Unveiling the role of new physics in lepton flavor violating decay modes $b \to s\ell_1\ell_2$ through model independent analysis

Aishwarya Bhatta

National Institute of Sciences Education and Research, Bhubaneswar

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Why Study LFV Decays?

- In the Standard Model (SM), lepton flavor is conserved in flavor-changing neutral current (FCNC) processes.
- LFV decays (e.g., $b \to s\ell_1\ell_2$) are **highly suppressed** in SM due to tiny neutrino mass effects.
- Any observed LFV signal would be a **clear sign of new physics (NP)**.

Beyond Standard Model (BSM) Predictions:

- **Leptoquarks**: Introduce new couplings between quarks and leptons.
- **Z' Bosons**: Mediate FCNC transitions in the lepton sector.
- **Supersymmetry (SUSY)**: Allows LFV through slepton mixings.
- **Two-Higgs-Doublet Models (2HDM)**: Introduce Higgs-mediated LFV interactions.
- **Composite Higgs Models**: Predict nontrivial flavor structures.

Experimental Motivation:

- Recent anomalies in $b \to s\ell^+\ell^-$ (e.g., R_K, R_{K^*}) hint at potential LFV effects.
- LHCb and Belle II can probe rare LFV decays like $B \to K\mu e$.
- Other LFV searches (e.g., $\tau \to 3\mu$, $\mu \to e\gamma$) provide complementary tests.

Introduction

- **Motivation:** Anomalies in $b \to s\ell^+\ell^-$ transitions suggest the need to explore lepton flavor-violating (LFV) decays ($b \to s\ell_1\ell_2$, $\ell_1 \neq \ell_2$).
- **Beyond SM:** LFV is forbidden in the Standard Model but naturally arises in extensions like vector-like fermions and Z' bosons.
- **Focus:** Study key decay modes:
  - $B \to K^*\ell_1\ell_2$, $B \to \phi\ell_1\ell_2$
  - $B \to {K_2}^*\ell_1\ell_2$, $\Lambda_b \to \Lambda\ell_1\ell_2$
- **Approach:** Use a model-independent framework with the general effective Hamiltonian and derive angular decay distributions.
- **Results:** Provide bounds on branching ratios and leptonic forward-backward asymmetry, offering insights into underlying physics.

Theoretical Framework

The effective Hamiltonian for $b \to s\ell_1^- \ell_2^+$ decay is given by:

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_{em}}{\pi} \sum_{i=9,10,S,P} \left(C_i^{\ell_1 \ell_2} \mathcal{O}_i^{\ell_1 \ell_2} + C_i'^{\ell_1 \ell_2} \mathcal{O}_i'^{\ell_1 \ell_2} \right), \quad (1)$$

where G_F is the Fermi coupling constant, and $V_{tb}V_{ts}^*$ are CKM matrix elements.

- Relevant operators for the process:

$$\begin{aligned} \mathcal{O}_9^{(\prime)} &= \left[\bar{s}\gamma^\mu P_{L(R)} b\right]\left[\ell_2 \gamma_\mu \ell_1\right], \quad \mathcal{O}_{10}^{(\prime)} = \left[\bar{s}\gamma^\mu P_{L(R)} b\right]\left[\ell_2 \gamma_\mu \gamma_5 \ell_1\right], \\ \mathcal{O}_S^{(\prime)} &= \left[\bar{s} P_{R(L)} b\right]\left[\ell_2 \ell_1\right], \quad \mathcal{O}_P^{(\prime)} = \left[\bar{s} P_{R(L)} b\right]\left[\ell_2 \gamma_5 \ell_1\right]. \end{aligned} \quad (2)$$

- $\mathcal{O}_{9,10,S,P}$: vector, axial-vector, scalar, and pseudoscalar operators.
- Primed operators ($\mathcal{O}_i'$): obtained by flipping chirality.
- Wilson coefficients $C_{9,10,S,P}^{(\prime)}$: zero in SM but non-zero in new physics scenarios.
- In SM: ℓ_1, ℓ_2 are same-flavor leptons (typically ℓ).

LFV Decay Constraints and Observables

- **Focus:** Analyze constraints on Wilson coefficients using branching ratios of mesonic LFV decays:
  - $\bar{B}_s \to \ell_1^- \ell_2^+$
  - $B \to K \ell_1^- \ell_2^+$
- Experimental upper limits (90% C.L.) for key decay modes:

Observable	Experimental Limit
$\mathcal{B}(B_s \to \mu^\pm \tau^\mp)$	4.2×10^{-5} [1]
$\mathcal{B}(B^+ \to K^+ \mu^- \tau^+)$	3.9×10^{-5} [2]
$\mathcal{B}(B^+ \to K^+ \mu^+ \tau^-)$	4.5×10^{-5} [3]

Table: Experimental upper limits for LFV B decays.

- The corresponding χ^2 is defined as

$$\chi^2(C_{\rm NP}) = \sum \frac{(\mathcal{O}^{\rm th}(C_{\rm NP}) - \mathcal{O}^{\rm Expt})^2}{(\Delta\mathcal{O}^{\rm Expt})^2 + (\Delta\mathcal{O}^{\rm SM})^2}\,. \tag{3}$$

[1] Phys. Rev. Lett. 123 (21) (2019) 211801 [2]J. High Energy Phys. 06 (2020) 129. [3]Phys. Rev. D 86 (2012) 012004.

Branching Ratios for LFV Decay Modes

Branching ratio for $\bar{B}_s \to \ell_1^- \ell_2^+$:

$$\mathcal{B}(\bar{B}_s \to \ell_1^- \ell_2^+) = \frac{\tau_{B_s}}{64\pi^3} \frac{\alpha_{\text{em}}^2 G_F^2 |V_{tb} V_{ts}^*|^2}{m_{B_s}^3} f_{B_s}^2 \, \lambda^{1/2}(m_{B_s}^2, m_{\ell_1}^2, m_{\ell_2}^2)$$
$$\times \Big\{ [m_{B_s}^2 - (m_{\ell_1} - m_{\ell_2})^2] \Big| (m_{\ell_1} + m_{\ell_2}) C_{10-} + \frac{m_{B_s}^2}{m_b + m_s} C_{P-} \Big|^2$$
$$+ [m_{B_s}^2 - (m_{\ell_1} + m_{\ell_2})^2] \Big| (m_{\ell_1} - m_{\ell_2}) C_{9-} + \frac{m_{B_s}^2}{m_b + m_s} C_{S-} \Big|^2 \Big\}. \quad (4)$$

Branching ratio for $B^+ \to K^+ \ell_1^- \ell_2^+$:

$$\mathcal{B}(B^+ \to K^+ \ell_1^- \ell_2^+) = 10^{-8} \Big\{ c_{\ell_1\ell_2}^{S} \, |C_{S+}|^2 + c_{\ell_1\ell_2}^{P} \, |C_{P+}|^2 + c_{\ell_1\ell_2}^{9+} \, |C_{9+}|^2$$
$$+ c_{\ell_1\ell_2}^{10+} \, |C_{10+}|^2 + c_{\ell_1\ell_2}^{S9} \text{Re}[C_{S+}^* C_{9+}] + c_{\ell_1\ell_2}^{P10} \text{Re}[C_{P+}^* C_{10+}] \Big\}. \quad (5)$$

$c_{\ell_1\ell_2}^{9+}$	$c_{\ell_1\ell_2}^{10+}$	$c_{\ell_1\ell_2}^{S}$	$c_{\ell_1\ell_2}^{P}$	$c_{\ell_1\ell_2}^{S9}$	$c_{\ell_1\ell_2}^{P10}$
1.09	1.14	1.47	1.58	−1.35	1.66

Table: The predictions for the coefficients governing $B^+ \to K^+ \ell_1^- \ell_2^+$ decays ($\ell_1^- = \mu^-$, $\ell_2^+ = \tau^+$)

Exploration of 2D Scenarios for Wilson Coefficients

- We analyze two distinct 2D scenarios for new physics (NP) Wilson coefficients:

Scenario I:

$$C_9^{\ell_1\ell_2} \neq 0,\ C_{10}^{\ell_1\ell_2} \neq 0,\ C_S^{\ell_1\ell_2} = C_P^{\ell_1\ell_2} = 0$$

Scenario II:

$$C_9^{\ell_1\ell_2} = -C_{10}^{\ell_1\ell_2},\ C_S^{\ell_1\ell_2} = -C_P^{\ell_1\ell_2}$$

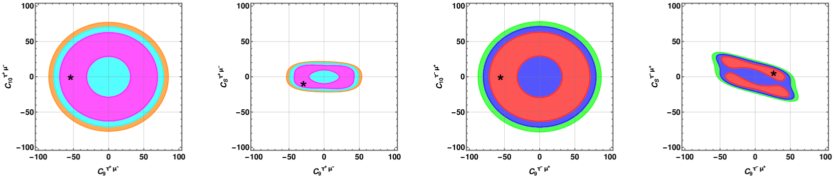

Figure: Allowed parameter space combining different Wilson coefficients, constrained by 90% C.L. upper limits on $\bar{B}_s \to \ell_1^- \ell_2^+$ and $B \to K \ell_1^- \ell_2^+$ decays.

- The best-fit value of $C_9 = -29.234, C_{10} = 2.3 \times 10^{-2}, C_S = -8.941, C_P = 8.941$ are taking into consideration.

$B \to (K^*, \phi)\ell_1^- \ell_2^+$

q^2-dependent differential branching ratio, is expressed as [4,5]

$$\frac{d\mathcal{B}}{dq^2} = \frac{1}{4}[3I_1^c(q^2) + 6I_1^s(q^2) - I_2^c(q^2) - 2I_2^s(q^2)]. \quad (6)$$

Similarly, the forward-backward asymmetry and lepton polarisation asymmetry, are given as

$$A_{\rm FB}(q^2) = \frac{3I_6^s(q^2) + 3/2 I_6^c(q^2)}{3I_1^c(q^2) + 6I_1^s(q^2) - I_2^c(q^2) - 2I_2^s(q^2)}, \quad (7)$$

$$F_{\rm L}(q^2) = \frac{3I_1^c(q^2) - I_2^c(q^2)}{3I_1^c(q^2) + 6I_1^s(q^2) - I_2^c(q^2) - 2I_2^s(q^2)}. \quad (8)$$

- The form factors associated with the transversity amplitude are obtained using the LCSR method.

[4] Phys. C 46 (1990) 93. [5] Eur. Phys. J. C 76 (3) (2016) 134.

$B \to K^* \ell_1 \ell_2$

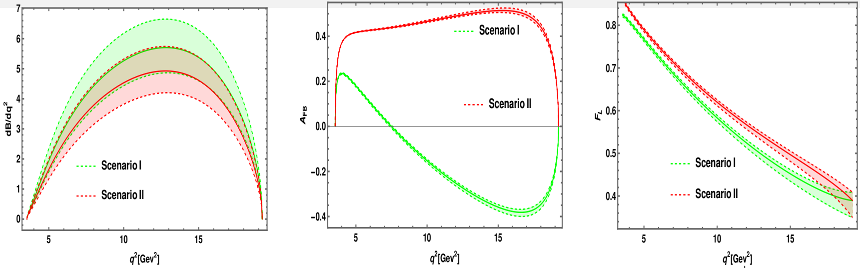

Figure: Branching ratio (left), A_{FB}(middle) and F_L(right) of $B \to K^* \tau^+ \mu^-$.

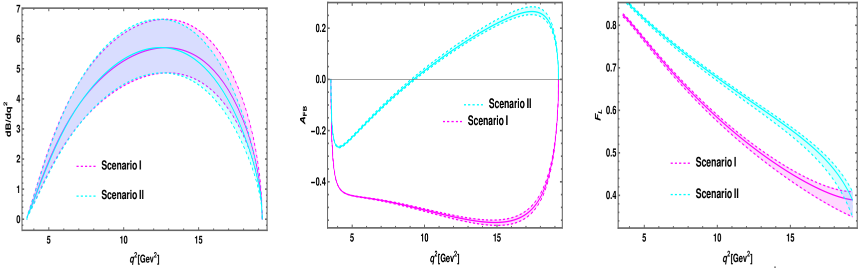

Figure: Branching ratio (left), A_{FB}(middle) and F_L(right) of $B \to K^* \tau^- \mu^+$.

$B \to \phi \ell_1 \ell_2$

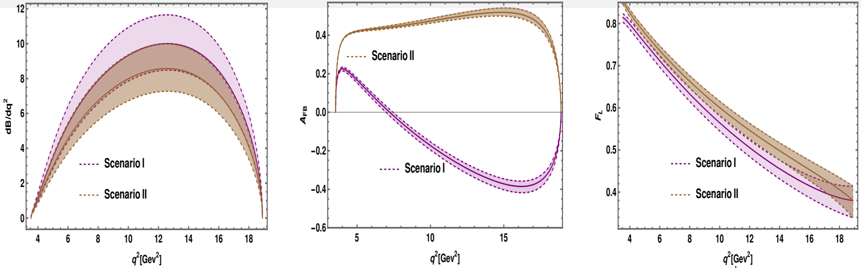

Figure: Branching ratio (left), A_{FB}(middle) and F_L(right) of $B \to \phi \tau^+ \mu^-$.

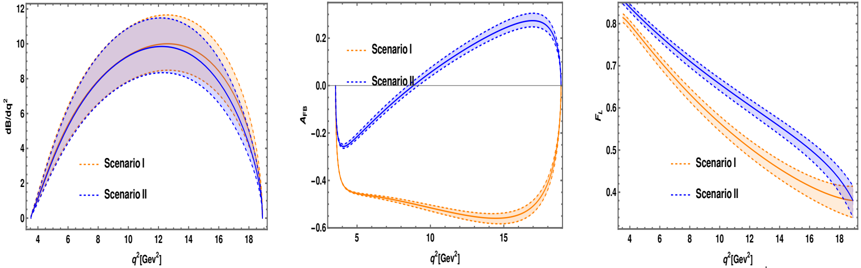

Figure: Branching ratio (left), A_{FB}(middle) and F_L(right) of $B \to \phi \tau^- \mu^+$.

$B \to K_2^* \ell_1 \ell_2$

The differential decay distribution describing three body $B \to K_2^* \ell_1 \ell_2$ decay can be expressed as [6]

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = A(q^2) + B(q^2)\cos\theta_\ell + C(q^2)\cos^2\theta_\ell \,, \tag{9}$$

- Where θ_ℓ is the leptonic polar angle which describes the angle made by lepton ℓ_1 to the dilepton rest frame.

The differential decay rate and lepton FBA can be given as:

$$\frac{d\Gamma}{dq^2} = 2\left(A + \frac{C}{3}\right), \quad A_{\rm FB}(q^2) = \frac{B}{2\left(A + \frac{C}{3}\right)} \tag{10}$$

[6] J. Phys. G 50 (9) (2023) 095003.

$B \to K_2{}^* \ell_1 \ell_2$

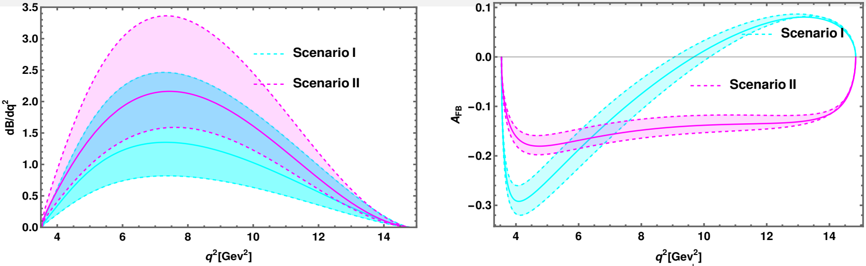

Figure: Branching ratio (left) and A_{FB}(right) of $B \to K_2{}^* \tau^+ \mu^-$.

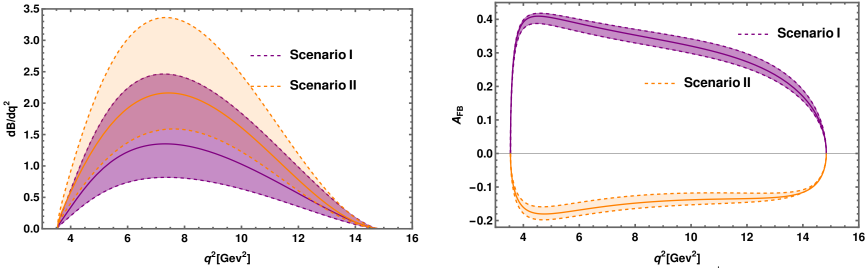

Figure: Branching ratio (left)and A_{FB}(right) of $B \to K_2{}^* \tau^- \mu^+$.

$\Lambda_b \to \Lambda \ell_1 \ell_2$

the differential branching ratio of $\Lambda_b \to \Lambda \ell_1 \ell_2$ as follows [7]:

$$\frac{d^2\mathcal{B}}{dq^2 d\cos\theta_l} = \frac{3}{2}(K_{1ss}\sin^2\theta_l + K_{1cc}\cos^2\theta_l + K_{1c}\cos\theta_l) \ . \quad (11)$$

- Here, θ_ℓ is the lepton emission angle, varying within $-\pi \leq \theta_\ell \leq \pi$.

The resulting differential branching ratio and the FBA (Forward-backward asymmetry) are given by:

$$\frac{d\mathcal{B}}{dq^2} = 2K_{1ss} + K_{1cc}, \quad A_{\rm FB}^{\ell} = \frac{3}{2}\frac{K_{1c}}{K_{1ss} + K_{1cc}}\,, \quad (12)$$

- The squared dilepton invariant mass, q^2, ranges as:

$$(m_1 + m_2)^2 \leq q^2 \leq (m_{\Lambda_b} - m_\Lambda)^2.$$

[7] Eur. Phys. J. C 79 (12) (2019) 1005.

$\Lambda_b \to \Lambda \ell_1 \ell_2$

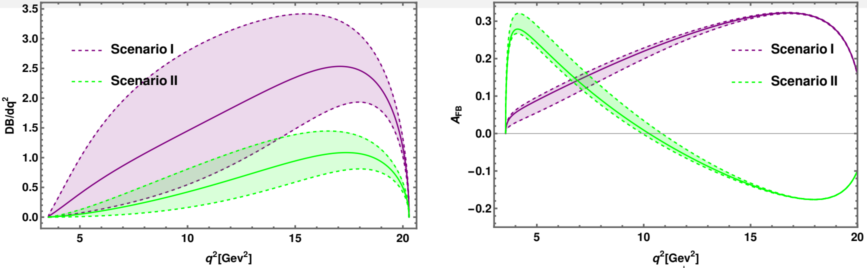

Figure: Branching ratio (left) and A_{FB}(right) of $\Lambda_b \to \Lambda \tau^+ \mu^-$.

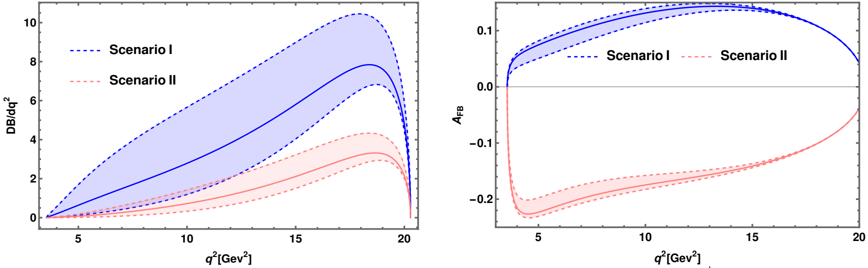

Figure: Branching ratio (left)and A_{FB}(right) of $\Lambda_b \to \Lambda \tau^- \mu^+$.

Predicted Upper Limits

Scenario	Decay Mode	$\mathcal{B}$	$\mathcal{A}_{FB}$	$\mathcal{F}_L$
Scenario I	$B \to K^* \tau^+ \mu^-$	$\leq 6.54 \times 10^{-5}$	≤ -0.156	≤ 0.563
	$B \to K^* \tau^- \mu^+$	$\leq 6.51 \times 10^{-5}$	≤ -0.490	≤ 0.561
	$B_s \to \phi \tau^+ \mu^-$	$\leq 1.127 \times 10^{-5}$	≤ -0.164	≤ 0.550
	$B_s \to \phi \tau^- \mu^+$	$\leq 1.123 \times 10^{-5}$	≤ -0.491	≤ 0.557
	$B \to {K_2}^* \tau^+ \mu^-$	$\leq 9.131 \times 10^{-6}$	≤ -0.056	-
	$B \to {K_2}^* \tau^- \mu^+$	$\leq 9.131 \times 10^{-6}$	≤ -0.056	-
	$\Lambda_b \to \Lambda \tau^+ \mu^-$	$\leq 2.63 \times 10^{-5}$	≤ 0.223	-
	$\Lambda_b \to \Lambda \tau^- \mu^+$	$\leq 6.58 \times 10^{-5}$	≤ 0.111	-
Scenario II	$B \to K^* \tau^+ \mu^-$	$\leq 5.60 \times 10^{-5}$	≤ 0.452	≤ 0.596
	$B \to K^* \tau^- \mu^+$	$\leq 6.414 \times 10^{-5}$	≤ 0.055	≤ 0.642
	$B_s \to \phi \tau^+ \mu^-$	$\leq 1.577 \times 10^{-5}$	≤ 0.455	≤ 0.583
	$B_s \to \phi \tau^- \mu^+$	$\leq 1.087 \times 10^{-5}$	≤ 0.066	≤ 0.627
	$B \to {K_2}^* \tau^+ \mu^-$	$\leq 1.416 \times 10^{-6}$	≤ -0.142	-
	$B \to {K_2}^* \tau^- \mu^+$	$\leq 1.416 \times 10^{-6}$	≤ -0.142	-
	$\Lambda_b \to \Lambda \tau^+ \mu^-$	$\leq 1.673 \times 10^{-5}$	≤ -0.012	-
	$\Lambda_b \to \Lambda \tau^- \mu^+$	$\leq 9.63 \times 10^{-5}$	≤ -0.160	-

Table: Predicted upper limits of $\mathcal{B}$ and $\mathcal{A}_{\mathcal{FB}}$ for the $B \to (K^*, \phi)\tau^\pm\mu^\mp$, and $B \to K_2^*\tau^\pm\mu^\mp$ and $\Lambda_b \to \Lambda\tau^\pm\mu^\mp$ decays with $\mathcal{F}_{\mathcal{L}}$ prediction for $B \to (K^*, \phi)\tau^\pm\mu^\mp$.

Summary

- The observation of any LFV decays indicates a clear signal of the presence of NP beyond the Standard Model, as such decays are strictly forbidden within its framework.
- In this work we investigated branching fractions, forward-backward asymmetry, and lepton polarization asymmetry for $B_{(s)} \to (\phi, K^*, K_2^*)\tau^\pm\mu^\mp$ and $\Lambda_b \to \Lambda\tau^\pm\mu^\mp$ processes.
- Predicted branching ratios:
  - $\Lambda_b \to \Lambda\tau^\pm\mu^\mp$, $B \to K^*\tau^\pm\mu^\mp$ and $B_s \to \phi\tau^\pm\mu^\mp \sim \mathcal{O}(10^{-5})$.
  - $B \to K_2^*\tau^\pm\mu^\mp \sim \mathcal{O}(10^{-6})$.
- Observed zero-crossing in forward-backward asymmetry for $\Lambda_b \to \Lambda\tau^+\mu^-$ and $B \to (K_2^*, \phi, K^*)\tau^+\mu^-$ decays in scenario I and $B \to (K^*, \phi)\tau^+\mu^-$ decays in scenario II.
- Conclusion:
  - Predicted values are substantial and within the reach of current or future experimental limits.
  - Detection of such decays in future experiments would offer definitive evidence of new physics.

Thank You.