Λ(1405) in chiral dynamics and related topics

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Physics of the Λ(1405)

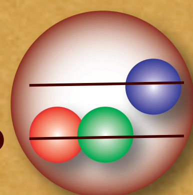
$\Lambda(1405) : J^P = 1/2^-, I = 0$

(PDG)

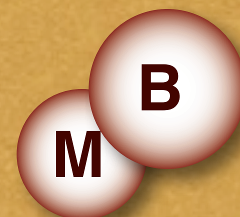
mass : 1406.5 ± 4.0 MeV, width : 50 ± 2 MeV

decay mode: $\Lambda(1405) \to (\pi\Sigma)_{I=0}$ **100%**

"naive" quark model
: p-wave ~1600 MeV?



N. Isgur, G. Karl, PRD18, 4187 (1978)



Coupled channel
multi-scattering

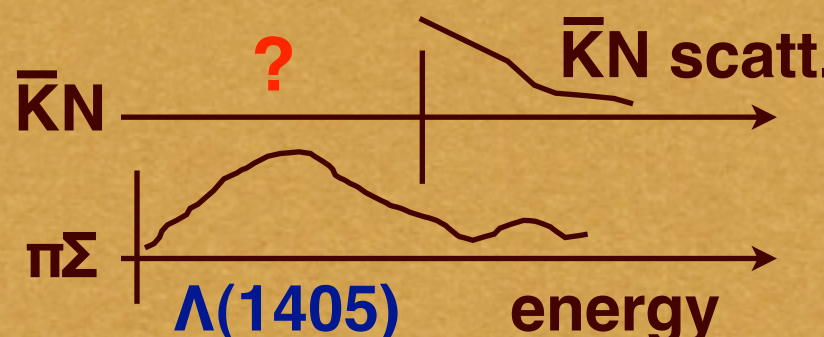
R.H. Dalitz, T.C. Wong,
G. Rajasekaran, PR153, 1617 (1967)

$\bar{K}N$ interaction below threshold

T. Hyodo, W. Weise, PRC 77, 035204 (2008)

--> $\bar{K}N$ potential, kaonic nuclei

A. Dote, T. Hyodo, W. Weise,
NPA804, 197 (2008); PRC 79, 014003 (2009)



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- Introduction
- Λ(1405) in chiral SU(3) dynamics

  T. Hyodo, D. Jido, arXiv:1104.4474, to appear in Prog. Part. Nucl. Phys.

  - Theoretical framework
  - Pole structure of Λ(1405)
  - Meson-baryon nature of Λ(1405)
- Recent developments + future perspective
  - Toward a realistic $\bar{K}N$-πΣ interaction
  - Hadron structure in heavy ion collisions
- Summary

Chiral symmetry breaking in hadron physics

Chiral symmetry: QCD with massless quarks

Consequence of chiral symmetry breaking in hadron physics

- **appearance of the Nambu-Goldstone (NG) boson**

  $m_\pi \sim 140 \text{ MeV}$

- **dynamical generation of hadron masses**

  $M_p \sim 1 \text{ GeV} \sim 3M_q, \quad M_q \sim 300 \text{ MeV} \quad v.s. \quad 3-7 \text{ MeV}$

- **constraints on the NG-boson--hadron interaction**

  low energy theorems <-- current algebra

  systematic low energy ($m,p/4\pi f_\pi$) expansion: ChPT

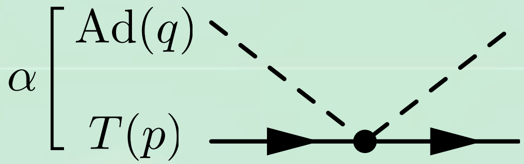
Chiral symmetry and its breaking

$$SU(3)_R \otimes SU(3)_L \to SU(3)_V$$

Underlying QCD <==> observed hadron phenomena

s-wave low energy interaction

Low energy NG boson (Ad) + target hadron (T) scattering



$$= \frac{1}{f^2}\frac{p\cdot q}{2M_T}\langle \boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle_\alpha + \mathcal{O}\left(\left(\frac{m}{M_T}\right)^2\right)$$

Projection onto s-wave: Weinberg-Tomozawa (WT) term

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

$$V_{ij} = -\frac{C_{ij}}{4\boxed{f^2}}\boxed{(\omega_i+\omega_j)}$$

energy dependence (derivative coupling)

decay constant of π (g_V=1)

$$C_{ij} = \sum_\alpha C_{\alpha,T}\begin{pmatrix} 8 & T & \| & \alpha \\ I_{M_i},Y_{M_i} & I_{T_i},Y_{T_i} & \| & I,Y\end{pmatrix}\begin{pmatrix} 8 & T & \| & \alpha \\ I_{M_j},Y_{M_j} & I_{T_j},Y_{T_j} & \| & I,Y\end{pmatrix}$$

$$C_{\alpha,T} = \langle 2\boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle_\alpha = C_2(T) - C_2(\alpha) + 3$$

Group theoretical structure and flavor SU(3) symmetry determines the sign and the strength of the interaction

Systematic improvement by ChPT

Scattering amplitude and unitarity

Unitarity of S-matrix: Optical theorem

$$\mathrm{Im}[T^{-1}(s)] = \frac{\boxed{\rho(s)}}{2}$$

phase space of two-body state

General amplitude by dispersion relation

$$T^{-1}(\sqrt{s}) = \boxed{\sum_i \frac{R_i}{\sqrt{s}-W_i} + \tilde{a}(s_0)} + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

R_i, W_i, a: to be determined by chiral interaction

Identify dispersion integral = loop function G, the rest = V^{-1}

$$\boxed{T(\sqrt{s}) = \frac{1}{V^{-1}(\sqrt{s}) - G(\sqrt{s};a)}}$$

Scattering amplitude

The function V is determined by the matching with ChPT

$$T^{(1)} = V^{(1)}, \quad T^{(2)} = V^{(2)}, \quad T^{(3)} = V^{(3)} - V^{(1)}GV^{(1)}, \quad \dots$$

Amplitude T: consistent with chiral symmetry + unitarity

Chiral unitary approach

Meson-baryon scattering amplitude

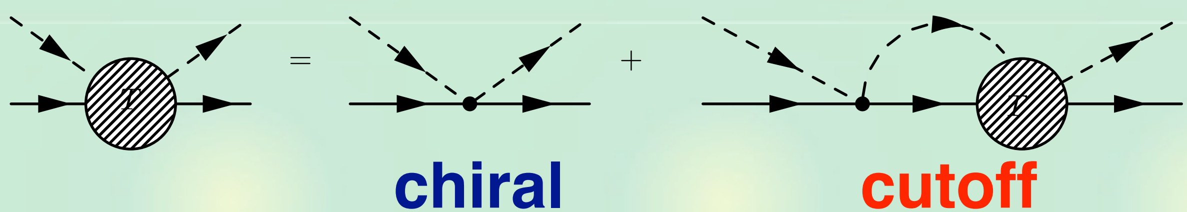
- Interaction <-- chiral symmetry

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

- Amplitude <-- unitarity in coupled channels

R.H. Dalitz, T.C. Wong, G. Rajasekaran, Phys. Rev. 153, 1617 (1967)

$$T = \frac{1}{1 - VG} V$$

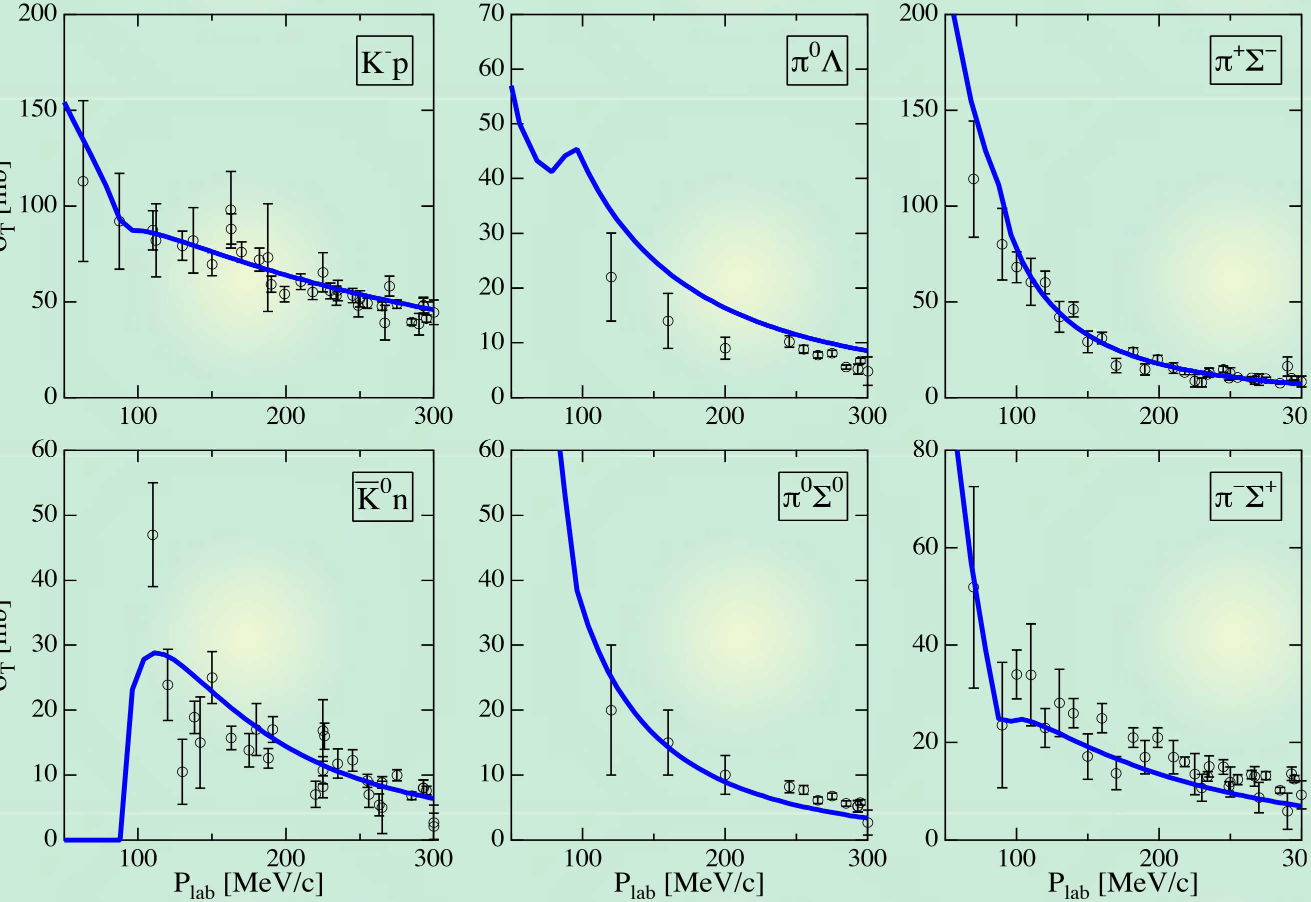


N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

It works successfully, also in S=0 sector, meson-meson scattering sectors, systems including heavy quarks, ...

A simple model (1 parameter) v.s. experimental data

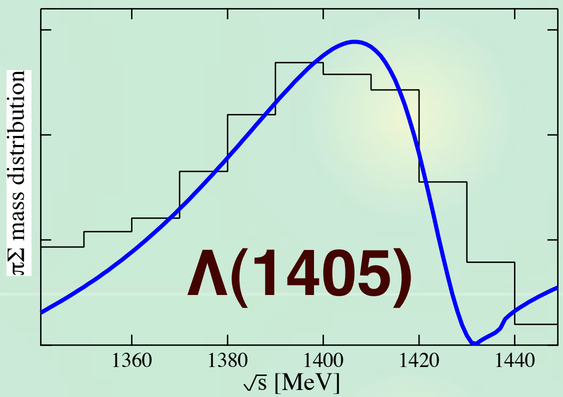
Total cross section of K-p scattering



Branching ratio

	γ	R_c	R_n
exp.	2.36	0.664	0.189
theo.	1.80	0.624	0.225

πΣ spectrum



T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, PRC68, 018201 (2003); PTP 112, 73 (2004)

Good agreement with data above, at, and below $\bar{K}N$ threshold

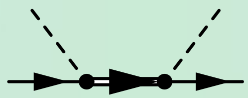
more quantitatively --> fine tuning, higher order terms,...

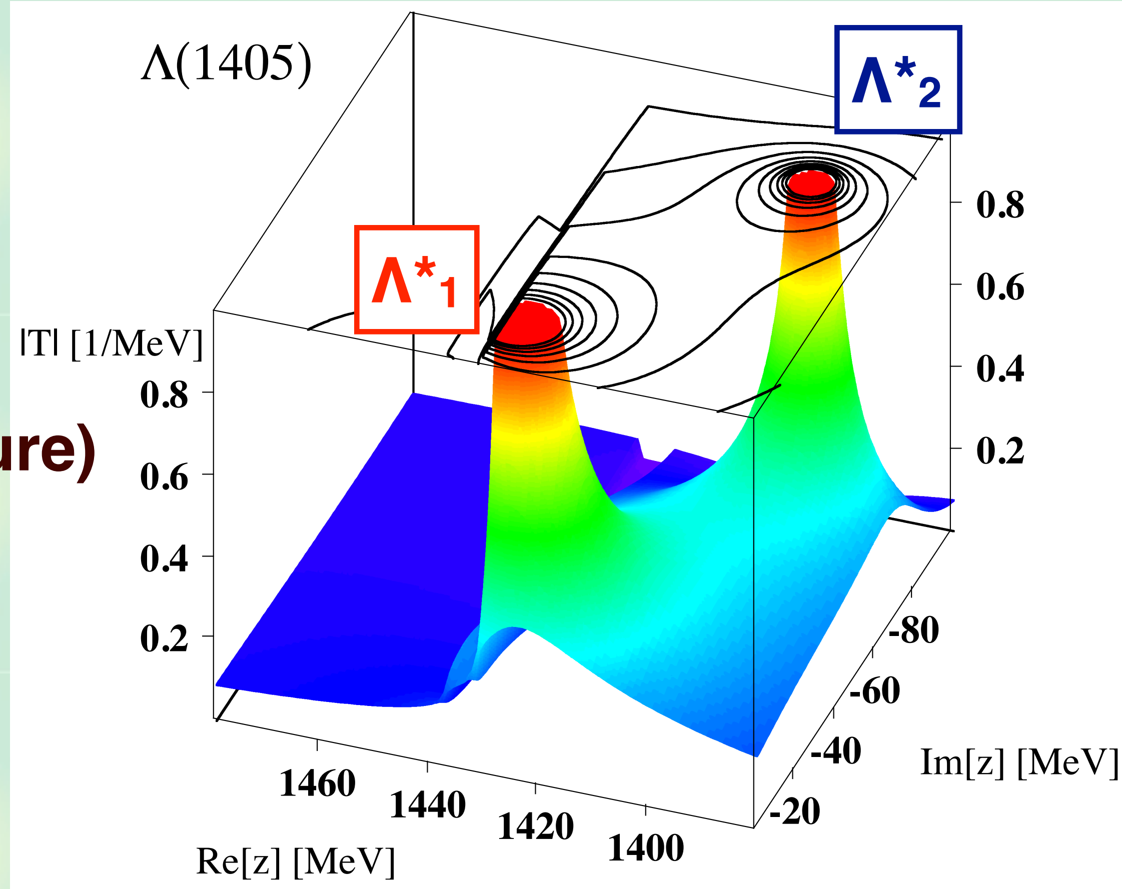
Pole structure in the complex energy plane

Resonance state ~ pole of the scattering amplitude

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003);
T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$

$\sim$ 



Two poles for one resonance (bump structure)

--> Superposition of two states ?

--> different πΣ spectra?

What is the origin of this structure?

Origin of the two-pole structure

Leading order chiral interaction for $\bar{K}N$-πΣ channel

T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

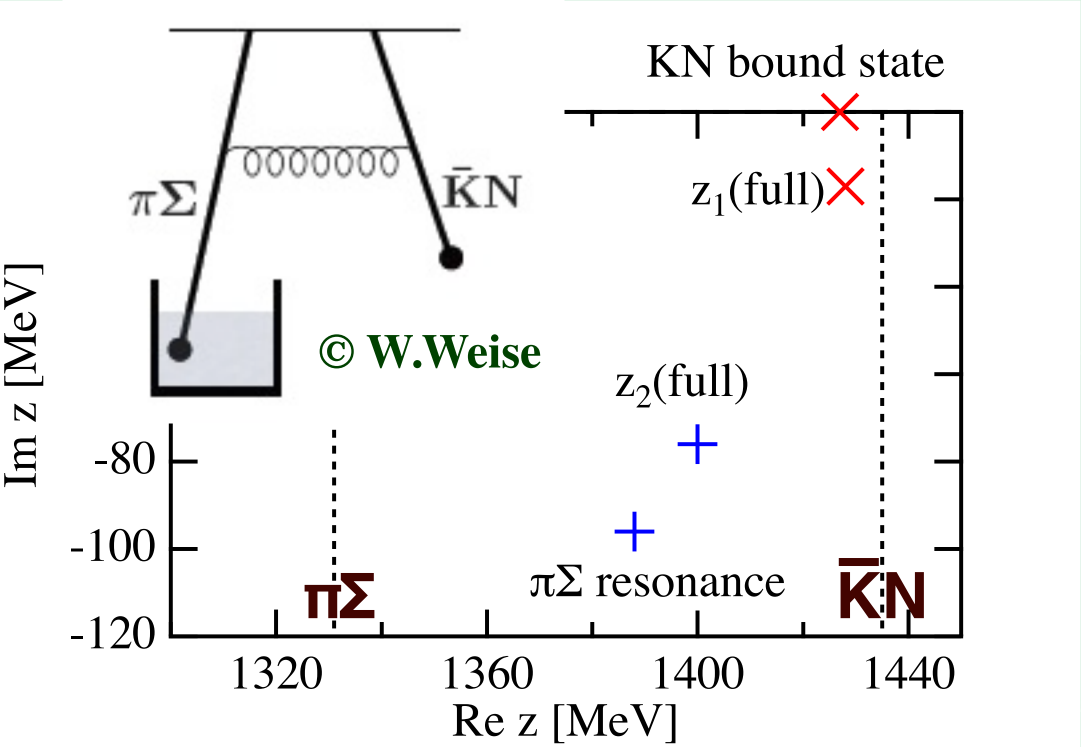
$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

$$\begin{array}{cc} & \begin{array}{cc} \bar{K}N & \pi\Sigma \end{array} \\ C_{ij} = & \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix} \end{array}$$

at threshold

$$\omega_i \sim m_i, \quad 3.3 m_\pi \sim m_K$$

$$\Rightarrow V_{\bar{K}N} \sim 2.5 V_{\pi\Sigma}$$

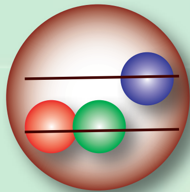
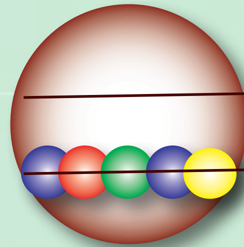
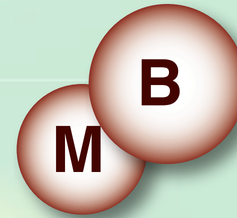


Very strong attraction in $\bar{K}$N (higher energy) --> bound state
Strong attraction in πΣ (lower energy) --> resonance

Two poles also emerge with NLO contributions.

Structure of hadron resonances

Possible structures of Λ(1405)

$|\,\Lambda(1405)\,\rangle =$  $+$  $+$ 

$+ \dots$

3-quark 5-quark molecule

3-quark state: constituent quark model with l=1

5-quark state: constituent quark model with l=0

hadronic molecule: driven by hadronic interaction

All the components should mix with each other.

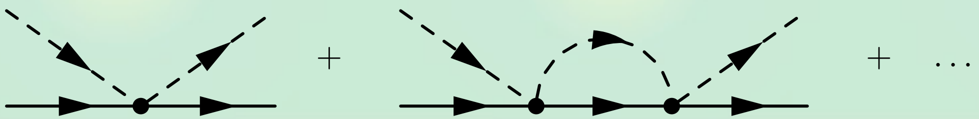
==> Theoretical investigation of the dominant structure

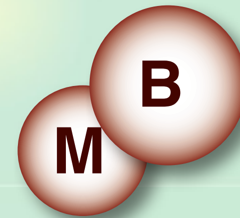
Dynamical state and CDD pole

Resonances in two-body scattering

- Knowledge of interaction (potential)
- Experimental data (cross section, phase shift,...)

(a) dynamical state: molecule, quasi-bound, ...

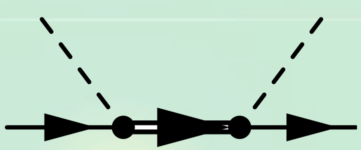


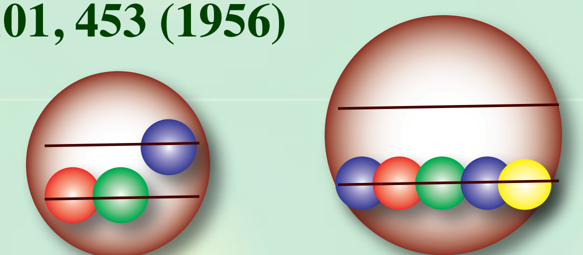


... in the present case : meson-baryon molecule

(b) CDD pole: elementary, independent, ...

L. Castillejo, R.H. Dalitz, F.J. Dyson, Phys. Rev. 101, 453 (1956)





... in the present case : 3-quark state or 5-quark state

Resonances in chiral dynamics -> (a) dynamical?

CDD pole contribution in chiral unitary approach

Amplitude in chiral unitary model

$$T = \frac{1}{\boxed{V^{-1}} - \boxed{G}}$$

V : interaction kernel

G : loop integral

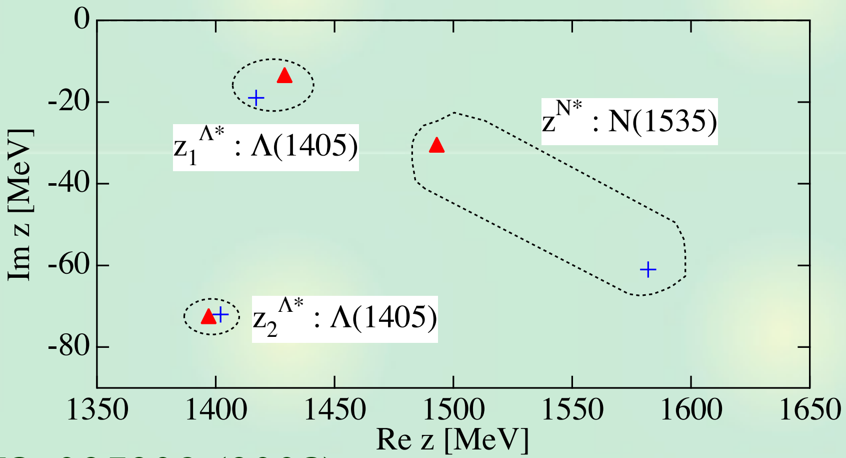
Known CDD pole contribution : those in V

The loop function G can contain the CDD pole contribution.

We propose "natural renormalization scheme" to exclude CDD pole contribution in G (subtraction constant).

N(1535) in πN scattering
--> dynamical + CDD pole

Λ(1405) in $\bar{K}$N scattering
--> mostly dynamical



T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008).

Nc scaling in the model

Nc : number of color in QCD
Hadron effective theory / quark structure

The Nc behavior is known from the general argument.
<-- introducing Nc dependence in the model,
analyze the resonance properties with respect to Nc

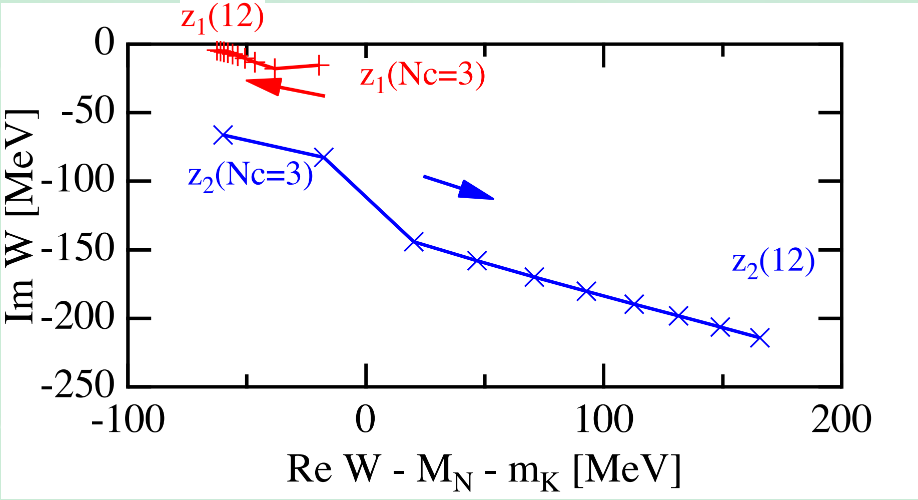
J.R. Pelaez, Phys. Rev. Lett. 92, 102001 (2004)

Nc scaling of (excited) qq...q baryon

$$M_R \sim \mathcal{O}(N_c), \quad \Gamma_R \sim \mathcal{O}(1)$$

Result of chiral dynamics

$$\Gamma_R \neq \mathcal{O}(1)$$

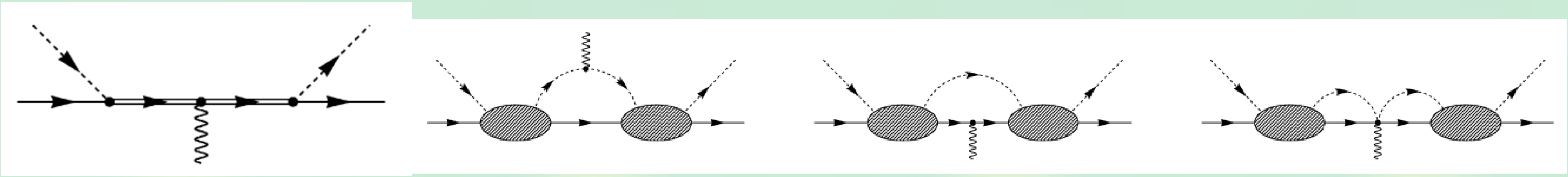


--> non-qqq structure of the Λ(1405)

T. Hyodo, D. Jido, L. Roca, Phys. Rev. D77, 056010 (2008);
L. Roca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65-87 (2008).

Electromagnetic properties

Attaching photon to resonance
--> em properties : rms, form factors,...



Evaluated mean squared radii :

$$\sqrt{\langle x^2 \rangle} \sim 1.69 \text{ fm}$$

Λ(1405) has spatially large size.   c.f. nucleon: ~0.88 [fm]

--> support the meson-baryon (or 5-quark) picture

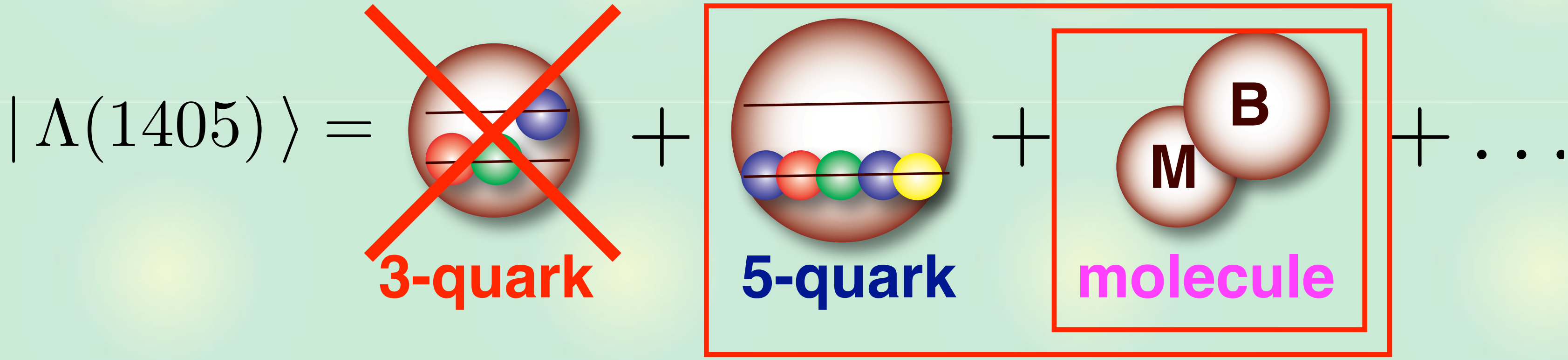
Computation at finite Q^2

--> form factor $F(Q^2)$, density distribution ρ(r)

T. Sekihara, T. Hyodo, D. Jido, Phys. Lett. B669, 133-138 (2008);
T. Sekihara, T. Hyodo, D. Jido, Phys. Rev. C 83, 055202 (2011).

Structure of Λ(1405)

Possible structures of Λ(1405)



Dynamical or CDD? --> dominance of the MB component

Analysis of Nc scaling --> non-qqq sqructure

Electromagnetic properties --> large spatial size

The most plausible scenario is the hadronic molecule
(how can we distinguish MB from 5q? --> later)

Summary 1

We study the $\bar{K}N$-$\pi\Sigma$ system and $\Lambda(1405)$ based on chiral SU(3) symmetry and unitarity

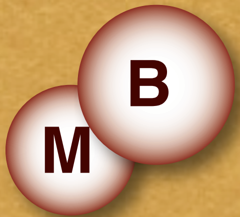
- **Chiral low energy theorem constrains the NG boson dynamics.**

- **Two poles for $\Lambda(1405)$**

  <-- attractive $\bar{K}N$ and $\pi\Sigma$ interactions

- **Structure of $\Lambda(1405)$**

  <-- meson-baryon molecule



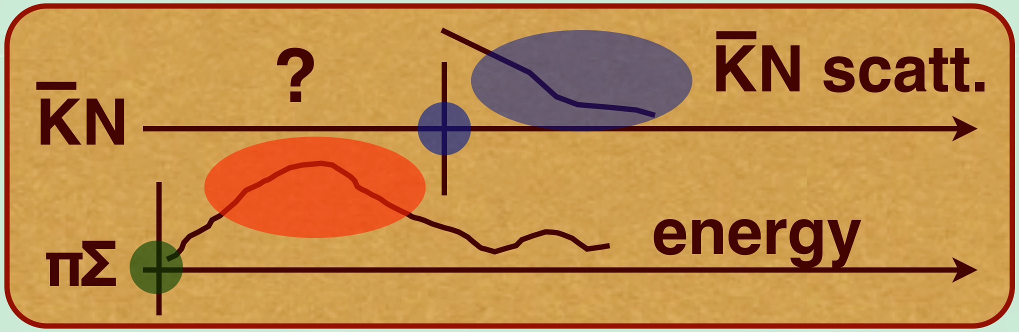
T. Hyodo, D. Jido, arXiv:1104.4474, to appear in Prog. Part. Nucl. Phys.

Experimental constraints for S=-1 MB scattering

K-p total cross sections (bubble chamber, large errors)

Precise data at $\bar{K}N$ threshold

- threshold branching ratios (old but accurate)
- K-p scattering length <-- SIDDHARTA exp.



πΣ mass spectra

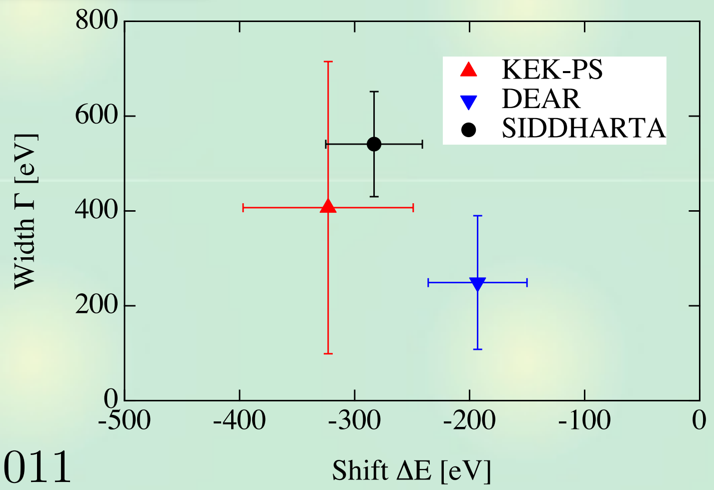
- new data is becoming available (LEPS, CLAS, HADES,...)
- not normalized <-- to be predicted?

πΣ threshold behavior (so far no data)

Constraints from $\bar{\mathrm{K}}$N data

- K-p total cross sections

$$K^- p \to (K^- p, \bar{K}^0 n, \pi^0\Lambda, \pi^0\Sigma^0, \pi^+\Sigma^-, \pi^-\Sigma^+)$$



- Threshold branching ratios

$$\gamma = \frac{\Gamma(K^- p \to \pi^+\Sigma^-)}{\Gamma(K^- p \to \pi^-\Sigma^+)} = 2.36 \pm 0.04$$

$$R_c = \frac{\Gamma(K^- p \to \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^- p \to \text{all inelastic channels})} = 0.664 \pm 0.011$$

$$R_n = \frac{\Gamma(K^- p \to \pi^0\Lambda)}{\Gamma(K^- p \to \text{neutral states})} = 0.189 \pm 0.015$$

R.J. Nowak *et al.*, Nucl. Phys. B139, 61 (1978); D.N. Tovee *et al.*, *ibid*, B33, 493 (1971)

- Shift and width of 1s level of kaonic hydrogen (SIDDHARTA)

$$\Delta E = -283 \pm 36 \pm 6 \text{ eV}, \quad \Gamma = 541 \pm 89 \pm 22 \text{ eV}$$

Bazzi, *et al.*, arXiv:1105.3090 [nucl-ex]

$$\Delta E - \frac{i}{2}\Gamma = -2\alpha^3\mu_c^2 a_{K^-p}[1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}]$$ **<-- scattering length**

U.-G. Meissner, U. Raha, A. Rusetsky, Eur. Phys. J. C35, 349 (2004)

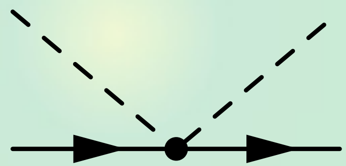
Construction of the realistic amplitude

Systematic chi2 fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, in preparation

Interaction kernel: NLO ChPT

1) WT term

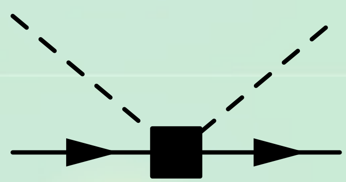


$\mathcal{O}(p)$

2) Born terms

$\mathcal{O}(p)$

3) NLO terms



$\mathcal{O}(p^2)$

Parameters: 6 cutoffs + 7 low energy constants

Error analysis --> sensitivity on the K-p scattering length

πΣ threshold behavior

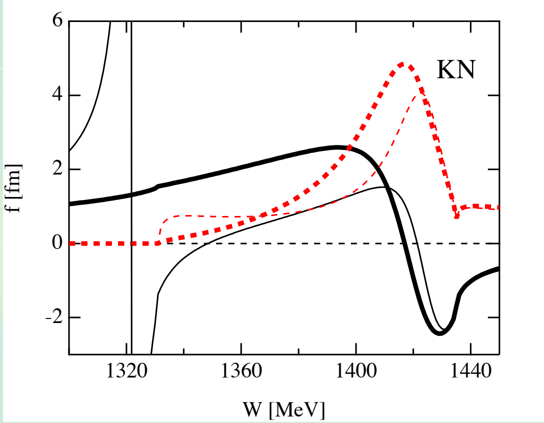
Effect of the πΣ threshold data for $\bar{K}$N-πΣ amplitude

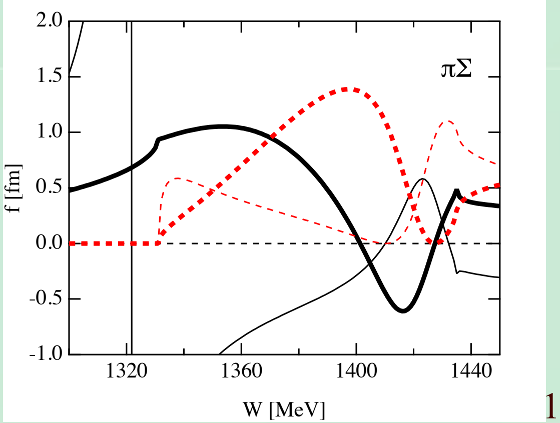
Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki, arXiv:1101.5190 [nucl-th], to appear in Prog. Theor. Phys.

Extrapolations with a given $\bar{K}$N(I=0) scattering length
--> uncertainty in subthreshold

Model	A1	A2	B E-dep	B E-indep
parameter ($\pi\Sigma$)	$d_{\pi\Sigma} = -1.67$	$d_{\pi\Sigma} = -2.85$	$\Lambda_{\pi\Sigma} = 1005$ MeV	$\Lambda_{\pi\Sigma} = 1465$ MeV
parameter ($\bar{K}N$)	$d_{\bar{K}N} = -1.79$	$d_{\bar{K}N} = -2.05$	$\Lambda_{\bar{K}N} = 1188$ MeV	$\Lambda_{\bar{K}N} = 1086$ MeV
pole 1 [MeV]	$1422 - 16i$	$1425 - 11i$	$1422 - 22i$	$1423 - 29i$
pole 2 [MeV]	$1375 - 72i$ (R)	1321 (B)	$1349 - 54i$ (R)	1325 (V)
$a_{\pi\Sigma}$ [fm]	0.934	-2.30	1.44	5.50
r_e [fm]	5.02	5.89	3.96	0.458
$a_{\bar{K}N}$ [fm] (input)	$-1.70 + 0.68i$	$-1.70 + 0.68i$	$-1.70 + 0.68i$	$-1.70 + 0.68i$

subthreshold behavior



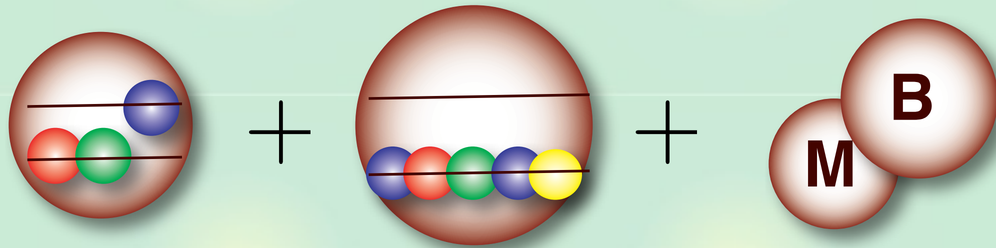


<-- πΣ scattering length, effective range

Structure of hadron resonances

Possible structures of Λ(1405)

$$| \Lambda(1405) \rangle = \quad + \quad + \quad + \dots$$



3-quark 5-quark molecule

3-quark state: constituent quark model with l=1

5-quark state: constituent quark model with l=0

hadronic molecule: driven by hadronic interaction

All the components should mix with each other.

==> Experimental investigation of the dominant structure

Hadron structure in experiments

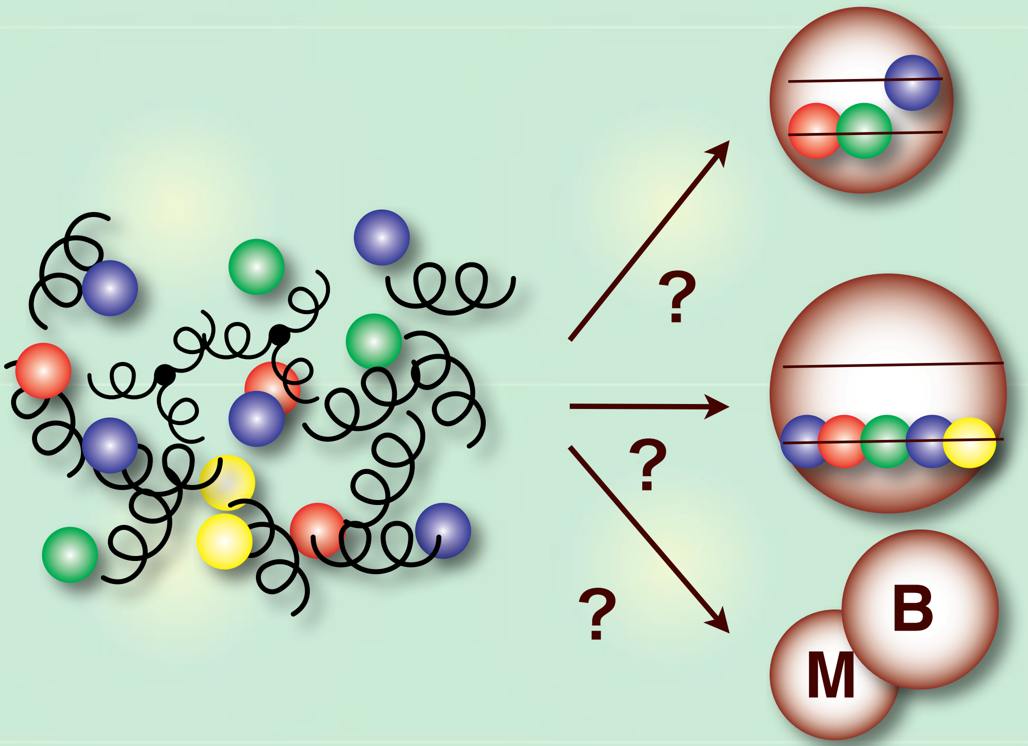
Hadron production yield in heavy ion collisions

PRL **106**, 212001 (2011) PHYSICAL REVIEW LETTERS week ending 27 MAY 2011

Identifying Multiquark Hadrons from Heavy Ion Collisions

Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1,2] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,3]

(ExHIC Collaboration)



statistical model

- thermal equilibrium
- well reproduce the (normal) hadron yield

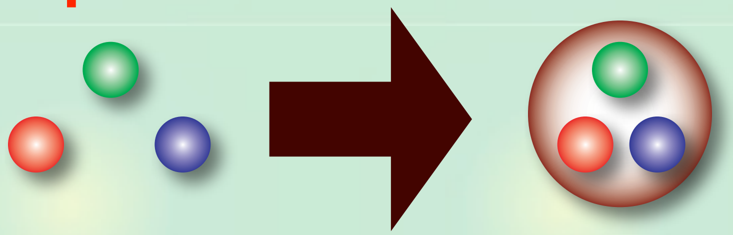
coalescence model

- overlap of density matrix of constituents
- inner structure

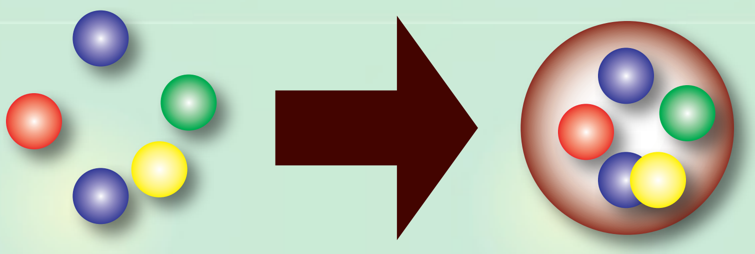
Results of the production yield

Ratio of coalescence model/statistical model

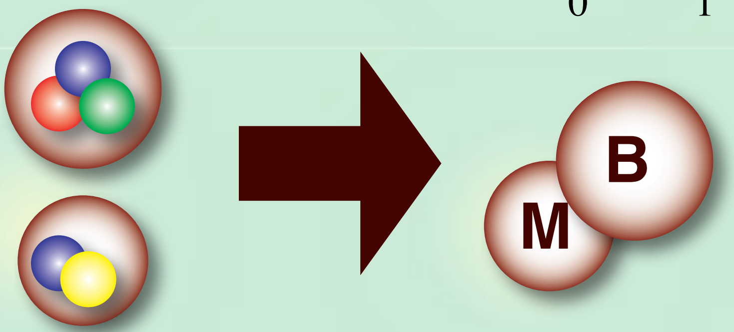
(a) 3-quark

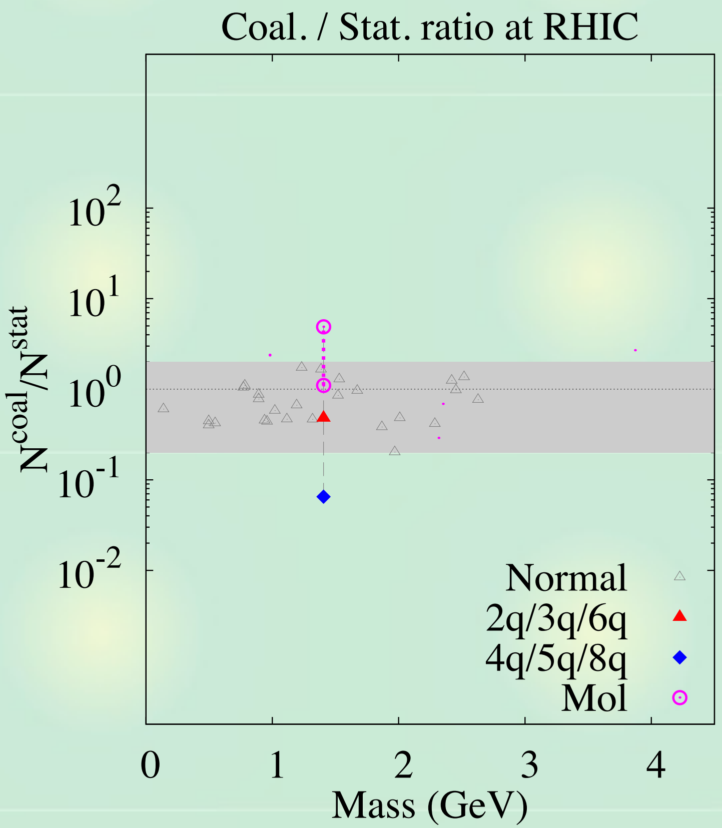


(b) 5-quark



(c) molecule





Different structure is reflected in the production yield

Summary 2

Recent developments of study of $\Lambda(1405)$

- **For more quantitative discussion,**
  - **New $\bar{K}N$ threshold data**
    & systematic chi2 analysis with NLO

    Y. Ikeda, T. Hyodo, W. Weise, in preparation

  - **threshold information of $\pi\Sigma$ channel**

    Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki,
    arXiv:1101.5190 [nucl-th], to appear in Prog. Theor. Phys.

- **For verification of internal structure,**
  - **production yield in heavy ion collisions**

    S. Cho, *et al.* [ExHIC col.], Phys. Rev. Lett. 106, 212001 (2011)