A new N* resonance as a hadronic molecular state

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collaboration with

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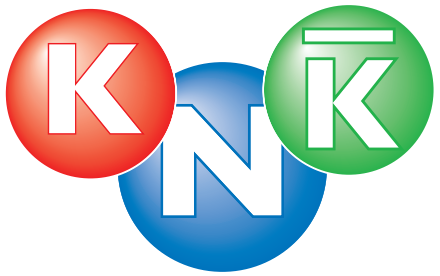
new N* resonance at around 1910 MeV

20~40 MeV blow $KK^{bar}N$ threshold (1930 MeV)

hadronic molecular state

Kaons are constituents

N*



References

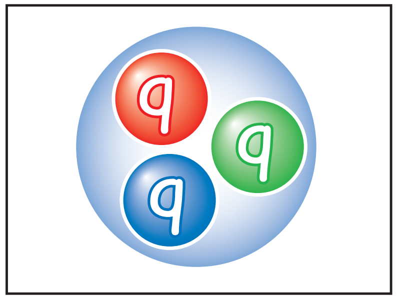
D. Jido and Y. Kanada-En'yo, **Phys. Rev. C78, 035203 (2008)**

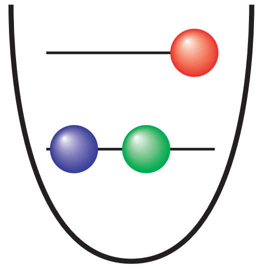
See also for Ξ*: Y. Kanada-En'yo and D. Jido, **Phys. Rev. C78, 025212 (2008)**

Introduction

So far, the structure of baryons has been investigated in quark models.

symmetries of quarks play a major role



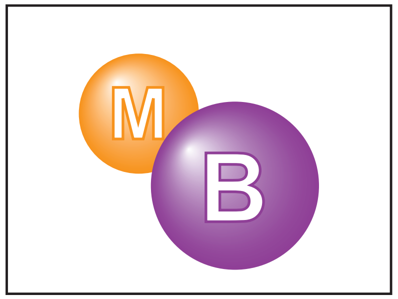


shell model picture

Baryon resonances : decay with strong interactions

large meson-baryon components

meson-baryon dynamics is also important



cluster picture

- inter-hadron distance is larger than quark dynamics
- difference in range of dynamics

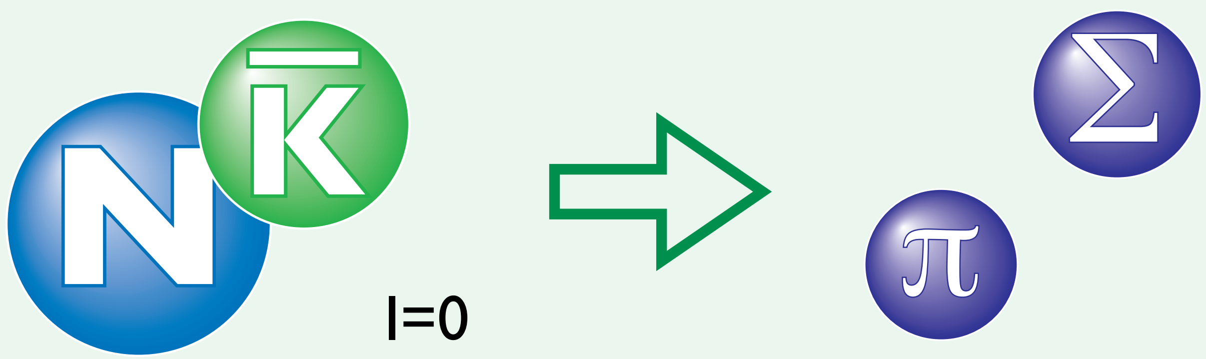
What is hadronic molecular state ?

- system of multiple hadrons described by hadron dynamics

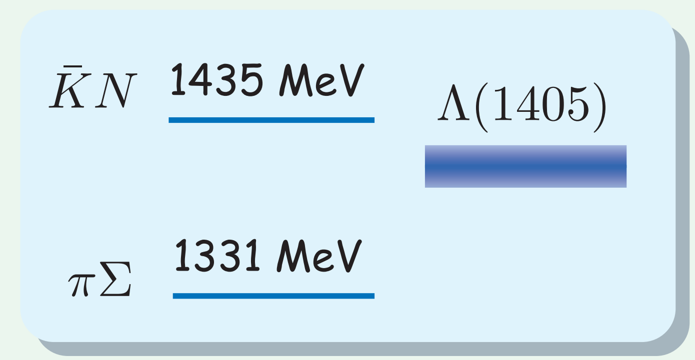
typical constituents are ground states hadrons

octet meson: π, K, η
octet baryons: N, Λ, Σ, Ξ

Λ(1405) : one of the historical examples



I=0



have been considered as a quasi-bound state of K^bar N since late 50's

Dalitz, Tuan, PRL 2, 425 ('59)

Recently this idea has been developed to light nuclear system

Akaishi, Yamazaki, PRC 65, 044005 ('02)

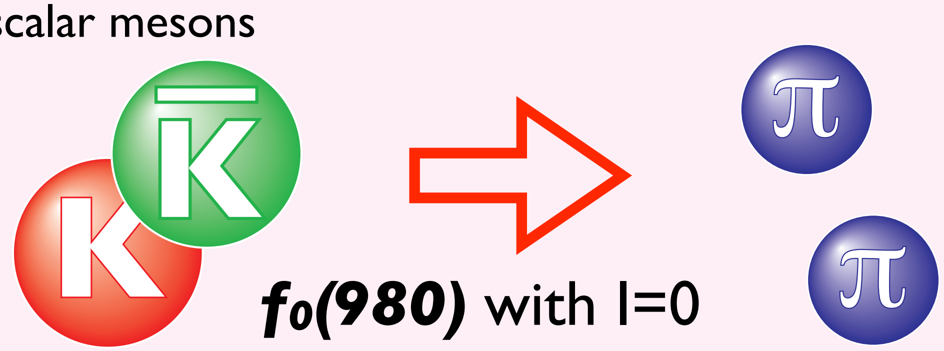
Λ(1405) is described as a superposition of two states.

DJ, Oller, Oset, Ramos, Meissner NPA725, 181 ('03)

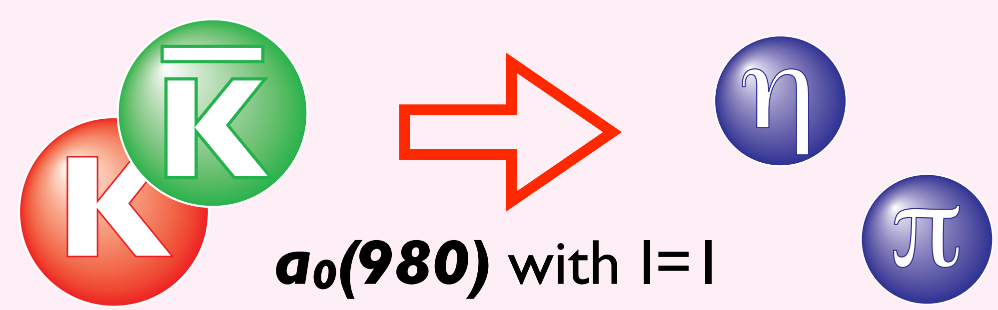
f_0(980), a_0(980) : the candidates of KK^bar QBS

Weinstein, Isgur, PRL 48, 659 ('90)

scalar mesons



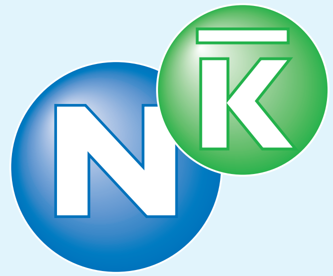
f_0(980) with I=0



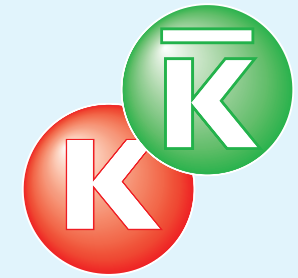
a_0(980) with I=1

What is hadronic molecular state ?

$\Lambda(1405)$



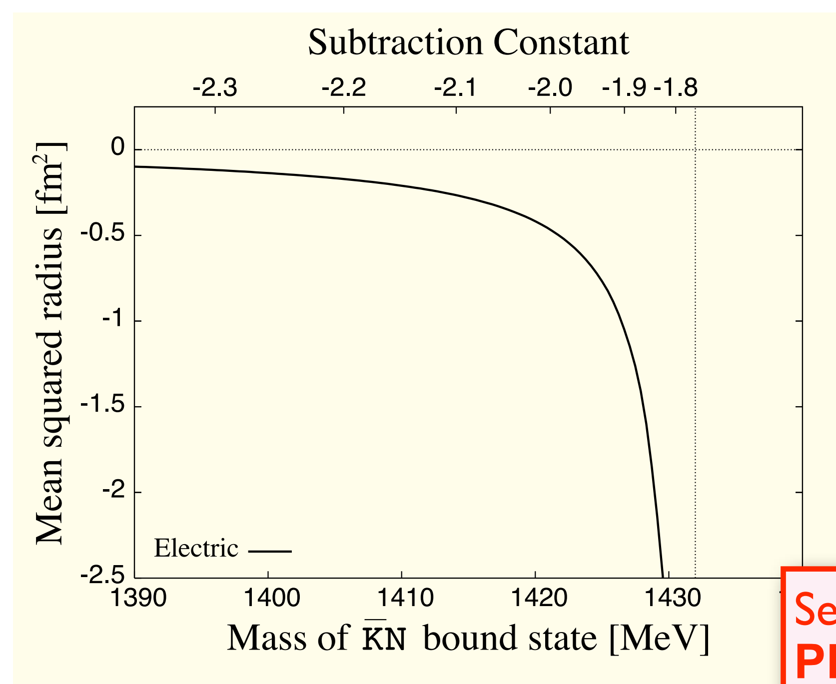
$f_0(980)$, $a_0(980)$



- ***weakly bound system with large width***
  - typical binding energy ~ 10-30 MeV
  - decay width ~ 50 MeV (strong interactions)

quasi-bound state

- ***constituents keep their identity***
  - spatially extended (large size)
  - typically more than 1 fm
- ***fragile system***
  - softer form factors
  - strong energy dependence in production



charge radius of $\Lambda(1405)$ as $K^{bar}N$ bound state

Sekihara, Hyodo, DJ
PLB669, 133 (2008)

quark degrees of freedom may be less important

Peculiarities of K meson

small binding energy ~ 10-30 MeV   small kinetic energy

- **heavy particle** compared with kinetic energy

  half of nucleon mass

  cf. pion $m_\pi \approx 140$ MeV

  non-relativisitc potential model

isospin averaged mass

$$m_K = 495.7 \text{ MeV}$$
$$m_N = 938.9 \text{ MeV}$$

- **Nambu-Goldstone boson**

  smaller mass compared with typical hadron mass scale

  strong s-wave attraction in $K^{bar}N$

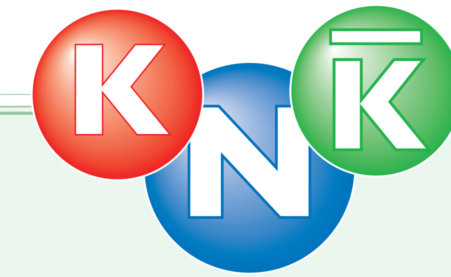
  chiral effective theory   momentum expansion

  s-wave int. proportional to K energy

Kaons are different from pions in the energies of our interest !!

$K\bar{K}N$ system with I=1/2, $J^P=1/2^+$

simplest multi-kaon baryonic system:



s-wave

assumption

non-relativistic treatment of kaons

Λ(1405) is a quasi-bound state of $K^{bar}N$

$f_0(980)$ and $a_0(980)$ are quasi-bound states of KK^{bar}

Binging energy is important for "fate" of hadronic molecular state

A) 3-body System > 2-body BS + hadron

fall apart, large width

B) 3-body BS < 2-body BS + hadron

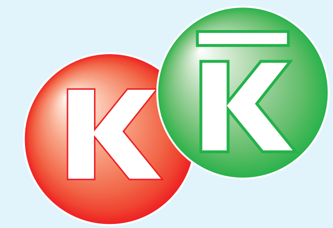
quasi-stable

C) 3-body BS << 2-body BS + hadron

molecular picture broken down → different approaches are necessary

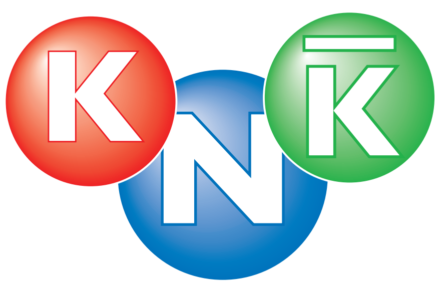
large width of two-body decay **3-body → 2-body**

Two-body interactions

Λ(1405)  $f_0(980)$, $a_0(980)$ 

Interactions in KK^{bar}N system

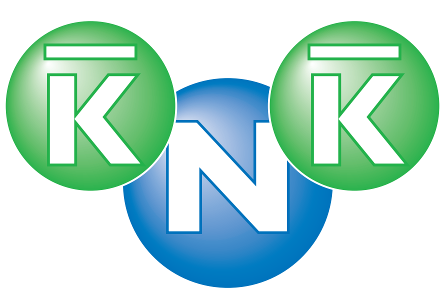
N*



		I=0	I=1	threshold
$\bar{K}N$	attraction	$\Lambda(1405)$	weak attraction	1434.6 MeV
$K\bar{K}$		$f_0(980)$	$a_0(980)$	991.4 MeV
KN	repulsion	very weak	strong repulsion	1434.6 MeV

Interactions in K^{bar}K^{bar}N system

Ξ*



		I=0	I=1	threshold
$\bar{K}N$	attraction	$\Lambda(1405)$	weak attraction	1434.6 MeV
$\bar{K}\bar{K}$	repulsion	weak	strong repulsion	991.4 MeV

Formulation for three-body system

non-relativistic potential model

Hamiltonian

$$H = T + V_{\bar{K}N}(r_1) + V_{KN}(r_2) + V_{K\bar{K}}(r_3),$$

two-body effective interactions

local potentials obtained by s-wave two-body scattering

Gaussian potential $V(r) = U \exp\left[-(r/b)^2\right]$

complex potentials to implement coupled-channels effects

ex: $\bar{K}N \to \pi\Sigma$

no three-body interactions

no transitions to two hadrons $\bar{K}\bar{K}N \to MB$

will be suppressed in hadronic molecular states

recipe

1st : solve Schrödinger eq. without imaginary potential in variational method

obtain wavefunction Ψ and real part of energy

2nd: estimate imaginary part of energy $E^{\mathrm{Im}} = \langle\Psi|\mathrm{Im}V|\Psi\rangle.$

Effective interactions

Gaussian potential $V(r) = U \exp\left[-(r/b)^2\right]$

$\bar{K}N$
attractive

HW-HNJH and AY potentials

binding energy : 11 MeV (HW), 31MeV (AY)

K^{bar}-N distance : **1.9 fm** (HW), **1.4 fm** (AY)

$K\bar{K}$
attractive

reproduce masses and widths of f_0 and a_0

mass: 980 MeV, width: 60 MeV

reproduced

binding energy : 11 MeV

K-K^{bar} distance : **2.1 fm**

PDG

mass: 980±10 MeV
width: 40~100 MeV
mass: 984±1.2 MeV
width: 50~100 MeV

KN
repulsive

reproduce scattering lengths

experimental data

$$a_{KN}^{I=0} = -0.035 \text{ fm}$$

$$a_{KN}^{I=1} = -0.310 \pm 0.003 \text{ fm}$$

Results of $KK^{bar}N$ system **N* at 1910 MeV**

DJ, Y. Kanada-En'yo, **PRC78, 035203 (2008)**

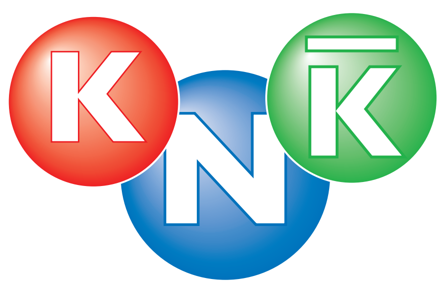
$K\bar{K}N$ is bound blow thresholds of Λ(1405)+K, $a_0(f_0)$+N

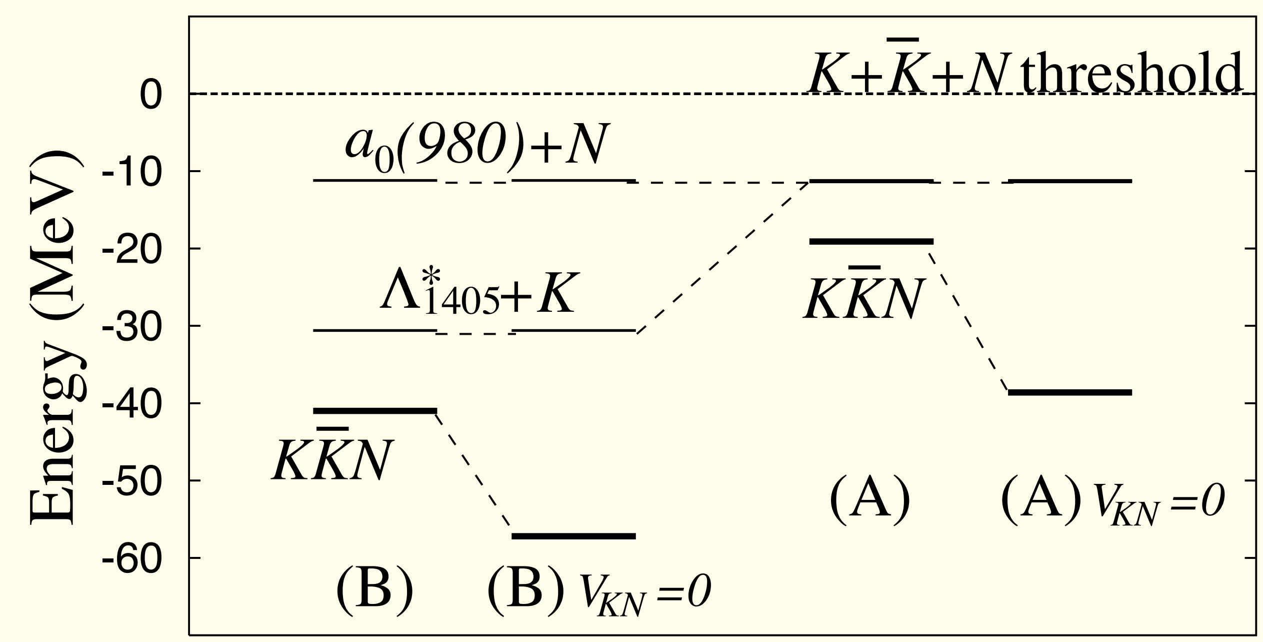
- loosely bound system

	binding energy	width
HW:	**19 MeV**	**88 MeV**
AY:	**39 MeV**	**98 MeV**

sum of those of isolated two-particle systems

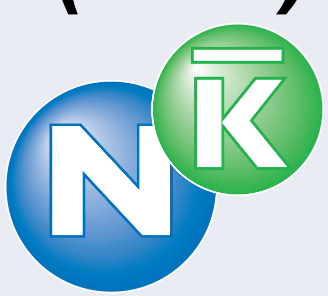
N*





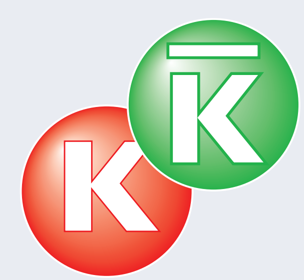
threshold of $KK^{bar}N$ 1930 MeV

Λ(1405)



	binding energy	width
HW:	11 MeV	44 MeV
AY:	31 MeV	40 MeV

f_0(980), a_0(980)



binding energy

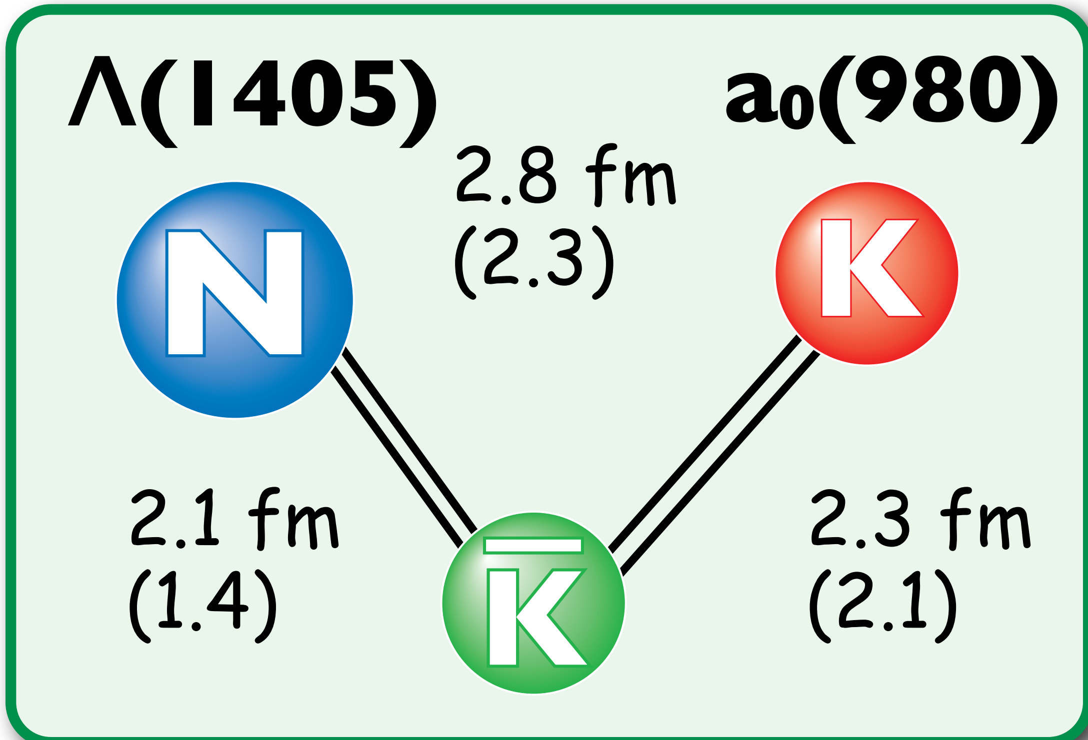
11 MeV 60 MeV

Faddeev calculation also reproduces this resonance

Martinez Torres, Khemchandani, Oset, arXiv:0812.2235 [nucl-th]

Structure of N*(1910)

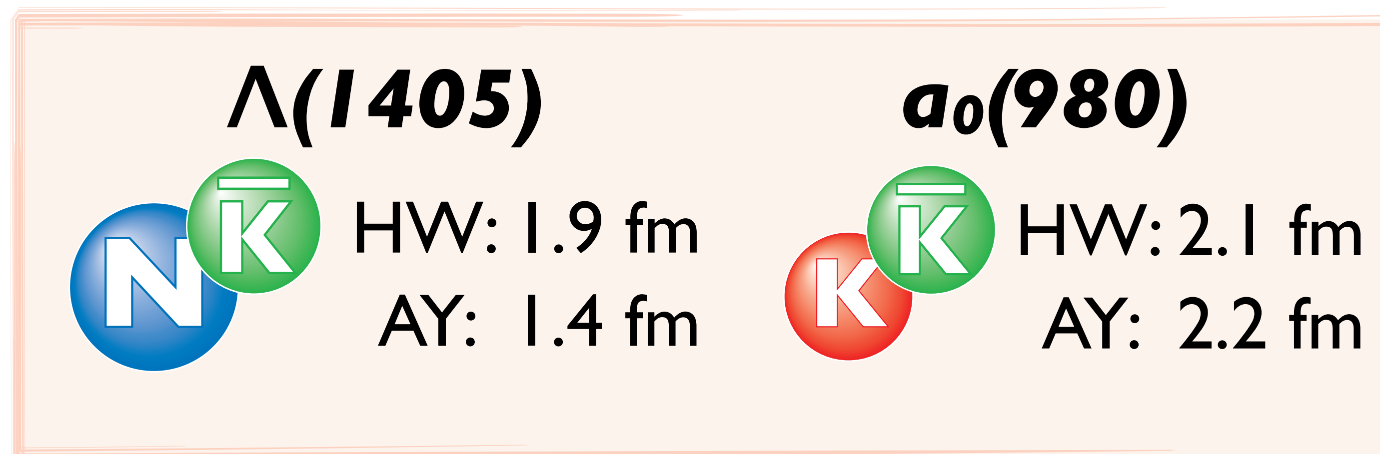
spatial structure



hadron-hadron distances are comparable with nucleon-nucleon distances in nuclei

r.m.s radius: **1.7 fm** cf. 1.4 fm for ^{4}He

mean hadron density: **0.07 hadrons/fm^3**



- coexistence of two quasi-bound states keeping their characters

Λ(1405)+K a_0(980)+N

- main decay modes

$\pi\Sigma K$ from Λ(1405)

$\pi\eta N$ from a_0(980)

Two-body decay of N*

possible two-body decay modes based on geometrical argument

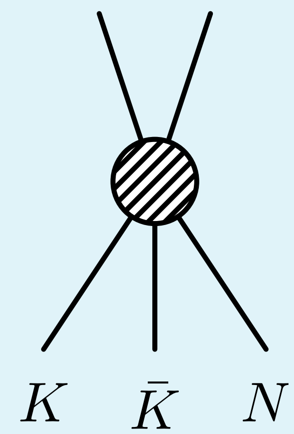
$$(K\bar{K}N) \rightarrow \pi N,\ \eta N,\ K\Lambda,\ K\Sigma$$

radius of system ~ 1.7 fm spatially extended

two-body decays are strongly suppressed

(a) contact interaction

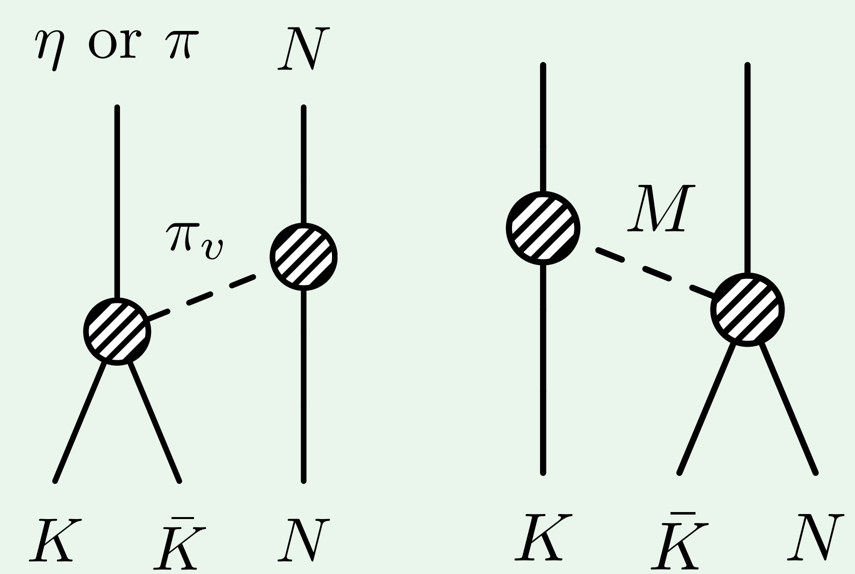
- three particles at a point → $(\text{density})^2$
- suppose radius of typical quark-model-like resonance to be 0.8 fm
- suppression factor: $(0.8\text{ fm}/\ 1.7\text{ fm})^6 \sim 0.01$



(b) virtual meson exchanges

- two-body decays without meson-exchange is impossible due to energy conservation.
- two-body transitions
- suppression factor: $(0.8\text{ fm}/\ 1.7\text{ fm})^3 \sim 0.1$
- finite range of virtual meson exchange

there is further suppression



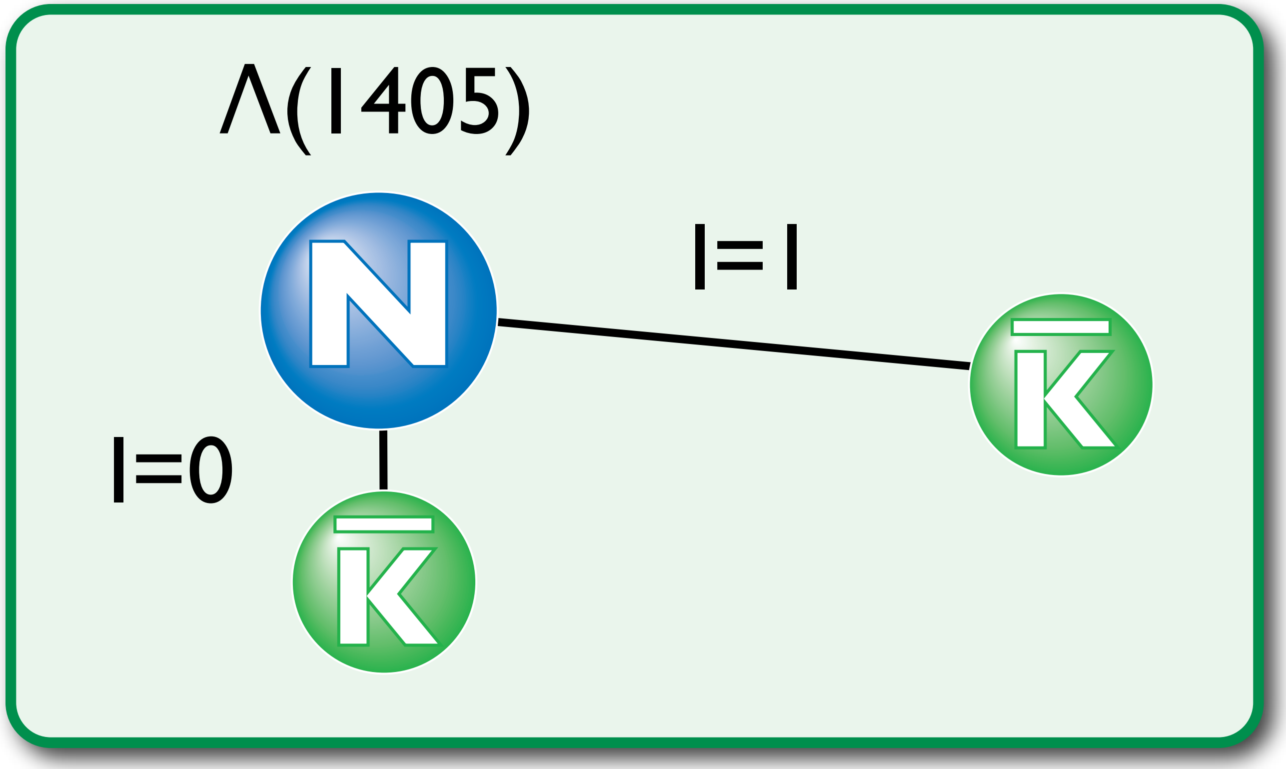
main two-body decay mode: ηN

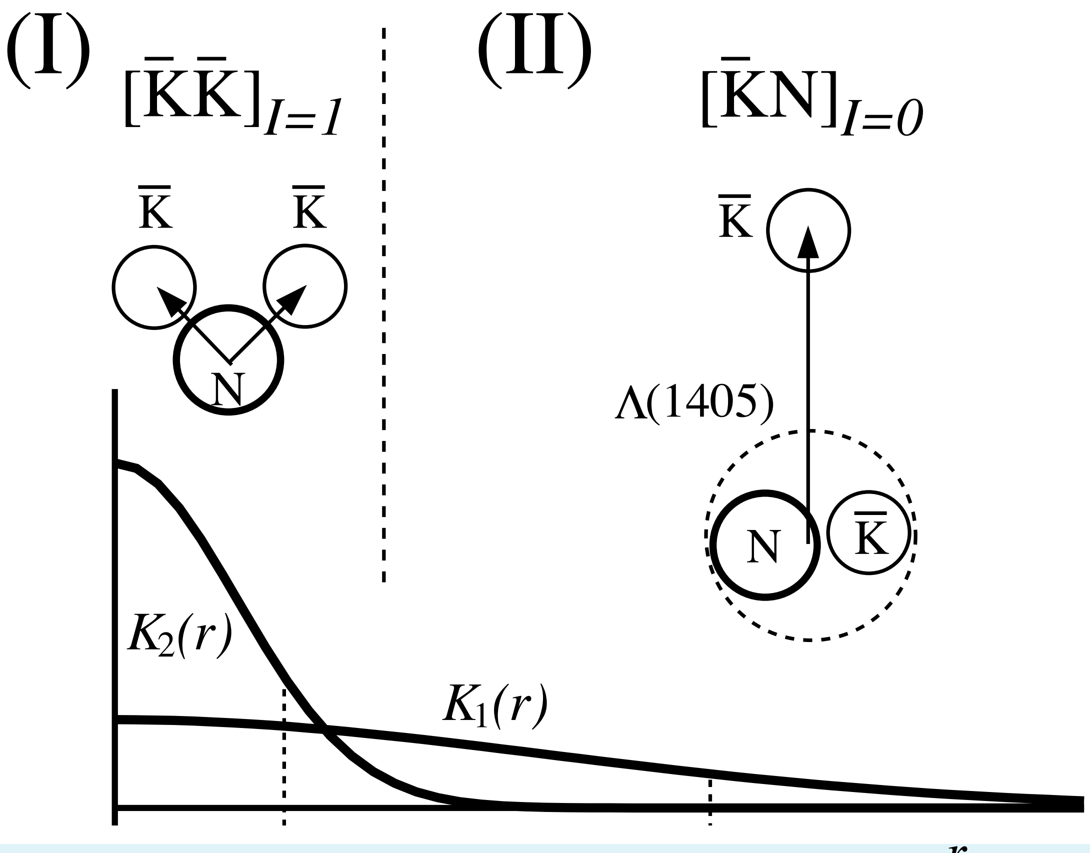
$\bar{K}\bar{K}N$ system with I=1/2, J^P=1/2$^+$ Ξ^*

Once Λ(1405) forms in a K^{bar}N system with I=0, another K^{bar} and N has dominantly I=1 component, which is weak attraction. This is not enough to overcome the repulsive $K^{bar}K^{bar}$ interaction.

very weak binding

binding energy ~ 2 MeV





Y. Kanada-En'yo, DJ, **PRC78, 025212 (2008)**

Summary

hadronic molecular state

- system of multiple hadrons described by hadron dynamics
- weakly bound and spatially extended system

Λ(1405), f_0(980), a_0(980)

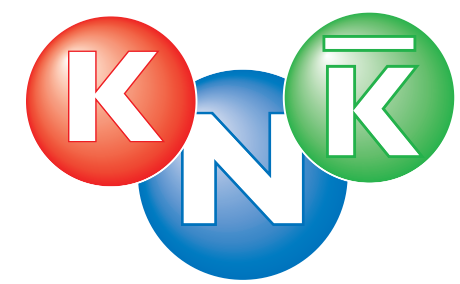
explore possibilities for three-body HMS

- non-relativistic potential model
- $K\bar{K}N$ system as N*(1910)

binding energy : 20~40 MeV, width : 90~100 MeV
radius : 1.7 fm
interhadron distance : ~ 2 fm

keeping properties of the subsystems

N*



- main decay modes

$\pi\Sigma K$	from Λ(1405)
$\pi\eta N$	from a_0(980)
ηN	small two-body decay

Double pole structute of Λ(1405)

DJ, Oller, Oset, Ramos, Meissner
NPA725, 181 ('03)

Λ(1405) is a superposition of two states.

there are two attractive channels

group theoretically SU(3) singlet and octet

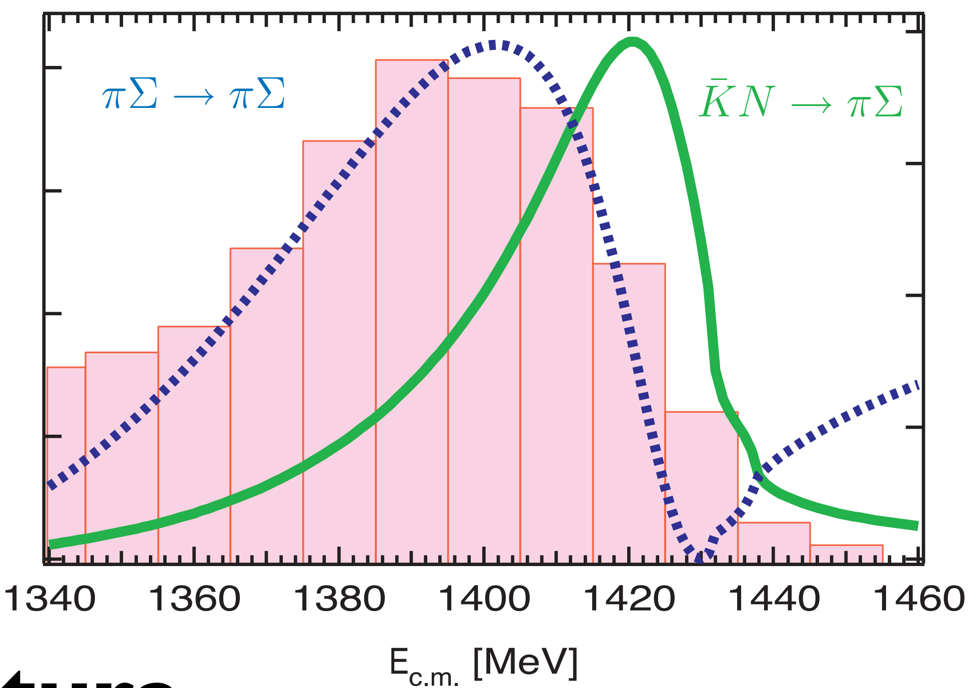
physically $K^{bar}N$, πΣ

Λ(1405) below threshold of $\bar{K}N$

pole 1 : 1390 - 66i
- wider width
- strongly couples to πΣ state

pole 2 : 1426 - 16i
- narrower width
- dominantly couples to $\bar{K}N$ state

πΣ Mass distribution



Implication of double pole structure

Λ(1405) spectrum is dependent on channels

Resonance position in $K^{bar}N$ channel ~1420 MeV with narrower width

not 1405 MeV

This 15 MeV difference is important for $K^{bar}N$ interactions

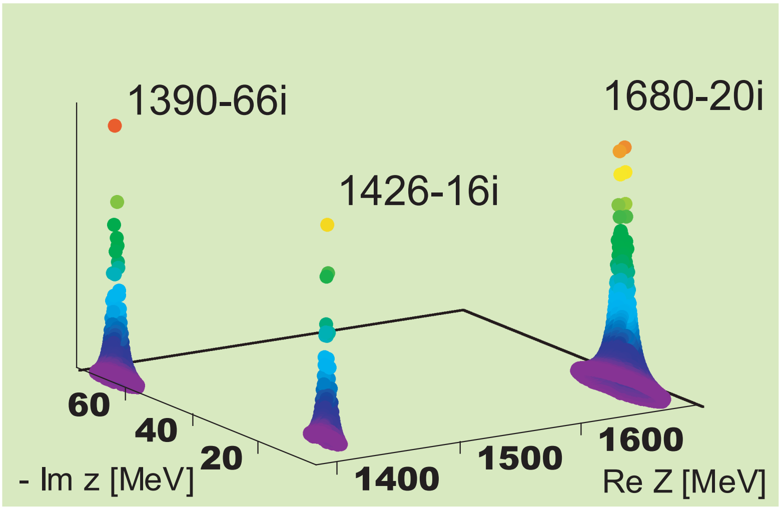
Double pole structure of Λ(1405)

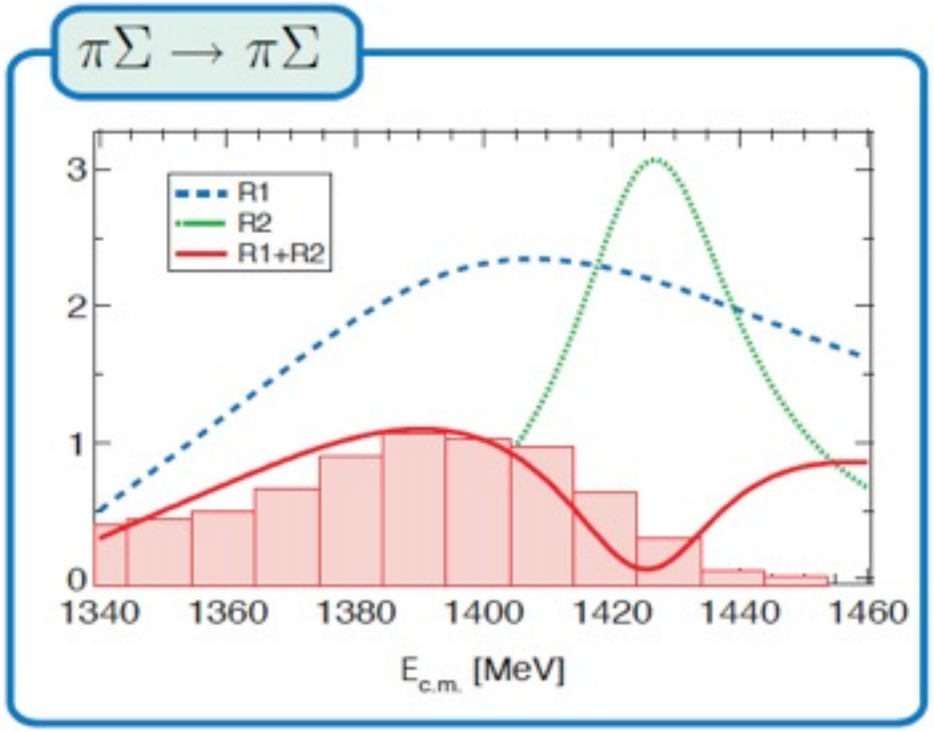
DJ, Oller, Oset, Ramos, Meissner, NPA725, 181 ('03)

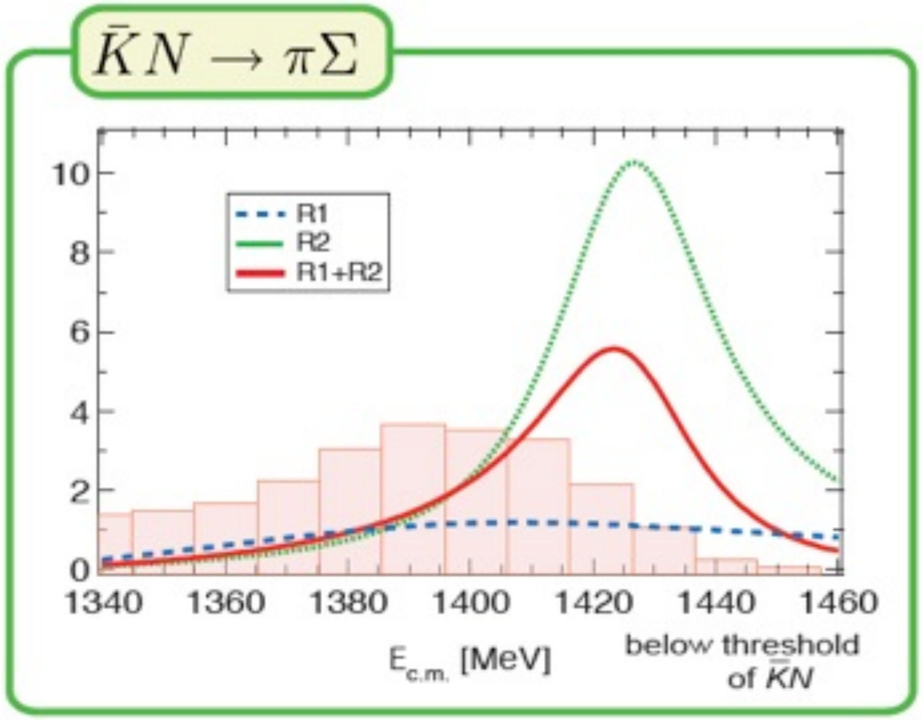
Λ(1405) is a superposition of two states having different properties.

pole 1: **1390 MeV, width 132 MeV**
strongly couples to **πΣ state**

pole 2: **1426 MeV, width 32 MeV**
dominantly couples to **K^{bar}N state**







two attractive channels: K^{bar}N and πΣ

Hyodo, Weise, PRC77, 035204 ('08)

essentially, pole 1: **πΣ resonance**, pole 2: **KbarN bound state**

Subthreshold properties of $K^{bar}N$

DJ, Oset, Sekihara, in progress

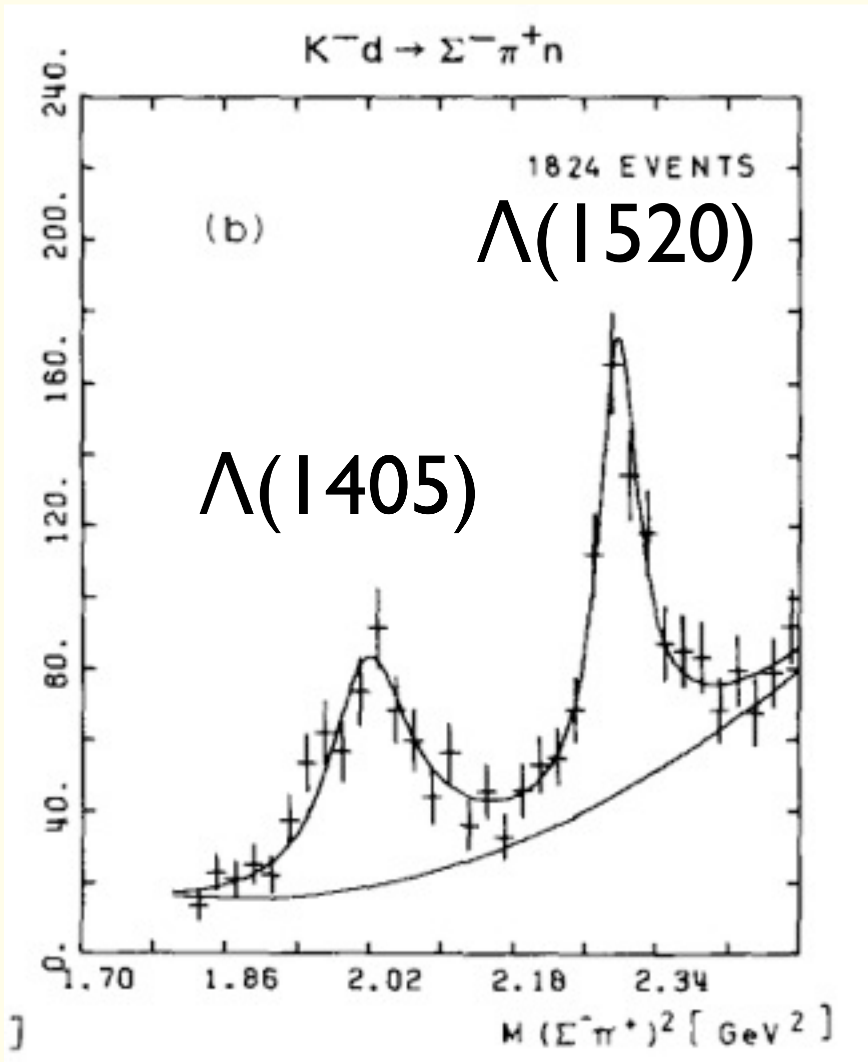
Λ(1405) spectra in $K^{bar}N$ channel

$\bar{K}N \to \Lambda(1405)$

$$K^- d \to \Lambda(1405) n$$

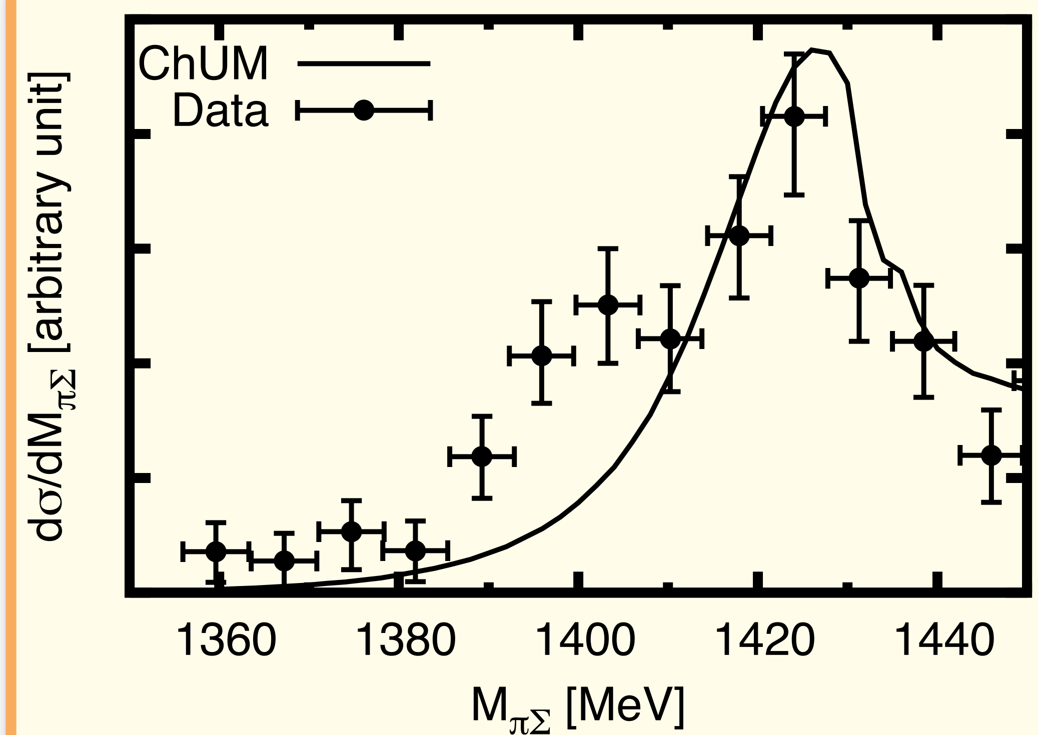
Braun et al. NPB129,1,('77)

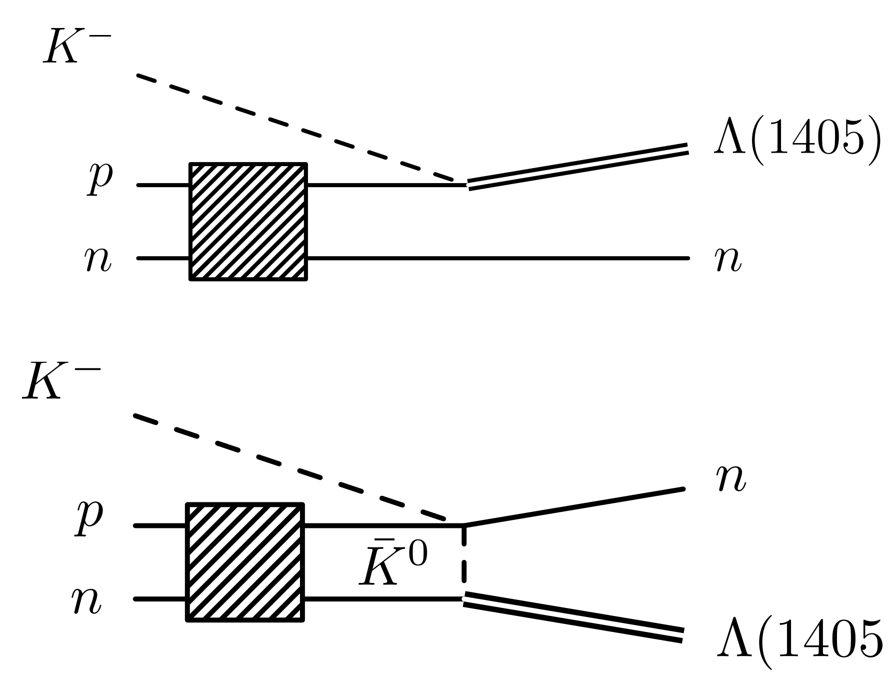
bubble chamber



$$K^- d \to \pi^+ \Sigma^- n$$

peak position 1420 MeV





Structure of Baryon Resonances

Baryon resonances : decay with strong interactions

in understanding the structure of baryon resonances

dynamical aspect (hadron dynamics)

decaying resonance → large hadronic components

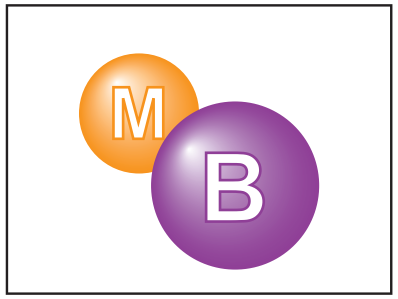
hadron dynamics is important

symmetry aspect (quark dynamics)

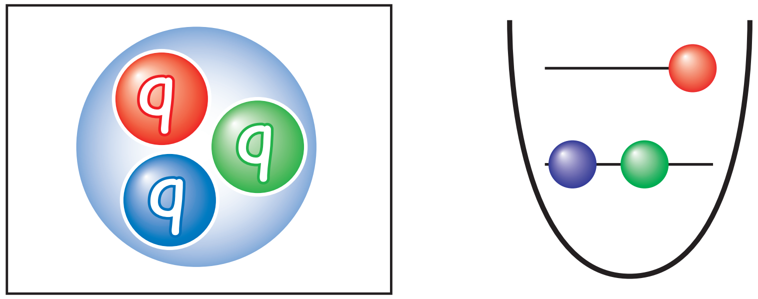
symmetry in terms of quarks

ex. chiral partners: N(1535) chiral partner of nucleon ??

cluster picture



shell model picture



- difference in range of dynamics
- meson cloud effects

Effective interactions

$\bar{K}N$ $$V_{\bar{K}N} = U_{\bar{K}N}^{I=0} \exp\left[-(r/b)^2\right] + U_{\bar{K}N}^{I=1} \exp\left[-(r/b)^2\right]$$

Hyodo-Weise potential (HW-HNJH) PRC77,035204 (08)

derived from chiral unitary approach

energy dependent, but small in energy of interest

resonance position ~ **1420 MeV** (double pole structure)

interaction range b= 0.47 fm

Akaishi-Yamazaki potential (AY) PRC64,044005 (02)

obtained phenomenologically

I=0 : reproduce Λ(1405) as quasi-bound state of $K^{bar}N$

mass: **1405 MeV**, width: 40 MeV

I=1: scattering and Konic atom data

interaction range b= 0.66 fm

Λ(1405) as Quasi-bound state of K^bar N

$\Lambda(1405)$ $J^\pi = 1/2^-, \; I = 0, \; S = -1, \; Q = 0$

- most established resonance, seen in many exp. clearly
- mass : 1406.5 ± 4.0 MeV, (below $K^- p$ threshold)
- width : 50 ± 2 MeV (PDG)
- decay mode $\Lambda(1405) \to (\Sigma\pi)_{I=0}$ 100 % **s-wave**

$\bar{K}N$ 1435 MeV

$\Lambda(1405)$

$\pi\Sigma$ 1331 MeV

chiral unitary model

Hyodo, Jido, Hosaka, PRC78, 025203 ('08)

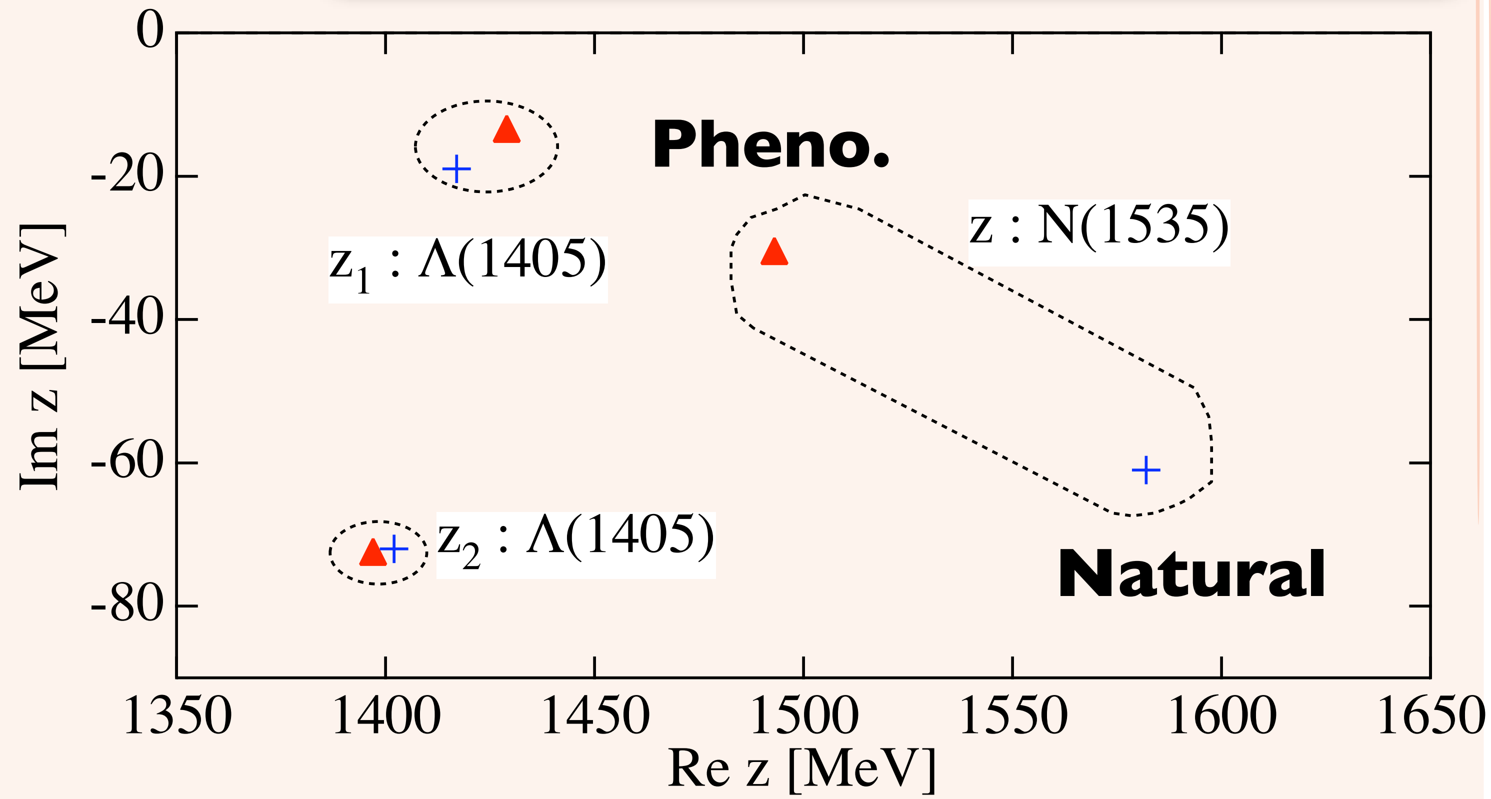
model parameters tuned so as to

a) exclude quark-originated states theoretically

+ **Natural**

b) reproduce scattering data

▲ **Pheno.**



Λ(1405) has mostly meson-baryon components.