Identification of a visible cusp structure in $\Lambda_c \to pK^- \pi^+$

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Mainly based on arXiv:1906.07942

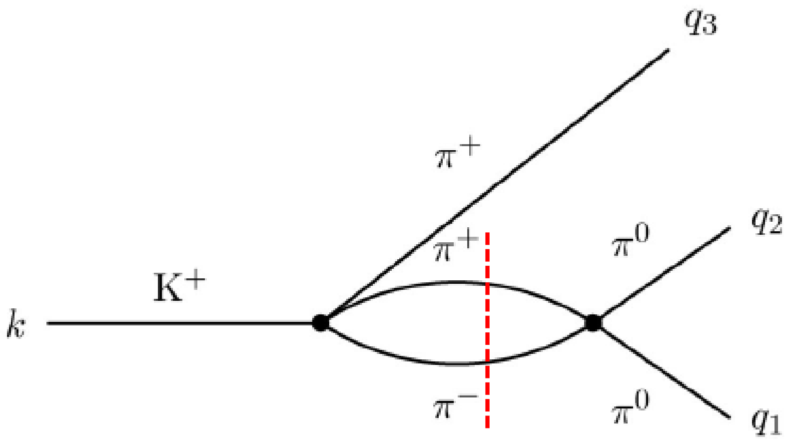
Hadron 2019, Guilin, August 20, 2019

Outline

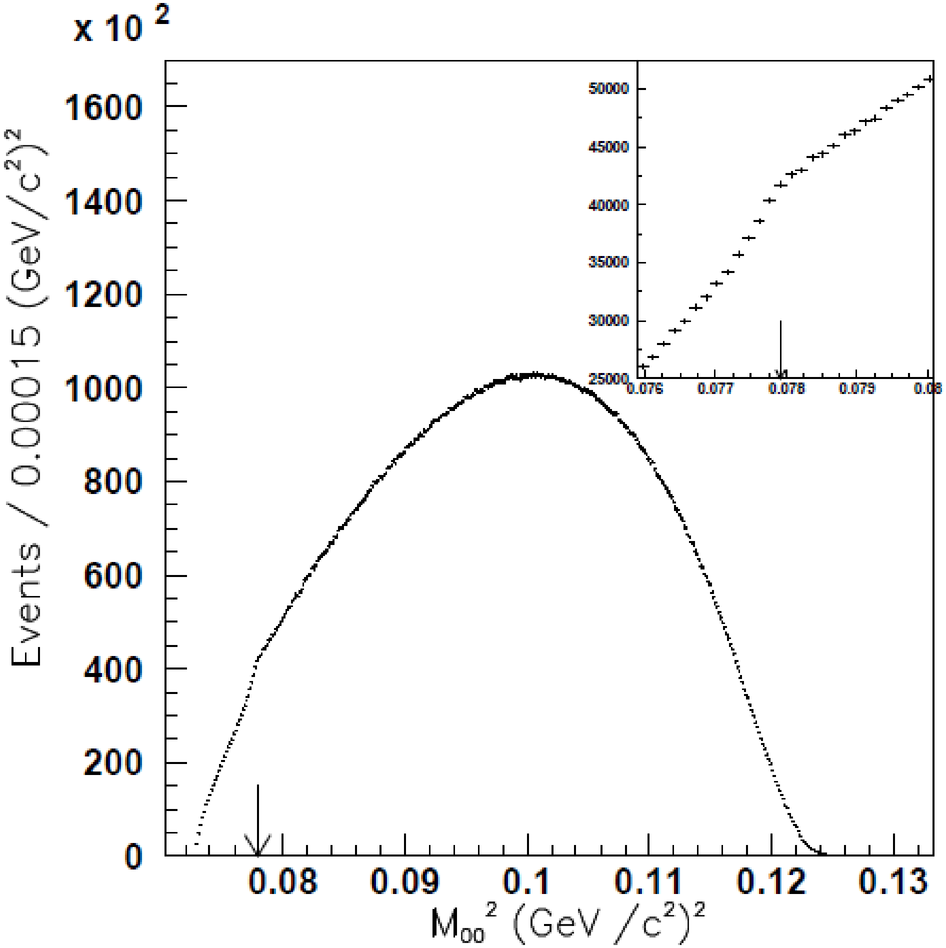
- **Brief review of Cusp phenomena**
- **Narrow resonance-like structure "*X(1663)*" in $\Lambda_c \to pK^- \pi^+$**
- **Threshold cusp enhanced by the nearby triangle singularity**
- **Summary**

Cusp effect

Induced by the charge-exchange rescattering $\pi^+\pi^- \rightarrow \pi^0\pi^0$



Two-body cut



Budini & Fonda, PRL6,419(1961);
Cabibbo, PRL93,121801(2004);

Branching ratio

$K^+ \rightarrow \pi^+\pi^-\pi^+$ $((5.59 \pm 0.04)\%)$

much larger than

$K^+ \rightarrow \pi^0\pi^0\pi^+$ $((1.761 \pm 0.022)\%)$

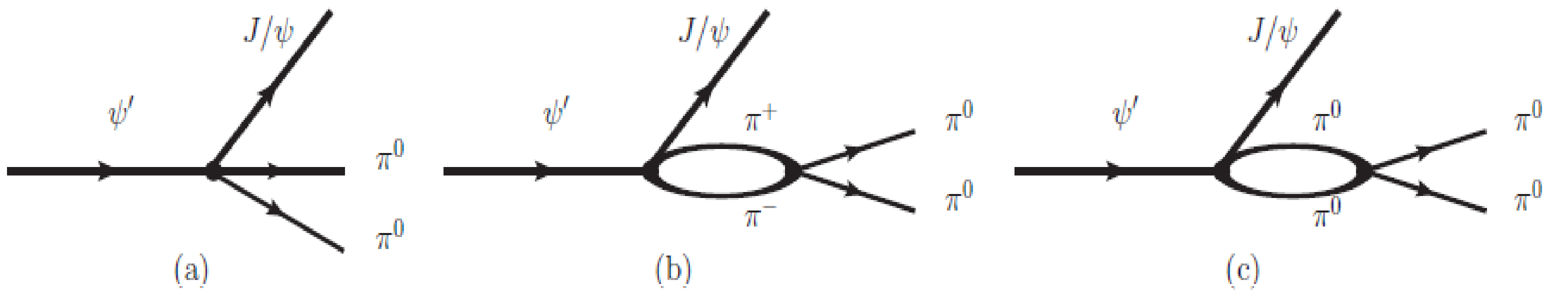
NA48/2, PLB633,173 (2006)
6×10^7 events

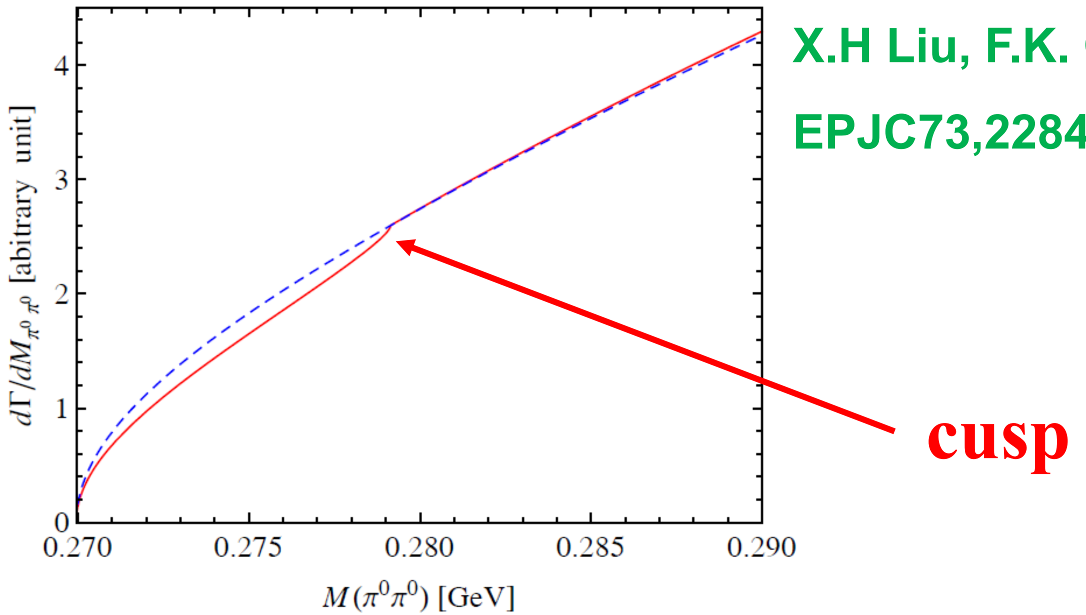
Cusp effect

Could be used to extract the $\pi\pi$ scattering length

K→3π, one of the most accurate experiments

Heavy quarkonium dipion transitions: $\psi' \to J/\psi\pi^0\pi^0$, $\Upsilon(3S) \to \Upsilon(2S)\pi^0\pi^0$ (better)



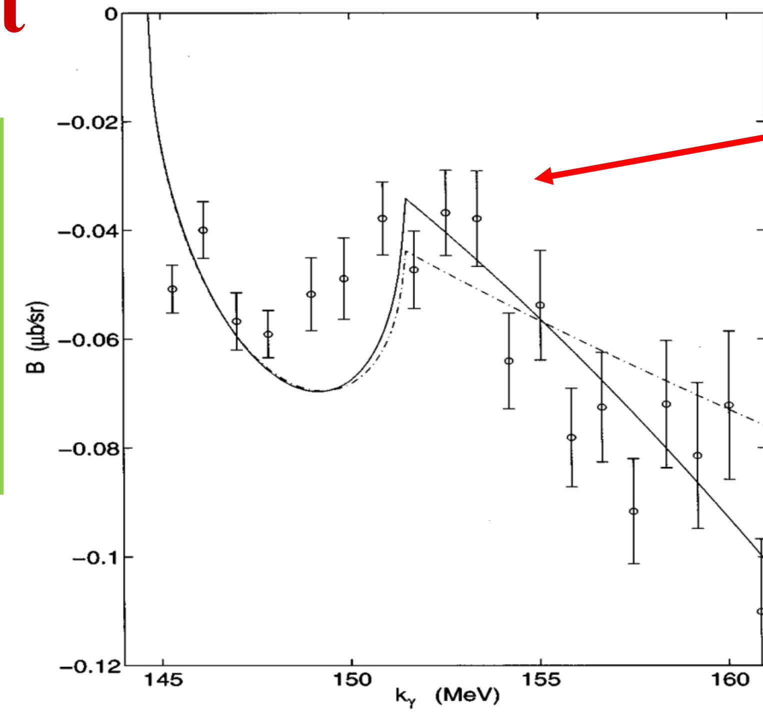


X.H Liu, F.K. Guo, E. Epelbaum, EPJC73,2284(2013)

Cusp effect

Early study:

E.P. Wigner, *"On the Behavior of Cross Sections Near Thresholds"*, PR73, 1002 (1948)



$$\gamma p \longrightarrow \pi^+ n \longrightarrow \pi^0 p$$

A.M. Bernstein et al, *"Observation of a unitary cusp in the threshold $\gamma p \to \pi^0 p$ reaction"*, PRC55, 1509(1997)

Threshold of final states < Threshold of intermediate states

D. V. Bugg, *"Reinterpreting several narrow 'resonances' as threshold cusps"*, PLB598, 8 (2004):

The threshold ppbar peak in BES data for J/ψ→ *γppbar* may be fitted as a cusp;

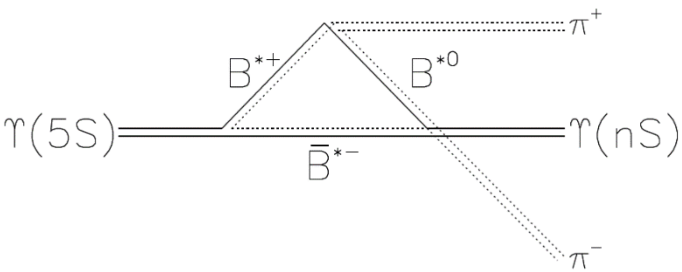
a cusp at the *ΣN* threshold $K^- d \to \pi^-(\Lambda p)$

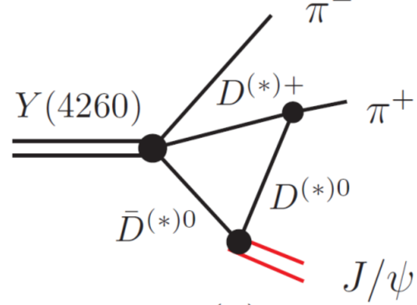
…

Difficult to observe: high statistics; perfect energy resolution; clear background

Cusp effect

➢ **Possible correlation with some XYZ states: *Z_b(10610/10650), Z_c(3900), Z_c(4020)***





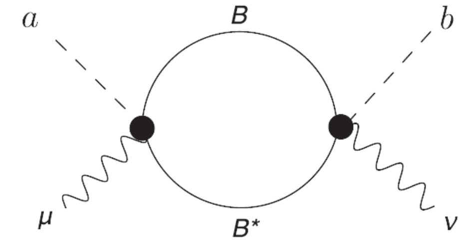
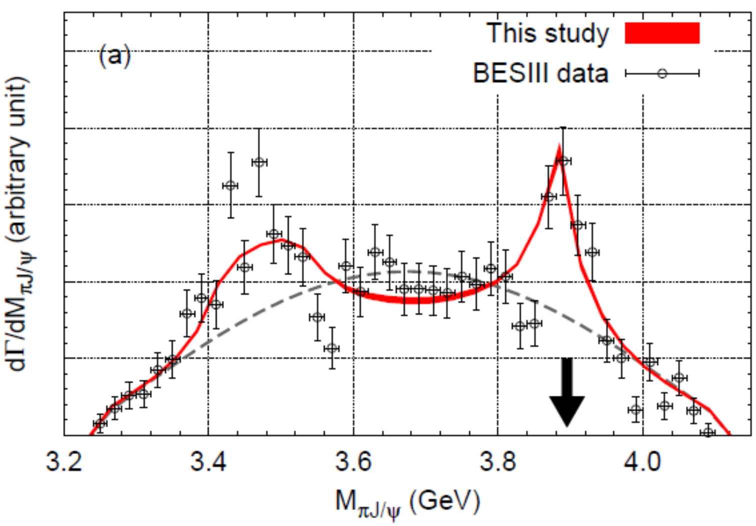


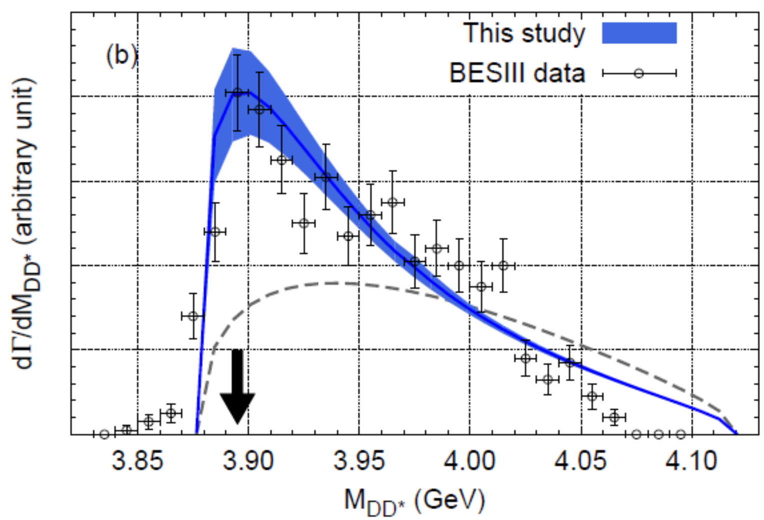
FIG. 1. Coupled channels in $\Upsilon\pi$ scattering.

**D.V. Bugg,
EPL96, 11002(2011)**

**D.Y. Chen, X. Liu,
PRD88, 11002(2013)**

**E. Swanson,
PRD91, 034009(2015)**

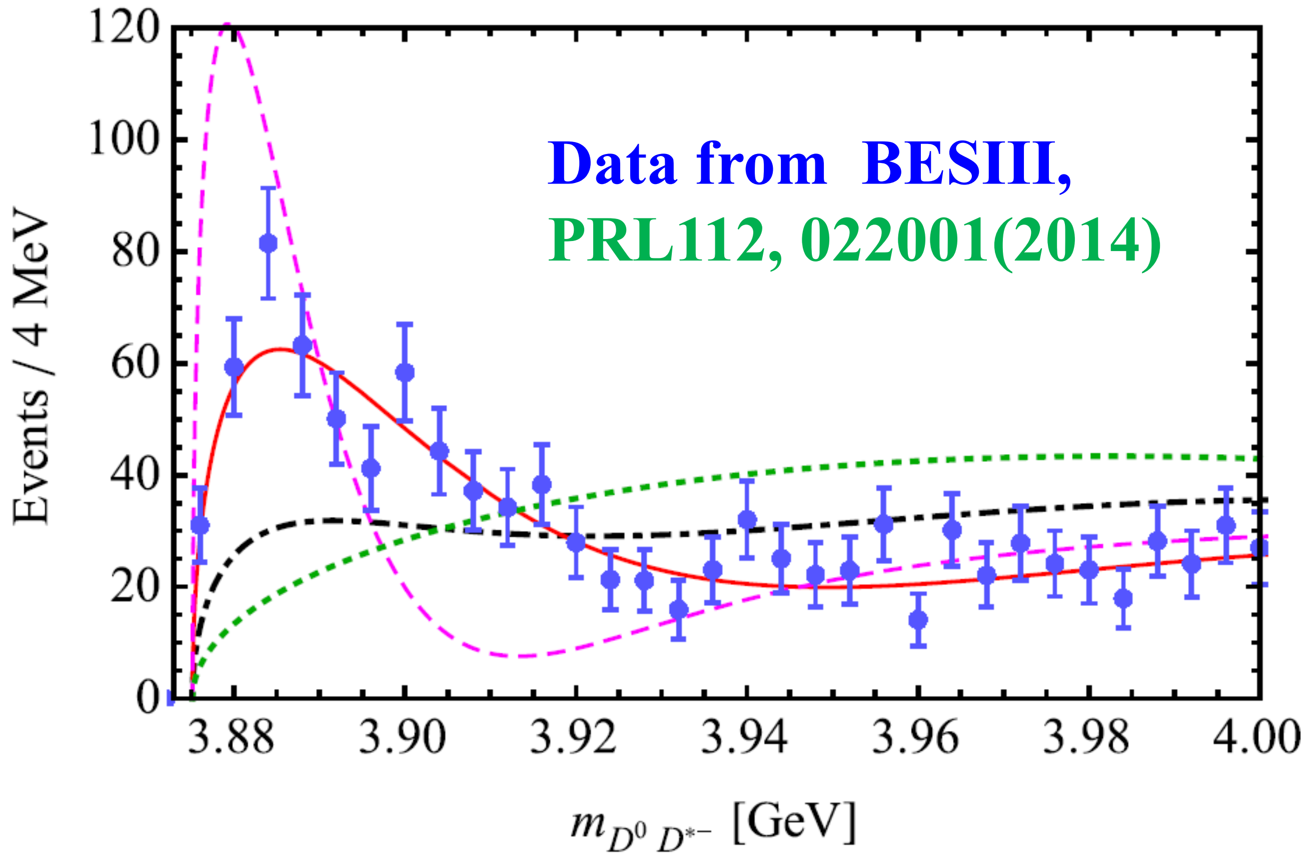




Y. Ikeda [HAL QCD Collaboration], arXiv:1706.07300 **Strong J/ψπ-DD* coupling**

Cusp effect

- **A sharp peak cannot be resulted by a pure threshold cusp in the elastic channel [Guo, Hanhart, Wang, Zhao, PRD91, 051504(2015)]: *Z_c(3900)* was also observed in the DD* invariant mass distributions**

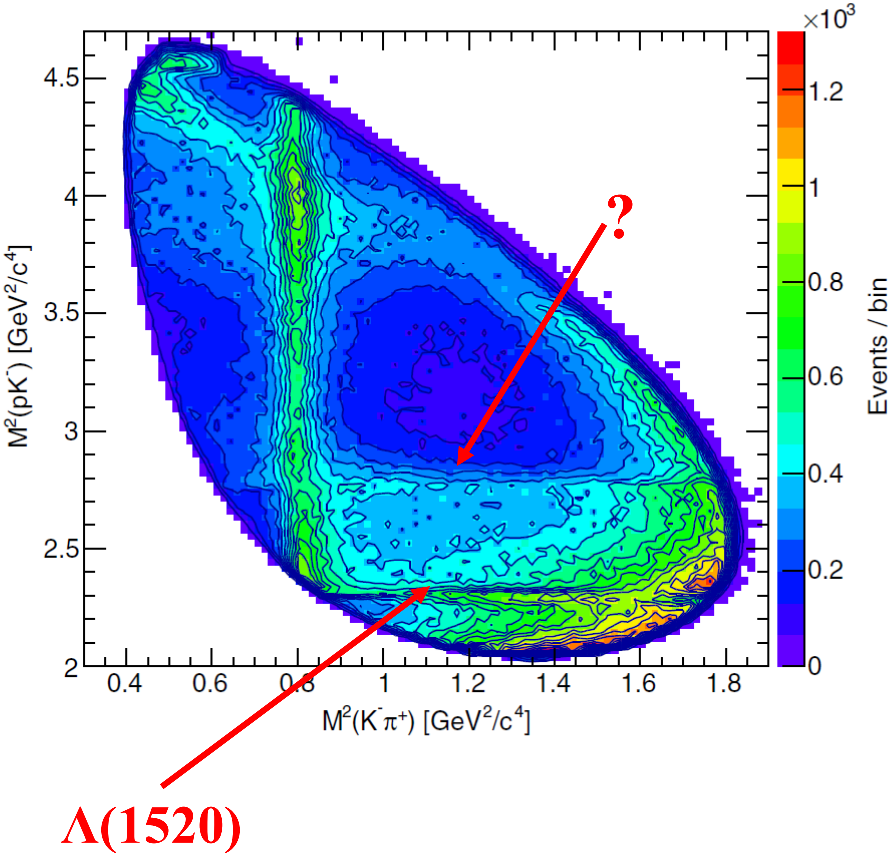


Observation of "X(1663)"

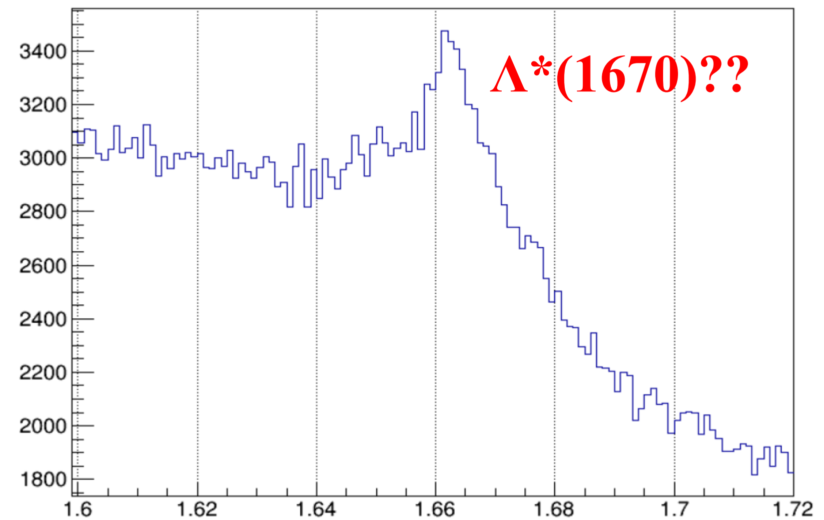
Dalitz plot for $\Lambda_c \to pK^- \pi^+$

Belle, PRL117,011801(2016)

1.452 × 10^6 events



■ 1D projection -- $M(pK^-)$



- ✓ Bin width: 1 MeV
- ✓ M≈1663 MeV
- ✓ Γ ≈10 MeV
- ✓ $\Lambda\eta$ threshold: 1663.545 MeV

From C.P. Shen's talk, no published result concerning "X(1663)"

Observation of “X(1663)”

Hyperons around 1663 MeV [PDG]

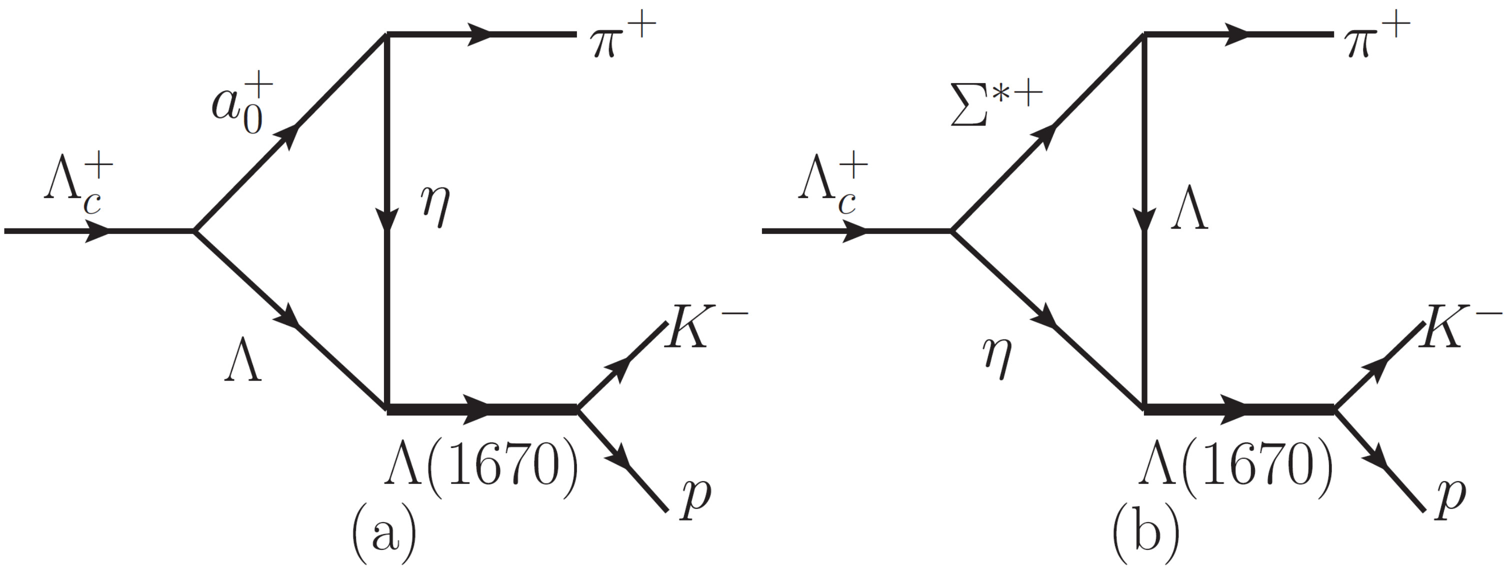
[MeV]	Mass	Width	J^P
X(1663)	1663	~10	?
Λ*(1670)	1660 to 1680 ≈1670	25 to 50 ≈35	1/2-
Λ*(1690)	1685 to 1695 ≈1690	50 to 70 ≈60	3/2-
Σ*(1660)	1630 to 1690 ≈1660	40 to 200 ≈100	1/2+
Σ*(1670)	1665 to 1685 ≈1670	40 to 80 ≈60	3/2-

No established hyperons correspond to this “X(1663)”

Two groups claim there is a narrow Λ* with J=3/2:

- **Liu & Xie [PRC85, 038201; PRC86,055202]**
  J^P=3/2-(D03), M=1668.5±0.5 MeV, Γ=1.5±0.5 MeV
- **Kamano *et al.* [PRC90, 065204; PRC92, 025205]**
  J^P=3/2+(P03), M=1671+2-8 MeV, Γ=10+22-4 MeV

Contributions from rescattering processes



- ✓ **Cabibbo-favored process**
- ✓ **Strong couplings**
- ✓ **Exp. value:** $Br(\Lambda_c \to \Lambda\eta\pi^+) \sim (2.2 \pm 0.5)\%$

  $Br(\Lambda_c \to \Sigma(1385)\,\eta \to \Lambda\eta\pi^+) \sim (1.06 \pm 0.32)\%$

Experimental data concerning $\Lambda_c \to \Lambda\eta\pi^+$

CLEO, PRL74,3534 (1995)

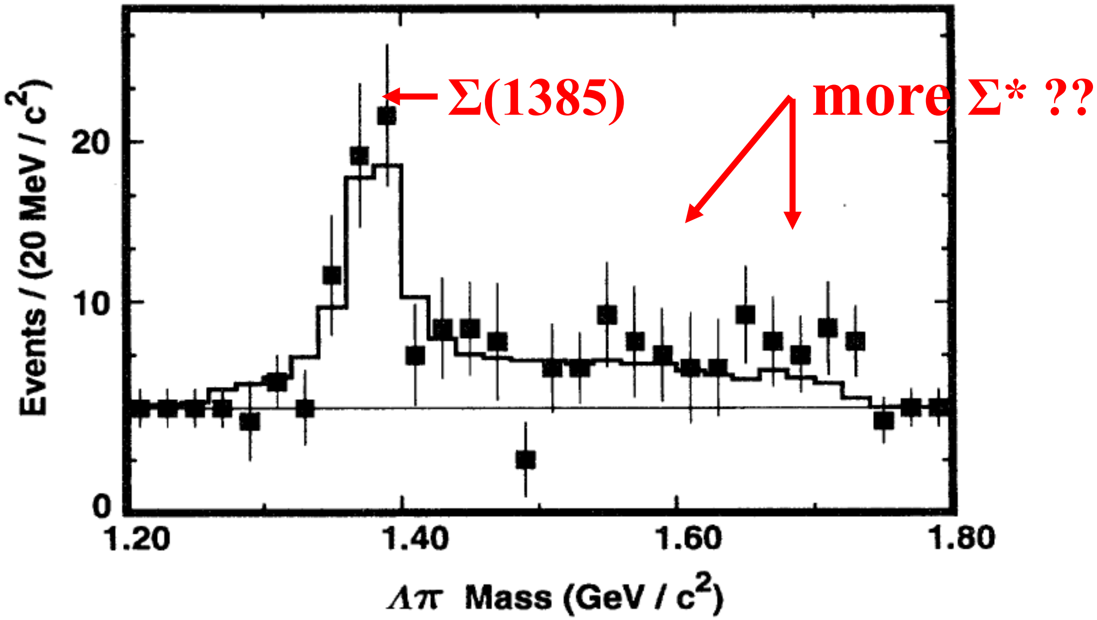


FIG. 3. The $\Lambda\pi^+$ invariant mass distribution for $\Lambda_c^+ \longrightarrow \Lambda\eta\pi^+$ candidates showing the $\Sigma^{*+}(1385)$ resonance. The points are data and the histogram is a fit to a Breit-Wigner signal and a phase space background, both of which include the effects of detector acceptance and resolution.

$a_0 \longrightarrow \eta\pi^+$. We searched for the Λa_0 decay. However, because the a_0 width is quite large and not well measured ($50-300$ MeV$/c^2$) [5], we could not constrain the Λa_0 decay component.

Kinematic region of triangle singularity (TS)

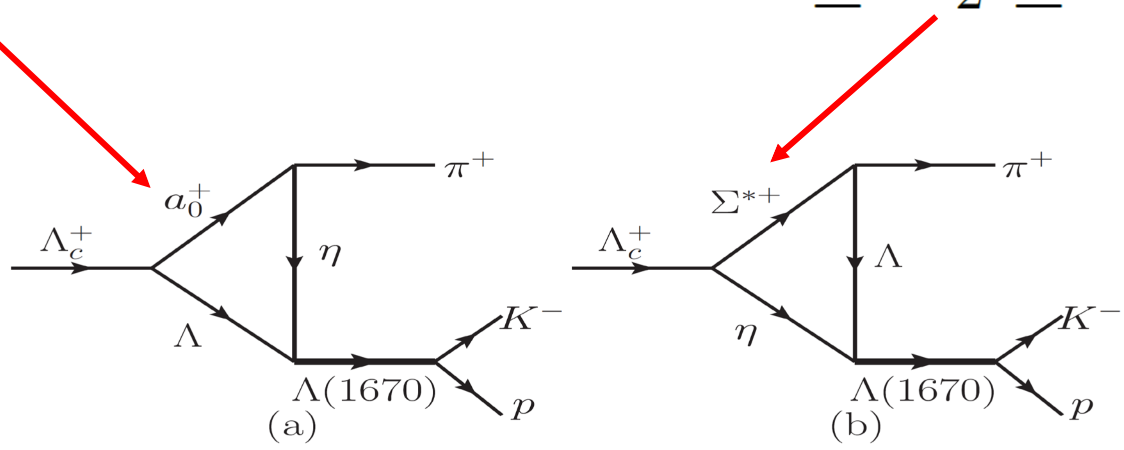
$$\frac{m_1 m_{\pi^+}^2 + m_3 M_{\Lambda_c^+}^2}{m_1 + m_3} - m_1 m_3 \leq m_2^2 \leq (M_{\Lambda_c^+} - m_1)^2$$

$$(m_1 + m_3)^2 \leq s^- \leq (m_1 + m_3)^2 + \frac{m_1[(m_2 - m_3)^2 - m_{\pi^+}^2]}{m_2}$$

Liu, Oka, Zhao, PLB753,297 (2016)

$1.06 \leq m_2 \leq 1.17$ GeV

$1.70 \leq m_2 \leq 1.74$ GeV



TS location

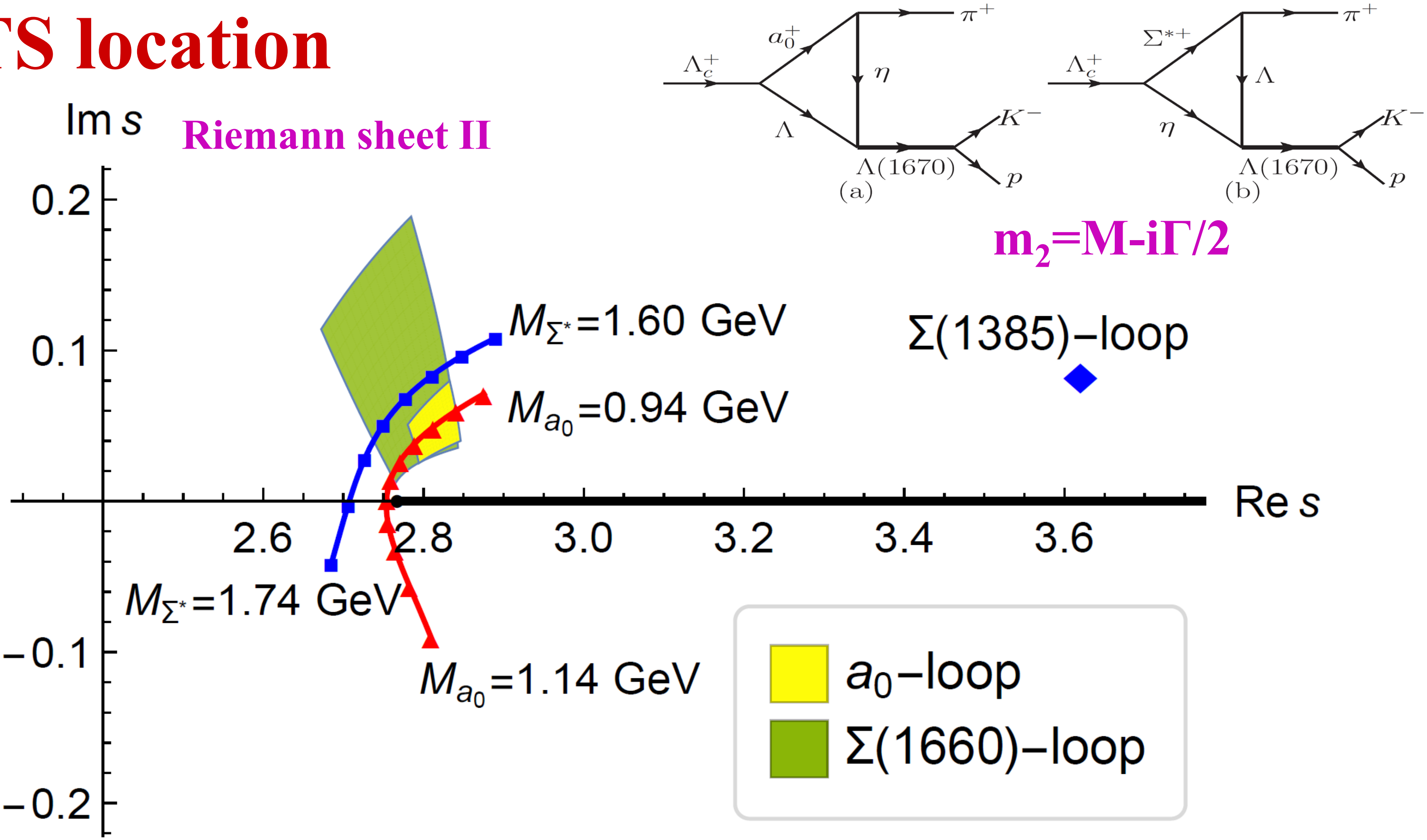


FIG. 2: The TS location of $\mathcal{T}(s, m_2^2)$ in the complex s-plane. The thick line on the real axis represents the unitary cut starting from $s_{\rm th}$. The trajectory marked with triangle (box) is obtained by varying M_{a_0} (M_{Σ^*}) and fixing $\Gamma_{a_0} = 75$ MeV ($\Gamma_{\Sigma^*} = 100$ MeV).

Rescattering Amplitude

$$\mathcal{T} = \frac{1}{s - M^2_{\Lambda(1670)} + iM_{\Lambda(1670)}\Gamma_{\Lambda(1670)}}$$
$$\times \int \frac{d^4q_1}{(2\pi)^4} \frac{\mathcal{A}}{(q_1^2 - m_1^2)(q_2^2 - m_2^2)(q_3^2 - m_3^2)},$$

with $\mathcal{A} = \mathcal{M}(\Lambda_c^+ \to \Lambda a_0^+)\mathcal{M}(a_0^+ \to \eta\pi^+)\mathcal{M}(\eta\Lambda \to \Lambda(1670))\mathcal{M}(\Lambda(1670) \to K^-p)$ and $\mathcal{A} = \mathcal{M}(\Lambda_c^+ \to \eta\Sigma^{*+})\mathcal{M}(\Sigma^{*+} \to \Lambda\pi^+)\mathcal{M}(\eta\Lambda \to \Lambda(1670))\mathcal{M}(\Lambda(1670) \to K^-p)$ for a_0-loop and Σ^*-loop

$$\mathcal{M}(\Lambda_c^+ \to \Lambda a_0^+/\eta\Sigma^{*+}) = g_A\bar{u}_f u_i + ig_B\bar{u}_f\gamma_5 u_i$$

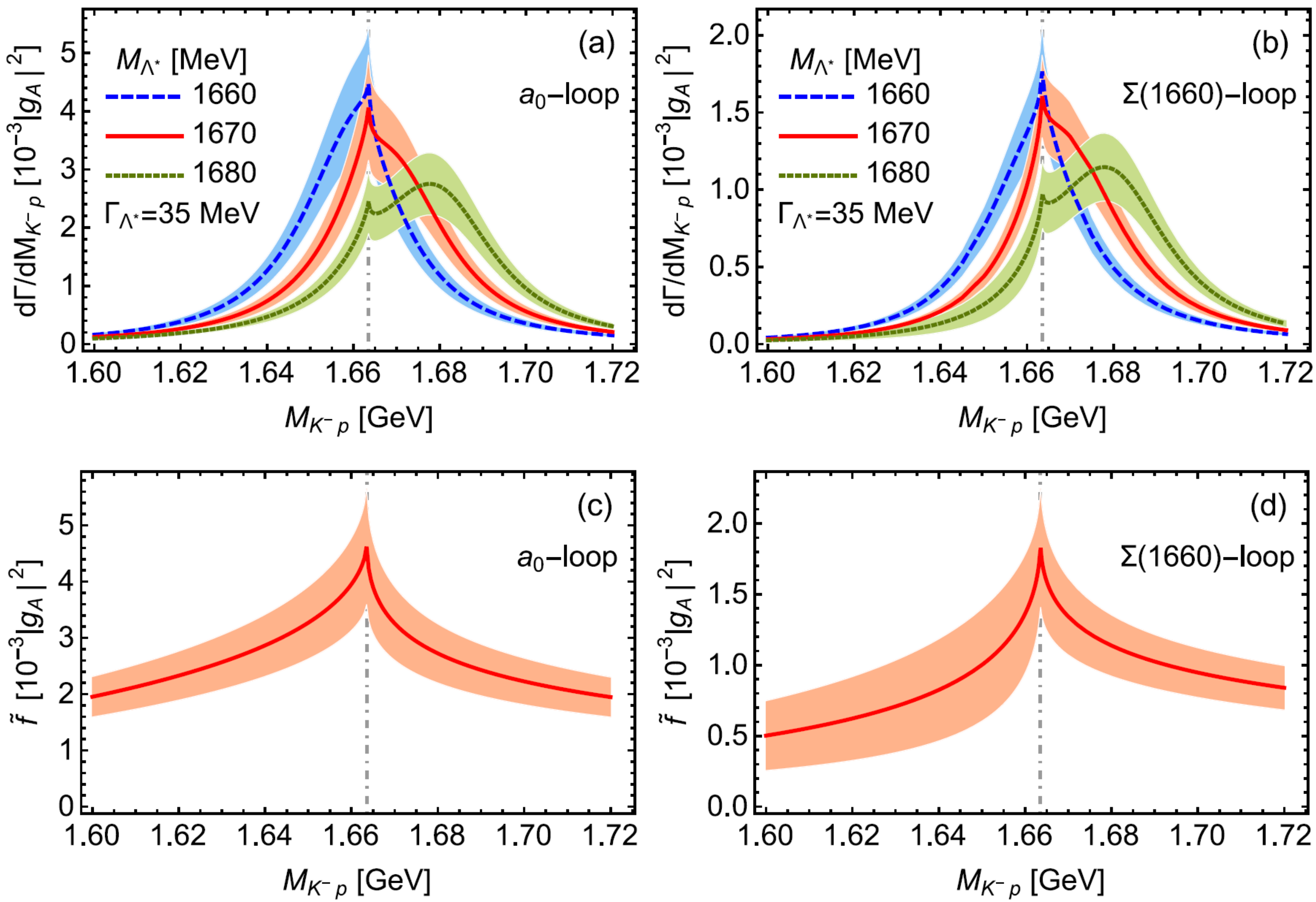
Estimation:

$R \equiv |g_B|/|g_A|$ **~1**

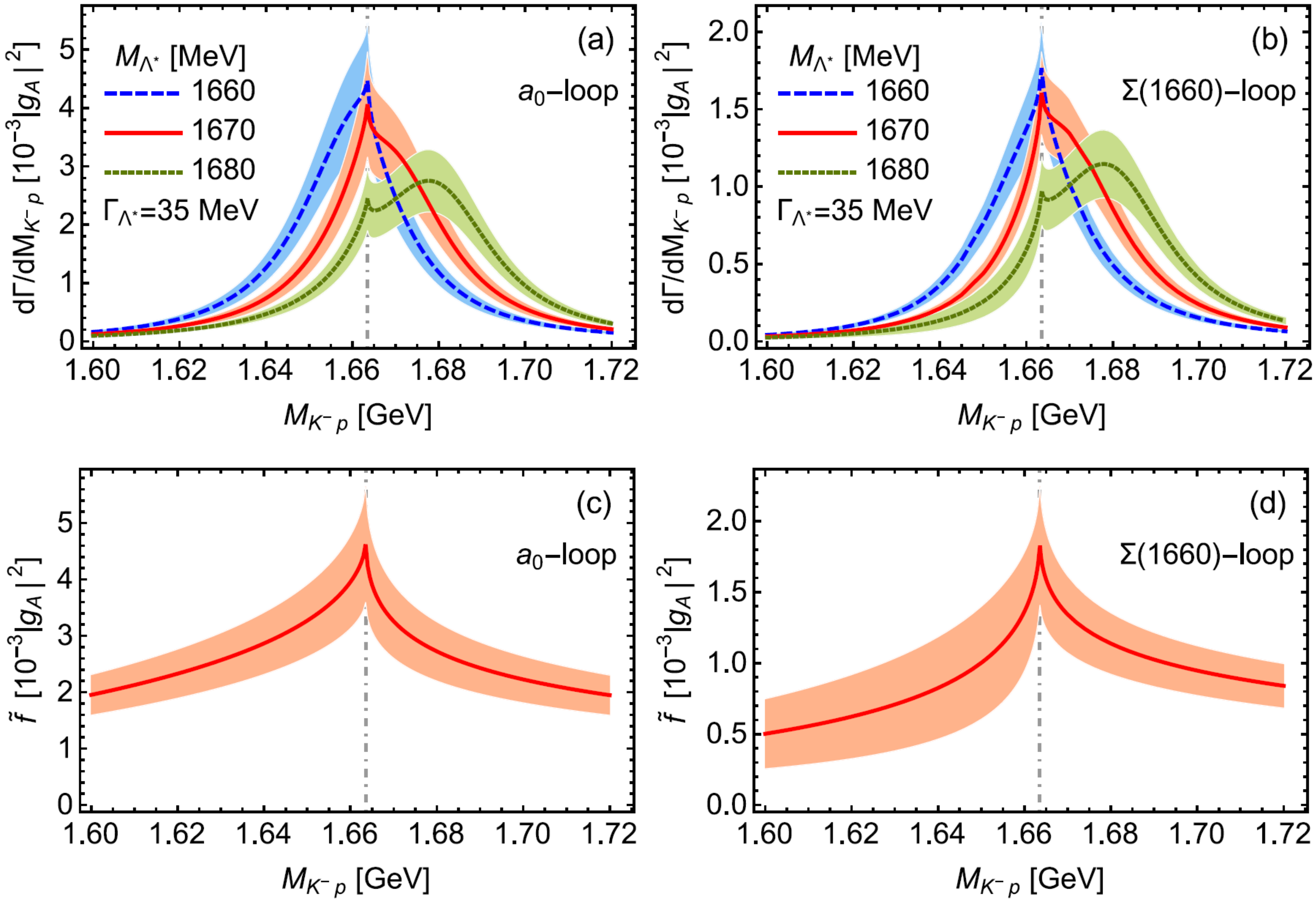
$|g_A|^2_{\max} \approx 0.32\ \mathrm{GeV}^{-1}/\tau_{\Lambda_c}$ for Λa_0^+ channel

$|g_A|^2_{\max} \approx 3.14\ \mathrm{GeV}^{-1}/\tau_{\Lambda_c}$ for $\Sigma(1660)\eta$ channel

Invariant Mass Distributions



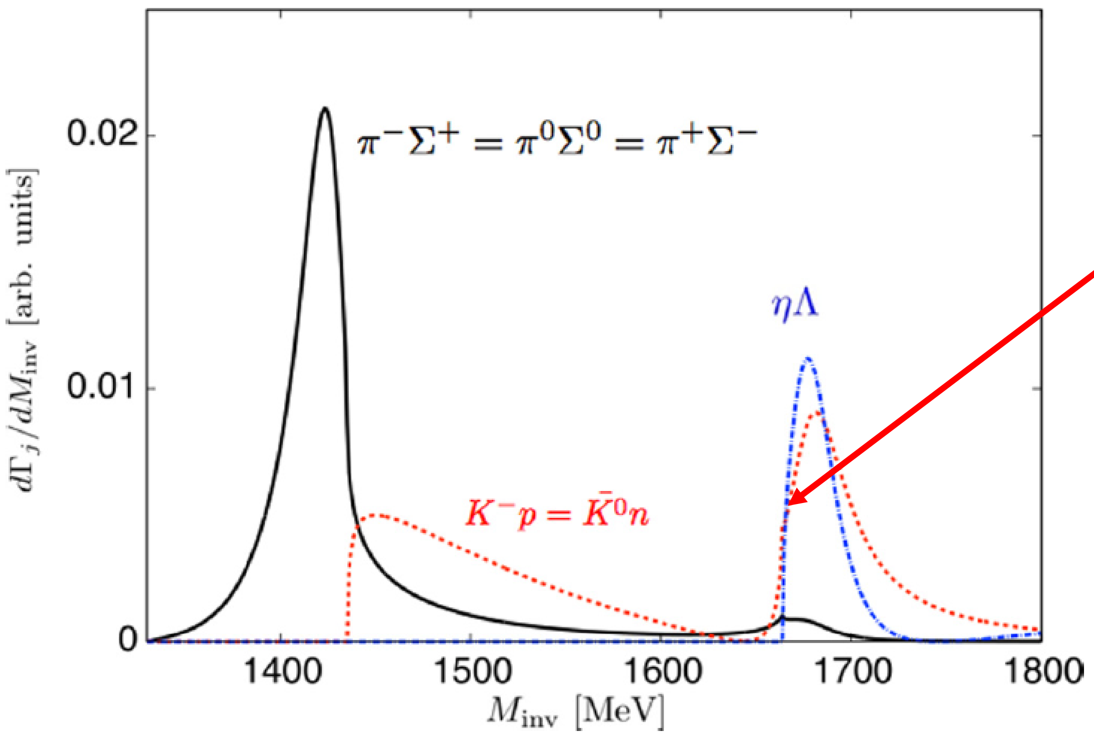
Invariant Mass Distributions



$$\tilde{f}(M_{K^-p}) = \left| \frac{s - M_{\Lambda^*}^2 + i M_{\Lambda^*} \Gamma_{\Lambda^*}}{M_{\Lambda^*} \Gamma_{\Lambda^*}} \right|^2 \times \frac{d\Gamma}{dM_{K^-p}}$$

Invariant Mass Distributions

The narrow resonance-like structure "X(1663)" is not simply resulted from the threshold cusp and Λ(1670) interference

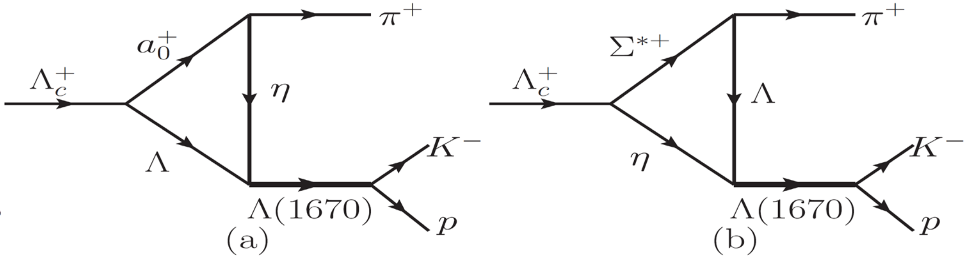


Tiny cusp at $\Lambda\eta$ threshold

FIG. 6. (Color online) Invariant mass distribution of the decay $\Lambda_c^+ \to \pi^+ MB$. The solid, dotted, and dash-dotted lines represent the $\bar{K}N = \{K^-p,\ \bar{K}^0 n\}$, $\pi\Sigma = \{\pi^0\Sigma^0,\ \pi^-\Sigma^+,\ \pi^+\Sigma^-\}$, and $\eta\Lambda$ channels, respectively. The meson-baryon amplitude is taken from Ref. [19], where the Λ(1520) contribution in d wave is not included.

K. Miyahara, T. Hyodo, E. Oset, PRC92,055204 (2015)

Argand plot



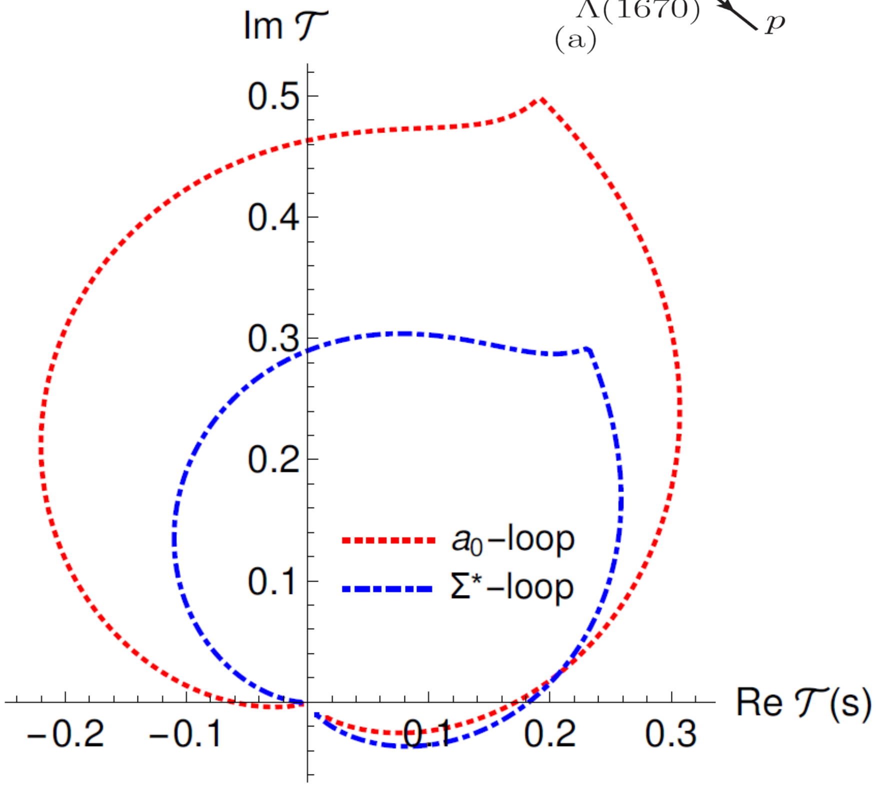


FIG. 4: Argand plot of the rescattering amplitude, with s increasing from $(M_{K^-}+m_p)^2$ to $(M_{\Lambda_c^+}-m_{\pi^+})^2$ counterclockwise. The mass and width of $\Lambda^*(1670)$ are taken to be PDG averaged values.

Summary

- **The narrow resonance-like structure observed by Belle in *Kp* invariant mass spectrum can be identified as a cusp phenomenon resulted from the rescatterings:**
- **The cusp is enhanced and narrowed by the nearby unphysical TSs.**
- **No established narrow hyperons in the vicinity of $\Lambda\eta$ threshold.**
- **Huge data sample, very narrow bin width ~ 1 MeV**

- **Direct prediction:**
  - **$\Lambda\eta$ also strongly couples to the $\Sigma\pi$ channel around 1670 MeV, one can expect that the similar cusp could also be observed in $\Lambda_c \to \Sigma\pi\pi$ decays**

Thanks!