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Study of $J^P = 1/2^-$ low-lying excited baryons in Λ_c^+ three-body decays

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Collaborators:

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CPL 43, 050203(2026)

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01 **Introduction**

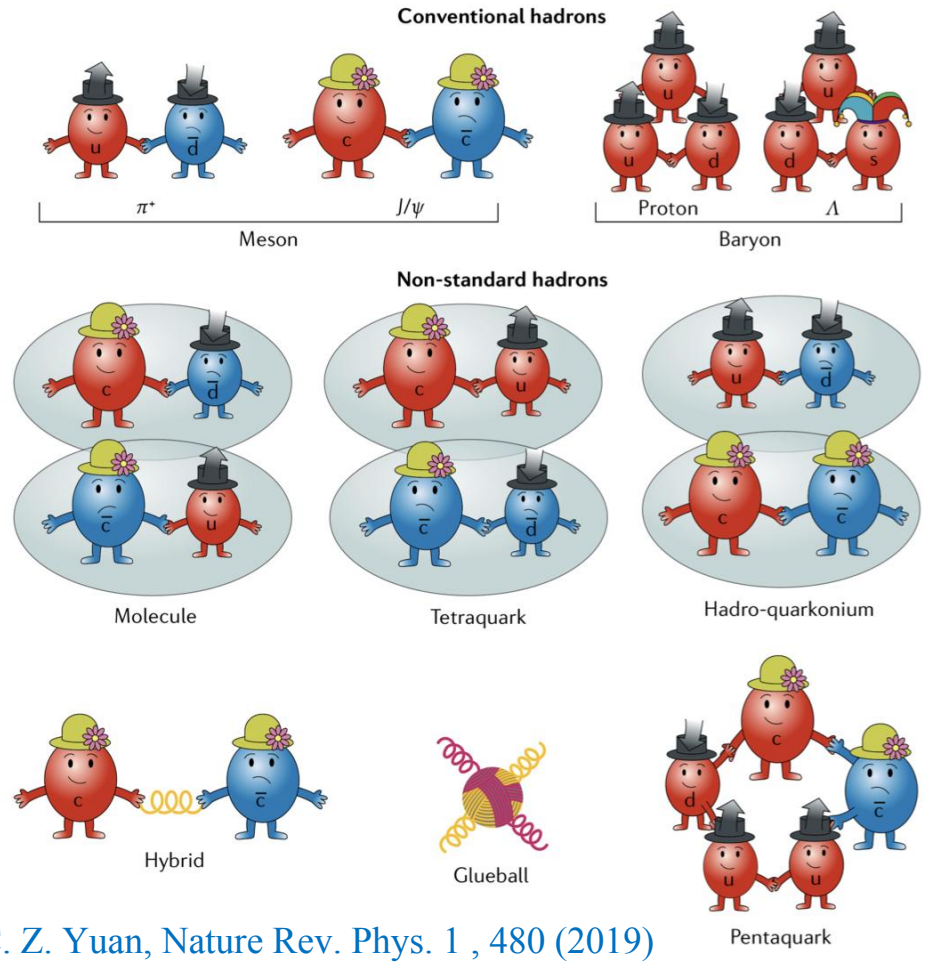
02 The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

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Introduction

- **The decays of Λ_c^+ and meson-baryon interaction**



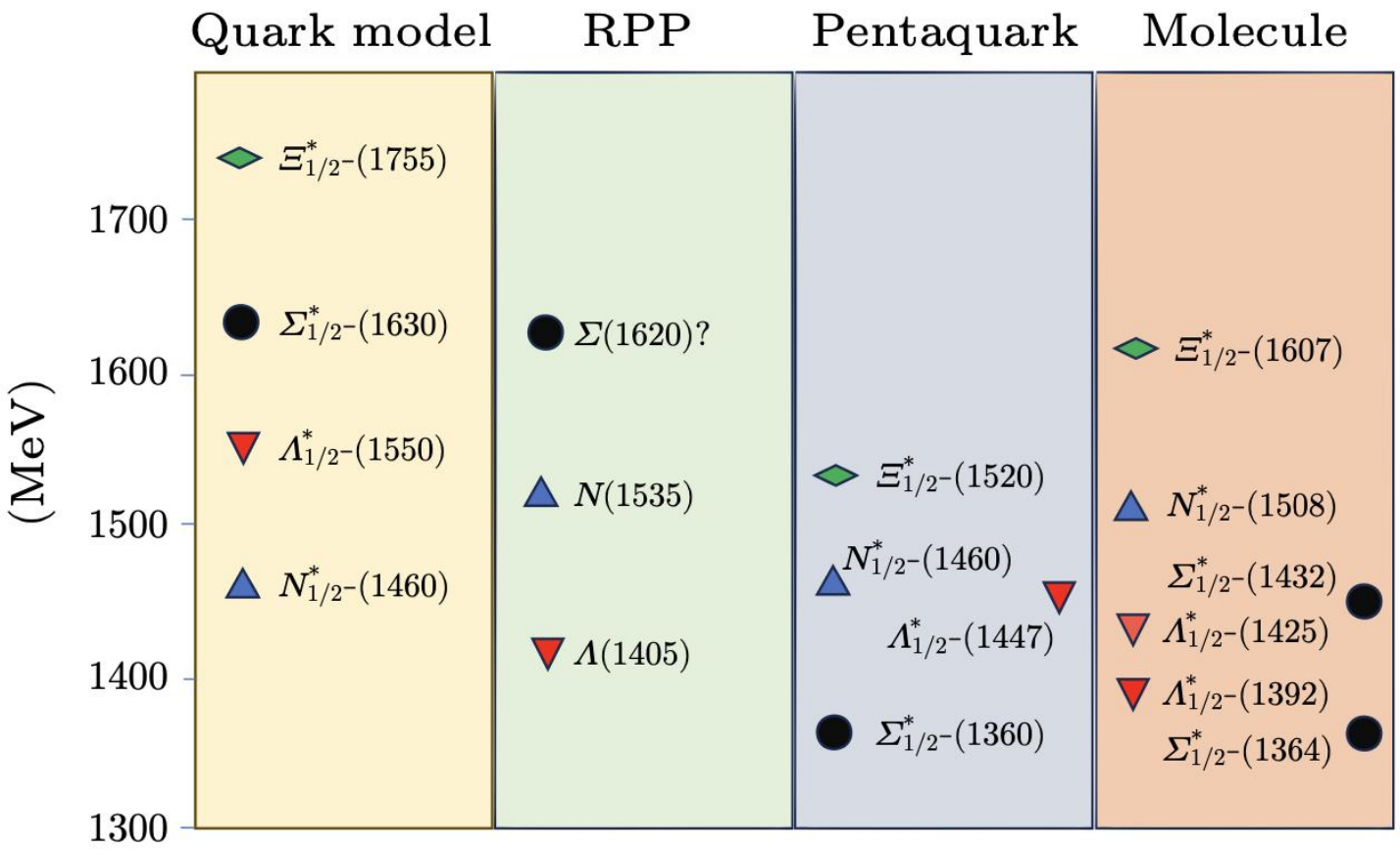
C. Z. Yuan, Nature Rev. Phys. 1 , 480 (2019)

✓ **Meson-baryon interaction:** A crucial approach to probing the dynamic structure of baryon resonances.

✓ The Λ_c^+, as the first observed charmed baryon, with a large number of decay modes, has been valued by BESIII, Belle, CLEO and LHCb Collaborations.

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 unclear nature of $\Lambda(1670)$**

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

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

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

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

Introduction ($\Lambda(1/2^-)$)

$\Lambda(1405)$: two-pole structure

- lower pole: above the $\pi\Sigma$ threshold, also called $\Lambda(1380)$.
- higher pole: below the $\bar{K}N$ threshold, is known as $\Lambda(1405)$, $\bar{K}N$ molecular state.

E. Oset and A. Ramos, Nucl. Phys. A **635**, 99-120 (1998)
D. Jido, J. A. Oller, E. Oset, A. Ramos and U. G. Meissner, Nucl. Phys. A **725**, 181-200 (2003)
T. Hyodo and W. Weise, Phys. Rev. C 77, 035204 (2008)
Z. Zhuang, R. Molina, J. X. Lu and L. S. Geng, Sci. Bull. **70**, 1953-1961 (2025)

$\Lambda(1670)$: What is the physical nature?

- traditional three-quark state

X. H. Zhong and Q. Zhao, Phys. Rev. C 79, 045202 (2009)
A. Starostin et al. (Crystal Ball Collaboration), Phys. Rev. C 64, 055205 (2001)

- dynamically generated molecule from coupled-channel interactions like $\bar{K}N$, $\eta\Lambda$, and $\pi\Sigma$

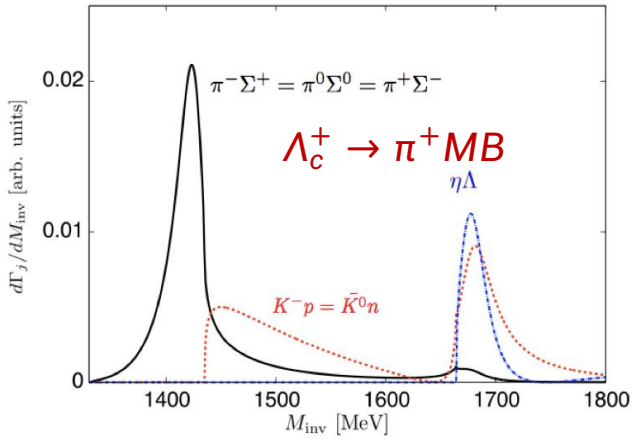
K. Miyahara, T. Hyodo, and E. Oset, Phys. Rev. C 92, 055204 (2015)
J. J. Xie and L. S. Geng, Eur. Phys. J. C 76, 496 (2016)
Z. Y. Wang, S. Q. Luo, Z. F. Sun, C. W. Xiao, and X. Liu, Phys. Rev. D 106, 096026 (2022)

- bare three-quark basis state that mixes with the $\pi\Sigma$, $\bar{K}N$, $\eta\Lambda$, and $K\Xi$ meson-baryon channels

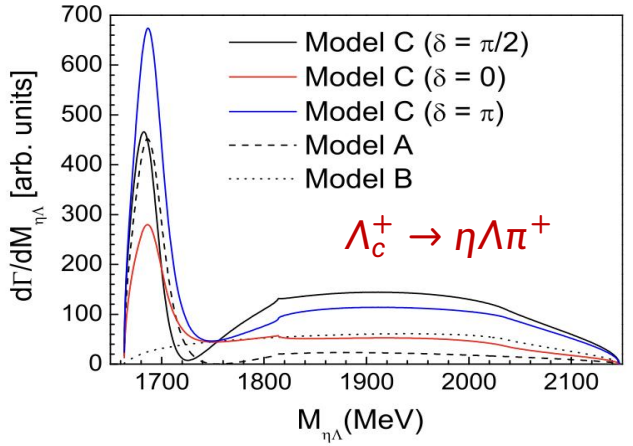
J. J. Liu, Z. W. Liu, K. Chen, D. Guo, D. B. Leinweber, X. Liu, and A. W. Thomas, Phys. Rev. D 109, 054025 (2024)

Introduction ($\Lambda(1/2^-)$)

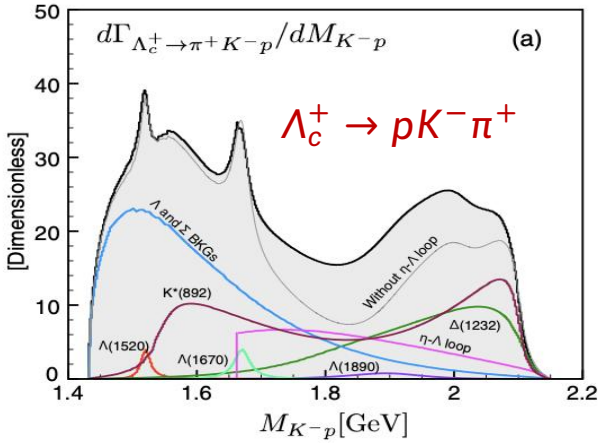
- **Theoretical prediction** for the invariant mass spectrum of $\Lambda(1670)$



K. Miyahara, T. Hyodo and E. Oset, Phys. Rev. C 92, 055204(2015)

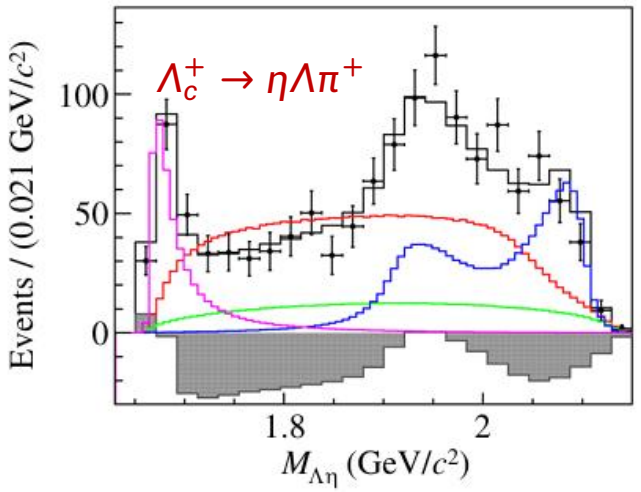


J. J. Xie and L. S. Geng, Eur. Phys. J. C 76, 496 (2016)

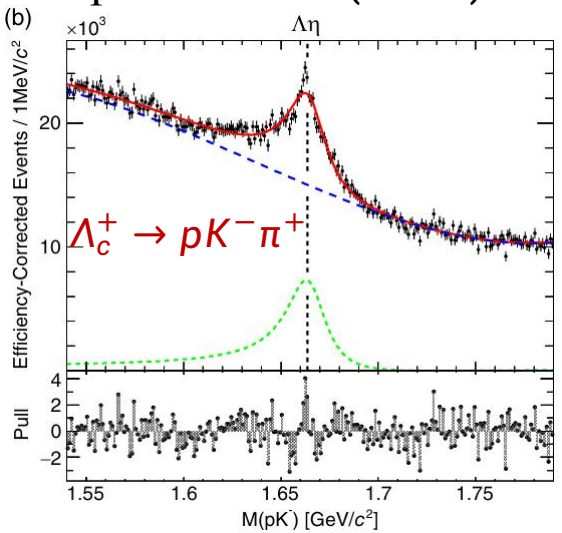


J. K. Ahn, S. Yang and S. I. Nam, Phys. Rev. D 100, 034027 (2019)

- **Experimental study** of the invariant mass spectrum of $\Lambda(1670)$

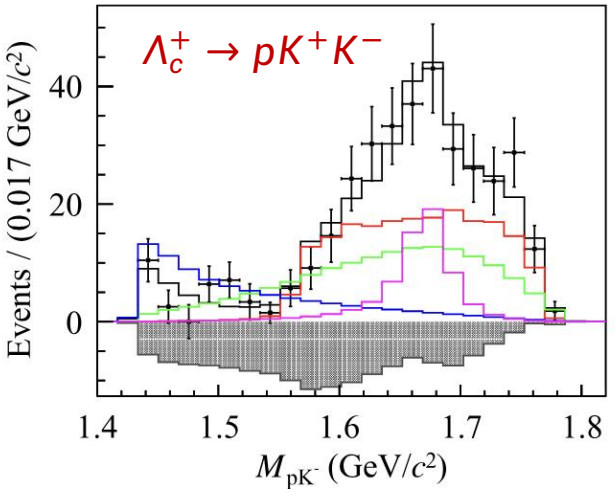


BESIII, Phys. Rev. Lett. **134**, 021901 (2025)



Belle, Phys. Rev. D **108**, L031104 (2023)

BESIII, Phys. Rev. D **114**, no.3, 032008 (2026)



Introduction ($\Sigma(1/2^-)$)

$\Sigma(1/2^-)$: remains poorly established

☐ Predicted theoretically

✓ **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 $\pi\Sigma$.

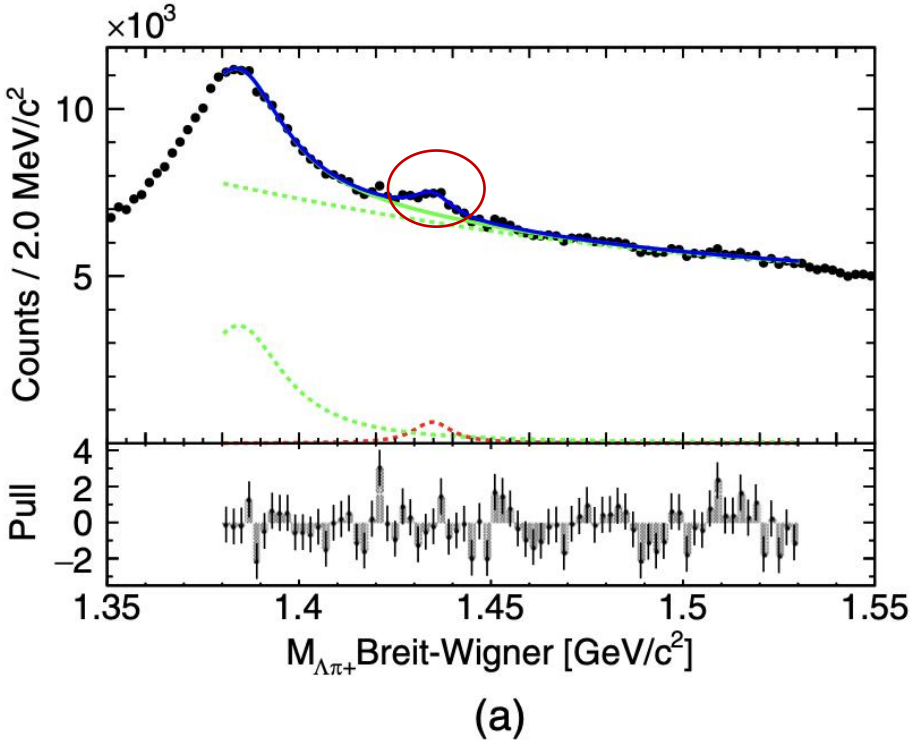
J. J. Xie and E. Oset, Phys. Lett. B **792**, 450-453 (2019)
Y. Y. Li, J. Song, E. Oset, W. H. Liang and R. Molina, Eur. Phys. J. C **85**, no.9, 1086 (2025)
W. T. Lyu, S. C. Zhang, G. Y. Wang, J. J. Wu, E. Wang, L. S. Geng and J. J. Xie, Phys. Rev. D **110**, no.5, 054020 (2024)

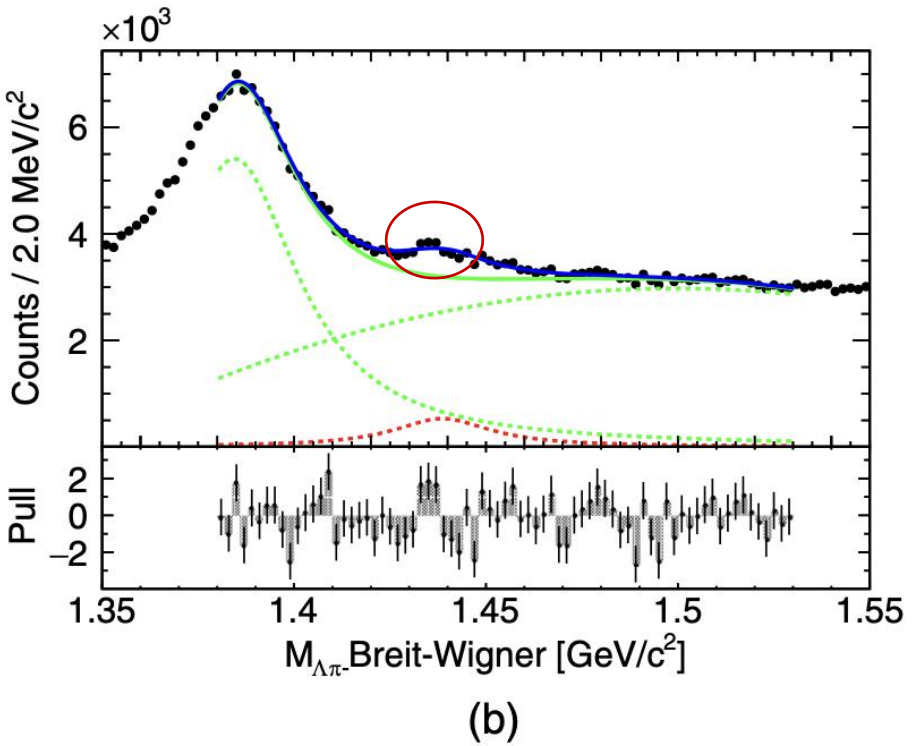
Introduction ($\Sigma(1/2^-)$)

- Observed experimentally
- ✓ **$\Sigma^*(1/2^-)$ in Λ_c^+ four-body decays**

Mode	$E_{\rm BW}$ (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)

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01 Introduction

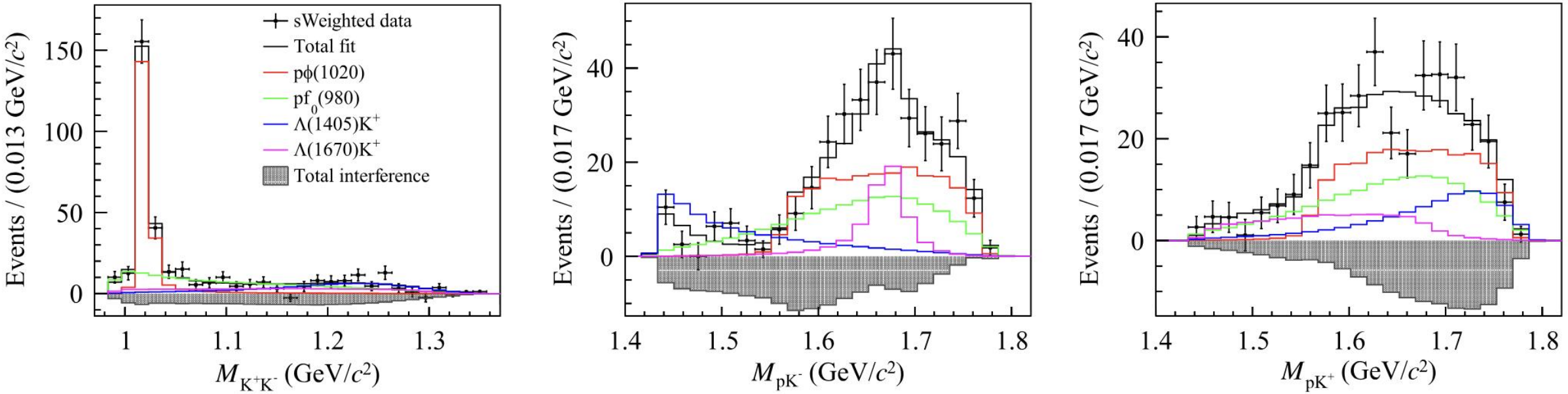
02 The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

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The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

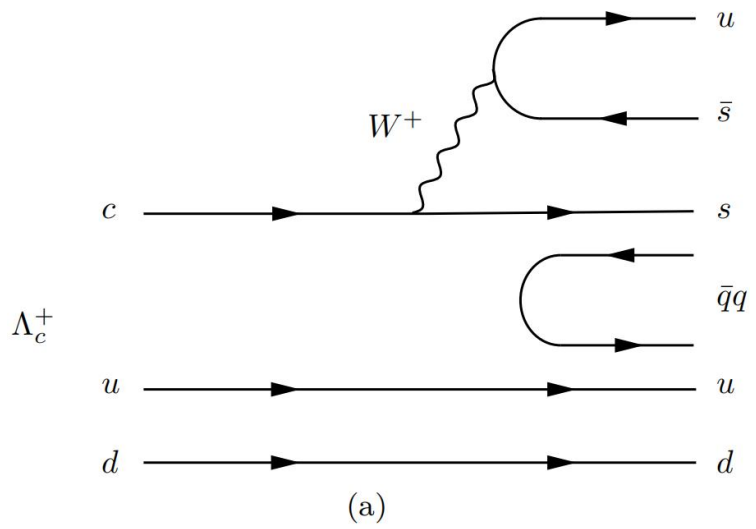
- The BESIII Collaboration measured the invariant mass distributions and performed a partial wave analysis of the $\Lambda_c^+ \to pK^+K^-$ decay.



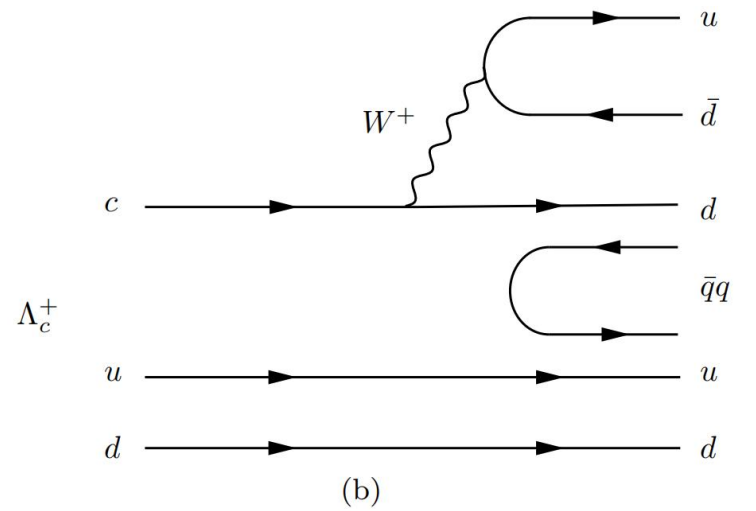
M. Ablikim et al. [BESIII], Phys. Rev. D **114**, no.3, 032008 (2026)

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- **External emission mechanisms**



(a)



(b)

$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} u\bar{s}s(\bar{q}q)(ud-du)\chi_{MA}$$

$$\Rightarrow \frac{1}{\sqrt{2}} K^+ \sum P_{3i} q_i \, (ud-du)\chi_{MA}$$

$$\Rightarrow K^+ \left(\frac{1}{\sqrt{2}} K^- p + \frac{1}{\sqrt{2}} \overline{K}^0 n + \frac{1}{3}\eta\Lambda \right)$$

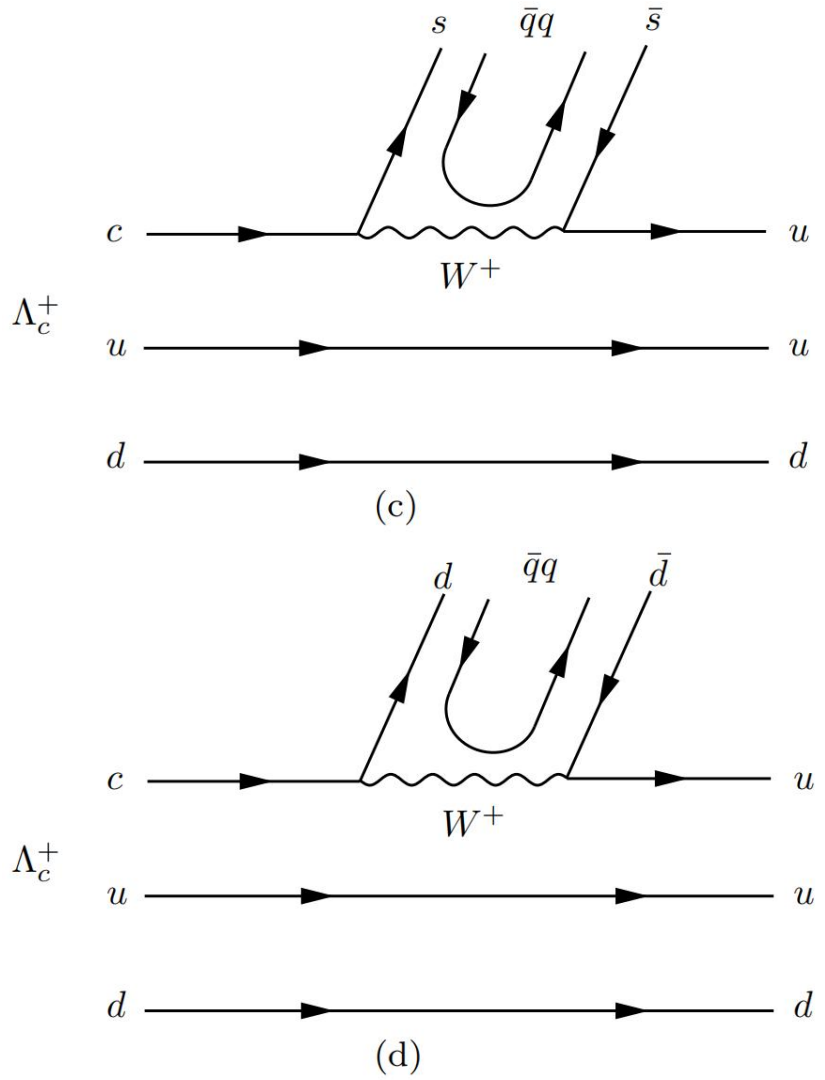
$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} u\bar{d}d(q\bar{q})(ud-du)\chi_{MA}$$

$$\Rightarrow \frac{1}{\sqrt{2}} \pi^+ \sum M_{2i} q_i \, (ud-du)\chi_{MA}$$

$$\Rightarrow \pi^+ \left(\frac{1}{\sqrt{2}} \pi^- p + \frac{1}{\sqrt{6}} \eta n - \frac{1}{2} \pi^0 n - \frac{1}{\sqrt{3}} K^0 \Lambda \right)$$

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- **Internal emission mechanisms**



$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} s(\bar{q}q)\bar{s}u(ud-du)\chi_{MA}$$

$$\Rightarrow \sum P_{3i}P_{i3}\frac{1}{\sqrt{2}} u(ud-du)\chi_{MA}$$

$$\Rightarrow \left(\frac{1}{\sqrt{2}}K^+K^- + \frac{1}{\sqrt{2}}K^0\overline{K}^0 + \frac{1}{3\sqrt{2}}\eta\eta\right)p$$

$$\Lambda_c^+ \Rightarrow \frac{1}{\sqrt{2}} c(ud-du)\chi_{MA} \Rightarrow \frac{1}{\sqrt{2}} d(\bar{q}q)\bar{d}u(ud-du)\chi_{MA}$$

$$\Rightarrow \sum P_{2i}P_{i2}\frac{1}{\sqrt{2}} u(ud-du)\chi_{MA}$$

$$\Rightarrow \left(\frac{1}{\sqrt{2}}\pi^-\pi^+ + \frac{1}{3\sqrt{2}}\eta\eta - \frac{1}{\sqrt{3}}\pi^0\eta + \frac{1}{2\sqrt{2}}\pi^0\pi^0 + \frac{1}{\sqrt{2}}K^0\overline{K}^0\right)p$$

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

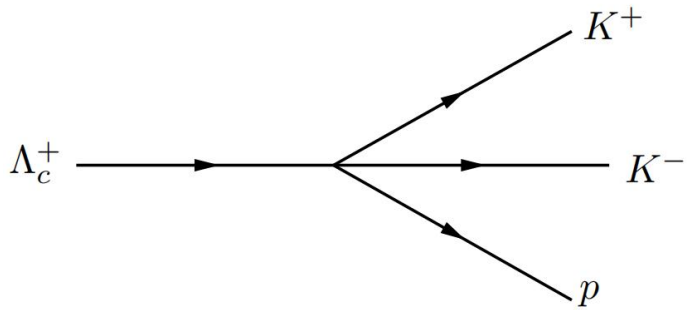
- **Dynamic Production of $\Lambda(1405)$ and $\Lambda(1670)$**

$$\mathcal{T}^{tree} = V_{MB}(C h_{K^-p} + h_{K^+K^-})$$

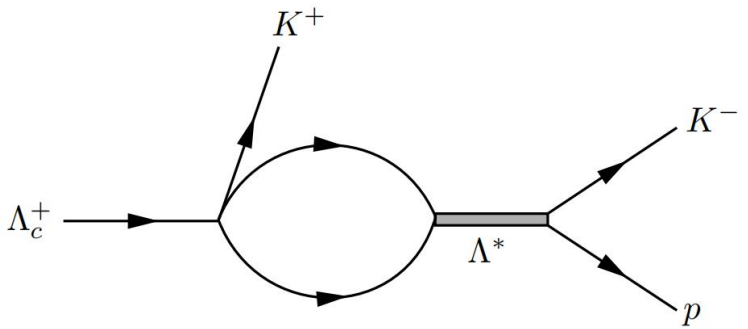
$$\mathcal{T}^{MB} = V_{MB}\left[C\sum_i h_i\, G_i(M_{\text{inv}})\, t_{i\to K^-p}(M_{\text{inv}}) + h_{K^+K^-} G_{K^-p}(M_{\text{inv}})\, t_{K^-p\to K^-p}(M_{\text{inv}})\right]$$

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

- Final states interaction



(a)



(b)

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

✓ 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:

$$G_l(\sqrt{s}) = \frac{2M_l}{16\pi^2}\{a_l(\mu) + ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}ln\frac{m_l^2}{M_l^2}$$

$$+ \frac{|\vec{q}|}{\sqrt{s}}[\ln(s - (M_l^2 - m_l^2) + 2|\vec{q}|\sqrt{s})$$

$$+ \ln(s + (M_l^2 - m_l^2) + 2|\vec{q}|\sqrt{s}) - \ln(-s + (M_l^2 - m_l^2)$$

$$+2|\vec{q}|\sqrt{s} - \ln(-s - (M_l^2 - m_l^2) + 2|\vec{q}|\sqrt{s})]\}$$

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

✓ The subtraction constant:

$a_{\bar{K}N} = -1.84$, $a_{\pi\Sigma} = -2.00$, $a_{\pi\Lambda} = -1.83$,

$a_{\eta\Lambda} = -2.25$, $a_{\eta\Sigma} = -2.38$, $a_{K\Xi} = -2.776$.

S. C. Zhang, M. Y. Duan, W. T. Lyu, G. Y. Wang, J. Y. Zhu and E. Wang, Eur. Phys. J. C **84**, no.12, 1253 (2024)

Table I
C_{ij} coefficients of Eq. (7). $C_{ji} = C_{ij}$

	K^-p	$\bar{K}^0n$	$\pi^0\Lambda$	$\pi^0\Sigma^0$	$\eta\Lambda$	$\eta\Sigma^0$	$\pi^+\Sigma^-$	$\pi^-\Sigma^+$	$K^+\Xi^-$	$K^0\Xi^0$
K^-p	2	1	$\frac{\sqrt{3}}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{\sqrt{3}}{2}$	0	1	0	0
$\bar{K}^0n$		2	$-\frac{\sqrt{3}}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$-\frac{\sqrt{3}}{2}$	1	0	0	0
$\pi^0\Lambda$			0	0	0	0	0	0	$\frac{\sqrt{3}}{2}$	$-\frac{\sqrt{3}}{2}$
$\pi^0\Sigma^0$				0	0	0	2	2	$\frac{1}{2}$	$\frac{1}{2}$
$\eta\Lambda$					0	0	0	0	$\frac{3}{2}$	$\frac{3}{2}$
$\eta\Sigma^0$						0	0	0	$\frac{\sqrt{3}}{2}$	$-\frac{\sqrt{3}}{2}$
$\pi^+\Sigma^-$							2	0	1	0
$\pi^-\Sigma^+$								2	0	1
$K^+\Xi^-$									2	1
$K^0\Xi^0$										2

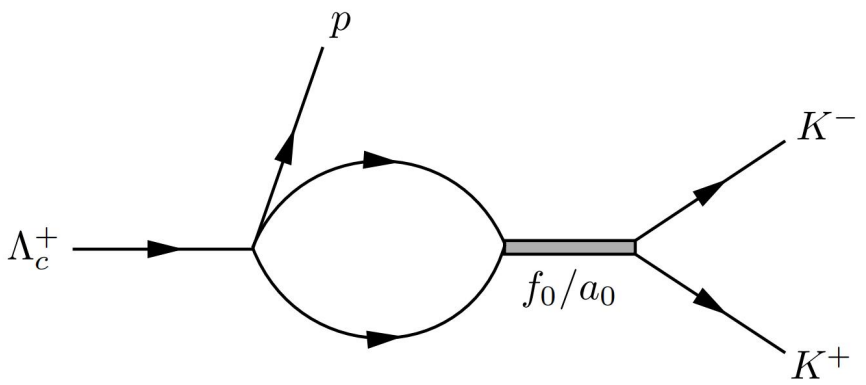
E. Oset and A. Ramos, Nucl. Phys. A 635, 99 (1998)

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- **Dynamic Production of $f_0(980)$ and $a_0(980)$**

$$
\begin{aligned}
&\mathrm{T}^{MM} \\
&= V_{MM}\{Ch_{K^-p}G_{K^+K^-}t_{K^+K^-\to K^+K^-} + Ch_{\pi^-p}G_{\pi^+\pi^-}t_{\pi^+\pi^-\to K^+K^-} \\
&+ [h_{K^+K^-}G_{K^+K^-}t_{K^+K^-\to K^+K^-} + h_{K^0\overline{K}^0}G_{K^0\overline{K}^0}t_{K^0\overline{K}^0\to K^+K^-} + 2 \\
&\times \frac{1}{2} h_{\eta\eta}G_{\eta\eta}\tilde{t}_{\eta\eta\to K^+K^-}] \\
&+ \left[h_{\pi^+\pi^-}G_{\pi^+\pi^-}t_{\pi^+\pi^-\to K^+K^-} + 2 \times \frac{1}{2} h_{\eta\eta}G_{\eta\eta}\tilde{t}_{\eta\eta\to K^+K^-}\right. \\
&+ h_{\pi^0\eta}G_{\pi^0\eta}t_{\pi^0\eta\to K^+K^-} + 2 \times \frac{1}{2} h_{\pi^0\pi^0}G_{\pi^0\pi^0}\tilde{t}_{\pi^0\pi^0\to K^+K^-} \\
&\left. + h_{K^0\overline{K}^0}G_{K^0\overline{K}^0}t_{K^0\overline{K}^0\to K^+K^-}]\right\}
\end{aligned}
$$

- Final states interaction



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

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- By taking $G_{K^0\overline{K}^0} = G_{K^+K^-}$,

$$T^{MM}$$

$$= V_{MM}\left\{(C\mathrm{h}_{\pi^-p} + \mathrm{h}_{\pi^+\pi^-})G_{\pi^+\pi^-}t_{\pi^+\pi^-\to K^+K^-} + \frac{3+C}{2}\mathrm{h}_{K^0\overline{K}^0}G_{K^0\overline{K}^0}(t_{K^0\overline{K}^0\to K^+K^-} + t_{K^+K^-\to K^+K^-}) + 2\mathrm{h}_{\eta\eta}G_{\eta\eta}\tilde{t}_{\eta\eta\to K^+K^-}\right.$$

$$\left. + \mathrm{h}_{\pi^0\pi^0}G_{\pi^0\pi^0}\tilde{t}_{\pi^0\pi^0\to K^+K^-}\right\} + V_{MM}\left\{\mathrm{h}_{\pi^0\eta}G_{\pi^0\eta}t_{\pi^0\eta\to K^+K^-} + \frac{1-C}{2}\mathrm{h}_{K^0\overline{K}^0}G_{K^0\overline{K}^0}(t_{K^0\overline{K}^0\to K^+K^-} + t_{K^+K^-\to K^+K^-})\right\}$$

$$= t^{MM}_{I=0} + t^{MM}_{I=1}$$

where $\tilde{t}_{\eta\eta\to i} = \sqrt{2}t_{\eta\eta\to i}$ and $\tilde{t}_{\pi^0\pi^0\to i} = \sqrt{2}t_{\pi^0\pi^0\to i}$

- ✓ **5 coupled channels for $I = 0$**: $\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, $K^0\overline{K}^0$, $\eta\eta$;
- ✓ **3 coupled channels for $I = 1$**: K^+K^-, $K^0\overline{K}^0$, $\pi^0\eta$.

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

✓ The Bethe-Salpeter equation

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

✓ The loop function

$$G = i \int \frac{d^4}{(2\pi)^4} \frac{1}{(P-q)^2 - m_1^2 + i\epsilon} \frac{1}{q^2 - m_2^2 + i\epsilon} = \int_0^{q_{max}} \frac{\boldsymbol{q}^2 d\boldsymbol{q}}{(2\pi)^2} \frac{\omega_1 + \omega_2}{\omega_1 \omega_2} \frac{1}{s - (\omega_1 + \omega_2)^2 + i\epsilon}$$

$q_{max} = 600$ MeV

✓ An exponential smoothing factor

$$Gt(M_{K^+K^-}) = Gt(M_{cut}) e^{-\alpha(M_{K^+K^-} - M_{cut})}$$

$$M_{cut} = 1100 \text{ MeV}, \quad \alpha = 0.0054 \text{ MeV}^{-1}$$

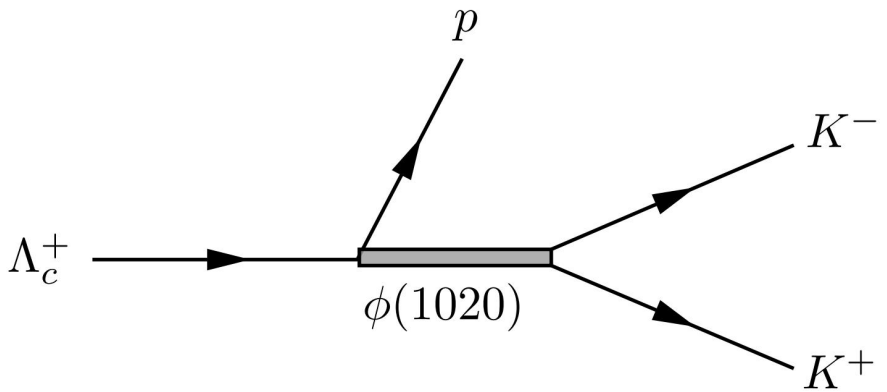
Z. Wang, Y. Y. Wang, E. Wang, D. M. Li and J. J. Xie, Eur. Phys. J. C **80,** no.9, 842 (2020)
V. R. Debastiani, W. H. Liang, J. J. Xie and E. Oset, Phys. Lett. B **766**, 59-64 (2017)
X. H. Zhang, H. Zhang, B. C. Ke, L. J. Liu, D. M. Li and E. Wang, Phys. Rev. D **110**, no.11, 114050 (2024)

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- **Contribution from the $\phi(1020)$**

$$\mathrm{T}^{\phi}_{s_p s_{\Lambda_c}} = \frac{V_{\phi(1020)}\,|\boldsymbol{p}^*_{K^+}|\,|\boldsymbol{p}^*_{p}|}{M^2_{K^+K^-} - m^2_{\phi} + i m_{\phi}\tilde{\Gamma}_{\phi}(M_{K^+K^-})}\,\chi^{\dagger}_{s_p}[\cos\theta\,\mathbf{1} + i\,r_T\sin\theta\,\boldsymbol{\sigma}\cdot\hat{\boldsymbol{n}}]\chi_{s_{\Lambda_c}}$$

$\chi^{\dagger}_{s_p}$, $\chi_{s_{\Lambda_c}}$: Pauli spinors; $\boldsymbol{\sigma}$: Pauli spin operator; Decay plane unit normal: $\hat{\boldsymbol{n}} = \frac{\boldsymbol{p}^*_p \times \boldsymbol{p}^*_{K^+}}{|\boldsymbol{p}^*_{K^+}|\,|\boldsymbol{p}^*_p|\sin\theta}$.



- Unpolarized spin-averaged amplitude:

$$|\mathrm{T}^{\phi(1020)}|^2 \equiv \frac{1}{2}\sum_{s_{\Lambda_c}, s_p}\left|\mathrm{T}^{\phi}_{s_p s_{\Lambda_c}}\right|^2 = \frac{V_{\phi(1020)}\,|\boldsymbol{p}^*_{K^+}|\,|\boldsymbol{p}^*_{p}|\left[\cos^2\theta + |r_T|^2\sin^2\theta\right]}{M^2_{K^+K^-} - m^2_{\phi} + i m_{\phi}\tilde{\Gamma}_{\phi}(M_{K^+K^-})}$$

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- Unpolarized spin-averaged amplitude:

$$|\mathrm{T}^{\phi(1020)}|^2 \equiv \frac{1}{2}\sum_{s_{\Lambda_c},s_p}\left|\mathrm{T}^{\phi}_{s_p s_{\Lambda_c}}\right|^2 = \frac{V_{\phi(1020)}\,|\boldsymbol{p}^*_{K^+}|\,|\boldsymbol{p}^*_{p}|\left[\cos^2\theta + |r_T|^2\sin^2\theta\right]}{M^2_{K^+K^-} - m^2_\phi + i\,m_\phi\,\tilde{\Gamma}_\phi(M_{K^+K^-})}$$

$$\tilde{\Gamma}_\phi(M_{K^+K^-}) = \Gamma_\phi\left[\frac{\sqrt{M^2_{K^+K^-} - 4m_K^2}}{\sqrt{m^2_\phi - 4m_K^2}}\right]^3$$

Model A: $m_\phi = 1019.46$ MeV, $\Gamma_\phi = 4.25$ MeV;

S. Navas et al. [Particle Data Group], Phys. Rev. D **110**, no.3, 030001 (2024)

Model B: m_ϕ, Γ_ϕ as free parameters.

The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- **The total amplitude**

$$|\mathcal{T}^{Total}|^2 = |\mathcal{T}^{tree} + \mathcal{T}^{MB} e^{i\phi_1\pi} + \mathcal{T}^{MM} e^{i\phi_2\pi}|^2 + |\mathcal{T}^{\phi(1020)}|^2$$

- **The invariant mass distributions for the process $\Lambda_c^+ \to pK^+K^-$:**

$$\frac{d^2\Gamma}{dM_{pK^-}dM_{K^+K^-}} = \frac{1}{(2\pi)^3}\frac{M_p}{2M^2_{\Lambda_c^+}}|\mathcal{T}^{Total}|^2 M_{pK^-}M_{K^+K^-}$$

- **Detector resolution convolution:**

$$F_{\text{conv}}(M_{\text{rec}}) = \int_{M_{K^+K^-}-3\sigma_1}^{M_{K^+K^-}+3\sigma_1} F(M)\, R(M_{\text{rec}}, \text{M})\, dM$$

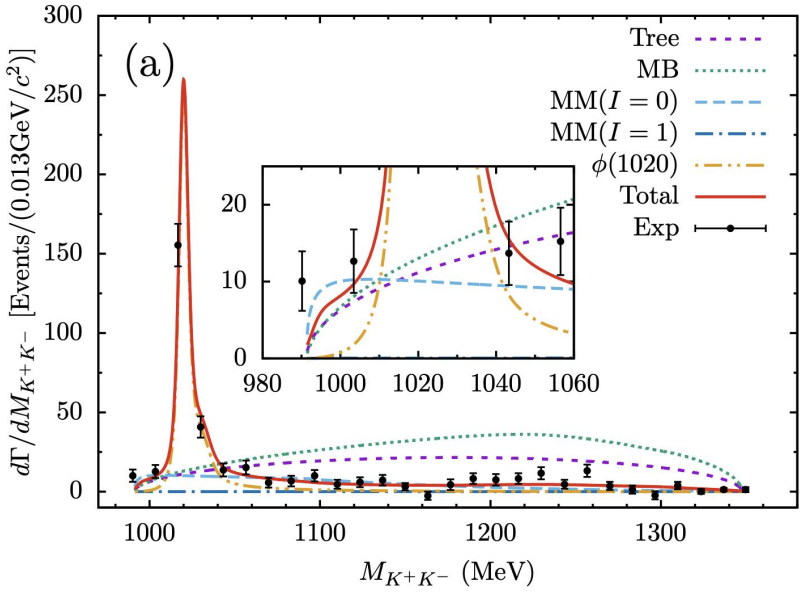
$$F(M_{K^+K^-}) = \frac{d\Gamma}{dM_{K^+K^-}} = \int_{M_{pK^-}^{min}}^{M_{pK^-}^{max}} \frac{d^2\Gamma}{dM_{pK^-}dM_{K^+K^-}} dM_{pK^-}, \quad R(M_{\text{rec}}, \text{M}) = \sum_{i=1}^{2} \frac{a_i}{\sqrt{2\pi}\sigma_i} exp\left[-\frac{(M_{\text{rec}} - \text{M} - \delta_i)^2}{2\sigma_i^2}\right]$$

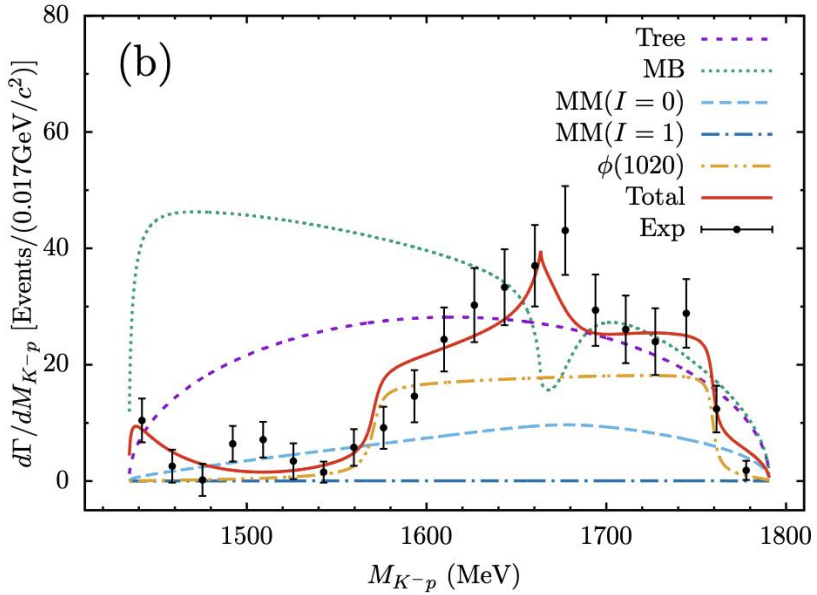
M. Ablikim et al. [BESIII], Phys. Rev. D **114** (2026) no.3,032008
Q. Huang, Y. J. Zeng, X. R. Lyu, R. G. Ping and J. J. Wu, arXiv:2608.29006 [hep-ph]

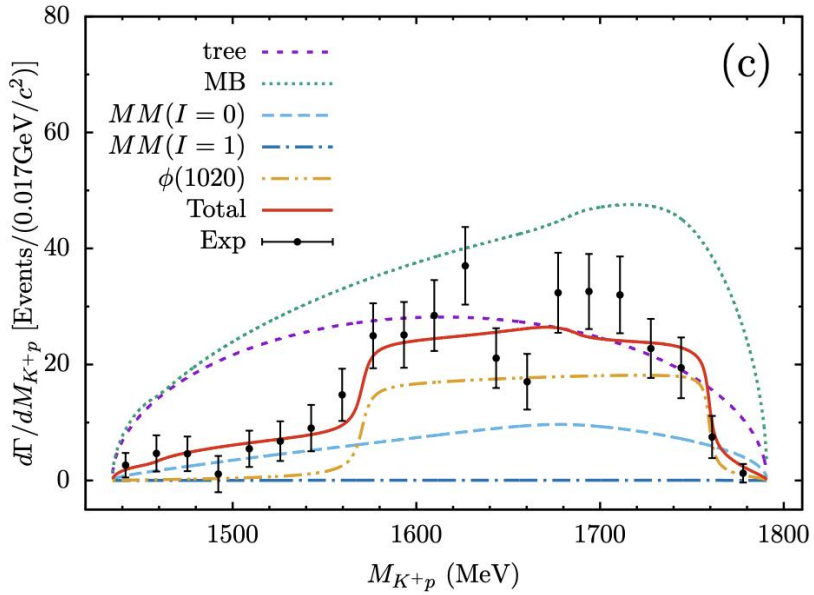
The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- **Model A: χ^2/d.o.f. = 1.28**

Parameter	V_{MB}	V_{MM}	$V_{\phi(1020)}$	r_T	ϕ_1	ϕ_2
Model A	$(12.48 \pm 1.25) \times 10^{-2}$	$(8.08 \pm 2.35) \times 10^{-2}$	$(5.68 \pm 0.50) \times 10^{-2}$	1.02 ± 0.12	0.32 ± 0.05	-0.59 ± 0.12





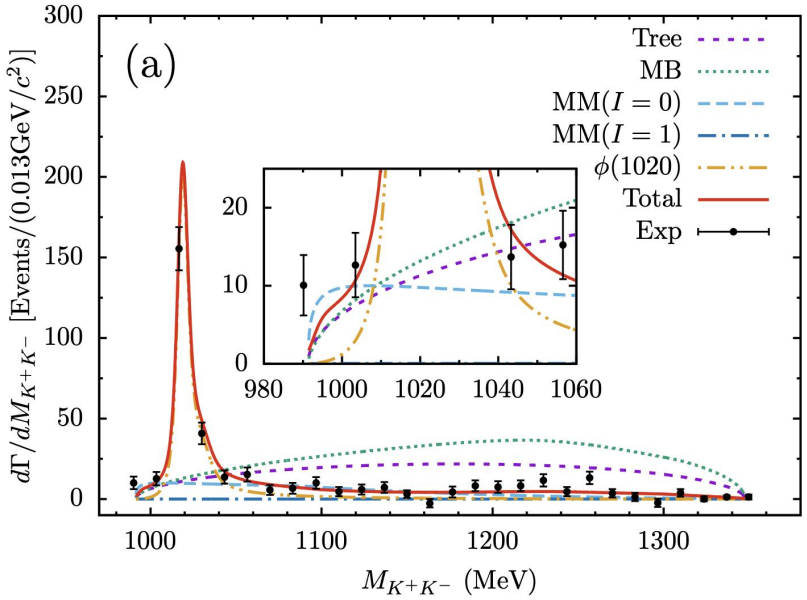


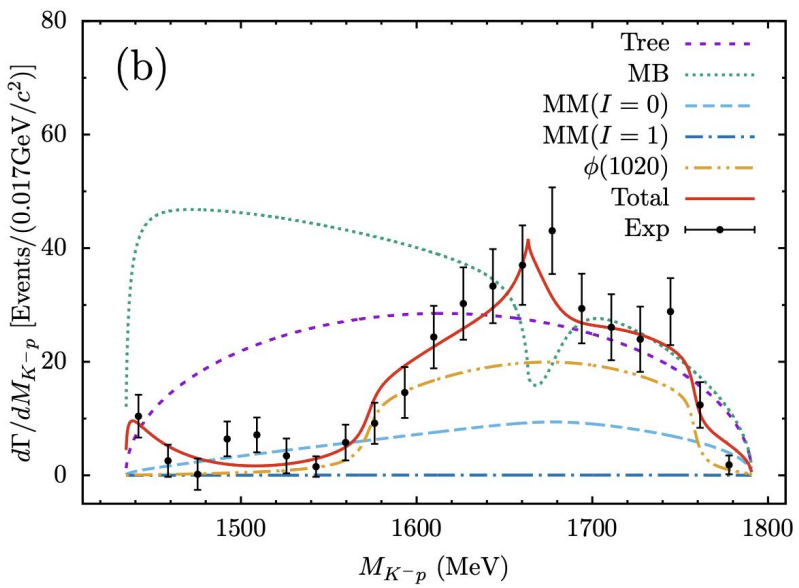
The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

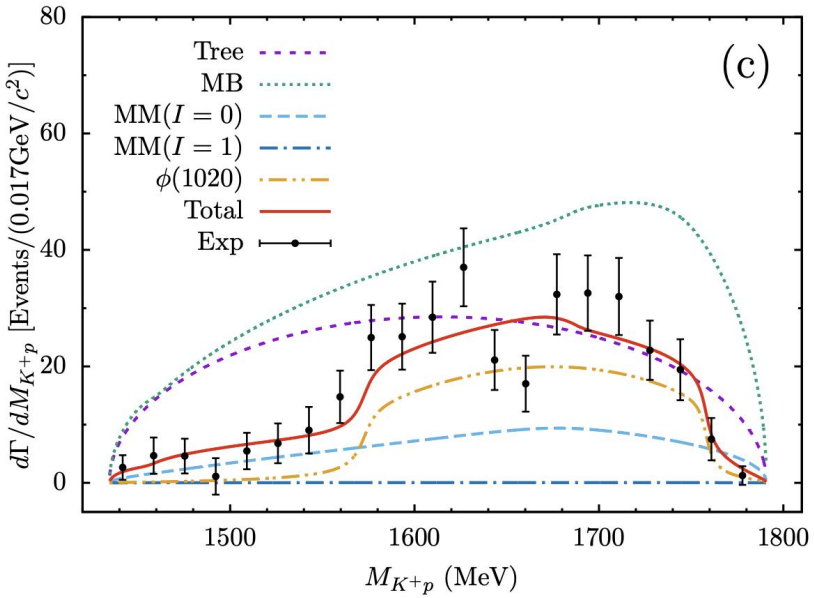
- **Model B: χ^2/d.o.f. = 1.06**

Parameter	V_{MB}	V_{MM}	$V_{\phi(1020)}$	$m_{\phi(1020)}$
Model B	$(12.55 \pm 1.28) \times 10^{-2}$	$(7.96 \pm 2.56) \times 10^{-2}$	$(5.96 \pm 0.91) \times 10^{-2}$	1018.47 ± 0.37

Parameter	r_T	ϕ_1	ϕ_2	$\Gamma_{\phi(1020)}$
Model B	1.24 ± 0.21	0.32 ± 0.05	3.41 ± 0.12	5.98 ± 1.20

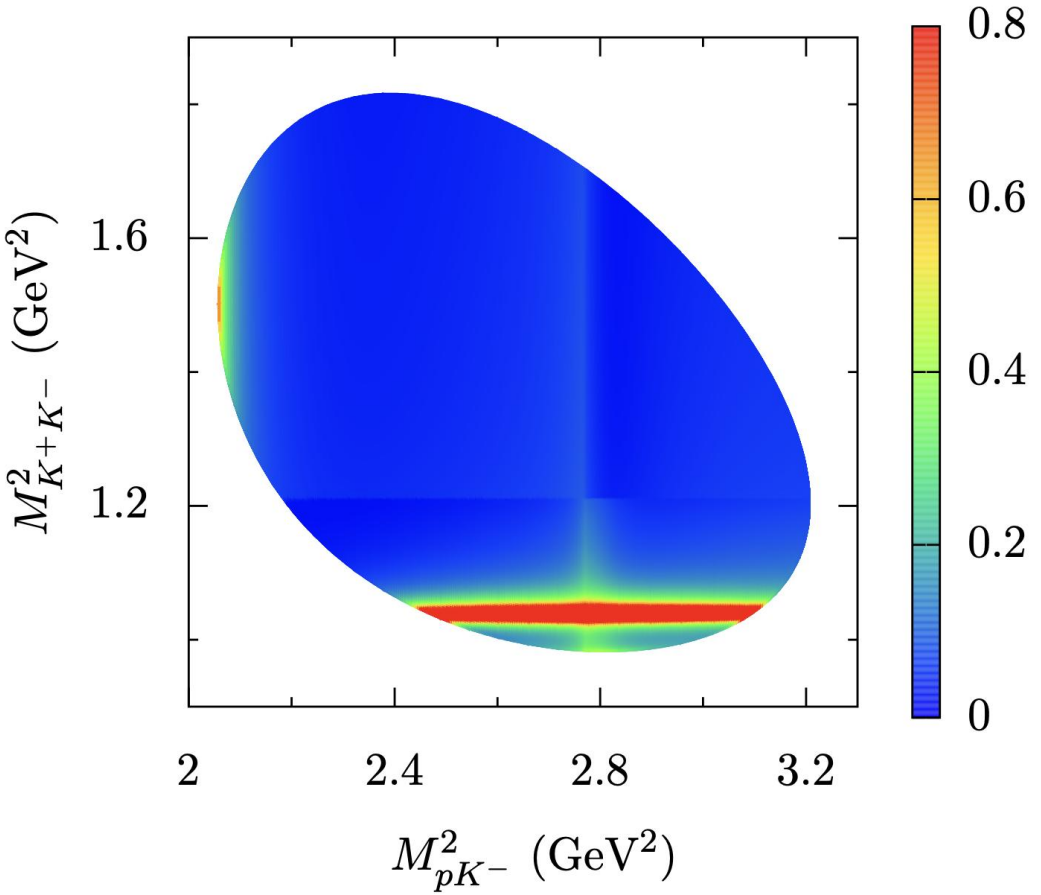






The $\Lambda(1670)$ in $\Lambda_c^+ \to pK^+K^-$

- **Model B: χ^2/d.o.f. = 1.06**



$M^2_{pK^-}$ vs $M^2_{K^+K^-}$

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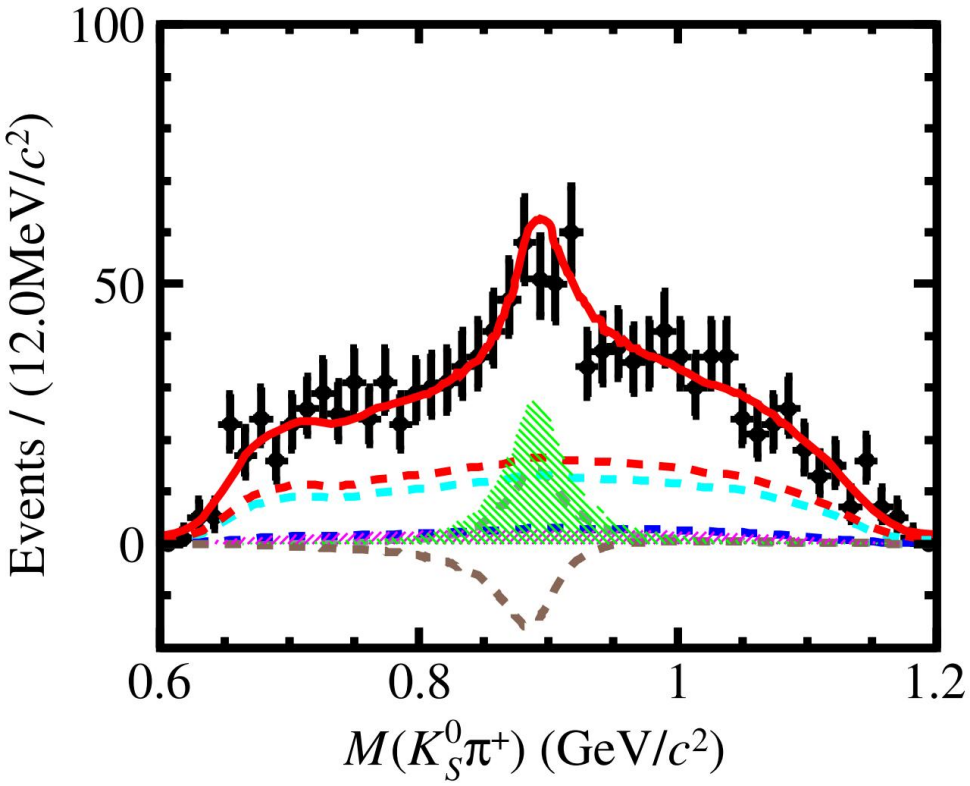
03 The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0\pi^+$

04 Summary

The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

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

- $\mathcal{B}(\Lambda_c^+ \to \Lambda K_S^0 \pi^+) = (1.73 \pm 0.26 \pm 0.01) \times 10^{-3}$
- 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.

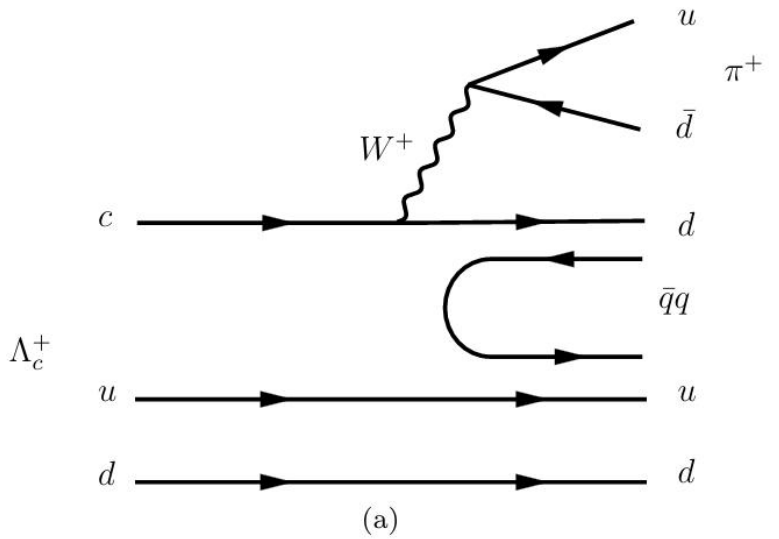


M. Ablikim *et al*. [BESIII],
Phys. Rev. D **111**, no.1, 012014 (2025)

The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

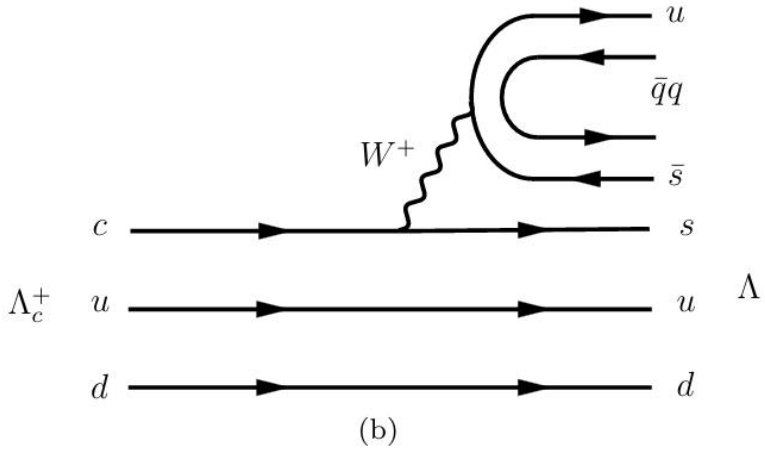
- **External emission mechanisms**

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



(a)

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

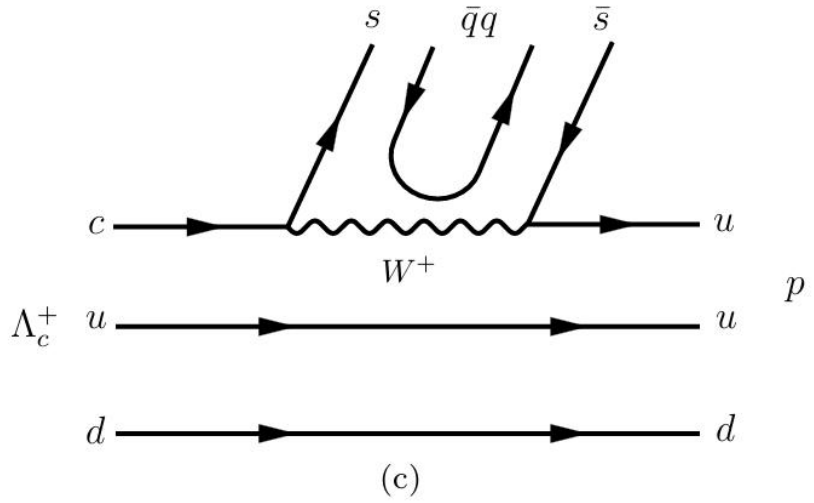


(b)

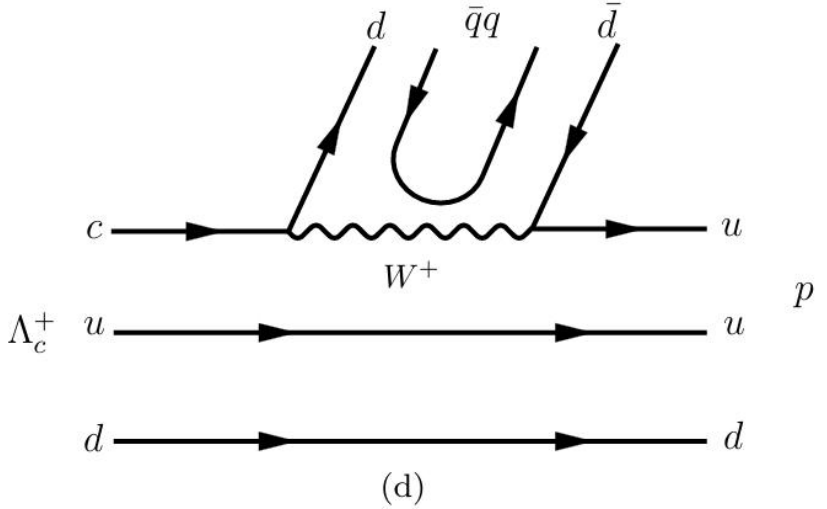
The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

- **Internal emission mechanisms**

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



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



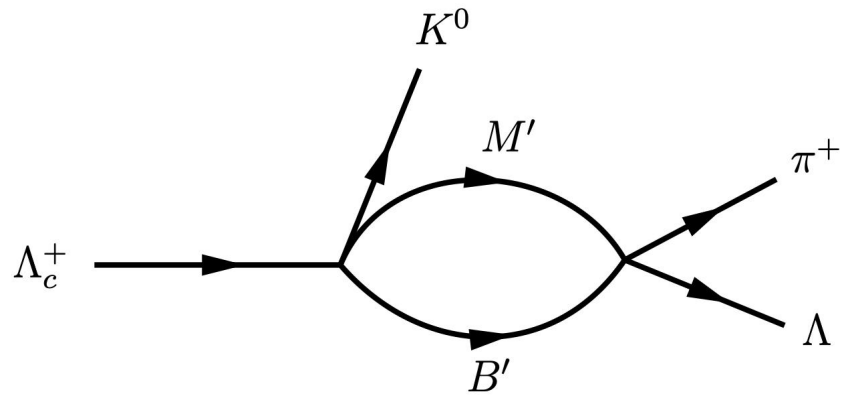
The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

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

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

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

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



✓ 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:

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

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

The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

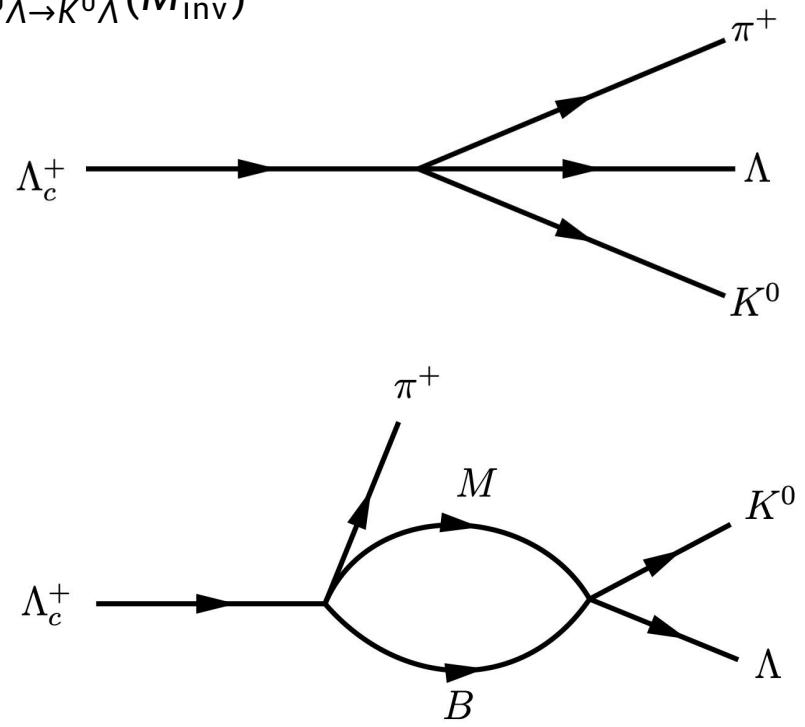
- The scattering matrix for the mechanism of $\Lambda_c^+ \to \pi^+ MB \to \pi^+ K^0 \Lambda$ is given by

$$\mathcal{T}^{Tree} = V_P\left(\mathrm{h}_{K^0\Lambda} + \mathrm{h}_{\pi^+K^0}\right)$$

$$\mathcal{T}^{N(1535)} = V_P\left[\sum_i \mathrm{h}_i\, \tilde{G}_i(M_{\mathrm{inv}})\, t_{i\to K^0\Lambda}(M_{\mathrm{inv}}) + \mathrm{h}_{\pi^+K^0}\tilde{G}_{K^0\Lambda}(M_{\mathrm{inv}})\, t_{K^0\Lambda\to K^0\Lambda}(M_{\mathrm{inv}})\right.$$

$$\left. + \frac{1}{C}\mathrm{h}_{\pi^-\pi^+}\tilde{G}_{\pi^-p}(M_{\mathrm{inv}})\, t_{\pi^-p\to K^0\Lambda}(M_{\mathrm{inv}})\right]$$

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



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

✓ 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)

The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

- **Contribution from the $K^*(892)$**

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

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

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

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

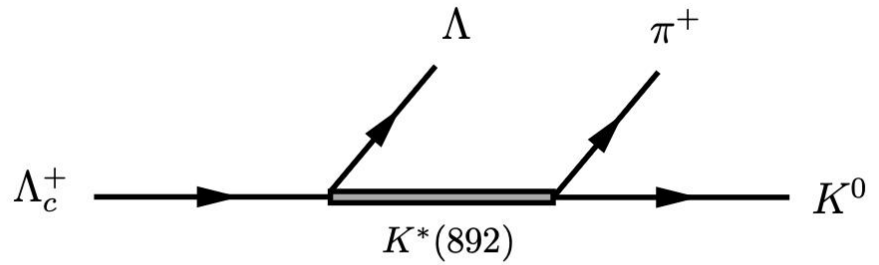


FIG. 3: Mechanisms for the $\Lambda_c^+ \to \Lambda K^0 \pi^+$ decay via the intermediate $K^*(892)$.

- 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}

The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

- **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:

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

- In total we have 3 free parameters:

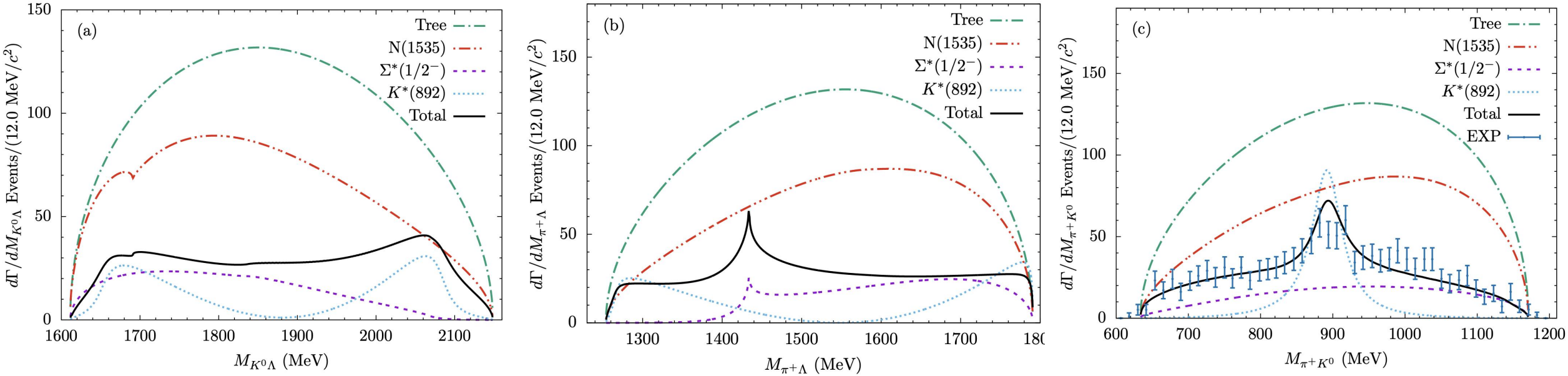
  the phase angles: $\phi = (1.73 \pm 0.11)\pi$, $\phi' = (1.57 \pm 0.06)\pi$;

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

The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

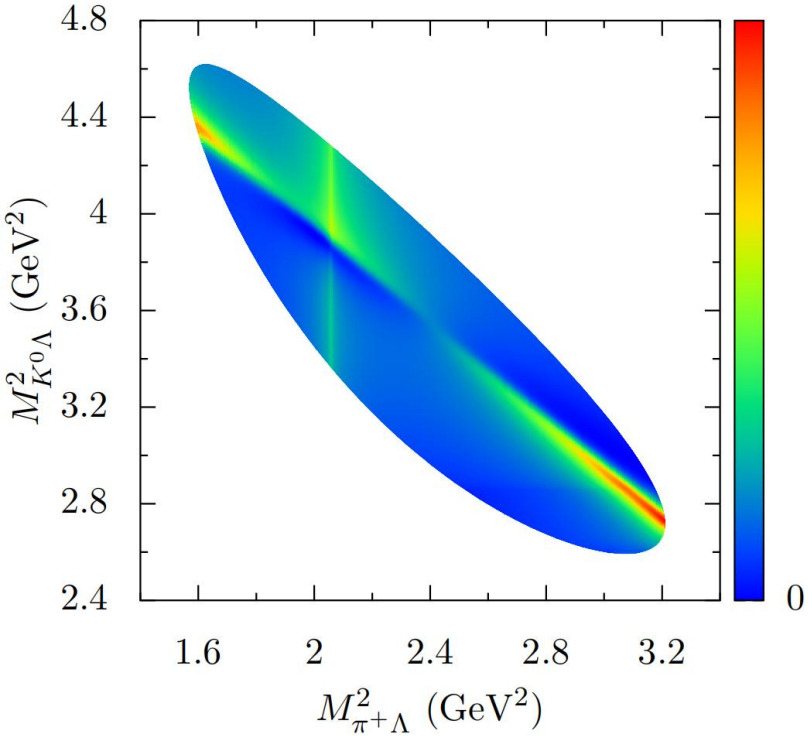
- The invariant mass distributions with phase interference

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

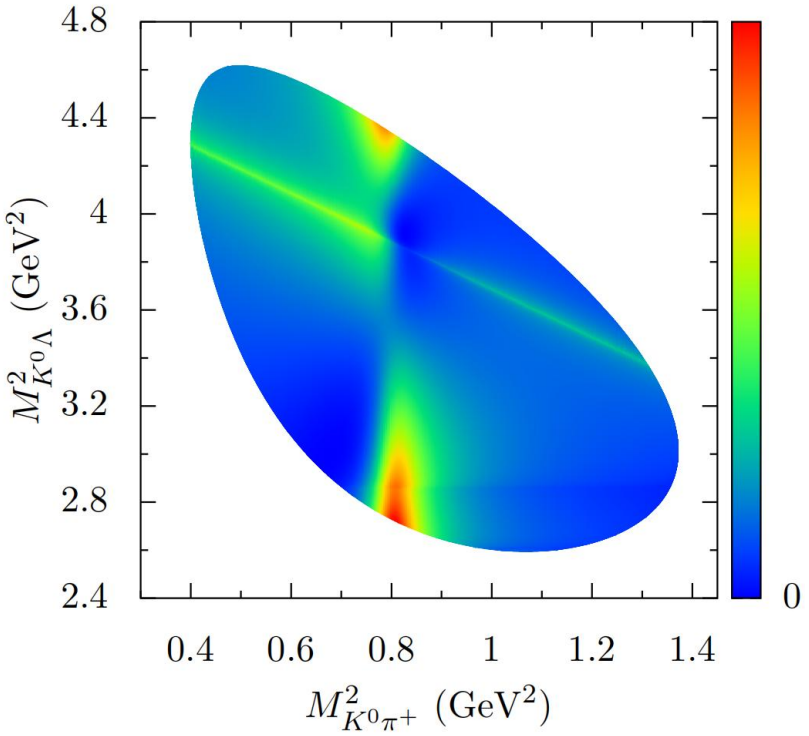


The $\Sigma^*(1/2^-)$ in $\Lambda_c^+ \to \Lambda K^0 \pi^+$

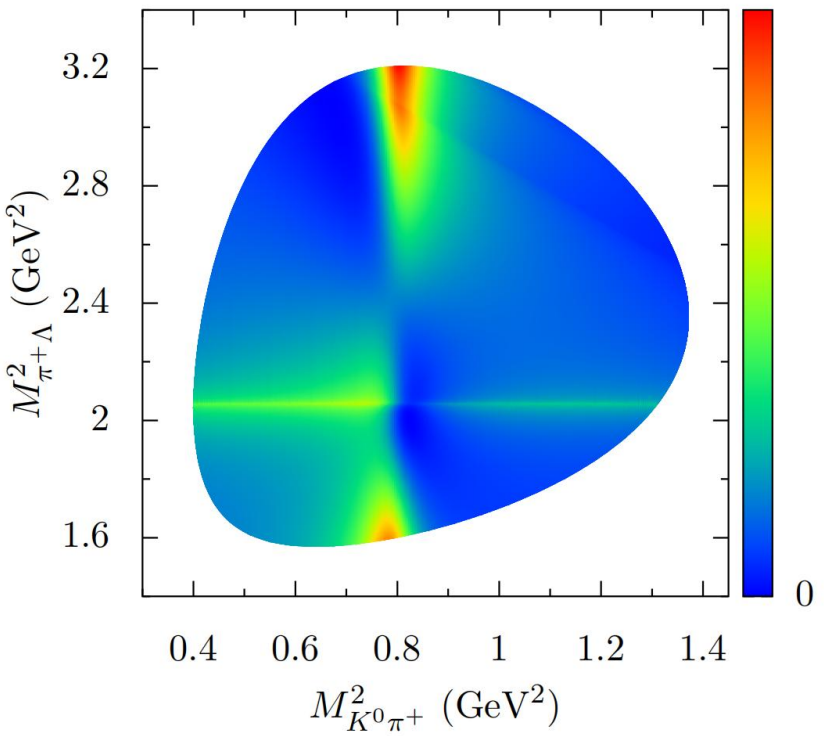
- The Dalitz plots



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



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



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

郑州大学
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04 **Summary**

Summary

$\Lambda(1670)$

- By considering **the *S*-wave meson-baryon interaction, meson-meson interaction** and the contribution of $\phi(1020)$, we studied the $\Lambda_c^+ \to pK^+K^-$ decay.
- We predicted **a clear cusp structure around 1670 MeV** in **the pK^- invariant mass distribution**, which is consistent with existing experimental results.

$\Sigma(1/2^-)$

- By considering **the *S*-wave meson-baryon interaction** and the contribution of **$K^*(892)$** , we studied the $\Lambda_c^+ \to \Lambda K^0\pi^+$ decay.
- We predicted **a distinct cusp structure around 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 $J^P = 1/2^-$ low-lying excited baryons.

Thank you for attention!