Longitudinal polarization asymmetry of leptons in pure leptonic B decays

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The longitudinal polarization asymmetry of leptons in $B_q \to l^+ l^-$ ($q=d,s$ and $l=e,\mu,\tau$) decays is investigated. The analysis is done in a general manner by using the effective operator approach. It is shown that the longitudinal polarization asymmetry should provide a direct search for the scalar and pseudoscalar type interactions that are induced in all variants of Higgs-doublet models.

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It has already been pointed out [1–4] that the pure leptonic B decays $B_q \to l^+ l^-$ ($q=d,s$ and $l=e,\mu,\tau$) are very good probes to test new physics beyond the standard model (SM), mainly to reveal the Higgs sector. This previous work was focused on the contributions induced by the scalar and pseudoscalar interactions realized in Higgs-doublet models. Within the SM, the decays are dominated by the Z penguin and the box diagrams, which are helicity suppressed. We note that Higgs-doublet models can generally enhance the branching ratio significantly. Also, as discussed in recent work, the decays are strongly correlated with the semileptonic B decays [4] and even with the muon anomalous magnetic moment [5]. Experimentally, it is expected that present and the forthcoming experiments on B physics (B factories) can probe the flavor sector with high precision [6].

If we detect a large discrepancy between the theoretical estimation of the decay branching fractions and the actually observed experimental results, then this could be evidence either of new physics or of our lack of knowledge of the decay constants of B mesons, f_{B_q}. Therefore, the main interest should be direct observation of new physics contributions belonging to the non-SM interactions, i.e., the scalar and pseudoscalar interactions, because within the SM the decay is only through the axial vector interactions. Here we propose a new observable, namely, the longitudinal polarization asymmetry of leptons ($\mathcal{A}_{\rm LP}$) in $B_q \to l^+ l^-$ ($q=d,s$ and $l=e,\mu,\tau$) decays. Although the measurement may be very difficult and challenging, we point out that this observable is very sensitive to those non-SM new interactions, and provides direct evidence of their existence. We note that the idea of measuring $\mathcal{A}_{\rm LP}$ and CP violation in $K_L \to \mu^+ \mu^-$ decay to look for new physics has been previously considered in several papers [7]. However, we would like to mention that those observables are quite different in the B decay system [8,9]: In the K system the initial CP eigenstate can be determined due to the large lifetime difference of $K_{L,S}$, while this determination is not possible in the case of the B meson system. Therefore, we cannot discuss the $B_q \to l^+ l^-$ decays in the same manner as these previous references.

Taking into account all possible four-Fermi operators that could contribute to $B_q \to l^+ l^-$, these processes are governed by the following effective Hamiltonian [10]:

$$\mathcal{H}_{\rm eff} = -(G_F\alpha/2\sqrt{2}\pi)(V_{tq}^* V_{tb})\{\mathcal{C}_{\rm AA}(\bar{q}\gamma_\mu\gamma_5 b)(\bar{l}\gamma^\mu\gamma_5 l) + \mathcal{C}_{\rm PS}(\bar{q}\gamma_5 b)(\bar{l}l) + \mathcal{C}_{\rm PP}(\bar{q}\gamma_5 b)(\bar{l}\gamma_5 l)\}, \tag{1}$$

by normalizing all terms with the overall factors of the SM. In particular, within the SM one has $\mathcal{C}_{\rm PS}^{\rm SM} = \mathcal{C}_{\rm PP}^{\rm SM} \simeq 0$ and $\mathcal{C}_{\rm AA}^{\rm SM} = Y(x_{t_W})/\sin^2\theta_W$, where $Y(x_{t_W})$ is the Inami-Lim function [11] with $x_{t_W} = (m_t/M_W)^2$. The contributions proportional to $m_{d,s}$ are neglected, and the neutral Higgs contributions in $\mathcal{C}_{\rm PS}^{\rm SM}$ and $\mathcal{C}_{\rm PP}^{\rm SM}$ are proportional to $(m_l m_b)/m_W^2$, and therefore also neglected.

After using the PCAC (partial conservation of axial vector current) ansatz to derive the relation between the operators, the most general matrix element for the decay is

$$\mathcal{M} = i f_{B_q}\frac{G_F\alpha}{2\sqrt{2}\pi}V_{tq}^* V_{tb}\left[\left(2m_l\mathcal{C}_{\rm AA} - \frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PP}\right)\bar{l}\gamma_5 l - \frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\bar{l}l\right]. \tag{2}$$

Using Eq. (2), the branching ratio for $B_q \to l^+ l^-$ becomes

$$\mathcal{B}(B_q \to l^+ l^-) = \frac{G_F^2\alpha^2}{64\pi^3}|V_{tq}^* V_{tb}|^2 \tau_{B_q} f_{B_q}^2 m_{B_q}\sqrt{1-\frac{4m_l^2}{m_{B_q}^2}} \times\left[\left|2m_l\mathcal{C}_{\rm AA} - \frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PP}\right|^2 + \left(1-\frac{4m_l^2}{m_{B_q}^2}\right) \times\left|\frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\right|^2\right], \tag{3}$$

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where τ_{B_q} is the lifetime of the B_q meson. Remarkably, the QCD correction in this decay mode is negligible. As can easily be seen, a significant branching ratio within the SM could be expected only for $l=\tau,\mu$ due to the lepton mass dependence.

We now define an observable using the lepton polarization. Since in the dilepton rest frame we can define only one direction, the lepton polarization vectors in each lepton's rest frame are defined as

$$\overline{s}^{\mu}_{l^\pm}=(0,\pm p_-/|p_-|), \tag{4}$$

and in the dilepton rest frame they are boosted to

$$s^{\mu}_{l^\pm}=(|p_-|/m_l,\pm E_l p_-/m_l|p_-|), \tag{5}$$

where E_l is the lepton energy. Finally, the longitudinal polarization asymmetry of the final leptons in $B_q\to l^+l^-$ is defined as follows:

$$\mathcal{A}^{\pm}_{\rm LP}\equiv\frac{[\Gamma(s_{l^-},s_{l^+})+\Gamma(\mp s_{l^-},\pm s_{l^+})]-[\Gamma(\pm s_{l^-},\mp s_{l^+})+\Gamma(-s_{l^-},-s_{l^+})]}{[\Gamma(s_{l^-},s_{l^+})+\Gamma(\mp s_{l^-},\pm s_{l^+})]+[\Gamma(\pm s_{l^-},\mp s_{l^+})+\Gamma(-s_{l^-},-s_{l^+})]}, \tag{6}$$

and it becomes

$$\mathcal{A}_{\rm LP}(B_q\to l^+l^-)=\frac{2\sqrt{1-4m_l^2/m_{B_q}^2}\,{\rm Re}\{[m_{B_q}^2/(m_b+m_q)]\mathcal{C}_{\rm PS}[2m_l\mathcal{C}_{\rm AA}-m_{B_q}^2/(m_b+m_q)\mathcal{C}_{\rm PP}]\}}{|2m_l\mathcal{C}_{\rm AA}-[m_B^2/(m_b+m_q)]\mathcal{C}_{\rm PP}|^2+(1-4m_l^2/m_{B_q}^2)|[m_{B_q}^2/(m_b+m_q)]\mathcal{C}_{\rm PS}|^2}, \tag{7}$$

with $\mathcal{A}^+_{\rm LP}=\mathcal{A}^-_{\rm LP}\equiv\mathcal{A}_{\rm LP}$. It is clear that within the SM $\mathcal{A}_{\rm LP}(B_q\to l^+l^-)\simeq 0$ and becomes nonzero if and only if $\mathcal{C}_{\rm PS}\neq 0$. Therefore, this observable would be the best probe to search for new physics induced by the pseudoscalar type interactions. We also remark that the dependence on the flavor of the valence quark in $\mathcal{A}_{\rm LP}(B_q\to l^+l^-)$ is tiny, and therefore the lepton longitudinal polarization asymmetry is almost the same for $q=d$ or $q=s$.

Before considering physics beyond the SM, let us briefly review the SM predictions for the processes. For consistency, the top mass is rescaled from its pole mass $m_t=175\pm 5$ GeV, to the modified minimal subtraction scheme ($\overline{\rm MS}$) mass $m_t(\overline{\rm MS})=167\pm 5$ GeV. For numerical calculations throughout the paper, we use the world-averaged values for all other parameters [12]: i.e.,

$$m_{B_q^0}=5279.2\pm 1.8\ \text{MeV},\quad m_W=80.41\pm 0.10\ \text{GeV},$$

$$\tau_{B_q^0}=1.56\pm 0.04\ \text{ps}^{-1},\ \ m_e=0.5\ \text{MeV},\ \ m_\mu=105.7\ \text{MeV},$$

$$m_\tau=1777\ \text{MeV},\quad \sin^2\theta_W(\overline{\rm MS})=0.231,\quad \alpha=1/129,$$

$$f_{B_d}=210\pm 30\ \text{MeV},\quad f_{B_s}=245\pm 30\ \text{MeV}[13].$$

Within the SM and by using the experimental bounds on the Wolfenstein parametrization $(A,\lambda)=(0.819\pm 0.035,0.2196\pm 0.0023)$ together with the unitarity of the Cabibbo-Kobayashi-Mashowa (CKM) matrix [12,14], we get

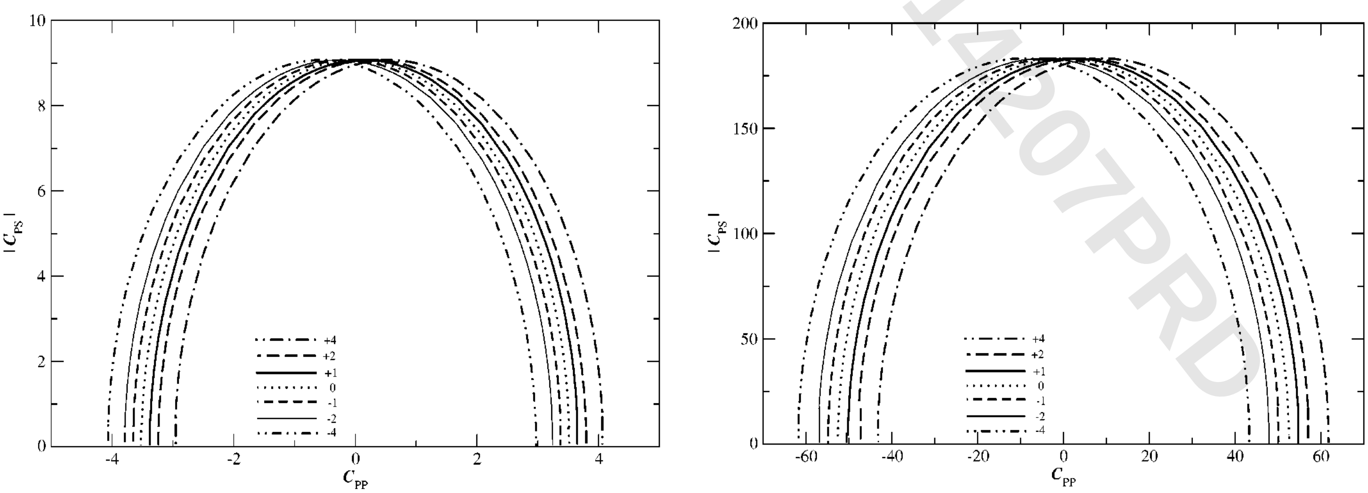

FIG. 1. The upper bounds for $\mathcal{C}_{\rm PP}$ vs $|\mathcal{C}_{\rm PS}|$ for $\mathcal{C}_{\rm AA}=(-4,-2,-1,0,+1,+2,+4)\times\mathcal{C}^{\rm SM}_{\rm AA}$ using the experimental bound on $\mathcal{B}(B_s\to\mu^+\mu^-)$ (left), and the indirect experimental bound on $\mathcal{B}(B_s\to\tau^+\tau^-)$ (right).

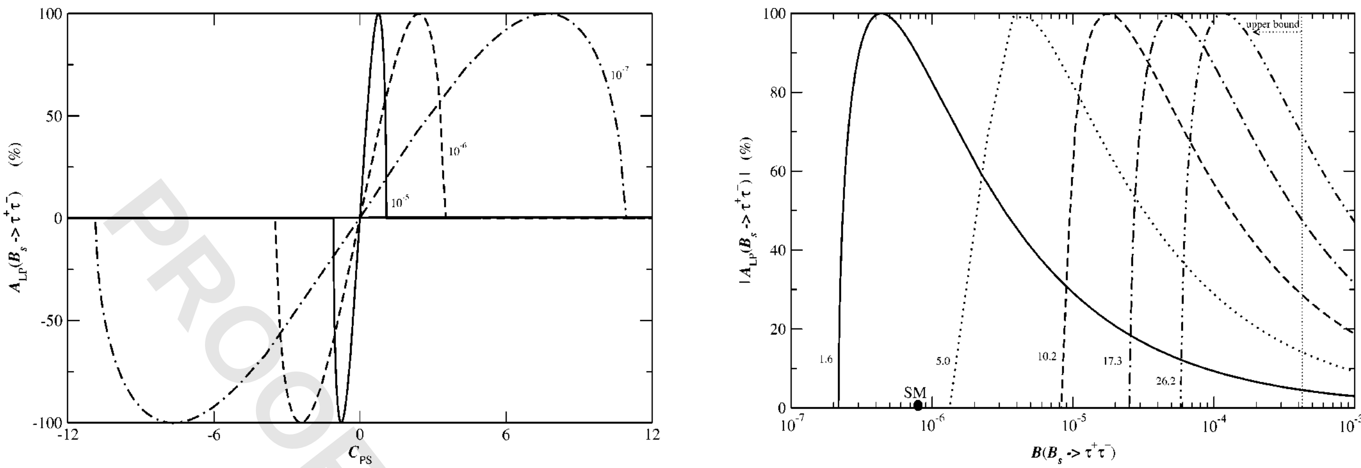

FIG. 2. The correlation between $\mathcal{A}_{\rm LP}(B_s\to\tau^+\tau^-)$ and $\mathcal{C}_{\rm PS}$ for various $\mathcal{B}(B_s\to\tau^+\tau^-)=10^{-5},10^{-6},10^{-7}$ (left); and the correlation between $\mathcal{A}_{\rm LP}(B_s\to\tau^+\tau^-)$ and $\mathcal{B}(B_s\to\tau^+\tau^-)$ for various $\mathcal{C}_{\rm PS}=1.6,5.0,10.2,17.3,26.2$ (right).

$$
\begin{aligned}
|V_{ts}| &\approx A\lambda^2 = 0.0395\pm 0.0019,\\
|V_{td}| &\approx A\lambda^3\sqrt{(1-\rho)^2+\eta^2} = 0.004\text{–}0.013.
\end{aligned}
\tag{8}
$$

Adopting the next-to-leading order result for $Y(x_{t_W})$ [15] and using the central values for all input parameters, leads to the following SM predictions:

$$
\mathcal{B}(B_d\to l^+l^-)=\begin{cases}
3.4\times 10^{-15}\left(\dfrac{f_{B_d}}{210\ \text{MeV}}\right)^2, & l=e,\\[2mm]
1.5\times 10^{-10}\left(\dfrac{f_{B_d}}{210\ \text{MeV}}\right)^2, & l=\mu,\\[2mm]
3.2\times 10^{-8}\left(\dfrac{f_{B_d}}{210\ \text{MeV}}\right)^2, & l=\tau,
\end{cases}
\tag{9}
$$

$$
\mathcal{B}(B_s\to l^+l^-)=\begin{cases}
8.9\times 10^{-14}\left(\dfrac{f_{B_s}}{245\ \text{MeV}}\right)^2, & l=e,\\[2mm]
4.0\times 10^{-9}\left(\dfrac{f_{B_s}}{245\ \text{MeV}}\right)^2, & l=\mu,\\[2mm]
8.3\times 10^{-7}\left(\dfrac{f_{B_s}}{245\ \text{MeV}}\right)^2, & l=\tau.
\end{cases}
\tag{10}
$$

These predictions should be confronted with the present experimentally known bounds of $\mathcal{B}(B_q\to l^+l^-)$ at 95% C.L. [16],

$$\mathcal{B}(B_d\to\mu^+\mu^-)<8.6\times 10^{-7}, \tag{11}$$

$$\mathcal{B}(B_s\to\mu^+\mu^-)<2.6\times 10^{-6}. \tag{12}$$

To analyze the decay processes and simulataneously find a possible new physics signal, we first employ the experimental bound of the branching ratio which constraints the coefficients ($\mathcal{C}'$s) more strictly after comparing the theoretical predictions with the known experimental bounds, i.e., $\mathcal{B}(B_s\to\mu^+\mu^-)$ [see Eqs. (9)–(12)], and obtain the allowed region on the $\mathcal{C}_{\rm PS}$-$\mathcal{C}_{\rm PP}$ parameter space for various values of $\mathcal{C}_{\rm AA}$. This is shown in the left-hand figure of Fig. 1. In the right-hand figure the bound is obtained by using the indirect experimental bound $\mathcal{B}(B_s\to\tau^+\tau^-)<4.3\times 10^{-4}$ [17]. Furthermore, suppose that the branching ratio is measured first; then it must be worth showing a general correlation between the branching ratio and the longitudinal polarization asymmetry represented by the equation

$$
\begin{aligned}
&\mathcal{A}_{\rm LP}(B_q\to l^+l^-)\\
&\quad=\pm\frac{2a_q\sqrt{1-4m_l^2/m_{B_q}^2}}{\mathcal{B}(B_q\to l^+l^-)}\,\mathrm{Re}\left[\frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\right.\\
&\qquad\left.\times\sqrt{\frac{\mathcal{B}(B_q\to l^+l^-)}{a_q}-\left(1-\frac{4m_l^2}{m_{B_q}^2}\right)\left|\frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\right|^2}\,\right],
\end{aligned}
\tag{13}
$$

by eliminating $\mathcal{C}_{\rm AA}$ and $\mathcal{C}_{\rm PP}$ in Eqs. (3) and (7), where the constant a_q is defined as

$$a_q\equiv(G_F^2\alpha^2/64\pi^3)\,|V_{tq}^*V_{tb}|^2\tau_{B_q}f_{B_q}^2m_{B_q}\sqrt{1-4m_l^2/m_{B_q}^2}. \tag{14}$$

This is depicted in Fig. 2. The left-hand figure shows a correlation between $\mathcal{A}_{\rm LP}(B_s\to\tau^+\tau^-)$ and $\mathcal{C}_{\rm PS}$ for various $\mathcal{B}(B_s\to\tau^+\tau^-)$, while the right-hand one is between $\mathcal{A}_{\rm LP}(B_s\to\tau^+\tau^-)$ and $\mathcal{B}(B_s\to\tau^+\tau^-)$ for various $\mathcal{C}_{\rm PS}$.

As a specific example for the case in which $\mathcal{C}_{\rm PS}$ is nonzero, we adopt the type II two-Higgs-doublet model (2HDM-II). In this model $\mathcal{C}_{\rm AA}^{\rm 2HDM\text{-}II}=\mathcal{C}_{\rm AA}^{\rm SM}$, while[1]

[1]We take the latest results calculated in [2] by neglecting the subleading terms in $\tan\beta$. Note that the results are consistent with [4] if one drops the contributions from trilinear coupling.

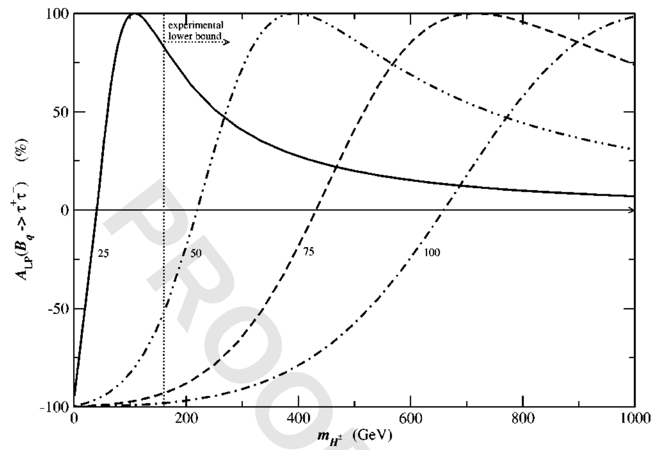

FIG. 3. The longitudinal polarization asymmetry of τ's, $\mathcal{A}_{\rm LP}(B_q \to \tau^+\tau^-)$, as a function of $m_{H^\pm}$ for various $\tan\beta = 25,50,75,100$.

$$\mathcal{C}_{\rm PS}^{\rm 2HDM\text{-}II} = \mathcal{C}_{\rm PP}^{\rm 2HDM\text{-}II} = \frac{m_l(m_b+m_q)}{4M_W^2 \sin^2\theta_W}\tan^2\beta \frac{\ln x_{H^\pm t}}{x_{H^\pm t}-1}, \quad (15)$$

at the large $\tan\beta$ limit [2–4], and $x_{H^\pm t} = (m_{H^\pm}/m_t)^2$. Some particular cases in the right-hand figure of Fig. 2 can be realized by, for instance, $(m_{H^\pm}, \tan\beta) = (200\ \text{GeV},40)$ for $\mathcal{C}_{\rm PS} = 1.6$, (200 GeV,70) for $\mathcal{C}_{\rm PS} = 5.0$, (200 GeV,100) for $\mathcal{C}_{\rm PS} = 10.2$, (200 GeV,130) for $\mathcal{C}_{\rm PS} = 17.3$, and (200 GeV,160) for $\mathcal{C}_{\rm PS} = 26.2$.

Finally, in Fig. 3 we show the dependences of $\mathcal{A}_{\rm LP}(B_q \to \tau^+\tau^-)$ on $m_{H^\pm}$ and $\tan\beta$. For real experimental analyses, we recommend $B_s \to \tau^+\tau^-$ decays because the energy of the final τ's is high enough for them to decay further to energetic secondary particles, so their longitudinal polarization may well be measured in hadronic B factories. Although the τ's are difficult to reconstruct in a hadronic background, we need precisely such a reconstruction from their decay products to allow measurements of the longitudinal polarization of the τ's.

In conclusion, we have considered a general analysis exploring the longitudinal polarization asymmetry of leptons in $B_q \to l^+l^-$ decays. We have shown that this observable should provide a direct measurement of the physics of scalar and pseudoscalar type interactions. We also note that more information about these new interactions can be obtained by combining the present analysis with the other observables from $B \to X_q l^+ l^-$ [18].

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