Test the two-pole structure of the $\Xi(1820)$ state

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2025 年轻强子专题研讨会

2025年5月8-12日, 安阳

Based on: R. Molina, WHL, C.W. Xiao, Z.F. Sun, E. Oset, PLB856 (2024) 138872;
WHL, R. Molina, E. Oset, PRD110 (2024) 036005;
M.Y. Duan, J. Song, WHL, E. Oset, EPJC84 (2024) 947.

Outline

- Introduction: two-pole structure and the $\Xi(1820)$ state
- Reactions testing the two states of $\Xi(1820)$
  - $\psi(3686) \to \bar{\Xi}^+ K^- \Lambda$
  - $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$
  - $\Omega_c \to \pi\pi\Xi^*,\ \eta\pi\Xi^*$
- Summary

◆ Introduction: two-pole structure and the $\Xi(1820)$ state

- **Two-pole structure:** $\Lambda(1405)$

  Oller, Meißner, PLB500(2001)263;

  Jido, Oller, Oset, Ramos, Meißner, NPA725(2003)181

Pseudoscar meson – baryon($\frac{1}{2}^+$) interaction in $S=-1$ sector, from LO of chiral Lagrangians.

Detailed review papers:

Meißner, Symmetry 12(2020)981;

Mai, Eur.Phys.J.ST 230 (2021)1593.

Other two-pole states:

$$D_0^*(2300), K_1(1270), Y(4260), \cdots$$

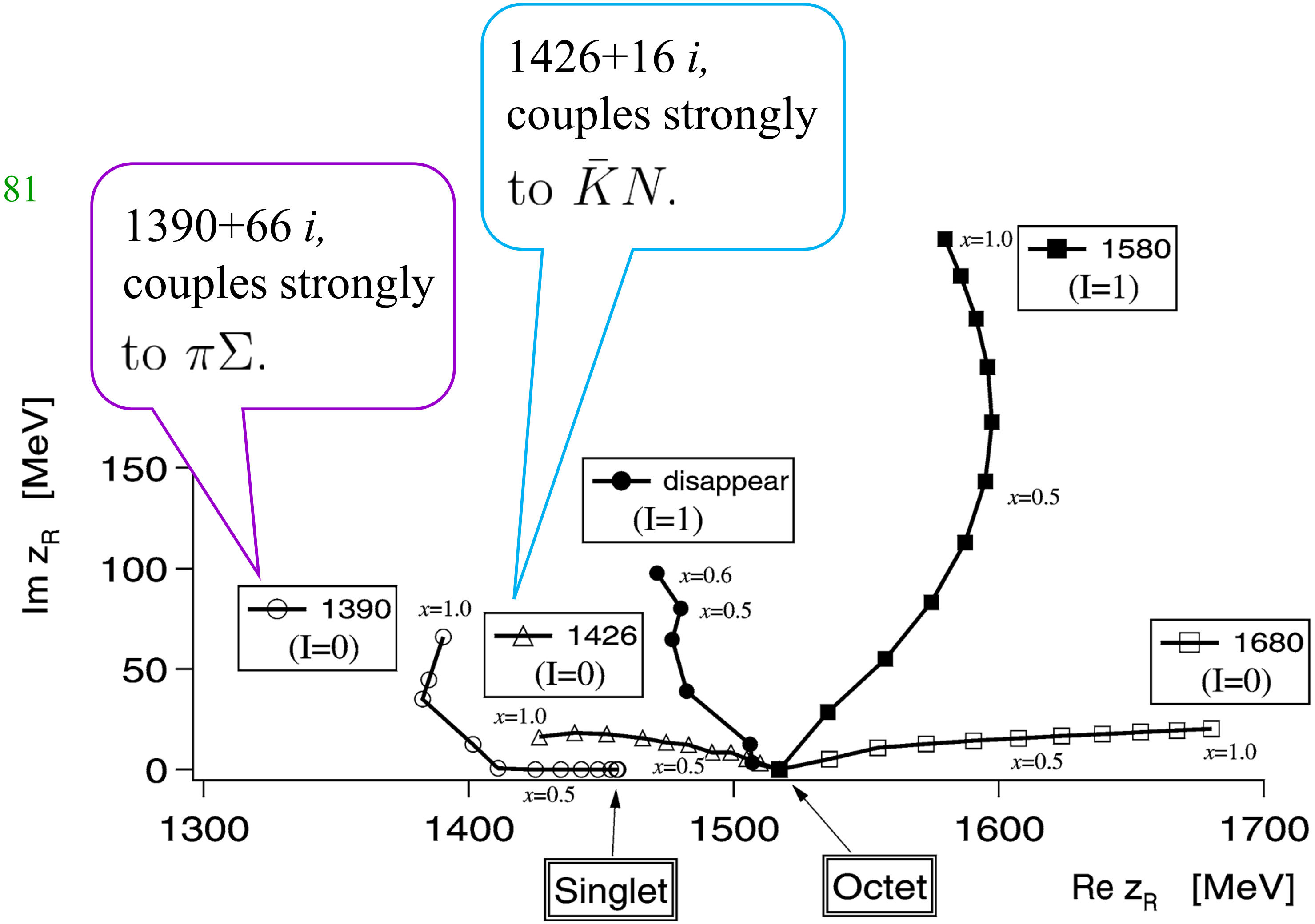


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x=0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

◆ Introduction: two-pole structure and the Ξ(1820) state

- **Two states of Ξ(1820)**

Sarkar, Oset, Vicente Vacas, NPA750(2005)294;
Molina, WHL, Xiao, Sun, Oset, PLB856(2024) 138872.

The work of Λ(1405) was extended to
pseudoscar meson – baryon($\frac{3}{2}^+$) interaction.

Four coupled channels : $(S=-2)$ $\Sigma^*\bar{K}$, $\Xi^*\pi$, $\Xi^*\eta$, ΩK
[1878] [1669] [2078] [2165]

Transition potential:

$$V_{ij} = -\frac{1}{4f^2} C_{ij}(k^0 + k'^0);\ f = 1.28 f_\pi,\ f_\pi = 93\,\mathrm{MeV},$$

Bethe-Salpeter (BS) equation: $T = [1 - VG]^{-1} V.$

C_{ij}	$\Sigma^*\bar{K}$	$\Xi^*\pi$	$\Xi^*\eta$	ΩK
$\Sigma^*\bar{K}$	2	1	3	0
$\Xi^*\pi$		2	0	$\frac{3}{\sqrt{2}}$
$\Xi^*\eta$			0	$\frac{3}{\sqrt{2}}$
ΩK				3

Table 2
Pole positions and couplings for $q_{max} = 830$ MeV. All quantities are given in units of MeV.

Poles	$\lvert g_i\rvert$	g_i	channels
$\boxed{1824 - 31i}$	3.22	$3.22 - 0.096i$	$\bar{K}\Sigma^*$
	1.71	$1.55 + 0.73i$	$\pi\Xi^*$
	2.61	$2.58 - 0.38i$	$\eta\Xi^*$
	1.62	$1.47 + 0.67i$	$K\Omega$
$\boxed{1875 - 130i}$	2.13	$0.29 + 2.11i$	$\bar{K}\Sigma^*$
	3.04	$-2.07 + 2.23i$	$\pi\Xi^*$
	2.20	$1.11 + 1.90i$	$\eta\Xi^*$
	3.03	$-1.77 + 2.45i$	$K\Omega$

Two poles correspond to Ξ(1820).

◆ Reactions testing the two states of Ξ(1820): $\psi(3686) \to \bar{\Xi}^+ K^- \Lambda$

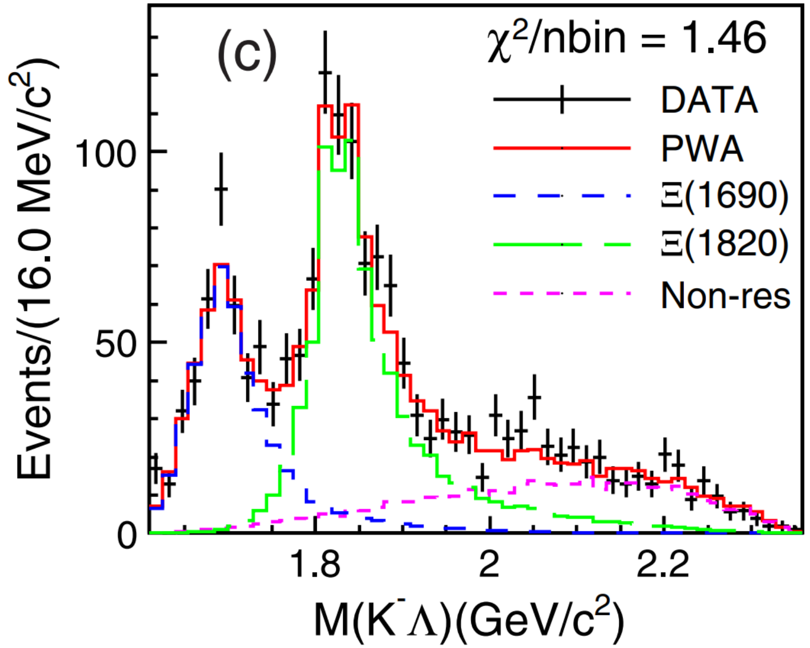
- $\psi(3686) \to \bar{\Xi}^+ K^- \Lambda$

BESIII, PRD109(2024)072008;

➤ New results from BESIII

TABLE VI. Results obtained for $I(J^P)$, mass and width for each component. The first (second) uncertainty is statistical (systematic).

Resonance	$I(J^P)$	M (MeV/c^2)	Γ (MeV)
$\Xi(1690)^-$	$1/2(1/2^-)$	$1685^{+3}_{-2} \pm 12$	$81^{+10}_{-9} \pm 20$
$\Xi(1820)^-$	$1/2(3/2^-)$	$1821^{+2}_{-3} \pm 3$	$73^{+6}_{-5} \pm 9$



PDG estimate: $\mathbf{M}^{\rm PDG}_{\mathbf{\Xi(1820)}} = \mathbf{1823 \pm 5}$ MeV, $\quad \mathbf{\Gamma}^{\rm PDG}_{\mathbf{\Xi(1820)}} = \mathbf{24^{+15}_{-10}}$ MeV

The width of Ξ(1820) is much bigger, and incompatible with that of PDG!

One or two states for Ξ(1820)?

◆ Reactions testing the two states of Ξ(1820)

- Two states of Ξ(1820) in $\psi(3686) \to \bar{\Xi}^+ K^- \Lambda$
  - ✓ The first test

The amplitude is of the type

$$t = \sum_{i,j} A_j \, \vec{\epsilon}_\psi \cdot \vec{p}_{\bar{\Xi}} \, G_j(PB^*) \, T_{ji} \, C_i \, \tilde{k}^2$$

$$\sim \sum_{i,j} D_{ij} \, \tilde{k}^2 \, \vec{\epsilon}_\psi \cdot \vec{p}_{\bar{\Xi}} \, T_{ji},$$

The invariant mass distribution:

$$\frac{d\Gamma}{dM_{\rm inv}(K^-\Lambda)} = \frac{1}{(2\pi)^3} \frac{1}{4M_\psi^2} \, p_{\bar{\Xi}} \, \tilde{k} \, \bar{\sum} |t|^2$$

$$= W \, p_{\bar{\Xi}}^3 \, \tilde{k}^5 \sum_{ij} \left| D_{ij} \, T_{ji} \right|^2,$$

Back ground: $C \, p_{\bar{\Xi}} \, \tilde{k},$

with W and C arbitrary weights.

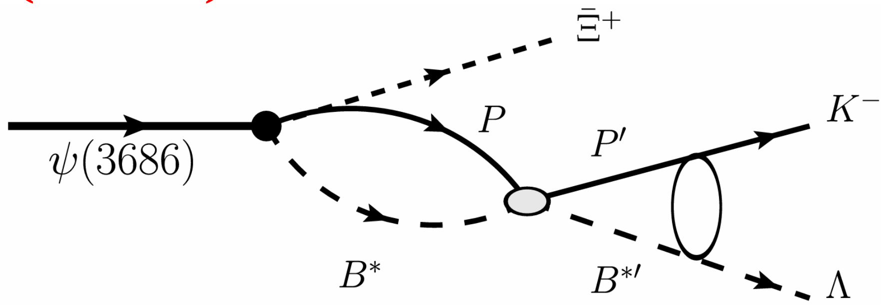


Fig. 1. The resonant mechanism for the production of $\bar{\Xi}^+ K^- \Lambda$ in the $\psi(3686)$ decay. $P\,(P')$ and $B^*\,(B^{*\prime})$ stand for pseudoscalar meson and decuplet baryon, respectively.

✓ The second test

$$\frac{A}{M_{\rm inv} - M_{R_1} + i\frac{\Gamma_1}{2}} + \frac{B}{M_{\rm inv} - M_{R_2} + i\frac{\Gamma_2}{2}},$$

R1, the narrower Ξ(1820) state with lower mass.

R2, the wider Ξ(1820) state with higher mass.

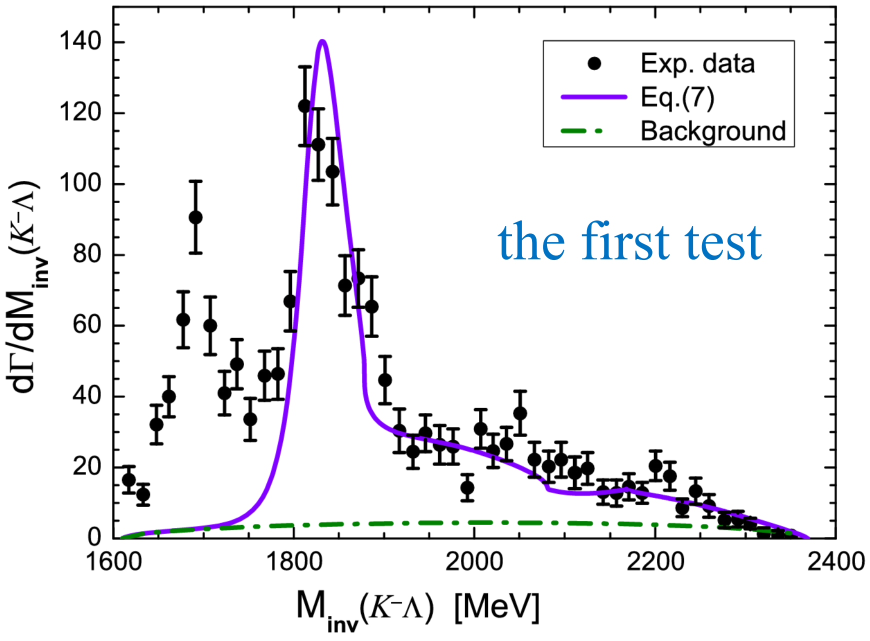
Adjust the coefficients A and B to fit the data.

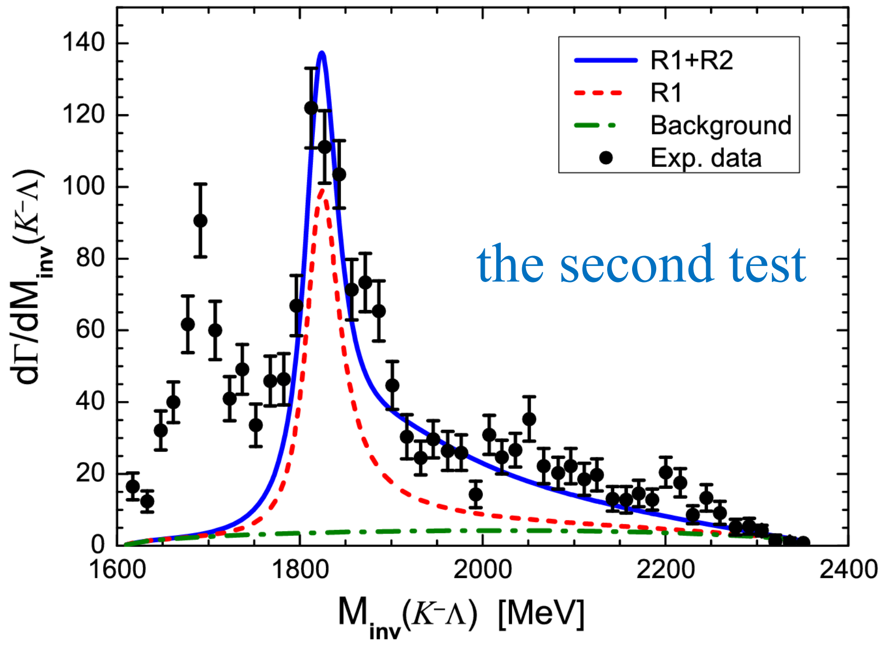
◆ Reactions testing the two states of Ξ(1820): $\psi(3686) \to \bar{\Xi}^+ K^- \Lambda$

- Two states of Ξ(1820) in $\psi(3686) \to \bar{\Xi}^+ K^- \Lambda$

✓ Same background in the two test cases.

✓ The coefficients A and B are found to have about the same strength.





✓ A fair description of the data is obtained, supporting the two states of Ξ(1820).

✓ Mostly the narrow resonance at 1824 MeV shows up, with the wider resonance providing strength in the higher energy region.

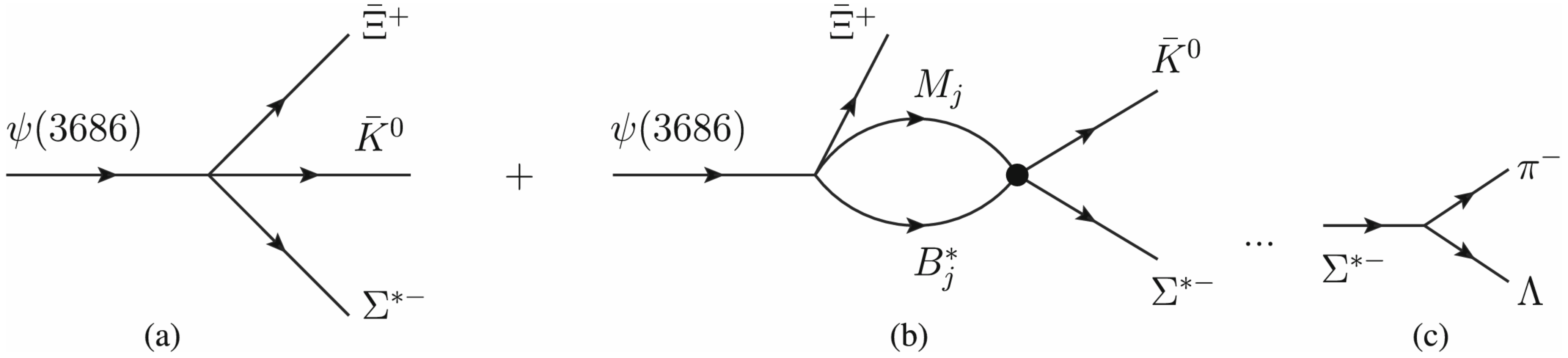
◆ Reactions testing the two states of Ξ(1820): $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$

- $\psi(3686) \to \bar{\Xi}^+ \underline{\bar{K}^0 \Sigma^{*-}} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$

with a threshold ~1880 MeV

Coupled channels: $\bar{K}^0 \Sigma^{*-}$, $K^- \Sigma^{*0}$, $\pi^0 \Xi^{*-}$, $\eta \Xi^{*-}$, $\pi^- \Xi^{*0}$, $K^0 \Omega^-$

The mechanism for $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-}$:



tree level

rescattering of the meson-baryon coupled channels

$\Sigma * - \to \pi^- \Lambda$

◆ Reactions testing the two states of Ξ(1820): $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$

The decay amplitude for $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-}$:

2-body scattering amplitudes

$$t = C \langle B^* \,|\, (\mathbf{S}^+ \times \mathbf{p}_{\bar{\Xi}^+}) \cdot \boldsymbol{\epsilon} \,|\, \Xi^- \rangle \, t', \qquad t' = W_{\bar{K}^0 \Sigma^{*-}} + \sum_j W_j \, G_j \, \boxed{t_{j, \bar{K}^0 \Sigma^{*-}}},$$

B^* is the baryon of the $\frac{3}{2}^+$ multiplet,

$\boldsymbol{\epsilon}$ the vector polarization of the $\psi(3686)$

$\mathbf{S}^+$ is the spin transition operator from spin $\frac{1}{2}$ to $\frac{3}{2}$

Table 2 W_j Clebsch–Gordan coefficients for the different coupled channels

Channels	$\bar{K}^0 \Sigma^{*-}$	$K^- \Sigma^{*0}$	$\pi^0 \Xi^{*-}$	$\eta \Xi^{*-}$	$\pi^- \Xi^{*0}$	$K^0 \Omega^-$
W_j	$-\sqrt{\frac{2}{15}}$	$-\sqrt{\frac{1}{15}}$	$\sqrt{\frac{1}{15}}$	$-\sqrt{\frac{1}{5}}$	$-\sqrt{\frac{2}{15}}$	$\sqrt{\frac{2}{5}}$

The mass distribution for the decay $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-}$:

$$\frac{d\Gamma}{dM_{\rm inv}(\bar{K}^0 \Sigma^{*-})} = \frac{1}{(2\pi)^3} \frac{1}{4M_\psi^2} p_{\bar{\Xi}^+} \tilde{p}_{\bar{K}^0} \bar{\sum} \sum |t|^2 2M_{\bar{\Xi}^+} 2M_{\Sigma^{*-}}$$

$$= \frac{1}{(2\pi)^3} \frac{C'}{4M_\psi^4} p^3_{\bar{\Xi}^+} \tilde{p}_{\bar{K}^0} |t'|^2,$$

Reactions testing the two states of $\Xi(1820)$: $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$

The mass distribution for $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$:

$$\frac{d\Gamma}{dM_{\rm inv}(\bar{K}^0\Sigma^{*-})\,dM_{\rm inv}(\Sigma^{*-})} = -\frac{1}{\pi}\,{\rm Im}\frac{\frac{\Gamma_{\pi^-\Lambda}}{\Gamma_{\Sigma^{*-}}}}{M_{\rm inv}(\Sigma^{*-}) - M_{\Sigma^{*-}} + i\,\frac{\Gamma_{\Sigma^{*-}}(M_{\rm inv}(\Sigma^{*-}))}{2}} \cdot \frac{1}{(2\pi)^3}\,\frac{C'}{4M_\psi^4}\,p^3_{\bar{\Xi}^+}\,\tilde{p}_{\bar{K}^0}\,|t'|^2,$$

with the energy dependence of the Σ^{*-} width as

$$\Gamma_{\Sigma^{*-}}\left(M_{\rm inv}(\Sigma^{*-})\right) = \Gamma_{\rm on}\,\frac{M_{\Sigma^{*-}}}{M_{\rm inv}(\Sigma^{*-})}\left(\frac{\tilde{p}_\pi}{\tilde{p}_{\pi,{\rm on}}}\right)^3,$$

with $\Gamma_{\rm on}$ the width of Σ^{*-}, $\Gamma_{\pi^-\Lambda}/\Gamma_{\Sigma^{*-}} = 87\%$.

$$\tilde{p}_\pi = \frac{\lambda^{1/2}\left(M^2_{\rm inv}(\Sigma^{*-}), m_\pi^2, m_\Lambda^2\right)}{2\,M_{\rm inv}(\Sigma^{*-})}, \qquad \tilde{p}_{\pi,{\rm on}} = \frac{\lambda^{1/2}\left(m^2_{\Sigma^{*-}}, m_\pi^2, m_\Lambda^2\right)}{2\,m_{\Sigma^{*-}}}.$$

◆ Reactions testing the two states of Ξ(1820): $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$

- ✓ There is destructive interference of the tree level and the two Ξ(1820) states.
- ✓ The actual mass distribution differs appreciably from phase space.
- ✓ The phase space for $\bar{K}^0\Sigma^{*-}$ production reduces the effect of the lower mass Ξ(1820).
- ✓ The excess of strength above 1900 MeV is due to the wide Ξ(1820) state with higher mass.

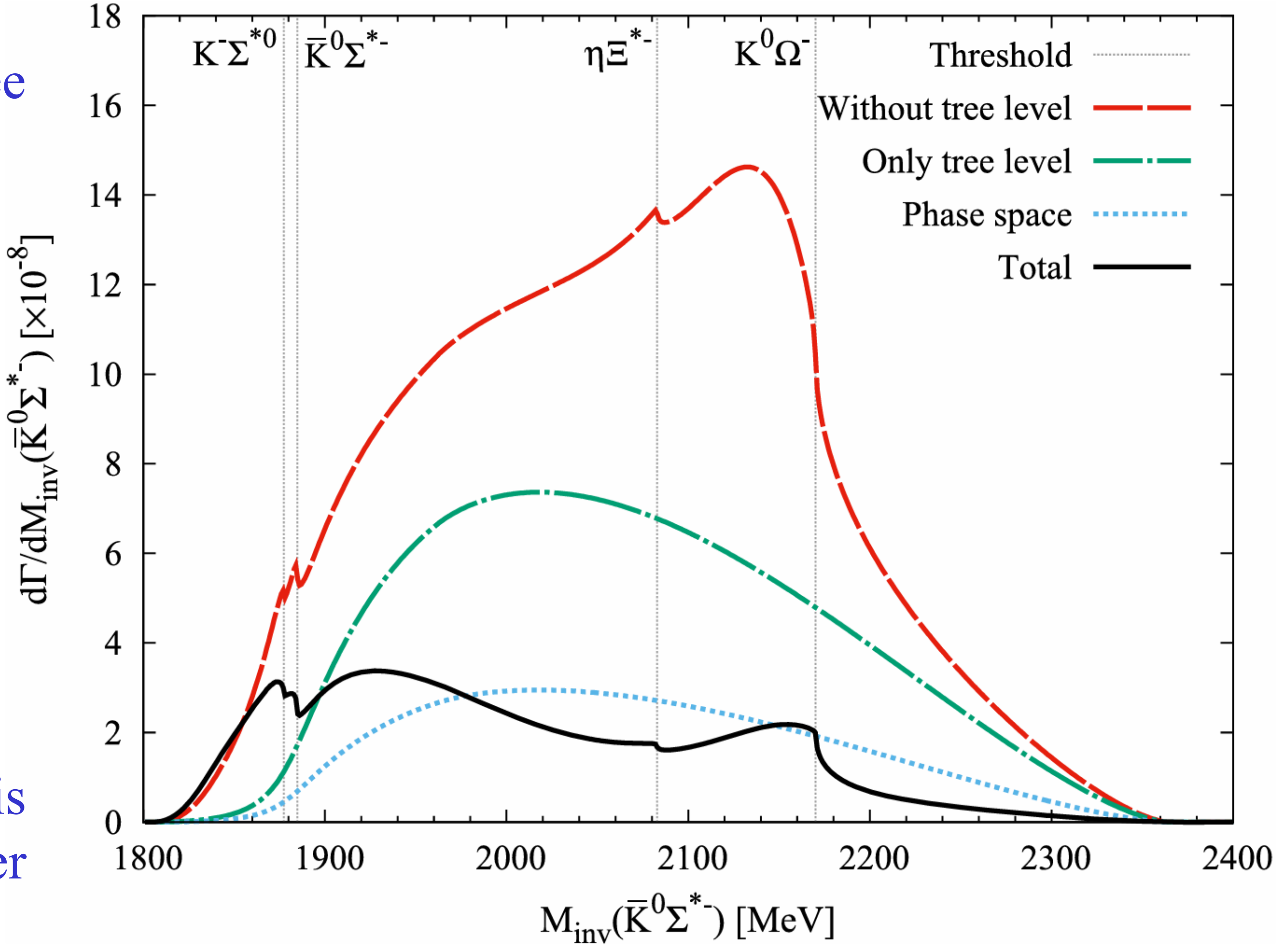


Fig. 2 $d\Gamma/dM_{\rm inv}(\bar{K}^0\Sigma^{*-})$ with different options.

The proposed reaction is particularly suited to show the effect of the higher Ξ(1820) state.

Reactions testing the two states of Ξ(1820): $\Omega_c^0 \to \pi(\eta)\pi\Xi^*$

single Cabibbo suppressed

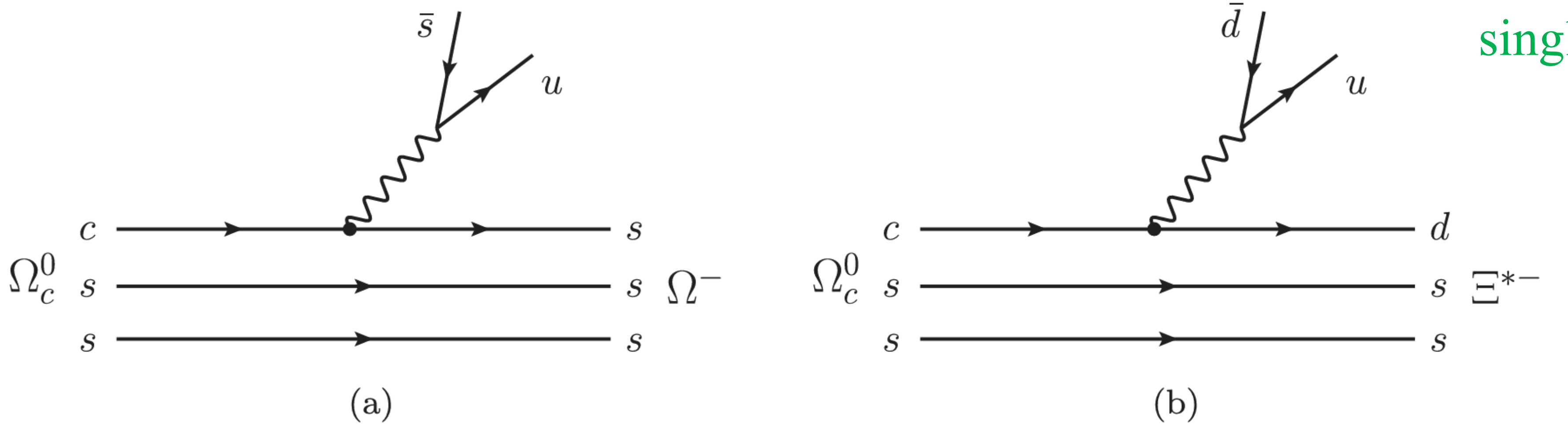


FIG. 1. The two topological structures with external emission that lead to Ω^- (a) and Ξ^{*-} (b) in the final state.

Hadronization:

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

$$u\bar{s} \to \sum_i u\bar{q}_i q_i \bar{s} = P_{1i}P_{i3} = (P^2)_{13} = \left(\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}}\right)K^+ + \pi^+K^0 - \frac{1}{\sqrt{3}}K^+\eta.$$

$$u\bar{d} \to \sum_i u\bar{q}_i q_i \bar{d} = P_{1i}P_{i2} = (P^2)_{12} = \left(\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}}\right)\pi^+ + \pi^+\left(-\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}}\right) + K^+\bar{K}^0.$$

◆ Reactions testing the two states of Ξ(1820): $\Omega_c^0 \to \pi(\eta)\underbrace{\pi\Xi^*}$

with a threshold ~1670 MeV

To generate the $\Xi(1820)$ resonance in the final state, we have to allow one of the mesons to interact with the Ω^- or Ξ^{*-} .

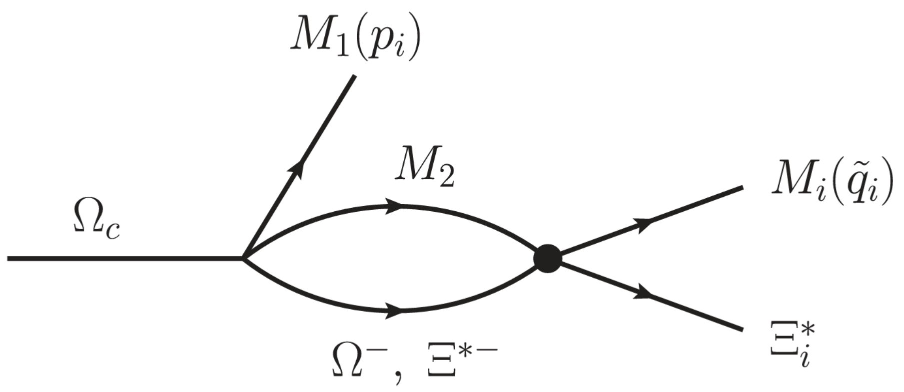


FIG. 2. Final state interaction of a meson with the baryon of the decuplet $3/2^+$. The dot indicates the transition matrix element from $M_2\Omega^-(\Xi^{*-})$ to a final $M_i\Xi_i^*$ state.

We have 6 possible reactions:

$\Omega_c^0 \to \pi^+\pi^0\Xi^{*-}$ (with tree level)

$\Omega_c^0 \to \pi^+\pi^-\Xi^{*0}$

$\Omega_c^0 \to \pi^0\pi^+\Xi^{*-}$ (with tree level)

$\Omega_c^0 \to \pi^0\pi^0\Xi^{*0}$

$\Omega_c^0 \to \eta\pi^+\Xi^{*-}$

$\Omega_c^0 \to \eta\pi^0\Xi^{*0}$

where the first meson corresponds to the external one of the weak vertex and the second one to the final state.

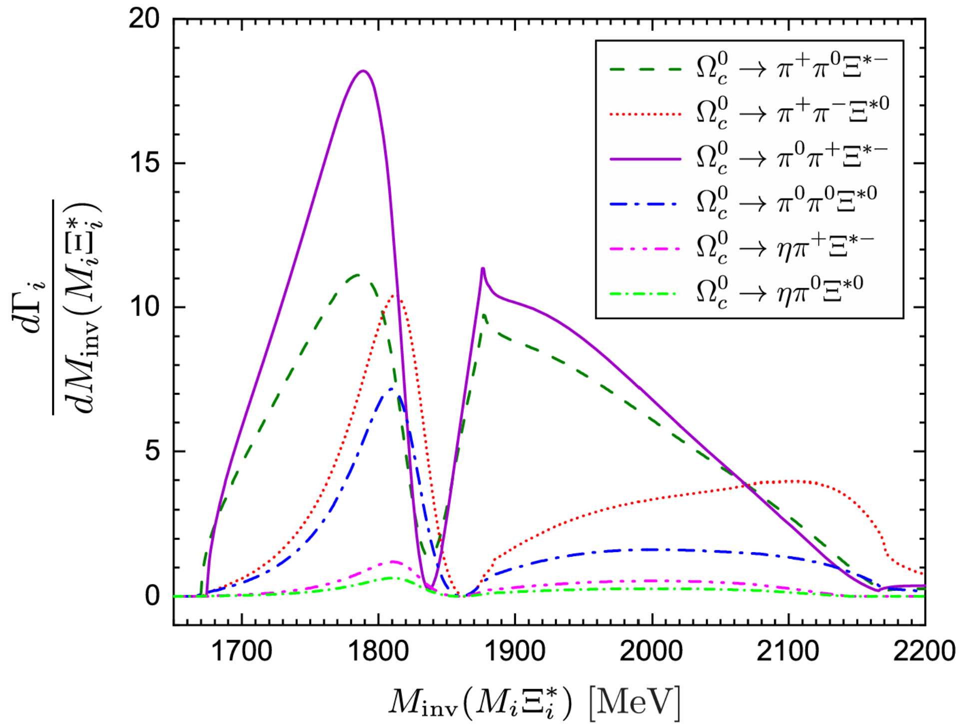
◆ Reactions testing the two states of Ξ(1820): $\Omega_c^0 \to \pi(\eta)\pi\Xi^*$

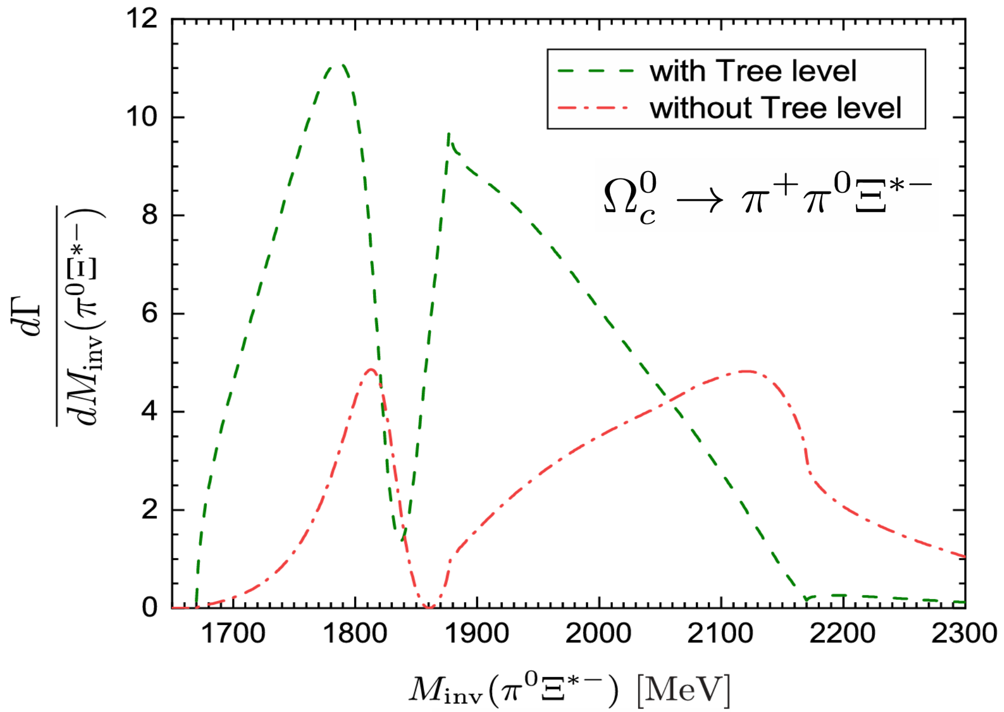
The mass distribution for the final $M_i\Xi_i^*$ pair is given by

$$\frac{d\Gamma_i}{dM_{\text{inv}}(M_i\Xi_i^*)} = \frac{1}{(2\pi)^3}\frac{1}{4M_{\Omega_c}^2} p_i\tilde{q}_i \bar{\sum}\sum |t_i|^2 \quad (i = 1 \sim 6),$$

$$t_i = C\langle\Xi^*(3/2^+)|\vec{S}^+ \cdot \vec{p}_i|\Omega_c^0\rangle\tilde{t}_i, \qquad \bar{\sum}\sum |t_i|^2 = C^2\frac{2}{3}\vec{p}_i^2|\tilde{t}_i|^2.$$

◆ Reactions testing the two states of Ξ(1820): $\Omega_c^0 \to \pi(\eta)\pi\Xi^*$





✓ The shapes of the mass distributions for the reactions are different from each other.

✓ In common: there is a dip in the mass distribution around 1850 MeV, due to the destructive interference of the two resonances.

✓ The reactions without tree level contribution, show more clearly the effect of the two Ξ(1820) state.

Summary

- ✓ The chiral unitary approach for the interaction of pseudoscalar mesons with the baryons of the decuplet predicts two states for the $\Xi(1820)$, one at 1824 MeV with a width of 62 MeV, and a second one at 1875 MeV with a large width of 260 MeV.

- ✓ With the contribution of the two $\Xi(1820)$ states, a fair description of the BESIII data for the $\psi(3686) \to \bar{\Xi}^+ K^- \Lambda$ decay is obtained, supporting the two-pole structure of the $\Xi(1820)$ state.

- ✓ We propose the reaction $\psi(3686) \to \bar{\Xi}^+ \bar{K}^0 \Sigma^{*-} \to \bar{\Xi}^+ \bar{K}^0 \pi^- \Lambda$ to show evidence for the existence of two $\Xi(1820)$ states. The phase space for $\bar{K}^0 \Sigma^{*-}$ production reduces the effect of the lower mass state, magnifying the effect of the higher mass state that shows clearly over the phase space.

- ✓ The $\Omega_c^0 \to \pi^+\pi^-\Xi^{0*}, \pi^0\pi^0\Xi^{0*}, \eta\pi^+\Xi^{*-}, \eta\pi^0\Xi^{*0}$ decays, being free of a tree level contribution, show clearly the effect of the two $\Xi(1820)$ state. The lower mass one is clearly seen as a sharp peak in the $\pi\Xi^*$ mass distributions, but the higher mass one manifests itself through an interference with the lower one that leads to a dip in the mass distribution around 1850 MeV.

Thank you for your attention!