrm{Br}_{B_s \to 2S \to 4\mu} \simeq 2 \times 10^{-7} \times \lambda_{H_1}^2 \lambda_{SS}^{1/2} \times \mathrm{Br}_{S \to 2\mu}^2. \quad (15)$$

Assuming a similar sensitivity to the four-muon channel as for $\mu \bar{\mu}$ at CDF [39], we conclude that the Tevatron experiments can probe $\lambda_{H_1}^2 \times \mathrm{Br}_{S \to 2\mu}^2$ at the $\mathcal{O}(0.1)$ level. A tension in the parameters arises if (15) is to be maximized: larger values of λ_{H_1} imply larger values of m_S where $\mathrm{Br}_{S \to 2\mu}$ diminishes. If $\mathrm{Br}_{S \to 2\mu} \ll 1$, searches for $l\bar{l}\pi^+\pi^-$ and $l\bar{l}K^+K^-$ final states with two hadrons reconstructing the same invariant mass might be more advantageous than the search for fully leptonic decays of both S scalars.

III. RARE B DECAYS THROUGH THE $U(1)_S$ SECTOR

In this section we will discuss B decays via the combined Higgs and vector portals,

$$\mathcal{L}_{\text{Higgs+Vector}} = -\lambda(H^\dagger H)(H'^\dagger H') - \frac{\kappa}{2} F_{\mu\nu} F'_{\mu\nu}, \quad (16)$$

where H' is a new scalar field charged under an additional $U(1)_S$ gauge group, while the SM is $U(1)_S$-neutral. The vector portal in (16) is the minimal possibility [40], although other options that involve the gauging of anomaly-free SM quantum numbers are also plausible [41]. The gauging of the scalar coupled via the Higgs portal has two important consequences. First, as emphasized in many papers (see, e.g. [18,42,43]), the yield of leptons in the final state can be enhanced, as the decay of the physical excitation h' may proceed via the intermediate vector states of $U(1)_S$ which in turn cascade to leptons:

$$h' \to VV \to l\bar{l}l\bar{l}. \quad (17)$$

The vectors decay with equal probability to different (charged) lepton species, so that the decay to electrons is no longer suppressed. The decay chain (17) is efficient if $m_{h'} > 2m_V$, and the relative branching of V to leptons for the minimal portal is regulated by the well-measured process $\gamma^* \to$ hadrons [43] characterized by the $R(s)$ ratio. A second important consequence is that the decay chain (17) is likely to be very prompt, occurring within the detector even for very small values of κ.

We first address $B \to KV$ decays within the pure vector portal model. In this case, on account of (2), there is no particular enhancement. Calculation of the decay width involves the familiar Z and γ penguins, with the vector particle attached via kinetic mixing. The result turns out to be very small, and for $m_V \sim 1$ GeV, we find

$$\mathrm{Br}_{B \to KV} \sim 6 \times 10^{-7} \kappa^2. \quad (18)$$

This channel appears to be less sensitive to the kinetic mixing parameter κ than existing limits from other low-energy precision experiments [18,43,44][4].

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[4]Further model-dependent sensitivity to the kinetic mixing parameter may be obtained with cosmic- and gamma-ray experiments and neutrino telescopes [45].

The next process we consider is $B \to K(K^*)h' \to K(K^*)VV \to K(K^*)l\bar{l}l\bar{l}$. Utilizing the results (8), we obtain

$$\text{Br}_{B \to K(K^*)l\bar{l}l\bar{l}} \simeq 0.5 \times \left(\frac{\lambda v' v}{m_h^2}\right)^2 \frac{1}{(1 + R(m_V)/2)^2}, \quad (19)$$

having assumed that $\Gamma_{V \to e\bar{e}} = \Gamma_{V \to \mu\bar{\mu}}$. From (19), one can infer rather strong $\mathcal{O}(10^{-4})$ sensitivity to the mixing parameter $\lambda v v' m_h^{-2}$. However, it is important to bear in mind that the naturalness limits on λ are also quite strong, $\lambda v^2 \lesssim \mathcal{O}(m_{h'}^2)$, and therefore (19) is not probing the natural strength of the Higgs portal.

A particularly interesting aspect of the combined Higgs and vector portals is that the decay $B^0 \to VV$ can proceed through an off-shell $h - h'$ propagator. At first, it may appear that this process is insignificant, as both $h - h'$ mixing and the $h' - V - V$ vertex are proportional to v', naively suggesting strong suppression for a light vector. However, it turns out that the longitudinal vector modes in the final state cancel this v' dependence so that the result remains finite in the $m_V \to 0$ limit,

$$\text{Br}_{B_s \to VV} = 4 \times 10^{-5} \times \lambda^2 \lambda_{VV}^{1/2}$$
$$\times \frac{1 - 4m_V^2/m_B^2 + 12m_V^4/m_B^4}{(1 - m_{h'}^2/m_B^2)^2}, \quad (20)$$

where we have taken $m_h = 115$ GeV. This decay leads to four leptons in the final state, and there is a possible enhancement of the rate for $m_{h'}$ close to m_B.

Finally, the cascade decay $B \to 2h' \to 4V \to 4(l\bar{l})$ leads to eight leptons in the final state. The rate for this process may be enhanced in the two-Higgs doublet model, and reach $\mathcal{O}(10^{-7}) \times \lambda_{H_1}^2$. Therefore, probes of this signature at a level better than 1 part in 10^7 at the Tevatron are well-motivated.

IV. CONCLUSIONS

We have shown that rare decays of B mesons to semi-leptonic or fully leptonic final states can, via the B factory data sets, be a sensitive probe for new light states coupled through the Higgs and axion portals. The results of Sec. II indicate that existing data allows for a probe of neutral scalars coupled through the Higgs portal down to mixing angles as small as 10^{-3}–10^{-4}. In addition, the axion portal coupling to the top quark can be tested at an impressive level of sensitivity, $f_q \sim 10^3$ TeV.

We have also shown that a combination of vector and Higgs portals, e.g. gauging of the scalar field coupled to $H^\dagger H$, can enhance sensitivity through the multilepton decays of the scalars. Among the novel signatures that we believe can be efficiently probed at both (super-) B factories and hadron colliders are the $K(K^*) + 2(l\bar{l})$, $2(l\bar{l})$ and $4(l\bar{l})$ final states. As far as we are aware, these final states have not been explored to date and thus represent a new opportunity to access light mediators.

Finally, we should mention that while we have focused on B decays, and similar studies in the kaon sector have a long history, further sensitivity to these portal couplings may arise in the charm sector, via D decays.

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