PROCEEDINGS OF SCIENCE

Missing energy in rare B-decays in the light of GeV scale dark matter

Ajay Kumar Yadav,[a,*] Shivaramakrishna Singirala,[b] Manas Kumar Mohapatra[b] and Suchismita Sahoo[a]

[a] *Department of Physics, Central University of Karnataka, Kalaburagi-585367, India*

[b] *School of Physics, University of Hyderabad, Hyderabad-500046, India*

E-mail: yadavajaykumar286@gmail.com, krishnas542@gmail.com, manasmohapatra12@gmail.com, suchismita@cuk.ac.in

Belle-II has reported a 2.8 sigma deviation from standard model prediction in the branching ratio of $B^+ \to K^+$ +inv decay mode. We enlighten this missing energy using a GeV scale scalar dark matter in an anomaly-free $U(1)_{B-L}$ framework. The new vector and scalar bosons coming from the gauge extension act as mediators for dark matter by providing annihilation channels and also participate in $b \to s$ transition through one loop penguin diagrams. We constrain the new parameters by using consistency with existing bounds on $B \to K^*\nu\bar{\nu}$ branching ratio performed at the Belle II experiment and from Dark matter relic density, direct detection, and collider. We analyse couplings between the mediator and the SM fermions as well as the dark matter particle. We then investigate the $b \to s\nu\bar{\nu}$ decay modes such as $B \to (K^+, K^*)\nu\bar{\nu}$, $B_s \to (\eta, \eta')\nu\bar{\nu}$,$B_s \to \phi\nu\bar{\nu}$ and $B_c \to (D_s, D_s^*)\nu\bar{\nu}$ in a common parameter space, meeting the current experimental bounds of both sectors simultaneously.

16th International Conference on Heavy Quarks and Leptons (HQL2023)
28 November-2 December 2023
TIFR, Mumbai, Maharashtra, India

*Speaker

PoS(HQL2023)082

1. Introduction

Despite the overall agreement between the observed data in various B decays and the predictions of the Standard Model (SM), a profoundly successful framework unveiling the fundamental constituents of the universe, intriguing discrepancies have emerged in specific measurements, revealing substantial deviations of $(2-3)\sigma$. Recent measurements from LHCb in December 2022 [2] demonstrate persistent violations in the lepton non-universality (LNU) parameters $R_{K^{(*)}}$ with 0.2σ deviation. Beside this, the Belle II experiment [1] has reported the first measurement of $B^+ \to K^+ \nu\bar{\nu}$, revealing a branching ratio:

$$\mathcal{BR}(B^+ \to K^+\nu\bar{\nu})^{Exp} = (2.4 \pm 0.7)\times 10^{-5}, \quad \mathcal{BR}(B^+ \to K^+\nu\bar{\nu})^{SM} = (5.06 \pm 0.14 \pm 0.28)\times 10^{-6},$$

which deviates from the SM by 2.8σ. Here, the undetected neutrinos carry away a portion of the energy and momentum, contributing to the missing energy. The SM must be supplemented with additional symmetries or particles to fix this missing energy anomaly. Among several beyond SM frameworks, $U(1)_{B-L}$ gauge extensions stand in the front row for simplicity with a dark matter pair. In our work, section 2 is about the model description and the constraints on new parameters are discussed in section 3. Section 4 discusses the implication on $b \to s\nu_l\bar{\nu}_l$ decay modes within the context of the SMEFT approach and the the conclusive remarks are provided in section 5.

2. Model Description

To invoke the missing energy as dark matter, we provide a simple case of singlet scalar dark matter in the context of $U(1)_{\rm B-L}$ extension of SM. For anomaly cancellation, we supplement with three Majorana right-handed neutrinos (N_{iR} with $i = 1, 2, 3$), each charged -1 under the new $U(1)$. Additionally, we include two singlet scalars, ϕ (spontaneously breaks the new $U(1)$) and $\phi_{\rm DM}$ (possible dark matter candidate) with $B - L$ charges 2 and 1/3 respectively. After spontaneous symmetry breaking, ϕ attains a vev v_2 and the new gauge field Z' obtains a mass $M_{Z'} = 2g_{\rm BL}v_2$, where $g_{\rm BL}$ is new gauge coupling. The relevant interaction Lagrangian is provided as follows

$$\mathcal{L}' = g_{\rm BL}\left(-\frac{1}{3}\overline{Q}_L Z'_\mu\gamma^\mu Q_L - \frac{1}{3}\overline{u}_R Z'_\mu\gamma^\mu u_R - \frac{1}{3}\overline{d}_R Z'_\mu\gamma^\mu d_R + \overline{\ell}_L Z'_\mu\gamma^\mu \ell_L + \overline{e}_R Z'_\mu\gamma^\mu e_R\right) + i\overline{N}_{iR}\left(\partial\!\!\!/ + ig_{\rm BL}Z'_\mu\gamma^\mu\right)N_{iR}$$
$$- \frac{y_{\alpha\beta}}{2}\left(\sum_{\alpha,\beta=1}^{3}\overline{N^c_{\alpha R}}N_{\beta R}\,\phi + h.c.\right) + \left|\left(\partial_\mu - 2ig_{\rm BL}Z'_\mu\right)\phi\right|^2 + \left|\left(\partial_\mu - \frac{1}{3}ig_{\rm BL}\,Z'_\mu\right)\phi_{\rm DM}\right|^2 - V\left(H,\phi,\phi_{\rm DM}\right) + \mathcal{L}_{\rm SM},$$

with the scalar potential of the model is

$$V(H,\phi,\phi_{\rm DM}) = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_\phi^2\phi^\dagger\phi + \lambda_\phi(\phi^\dagger\phi)^2 + \mu_{\rm DM}^2\phi^\dagger_{\rm DM}\phi_{\rm DM} + \lambda_{\rm DM}(\phi^\dagger_{\rm DM}\phi_{\rm DM})^2$$
$$+ \lambda_{H\phi}(H^\dagger H)(\phi^\dagger\phi) + \lambda_{\rm HD}(H^\dagger H)(\phi^\dagger_{\rm DM}\phi_{\rm DM}) + \lambda_{\rm D\phi}(\phi^\dagger\phi)(\phi^\dagger_{\rm DM}\phi_{\rm DM}), \tag{1}$$

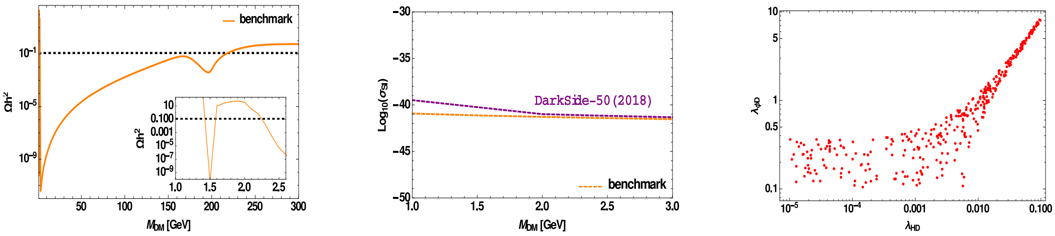
where $\phi_{\rm DM} = \frac{S+iA}{\sqrt{2}}$. The two CP-even scalars of H and ϕ mix to obtain two mass eigenstates, namely H_1 (125 GeV observed Higgs at LHC) and a lighter scalar H_2 (mass less than 5 GeV).

PoS(HQL2023)082

3. Dark matter phenomenology

The scalar DM can annihilate via scalar bosons (H_1, H_2) or Z'. We try to focus in scalar portal to obtain a light DM (mass < 2.5 GeV) in order to explain the missing energy signal in B-meson decays in the subsequent section. The annihilation channels include $SS(AA) \to f\bar{f}$ where f denotes quark-antiquark and lepton-antilepton pairs, which are s-channel processes. Hence, a resonance is noticed near $M_{\text{DM}} = \frac{M_{H_2}}{2}$, shown in the left panel of Fig.1(a). Moving on to direct detection, the DM-nucleon cross section is computed and the spin-independent cross section vs DM mass is projected in the middle panel. It is found that the cross-section is well below the experimental upper limit of DarkSide-50 [3]. We have used LanHEP and micrOMEGAs packages for the DM study, and the Feynman diagrams are provided in the left panel of Figure 2(a).

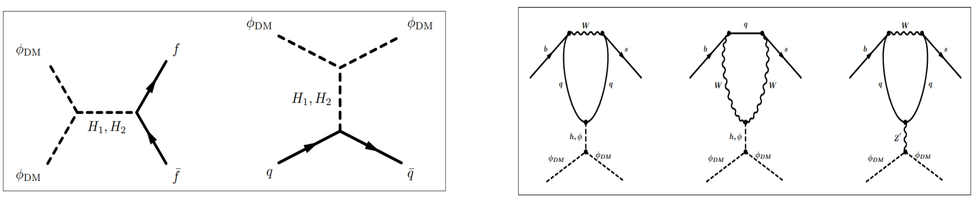
Constraint on Higgs invisible width can limit the scalar couplings as Higgs can decay to light scalars (S, A, H_2). Right most panel projects the same with the constraint 18% of total width [4].



(a) (b) (c)

Figure 1: (a) Relic density vs DM mass with $M_{H_2} = 3$ GeV (b) WIMP-nucleon spin-independent cross section with DM mass (c) Constraint on scalar couplings from Higgs invisible width.

3.1 Flavor phenomenology



(a) (b)

Figure 2: Feynman diagrams contributing to (a)relic density and direct detection;(b)missing energy

In $B \to K$+Missing Energy, the disagreement between theoretical and experimental branching ratio implies the presence of a new source of missing energy which can be a pair of DM [Figure 2(b)]

$$\mathcal{BR}(B \to K + \not{E}) = \mathcal{BR}(B \to K\nu\bar{\nu}) + \mathcal{BR}(B \to K\phi_{DM}\phi_{DM}) \tag{2}$$

4. Implication on $b \to s\nu_l\bar{\nu}_l$ Decay Modes

The general effective Hamiltonian for $b \to s\nu\bar{\nu}$ decay mode is

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*}(C_L^{\nu}O_L^{\nu} + C_R^{\nu}O_R^{\nu}) + h.c., \tag{3}$$

Branching Ratio	Values in SM	Values in $U(1)_{B-L}$ Model	Experimental limit
$B^0 \to K^{*0}\nu\bar{\nu}$	1.6285×10^{-6}	3.91×10^{-6}	$< 1.8 \times 10^{-5}$
$B_s \to \phi\nu\bar{\nu}$	2.262×10^{-6}	5.423×10^{-6}	$< 5.4 \times 10^{-3}$
$B \to \eta\nu\bar{\nu}$	0.61×10^{-6}	1.47×10^{-6}	$\cdots$
$B \to \eta'\nu\bar{\nu}$	0.37×10^{-6}	0.97×10^{-6}	$\cdots$
$B_c^+ \to D_s^+\nu\bar{\nu}$	0.185×10^{-6}	0.52×10^{-6}	$\cdots$
$B_c^+ \to D_s^{*+}\nu\bar{\nu}$	0.086×10^{-6}	0.215×10^{-6}	$\cdots$

Table 1: Predicted branching ratios of $b \to s\nu\bar{\nu}$ channels in the proposed $U(1)_{B-L}$ model.

where $C_L^\nu = -6.38 \pm 0.06$ and $C_R^\nu = 0$ in SM and the 6-D operators are

$$O_L^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu), \qquad O_R^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

For $B \to (P/V)\nu_l\bar{\nu}_l$ decays, the branching ratio:

$$\frac{d\mathcal{BR}(B \to P\nu_l\bar{\nu}_l)}{dq^2} = \frac{G_F^2\alpha^2}{256\pi^5 m_B^3}\tau_B \mid V_{tb}V_{ts}^* \mid^2 \lambda^{3/2}(m_B^2, m_P^2, q^2) \times [f_+(q^2)]^2 \mid C_L^\nu \mid^2$$

$$\frac{d\mathcal{BR}(B \to V\nu_l\bar{\nu}_l)}{dq^2} = 3\tau_B[|A_\perp|^2+|A_\parallel|^2+|A_0|^2]$$ where, $A_{\perp,\parallel,0}$ are the transversity amplitudes Ref[5]

In our analysis, we used form factor in lattice QCD and relativistic quark model as Ref.[7],[8],[5] and numerical values from PDG Live.

5. Conclusion

We addressed the $B \to K+$ missing energy anomaly in the $U(1)_{B-L}$ model with the consideration that the missing energy is due to the presence of GeV scale scalar dark matter. We then estimate the branching ratios of other $b \to s\nu_l\bar{\nu}_l$ modes which are found to be within the experimental limit.

References

[1] A.Glazov (Belle II), "News from Belle II," EPS conference 2023.

[2] LHCb collaboration: R. Aaij et al., "Test of lepton universality in $b \to sl\bar{l}$ decays",Phys. Rev. Lett. **131**,051803 (2023).

[3] P. Agnes et al. (DarkSide Collaboration), Phys. Rev. D **98**, 102006 (2018).

[4] Armen Tumasyan et al. (CMS Collaboration) Phys. Rev. D **105**, 092007 (2022).

[5] M. K. Mohapatra, N. Rajeev, and R. Dutta, Physical Review D **105**, 115022 (2022); Rajeev, N. and Dutta, Rupak, Physical Review D **105**, 115028 (2022).

[6] Singirala, S.et al., Eur. Phys. J. Plus 133, 477 (2018); Mishra, S. et al., J. Phys. G **48**,7 (2021).

[7] W. G. Parrott et al. [HPQCD], Phys. Rev. D **107**, 014510 (2023).

[8] A. Bharucha, D. M. Straub and R. Zwicky, JHEP **08**, 098 (2016).