EPJ Web of Conferences **312**, 05001 (2024)
*FPCP 2024*

https://doi.org/10.1051/epjconf/202431205001

# Exploring Flavor Anomalies and Dark Matter in $U(1)_{L_e-L_\mu}$ model with a scalar Leptoquark

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**Abstract.** We explore $U(1)_{L_e-L_\mu}$ gauge extension of the Standard model with particle content enlarged by three neutral fermions, of which the lightest one contributes to dark matter content of the Universe. The scalar sector is enriched with a scalar leptoquark doublet to investigate flavor anomalies in $B$-meson sector, an additional inert scalar doublet to realize neutrino mass at one loop and a scalar singlet to spontaneously break the new $U(1)$. We discuss dark matter relic density and direct detection cross section in scalar and gauge portals. New physics contribution for transition comes from penguin diagrams with $Z'$, leptquark and new fermions. We analyze the constraints on the model parameters from the established observables such as $P_5'$, $\text{Br}(B \to (K^{(*)}, \phi)\mu\mu)$, and $\text{Br}(B_s \to \mu\mu)$ processes. Utilizing the permissible parameter space consistent with both flavor and dark sectors, we discuss the impact on various observables such as branching ratio and Lepton polarisation asymmetry of the $\Lambda_b \to \Lambda^* \ell^+ \ell^-$ decay channel.

## 1 Introduction

The exploration of physics beyond the Standard Model (SM) through the study of $B$ meson decays has drawn considerable interest in recent years and is poised to remain a dynamic area of research. By carefully examining various $B$ decays, we may uncover compelling evidence of new physics (NP) originating from the $B$ sector. At the Large Hadron Collider (LHC) at CERN, particularly through the LHCb experiment, and in parallel with the Belle II experiment at KEK, researchers gain vital insights into the behavior of $b$ quark decays. Semileptonic $B$ meson decays, especially those involving flavor-changing neutral currents ($b \to s$) and charged currents ($b \to c/u$), offer a critical avenue for probing NP beyond the SM.

While several anomalies have been detected in these decay channels, none of the current measurements have yet reached the level of statistical significance needed to conclusively establish the presence of NP. However, with the planned upgrades to the LHC, which promise larger data samples and enhanced precision, it is expected that systematic uncertainties in existing measurements will be significantly reduced, potentially providing clearer evidence.

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Among the most compelling observables in $b \to s\ell\ell$ transitions, which are central to the search for NP, are the lepton flavor universality (LFU) violating ratios $R_K$ and $R_{K^*}$, defined as

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)} \,. \tag{1}$$

Recent updates from LHCb [1, 2] have affirmed that the measured values of certain observables align well with their Standard Model (SM) predictions, typically of order unity. Nonetheless, several other observables within the $b \to s\ell\ell$ transitions, such as the well-known $P_5'$ observable and the branching fractions of various decay modes, exhibit deviations from SM predictions by a few sigma. Specifically, the LHCb [3, 4] and ATLAS [5] collaborations have reported a $3.3\sigma$ deviation in the measurement of $P_5'$ from the SM expectation. The branching ratio for the $B_s \to \phi\mu^-\mu^+$ decay mode shows a $3.3\sigma$ discrepancy [6, 7] in the $q^2$ range of $[1.1, 6.0]$ GeV$^2$. Additionally, the measurements of $R_{K_S^0}$ and $R_{K^{*+}}$ [8] diverge from their SM predictions by $1.4\sigma$ and $1.5\sigma$, respectively. These findings suggest that the possibility of New Physics (NP) in the flavor-changing neutral current (FCNC) mediated transitions $b \to s\ell\ell$ cannot yet be ruled out.

In response to the $b \to s\ell\ell$ anomalies, we propose an extension of the Standard Model (SM) gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y$, by incorporating a local $U(1)_{L_e-L_\mu}$ symmetry. This framework, due to its simplicity, presents a compelling avenue for investigating the phenomenology of dark matter, neutrinos, and the observed flavor anomalies. The introduction of color triplet particles offers a promising strategy for probing the flavor sector while also establishing a potential link to the dark sector. In this scenario, leptoquarks (LQs) are particularly advantageous as they address flavor anomalies and act as mediators between the visible and dark sectors. Previous studies have explored these motivations extensively [9–11]. The $Z'$ gauge boson arising from the extended $U(1)$ symmetry and the scalar leptoquark (SLQ) are central to resolving issues within the flavor sector. Here, we aim to determine whether the observed anomalies in rare leptonic and semileptonic decays, specifically those involving $b \to s\ell^+\ell^-$ transitions, can be explained within this framework. Our study will emphasize the model's implications for both dark matter and the flavor sectors, with a particular focus on the decay channels $\Lambda_b \to \Lambda^*\ell^+\ell^-$. Numerous studies have previously examined these decay processes [12–16].

The paper is structured as follows. We describe the particle content, relevant Lagrangian and interaction terms, pattern of symmetry breaking in section-II. We derive the mass eigenstates of the new fermions and the scalar spectrum in section-III. Section-IV contains the constraint on the new parameters obtained from the existing anomalies in the flavor sector mediating $b \to s\mu^+\mu^-$ transitions. We then investigate the impact of additional $U(1)_{L_e-L_\mu}$ gauge symmetry on the $\Lambda_b \to \Lambda^*\ell^+\ell^-$ decay observables in section-V. We summarize our findings in Section-VI.

## 2 Theoretical Framework

### 2.1 The Model

We investigate the well-established anomaly-free $U(1)_{L_e-L_\mu}$ extension of the Standard Model, incorporating three additional neutral fermions $N_e, N_\mu, N_\tau$ with $L_e - L_\mu$ charges of $+1$, $-1$, and 0, respectively. To spontaneously break the local $U(1)_{L_e-L_\mu}$ gauge symmetry, we introduce a scalar singlet $\phi_2$ with a charge of $+2$ under the new $U(1)$. The model also includes an inert doublet $\eta$ and a scalar leptoquark $\tilde{R}_2(3, 2, 1/6)$, assigned $L_e - L_\mu$ charges of $+1$ and $+2$, respectively. An additional $Z_2$ symmetry is imposed, under which all new fermions, as well as $\eta$ and the leptoquark, are odd, while the remaining fields are even. The particle content

| | Field | $SU(3)_C \times SU(2)_L \times U(1)_Y$ | $U(1)_{L_e-L_\mu}$ | $Z_2$ |
|---|---|---|---|---|
| Fermions | $Q_L \equiv (u,d)_L^T$ | $(\mathbf{3},\mathbf{2},1/6)$ | 0 | + |
| | $u_R$ | $(\mathbf{3},\mathbf{1},2/3)$ | 0 | + |
| | $d_R$ | $(\mathbf{3},\mathbf{1},-1/3)$ | 0 | + |
| | $\ell_{\alpha L} \equiv (\nu_\alpha,\alpha)_L,\ \alpha=e,\mu,\tau$ | $(\mathbf{1},\mathbf{2},-1/2)$ | $1,-1,0$ | + |
| | $\ell_R \equiv \alpha_R,\ \alpha=e,\mu,\tau$ | $(\mathbf{1},\mathbf{1},-1)$ | $1,-1,0$ | + |
| | $N_e, N_\mu, N_\tau$ | $(\mathbf{1},\mathbf{1},0)$ | $1,-1,0$ | − |
| Scalars | $H$ | $(\mathbf{1},\mathbf{2},\ 1/2)$ | 0 | + |
| | $\eta$ | $(\mathbf{1},\mathbf{2},\ 1/2)$ | 0 | − |
| | $\phi_2$ | $(\mathbf{1},\mathbf{1},\ 0)$ | 2 | + |
| | $\tilde{R}_2$ | $(\mathbf{3},\mathbf{2},1/6)$ | 1 | − |

**Table 1.** Fields and their charges of the proposed $U(1)_{L_e-L_\mu}$ model.

and their associated charges are summarized in Table 1. The Lagrangian of the present model can be written as

$$\begin{aligned}
\mathcal{L}_f =& -\frac{1}{2}M_{\tau\tau}\overline{N_\tau^c}N_\tau - \left(\frac{f_e}{2}\overline{N_e^c}N_e\phi_2^\dagger + \frac{f_\mu}{2}\overline{N_\mu^c}N_\mu\phi_2 + \text{h.c.}\right) - \frac{1}{2}M_{e\mu}(\overline{N_e^c}N_\mu + \overline{N_\mu^c}N_e) \\
&- \sum_{l=e,\mu,\tau}\left(Y_{ll}(\overline{\ell_L})_l\tilde{\eta}N_{lR} + \text{h.c.}\right) - \left(y_{qRN}\ \overline{Q_L}\tilde{R}_2N_{\mu R} + \text{h.c.}\right), \\
\mathcal{L}_{G-f} =& \left(-g_{e\mu}\bar{e}\gamma^\mu e + g_{e\mu}\bar{\mu}\gamma^\mu\mu - g_{e\mu}\overline{\nu_e}\gamma^\mu(1-\gamma^5)\nu_e + g_{e\mu}\overline{\nu_\mu}\gamma^\mu(1-\gamma^5)\nu_\mu\right)Z'_\mu \\
&- g_{e\mu}\overline{N_e}Z'_\mu\gamma^\mu\gamma^5N_e + g_{e\mu}\overline{N_\mu}Z'_\mu\gamma^\mu\gamma^5N_\mu, \\
\mathcal{L}_S =& \left|\left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a\cdot\mathbf{W}_\mu^a - \frac{g'}{6}B_\mu + g_{e\mu}Z'_\mu\right)\tilde{R}_2\right|^2 + \left|\left(i\partial_\mu - 2g_{e\mu}Z'_\mu\right)\phi_2\right|^2 \\
&+ \left|\left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a\cdot\mathbf{W}_\mu^a - \frac{g'}{2}B_\mu\right)\eta\right|^2 - V(H,\tilde{R}_2,\eta,\phi_2).
\end{aligned} \tag{2}$$

The fermion and scalar mass matrices take the form

$$M_N = \begin{pmatrix} \frac{1}{\sqrt{2}}f_ev_2 & M_{e\mu} \\ M_{e\mu} & \frac{1}{\sqrt{2}}f_\mu v_2 \end{pmatrix}, \quad M_S = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H2}vv_2 \\ \lambda_{H2}vv_2 & 2\lambda_2v_2^2 \end{pmatrix}. \tag{3}$$

One can diagonalize the above mass matrices by $U^T_{\delta(\zeta)}M_{N(S)}U_{\delta(\zeta)} = \text{diag}\ [M_{N_1(H_1)}, M_{N_2(H_2)}]$, where

$$U_\theta = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \tag{4}$$

with $\zeta = \frac{1}{2}\tan^{-1}\left(\frac{\lambda_{H2}vv_2}{\lambda_2v_2^2 - \lambda_Hv^2}\right)$ and $\delta = \frac{1}{2}\tan^{-1}\left(\frac{2M_{e\mu}}{(f_\mu - f_e)(v_2/\sqrt{2})}\right)$. We denote the scalar mass eigenstates as $H_1$ and $H_2$, with $H_1$ is assumed to be observed Higgs at LHC with $M_{H_1} = 125.09$ GeV and $v = 246$ GeV. We indicate $N_1$ and $N_2$ coming from the mass matrix $M_N$ to be the fermion mass eigenstates, with the lightest one ($N_1$) as the probable dark matter candidate in the present work.

### 2.2 General Effective Hamiltonian

The most general effective Hamiltonian mediating the $b \to s l^+ l^-$ transition is given by [17]

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ \sum_{i=1}^{6} C_i(\mu) O_i + \sum_{i=9,10} \left( C_i(\mu) O_i + C_i'(\mu) O_i' \right) \right], \tag{5}$$

where $G_F$ is the Fermi constant, $V_{tb}V_{ts}^*$ denote the CKM matrix elements, $C_i$'s stand for the Wilson coefficients evaluated at the renormalized scale $\mu = m_b$ [18] and the values are listed in Table 2 .

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7^{\rm eff}$ | $C_8^{\rm eff}$ | $C_9$ | $C_{10}$ |
|---|---|---|---|---|---|---|---|---|---|
| −3.001 | 1.008 | −0.0047 | −0.0827 | 0.0003 | 0.0009 | −0.2969 | −0.1642 | 4.2607 | −4.2453 |

**Table 2.** The SM Wilson coefficients computed at the scale $\mu = 4.6$ GeV [18].

Here $O_i$'s represent dimension-six operators responsible for leptonic/semileptonic processes, given as

$$O_9^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma^\mu P_{L(R)} b)(\bar{l}\gamma_\mu l) , \qquad O_{10}^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma^\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l) , \tag{6}$$

where, $\alpha_{\rm em}$ is the fine-structure constant, $P_{L,R} = (1 \mp \gamma_5)/2$ are the chiral operators. The one-loop diagrams contributing non-zero values to the rare $b \to sll$ processes can arise through the exchange of $Z', H_{1,2}$ particles, forming penguin diagrams with the scalar leptoquark $\tilde{R}_2^{-1/3}$ and $N_{1,2}$ particles within the loop, as depicted in Fig. 1.

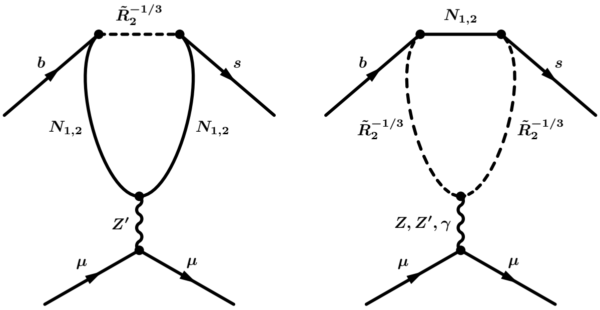

**Figure 1.** Allowed penguin diagrams illustrating the $b \to s\mu\mu$ transition in the model.

In the presence of $Z'$ exchanging one loop diagram, the The new Wilson coefficient is given as,

$$C_9^{\rm NP} = -\frac{1}{4\pi} \frac{\sqrt{2}}{4G_F m_{Z'}^2} \frac{1}{\alpha_{em}} \frac{y_{qRN}^2 g_{e\mu}^2}{V_{tb}V_{ts}^*} \mathcal{R}(a, b). \tag{7}$$

Here $\mathcal{R}(a, b)$ is the loop function with $a(b) = \frac{m_{N_{1(2)}}^2}{m_{LQ}^2}$ where $a = \frac{m_{N_1}^2}{m_{LQ}^2}$ and $b = \frac{m_{N_2}^2}{m_{LQ}^2}$.

## 3 Constraints on new Physics couplings

In this section, our objective is to constrain the model parameters associated with LQ and $Z'$ couplings such as ($g_{e\mu}$ vs. $m_{Z'}$) and ($y_{mN}$ vs. $m_N$) by analyzing the Br($B \to K\mu\mu$), Br($B \to K^*\mu\mu$), Br($B_s \to \phi\mu\mu$) decay modes, along with the measurement of the well-known $P_5'$ observable in $B \to K^*\mu\mu$ process, which involves $b \to s\ell\ell$ transitions. This is depicted in Fig. 2.

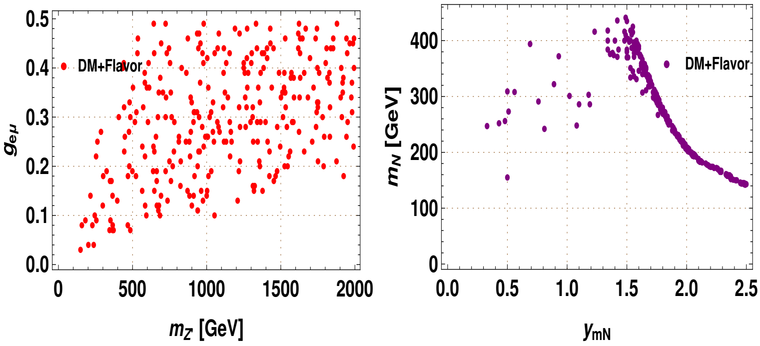

**Figure 2.** Allowed penguin diagrams illustrating the $b \to s\mu\mu$ transition in the model.

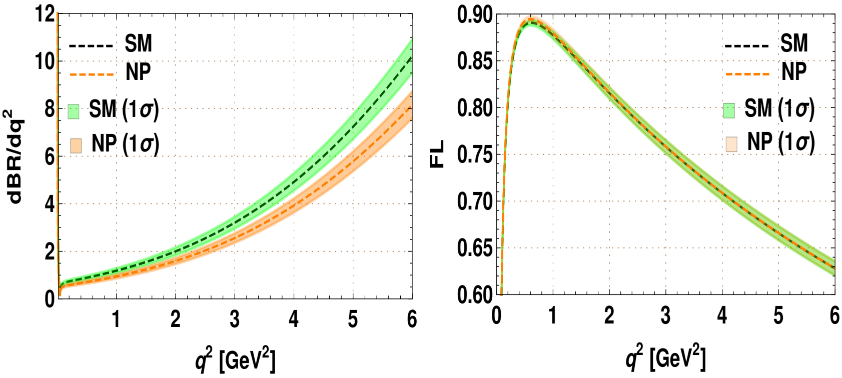

**Figure 3.** Branching ratio and the Polarisation asymmetry of $\Lambda_b \to \Lambda^*(1520)\mu^+\mu^-$ process

## 4 Analysis of $\Lambda_b \to \Lambda^*(\to pK)\ell^+\ell^-$ Process

From the four-fold differential decay distribution [19], the differential branching ratio $d\mathcal{B}/dq^2$ and the lepton forward-backward asymmetry $A^l_{FB}(q^2)$ are defined as

$$\begin{aligned}\frac{d\mathcal{B}}{dq^2} &= \frac{1}{3}\Big[K_{1cc} + 2K_{1ss} + 2K_{2cc} + 4K_{2ss} + 2K_{3ss}\Big],\\ A^{\ell}_{\rm FB} &= \frac{3(K_{1c} + 2K_{2c})}{2\Big[K_{1cc} + 2K_{1ss} + 2K_{2cc} + 4K_{2ss} + 2K_{3ss}\Big]}.\end{aligned} \tag{8}$$

- **Branching ratio**: The presence of NP coupling reduces the branching ratio. However, in the low $q^2$ region, it becomes consistent with the SM contribution.
- **Lepton-Polarisation asymmetry**: We do not observe any new physics signatures despite the presence of NP coefficients.

## 5 Conclusion

- We have investigated $U(1)_{L_e-L_\mu}$ extension of SM for a correlative study of dark matter and flavor anomalies.
- With three heavy neutral fermions, $\tilde{R}_2(3, 2, 1/6)$ scalar leptoquark and a $U(1)$ associated $Z'$, the model can provide new physics contribution to $b \to s$ transition (penguin loop).
- We have studied the $\Lambda_b \to \Lambda^*(\to pK)\mu\mu$ process pertaining to $b \to s\mu\mu$ transition.
- The differential branching ratio deviates, and also quite distinguishable from the SM contributions.

## References

[1] Aaij, R. and others, Test of lepton universality in $b \to s\ell^+\ell^-$ decays, Phys.Rev.Lett. 131 (2023) 5, 051803 https://doi:10.1103/PhysRevLett.131.051803

[2] Aaij, R. and others, Measurement of lepton universality parameters in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays, Phys.Rev.D 108 (2023) 3, 032002 https://doi:10.1103/PhysRevD.108.032002

[3] Aaij, R. and others, Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$, Phys.Rev.Lett. 111 (2013) 191801, https://doi:10.1103/PhysRevLett.111.191801

[4] Aaij, R. and others, Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb$^{-1}$ of integrated luminosity, JHEP 02 (2016) 104, https://doi:10.1007/JHEP02(2016)104

[5] Aaboud, Morad and others, Angular analysis of $B^0_d \to K^*\mu^+\mu^-$ decays in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, JHEP 10 (2018) 047, https://doi:10.1007/JHEP10(2018)047

[6] Aaij, Roel and others, Branching Fraction Measurements of the Rare $B^0_s \to \phi\mu^+\mu^-$ and $B^0_s \to f_2'(1525)\mu^+\mu^-$- Decays, Phys.Rev.Lett. 127 (2021) 15, 151801, https://doi:10.1103/PhysRevLett.127.151801

[7] Aaij, Roel and others, Angular analysis and differential branching fraction of the decay $B^0_s \to \phi\mu^+\mu^-$, JHEP 09 (2015) 179, https://doi:10.1007/JHEP09(2015)179

[8] Aaij, Roel and others, Tests of lepton universality using $B^0 \to K^0_S\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays, Phys.Rev.Lett. 128 (2022) 19, 191802, https://doi:10.1103/PhysRevLett.128.191802

[9] Baek, Seungwon, Dark matter contribution to $b \to s\mu^+\mu^-$ anomaly in local $U(1)_{L_\mu - L_\tau}$ model, Phys.Lett.B 781 (2018) 376-382, https://doi:10.1016/j.physletb.2018.04.012

[10] Arcadi, Giorgio and Dutra, Maíra and Ghosh, Pradipta and Lindner, Manfred and Mambrini, Yann and Pierre, Mathias and Profumo, Stefano and Queiroz, Farinaldo S., The waning of the WIMP? A review of models, searches, and constraints, Eur.Phys.J.C 78 (2018) 3, 203, https://doi:10.1140/epjc/s10052-018-5662-y

[11] Allahverdi, Rouzbeh and Dev, P. S. Bhupal and Dutta, Bhaskar, A simple testable model of baryon number violation: Baryogenesis, dark matter, neutron–antineutron oscillation and collider signals, Phys.Lett.B 779 (2018) 262-268, https://doi:10.1016/j.physletb.2018.02.019

[12] Li, Yu-Shuai and Jin, Su-Ping and Gao, Jing and Liu, Xiang, Transition form factors and angular distributions of the Λb→Λ(1520)(→NK⁻)ℓ+ℓ- decay supported by baryon spectroscopy Phys.Rev.D 107 (2023) 9, 093003 https://doi:10.1103/PhysRevD.107.093003

[13] Xing, Zhi-Peng and Huang, Fei and Wang, Wei, Angular distributions for Λb→ΛJ*(pK-)J/ψ(→ℓ+ℓ-) decays, Phys.Rev.D 106 (2022) 11, 114041 https://doi:10.1103/PhysRevD.106.114041

[14] Das, Nilakshi and Dutta, Rupak, New physics analysis of $\Lambda_b \to (\Lambda^*(\to pK^-), \Lambda(\to p\pi))(\mu^+\mu^-, \nu\bar{\nu})$ baryonic decays under SMEFT framework, Phys.Rev.D 108 (2023) 9, 095051 https://doi:10.1103/PhysRevD.108.095051

[15] Meinel, Stefan and Rendon, Gumaro, $\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$ form factors from lattice QCD, Phys.Rev.D 103 (2021) 7, 074505 https://doi:10.1103/PhysRevD.103.074505

[16] Roy, Shibasis and Sain, Ria and Sinha, Rahul, Lepton mass effects and angular observables in $\Lambda_b \to \Lambda(\to p\pi)\ell^+\ell^-$, Phys.Rev.D 96 (2017) 11, 116005, https://doi:10.1103/PhysRevD.96.116005

[17] Bobeth, Christoph and Misiak, Mikolaj and Urban, Jorg, Photonic penguins at two loops and $m_t$ dependence of $BR[B \to X_s l^+ l^-]$, Nucl.Phys.B 574 (2000) 291-330, https://doi:10.1016/S0550-3213(00)00007-9

[18] Hou, Wei-Shu and Kohda, Masaya and Xu, Fanrong, Rates and asymmetries of $B \to \pi\ell^+\ell^-$ decays, Phys.Rev.D 90 (2014) 1, 013002, https://doi:10.1103/PhysRevD.90.013002

[19] Das, Diganta and Das, Jaydeb, The $\Lambda_b \to \Lambda^*(1520)(\to N\bar{K})\ell^+\ell^-$ decay at low-recoil in HQET, JHEP 07 (2020) 002, https://doi:10.1007/JHEP07(2020)002