# The first observation of narrow peak and isospin-violating Lambda(1405) production

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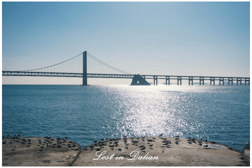
**大连 is an important port city located at Northeast of China**
**$\Longrightarrow$ the southern tip of the Liaodong Peninsula**




# Outline

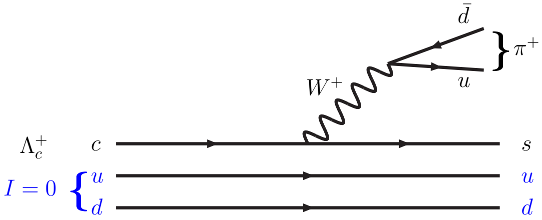
- $\Lambda_c^+ \to \pi^+ \bar{K}^* N$ **(exp data)**
- **triangle singularities**
- **The dynamical origin of the** $\Lambda(1405)$
- **The** $\Lambda_c \to \pi^+\pi^0\pi^0\Sigma^0$ **and isospin forbidden** $\Lambda(1405)$ **production**

**L. R. Dai, R. Pavao, S. Sakai & E. Oset, PRD97(2018)116004**

**Anomalous enhancement of the isospin-violating $\Lambda(1405)$ production by a triangle singularity in $\Lambda_c \to \pi^+\pi^0\pi^0\Sigma^0$**

# $\Lambda_c^+ \to \pi^+ \bar{K}^* N$ weak decay

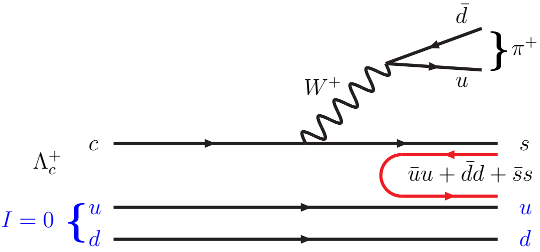
## decay mechanism at quark level




At the quark level, the **Cabibbo-allowed vertex** is formed through an **external emission** of a $W$ boson which is also color-favored, producing a $u\bar{d}$ pair that forms the $\pi^+$, with the **remaining *sud* quarks hadronizing ...**

# Hadronization

## through $\bar{q}q$ creation with vacuum quantum numbers




$ud(I = 0)$ **spectators** $\Longrightarrow$ also have $I = 0$ in the final state

This, added to the $s$ quark that has no isospin, gives us $I = 0$ for the **final baryon before the hadronization**, and this continues to be the case **after the hadronization** which is based on strong interaction.

$$H = \sum_{i=1}^{3} s\bar{q}_i q_i \frac{1}{\sqrt{2}}(ud - du) = \sum_{i=1}^{3} M_{3i} q_i \frac{1}{\sqrt{2}}(ud - du) \tag{1}$$

$$M = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix}$$

$$M \to V = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

## Wave functions of mesons

$$\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})\,, \qquad \rho^+ = u\bar{d}\,, \qquad \rho^- = d\bar{u}\,,$$

$$\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\,, \qquad \phi = s\bar{s}\,,$$

$$K^{*0} = d\bar{s}\,, \qquad K^{*-} = s\bar{u}\,, \qquad K^{*+} = u\bar{s}\,, \qquad \bar{K}^{*0} = s\bar{d}\,.$$

$$H = K^{*-}u\frac{1}{\sqrt{2}}(ud - du) + \bar{K}^{*0}d\frac{1}{\sqrt{2}}(ud - du) + \phi s\frac{1}{\sqrt{2}}(ud - du) \quad (2)$$

## Wave functions of baryons

$$p = \frac{1}{\sqrt{2}}u(ud - du)\,, \qquad n = \frac{1}{\sqrt{2}}d(ud - du)\,,$$

$$\Lambda = \frac{1}{2\sqrt{3}}[u(ds - sd) + d(su - us) - 2s(ud - du)]\,,$$

$$\Sigma^0 = \frac{1}{2}[u(ds - sd) - d(su - us)]\,.$$

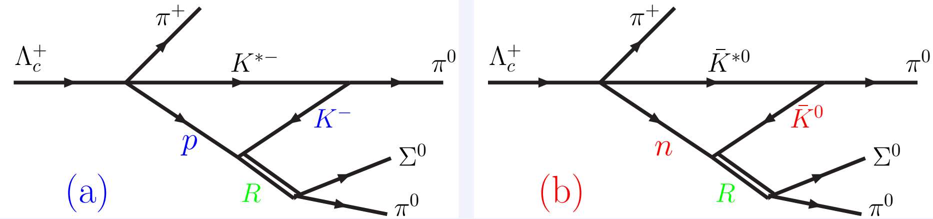
## After the hadronization

$$H = K^{*-}p + \bar{K}^{*0}n - \sqrt{\frac{2}{3}}\phi\Lambda \quad (3)$$

◇ **neglect the $\phi\Lambda$ component $\Longleftarrow$ not contribute to triangle singularity mechanism**

◇ $s\frac{1}{\sqrt{2}}(ud - du)$ **has zero overlap with $\Sigma^0 \Longrightarrow \phi\Sigma^0$ component not appear** $(I = 1)$

# Triangle mechanism with singularity

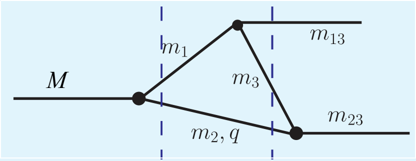



**Isospin forbidden** 1) **cancellation** of diagrams if **equal masses**; 2) The **different masses** of the kaons make the cancellation partial and we can see the $\Lambda(1405)$ [PRD97,116004]

**Triangle Singularity if three intermediate particles are on shell and $K^*$ and $\pi^0$ are parallel $\Longrightarrow$ the mechanism generates a singularity in the amplitude for zero width of the $K^*$, or a peak if the width is considered [L. D. Landau, Nucl. Phys. 13 (1959) 181]**

# Triangle Singularity (TS)

**L. D. Landau, Nucl. Phys. 13 (1959) 181;**
**Coleman, Norton, Nuovo Cim. 38 (1965)438**




**Triangle singularity** at the physical boundary can be obtained **by solving the equation**

$$q_{\rm on+} = q_{a-}, \quad \text{with} \quad q_{\rm on+} = \frac{1}{2M}\sqrt{\lambda(M^2, m_1^2, m_2^2)}, \;\; q_{a-} = \gamma\,(\beta\, E_2^* - p_2^*)\,, \tag{4}$$

where $E_2^* = (m_{23}^2 + m_2^2 - m_3^2)/(2m_{23})$ and $p_2^* = \sqrt{\lambda(m_{23}^2, m_2^2, m_3^2)}/(2m_{23})$

**see 1)E. Oset's talk at session 5 (8:55 am, 20/8);**
**2) H. X. Chen's talk at session 5 (9:55 am, 20/8);**
**3) also P. Pavao's talk at session 5(11:30 am, 20/8)**

**More details in M. Bayar, F. Aceti, F. K. Guo & E. Oset, PRD 94, 074039 (2016)**

# Triangle Singularity

◇ **TS in simulating a resonance**

**requires very special kinematics → process dependent !!!**

**In explaining successfully the COMPASS "$a_1(1420)$" peak**

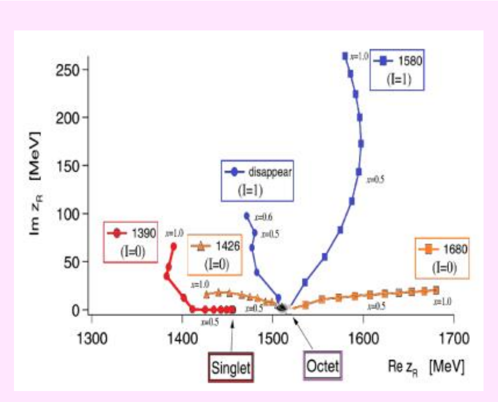
[1] Mikhasenko, Ketzer & Sarantsev, PRD91,094015;
[2]Aceti, Dai & Oset, "$a_1(1420)$ **peak as the** $\pi f_0(980)$ **decay mode of the** $a_1(1260)$ ", PRD94(2016)096015

◇ **In some particular modes, the production rate is enhanced by the presence of a TS in the reaction mechanism.**

# $\bar{K}N$ Interaction and $\Lambda(1405)$ resonance

**E. Oset & A. Ramos, Nucl. Phys. A 635 (1998) 99;**

**D. Jido, J. A. Oller, E. Oset, A. Ramos & U. G. Meissner, Nucl. Phys. A 725 (2003) 181**




| | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| $K^-p$ | $\bar{K}^0n$ | $\pi^0\Lambda$ | $\pi^0\Sigma^0$ | $\eta\Lambda$ |
| 6 | 7 | 8 | 9 | 10 |
| $\eta\Sigma^0$ | $\pi^+\Sigma^-$ | $\pi^-\Sigma^+$ | $K^+\Xi^-$ | $K^0\Xi^0$ |

$$t_3 \equiv t_{\bar{K}N\to\pi^0\Sigma^0} \; ,$$

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

**where $V_{ij}$ are obtained from the chiral Lagrangians [NPA635(1999)99]**

**$G$ is the meson-baryon loop function for the intermediate states**

**Very good reproduction is obtained of scattering data and the threshold parameters**

**Two $\Lambda(1405)$ are generated from this interaction**

# $\Lambda_c^+ \to \pi^+ \bar{K}^* N$

**since the $\Lambda_c^+ \to \pi^+ K^{*-} p$ process can proceed via *s*-wave, the amplitude**

$$t_{\Lambda_c^+ \to \pi^+ K^{*-} p} = A \vec{\sigma} \cdot \vec{\epsilon},$$

**where a scalar function is made between the spin and the $\bar{K}^*$ polarization.**

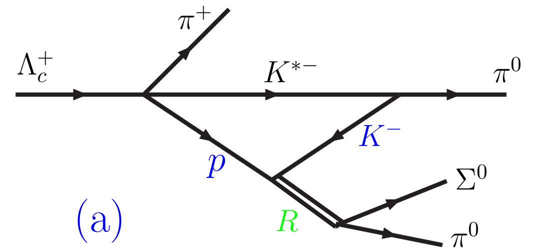
**The $K^{*-} p$ invariant mass distribution**

$$\frac{d\Gamma_{\Lambda_c^+ \to \pi^+ K^{*-} p}}{dM_{\text{inv}}(K^{*-} p)} = \frac{1}{(2\pi)^3} \frac{2M_{\Lambda_c^+} 2M_p}{4M_{\Lambda_c^+}^2} p_{\pi^+} \widetilde{p}_{K^{*-}} \overline{\sum} \sum \left| t_{\Lambda_c^+ \to \pi^+ K^{*-} p} \right|^2 ,$$

**where $p_{\pi^+}$ is the momentum of $\pi^+$ in the $\Lambda_c^+$ rest frame, and $\widetilde{p}_{K^{*-}}$ is the momentum of $K^{*-}$ in the $K^{*-} p$ rest frame**

**By calculating the width of this decay, using the experimental branching ratio of this decay $Br(\Lambda_c^+ \to \pi^+ K^{*-} p) = (1.5 \pm 0.5) \times 10^{-2}$ [PRD98(2018)030001], we can determine the value of the constant $|A|$. [PRD97, 116004]**

# For the first diagram



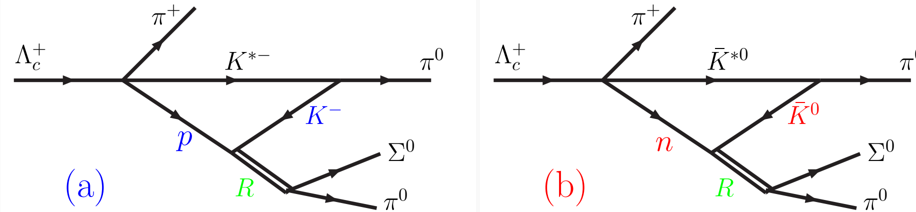

$$t_{\Lambda_c^+\to\pi^+\pi^0\pi^0\Sigma^0} = -A\,\frac{1}{\sqrt{2}}\,g\,\vec{\sigma}\cdot\vec{k}\;t_{K^-p\to\pi^0\Sigma^0}\;t_T\,,$$

**where** $t_T \equiv t_T(m_{K^{*-}}, M_p, m_{K^-})$ **for the triangle loop function for the decay**

$$t_T = i\int \frac{d^4q}{(2\pi)^4}\,\frac{2M_p}{q^2-M_p^2+i\epsilon}\,\frac{(2+\frac{\vec{q}\cdot\vec{k}}{\vec{k}^2})}{(P-q)^2-m_{K^{*-}}^2+i\epsilon}\,\frac{1}{(P-q-k)^2-m_{K^-}^2+i\epsilon}\,.$$

# Include first and second diagrams

$\Longrightarrow$ **the isospin-breaking effect**




## The final differential distributions

$$\frac{1}{\Gamma_{\Lambda_c^+}}\frac{d^2\Gamma}{dM_{\mathbf{inv}}(\pi^0\Lambda(1405))dM_{\mathbf{inv}}(\pi^0\Sigma^0)} = \frac{1}{(2\pi)^5}\frac{M_{\Sigma^0}}{M_{\Lambda_c^+}}\widetilde{p}_{\pi^+}\widetilde{q}_{\Sigma^0}\frac{1}{2}g^2\frac{A^2}{\Gamma_{\Lambda_c^+}}|\vec{k}|^3$$
$$\times\left|t_T(m_{K^{*-}},M_p,m_{K^-})t_{K^-p\to\pi^0\Sigma^0} - t_T(m_{\bar{K}^{*0}},M_n,m_{\bar{K}^0})t_{\bar{K}^0n\to\pi^0\Sigma^0}\right|^2 .$$

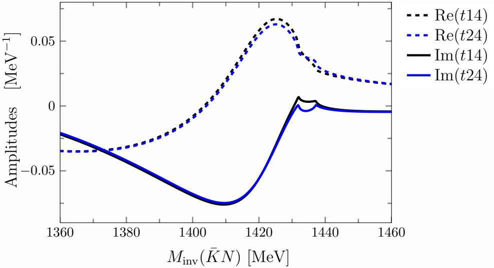
**PRD97, 116004**

# The final results

## $\bar{K}N$ Interaction (real & imaginary parts )

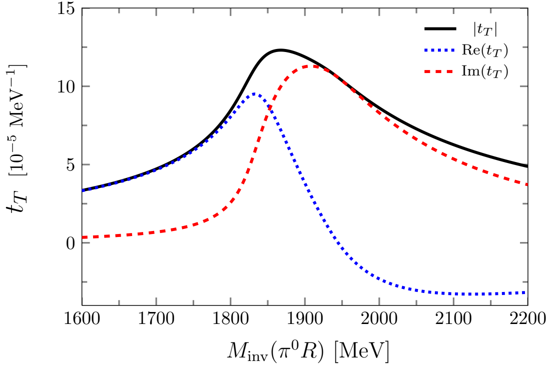
$$\begin{cases} t_{14} & t_{K^- p \to \pi^0 \Sigma^0} \\ t_{24} & t_{\bar{K}^0 n \to \pi^0 \Sigma^0} \end{cases}$$

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| $K^- p$ | $\bar{K}^0 n$ | $\pi^0 \Lambda$ | $\pi^0 \Sigma^0$ | $\eta \Lambda$ | $\eta \Sigma^0$ | $\pi^+ \Sigma^-$ | $\pi^- \Sigma^+$ | $K^+ \Xi^-$ | $K^0 \Xi^0$ |



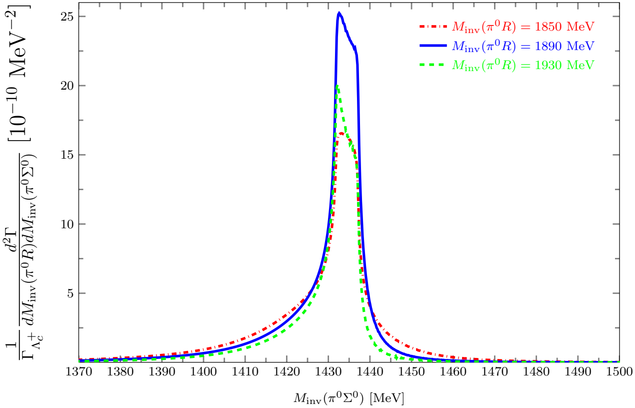
# Triangle amplitude

**peak of $t_T(m_{K^{*-}}, M_p, m_{K^-})$** $M_{\rm inv}(R) \equiv M_{\rm inv}(\pi^0\Sigma^0)$ **fixed at 1420 MeV**




- **real part** $\mathrm{Re}(t_T) \sim 1838$ **MeV** $\Longrightarrow$ **related to the** $K^{*-}p$ **threshold**
- **imaginary part** $\mathrm{Im}(t_T) \sim 1908$ **MeV, dominating for the larger invariant masses for** $\pi^0 R$ $\Longrightarrow$ **due to the triangle singularity**
- **absolute value** $|t_T| \sim 1868$ **MeV**

# The remarkable observation of a peak




**FIRST TIME!!!**

**7 MeV!!!**
**Unusual narrow width**

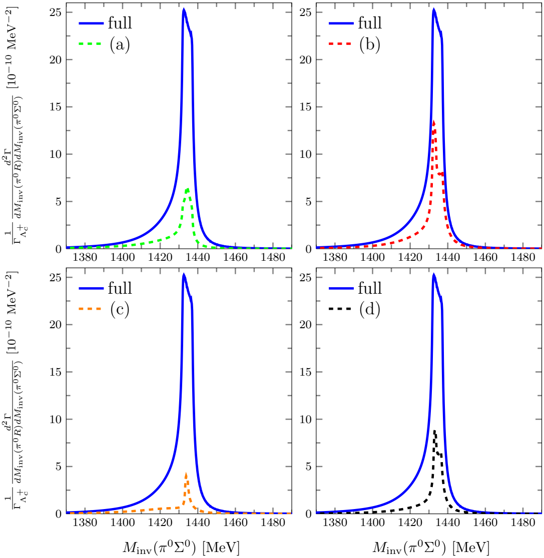
The remarkable observation of a peak tied to the $\Lambda(1405)$ state close to the $\bar{K}N$ threshold of 1432 MeV.

It is also remarkably narrow and is tied to the difference of masses, **mostly from the $K^-$ and $\bar{K}^0$ mass difference (see next page)**

# Discussion on separate effects

## Double differential width of $\Lambda_c^+ \to \pi^+\pi^0\pi^0\Sigma^0$

**Fixed at $M_{\text{inv}}(\pi^0 R) = 1890\text{MeV}$**




**(a) scattering amplitude $t_{K^-p\to\pi^0\Sigma^0}$, $t_{\bar{K}^0 n\to\pi^0\Sigma^0}$ with the physical masses (isospin violation)**
**but Triangle loop $m_p = m_n$, $m_{\bar{K}^0} = m_{K^-}$ (isospin symmetric);**
**(b) $t_{K^-p\to\pi^0\Sigma^0}$, $t_{\bar{K}^0 n\to\pi^0\Sigma^0}$ isospin symmetric (equal) and physical masses for $p, n, K^-, \bar{K}^0$;**

**(c) scattering amplitude isospin symmetric, $m_{\bar{K}^0} = m_{K^-}$, but $m_p$ and $m_n$ with their physical values**
**(d) scattering amplitude isospin symmetric, $m_p = m_n$, but $m_{\bar{K}^0}$ and $m_{K^-}$ with their physical values**

**It can be seen that the peak comes mostly from the $K^-$ and $\bar{K}^0$ mass difference**

**[PRD97,116004]**

# History!!!

## Isospin forbidden reactions

## $f_0(980)$ and $a_0(980)$

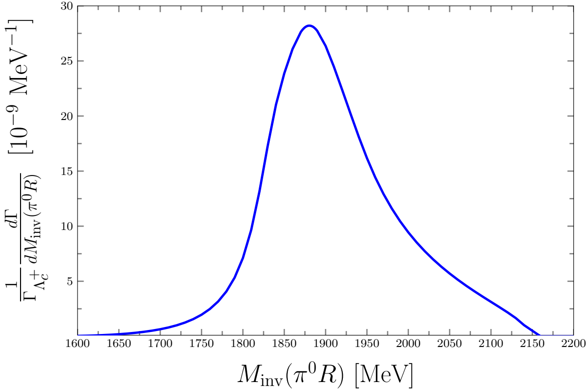
The apperance of a **narrow resonance** in the isospin forbidden reactions due to **different kaon masses** also appears in the $f_0(980)$ or $a_0(980)$ isospin forbidden production

"Investigation of a0-f0 mixing", C. Hanhart, B. Kubis and J. R. Pelaez, Phys. Rev. D 76 (2007) 074028

"**Isospin violation** in $J/\Psi \to \phi\pi^0\eta$ decay and the $f_0 - a_0$ mixing", L. Roca, Phys. Rev. D 88 (2013) 014045

"**Isospin breaking** and $f_0(980)$-$a_0(980)$ mixing in the $\eta(1405) \to \pi^0 f_0(980)$ reaction", F. Aceti, W. H. Liang, E. Oset, J. J. Wu and B. S. Zou, Phys. Rev. D 86 (2012) 114007

# Differential distribution and branching ratio




**a clear peak**

**triangle singularity!!!**

$$Br(\Lambda_c^+ \to \pi^+ \pi^0 \Lambda(1405); \Lambda(1405) \to \pi^0 \Sigma^0)$$
$$= (4.17 \pm 1.39) \times 10^{-6}$$

$\Longrightarrow$ **this number** is within **a measurable range!!!**

**The errors come from the experimental errors in the branching ratio of** $Br(\Lambda_c^+ \to \pi^+ K^{*-} p)$

# Conclusions

**Triangle singularities show a great potential to enhance suppressed processes.**

**In the present case we showed how the $\Lambda(1405)$ could be produced in an isospin forbidden mode.**

**It stresses the nature of this resonance as dynamically generated from the meson-baryon interaction, resulting from cancellation of diagrams involving the $\bar{K}N \to \pi\Sigma$ amplitudes.**

**one signal of this is the narrow shape of the resonance, which would not be justified if the resonance was a genuine state.**

**Triangle singularity also enhances the production of resonances that appear around the singular point.**

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**THE ENDING!!!**