Baryon resonances as hadronic molecular states

D. Jido
(Yukawa Institute, Kyoto)

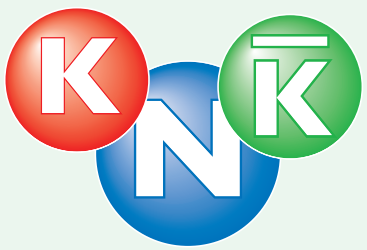
in collaboration with

Y. Kanada-En'yo (YITP)

$\Lambda(1405)$ in few-body systems

three-body quasibound states

N*



Introduction

Baryon resonances : decay with strong interactions

in understanding the structure of baryon resonances

dynamical aspect (hadron dynamics)

decaying resonance → large hadronic components

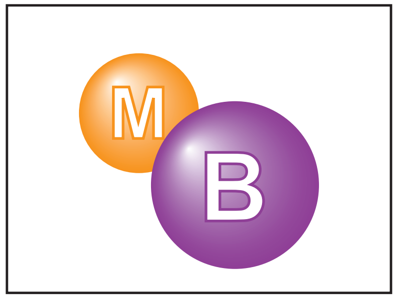
hadron dynamics is important

symmetry aspect (quark dynamics)

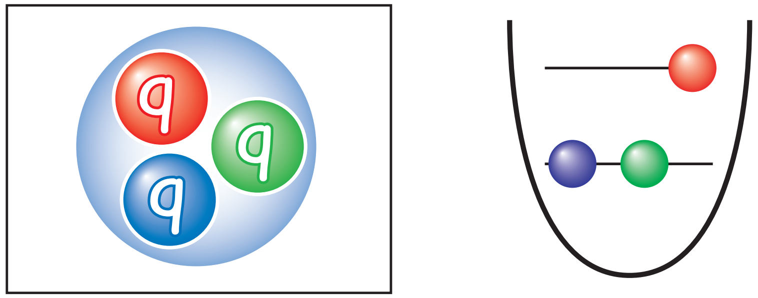
symmetry in terms of quarks

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

cluster picture



shell model picture



- difference in range of dynamics
- meson cloud effects

Hadronic molecular states

- *system of multiple hadrons described by hadron dynamics*

  typical constituents are ground states hadrons

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

  mesons are key ingredients (potential picture ok ?)

- *constituents keep their identity*

  typical binding energy ~ 10-20 MeV   weakly bound system

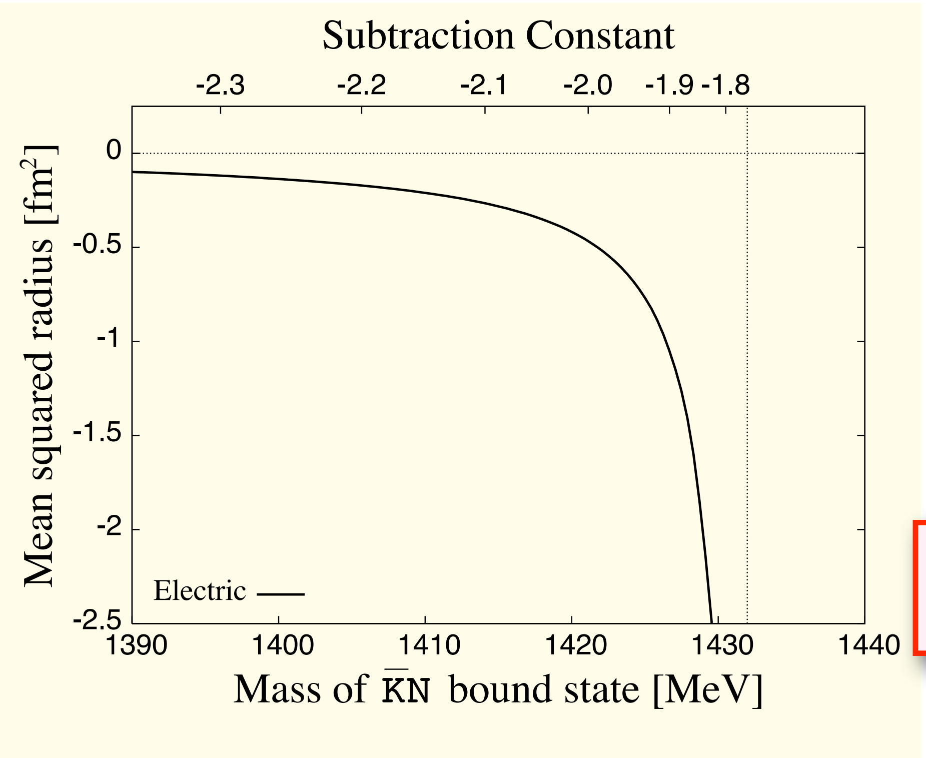
  decay width ~ 50 MeV (strong interactions)   **quasi-bound state**

- *spatially extended (large size)*

  typically more than 1 fm

- *softer form factors*

  strong energy dependence
  in production



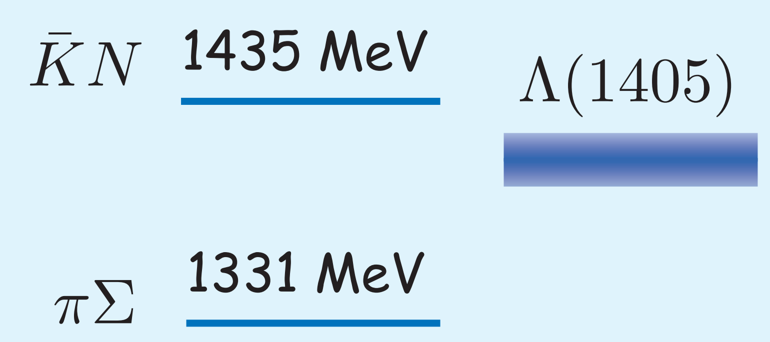
Sekihara, Hyodo, DJ
PLB669, 133 (2008).

quark degrees of freedom may be less important

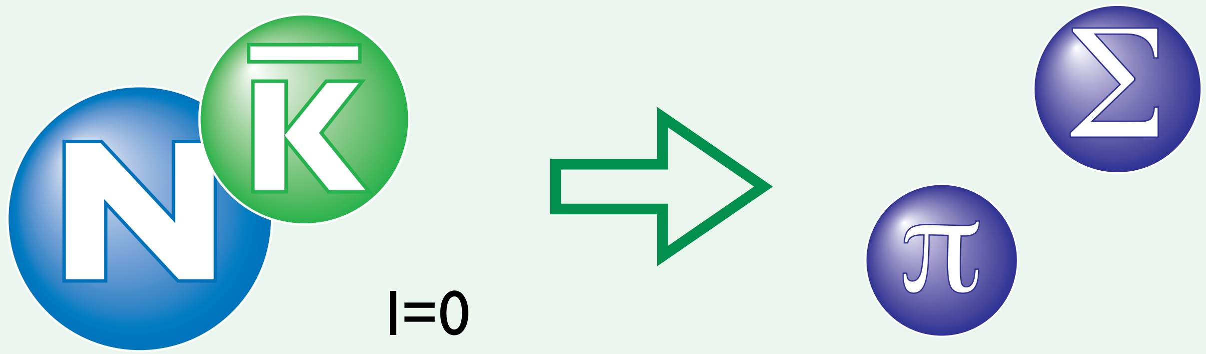
Λ(1405) as Quasi-bound state of K^barN

Λ(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**



Λ(1405) : quasi-bound states of K^barN



have been considered as a quasi-bound state of K^barN 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)

important to understand kaons in nuclei

Λ(1405) is composed mostly of meson-baryon components.

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

Double pole structute of Λ(1405)

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

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

there are two attractive channels

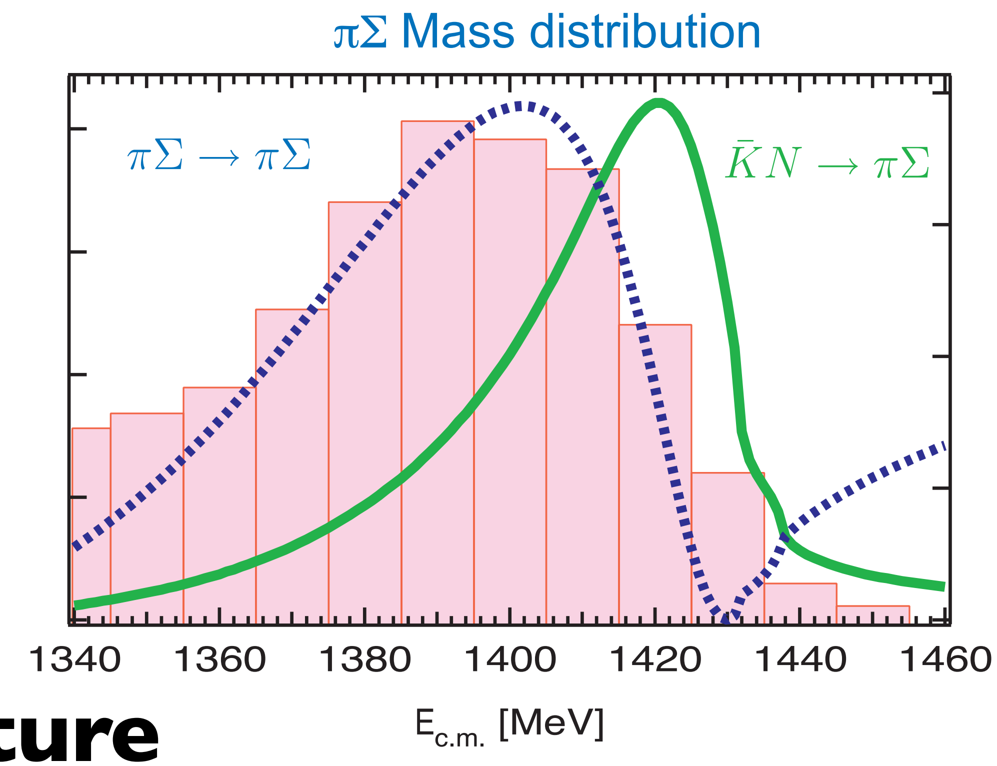
group theoretically — SU(3) singlet and octet

physically — K^bar N and πΣ [Hyodo, Weise, PRC77, 035204 (08)]

Λ(1405) — below threshold of $\bar{K}N$

pole 1 : 1390 - 66i
- wider width
- strongly couples to $\pi\Sigma$ state

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



Implication of double pole structure

Λ(1405) spectrum is dependent on channels

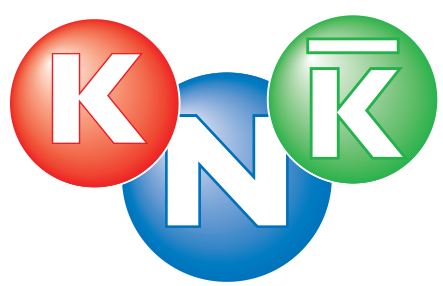
Resonance position in K^bar N channel ~1420 MeV with narrower width instead of 1405 MeV

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

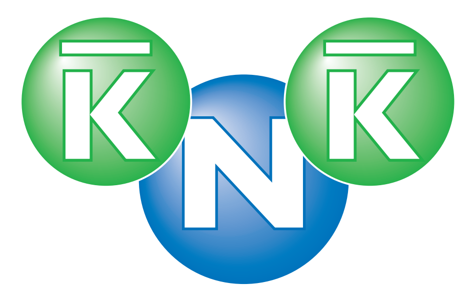
Λ(1405) in few-body systems ~hadronic molecule states with kaons~

three-body quasibound states $I=1/2,\ J^P=1/2^+$

N*



Ξ*



in collaboration with **Y. Kanada-En'yo** (YITP, Kyoto)

References

Y. Kanada-En'yo and D. Jido, **Phys. Rev. C78, 025212 (2008)**

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

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 $m_\pi \approx 140\ \mathrm{MeV}$

    non-relativisitc potential model

isospin averaged mass

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

- **Nambu-Goldstone boson**

    smaller mass compared with typical hadron mass scale

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

        chiral effective theory   momentum expansion

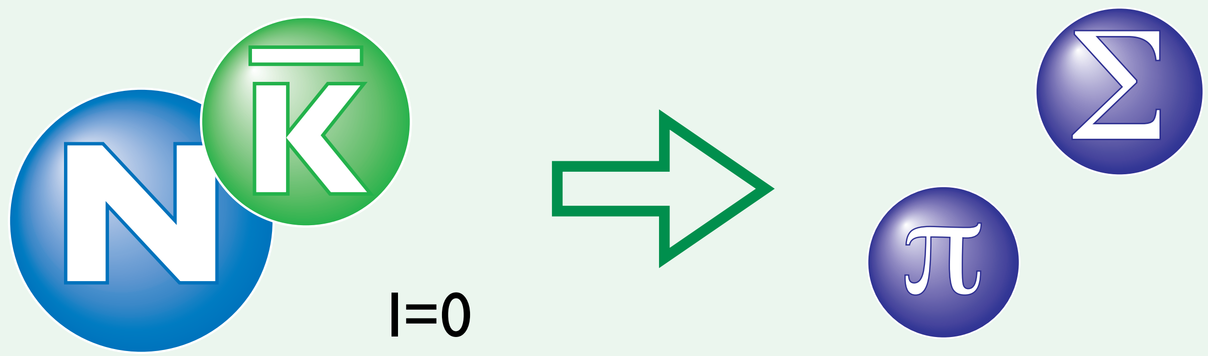
        s-wave int. proportional to K energy

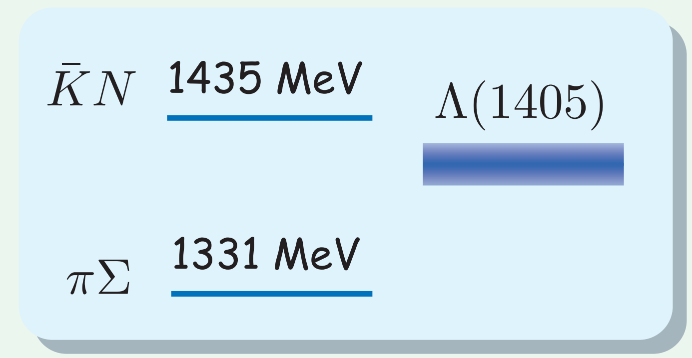
Kaons are different from pions in the energies of our interest !!

Hadronic molecular states in two-body sys.

Assumption:

Λ(1405) : one of the historical examples





have been considered as a quasi-bound state of K^bar N since late 50's — Dalitz, Tuan, PRL 2, 425 ('59)

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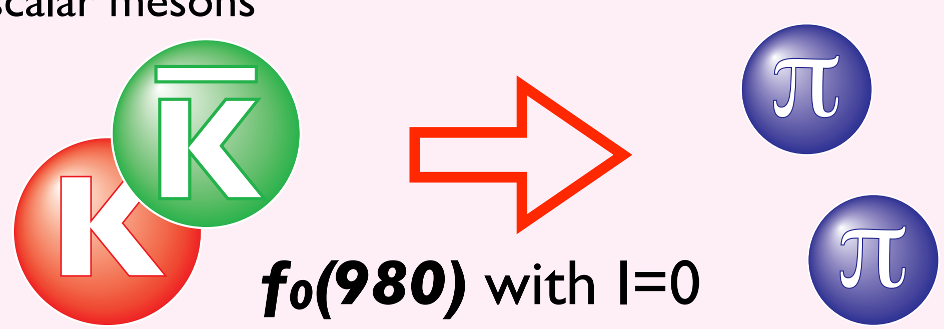
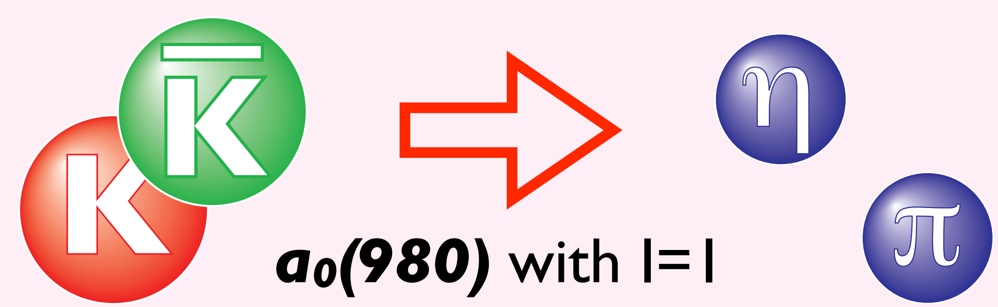
Λ(1405) is described as a superposition of two states. — DJ, Oller, Oset, Ramos, Meissner NPA725, 181 ('03)

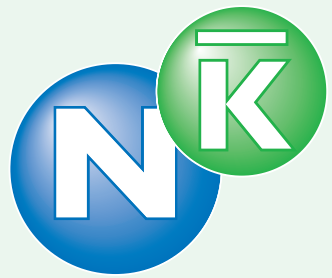
f_0(980), a_0(980) : the candidates of KK^bar QBS — Weinstein, Isgur, PRL 48, 659 ('90)

scalar mesons

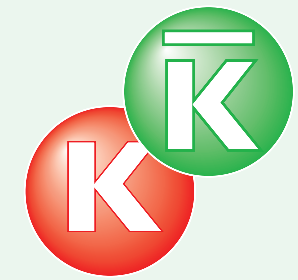




Λ(1405)

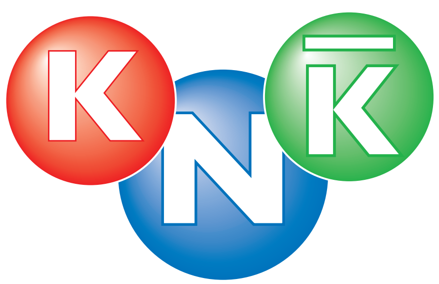


$f_0(980)$, $a_0(980)$



Interactions in KK^bar N system

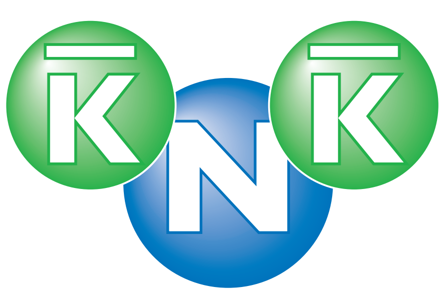
N*



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

Interactions in K^bar K^bar N system

Ξ*



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attraction	$\bar{K}N$	$\Lambda(1405)$	weak attraction	1434.6 MeV
repulsion	$\bar{K}\bar{K}$	weak	strong repulsion	991.4 MeV

Formulation for three-body system: $K\bar{K}N$ and $\bar{K}\bar{K}N$

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

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

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

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

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

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

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

Result KK^{bar}N — N* around 1900 MeV

$K\bar{K}N$ 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

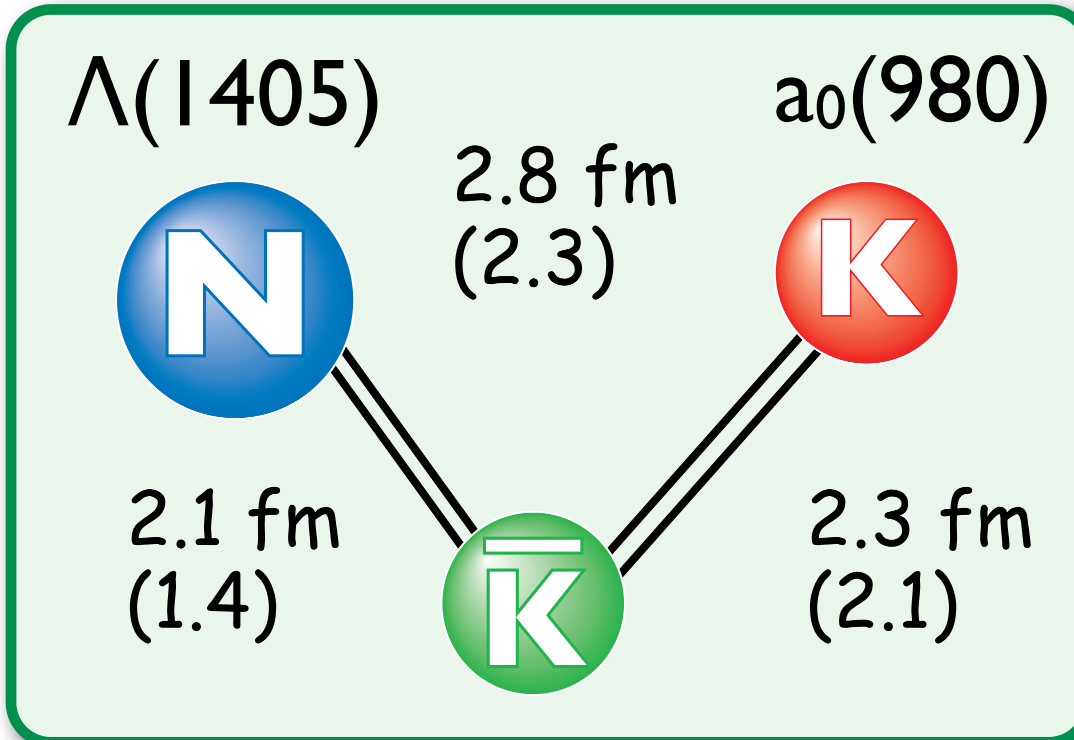
- coexistence of two quasi-bound states keeping their characters

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 systems	HW	AY
$\bar{K}$-N B.E. (MeV)	11	31
width (MeV)	44	20
K-$\bar{K}$ B.E. (MeV)	11	11
width (MeV)	60	60
$\bar{K}$-N distance (fm)	1.9	1.4
K-$\bar{K}$ distance (fm)	2.1	2.2

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

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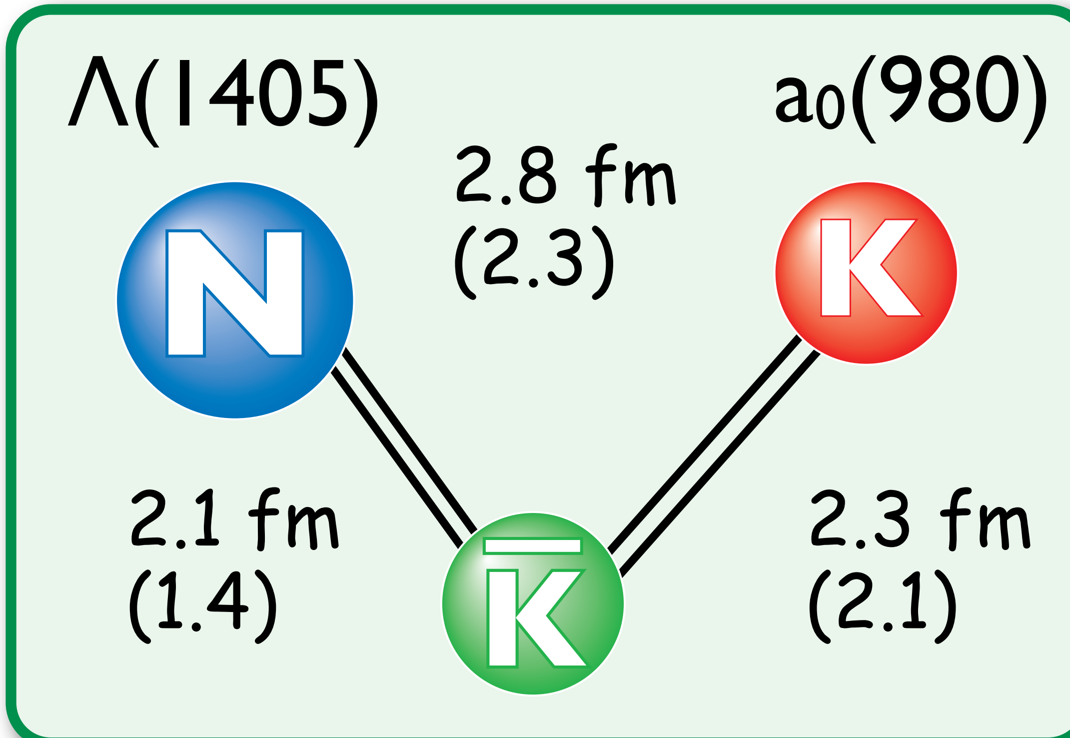

spacial structure

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

r.m.s radius (1.7 fm) is larger than that of ^{4}He (1.4 fm)

mean hadron density: 0.07 hadrons/(fm^3)

two-body systems	HW	AY
$\bar{K}$-N B.E. (MeV)	11	31
width (MeV)	44	20
K-$\bar{K}$ B.E. (MeV)	11	11
width (MeV)	60	60
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K-$\bar{K}$ distance (fm)	2.1	2.2

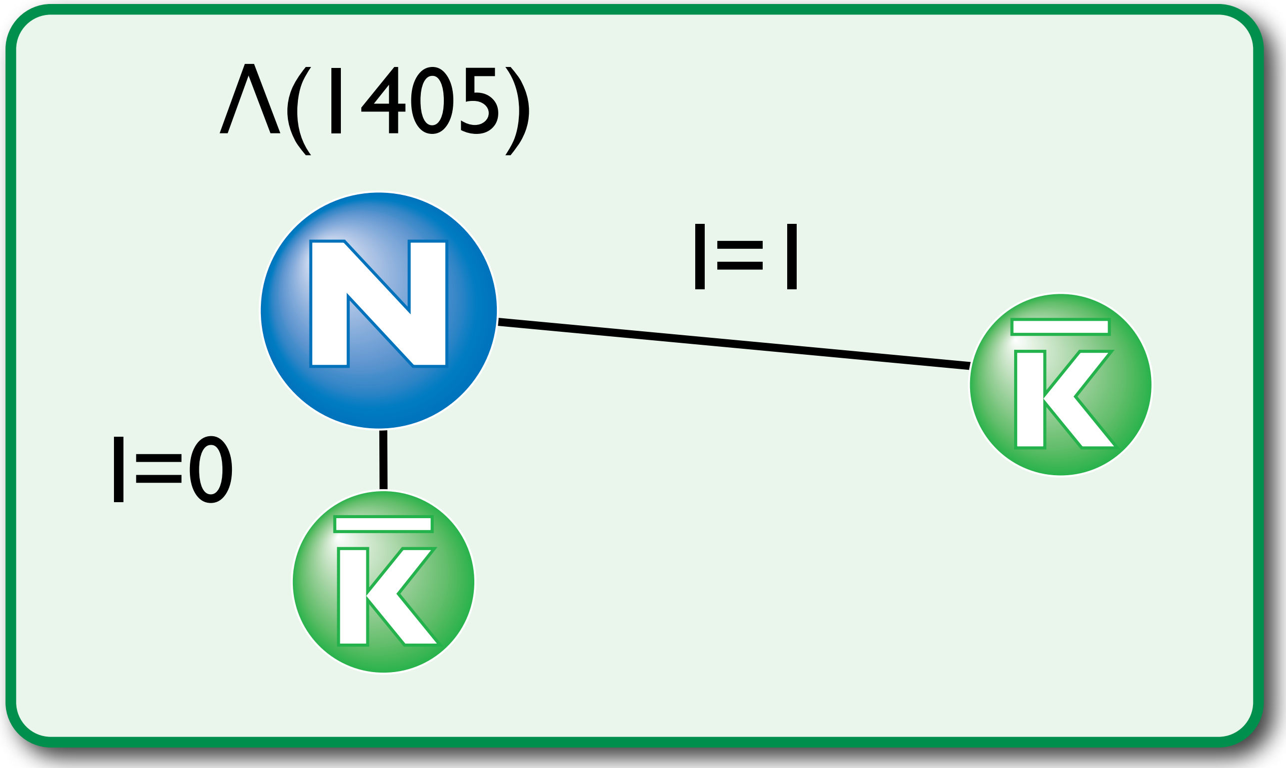
DJ, Y. Kanada-En'yo, **PRC78, 035203 (2008)**

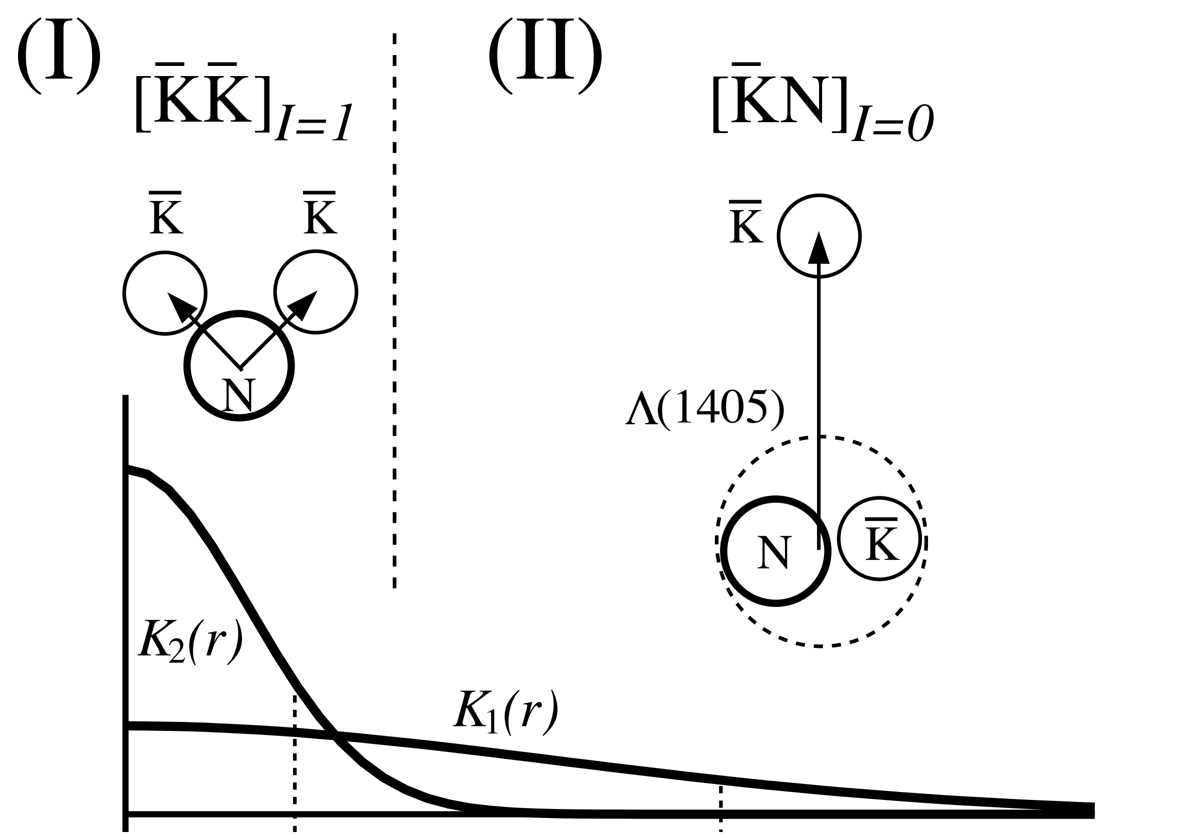
$\bar{K}\bar{K}N$ system with I=1/2, J^P=1/2$^+$ (Ξ*)

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)**

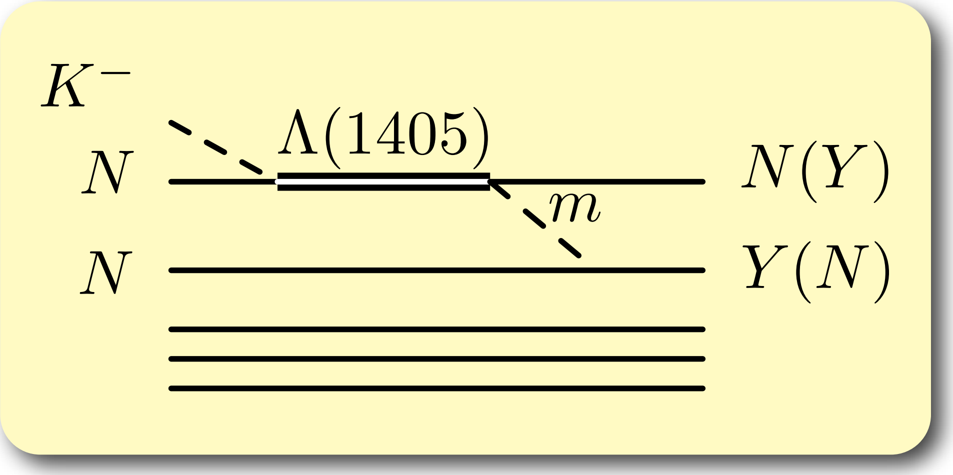
Decay properties of Kaonic nuclei

Sekihara, DJ, Y. Kanada-En'yo,
in progress

活発なK中間子原子核構造・生成研究

picture

$\bar{K}$ と核子で Λ(1405) が作られ、
核内でΛ(1405) が 崩壊

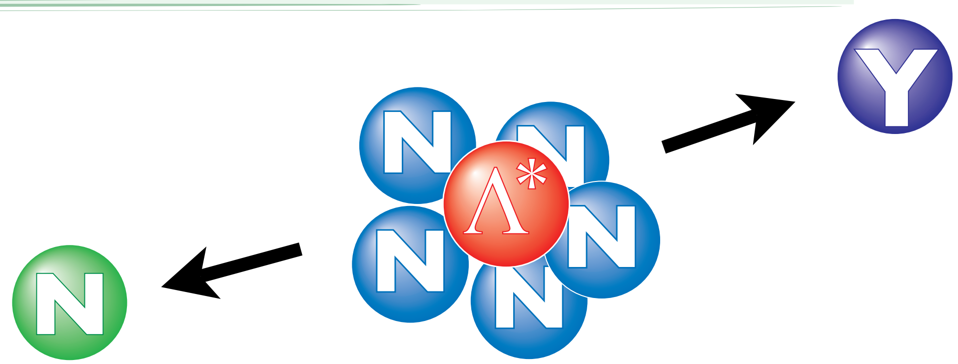


Λ(1405) がK中間子吸収の doorway state

K中間子原子核を Λ* ハイパー核として見る

この描像が正しいかどうかは、核中で Λ* がどれだけ個性を保っているかによる

- ハドロン分子状態の束縛エネルギー：数十MeV
  より深い束縛なら、別のピクチャーが必要
- 理論的には、ハイパー核のテクニックが使える



崩壊モードから性質を調べることができないか？

特に、nonmesonic (nonpionic) decay (最も基本的な多体効果)

Summary

keyword : **hadronic molecular state**

Λ(1405) = Quasi-bound state of $K^{bar}N$

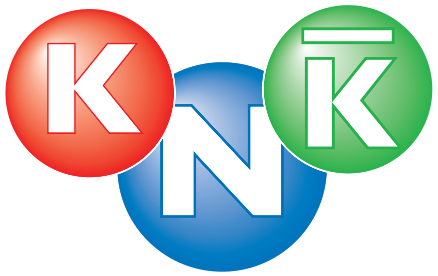
- Λ(1405) in few-body systems

Λ(1405) keeps its identity in few-body systems

nuclear physics

potential picture, coupled channel approach

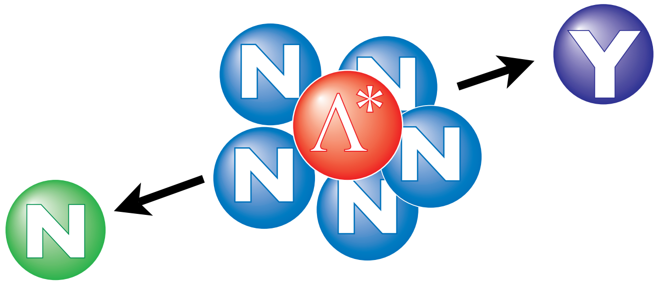
N*



- Decay properties of Kaonic nuclei

Kaonic nuclei = Λ* hypernuclei

decay pattern of non-mesonic decay



Backup slides

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)

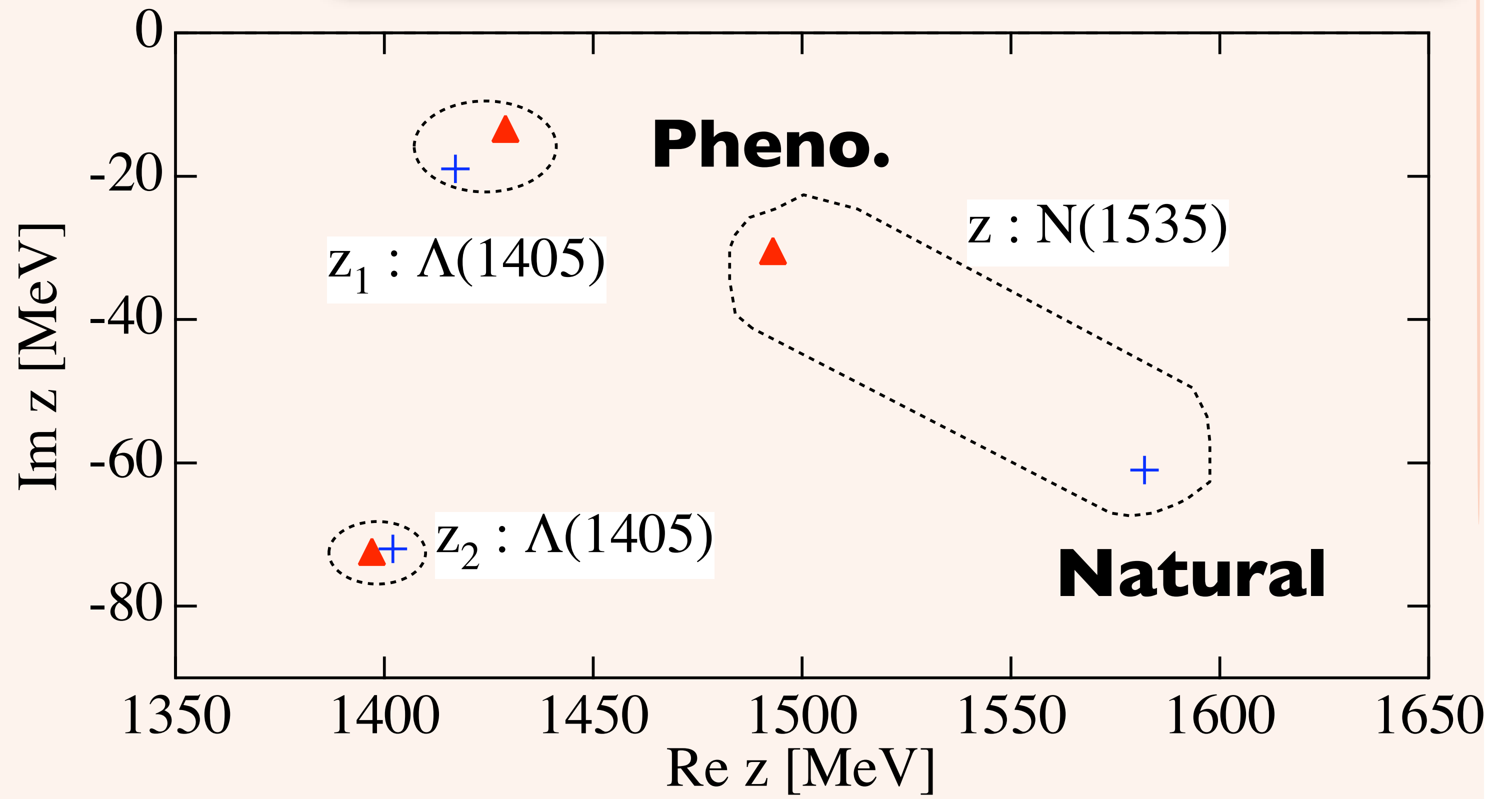
model parameters tuned so as to

a) exclude quark-originated states theoretically

+ **Natural**

b) reproduce scattering data

▲ **Pheno.**



Λ(1405) has mostly meson-baryon components.

Result $K\bar{K}N$

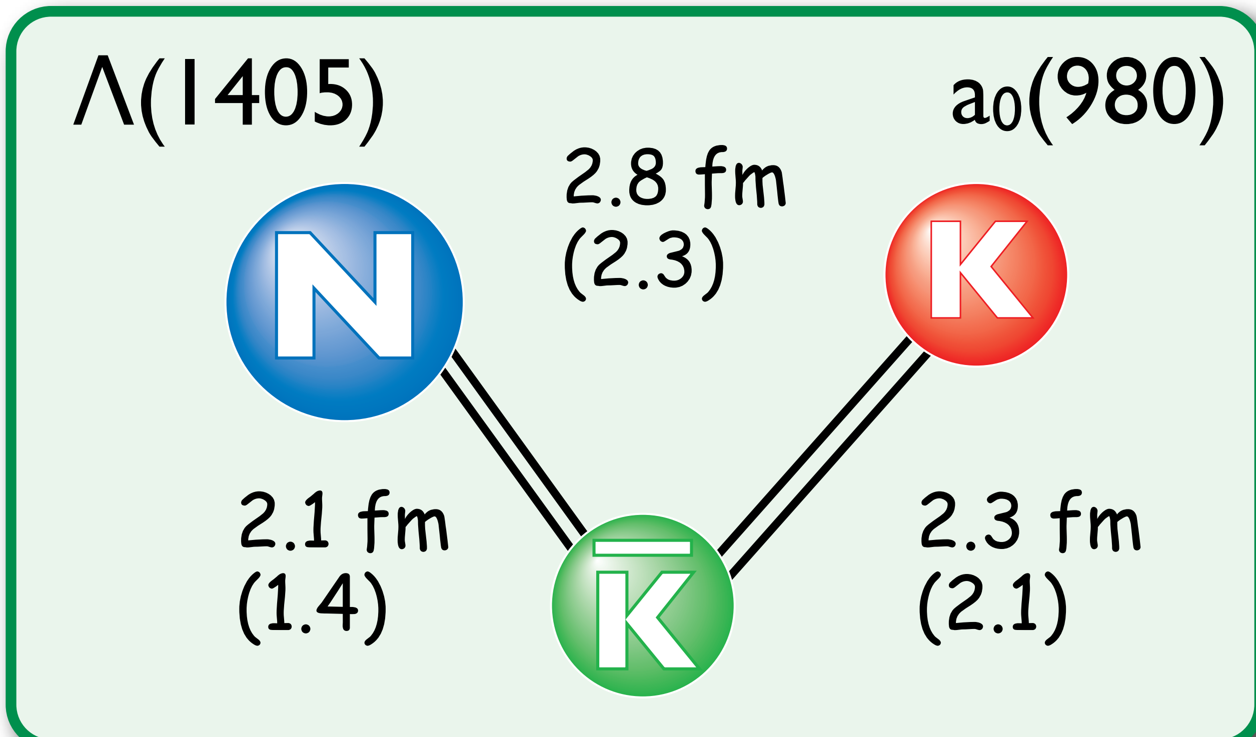
- main decay modes

$\pi\Sigma K$ from Λ(1405)

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

- KN repulsion important

Without the KN repulsion, the quasi-bound state would be more bound and have much larger width.



Parameter set	(A)	(A)	(B)	(B)
$V_{\bar{K}N}$	HW-HNJH	HW-HNJH	AY	AY
V_{KN}	On	Off	On	Off
ReE	−19	−39	−41	−57
$\langle T \rangle$	169	282	175	227
$\langle \mathrm{Re}V \rangle$	−188	−320	−216	−284
ImE	−44	−72	−49	−63
$\langle \mathrm{Im}V^{I=0}_{\bar{K}N} \rangle$	−17	−30	−19	−23
$\langle \mathrm{Im}V^{I=1}_{\bar{K}N} \rangle$	−1	0	0	0
$\langle \mathrm{Im}V^{I=0}_{K\bar{K}} \rangle$	−1	−10	−4	−10
$\langle \mathrm{Im}V^{I=1}_{K\bar{K}} \rangle$	−25	−31	−25	−31
$\langle T_{\bar{K}N} \rangle$	113	185	131	157
$\langle \mathrm{Re}V^{I=0}_{\bar{K}N} \rangle$	−87	−152	−139	−162
$\langle \mathrm{Re}V^{I=1}_{\bar{K}N} \rangle$	−2	0	0	0
Re$\mathcal{E}_{\bar{K}N}$	25	33	−9	−4
Re$\mathcal{E}^{I_1=0}_{\bar{K}N}$	−6	−4	−28	−27
$\langle T_{K\bar{K}} \rangle$	104	162	86	115
$\langle \mathrm{Re}V^{I=0}_{K\bar{K}} \rangle$	−4	−42	−11	−31
$\langle \mathrm{Re}V^{I=1}_{K\bar{K}} \rangle$	−101	−127	−75	−92
Re$\mathcal{E}_{K\bar{K}}$	−1	−7	−1	−7
$\langle T_{KN} \rangle$	59	108	55	83
$\langle \mathrm{Re}V^{I=0}_{KN} \rangle$	0	0	0	0
$\langle \mathrm{Re}V^{I=1}_{KN} \rangle$	6	0	10	0
Re$\mathcal{E}_{KN}$	65	108	65	83

Subthreshold properties of $K^{bar}N$

$K^- d \to \Lambda(1405) n$ in chiral unitary model

in collaboration with
E. Oset (Valencia) and **T. Sekihara** (Kyoto)

Subthreshold properties of K^{bar}N

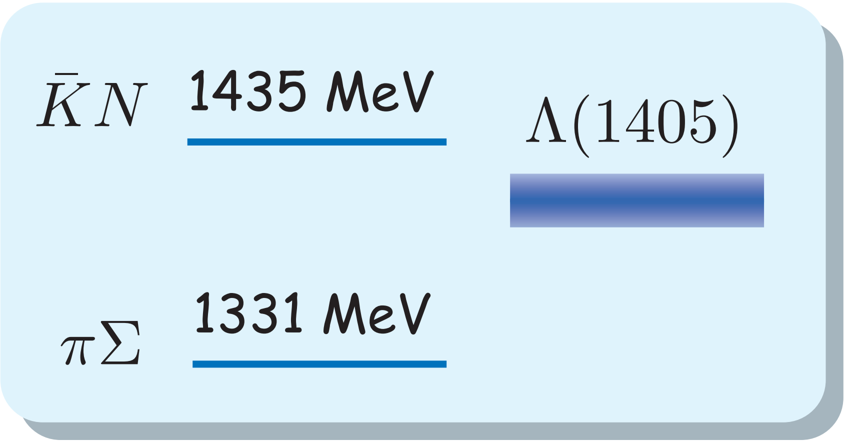
DJ, Oset, Sekihara, in preparation

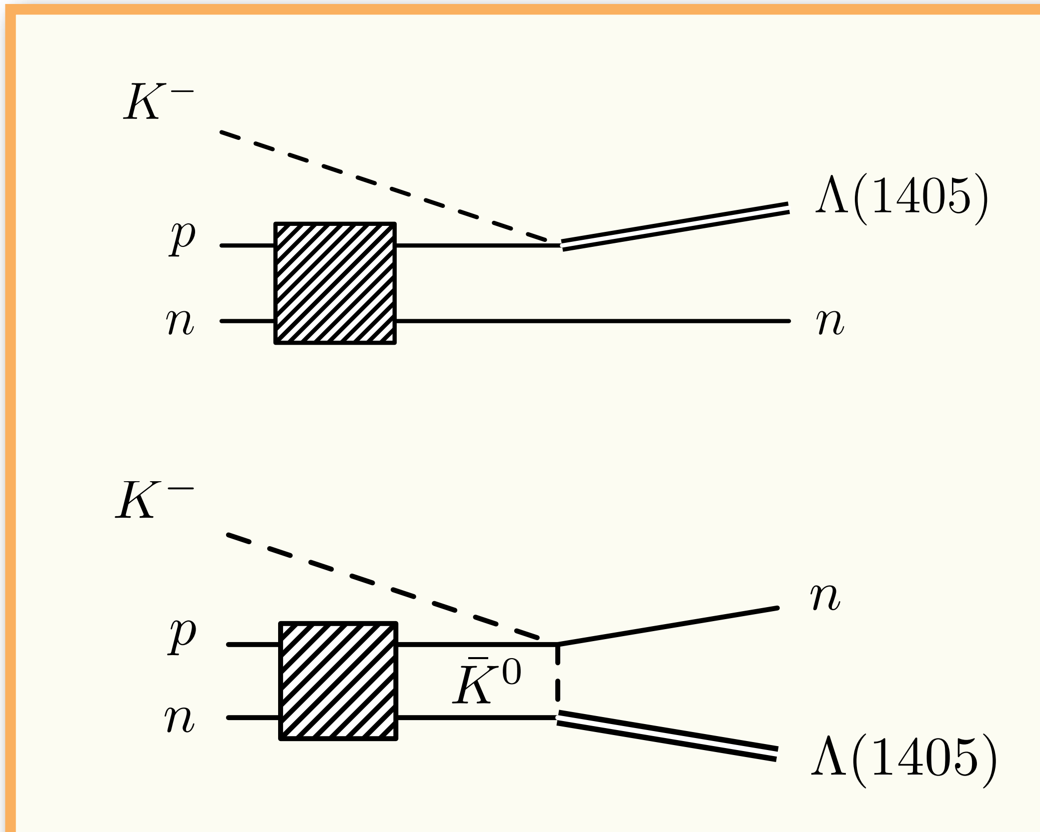
to confirm the Λ(1405) resonance position in K^{bar}N channel

Λ(1405) spectrum in K^{bar}N channel

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

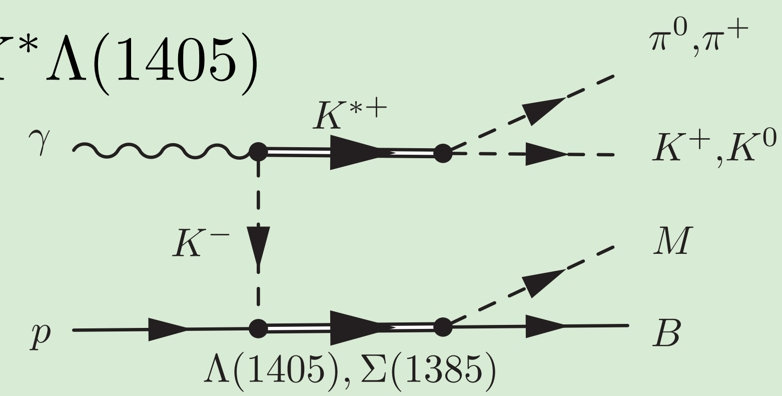
$$K^- d \to \Lambda(1405) n$$





K^* photoproduction

$$\gamma p \to K^* \Lambda(1405)$$



Hyodo, Hosaka, Vacas, Oset, PLB593, 75 (04)

Subthreshold properties of $K^{bar}N$

DJ, Oset, Sekihara, in preparation

Experiment

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

πΣ invariant mass spectrum

initial K momentum

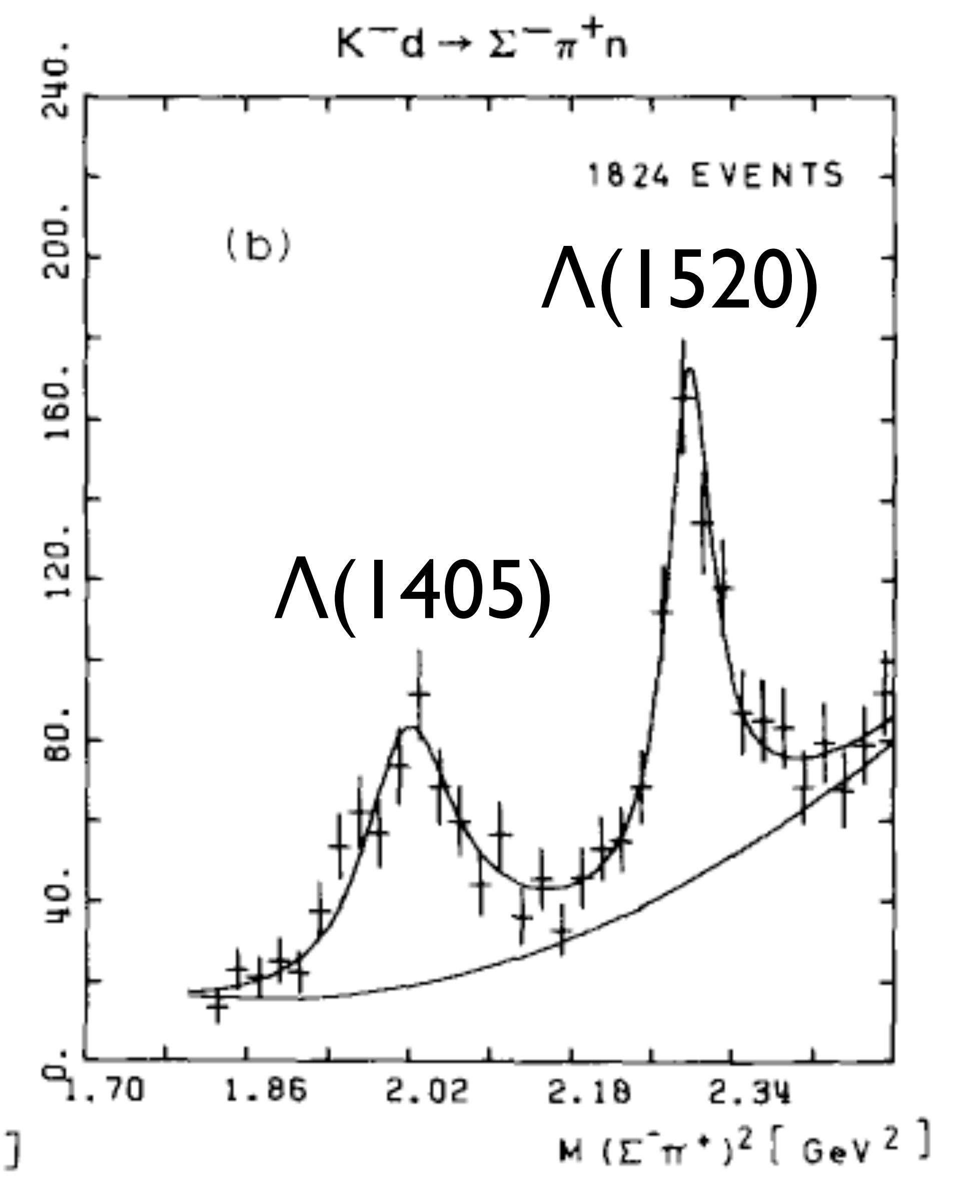
686 ~ 844 MeV/c

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

cross section

410 ± 100 μb

bubble chamber



peak position 1420 MeV

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

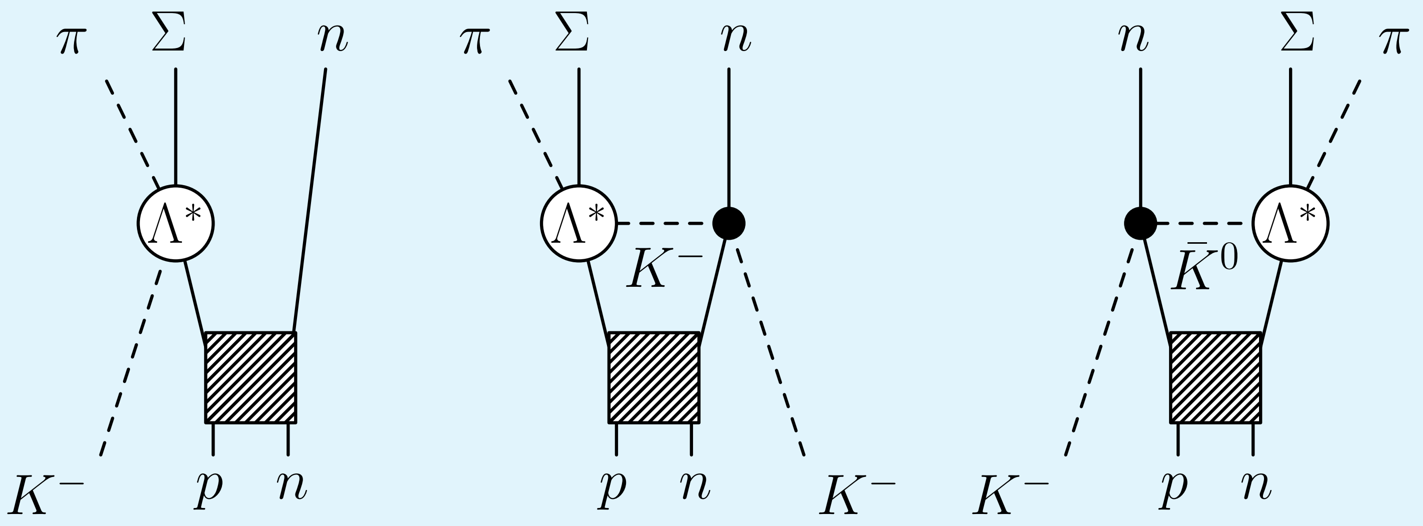
Subthreshold properties of K^bar N

DJ, Oset, Sekihara, in preparation

chiral unitary model

Λ*: T-matrix by ChUM

K momentum: 800 MeV/c



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

Subthreshold properties of K^bar N

DJ, Oset, Sekihara, in preparation

chiral unitary model

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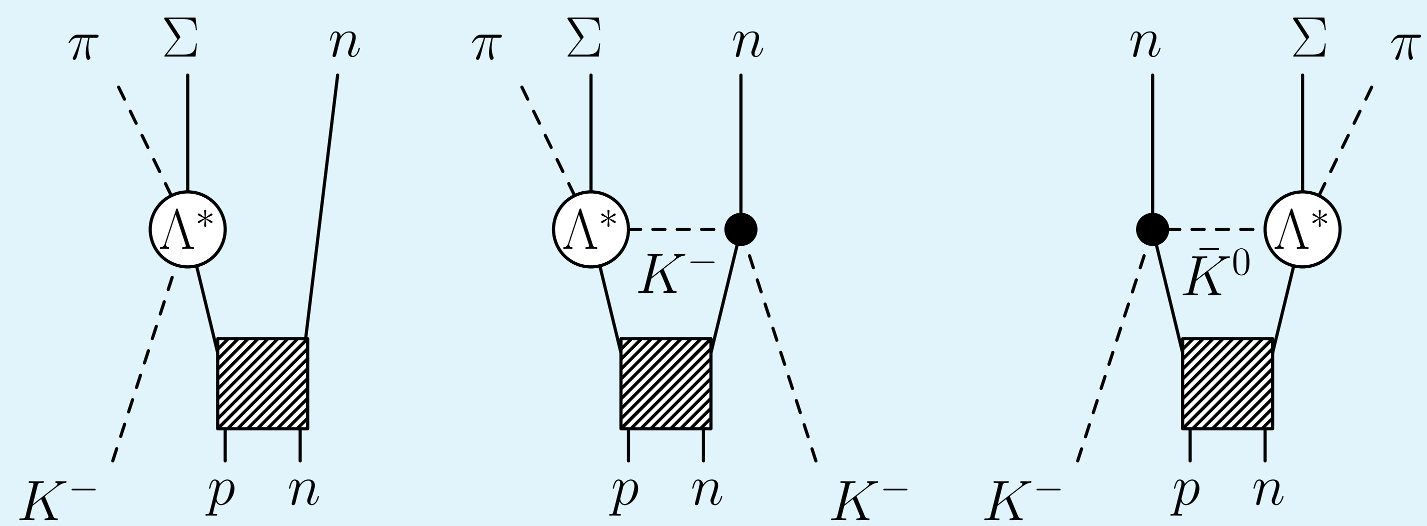
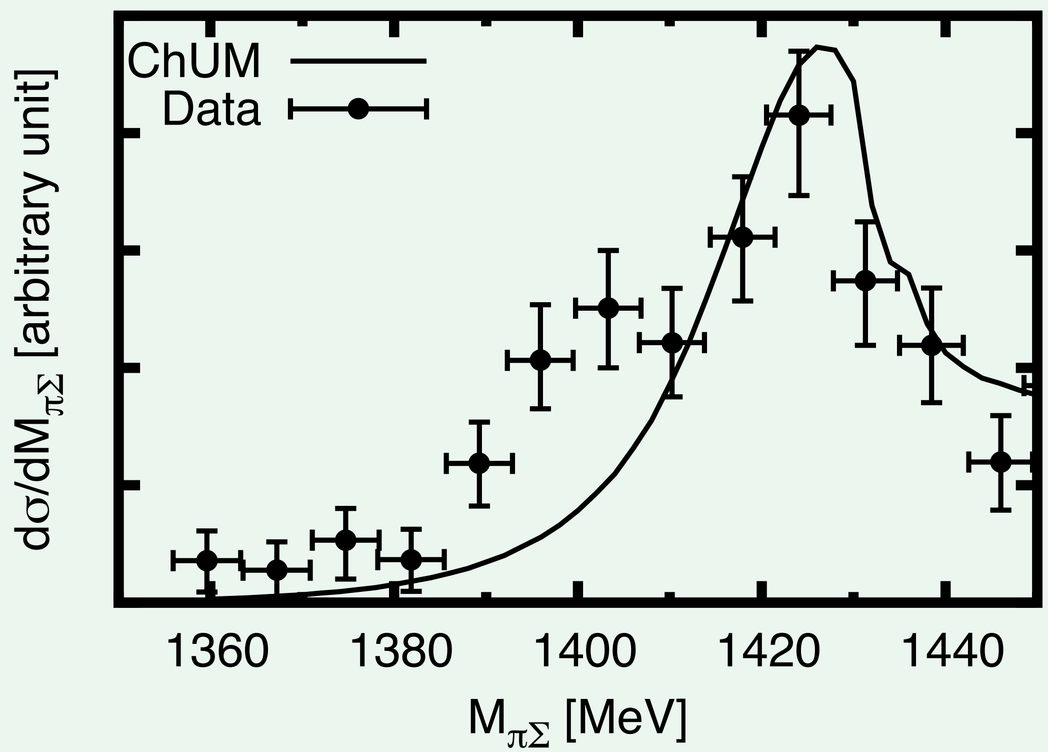
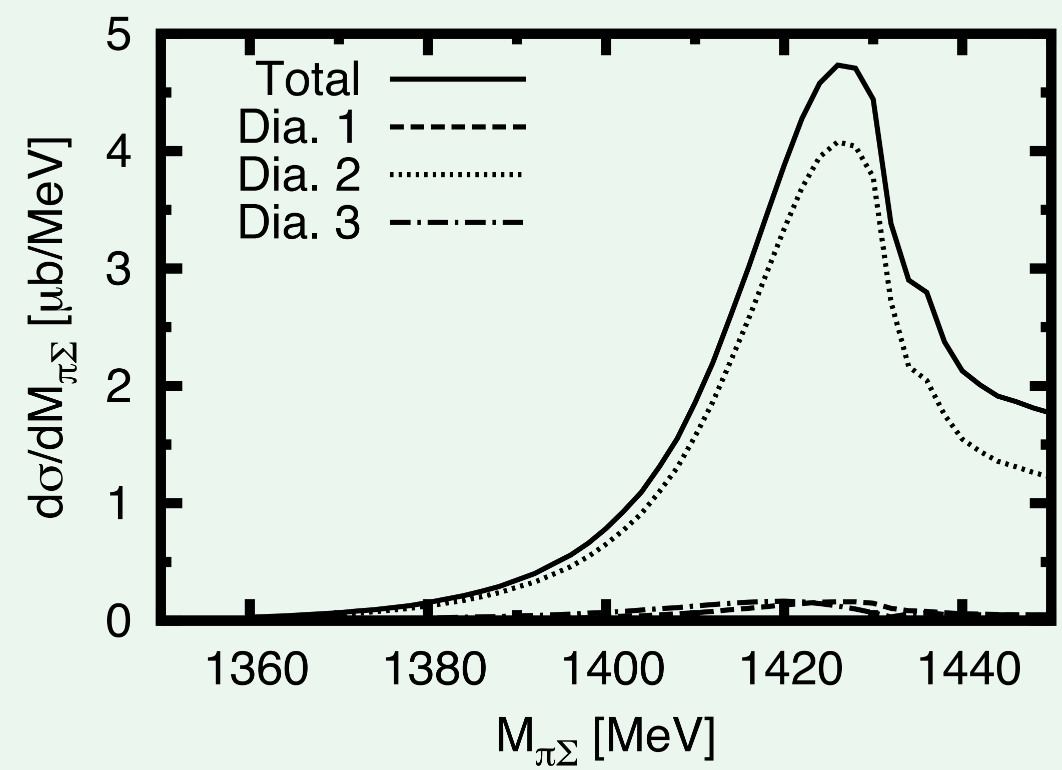
K momentum: 800 MeV/c



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





$K^- d \to \Lambda(1405) n$ cross section ~380 μb (exp. 410 ± 100 μb)

Subthreshold properties of $K^{bar}N$

DJ, Oset, Sekihara, in preparation

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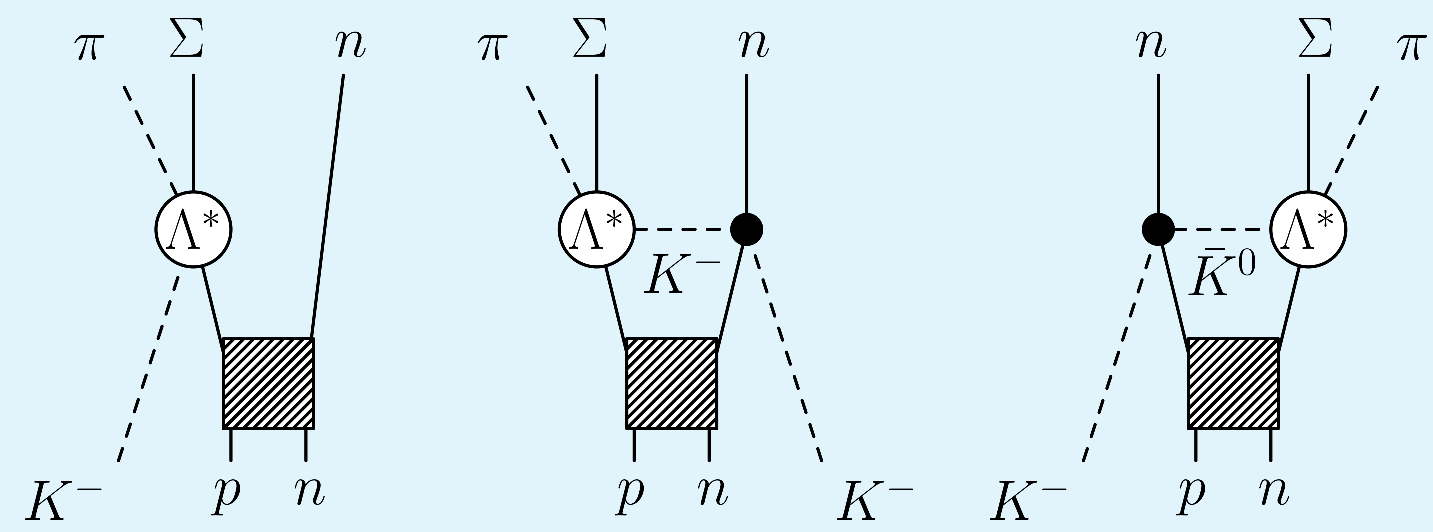
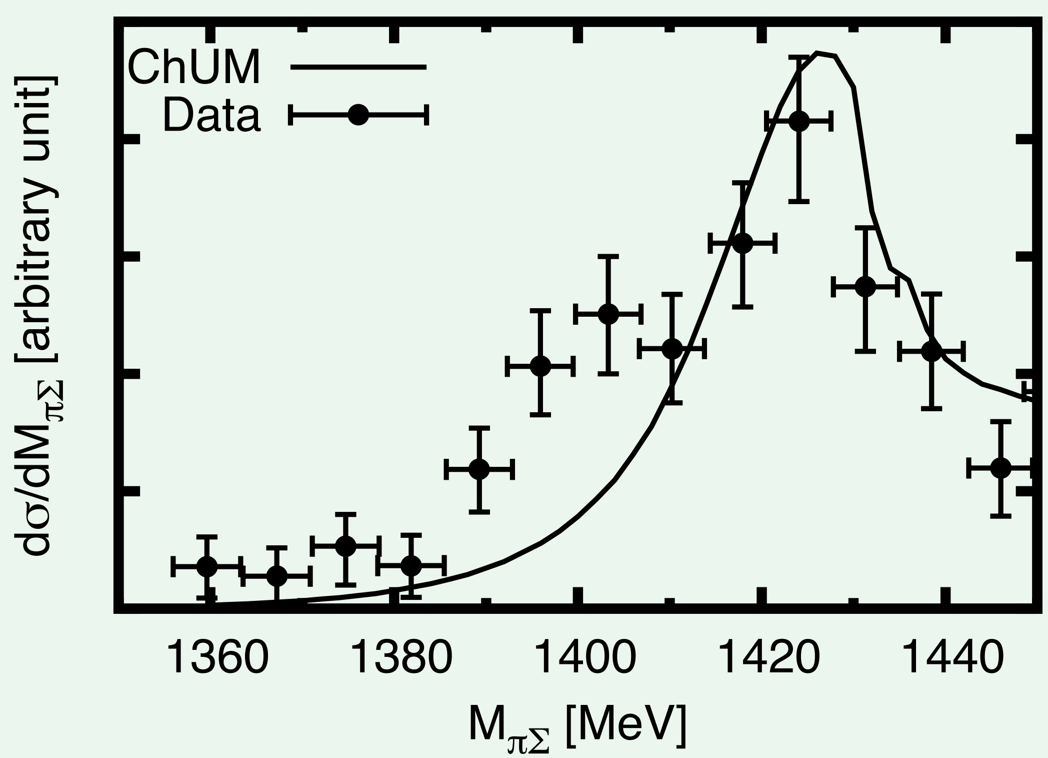
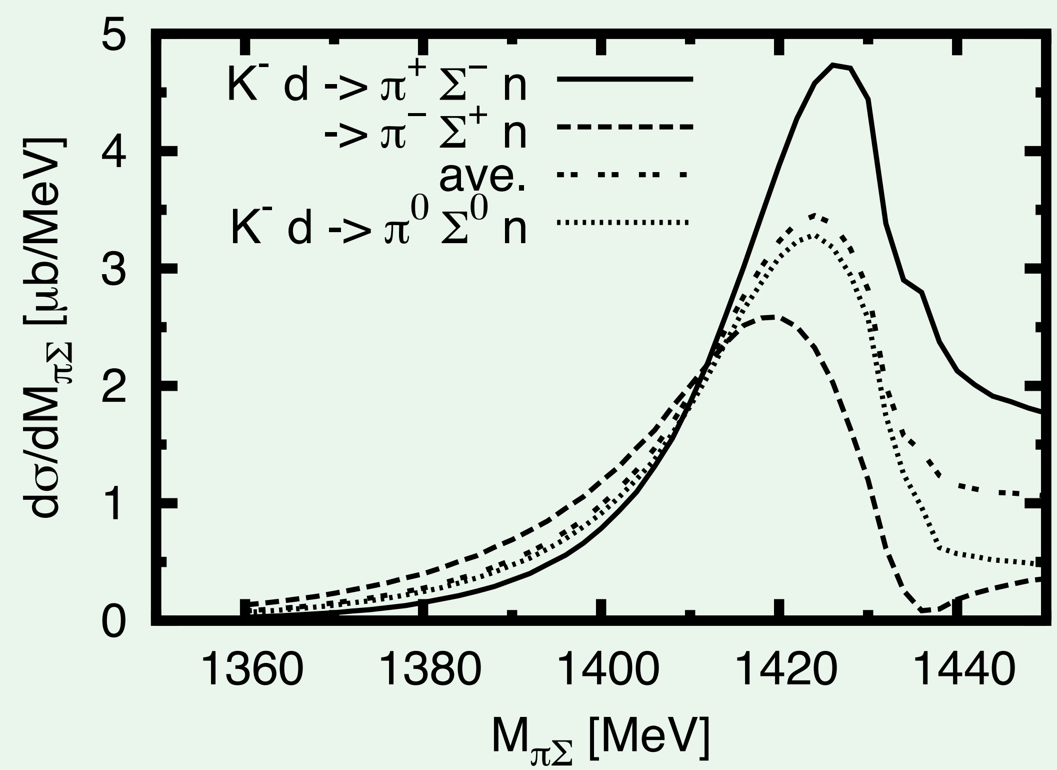
Λ^*: T-matrix by ChUM

K momentum: 800 MeV/c



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





$K^- d \to \Lambda(1405) n$ cross section ~380 μb (exp. 410 ± 100 μb)