Lepton flavour violating $\Sigma_b \to \Sigma l_1 l_2$ decays in Z' model

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Contents

Brief description:

- Inspired by the various LHCb results of lepton flavour violation on $b \to s$ transition we study the lepton flavour violating $\Sigma_b \to \Sigma l_1 l_2$ decays in terms of transversity amplitudes in non-universal Z' model.
- These lepton flavour violating (LFV) processes are extremely suppressed in the Standard Model (SM) because the expected levels at the SM lie far below current experimental sensitivities. In particular, the branching fractions of $B_d \to \tau^{\pm}\mu^{\mp}$and $B_s \to \tau^{\pm}\mu^{\mp}$ decays are obtained in the SM of order of 10^{-54} [1] whereas experimentally they are constrained at the order of 10^{-5} by BaBar and LHCb with 90% and 95% confidence level respectively [2, 3].
- To explain the discrepancies we need to include New Physics (NP).
- In this work we will study the differential branching fractions of LFV decays $\Sigma_b \to \Sigma l_1 l_2$ induced by the quark level transition b$\to sl_1 l_2$ in Z' model where l_1 and l_2 are charged leptons of different flavours. We constrain the NP couplings using several experimental upper limits. .

Why New Physics?

Though the standard model (SM) of particle physics is an outstandingly successful model, there are some sectors where it fails.

- The SM is unable to adopt some fundamental theory incorporating the gravity.
- It cannot explain dark matter, the dominance of matter; fails to prove the existence of massive neutrinos as well as neutrino oscillations.
- The most tantalizing B anomalies are the hot topic nowadays.

Introduction of BSM

- ✓ We have incorporated an additional $U(1)'$ group with the SM gauge group to explain the anomalies considering the contribution of Z' boson.
- ✓ The neutral Z' boson is a colourless and short-lived particle. It is expected to observe Z' through its possible decay products or some interference effects.
- ✓ The particle is not observed till now, different NP theories and accelerators restrict the Z' mass differently.

Attractiveness of baryonic decays

- **Baryons are made of three quarks (one heavy quark and two lighter quarks)**. At the time of interaction the heavy quark escapes from baryonic structure and the quantum numbers (as colour, helicity and momentum) of the lighter part are conserved.

- Though experimentalists paid more attention to mesonic channels over the years but the baryonic ones also have very exciting saga which can probe NP successfully.

- The helicity structure of the effective Hamiltonian is illustrated for b decays of baryons but not for mesons. Previously we have studied the LFV Λ_b^0 decays in terms of hadronic and leptonic helicity amplitudes.

- Another interesting fact is that the kinematic observables for baryons involve the spin which enhances the number of degrees of freedom for bound state of baryons in comparison with the mesons.

Theoretical Framework:

We start to build the effective Hamiltonian with the lepton flavour violating $b \to s l_1^+ l_2^-$ transition. In this case NP particle Z' will couple with leptons of different family. The Hamiltonian can be written as [4],

$$\mathcal{H}^{eff} = -\frac{G_F \alpha}{2\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_{i=9,10} C_i' O_i' + h.c., \quad (1)$$

The primed parts represent the NP contributions in terms of Wilson Coefficients. Actually the CKM matrix elements $V_{tb}V_{ts}^*$ are included due to the virtual effects induced by $t\bar{t}$ contributions.

Theoretical Framework:

- It is to be noted that these LFV decays occur at tree level in our model; therefore the NP is included in such a way that the contributions for $t\bar{t}$ loops are cancelled.

- Moreover in the SM, there is an electromagnetic operator O_7 that contributes in $b \to sll$ transition but not in LFV part.

- Non-universal Z' model is basically sensitive for the semileptonic operators including NP contributions in C_9' and C_{10}' [5]. Here,

$$O_9' = \left[\bar{s}\gamma_\mu(1-\gamma_5)b\right]\left[\bar{l}_1\gamma^\mu l_2\right] \text{ and}$$
$$O_{10}' = \left[\bar{s}\gamma_\mu(1-\gamma_5)b\right]\left[\bar{l}_1\gamma^\mu \gamma_5 l_2\right]. \quad (2)$$

Observable of investigation: The $\Sigma_b \to \Sigma l_1 l_2$ decays

We have adopted the kinematics from ref. [6]. Proceeding with these considerations we have found the differential decay rate of the above decay as,

$$\frac{d\mathcal{B}}{dq^2} = 2K_{1ss} + K_{1cc}.$$

Here K terms are the angular coefficients and expressed in terms of transversity amplitudes. The form factors are taken from ref. [7].

Observable of investigation:

The expressions of angular coefficients are

$$K_{1cc} = \frac{1}{2}\left(\left|A_{\parallel 1}^{R}\right|^2 + \left|A_{\perp 1}^{R}\right|^2 + \{R \leftrightarrow L\}\right) + \frac{\left(m_i^2 + m_j^2\right)}{2q^2}\left[\left(\left|A_{\parallel 0}^{R}\right|^2 + \left|A_{\perp 0}^{R}\right|^2 - \left|A_{\parallel 1}^{R}\right|^2 - \left|A_{\perp 1}^{R}\right|^2 + \{R \leftrightarrow L\}\right) + \left(\left|A_{\parallel t}\right|^2 + |A_{\perp t}|^2\right)\right] + \frac{\left(m_i^2 m_j^2\right)}{q^2}\left[2Re(A_{\perp 0}^{R} A_{\perp 0}^{*L} + A_{\perp 1}^{R} A_{\perp 1}^{*L} + \{\perp \leftrightarrow \parallel\})\right] - \frac{\left(m_i^2 - m_j^2\right)^2}{4q^4}\left[\left(\left|A_{\parallel 0}^{R}\right|^2 + \left|A_{\perp 0}^{R}\right|^2 + \{R \leftrightarrow L\}\right) + \left(\left|A_{\parallel t}\right|^2 + |A_{\perp t}|^2\right)\right]$$

$$K_{1ss} = \frac{1}{4}\left(2\left|A_{\parallel 0}^{R}\right|^2 + \left|A_{\parallel 1}^{R}\right|^2 + 2\left|A_{\perp 0}^{R}\right|^2 + \left|A_{\perp 1}^{R}\right|^2 + \{R \leftrightarrow L\}\right) - \frac{\left(m_i^2 + m_j^2\right)}{2q^2}\left[\left(\left|A_{\parallel 0}^{R}\right|^2 + \left|A_{\perp 0}^{R}\right|^2 + \{R \leftrightarrow L\}\right) - (|A_{\perp t}|^2 + \{\perp \leftrightarrow \parallel\})\right] + \frac{\left(m_i^2 m_j^2\right)}{q^2}\left[2Re(A_{\perp 0}^{R} A_{\perp 0}^{*L} + A_{\perp 1}^{R} A_{\perp 1}^{*L} + \{\perp \leftrightarrow \parallel\})\right] - \frac{\left(m_i^2 - m_j^2\right)^2}{4q^4}\left[\left(\left|A_{\parallel 1}^{R}\right|^2 + \left|A_{\perp 1}^{R}\right|^2 + \{R \leftrightarrow L\}\right) + 2\left(\left|A_{\parallel t}\right|^2 + |A_{\perp t}|^2\right)\right], \quad (3)$$

Role of Z' model:

As O_9' and O_{10}' are the electro-weak operators, so the modification in Z' model is done on the Wilson co-efficients C_9' and C_{10}' as,

$$C_9' = \frac{4\pi B_{sb}^L}{\alpha V_{tb} V_{ts}^*}\left(B_{l_1 l_2}^L + B_{l_1 l_2}^R\right),$$

$$C_{10}' = \frac{4\pi B_{sb}^L}{\alpha V_{tb} V_{ts}^*}\left(B_{l_1 l_2}^L - B_{l_1 l_2}^R\right).$$

The coupling parameters are taken as Table- 1

Scenarios	$\lvert B_{sb}\rvert \times 10^{-3}$	φ_s^l (in degree)
S_2	(1.09 ± 0.22)	$(-72 \pm 7)^\circ$
S_1	(2.20 ± 0.15)	$(-82 \pm 4)^\circ$

Table- 1: Numerical values of coupling parameters [arXiv: 0907.4408 [hep-ph]]

Numerical Analysis

- We have studied the variation of differential branching ratio with respect to the leptonic couplings within the whole kinematically accessible physical range of q^2. Here, we have made two considerations as,

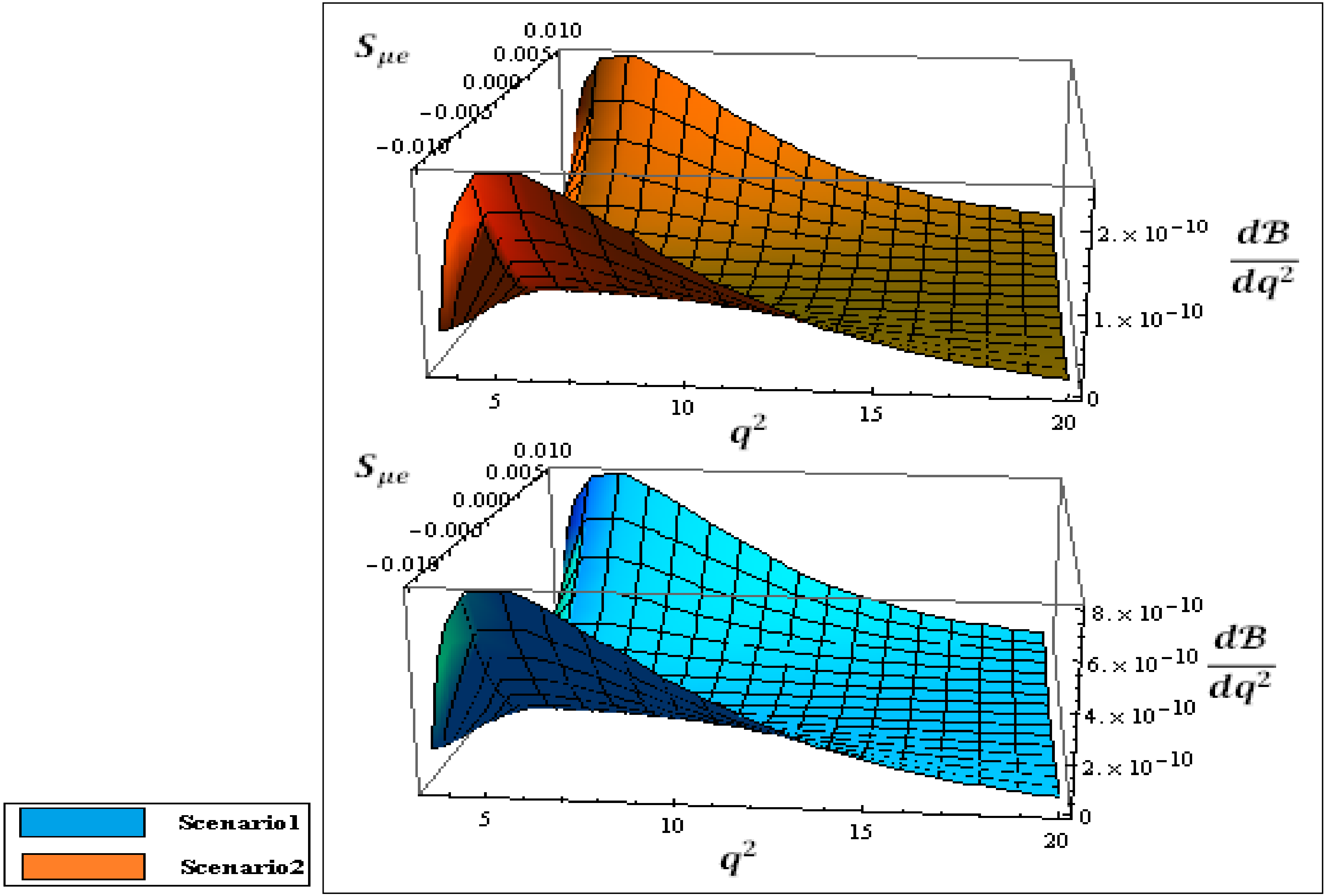
  i) we have formulated the leptonic couplings as: $S_{l_1 l_2} = \left(B^L_{l_1 l_2} + B^R_{l_1 l_2}\right)$ and $D_{l_1 l_2} = \left(B^L_{l_1 l_2} - B^R_{l_1 l_2}\right)$ and

  ii) $C_9' = -C_{10}'$.

- In Fig. 1 and Fig. 2 we have varied differential branching ratio with respect to NP couplings within allowed kinematic region of q^2 for $\Sigma_b \to \Sigma \mu^- e^+$and $\Sigma_b \to \Sigma \tau^- \mu^+$respectively.

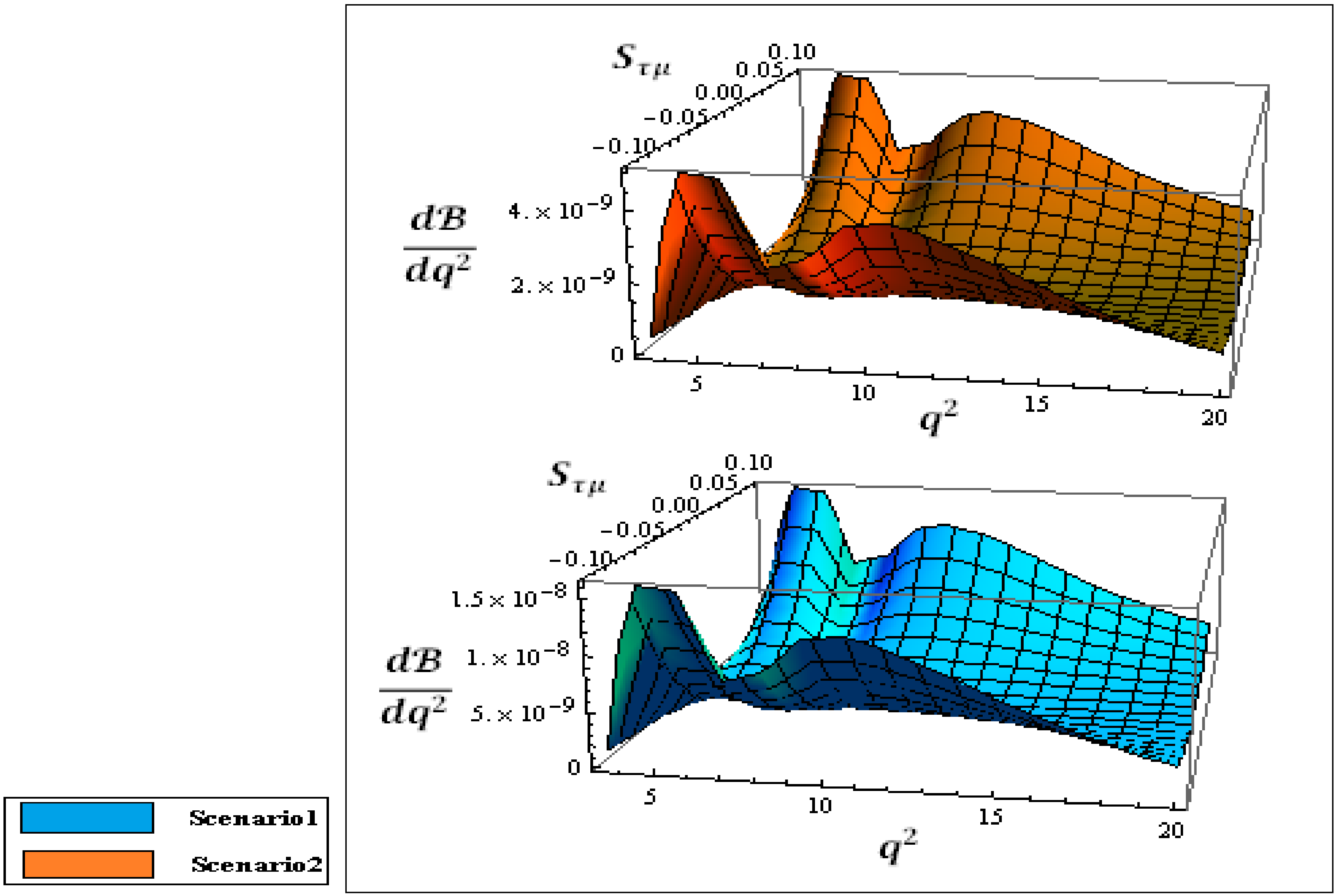
- In Fig. 1, we have taken the range of leptonic couplings from (-0.01) to 0.01 and in Fig. 2 from (-0.1) to 0.1 [Our previous work: ***Eur. Phys. J C*****, Vol. 81, pp: 493 (2021)**].

- To magnify the influence of NP in the observables we have considered the maximum values of the NP couplings $|B_{sb}|$ and φ_s^l.



$S_{\mu e}$
0.010
0.005
0.000
−0.005
−0.010
$2.\times 10^{-10}$
$1.\times 10^{-10}$
0
$\frac{dB}{dq^2}$
5
10
15
20
q^2
$S_{\mu e}$
0.010
0.005
0.000
−0.005
−0.010
$8.\times 10^{-10}$
$6.\times 10^{-10}$
$4.\times 10^{-10}$
$2.\times 10^{-10}$
0
$\frac{dB}{dq^2}$
5
10
15
20
q^2
Scenario1
Scenario2

Fig. 1



$S_{\tau\mu}$
0.10
0.05
0.00
-0.05
-0.10
$\frac{dB}{dq^2}$
$4.\times10^{-9}$
$2.\times10^{-9}$
0
5
10
15
20
q^2
$S_{\tau\mu}$
0.10
0.05
0.00
-0.05
-0.10
$\frac{dB}{dq^2}$
1.5×10^{-8}
$1.\times10^{-8}$
$5.\times10^{-9}$
0
5
10
15
20
q^2
Scenario1
Scenario2

Fig. 2

Numerical Analysis

The predicted values of differential branching ratios are recorded in Table-2.

Table-2 ⇨

Kinematic region $\left(q^2\right)$ (in GeV^2)	$d\mathcal{B}/dq^2$ for $\Sigma_b \to \Sigma\mu^- e^+$		$d\mathcal{B}/dq^2$ for $\Sigma_b \to \Sigma\tau^- \mu^+$	
	1st Scenario	2nd Scenario	1st Scenario	2nd Scenario
$q^2 = 6$	$\left(7.93 \times 10^{-10}\right)$	$\left(2.46 \times 10^{-10}\right)$	$\left(1.50 \times 10^{-8}\right)$	$\left(4.70 \times 10^{-9}\right)$
$q^2 = 12$	$\left(2.02 \times 10^{-10}\right)$	$\left(6.26 \times 10^{-11}\right)$	$\left(4.51 \times 10^{-9}\right)$	$\left(3.58 \times 10^{-9}\right)$
$q^2 = 18$	$\left(4.82 \times 10^{-11}\right)$	$\left(1.49 \times 10^{-11}\right)$	$\left(2.24 \times 10^{-9}\right)$	$\left(1.40 \times 10^{-9}\right)$

Conclusion

- The differential branching fraction value is greater at low q^2 region and the value gradually drops at high q^2 region. For $\Sigma_b \to \Sigma\tau^-\mu^+$ decay, there is a drop at $q^2 = 7$ GeV^2, then the value of the observable rises at $q^2 = 10.5$ GeV^2.

- Another thing is that the differential branching ratio enhances for scenario 1 which indicates the sensitivity of NP on the decay.

- The study of these LFV decays may fabricate the future of BSM physics more vibrantly and would help the experimental communities to access it at the LHCb.

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THANK YOU

Backups

Non-universal Z' model

In this thesis, we have incorporated an additional $U(1)'$ group with the SM gauge group and tried to explain the anomalies with the existence of a neutral gauge boson, Z' boson.

The neutral Z' boson is a colourless and short-lived particle. It is expected to observe Z' through its possible decay products or some interference effects.

Different NP theories and accelerators restrict the Z' mass differently.

Status of Z'boson at the accelerators:

- ✓ EW data of weak neutral current processes and mixing between $Z - Z'$: $M_{Z'} > \mathcal{O}(500)$ GeV [8]
- ✓ Tevatron: $M_{Z'} > \mathcal{O}(800)$ GeV [9]
- ✓ ATLAS Collab.: (i) $M_{Z'} \sim 0.5 - 2.5$ TeV; (ii) $M_{Z'_{SSM}} > 1.90$ TeV; (iii) $M_{Z'_{SFM}} > 1.82 - 2.17$ TeV [10] at $\sqrt{s} = 13$ TeV
- ✓ CMS Collab.: (i) $M_{Z'_{SSM}} > 4.50$ TeV; (ii) $M_{Z'_{\psi}} > 3.90$ TeV [11]

Status of Z'boson at theory:

- ✓ Sahoo et al.: $M_{Z'} \sim 1352 - 1665$ GeV [12]
- ✓ Oda et al.: $M_{Z'} \leq 6$ TeV
- ✓ Bandopadhyay et al.: $M_{Z'} > 4.4\,TeV$
- ✓ Recent data of B_s mixing: $M_{Z'} < 6$ TeV
- ✓ Luzio et al.: $M_{Z'} \leq 9$ TeV [13]

Constraints on LFV leptonic couplings

We have plotted the branching ratios for $b \to s\mu^+e^-$ and $b \to s\tau^+\mu^-$ transition according to their experimental bounds and found the constraints on $\mu - e - Z'$ coupling and $\tau - \mu - Z'$ coupling in Fig. (3a) and Fig. (3b) respectively.

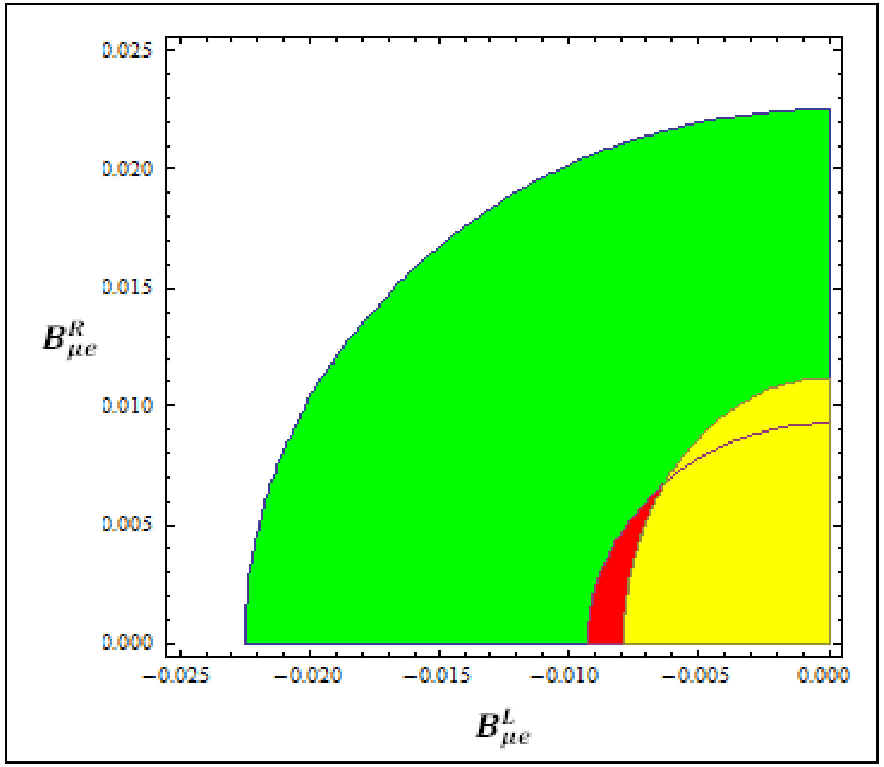

Fig. 3a

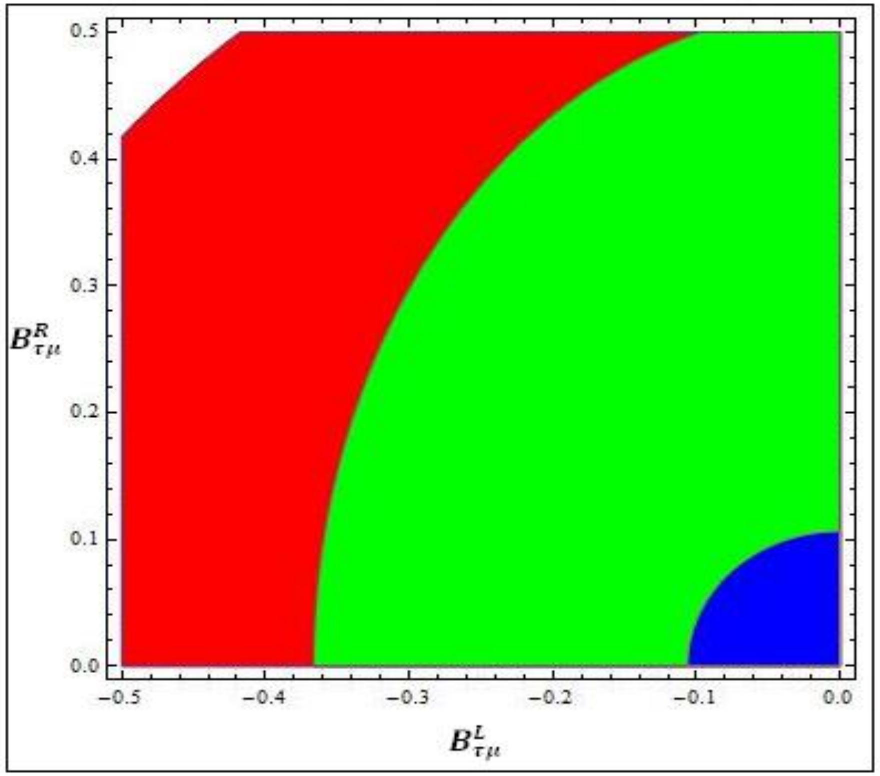

Fig. 3b

We have structured the Wilson coefficients incorporating NP terms as

$$C_9' = \frac{4\pi B_{sb}^L}{\alpha V_{tb} V_{ts}^*} \left(B_{l_1 l_2}^L + B_{l_1 l_2}^R\right),$$
$$C_{10}' = \frac{4\pi B_{sb}^L}{\alpha V_{tb} V_{ts}^*} \left(B_{l_1 l_2}^L - B_{l_1 l_2}^R\right).$$

$\Longrightarrow$

$$\left\{ \begin{array}{l} S_{l_1 l_2} = \left(B_{l_1 l_2}^L + B_{l_1 l_2}^R\right) \\ D_{l_1 l_2} = \left(B_{l_1 l_2}^L - B_{l_1 l_2}^R\right) \end{array} \right\}$$

✓ We have taken the following NP couplings in our investigation.

Table- 3: Maximum values of NP couplings

Quark couplings						
Scenarios	$\lvert B_{sb} \rvert$	φ_s^l	Leptonic couplings			
S_1	(1.31×10^{-3})	$(-65)^\circ$	$S_{\mu e}$	0.0079	$S_{\tau\mu}$	0.11
S_2	(2.35×10^{-3})	$(-78)^\circ$	$D_{\mu e}$	-0.0079	$D_{\tau\mu}$	-0.11