Possible existence of double-pole structure of "K^-pp"?

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1. Introduction

2. Method
   - Feshbach projection of coupled-channel Complex Scaling Method

3. Result
   - "K^-pp" as a $K^{bar}NN$-πYN system with ccCSM+Feshbach method

4. Double pole of "K^-pp"?

5. Summary and future plan

研究会「原子核媒質中のハドロン研究 III」
19. Oct. '15 @ KEK東海キャンパス（東海一号館）

1. Introduction

1. Introduction

Kaonic nuclei = Exotic system !?

- Strong $K^{bar}N$ attraction ← Λ(1405) ~ quasi-bound state of I=0 $K^{bar}N$
  - Deeply bound (Total B.E. ~100MeV)
  - Quasi-stable (πΣ decay mode closed)
  - Highly dense state … anti-kaon attracts nucleons

Y. Akaishi and T. Yamazaki, PRC65, 044005 (2002)
A. Dote, H. Horiuchi, Y. Akaishi and T. Yamazaki, PRC70, 044313 (2004)

"K^-pp" = A prototype of kaonic nuclei

Experimental search for "K^-pp"

- FINUDA : K^- stopped on Li, C, Al target
  PRL 94, 212303 (2005)
- DISTO : $p + p \rightarrow p + \Lambda + K^+$ at T_p=2.85 GeV
  PRL104, 132502 (2010)
- J-PARC E27 : $d(\pi^+, K^+) X$ at P_π= 1.69 GeV/c
  PTEP 021D01 (2015)

Signal at ~100 MeV below K^-pp threshold

- J-PARC E15 : $^3He(K^-, n) X$ at P_K = 1 GeV/c
  PTEP 2015, 061D01

Attraction below K^-pp threshold

- LEPS/SPring8 : $d(\gamma, \pi^+K^+) X$ at E_γ = 1.5 – 2.4 GeV
  PLB 728, 616 (2014)

No evidence of deeply bound K^-pp

Theoretical studies of "K^-pp"

$B(K^-pp)$ < 100 MeV

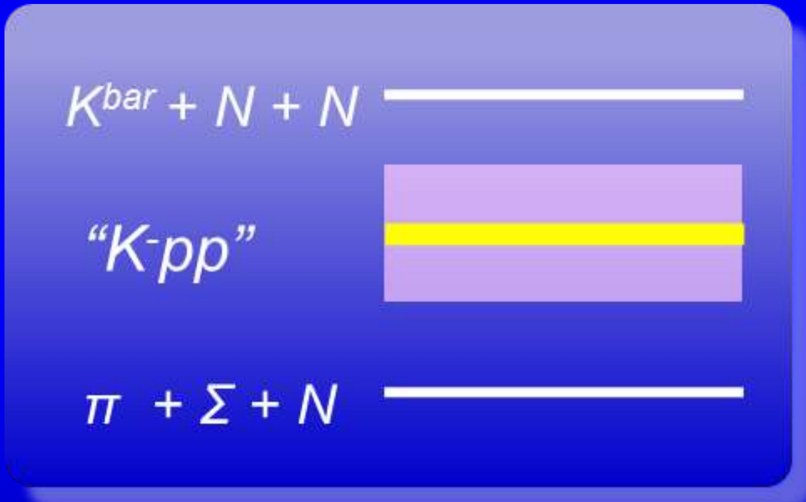
	Dote-Hyodo-Weise PRC79, 014003(2009)	Akaishi-Yamazaki PRC76, 045201(2007)	Barnea-Gal-Livertz PLB712, 132 (2012)	Ikeda-Kamano-Sato PTP124, 533 (2010)	Shevchenko-Gal-Mares PRC76, 044004(2007)
$B(K^-pp)$	20±3	47	16	9～16	50～70
$\Gamma_{mesonic}$	40～70	61	41	34～46	90～110

- *Λ(1405) = Resonant state & $K^{bar}N$ coupled with πΣ*

- *"K^-pp" … Resonant state of*
  $K^{bar}NN$-πYN coupled-channel system

  Doté, Hyodo, Weise, PRC79, 014003(2009). Akaishi, Yamazaki, PRC76, 045201(2007)
  Ikeda, Sato, PRC76, 035203(2007). Shevchenko, Gal, Mares, PRC76, 044004(2007)
  Barnea, Gal, Liverts, PLB712, 132(2012)

- ***Resonant state***
- ***Coupled-channel system***



⇒ ***"coupled-channel Complex Scaling Method"***

S. Aoyama, T. Myo, K. Kato, K. Ikeda, PTP116, 1 (2006)
T. Myo, Y. Kikuchi, H. Masui, K. Kato, PPNP79, 1 (2014)

Complex Scaling Method

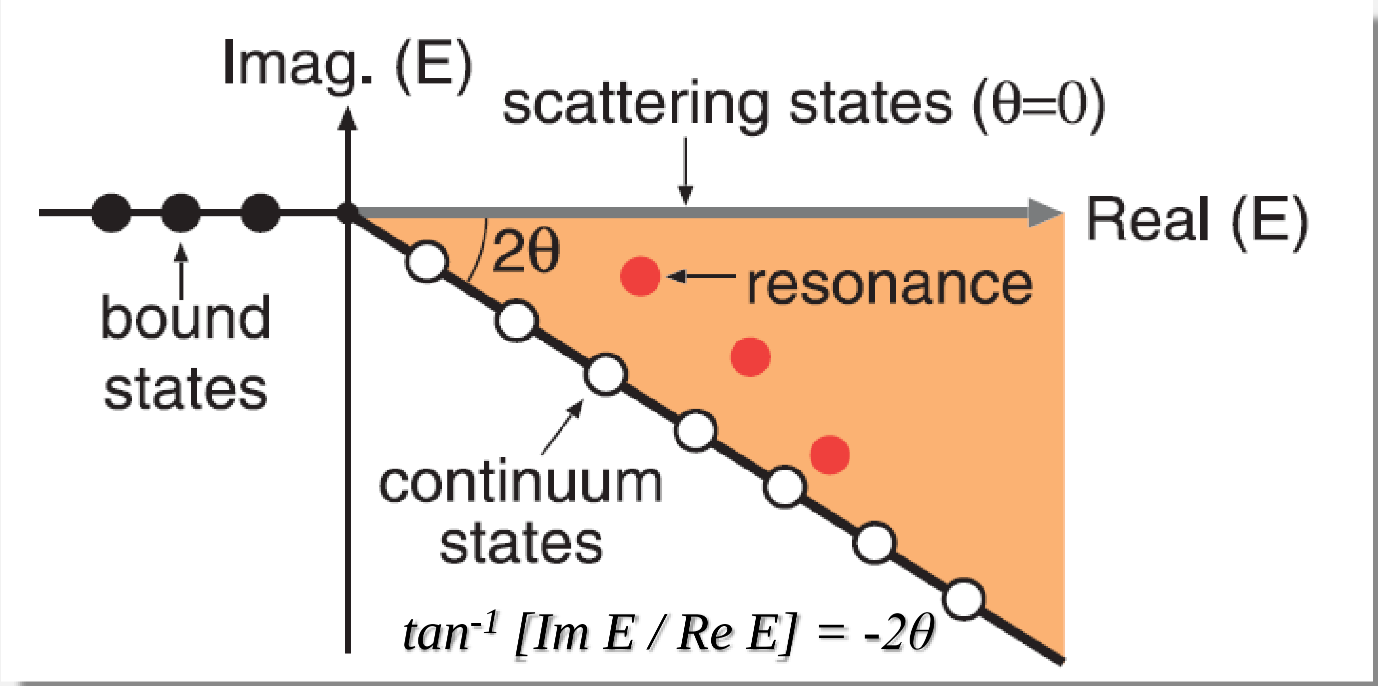
… Powerful tool for resonance study of many-body system

Complex rotation (Complex scaling) of coordinate

Resonance wave function → L^2 integrable

$$U(\theta): \quad \mathbf{r} \to \mathbf{r}\, e^{i\theta}, \quad \mathbf{k} \to \mathbf{k}\, e^{-i\theta}$$

Diagonalize $H_\theta = U(\theta)\, H\, U^{-1}(\theta)$ with Gaussian base,



- *Continuum state appears on 2ϑ line.*
- *Resonance pole is off from 2ϑ line, and independent of ϑ. (ABC theorem)*

Chiral SU(3) potential with a Gaussian form

A. D., T. Inoue, T. Myo, Nucl. Phys. A 912, 66 (2013)

• Anti-kaon = Nambu-Goldstone boson

⇒ Chiral SU(3)-based $K^{bar}N$ potential

- Weinberg-Tomozawa term of effective chiral Lagrangian
- Gaussian form in r-space
- Semi-rela. / Non-rela.
- Based on Chiral SU(3) theory

→ **Energy dependence**

A non-relativistic potential (NRv2c)

$$V_{ij}^{(I=0,1)}(r) = -\frac{C_{ij}^{(I=0,1)}}{8 f_\pi^2}\left(\omega_i + \omega_j\right)\sqrt{\frac{1}{m_i\, m_j}}\; g_{ij}(r)$$

$$g_{ij}(r) = \frac{1}{\pi^{3/2} d_{ij}^3} \exp\left[-\left(r/d_{ij}\right)^2\right]$$: Gaussian form

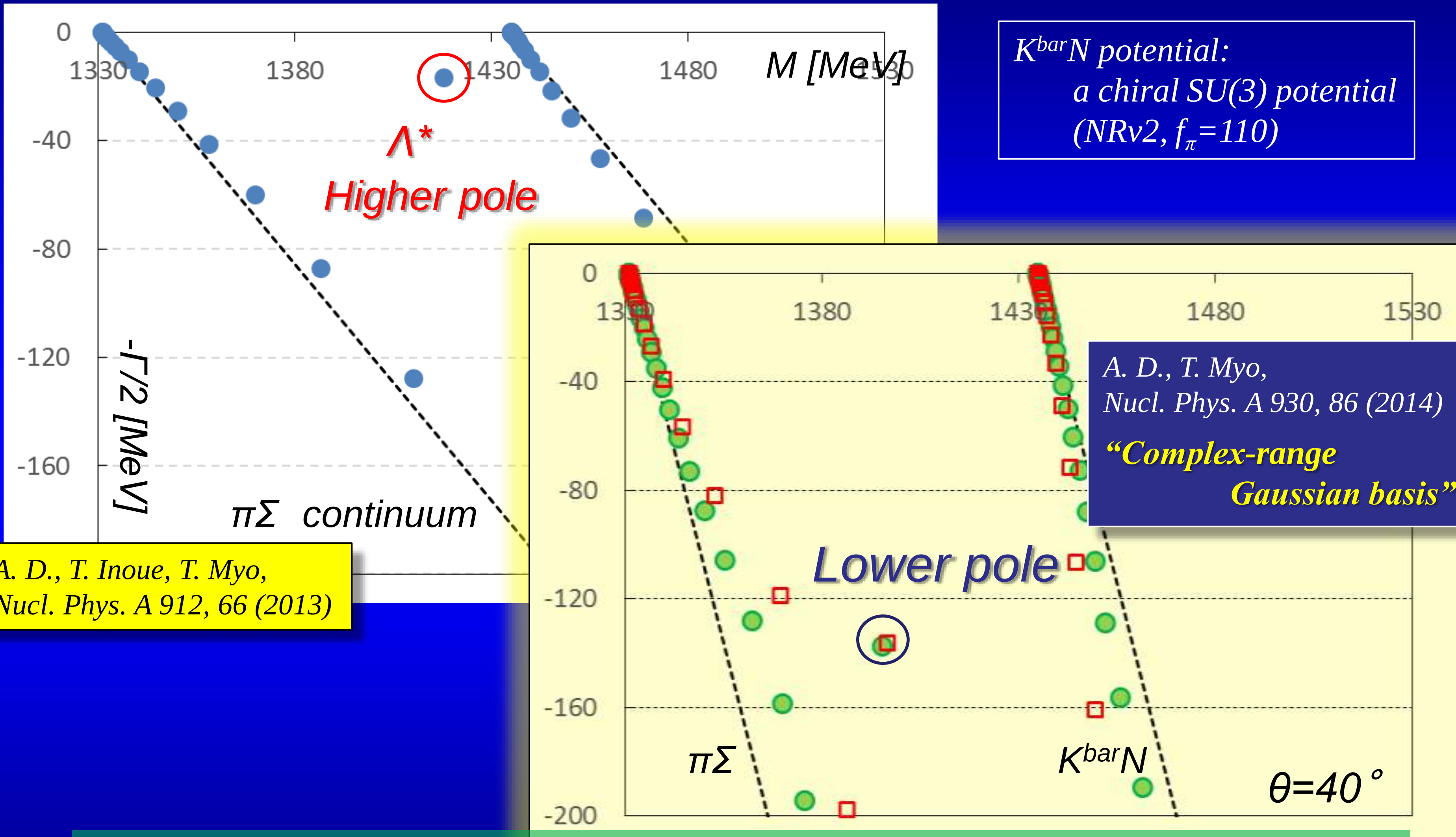
ω_i: meson energy

Constrained by $K^{bar}N$ scattering length

$a_{KN(I=0)}$ = -1.70+i0.67fm, $a_{KN(I=1)}$ = 0.37+i0.60fm A. D. Martin, NPB179, 33(1979)

Λ(1405) on coupled-channel Complex Scaling Method

$K^{bar}N$ potential:
a chiral SU(3) potential
(NRv2, f_π=110)



A. D., T. Inoue, T. Myo,
Nucl. Phys. A 912, 66 (2013)

A. D., T. Myo,
Nucl. Phys. A 930, 86 (2014)

"Complex-range
Gaussian basis"

Double-pole structure of Λ(1405)

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.-G. Meißner, Nucl. Phys. A 725 (2003) 181

2. Method

- ***Feshbach projection on coupled-channel Complex Scaling Method***

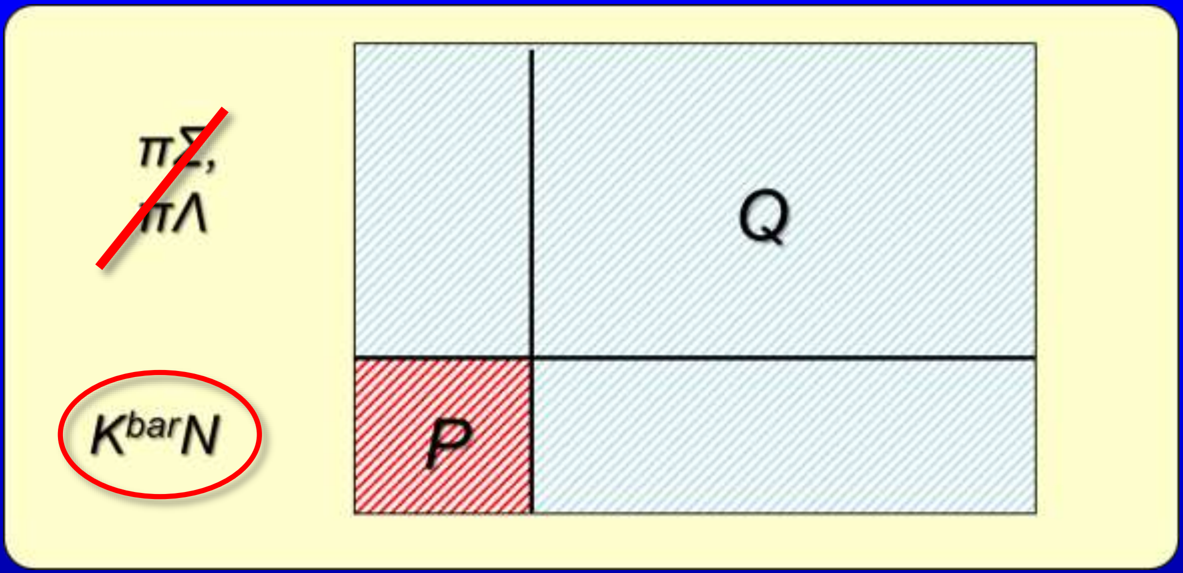
"ccCSM+Feshbach method"

A. D., T. Inoue, T. Myo, PTEP 2015, 043D02 (2015)

ccCSM+Feshbach method

- *Λ(1405) = two-body system of $K^{bar}N$-πΣ*
  → Explicitly treat coupled-channel problem

- *"$K^{-}pp$" = three-body system of $K^{bar}NN$-πYN*
  … High computational cost



For economical treatment of "$K^{-}pp$", we construct an effective $K^{bar}N$ single-channel potential by means of Feshbach projection on CSM.

Formalism of ccCSM + Feshbach method

Elimination of channels by Feshbash method

Schrödinger eq.
in model space "P" and out of model space "Q"

$$\begin{pmatrix} T_P + v_P & V_{PQ} \\ V_{QP} & T_Q + v_Q \end{pmatrix} \begin{pmatrix} \Phi_P \\ \Phi_Q \end{pmatrix} = E \begin{pmatrix} \Phi_P \\ \Phi_Q \end{pmatrix}$$

Schrödinger eq. in P-space :

$$\left(T_P + U_P^{Eff}(E) \right) \Phi_P = E\,\Phi_P$$

Effective potential for P-space

$$U_P^{Eff}(E) = v_P + V_{PQ}\, G_Q(E) V_{QP}$$

Q-space Green function:

$$G_Q(E) = \frac{1}{E - H_{QQ}}$$

Extended Closure Relation in Complex Scaling Method

$$H_{QQ}^{\theta} \left| \chi_n^{\theta} \right\rangle = \varepsilon_n^{\theta} \left| \chi_n^{\theta} \right\rangle$$

$$H_{QQ}^{\theta} = U(\theta) H_{QQ} U^{-1}(\theta)$$

$$\int_C \sum_{R+B} \left| \chi_n^{\theta} \right\rangle \left\langle \chi_n^{\theta} \right| = 1$$

Diagonalize H^{θ}_{QQ} with **Gaussian base**,

$$\sum_n \left| \chi_n^{\theta} \right\rangle \left\langle \chi_n^{\theta} \right| \approx 1$$

Well approximated

T. Myo, A. Ohnishi and K. Kato, PTP 99, 801 (1998)
R. Suzuki, T. Myo and K. Kato, PTP 113, 1273 (2005)

Express the $G_Q(E)$ with **Gaussian base** using ECR

$$G_Q^{\theta}(E) = \frac{1}{E - H_{QQ}^{\theta}} \approx \sum_n \left| \chi_n^{\theta} \right\rangle \frac{1}{E - \varepsilon_n^{\theta}} \left\langle \chi_n^{\theta} \right|$$

$$U_P^{Eff}(E) = v_P + V_{PQ}\, \underbrace{U^{-1}(\theta) G_Q^{\theta}(E) U(\theta)}_{G_Q(E)}\, V_{QP}$$

$\left\{ \left| \chi_n^{\theta} \right\rangle \right\}$: expanded with Gaussian base.

Apply ccCSM + Feshbach method to K^-pp

"K^-pp" … $K^{bar}NN$ - $\pi\Sigma N$ - $\pi\Lambda N$ ($J^\pi=0^-$, $T=1/2$)

For the two-body system, $P = K^{bar}N$, $Q = \pi Y$

$$V\left(K^{bar}N-\pi Y; I=0,1\right)$$
$$V\left(\pi Y-\pi Y' \quad ; I=0,1\right)$$

→ **Feshbach + ccCSM** →

$$U^{Eff}_{K^{bar}N(I=0,1)}\left(E\right)$$

- Schrödinger eq. for $K^{bar}NN$ channel :

$$\left(T_{K^{bar}NN}+V_{NN}+\sum_{i=1,2}U^{Eff}_{K^{bar}N_i(I)}\left(E_{K^{bar}N}\right)\right)\Phi_{K^{bar}NN} = E\,\Phi_{K^{bar}NN}$$

- Trial wave function

$$\left|"K^-pp"\right\rangle = \sum_a C_a^{(KNN,1)}\left\{G_a^{(KNN,1)}\left(\mathbf{x}_1^{(3)},\mathbf{x}_2^{(3)}\right)+G_a^{(KNN,1)}\left(-\mathbf{x}_1^{(3)},\mathbf{x}_2^{(3)}\right)\right\}\left|S_{NN}=0\right\rangle\left|\left[K\left[NN\right]_1\right]_{T=1/2}\right\rangle$$

Ch. 1: $K^{bar}NN$, NN: ^1E

$$+\sum_a C_a^{(KNN,2)}\left\{G_a^{(KNN,2)}\left(\mathbf{x}_1^{(3)},\mathbf{x}_2^{(3)}\right)-G_a^{(KNN,2)}\left(-\mathbf{x}_1^{(3)},\mathbf{x}_2^{(3)}\right)\right\}\left|S_{NN}=0\right\rangle\left|\left[K\left[NN\right]_0\right]_{T=1/2}\right\rangle$$

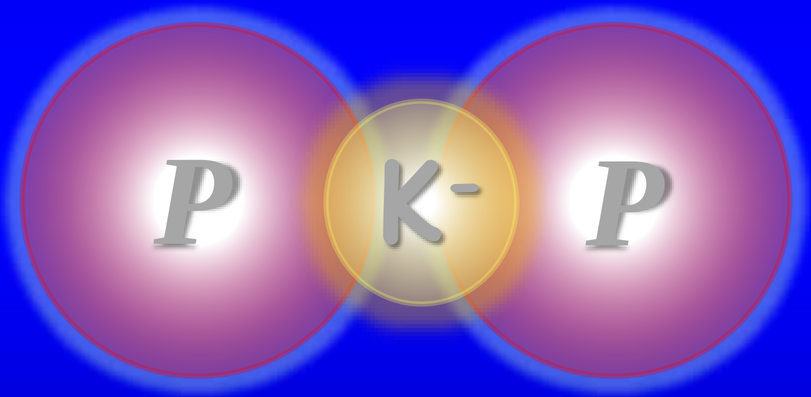
Ch. 2: $K^{bar}NN$, NN: ^1O

- Basis function = Correlated Gaussian
  …including 3-types Jacobi-coordinates

$$G_a^{(KNN,i)}\left(\mathbf{x}_1^{(3)},\mathbf{x}_2^{(3)}\right)=N_a^{(KNN,i)}\exp\left[-\left(\mathbf{x}_1^{(3)},\mathbf{x}_2^{(3)}\right)A_a^{(KNN,i)}\begin{pmatrix}\mathbf{x}_1^{(3)}\\ \mathbf{x}_2^{(3)}\end{pmatrix}\right]$$

3. Result

Three-body "K⁻pp" resonance
on ccCSM+Feshbach projection

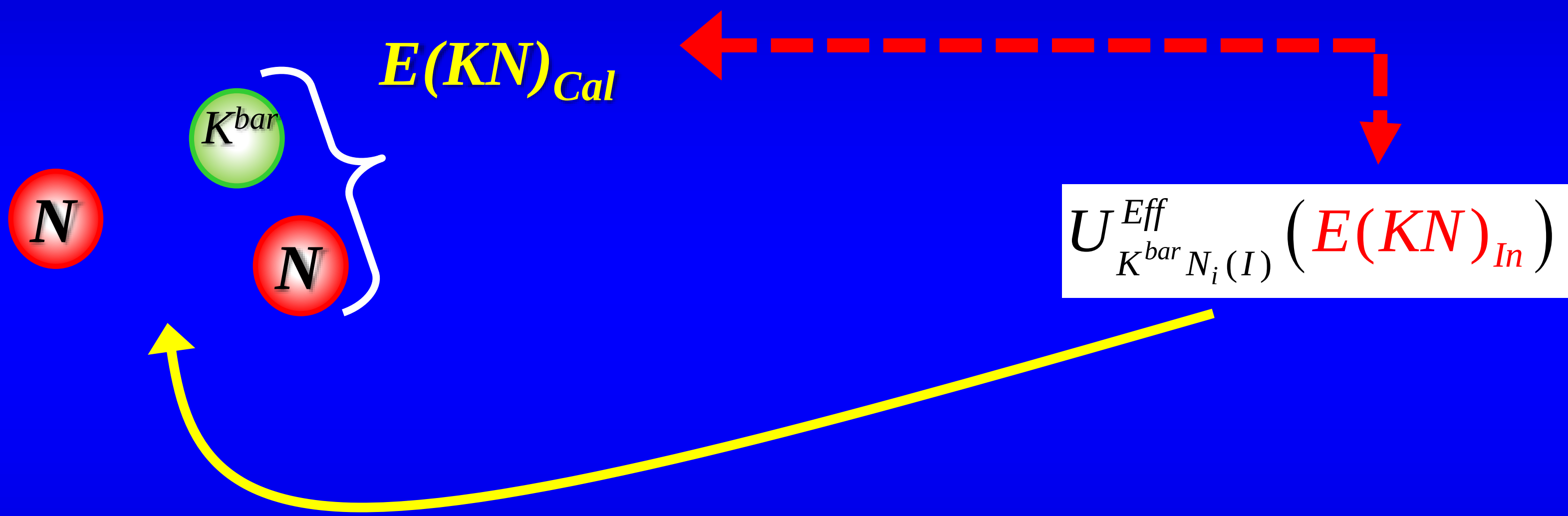


"$K^{-}pp$" =

$K^{bar}NN - \pi\Sigma N - \pi\Lambda N$ ($J^{\pi} = 0^{-}$, $T=1/2$)

Self-consistency for complex $K^{bar}N$ energy

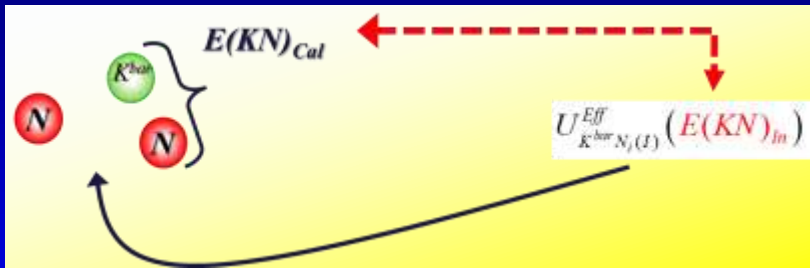
Effective $K^{bar}N$ potential has energy dependence…



- $E(KN)_{In}$: assumed in the $K^{bar}N$ potential
- $E(KN)_{Cal}$: calculated with the obtained $K^{-}pp$

When $E(KN)_{In} = E(KN)_{Cal}$,
a self-consistent solution is obtained.

Self-consistency for complex $K^{bar}N$ energy



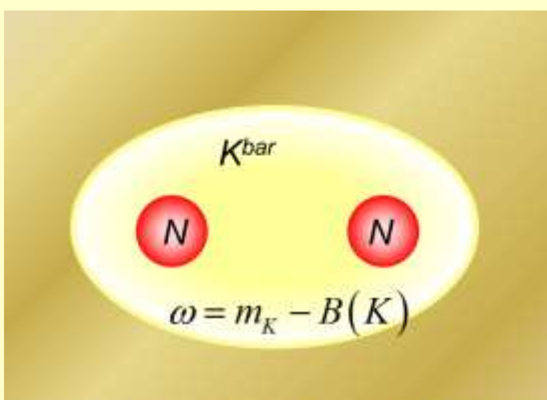
How to determine the two-body energy in the three-body system?

A. D., T. Hyodo, W. Weise, PRC79, 014003 (2009)

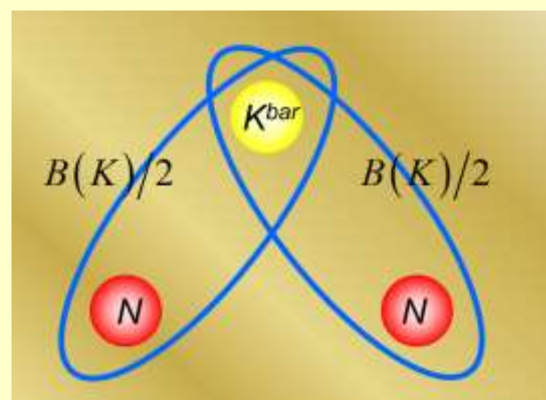
1. *Kaon's binding energy:* $B(K) \equiv -\left\{ \langle H \rangle - \langle H_{NN} \rangle \right\}$ H_{NN} *: Hamiltonian of two nucleons*

2. *Define a K^{bar}N-bond energy in two ways*

$$E_{KN} = M_N + \omega = \begin{cases} M_N + m_K - B(K) & : \text{Field picture} \\ M_N + m_K - B(K)/2 & : \text{Particle picture} \end{cases}$$



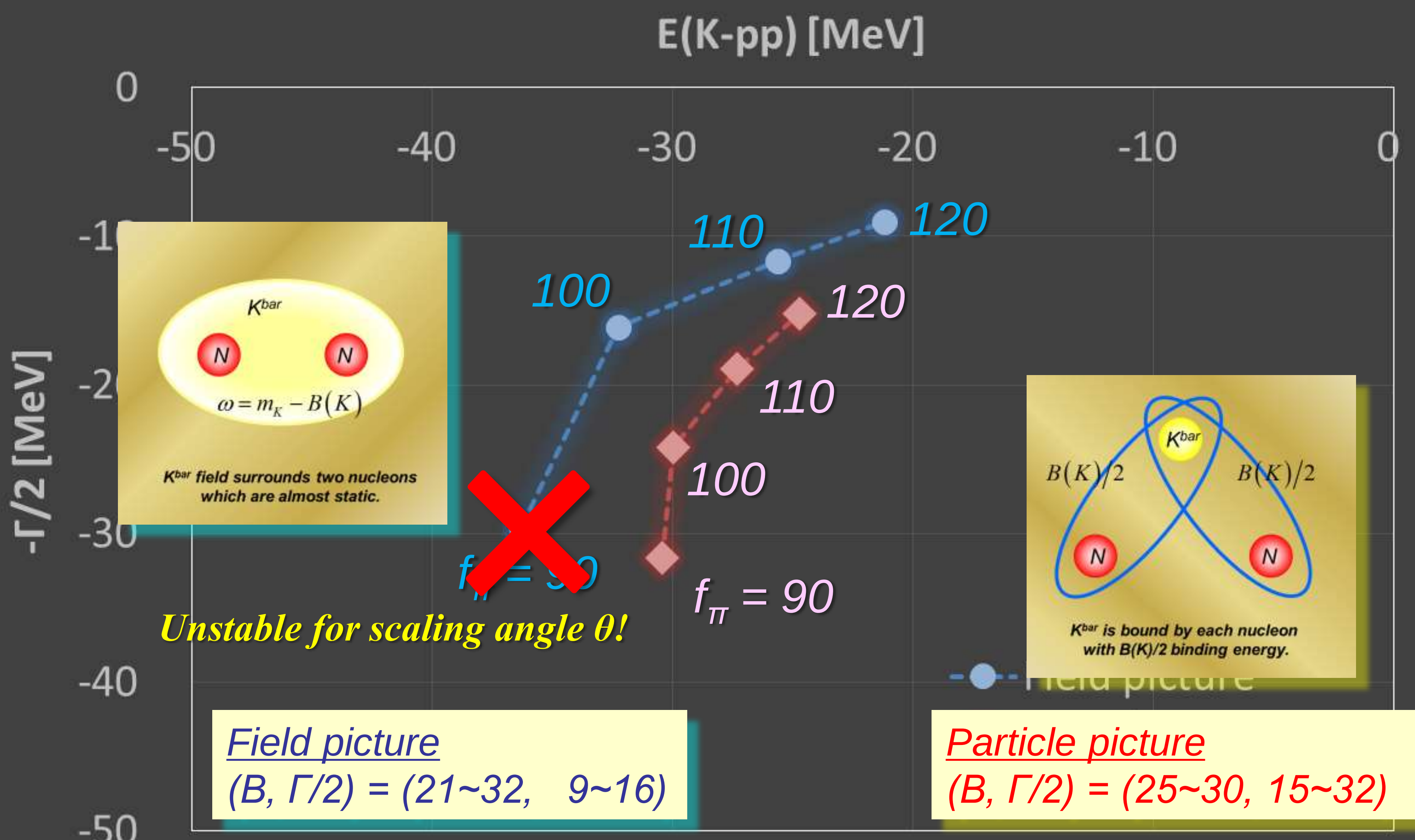
Field picture



Particle picture

Self-consistent results f_π=90~120MeV

NN pot. : Av18 (Central)
$K^{bar}N$ pot. : NRv2c potential
(f_π=90 - 120MeV)

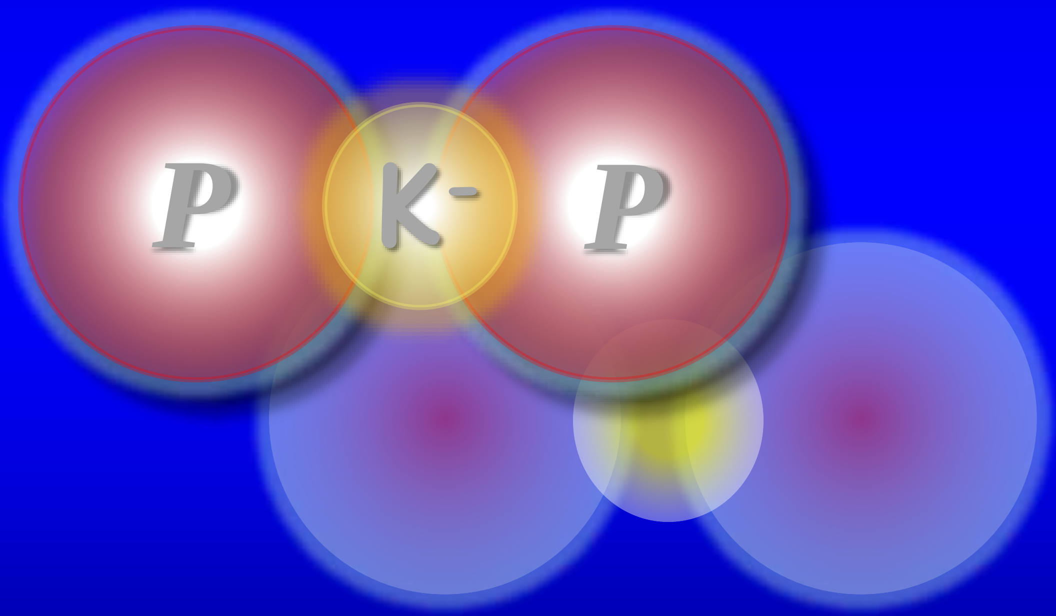


Unstable for scaling angle θ!

Field picture
(B, Γ/2) = (21~32, 9~16)

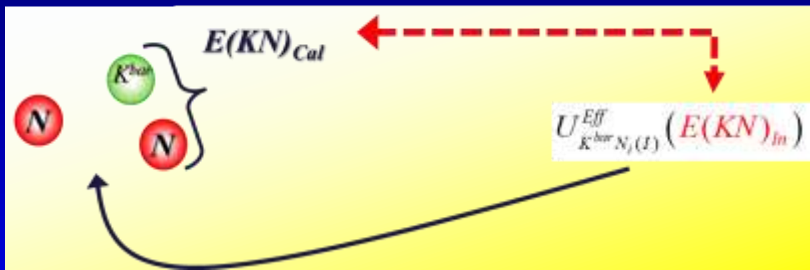
Particle picture
(B, Γ/2) = (25~30, 15~32)

4. Double pole of "K⁻pp"?



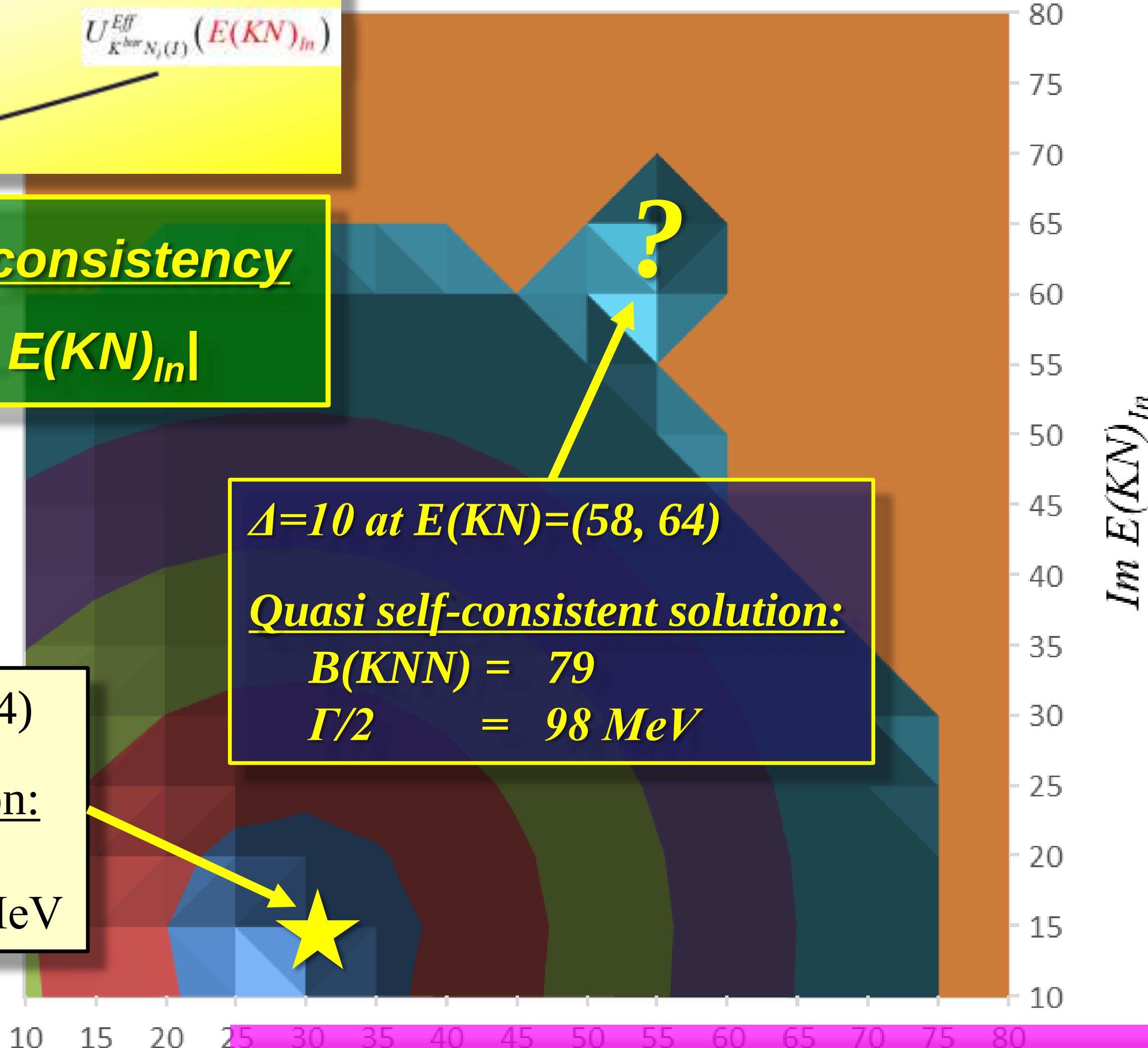
Quasi self-consistent solution

NRv2c (f_π=110 MeV)
Particle picture



Indicator of self-consistency

$\Delta = |E(KN)_{Cal} - E(KN)_{In}|$



Δ=10 at E(KN)=(58, 64)

Quasi self-consistent solution:
B(KNN) = 79
Γ/2 = 98 MeV

Δ=0 at E(KN)=(29, 14)

Self-consistent solution:
B(KNN) = 27.3
Γ/2 = 18.9 MeV

"Double pole of K^-pp" ?

Double-pole structure in "K^-pp"?

- ✓ Quasi self-consistent solution is obtained …
  (B(KNN), Γ/2) = (62～79, 74～104) MeV for f_π=90～120 MeV
  with Particle picture
- ✓ Such solutions are not obtained with Field picture.

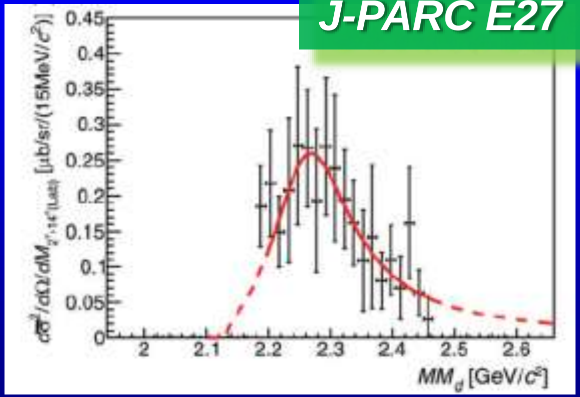
- A Faddeev-AGS calc. has predicted the double-pole structure of "K^-pp".

  Lower pole : (B(KNN), Γ/2) = (67～89, 122～160) MeV
  Higher pole : (B(KNN), Γ/2) = (9～16, 17～23) MeV

  Y. Ikeda, H. Kamano, and T. Sato, PTP 124, 533 (2010)

- Relation to signals observed by J-PARC E27, DISTO?

J-PARC E27



Signal at ~100 MeV below K^{bar}NN thr.

Lower pole of "K^-pp" ($J^\pi=0^-$, I=1/2)
… "K^-pp" has two poles similarly to Λ(1405).
The lower pole appears.

Partial restoration of chiral symmetry
… K^{bar}N potential is enhanced by 17%.
S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad., Ser. B 89, 418 (2013)

Pion assisted dibaryon "Y = πΣN-πΛN ($J^\pi=2^+$, I=3/2)"
A. Gal, arXiv:1412.0198 (Proceeding of EXA2014)

5. Summary and future plans

5. Summary

A prototype of K^{bar} nuclei "K^-pp" = Resonance state of $K^{bar}NN$-πYN coupled system

"coupled-channel Complex Scaling Method + Feshbach projection"

… *Represent the Q-space Green function with the Extended Complete Set well approximated by Gaussian base*

⇒ *Eliminate πY channels to reduce the problem to a $K^{bar}NN$ single channel problem.*

K^-pp studied with ccCSM+Feshbch method

- *Used a Chiral SU(3)-based potential (Gaussian form in r-space)*
- *Self-consistency for $K^{bar}N$ complex energy (Field and Particle pictures)*

K^-pp ($J^\pi=0^-$, $T=1/2$) …. (B, $\Gamma/2$) ≒ (20~30, 10~30) MeV

- *Quasi self-consistent solution in case of Particle picture*

  … *Deeper binding and larger decay width*

K^-pp ($J^\pi=0^-$, $T=1/2$) …. (B, $\Gamma/2$) ≒ (60~80, 75~105) MeV

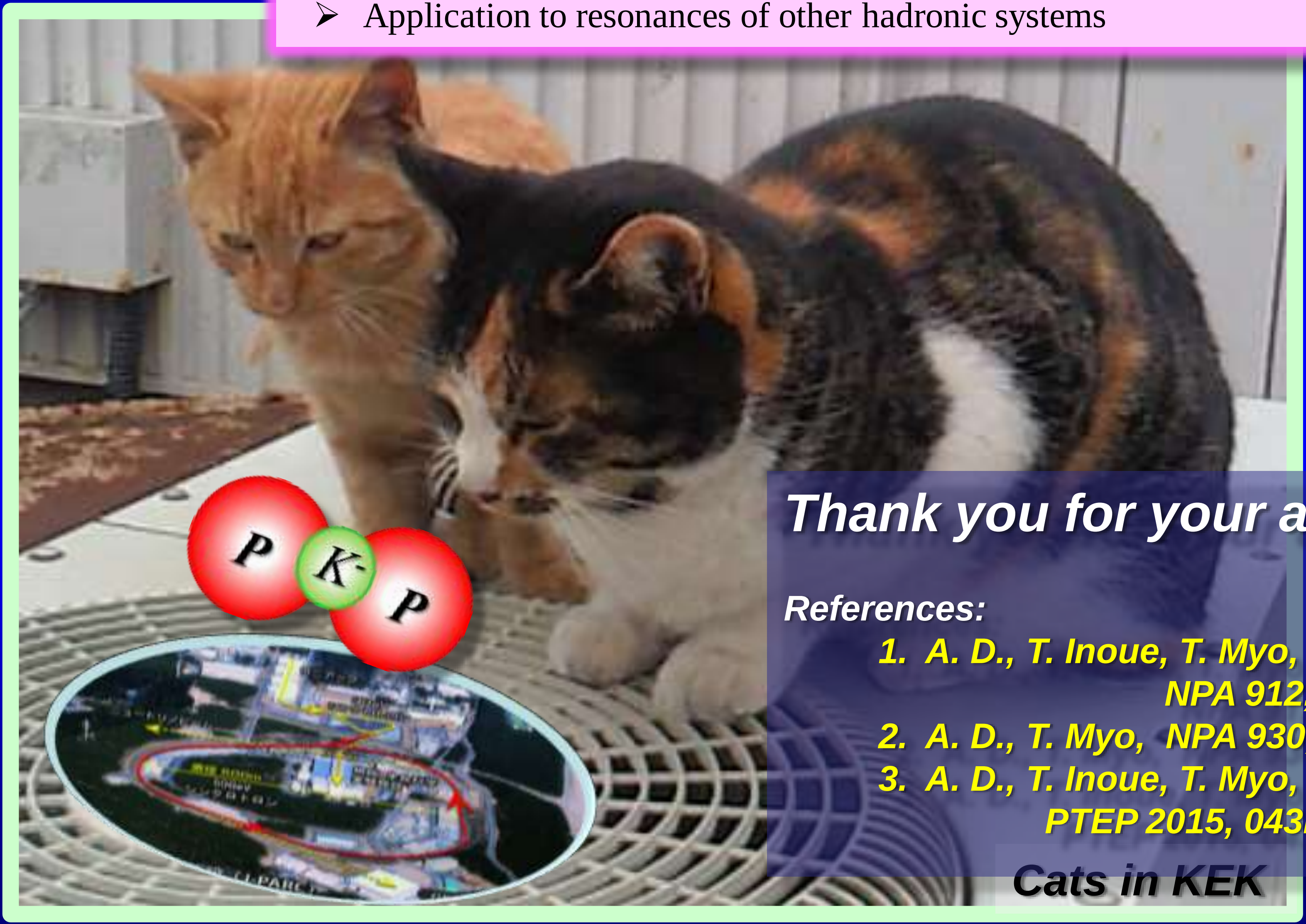
"K^-pp" has a double-pole structure similarly to $\Lambda(1405)$?

- *Relation to the K^-pp search experiments*

The signal observed in J-PARC E27 is considered to correspond to the lower pole of "K^-pp"??
J-PARC E15 may pick up the higher pole of "K^-pp"???

5. Future plans

- Full-coupled channel calculation of *K^-pp*
  … *Detailed study for the double pole structure of K^-pp*
- Application to resonances of other hadronic systems



Thank you for your attention!

References:

1. *A. D., T. Inoue, T. Myo, NPA 912, 66 (2013)*
2. *A. D., T. Myo, NPA 930, 86 (2014)*
3. *A. D., T. Inoue, T. Myo, PTEP 2015, 043D02 (2015)*