The Forward-Backward Asymmetry in the 
$B \rightarrow \pi \ell^+\ell^-$ Decay

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Abstract

Using the most general effective Hamiltonian comprising scalar, vector and tensor type interactions, we have written the branching ratio, the forward-backward (FB) asymmetry and the normalized FB asymmetry as functions of the new Wilson coefficients. It is found that the branching ratio depends on all new coefficients, but the dependence of asymmetries on coefficients could be analyzed only for one Wilson coefficient.
1 Introduction

The flavour-changing neutral current (FCNC) processes provide an excellent testing ground for the Standard Model (SM), and are possibly the most sensitive to the various extensions to the SM, because these transitions occur at the loop level in the SM. Among all the FCNC phenomena, the rare decays of B-mesons are especially important [1], since one can both test the SM and search for the new physics beyond it.

The rare B-decays induced by $b \rightarrow s(d)\ell^+\ell^-$ transitions at quark level have received a lot of attention, since they can be used to determine the parameters of the SM, such as the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements [2]. Many useful observables, such as branching ratio, CP-asymmetry, lepton asymmetry etc., in the decays of B-mesons induced by $b \rightarrow s(d)\ell^+\ell^-$ transitions has been investigated in the literature in the framework of the SM and its extensions [3, 4, 5, 7, 8, 9, 10]. Another interesting observable is the forward-backward asymmetry, because the forward-backward asymmetry may become zero for the certain value of the dilepton invariant mass for the $B \rightarrow K^*\ell^+\ell^-$ decay [11]. On the other hand the lepton asymmetry is zero for the exclusive $B \rightarrow K\ell^+\ell^-$ decay within the SM [11, 12]. This quantity and its zero position have been also investigated for different decays within the SM and its various extensions [13, 14, 15, 16]. It has been found that the new Wilson coefficients could contribute to the zero position of the forward-backward asymmetry and the zero position is most sensitive to the coefficients [13].

In the present work, following to [2], we study the forward-backward asymmetry in the exclusive $B \rightarrow \pi\ell^+\ell^-$ decay, using the most general effective Hamiltonian which has new Wilson coefficients and analyze the contributions coming from these coefficients within this model.

The organization of this work as follows. In Section II, starting from the most general effective Hamiltonian, we compute the differential decay width of the $B \rightarrow \pi\ell^+\ell^-$ decay, and the forward-backward asymmetry for this decay. In Section III, we carry out the numerical analysis to study the dependence of the asymmetry on the new Wilson coefficients and finally we conclude in Section IV.
2 Decay Width and Forward-Backward Asymmetry

The semileptonic decay $b \to d \ell^+ \ell^-$ is described by effective Hamiltonian, at the quark level as:

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

where the full set of the operators $O_i(\mu)$ in the SM are given in [17]. The effective coefficient of the operator $O_9(\mu)$ can be defined as:

$$C_{\text{eff}}^9(\hat{s}) = C_9 + g(z, \hat{s}) (3C_1 + C_2 + 3C_3 + C_4 + 3C_5 + C_6)$$

$$- \frac{1}{2} g(1, \hat{s}) (4C_3 + 4C_4 + 3C_5 + C_6) - \frac{1}{2} g(0, \hat{s}) (C_3 + 3C_4)$$

$$+ \frac{1}{2} (3C_3 + 3C_4 + 3C_5 + C_6).$$

(2)

Here, $\hat{s} = q^2/m_B^2$ where $q$ is the momentum transfer and $z = m_c/m_b$. The functions $g(z, \hat{s}), g(1, \hat{s})$ and $g(0, \hat{s})$ can be found in [18].

Neglecting the $d$ quark mass, the above Hamiltonian leads to the following matrix element for the $b \to d \ell^+ \ell^-$ decay:

$$\mathcal{M} = \frac{G_F \alpha}{\sqrt{2} \pi} V_{tb} V_{td}^* \left[ (C_{\text{eff}}^9 - C_{10}) \bar{d}_L \gamma_\mu b_L \bar{\ell}_L \gamma^\mu \ell_L 
+ (C_{\text{eff}}^9 + C_{10}) \bar{d}_L \gamma_\mu b_R \bar{\ell}_R \gamma^\mu \ell_R 
- 2C_{T\text{eff}}^9 \hat{m}_b \hat{d}_i \sigma_{\mu \nu} \frac{\hat{q}^\nu}{\hat{s}} R \hat{b} \hat{\ell} \gamma^\mu \ell \right],$$

(3)

Where, $L/R = (1 \mp \gamma^5)/2$, $\hat{m}_b = m_b/m_B$ and $b(d)_{L,R} = [(1 \mp \gamma^5)/2]b(d)$. The matrix element for the $b \to d \ell^+ \ell^-$ decay coming from the most general effective Hamiltonian reads as [19]

$$\mathcal{M} = \frac{G_F \alpha}{\sqrt{2} \pi} V_{tb} V_{td}^* \left[ C_{LL} \bar{d}_L \gamma_\mu b_L \bar{\ell}_L \gamma^\mu \ell_L 
+ C_{LR} \bar{d}_L \gamma_\mu b_R \bar{\ell}_R \gamma^\mu \ell_R 
+ C_{RL} \bar{d}_R \gamma_\mu b_R \bar{\ell}_L \gamma^\mu \ell_L 
+ C_{RR} \bar{d}_R \gamma_\mu b_L \bar{\ell}_L \gamma^\mu \ell_R 
+ C_T \bar{d}_\sigma_{\mu \nu} b_\ell \sigma^{\mu \nu} + iC_{TE} \bar{d}_\sigma_{\mu \nu} b_\ell \sigma_{\alpha \beta} \ell^{\mu \alpha \beta} \right].$$

(4)
The matrix element of the effective Hamiltonian over $\pi$ and $B$ meson states in the $B \to \pi\ell^+\ell^-$ decay are parametrized in terms of the form factors, and to calculate the amplitude of the $B \to \pi\ell^+\ell^-$ decay, we need

$$\langle \pi \mid \bar{d}\gamma_{\mu}b \mid B \rangle = (P_{\mu} - \frac{1}{T} - \frac{m_{\pi}^2}{s} q_{\mu}) f_+ + \frac{1 - \frac{m_{\pi}^2}{T}}{s} q_{\mu} f_0,$$

with $f_+(0) = f_0(0)$,

$$\langle \pi \mid \bar{d}\sigma_{\mu\nu}b \mid B \rangle = -i(P_{\mu} q_{\nu} - P_{\nu} q_{\mu}) \frac{f_T}{m_B + m_\pi},$$

$$\langle \pi \mid \bar{d}i\sigma_{\mu\nu}q^{\prime}b \mid B \rangle = \left[ P_{\mu} q_{\nu}^2 - (m_B^2 - m_\pi^2) q_{\mu} \right] \frac{f_T}{m_B + m_\pi},$$

$$\langle \pi \mid \bar{d}b \mid B \rangle = \frac{m_B(1 - \frac{m_{\pi}^2}{s})}{m_b} f_0,$$

where $P = p_1 + p_2$, $p_1$ and $p_2$ are the four momenta of the $B$ and $\pi$ mesons, respectively. Using the matrix elements (5)-(8), we obtain the amplitude for $B \to \pi\ell^+\ell^-$ decay as:

$$\mathcal{M} = \frac{G_F}{\sqrt{2\pi}} V_{tb}V_{td}^* \left[ A' P_{\mu}(\bar{\ell}\gamma_{\mu}\ell) + B' q_{\mu}(\bar{\ell}\gamma_{\mu}\ell) + C' P_{\mu}(\bar{\ell}\gamma_{\mu}\gamma_5\ell) + D' q_{\mu}(\bar{\ell}\gamma_{\mu}\gamma_5\ell) + A(\bar{\ell}\ell) + B(\bar{\ell}\gamma_{5}\ell) + iC(P_{\mu} q_{\nu} - P_{\nu} q_{\mu})(\bar{\ell}\sigma_{\mu\nu}\ell) + D(P_{\mu} q_{\nu} - P_{\nu} q_{\mu})(\epsilon^{\mu\nu\alpha\beta}\bar{\ell}\sigma_{\alpha\beta}\ell) \right],$$

where

$$A' = (2C_9^{\text{eff}} + C_{LL} + C_{LR} + C_{RL} + C_{RR}) f_+ - 4\hat{m}_b C_7^{\text{eff}} \frac{f_T}{1 - \frac{m_{\pi}^2}{s}},$$

$$B' = (2C_9^{\text{eff}} + C_{LL} + C_{LR} + C_{RL} + C_{RR}) f_- + 4\hat{m}_b C_7^{\text{eff}} \frac{1 - \frac{m_{\pi}^2}{s}}{s} f_T,$$

$$C' = \left[ 2C_{10} + C_{LR} + C_{RL} - (C_{LL} + C_{RL}) \right] f_+,$$

$$D' = \left[ 2C_{10} + C_{LR} + C_{RL} - (C_{LL} + C_{RL}) \right] f_-,$$

$$A = (C_{LRLR} + C_{LRRL} + C_{RLRR} + C_{RRLL}) \frac{m_B(1 - \frac{m_{\pi}^2}{s})}{\hat{m}_b} f_0,$$

$$B = \left[ C_{LRLR} + C_{LRRL} - (C_{LLR} + C_{RLRR}) \right] \frac{m_B(1 - \frac{m_{\pi}^2}{s})}{\hat{m}_b} f_0,$$

$$C = -4C_7 \frac{f_T}{m_B + m_\pi},$$

$$D = 4C_{TE} \frac{f_T}{m_B + m_\pi}.$$
with
\[ f_- = \frac{1 - \hat{m}_\pi^2}{\hat{s}} (f_0 - f_+) \, . \]

We would like to note that in calculating the double-decay width we take into account of the massless case. However, the calculation for the massive case is given in the Appendix. Using the matrix element in Eq.(9), the double differential decay width can be calculated as:
\[ \frac{d^2 \Gamma}{d \hat{s} d \cos \theta} = \frac{G_F^2 \alpha^2}{2 \sqrt{3} \pi^5} |V_{tb} V_{td}^*|^2 m_B^3 \lambda^{1/2} (1, \hat{m}_\pi, \hat{s}) \times \left[ - \left( \left| A' \right|^2 + \left| C' \right|^2 \right) \lambda + 4 \hat{s} \hat{m}_B^2 \left( \left| C \right|^2 + 4 \left| D \right|^2 \right) \right] \cos^2 \theta \\
- \left[ 16 Re \left( D'D^* \right) + Re(A'C^*) + 8 Re(BD^*) \right] \lambda^{1/2} \hat{s} \cos \theta \\
+ \left( \left| A' \right|^2 + \left| C' \right|^2 \right) \lambda + \left( \left| A \right|^2 + \left| B \right|^2 \right) \frac{\hat{s}}{m_B^2} \right] \, . \] (10)

where \( \lambda(1, \hat{m}_\pi^2, \hat{s}) = 1 + \hat{m}_\pi^4 + \hat{s}^2 - 2 \hat{m}_\pi^2 \hat{s} - 2 \hat{m}_\pi^2 - 2 \hat{s} \) and \( \theta \) is the angle between the four momenta of \( \pi \) meson and \( \ell^- \) in the dilepton CMS-frame. The kinematical variables are bounded as
\[ -1 \leq \cos \theta \leq 1 \, , \]
\[ 4 \hat{m}_\ell^2 \leq \hat{s} \leq (1 - \hat{m}_\pi)^2 \, . \]

From Eq.(10) one can easily obtain the single differential decay rate
\[ \frac{d \Gamma}{d \hat{s}} = \frac{G_F^2 \alpha^2}{2 \sqrt{13} \pi^5} |V_{tb} V_{td}^*|^2 m_B^3 \lambda^{1/2} (1, \hat{m}_\pi, \hat{s}) \times \left[ \left( \left| A' \right|^2 + \left| C' \right|^2 \right) \lambda + \hat{s} \left( \frac{3}{2 m_B^2} \left( \left| A \right|^2 + \left| B \right|^2 \right) + 2 \lambda m_B^2 \left( \left| C \right|^2 + 4 \left| D \right|^2 \right) \right) \right] \] (11)

On the other hand, the normalized asymmetry is defined as
\[ \frac{d \hat{A}_{FB}}{d \hat{s}} = \frac{d A_{FB}/d \hat{s}}{d \Gamma/d \hat{s}} = \frac{\int_{-1}^{1} (d^2 \Gamma/d \hat{s} d \cos \theta) - \int_{-1}^{0} (d^2 \Gamma/d \hat{s} d \cos \theta)}{\int_{-1}^{1} (d^2 \Gamma/d \hat{s} d \cos \theta) + \int_{-1}^{0} (d^2 \Gamma/d \hat{s} d \cos \theta)} \, , \] (12)

where \( d A_{FB}/d \hat{s} \) is the FB asymmetry and can be expressed with the help of Eq.(10) as
\[ \frac{d A_{FB}}{d \hat{s}} = \frac{G_F^2 \alpha^2}{2 \sqrt{14} \pi^5} |V_{tb} V_{td}^*|^2 m_B^3 \lambda^{1/2} (1, \hat{m}_\pi, \hat{s}) \hat{s} \times \left[ - 32 Re \left( D'D^* \right) - 2 Re(A'C^*) - 16 Re(BD^*) \right] \, . \] (13)
From Eqs.(11) and (13), one can see that the single differential decay rate depends on also the square of all Wilson coefficients near the other terms, but it is not the case for the FB asymmetry. One notes that only the real part of the products of the auxiliary functions A, B, C, D and $D'$ contribute to the FB asymmetry, that is the FB asymmetry is zero for the $B \to \pi \ell^+ \ell^-$ decay in the SM.

### 3 Numerical Analysis

The numerical values of the input parameters we used in our analysis are the following:

$$m_B = 5.28 \text{ GeV}, m_\pi = 0.14 \text{ GeV}, m_b = 4.8 \text{ GeV}, m_c = 1.4 \text{ GeV},$$

$$1/\alpha = 129, G_F = 1.6639 \times 10^{-5} \text{ GeV}^2, |V_{tb}V_{td}^*| = 0.011.$$  

The values of the Wilson coefficients within the SM are given in Table I, on the other hand we assume that all new Wilson coefficients are real in the numerical analysis. In order to complete the analysis we need the parametrization of the form factors. For the values of that, we have used the results of [20]. According to these results the form factors can be parameterized as

$$F(\hat{s}) = \frac{F(0)}{1 - a_F \hat{s} + b_F \hat{s}^2}. \quad (14)$$

where the parameters $F(0), a_F$ and $b_F$ for each form factor are given in Table 2.

In our numerical analysis to investigate the dependence of the FB asymmetry, the normalized FB asymmetry and the branching ratio to the Wilson coefficients we consider two cases where one of the new coefficients has two values $\pm |C_{10}|$, the others are set to zero. From Eq.(13), after some calculations, one can see that all terms which contribute to the FB asymmetry have the form of product of any two new coefficients.

| $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| -0.248 | 1.107 | 0.011 | -0.026 | 0.007 | -0.031 | -0.313 | 4.344 | 4.669 |

Table 1: Values of the SM Wilson coefficients.
except one. According to this result, we plot the dependence of the FB asymmetry on $\hat{s}$ for the $B \to \pi\ell^+\ell^-$ decay for $C_{TE} = \pm |C_{10}|$ in Fig.(1).

At first glance, we see that there is a linear dependence between the FB asymmetry and the Wilson coefficient $C_{TE}$ for these cases. When $C_{TE} = -|C_{10}|$, $C_{TE}$ gives a positive contribution to the FB asymmetry.

However, when $C_{TE} = +|C_{10}|$ case, the contribution is negative. In both cases, as $\hat{s}$ increases from 0.1 to 0.9, the contribution of $C_{TE}$ increases in positive and negative direction. The contributions of $C_{TE} = \pm |C_{10}|$ are symmetric with respect to the zero axis.

With the help of Eq.(11) we plot the dependence of the branching ratio of the $B \to \pi\ell^+\ell^-$ decay to the new Wilson coefficients with respect to $\hat{s}$. The results are shown in Figs. (2)-(6). The contribution of $C_{RL}(C_{LR})$ to the branching ratio is the same of $C_{LL}(C_{RR})$. The contributions of $C_{LRRL}, C_{RLLR}$ and $C_{RLRL}$ are the same of $C_{LRLR}$. Be-

\[ \begin{array}{ccc}
F(0) & \alpha_F & \beta_F \\
0.305 & 1.29 & 0.206 \\
0.305 & 0.266 & -0.752 \\
0.296 & 1.28 & 0.193 \\
\end{array} \]

Table 2: Form factors for the $B \to \pi$ transition.
cause of that we give only the figures for the new Wilson coefficients $C_{LL}, C_{RR}, C_{LRR}, C_T$ and $C_{TE}$. The scalar and tensor type coefficients give the same contributions for $+|C_{10}|$ and $-|C_{10}|$. These plots show that all new coefficients give positive contributions to the branching ratio and this observable is the most sensitive to $C_{LL}$. In Fig.(7) we show the dependence of the normalized FB asymmetry to the new Wilson coefficient $C_{TE}$. The normalized FB asymmetry depends on one of the new coefficients like in the case of the FB asymmetry. In this case, the dependence of the normalized FB asymmetry is symmetric with respect to the zero axis and $C_{TE} = -|C_{10}|$ gives a negative contribution, and $C_{TE} = +|C_{10}|$ gives a positive one.

\[
\text{Figure 2: The dependence of the branching ratio on } \hat{s} \text{ for } B \rightarrow \pi \ell^+ \ell^- \text{ decay corresponding to the cases } C_{LL} = -|C_{10}| \text{(bottom curve) and } C_{LL} = +|C_{10}| \text{(top curve).}
\]

4 Conclusion

In the present work we have calculated the FB asymmetry, the normalized FB asymmetry and the branching ratio within the most general model of the $B \rightarrow \pi \ell^+ \ell^-$ decay. As we expected, the FB asymmetry is zero for the $B \rightarrow \pi \ell^+ \ell^-$ decay within the SM. We have analyzed the dependence of these observable to the new Wilson coefficients coming from the most general model.

It is found that there is a linearity between the FB asymmetry and the new coefficient $C_{TE}$. The contribution coming from $C_{TE} = -|C_{10}|$ is larger than that of $C_{TE} = +|C_{10}|$. The normalized FB asymmetry depends on only the coefficient $C_{TE}$. The contribution
Figure 3: The dependence of the branching ratio on $\hat{s}$ for $B \to \pi\ell^+\ell^-$ decay corresponding to the cases $C_{RR} = -|C_{10}|$ (bottom curve) and $C_{RR} = +|C_{10}|$ (top curve).

Figure 4: The dependence of the branching ratio on $\hat{s}$ for $B \to \pi\ell^+\ell^-$ decay corresponding to the cases $C_{LRLR} = \pm|C_{10}|$. 
Figure 5: The dependence of the branching ratio on $\hat{s}$ for $B \to \pi \ell^+ \ell^-$ decay corresponding to the cases $C_T = \pm |C_{10}|$.

Figure 6: The dependence of the branching ratio on $\hat{s}$ for $B \to \pi \ell^+ \ell^-$ decay corresponding to the cases $C_{TE} = \pm |C_{10}|$. 
Figure 7: The dependence of the normalized FB asymmetry on $\hat{s}$ for $B \rightarrow \pi \ell^+ \ell^-$ decay corresponding to the cases $C_{TE} = -|C_{10}|$ (top curve) and $C_{TE} = +|C_{10}|$ (bottom curve).

The branching ratio depends on all new Wilson coefficients, but some of the contributions of the coefficients are the same with each other. The branching ratio is the most sensitive to $C_{LL}$. In vector type interactions, the coefficient $C_{TE}$ gives large contribution than that of $C_T$.

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APPENDIX

In the appendix we give the results for the massive lepton case. First, we write the double differential decay width in terms of the auxiliary functions with the same kinematical variables

\[
\frac{d^2 \Gamma}{ds d \cos \theta} = \frac{G_F^2 \alpha^2}{212 \pi^5} |V_{td} V_{*td}|^2 m_B^3 \lambda^{1/2}(1, \hat{m}_\pi, \hat{s}) \times \left[ \lambda \left( \frac{1}{4} \left( |A'|^2 + |C'|^2 \right) + 2m_\ell \text{Re}(A'C^*) \right) + \hat{m}_\ell^2 \left( \left| C' \right|^2 (2 + 2\hat{m}_\pi^2 - \hat{s}) + \left| D' \right|^2 \hat{s} \right) + (1 - \hat{m}_\pi^2) \left( 2\hat{m}_\pi^2 \text{Re}(C'D^{*}) + \frac{\hat{m}_\ell}{m_B} \text{Re}(C'B^*) \right) + \frac{\hat{s}}{m_B^2} \left[ \hat{m}_\ell \text{Re}(D'B^*) + \frac{1}{4} \left( |B|^2 + \nu^2 |A|^2 \right) \right] + \lambda \hat{s} m_B^2 |C|^2 (1 - \nu^2) - \nu \lambda^{1/2} \left[ \frac{\hat{m}_\ell}{m_B} \text{Re}(A'A^*) - 4m_\ell (\hat{m}_\pi^2 - 1) \text{Re}(C'D^*) \right] + \hat{s} \left[ 4 \text{Re}(D'D^*) + 2 \text{Re}(DB^*) + \frac{1}{4} \text{Re}(AC^*) \right] \right] \cos \theta.
\]

From this equation the single decay rate and the FB asymmetry is given as follows

\[
\frac{d \Gamma}{d \hat{s}} = \frac{G_F^2 \alpha^2}{212 \pi^5} |V_{td} V_{*td}|^2 m_B^3 \lambda^{1/2}(1, \hat{m}_\pi, \hat{s}) \times \left[ \lambda \left( 1 - \frac{1}{3} \nu^2 \right) \left( |A'|^2 + |C'|^2 \right) + 4\hat{m}_\ell^2 \left| C' \right|^2 (2 + 2\hat{m}_\pi^2 - \hat{s}) \right] + 4\hat{m}_\ell^2 \hat{s} \left| D' \right|^2 + \frac{\hat{s}}{m_B^2} \left( |B|^2 + \nu^2 |A|^2 \right) + 8\hat{m}_\ell^2 (1 - \hat{m}_\pi^2) \text{Re}(C'D^*) + 8m_\ell \lambda \text{Re}(A'C^*) + 4\frac{\hat{m}_\ell}{m_B} (1 - \hat{m}_\pi^2) \text{Re}(C'B^*) + \frac{4}{3} \lambda \hat{s} m_B^2 \left[ 3 |C|^2 + 2\nu^2 \left( 2 |D|^2 - |C|^2 \right) \right] + 4\frac{\hat{m}_\ell}{m_B} \hat{s} \text{Re}(D'B^*) \right],
\]

\[
\frac{dA_{FB}}{d \hat{s}} = \frac{G_F^2 \alpha^2}{212 \pi^5} |V_{td} V_{*td}|^2 m_B^3 \nu \lambda(1, \hat{m}_\pi, \hat{s}) \times \left[ 4m_\ell (\hat{m}_\pi^2 - 1) \text{Re}(C'D^*) - \frac{\hat{m}_\ell}{m_B} \text{Re}(A'A^*) - 4\hat{s} \text{Re}(D'D^*) - \frac{1}{4} \hat{s} \text{Re}(AC^*) - 2\hat{s} \text{Re}(BD^*) \right].
\]
in the above equations $v = \sqrt{1 - \frac{4m^2}{s}}$ is the lepton velocity in the CMS-frame of leptons.

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