Pentaquarks in semileptonic $\Lambda_b$ decays

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Abstract

In terms of $P_{c1,c2} = P_c(4380,4450)^+$ as the hidden charm pentaquark states to consist of $c\bar{c}uud$, we study the semileptonic $\Lambda_b \to (P_{c1,c2} \rightarrow) J/\psi p \ell^- \bar{\nu}_\ell$ decays. In our discussion, while the main contribution to $\Lambda_b \to K^- J/\psi p$ is from the non-perturbative process via the doubly charmful $b \to c\bar{c}s$ transition, we propose that the $\Lambda_b \to P_{c1,c2} \rightarrow J/\psi p$ transitions are partly contribute to the $\Lambda_b \to K^- (P_{c1,c2} \rightarrow) J/\psi p$ decays, in which the required $c\bar{c}$ pair is formed by the sea quarks, intrinsic charm, or both. We predict that $\mathcal{B}(\Lambda_b \to J/\psi p \ell^- \bar{\nu}_\ell) = (2.04^{+4.82}_{-1.57}, 1.75^{+4.14}_{-1.35}) \times 10^{-6}$ for $\ell = (e, \mu)$, which are about two orders of magnitude smaller than the observed decay of $\Lambda_b \to p \mu \bar{\nu}_\mu$. We also explore the angular correlations for the $J/\psi p$ and $\ell^- \bar{\nu}_\ell$ pairs. Our results of the decay branching ratios and angular asymmetries in $\Lambda_b \to J/\psi p \ell^- \bar{\nu}_\ell$, accessible to the ongoing experiments at the LHCb, can be used to improve the understanding of the hidden charm pentaquark states.
I. INTRODUCTION

In the $J/\psi p$ invariant spectrum of the $\Lambda_b \rightarrow J/\psi p K^-$ decay, the two resonant states $P_{c1,c2} = P_c(4380, 4450)^+$ have been identified as the hidden charm pentaquark states of $c\bar{c}uud$ [1–3], which are in accordance with the theoretical predictions of the pentaquark to consist of the $c\bar{c}$ pair [4–7]. After the observation, the theoretical studies have been mainly concerning the pentaquark structure [8], such as those examined in the diquark-diquark-antiquark models [9–12], taken as the baryon-meson bound states of $\Sigma_c \bar{D}^*$, $\Sigma_c^* \bar{D}^*$ and $\chi_{c1} p$ [13–17] or the genuine multiquark states [18]. On the other hand, the data can be interpreted with the kinematical effects related to the so-called triangle singularity [19–21], which may be viewed to be opposite the pentaquark scenario [16, 22]. The pentaquark productions, such as the $b$-baryon decays [23, 24], photo-productions [25–27] and $\pi$-$p$ collision [28] have been also examined.

The $\Lambda_b \rightarrow M^- J/\psi p$ decays via the $b \rightarrow c\bar{c}q$ transitions with $q = s(d)$ for $M = K(\pi)$ have two types of the diagrams as shown in Figs. 1a and 1b. The first one in Fig. 1a proceeds with the direct $\Lambda_b \rightarrow pM$ and indirect $\Lambda_b \rightarrow N^* \rightarrow pM$ transitions, accompanying the recoiled $J/\psi$ vector meson, with $N^*$ denoted as a higher wave baryon state. This type of the diagrams makes the main contributions to the total decay branching ratios of $\Lambda_b \rightarrow (\pi^-, K^-) J/\psi p$. The second type is illustrated in Fig. 1b, which involves the non-perturbative processes with the resonant $\Lambda_b \rightarrow K^-(P_{c1,c2} \rightarrow) J/\psi p$ decays as studied in Refs. [20, 22, 23, 30]. On the other hand, $\Lambda_b \rightarrow M(P_{c1,c2} \rightarrow) J/\psi p$ can also be produced via the charmless $b \rightarrow u\bar{u}q$ transition [24] as depicted in Figs. 1c and 1d, in which the required $c\bar{c}$ pair comes from the sea quarks (gluon splitting) or the intrinsic charms within $\Lambda_b$ and $p$ [31–35, 40], along with the $\Lambda_b \rightarrow P_{c1,c2} \rightarrow J/\psi p$ transitions and the recoiled $M$. The current experimental measurements on $\Lambda_b \rightarrow M^- J/\psi p$ by the LHCb Collaboration can be summarized as follows:

$$B(\Lambda_b \rightarrow K^- J/\psi p) = (3.17 \pm 0.04 \pm 0.07 \pm 0.34^{+0.45}_{-0.28}) \times 10^{-4} [1]$$
$$B(\Lambda_b \rightarrow \pi^- J/\psi p) = (2.61 \pm 0.09 \pm 0.13^{+0.47}_{-0.37}) \times 10^{-5} [1]$$
$$B(\Lambda_b \rightarrow K^- (P_{c1} \rightarrow) J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.37}) \times 10^{-5} [29]$$
$$B(\Lambda_b \rightarrow K^- (P_{c2} \rightarrow) J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5} [29]$$
$$\Delta A_{CP} \equiv A_{CP}(\Lambda_b \rightarrow J/\psi p \pi^-) - A_{CP}(\Lambda_b \rightarrow J/\psi p K^-) = (5.7 \pm 2.4 \pm 1.2)\% [37]$$
$$R_{\pi K} \equiv \frac{B(\Lambda_b \rightarrow J/\psi p \pi^-)}{B(\Lambda_b \rightarrow J/\psi p K^-)} = 0.0824 \pm 0.0025 \pm 0.0042 [37]$$
\[ \mathcal{R}_{\pi K}(\mathcal{P}_{c1}) = \frac{\mathcal{B}(\Lambda_b \to \mathcal{P}_{c1}\pi^-)}{\mathcal{B}(\Lambda_b \to \mathcal{P}_{c1}K^-)} = 0.050 \pm 0.016_{-0.016}^{+0.026} \pm 0.025 \] for \\
\[ \mathcal{R}_{\pi K}(\mathcal{P}_{c2}) = \frac{\mathcal{B}(\Lambda_b \to \mathcal{P}_{c2}\pi^-)}{\mathcal{B}(\Lambda_b \to \mathcal{P}_{c2}K^-)} = 0.033_{-0.014}^{+0.011} \pm 0.009 \] (1).

To understand the difference of the CP asymmetries in Eq. (1), it is clear that the third type of the diagrams is needed as it is the only possible source to provide the weak CP violating phase from the CKM element of \( V_{ub} \). As a result, we have obtained that \( \mathcal{A}_{CP}(\Lambda_b \to \pi^- (\mathcal{P}_{c1,c2} \to J/\psi p)) = (-7.4 \pm 0.9)\% \), and \( \mathcal{A}_{CP}(\Lambda_b \to K^- (\mathcal{P}_{c1,c2} \to J/\psi p)) = (+6.3 \pm 0.2)\% \). In addition, we have shown that \( \mathcal{B}(\Lambda_b \to \pi^- (\mathcal{P}_{c1,c2} \to J/\psi p))/\mathcal{B}(\Lambda_b \to K^- (\mathcal{P}_{c1,c2} \to J/\psi p)) = 0.58 \pm 0.05 \) based on Figs. 1b and 1l, whereas Fig. 1b via \( b \to c\bar{c}q \) leads to that \( \mathcal{B}(\Lambda_b \to \pi^- (\mathcal{P}_{c1,c2} \to J/\psi p))/\mathcal{B}(\Lambda_b \to K^- (\mathcal{P}_{c1,c2} \to J/\psi p)) \approx 0.07 - 0.08 \) from the nonfactorizable diagram in Fig. 1b, which is preferred by the data to give the main contribution, the apparently large uncertainties of \( \mathcal{R}_{\pi K}(\mathcal{P}_{c1}, \mathcal{P}_{c2}) \) still make the room for the other pentaquark productions as those in Figs. 1f and 1l.

As shown in Fig. 1f, it is interesting to note that the \( \Lambda_b \to \mathcal{P}_{c1,c2} \) transitions proposed to explain \( \Lambda_b \to K^- \mathcal{P}_{c1,c2} \) would simultaneously induce the semileptonic \( \Lambda_b \to \mathcal{P}_{c1,c2} \ell^- \bar{\nu}_\ell \) decays, similar to \( \Lambda_b \to p\ell^- \bar{\nu}_\ell \) associated with the \( \Lambda_b \to p \) transition, with the only difference being that \( \mathcal{P}_{c1,c2} \) contain the additional \( c\bar{c} \) pair compared to \( p \). It is feasible that the semileptonic \( \Lambda_b \to (\mathcal{P}_{c1,c2} \to J/\psi p\ell^- \bar{\nu}_\ell \) decays can be used to explore the resonant pentaquark states, while the \( B_c^- \to X(3872)\ell\bar{\nu}_\ell \) decays, proposed recently in Ref. 38, 39, tackle the tetraquark state (the four-quark bound state). Note that, as in Refs. 42, 44, the semileptonic \( b \)-hadron decays have been successfully used to extract \( V_{ub} \), test new physics, determine the form factors, and seek the intrinsic charm. In this report, we will study the semileptonic \( \Lambda_b \to (\mathcal{P}_{c1,c2} \to J/\psi p\ell^- \bar{\nu}_\ell \) decays to be connected with the pentaquark productions in the hadronic \( \Lambda_b \) decays. Unlike the previous extraction of the information of the resonant \( \Lambda_b \to (\mathcal{P}_{c1,c2} \to J/\psi p \) transitions in Ref. 24, which assumes that Figs. 1f and 1l dominate \( \Lambda_b \to M(\mathcal{P}_{c1,c2} \to J/\psi p \), we will include the pentaquark contributions from Figs. 1f-1l as well as the new experimental inputs of \( \mathcal{R}_{\pi K}(\mathcal{P}_{c1}, \mathcal{P}_{c2}) \) to re-extract the information. With the new extraction, we will then study the \( \Lambda_b \to (\mathcal{P}_{c1,c2} \to J/\psi p\ell^- \bar{\nu}_\ell \) decay,
FIG. 1. Three types of diagrams for the $\Lambda_b \to MJ/\psi p$ decays, where (a) is the first one without $\mathcal{P}_c$, and (b) and (c,d) correspond to the second and third ones through the $\Lambda_b \to MP_c(\to J/\psi p)$ processes via the doubly charmful $b \to c\bar{c}q$ and $b \to u\bar{u}q$ transitions, respectively, while (e) is the diagram for the semileptonic $\Lambda_b \to \mathcal{P}_c(\to J/\psi p)\ell^-\bar{\nu}_\ell$ decays.

which can be clearly tested if there exist the third types of the contributions via $b \to u\bar{u}q$, apart from the second ones via $b \to c\bar{c}q$, measured as the main contributions of the resonant $\Lambda_b \to M(\mathcal{P}_{c1,c2} \to J/\psi p)$ decays.

II. FORMALISM

In terms of the effective Hamiltonian of $b \to u\ell\bar{\nu}_\ell$ at the quark level from Fig. [2], given by

$$\mathcal{H}(b \to u\ell^-\bar{\nu}_\ell) = \frac{G_F V_{ub}}{\sqrt{2}} \bar{u} \gamma_\mu (1 - \gamma_5) b \bar{\ell} \gamma^\mu (1 - \gamma_5) \nu_\ell,$$

(2)

the amplitude for the $\Lambda_b \to (\mathcal{P}_c \to J/\psi p\ell^-\bar{\nu}_\ell$ decay with $\ell = (e$ or $\mu$) can be derived as

$$\mathcal{A}(\Lambda_b \to (\mathcal{P}_c \to J/\psi p\ell^-\bar{\nu}_\ell) = \frac{G_F V_{ub}}{\sqrt{2}} \langle J/\psi p | \bar{u} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle \bar{\ell} \gamma^\mu (1 - \gamma_5) \nu_\ell .$$

(3)

In accordance with the pentaquark observations in the resonant $\Lambda_b \to K^- (\mathcal{P}_{c1,c2} \to J/\psi p$ decays, the matrix elements in Eq. (3) for the resonant $\Lambda_b \to \mathcal{P}_c \to J/\psi p$ transition can be written as

$$\langle J/\psi p | \bar{u} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle = \mathcal{R}_{\mathcal{P}_c} \langle \mathcal{P}_c | \bar{u} \gamma_\mu (1 - \gamma_5) b | \Lambda_b \rangle$$

(4)

$$= \mathcal{R}_{\mathcal{P}_c} (\epsilon \cdot q) \bar{u}_p (\bar{F}_{\mathcal{P}_c \gamma_\mu} - \bar{G}_{\mathcal{P}_c \gamma_\mu \gamma_5}) u_{\Lambda_b} ,$$
where \( \varepsilon^\mu \) is the \( J/\psi \) four-polarization, \( q^\mu \) is the momentum transfer, \( F_{P_c} (G_{P_c}) \) represents the vector (axial-vector) form factors, and \( R_{P_c} \) corresponds to the Breit-Wigner factor, given by

\[
R_{P_c} = \frac{i}{(t - m_{P_c}^2) + im_{P_c}\Gamma_{P_c}},
\]

with \( t = (p_{J/\psi} + p_\nu)^2 \). As an intermediate state, the \( P_c \) spin, no matter 3/2 or 5/2, has been summed over, included in \( F_{P_c} \) and \( G_{P_c} \).

To describe the four-body \( \Lambda_b \to J/\psi p\ell^- \bar{\nu}_\ell \) decay, we need five kinematic variables: \( s = (p_\ell + p_\nu)^2 \), \( t = (p_{J/\psi} + p_p)^2 \), and the three angles \( (\theta_H, \theta_L, \phi) \) shown in Fig. 2 \[46, 47\]. As seen in Fig. 2, the angle \( \theta_H(L) \) is between \( \vec{p}_{J/\psi} (\vec{p}_\ell) \) in the \( J/\psi p \) \( (\ell^- \bar{\nu}) \) rest frame and the line of flight of the \( J/\psi p \) \( (\ell^- \bar{\nu}) \) system in the \( \Lambda_b \) rest frame, while the angle \( \phi \) is between the \( J/\psi p \) and \( \ell^- \bar{\nu} \) planes, defined by the momenta of the \( J/\psi p \) and \( \ell^- \bar{\nu} \) pairs, respectively, in the \( \Lambda_b \) rest frame. The partial decay width reads \[48\]

\[
d\Gamma = \frac{|\mathcal{A}|^2}{4(4\pi)^6m_{\Lambda_b}^6}X\beta_H\beta_L ds dt d\cos\theta_H d\cos\theta_L d\phi,
\]

where \( X, \beta_H \), and \( \beta_L \) are given by

\[
X = \left[ \frac{1}{4}(m_{\Lambda_b}^2 - s - t)^2 - st \right]^{1/2},
\]

\[
\beta_H = \frac{1}{t}\lambda^{1/2}(t, m_{J/\psi}^2, m_p^2),
\]

\[
\beta_L = \frac{1}{s}\lambda^{1/2}(s, m_\ell^2, m_\nu^2),
\]

respectively, with \( \lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca \). The regions for the five variables
of the phase space are given by
\[ (m_\ell + m_\bar{\nu})^2 \leq s \leq (m_{\Lambda_b} - \sqrt{t})^2, \]
\[ (m_{J/\psi} + m_p)^2 \leq t \leq (m_{\Lambda_b} - m_\ell - m_\bar{\nu})^2, \]
\[ 0 \leq \theta_{H,L} \leq \pi, \ 0 \leq \phi \leq 2\pi. \] (8)

III. NUMERICAL RESULTS AND DISCUSSIONS

For the numerical analysis, in the Wolfenstein parameterization \( V_{ub} = A\lambda^3(\rho - i\eta) \) is presented with \((\lambda, A, \rho, \eta) = (0.225, 0.814, 0.120 \pm 0.022, 0.362 \pm 0.013) \) \[45\]. The masses and the decay widths of \( \mathcal{P}_{c1,c2} \) are measured as \[1\]
\[ (m_{\mathcal{P}_{c1}}, \Gamma_{\mathcal{P}_{c1}}) = (4380 \pm 8 \pm 29, 205 \pm 18 \pm 86) \text{ MeV}, \]
\[ (m_{\mathcal{P}_{c2}}, \Gamma_{\mathcal{P}_{c2}}) = (4449.8 \pm 1.7 \pm 2.5, 39 \pm 5 \pm 19) \text{ MeV}. \] (9)

In equation of motion, \( \bar{F}_{\mathcal{P}_{c1,c2}} \) via the (axial)vector currents can be related to \( F_{\mathcal{P}_{c1,c2}} \) defined in Ref. \[24\] as the form factors of the resonant \( \Lambda_b \to \mathcal{P}_{c1,c2} \to J/\psi p \) transitions in Figs. 1c and 1d via the (pseudo)scalar currents, given by
\[ \bar{F}_{\mathcal{P}_{c1,c2}} = \frac{m_b - m_s}{m_{\Lambda_b} - m_p} F_{\mathcal{P}_{c1,c2}}, \quad \bar{G}_{\mathcal{P}_{c1,c2}} = \frac{m_b + m_s}{m_{\Lambda_b} + m_p} F_{\mathcal{P}_{c1,c2}}. \] (10)

The new observations of \( R_{\pi K}(\mathcal{P}_{c1}, \mathcal{P}_{c2}) = (0.050 \pm 0.039, 0.033 \pm 0.021) \) in Eq. (1) favor the nonfactorizable diagram in Fig. 1b as the main contribution. Nonetheless, due to the large uncertainties, it still leaves the room for the charmless \( b \to u\bar{u}q \) transitions in Figs. 1c and 1d, such that the new extractions of \( F_{\mathcal{P}_{c1,c2}} \) for the resonant \( \Lambda_b \to \mathcal{P}_{c1,c2} \to J/\psi p \) transitions are needed. Subsequently, we follow the numerical analysis in Ref. [24] to perform the fitting, where the previously ignored contribution from diagram in Fig. 1c has been taken into account, such that we obtain \( F_{\mathcal{P}_{c1}} = 2.8 \pm 4.3 \) and \( F_{\mathcal{P}_{c2}} = 1.6 \pm 1.5 \). Note that the form factors \( F_{\mathcal{P}_{c1,c2}} \) correspond to the amount of the intrinsic charms. According to Ref. [40], the intrinsic charm (IC) components are estimated to be 1%, 4% and > 4% within the proton, \( B \) meson and \( \Lambda_b \) baryon, respectively, such that the \( \Lambda_b \to pJ/\psi(K^-, \pi^-) \) and \( pJ/\psi\ell\nu_\ell \) decays with both \( \Lambda_b \) and \( p \) are more favourable to produce the pentaquark states. However, due to the theoretical difficulty, caused by the \( c\bar{c} \) pair added to produce the \( \mathcal{P}_{c1,c2} \) states, the current calculations based on QCD models cannot directly relate \( F_{\mathcal{P}_{c1,c2}} \) to the IC components yet. Fortunately, the currently improved data allow us to extract \( F_{\mathcal{P}_{c1}} \) and \( F_{\mathcal{P}_{c2}} \), though the newly
extracted values are smaller than the ones in Ref. [24]. We hence predict the branching ratios and the \( m_{J/\psi p} \) spectra for \( \Lambda_b \to J/\psi p \ell \bar{\nu}_\ell \) in Table I and Fig. 3 respectively. Note that the tau lepton mode is forbidden due to \( m_{\Lambda_b} < m_{J/\psi p} + m_{\tau^- \bar{\nu}_\tau} \). From Eq. (6), we can evaluate the integrated angular distribution asymmetries, defined by

\[
\mathcal{A}_{\theta_i} \equiv \frac{\int_{0}^{1} \frac{d\mathcal{B}}{d\cos \theta_i} d\cos \theta_i - \int_{-1}^{0} \frac{d\mathcal{B}}{d\cos \theta_i} d\cos \theta_i}{\int_{0}^{1} \frac{d\mathcal{B}}{d\cos \theta_i} d\cos \theta_i + \int_{-1}^{0} \frac{d\mathcal{B}}{d\cos \theta_i} d\cos \theta_i}, \quad (i = H, L).
\]

(11)

Our numerical results are given in Table I, which are in accordance with the angular distributions in Figs. 3c and 3d.

In Table I, the \( \Lambda_b \to J/\psi p \ell \bar{\nu}_\ell \) decays with the single \( \mathcal{P}_{c1} \) and \( \mathcal{P}_{c2} \) and the combined \( \mathcal{P}_{c1,c2} \) contributions all present the branching ratios of order \( 10^{-7} - 10^{-6} \), which are accessible to the measurements at the LHCb. Because of the constructive interference between the two pentaquark states, \( \mathcal{B}(\Lambda_b \to (\mathcal{P}_{c1,c2} \to)J/\psi p \ell \bar{\nu}_\ell) > \mathcal{B}(\Lambda_b \to (\mathcal{P}_{c1} \to)J/\psi p \ell \bar{\nu}_\ell) + \mathcal{B}(\Lambda_b \to (\mathcal{P}_{c2} \to)J/\psi p \ell \bar{\nu}_\ell) \), as illustrated in Figs. 3a and 3b. Note that \( \mathcal{B}(\Lambda_b \to J/\psi p e^- \bar{\nu}_e) > \mathcal{B}(\Lambda_b \to J/\psi p e^- \bar{\nu}_e) \) is due to the fact that \( m_e < m_\mu \) allows a more phase space for the integration. We note that, although the \( c\bar{c} \) formation leads to the suppression of \( \mathcal{O}(1/m_c^4) \) for the probability [40], which is estimated in QCD models, the nonperturbative effects may exist to compensate the short contribution. For example, the intrinsic charms are due to the quantum fluctuation within the hadron, which cause a less suppression of \( 1/m_c^2 \) [41]. Therefore, since the so-called hidden charm \( \mathcal{P}_{c1,c2} \) pentaquark states have the additional \( c\bar{c} \) quark pair compared to the proton, it is reasonable to see that \( \mathcal{B}(\Lambda_b \to p \mu^- \bar{\nu}_\mu) = 

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
modes & \( \mathcal{B} \times 10^6 \) & \( \mathcal{A}_{\theta_H} \) & \( \mathcal{A}_{\theta_L} \) \\
\hline
\( \Lambda_b \to (\mathcal{P}_{c1} \to)J/\psi pe^- \bar{\nu}_e \) & 0.49^{+2.71}_{-1.49} \pm 0.04 & 33.2\% & -51.9\% \\
\( \Lambda_b \to (\mathcal{P}_{c2} \to)J/\psi pe^- \bar{\nu}_e \) & 0.81^{+2.20}_{-0.80} \pm 0.06 & 38.7\% & -51.6\% \\
\( \Lambda_b \to (\mathcal{P}_{c1,c2} \to)J/\psi pe^- \bar{\nu}_e \) & 2.04^{+4.82}_{-1.56} \pm 0.15 & (36.5^{+2.6}_{-2.5}\%) \% \ (-51.7^{+0.2}_{-0.2}\%) \% \\
\hline
\( \Lambda_b \to (\mathcal{P}_{c1} \to)J/\psi p \mu^- \bar{\nu}_\mu \) & 0.45^{+2.34}_{-0.45} \pm 0.03 & 33.5\% & -50.7\% \\
\( \Lambda_b \to (\mathcal{P}_{c2} \to)J/\psi p \mu^- \bar{\nu}_\mu \) & 0.69^{+1.88}_{-0.68} \pm 0.05 & 39.2\% & -50.2\% \\
\( \Lambda_b \to (\mathcal{P}_{c1,c2} \to)J/\psi p \mu^- \bar{\nu}_\mu \) & 1.75^{+4.14}_{-1.34} \pm 0.13 & (37.0^{+2.7}_{-3.3}\%) \% \ (-50.4^{+0.2}_{-0.3}\%) \% \\
\hline
\end{tabular}
\caption{The numerical results of the branching ratios and the angular distribution asymmetries for the semileptonic \( \Lambda_b \to J/\psi p \ell \bar{\nu}_\ell \) decays, where the first and second errors for \( \mathcal{B} \) are from the form factors and \( |V_{ub}| \), respectively, while those for \( \mathcal{A}_{\theta_H,L} \) are from the form factors.}
\end{table}
FIG. 3. In the first line, the $m_{J/\psi p}$ spectra of (a) $\Lambda_b \rightarrow J/\psi p\bar{\nu}_e$ and (b) $\Lambda_b \rightarrow J/\psi p\mu\bar{\nu}_\mu$ are drawn with the dash, dotted, and solid lines for the $P_{c1}\rightarrow J/\psi p$, $P_{c2}\rightarrow J/\psi p$, and interfering $P_{c1,c2}\rightarrow J/\psi p$ decays. In the second line, the angular distribution of (c) $\Lambda_b \rightarrow (P_{c1,c2}\rightarrow)J/\psi p\bar{\nu}_e$ and (d) $\Lambda_b \rightarrow (P_{c1,c2}\rightarrow)J/\psi p\mu\bar{\nu}_\mu$ are drawn with the dash and dotted lines for $\cos \theta_H$ and $\cos \theta_L$, respectively.

$(4.1 \pm 1.0) \times 10^{-4}$ [42] is $O(10^2)$ larger than those of $\mathcal{B}(\Lambda_b \rightarrow (P_{c1,c2}\rightarrow)J/\psi p\ell^-\bar{\nu}_\ell)$. The angular distribution asymmetries in Table II demonstrates that the $J/\psi p$ and $\ell^-\bar{\nu}_\ell$ pairs are highly polarized. We remark that the asymmetry of $A_{\theta_L} \sim -50\%$ for the $\ell^-\bar{\nu}_\ell$ pair is reasonable, since the left-handed structure of the current $\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell$ inherits the left-handed feature of the $W$-boson, which is also highly polarized. On the other hand, with the structure of $\bar{u}_p(F_{P_L}\gamma_\mu - G_{P_L}\gamma_\mu\gamma_5)u_{\Lambda_b}$ in Eq. (11) for the resonant $\Lambda_b \rightarrow P_c \rightarrow J/\psi p$ transition, the hadronic current is left-handed, which corresponds to our model. Note that there is no error for $A_{\theta_{H,L}}$ with the single $P_{c1}$ and $P_{c2}$ contributions since all the uncertainties have been canceled in Eq. (11).
IV. CONCLUSIONS

We have studied the semileptonic $\Lambda_b \rightarrow (P_{c1,c2} \rightarrow) J/\psi p \ell^- \bar{\nu}_\ell$ decays with the $\Lambda_b \rightarrow P_{c1,c2} \rightarrow J/\psi p$ transition form factors as those proposed to explain the pentaquark states in the $\Lambda_b \rightarrow K^- (P_{c1,c2} \rightarrow) J/\psi p$ decays. We have found that $\mathcal{B}(\Lambda_b \rightarrow J/\psi p \ell^- \bar{\nu}_\ell) = (2.04^{+4.82}_{-1.57}, 1.75^{+4.14}_{-1.35}) \times 10^{-6}$ for $\ell = (e, \mu)$, for $\ell = (e, \mu)$, which are about 100 times smaller than the observed decay of $\Lambda_b \rightarrow p \mu \bar{\nu}_\mu$. We have also shown the angular distribution asymmetries for the $J/\psi p$ and $\ell^- \bar{\nu}_\ell$ pairs. Our results for the decay branching ratio and asymmetries in $\Lambda_b \rightarrow (P_{c1,c2} \rightarrow) J/\psi p \ell^- \bar{\nu}_\ell$ are accessible to the experiments at the LHCb, which will clearly improve the knowledge of the hidden charm pentaquark states.

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