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

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第九届强子谱和强子结构研讨会

河南师范大学

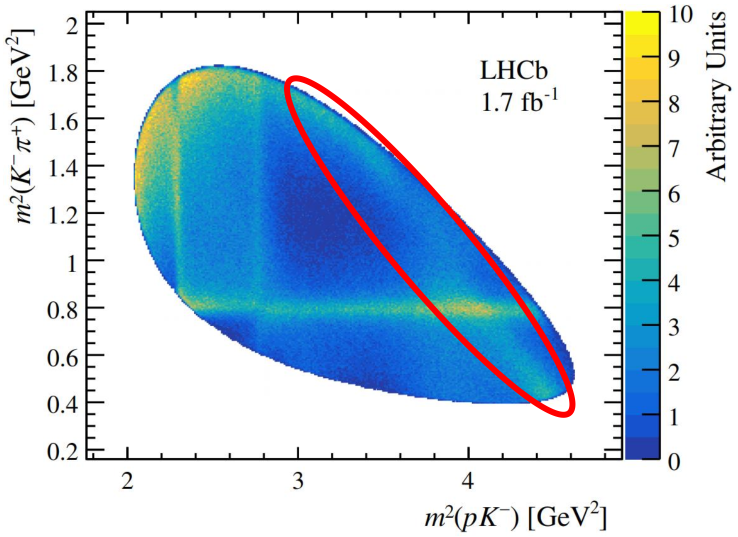
2026.08.20

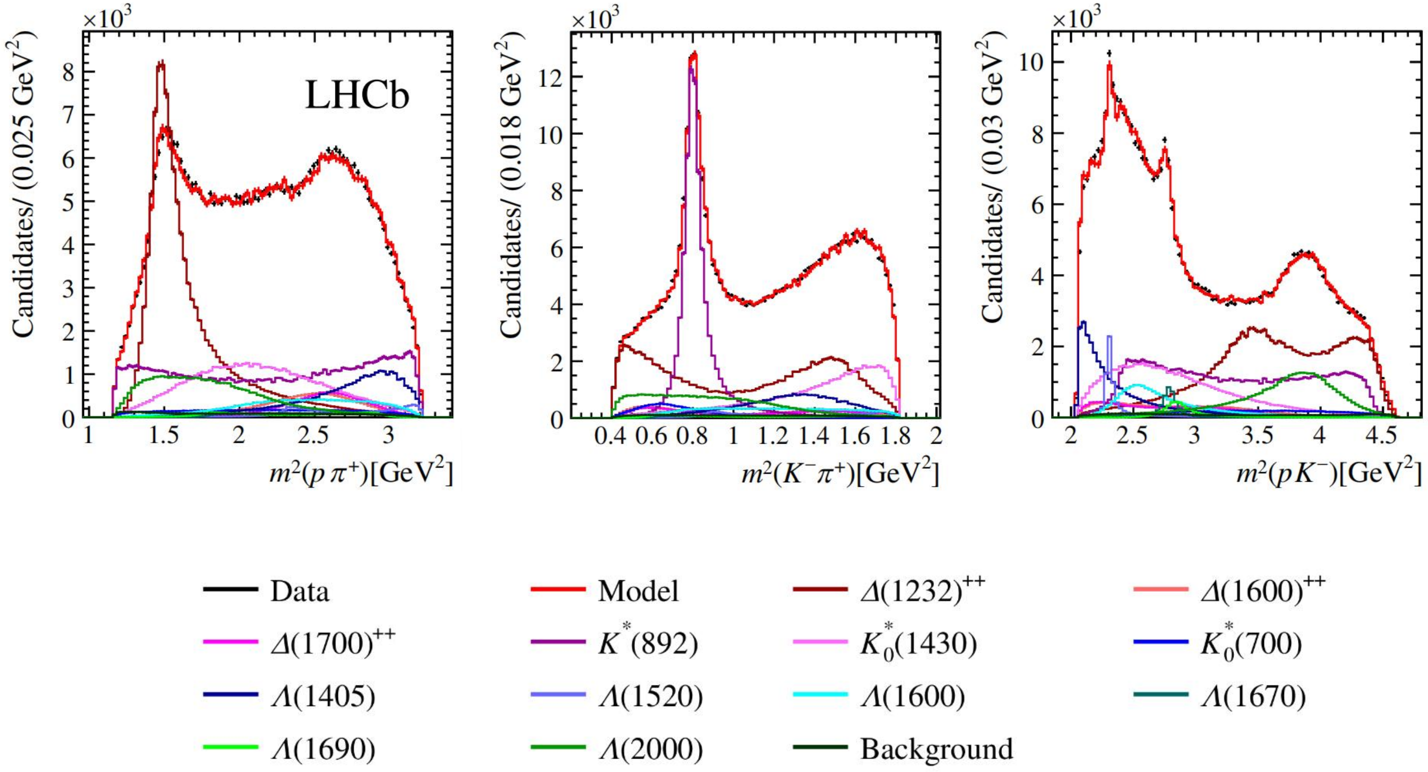
Content

- Introduction & Motivation
- Theoretical Framework
- Results
- Summary

Content

$\Lambda_c^+ \to K^-\pi^+p$





- Vertical bands: $\Lambda(1520), \Lambda(1670), \Lambda(1405)\cdots$ $\Lambda \to pK^-$
- Horizontal bands: $K^*(892)\cdots$ $K^* \to K^-\pi^+$
- Diagonal bands: $\Delta(1232)^{++}\cdots$ $\Delta^{++} \to p\pi^+$

LHCb, Phys.Rev.D 108 (2023), 012023

How is $\Delta(1232)^{++}$ produced?

Introduction & Motivation

Δ(1232) $I(J^P) = 3/2(3/2^+)$

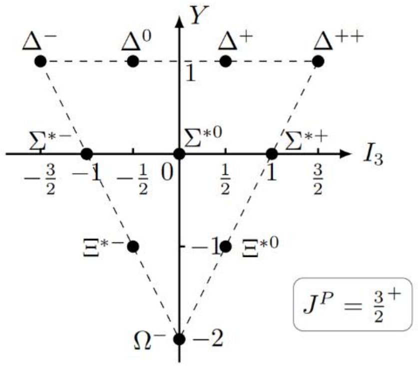
- $\mathcal{B}[(\Delta(1232) \to N\pi)] = 99.4\%$

$$M_{BW} = 1232 \pm 2\text{MeV} \quad \Gamma_{BW} = 117 \pm 3\text{MeV}$$
$$M_{pole} = 1210 \pm 1\text{MeV} \quad \Gamma_{pole} = 100 \pm 2\text{MeV}$$

➢ **Theoretical explanations:**

- Baryon decuplet

Intermediate resonance in s-channel process



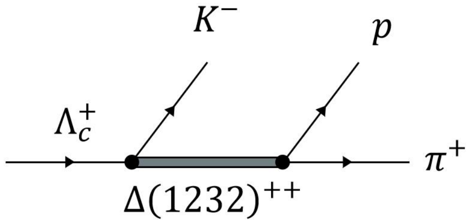
- Composite πN molecular state

Wave function contains a substantial πN component

Eur.Phys.J.A 50 (2014), 57

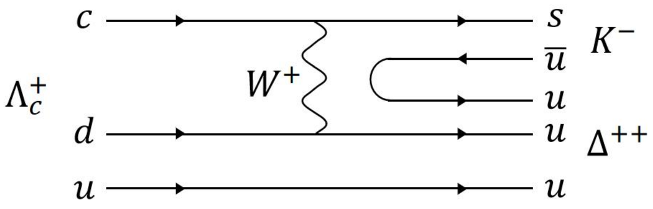
JPS Conf.Proc. 10 (2016), 022005

Phys.Rev.C 93 (2016), 035204



- s-channel

Phys.Rev.C 85 (2012), 054003
Chin.Phys.C 49 (2025), 063102

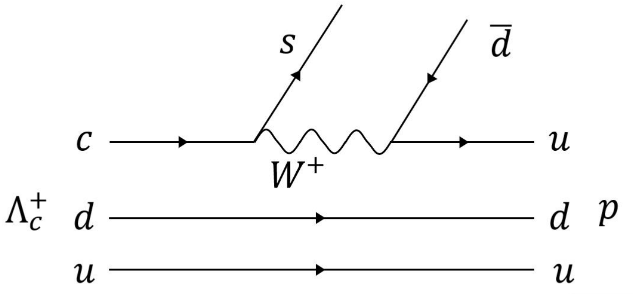


- Color-suppressed W^+ exchange diagram

Small contribution!

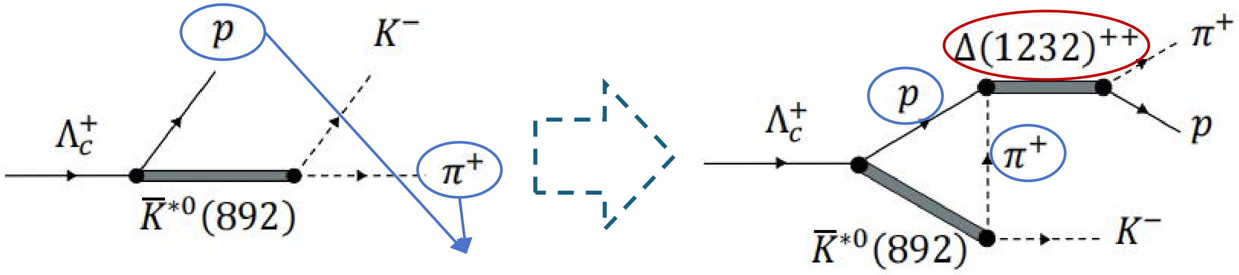
Phys.Rev.D 81 (2010), 074031
Phys.Rev.C 95 (2017), 035212

In our work,



- W^+ internal emission mechanism

Assume ud diquark as a spectator.



Rescattering

$\Delta(1232)^{++}$ production via rescattering mechanism

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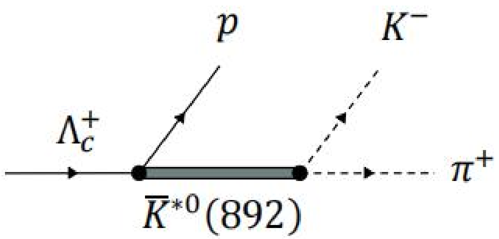
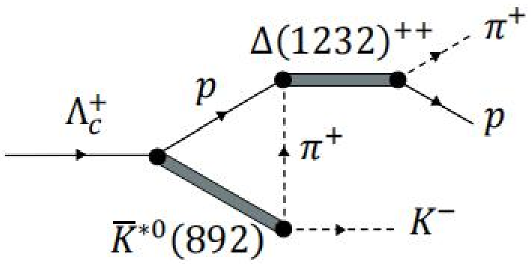
Production of $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$



Tree-level $\bar{K}^{*0}(892)$ production



$\Delta(1232)^{++}$ production via rescattering mechanism

- $\Delta(1232)^{++}$
  - produced through the interaction of $\pi^+ p$
  - exists as a simple Breit-Wigner resonance
  - **Model I**: pole parameters of $\Delta(1232)$
  - **Model II**: Breit-Wigner parameters of $\Delta(1232)$

Effective Lagrangians:

$$\mathcal{L}_{\Lambda_c^+ p\bar{K}^{*0}} = -g_{\Lambda_c^+ p\bar{K}^{*0}} \bar{\Lambda}_c^+ (g^{\rm PV}_{\Lambda_c^+ p\bar{K}^{*0}} \gamma_5 + g^{\rm PC}_{\Lambda_c^+ p\bar{K}^{*0}}) \gamma^\mu \bar{K}^{*0}_\mu p + \text{h.c.}$$

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

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

$$g^{\rm PV}_{\Lambda_c^+ p\bar{K}^{*0}} = g^{\rm PC}_{\Lambda_c^+ p\bar{K}^{*0}} = 1$$

Coupling constants:

$g_{\Lambda_c^+ p\bar{K}^{*0}}$ $\quad g_{\Delta^{++}\pi^+ p}$ $\quad g_{\bar{K}^{*0}\pi^+ K^-}$

$$\Gamma_{\Lambda_c^+ \to p\bar{K}^{*0}} = \frac{g^2_{\Lambda_c^+ p\bar{K}^{*0}} |\vec{p}_p|}{2\pi M_{\Lambda_c^+} m^2_{\bar{K}^{*0}}} [E_p (M^2_{\Lambda_c^+} + m_p^2 + 2m^2_{\bar{K}^{*0}}) - 2M_{\Lambda_c^+} m_p^2]$$

$$\Gamma_{\Delta^{++} \to \pi^+ p} = \frac{g^2_{\Delta^{++}\pi^+ p} (E_p + m_p) |\vec{p}_p|^3}{12\pi m_\Delta m_\pi^2}$$

$$\Gamma_{\bar{K}^{*0} \to \pi^+ K^-} = \frac{2 g^2_{\bar{K}^{*0}\pi^+ K^-} |\vec{p}_K|^3}{3\pi m^2_{\bar{K}^{*0}}}$$

Production of $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$

Amplitudes:

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

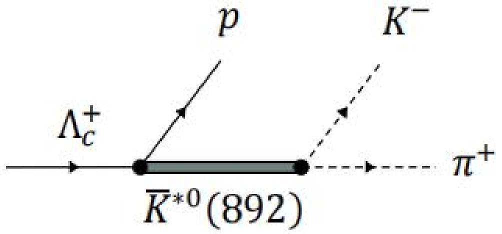
$$\mathcal{M}_b = \frac{g^2_{\Delta^{++}\pi^+ p} g_{\Lambda_c^+ p \bar{K}^{*0}} g_{\bar{K}^{*0}\pi^+ K^-}}{m_3^2} \bar{u}(p_2) p_{1\mu} G^{\mu\nu}_{3/2}(p_1+p_2, m_\Delta, \Gamma_\Delta) \times \int \frac{\mathrm{d}^4 q_1}{(2\pi)^4} q_{3\nu} G_{1/2}(q_2, m_2, \epsilon)(\gamma_5+1)\gamma_\alpha G_1^{\alpha\beta}(q_1,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

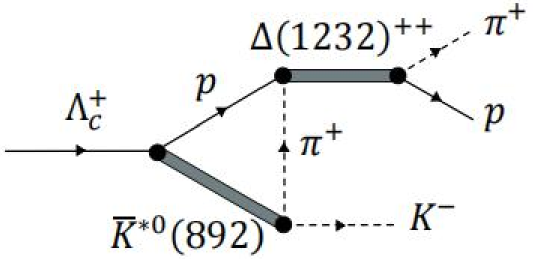
$$G_J(q,m,\Gamma) = \frac{i\mathcal{P}_J(q,m)}{q^2 - m^2 + im\Gamma}$$

$$\mathcal{P}_0 = 1 \qquad \mathcal{P}_1^{\mu\nu} = -g^{\mu\nu} + \frac{q^\mu q^\nu}{m^2}$$

$$\mathcal{P}_{1/2} = \not{q} + m \qquad \mathcal{P}_{3/2}^{\mu\nu} = (\not{q}+m)P_{3/2}^{\mu\nu}(q)$$

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

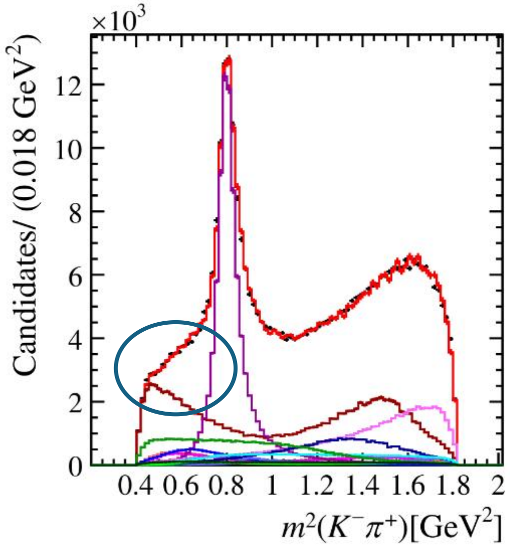




Form Factor

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

Dynamically generated κ

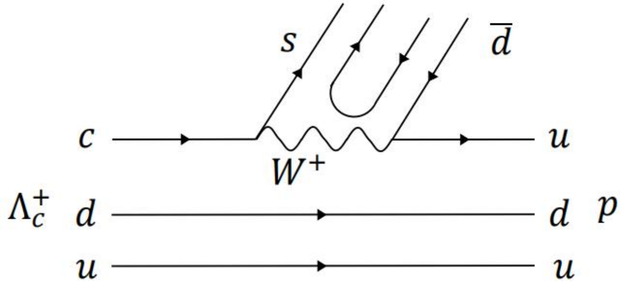


- $K_0^*(700)$ (also known as κ) $\quad I(J^P) = 1/2(0^+)$

From S-wave pseudoscalar meson-pseudoscalar meson interaction

Phys.Rept 969 (2022), 1

Phys.Lett.B 866 (2025), 139552



Quark level diagram

Phys.Rev.D 96 (2017), 054009

Eur.Phys.J.C 80 (2020), 842

Hadronization process:

$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du) \Rightarrow \frac{1}{\sqrt{2}} sW^+(ud-du)$$

$$\Rightarrow \frac{1}{\sqrt{2}} s\bar{d}u(ud-du) \Rightarrow s(\bar{u}u+\bar{d}d+\bar{s}s)\bar{d}p$$

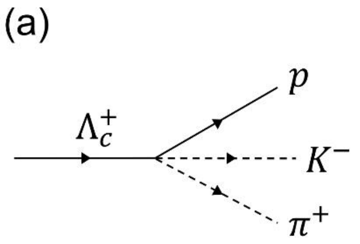
$$= \left(\sum_i M_{3i}M_{i2}\right) p$$

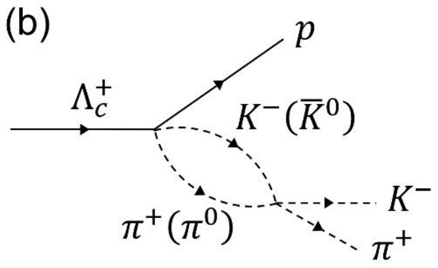
$SU(3)$ pseudoscalar meson matrix M:

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

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

Dynamically generated κ





(a) Direct $K^-\pi^+p$ vertex at tree level

(b) S-wave final-state interaction of $K^-\pi^+$

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

Amplitude:

$$\mathcal{M}_\kappa = V_p\Big[1 + G_{K^-\pi^+}(M_{K^-\pi^+})T_{K^-\pi^+\to K^-\pi^+}(M_{K^-\pi^+}) - \frac{1}{\sqrt{2}}G_{\bar{K}^0\pi^0}(M_{K^-\pi^+})T_{\bar{K}^0\pi^0\to K^-\pi^+}(M_{K^-\pi^+})\Big]$$

Loop function G regularized with a three-momentum cutoff:

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

$q_{max} = 600\text{MeV}$

$$\boxed{T = [1-VG]^{-1}V}$$

Eur.Phys.J.C 81 (2021), 268

Symmetric matrix elements of V:

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

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

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

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

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

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

1: π^+K^-

2: $\pi^0\bar{K}^0$

3: $\eta\bar{K}^0$

Eur.Phys.J.C 81 (2021), 268

Phys.Rev.D 76 (2007), 074016

Total amplitude

- Total amplitude for $\Lambda_c^+ \to K^-\pi^+ p$ decay: $$|\overline{\mathcal{M}}|^2 = C\left(\frac{1}{2}|\mathcal{M}_{\mathrm{a}} + \mathcal{M}_{\mathrm{b}}|^2 + |\mathcal{M}_{\kappa}|^2\right)$$

- Double differential width: $$\frac{d^2\Gamma}{dM^2_{K^-\pi^+}dM^2_{\pi^+p}} = \frac{1}{(2\pi)^3}\frac{1}{32M^3_{\Lambda_c^+}}|\overline{\mathcal{M}}|^2$$

$$(M^2_{\pi^+K^-})_{\min} = (E_{\pi^+} + E_{K^-})^2 - \left(\sqrt{E^2_{\pi^+} - m^2_{\pi^+}} + \sqrt{E^2_{K^-} - m^2_{K^-}}\right)^2$$

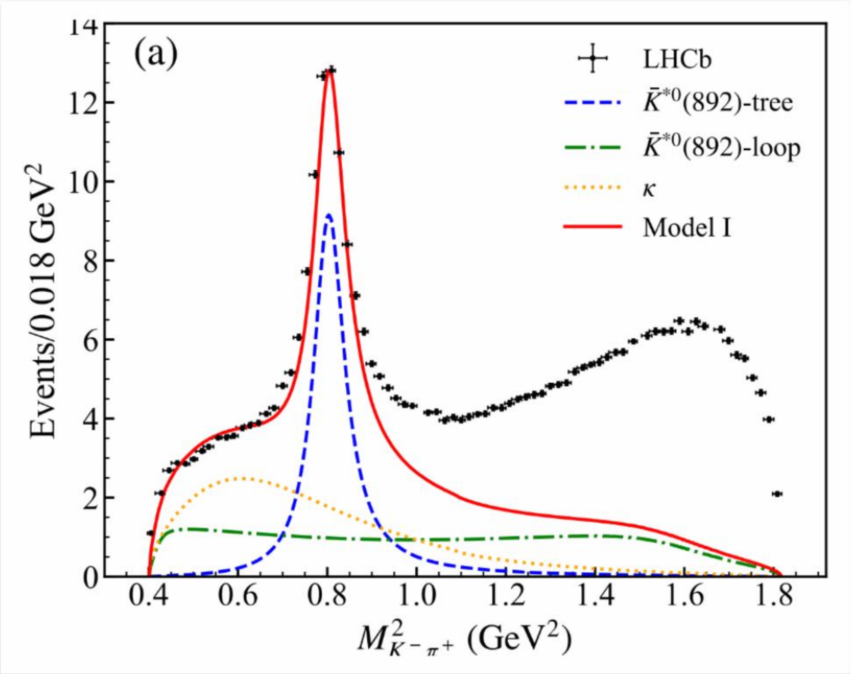
$$(M^2_{\pi^+K^-})_{\max} = (E_{\pi^+} + E_{K^-})^2 - \left(\sqrt{E^2_{\pi^+} - m^2_{\pi^+}} - \sqrt{E^2_{K^-} - m^2_{K^-}}\right)^2$$

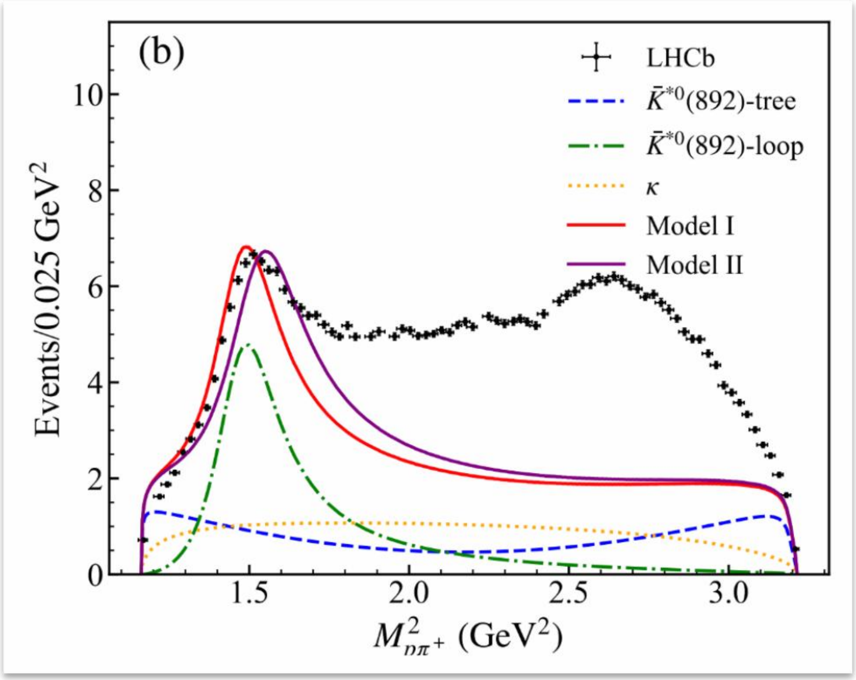
Content

Results

- Free parameters: V_P C Λ

		$g_{\Lambda_c^+ p \bar{K}^{*0}}$	$g_{\bar{K}^{*0}\pi^+ K^-}$	$M_{\Delta(1232)}$	$\Gamma_{\Delta(1232)}$	$g_{\Delta^{++}\pi^+ p}$	V_P	C	Λ
Pole parameters	**Model I**	3.96×10^{-7}	4.40	1210 MeV	100 MeV	2.27	4×10^{-5}	4×10^{13}	1.3 GeV
Breit-Wigner parameters	**Model II**			1232 MeV	117 MeV	2.14			1.5 GeV

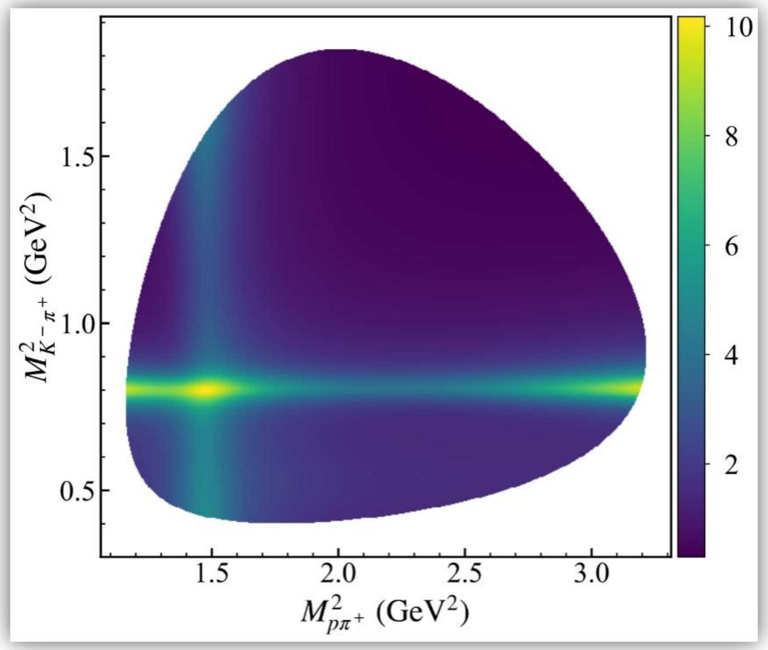




- **Model I** excellently reproduces experimental data.

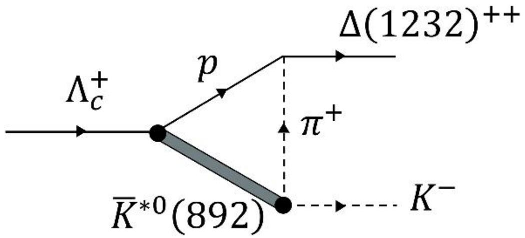
Results

Dalitz plot:



- The visible bands correspond to the $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$ signals;
- Low-lying Λ^* excited states, *e.g.*, $\Lambda(1520)$, $\Lambda(1670)$, are separated from the $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$ bands.

Production ratio:



$$\Gamma_{\Lambda_c^+\to\Delta(1232)^{++}K^-} = \frac{|\vec{p}_4|}{16\pi M^2_{\Lambda_c^+}}|\mathcal{M}'|^2$$

- Branching fraction ratio:

$$R^{\mathrm{I}} = \frac{\mathcal{B}[\Lambda_c^+ \to \Delta(1232)^{++}K^-]}{\mathcal{B}[\Lambda_c^+ \to p\bar{K}^{*0}(892)]} = 0.52$$

$$R^{\mathrm{II}} = \frac{\mathcal{B}[\Lambda_c^+ \to \Delta(1232)^{++}K^-]}{\mathcal{B}[\Lambda_c^+ \to p\bar{K}^{*0}(892)]} = 0.54$$

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Summary

- We propose a $\boldsymbol{\pi^+ p}$ **final-state rescattering mechanism** for $\Delta(1232)^{++}$ production in $\Lambda_c^+ \to K^-\pi^+ p$ decay.

- Besides the contributions of $\bar{K}^{*0}(892)$ and $\Delta(1232)^{++}$, we also include $\boldsymbol{\bar{K}_0^*(700)}$ generated dynamically from the S-wave $K\pi$ final state interaction.

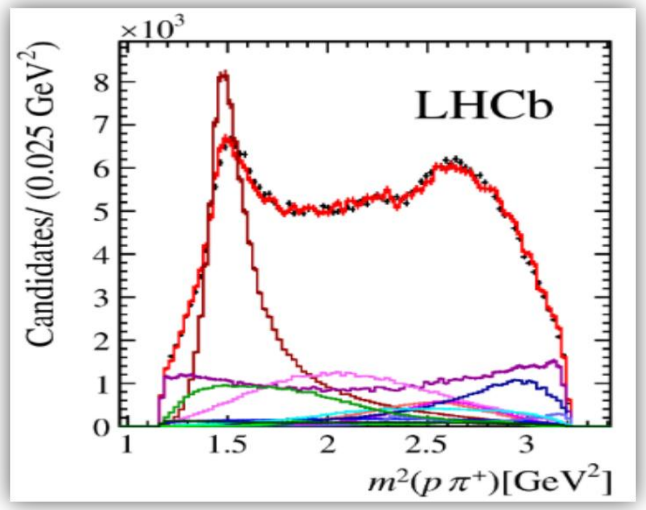
- **Pole parameters** of $\Delta(1232)$ yield an improved description of experimental data compared to Breit-Wigner parameters.

- $\mathcal{B}[\Lambda_c^+ \to \Delta(1232)^{++}K^-]/\mathcal{B}[\Lambda_c^+ \to p\bar{K}^{*0}(892)] \approx 0.5$

Thank you very much for your attention!

- Experimental ratio:

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



The predicted branching fraction ratio $\mathcal{B}[\Lambda_c^+ \to \Delta(1232)^{++}K^-]/\mathcal{B}[\Lambda_c^+ \to p\bar{K}^{*0}(892)] \approx 0.5$ is lower than the experimentally measured value, suggesting that **interference effects** are significant.