

Final-state rescattering mechanism of the $\Delta(1232)^{++}$ production in $\Lambda_c^+ \rightarrow K^- \pi^+ p$ decay

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We investigate the production of the $\Delta(1232)^{++}$ resonance in the charmed baryon weak decay $\Lambda_c^+ \rightarrow K^- \pi^+ p$, focusing on the $\pi^+ p$ final-state rescattering mechanism. The direct W^+ exchange diagram is expected to be suppressed, hence we adopt the W^+ internal emission process $\Lambda_c^+ \rightarrow p \bar{K}^{*0}(892)$ followed by the subsequent decay $\bar{K}^{*0} \rightarrow K^- \pi^+$ as the dominant source of the final state particles. The $\Delta(1232)^{++}$ resonance is then generated via $\pi^+ p$ rescattering within a triangle loop mechanism. Our calculations incorporate both the tree-level $\bar{K}^{*0}(892)$ and the dynamically generated $\bar{K}_0^*(700)$ state arising from the S -wave $K\pi$ final state interaction. We find that our theoretical results can reproduce the bump and peak structures in the $K^- \pi^+$ invariant mass distributions for the $\bar{K}_0^*(700)$ and $\bar{K}^{*0}(892)$, respectively. Meanwhile, the peak for the $\Delta(1232)^{++}$ in the $\pi^+ p$ invariant mass distributions is also well described. The $\Delta(1232)^{++}$ signal naturally emerges from rescattering effects, and adopting the pole parameters of $\Delta(1232)$ resonance yields an improved description of the experimental data. In addition, we obtain a branching fraction ratio $\mathcal{B}[\Lambda_c^+ \rightarrow \Delta(1232)^{++} K^-] / \mathcal{B}[\Lambda_c^+ \rightarrow p \bar{K}^{*0}(892)] \approx 0.5$, which is lower than the experimentally measured value. This discrepancy suggests that interference effects are likely significant in this decay process. Future high-precision measurements will further verify the proposed rescattering mechanism.

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I. INTRODUCTION

The multi-body nonleptonic decays of charmed baryons are useful processes for studying the nature of hadronic resonances [1–3]. The Λ_c^+ weak decays have been used to investigate the $\Lambda(1405)$ and $\Lambda(1670)$ resonances [4–8], the $\Sigma(1385)$ and a possible $\Sigma(1380)$ state [9–11], the $N(1535)$ resonance [12–15], the $f_0(980)$ and $a_0(980)$ resonances [16,17], and the $\Xi^*(1690)$ resonance [18]. These studies clearly demonstrate that the Λ_c^+ weak decays provide a valuable source for investigating low-lying hadronic states.

Great progress has been made in experimental measurements of Λ_c^+ hadronic weak decays [19–29]. The $\Lambda_c^+ \rightarrow \Lambda \pi^+ \eta$ decay was measured by the BESIII Collaboration [30,31], where the $a_0(980)^+$ production was observed for the first time, and evidence for the potential pentaquark state $\Sigma(1380)^+$ was found in the $\pi^+ \Lambda$ system. In Ref. [32], evidence for the production of $N^*(1535)$ resonance with $N(1535)^+ \rightarrow p \eta$ was found in the $\Lambda_c^+ \rightarrow K_S^0 p \eta$ decay by the Belle Collaboration. These rich experimental results have promoted extensive theoretical interest in studying low-lying hadronic states and related topics.

Among the three-body Λ_c^+ hadronic weak decays, $\Lambda_c^+ \rightarrow K^- \pi^+ p$ has attracted sustained experimental and theoretical interest [33–36] due to its large branching fraction [19,20,37,38], and its complex intermediate resonant structures [33,35,39]. A recent amplitude analysis of $\Lambda_c^+ \rightarrow p K^- \pi^+$ decay performed by the LHCb Collaboration reveals a pronounced diagonal band associated with the $\Delta(1232)^{++}$ resonance in the Dalitz plot constructed from $m_{K^- \pi^+}^2$ versus $m_{p K^-}^2$. A clear peak of the $\Delta(1232)^{++}$

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resonance is also found in the $\pi^+ p$ invariant mass spectrum around $M_{\pi^+ p}^2 \sim 1.5 \text{ GeV}^2$ [36]. Moreover, the $\bar{K}^{*0}(892)$ resonance yields a substantial contribution, manifesting as a clear peak in the $K^-\pi^+$ invariant mass distribution. Contributions from excited hyperon Λ states are also present in the $K^- p$ subsystem.

The $\Delta(1232)$ resonance, carrying quantum numbers $I(J^P) = 3/2(3/2^+)$, was initially observed by Anderson, Fermi, and their colleagues via πp scattering measurements [40]. As the lightest excited baryon resonance, it has Breit-Wigner mass of $1232 \pm 2 \text{ MeV}$ and a decay width of $117 \pm 3 \text{ MeV}$, while its pole mass and pole width are $1210 \pm 1 \text{ MeV}$ and $100 \pm 2 \text{ MeV}$, respectively. The dominant decay channel of $\Delta(1232)$ proceeds into the πN final states. Within the constituent quark model and under flavor $SU(3)$ symmetry, it belongs to the baryon decuplet. The $\Delta(1232)$ is widely adopted as an intermediate resonance produced via the s -channel process [41,42]. Experimentally, the LEPs2/BGOegg Collaboration observed a clear $\Delta(1232)$ peak in the $\pi^0 p$ invariant mass spectrum, which further confirms its important role in relevant reactions [43]. Moreover, the $\Delta(1232)$ resonance has also been interpreted as a composite πN molecular state. Theoretical studies indicate that its wave function contains a substantial πN component [44–46].

In the $\Lambda_c^+ \rightarrow K^-\pi^+ p$ decay, if the $\Delta(1232)^{++}$ were produced as an intermediate state in the s channel, at the quark level the process would proceed through a color-suppressed W^+ exchange diagram ($c + d \rightarrow s + u$). Such contributions are generally small [1,47–49] and therefore cannot account for the large signal observed experimentally. Thus, we adopt the W^+ internal emission mechanism, assuming that the ud diquark ($I = 0$) in the Λ_c^+ acts as a spectator. This leads to the decay chain $\Lambda_c^+ \rightarrow p \bar{K}^{*0}(892) \rightarrow K^-\pi^+ p$, from which the $\Delta(1232)^{++}$ is subsequently produced through the final-state rescattering of $\pi^+ p$. Within this framework, we study the productions of $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$ resonances in the $\Lambda_c^+ \rightarrow K^-\pi^+ p$ decay using the effective Lagrangian approach. To better describe the event concentration in the low-energy region of the $K^-\pi^+$ invariant mass distribution, we also include the contribution of the $\bar{K}_0^{*0}(700)$ resonance with $I(J^P) = 1/2(0^+)$ (denoted as κ), which is dynamically generated from the S -wave pseudoscalar meson-pseudoscalar meson interaction [50,51]. We present the $K^-\pi^+$ and $p\pi^+$ invariant mass distributions, as well as the Dalitz plot of $M_{K^-\pi^+}^2$ and $M_{p\pi^+}^2$, for the $\Lambda_c^+ \rightarrow K^-\pi^+ p$ decay. It is shown that the bump and peak structures in the $K^-\pi^+$ invariant mass distributions for the κ and $\bar{K}^{*0}(892)$ resonances can be well reproduced. Meanwhile, the peak for the $\Delta(1232)^{++}$ in the $\pi^+ p$ invariant mass distributions can be also well described.

¹In what follows, we will use κ to denote $K_0^{*0}(700)$ since the scalar meson $K_0^{*0}(700)$ is also known as κ .

The paper is organized as follows. In Sec. II, we present the theoretical formalism for the production of κ , $\bar{K}^{*0}(892)$, and $\Delta(1232)^{++}$ in the $\Lambda_c^+ \rightarrow K^-\pi^+ p$ decay. In Sec. III the numerical results and discussions are presented, and finally a brief summary is given in Sec. IV.

II. FORMALISM

In this section, we present the theoretical decay formalism for the process $\Lambda_c^+ \rightarrow K^-\pi^+ p$. In Sec. II A, we describe the S -wave $K\pi$ final-state interaction, from which the scalar meson κ is dynamically generated. In Sec. II B, we introduce the tree-level $\bar{K}^{*0}(892)$ contribution and the $\Delta(1232)^{++}$ contribution generated through $\pi^+ p$ rescattering. Finally, in Sec. II C, the formulas used to calculate the $K^-\pi^+$ and $p\pi^+$ invariant mass distributions for the $\Lambda_c^+ \rightarrow K^-\pi^+ p$ decay are given.

A. Dynamically generated scalar meson κ from the S -wave $K\pi$ final-state interaction

Following previous works [12,16,17], we consider the W^+ internal emission mechanism for the $\Lambda_c^+ \rightarrow K^-\pi^+ p$ process, which is illustrated in Fig. 1. In this mechanism, the c quark in Λ_c^+ decays into an s quark and a W^+ boson, followed by the W^+ boson decays into an $u\bar{d}$ pair. Under the spectator assumption, the ud diquark in the Λ_c^+ combines with the u quark from the weak decay to form the final proton. The remaining $s\bar{d}$ pair hadronizes into two pseudoscalar mesons by combining with a $\bar{q}q$ pair with the quantum numbers of the vacuum. This hadronization process can be written as

$$\begin{aligned} \Lambda_c^+ &\Rightarrow \frac{1}{\sqrt{2}} c(ud - du) \Rightarrow \frac{1}{\sqrt{2}} sW^+(ud - du) \\ &\Rightarrow \frac{1}{\sqrt{2}} s\bar{d}u(ud - du) \Rightarrow s(\bar{u}u + \bar{d}d + \bar{s}s)\bar{d}p \\ &= \left(\sum_i M_{3i} M_{i2} \right) p. \end{aligned} \quad (1)$$

Here, M denotes the $SU(3)$ pseudoscalar meson matrix

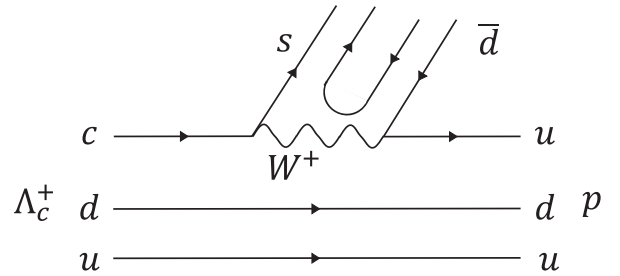


FIG. 1. Quark level diagram for the charm quark in the Λ_c^+ decaying into a strange quark and a $\bar{d}u$ pair. The proton is formed by the up quark and the spectator ud diquark in the Λ_c^+ .

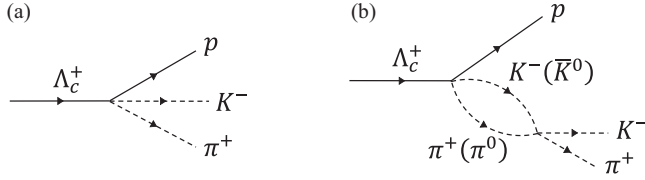


FIG. 2. Diagrams for the $\Lambda_c^+ \rightarrow K^- \pi^+ p$ decay: (a) direct $K^- \pi^+ p$ vertex at tree level; (b) final-state interaction of the $K^- \pi^+$.

$$M = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} & K^0 \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} \end{pmatrix}, \quad (2)$$

where we have ignored the η' term as done in Refs. [48,52], because of its relatively large mass. Substituting the pseudoscalar meson matrix into Eq. (1) yields

$$\Lambda_c^+ \Rightarrow \left(K^- \pi^+ - \frac{1}{\sqrt{2}} \bar{K}^0 \pi^0 \right) p. \quad (3)$$

The first term in Eq. (3) indicates that the $K^- \pi^+ p$ final state can be produced directly as depicted in Fig. 2(a). In addition, the $K^- \pi^+$ pair can also be dynamically generated from the S -wave interaction involving $K^- \pi^+$ and $\bar{K}^0 \pi^0$, as presented in Fig. 2(b).

Then, the decay amplitude associated with the above hadronization process can be written as

$$\mathcal{M}_\kappa = V_p \left[1 + G_{K^- \pi^+}(M_{K^- \pi^+}) T_{K^- \pi^+ \rightarrow K^- \pi^+}(M_{K^- \pi^+}) - \frac{1}{\sqrt{2}} G_{\bar{K}^0 \pi^0}(M_{K^- \pi^+}) T_{\bar{K}^0 \pi^0 \rightarrow K^- \pi^+}(M_{K^- \pi^+}) \right], \quad (4)$$

where V_p is an overall normalization constant including the weak decay contribution. We assume V_p to be constant and determine it from the experimental data on the κ production. $M_{K^- \pi^+}$ denotes the invariant mass of the $K^- \pi^+$ system. Besides, G and T are the meson-meson loop function and the two-body scattering amplitudes, respectively, both of which depend on the invariant variable $s = M_{K^- \pi^+}^2$. The loop function G is regularized with a three-momentum cutoff,

$$16\pi^2 s G(s) = \sigma \left(\arctan \frac{s + m_1^2 - m_2^2}{\sigma \lambda_1} + \arctan \frac{s - m_1^2 + m_2^2}{\sigma \lambda_2} \right) - \left[(s + m_1^2 - m_2^2) \times \ln \frac{(1 + \lambda_1) q_{\max}}{m_1} + (s - m_1^2 + m_2^2) \ln \frac{(1 + \lambda_2) q_{\max}}{m_2} \right], \quad (5)$$

where σ , λ_1 , and λ_2 are defined as

$$\sigma = [-(s - (m_1 + m_2)^2)(s - (m_1 - m_2)^2)]^{1/2}, \quad (6)$$

$$\lambda_{1,2} = \sqrt{1 + \frac{m_{1,2}^2}{q_{\max}^2}}. \quad (7)$$

Here, m_1 and m_2 are the masses of the two mesons in the loop. In this work, we take the cutoff parameter $q_{\max} = 600$ MeV, as used in Ref. [53].

The two-body scattering amplitude T is obtained by solving the Bethe-Salpeter equation within the chiral unitary approach [54–56],

$$T = [1 - VG]^{-1}V. \quad (8)$$

As done in Refs. [53,57], the symmetric matrix elements of V can be written as

$$V_{11} = -\frac{1}{6f^2} \left(\frac{3}{2}s - \frac{3}{2s}(m_\pi^2 - m_K^2)^2 \right), \quad (9)$$

$$V_{12} = \frac{1}{2\sqrt{2}f^2} \left(\frac{3}{2}s - m_\pi^2 - m_K^2 - \frac{(m_\pi^2 - m_K^2)^2}{2s} \right), \quad (10)$$

$$V_{22} = -\frac{1}{4f^2} \left(-\frac{s}{2} + m_\pi^2 + m_K^2 - \frac{(m_\pi^2 - m_K^2)^2}{2s} \right), \quad (11)$$

$$V_{13} = \frac{1}{2\sqrt{6}f^2} \left(\frac{3}{2}s - \frac{7}{6}m_\pi^2 - \frac{1}{2}m_\eta^2 - \frac{1}{3}m_K^2 + \frac{3}{2s}(m_\pi^2 - m_K^2)(m_\eta^2 - m_K^2) \right), \quad (12)$$

$$V_{23} = -\frac{1}{4\sqrt{3}f^2} \left(\frac{3}{2}s - \frac{7}{6}m_\pi^2 - \frac{1}{2}m_\eta^2 - \frac{1}{3}m_K^2 + \frac{3}{2s}(m_\pi^2 - m_K^2)(m_\eta^2 - m_K^2) \right), \quad (13)$$

$$V_{33} = -\frac{1}{4f^2} \left(-\frac{3}{2}s - \frac{2}{3}m_\pi^2 + m_\eta^2 + 3m_K^2 - \frac{3}{2s}(m_\eta^2 - m_K^2)^2 \right). \quad (14)$$

Here, the subscripts 1, 2, and 3 correspond to the channels $\pi^+ K^-$, $\pi^0 \bar{K}^0$, and $\eta \bar{K}^0$, respectively. The pion decay constant is taken as $f = 93$ MeV. The isospin averaged meson masses are $m_\pi = 138.04$ MeV, $m_K = 494.99$ MeV, and $m_\eta = 547.86$ MeV [38]. Within this coupled-channel S -wave interaction, the κ resonance is dynamically generated and mainly contributes to the low-energy region of the $K^- \pi^+$ invariant mass spectrum.

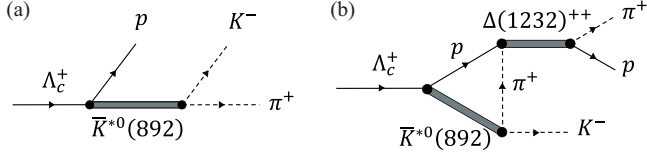


FIG. 3. Mechanism for the production of $\bar{K}^{*0}(892)$ via tree diagram (a) and the production of $\Delta(1232)^{++}$ via triangle loop diagram (b) for the process $\Lambda_c^+(p_0) \rightarrow \pi^+(p_1)p(p_2)K^-(p_3)$. The intermediate particles in the triangle loop diagram are $\bar{K}^{*0}(q_1, m_1)$, $p(q_2, m_2)$, and $\pi^+(q_3, m_3)$, where q_i and m_i denote their four-momenta and masses, respectively.

B. Tree-level $\bar{K}^{*0}(892)$ production and the $\Delta(1232)^{++}$ production via rescattering mechanism

In Fig. 3, we show the tree level diagram and triangle diagram for the production of $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$, respectively, in the $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay. In Fig. 3(a), the $\bar{K}^{*0}(892)$ resonance is formed from the $s\bar{d}$ pair, and the u quark originated from the weak decay and the ud diquark in the Λ_c^+ form the proton corresponding to the mechanism of Fig. 1. After this hadronization, the $\bar{K}^{*0}$ then decays into $K^-\pi^+$ in the final state. For the $\Delta(1232)^{++}$ production, we consider the triangle diagram shown in Fig. 3(b), in which the $\Delta(1232)^{++}$ is produced through the rescattering of $\pi^+p \rightarrow \Delta(1232)^{++}$.

To evaluate the decay amplitude corresponding to the Feynman diagrams shown in Fig. 3, we adopt the following relevant effective Lagrangians as used in previous studies [35,42,58,59]

$$\mathcal{L}_{\Lambda_c^+ p \bar{K}^{*0}} = -g_{\Lambda_c^+ p \bar{K}^{*0}} \bar{\Lambda}_c^+ (g_{\Lambda_c^+ p \bar{K}^{*0}}^{\text{PV}} \gamma_5 + g_{\Lambda_c^+ p \bar{K}^{*0}}^{\text{PC}}) \times \gamma^\mu \bar{K}_\mu^{*0} p + \text{H.c.}, \quad (15)$$

$$\mathcal{L}_{\bar{K}^{*0} \pi^+ K^-} = i g_{\bar{K}^{*0} \pi^+ K^-} \bar{K}_\mu^{*0} (\pi^+ \partial^\mu K^- - K^- \partial^\mu \pi^+) + \text{H.c.}, \quad (16)$$

$$\mathcal{L}_{\Delta^{++} \pi^+ p} = -\frac{i g_{\Delta^{++} \pi^+ p}}{m_{\pi^+}} \bar{\Delta}_\mu^{++} (\partial^\mu \pi^+) p + \text{H.c.} \quad (17)$$

Here, $g_{\Lambda_c^+ p \bar{K}^{*0}}^{\text{PV}}$ and $g_{\Lambda_c^+ p \bar{K}^{*0}}^{\text{PC}}$ denote the parity-violating (PV) and parity-conserving (PC) weak couplings, which are associated with different partial wave contributions. For

simplicity, we set $g_{\Lambda_c^+ p \bar{K}^{*0}}^{\text{PV}} = g_{\Lambda_c^+ p \bar{K}^{*0}}^{\text{PC}} = 1$ and absorb this common coupling into an effective coupling constant $g_{\Lambda_c^+ p \bar{K}^{*0}}$ [9,12,34]. The coupling constants $g_{\Lambda_c^+ p \bar{K}^{*0}}$, $g_{\Delta^{++} \pi^+ p}$, and $g_{\bar{K}^{*0} \pi^+ K^-}$ are determined from the corresponding partial decay widths,

$$\Gamma_{\Lambda_c^+ \rightarrow p \bar{K}^{*0}} = \frac{g_{\Lambda_c^+ p \bar{K}^{*0}}^2 |\vec{p}_p|}{2\pi M_{\Lambda_c^+} m_{\bar{K}^{*0}}^2} [E_p (M_{\Lambda_c^+}^2 + m_p^2 + 2m_{\bar{K}^{*0}}^2) - 2M_{\Lambda_c^+} m_p^2], \quad (18)$$

$$\Gamma_{\Delta^{++} \rightarrow \pi^+ p} = \frac{g_{\Delta^{++} \pi^+ p}^2 (E_p + m_p) |\vec{p}_p|^3}{12\pi m_\Delta m_\pi^2}, \quad (19)$$

$$\Gamma_{\bar{K}^{*0} \rightarrow \pi^+ K^-} = \frac{2g_{\bar{K}^{*0} \pi^+ K^-}^2 |\vec{p}_K|^3}{3\pi m_{\bar{K}^{*0}}^2}, \quad (20)$$

where $|\vec{p}_p|$ and $|\vec{p}_K|$ are the three momenta in the rest frame of the corresponding decaying particle, and $E_p = \sqrt{|\vec{p}_p|^2 + m_p^2}$. These partial decay widths can be easily obtained from the total decay width and the corresponding branching fractions ($\mathcal{B}$). Using the masses and partial widths shown in Table I, the corresponding coupling constants are obtained, which are also listed in Table I. To determine whether $\Delta(1232)^{++}$ is produced through the interaction of π^+p or exists as a simple Breit-Wigner resonance, we employed two models. In Model I, we set the mass and width of $\Delta(1232)$ to its pole mass and width as quoted in the Particle Data Group [38], while in Model II, they are set to the Breit-Wigner mass and width [38].

With the effective Lagrangians given above, one can easily obtain the invariant decay amplitudes corresponding to Figs. 3(a) and 3(b) as

$$\mathcal{M}_a = -g_{\Lambda_c^+ p \bar{K}^{*0}} g_{\bar{K}^{*0} \pi^+ K^-} \bar{u}(p_2) (\gamma_5 + 1) \gamma_\mu \times G_1^{\mu\nu} (p_1 + p_3, m_{\bar{K}^{*0}}, \Gamma_{\bar{K}^{*0}}) (p_3 - p_1)_\nu u(p_0), \quad (21)$$

TABLE I. Spin parities, masses, total widths, branching ratios, and extracted coupling constants for the Λ_c^+ , $\bar{K}^{*0}(892)$, and $\Delta(1232)^{++}$. The couplings are obtained from Eqs. (18)–(20). For the $\Delta(1232)^{++}$, Model I uses the pole parameters, while Model II uses the Breit-Wigner parameters [38].

State	Spin-parity(J^P)	Mass (MeV)	Width (MeV)	$\mathcal{B}$	Coupling
Λ_c^+	$1/2^+$	2286.46	3.25×10^{-9}	$(1.41 \pm 0.07)\%$	$g_{\Lambda_c^+ p \bar{K}^{*0}} = 3.96 \times 10^{-7}$
$\bar{K}^{*0}(892)$	1^-	895.55	47.30	$(99.754 \pm 0.021)\%$	$g_{\bar{K}^{*0} \pi^+ K^-} = 4.40$
$\Delta(1232)^{++}$ (Model I)	$3/2^+$	1210	100	99.4%	$g_{\Delta^{++} \pi^+ p} = 2.27$
$\Delta(1232)^{++}$ (Model II)	$3/2^+$	1232	117	99.4%	$g_{\Delta^{++} \pi^+ p} = 2.14$

$$\begin{aligned}
\mathcal{M}_b &= \frac{g_{\Delta^{++}\pi^+p}^2 g_{\Lambda_c^+ p \bar{K}^{*0}} g_{\bar{K}^{*0} \pi^+ K^-}}{m_3^2} \bar{u}(p_2) p_{1\mu} \\
&\times G_{3/2}^{\mu\nu}(p_1 + p_2, m_\Delta, \Gamma_\Delta) \int \frac{d^4 q_1}{(2\pi)^4} q_{3\nu} G_{1/2}(q_2, m_2, \epsilon) \\
&\times (\gamma_5 + 1) \gamma_\alpha G_1^{\alpha\beta}(q_1, m_1, \Gamma_{\bar{K}^{*0}}) (p_3 - q_3)_\beta \\
&\times G_0(q_3, m_3, \epsilon) u(p_0) F(q_3^2, m_3^2), \quad (22)
\end{aligned}$$

where ϵ is an infinitesimal quantity. The m_Δ and Γ_Δ stand for the mass and width of the $\Delta(1232)^{++}$ resonance, respectively. The propagators appearing in the above equations are written in the unified form

$$G_J(q, m, \Gamma) = \frac{i\mathcal{P}_J(q, m)}{q^2 - m^2 + im\Gamma}, \quad (23)$$

where $J = 0, 1, 1/2, 3/2$ denotes the spin of the intermediate particle. The numerator structures are

$$\begin{aligned}
\mathcal{P}_0 &= 1, & \mathcal{P}_1^\mu &= -g^{\mu\nu} + \frac{q^\mu q^\nu}{m^2}, \\
\mathcal{P}_{1/2} &= \not{q} + m, & \mathcal{P}_{3/2}^{\mu\nu} &= (\not{q} + m) P_{3/2}^{\mu\nu}(q),
\end{aligned}$$

with

$$P_{3/2}^{\mu\nu}(q) = -g^{\mu\nu} + \frac{1}{3} \gamma^\mu \gamma^\nu + \frac{\not{q}}{3q^2} (\gamma^\mu q^\nu - q^\mu \gamma^\nu) + \frac{2q^\mu q^\nu}{3q^2}.$$

For the triangle loop diagram, $\mathcal{M}_b$, a form factor $F(q^2, m^2)$ is introduced to account for off-shell effects and the internal structure of the exchanged particle [60–66]. It also suppresses the ultraviolet behavior of the loop integral. In this work, we adopt the monopole form factor, as used in Refs. [67,68],

$$F(q^2, m^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}, \quad (24)$$

where q and m are the four-momentum and mass of the exchanged π^+ meson, respectively. The Λ is a cutoff parameter, whose value will be determined by comparing the theoretical calculations with the experimental measurements.

C. Invariant mass distributions for the $\Lambda_c^+ \rightarrow K^- \pi^+ p$ decay

Combining the S -wave $K\pi$ final-state interaction, the tree-level $\bar{K}^{*0}$ production, and the triangle loop diagram, the decay amplitude of the process $\Lambda_c^+ \rightarrow K^- \pi^+ p$ is constructed from $\mathcal{M}_\kappa$, $\mathcal{M}_a$, and $\mathcal{M}_b$. The first component is $\mathcal{M}_\kappa$, which describes the hadronization followed by the S -wave $K\pi$ interaction within the chiral unitary approach. The other two components, $\mathcal{M}_a$ and $\mathcal{M}_b$, are evaluated using the effective Lagrangian approach for the tree-level

and triangle loop diagrams, respectively. In these decay amplitudes, the $\bar{K}^{*0}(892)$ acts as the intermediate particle, while the $\Delta(1232)^{++}$ is produced through $\pi^+ p$ final-state rescattering. Therefore, the total amplitude squared can be written as²

$$|\bar{\mathcal{M}}|^2 = C \left(|\mathcal{M}_\kappa|^2 + \frac{1}{2} |\mathcal{M}_a + \mathcal{M}_b|^2 \right), \quad (25)$$

where the factor $1/2$ accounts for the average over the spins of the initial Λ_c^+ . The factor C is an overall normalization factor which is introduced to scale the theoretical invariant mass distributions to match the experimental measurements of the selected candidates. Subsequently, the double differential width of the $\Lambda_c^+ \rightarrow K^- \pi^+ p$ decay is given by [38]

$$\frac{d^2\Gamma}{dM_{K^- \pi^+}^2 dM_{\pi^+ p}^2} = \frac{1}{(2\pi)^3} \frac{1}{32M_{\Lambda_c^+}^3} |\bar{\mathcal{M}}|^2. \quad (26)$$

Then the invariant mass squared distributions $d\Gamma/dM_{K^- \pi^+}^2$ and $d\Gamma/dM_{\pi^+ p}^2$ can be obtained by integrating Eq. (26) over the other invariant-mass variable within the physical phase space. For a given value of $M_{\pi^+ p}^2$, the kinematically allowed range of $M_{K^- \pi^+}^2$ is

$$\begin{aligned}
(M_{\pi^+ K^-}^2)_{\min} &= (E_{\pi^+} + E_{K^-})^2 \\
&\quad - (\sqrt{E_{\pi^+}^2 - m_{\pi^+}^2} + \sqrt{E_{K^-}^2 - m_{K^-}^2})^2, \\
(M_{\pi^+ K^-}^2)_{\max} &= (E_{\pi^+} + E_{K^-})^2 \\
&\quad - (\sqrt{E_{\pi^+}^2 - m_{\pi^+}^2} - \sqrt{E_{K^-}^2 - m_{K^-}^2})^2,
\end{aligned}$$

where E_{π^+} and E_{K^-} are the energies of particles π^+ and K^- in the $\pi^+ p$ rest frame, respectively, and are given by

$$\begin{aligned}
E_{\pi^+} &= \frac{M_{\pi^+ p}^2 + M_{\pi^+}^2 - M_p^2}{2M_{\pi^+ p}}, \\
E_{K^-} &= \frac{M_{\Lambda_c^+}^2 - M_{\pi^+ p}^2 - M_{K^-}^2}{2M_{\pi^+ p}}.
\end{aligned}$$

III. NUMERICAL RESULTS

With the above formalism, we then calculate the invariant mass distributions of the process $\Lambda_c^+ \rightarrow K^- \pi^+ p$. There are three free parameters to be obtained by fitting to the experimental data on the bump structure of κ , the $\bar{K}^{*0}$ peak, and the Δ^{++} peak: (1). V_p for the weak and hadronization strength related to the S -wave $K\pi$ interaction of Fig. 2 to

²The interference between $\mathcal{M}_\kappa$ and $\mathcal{M}_a + \mathcal{M}_b$ is neglected. Since the $K^- \pi^+$ interaction corresponds to an S -wave component in one amplitude and P -wave component in the other, their interference is expected to be sufficiently small and can be safely omitted.

produce the κ state; (2). the global factor C to match the theoretical calculations with the experimental measurements; (3). the cutoff parameter Λ for the exchanged π^+ meson in the triangle loop diagram as shown in Fig. 3(b).

With the parameters listed in Table I, along with the obtained global normalization factor of $C = 4 \times 10^{13}$ and $V_p = 4 \times 10^{-5}$ to match the selected candidates in experiment, we evaluate the $K^-\pi^+$ and $p\pi^+$ invariant mass distributions for the $\Lambda_c^+ \rightarrow K^-\pi^+p$ decay in both Model I and Model II. In Fig. 4, we present the theoretical results compared with the experimental data [36]. The figure shows the individual contributions from the tree-level $\bar{K}^{*0}(892)$ diagram, the triangle loop diagram associated with the $\Delta(1232)^{++}$, the dynamically generated κ state, and the total contributions for both Model I and Model II. In our calculations, the cutoff parameter is determined as $\Lambda = 1.3$ GeV for Model I and $\Lambda = 1.5$ GeV for Model II, respectively.

As illustrated in Fig. 4(a), the prominent $\bar{K}^{*0}(892)$ peak in the $K^-\pi^+$ invariant mass spectrum is successfully reproduced by the tree-level amplitude. Additionally, the $\bar{K}^{*0}(892)$ loop amplitude provides an almost constant background across the $K^-\pi^+$ spectrum. However, these contributions combined still fail to account for the event yield in the low-energy region. As indicated by the orange dotted curve in Fig. 4(a), this missing yield is successfully filled by the κ resonance, which is dynamically generated from the S -wave $K\pi$ final-state interaction.

Turning to the $p\pi^+$ invariant mass distribution in Fig. 4(b), the π^+p final-state rescattering mechanism, driven by the aforementioned tree-level $\bar{K}^{*0}(892)$ diagram, naturally generates the $\Delta(1232)^{++}$ peak.³ A detailed comparison reveals a visible difference between the two parametrizations: Model I, which utilizes the pole mass and width (red solid curve), excellently reproduces the experimental data. In contrast, Model II, based on the Breit-Wigner parameters (purple solid curve), yields a broader distribution with its peak deviating from the experimental position toward a higher invariant mass. The observation that the pole parametrization provides a better description of the LHCb measurements than the conventional Breit-Wigner form indicates that the $\Delta(1232)$ in the $\Lambda_c^+ \rightarrow K^-\pi^+p$ decay is more likely to dynamically originate from the π^+p rescattering process.

Furthermore, to visualize the phase space distribution generated by our amplitude model, we present the theoretical Dalitz plot for the $\Lambda_c^+ \rightarrow K^-\pi^+p$ decay in Fig. 5. In line with the production mechanisms discussed in this work, the plot displays distinct resonance bands

³Theoretical results for the $p\pi^+$ invariant mass distributions are scaled by an extra factor of 25/18 to match the different bin widths of the experimental data: 0.018 GeV² for the $K^-\pi^+$ invariant mass distributions and 0.025 GeV² for the $p\pi^+$ invariant mass distributions.

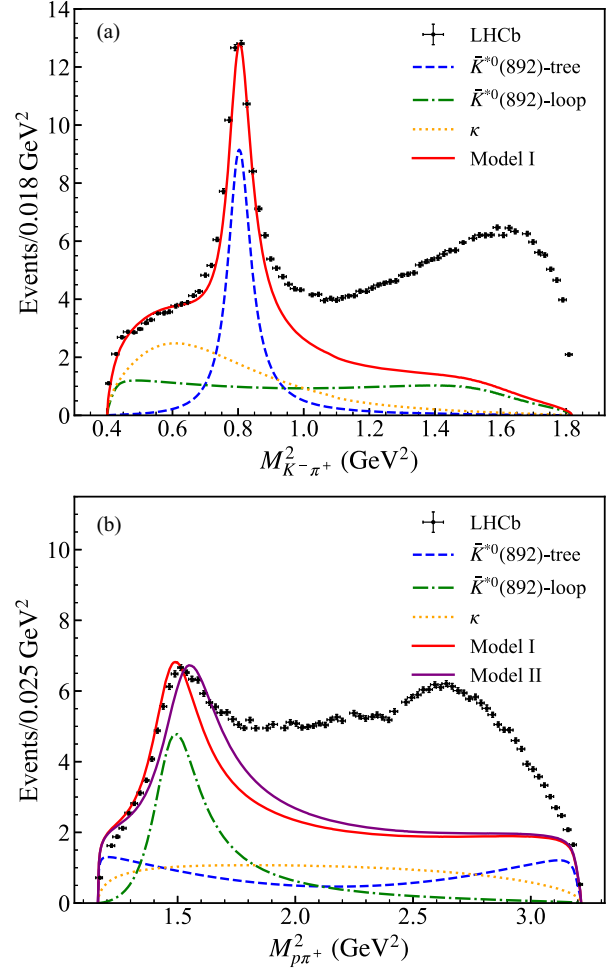


FIG. 4. Invariant mass distributions for the $\Lambda_c^+ \rightarrow K^-\pi^+p$ decay: (a) $M_{K^-\pi^+}^2$ distribution; (b) $M_{p\pi^+}^2$ distribution. Curves labeled as “ $\bar{K}^{*0}(892)$ -tree,” “ $\bar{K}^{*0}(892)$ -loop,” and “ κ ” show the results obtained with $\mathcal{M}_a$, $\mathcal{M}_b$, and $\mathcal{M}_c$, respectively. Curves labeled as “Model I” and “Model II” represent the total contributions of Eq. (25) obtained with the pole and Breit-Wigner masses and widths of the $\Delta(1232)^{++}$, respectively. The experimental data are taken from Ref. [36] measured by the LHCb Collaboration.

corresponding exclusively to the $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$ states. It can be seen from Fig. 5 that the kinematic production region for low-lying excited Λ states [for example, $\Lambda(1520)$ and $\Lambda(1670)$] in the K^-p system is well separated from those of $\bar{K}^{*0}$ and Δ^{++} . Their contributions can therefore be safely ignored. Even if they do have some contributions, they will contribute as a background and leave the line shapes of the $K^-\pi^+$ and $p\pi^+$ invariant mass distributions unchanged.

Finally, to quantify the yield of the $\Delta(1232)^{++}$ resonance, we evaluate the production ratio of Δ^{++} resonance in the $\Lambda_c^+ \rightarrow K^-\Delta(1232)^{++}$ process with the intermediate triangle loop diagrams as shown in Fig. 3(b). The corresponding partial decay width is given by

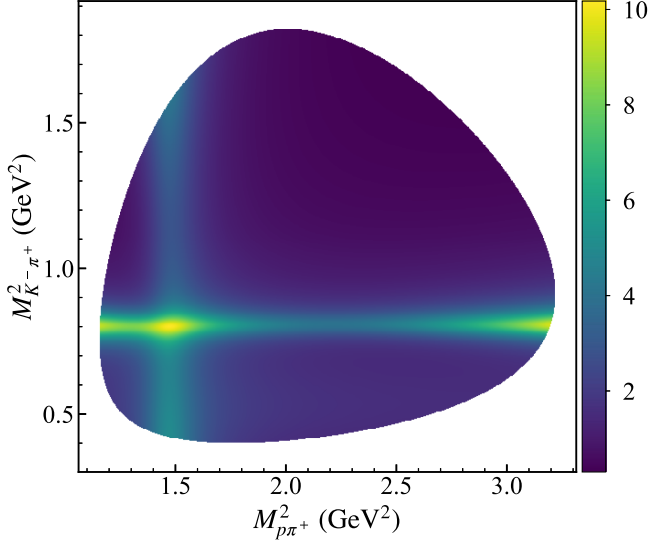


FIG. 5. Dalitz plot for the invariant masses of $K^-\pi^+$ and $p\pi^+$ for the $\Lambda_c^+ \rightarrow K^-\pi^+p$ decay.

$$\Gamma_{\Lambda_c^+ \rightarrow \Delta(1232)^{++}K^-} = \frac{|\vec{p}_4|}{16\pi M_{\Lambda_c^+}^2} |\mathcal{M}'|^2, \quad (27)$$

where $|\vec{p}_4|$ is the momentum of $\Delta(1232)^{++}$ (or K^-) in the Λ_c^+ rest frame, and the decay amplitude $\mathcal{M}'$ is expressed as

$$\begin{aligned} \mathcal{M}' = & \frac{g_{\Delta^{++}\pi^+p} g_{\Lambda_c^+ p \bar{K}^{*0}} g_{\bar{K}^{*0} \pi^+ K}}{m_3} \bar{u}^\mu(p_4) \int \frac{d^4 q_1}{(2\pi)^4} q_{3\mu} \\ & \times G_{1/2}(q_2, m_2, \epsilon) (\gamma_5 + 1) \gamma_\alpha G_1^{\alpha\beta}(q_1, m_1, \Gamma_{\bar{K}^{*0}}) \\ & \times (p_3 - q_3)_\beta G_0(q_3, m_3, \epsilon) u(p_0) F(q_3^2, m_3^2). \end{aligned} \quad (28)$$

Using Eqs. (18) and (27), we can deduce the branching fraction ratio of the $\Lambda_c^+ \rightarrow \Delta(1232)^{++}K^-$ decay to the $\Lambda_c^+ \rightarrow p\bar{K}^{*0}(892)$ decay. For Model I, we obtain

$$R^{\text{I}} = \frac{\mathcal{B}[\Lambda_c^+ \rightarrow \Delta(1232)^{++}K^-]}{\mathcal{B}[\Lambda_c^+ \rightarrow p\bar{K}^{*0}(892)]} = 0.52, \quad (29)$$

and similarly, for Model II,

$$R^{\text{II}} = \frac{\mathcal{B}[\Lambda_c^+ \rightarrow \Delta(1232)^{++}K^-]}{\mathcal{B}[\Lambda_c^+ \rightarrow p\bar{K}^{*0}(892)]} = 0.54. \quad (30)$$

For comparison, the corresponding experimental ratio is determined to be [38]

$$R^{\text{exp}} = \frac{\mathcal{B}[\Lambda_c^+ \rightarrow \Delta(1232)^{++}K^-]}{\mathcal{B}[\Lambda_c^+ \rightarrow p\bar{K}^{*0}(892)]} = 1.27 \pm 0.09. \quad (31)$$

As seen from the above results, the theoretical predictions ($R \approx 0.5$) are noticeably smaller than the experimental central value ($R^{\text{exp}} \approx 1.27$). This discrepancy can be largely attributed to the complex interference patterns inherent in the three-body decay dynamics. In the experimental amplitude analysis, the isolated contribution of the $\Delta(1232)^{++}$ actually exceeds the overall experimental data points in the peak region, indicating significant destructive interference with other amplitudes to reproduce the measured spectrum [36]. In contrast, our dynamical model favors a constructive interference pattern. Consequently, our model requires a relatively smaller isolated $\Delta(1232)^{++}$ contribution to properly describe the same data, naturally resulting in a smaller theoretical ratio. This is consistent with that the predictions that the $\Lambda_c^+ \rightarrow \Delta^{++}K^-$ decay would proceed through a color-suppressed W^+ exchange diagram ($c + d \rightarrow s + u$), which generally gives small contributions [1,47–49].

IV. SUMMARY

In this work, we investigated the $\Lambda_c^+ \rightarrow K^-\pi^+p$ decay to elucidate the production mechanisms of the involved resonances, with a particular focus on the production of $\Delta(1232)^{++}$ state in the π^+p system. Within our framework, the tree-level $\Lambda_c^+ \rightarrow p\bar{K}^{*0}(892) \rightarrow K^-\pi^+p$ decay was evaluated using the effective Lagrangian approach, which properly accounted for the dominant $\bar{K}^{*0}(892)$ peak. Driven by this initial process, the $\Delta(1232)^{++}$ state was dynamically generated via the subsequent rescattering of π^+p through a triangle loop mechanism. Furthermore, to address the low-energy region of the $K^-\pi^+$ spectrum, we employed the chiral unitary approach to incorporate the κ contribution, which is dynamically generated by the S -wave $K^-\pi^+$ final-state interaction.

Our numerical results were compared with the LHCb measurements for the process $\Lambda_c^+ \rightarrow K^-\pi^+p$. The tree-level process reproduced the dominant $\bar{K}^{*0}(892)$ peak in the $K^-\pi^+$ invariant mass spectrum, and the $\Delta(1232)^{++}$ peak was also captured by the π^+p rescattering. To further investigate the nature of the $\Delta(1232)^{++}$, we tested two parametrizations: the pole parameters (Model I) and the conventional Breit-Wigner form (Model II). The calculation showed that Model I yielded a better description of the experimental data. This implies that the π^+p final-state rescattering plays a substantial role in the $\Delta(1232)^{++}$ production in this specific decay.

Finally, we calculated the branching fraction ratio $\mathcal{B}[\Lambda_c^+ \rightarrow \Delta(1232)^{++}K^-]/\mathcal{B}[\Lambda_c^+ \rightarrow p\bar{K}^{*0}(892)]$. The theoretical prediction (~ 0.5) is smaller than the experimental measurement (1.27 ± 0.09). A possible explanation for this difference is that the destructive interference in the experimental amplitude analysis leads to a larger isolated $\Delta(1232)^{++}$ fraction, whereas our dynamical model features constructive interference. Future experimental

measurements at BESIII, Belle II, and LHCb are expected to clarify these interference effects and test our model calculations.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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