郑州大学
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Search for the low-lying excited baryon $\Sigma^*(1/2^-)$ through process $\Lambda_c^+ \to \Lambda K^0 \pi^+$

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arXiv:2601.12778

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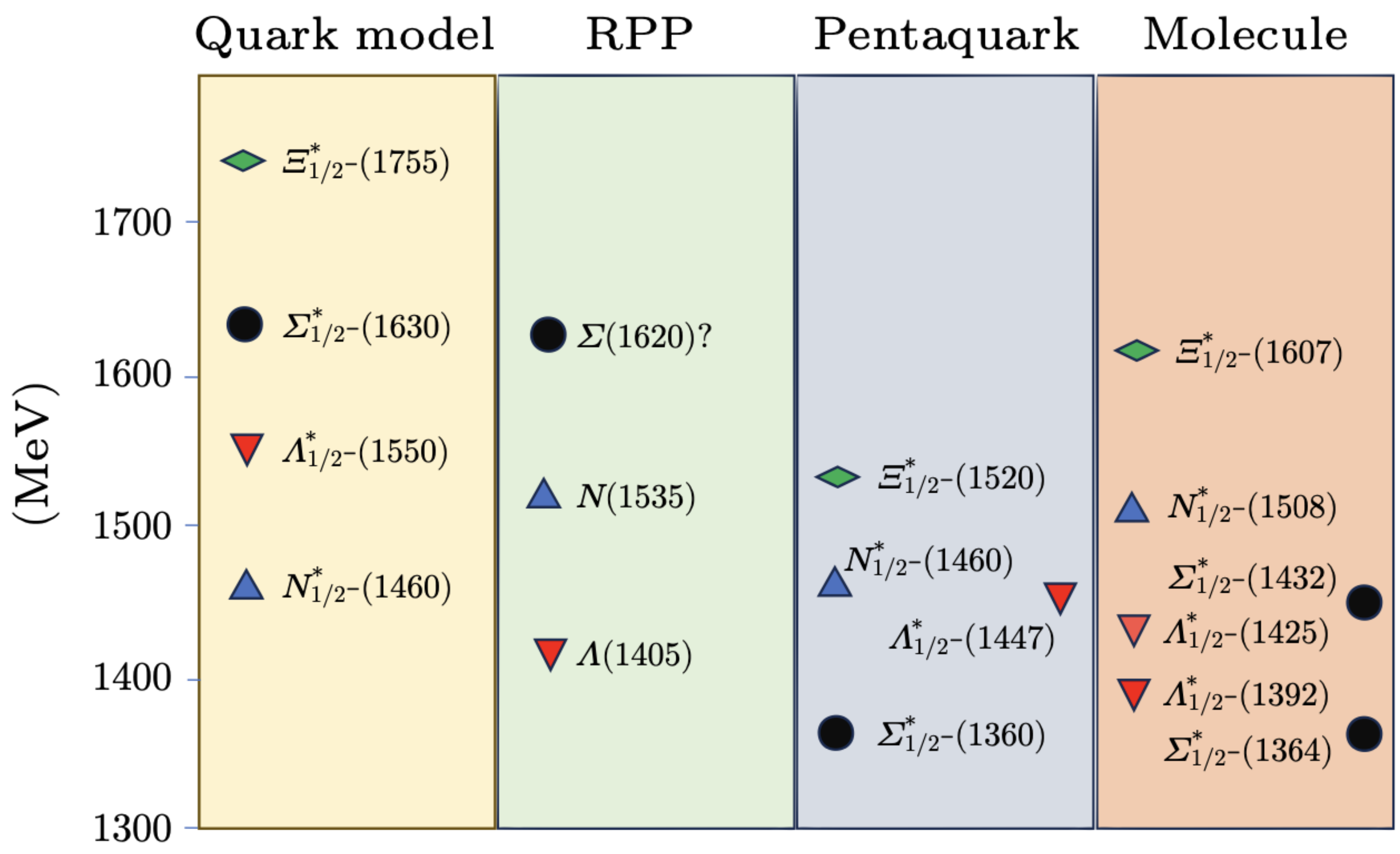
Introduction

- **Masses of the low-lying excited baryons with $J^P = 1/2^-$**



E. Wang, L. S. Geng, J. J. Wu, J. J. Xie and B. S. Zou,
Chin. Phys. Lett. **41**, no.10, 101401 (2024)

✓ **Mass reverse problem**

$N(1535)\ J^P = 1/2^-\ n=1\ L=1$

$N(1440)\ J^P = 1/2^+\ n=2\ L=0$

- Naive quark model

  $N(1535) < N(1440)$

- Experiment

  $N(1535) > N(1440)$

✓ **The missing low-lying $\Sigma^*(1/2^-)$**

$\Lambda(1405)\ J^P = 1/2^-\ \bar{K}N$

$\Sigma^*(1/2^-)$ **unestablished**

$\Sigma(1620)\ J^P = 1/2^-$ **one star** in RPP

Introduction

- **The chiral unitary approach**

Theoretical studies predict a $\Sigma^*(1/2^-)$ with a mass near the $\bar{K}N$ threshold, generated from S-wave meson-baryon interactions in the strangeness $S = -1$ sector.

K. P. Khemchandani, A. Martínez Torres and J. A. Oller, Phys. Rev. C **100**, no.1, 015208 (2019)
Y. Kamiya, K. Miyahara, S. Ohnishi, Y. Ikeda, T. Hyodo, E. Oset and W. Weise, Nucl. Phys. A **954**, 41-57 (2016)
J. A. Oller, Eur. Phys. J. A **28**, 63-82 (2006)

- **The effective Lagrangian approach**

The $\Sigma^*(1380)(J^P = 1/2^-)$ state plays a role in the $K\Sigma^*$ photoproduction and the $K^-p \to \Lambda\pi^-\pi^+$ reaction.

P. Gao, J. J. Wu and B. S. Zou, Phys. Rev. C **81**, 055203 (2010)
J. J. Wu, S. Dulat and B. S. Zou, Phys. Rev. C **81**, 045210 (2010)

- **$\Sigma^*(1/2^-)$ in Λ_c^+ four-body and three-body decays**

The $\Sigma^*(1/2^-)$ makes a significant contribution to the invariant mass spectra of $\pi\Lambda$ and $\pi\Sigma$.

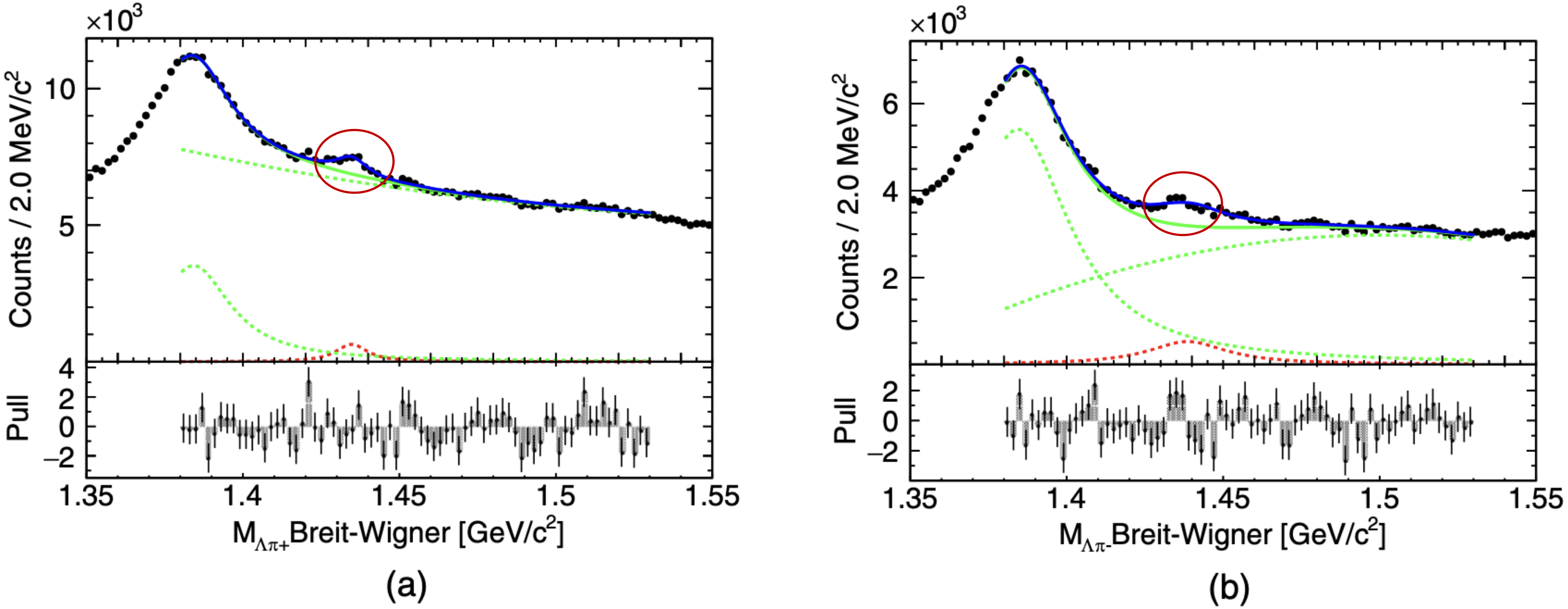
J. J. Xie and E. Oset, Phys. Lett. B **792**, 450-453 (2019)
Y. Y. Li, J. Song, E. Oset, W. H. Liang and R. Molina, Eur. Phys. J. C **85**, no.9, 1086 (2025)
W. T. Lyu, S. C. Zhang, G. Y. Wang, J. J. Wu, E. Wang, L. S. Geng and J. J. Xie, Phys. Rev. D **110**, no.5, 054020 (2024)

Introduction

- $\boldsymbol{\Sigma^*(1/2^-)}$ **in** $\boldsymbol{\Lambda_c^+}$ **four-body decays**

Mode	E_{BW} (MeV/c^2)	Γ (MeV/c^2)	χ^2/NDF
$\Lambda\pi^+$	1434.3 ± 0.6	11.5 ± 2.8	74.4/68
$\Lambda\pi^-$	1438.5 ± 0.9	33.0 ± 7.5	92.3/68

$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$

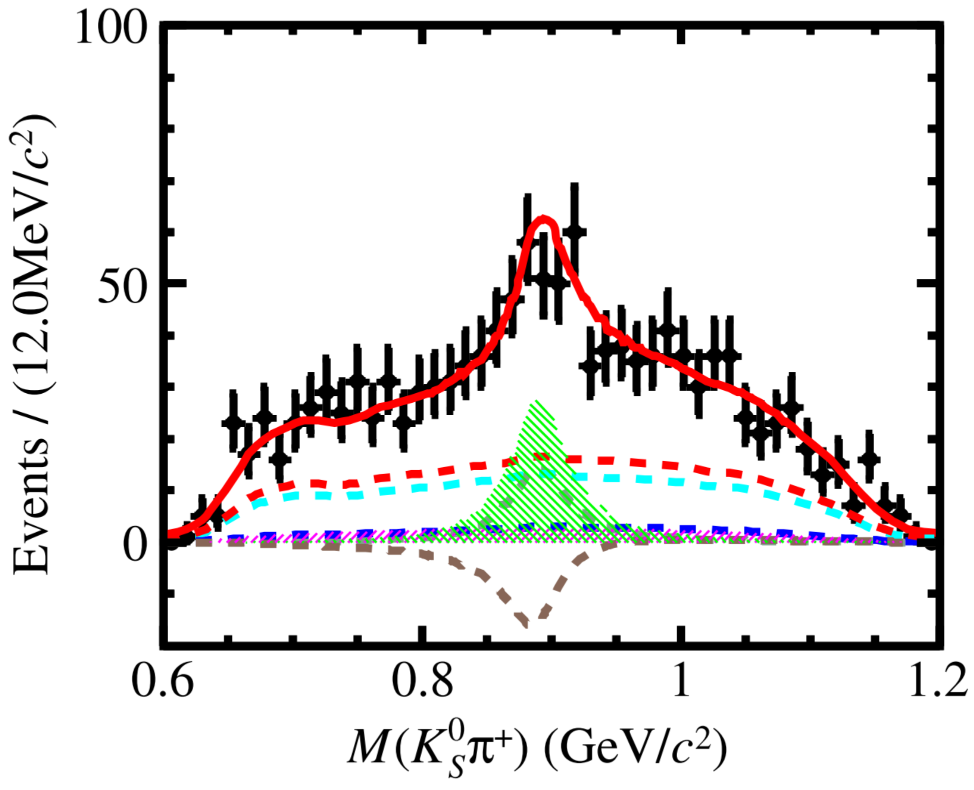


Y. Ma *et al.* [Belle], Phys. Rev. Lett. **130**, no.15, 151903 (2023)

Introduction

$\Lambda_c^+ \to \Lambda K^0 \pi^+$

- $\mathcal{B}(\Lambda_c^+ \to \Lambda K_S^0 \pi^+) = (1.73 \pm 0.26 \pm 0.01) \times 10^{-3}$
- From the BESIII data, we can determine the relevant parameters and predict the invariant mass distributions of ΛK^0 and $\Lambda \pi^+$ in the $\Lambda_c^+ \to \Lambda K^0 \pi^+$ process.
- According to the predictions for the $\Lambda\pi$ channel, we search for the $\Sigma^*(1/2^-)$ in the $\Lambda\pi$ invariant mass distribution.

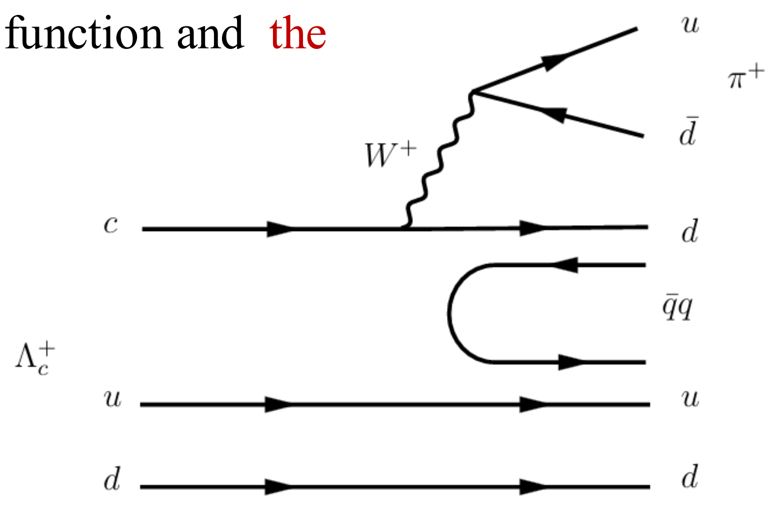


M. Ablikim *et al.* [BESIII],
Phys. Rev. D **111**, no.1, 012014 (2025)

Formalism

- For **the external emission mechanism**, at the quark level, using the Λ_c wave function and the wave functions of the octet of baryon, we have

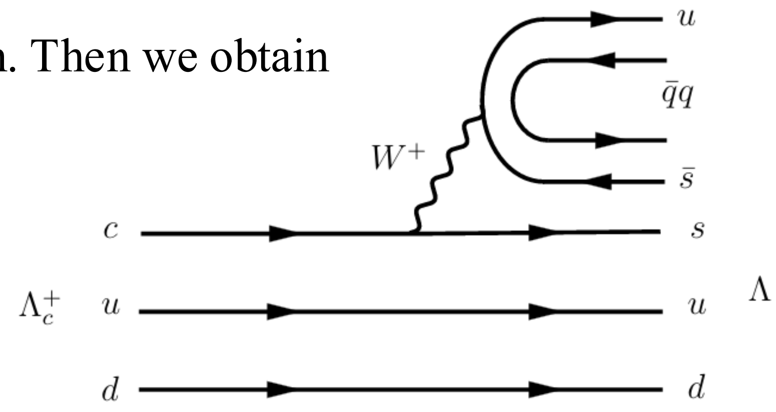
$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} u\bar{d}d(q\bar{q})(ud-du)\chi_{MA}$$
$$\Rightarrow \frac{1}{\sqrt{2}} \pi^+ \sum M_{2i} q_i \,(ud-du)\chi_{MA}$$
$$\Rightarrow \pi^+ \left(\frac{1}{\sqrt{2}}\pi^- p + \frac{1}{2}\pi^0 n + \frac{1}{\sqrt{6}}\eta n + \frac{1}{\sqrt{3}} K^+ \Lambda\right)$$



(a)

- Similarly, we consider that the c quark in Λ_c decays into a W^+ boson and an s quark, while the $u\bar{s}$ pair from the W^+ boson decay interacts with the $\bar{q}q$ pair created from the vacuum. Then we obtain

$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} u(\bar{q}q)\bar{s}s(ud-du)\chi_{MA}$$
$$\Rightarrow \sum M_{1i} M_{i3} \frac{1}{\sqrt{2}} s(ud-du)\chi_{MA}$$
$$\Rightarrow \left(\frac{1}{\sqrt{6}}\pi^0 K^+ + \frac{1}{\sqrt{3}}\pi^+ K^0\right)\Lambda$$

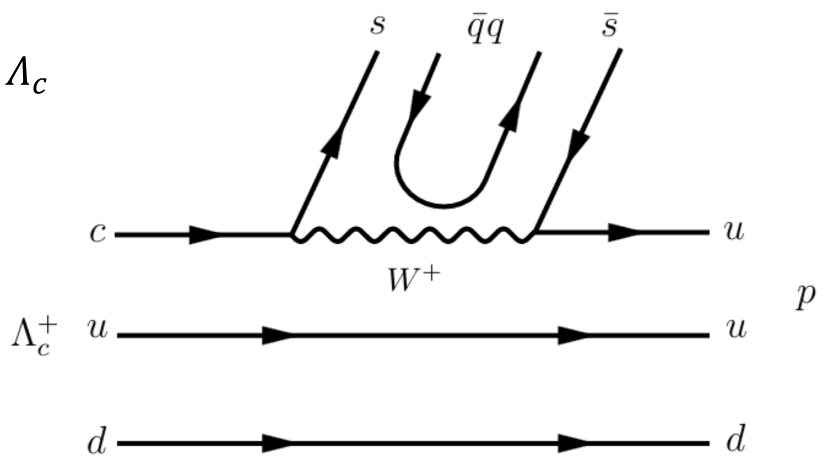


(b)

Formalism

- For **the internal emission mechanism**, at the quark level and using the Λ_c wave function, we have

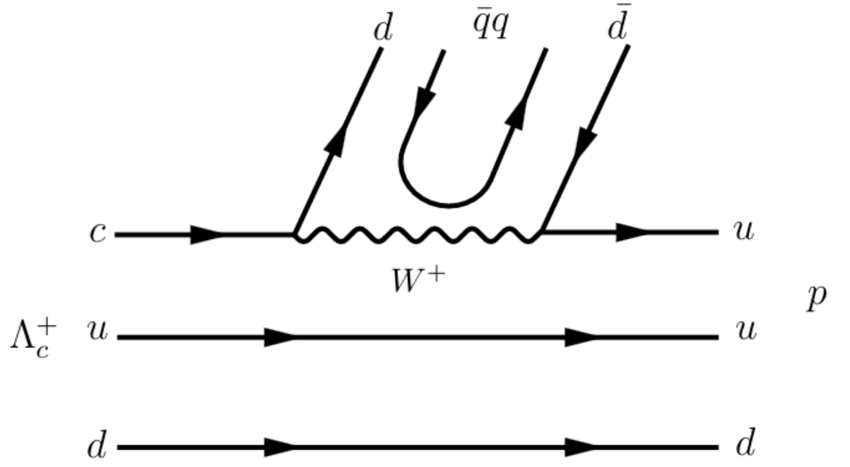
$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} s(\bar{q}q)\bar{s}u(ud-du)\chi_{MA}$$
$$\Rightarrow \sum M_{3i}M_{i3}\frac{1}{\sqrt{2}}u(ud-du)\chi_{MA}$$
$$\Rightarrow \left(\frac{1}{\sqrt{2}}K^-K^+ + \frac{1}{\sqrt{2}}\bar{K}^0K^0 + \frac{1}{3\sqrt{2}}\eta\eta\right)p$$



(c)

- Similarly, we can obtain

$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} d(\bar{q}q)\bar{d}u(ud-du)\chi_{MA}$$
$$\Rightarrow \sum M_{2i}M_{i2}\frac{1}{\sqrt{2}}u(ud-du)\chi_{MA}$$
$$\Rightarrow \left(\frac{1}{\sqrt{2}}\pi^-\pi^+ + \frac{1}{3\sqrt{2}}\eta\eta - \frac{1}{\sqrt{3}}\eta\pi^0 + \frac{1}{2\sqrt{2}}\pi^0\pi^0 + \frac{1}{\sqrt{2}}\bar{K}^0K^0\right)p$$



(d)

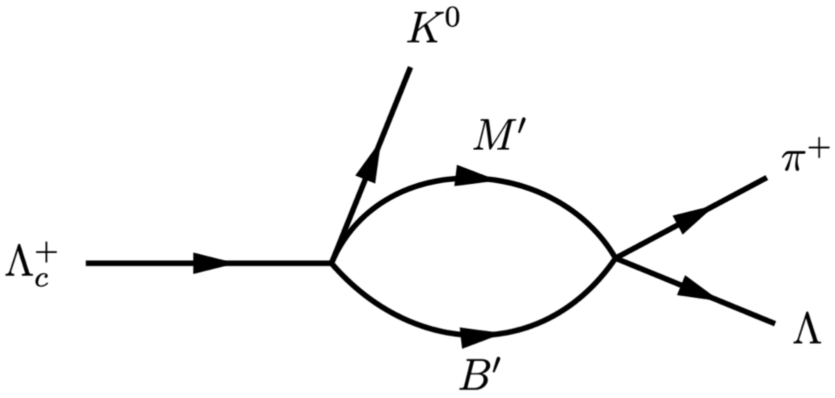
Formalism (amplitude of the $\Sigma^*(1/2^-)$)

- The scattering matrix for the mechanism of $\Lambda_c^+ \to K^0 M' B' \to K^0 \pi^+ \Lambda$ is given by

$$\mathcal{T}^{\Sigma^*(1/2^-)} = V_P [h_{K^0\Lambda} G_{\pi^+\Lambda}(M_{\text{inv}}) t_{\pi^+\Lambda\to\pi^+\Lambda}(M_{\text{inv}}) + h_{\pi^+K^0} G_{\pi^+\Lambda}(M_{\text{inv}}) t_{\pi^+\Lambda\to\pi^+\Lambda}(M_{\text{inv}}) + \frac{2}{C} h_{\bar{K}^0K^0} G_{\bar{K}^0p}(M_{\text{inv}}) t_{\bar{K}^0p\to\pi^+\Lambda}(M_{\text{inv}})]$$

$$h_{K^0\Lambda} = h_{\pi^+K^0} = \frac{1}{\sqrt{3}}, h_{\bar{K}^0K^0} = \frac{1}{\sqrt{2}}$$

- 3 coupled channels: $\bar{K}N, \pi\Sigma, \pi\Lambda$.



✓ The Bethe-Salpeter equation: $T = [1 - VG]^{-1} V$

$$V_{ij} = -C_{ij} \frac{1}{4f^2} (2\sqrt{s} - M_i - M_j) \times \left(\frac{M_i + E_i}{2M_i}\right)^{1/2} \left(\frac{M_j + E_j}{2M_j}\right)^{1/2}$$

✓ The loop function:

$$G_l(\sqrt{s}) = \frac{2M_l}{16\pi^2} \Big(a_l(\mu) + ln \frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} ln \frac{m_l^2}{M_l^2} + \frac{|\vec{q}|}{\sqrt{s}} [\ln(s - (M_l^2 - m_l^2) + 2|\vec{q}|\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2|\vec{q}|\sqrt{s}) - \ln(-s + (M_l^2 - m_l^2) + 2|\vec{q}|\sqrt{s} - \ln(-s - (M_l^2 - m_l^2) + 2|\vec{q}|\sqrt{s})] \Big)$$

L. Roca and E. Oset, Phys. Rev. C **88**, no.5, 055206 (2013)

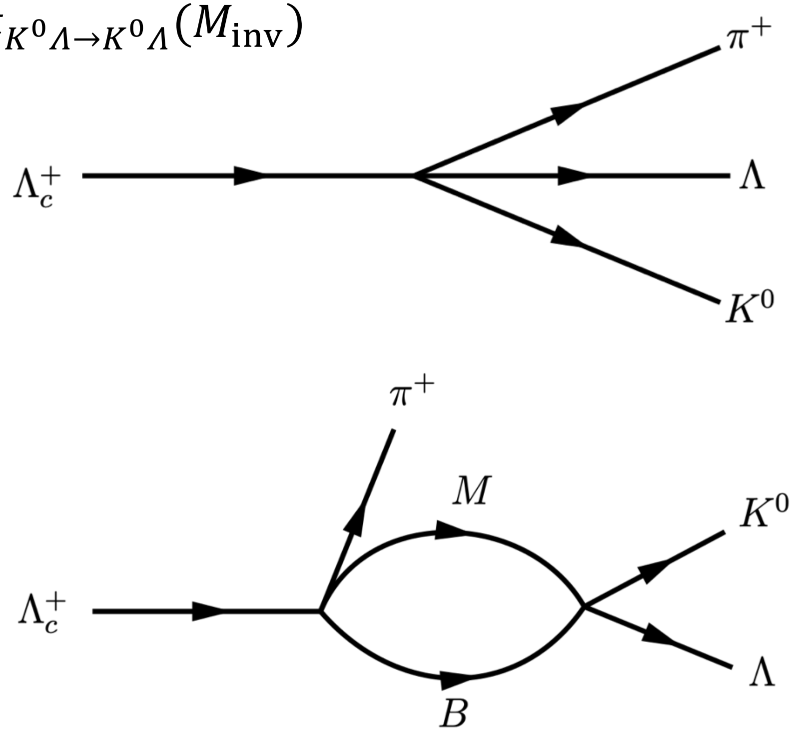
Formalism (amplitude of the tree and $N(1535)$)

- The scattering matrix for the mechanism of $\Lambda_c^+ \to \pi^+ MB \to \pi^+ K^0 \Lambda$ is given by

$$\mathcal{T}^{Tree} = V_P (h_{K^0\Lambda} + h_{\pi^+K^0})$$

$$\mathcal{T}^{N(1535)} = V_P \left[\sum_i h_i \tilde{G}_i(M_{\rm inv}) t_{i\to K^0\Lambda}(M_{\rm inv}) + h_{\pi^+K^0} \tilde{G}_{K^0\Lambda}(M_{\rm inv}) t_{K^0\Lambda\to K^0\Lambda}(M_{\rm inv}) + \frac{1}{C} h_{\pi^-\pi^+} \tilde{G}_{\pi^-p}(M_{\rm inv}) t_{\pi^-p\to K^0\Lambda}(M_{\rm inv}) \right]$$

$$h_{\pi^-p} = h_{\pi^-\pi^+} = \frac{1}{\sqrt{2}}, h_{\pi^0 n} = -\frac{1}{2},$$
$$h_{\eta n} = \frac{1}{\sqrt{6}}, h_{K^0\Lambda} = h_{\pi^+K^0} = \frac{1}{\sqrt{3}}$$



- 6 coupled channels: $K^+\Sigma^-, K^0\Sigma^0, K^0\Lambda, \pi^-p, \pi^0 n, \eta n$.

✓ The loop function: $\tilde{G}_l = \int_0^{q_{max}} \frac{2M_l}{(2\pi)^2} \frac{|\vec{q}|^2(\omega_1+\omega_2)dq}{\omega_1\omega_2[s-(\omega_1+\omega_2)^2]}$

J. X. Lu, E. Wang, J. J. Xie, L. S. Geng and E. Oset, Phys. Rev. D **93**, 094009 (2016)

Formalism (amplitude of the $K^*(892)$)

- The decay amplitude for the mechanism of $\Lambda_c^+ \to \Lambda K^*(892) \to \Lambda K^0 \pi^+$ is given by

$$\mathcal{T}^{K^*} = V_P' \frac{|\vec{p}_{\pi^+}||\vec{p}_{\Lambda}|cos\theta}{M^2_{\pi^+K^0} - M^2_{K^*} + iM_{K^*}\Gamma_{K^*}}$$

$$|\vec{p}_{\pi^+}| = \frac{\lambda^{1/2}\left(M^2_{\pi^+K^0}, m^2_{\pi^+}, m^2_{K^0}\right)}{2M_{\pi^+K^0}}$$

$$|\vec{p}_{\Lambda}| = \frac{\lambda^{1/2}\left(M^2_{\Lambda_c^+}, m^2_{\Lambda}, M^2_{\pi^+K^0}\right)}{2M_{\pi^+K^0}}$$

$$cos\theta = \frac{M^2_{\Lambda K^0} - M^2_{\Lambda_c^+} - m^2_{\pi^+} + 2P^0_{\Lambda_c^+}P^0_{\pi^+}}{2|\vec{p}_{\pi^+}||\vec{p}_{\Lambda}|}$$

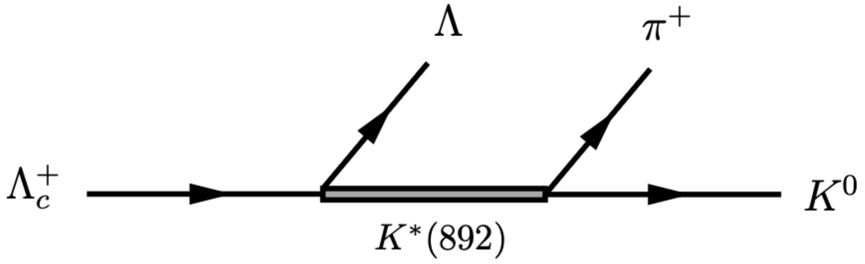


FIG. 3: Mechanisms for the $\Lambda_c^+ \to \Lambda K^0 \pi^+$ decay via the intermediate $K^*(892)$.

- V_P and V_P' are obtainable from the branching ratios of intermediate processes

Parameters	V_P (MeV^{-1})	V_P' (MeV^{-1})
Values	1.60×10^{-8}	3.07×10^{-9}

Formalism

- **The total decay amplitude:**

$$|\mathcal{T}|^2 = \left|\mathcal{T}^{Tree} + \mathcal{T}^{N(1535)} + \mathcal{T}^{\Sigma^*(1/2^-)} e^{i\phi} + \mathcal{T}^{K^*} e^{i\phi'}\right|^2$$

- Then the double differential width:

$$\frac{d^2\Gamma}{dM_{K^0\Lambda} dM_{\pi^+\Lambda}} = \frac{1}{(2\pi)^3} \frac{M_\Lambda M_{K^0\Lambda} M_{\pi^+\Lambda}}{2M_{\Lambda_c^+}^2} |\mathcal{T}|^2$$

- In total we have 3 free parameters:

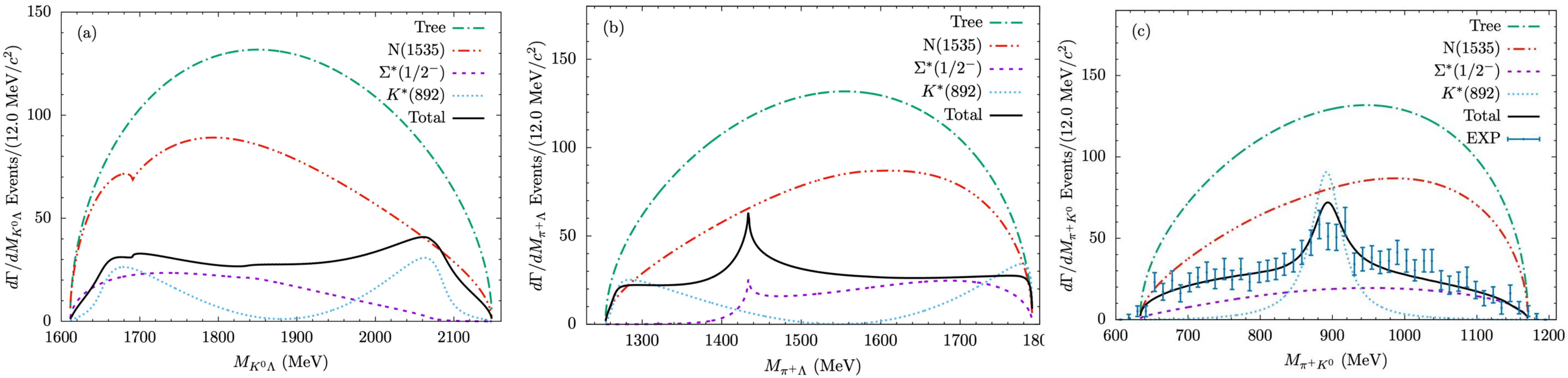
  the phase angles: $\phi = (1.73 \pm 0.11)\pi$, $\phi' = (1.57 \pm 0.06)\pi$;

  a normalization constant $(1.22 \pm 0.26) \times 10^{15}$.

Result

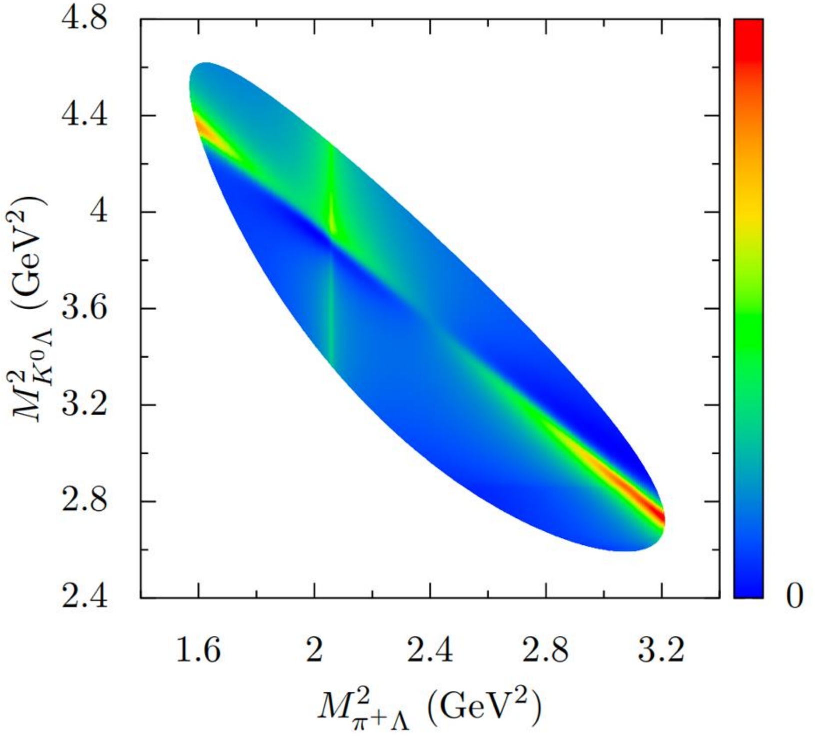
➢ The invariant mass distributions with phase interference

$$|\mathcal{T}|^2 = \left|\mathcal{T}^{Tree} + \mathcal{T}^{N(1535)} + \mathcal{T}^{\Sigma^*(1/2^-)} e^{i\phi} + \mathcal{T}^{K^*} e^{i\phi'}\right|^2$$

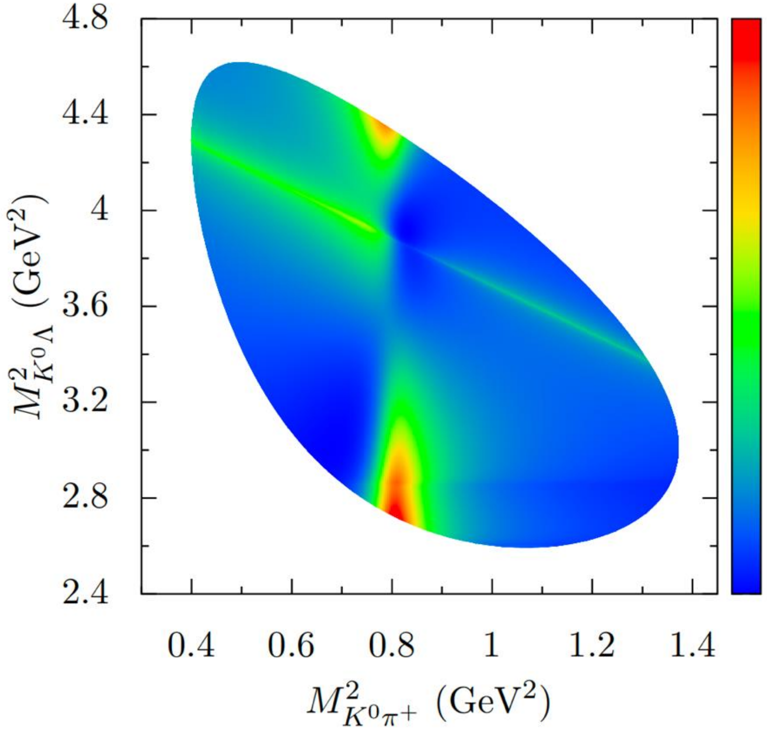


Result

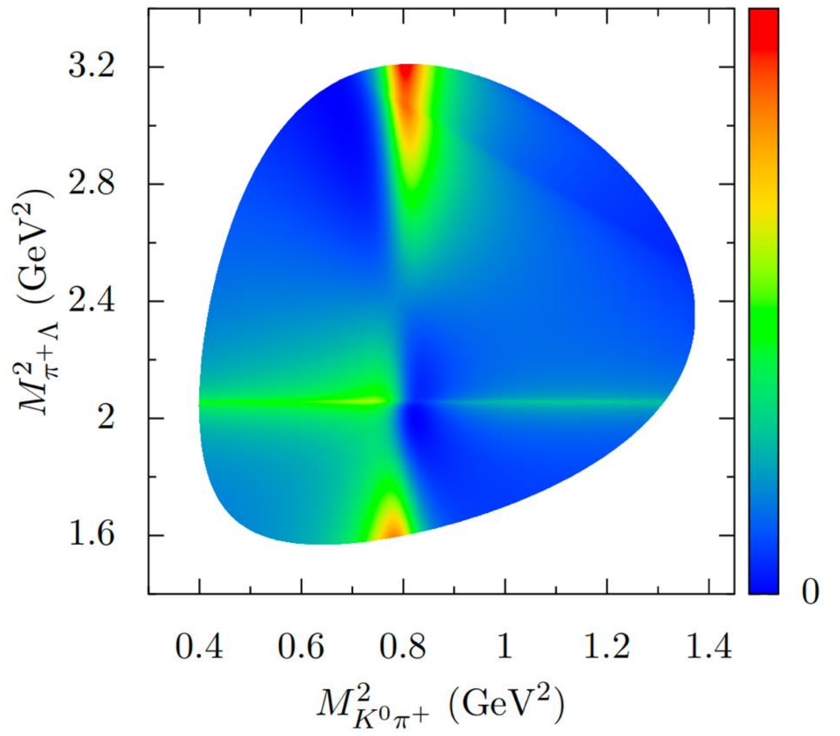
- The Dalitz plots



$M^2_{\pi^+\Lambda}$ vs $M^2_{K^0\Lambda}$



$M^2_{K^0\pi^+}$ vs $M^2_{K^0\Lambda}$



$M^2_{K^0\pi^+}$ vs $M^2_{\pi^+\Lambda}$

Summary

- $\Sigma^*(1/2^-)$ has been theoretically predicted and experimentally observed. Verifying and confirming its existence via more decay processes is crucial for perfecting the baryon spectrum.
- We study the process $\Lambda_c^+ \to \Lambda K^0\pi^+$ by considering S-wave meson-baryon interactions and the $K^*(892)$ intermediate resonance. Our model successfully reproduces the BESIII $K_S^0\pi^+$ invariant mass distribution.
- We calculate the invariant mass distributions for ΛK^0 and $\Lambda\pi^+$, and predict a clear cusp structure near 1430 MeV in the $\Lambda\pi^+$ invariant mass distribution, which is associated with the predicted $\Sigma^*(1/2^-)$.
- Future precise measurements will deepen our understanding of the nature of $\Sigma^*(1/2^-)$.

Thank you for attention !