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# Semileptonic baryonic $B$ decays

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**Abstract** We study the semileptonic $B \to \mathbf{B}\bar{\mathbf{B}}' L\bar{L}'$ decays with $\mathbf{B}\bar{\mathbf{B}}'$ ($L\bar{L}'$) representing a baryon (lepton) pair. Using the new determination of the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors, we obtain $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (5.4 \pm 2.0) \times 10^{-6}$ agreeing with the current data. Besides, $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu}) = (3.5 \pm 1.0) \times 10^{-8}$ is calculated to be 20 times smaller than the previous prediction. In particular, we predict $\mathcal{B}(\bar{B}^0_s \to p\bar{\Lambda}e^-\bar{\nu}_e, p\bar{\Lambda}\mu^-\bar{\nu}_\mu, p\bar{\Lambda}\tau^-\bar{\nu}_\tau) = (2.1\pm0.6, 2.1\pm0.6, 1.7\pm 1.0) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0_s \to \Lambda\bar{\Lambda}\nu\bar{\nu}) = (0.8 \pm 0.2) \times 10^{-8}$, which can be accessible to the LHCb experiment.

## 1 introduction

In the non-leptonic baryonic $B$ decays, the observation of $B \to p\bar{p}(\pi, K^{(*)}, D^{(*)})$ and $B^- \to \Lambda\bar{p}(J/\psi, \gamma)$ suggests the unique existence of the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition [1–3], with which the $CP$ asymmetries of $B^- \to p\bar{p}(\pi^-, K^{(*)-})$ [4, 5] and the branching fractions of $B^- \to \Lambda\bar{p}D^{(*)0}$, $\bar{B}^0 \to \Sigma^0\bar{\Lambda}D^0$ [6] have been predicted, and verified by the later measurements [7].

The semileptonic $B$ decays of $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ and $B^- \to \Lambda\bar{p}\nu_\ell\bar{\nu}_\ell$ with $\ell$ denoting $e$, $\mu$ or $\tau$ can provide another evidence for the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition [8,9]. Like the studies of the semileptonic $B^- \to \pi^+\pi^-\ell^-\bar{\nu}_\ell$ decays [10,11], the full dibaryon invariant mass spectrum can be used to test the possible co-existence of the resonant and non-resonant contributions. Therefore, we have predicted $\mathcal{B}(B^- \to p\bar{p}e^-\bar{\nu}_e) = (1.04 \pm 0.26 \pm 0.12) \times 10^{-4}$ [8] and $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu}) = (7.9\pm1.9)\times10^{-7}$ [9]. We have also predicted $\mathcal{R}_{e/\mu} \equiv \mathcal{B}(B^- \to p\bar{p}e^-\bar{\nu}_e)/\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) \simeq 1$ [8]. By contrast, the pole model argument leads to the evaluation of $\mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}'\ell\bar{\nu}_\ell) = 10^{-5} - 10^{-6}$ [12].

Experimentally, it has been measured that [13–16]

$$
\begin{aligned}
&\mathcal{B}_{ex}(B^- \to p\bar{p}e^-\bar{\nu}_e) = (5.8 \pm 3.7 \pm 3.6)\\
&\quad\times10^{-4}\ (< 1.2 \times 10^{-3})\ \text{[Cleo]}\\
&\mathcal{B}_{ex}(B^- \to p\bar{p}e^-\bar{\nu}_e) = (8.2^{+3.7}_{-3.2} \pm 0.6)\\
&\quad\times10^{-6}\ \text{[Belle]}\\
&\mathcal{B}_{ex}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (3.1^{+3.1}_{-2.4} \pm 0.7)\\
&\quad\times10^{-6}\ \text{[Belle]}\\
&\mathcal{B}_{ex}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (5.27^{+0.23}_{-0.24} \pm 0.21 \pm 0.15)\\
&\quad\times10^{-6}\ \text{[LHCb]}\\
&\mathcal{B}_{ex}(B^- \to \Lambda\bar{p}\nu\bar{\nu}) = (0.4 \pm 1.1 \pm 0.6)\\
&\quad\times10^{-5}\ (< 3.0 \times 10^{-5})\ \text{[Babar]}.
\end{aligned}
\tag{1}
$$

The threshold effect commonly observed in $B \to \mathbf{B}\bar{\mathbf{B}}'M$ is also observed in $B^- \to p\bar{p}\mu^-\bar{\nu}_e$ [15], which is drawn as a peak around the threshold area of $m_{\mathbf{B}\bar{\mathbf{B}}'} \simeq m_{\mathbf{B}} + m_{\bar{B}'}$ in the $\mathbf{B}\bar{\mathbf{B}}'$ invariant mass spectrum. There is no sign that the $B$ to $\mathbf{B}\bar{\mathbf{B}}'$ transition receives a resonant contribution. Nonetheless, it is clearly seen that $\mathcal{B}_{ex}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu)$ is 20 times smaller than the prediction [8]. This has been pointed out as the theoretical challenge to alleviate the discrepancy [17]. On the other hand, the ratio $\mathcal{R}_{e/\mu} \simeq 1$ as a test of the lepton universality is not conclusive, and the prediction of $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu})$ is within the experimental upper bound.

In Ref. [6], the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors ($F_{\mathbf{B}\bar{\mathbf{B}}'}$) are extracted with the data from $B \to \mathbf{B}\bar{\mathbf{B}}'M$, which cause the overestimation of $\mathcal{B}(B \to p\bar{p}\ell\bar{\nu})$. With the same theoretical inputs, $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu})$ might be overestimated as well [9]. A question is hence raised: whether there exist the universal $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors to explain the nonleptonic and semileptonic baryonic $B$ decays.

In this paper, we propose to perform a new global fit, in order to accommodate the current data of $B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$ with $L\bar{L}'$ denoting a lepton pair and $B \to \mathbf{B}\bar{\mathbf{B}}'M$. With $F_{\mathbf{B}\bar{\mathbf{B}}'}$ determined from the new global fit, we will re-investigate $B^- \to \Lambda\bar{p}\nu\bar{\nu}$. Since LHCb has been able to accumulate more events for the $\bar{B}^0_s$ decays, we will study $\bar{B}^0_s \to p\bar{\Lambda}\ell^-\bar{\nu}$ and $\bar{B}^0_s \to \Lambda\bar{\Lambda}\nu\bar{\nu}$ decays for future measurements.

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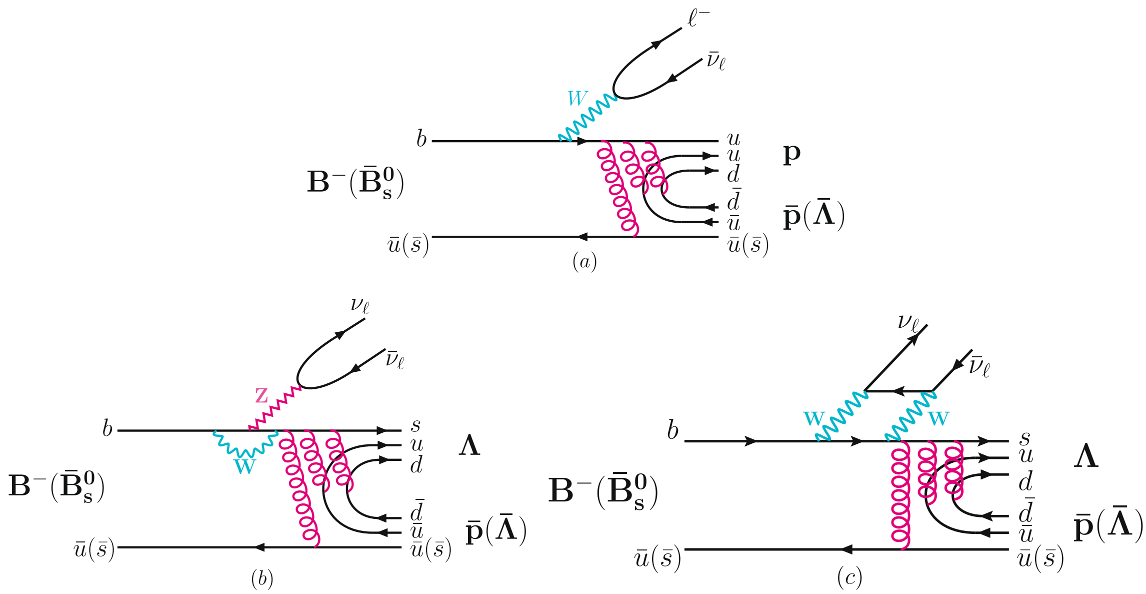


**Fig. 1** Feynman diagrams for the $B \to \mathbf{B\bar{B}}' L\bar{L}'$ decays, where (*a*) depicts $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ and $\bar{B}^0_s \to p\bar{\Lambda}\ell^-\bar{\nu}_\ell$, while (*b, c*) $B^- \to \Lambda\bar{p}\nu_\ell\bar{\nu}_\ell$ and $\bar{B}^0_s \to \Lambda\bar{\Lambda}\nu_\ell\bar{\nu}_\ell$

## 2 Formalism

The semileptonic baryonic $B$ decays come from the quark-level $b \to u\ell\bar{\nu}_\ell$ and $b \to s\nu_\ell\bar{\nu}_\ell$ processes. In Fig. 1a, $b \to u\ell\bar{\nu}_\ell$ appear as the tree-level $b \to uW$, $W \to \ell\bar{\nu}_\ell$ decays. Due to the loop contributions from the penguin-level $b \to sZ$, $Z \to \nu_\ell\bar{\nu}_\ell$ and box diagrams in Fig. 1b,c, respectively [18], $b \to s\nu_\ell\bar{\nu}_\ell$ can be rarer than $b \to u\ell\bar{\nu}_\ell$. The effective Hamiltonians for the above semileptonic $b$ decays are given by [18,19]

$$
\begin{aligned}
&\mathcal{H}(b \to u\ell\bar{\nu}_\ell) = \frac{G_F V_{ub}}{\sqrt{2}}\, \bar{u}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell \\
&\mathcal{H}(b \to s\nu_\ell\bar{\nu}_\ell) \\
&\quad = \frac{G_F}{\sqrt{2}}\frac{\alpha_{em}}{2\pi\sin^2\theta_W}\lambda_t D(x_t)\bar{s}\gamma_\mu(1-\gamma_5)b\bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell
\end{aligned}
\tag{2}
$$

where $G_F$ is the Fermi constant, $V_{ub}$ and $\lambda_t \equiv V^*_{ts}V_{tb}$ are the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements, and $D(x_t)$ with $x_t \equiv m_t^2/m_W^2$ is the top-quark loop function [18–21]. According to $\mathcal{H}(b \to u\ell\bar{\nu}_\ell, s\nu_\ell\bar{\nu}_\ell)$, the amplitudes of $B \to \mathbf{B\bar{B}}' L\bar{L}'$ with $L\bar{L}' = (\ell\bar{\nu}_\ell, \nu_\ell\bar{\nu}_\ell)$ can be derived as [8,9]

$$
\begin{aligned}
&\mathcal{M}(B \to \mathbf{B\bar{B}}'\ell^-\bar{\nu}_\ell) \\
&\quad = \frac{G_F V_{ub}}{\sqrt{2}}\langle \mathbf{B\bar{B}}'|\bar{u}\gamma_\mu(1-\gamma_5)b|B\rangle\; \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell, \\
&\mathcal{M}(B \to \mathbf{B\bar{B}}'\nu_\ell\bar{\nu}_\ell) \\
&\quad = \frac{G_F}{\sqrt{2}}\frac{\alpha_{\rm em}}{2\pi\sin^2\theta_W}\lambda_t D(x_t)\langle \mathbf{B\bar{B}}'|\bar{s}\gamma_\mu(1-\gamma_5)b|B\rangle \\
&\qquad \times\, \bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell,
\end{aligned}
\tag{3}
$$

with $\langle \mathbf{B\bar{B}}'|(\bar{q}b)|B\rangle$ representing the matrix elements of the $B$ meson to $\mathbf{B\bar{B}}'$ transition. In Fig. 1a–c, $B \to \mathbf{B\bar{B}}' L\bar{L}'$ occur as $B^- \to p\bar{p}\ell\bar{\nu}_\ell$, $\Lambda\bar{p}\nu_\ell\bar{\nu}_\ell$ and $\bar{B}^0_s \to p\bar{\Lambda}\ell\bar{\nu}_\ell$, $\Lambda\bar{\Lambda}\nu_\ell\bar{\nu}_\ell$ for our study.

The amplitudes of the non-leptonic $B \to \mathbf{B\bar{B}}' M$ decays have two forms [1,22,23]: $\mathcal{M}_C \propto \langle \mathbf{B\bar{B}}'|(\bar{q}q')|0\rangle \times \langle M|(\bar{q}b)|B\rangle$ and $\mathcal{M}_T \propto \langle M|(\bar{q}q')|0\rangle\langle \mathbf{B\bar{B}}'|(\bar{q}b)|B\rangle$, where $\mathcal{M}_C$ denotes the current amplitude with $\mathbf{B}\bar{B}'$ produced from the quark current [22–26], and $\mathcal{M}_T$ the transition amplitude with $\mathbf{B}\bar{B}'$ from the $B$ meson transition [1–3]. Clearly, $\mathcal{M}_T(B \to \mathbf{B\bar{B}}' M)$ and $B \to \mathbf{B\bar{B}}' L\bar{L}'$ can be related by $\langle \mathbf{B\bar{B}}'|(\bar{q}b)|B\rangle$ [8,9]. As seen in Fig. 2, $B \to p\bar{p}M$ with $M = (\pi, K)$, $B \to p\bar{p}V$ with $V = (\rho, K^*)$, and $\bar{B}^0 \to p\bar{p}D^{0(*)}$ involve the transition amplitudes, given by [1,27–29]

$$
\begin{aligned}
&\mathcal{M}(B \to p\bar{p}M) = \frac{G_F}{\sqrt{2}}(\hat{\mathcal{M}}_1 + \hat{\mathcal{M}}_6) \\
&\hat{\mathcal{M}}_1 = \alpha_1^{qq'}\langle M|\bar{q}'\gamma_\mu(1-\gamma_5)u|0\rangle\langle p\bar{p}|\bar{q}\gamma^\mu(1-\gamma_5)b|B\rangle \\
&\hat{\mathcal{M}}_6 = \alpha_6^{qq'}\langle M|\bar{q}'(1+\gamma_5)u|0\rangle\langle p\bar{p}|\bar{q}(1-\gamma_5)b|B\rangle \\
&\mathcal{M}(B \to p\bar{p}V) = \frac{G_F}{\sqrt{2}}\alpha_1^{qq'}\langle V|\bar{q}'\gamma_\mu(1-\gamma_5)u|0\rangle \\
&\quad \times\langle p\bar{p}|\bar{q}\gamma^\mu(1-\gamma_5)b|B\rangle \\
&\mathcal{M}(\bar{B}^0 \to p\bar{p}D^{0(*)}) = \frac{G_F}{\sqrt{2}}V_{cb}V^*_{ud}a_2\langle D^{0(*)}|\bar{c}\gamma_\mu \\
&\quad \times(1-\gamma_5)u|0\rangle\langle p\bar{p}|\bar{d}\gamma^\mu(1-\gamma_5)b|\bar{B}^0\rangle
\end{aligned}
\tag{4}
$$

with $(q, q') = (u, d)$ for $B^- \to p\bar{p}\pi^-$ and $B^- \to p\bar{p}\rho^-$, $(q, q') = (u, s)$ for $B^- \to p\bar{p}K^-$ and $B^- \to p\bar{p}K^{*-}$, and $(q, q') = (d, s)$ for $\bar{B}^0 \to p\bar{p}\bar{K}^0$ and $\bar{B}^0 \to p\bar{p}\bar{K}^{*0}$. The

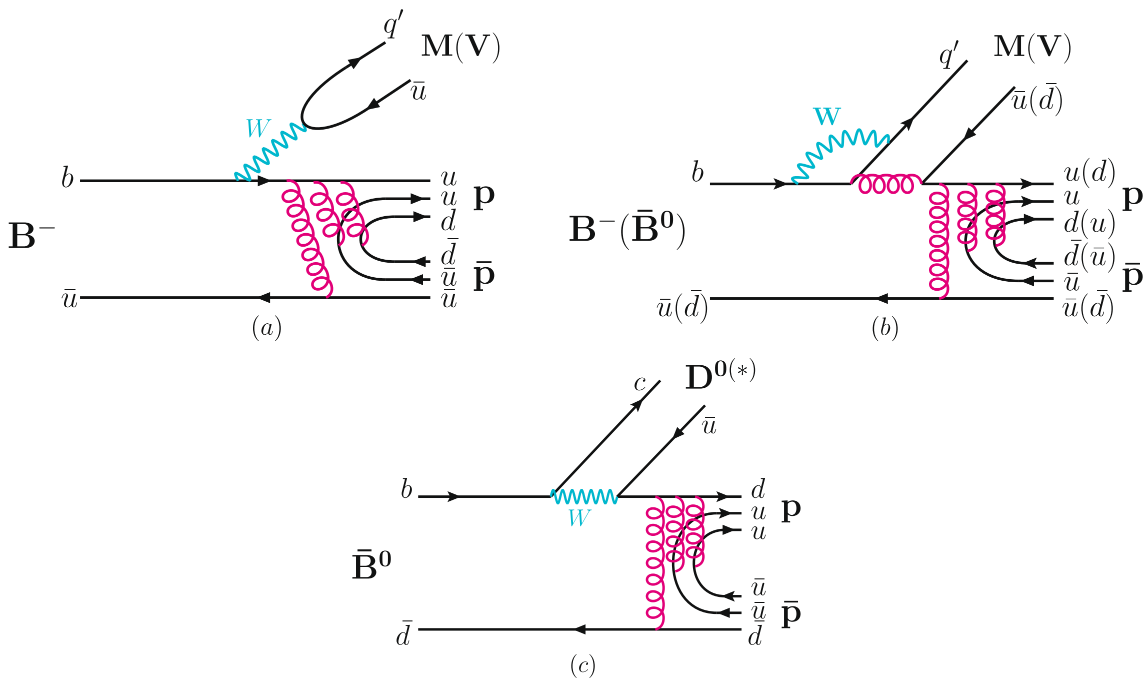


**Fig. 2** Feynman diagrams for the three-body baryonic $B$ decays, where $(a, b)$ and $(c)$ depict $B \to p\bar{p}M(V)$ and $\bar{B}^0 \to p\bar{p}D^{0(*)}$, respectively

parameters in Eq. (4) result from the factorization approach [30], written as

$$
\begin{aligned}
\alpha_1^{uq'} &= V_{ub}V_{uq'}^* a_1 - V_{tb}V_{tq'}^* a_4 \\
\alpha_1^{ds} &= -V_{tb}V_{ts}^* a_4 \\
\alpha_6^{uq'} &= \alpha_6^{dq'} = V_{tb}V_{tq'}^* 2a_6
\end{aligned}
\tag{5}
$$

with $a_i = c_i^{eff} + c_{i\pm1}^{eff}/N_c$ for $i$ =odd (even), where $c_i^{eff}$ are the effective Wilson coefficients, and $N_c$ the color number [30].

The matrix elements of the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition in Eqs. (3) and (4) can be presented as [1,3,6,17,27–29]

$$
\begin{aligned}
\langle \mathbf{B}\bar{\mathbf{B}}'|V_\mu^b|B\rangle &= i\bar{u}[g_1\gamma_\mu + g_2 i\sigma_{\mu\nu}p^\nu + g_3 p_\mu \\
&\quad + g_4(p_{\bar{\mathbf{B}}'}+p_{\mathbf{B}})_\mu + g_5(p_{\bar{\mathbf{B}}'}-p_{\mathbf{B}})_\mu]\gamma_5 v \\
\langle \mathbf{B}\bar{\mathbf{B}}'|A_\mu^b|B\rangle &= i\bar{u}[f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}p^\nu + f_3 p_\mu \\
&\quad + f_4(p_{\bar{\mathbf{B}}'}+p_{\mathbf{B}})_\mu + f_5(p_{\bar{\mathbf{B}}'}-p_{\mathbf{B}})_\mu]v \\
\langle \mathbf{B}\bar{\mathbf{B}}'|S^b|B\rangle &= i\bar{u}[\bar{g}_1 \not{p} + \bar{g}_2(E_{\bar{\mathbf{B}}'}+E_{\mathbf{B}}) + \bar{g}_3(E_{\bar{\mathbf{B}}'}-E_{\mathbf{B}})]\gamma_5 v \\
\langle \mathbf{B}\bar{\mathbf{B}}'|P^b|B\rangle &= i\bar{u}[\bar{f}_1 \not{p} + \bar{f}_2(E_{\bar{\mathbf{B}}'}+E_{\mathbf{B}}) + \bar{f}_3(E_{\bar{\mathbf{B}}'}-E_{\mathbf{B}})]v
\end{aligned}
\tag{6}
$$

with $V_\mu^b(A_\mu^b) \equiv \bar{q}\gamma_\mu(\gamma_5)b$, $S^b(P^b) \equiv \bar{q}b$, and $p_\mu \equiv (p_B - p_{\mathbf{B}} - p_{\bar{\mathbf{B}}'})_\mu$. $F_{\mathbf{B}\bar{\mathbf{B}}'} \equiv (g_i, f_i, \bar{g}_j, \bar{f}_j)$ with $i = 1, 2, \ldots, 5$ and $j = 1, 2, 3$ are the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors.

$F_{\mathbf{B}\bar{\mathbf{B}}'}$ are momentum dependent. In terms of perturbative QCD (pQCD) counting rules [1,3,6,28,31–33], one parameterizes that

$$
\begin{aligned}
f_i &= \frac{D_{f_i}}{t^3} \quad g_i = \frac{D_{g_i}}{t^3} \\
\bar{f}_j &= \frac{D_{\bar{f}_j}}{t^3} \quad \bar{g}_j = \frac{D_{\bar{g}_j}}{t^3}
\end{aligned}
\tag{7}
$$

with $t \equiv (p_{\mathbf{B}} + p_{\bar{\mathbf{B}}'})^2$. For $F_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/t^n$, $n = 3$ corresponds to the three gluon propagators, which are drawn in Figs. 1a–c and 2a–c. Since $V_\mu^b$ and $A_\mu^b$ can be combined as the right-handed chiral current $R_\mu = (V_\mu^b + A_\mu^b)/2$, and the baryon decomposed of the right and left-handed states, that is, $|\mathbf{B}_{R+L}\rangle = |\mathbf{B}_R\rangle + |\mathbf{B}_L\rangle$, it leads to [6,17]

$$
\begin{aligned}
&\langle \mathbf{B}_{R+L}\bar{\mathbf{B}}'_{R+L}|R_\mu|B\rangle \\
&\quad = i m_b \bar{u}\gamma_\mu\left[\frac{1+\gamma_5}{2}G_R + \frac{1-\gamma_5}{2}G_L\right]v \\
&\quad\quad + i\bar{u}\gamma_\mu \not{p}_b\left[\frac{1+\gamma_5}{2}G_R^k + \frac{1-\gamma_5}{2}G_L^k\right]v
\end{aligned}
\tag{8}
$$

where $|B_q\rangle \sim \bar{b}\gamma_5 q|0\rangle$ has been used. As the chiral charge, $Q \equiv R_{\mu=0}$ annihilates the $b$ quark, and creates a valence quark in $\mathbf{B}$, while the spectator quark in the $B$ meson is transformed as a valence quark ($\bar{q}_i$) in $\bar{\mathbf{B}}'$. We hence obtain $G_{R,L}^{(k)}$ as the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors in the chiral representation. When the chirality states of a spinor $(R, L)$ are taken as the helicity states $(\uparrow, \downarrow)$, one can see $\bar{q}_i$ with the helicity to be (anti-)parallel $[||(\overline{||})]$ to the helicity of $\bar{\mathbf{B}}'$, such that the chiral charge acting on $\bar{q}_i$ can be more explicitly defined as

$Q_{||(\overline{||})}(i)$ $(i = 1, 2, 3)$. We thus derive that

$$G_{R(L)} \propto e^{R(L)}_{||} G_{||} + e^{R(L)}_{\overline{||}} G_{\overline{||}}$$
$$G^k_{R(L)} \propto \bar{e}^{R(L)}_{||} G^k_{||} + \bar{e}^{R(L)}_{\overline{||}} G^k_{\overline{||}} \quad (9)$$

where $e^{R(L)}_{||}$ and $e^{R(L)}_{\overline{||}}$ sum over the weight factors of $\mathbf{B}_{R(L)}\bar{\mathbf{B}}'_{R(L)}$, and $\bar{e}^{R(L)}_{||}$ and $\bar{e}^{R(L)}_{\overline{||}}$ those of $\mathbf{B}_{L(R)}\bar{\mathbf{B}}'_{R(L)}$. By defining $G^{(k)}_{||(\overline{||})} \equiv D^{(k)}_{||(\overline{||})}/t^3$ $(k = 2, 3, \ldots, 5)$, we relate the two sorts of the form factors as [1,3,28]

$$\begin{aligned}
D_{g_1} &= \frac{5}{3}D_{||} - \frac{1}{3}D_{\overline{||}} D_{f_1} = \frac{5}{3}D_{||} + \frac{1}{3}D_{\overline{||}} D_{g_k} \\
&= \frac{4}{3}D^k_{||} = -D_{f_k} \\
D_{g_1} &= \frac{1}{3}D_{||} - \frac{2}{3}D_{\overline{||}} D_{f_1} = \frac{1}{3}D_{||} + \frac{2}{3}D_{\overline{||}} D_{g_k} \\
&= \frac{-1}{3}D^k_{||} = -D_{f_k} \\
D_{g_1} &= D_{f_1} = -\sqrt{\frac{3}{2}}D_{||} D_{g_k} = -D_{f_k} = -\sqrt{\frac{3}{2}}D^k_{||} \\
D_{g_1} &= D_{f_1} = \sqrt{\frac{3}{2}}D_{||} D_{g_k} = -D_{f_k} = \sqrt{\frac{3}{2}}D^k_{||} \\
D_{g_1} &= D_{f_1} = D_{||} \; D_{g_k} = -D_{f_k} = -D^k_{||}
\end{aligned} \quad (10)$$

for $\langle p\bar{p}|(\bar{u}b)|B^-\rangle$, $\langle p\bar{p}|(\bar{d}b)|\bar{B}^0\rangle$, $\langle \Lambda\bar{p}|(\bar{s}b)|B^-\rangle$, $\langle p\bar{\Lambda}|(\bar{u}b)|\bar{B}^0_s\rangle$, and $\langle \Lambda\bar{\Lambda}|(\bar{s}b)|\bar{B}^0_s\rangle$, respectively. Likewise, we perform a derivation for $\bar{g}_j$ $(\bar{f}_j)$ through the (pseudo-)scalar current, which leads to [28,29]

$$\begin{aligned}
D_{\bar{g}_1} &= \frac{5}{3}\bar{D}_{||} - \frac{1}{3}\bar{D}_{\overline{||}} \; D_{\bar{f}_1} = \frac{5}{3}\bar{D}_{||} + \frac{1}{3}\bar{D}_{\overline{||}} \; D_{\bar{g}_{2,3}} \\
&= \frac{4}{3}\bar{D}^{2,3}_{||} = -D_{\bar{f}_{2,3}} \\
D_{\bar{g}_1} &= \frac{1}{3}\bar{D}_{||} - \frac{2}{3}\bar{D}_{\overline{||}} \; D_{\bar{f}_1} = \frac{1}{3}\bar{D}_{||} + \frac{2}{3}\bar{D}_{\overline{||}} \; D_{\bar{g}_{2,3}} \\
&= \frac{-1}{3}\bar{D}^{2,3}_{||} = -D_{\bar{f}_{2,3}}
\end{aligned} \quad (11)$$

for $\langle p\bar{p}|(\bar{u}b)|B^-\rangle$ and $\langle p\bar{p}|(\bar{d}b)|\bar{B}^0\rangle$, respectively. Note that $R(L) \sim\uparrow (\downarrow)$ is based on the approximation with the large energy transfer, which is conveniently presented as $t \to \infty$. It is also derived that the correction term is of order $m_q/\sqrt{t}$ [31–33]. In fact, $\sqrt{t}$ of a few GeV has been large enough to suppress the correction term [33]. Consequently, the relations with the chirality (helicity) symmetry are shown to be able to describe the scattering processes [33]. For the baryonic $B$ decays, $\sqrt{t} > 2$ GeV is also sufficient for the holding of the relations in Eqs. (10) and (11).

The four-body $B(p_B) \to \mathbf{B}(p_\mathbf{B})\bar{\mathbf{B}}'(p_{\bar{\mathbf{B}}'})L(p_L)\bar{L}'(p_{\bar{L}'})$ decay involves five kinematic variables in the phase space, that is, $s \equiv (p_L + p_{\bar{L}'})^2 \equiv m^2_{L\bar{L}'}$, $t$, and $(\theta_\mathbf{B}, \theta_\mathbf{L}, \phi)$ [34–36]. As depicted in Fig. 3, the angle $\theta_{\mathbf{B}(\mathbf{L})}$ is between $\vec{p}_\mathbf{B}$ $(\vec{p}_L)$ in the $\mathbf{B}\bar{B}'$ $(L\bar{L}')$ rest frame and the line of flight of the $\mathbf{B}\bar{B}'$

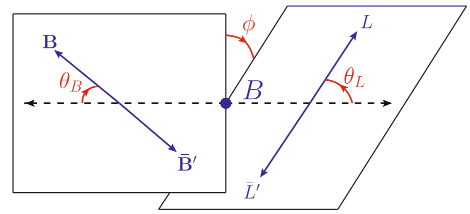


**Fig. 3** The angular variables $\theta_\mathbf{B}$, $\theta_L$ and $\phi$ depicted for the four-body $B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$ decays

$(L\bar{L}')$ system in the $B$ meson rest frame. The angle $\phi$ is from the $\mathbf{B}\bar{B}'$ plane to the $L\bar{L}'$ plane defined by the momenta of the $\mathbf{B}\bar{B}'$ pair and $L\bar{L}'$ pair in the $B$ meson rest frame, respectively. The partial decay width then reads [8,9]

$$d\Gamma = \frac{|\bar{\mathcal{M}}|^2}{4(4\pi)^6 m^3_B} X\alpha_\mathbf{B}\alpha_\mathbf{L}\, ds\, dt\, d\cos\theta_\mathbf{B}\, d\cos\theta_\mathbf{L}\, d\phi \quad (12)$$

where $X = [(m^2_B - s - t)^2/4 - st]^{1/2}$, $\alpha_\mathbf{B} = \lambda^{1/2}(t, m^2_\mathbf{B}, m^2_{\bar{\mathbf{B}}'})/t$, and $\alpha_\mathbf{L} = \lambda^{1/2}(s, m^2_L, m^2_{\bar{L}'})/s$, with $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$. For integration, the allowed ranges of the five variables are $(m_L + m_{\bar{L}'})^2 \le s \le (m_B - \sqrt{t})^2$, $(m_\mathbf{B} + m_{\bar{\mathbf{B}}'})^2 \le t \le (m_B - m_L - m_{\bar{L}'})^2$, $0 \le \theta_{\mathbf{B},\mathbf{L}} \le \pi$, and $0 \le \phi \le 2\pi$. The partial decay width of $B(p_B) \to \mathbf{B}(p_\mathbf{B})\bar{\mathbf{B}}'(p_{\bar{\mathbf{B}}'})M(p_M)$ involves two variables in the phase space, given by [3,28]

$$d\Gamma = \frac{\beta^{1/2}_\mathbf{B}\beta^{1/2}_t}{(8\pi m_B)^3}|\bar{\mathcal{M}}|^2\, dt\, d\cos\theta \quad (13)$$

where $\beta_\mathbf{B} = [1 - (m_\mathbf{B} + m_{\bar{\mathbf{B}}'})^2/t][1 - (m_\mathbf{B} - m_{\bar{\mathbf{B}}'})^2/t]$, $\beta_t = [(m_B + m_M)^2 - t][(m_B - m_M)^2 - t]$, and $\theta$ is the angle between the meson and baryon moving directions in the $\mathbf{B}\bar{B}'$ rest frame. The allowed regions of the variables are $-1 < \cos\theta < 1$ and $(m_\mathbf{B} + m_{\bar{\mathbf{B}}'})^2 < t < (m_B - m_M)^2$. For the global fit in the next section, we define the $CP$ asymmetry [4,37], and angular asymmetries of $B \to \mathbf{B}\bar{\mathbf{B}}'M$ [3,26,28] and $B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$ [8,9], written as

$$\begin{aligned}
\mathcal{A}_{CP} &\equiv \frac{\Gamma(B \to \mathbf{B}\bar{\mathbf{B}}'M) - \Gamma(\bar{B} \to \mathbf{B}\bar{\mathbf{B}}'\bar{M})}{\Gamma(B \to \mathbf{B}\bar{\mathbf{B}}'M) + \Gamma(\bar{B} \to \mathbf{B}\bar{\mathbf{B}}'\bar{M})} \\
\mathcal{A}_{FB,\theta_i} &\equiv \frac{\Gamma(\cos\theta_i > 0) - \Gamma(\cos\theta_i < 0)}{\Gamma(\cos\theta_i > 0) + \Gamma(\cos\theta_i < 0)}
\end{aligned} \quad (14)$$

where $\bar{B} \to \mathbf{B}\bar{\mathbf{B}}'\bar{M}$ represents the anti-particle decay.

## 3 Numerical results and discussions

In the numerical analysis, the CKM matrix elements in the Wolfenstein parameterization read [7]

$$V_{ub} = A\lambda^3(\rho - i\eta),\; V_{ud} = 1 - \lambda^2/2,\; V_{us} = \lambda,$$
$$V_{cb} = A\lambda^2,\; V_{tb} = 1,\; V_{td} = A\lambda^3,\; V_{ts} = -A\lambda^2 \quad (15)$$

**Table 1** The effective Wilson coefficients $c_i^{eff}$ $(i = 1, 2, \ldots, 6)$ for $b$ and $\bar{b}$ decays

| $c_i^{eff}$ | $b \to d\ (\bar{b} \to \bar{d})$ | $b \to s\ (\bar{b} \to \bar{s})$ |
|---|---|---|
| $c_1^{eff}$ | 1.168 (1.168) | 1.168 (1.168) |
| $c_2^{eff}$ | −0.365 (−0.365) | −0.365 (−0.365) |
| $10^4 c_3^{eff}$ | $238.0 + 12.7i\ (257.4 + 46.1i)$ | $243.3 + 31.2i\ (240.9 + 32.3i)$ |
| $10^4 c_4^{eff}$ | $-497.0 - 38.0i\ (-555.2 - 138.3i)$ | $-512.8 - 93.7i\ (-505.7 - 96.8i)$ |
| $10^4 c_5^{eff}$ | $145.5 + 12.7i\ (164.7 + 46.1i)$ | $150.7 + 31.2i\ (148.4 + 32.3i)$ |
| $10^4 c_6^{eff}$ | $-633.8 - 38.0i\ (-692.0 - 138.3i)$ | $-649.6 - 93.7i\ (-642.6 - 96.8i)$ |

with $(\lambda, A, \rho, \eta) = (0.225, 0.826, 0.163 \pm 0.010, 0.357 \pm 0.010)$.

From Refs. [18–21], we adopt $D(x)$ as

$$\begin{aligned}
D(x) &= D_0(x) + \frac{\alpha_s}{4\pi} D_1(x),\\
D_0(x) &= \frac{x}{8}\left[-\frac{2+x}{1-x} + \frac{3x-6}{(1-x)^2} ln(x)\right],\\
D_1(x) &= -\frac{23x + 5x^2 - 4x^3}{3(1-x)^2} + \frac{x - 11x^2 + x^3 + x^4}{(1-x)^3} ln(x)\\
&\quad + \frac{8x + 4x^2 + x^3 - x^4}{2(1-x)^3} ln^2(x)\\
&\quad - \frac{4x - x^3}{(1-x)^2} L_2(1-x) + 8x \frac{\partial D_0(x)}{\partial x} ln(\mu^2/m_W^2),
\end{aligned} \tag{16}$$

where $L_2(1-x) \equiv \int_1^x ln(t)/(1-t)dt$ and $\mu = m_b$. For $B \to p\bar{p}M(V)$ and $\bar{B}^0 \to p\bar{p}D^{0(*)}$, we present $c_i^{eff}$ in Table 1, where $b$ and $\bar{b}$ decays are both considered, together with the decay constants $(f_\pi, f_K, f_\rho, f_{K^*}) = (130.2 \pm 1.2, 155.7 \pm 0.3, 210.6 \pm 0.4, 204.7 \pm 6.1)$ MeV [7,38] and $(f_D, f_{D^*}) = (208.9 \pm 6.5, 252.2 \pm 22.7)$ MeV [28,39]. In the generalized edition of the factorization [30,37], $N_c$ is taken as the effective color number with $N_c^{(eff)} = (2, 3, \infty)$, in order that the non-factorizable QCD corrections can be estimated.

Using the minimum $\chi^2$-fit of

$$\chi^2 = \sum \left(\frac{\mathcal{O}^i_{th} - \mathcal{O}^i_{ex}}{\sigma^i_{ex}}\right)^2 + \left(\frac{|V_{ub}|_{th} - |V_{ub}|_{ex}}{\sigma_{|V_{ub}|_{ex}}}\right)^2 \tag{17}$$

we test if the observables of non-leptonic and semileptonic baryonic $B$ decays can both be interpreted, where $\mathcal{O}^i_{th}$ stand for the theoretical calculations of $\mathcal{B}$, $\mathcal{A}_{CP}$ and $\mathcal{A}_{FB}$, while $\mathcal{O}^i_{ex}$ the experimental inputs in Table 2, together with $\sigma^i_{ex}$ the experimental errors. Since the $V_{ub}$ in Eq. (3) is for the exclusive baryonic $B_{(s)}$ decays, which can be different from that in the inclusive ones [40–42], we choose $|V_{ub}|_{ex} = (3.43 \pm 0.32) \times 10^{-3}$ determined from the $\bar{B}_s^0$ and baryonic $\Lambda_b$ decays [7] as our experimental input in Eq. (17).

With 16 experimental inputs from Table 2 and $|V_{ub}|_{ex}$, we fit $(D_{||}, D_{\overline{||}}, D_{2,3,4,5})$ and $(\bar{D}_{||}, \bar{D}_{\overline{||}}, \bar{D}_{2,3})$ in Eqs. (10) and (11), respectively, and $|V_{ub}|_{th}$, which amount to 11 parameters, such that the number of degrees of freedom denoted by $d.n.f$ is counted as $d.n.f = 16 - 11 = 5$. As a result, we obtain $\chi^2/n.d.f = 1.86$ as a measure of the global fit, and extract that

**Table 2** Experimental data for the $B^- \to p\bar{p}\ell^-\nu_\ell$ and $B \to p\bar{p}M_{(c)}$ decays, where the notation † for $\mathcal{A}_{FB}$ denotes the contribution from $m_{p\bar{p}} < 2.85$ GeV, and $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu)$ has combined the Belle and LHCb data in Eq. (1)

| Decay modes | Data |
|---|---|
| $10^6\mathcal{B}(B^- \to p\bar{p}e^-\bar{\nu}_e)$ | $8.2 \pm 3.8$ [14] |
| $10^6\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu)$ | $5.2 \pm 0.4$ [14,15] |
| $10^6\mathcal{B}(B^- \to p\bar{p}\pi^-)$ | $1.62 \pm 0.20$ [7] |
| $10^6\mathcal{B}(B^- \to p\bar{p}K^-)$ | $5.9 \pm 0.5$ [7] |
| $10^6\mathcal{B}(\bar{B}^0 \to p\bar{p}\bar{K}^0)$ | $2.66 \pm 0.32$ [7] |
| $10^2\mathcal{A}_{CP}(B^- \to p\bar{p}\pi^-)$ | $0 \pm 4$ [7] |
| $10^2\mathcal{A}_{CP}(B^- \to p\bar{p}K^-)$ | $0 \pm 4$ [7] |
| $10^2\mathcal{A}_{FB}(B^- \to p\bar{p}\pi^-)$ | $(-40.9 \pm 3.4)^\dagger$ [43] |
| $10^2\mathcal{A}_{FB}(B^- \to p\bar{p}K^-)$ | $(49.5 \pm 1.4)^\dagger$ [43] |
| $10^6\mathcal{B}(B^- \to p\bar{p}\rho^-)$ | $4.6 \pm 1.3$ [7] |
| $10^6\mathcal{B}(B^- \to p\bar{p}K^{*-})$ | $3.4 \pm 0.8$ [45] |
| $10^6\mathcal{B}(\bar{B}^0 \to p\bar{p}\bar{K}^{*0})$ | $1.2 \pm 0.3$ [45] |
| $10^2\mathcal{A}_{CP}(B^- \to p\bar{p}K^{*-})$ | $21 \pm 16$ [7] |
| $10^4\mathcal{B}(\bar{B}^0 \to p\bar{p}D^0)$ | $1.04 \pm 0.07$ [7] |
| $10^4\mathcal{B}(\bar{B}^0 \to p\bar{p}D^{*0})$ | $0.99 \pm 0.11$ [7] |

$$\begin{aligned}
&(D_{||}, D_{\overline{||}}) = (11.2 \pm 43.5, 332.3 \pm 17.2)\ \text{GeV}^5\\
&(D^2_{||}, D^3_{||}, D^4_{||}, D^5_{||}) = (47.7 \pm 10.1, 442.2 \pm 103.4, -38.7\\
&\quad \pm 9.6, 80.7 \pm 27.2)\ \text{GeV}^4\\
&(\bar{D}_{||}, \bar{D}_{\overline{||}}, \bar{D}^2_{||}, \bar{D}^3_{||})\\
&\ = (-59.9 \pm 12.9, 23.8 \pm 6.8, 90.9 \pm 11.1, 131.7\\
&\quad \pm 330.7)\ \text{GeV}^4
\end{aligned} \tag{18}$$

with $N_c^{eff} = 2$ and $\infty$ for $B \to p\bar{p}M(V)$ and $B \to p\bar{p}D^{0(*)}$, respectively. Using the parameters in Eq. (18), we calculate the branching fractions and angular asymmetries of $B^- \to p\bar{p}\ell\bar{\nu}$, $\Lambda\bar{p}\nu\bar{\nu}$ and $\bar{B}_s^0 \to p\bar{\Lambda}\ell\bar{\nu}$, $\Lambda\bar{\Lambda}\nu\bar{\nu}$, of which the results are compared with the experimental data

**Table 3** Our calculations for the semileptonic $B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$ decays. For $\mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}'\ell\bar{\nu}_\ell)$, the values in the parentheses correspond to $\ell = (e, \mu, \tau)$, where the first and second errors come from $|V_{ub}|$ and the form factors in Eq. (18), respectively. For $\mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}'\nu\bar{\nu}) = \Sigma_\ell \mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}'\nu_\ell\bar{\nu}_\ell)$ and $\mathcal{A}_{FB}(B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}')$, the errors take into account the uncertainties of the form factors in Eq. (18)

| Decay modes | This work | Data |
|---|---|---|
| $10^6\mathcal{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell)$ | $(5.3 \pm 1.1 \pm 1.7, 5.4 \pm 1.1 \pm 1.7, 7.6 \pm 1.5 \pm 3.9)$ | $(8.2 \pm 3.8$ [14], $5.2 \pm 0.4$ [14,15],–) |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{B}}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell)$ | $(1.4 \pm 12.6, 1.4 \pm 12.6, 1.4 \pm 12.6)$ | – |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{L}}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell)$ | $(-41.7 \pm 21.4, -41.2 \pm 20.4, -2.1 \pm 5.0)$ | – |
| $10^6\mathcal{B}(\bar{B}^0_s \to p\bar{\Lambda}\ell^-\bar{\nu}_\ell)$ | $(2.1 \pm 0.4 \pm 0.5, 2.1 \pm 0.4 \pm 0.5, 1.7 \pm 0.3 \pm 0.9)$ | – |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{B}}(\bar{B}^0_s \to p\bar{\Lambda}\ell^-\bar{\nu}_\ell)$ | $(25.7 \pm 11.4, 25.0 \pm 11.3, -3.5 \pm 2.7)$ | – |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{L}}(\bar{B}^0_s \to p\bar{\Lambda}\ell^-\bar{\nu}_\ell)$ | $(-44.1 \pm 10.8, -43.7 \pm 10.3, 0.4 \pm 5.5)$ | – |
| $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu})$ | $(3.5 \pm 1.0) \times 10^{-8}$ | $(0.4 \pm 1.3) \times 10^{-5}$ $(< 3 \times 10^{-5})$ [16] |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{B}}(B^- \to \Lambda\bar{p}\nu\bar{\nu})$ | $22.8 \pm 11.2$ | – |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{L}}(B^- \to \Lambda\bar{p}\nu\bar{\nu})$ | $-40.9 \pm 8.3$ | – |
| $\mathcal{B}(\bar{B}^0_s \to \Lambda\bar{\Lambda}\nu\bar{\nu})$ | $(0.8 \pm 0.2) \times 10^{-8}$ | – |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{B}}(\bar{B}^0_s \to \Lambda\bar{\Lambda}\nu\bar{\nu})$ | $24.4 \pm 11.8$ | – |
| $10^2\mathcal{A}_{FB,\theta_\mathbf{L}}(\bar{B}^0_s \to \Lambda\bar{\Lambda}\nu\bar{\nu})$ | $-40.1 \pm 8.0$ | – |

in Table 3. We also draw the $p\bar{p}$ invariant mass spectrum for $B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$ in Fig. 4.

## 4 Discussions and conclusions

Since $\chi^2/n.d.f = 1.86$ presents a reasonable fit, it indicates that the most recent data in Table 2 can be explained. It is interesting to note that $\mathcal{B}(B^- \to p\bar{p}\pi^-, p\bar{p}\rho^-)$ [3,4] were once overestimated [7,43,44], and the relation of $\mathcal{A}_{FB}(B^- \to p\bar{p}\pi^-) \simeq \mathcal{A}_{FB}(B^- \to p\bar{p}K^-)$ [3] was not verified by the measurements [43,44]. This is due to $F_{\mathbf{B}\bar{\mathbf{B}}'}$ determined by the $B \to p\bar{p}K$ data [3], while $B \to p\bar{p}K$ are in fact the penguin dominated decays with $\hat{\mathcal{M}}_6 \propto \langle p\bar{p}|(S-P)^b|B\rangle$ to give the main contribution. To avoid the inconsistency unable to be solved at that time, one performed the extraction of Ref. [6] that excluded $\mathcal{B}(B^- \to p\bar{p}K^-)$, $\mathcal{B}(\bar{B}^0 \to p\bar{p}\bar{K}^0)$, and $\mathcal{A}_{FB}(B^- \to p\bar{p}K^-)$, in order that the more associated tree dominated decays of $B \to p\bar{p}(\pi, \rho)$, $\bar{B}^0 \to p\bar{p}D^{0(*)}$, and $B \to \mathbf{B}\bar{\mathbf{B}}L\bar{L}'$ can be studied. However, it resulted in an unsatisfactory global fit not to accommodate the all data.

As $F_{\mathbf{B}\bar{\mathbf{B}}'}$ determined in this work can be universal for the non-leptonic and semileptonic decay channels, we calculate $\mathcal{B}(B^- \to p\bar{p}e^-\bar{\nu}_e) = (5.3 \pm 2.0) \times 10^{-6}$ and $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (5.4 \pm 2.0) \times 10^{-6}$ agreeing with the experimental values. Moreover, we revisit $B^- \to \Lambda\bar{p}\nu\bar{\nu}$, and obtain $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu}) = (3.5 \pm 1.0) \times 10^{-8}$ 20 times smaller than the number of Ref. [9].

Like the theoretical illustration in $B \to \mathbf{B}\bar{\mathbf{B}}'$ and $B \to \mathbf{B}\bar{\mathbf{B}}'M$ [29,46], the gluon propagators of Fig. 1a–c play the key role in the $\mathbf{B}\bar{\mathbf{B}}'$ formation of $B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$, where two of them provide the valence quarks in $\mathbf{B}\bar{B}'$, while the another one speeds up the spectator quark in $B$. Accordingly, the approach of pQCD counting rules derives that $F_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/t^3$.

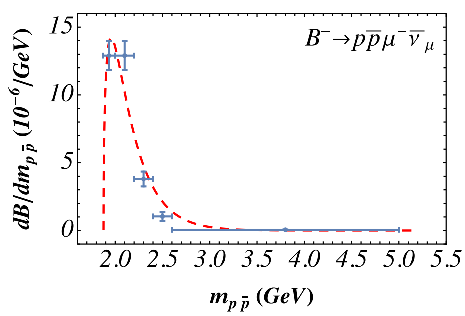


**Fig. 4** The $p\bar{p}$ invariant mass spectrum of $B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$, where the data points are from LHCb [15]

One can test the momentum dependence of $B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$, which is by scanning the partial branching fraction as a function of $\sqrt{t} = m_{p\bar{p}}$. In Fig. 4, as we draw the line to agree with the five data points [15]; particularly, those around the area of $\sqrt{t} \sim m_\mathbf{B} + m_{\bar{\mathbf{B}}'}$ for the threshold effect, it is shown that $F_{\mathbf{B}\bar{\mathbf{B}}'}$ as a function of $1/t$ can describe $B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$.

By normalizing the prediction of the pQCD model [8], LHCb draws the $m_{p\bar{p}}$ spectrum of $B^- \to p\bar{p}\mu\bar{\nu}$ in Fig. 4 of Ref. [15], where the line is higher and narrower than our result. The difference is caused by the fact that the line of of Ref. [15] is chosen to more agree with the two data points around $m_{p\bar{p}} \sim 2.5$ GeV. Subsequently, the peak should reach $17 \times 10^{-6}$ to be above the data point around $m_{p\bar{p}} \sim 2$ GeV for integrating over the partial branching fraction as large as $\mathcal{B} \simeq 5 \times 10^{-6}$. In comparison, our result prefers to agree with the threshold data points; however, requiring some broadening to give a sufficient branching fraction.

The decay channel $\bar{B}_s^0 \to \Lambda\bar{p}K^+(\bar{\Lambda}pK^-)$ is the first observation of a baryonic $\bar{B}_s^0$ decay [47], whose branching fraction $\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{p}K^+ + \bar{\Lambda}pK^-) = 5.46 \times 10^{-6}$ is as large as those of the three-body baryonic $B^-$ ($\bar{B}^0$) decays. Hence, the semileptonic baryonic $\bar{B}_s^0$ decay is supposed to be compatible with $B^- \to p\bar{p}\ell\bar{\nu}_\ell$. In our prediction, we present

$$\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}e^-\bar{\nu}_e, p\bar{\Lambda}\mu^-\bar{\nu}_\mu) = (2.1\pm0.6, 2.1\pm0.6)\times10^{-6} \quad (19)$$

which are accessible to the LHCb experiment, whereas $\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{\Lambda}\nu\bar{\nu}) = (0.8 \pm 0.2) \times 10^{-8}$ is relatively small.

Because of $m_\tau \gg m_{e,\mu}$ that strongly shrinks the phase space, it is anticipated that $\mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}'\tau\bar{\nu}) \ll \mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}'e\bar{\nu}, \mathbf{B}\bar{\mathbf{B}}'\mu\bar{\nu})$. Nonetheless, the amplitude of Eq. (3) and the matrix elements of Eq. (6) result in

$$i\bar{u}(g_3\gamma_5 - f_3)v\; m_\ell\bar{u}_\ell\gamma_\mu(1 + \gamma_5)v_{\bar{\nu}} \quad (20)$$

in $\mathcal{M}(B \to \mathbf{B}\bar{\mathbf{B}}'\ell\bar{\nu})$, where $m_\tau$ is able to enhance the decay. We thus obtain

$$\mathcal{B}(B^- \to p\bar{p}\tau^-\bar{\nu}_\tau) = (7.6 \pm 4.2) \times 10^{-6}$$
$$\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}\tau^-\bar{\nu}_\tau) = (1.7 \pm 1.0) \times 10^{-6} \quad (21)$$

as large as their counterparts. Likewise, the mass effect can be found in $\mathcal{M}(B \to \tau\bar{\nu}) \propto m_\tau\bar{u}_\tau(1 + \gamma_5)v_{\bar{\nu}}$ [48,49] and $\mathcal{M}(B \to \mathbf{B}_c\bar{\mathbf{B}}') \propto m_c\langle\mathbf{B}_c\bar{\mathbf{B}}'|\bar{c}(1 + \gamma_5)q|0\rangle$ [50], where $m_\tau$ and $m_c$ alleviate the decays from helicity suppression.

We study the angular asymmetries of the semileptonic $B \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$ decays. While $\mathcal{A}_{FB,\theta_\mathbf{B}}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell)$ are around several percents, $\mathcal{A}_{FB,\theta_\mathbf{B}}(\bar{B}_s^0 \to p\bar{\Lambda}e^-\bar{\nu}_e, p\bar{\Lambda}\mu^-\bar{\nu}_\mu)$ and $\mathcal{A}_{FB,\theta_\mathbf{B}}(\bar{B}_s^0 \to \Lambda\bar{\Lambda}\nu\bar{\nu})$ can be around 25%. Like the three-body baryonic $B$ decays [3,26,28], this implies a theoretical sensitivity for $F_{\mathbf{B}\bar{\mathbf{B}}'}$ to be confirmed by future measurements.

In summary, we have investigated the semiletonic $B^-(\bar{B}_s^0) \to \mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$ decays with $L\bar{L}' = (\ell\bar{\nu}_\ell, \nu\bar{\nu})$. We have newly extracted the $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors with the global fit that includes the data of $B \to p\bar{p}M(V)$, $\bar{B}^0 \to p\bar{p}D^{0(*)}$ and $B \to p\bar{p}e^-\bar{\nu}_e, p\bar{p}\mu^-\bar{\nu}_\mu$ decays. In our demonstration, $\mathcal{B}(B^- \to p\bar{p}e^-\bar{\nu}_e, p\bar{p}\mu^-\bar{\nu}_\mu)$ once overestimated to be as large as $10^{-4}$ has been reduced to be around $5 \times 10^{-6}$, in agreement with the current data. We have also presented $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu}) = (3.5 \pm 1.0) \times 10^{-8}$. It has been found that $\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}e^-\bar{\nu}_e, p\bar{\Lambda}\mu^-\bar{\nu}_\mu, p\bar{\Lambda}\tau^-\bar{\nu}_\tau) = (2.1 \pm 0.6, 2.1 \pm 0.6, 1.7 \pm 1.0) \times 10^{-6}$ and $\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{\Lambda}\nu\bar{\nu}) = (0.8 \pm 0.2) \times 10^{-8}$ can be promising for future measurements.

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