Published by Institute of Physics Publishing for SISSA
Received: *March 11, 2005*
Accepted: *April 13, 2005*
Published: *May 4, 2005*

The exclusive $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay with the fourth generation

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Abstract: The exclusive $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay is analyzed in the fourth generation model. We studied the sensitivity of the physical observables such as the branching ratio and the forward-backward asymmetry of this process to the model parameters, namely, the mass of the fourth generation up-type quark t' and the fourth generation CKM matrix element $V^*_{t's}V_{t'b}$ by using two possible solutions of the latter and the experimental results on branching ratios for $B_s \to X_s\gamma$ and $B_s \to X_c\ell\bar{\nu}$. It has been found that these observables are almost the same as the SM predictions when $V^*_{t's}V_{t'b}$ is positive. However, when it is negative, they are essentially very sensitive to the fourth generation model and can serve as efficient tools in search of the fourth generation.

Keywords: Beyond Standard Model,Rare Decays,Weak Decays.

Contents

1. Introduction

As is well known, the inclusive decays $B \to X_{s,d}\ell^+\ell^-$ and the corresponding exclusive processes, $B \to M\ell^+\ell^-$ with $M = K, K^*, \rho$, etc., are very sensitive to the flavor structure of the SM and have been studied in great detail by many authors (for a review see [1] and references therein). Being FCNC processes, they are forbidden in the Born approximation and hence are very useful for testing the various new physics scenarios like the two Higgs doublet models (2HDM) [2] , Minimal Supersymmetric extension of the SM (MSSM) [3], fourth generation models [4, 5], etc. For these reasons studying the transitions induced by the FCNC constitute one of the main research directions of the two operating B factories BaBar and Belle [6].

The $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay is another exclusive process which is described at quark level by the $b \to s\ell^+\ell^-$ transition. Being a baryonic decay, unlike mesonic case, it can maintain the helicity structure of the effective hamiltonian for the $b \to s$ transition and hence can provide information about the the handedness of these quarks. From experimental point of view, it is also promising since large number of Λ_b baryons are expected to be produced in Tevatron, LHC, etc., which will make it possible to check the model predictions of its various decay channels. In addition, as mentioned before, the "heavy meson" $\to$ "light meson" transitions like $B \to K(K^*)\ell\bar{\ell}$ decays have been studied systematically in both the SM and beyond. It is now natural to ask which physical quantity is the most sensitive to the new physics in the "heavy baryon" $\to$ "light baryon" case. Indeed, there are quite a lot of studies that have been considered baryonic $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay in the framework of the SM, 2HDM, MSSM and also in a model independent way in the literature. The SM and the new physics effects on the differential decay rates and various polarization asymmetries of the $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay under the approximation of the HQET can be found in [7−10]. In addition, time-reversal violating effects with polarized Λ are investigated in [11] and shown that the transverse Λ polarization can be as large as 50% in SUSY theories. There are also a number of model independent analysis of the various physical observables associated with the exclusive $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay [12−16], which reports the mode as a very useful tool for establishing the new physics as well as discussing the magnitude and the sign of the various Wilson coefficients.

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In this paper we investigate the exclusive process $\Lambda_b \to \Lambda\,\ell^+\ell^-$ in the so-called four generation SM. The main motivation of this model comes from the fact that the SM does not fix the number of generations. In addition, flavor democracy favors the four generation case for the SM [17]. Moreover, there is not any experimental evidence that excludes such extra generations provided that neutrino of this generation is heavy, i.e., $m_{\nu'} \geq m_Z/2$ [18]. The possible results of fourth generation in low energy physics have been researched in many works (see for example [19 − 25]). In refs. [26 − 32], contribution of the fourth generation to the electroweak radiative corrections were considered. Even the possibility of only fourth generation quarks and neutrino were considered in [33] and [34], respectively.

Although there are several theoretical schemes to introduce the fourth generation in the SM, since experimental evidence show that SM works extremely well, it would be interesting to consider its most economical and simple version [5]. In this model, limited to the non-SUSY case, it is introduced an up-like quark t', a down-like quark b', a lepton τ' and a heavy neutrino ν' in the SM. The properties of these new fermions are all the same as their corresponding counterparts of other three generations except their masses and the CKM mixings. The effects of the fourth generation to rare decays have been also studied in many works [35 − 41].

It is well known that the main theoretical uncertainty related to the exclusive processes in general are related to decay form factors, i.e., the matrix elements of the effective hamiltonian between the initial and the final mesons or baryons. In case of baryonic $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay, although there are also a lot of form factors to describe the matrix elements for $\Lambda_b \to \Lambda$, as being a heavy-to-light decay, one can use the heavy quark effective theory (HQET), in which the heavy symmetries restrict the number of form factors. Although these heavy quark symmetries are expected to work best at the point of maximal momentum transfer, whereas the phase space of the decay under consideration is at the opposite side of the spectrum, heavy quark symmetry is still used as a reasonable model assumption for the form factors. Indeed, it has been shown that this procedure greatly simplifies the analysis and reduces the number of form factors to two [42 − 46].

The paper is organized as follows: In section 2, we present the necessary theoretical expressions for the $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay, such as the QCD corrected effective hamiltonian and baryonic matrix elements in terms of the related form factors, as well as the expressions of the physical observables we investigate in this work, namely, differential branching ratio and forward-backward asymmetry for the decay $\Lambda_b \to \Lambda\,\ell^+\ell^-$. Section 3 is devoted to the numerical analysis and its discussion.

2. Effective hamiltonian and the form factors

At the quark level $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay is induced by the transition $b \to s\ell^+\ell^-$, which is, in the SM, described by the effective hamiltonian

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}}\, V_{ts}^* V_{tb} \left\{ \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu) \right\}, \qquad (2.1)$$

where the expressions of the operators $O_i(\mu)$ and corresponding renormalized Wilson coefficients $C_i(\mu)$ can be found in [47, 48]. Neglecting the mass of the s quark, from eq. (2.1), free quark decay amplitude is written as

$$\mathcal{M} = \frac{\alpha\, G_F}{2\sqrt{2}\pi} V_{ts}^* V_{tb} \Big\{ C_9^{\rm eff}(\mu)\ \bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma^\mu\ell + C_{10}(\mu)\ \bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma^\mu\gamma_5\ell - \\ - 2C_7^{\rm eff}(\mu)\ \frac{m_b}{q^2}\bar{s}i\sigma_{\mu\nu}q^\nu(1+\gamma_5)b\,\bar{\ell}\gamma^\mu\ell \Big\}, \tag{2.2}$$

where $q = p_{\Lambda_b} - p_\Lambda$ is the momentum transfer. We note that besides the short-distance (SD) contributions, long-distance (LD) ones such as that from $\bar{c}c$ resonant states of $\psi, \psi', \ldots$ etc. are also important for the decay rate. Assuming that in $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decays the parametrization of the contributions from LD effects is the same as that in the B-meson decays, it is possible to include them through the redefinition of the corresponding Wilson coefficient:

$$C_9^{\rm eff}(\mu) \to C_9^{pert}(\mu) + Y_{reson}(\hat{s}')\,, \tag{2.3}$$

where

$$Y_{\rm reson}(\hat{s}') = -\frac{3\pi}{\alpha^2}\kappa \sum_{V_i=\psi_i} \frac{\Gamma(V_i \to \ell^+\ell^-) m_{V_i}}{\hat{s}' m_b^2 - m_{V_i} + i m_{V_i}\Gamma_{V_i}} \times \\ \times [3C_1(\mu) + C_2(\mu) + 3C_3(\mu) + C_4(\mu) + 3C_5(\mu) + C_6(\mu)]\,, \tag{2.4}$$

and

$$C_9^{pert}(\mu) = C_9^{SM}(\mu) + h(\tilde{z},\hat{s}')[3C_1(\mu) + C_2(\mu) + 3C_3(\mu) + C_4(\mu) + 3C_5(\mu) + C_6(\mu)] - \\ -\frac{1}{2}h(1,\hat{s}')\,(4C_3(\mu) + 4C_4(\mu) + 3C_5(\mu) + C_6(\mu)) - \\ -\frac{1}{2}h(0,\hat{s}')\,[C_3(\mu) + 3C_4(\mu)] + +\frac{2}{9}\,(3C_3(\mu) + C_4(\mu) + 3C_5(\mu) + C_6(\mu))\,, \tag{2.5}$$

$\hat{s}' = q^2/m_b^2$ and $\tilde{z} = m_c/m_b$. The functions $h(\tilde{z},\hat{s}')$ arise from the one loop contributions of the four quark operators O_1,...,O_6 and their explicit forms can be found in [47, 48]. The phenomenological parameter κ in eq. (2.4) is determined so as to reproduce the correct value of the branching ratio $BR(\Lambda_b \to \Lambda\ J/\psi\ \to \Lambda\ell^+\ell^-) = BR(\Lambda_b \to \Lambda\ J/\psi) BR(J/\psi \to\ \ell^+\ell^-)$. It is possible to show that κ factors in the Λ_b case are almost the same as that in the B meson one [8].

As noted in section 1, in the model we consider in this work, the fourth generation is introduced in the same way as the three generations in the SM. Hence the operator basis is exactly the same as in the SM while the values of Wilson coefficients in eq. (2.2) changes according to

$$C_7^{\rm eff} \to C_7^{eff\,SM} + \frac{V_{t's}^* V_{t'b}}{V_{ts}^* V_{tb}} C_7'\,, \\ C_9^{\rm eff} \to C_9^{eff\,SM} + \frac{V_{t's}^* V_{t'b}}{V_{ts}^* V_{tb}} C_9'\,, \\ C_{10} \to C_{10}^{SM} + \frac{V_{t's}^* V_{t'b}}{V_{ts}^* V_{tb}} C_{10}'\,, \tag{2.6}$$

where $V_{t'b}$ and $V_{t's}$ are the elements of 4×4 Cabibbo-Kobayashi-Maskawa (CKM) matrix. In the above expressions, primed terms C_i' describe the contribution of the fourth generation up quark t' at the loop level, which can be easily obtained from the corresponding SM counterparts by the substitution, $m_t \to m_{t'}$.

Now, we calculate the branching ratio (BR) and the forward-backward asymmetry (A_{FB}) of the $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay in the fourth generation model. In order to find these physically measurable quantities at hadronic level, we need the matrix elements $\langle\Lambda(p_\Lambda)|\bar{s}\gamma_\mu(1-\gamma_5)b|\Lambda_b(p_{\Lambda_b})\rangle$ and $\langle\Lambda(p_\Lambda)|\bar{s}i\sigma_{\mu\nu}q^\nu(1+\gamma_5)b|\Lambda_b(p_{\Lambda_b})\rangle$, which are generally parametrized in the following way [8, 10, 49]

$$\begin{aligned}\langle\Lambda\,|\bar{s}\gamma_\mu(1-\gamma_5)b|\,\Lambda_b\rangle &= \bar{u}_\Lambda\Big[(f_1-\gamma_5 g_1)\gamma_\mu + i(f_2-\gamma_5 g_2)\sigma_{\mu\nu}q^\nu + (f_3-\gamma_5 g_3)q_\mu\Big]u_{\Lambda_b}\,,\\ \langle\Lambda\,|\bar{s}i\sigma_{\mu\nu}q^\nu(1+\gamma_5)b|\,\Lambda_b\rangle &= \bar{u}_\Lambda\Big[(f_1^T+g_1^T\gamma_5)\gamma_\mu + i(f_2^T+g_2^T\gamma_5)\sigma_{\mu\nu}q^\nu + \\ &\qquad + (f_3^T+g_3^T\gamma_5)q_\mu\Big]u_{\Lambda_b}\,. \end{aligned} \tag{2.7}$$

As seen from these equations, there are 12 form factors to describe the $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decays. However, as being a "heavy $\to$ light" transition, one can make use of the following relation, which results from using the HQET [42–44]

$$\langle\Lambda(p_\Lambda)\,|\bar{s}\Gamma b|\,\Lambda(p_{\Lambda_b})\rangle = \bar{u}_\Lambda\Big[F_1(q^2) + \not{v}F_2(q^2)\Big]\Gamma u_{\Lambda_b}\,, \tag{2.8}$$

where Γ is an arbitrary Dirac structure and $v^\mu = p^\mu_{\Lambda_b}/m_{\Lambda_b}$ is the four-velocity of Λ_b. By comparing the general form of the form factors with (2.8), one can obtain [8, 10, 49]

$$\begin{aligned} g_1 = f_1 = f_2^T = g_2^T &= F_1 + \sqrt{r}F_2\,,\\ g_2 = f_2 = g_3 = f_3 &= \frac{F_2}{m_{\Lambda_b}}\,,\\ g_1^T = f_1^T &= \frac{F_2}{m_{\Lambda_b}}q^2\,, \qquad g_3^T = \frac{F_2}{m_{\Lambda_b}}\left(m_{\Lambda_b}+m_\Lambda\right)\,,\\ f_3^T &= -\frac{F_2}{m_{\Lambda_b}}\left(m_{\Lambda_b}-m_\Lambda\right)\,, \end{aligned} \tag{2.9}$$

where $r = m_\Lambda^2/m_{\Lambda_b}^2$, which greatly simplifies the analysis by reducing the number of form factors to two, F_1 and F_2.

Using (2.7)-(2.9), we can put the the matrix element of the $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decays in eq. (2.2) into the following form:

$$\begin{aligned}\mathcal{M} = \frac{\alpha\,G_F}{4\sqrt{2}\pi}V_{ts}^*V_{tb}\bigg\{&\bar{\ell}\gamma^\mu\ell\,\bar{u}_\Lambda\Big[A_1\gamma_\mu(1+\gamma_5) + B_1\gamma_\mu(1-\gamma_5) + \\ &\qquad + i\sigma_{\mu\nu}q^\nu[A_2(1+\gamma_5)+B_2(1-\gamma_5)] + \\ &\qquad + q_\mu[A_3(1+\gamma_5)+B_3(1-\gamma_5)]\Big]u_{\Lambda_b} + \\ &+ \bar{\ell}\gamma^\mu\gamma_5\ell\,\bar{u}_\Lambda\Big[E_1\,\gamma_\mu(1-\gamma_5) + iE_2\,\sigma_{\mu\nu}q^\nu(1-\gamma_5) + E_3\,q_\mu(1-\gamma_5)\Big]u_{\Lambda_b}\bigg\}\,,\end{aligned} \tag{2.10}$$

where

$$
\begin{aligned}
A_1 &= -\frac{4m_b}{m_{\Lambda_b}}\, F_2\, C_7^{\rm eff}\,, \\
B_1 &= 2(F_1 + \sqrt{r}F_2)\, C_9^{\rm eff}\,, \\
A_2 &= -\frac{4m_b}{q^2}\, (F_1 + \sqrt{r}F_2)\, C_7^{\rm eff}\,, \\
B_2 &= \frac{2F_2}{m_{\Lambda_b}}\, C_9^{\rm eff}\,, \\
A_3 &= -\frac{4m_b m_\Lambda}{q^2 m_{\Lambda_b}}\, F_2\, C_7^{\rm eff}\,, \\
B_3 &= \frac{4m_b}{q^2}\, F_2\, C_7^{\rm eff} \\
E_1 &= 2(F_1 + \sqrt{r}F_2)\, C_{10}\,, \\
E_2 &= E_3 = \frac{2F_2}{m_{\Lambda_b}}\, C_{10}\,.
\end{aligned}
\tag{2.11}
$$

After some standard algebra, the matrix element in eq. (2.10) leads to the following double differential decay rate

$$
\frac{d^2\Gamma}{d\hat{s}dz} = \frac{\alpha^2 G_F^2 m_{\Lambda_b}^3}{2^{12}\pi^5}\, |V_{tb}V_{ts}^*|^2\, v\sqrt{\lambda}\, \Big(\mathcal{T}_0(\hat{s}) + \mathcal{T}_1(\hat{s})z + \mathcal{T}_2(\hat{s})z^2\Big)\,. \tag{2.12}
$$

Here $\lambda = -1 + r^2 + \hat{s}^2 - 2r - 2\hat{s} - 2r\hat{s}$, $v = \sqrt{1 - \frac{4(m_\ell/m_{\Lambda_b})^2}{\hat{s}}}$, $\hat{s} = q^2/m_{\Lambda_b}^2$, $z = \cos\theta$, where θ is the angle between the three-momentum of the ℓ^- lepton and that of the Λ_b-meson in the center of mass frame of the dileptons $\ell^+\ell^-$, and the functions $\mathcal{T}_0(\hat{s}), \mathcal{T}_1(\hat{s})$ and $\mathcal{T}_2(\hat{s})$ are given by

$$
\begin{aligned}
\mathcal{T}_0(\hat{s}) &= 8m_\ell^2 m_{\Lambda_b}^2 \hat{s}(1 + r - \hat{s})\,|E_3|^2 + 16m_\ell^2 m_{\Lambda_b}\sqrt{r}\Big((1 - r + \hat{s})\mathrm{Re}[E_1^* E_3]\Big) + \\
&\quad +8(2m_\ell^2 + m_{\Lambda_b}^2\hat{s})\Big\{(1 - r + \hat{s})m_{\Lambda_b}\sqrt{r}\,\mathrm{Re}[A_1^* A_2 + B_1^* B_2] - \\
&\qquad - m_{\Lambda_b}(1 - r - \hat{s})\mathrm{Re}[A_1^* B_2 + A_2^* B_1] - \\
&\qquad - 2\sqrt{r}\Big(\mathrm{Re}[A_1^* B_1] + m_{\Lambda_b}^2\hat{s}\mathrm{Re}[A_2^* B_2]\Big)\Big\} + \\
&\quad +2\Big(4m_\ell^2(1 + r - \hat{s}) + m_{\Lambda_b}^2\Big[(1 - r)^2 - \hat{s}^2\Big]\Big)\,\Big(|A_1|^2 + |B_1|^2\Big) + \\
&\quad +2m_{\Lambda_b}^2\Big(4m_\ell^2\Big[\lambda + (1 + r - \hat{s})\hat{s}\Big] + m_{\Lambda_b}^2\hat{s}\Big[(1 - r)^2 - \hat{s}^2\Big]\Big)\,\Big(|A_2|^2 + |B_2|^2\Big) - \\
&\quad -2\Big(4m_\ell^2(1 + r - \hat{s}) - m_{\Lambda_b}^2\Big[(1 - r)^2 - \hat{s}^2\Big]\Big)\,|E_1|^2 + \\
&\quad +2m_{\Lambda_b}^3\hat{s}v^2\Big(4(1 - r + \hat{s})\sqrt{r}\,\mathrm{Re}[E_1^* E_2] - m_{\Lambda_b}\Big[(1 - r)^2 - \hat{s}^2\Big]\,|E_2|^2\Big)\,,
\end{aligned}
\tag{2.13}
$$

$$
\begin{aligned}
\mathcal{T}_1(\hat{s}) &= -8m_{\Lambda_b}^2\sqrt{\lambda}\; v\,\hat{s}\Big\{\mathrm{Re}[B_1^* E_1] - m_{\Lambda_b}\mathrm{Re}[A_2^* E_1 - A_1^* E_2] + \\
&\qquad + m_{\Lambda_b}^2(1 - r)\mathrm{Re}[B_2^* E_2] - m_{\Lambda_b}\sqrt{r}\mathrm{Re}[B_2^* E_1 + B_1^* E_2]\Big\}\,,
\end{aligned}
\tag{2.14}
$$

$$
\mathcal{T}_2(\hat{s}) = -2m_{\Lambda_b}^2 v^2\lambda\,\Big(|A_1|^2 + |B_1|^2 + |E_1|^2 - m_{\Lambda_b}^2\hat{s}\,\left(|A_2|^2 + |B_2|^2 + |E_2|^2\right)\Big)\,. \tag{2.15}
$$

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The lepton forward-backward asymmetry A_{FB} is another observable that can give more precise information at hadronic level. Since the new physics effects can shift the position of the zero value of A_{FB}, it may be a powerful tool for investigating the physics beyond the SM. We write definition of normalized A_{FB} as

$$A_{FB}(\hat{s}) = \frac{\int_0^1 dz \frac{d\Gamma}{dz} - \int_{-1}^0 dz \frac{d\Gamma}{dz}}{\int_0^1 dz \frac{d\Gamma}{dz} + \int_{-1}^0 dz \frac{d\Gamma}{dz}} . \tag{2.16}$$

For the $\Lambda_b \to \Lambda \, \ell^+\ell^-$ decay, it is calculated to be

$$A_{FB}(\hat{s}) = \frac{1}{2} \frac{\Big(v \, \sqrt{\lambda} \, \mathcal{T}_1(\hat{s})\Big)}{\Big(v \, \sqrt{\lambda} \, (\mathcal{T}_0(\hat{s}) + \frac{1}{3}\mathcal{T}_2(\hat{s}))\Big)} . \tag{2.17}$$

We finally note that we can also discuss the channel $\Lambda_b \to \Lambda \bar{\nu}\nu$ by performing the following replacements in the expressions obtained for $\Lambda_b \to \Lambda \, \ell^+\ell^-$ decay:

$$m_\ell \to 0 \, , \quad C_7^{\rm eff} \to 0 \, , \quad C_9^{\rm eff} \to \frac{X(x_t)}{\sin^2\theta_W} \, , \quad C_{10} \to -C_9^{\rm eff} \, , \tag{2.18}$$

where [50]

$$X(x_t) = \frac{x_t}{8} \left[\frac{x_t + 2}{x_t - 1} + 3 \frac{x_t - 2}{(x_t - 1)^2} \log x_t \right] , \tag{2.19}$$

with $x_t = m_t^2/m_W^2$. Then, we explicitly have

$$\frac{d^2\Gamma^{\nu\nu}}{d\hat{s}dz} = 3 \frac{\alpha^2 G_F^2 m_{\Lambda_b}^3}{2^{12}\pi^5} \left| V_{ts}^* V_{tb} \right|^2 \sqrt{\lambda} \, (\mathcal{T}_0^{\nu\nu}(\hat{s}) + \mathcal{T}_1^{\nu\nu}(\hat{s}) z + \mathcal{T}_2^{\nu\nu}(\hat{s}) z^2) \, , \tag{2.20}$$

where

$$\begin{aligned}
\mathcal{T}_0^{\nu\nu}(\hat{s}) &= 2m_{\Lambda_b}^2 \Big\{ 4m_{\Lambda_b}\sqrt{r}(1 - r + \hat{s}) \Big(\hat{s}{\rm Re}[B_1^* B_2] + {\rm Re}[E_1^* E_2] \Big) + ((1-r)^2 - \hat{s}^2) \times \\
&\quad \times \Big(|B_1|^2 + |E_1|^2 + m_{\Lambda_b}^2 \hat{s} (|B_2|^2 - |E_2|^2) \Big) \Big\} \, , &(2.21)\\
\mathcal{T}_1^{\nu\nu}(\hat{s}) &= -8m_{\Lambda_b}^2 \sqrt{\lambda} \, \hat{s} \Big\{ {\rm Re}[B_1^* E_1] + m_{\Lambda_b}^2 (1-r) {\rm Re}[B_2^* E_2] - \\
&\quad - m_{\Lambda_b}\sqrt{r} {\rm Re}[B_2^* E_1 + B_1^* E_2] \Big\} \, , &(2.22)\\
\mathcal{T}_2^{\nu\nu}(\hat{s}) &= -2m_{\Lambda_b}^2 \lambda \Big(|B_1|^2 + |E_1|^2 - m_{\Lambda_b}^2 \hat{s} \, (|A_2|^2 + |B_2|^2 + |E_2|^2) \Big) \, . &(2.23)
\end{aligned}$$

3. Numerical results and discussion

In this section we present the numerical analysis of the exclusive $\Lambda_b \to \Lambda \, \ell^+\ell^-$ decay in the fourth generation model. The input parameters we used in this analysis are as follows:

$$\begin{aligned}
m_{\Lambda_b} &= 5.624 \, GeV \, , \; m_\Lambda = 1.116 \, GeV \, , \; m_b = 4.8 \, GeV \, , \; m_c = 1.35 \, GeV \, , \; m_\tau = 1.778 \, GeV \\
m_\mu &= 0.105 \, GeV \, , \; |V_{tb}V_{ts}^*| = 0.045 \, , \; \alpha^{-1} = 129 \, , \; G_F = 1.166 \times 10^{-5} \, GeV^{-2} \, , \\
\kappa &= 2.3 \, , \; BR(B \to X_s\gamma) = 3.15 \times 10^{-4} \, , \; BR(B \to X_c e\bar{\nu}) = 0.104 \, . &(3.1)
\end{aligned}$$

As for the form factors of the $\Lambda_b \to \Lambda$ transition, we use the results from QCD sum rule approach in combination with HQET [42, 51], which can be written in the following form

$$F(\hat{s}) = \frac{F(0)}{1 - a_F\ \hat{s} + b_F \hat{s}^2}\,, \qquad (3.2)$$

where the values of the parameters $F(0)$, a_F and b_F are given in table 1.

	$F(0)$	a_F	b_F
F_1	0.462	-0.0182	-0.000176
F_2	-0.077	-0.0685	0.00146

Table 1: The form factors of the transition $\Lambda_b \to \Lambda$ calculated in the QCD sum rule approach.

We note that there are five possible resonances in the $c\bar{c}$ system that can contribute to the decay under consideration and to calculate them, we need to divide the integration region for $\hat{s}$ into three parts for $\ell = e, \mu$ so that we have $4m_\ell^2/m_{\Lambda_b}^2 \le \hat{s} \le (m_{\psi_1} - 0.02)^2/m_{\Lambda_b}^2$, $(m_{\psi_1} + 0.02)^2/m_{\Lambda_b}^2 \le \hat{s} \le (m_{\psi_2} - 0.02)^2/m_{\Lambda_b}^2$ and $(m_{\psi_2} + 0.02)^2/m_{\Lambda_b}^2 \le \hat{s} \le (m_{\Lambda_b} - m_\Lambda)^2/m_{\Lambda_b}^2$, while for $\ell = \tau$ it takes the form given by $4m_\tau^2/m_{\Lambda_b}^2 \le \hat{s} \le (m_{\psi_2} - 0.02)^2/m_{\Lambda_b}^2$ and $(m_{\psi_2} + 0.02)^2/m_{\Lambda_b}^2 \le \hat{s} \le (m_B - m_\Lambda)^2/m_{\Lambda_b}^2$. Here, m_{ψ_1} and m_{ψ_2} are the masses of the first and the second resonances, respectively.

The values of the mass of the fourth generation up-type quark $m_{t'}$ and the fourth generation CKM matrix element $V_{t's}^* V_{t'b}$ remain as free parameters of the model. It is possible to obtain some restrictions on these quantities from the existing experimental data. We should also note that existence of extra generations can affect present constraints on CKM matrix elements to some extend and therefore they should be calculated with the possibility of a new family using present experiments. Along this line, in [54], using the measured values on BRs of $B \to X_s \gamma$ and $B \to K(K^*)\ell\bar{\ell}$ decays, together with the unitarity condition, allowed regions for $|V_{tb}V_{ts}^*|$ and $|V_{t'b}V_{t's}^*|$ are determined as a function of the t' quark mass. The main conclusion from this analysis is that $0.036 \le |V_{tb}V_{ts}^*| \le 0.044$, while $|V_{t'b}V_{t's}^*|$ are mainly distributed around 0.01. Since the SM value $V_{tb}V_{ts}^* = 0.045$ is very close being in this range, in our numerical calculations we have fixed it by this value.

Now, in order to constrain the CKM factor $V_{t's}^* V_{t'b}$ as a function of the t' quark mass we follow the approach in ref. [37], which uses the experimental results on $B \to X_s \gamma$ and $B \to X_c e \bar{\nu}_e$ decays. For this, we first write, in the leading logarithmic approximation

$$R = \frac{\mathcal{B}(B \to X_s \gamma)}{\mathcal{B}(B \to X_c e \bar{\nu}_e)} = \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2}\,\frac{6\alpha\,|C_7^{\rm eff}|^2}{\pi f(\hat{m}_c)\kappa(\hat{m}_c)}\,, \qquad (3.3)$$

where $\hat{m}_c = m_c/m_b$ and the phase factor $f(\hat{m}_c)$ and $\mathcal{O}(\alpha_s)$ QCD correction factor $\kappa(\hat{m}_c)$ [52] of $b \to c\ell\bar{\nu}$ are given by

$$\begin{aligned} f(\hat{m}_c) &= 1 - 8\hat{m}_c^2 + 8\hat{m}_c^6 - \hat{m}_c^8 - 24\hat{m}_c^4 \ln(\hat{m}_c)\,, \\ \kappa(\hat{m}_c) &= 1 - \frac{2\alpha_s(m_b)}{3\pi}\left[\left(\pi^2 - \frac{31}{4}\right)(1 - \hat{m}_c)^2 + \frac{3}{2}\right]. \end{aligned} \qquad (3.4)$$

Then, substituting eq. (2.6) into eq. (3.3) and solving it for $V_{t's}^* V_{t'b}$, we get

$$V_{t's}^* V_{t'b}^{(\pm)} = \left[\pm\sqrt{\frac{\pi R\,|V_{cb}|^2 f(\hat{m}_c)\kappa(\hat{m}_c)}{6\alpha\,|V_{ts}^* V_{tb}|^2}} - C_7^{effSM}\right]\frac{V_{ts}^* V_{tb}}{C_7'}\,, \qquad (3.5)$$

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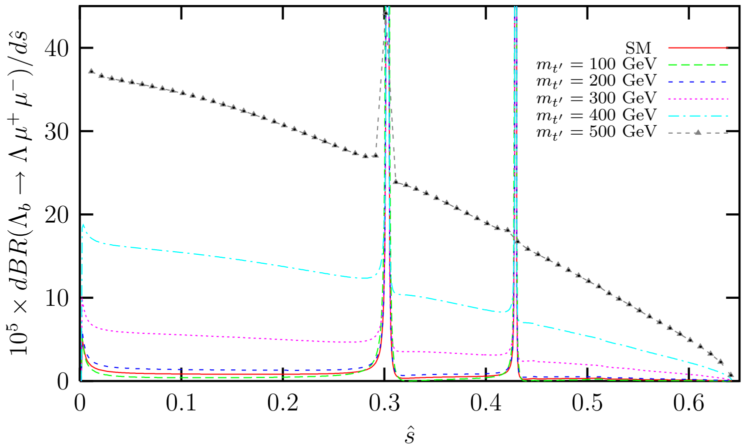

Figure 1: The differential BRs of $\Lambda_b \to \Lambda\mu^+\mu^-$ as a function of $\hat{s}$ at different values of $m_{t'}$ for $V_{t's}^* V_{t'b}^{(+)}$ solution of eq. (3.5)

where the superscripts (+) and (−) correspond to the respective signs in front of the square root. The values of $V_{t's}^* V_{t'b}$ for different choices of the $m_{t'}$ are listed in table 2.

$m_{t'}$ (GeV)	50	100	200	300	400	500
$V_{t's}^* V_{t'b}^{(+)} \times 10^2$	−13.22	−10.77	−8.88	−8.17	−7.82	−7.62
$V_{t's}^* V_{t'b}^{(-)} \times 10^3$	2.55	2.07	1.71	1.57	1.50	1.47

Table 2: The numerical values of $V_{t's}^* V_{t'b}$ for different values of $m_{t'}$.

We note that with the values of the CKM matrix elements in the SM [53], the values of $V_{t's}^* V_{t'b}^{(\pm)}$ satisfy the unitarity condition of the CKM matrix, given by

$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} + V_{t's}^* V_{t'b} = 0\,, \tag{3.6}$$

since the first three terms is about $7.6 \times 10^{-2} \pm 0.6 \times 10^{-2}$ provided that $V_{t's}^* V_{t'b}$ is within this error range.

In the following, we give the results of our calculations about the dependencies of the differential branching ratio $dBR/d\hat{s}$ and differential forward-backward asymmetry $A_{FB}(\hat{s})$ of the $\Lambda_b \to \Lambda\ell^+\ell^-$ decays for $\ell = \mu, \tau, \nu$ on the dimensionless momentum transfer $\hat{s}$, and also dependencies of the BR on the model parameters. The results are presented by a series of graphs for $V_{t's}^* V_{t'b}^{(+)}$ and $V_{t's}^* V_{t'b}^{(-)}$ solutions of eq. (3.5).

In figures 1–3, we plot the differential BRs of $\Lambda_b \to \Lambda\ell^+\ell^-$ decays for $\ell = \mu, \tau, \nu$ as a function of $\hat{s}$ at different values of $m_{t'}$ for $V_{t's}^* V_{t'b}^{(+)}$ solution of eq. (3.5). We also present the dependence of the integrated BRs of these decay channels on $m_{t'}$ in figures 4–6. From these figures we see that the SM prediction can be strongly enhanced by the fourth generation model for the choice $V_{t's}^* V_{t'b}^{(+)}$ and this enhancement increases with the increasing values of $m_{t'}$. For example, at $m_{t'} = 300\,\text{GeV}$, the BRs are enhanced 5 (6.5) times in comparison to the SM predictions for μ, τ (ν) channels. We also observe from these figures that values for the BRs predicted by the fourth generation model is less than those by the SM when $m_{t'} \le m_t$ for all channels.

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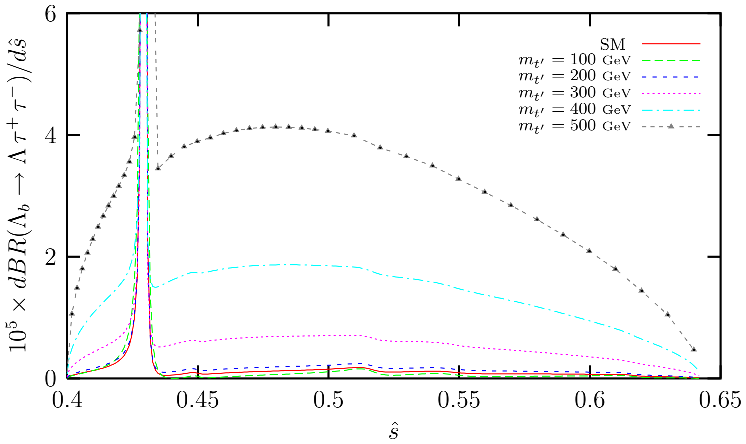

Figure 2: The same as figure (1), but for the decay $\Lambda_b \to \Lambda \tau^+ \tau^-$.

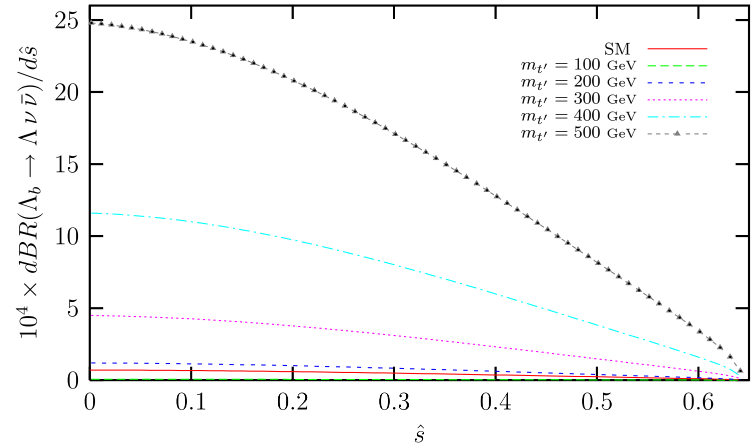

Figure 3: The same as figure (1), but for the decay $\Lambda_b \to \Lambda \nu \bar{\nu}$.

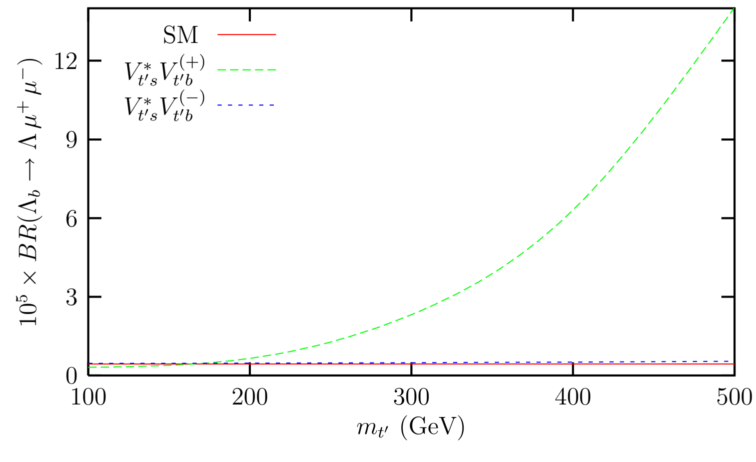

Figure 4: The integrated BRs of $\Lambda_b \to \Lambda \mu^+ \mu^-$ as a function of $m_{t'}$.

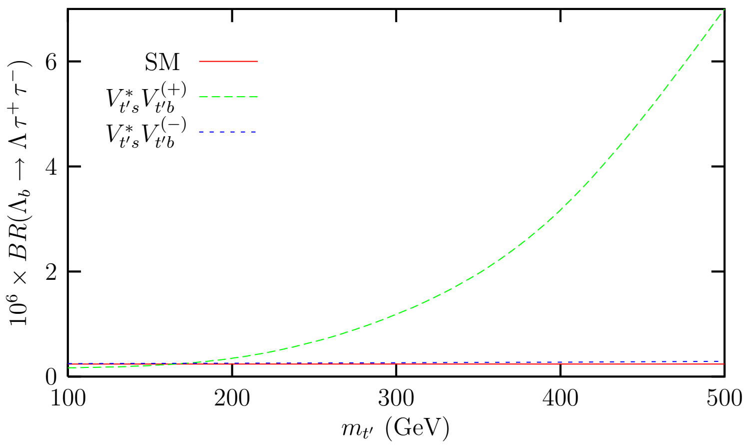

Figure 5: The same as figure (4), but for the decay $\Lambda_b \to \Lambda \tau^+ \tau^-$.

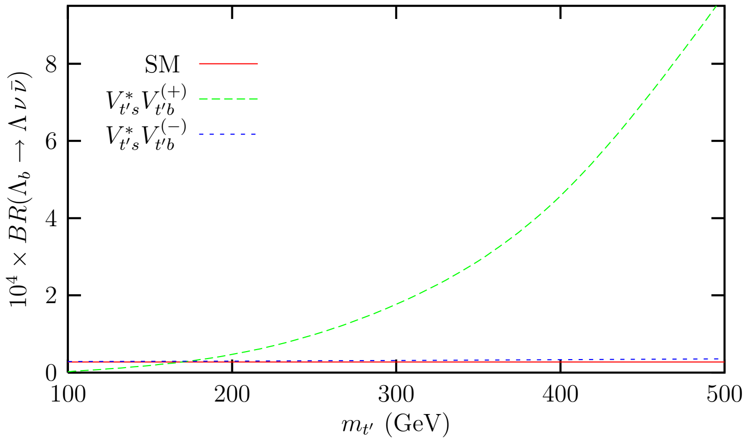

Figure 6: The same as figure (4), but for the decay $\Lambda_b \to \Lambda \nu \bar{\nu}$.

The dependence of the $A_{FB}(\hat{s})$ of $\Lambda_b \to \Lambda \ell^+ \ell^-$ decays for $\ell = \mu, \tau$ on $\hat{s}$ at different values of $m_{t'}$ for $V_{t's}^* V_{t'b}^{(+)}$ solution of eq. (3.5) are presented in figures 7 and 8. We observe that $A_{FB}(\hat{s})$ is also very sensitive to the fourth generation effects for the choice $V_{t's}^* V_{t'b}^{(+)}$. We note that, for $m_{t'}$, in addition to the values considered for BRs calculations, we have also considered the value $m_{t'} = 50\,\mathrm{GeV}$. While this choice does not produce anything interesting for the BRs, for $A_{FB}(\hat{s})$, its behavior is very different from all other choices of $m_{t'}$. As it is seen from figures 7 and 8, when $m_{t'} = 50\,\mathrm{GeV}$, A_{FB} is completely opposite to the SM prediction and can have positive values for both channels, μ and τ, while this is not possible for the other choices of $m_{t'}$. Therefore, experimental determination of the sign of A_{FB} can be very useful for establishing new physics.

In figures 9–13, we plot the differential BRs and $A_{FB}(\hat{s})$ for $\Lambda_b \to \Lambda \ell^+ \ell^-$ decays for $\ell = \mu, \tau, \nu$ as a function of $\hat{s}$ at different values of $m_{t'}$ for $V_{t's}^* V_{t'b}^{(-)}$ solution of eq. (3.5). We see from these figures that the curves corresponding to the different values of $m_{t'}$ in the fourth generation model and the SM curve almost coincide (see also figures 4–6). This is an expected result, since $V_{t's}^* V_{t'b}^{(-)} \sim 10^{-3}$, while $V_{ts}^* V_{tb} \sim 10^{-2}$ so that the effect of fourth generation is small in this case.

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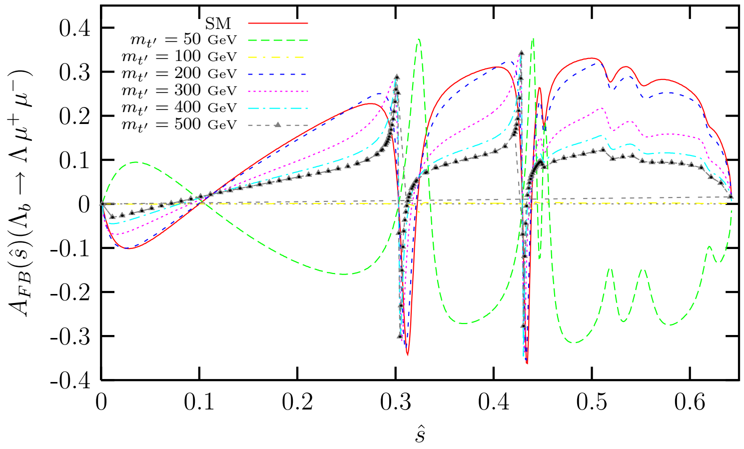

Figure 7: The differential A_{FB} of $\Lambda_b \to \Lambda\mu^+\mu^-$ as a function of $\hat{s}$ at different values of $m_{t'}$ for $V_{t's}^* V_{t'b}^{(+)}$ solution of eq. (3.5).

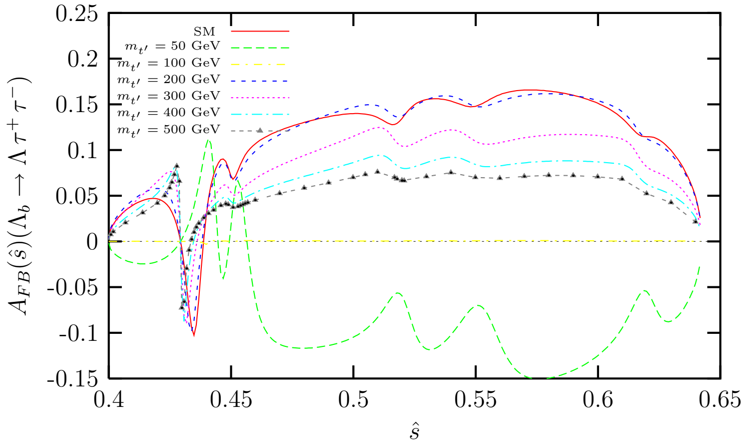

Figure 8: The same as figure (7), but for the decay $\Lambda_b \to \Lambda\tau^+\tau^-$.

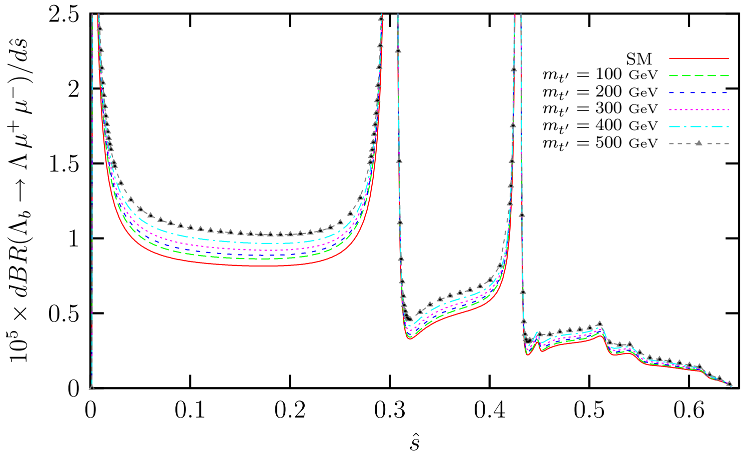

Figure 9: The differential BRs of $\Lambda_b \to \Lambda\mu^+\mu^-$ as a function of $\hat{s}$ at different values of $m_{t'}$ for $V_{t's}^* V_{t'b}^{(-)}$ solution of eq. (3.5).

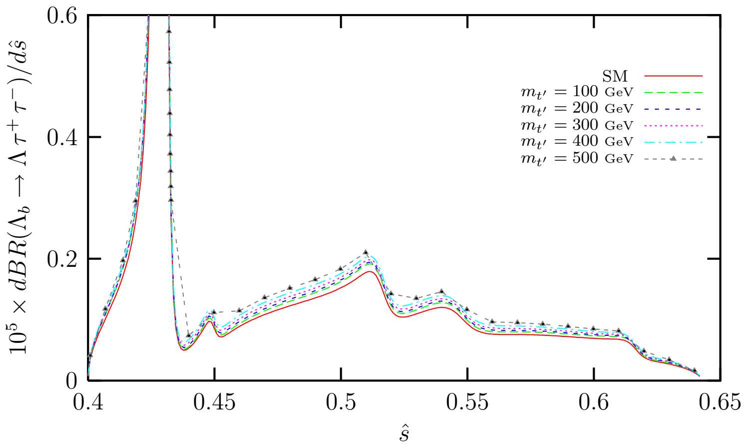

Figure 10: The same as figure (9), but for the decay $\Lambda_b \to \Lambda \tau^+ \tau^-$.

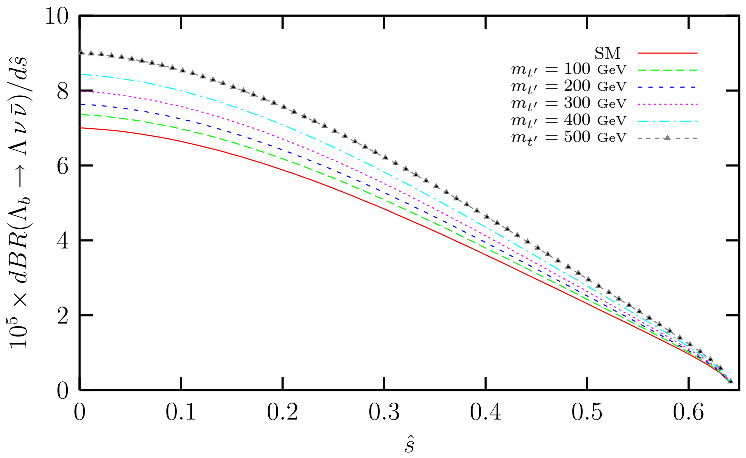

Figure 11: The same as figure (9), but for the decay $\Lambda_b \to \Lambda \nu \bar{\nu}$.

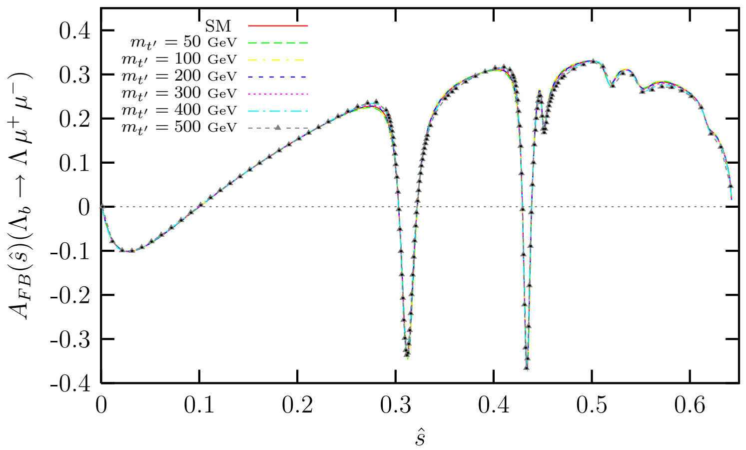

Figure 12: The differential A_{FB} of $\Lambda_b \to \Lambda \mu^+ \mu^-$ as a function of $\hat{s}$ at different values of $m_{t'}$ for $V_{t's}^* V_{t'b}^{(-)}$ solution of eq. (3.5).

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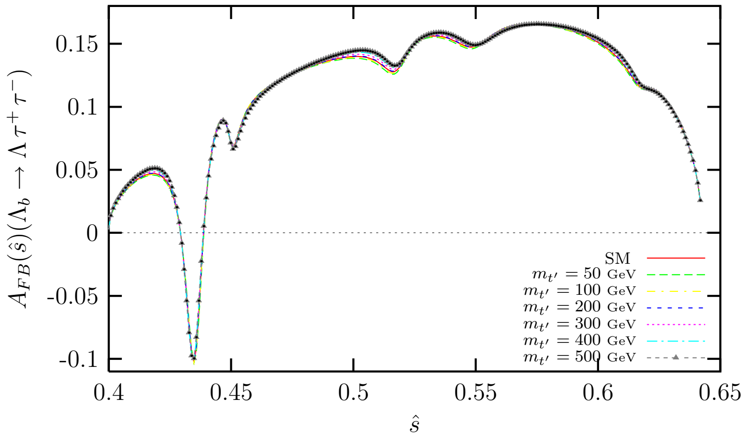

Figure 13: The same as figure (12), but for the decay $\Lambda_b \to \Lambda\tau^+\tau^-$.

In conclusion, we have investigated the physical observables, BR and A_{FB} related to the exclusive $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay in the fourth generation model. We have found that these observables are highly sensitive to the fourth generation model when the value of the fourth generation CKM factor $V^*_{t's}V_{t'b}$ is negative, while they are almost the same as the SM predictions when it is positive. Therefore, $\Lambda_b \to \Lambda\,\ell^+\ell^-$ decay can provide a possible probe to test the fourth generation model if $V^*_{t's}V_{t'b}$ is negative.

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