

Constraints on light mediators: confronting dark matter searches with B physics

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Light scalars appear in many well-motivated extensions of the Standard Model including supersymmetric models with additional gauge singlets. Such scalars could mediate the interactions between dark matter and nuclei, giving rise to the tentative signals observed by several dark matter direct detection experiments including CDMS-Si. In this letter, we derive strong new limits on light scalar mediators by using the LHCb, Belle and BaBar searches for rare Υ and B decays. These limits rule out significant parts of the parameter space favored by CDMS-Si. Nevertheless, as current searches are not optimized for investigating weakly coupled light scalars, a further increase in experimental sensitivity could be achieved by relaxing requirements in the event selection.

I. INTRODUCTION

Recent results in dark matter (DM) direct detection, notably the excesses over the expected background seen by CDMS-Si [1], CoGeNT [2] and CRESST-II [3] as well as the long-standing annual modulation signal seen by DAMA [4] have been interpreted as relatively light DM with mass $m_\chi \lesssim 10$ GeV. While the cross sections inferred from DAMA and CRESST-II are in strong tension with null results from other leading experiments such as XENON [5, 6], the CDMS-Si signal can be (marginally) consistent with all other searches even under the standard assumption of elastic spin-independent scattering [7]. This makes an interpretation in the context of simple DM models particularly attractive. In this letter, we will concentrate on the case where a scalar field mediates the interactions between DM and nuclei. Collider searches have severely restricted the available model parameter space. Very heavy scalar mediators are basically ruled out for the cross sections of interest due to monojet searches, even for the case of Higgs-like couplings [8, 9]. Light mediators, however, are much harder to constrain as they increase the relative sensitivity of direct DM searches with respect to colliders.

In this letter, we study bounds on scalars with reduced Higgs-like couplings to SM states which are lighter than the DM. In particular we derive constraints coming from Υ and B meson decays at Belle, BaBar and LHCb. While these bounds apply generally to light scalars coupled to the SM, they are particularly interesting when the scalar mediates interactions with the DM. In this case, the bound on the coupling of the scalar to SM states can be rephrased as a bound on the DM direct detection cross section. We find that the resulting bounds are very stringent and rule out much of the remaining parameter space which was considered viable as an explanation for the recent experimental hints in DM searches.

II. A GENERIC MODEL

For the purpose of this letter we study a model with light (Majorana) fermionic DM χ which is coupled to the SM via a light (CP-even) scalar ϕ ,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{y m_f}{v} \phi \bar{f} f - \frac{1}{2} \kappa \phi \bar{\chi} \chi, \quad (1)$$

where $v \simeq 246$ GeV denotes the electroweak vev. Here we assumed that the couplings of ϕ to the SM fermions f scale with their mass m_f which is the case if the couplings are induced via the Higgs portal [10].¹ This simple model is a natural limit of singlet extensions [12] of the Minimal Supersymmetric Standard Model (MSSM), where ϕ and χ stem from the same supermultiplet.² As far as the experimental constraints on the scalar ϕ are concerned, only its interactions with the SM are relevant, while its couplings to DM can be ignored as long as the decay of ϕ into DM is kinematically forbidden. However, it is interesting to assume that this scalar mediates the predominant interactions between the visible and the dark sector as in our model. In this case the coupling κ can be inferred from requiring the correct relic density of the DM, $\Omega_\chi h^2 = 0.1199$ [16]. Then, the limit on the coupling y as a function of the mediator mass m_ϕ can be rephrased as a limit on the DM direct detection cross section.

For the case we study here, $m_\phi < m_\chi$, the annihilation of DM in the early universe is typically dominated by the process $\chi\chi \rightarrow \phi\phi$. The corresponding annihilation cross section can be estimated as $\sigma v_{\text{rel}} \simeq \sigma_1 v_{\text{rel}}^2$ with [12, 17]

$$\sigma_1 = \frac{\kappa^4 m_\chi}{24\pi} \sqrt{m_\chi^2 - m_\phi^2} \frac{9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4}{(2m_\chi^2 - m_\phi^2)^4} \quad (2)$$

and v_{rel} denoting the relative velocity. For p -wave suppressed annihilations and $m_\chi = 5 - 10$ GeV the DM

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¹ To obtain the Higgs portal induced couplings of ϕ to SM fields in the given form, one has to integrate out the Higgs boson [11].

² Such general singlet extensions of the MSSM have been motivated in [13–15].

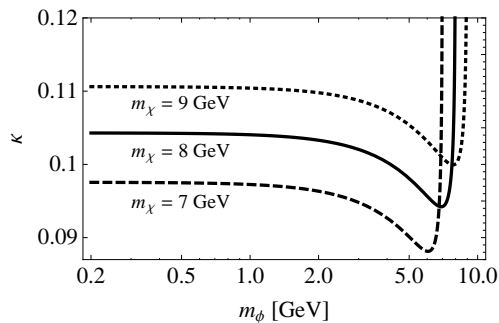


FIG. 1. Relic density as a function of the coupling κ and the mediator mass m_ϕ for $m_\chi = 7, 8, 9$ GeV.

relic density is achieved for $\sigma_1 \simeq 1.6 \cdot 10^{-25} \text{cm}^3/\text{s}$ (see e.g. [17]). We have cross checked the analytic approximation by implementing the model into `CalcHep` [18] and using `MicrOmegas` [19–21] for the relic density calculation. We find excellent agreement. The coupling κ which yields the correct relic density for a given mass m_ϕ is shown in Fig. 1. The inferred value of κ is rather insensitive to m_ϕ and the precise value of m_χ . Except in the case of strong phase space suppression, we find $\kappa \simeq 0.1$. Note that due to the p -wave nature of the annihilation, the model automatically evades the strong constraints on light DM arising from indirect detection (see e.g. [22–25]).

The (spin-independent) DM nucleon cross section is dominated by ϕ exchange and can be written as

$$\begin{aligned} \sigma_n &= \frac{4\mu_\chi^2}{\pi} \left(\frac{y\kappa}{2vm_\phi^2} \right)^2 m_n^2 (f_u^n + f_d^n + f_s^n + 6/27 f_G)^2 \\ &\simeq 10^{-40} \text{cm}^2 \left(\frac{\kappa}{0.1} \right)^2 \left(\frac{y}{0.01} \right)^2 \left(\frac{\text{GeV}}{m_\phi} \right)^4, \end{aligned} \quad (3)$$

with m_n the nucleon mass and μ_χ the reduced mass of the DM-nucleon system. $f_{u,d,s}^n$ and f_G are the scalar coefficients for the quark and gluon content of the nucleon which we take from [26].³ This has to be compared with the cross section $\sigma_n \simeq 10^{-42} - 10^{-40} \text{cm}^2$ suggested by the CDMS-Si result. If we take κ to be fixed by the relic density requirement, the cross section only depends on the coupling y for a given mediator mass m_ϕ . In the next section we therefore study constraints on this coupling from rare decays.

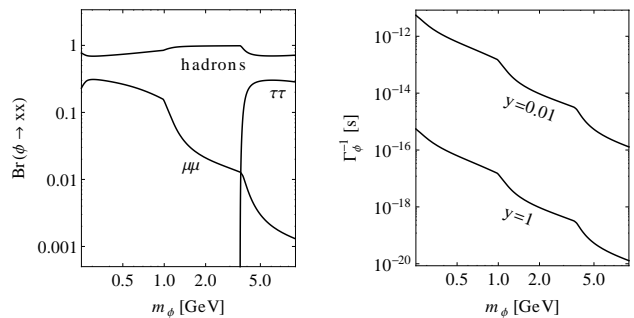


FIG. 2. Branching fraction of the light scalar ϕ into muons, taus and hadronic final states (left panel). Lifetime of ϕ for two different values of the coupling y (right panel).

III. CONSTRAINTS ON LIGHT MEDIATORS FROM Υ AND B MESON DECAYS

For comparison with experimental results we have to determine the decay pattern of ϕ . The decay rate into muons is given as

$$\Gamma(\phi \rightarrow \mu\mu) \equiv \Gamma_{\mu\mu} = \frac{G_F m_\phi}{4\sqrt{2}\pi} y^2 m_\mu^2 \beta_\mu^3, \quad (4)$$

where G_F is the Fermi constant and we defined $\beta_\mu = \sqrt{1 - 4m_\mu^2/m_\phi^2} \Theta(m_\phi - 2m_\mu)$ with the Heaviside function accounting for the kinematical threshold of the decay mode. In order to determine the branching fraction into hadronic final states, we follow [27] and use the perturbative spectator model matched to chiral perturbation theory at the QCD scale. This leads to the following relative decay rates into muons, π^- , K^- , η^- , D -mesons, taus and gluons

$$\begin{aligned} \Gamma_{\mu\mu} : \Gamma_{\pi\pi} : \Gamma_{KK} : \Gamma_{\eta\eta} : \Gamma_{DD} : \Gamma_{\tau\tau} : \Gamma_{gg} \\ = m_\mu^2 \beta_\mu^3 : 3(m_u^2 + m_d^2) \beta_\pi^3 : 3 \frac{9}{13} m_s^2 \beta_K^3 : 3 \frac{4}{13} m_s^2 \beta_\eta^3 : \\ m_c^2 \beta_D^3 : m_\tau^2 \beta_\tau^3 : \left(\frac{\alpha_s m_\phi}{3\pi} \right)^2 (6 - 2\beta_\pi^3 - \beta_K^3). \end{aligned} \quad (5)$$

The effective light quark masses as well as α_s are determined from the matching which yields $m_u = m_d = 50$ MeV, $m_s = 450$ MeV and $\alpha_s = 0.47$ [27]. In the left panel of Fig. 2, we depict the resulting branching ratio into muons, taus and the summed branching into hadronic final states.⁴ The lifetime of the scalar $\Gamma_\phi^{-1} = (\Gamma_{\mu\mu} + \Gamma_{\pi\pi} + \dots)^{-1}$ is shown in the right panel of Fig. 2. Note that for $\Gamma_\phi^{-1} \gtrsim 10^{-12}$ s the decay length of ϕ becomes relevant on detector scales.

³ Note that in the given model, the cross sections for scattering off protons and neutrons are virtually indistinguishable.

⁴ Our estimate of the branching fractions does not include bound state effects. We expect some deviations if m_ϕ resides in the vicinity of a scalar resonance.

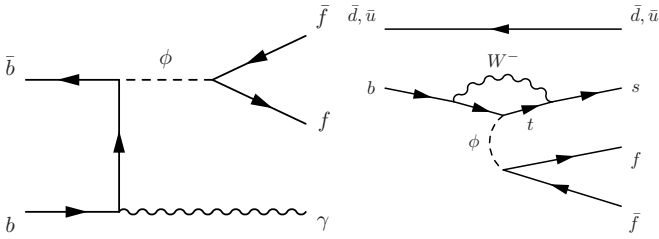


FIG. 3. Rare decays of Υ (left) and B mesons (right) mediated by the light scalar ϕ .

A. Υ decays

If $m_\phi \lesssim 10$ GeV, the light scalar can mediate the radiative decay $\Upsilon \rightarrow \gamma \phi$ with ϕ decaying further into mesons or leptons [28] (see left panel of Fig. 3). In order to factor out uncertainties, it is reasonable to express the corresponding branching ratio in the form

$$\frac{\text{Br}(\Upsilon(nS) \rightarrow \gamma \phi)}{\text{Br}(\Upsilon(nS) \rightarrow ee)} = \frac{y^2 G_F m_b^2}{\sqrt{2} \pi \alpha} \mathcal{F} \left(1 - \frac{m_\phi^2}{m_\Upsilon^2(nS)} \right), \quad (6)$$

where α is the Sommerfeld constant, m_b is the bottom mass and \mathcal{F} a correction function which includes higher order QCD processes [29, 30] as well as bound state effects appearing when m_ϕ approaches the kinematical endpoint [31, 32]. A parameterization of \mathcal{F} which includes both effects without double counting can be extracted from Fig. 1 in [33].⁵ The branching fractions $\text{Br}(\Upsilon(nS) \rightarrow ee)$ can be taken from [34].

Experimental constraints

Turning to experiments, the BaBar collaboration has recently published several searches for light scalars in Υ decays. The results were presented in the form of upper limits on the product $\text{Br}(\Upsilon \rightarrow \gamma \phi) \times \text{Br}(\phi \rightarrow xx)$ with xx being muons [35], taus [36], gluons [37] and general hadronic final states [38]. These can be translated into constraints on the coupling y of the scalar ϕ to SM fields by using (6) and the branching fractions from (5). The strongest bounds arise from $\tau\tau$ and hadronic final states; they are presented in Fig. 5.

B. B meson decays

The scalar ϕ also gives rise to an effective flavor violating coupling $b-s-\phi$ which is obtained by integrating

out the W -top-loop. One finds [11]

$$\mathcal{L}_{\phi sb} = \frac{y m_b}{v} \frac{3\sqrt{2} G_F m_t^2 V_{ts}^* V_{tb}}{16\pi^2} \times \phi \bar{s}_L b_R + \text{h.c.}, \quad (7)$$

with V_{ts} and V_{tb} denoting the CKM elements. We follow [39] and use the one-loop $\overline{\text{MS}}$ top mass $m_t = 165$ GeV in the above expression.

For $m_\phi \lesssim 5$ GeV, the scalar can mediate rare decays of B mesons. The most constraining mode is $B \rightarrow K + \phi$ for which the decay rate can be written as

$$\Gamma^{B \rightarrow K \phi} = \left(\frac{y m_b}{v} \frac{3\sqrt{2} G_F m_t^2 |V_{ts}^* V_{tb}|}{16\pi^2} \right)^2 |\langle K | \bar{s}_L b_R | B \rangle|^2 \times \frac{\sqrt{(m_B^2 - (m_K + m_\phi)^2)(m_B^2 - (m_K - m_\phi)^2)}}{16\pi m_B^3}, \quad (8)$$

which agrees well with the numerical formula presented in [11]. For the corresponding matrix element we use the parametrization [40]

$$\langle K | \bar{s}_L b_R | B \rangle = \frac{1}{2} \frac{(m_B^2 - m_K^2)}{m_b - m_s} f_0(q^2) \quad \text{with} \quad f_0(q^2) = \frac{0.33}{1 - q^2/38 \text{ GeV}^2}, \quad (9)$$

with the transferred momentum $q^2 = m_\phi^2$. This parametrization is in good agreement with a more recent determination of $f_0(q^2)$ [41]. The uncertainty of $f_0(q^2)$ is at the level of $\sim 10\%$ [40].

Experimental constraints

The above decay mode would contribute to the rare process $B \rightarrow K + \mu\mu$ via ϕ decaying into a pair of muons (see right panel of Fig. 3). As interference effects can be neglected – the intermediate ϕ is on-shell – this contribution simply adds to the SM one. The comparison with observation is still not straightforward as the experiments probe a regime of the coupling $y < 0.01$, where the lifetime of ϕ becomes non-negligible (see Fig. 2). If the scalar travels a macroscopic distance in the detector, this would affect the event reconstruction performed in the experimental analyses. Events with a too large displacement Δd of the ϕ -decay vertex from the primary interaction point would fail criteria on the vertex quality and be rejected as background. At LHCb B mesons are produced with a higher boost than at B factories. This typically leads to a larger displacement Δd and to more events being rejected. Therefore the lower sensitivity of B factories compared to LHCb is partially compensated as they miss less of the signal events. We hence consider the measurements of $B \rightarrow K + \ell\ell$ at both, LHCb [42] and Belle [43].⁶ Note that $\ell = \mu$ at LHCb, while $\ell = \mu, e$ at Belle.

⁵ Here we use the estimate (B) from Fig. 1 in [33] which treats theoretical uncertainties in a slightly more conservative way.

⁶ BaBar has also performed a search for $B \rightarrow K + \ell\ell$ with sensitivity very similar to Belle [44].

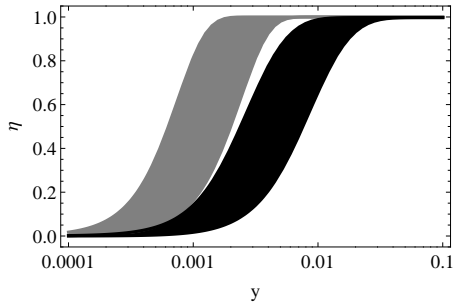


FIG. 4. Detection efficiency at LHCb (black) and Belle (gray) as a function of the light scalar coupling y for fixed $m_\phi = 1$ GeV. The width of the bands arises from the uncertainty in the determination of η (see text). For $y \gtrsim 0.1$ the efficiency approaches unity as ϕ decays promptly on detector scales. For $y \lesssim 0.01$ the lifetime of ϕ becomes non-negligible leading to a displacement of the ϕ decay vertex. In this case, the efficiency decreases rapidly.

In order to constrain the coupling of ϕ to SM matter, we must take into account the efficiency η of LHCb and Belle for reconstructing ϕ -induced decays as a function of m_ϕ and y . Assuming that events with a displacement $\Delta d > d_{\text{max}}$ are rejected, we have

$$\eta(m_\phi, y) = \int_0^\infty dp_\phi f(p_\phi) \left[1 - \exp\left(-\frac{m_\phi \Gamma_\phi d_{\text{max}}}{p_\phi}\right) \right] \quad (10)$$

with $f(p_\phi)$ the momentum distribution of ϕ . For LHCb we infer $f(p_\phi)$ from a large event sample generated with the Monte Carlo generator PYTHIA [45], where we applied the appropriate pseudorapidity cuts in order to reject events which happen partially or fully outside the detector.⁷ In LHCb analyses with similar event selection as in [42] but with significant backgrounds from open charm decays, the vertex selection criteria remove a large fraction, but not all of the charmed mesons [47]. This suggests a value of d_{max} in the range 2 mm – 2 cm which we have used in our analysis. As a cross check for our description of the detection efficiency of long-lived particles, we have determined η for the Majorana neutrinos searches in [48]. Our prediction of η using the indicated range of d_{max} is in good agreement with efficiencies provided by the collaboration in Fig. 14 of [48]. The determination of the efficiency for Belle proceeds analogously. We take the same range $d_{\text{max}} = 2$ mm – 2 cm as for LHCb. In order to verify that this assumption is justi-

⁷ As a cross check we have determined the mean energy of the parent B mesons passing the pseudorapidity cuts which we found to be around 100 GeV depending slightly on m_ϕ . This is in very good agreement with the value inferred from the more sophisticated LHCb detector simulation [46].

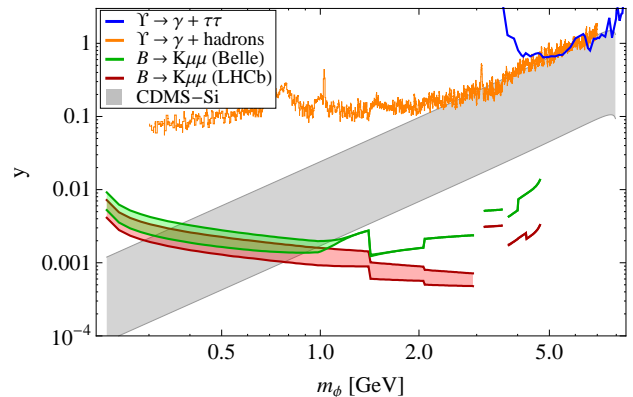


FIG. 5. Constraints on the coupling y from B and Υ decays. The gray band indicates the range of DM-nucleon cross sections consistent with the CDMS-Si signal (for $m_\chi = 8$ GeV). The regions $m_\phi = 2.95 - 3.18$ GeV and $m_\phi = 3.59 - 3.77$ GeV are vetoed in the experimental searches for rare B decays.

fied, we have used the information from [49].⁸ In Fig. 4, we depict η for LHCb and Belle. Due to the larger boosts at LHCb, the corresponding η decreases more rapidly towards smaller y . For the example of $m_\phi = 1$ GeV, we see that in both experiments couplings $y \ll 10^{-3}$ cannot be constrained due to the loss in efficiency.

To set upper bounds on y , we employ the binned distribution of the branching ratio $B \rightarrow K + \ell\ell$ in the dilepton invariant mass $m_{\ell\ell}$. For ϕ -induced decays $m_{\ell\ell} = m_\phi$, i.e. m_ϕ determines the bin in which the signal would occur. Using the SM distribution of $\text{Br}(B \rightarrow K + \mu\mu)$ from [42]⁹, we calculate, bin by bin, the 90% CL upper limit on the difference in branching compared to the SM. For this, we employ the Feldman-Cousins approach [50]. This limit is then translated into a constraint on the coupling y by making use of (5), (8) and (10).

IV. RESULTS AND SUMMARY

In this letter, we have presented new severe constraints on light scalar particles with reduced Higgs-like couplings to the SM. For this we considered the most recent searches for rare Υ and B decays performed at LHCb

⁸ In [49] Belle has performed a search for light scalars with subsequent decay to muons in the very narrow mass window $m_\phi = 212 - 300$ MeV. In the analysis, it was pointed out that the detection efficiency is only marginally affected for lifetimes $\Gamma_\phi^{-1} < 10^{-12}$ s. With our description of the efficiency and $d_{\text{max}} = 2$ mm – 2 cm one would obtain $\eta = 0.5 - 0.99$ for $\Gamma_\phi^{-1} = 10^{-12}$ s in this example, showing that it is justified to use our range for d_{max} .

⁹ For the sake of a conservative approach, we use the lower end of the band provided in [42]. In the energy range 2.9 – 3.8 GeV, where no SM prediction is given, we conservatively set it to zero.

and B factories. We carefully included detector effects related to the finite lifetime of the light scalar.

Our main results are summarized in Fig. 5, where we depict the resulting constraints on the reduced coupling y of a light scalar ϕ to SM fields. An additional bound not shown in Fig. 5 comes from LEP and constrains y to be $y \lesssim 0.1$ for $m_\phi \leq 10$ GeV [51]. The searches for radiative Υ decays have reached a similar sensitivity as LEP. If m_ϕ resides below the B meson mass, considerably tighter constraints on y are obtained from rare B decays. We should emphasize that the limits shown in Fig. 5 are valid independently of any assumptions about the dark sector, as long as the decay of ϕ into DM is kinematically forbidden.

However, interesting bounds on the DM direct detection cross section can be obtained if ϕ mediates the interactions of DM with nuclei. After fixing the coupling between DM and ϕ by requiring the correct DM relic density, the cross section σ_n of DM with nucleons is uniquely determined by the coupling y . In Fig. 5, we show the range in the coupling y , where σ_n is consistent with the observed CDMS-Si signal. For illustration, we have fixed $m_\chi = 8$ GeV, corresponding to the CDMS-Si favoured cross section $\sigma_n = 4 \cdot 10^{-42} - 8 \cdot 10^{-41} \text{cm}^2$ at 90% CL [1]. It can be seen that the coupling required to obtain a sufficiently large σ_n is excluded for $m_\phi \simeq 1 - 5$ GeV unless m_ϕ falls in the close vicinity of the charmed resonances. This conclusion is obtained for standard nuclear- and astro-

physics assumptions. It is hardly affected if we vary the DM mass within the reasonable range $m_\chi = 6 - 10$ GeV.¹⁰

We consider the remaining viable parameter region with mediator masses between 5 GeV and m_χ particularly appealing as similar masses for both, DM and mediator, can naturally arise in supersymmetric models [12]. Upcoming searches for radiative Υ decays with increased sensitivity could probe this intriguing region of parameter space. For mediator masses $m_\phi \lesssim 5$ GeV, the sensitivity of the existing searches can already be significantly increased. In particular LHCb already probes highly suppressed couplings of the mediator to SM fields, for which the scalar has a macroscopic decay length in the detector. By a modification of the event selection, the efficiency for such displaced decays could be optimized.

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¹⁰ While the CDMS-Si result alone is consistent with $m_\chi > 10$ GeV, this possibility is safely excluded by other dark matter searches, in particular XENON – even with the most conservative assumptions about experimental uncertainties [6].

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