Systematic study on production of hidden-bottom pentaquark via $\gamma p$ and $\pi^- p$ scatterings

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In this work, the production of hidden-bottom pentaquark $P_b$ states via $\gamma p$ and $\pi^- p$ scatterings is studied within an effective Lagrangian approach and the vector-meson-dominance mechanism. For the $P_b$ production in the process $\gamma p \rightarrow Tp$, the dipole Pomeron model is employed to calculate the background contribution, and the experimental data can be well described. For the process $\pi^- p \rightarrow Tn$, the Reggeized $t$-channel with $\pi$ exchange is considered as the main background for the $P_b$ production. The cross section from $t$-channel $\pi$ exchange is very small due to weak coupling of $P_b$ state to the $\pi n$ channel predicted theoretically. Near the threshold, two-peak structure from the states $P_b(11080)$ and $P_b(11125)$ can be observed if energy bin width is chosen as 0.01 GeV, and the same result is obtained in the $\pi^- p$ scattering. Moreover, by taking the branching ratio of $Br[P_b \rightarrow \pi N] = 0.05\%$, the numerical result shows that the average value of cross section from the $P_b$ state produced in the $\gamma p$ or $\pi^- p$ scattering reaches at least 0.1 nb with a bin of 0.1 GeV. Even if we reduce the branching ratio of the $P_b$ state into $\pi N$ channel by one order, the theoretical average of the cross section from $P_b$ production in $\pi^- p$ scattering can reach the order of 0.01 nb with a bin of 0.1 GeV, which means that the signal can still be clearly distinguished from the background. The experimental measurements and studies on the hidden-bottom pentaquark $P_b$ state production in the $\gamma p$ or $\pi^- p$ scattering near-threshold energy region around $W \approx 11$ GeV are strongly suggested, which are accessible at COMPASS and JPARC. Particularly, the result of the photoproduction suggests that it is very promising to observe the hidden-bottom pentaquark at proposed EicC facility in China.

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I. INTRODUCTION

Recently, three narrow hidden-charm pentaquark states, $P_c(4312), P_c(4440)$ and $P_c(4457)$, were observed by the LHCb Collaboration [1]. It is interesting that $P_c(4440)$ and $P_c(4457)$ are two peaks, which are revolved from the previously discovered $P_c(4450)$ [2]. Moreover, it is found that these three $P_c$ states are quite narrow, and can be clearly seen in the $J/\Psi p$ invariant mass spectrum [1]. As it was mentioned in Ref. [1] that these three $P_c$ states are very good candidates of molecular states, but the explanations of them as tightly bound pentaquarks cannot be ruled out. Soon after these $P_c$ states were discovered, the attempts to understand their internal structure were performed in a large amount of theoretical models [3–19]. However, more experimental and theoretical research is still needed to justify which one of these explanations is the real origin of these exotic states. Moreover, as shown in the PDG [20], although many exotic hadrons were listed, most of them were observed in the electron-positron or proton-proton collision. Hence, production of these exotic hadrons in more different mechanisms is very important to understand their nature.

Up to now, the hidden-charm pentaquarks were only observed in the $\Lambda_b$ decay at LHCb. Production of the pentaquarks in other ways is very helpful to obtain the definite evidence for the $P_c$ states as genuine states. Different methods were proposed to detect the newly observed states $P_c$ including photoproduction [21, 22] and $\pi^- p$ scattering [23]. Recently, the measurement of the process $\gamma p \rightarrow J/\Psi p$ was reported by the GlueX Collaboration [24]. Although the signal of the $P_c$ state was not detected due to insufficient experimental precision, the branching ratio of the $P_c$ state decaying to $J/\Psi p$ given by the experiment is consistent with our previous theoretical prediction [22].

The hidden-charm pentaquark is a quark system composed of three light quarks and a charm quark pair. It is natural to extend it to the bottom sector to predict hidden-bottom pentaquark which contains a bottom quark pair. Such extension is more reasonable in the molecular state picture which is widely adopted to explain the $P_c$ states [3–5, 7, 11, 12, 16, 25, 26]. Due to the existence of the heavy quark symmetry, the $\Sigma_b^{(*)}\bar{B}$ interaction is analogous to the $\Sigma_c^{(*)}\bar{D}$ interaction, which will lead to the existence of hidden-bottom pentaquark. Such similarity has been found in the comparison between the states $Z_b(10610)$ and $Z_b(10650)$ in bottom sector and the states $Z_c(3900)$ and $Z_c(4020)$ in charm sector. Based on such justification, many predictions about the hidden-bottom pentaquarks have been given within different theoretical models [27–35].

It is interesting to study the possibility to observe such hidden-bottom pentaquark in future experiment. The $P_c$ states were observed in the $\Lambda_b$ decay at LHCb. However, it is impossible to find an analogous decay for hidden-bottom pentaquark. If we recall that such pentaquarks are composed of three light quarks and a heavy quark pair, it is reasonable to
produce them by exciting the nucleon by photon or pion meson to drag out a hidden-bottom quark pair. Hence, in the current work, we will study the possibility of production of hidden bottom pentaquark $P_b$ states via $\gamma p$ and $\pi^- p$ scatterings.

Because such states are still not observed in experiment, we need the theoretical decay width to make the prediction. One notices that in a recent paper [35], the authors predicted a series of hidden-bottom pentaquark state based on the observed three $P_c$ states using the hadron molecular state model, and the decay widths of these states into the $\Upsilon p$ channel were also provided in their work. The mass and decay properties of the $P_b(11080)$ state predicted in Ref. [35] are also consistent with the prediction about a $N^\ast(11100)$ state in Ref. [27].

In the current work, the production of the hidden-bottom pentaquark $P_b$ states via reactions $\gamma p \to \Upsilon p$ and $\pi^- p \to \Upsilon n$ will be investigated within the framework of an effective Lagrangian approach and the vector-meson-dominance (VMD) model. The basic Feynman diagrams of the reaction $\gamma p \to \Upsilon p$ are illustrated in Fig. 1 where the pentaquarks $P_b$ are produced through $s$- and $u$-channels. Fig. 1(c) depicts the Pomeron exchange process, which is considered as the mainly background contribution. Considering the off-shell effect of the intermediate $P_b$ states, the $u$-channel contribution in $\gamma p$ or $\pi^- p$ scattering will be neglected in our calculation.

![Feynman diagrams for the reaction $\gamma p \to \Upsilon p$.](image)

In Fig. 2(a)-(b), the Feynman diagrams are presented for describing the $P_b$ production in the reaction $\pi^- p \to \Upsilon n$ at tree level. Moreover, the Reggeized $t$ channel will be responsible for describing the main background, as depicted in Fig. 2(c).

![Feynman diagrams for the reaction $\pi^- p \to \Upsilon n$.](image)

This paper is organized as follows. After the introduction, we present the formalism including Lagrangians and amplitudes for the reactions $\gamma p \to \Upsilon p$ and $\pi^- p \to \Upsilon n$ in Section II. The numerical results of the cross section follow in Section III. Finally, the paper ends with a brief summary.

II. FORMALISM

A. Lagrangians for the $P_b$ production

Since the $P_b$ states have not been found experimentally, in this work, the spin-parity quantum number of the $P_b$ state is taken as $J^P = 1^-/2^-$ as suggested in Refs. [27, 35]. For describing the $P_b$ production in photon and pion induced processes, the following Lagrangians are needed [22, 23, 36–38],

$$\mathcal{L}_{\gamma NP_b} = \frac{e h}{2m_N} \tilde{N} \sigma_{\mu \nu} \partial^\nu A^\mu P_b + \text{H.c.},$$  \hspace{1cm} (1)

$$\mathcal{L}_{\pi NP_b} = g_{\pi NP_b} \tilde{N} \gamma_5 \gamma_\mu P_b \gamma^\mu + \text{H.c.},$$  \hspace{1cm} (2)

$$\mathcal{L}_{\pi NN} = \frac{g_{\pi NN}}{4\pi m_P} \frac{g_{\pi NN}}{m_N^2 - m_N^2} |\vec{p}_N| |\vec{p}_N|,$$  \hspace{1cm} (3)

where $N, A, P_b, \pi$, and $\Upsilon$ are the nucleon, photon, $P_b$ state, pion, and $\Upsilon$ meson fields, respectively. $\tau$ is the Pauli matrix.

The values of coupling constants $g_{\pi \Upsilon N}$ and $g_{\pi NN}$ can be derived from the corresponding decay width

$$\Gamma_{P_b \to \Upsilon N} = \frac{|\vec{p}^\text{c.m.}_\Upsilon|^2}{16\pi m_{P_b}^2} |\mathcal{M}_{P_b \to \Upsilon N}|^2,$$  \hspace{1cm} (4)

$$\Gamma_{P_b \to \pi NN} = \frac{3g_{\pi NN}^2 (m_N + E_N)}{4\pi m_{P_b}^2} |\vec{p}^\text{c.m.}_\pi|^2,$$  \hspace{1cm} (5)

with

$$|\vec{p}^\text{c.m.}_\Upsilon|^2 = \frac{\lambda (m_{P_b}^2, m_{\Upsilon}^2, m_N^2)}{2m_{P_b}},$$  \hspace{1cm} (6)

$$|\vec{p}^\text{c.m.}_\pi|^2 = \frac{\lambda (m_{P_b}^2, m_{\Upsilon}^2, m_N^2)}{2m_{P_b}},$$  \hspace{1cm} (7)

$$E_N = \sqrt{|\vec{p}^\text{c.m.}_N|^2 + m_N^2},$$  \hspace{1cm} (8)

where $\lambda$ is the Källen function with $\lambda(x, y, z) = \sqrt{(x-y-2z)^2 - 4yz}$, and $|\mathcal{M}_{P_b \to \Upsilon N}|$ is the decay amplitudes. The $m_{P_b}$, $m_{\Upsilon}$, $m_N$, and $m_\pi$ are the masses of $P_b$, $\Upsilon$, nucleon, and pion meson, respectively.

For the electromagnetic (EM) coupling $e h$ related to the $\gamma NN$ vertex, its value can be obtained from the strong coupling constant $g_{\pi \Upsilon N}$ within the VMD mechanism [39–41]. The EM coupling constants $e h$ are related to the coupling constants $g_{\pi \Upsilon N}$ as

$$e h = g_{\pi \Upsilon N} \frac{2m_N}{f_\Upsilon (m_{P_b}^2 - m_N^2)m\Upsilon} \times \sqrt{m_N^2 (m_N^2 + 4m_N m_{P_b} + m_{P_b}^2) + (m_{P_b}^2 - m_N^2)^2},$$  \hspace{1cm} (9)
The Lagrangian depicting the coupling of the meson \( \Upsilon \) with a photon reads as

\[
\mathcal{L}_{\Upsilon \gamma} = -\frac{e m_{\pi}}{f_{\pi}} V_\mu A^\mu,
\]

where \( f_\pi \) is the \( \Upsilon \) decay constant, respectively. Thus one gets the expression for the \( \Upsilon \rightarrow e^+e^- \) decay,

\[
\Gamma_{\Upsilon \rightarrow e^+e^-} = \frac{8e}{f_\pi} |\vec{p}_e^{\text{c.m.}}|^3 \frac{m_e^2}{3m_\Upsilon^2},
\]

where \( \vec{p}_e^{\text{c.m.}} \) denotes the three-momentum of an electron in the rest frame of the \( \Upsilon \) meson. The \( \alpha = e^2/4\pi = 1/137 \) is the electromagnetic fine structure constant. With the partial decay width of \( \Upsilon \rightarrow e^+e^- \) \([20]\), \( \Gamma_{\Upsilon \rightarrow e^+e^-} \approx 1.34 \text{ keV} \), one gets \( e/f_\pi \approx 0.0076 \).

Since the partial decay widths \( \Gamma_{\rho_b \rightarrow \gamma N N} \) of the \( P_b \) states have been predicted in Ref. [35], the EM couplings related to the \( \gamma NN \) vertices is also determined. In our previous work [23], the result shows that the experimental data point near the threshold is consistent with the contribution from the \( P_1(4312) \) state taking branching ratio \( \text{Br} \[P_1 \rightarrow \pi N] \approx 0.05\% \). In this paper, a small branching ratio of \( \text{Br} \[P_b \rightarrow \pi N] \approx 0.05\% \) will also be used to calculate the coupling constant \( g_{\rho_b \pi N} \). We will discuss this branching ratio in detail in the next section in conjunction with the values of cross section of \( P_b \) in the reaction \( \pi^- p \rightarrow \Upsilon n \). The obtained coupling constants are listed in Table I by assuming that the \( \pi N \) channel accounts for 0.05\% of total widths of \( P_b \) states.

| states            | \( \Gamma_{P_b \rightarrow \gamma NN} \) (MeV) | \( g_{\rho_b \pi N} \) | \( e/h \) | \( g_{\rho_b \pi NN} \)  |
|-------------------|------------------------------------------|----------------|------|----------------|
| \( P_1(10180) \) | 0.38                                     | 0.074           | 0.00016 | 0.00049        |
| \( P_1(11125) \) | 3.27                                     | 0.213           | 0.00045 | 0.00145        |

### B. Pomeron exchange and Reggeized \( t \) channel

For the \( P_b \) state photoproduction process, the Pomeron exchange is considered as the main background contribution. In this work, the dipole Pomeron model \([42, 43]\) is employed to calculate the cross section from the background contribution. The basic diagram is depicted in Fig. 1(c), where the \( Q^2 \) is the virtuality of the photon, and \( s \) and \( t \) are the Mandelstam variables. Generally, since the Regge model plays an important role in the high-energy process, a double Regge pole is also included in the dipole Pomeron model. Using the dipole Pomeron model and related parameters \([43]\), the cross section of the reaction \( \gamma p \rightarrow \Upsilon p \) can be calculated. Moreover, in Ref. [43], the result suggests that it may be more appropriate when the value of the coefficient \( N_{\Upsilon} \) is between \( N_{\rho} \) and \( N_{J/\psi} \).

In our calculation, by taking \( N_{\Upsilon} = \sqrt{2}/3 \), the obtained cross section in dipole Pomeron model is well consistent with the experimental data \([44-47]\), as shown in Fig. 3.

![FIG. 3. Cross section for the reaction \( \gamma p \rightarrow \Upsilon p \) with the dipole Pomeron model by taking the coefficient \( N_{\Upsilon} = \sqrt{2}/3 \). The green dashed, blue solid lines are for the Pomeron contributions with the \( Q^2 = 0 \) and 20 GeV, respectively. The experimental data are from Refs. [44-47].](#)

For the \( P_b \) production via the reaction \( \pi^- p \rightarrow \Upsilon n \), the background is mainly come from the \( t \) channel, \( \rho \) and \( \omega \) exchanges, as depicted in Fig. 2(c). Since the branching ratios of \( \Upsilon \) decaying into \( \rho \pi \) and \( \omega \pi \) channels are of the order of magnitude of \( 10^{-6} \), the contributions from the \( \rho \) and \( \omega \) exchanges should be very small and can be ignored. Therefore, in our calculation, only the contribution from the \( \pi \) exchange is considered. The effective Lagrangians for the vertices of \( \Upsilon \rho \pi \) and \( \pi NN \) read as

\[
\mathcal{L}_{\Upsilon \rho \pi} = -ig_{\Upsilon \rho \pi}(\rho^- \partial_\rho \pi^+ - \partial_\rho \pi^- \pi^+)\Upsilon^\mu,
\]

\[
\mathcal{L}_{\pi NN} = -ig_{\pi NN}\vec{N} \vec{\gamma}_5 \vec{\tau} \cdot \vec{\pi} N,
\]

where \( N, \pi \) and \( \Upsilon \) are the nucleon, the pion, and the \( \Upsilon \) meson fields, respectively. Here, the \( g_{\Upsilon \rho \pi}^2/4\pi = 12.96 \) is adopted \([48]\).

Moreover, the coupling constant \( g_{\Upsilon \rho \pi} \) can be determined from the decay width

\[
\Gamma_{\Upsilon \rightarrow \rho \pi} = \frac{g_{\Upsilon \rho \pi}^2}{6m_{\pi}^2} |\vec{q}|^3,
\]

where \( |\vec{q}| = \sqrt{m_{\Upsilon}^2 - 4m_{\pi}^2}/2 \). Taking the value of decay width \( \Gamma_{\Upsilon \rightarrow \rho \pi} \) as 0.027 keV \([20]\), one obtain the coupling constant \( g_{\Upsilon \rho \pi} \approx 0.0007 \).

Since the energy corresponding to the \( \pi^- p \rightarrow \Upsilon n \) reaction is above 10 GeV, the Reggeized treatment will be applied to the \( t \) channel process. Usually, one just need to replace the
Feynman propagator with the Regge propagator as

$$\frac{1}{t - m^2_{\pi}} \to \left( \frac{s}{s_{\text{scale}}} \right)^{\alpha_\pi^{\text{(t)}}} \frac{\pi \alpha_\pi^{\text{(t)}}}{\Gamma[1 + \alpha_\pi(t)]} \sin[\pi \alpha_\pi(t)] \tag{14}$$

where the scale factor $s_{\text{scale}}$ is fixed at 1 GeV. In addition, the Regge trajectories of $\alpha_\pi(t)$ is written as [23],

$$\alpha_\pi(t) = 0.7(t - m^2_{\pi}). \tag{15}$$

It can be seen that no free parameters have been added after the introduction of the Regge model.

C. Amplitude

Based on the Lagrangians above, the scattering amplitude for the reactions $\gamma p \to \Upsilon p$ and $\pi^- p \to \Upsilon n$ can be constructed as

$$-iM_{\gamma p \to \Upsilon p} = e^\mu_1(k_2)\bar{u}(p_2)\mathcal{A}_{\mu}(p_1)e^\nu_1(k_1), \tag{16}$$

$$-iM_{\pi^- p \to \Upsilon n} = e^\mu_1(k_2)\bar{u}(p_2)\mathcal{B}_\mu(p_1), \tag{17}$$

where $u$ is the Dirac spinor of nucleon, and $e^\mu_1$ and $e^\nu_1$ are the polarization vector of $\Upsilon$ meson and photon, respectively.

The reduced amplitude $\mathcal{A}_\mu$ for the $s$ channel $P_b$ photoproduction reads

$$\mathcal{A}_\mu = \frac{eh}{2m_N}g_{\gamma N\Upsilon}F_s(q^2)\gamma_\mu\gamma_5\gamma_\nu\frac{(q + m_{P_b})}{s - m^2_{P_b} + im_P\Gamma_{P_b}}\gamma_\rho k_1, \tag{18}$$

and the reduced amplitude $\mathcal{B}_\mu$ for the $s$ channel with $P_b$ and $t$ channel with $\pi$ exchanges are written as

$$\mathcal{B}_\mu^i = \sqrt{5}g_{\gamma s_{\pi}s_{\pi}N}g_{\pi N s_{\pi}N}F_s(q^2)\gamma_\mu\gamma_5\gamma_\nu\frac{(q + m_{P_b})}{s - m^2_{P_b} + im_P\Gamma_{P_b}}\gamma_\rho k_1, \tag{19}$$

$$\mathcal{B}_\mu^t = \sqrt{5}g_{\gamma s_{\pi}s_{\pi}N}g_{\pi N s_{\pi}N}F_s(q^2)\gamma_\mu\gamma_5\gamma_\nu\frac{(q + m_{P_b})}{s - m^2_{P_b} + im_P\Gamma_{P_b}}\gamma_\rho k_\nu, \tag{20}$$

where $s = (k_1 + p_1)^2$ and $t = (k_1 - k_2)^2$ are the Mandelstam variables.

For the $s$ channel with intermediate $P_b$ state, one adopts a general form factor to describe the size of hadrons as [22, 23, 38],

$$F_s(q^2) = \frac{\Lambda^4}{\Lambda^4 + (q^2 - m^2_{P_b})^2}, \tag{21}$$

where $q_\nu$ and $m_{P_b}$ are the four-momentum and mass of the exchanged $P_b$ state, respectively. For the heavier hadron production, the typical value of cutoff $\Lambda = 0.5$ GeV will be taken as used in Refs. [22, 23, 38].

For the $t$-channel meson exchanges [23, 38], the general form factor $F_t(q^2)$ consisting of $F_{\pi\pi} = (\Lambda^2 - m^2_\pi)/(\Lambda^2 - q_\pi^2)$ and $F_{s\pi} = (\Lambda^2 - m^2_\pi)/(\Lambda^2 - q^2_{\pi\pi})$ are taken into account. Here, $q_\pi$ and $m_\pi$ are 4-momentum and mass of the $\pi$ meson, respectively. The value of the cutoff $\Lambda_\pi$ is taken as 2.0 GeV, which is the same as that in Ref. [23].

III. NUMERICAL RESULTS

With the preparation in the previous section, the cross section of the reaction $\gamma p \to \Upsilon p$ can be calculated. The differential cross section in the center of mass (c.m.) frame is written as

$$\frac{d\sigma}{d\cos \theta} = \frac{1}{32\pi s^2} \left[ \frac{1}{k^2_{1\text{c.m.}}} \left( \sum_{J} |\mathcal{M}|^2 \right) \right], \tag{22}$$

with $J = 4$ for the $\gamma p \to \Upsilon p$ reaction and $J = 2$ for the reaction $\pi^- p \to \Upsilon n$. Here, $s = (k_1 + p_1)^2$, and $\theta$ denotes the angle of the outgoing $\Upsilon$ meson relative to $\pi/\gamma$ beam direction in the c.m. frame. $k^2_{1\text{c.m.}}$ and $k^2_{2\text{c.m.}}$ are the three-momenta of the initial photon beam and final $\Upsilon$ meson, respectively.

A. $P_b$ production in reaction $\gamma p \to \Upsilon p$

In Fig. 4 we present the total cross section for the reaction $\gamma p \to \Upsilon p$ from threshold to 800 GeV of the center of mass energy. It is found that the contribution from the state shows a very sharp peak near the threshold, and the experimental point at high energy is well consistent with the cross section of the Pomeron diffractive process.

FIG. 4. Total cross section for the reaction $\gamma p \to \Upsilon p$. The green dashed, red dotted, blue dot-dashed, and violet solid lines are for the Pomeron, the $P_0(11080)$, the $P_0(11125)$, and total contributions, respectively. The experimental data are taken from Refs. [44–47].

In order to more clearly distinguish the contributions from the $P_0$ states, in Fig. 5 we give the same results as Fig. 4 but with a reduced energy range. As can be seen from Fig. 5, when the energy bin width is chosen as 0.01 GeV, two distinct peaks can be seen around 11 GeV, which are derived from the contributions of states $P_0(11080)$ and $P_0(11125)$, respectively. Since the mass of $P_0(11080)$ and $P_0(11125)$ are very close...
to each other, if we increase the bin width to 0.1 GeV, it is difficult to distinguish the two peaks, and a larger bump may be formed.

Moreover, the result suggests that the theoretical average of the cross section from the $P_b(11080)$ is of a order of magnitude of 1 nb if the bin width is 0.01 GeV. If the bin width increases to 0.1 GeV, the theoretical average value of the cross section of $P_b(11080)$ becomes about 0.3 nb. In Refs. [49, 50], the cross section of process $\gamma p \rightarrow \Upsilon p$ at 11 GeV was estimated to be about 12 pb – 50 pb. Even if the background cross section can reach this magnitude, as long as the bin width is less than or equal to 0.1 GeV, the possibility of distinguishing the $P_b$ state from the background is great.

### B. $P_b$ production in reaction $\pi^- p \rightarrow \Upsilon n$

In Fig. 6, the total cross section of the interaction $\pi^- p \rightarrow \Upsilon n$ is presented. It can be seen that near the threshold, the background cross section from the $t$ channel is very small, even if we take a value of cutoff as 2.0 GeV. The main reason for this situation is that the branching ratio of $\Upsilon$ decaying into $\pi\pi$ channel is very small, and the branching ratios of $\Upsilon$ decaying to $\rho\pi$ and $\omega\pi$ channels are smaller and can be ignored. Near the threshold, we can see very sharp peaks, which come from the contribution of the $P_b$ states.

To more clearly distinguish the cross section at the threshold, we present more explicit near the threshold in Fig. 7, which is the same as the Fig. 6 except that the energy range is reduced. One find that the total cross section exhibits two peaks around the 11 GeV when the bin width is taken to be 0.01 GeV. According to our calculation, when the bin width is 0.1 GeV, branching ratio of $\text{Br}(P_b \rightarrow \pi N) \approx 0.05\%$, the theoretical average value of the cross section from the $P_b(11080)$ state reaches at least 0.1 nb in a bin interval, which is several orders of magnitude higher than the background cross section.

Even if we reduce the branching ratio of $P_b$ decaying into $\pi N$ channel two orders of magnitude, the theoretical average of the cross section from the $P_b(11080)$ can reach the order of 0.001 nb in the width of 0.1 GeV bin, which means that the signal is still clearly distinguished from the background.

### IV. SUMMARY AND DISCUSSION

The pentaquark is an important kind of the exotic hadron. The observation of the $P_c$ states at LHCb inspires us to predict...
the possible hidden-bottom pentaquark. Since it is impossible to decay from a heavy hadrons as $P_b$ states, it is interesting to study production of hidden-bottom pentaquarks through exciton nucleon by photon or pion. In this work, based on the effective field theory and the VMD mechanism, the production of the hidden-bottom pentaquark $P_b$ states via $\gamma p$ or $\pi^-p$ scattering is investigated.

For the background of the $P_b$ state photoproduction, it is thought that it mainly comes from the contribution of the Pomeron exchange. Using the dipole pomeron model, the experimental data of the interaction $\gamma p \rightarrow \Upsilon n$ can be well described. Near the threshold, when the bin width is 0.01 GeV, very sharp peaks from the $P_b$ states can be clearly distinguished in the cross sections. According to our calculation, even if the bin width is increased to 0.1 GeV, the cross section of the $P_b$ signal is still higher than the background, which means that the the vicinity of the center of mass energy of 11 GeV is the best energy window for searching for these $P_b$ states via the photoproduction process. It is suggested that experiments to search for the $P_b$ states through the $\gamma p$ scattering can be carried out, which is well within the capabilities of the COMPASS facility at CERN [51].

For the production of the $P_b$ states in the reaction $\pi^- p \rightarrow \Upsilon n$, the background is considered to be mainly derived from the contribution of the Reggeized $t$ channel with $\pi$ exchange. Since the branching ratio of the $P_b$ decaying into $\pi \pi$ channel is very small, the background cross section of the process $\pi^- p \rightarrow \Upsilon n$ is several orders of magnitude lower than the cross section from the $P_b$ signal. According to our calculation, even if the branching ratio of the the $P_b$ into $\pi\pi$ channel is reduced to 0.0005%, the average value of the cross section from $P_b(11080)$ contribution reaches an order of 0.001 nb/100 MeV, which is still much higher than the background contribution. Compared to the photoproduction process, the requirement of experimental precision for searching for these $P_b$ states by the $\pi^- p$ scattering may be lower, which indicates that searching for the process $P_b$ via $\pi^- p \rightarrow \Upsilon n$ may be a very important and promising way. Hence, an experimental study of the hidden bottom pentaquark $P_b$ states via the pion-induced reaction is strongly suggested, which can be carried on the J-PARC and COMPASS facilities [51, 52].

In addition, since both the electromagnetic $\gamma p$ and $ep$ reactions are very similar, we also look forward to finding and studying these hidden bottom pentaquark $P_b$ states through the $ep$ scattering process. Electromagnetic probes covering the above energy are expected to be produced on future EicC (Electron Ion Collider in China) facility in China. The accumulated luminosity with one-year run is about 50fb$^{-1}$ [53, 54]. Because such facility is usually impossible to run near a fixed energy point for a year, we make an estimation of one-day run, that is, an accumulated luminosity about 0.1 fb$^{-1}$. The number of events reaches $1 \times 10^7$/0.01 GeV near the mass of the $P_b$ state if we adopt a cross section 1 nb/0.01 GeV predicted in our calculation. Even after considering the efficiency and the uncertainty of theoretical prediction, which may depress the number of event by two or three orders of magnitude, the observation of hidden-bottom pentaquarks is still very promising at EicC.

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