Semileptonic *B* to scalar meson decays in the standard model with fourth generation

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We study the effects of the fourth generation of quarks on the total branching ratio and the lepton polarizations in $\bar{B}_0 \rightarrow K_0^*(1430)l^+l^-$ ($l = \mu, \tau$) decay. Taking the fourth generation quark mass $m_{t'}$ of about 400 to 600 GeV with the mixing angle $|V_{t'b}^* V_{t's}|$ in the range (0.05–1.4) $\times 10^{-2}$ and using the phase to be 80°, it is found that the branching ratio and lepton polarizations are quite sensitive to these fourth generation parameters. In the future, the experimental study of this decay will give us an opportunity to study new physics effects, precisely, to search for the fourth generation of quarks (t', b') in an indirect way.

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I. INTRODUCTION

The *CP* violation through the Cabibbo-Kobayashi-Maskawa (CKM) paradigm [1,2] in the standard model (SM) has been extremely successful in explaining most of the experimental data. However, in the past few year a lot more data were accumulated from the two *B* factories and also the improvement in the accuracy of some of the theoretical calculations led us to understand that several of the experimental results are difficult to explain within the standard model with three generations (SM3) [3–5]. This leads us to think about some beyond the SM3 scenarios and among them the simplest one is the standard model with the fourth generation (SM4). In this model the SM is enlarged by a complete sequential fourth family of quarks and leptons: a new (t', b') and (ν', l'), which are the heavy chiral doublets. A review and summary of the SM4 can be found in [6].

During the last years, a number of analysis were published with the goal of investigating the impact of the existence of a fourth generation on Higgs physics [7–9], electroweak precision tests [7,9–13], renormalization group effects [14,15], and flavor physics [16–31]. In addition to this, detailed analyses of supersymmetry in the presence of a fourth generation have recently been performed in [32,33].

In flavor physics the importance of the SM4 is in the flavor changing neutral currents (FCNC) which lies in the fact that on the one hand it contains much fewer parameters than other new physics (NP) scenarios like the littlest Higgs model with *T* parity, Randall-Sundrum models, or the general minimal supersymmetric standard model and on the other hand there is the possibility of having simultaneously sizable NP physics effects in the *K* and *B* systems compared to the above mentioned NP models. Moreover, having the same operator structure as that of the SM3, it implies that the nonperturbative uncertainties in the SM4 are at the same level as in the SM3. Recently, Buras *et al.* [29] performed a detailed analysis of nonminimal flavor violating effects in the K, B_d, and B_s system in the SM4 where they paid particular attention to the correlation between flavor observables and addressed within this framework a number of anomalies present in the experimental data. In addition to this, they have also studied the $D^0 - \bar{D}^0$ mixing in the SM4 where they calculated the size of allowed *CP* violation which is found at the observable level well beyond anything possible with CKM dynamics [34].

In this work we investigate the possibility of searching for NP in the $\bar{B}_0 \rightarrow K_0^*(1430)l^+l^-$ ($l = \mu$, τ), where $K_0^*(1430)$ is a scalar meson, using the fourth generation of quarks (t', b'). At the quark level this decay is governed by $b \rightarrow s$ transitions, which are at the forefront of indirect investigations of a fourth generation. In these FCNC transitions the fourth generation quarks (t'), like u, c, t quarks, contribute at loop level. Therefore, it modifies the corresponding Wilson coefficients which may have effects on branching ratio and lepton polarization asymmetries of $\bar{B}_0 \rightarrow K_0^*(1430)l^+l^-$ decay. Now the main job of investigating the semileptonic B meson decay is to properly evaluate the hadronic matrix elements for $B \rightarrow K_0^*(1430)$, namely, the transition form factors, which are governed by the nonperturbative QCD dynamics. Several methods exist in the literature to deal with this problem, such as the simple quark model, the light-front approach, QCD sum rules, light-cone QCD sum rules (LCSR), and the perturbative QCD factorization approach.

In our numerical analysis for $\bar{B}_0 \rightarrow K_0^*(1430)$ decays, we shall use the results of the form factors calculated by the LCSR approach in Ref. [35], and explore the effects of the fourth generation parameters ($m_{t'}$, $V_{t'b}^* V_{t's}$) on branching ratios and lepton polarization asymmetries. By incorporating the recent constraints $m_{t'} = 400$–600 GeV and $V_{t'b}V_{t's} = (0.05$–$1.4) \times 10^{-2}$ [28], our results show that the decay rates are quite sensitive to these parameters. Now the forward-backward asymmetry is zero in the SM3 for these decays because of the absence of the scalar-type coupling, and it remains as zero in the SM4 as there is no new operator in addition to the SM3 operators. The hadronic uncertainties associated with the form

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factors and other input parameters have negligible effects on the lepton polarization asymmetries, and this makes them efficient in establishing the NP. Here, we have also studied these asymmetries in the SM4 and found that the effects of the fourth generation parameters are quite significant in some regions of the parameter space of the SM4.

The paper is organized as follows: In Sec. II, we present the effective Hamiltonian for the semileptonic decay $\bar{B} \to K_0^* l^+ l^-$. Section III contains the parameterizations and numbers of the form factors for the said decay using the LCSR approach. In Sec. IV, we present the basic formulas of physical observables like decay rates and polarization asymmetries of final state lepton for the said decay. Section V is devoted to the numerical analysis where we study the sensitivity of these physical observables on the fourth generation parameter $(m_{t'}, V_{t'b}^* V_{t's})$. The main results are summarized in Sec. VI.

II. EFFECTIVE HAMILTONIAN

At quark level the decay $B \to K_0^*(1430) l^+ l^-$ is governed by the transition $b \to s l^+ l^-$ for which the effective Hamiltonian can be written as

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \sum_{i=1}^{10} C_i(\mu) O_i(\mu), \tag{1}$$

where $O_i(\mu)$ $(i = 1, \ldots, 10)$ are the four-quark operators and $C_i(\mu)$ are the corresponding Wilson coefficients at the energy scale μ, and the explicit expressions of these in the SM3 at next-to-leading order and next-to-next-leading logarithms are given in [36–46]. The operators responsible for $B \to K_0^*(1430) l^+ l^-$ are O_7, O_9, and O_{10}, and their form is given by

$$\begin{aligned} O_7 &= \frac{e^2}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \\ O_9 &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l), \\ O_{10} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l), \end{aligned} \tag{2}$$

with $P_{L,R} = (1 \pm \gamma_5)/2$. Now, the fourth generation comes into play in the same way as the three generation SM, i.e., the full set of operators remains the same as in the SM3. Therefore, the effect of the fourth generation displays itself by changing the values of Wilson coefficients $C_7(\mu)$, $C_9(\mu)$ and C_{10} via the virtual exchange of the fourth generation up-type quark t', which then takes the form

$$\lambda_t C_i \to \lambda_t C_i^{\text{SM}} + \lambda_{t'} C_i^{\text{new}}, \tag{3}$$

where $\lambda_f = V_{fb}^* V_{fs}$ and the explicit forms of the C_i's can be obtained from the corresponding expressions of the Wilson coefficients in the SM3 by substituting $m_t \to m_{t'}$. By adding an extra family of quarks, the CKM matrix of the SM3 is extended by another row and column which now becomes 4×4. The unitarity of which leads to

$$\lambda_u + \lambda_c + \lambda_t + \lambda_{t'} = 0.$$

Since $\lambda_u = V_{ub}^* V_{us}$ has a very small value compared to the others, we therefore ignore it. Then $\lambda_t \approx -\lambda_c - \lambda_{t'}$, and from Eq. (3), we have

$$\lambda_t C_i^{\text{SM}} + \lambda_{t'} C_i^{\text{new}} = -\lambda_c C_i^{\text{SM}} + \lambda_{t'}(C_i^{\text{new}} - C_i^{\text{SM}}). \tag{4}$$

One can clearly see that under $\lambda_{t'} \to 0$ or $m_{t'} \to m_t$ the term $\lambda_{t'}(C_i^{\text{new}} - C_i^{\text{SM}})$ vanishes, which is the requirement of the Glashow-Iliopoulos-Maiani mechanism. Taking the contribution of the t' quark in the loop the Wilson coefficients C_i's can be written in the following form:

$$\begin{aligned} C_7^{\text{tot}}(\mu) &= C_7^{\text{SM}}(\mu) + \frac{\lambda_{t'}}{\lambda_t} C_7^{\text{new}}(\mu), \\ C_9^{\text{tot}}(\mu) &= C_9^{\text{SM}}(\mu) + \frac{\lambda_{t'}}{\lambda_t} C_9^{\text{new}}(\mu), \\ C_{10}^{\text{tot}} &= C_{10}^{\text{SM}} + \frac{\lambda_{t'}}{\lambda_t} C_{10}^{\text{new}}, \end{aligned} \tag{5}$$

where we factored out the $\lambda_t = V_{tb}^* V_{ts}$ term in the effective Hamiltonian given in Eq. (1), and the last term in these expressions corresponds to the contribution of the t' quark to the Wilson coefficients. $\lambda_{t'}$ can be parameterized as

$$\lambda_{t'} = |V_{t'b}^* V_{t's}| e^{i\phi_{sb}}. \tag{6}$$

In terms of the above Hamiltonian, the free quark decay amplitude for $b \to s\ l^+ l^-$ in the SM4 can be derived as

$$\begin{aligned} \mathcal{M}(b \to s l^+ l^-) = -\frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \Big\{ & C_9^{\text{tot}} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l) \\ & + C_{10}^{\text{tot}} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l) \\ & - 2m_b C_7^{\text{tot}} \Big(\bar{s} i\sigma_{\mu\nu} \frac{q^\nu}{q^2} P_R b \Big)(\bar{l}\gamma^\mu l) \Big\}, \end{aligned} \tag{7}$$

where q^2 is the square of momentum transfer. The operator O_{10} cannot be induced by the insertion of four-quark operators because of the absence of the Z boson in the effective theory. Therefore, the Wilson coefficient C_{10} does not renormalize under QCD corrections and hence it is independent on the energy scale. In addition to this, the above quark level decay amplitude can receive contributions from the matrix element of four-quark operators, $\sum_{i=1}^{6} \langle l^+ l^- s | O_i | b \rangle$, which are usually absorbed into the effective Wilson coefficient $C_9^{\text{SM}}(\mu)$ and can usually be called C_9^{eff}, that one can decompose into the following three parts:

$$C_9^{\text{SM}} = C_9^{\text{eff}}(\mu) = C_9(\mu) + Y_{\text{SD}}(z, s') + Y_{\text{LD}}(z, s'),$$

where the parameters z and s' are defined as $z = m_c/m_b$, $s' = q^2/m_b^2$. $Y_{\text{SD}}(z, s')$ describes the short-distance contributions from four-quark operators far away from the $c\bar{c}$

resonance regions, which can be calculated reliably in the perturbative theory. The long-distance contributions $Y_{\rm LD}(z, s')$ from four-quark operators near the $c\bar{c}$ resonance cannot be calculated from first principles of QCD and are usually parameterized in the form of a phenomenological Breit-Wigner formula making use of the vacuum saturation approximation and quark-hadron duality. We will neglect the long-distance contributions in this work because of the absence of experimental data on $B \to J/\psi K_0^*(1430)$. The manifest expressions for $Y_{\rm SD}(z, s')$ can be written as [37]

$$\begin{aligned} Y_{\rm SD}(z, s') = {}& h(z, s')(3C_1(\mu) + C_2(\mu) + 3C_3(\mu) + C_4(\mu) \\ &+ 3C_5(\mu) + C_6(\mu)) - \tfrac{1}{2}h(1, s')(4C_3(\mu) \\ &+ 4C_4(\mu) + 3C_5(\mu) + C_6(\mu)) \\ &- \tfrac{1}{2}h(0, s')(C_3(\mu) + 3C_4(\mu)) + \tfrac{2}{9}(3C_3(\mu) \\ &+ C_4(\mu) + 3C_5(\mu) + C_6(\mu)), \end{aligned} \tag{8}$$

with

$$h(z, s') = -\frac{8}{9}\ln z + \frac{8}{27} + \frac{4}{9}x - \frac{2}{9}(2 + x)|1 - x|^{1/2} \times \begin{cases} \ln\left|\frac{\sqrt{1-x}+1}{\sqrt{1-x}-1}\right| - i\pi & \text{for } x \equiv 4z^2/s' < 1 \\ 2\arctan\frac{1}{\sqrt{x-1}} & \text{for } x \equiv 4z^2/s' > 1 \end{cases},$$

$$h(0, s') = \frac{8}{27} - \frac{8}{9}\ln\frac{m_b}{\mu} - \frac{4}{9}\ln s' + \frac{4}{9}i\pi. \tag{9}$$

Apart from this, the nonfactorizable effects [47–50] from the charm loop can bring about further corrections to the radiative $b \to s\gamma$ transition, which can be absorbed into the effective Wilson coefficient $C_7^{\rm eff}$. Specifically, the Wilson coefficient $C_7^{\rm eff}$ is given by [51]

$$C_7^{\rm SM}(\mu) = C_7^{\rm eff}(\mu) = C_7(\mu) + C_{b\to s\gamma}(\mu),$$

with

$$C_{b\to s\gamma}(\mu) = i\alpha_s\left[\frac{2}{9}\eta^{14/23}(G_1(x_t) - 0.1687) - 0.03C_2(\mu)\right], \tag{10}$$

$$G_1(x_t) = \frac{x_t(x_t^2 - 5x_t - 2)}{8(x_t - 1)^3} + \frac{3x_t^2\ln^2 x_t}{4(x_t - 1)^4}, \tag{11}$$

where $\eta = \alpha_s(m_W)/\alpha_s(\mu)$, $x_t = m_t^2/m_W^2$, $C_{b\to s\gamma}$ is the absorptive part for the $b \to sc\bar{c} \to s\gamma$ rescattering, and we have dropped out the tiny contributions proportional to the CKM sector $V_{ub}V_{us}^*$. In addition, $C_7^{\rm new}(\mu)$ can be obtained by replacing m_t with m_{tl} in the above expression. A similar replacement ($m_t \to m_{tl}$) has to be done for the other Wilson coefficients $C_9^{\rm eff}$ and C_{10} whose expressions are too lengthy to be given here, and their explicit expressions are given in Refs. [36–46].

III. PARAMETERIZATIONS OF MATRIX ELEMENTS AND FORM FACTORS IN THE LCSR

With the free quark decay amplitude available, we can proceed to calculate the decay amplitudes for semileptonic decays of $\bar{B}_0 \to K_0^*(1430)l^+l^-$ at the hadronic level, which can be obtained by sandwiching the free quark amplitudes between the initial and final meson states. Consequently, the following two hadronic matrix elements

$$\langle K_0^*(p)|\bar{s}\gamma_\mu\gamma_5 b|B_{q'}(p+q)\rangle,$$
$$\langle K_0^*(p)|\bar{s}\sigma_{\mu\nu}\gamma_5 q^\nu b|B_{q'}(p+q)\rangle$$

need to be computed as can be observed from Eq. (1). Generally, the above two matrix elements can be parameterized in terms of a series of form factors as

$$\langle K_0^*(p)|\bar{s}\gamma_\mu\gamma_5 b|B_{q'}(p+q)\rangle = -i[f_+(q^2)p_\mu + f_-(q^2)q_\mu], \tag{12}$$

$$\langle K_0^*(p)|\bar{s}\sigma_{\mu\nu}\gamma_5 q^\nu b|B_{q'}(p+q)\rangle = -\frac{1}{m_B + m_{K_0^*}}[(2p+q)_\mu q^2 - (m_B^2 - m_{K_0^*}^2)q_\mu]f_T(q^2). \tag{13}$$

The form factors are the nonperturbative quantities and to calculate them one has to rely on some nonperturbative approaches. Considering the distribution amplitudes up to twist-3, the form factors at small q^2 for $\bar{B}_0 \to K_0^* l^+l^-$ have been calculated in [35] using the LCSR. The dependence of form factors $f_i(q^2)(i = +, -, T)$ on momentum transfer s are parameterized in either the single pole form

$$f_i(q^2) = \frac{f_i(0)}{1 - a_i q^2/m_{B_0}^2}, \tag{14}$$

or the double-pole form

$$f_i(q^2) = \frac{f_i(0)}{1 - a_i q^2/m_{B_0}^2 + b_i q^4/m_{B_0}^4}, \tag{15}$$

in the whole kinematical region $0 < q^2 < (m_{B_0} - m_{K_0^*})^2$, while nonperturbative parameters a_i and b_i can be fixed by the magnitudes of form factors corresponding to the small momentum transfer calculated in the LCSR approach.

TABLE I. Numerical results for the parameters $f_i(0)$, a_i, and b_i involved in the double-pole fit of form factors (15) responsible for $\bar{B}_0 \to K_0^*(1430)l^+l^-$ decay up to the twist-3 distribution amplitudes of $K_0^*(1430)$ meson.

	$f_i(0)$	a_i	b_i
f_+	$0.97^{+0.20}_{-0.20}$	$0.86^{+0.19}_{-0.18}$	
f_-	$0.073^{+0.02}_{-0.02}$	$2.50^{+0.44}_{-0.47}$	$1.82^{+0.69}_{-0.76}$
f_T	$0.60^{+0.14}_{-0.13}$	$0.69^{+0.26}_{-0.27}$	

The results for the parameters a_i, b_i accounting for the q^2 dependence of form factors f_+, f_- and f_T are grouped in Table I.

IV. FORMULA FOR PHYSICAL OBSERVABLES

In this section, we are going to perform the calculations of some interesting observables in phenomenology like the decay rates, forward-backward asymmetry as well as the polarization asymmetries of the final state lepton. From Eq. (7), it is straightforward to obtain the decay amplitude for $\bar{B}_0 \to K_0^* l^+ l^-$ as

$$\mathcal{M}_{\bar{B}_0\to K_0^* l^+ l^-} = -\frac{G_F \alpha}{2\sqrt{2}\pi} V_{tb} V_{ts}^* [T_\mu^1 (\bar{l}\gamma^\mu l) + T_\mu^2 (\bar{l}\gamma^\mu \gamma_5 l)], \tag{16}$$

where the functions T_μ^1 and T_μ^2 are given by

$$T_\mu^1 = iC_9^{\rm tot} f_+(q^2) p_\mu + \frac{4im_b}{m_B + m_{K_0^*}} C_7^{\rm tot} f_T(q^2) p_\mu,$$
$$T_\mu^2 = iC_{10}^{\rm tot}(f_+(q^2) p_\mu + f_-(q^2) q_\mu). \tag{17}$$

Because of the equation of motion for lepton fields, the terms proportional to q_μ in T_μ^1, namely, $f_-(q^2)$ do not contribute to the decay amplitude.

A. The differential decay rates and forward-backward asymmetry of $\bar{B}_0 \to K_0^*(1430) l^+ l^-$

The semileptonic decay $\bar{B}_0 \to K_0^*(1430) l^+ l^-$ is induced by FCNCs. The differential decay width of $\bar{B}_0 \to K_0^*(1430) l^+ l^-$ in the rest frame of the $\bar{B}_0$ meson can be written as [52]

$$\frac{d\Gamma(\bar{B}_0 \to K_0^*(1430) l^+ l^-)}{dq^2} = \frac{1}{(2\pi)^3} \frac{1}{32 m_{\bar{B}_0}} \int_{u_{\min}}^{u_{\max}} |\tilde{M}_{\bar{B}_0\to K_0^*(1430) l^+ l^-}|^2 du, \tag{18}$$

where $u = (p_{K_0^*(1430)} + p_{l^-})^2$ and $q^2 = (p_{l^+} + p_{l^-})^2$; $p_{K_0^*(1430)}$, p_{l^+} and p_{l^-} are the four-momenta vectors of $K_0^*(1430)$, l^+, and l^-, respectively; $|\tilde{M}_{\bar{B}_0\to K_0^*(1430) l^+ l^-}|^2$ is the squared decay amplitude after integrating over the angle between the lepton l^- and $K_0^*(1430)$ meson. The upper and lower limits of u are given by

$$u_{\max} = (E^*_{K_0^*(1430)} + E^*_{l^-})^2 - \left(\sqrt{E^{*2}_{K_0^*(1430)} - m^2_{K_0^*(1430)}} - \sqrt{E^{*2}_{l^-} - m^2_{l^-}}\right)^2,$$
$$u_{\min} = (E^*_{K_0^*(1430)} + E^*_{l^-})^2 - \left(\sqrt{E^{*2}_{K_0^*(1430)} - m^2_{K_0^*(1430)}} + \sqrt{E^{*2}_{l^-} - m^2_{l^-}}\right)^2; \tag{19}$$

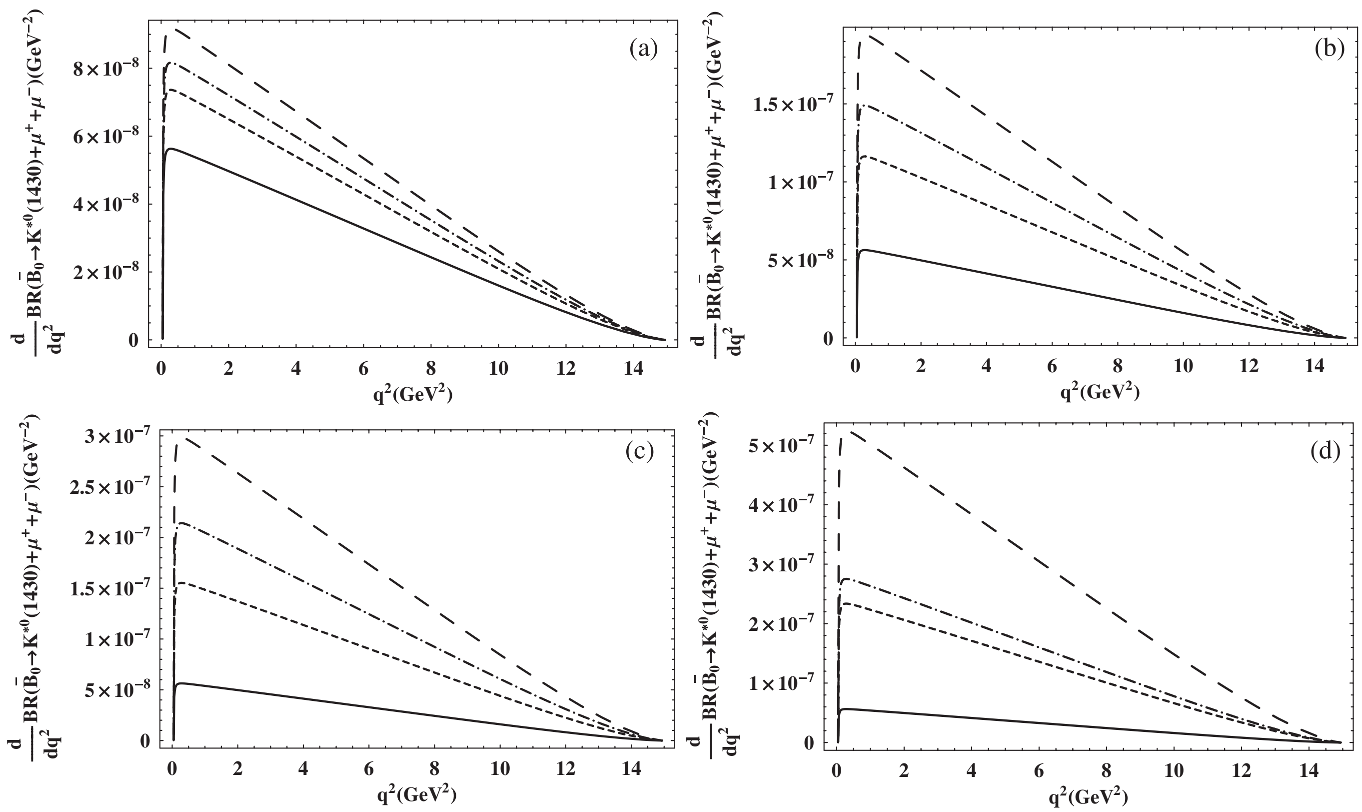

FIG. 1. The dependence of the branching ratio of $\bar{B}_0 \to K_0^*(1430)\mu^+\mu^-$ on q^2 for different values of $m_{t'}$ and $|V^*_{t'b}V_{t's}|$. $|V^*_{t'b}V_{t's}| = 0.002$, 0.006, 0.009, and 0.014 in (a), (b), (c), and (d), respectively. In all the graphs, the solid line corresponds to the SM, dashed line, dashed-dotted, and long dashed lines are for $m_{t'} = 200$ GeV, 400 GeV, and 600 GeV, respectively.

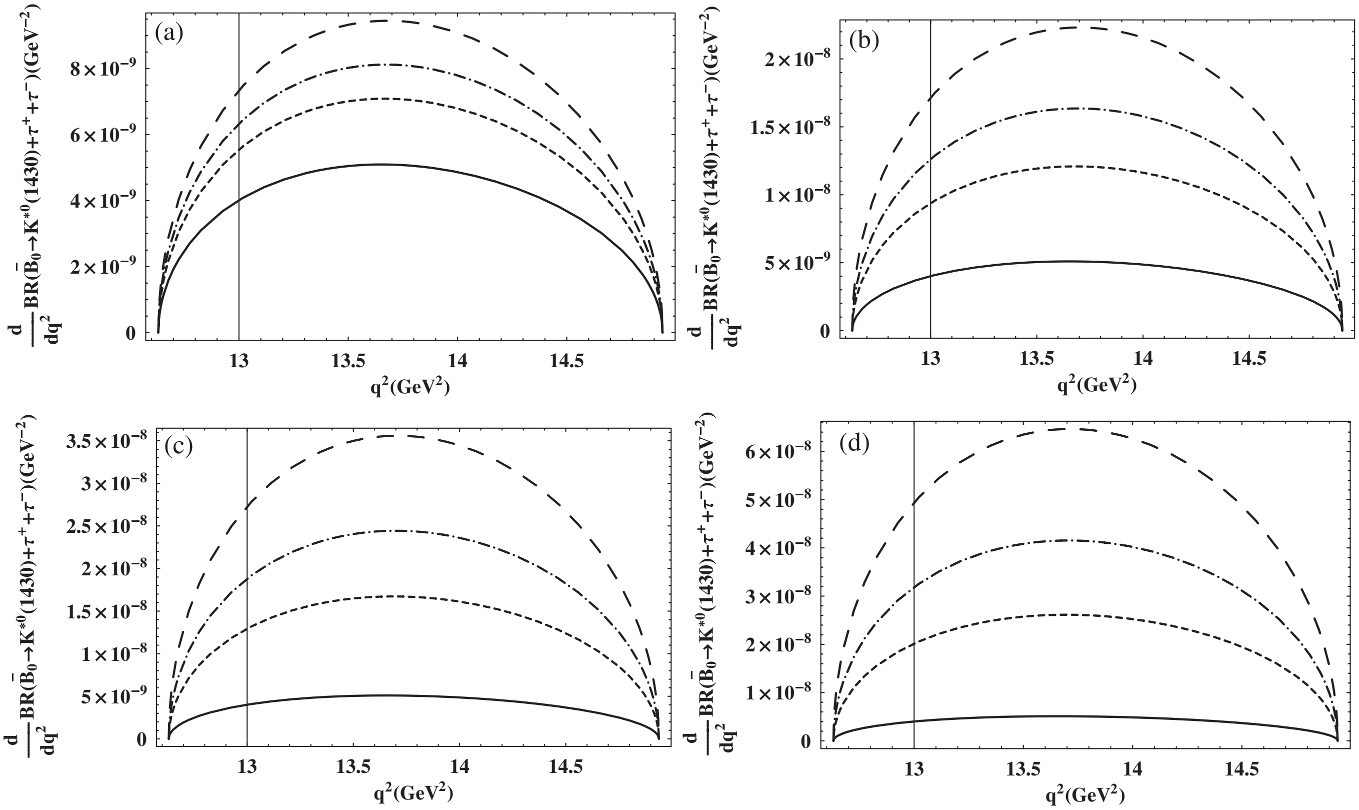

FIG. 2. The dependence of the branching ratio of $\bar{B}_0 \to K_0^*(1430)\tau^+\tau^-$ on q^2 for different values of $m_{t'}$ and $|V_{t'b}^* V_{t's}|$. The values of the fourth generation parameters and the legends are same as in Fig. 1

where the energies of $K_0^*(1430)$ and l^- in the rest frame of lepton pair $E^*_{K_0^*(1430)}$ and $E^*_{l^-}$ are determined as

$$E^*_{K_0^*(1430)} = \frac{m^2_{\bar{B}_0} - m^2_{K_0^*(1430)} - q^2}{2\sqrt{q^2}}, \quad E^*_l = \frac{q^2}{2\sqrt{q^2}}. \qquad (20)$$

Collecting everything together, one can write the general expression of the differential decay rate for $\bar{B}_0 \to K_0^*(1430)l^+l^-$ as

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{3072 m_B^3 \pi^5 q^2}\sqrt{1-\frac{4m_l^2}{q^2}}\sqrt{\lambda(m_B^2, m_{K_0^*}^2, q^2)} \times \{|A|^2(2m_l^2 + q^2)\lambda + 12q^2m_l^2(m_B^2 - m_{K_0^*}^2 - q^2) \times (CB^* + C^*B) + 12m_l^2q^4|C|^2 + |B|^2((2m_l^2+q^2) \times (m_B^4 - 2m_B^2m_{K_0^*}^2 - 2q^2m_{K_0^*}^2) + (m_{K_0^*}^2 - q^2)^2 + 2m_l^2(m_{K_0^*}^4 + 10tm_{K_0^*}^2 + q^4))\}, \qquad (21)$$

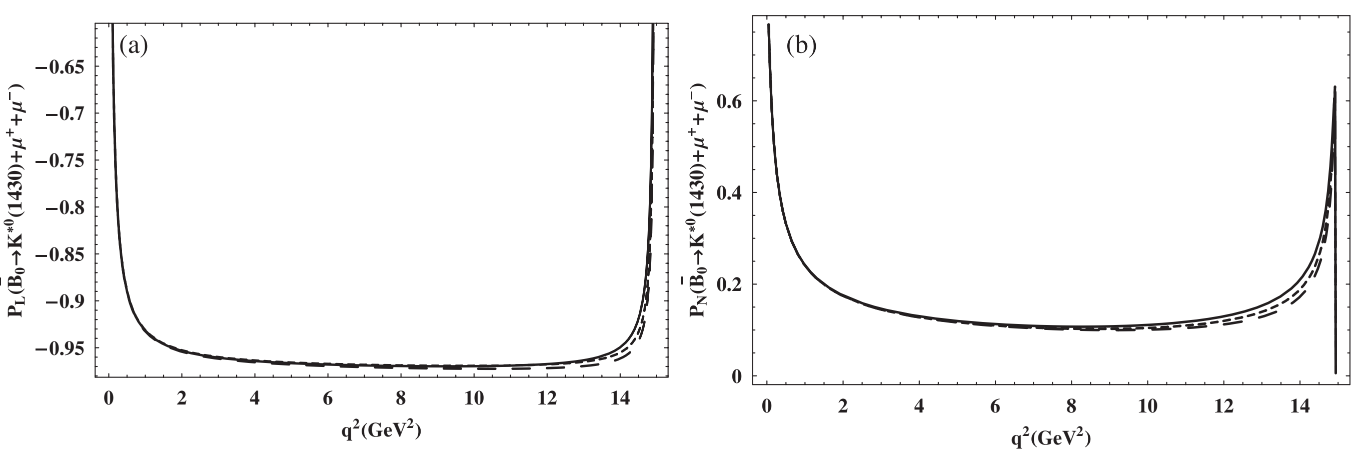

FIG. 3. The dependence of longitudinal (Fig. 3(a)) and normal lepton polarization (Fig. 3(b)) of $\bar{B}_0 \to K_0^*(1430)\mu^+\mu^-$ on q^2 for different values of the input parameters. The solid value corresponds to the central value, the dotted line is for the maximum value, and the long dashed line is for the minimum value of the input parameters.

where

$$\lambda = \lambda(m_B^2, m_{K_0^*}^2, q^2) \\ = m_B^4 + m_{K_0^*}^4 + q^4 - 2m_B^2 m_{K_0^*}^2 - 2m_{K_0^*}^2 q^2 - 2q^2 m_B^2. \tag{22}$$

The auxiliary functions are defined as

$$A = iC_9^{\rm tot} f_+(q^2) + \frac{4im_b}{m_B + m_{K_0^*}} C_7^{\rm tot} f_T(q^2)$$
$$B = iC_{10}^{\rm tot} f_+(q^2) \qquad C = iC_{10}^{\rm tot} f_-(q^2) \tag{23}$$

Just to make a comment, the form factor $f_-(q^2)$ is an order of magnitude smaller than the form factors $f_+(q^2)$ and $f_T(q^2)$; therefore, the value of auxiliary function C is suppressed by the same magnitude compared to A and B.

B. Lepton polarization asymmetries of $\bar{B}_0 \to K_0^*(1430) l^+ l^-$

In the rest frame of the lepton l^-, the unit vectors along longitudinal, normal, and transversal component of the l^- can be defined as [53]

$$s_L^{-\mu} = (0, \vec{e}_L) = \left(0, \frac{\vec{p}_-}{|\vec{p}_-|}\right),$$
$$s_N^{-\mu} = (0, \vec{e}_N) = \left(0, \frac{\vec{p}_{K_0^*} \times \vec{p}_-}{|\vec{p}_{K_0^*} \times \vec{p}_-|}\right), \tag{24}$$
$$s_T^{-\mu} = (0, \vec{e}_T) = (0, \vec{e}_N \times \vec{e}_L),$$

where $\vec{p}_-$ and $\vec{p}_{K_0^*}$ are the three-momenta of the lepton l^- and $K_0^*(1430)$ meson, respectively, in the center of mass frame of the l^+l^- system. The Lorentz transformation is used to boost the longitudinal component of the lepton polarization to the center of mass frame of the lepton pair as

$$(s_L^{-\mu})_{\rm CM} = \left(\frac{|\vec{p}_-|}{m_l}, \frac{E_l \vec{p}_-}{m_l|\vec{p}_-|}\right), \tag{25}$$

where E_l and m_l are the energy and mass of the lepton. The normal and transverse components remain unchanged under the Lorentz boost.

The longitudinal (P_L), normal (P_N), and transverse (P_T) polarizations of lepton can be defined as

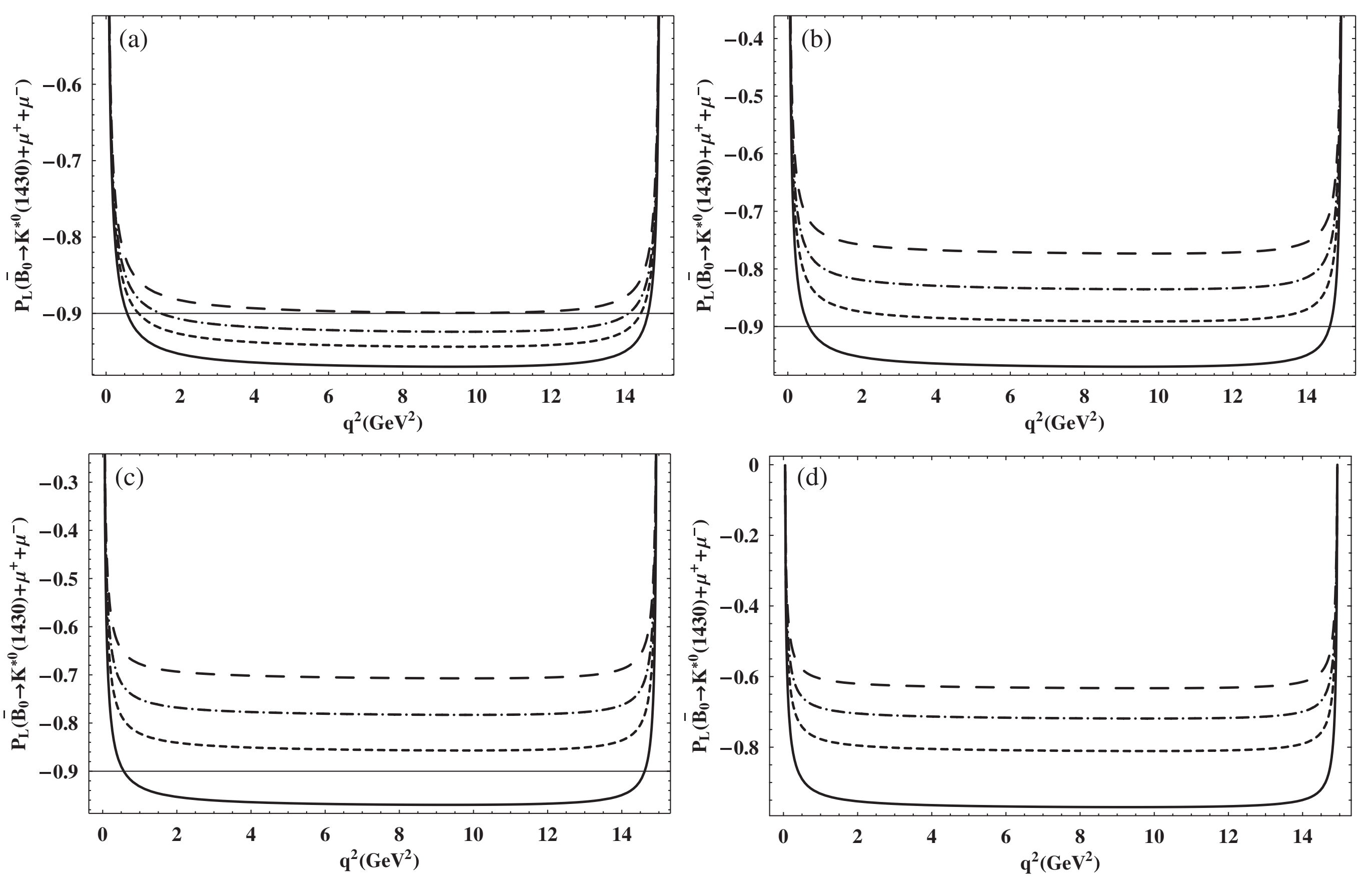

FIG. 4. The dependence of the longitudinal lepton polarization of $\bar{B}_0 \to K_0^*(1430)\mu^+\mu^-$ on q^2 for different values of $m_{t'}$ and $|V_{t'b}^* V_{t's}|$. The values of the fourth generation parameters and the legends are same as in Fig. 1

$$P_i^{(\mp)}(q^2) = \frac{\frac{d\Gamma}{dq^2}(\vec{\xi}^{\mp} = \vec{e}^{\mp}) - \frac{d\Gamma}{dq^2}(\vec{\xi}^{\mp} = -\vec{e}^{\mp})}{\frac{d\Gamma}{dq^2}(\vec{\xi}^{\mp} = \vec{e}^{\mp}) + \frac{d\Gamma}{dq^2}(\vec{\xi}^{\mp} = -\vec{e}^{\mp})}, \quad (26)$$

where $i = L, N, T$, and $\vec{\xi}^{\mp}$ is the spin direction along the leptons $l^{\mp}$. The differential decay rate for polarized lepton $l^{\mp}$ in $\bar{B}_0 \to K_0^*(1430)l^+l^-$ decay along any spin direction $\vec{\xi}^{\mp}$ is related to the unpolarized decay rate (18) with the following relation:

$$\frac{d\Gamma(\vec{\xi}^{\mp})}{dq^2} = \frac{1}{2}\left(\frac{d\Gamma}{dq^2}\right)[1 + (P_L^{\mp}\vec{e}_L^{\mp} + P_N^{\mp}\vec{e}_N^{\mp} + P_T^{\mp}\vec{e}_T^{\mp}) \cdot \vec{\xi}^{\mp}]. \quad (27)$$

We can achieve the expressions of longitudinal, normal, and transverse polarizations for $\bar{B}_0 \to K_0^*(1430)l^+l^-$ decays as collected below. The longitudinal lepton polarization can be written as [35]

$$P_L(q^2) = \left(1\bigg/\frac{d\Gamma}{dq^2}\right)\frac{\alpha^2 G_F^2 |V_{tb}^* V_{ts}|^2 \lambda^{3/2}(m_B^2, m_{K_0^*}^2, q^2)}{3072 m_B^3 \pi^5} \times \left(1 - \frac{4m_l^2}{q^2}\right)(AB^* + A^*B). \quad (28)$$

Similarly, the normal lepton polarization is

$$P_N(q^2) = \left(1\bigg/\frac{d\Gamma}{dq^2}\right)\frac{\alpha^2 G_F^2 |V_{tb}^* V_{ts}|^2 m_l}{4096 m_B^3 \pi^4 \sqrt{q^2}}\sqrt{1 - \frac{4m_l^2}{s}} \times [(m_B^2 - m_{K_0^*}^2 + q^2)(A^*B + AB^*) - 2q^2(A^*C + AC^*)], \quad (29)$$

and the transverse one is given by

$$P_T(q^2) = \left(1\bigg/\frac{d\Gamma}{dq^2}\right)\frac{-i\alpha^2 G_F^2 |V_{tb}^* V_{ts}|^2 \lambda^{1/2}(m_B^2, m_{K_0^*}^2, q^2)}{2048 m_B^3 \pi^4} \times m_l\left(1 - \frac{4m_l^2}{q^2}\right)(m_B^2 - m_{K_0^*}^2 + q^2)(B^*C - BC^*). \quad (30)$$

The $\frac{d\Gamma}{dq^2}$ appearing in the above equation is the one given in Eq. (21) and $\lambda(m_B^2, m_{K_0^*}^2, q^2)$ is the same as that defined in Eq. (22).

V. NUMERICAL ANALYSIS

In this section we will analyze the dependency of the total branching ratios and different lepton polarizations on the fourth generation SM parameters, i.e., the fourth generation quark mass ($m_{t'}$) and to the product of the quark mixing matrix $V_{t'b}^* V_{t's} = |V_{t'b}^* V_{t's}|e^{i\phi_{sb}}$. One of the main

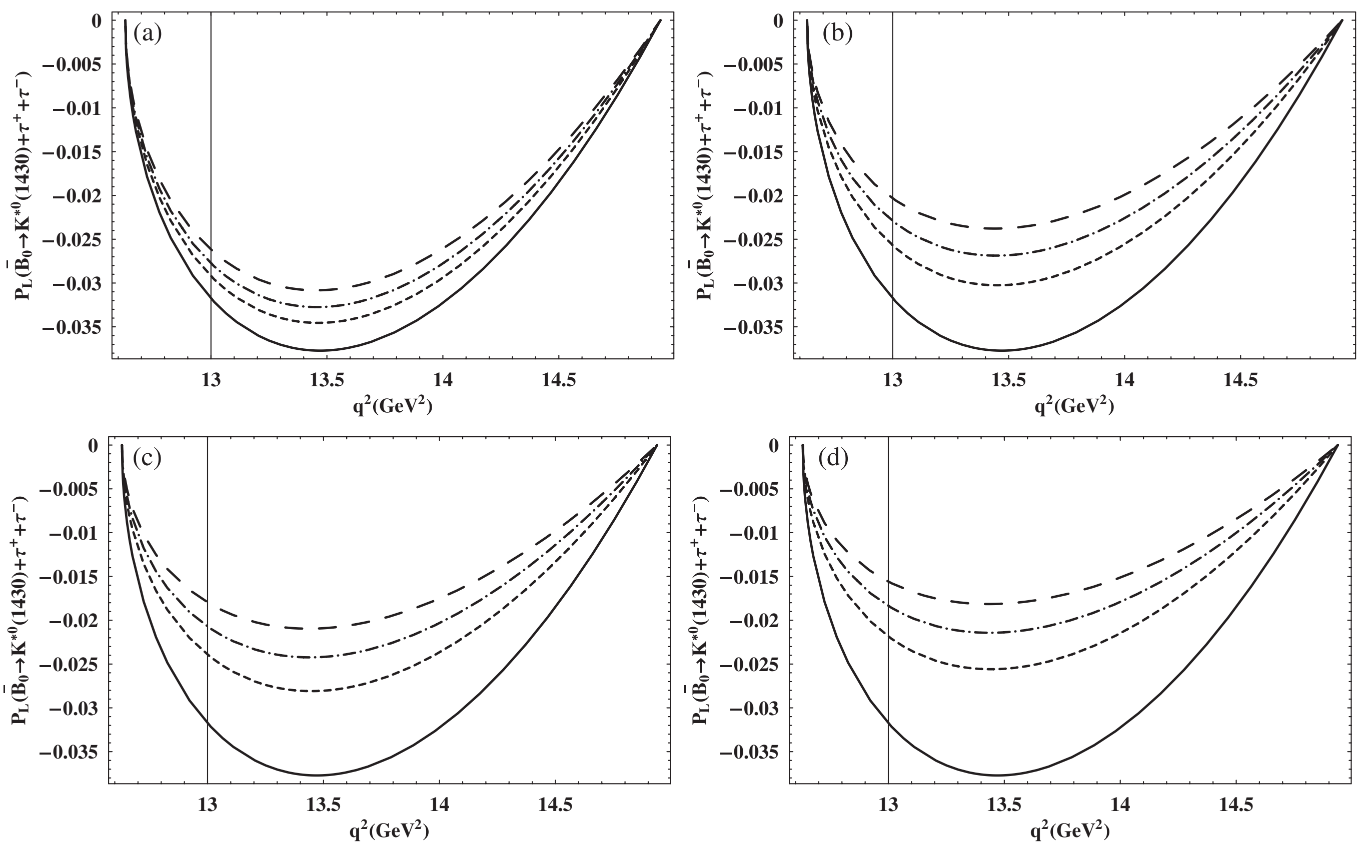

FIG. 5. The dependence of the longitudinal lepton polarization of $\bar{B}_0 \to K_0^*(1430)\tau^+\tau^-$ on q^2 for different values of $m_{t'}$ and $|V_{t'b}^* V_{t's}|$. The values of the fourth generation parameters and the legends are same as in Fig. 1.

input parameters is the form factors which are the nonperturbative quantities and one needs some model to calculate them. Here, we will use the form factors that were calculated using the LCSR [35], and their dependence on q^2 is given in Sec. II, and the corresponding values of the different parameters are listed in Table I. Also, we use the next-to-leading order approximation for the Wilson coefficients $C_i^{\rm SM}$ and $C_i^{\rm new}$ [37,44] at the renormalization point $\mu = m_b$. It has already been mentioned that besides the short-distance contributions in the $C_9^{\rm eff}$, there are the long-distance contributions resulting from the $c\bar{c}$ resonances like J/Ψ and its excited states. In the present study we do not take these long-distance effects into account and also we use the central value of the form factors and the other input parameters given in Table I.

In order to perform a quantitative analysis of physical observables, it is necessary to have the numerical values of the new parameters $(m_{t'}, |V^*_{t'b}V_{t's}|, \phi_{sb})$. In the forthcoming analysis, we use the constraints of Ref. [28] on the fourth generation parameters, where it is found that $m_{t'}$ varies from 400–600 GeV with the mixing angle $|V^*_{t'b}V_{t's}|$ in the range of about $(0.05–1.4) \times 10^{-2}$ and the value of CP-odd phase is from 0° to 80°. Keeping the value of the phase $\phi_{sb} = 80°$ and for different values of $m_{t'}$ and $|V^*_{t'b}V_{t's}|$ we will plot the physical observables with square of the momentum transfer q^2 to see their effects at small and large value of q^2.

The numerical results for the decay rates and polarization asymmetries of the lepton are presented in Figs. 1–7. Figures 1 and 2 describe the differential decay rate of $B \to K_0^*(1430)l^+l^-$, from which one can see that the fourth generation effects are quite distinctive from that of the SM3 both in the small and large momentum transfer region. At a small value of s, the dominant contribution comes from $C_7^{\rm tot}$, whereas at the large value of q^2 the major contribution is from the Z exchange, i.e., $C_{10}^{\rm tot}$ which is sensitive to the mass of the fourth generation quark $m_{t'}$. Furthermore, for both the channels, the branching ratios are enhanced sizably in terms of $m_{t'}$ and $|V^*_{t'b}V_{t's}|$, and for $m_{t'} = 600$ and $|V^*_{t'b}V_{t's}| = 1.4 \times 10^{-2}$ the branching ratios are increased by an order of magnitude.

As an exclusive decay, there are different sources of uncertainties involved in the calculation of the above said decay. The major uncertainties in the numerical analysis of $\bar{B}^0 \to K_0^*(1430)l^+l^-$ decay originated from the $\bar{B}^0 \to K_0^*(1430)$ transition form factors calculated in the LCSR approach as shown in Table I, which can bring about errors of almost 40% to the differential decay rate of the above

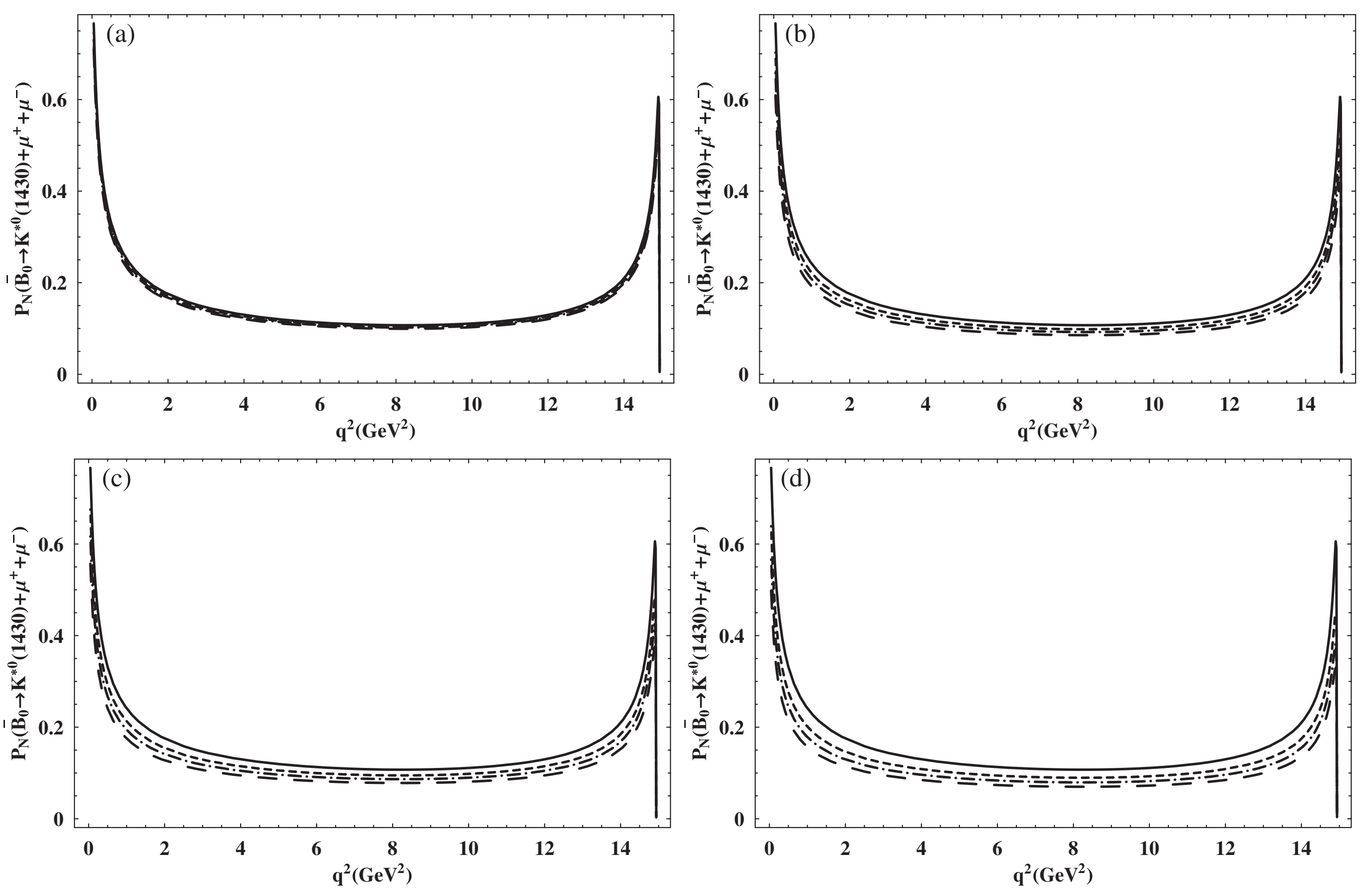

FIG. 6. The dependence of the normal lepton polarization of $\bar{B}_0 \to K_0^*(1430)\mu^+\mu^-$ on q^2 for different values of $m_{t'}$ and $|V^*_{t'b}V_{t's}|$. The values of the fourth generation parameters and the legends are same as in Fig. 1.

mentioned decay, which showed that it is not a very suitable tool to look for the new physics. The large uncertainties involved in the form factors are mainly from the variations of the decay constant of $K_0^*(1430)$ meson and the Gengenbauer moments in its distribution amplitudes. There are also some uncertainties from the strange quark mass m_s, which are expected to be very tiny because of the negligible role of m_s suppressed by the much larger energy scale of m_b. Moreover, the uncertainties of the charm quark and bottom quark mass are at the 1% level, which will not play a significant role in the numerical analysis and can be dropped safely. It also needs to be stressed that these hadronic uncertainties almost have no influence on the various asymmetries, including the lepton polarization asymmetry because of the serious cancellation among different polarization states, and this make them the best tool to look for physics beyond the SM. This has already been described in Ref. [35] and was shown in Figs. 3(a) and 3(b) for the longitudinal and normal lepton polarization asymmetries.

Figures 4(a)–4(d) show the dependence of longitudinal lepton polarization asymmetry for the $B \to K_0^* l^+ l^-$ decay on the square of momentum transfer for different values of $m_{t'}$ and $|V_{t'b}^* V_{t's}|$. The value of longitudinal lepton polarization for muon is around -1 in the SM3, and we have a significant deviation in this value in the SM4. Just in the case of $m_{t'} = 600$ and $|V_{t'b}^* V_{t's}| = 1.4 \times 10^{-2}$ the value of the longitudinal lepton polarization becomes -0.6, which will help us to see experimentally the SM4 effects in these flavor decays. In the large q^2 region, the longitudinal lepton polarization approaches zero both in the SM3 and SM4, which is due to the factor $\lambda(m_B^2, m_{K_0^*}^2, q^2)$ that approaches zero at the large value of q^2. Similar effects can been seen for the final state tauon (cf. Fig. 5) but the value for this case is too small to measure experimentally.

The dependence of normal lepton polarization asymmetries for $B \to K_0^* l^+ l^-$ on the momentum transfer square are presented in Figs. 6 and 7. In terms of Eq. (29), one can see that it is proportional to the mass of the final state lepton and for μ its value is expected to be small, and Figs. 6(a)–6(d) display it in the SM3 as well as the SM4 for the different values of the fourth generation parameters. In the SM4, one can see a slight shift from the SM3 value which, however, is too small to measure experimentally. Now, for the $\tau^+\tau^-$ channel, Eq. (29) we will have a large value of normal lepton polarization compared to the $\mu^+\mu^-$ case in the

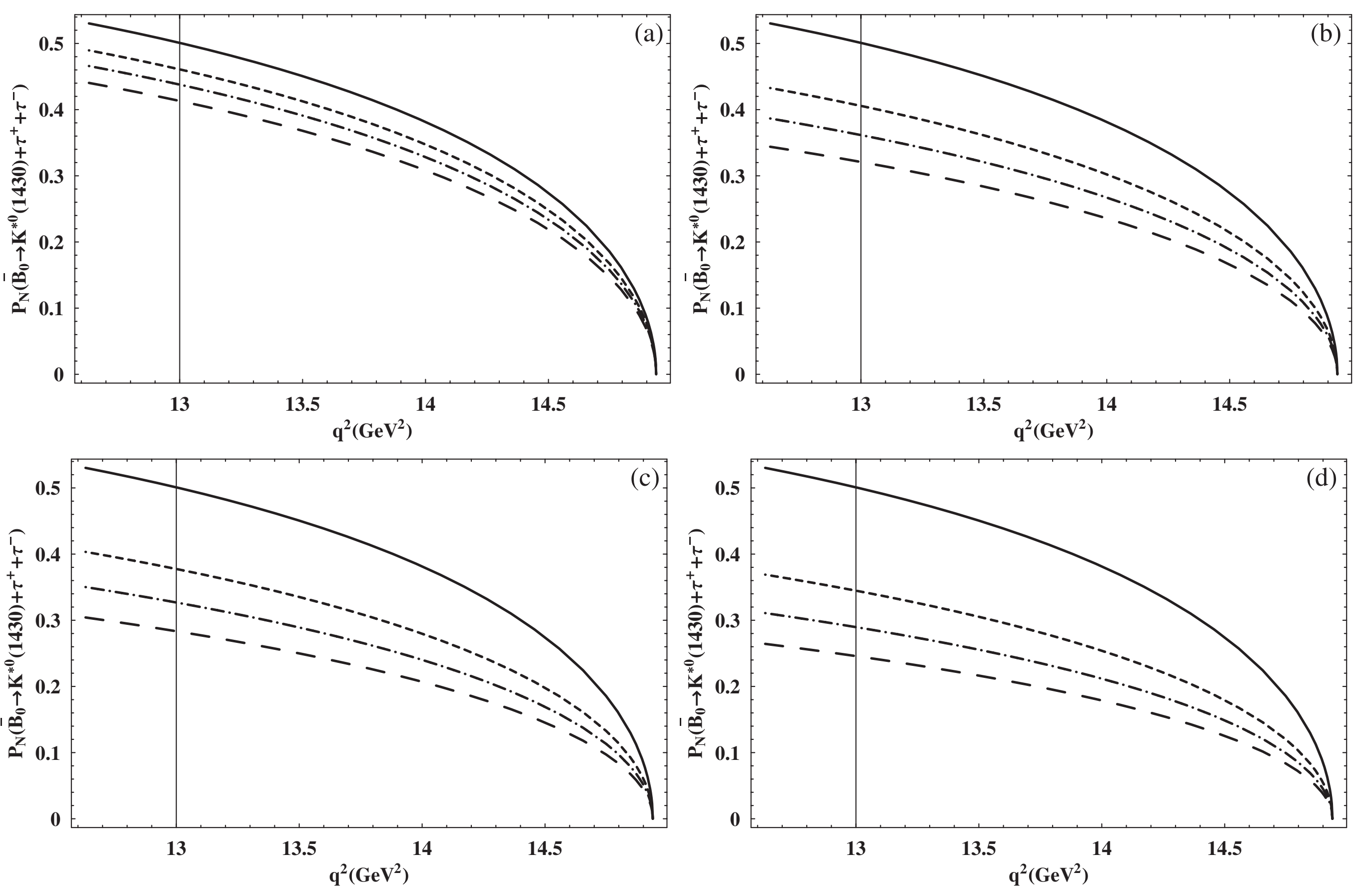

FIG. 7. The dependence of the normal lepton polarization of $\bar{B}_0 \to K_0^*(1430)\tau^+\tau^-$ on q^2 for different values of $m_{t'}$ and $|V_{t'b}^* V_{t's}|$. The values of the fourth generation parameters and the legends are same as in Fig. 1.

SM3. Figure 7 shows that there is a significant decrease in the value of P_N in the SM4 compared to the SM3, and its experimental measurement will give us some clue about the fourth generation of quarks.

Now, from Eq. (30) we can see that it is proportional to the lepton mass as well as to the form factor $f_-(q^2)$, which is an order of magnitude smaller than the $f_+(q^2)$ and $f_T(q^2)$. This makes the transverse lepton polarization asymmetry to be almost zero in the SM3 as well as in the SM4, and it is nonzero only in the models where we have new operators, e.g., scalar-type operators in the minimal supersymmetric standard model.

VI. CONCLUSIONS

We have carried out the study of invariant mass spectrum and polarization asymmetries of semileptonic decays $\bar{B}_0 \to K_0^*(1430)l^+l^-$ $(l = \mu,\ \tau)$ decays in the SM4. Particularly, we analyzed the sensitivity of these physical observables on the fourth generation quark mass $m_{t'}$ as well as the mixing angle $|V_{t'b}^* V_{t's}|$, and the main outcomes of this study can be summarized as follows:

The differential decay rates deviate sizably from that of the SM, especially both in the small and large momentum transfer regions. These effects are significant, and the branching ration increases by an order of magnitude for $m_{t'} = 600$ GeV and $|V_{t'b}^* V_{t's}| = 1.4 \times 10^{-2}$.

It has been shown in the literature [35] that the value of the forward-backward asymmetry for $\bar{B}_0 \to K_0^*(1430)l^+l^-$ is nonzero only in the models where we have the scalar-type operators (like supersymmetric models). Now, due to the absence of scalar-type operators in the SM3 as well as in the SM4 the forward-backward asymmetry for the decay $\bar{B}_0 \to K_0^*(1430)l^+l^-$ is zero in both these models.

The longitudinal, normal, and transverse polarizations of leptons are calculated in the SM4. It is found that the SM effects are very promising, which could be measured at future experiments and shed light on the new physics beyond the SM. It is hoped that this can be measurable at future experiments like the LHC and BTeV machines where a large number of $b\bar{b}$ pairs are expected to be produced.

In short, the experimental investigation of observables, like decay rates, forward-backward asymmetry, lepton polarization asymmetries, and the polarization asymmetries of $\bar{B}_0 \to K_0^*(1430)l^+l^-$ $(l = \mu,\ \tau)$ decay will be used to search for the SM4 effects and will help us to put constraints on the fourth generation parameters in an indirect way.

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