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Lepton polarization effects in $\Lambda_b \to \Lambda \ell^+ \ell^-$ decay in family non-universal Z' model

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ABSTRACT

Possible manifestation of the family non-universal Z' boson effects in lepton polarization in rare, exclusive baryonic $\Lambda_b \to \Lambda \ell^+ \ell^-$ decay is examined. It is observed that the double lepton polarizations P_{NN}, P_{TT} and P_{TN} are sensitive to the Z' contribution. Moreover, it is found that the values of the polarized forward–backward asymmetry $\mathcal{A}_{FB}^{LL}$ are different in Standard Model (SM) and family non-universal Z' model in different regions of q^2, and therefore can serve as an efficient tool for establishing new physics beyond the SM.

1. Introduction

Investigation of the rare decays described by the $b \to s(d)$ transitions represents one of the main directions of high energy physics. The attractive property of these decays is that they are forbidden at tree level in the Standard Model (SM) and appear only at loop level. Therefore these decays are quite promising for checking gauge structure of the theory at quantum level. These decays are also excellent candidates in search of new physics beyond the SM.

Rare decays in the B-meson sector described by $b \to s(d)$ transitions have been studied theoretically (see for example [1] and references therein) and experimentally in detail (see for example [2]).

Exclusive $\Lambda_b \to \Lambda \ell^+ \ell^-$, $\Lambda_b \to \Lambda \gamma$ decays in baryonic sector, which are described by $b \to s$ transition are also very interesting. The main advantage of these baryonic decays is that, unlike mesonic decays, they can give information about the helicity structure of the effective Hamiltonian [3].

The baryonic decays $\Lambda_b \to \Lambda \ell^+ \ell^-$, $\Lambda_b \to \Lambda \gamma$, $\Lambda_b \to \Lambda \bar{\nu} \nu$ induced by the flavor changing neutral current (FCNC) are studied comprehensively in many works [2,4–11]. The first step in experimental investigation of rare baryonic decays has recently been taken by the CDF Collaboration, and they announced the observation of the baryonic rare $\Lambda_b \to \Lambda \mu^+ \mu^-$ decay. LHCb Collaboration is planning to study this decay in the near future [13]. The experimental observation of this decay has stimulated researches for a more refined theoretical analysis of this subject.

As has already been noted, rare decays induced by $b \to s$ transition are quite promising for checking prediction of the SM and searching new physics beyond the SM. In this sense, the physical observables like branching ratio, forward–backward asymmetry $\mathcal{A}_{FB}$, single and double lepton polarization effects, polarized forward–backward asymmetry are very useful.

Recently we have studied the rare $\Lambda_b \to \Lambda \ell^+ \ell^-$ decay within non-universal Z' model [14]. The sensitivities of the branching ratio, forward–backward asymmetry, and asymmetry parameters due to the polarization of the Λ and Λ_b baryons, on Z' model parameters are investigated in detail.

In the present work we perform an analysis of the single and double lepton polarization effects, and polarized forward–backward asymmetries in the framework of the non-universal Z' model developed in [15]. It should also be noted here that, so far, the effects of non-universal Z' model in the B-meson sector have been studied in many works [16–18].

The outline of the Letter is as follows. In Section 2 we present the effective Hamiltonian responsible for the $b \to s \ell^+ \ell^-$ transition. In this section we also present the matrix element for the $\Lambda_b \to \Lambda \ell^+ \ell^-$ decay, and expressions of the polarized forward–backward asymmetries in the Z' model. In Section 3 the numerical results of these physical observables are given.

2. Theoretical framework

Neglecting doubly Cabibbo-suppressed contribution, the effective Hamiltonian responsible for the $b \to s \ell^+ \ell^-$ transition at $\mu = \mathcal{O}(m_b)$ scale is given as [19] (see also the first reference in [1]),

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu). \tag{1}$$

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The expressions of the local operators $\mathcal{O}_i(\mu)$ can be found in [19] and the first reference in [1]. The Wilson coefficients are calculated in numerous works (see for example [20] and the references therein). The matrix element for the $b \to s\ell^+\ell^-$ transition in SM is given by

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

where G_F is the Fermi constant, α_{em} is the fine structure constant, C_9^{eff}, C_{10} and C_7 are the relevant Wilson coefficients. V_{ij} are the elements of Kobayashi–Maskawa matrix.

The family non-universal Z' model considered in this work could lead to FCNC at tree level, as well as to the appearance of new weak phases. Appearance of FCNS at tree level can be attributed to the non-diagonal chiral coupling matrix. Assuming that the couplings of right-handed quarks with Z' boson are flavor diagonal, and neglecting Z–Z' mixing, the Z' part of the effective Hamiltonian is given by

$$H_{eff}^{Z'} = \frac{2G_F}{\sqrt{2}} V_{tb} V_{ts}^* \bigg[\frac{B_{sb}^L B_{\ell\ell}^L}{V_{tb} V_{ts}^*} \bar{s}\gamma_\mu (1-\gamma_5) b \bar{\ell}\gamma^\mu (1-\gamma_5)\ell + \frac{B_{sb}^L B_{\ell\ell}^R}{V_{tb} V_{ts}^*} \bar{s}\gamma_\mu (1-\gamma_5) b \bar{\ell}\gamma^\mu (1+\gamma_5)\ell \bigg], \tag{3}$$

which can be rewritten as

$$H_{eff}^{Z'} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \big(C_9^{Z'} \mathcal{O}_9 + C_{10}^{Z'} \mathcal{O}_{10} \big), \tag{4}$$

where

$$C_9^{Z'} = -\frac{g_S^2}{e^2} \frac{B_{sb}^L B_{\ell\ell}^R}{V_{tb} V_{ts}^*} S_{\ell\ell}^{LR},$$
$$C_{10}^{Z'} = \frac{g_S^2}{e^2} \frac{B_{sb}^L}{V_{tb} V_{ts}^*} \mathcal{D}_{\ell\ell}^{LR}, \tag{5}$$

and,

$$S_{\ell\ell}^{LR} = \big(B_{\ell\ell}^L + B_{\ell\ell}^R \big),$$
$$\mathcal{D}_{\ell\ell}^{LR} = \big(B_{\ell\ell}^L - B_{\ell\ell}^R \big). \tag{6}$$

The off-diagonal element B_{sb}^L might contain a new phase, and therefore can be written as $|B_{sb}^L| e^{i\varphi}$.

The essential point of this model is that Z' contribution does not lead to the appearance of any new operators that exist in the SM, and its contribution modifies the Wilson coefficients C_9 and C_{10}. As a result, in order to take Z' effects into account it is enough to make the following replacements in Eq. (2),

$$C_9^{eff} \to C_9^{eff} - \frac{4\pi}{\alpha_S}(28.82) \frac{B_{sb}^L}{V_{tb} V_{ts}^*} S_{\ell\ell}^{LR} = C_9^{tot},$$
$$C_{10} \to C_{10} + \frac{4\pi}{\alpha_S}(28.82) \frac{B_{sb}^L}{V_{tb} V_{ts}^*} \mathcal{D}_{\ell\ell}^{LR} = C_{10}^{tot}. \tag{7}$$

Our next task is to obtain the amplitude of the exclusive $\Lambda_b \to \Lambda\ell^+\ell^-$ decay. For this purpose we sandwich Eq. (2) between initial and final baryon states. Obviously, we need to determine the matrix elements,

$$\big\langle \Lambda(p) \big| \bar{s}\gamma_\mu (1-\gamma_5) b \big| \Lambda_b(p_B) \big\rangle, \quad \text{and}$$
$$\big\langle \Lambda(p) \big| \bar{s} i\sigma_{\mu\nu} q^\nu (1+\gamma_5) b \big| \Lambda_b(p_B) \big\rangle.$$

These matrix elements are parametrized in terms of the form factors as follows

$$\begin{aligned} \big\langle \Lambda(p) \big| \bar{s}\gamma_\mu (1-\gamma_5) b \big| \Lambda_b(p_B) \big\rangle &= \bar{u}_\Lambda(p) \big[f_1(q^2)\gamma_\mu + i f_2(q^2)\sigma_{\mu\nu} q^\nu + f_3(q^2) q_\mu \\ &\quad - g_1(q^2)\gamma_\mu\gamma_5 - i g_2(q^2)\sigma_{\mu\nu}\gamma_5 q^\nu \\ &\quad - g_3(q^2)\gamma_5 q_\mu \big] u_{\Lambda_b}(p_B), \end{aligned} \tag{8}$$

$$\begin{aligned} \big\langle \Lambda(p) \big| \bar{s} i\sigma_{\mu\nu} q^\nu (1+\gamma_5) b \big| \Lambda_b(p_B) \big\rangle &= \bar{u}_\Lambda(p) \big[f_1^T(q^2)\gamma_\mu + i f_2^T(q^2)\sigma_{\mu\nu} q^\nu \\ &\quad + f_3^T(q^2) q_\mu + g_1^T(q^2)\gamma_\mu\gamma_5 \\ &\quad + i g_2^T(q^2)\sigma_{\mu\nu}\gamma_5 q^\nu + g_3^T(q^2)\gamma_5 q_\mu \big] u_{\Lambda_b}(p_B), \end{aligned} \tag{9}$$

where $q^2 = (p_B - p_\Lambda)^2$ and f_i, g_i, f_i^T, g_i^T are the form factors responsible for the $\Lambda_b \to \Lambda$ transition.

Using Eqs. (7)–(9), one can easily obtain the matrix element of the $\Lambda_b \to \Lambda\ell^+\ell^-$ decay which is given by

$$\begin{aligned} M = \frac{G_F \alpha_{em}}{4\sqrt{2}\pi} V_{tb} V_{ts}^* \big\{ &\bar{\ell}\gamma^\mu \ell \bar{u}_\Lambda(p) \big[A_1 \gamma_\mu (1+\gamma_5) + B_1 \gamma_\mu (1-\gamma_5) \\ &+ i\sigma_{\mu\nu} q^\nu \big(A_2 (1+\gamma_5) + B_2 (1-\gamma_5) \big) \\ &+ q_\mu \big(A_3 (1+\gamma_5) + B_3 (1-\gamma_5) \big) \big] u_{\Lambda_b}(p_B) \\ &+ \bar{\ell}\gamma^\mu \gamma_5 \ell \bar{u}_\Lambda(p) \big[D_1 \gamma_\mu (1+\gamma_5) + E_1 \gamma_\mu (1-\gamma_5) \\ &+ i\sigma_{\mu\nu} q^\nu \big(D_2 (1+\gamma_5) + E_2 (1-\gamma_5) \big) \\ &+ q_\mu \big(D_3 (1+\gamma_5) + E_3 (1-\gamma_5) \big) \big] u_{\Lambda_b}(p_B) \big\}, \end{aligned} \tag{10}$$

where

$$A_1 = -\frac{2m_b}{q^2} C_7 \big(f_1^T + g_1^T \big) + C_9^{tot} (f_1 - g_1),$$
$$A_2 = A_1 (1 \to 2), \qquad A_3 = A_1 (1 \to 3),$$
$$B_i = A_i \big(g_i \to -g_i, g_i^T \to -g_i^T \big),$$
$$D_i = C_{10}^{tot} (f_1 - g_1), \qquad D_2 \to D_1 (1 \to 2),$$
$$D_3 \to D_1 (1 \to 3), \qquad E_i = D_i (g_i \to -g_i).$$

The matrix element for the $\Lambda_b \to \Lambda\ell^+\ell^-$ decay given in Eq. (10) is the starting for us for all further discussion. In order to calculate the double lepton polarization effects, we introduce the orthogonal unit vectors $s_i^{\pm\mu}$ in the rest frame of leptons,

$$s_L^{-\mu} = \big(0, \vec{e}_L^{\,-} \big) = \bigg(0, \frac{\vec{p}_-}{|\vec{p}_-|} \bigg),$$
$$s_N^{-\mu} = \big(0, \vec{e}_N^{\,-} \big) = \bigg(0, \frac{\vec{p}_\Lambda \times \vec{p}_-}{|\vec{p}_\Lambda \times \vec{p}_-|} \bigg),$$
$$s_T^{-\mu} = \big(0, \vec{e}_T^{\,-} \big) = \big(0, \vec{e}_N \times \vec{e}_L \big). \tag{11}$$

The unit vectors for the polarizations of ℓ^+ lepton can be obtained from Eq. (11) by making the replacement $\vec{p}_- \to \vec{p}_+$. Here, $\vec{p}_-(\vec{p}_+)$ and $\vec{p}_\Lambda$ are the three momenta of the $\ell^-(\ell^+)$ lepton and Λ baryon in the center of mass frame (CM) of the lepton pair. Transformation of the unit vector $s_i^{\pm\mu}$ from rest frame to CM of the leptons can done by Lorentz boosting. It should be noted here that, in performing Lorentz boosts transversal and normal components are unchanged, and only longitudinal component $s_L^{\pm\mu}$ is transformed. As a result we get

$$\big(s_L^{\pm\mu} \big)_{CM} = \bigg(\frac{|\vec{p}_\pm|}{m_\ell}, \frac{E_\ell \vec{p}_\pm}{m_\ell |\vec{p}_\pm|} \bigg). \tag{12}$$

Now we are ready to define the double lepton polarizations. Following [21] we define double and single lepton polarizations in the following way,

$$P_{ij}(q^2)=\frac{(\frac{d\Gamma(\vec{s}_i^-,\vec{s}_j^+)}{d\hat{s}}-\frac{d\Gamma(-\vec{s}_i^-,\vec{s}_j^+)}{d\hat{s}})-(\frac{d\Gamma(\vec{s}_i^-,-\vec{s}_j^+)}{d\hat{s}}-\frac{d\Gamma(-\vec{s}_i^-,-\vec{s}_j^+)}{d\hat{s}})}{(\frac{d\Gamma(\vec{s}_i^-,\vec{s}_j^+)}{d\hat{s}}+\frac{d\Gamma(-\vec{s}_i^-,\vec{s}_j^+)}{d\hat{s}})+(\frac{d\Gamma(\vec{s}_i^-,-\vec{s}_j^+)}{d\hat{s}}+\frac{d\Gamma(-\vec{s}_i^-,-\vec{s}_j^+)}{d\hat{s}})},$$

$$P_i(q^2)=\frac{\frac{d\Gamma(\vec{s}_i)}{d\hat{s}}-\frac{d\Gamma(-\vec{s}_i)}{d\hat{s}}}{\frac{d\Gamma(\vec{s}_i)}{d\hat{s}}+\frac{d\Gamma(-\vec{s}_i)}{d\hat{s}}}. \tag{13}$$

The first (second) subindex of P_{ij} represents polarization of lepton (anti-lepton).

In this work we also investigate the polarized forward–backward asymmetries, which are defined as

$$\begin{aligned}
\mathcal{A}_{FB}^{ij}(\hat{s}) &= \left(\frac{d\Gamma(\hat{s})}{d\hat{s}}\right)^{-1}\left\{\int_0^1 dz-\int_{-1}^0 dz\right\}\\
&\quad\times\left\{\left[\frac{d^2\Gamma(\hat{s},\vec{s}_i^-,\vec{s}_j^+)}{d\hat{s}\,dz}-\frac{d^2\Gamma(\hat{s},\vec{s}_i^-,-\vec{s}_j^+)}{d\hat{s}\,dz}\right]\right.\\
&\quad\left.-\left[\frac{d^2\Gamma(\hat{s},-\vec{s}_i^-,\vec{s}_j^+)}{d\hat{s}\,dz}-\frac{d^2\Gamma(\hat{s},-\vec{s}_i^-,-\vec{s}_j^+)}{d\hat{s}\,dz}\right]\right\}\\
&= \mathcal{A}_{FB}(\vec{s}_i^-,\vec{s}_j^+)-\mathcal{A}_{FB}(\vec{s}_i^-,-\vec{s}_j^+)-\mathcal{A}_{FB}(-\vec{s}_i^-,\vec{s}_j^+)\\
&\quad+\mathcal{A}_{FB}(-\vec{s}_i^-,-\vec{s}_j^+).
\end{aligned} \tag{14}$$

Using the same convention and notations used in [7], for the double lepton polarizations we get

$$\begin{aligned}
P_{LL} &= \frac{16m_{\Lambda_b}^4}{3\Delta}\operatorname{Re}\bigl\{-6m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}(1-\hat{r}_\Lambda+\hat{s})\\
&\quad\times\bigl[\hat{s}(1+v^2)(A_1A_2^*+B_1B_2^*)-4\hat{m}_\ell^2(D_1D_3^*+E_1E_3^*)\bigr]\\
&\quad+6m_{\Lambda_b}(1-\hat{r}_\Lambda-\hat{s})\bigl[\hat{s}(1+v^2)(A_1B_2^*+A_2B_1^*)\\
&\quad+4\hat{m}_\ell^2(D_1E_3^*+D_3E_1^*)\bigr]\\
&\quad+12\sqrt{\hat{r}_\Lambda}\hat{s}(1+v^2)(A_1B_1^*+D_1E_1^*+m_{\Lambda_b}^2\hat{s}A_2B_2^*)\\
&\quad+12m_{\Lambda_b}^2\hat{m}_\ell^2\hat{s}(1+\hat{r}_\Lambda-\hat{s})(|D_3|^2+|E_3|^2)\\
&\quad-(1+v^2)\bigl[1+\hat{r}_\Lambda^2-\hat{r}_\Lambda(2-\hat{s})+\hat{s}(1-2\hat{s})\bigr]\\
&\quad\times(|A_1|^2+|B_1|^2)-\bigl[(5v^2-3)(1-\hat{r}_\Lambda)^2+4\hat{m}_\ell^2(1+\hat{r}_\Lambda)\\
&\quad+2\hat{s}(1+8\hat{m}_\ell^2+\hat{r}_\Lambda)-4\hat{s}^2\bigr](|D_1|^2+|E_1|^2)\\
&\quad-m_{\Lambda_b}^2(1+v^2)\hat{s}\bigl[2+2\hat{r}_\Lambda^2-\hat{s}(1+\hat{s})-\hat{r}_\Lambda(4+\hat{s})\bigr]\\
&\quad\times(|A_2|^2+|B_2|^2)-2m_{\Lambda_b}^2\hat{s}v^2\bigl[2(1+\hat{r}_\Lambda^2)-\hat{s}(1+\hat{s})\\
&\quad-\hat{r}_\Lambda(4+\hat{s})\bigr](|D_2|^2+|E_2|^2)\\
&\quad+12m_{\Lambda_b}\hat{s}(1-\hat{r}_\Lambda-\hat{s})v^2(D_1E_2^*+D_2E_1^*)\\
&\quad-12m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}\hat{s}(1-\hat{r}_\Lambda+\hat{s})v^2(D_1D_2^*+E_1E_2^*)\\
&\quad+24m_{\Lambda_b}^2\sqrt{\hat{r}_\Lambda}\hat{s}(\hat{s}v^2D_2E_2^*+2\hat{m}_\ell^2D_3E_3^*)\bigr\},
\end{aligned} \tag{15}$$

$$\begin{aligned}
P_{LN} &= -P_{NL}=\frac{16\pi m_{\Lambda_b}^4\hat{m}_\ell\sqrt{\lambda}}{\Delta\sqrt{\hat{s}}}\operatorname{Im}\bigl\{(1-\hat{r}_\Lambda)(A_1^*D_1+B_1^*E_1)\\
&\quad+m_{\Lambda_b}\hat{s}(A_1^*E_3-A_2^*E_1+B_1^*D_3-B_2^*D_1)\\
&\quad+m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}\hat{s}(A_1^*D_3+A_2^*D_1+B_1^*E_3+B_2^*E_1)\\
&\quad-m_{\Lambda_b}^2\hat{s}^2(B_2^*E_3+A_2^*D_3)\bigr\},
\end{aligned} \tag{16}$$

$$\begin{aligned}
P_{LT} &= \frac{16\pi m_{\Lambda_b}^4\hat{m}_\ell\sqrt{\lambda}v}{\Delta\sqrt{\hat{s}}}\operatorname{Re}\bigl\{(1-\hat{r}_\Lambda)(|D_1|^2+|E_1|^2)\\
&\quad-\hat{s}(A_1D_1^*-B_1E_1^*)-m_{\Lambda_b}\hat{s}\bigl[B_1D_2^*+(A_2+D_2-D_3)E_1^*\\
&\quad-A_1E_2^*-(B_2-E_2+E_3)D_1^*\bigr]\\
&\quad+m_{\Lambda_b}^2\hat{s}(1-\hat{r}_\Lambda)(A_2D_2^*-B_2E_2^*)+m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}\hat{s}\bigl[A_1D_2^*\\
&\quad+(A_2+D_2+D_3)D_1^*-B_1E_2^*-(B_2-E_2-E_3)E_1^*\bigr]\\
&\quad-m_{\Lambda_b}^2\hat{s}^2(D_2D_3^*+E_2E_3^*)\bigr\},
\end{aligned} \tag{17}$$

$$\begin{aligned}
P_{TL} &= \frac{16\pi m_{\Lambda_b}^4\hat{m}_\ell\sqrt{\lambda}v}{\Delta\sqrt{\hat{s}}}\operatorname{Re}\bigl\{(1-\hat{r}_\Lambda)(|D_1|^2+|E_1|^2)\\
&\quad+\hat{s}(A_1D_1^*-B_1E_1^*)+m_{\Lambda_b}\hat{s}\bigl[B_1D_2^*+(A_2-D_2+D_3)E_1^*\\
&\quad-A_1E_2^*-(B_2+E_2-E_3)D_1^*\bigr]\\
&\quad-m_{\Lambda_b}^2\hat{s}(1-\hat{r}_\Lambda)(A_2D_2^*-B_2E_2^*)-m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}\hat{s}\bigl[A_1D_2^*\\
&\quad+(A_2-D_2-D_3)D_1^*-B_1E_2^*-(B_2+E_2+E_3)E_1^*\bigr]\\
&\quad-m_{\Lambda_b}^2\hat{s}^2(D_2D_3^*+E_2E_3^*)\bigr\},
\end{aligned} \tag{18}$$

$$\begin{aligned}
P_{NT} &= -P_{TN}=\frac{64m_{\Lambda_b}^4\lambda v}{3\Delta}\operatorname{Im}\bigl\{(A_1D_1^*+B_1E_1^*)\\
&\quad+m_{\Lambda_b}^2\hat{s}(A_2^*D_2+B_2^*E_2)\bigr\},
\end{aligned} \tag{19}$$

$$\begin{aligned}
P_{NN} &= \frac{32m_{\Lambda_b}^4}{3\hat{s}\Delta}\operatorname{Re}\bigl\{24\hat{m}_\ell^2\sqrt{\hat{r}_\Lambda}\hat{s}(A_1B_1^*+D_1E_1^*)\\
&\quad-12m_{\Lambda_b}\hat{m}_\ell^2\sqrt{\hat{r}_\Lambda}\hat{s}(1-\hat{r}_\Lambda+\hat{s})(A_1A_2^*+B_1B_2^*)\\
&\quad+6m_{\Lambda_b}\hat{m}_\ell^2\hat{s}\bigl[m_{\Lambda_b}\hat{s}(1+\hat{r}_\Lambda-\hat{s})(|D_3|^2+|E_3|^2)\\
&\quad+2\sqrt{\hat{r}_\Lambda}(1-\hat{r}_\Lambda+\hat{s})(D_1D_3^*+E_1E_3^*)\bigr]\\
&\quad+12m_{\Lambda_b}\hat{m}_\ell^2\hat{s}(1-\hat{r}_\Lambda-\hat{s})\\
&\quad\times(A_1B_2^*+A_2B_1^*+D_1E_3^*+D_3E_1^*)\\
&\quad-\bigl[\lambda\hat{s}+2\hat{m}_\ell^2(1+\hat{r}_\Lambda^2-2\hat{r}_\Lambda+\hat{r}_\Lambda\hat{s}+\hat{s}-2\hat{s}^2)\bigr]\\
&\quad\times(|A_1|^2+|B_1|^2-|D_1|^2-|E_1|^2)\\
&\quad+24m_{\Lambda_b}^2\hat{m}_\ell^2\sqrt{\hat{r}_\Lambda}\hat{s}^2(A_2B_2^*+D_3E_3^*)\\
&\quad-m_{\Lambda_b}^2\lambda\hat{s}^2v^2(|D_2|^2+|E_2|^2)\\
&\quad+m_{\Lambda_b}^2\hat{s}\bigl\{\lambda\hat{s}-2\hat{m}_\ell^2\bigl[2(1+\hat{r}_\Lambda^2)-\hat{s}(1+\hat{s})-\hat{r}_\Lambda(4+\hat{s})\bigr]\bigr\}\\
&\quad\times(|A_2|^2+|B_2|^2)\bigr\},
\end{aligned} \tag{20}$$

$$\begin{aligned}
P_{TT} &= \frac{32m_{\Lambda_b}^4}{3\hat{s}\Delta}\operatorname{Re}\bigl\{-24\hat{m}_\ell^2\sqrt{\hat{r}_\Lambda}\hat{s}(A_1B_1^*+D_1E_1^*)\\
&\quad-12m_{\Lambda_b}\hat{m}_\ell^2\sqrt{\hat{r}_\Lambda}\hat{s}(1-\hat{r}_\Lambda+\hat{s})(D_1D_3^*+E_1E_3^*)\\
&\quad-24m_{\Lambda_b}^2\hat{m}_\ell^2\sqrt{\hat{r}_\Lambda}\hat{s}^2(A_2B_2^*+D_3E_3^*)\\
&\quad-6m_{\Lambda_b}\hat{m}_\ell^2\hat{s}\bigl[m_{\Lambda_b}\hat{s}(1+\hat{r}_\Lambda-\hat{s})(|D_3|^2+|E_3|^2)\\
&\quad-2\sqrt{\hat{r}_\Lambda}(1-\hat{r}_\Lambda+\hat{s})(A_1A_2^*+B_1B_2^*)\bigr]\\
&\quad-12m_{\Lambda_b}\hat{m}_\ell^2\hat{s}(1-\hat{r}_\Lambda-\hat{s})\\
&\quad\times(A_1B_2^*+A_2B_1^*+D_1E_3^*+D_3E_1^*)\\
&\quad-\bigl[\lambda\hat{s}-2\hat{m}_\ell^2(1+\hat{r}_\Lambda^2-2\hat{r}_\Lambda+\hat{r}_\Lambda\hat{s}+\hat{s}-2\hat{s}^2)\bigr]\\
&\quad\times(|A_1|^2+|B_1|^2)\\
&\quad+m_{\Lambda_b}^2\hat{s}\bigl\{\lambda\hat{s}+\hat{m}_\ell^2\bigl[4(1-\hat{r}_\Lambda)^2-2\hat{s}(1+\hat{r}_\Lambda)-2\hat{s}^2\bigr]\bigr\}\\
&\quad\times(|A_2|^2+|B_2|^2)\\
&\quad+\bigl\{\lambda\hat{s}-2\hat{m}_\ell^2\bigl[5(1-\hat{r}_\Lambda)^2-7\hat{s}(1+\hat{r}_\Lambda)+2\hat{s}^2\bigr]\bigr\}\\
&\quad\times(|D_1|^2+|E_1|^2)-m_{\Lambda_b}^2\lambda\hat{s}^2v^2(|D_2|^2+|E_2|^2)\bigr\}.
\end{aligned} \tag{21}$$

Using the definition of single lepton polarization we find

$$P_L^{\mp} = \frac{64 m_{\Lambda_b}^4 \hat{s} v}{\Delta} \Big\{ \pm\sqrt{\hat{r}_\Lambda} \big(2\,\mathrm{Re}\big[A_1^* E_1 + B_1^* D_1\big] - m_{\Lambda_b}(1-\hat{r}_\Lambda+\hat{s})\,\mathrm{Re}\big[A_1^* D_2 + A_2^* D_1\big]\big) \mp m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}(1-\hat{r}_\Lambda+\hat{s})\,\mathrm{Re}\big[B_1^* E_2 + B_2^* E_1\big] \pm 2 m_{\Lambda_b}^2 \hat{s}\sqrt{\hat{r}_\Lambda}\,\mathrm{Re}\big[A_2^* E_2 + B_2^* D_2\big] \pm m_{\Lambda_b}(1-\hat{r}_\Lambda-\hat{s})\,\mathrm{Re}\big[A_1^* E_2 + A_2^* E_1 + B_1^* D_2 + B_2^* D_1\big] \mp \frac{1}{3\hat{s}}\big[1+\hat{r}_\Lambda^2+\hat{r}_\Lambda(\hat{s}-2)+\hat{s}(1-2\hat{s})\big]\,\mathrm{Re}\big[A_1^* D_1 + B_1^* E_1\big] \mp \frac{1}{3} m_{\Lambda_b}^2\big[2+\hat{r}_\Lambda(2\hat{r}_\Lambda-4-\hat{s})-\hat{s}(1+\hat{s})\big] \times \mathrm{Re}\big[A_2^* D_2 + B_2^* E_2\big] \Big\}, \tag{22}$$

$$P_T^{\mp} = \frac{16\pi m_{\Lambda_b}^3 \hat{m}_\ell \sqrt{\hat{s}\lambda}}{\Delta} \Big\{ -\big(|A_1|^2 - |B_1|^2\big) + 2 m_{\Lambda_b}\,\mathrm{Re}\big[A_1^* B_2 - A_2^* B_1\big] \mp m_{\Lambda_b}\,\mathrm{Re}\big[A_1^* E_3 - A_2^* E_1 + B_1^* D_3 - B_2^* D_1\big] + m_{\Lambda_b}^2(1-\hat{r}_\Lambda)\big(|A_2|^2 - |B_2|^2\big) + m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}\,\mathrm{Re}\big[2A_1^* A_2 - 2B_1^* B_2 \mp A_1^* D_3 \mp A_2^* D_1 \mp B_1^* E_3 \mp B_2^* E_1\big] - \frac{(1-\hat{r}_\Lambda)}{\hat{s}}\big(\pm\mathrm{Re}\big[A_1^* D_1 + B_1^* E_1\big]\big) \Big\}, \tag{23}$$

$$P_N^{\mp} = \frac{16\pi m_{\Lambda_b}^3 \hat{m}_\ell v \sqrt{\hat{s}\lambda}}{\Delta} \big\{ \pm\mathrm{Im}\big[A_1^* D_1 - B_1^* E_1\big] + m_{\Lambda_b}\big(\pm\mathrm{Im}\big[B_1^* D_2 - A_1^* E_2\big] + \mathrm{Im}\big[(\pm A_2 + D_2 + D_3)^* E_1\big] - \mathrm{Im}\big[(\pm B_2 - E_2 - E_3)^* D_1\big]\big) \mp m_{\Lambda_b}\big(m_{\Lambda_b}(1-\hat{r}_\Lambda)\,\mathrm{Im}\big[A_2^* D_2 - B_2^* E_2\big] + \sqrt{\hat{r}_\Lambda}\,\mathrm{Im}\big[A_1^* D_2 + A_2^* D_1\big]\big) + m_{\Lambda_b}\sqrt{\hat{r}_\Lambda}\,\mathrm{Im}\big[D_1^*(D_2 - D_3) - E_2^*(\pm B_1 + E_1) - E_1^*(\pm B_2 + E_3)\big] \big\}. \tag{24}$$

Using these definitions for the doubly-polarized FB asymmetries, we get the following results:

$$\mathcal{A}_{FB}^{LL} = \frac{32 m_{\Lambda_b}^5 \hat{s}\sqrt{\lambda} v}{\Delta} \mathrm{Re}\big[-\big\{m_{\Lambda_b}(1-\hat{r}_\Lambda)\big(A_2 D_2^* - B_2 E_2^*\big) + \sqrt{\hat{r}_\Lambda}\big(A_1 D_2^* + A_2 D_1^*\big)\big\} + \sqrt{\hat{r}_\Lambda}\big(B_1 E_2^* + B_2 E_1^*\big)\big], \tag{25}$$

$$\mathcal{A}_{FB}^{LT} = -\mathcal{A}_{FB}^{TL} = \frac{64 m_{\Lambda_b}^4 \hat{m}_\ell \lambda}{3\sqrt{\hat{s}}\Delta} \mathrm{Re}\big[-\big\{|A_1|^2 + |B_1|^2\big\} + m_{\Lambda_b}^2 \hat{s}\big\{|A_2|^2 + |B_2|^2\big\}\big], \tag{26}$$

$$\mathcal{A}_{FB}^{LN} = \mathcal{A}_{FB}^{NL} = \frac{64 m_{\Lambda_b}^4 \hat{m}_\ell \lambda v}{3\sqrt{\hat{s}}\Delta} \mathrm{Im}\big[-\big(A_1 D_1^* + B_1 E_1^*\big) + m_{\Lambda_b}^2 \hat{s}\big(A_2 D_2^* + B_2 E_2^*\big)\big], \tag{27}$$

$$\mathcal{A}_{FB}^{NT} = \mathcal{A}_{FB}^{TN} = \frac{64 m_{\Lambda_b}^4 \hat{m}_\ell^2 \sqrt{\lambda}}{\hat{s}\Delta} \mathrm{Im}\big[m_{\Lambda_b}\hat{s}\big\{A_1 E_3^* - A_2 E_1^* + B_1 D_3^* - B_2 D_1^*\big\} + m_{\Lambda_b}\hat{s}\sqrt{\hat{r}_\Lambda}\big(A_1 D_3^* + A_2 D_1^* + B_1 E_3^* + B_2 E_1^*\big) + (1-\hat{r}_\Lambda)\big(A_1 D_1^* + B_1 E_1^*\big) - m_{\Lambda_b}^2 \hat{s}^2\big(A_2 D_3^* + B_2 E_3^*\big)\big], \tag{28}$$

$$\mathcal{A}_{FB}^{NN} = \mathcal{A}_{FB}^{TT} = 0. \tag{29}$$

In the expressions for $\mathcal{A}_{FB}^{ij}$, the superscript indices i and j correspond to the lepton and anti-lepton polarizations, respectively, and Δ is determined from the differential decay rate,

$$\frac{d\Gamma}{d\hat{s}} = \frac{G_F \alpha_{em}^2}{8192\pi^5}\big|V_{tb}V_{ts}^*\big|^2 v\sqrt{\lambda(1,\hat{r}_\Lambda,\hat{s})}\,\Delta.$$

In all expressions the quantities $\lambda(1,\hat{r}_\Lambda,\hat{s})$, $\hat{s}$, $\hat{r}_\Lambda$, $\hat{m}_\ell$ and v are defined as $\lambda(1,\hat{r}_\Lambda,\hat{s}) = 1+\hat{r}_\Lambda^2+\hat{s}-2\hat{r}_\Lambda-2\hat{s}-2\hat{r}_\Lambda\hat{s}$, $\hat{s}=q^2/m_{\Lambda_b}^2$, $\hat{r}_\Lambda = m_\Lambda/m_{\Lambda_b}$, $\hat{m}_\ell = m_\ell/m_{\Lambda_b}$, and $v=\sqrt{1-\frac{4\hat{m}_\ell^2}{\hat{s}}}$.

Few words about the CP and T properties of the lepton polarizations and the polarized forward–backward asymmetries are in order.

We first analyze the terms involving triple product correlations. The terms involving single-spin or two-spin triple products are proportional to $\varepsilon_{\alpha\beta\rho\sigma} p_\Lambda^\alpha p_-^\beta s_-^\rho p_+^\sigma$ and $\varepsilon_{\alpha\beta\rho\sigma} p_{\Lambda_b}^\alpha p_\Lambda^\beta s_-^\rho s_+^\sigma$, respectively, which give the triple product correlations $\vec{p}_- \cdot (\vec{p}_+ \times \vec{s}_-)$ and $\vec{p}_\Lambda \cdot (\vec{s}_+ \times \vec{s}_-)$. These terms are T odd, and hence, CP odd from CPT invariance.

The other terms that do not contain triple products are T even, and correspondingly, CP even. Therefore P_N, P_{LN}, P_{TN} and $\mathcal{A}_{FB}^{NT}$ terms are T odd and CP odd, all remaining terms are T even and CP even.

3. Numerical analysis

In the previous section we present the expressions for double and single lepton polarizations in family non-universal Z' model. We now proceed with the numerical analysis of these physical observables. In addition to the input parameters in the SM, the considered version of the family non-universal Z' model contains four new parameters, namely, $|B_{sb}^L|$, φ_S^L, $B_{\ell\ell}^L$, $B_{\ell\ell}^R$. For the numerical analysis we use the constraints to the parameters $|B_{sb}^L|$ and φ_S^L obtained from the recent B_s^0–$\bar{B}_s^0$ mixing data measured at LHC and Tevatron. The latest results on the CP-violating phase φ_S^L and like-sign dimuon charge asymmetry A_{SL}^b of the semileptonic decays are

$-2\varphi_S^L = -43.5^{0}{}^{+21.8^0}_{-20.6^0} \pm 1.2^0$ [22],

$-59.6^0 \leqslant -2\varphi_S^L \leqslant 2.3^0$ [23],

$-2\varphi_S^L = 8.6^0 \pm 10.2^0$ [24],

$-2\varphi_S^L = -25.2^0 \pm 25.2^0 \pm 25.2^0 \pm 1.2^0$ [25],

$A_{SL}^b = (-7.87 \pm 1.72 \pm 0.93)\times 10^{-3}$ [26].

The question whether Z' model could explain all these recent results is studied in [27], and it is found that there is no room in the Z' for accommodation of all these data, especially for the A_{SL}^b. The constraints in this work are obtained from ΔM_S, φ_S and $\Delta\Gamma_S$ data. Following [27] we choose

$$\big|B_{sb}^L\big| = (0.4\pm 0.1)\times 10^{-2},$$
$$\varphi_S^L = 150^0 \pm 10^0,\ \text{or},\ -150^0 \pm 10^0.$$

The constraints to the $B_{\ell\ell}^L$ and $B_{\ell\ell}^R$ are obtained from the analysis of $B \to X_s\mu^+\mu^-$ [28], $B \to K^{(*)}\mu^+\mu^-$ [29,30] and $B \to \mu^+\mu^-$ [31], which lead to the results $B_{\ell\ell}^L = -9.0\times 10^{-3}$, $B_{\ell\ell}^R = 1.7\times 10^{-2}$.

For the form factors, which are the main input parameters in the numerical analysis, we use the results obtained in [32]. Moreover, in our calculations we take into account the errors for the parameters entering to the expressions of the form factors.

We have studied the sensitivities of single and double lepton polarizations on input parameters of family non-universal Z' model. We can summarize the result of our analysis as follows:

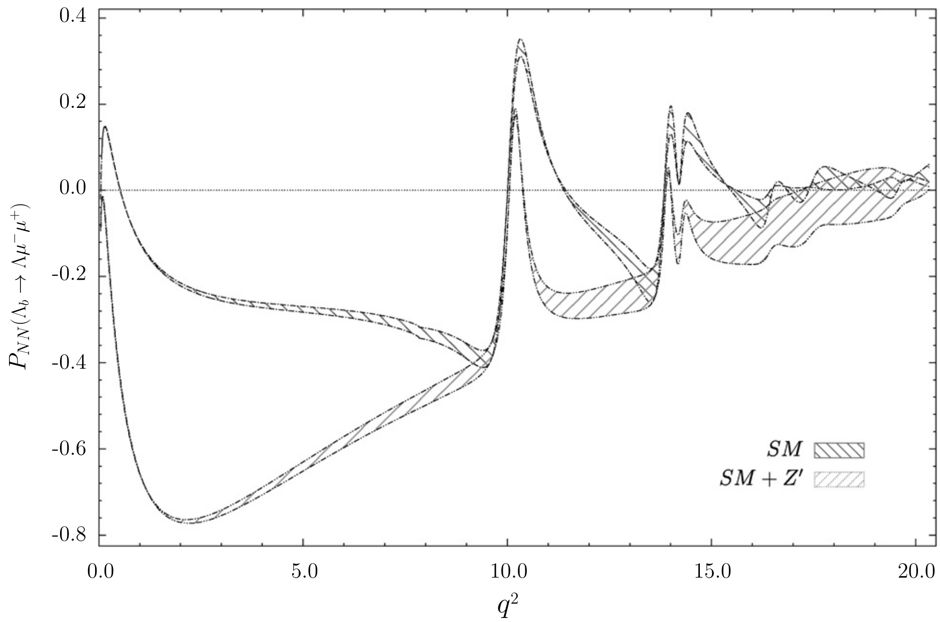

Fig. 1. The dependence of the double-lepton polarization asymmetry P_{NN} on q^2 for the $\Lambda_b \to \Lambda\mu^+\mu^-$ decay.

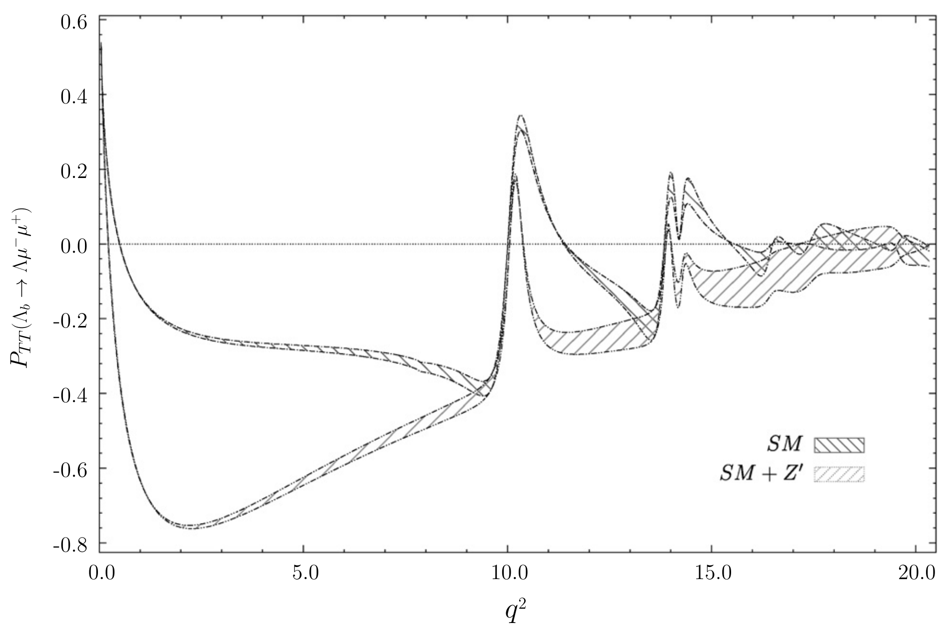

Fig. 2. The same as in Fig. 1, but for the double-lepton polarization asymmetry P_{TT}.

- P_L decreases maximally 5% in both scenarios compared to the SM prediction.
- The values of P_T and P_N practically do not change. Therefore we can conclude that single lepton polarization effects are not so efficient for establishing new physics in the framework of family non-universal Z' model.

As a result of the analysis of double lepton polarization we obtain that:

- Prediction for P_{LL} does coincide for both SM and family non-universal Z' model.
- Double lepton polarizations P_{NN}, P_{TT}, P_{NT} and P_{TN} are quite sensitive to the parameters of Z' model. As an example we present the q^2 dependence of P_{NN}, P_{TT} and P_{TN} in Figs. 1, 2 and 3, respectively. We observe from these figures that, in the region 1 GeV$^2 \leqslant q^2 \leqslant 8$ GeV^2, which is free of contributions from J/ψ resonances, there occurs considerable difference between the predictions of the SM and family non-universal Z' model.
- In Fig. 4 we present the dependence of the polarized forward–backward asymmetry $\mathcal{A}_{FB}^{LL}$ on q^2 in the SM and family non-universal Z' model. It follows from this figure that the zero position of $\mathcal{A}_{FB}^{LL}$ coincides in the SM and Z' models. But the values of $\mathcal{A}_{FB}^{LL}$ are different in different regions of q^2. For example, in the region 3 GeV$^2 \leqslant q^2 \leqslant 8.5$ GeV^2, $\mathcal{A}_{FB}^{LL}$ is different from zero in the SM model, while it is zero in the Z' model. Again, in the region 10.5 GeV$^2 \leqslant q^2 \leqslant 13.0$ GeV^2, $\mathcal{A}_{FB}^{LL}$ is positive and considerably far from zero, but it is negative and close to zero in the Z' model. Therefore measurement of the value and sign of $\mathcal{A}_{FB}^{LL}$ can give unambiguous information about the existence of new physics.

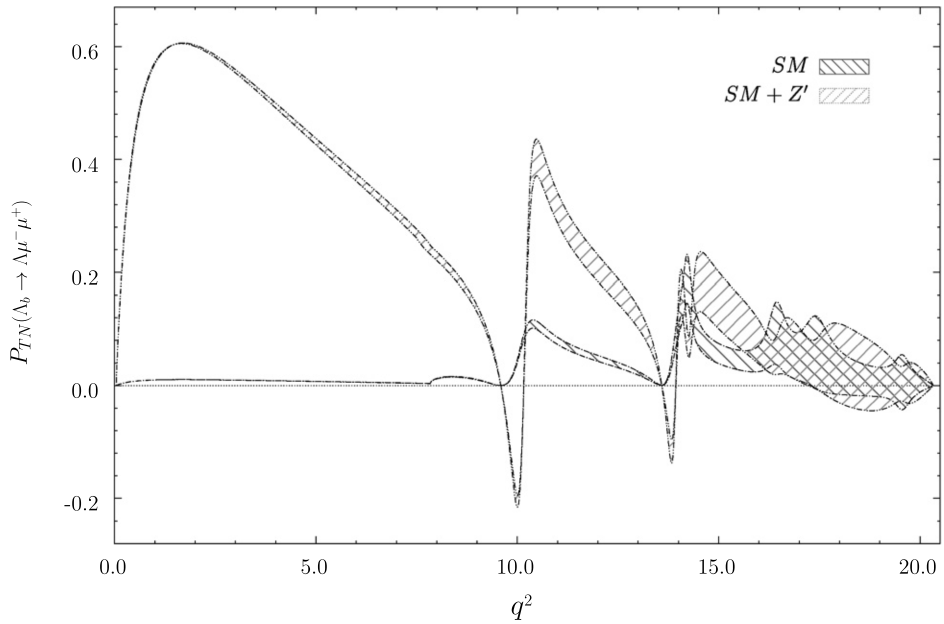

Fig. 3. The same as in Fig. 1, but for the double-lepton polarization asymmetry P_{TN}.

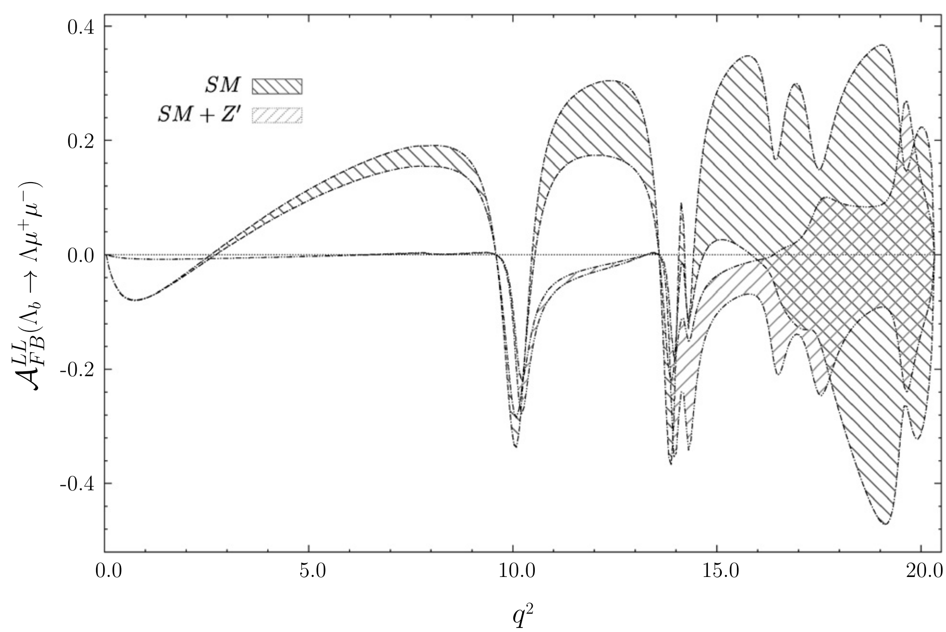

Fig. 4. The dependence of the double-lepton polarization asymmetry $\mathcal{A}_{FB}^{LL}$ on q^2 for the $\Lambda_b \to \Lambda\mu^+\mu^-$ decay.

We have also analyzed the remaining forward–backward asymmetries $\mathcal{A}_{FB}^{LN}$, $\mathcal{A}_{FB}^{NL}$, $\mathcal{A}_{FB}^{LT}$, $\mathcal{A}_{FB}^{TL}$, $\mathcal{A}_{FB}^{NT}$ and $\mathcal{A}_{FB}^{TN}$ and obtained that the contribution of new Z' bosons to these asymmetries are negligibly small.

Now we would like to discuss the prospect of measurement of the aforementioned asymmetries in experiments. For this aim it is necessary to calculate the average values of these asymmetries, which are defined as

$$\langle P\rangle = \frac{\int_{4m_\ell^2}^{(m_{\Lambda_b}-m_\Lambda)^2} P\,\frac{d\mathcal{B}}{dq^2}\,dq^2}{\int_{4m_\ell^2}^{(m_{\Lambda_b}-m_\Lambda)^2} \frac{d\mathcal{B}}{dq^2}\,dq^2},$$

where P stands for P_i, P_{ij} or $\mathcal{A}_{FB}^{ij}$.

In Tables 1 and 2, we present the average values of all polarization asymmetries for the $\Lambda_b \to \Lambda\mu^+\mu^-$ and $\Lambda_b \to \Lambda\tau^+\tau^-$ decays, respectively. We see from these tables that $\langle P_{NN}\rangle$, $\langle P_{NT}\rangle$ and $\langle P_{TT}\rangle$ in the $\Lambda_b \to \Lambda\mu^+\mu^-$ decay, and $\langle P_{LN}\rangle$ in the $\Lambda_b \to \Lambda\tau^+\tau^-$ decay exceed considerably the SM results. To the question whether these asymmetries can be measured in experiments, we comment as follows. Experimentally, to measure an asymmetry $\langle P\rangle$ of a decay with branching ratio $\mathcal{B}$ at $n\sigma$ level, necessary number of events is given by the expression,

$$N = \frac{n^2}{\mathcal{B}\langle P\rangle^2 s_1 s_2},$$

where s_1 and s_2 are the efficiencies of the detection of leptons. In our numerical calculations we use $s_i = 1$ for μ, and $s_i = 1/2$ for τ lepton, respectively.

Table 1
Average values of the double polarizations $\langle P_{ij} \rangle$, for the $\Lambda_b \to \Lambda \mu^+\mu^-$ decay. In these calculations central values of the form factors are used.

$\Lambda_b \to \Lambda \mu^+\mu^-$	SM	SM + Z'
$\langle P_{LL} \rangle$	−0.9808	−0.9858
$\langle P_{LN} \rangle$	0.0035	0.0311
$\langle P_{NL} \rangle$	−0.0035	−0.0311
$\langle P_{LT} \rangle$	0.0302	0.0136
$\langle P_{TL} \rangle$	0.0529	0.0107
$\langle P_{NN} \rangle$	−0.0469	−0.2918
$\langle P_{NT} \rangle$	−0.0346	−0.2537
$\langle P_{TN} \rangle$	0.0346	0.2537
$\langle P_{TT} \rangle$	−0.0479	−0.2835

Table 2
The same as Table 1, but for the $\Lambda_b \to \Lambda \tau^+\tau^-$ decay.

$\Lambda_b \to \Lambda \tau^+\tau^-$	SM	SM + Z'
$\langle P_{LL} \rangle$	0.3023	−0.1852
$\langle P_{LN} \rangle$	0.0261	0.1079
$\langle P_{NL} \rangle$	−0.0261	−0.1079
$\langle P_{LT} \rangle$	−0.0268	0.0194
$\langle P_{TL} \rangle$	0.0920	0.0023
$\langle P_{NN} \rangle$	0.3591	−0.1745
$\langle P_{NT} \rangle$	−0.0082	−0.0358
$\langle P_{TN} \rangle$	0.0082	0.0358
$\langle P_{TT} \rangle$	−0.4788	−0.0729

Using the average values of asymmetries and branching ratios $\mathcal{B}(\Lambda_b \to \Lambda \mu^+\mu^-) = (4.6 \pm 1.6) \times 10^{-6}$ [32], and $\mathcal{B}(\Lambda_b \to \Lambda \tau^+\tau^-) = (8.0 \pm 3.0) \times 10^{-7}$ [32], the required number of events at 3σ level are

- for the $\Lambda_b \to \Lambda \mu^+\mu^-$ decay

$$N = \begin{cases} 2.0 \times 10^7 & (\text{for } P_{NN} \text{ and } P_{TT}), \\ 3.0 \times 10^7 & (\text{for } P_{NT} \text{ and } P_{TN}), \end{cases} \tag{30}$$

- for the $\Lambda_b \to \Lambda \tau^+\tau^-$ decay

$$N = 4.50 \times 10^9 \quad (\text{for } P_{LN} \text{ and } P_{NL}). \tag{31}$$

It expected that LHCb would produce 10^{12} $\bar{b}b$ pairs. A comparison of this number and N listed above yields that it is possible to detect these asymmetries at LHCb. It should be mentioned here that, if experimental value of the branching ratio $\mathcal{B} = (1.73 \pm 0.42 \pm 0.55) \times 10^{-6}$ [12] of the for the $\Lambda_b \to \Lambda \mu^+\mu^-$ were used, the number of events presented above increase, approximately, by a factor of two.

As the concluding remark we can summarize our analysis as follows. Contributions of family non-universal Z' model to the single and double lepton polarizations, as well as polarized forward–backward asymmetry $\mathcal{A}_{FB}^{LL}$ in rare, exclusive baryonic $\Lambda_b \to \Lambda \ell^+\ell^-$ decay is studied. It is obtain that P_{NN}, P_{TT} and P_{TN} are quite sensitive to the Z' boson contributions. Moreover, it is found that the polarized forward–backward asymmetry $\mathcal{A}_{FB}^{LL}$ is also sensitive to the existence of Z' boson. Therefore, determination of the value of $\mathcal{A}_{FB}^{LL}$ is a very important information about new physics beyond the SM. Our calculations show that P_{NN}, $P_{NT}(P_{TN})$ for the $\Lambda_b \to \Lambda \mu^+\mu^-$ decay, and P_{LN} for the $\Lambda_b \to \Lambda \tau^+\tau^-$ decay could be detected at LHCb.

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