Theoretical study of the "K^-pp" system: Prototype system of kaonic nuclei

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(KEK Theory Center, IPNS / J-PARC branch)

1. Introduction

2. "K^-pp" investigated with ccCSM+Feshbach method
   - Outline of the methodology
   - Result with SIDDHARTA constraint for K^-p scattering length
   - Double pole of "K^-pp"?

Takashi Inoue (Nihon univ.)
Takayuki Myo (Osaka Inst. Tech.)

3. Discussion on "K^-pp"

4. Fully coupled-channel CSM study (On-going)

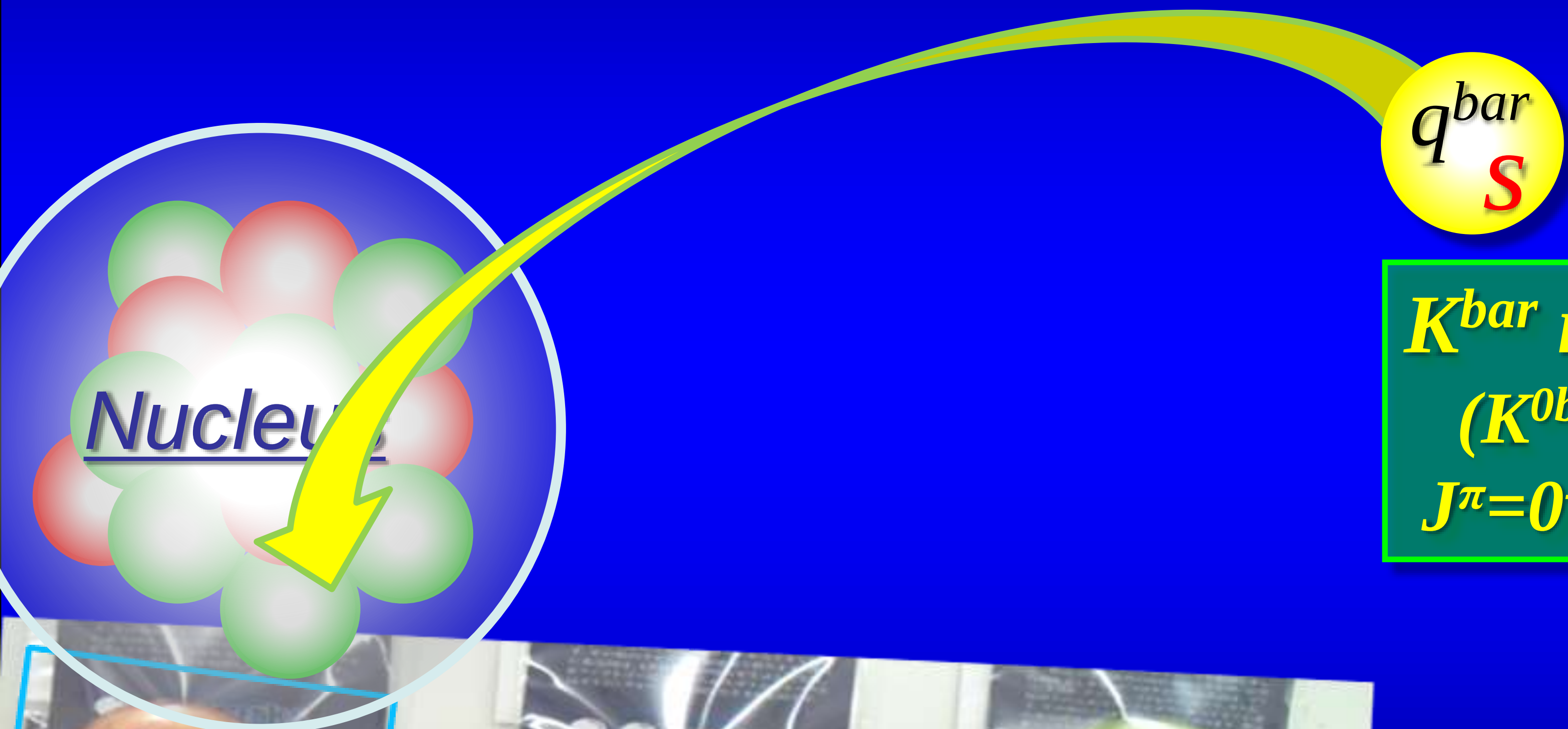
5. Summary, future plans and remarks

KEK theory center workshop on Hadron and Nuclear Physics in 2017 (KEK-HN-2017)
10. Jan, '17 @ Kobayashi Hall, Kenkyu-Honkan, KEK Tsukuba campus, Japan

1. Introduction

Kaonic nuclei

= Nuclear system with K^{bar} mesons

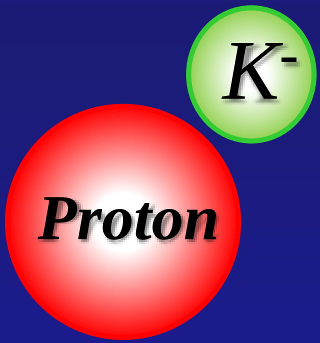


K^{bar} meson
(K^{0bar}, K^{-})
$J^{\pi}=0^{-}$, $I=1/2$

Introduce strange quarks (Strangeness) into a nucleus through mesons

cf) Hypernuclei: through baryons

... Hyperon (Λ, Σ, Ξ)



$K^{bar}N$ two-body system

- *Low energy scattering data, 1s level shift of kaonic hydrogen atom*
- *Hard to describe Λ(1405) with Quark Model as a 3-quark state*
- *Success of Chiral Unitary Model with a meson-baryon picture*

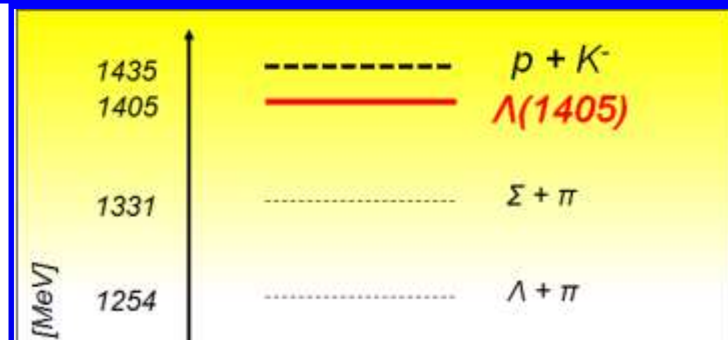
*Excited hyperon **Λ(1405)** = K^- proton quasi-bound state*

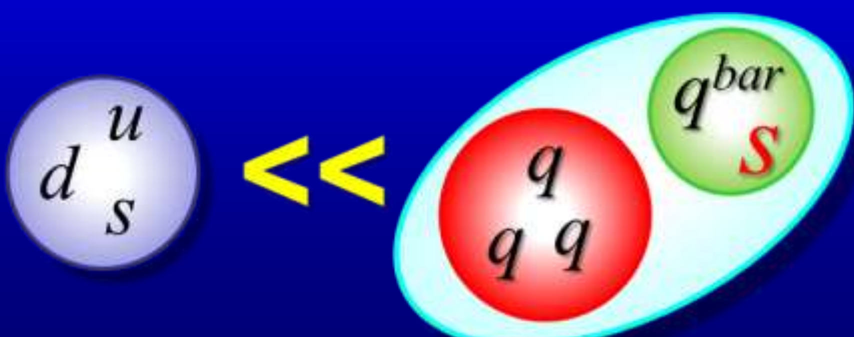
Excited hyperon Λ(1405)

Λ(1405) 1/2⁻ $I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1405.1^{+1.3}_{-1.0}$ MeV
Full width $\Gamma = 50 \pm 2$ MeV
Below $\overline{K}N$ threshold

Λ(1405) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	155

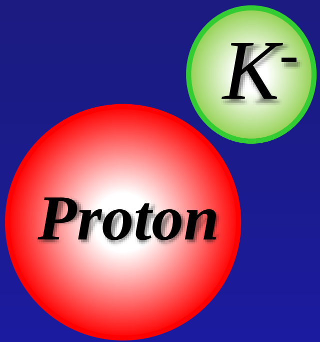




I=0 N-K^{bar} bound state

Not 3 quark state,
← A naive quark model fails.
N. Isgar and G. Karl, Phys. Rev. D18, 4187 (1978)

But rather a molecular state
T. Hyodo and D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)



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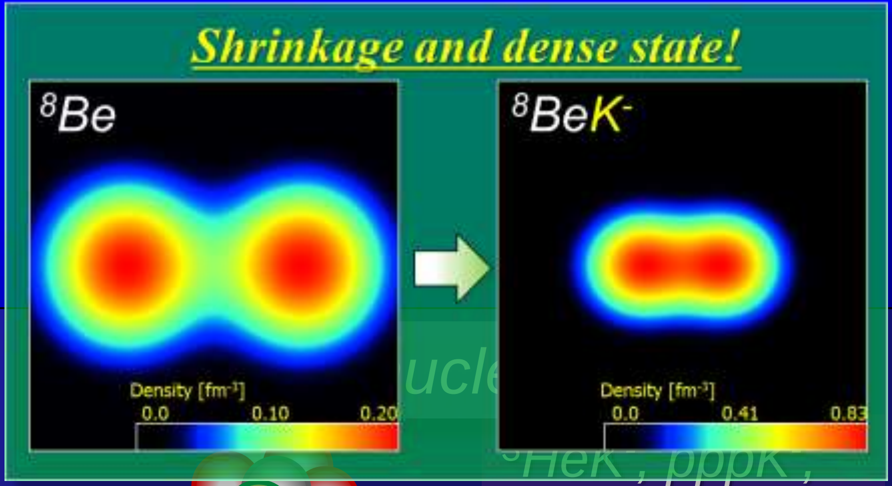
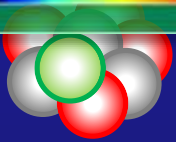
Strongly attractive $K^{bar}N$ potential

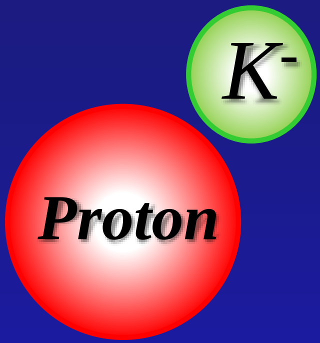


- *Doorway to **dense matter**†*
  → Chiral symmetry restoration in dense matter
- *Interesting structure†*
- *Neutron star*

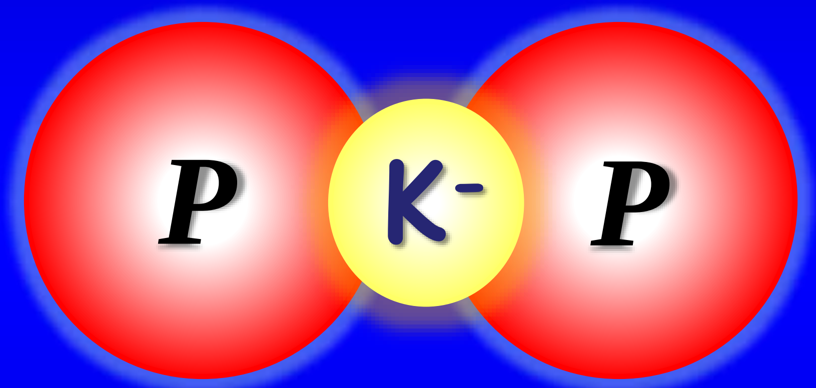


^{4}HeK$^-$, pppnK$^-$, …, ^{8}BeK$^-$, …

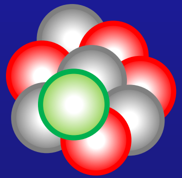
† A. D., H. Horiuchi, Y. Akaishi and T. Yamazaki, PRC70, 044313 (2004)



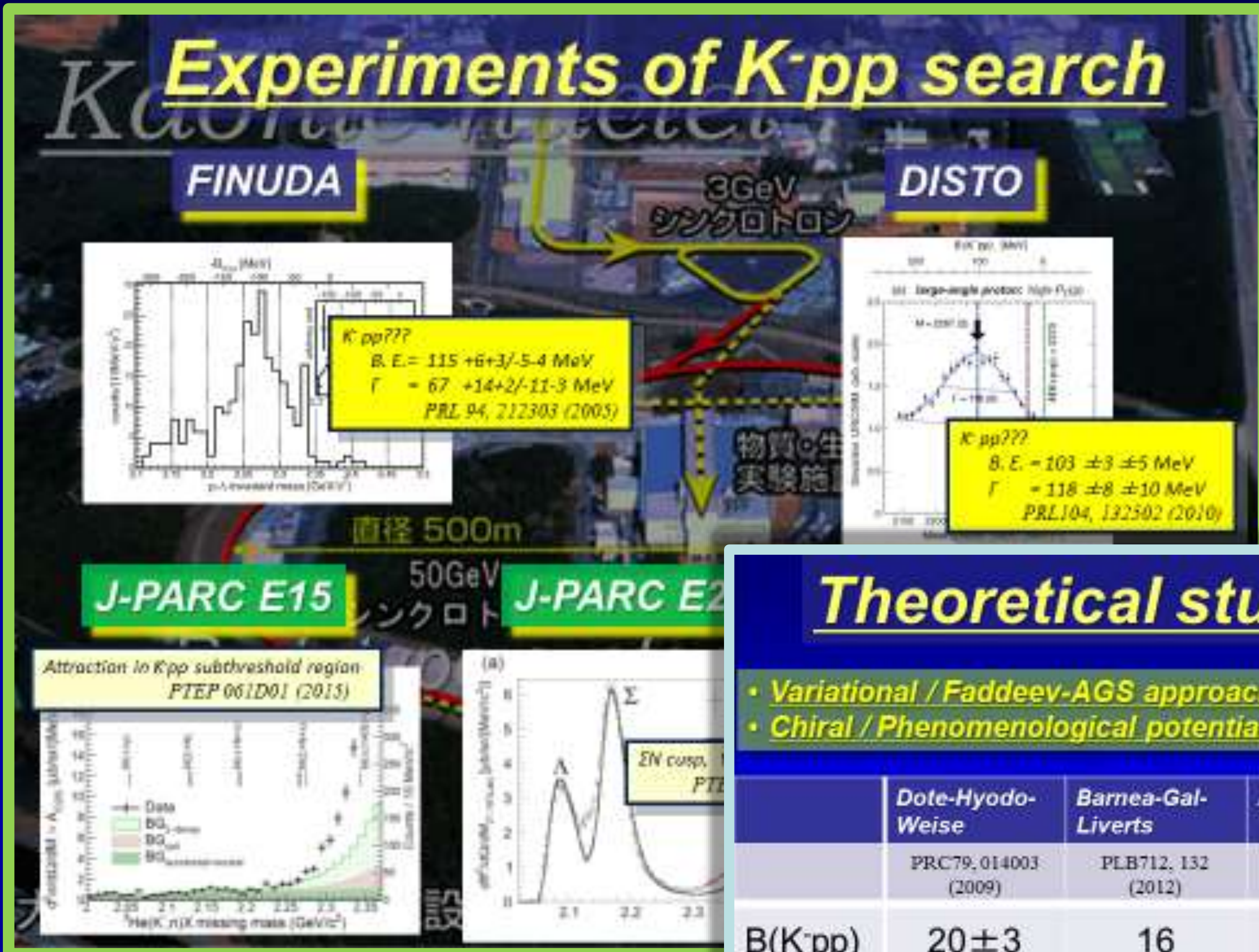
$K^{bar}N$ two-body system = Λ(1405)



Prototype system = K^- pp



Kaonic nuclei
= Nuclear many-body system with antikaons



Theoretical studies of "K-pp"

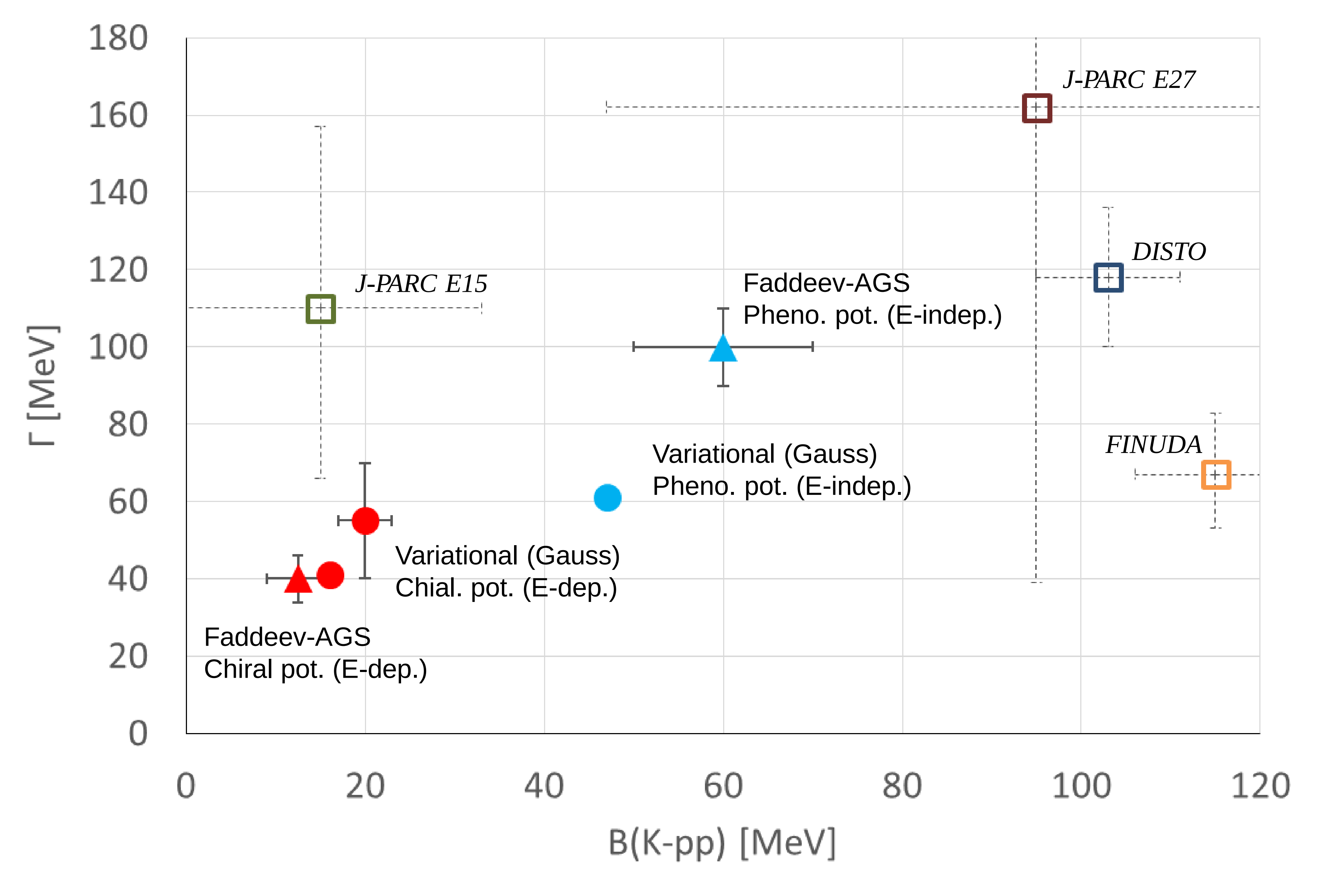
- Variational / Faddeev-AGS approaches
- Chiral / Phenomenological potentials

	Dote-Hyodo-Weise	Barnea-Gal-Liverts	Akaishi-Yamazaki	Ikeda-Kamano-Sato	Shevchenko-Gal-Mares
	PRC79, 014003 (2009)	PLB712, 132 (2012)	PRC76, 045201 (2007)	PTP124, 533 (2010)	PRC76, 044004 (2007)
B(K-pp)	20±3	16	47	9 ~ 16	50 ~ 70
Γ	40 ~ 70	41	61	34 ~ 46	90 ~ 110
Method	Variational (Gauss)	Variational (H. H.)	Variational (Gauss)	Faddeev-AGS	Faddeev-AGS
Potential	Chiral (E-dep.)	Chiral (E-dep.)	Pheno.	Chiral (E-dep.)	Pheno.

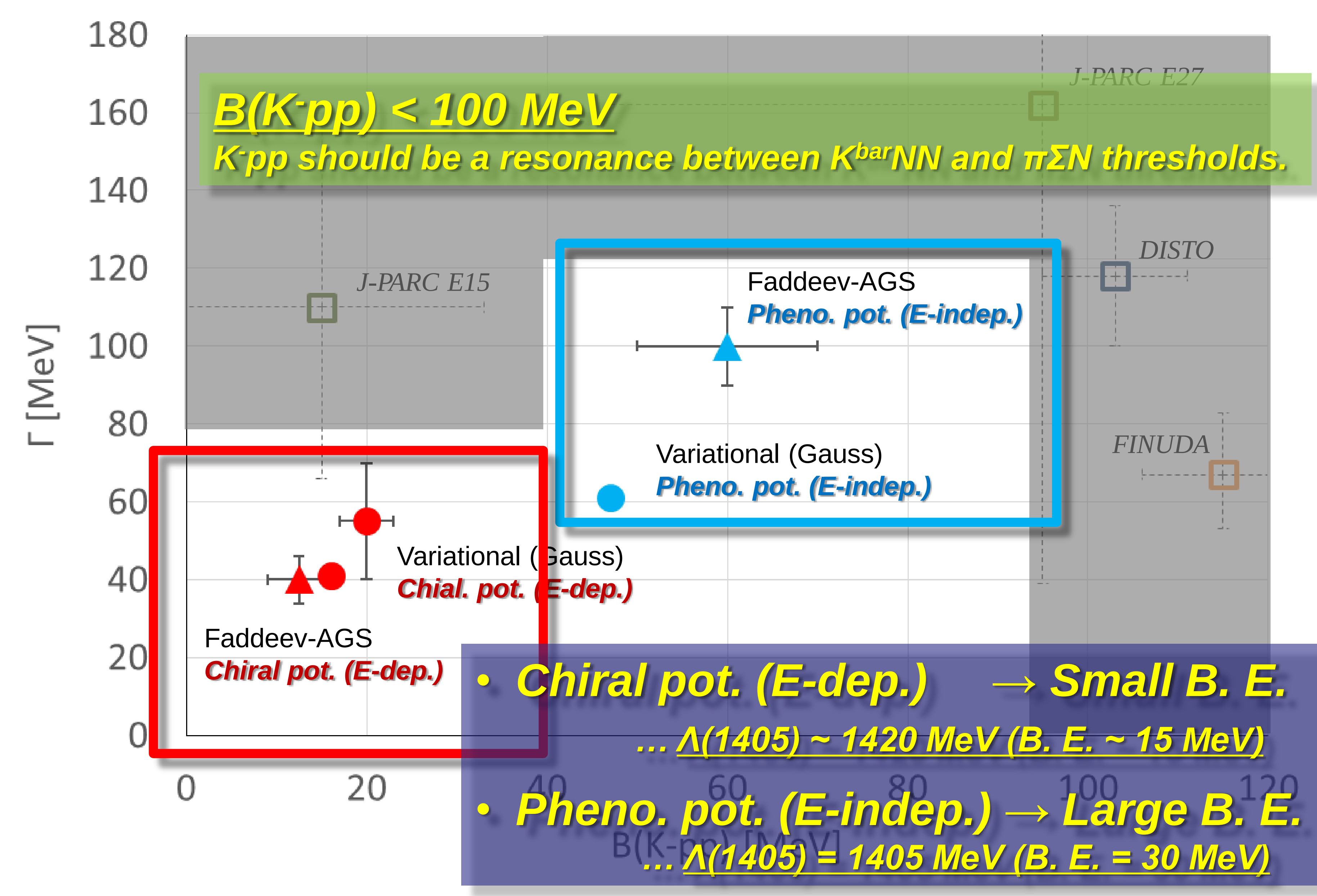
* Latest progress

- Systematic study of kaonic clusters (A+1 ≤ 7) with Stochastic Variational Method
  -->> Dr. S. Ohnishi's talk
- Study of kaonic clusters (A+1, A+2 ≤ 4) with Hyperspherical Harmonics approach in momentum-space (R. Y. Kezerashvili, et al., arXiv:1510.00478)

Current situation of "K-pp"



Theoretical studies of "K⁻pp"



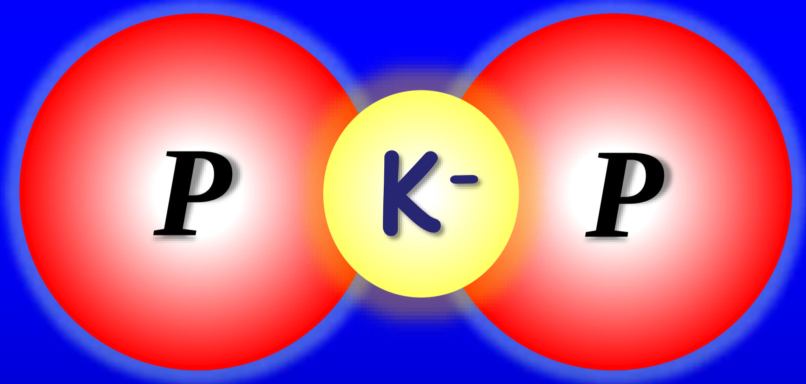
B(K⁻pp) < 100 MeV

K⁻pp should be a resonance between K^bar NN and πΣN thresholds.

- **Chiral pot. (E-dep.) → Small B. E.**
  … Λ(1405) ~ 1420 MeV (B. E. ~ 15 MeV)
- **Pheno. pot. (E-indep.) → Large B. E.**
  … Λ(1405) = 1405 MeV (B. E. = 30 MeV)

2. "K⁻pp" investigated with ccCSM+Feshbach method

Collaboration with
Takashi Inoue(Nihon univ.)
Takayuki Myo (Osaka Inst. Tech.)



"K⁻pp" =

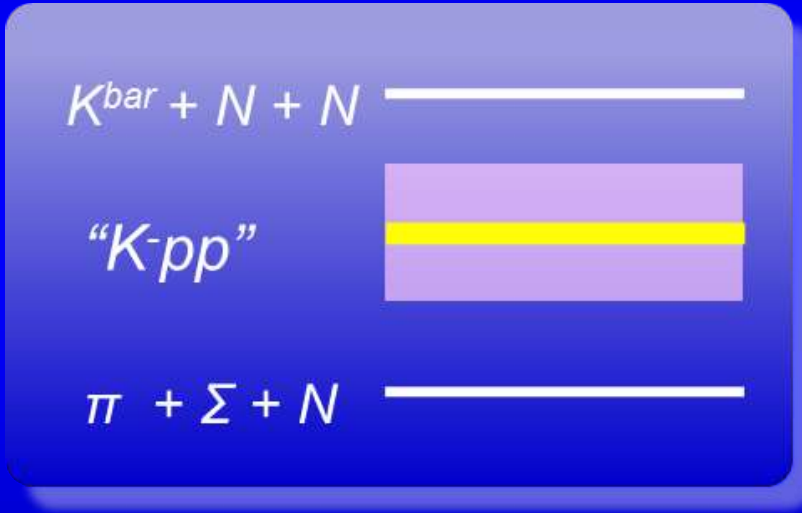
$K^{bar}NN - \pi\Sigma N - \pi\Lambda N$ ($J^{\pi} = 0^{-}$, $T=1/2$)

- $\Lambda(1405)$ = Resonant state & $K^{bar}N$ coupled with $\pi\Sigma$

- "$K^{-}pp$" … 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"

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)

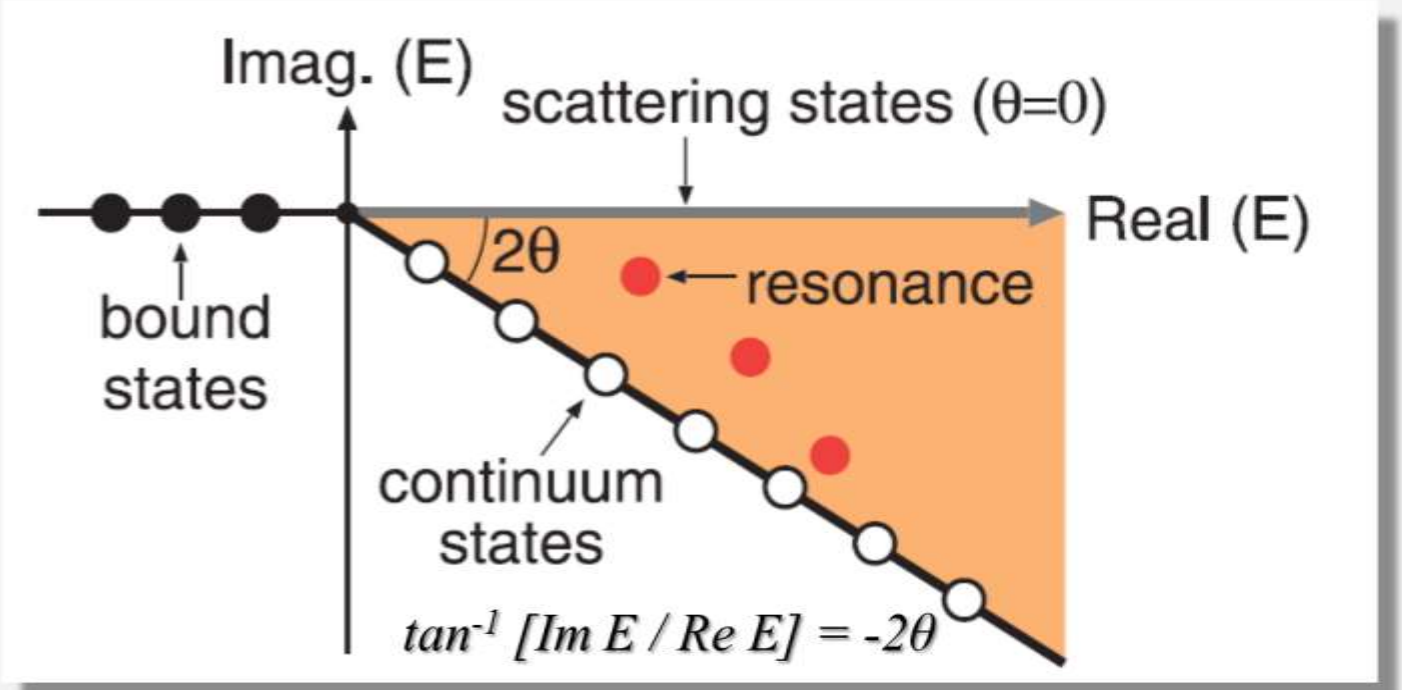
… Powerful tool for resonance study of many-body system

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)

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

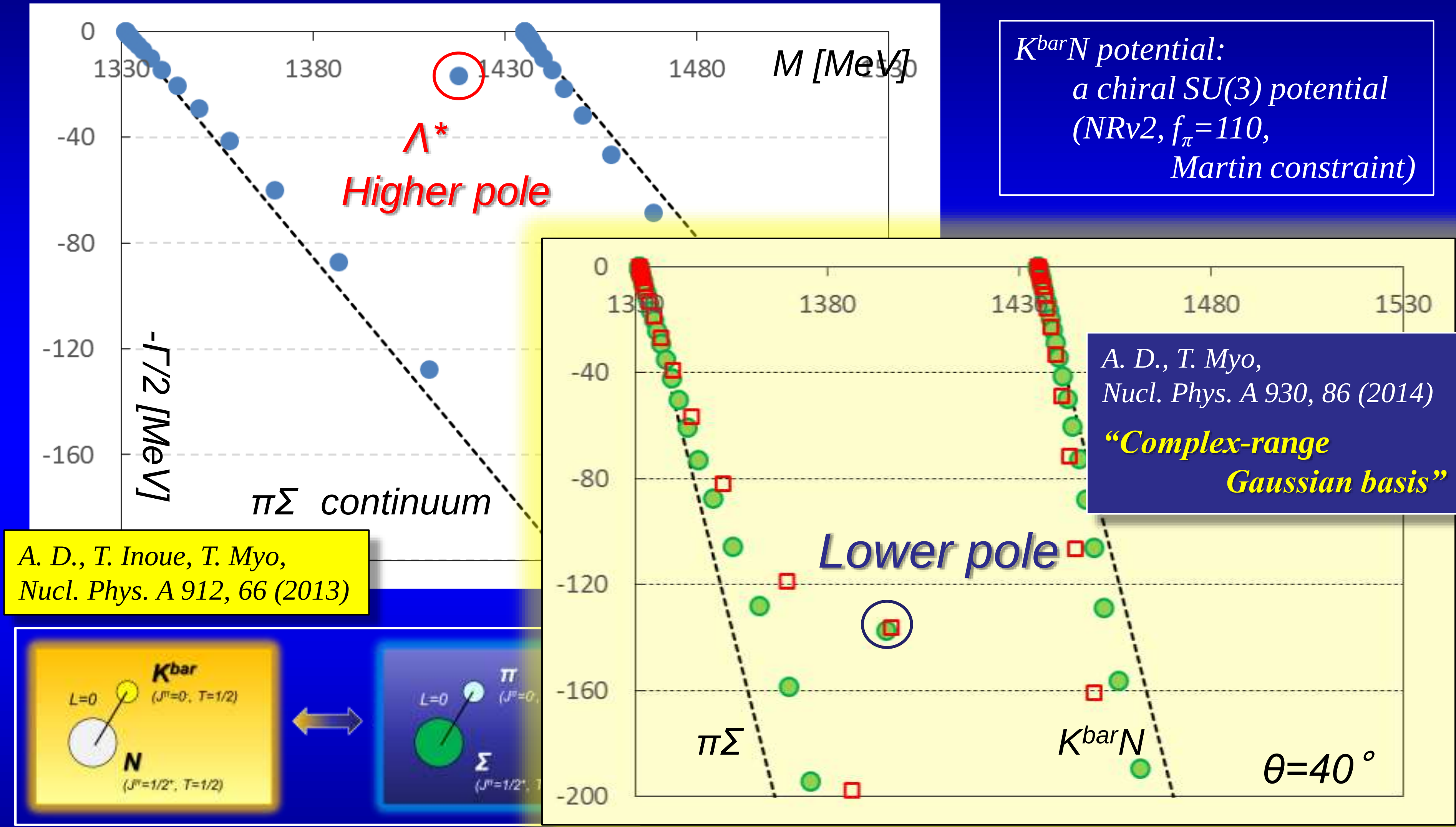
$$g_{ij}(r) = \frac{1}{\pi^{3/2} d_{ij}^3} \exp\left[-\left(r/d_{ij}\right)^2\right]$$: Gaussian form

ω_i: meson energy

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

- Old analysis by Martin
  $a_{KN(I=0)} = -1.70 + i0.67$ fm, $a_{KN(I=1)} = 0.37 + i0.60$ fm — A. D. Martin, NPB179, 33(1979)
- Analysis of **SIDDHARTA K^-p data** with **a coupled-channel chiral dynamics**
  $a_{K-p} = -0.65 + i0.81$ fm, $a_{K-n} = 0.57 + i0.72$ fm — Y. Ikeda, T. Hyodo and W. Weise, NPA 881, 98 (2012)

Λ(1405) pole with a chiral SU(3)-based potential



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

Double-pole structure of Λ(1405)

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

Outline: ccCSM+Feshbach calc. of "K$^-$pp"

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

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

Highly computational cost, due to the channel coupling

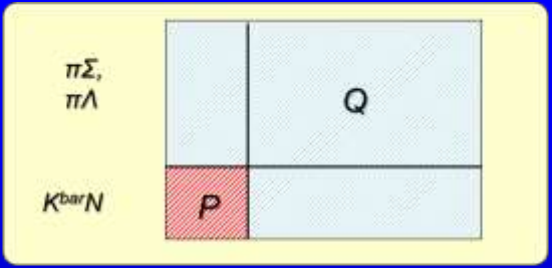
U^{Eff}_{KN}

Derive an effective $K^{bar}N$ single-channel potential by means of Feshbach projection on CSM.

"Extended Closure Relation"

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

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



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

$K^{bar}NN$ single-channel three-body problem with an effective $K^{bar}N$ potential

Outline: ccCSM+Feshbach calc. of "K⁻pp"

1. Solve the $K^{bar}NN$ three-body Schroedinger eq. with Gaussian Expansion Method

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

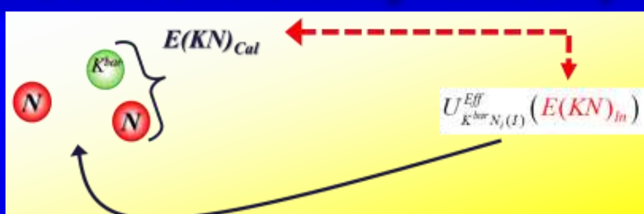
Trial wave function

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

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

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

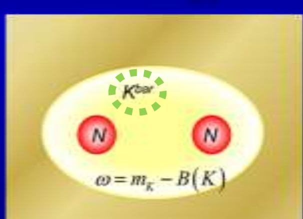
2. **Self-consistency for complex $K^{bar}N$ energy**



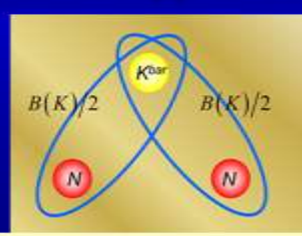
- $E(KN)_{In}$: assumed in the $K^{bar}N$ potential
- $E(KN)_{Cal}$: calculated with the obtained K^-pp

$$E(KN)_{In} = E(KN)_{Cal}$$

3. The energy of a $K^{bar}N$ pair in K^-pp is estimated in two ways.



Field picture



Particle picture

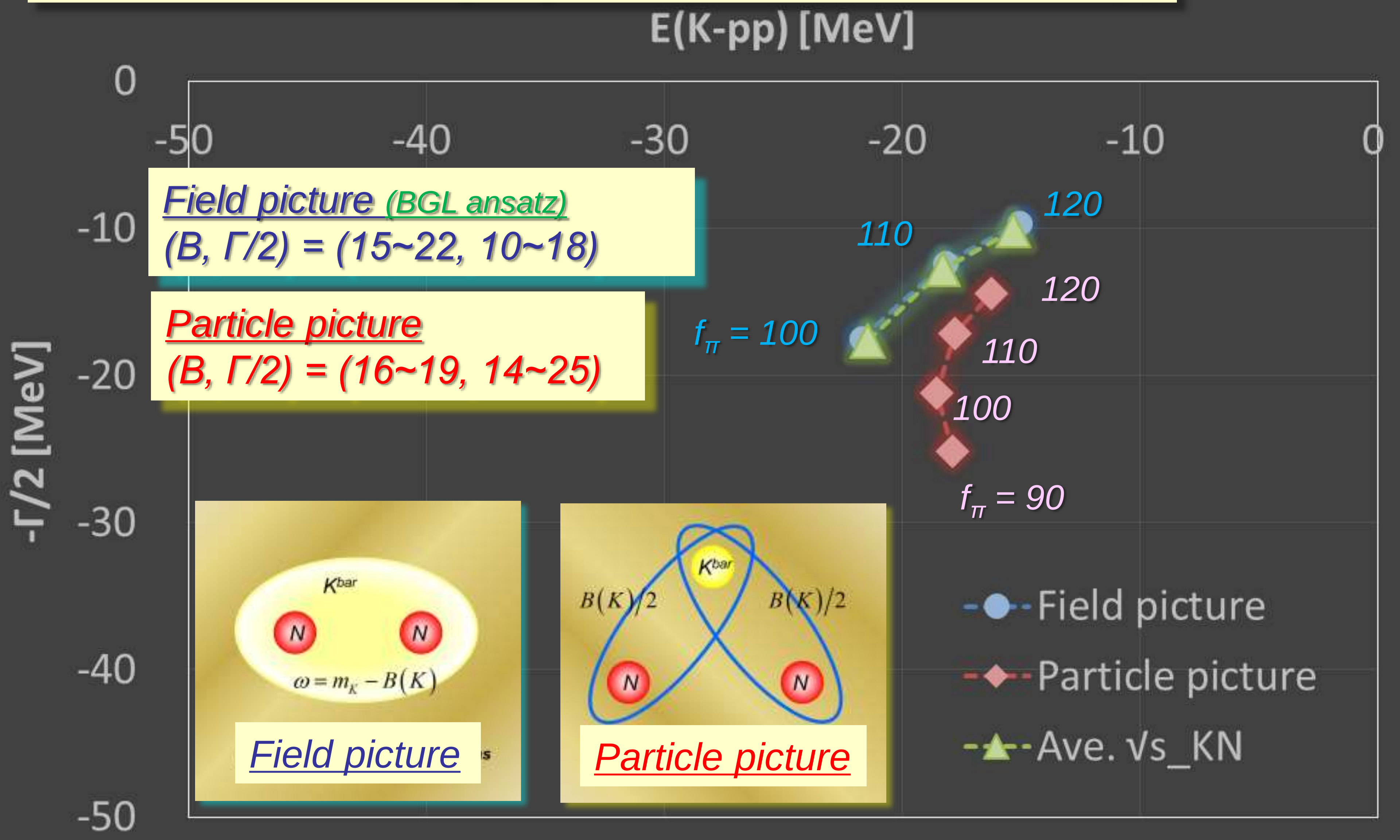
$$E(KN) = M_N + \omega = \begin{cases} M_N + m_K - B(K) & : \text{Field pict.} \\ M_N + m_K - B(K)/2 & : \text{Particle pict.} \end{cases}$$

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

Pole position of "K⁻pp"

NN pot. : Av18 (Central)
$K^{bar}N$ pot. : NRv2a-IHW pot.
(f_π=90 - 120MeV)

A chiral SU(3)-based potential constrained with
the latest $K^{bar}N$ scattering length data (based on "SIDDHARTA" exp.)



NN correlation density

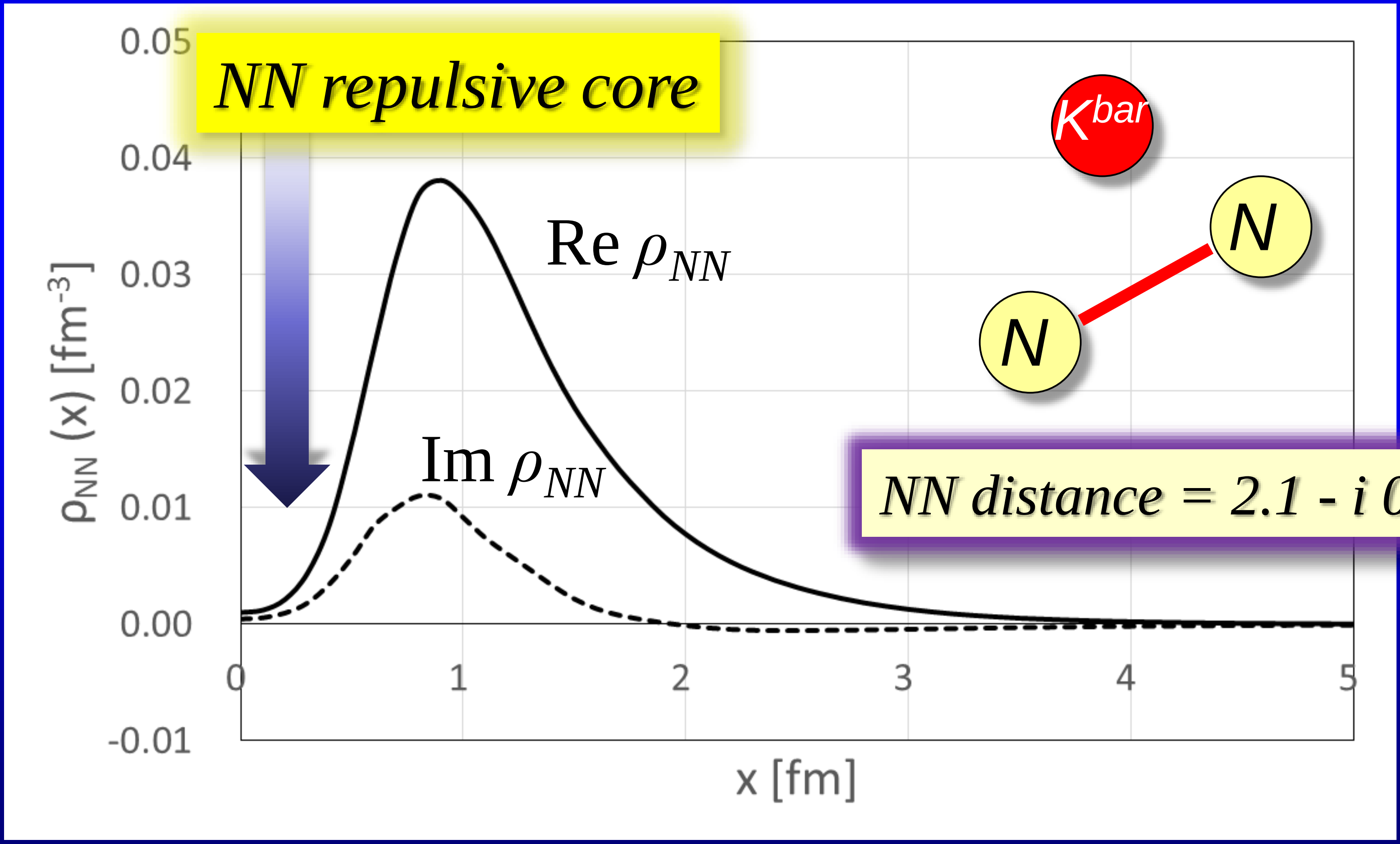
NN pot. : Av18 (Central)
K^{bar}N pot. : NRv2c potential
f_{π}=110, Particle pict.

Correlation density in Complex Scaling Method

$$\hat{\rho}_{NN,\theta}(\mathbf{x}) = \delta^3\left(\hat{\mathbf{r}}_{NN,\theta} - \mathbf{x}\right)$$

$$\hat{\mathbf{r}}_{XN,\theta} = \hat{\mathbf{r}}_{XN}\, e^{i\theta}$$

$$\rho_{NN}(\mathbf{x}) \equiv \left\langle \tilde{\Phi}_\theta \middle| \hat{\rho}_{XN,\theta}(\mathbf{x}) \middle| \Phi_\theta \right\rangle = e^{-3i\theta} \int d^3\mathbf{R}\, \Phi_\theta^2\left(\mathbf{x}e^{-i\theta}, \mathbf{R}\right)$$



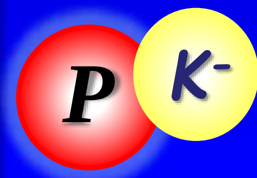
Dense matter or not?

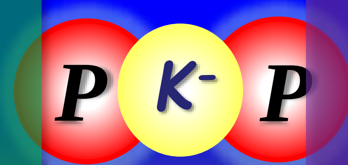
Chiral SU(3) potential (E-dep.)

B. E. (Λ^*) ~ 15 MeV
⇒ $\Lambda^* = \Lambda(1420)$

B. E. ("K^-pp") ~ 20 MeV
NN distance ~ 2.2 fm

⇒ ~ ρ_0 (=0.17 fm^{-3})





Pheno. potential (E-indep.)

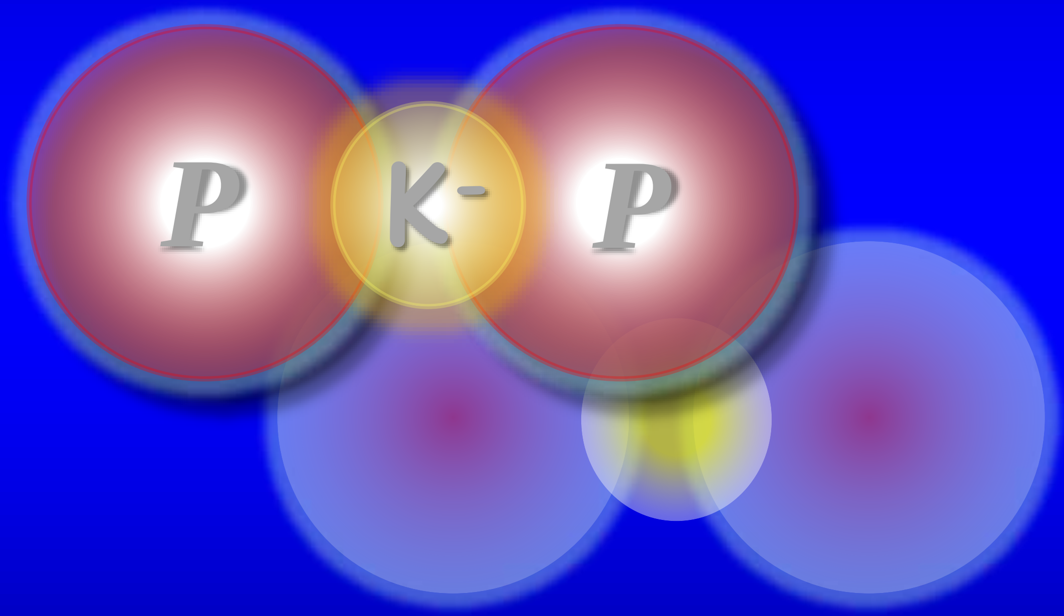
Y. Akaishi and T. Yamazaki, PRC 65, 044005 (2002)

B. E. (Λ^*) ~ 28 MeV
⇒ $\Lambda^* = \Lambda(1405)$

B. E. ("K^-pp") ~ 45 MeV
NN distance ~ 1.9 fm

⇒ ~ 1.6 ρ_0

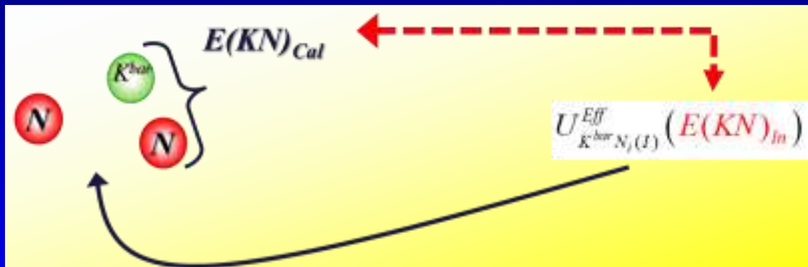
3. Discussion on “K^-pp”



Double pole of “K^-pp”?

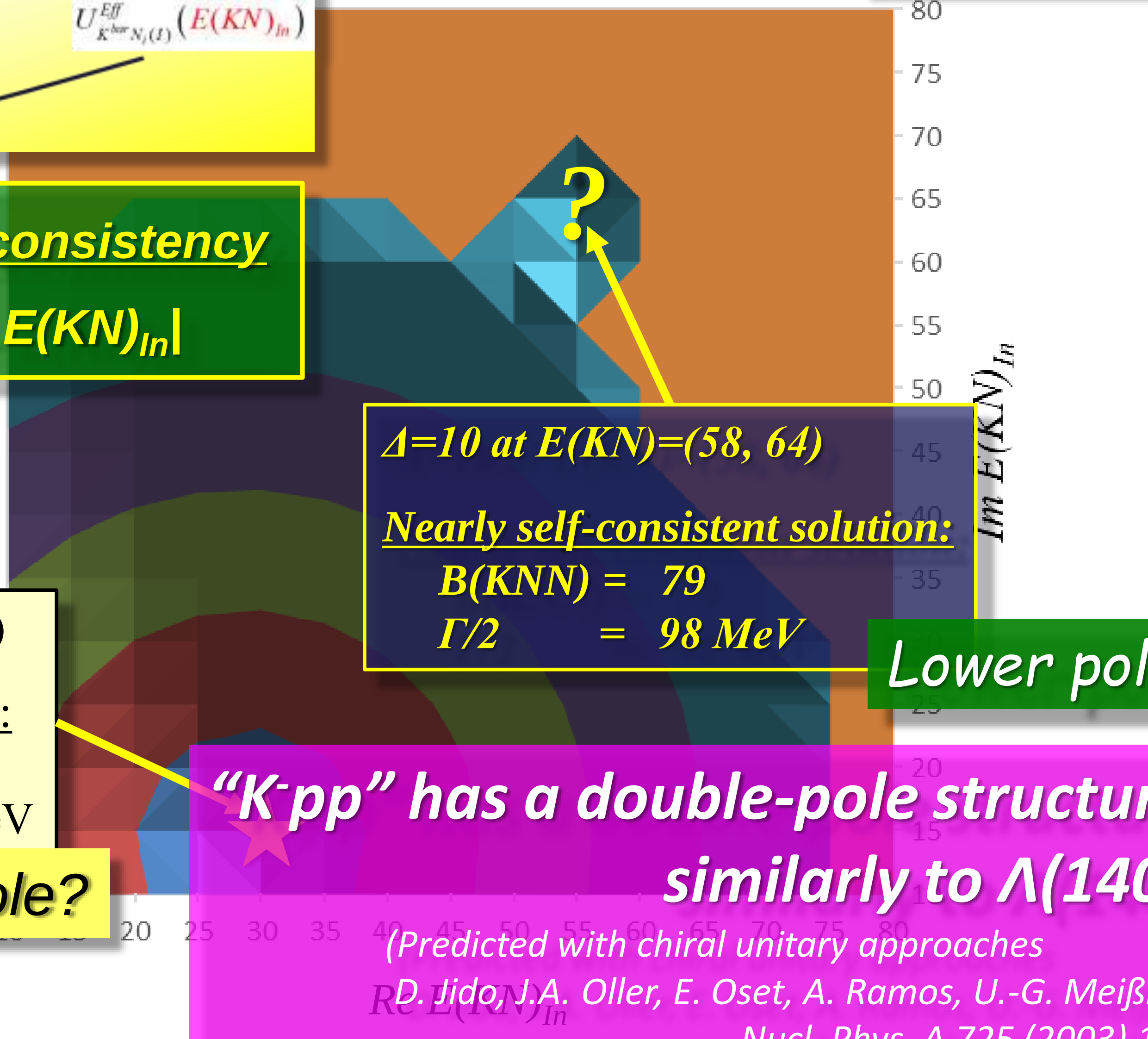
Double pole of “K⁻pp”?

Chiral pot.
(f_π=110 MeV, Martin)
Particle picture



Indicator of self-consistency

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



Δ=10 at E(KN)=(58, 64)

Nearly self-consistent solution:

B(KNN) = 79
Γ/2 = 98 MeV

Lower pole??

Δ=0 at E(KN)=(29, 14)

Self-consistent solution:

B(KNN) = 27.3
Γ/2 = 18.9 MeV

Higher pole?

“K⁻pp” has a double-pole structure similarly to Λ(1405) ?

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

K^-pp search at J-PARC

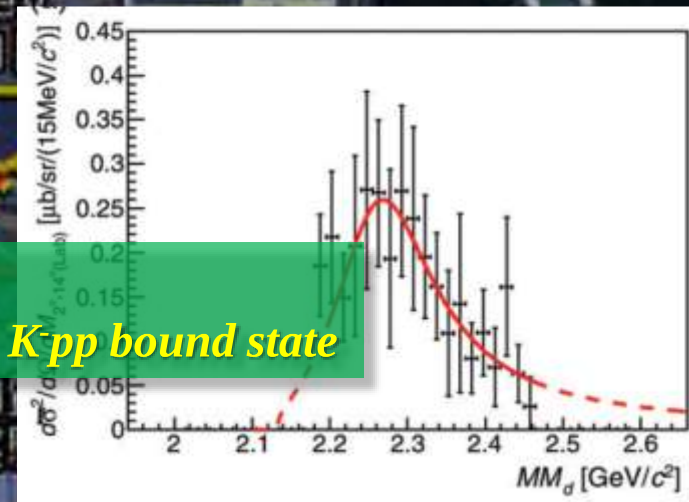
- *J-PARC E27*

d(π^+, K^+) P_π=1.7GeV/c

$$Mass = 2275^{+17+21}_{-18-30}\ MeV$$

$$\Gamma = 162^{+87+66}_{-45-78}\ MeV$$

Y. Ichkawa et al. PTEP 2015, 021D01



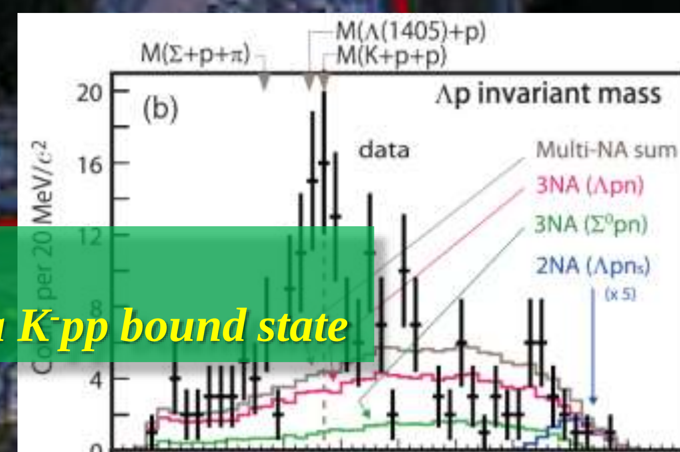
B_{Kpp} ~ 95 MeV
if the signal is a K^-pp bound state

- *J-PARC E15 (1^{st} run)*

^{3}He(inflight K^-, Λp)$n_{missing}$ P_K=1.0GeV/c

$$Mass = 2355^{+6}_{-8} \pm 12\ MeV$$

$$\Gamma = 110^{+19}_{-17} \pm 27\ MeV$$



B_{Kpp} ~ 15 MeV
if the signal is a K^-pp bound state

Y. Sada et al. PTEP 2016, 051D01

Comparison of Theor. and Exp.

DISTO

B = 103 ±3 ±5 MeV
Γ = 118 ±8 ±10 MeV

J-PARC E27

B ~ 95 MeV
Γ ~ 162 MeV

J-PARC E15

B ~ 16 MeV
Γ ~ 110 MeV
(Preliminary?)

-103
πΣN thr.

0 [MeV]
K^{bar}NN thr.

Double pole with a chiral potential (E-dep.)

B = 15~22
Γ = 20~50
SIDDHARTA

ccCSM+Feshbach

B = 60~80
Γ = 150~210

B = 21~32
Γ = 18~64
Martin

Faddeev-AGS
Y. Ikeda, H. Kamano, T. Sato,
PTP 124, 533 (2010)

B = 67~89
Γ = 244~320

B = 9~16
Γ = 34~66

Enhancement of K^{bar}N interaction (E-indep.)

Partial restoration of chiral symmetry?

B = 102

$V_{KN} \times 1.17$

B = 52

L=1 excited state

S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad., Ser. B 89, 418 (2013)

pion-assisted dibaryon

$B_{\pi\Sigma N}$ = 12~20
Γ = 5~8

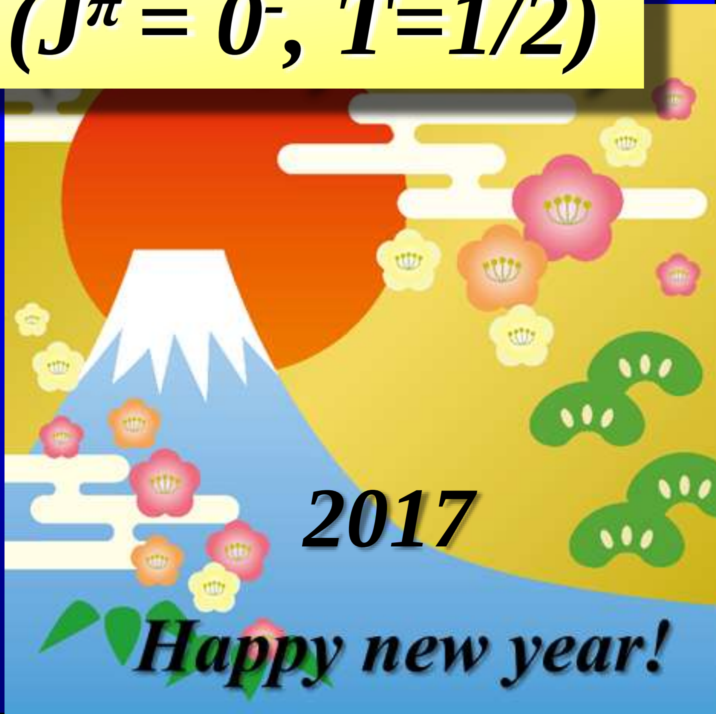
“ πΛN–πΣN system ($J^\pi = 2^+$, $T = 3/2$) ”

H. Garcilazo, A. Gal, NPA 897, 167 (2013)

4. Fully coupled-channel CSM study *(on-going)*

"K^-pp" =

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



Just diagonalize the Hamiltonian matrix!

$$H^{\theta}_{ij}$$

$K^{bar}NN$ - $K^{bar}NN$	$K^{bar}NN$ - $\pi\Sigma N$	$K^{bar}NN$ - $\pi\Lambda N$
*	$\pi\Sigma N$ - $\pi\Sigma N$	$\pi\Sigma N$ - $\pi\Lambda N$
*	*	$\pi\Lambda N$ - $\pi\Lambda N$

No channel elimination!!

- ***Hamiltonian***

$$H = T + V_{NN} + \sum_{\alpha,\beta = \bar{K}N, \pi\Sigma, \pi\Lambda} V_{(MB)\alpha-(MB)\beta}$$

- ***Wave function***

$$
\begin{aligned}
\left|"K^- pp"\right\rangle = & \sum_a C_a^{(K\{NN\}+)} G_a^{(K\{NN\}+)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{NN}=0\right\rangle \left|\left[K[NN]_1\right]_{T=1/2,\,Tz=1/2}\right\rangle \\
& + \sum_a C_a^{(K\{NN\}-)} G_a^{(K\{NN\}-)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{NN}=0\right\rangle \left|\left[K[NN]_0\right]_{T=1/2,\,Tz=1/2}\right\rangle \\
& + \sum_a C_a^{(\pi\{\Sigma N\}+)} G_a^{(\pi\{\Sigma N\}+)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{\Sigma N}=0\right\rangle \left|\left[[\pi\Sigma]_0 N\right]_{T=1/2,\,Tz=1/2}, \{\Sigma N\}_S\right\rangle \\
& + \sum_a C_a^{(\pi\{\Sigma N\}-)} G_a^{(\pi\{\Sigma N\}-)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{\Sigma N}=0\right\rangle \left|\left[[\pi\Sigma]_0 N\right]_{T=1/2,\,Tz=1/2}, \{\Sigma N\}_A\right\rangle \\
& + \sum_a C_a^{(\pi\{\Sigma N\}+)} G_a^{(\pi\{\Sigma N\}+)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{\Sigma N}=0\right\rangle \left|\left[[\pi\Sigma]_1 N\right]_{T=1/2,\,Tz=1/2}, \{\Sigma N\}_S\right\rangle \\
& + \sum_a C_a^{(\pi\{\Sigma N\}-)} G_a^{(\pi\{\Sigma N\}-)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{\Sigma N}=0\right\rangle \left|\left[[\pi\Sigma]_1 N\right]_{T=1/2,\,Tz=1/2}, \{\Sigma N\}_A\right\rangle \\
& + \sum_a C_a^{(\pi\{\Lambda N\}+)} G_a^{(\pi\{\Lambda N\}+)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{\Lambda N}=0\right\rangle \left|\left[[\pi\Lambda]_1 N\right]_{T=1/2,\,Tz=1/2}, \{\Lambda N\}_S\right\rangle \\
& + \sum_a C_a^{(\pi\{\Lambda N\}-)} G_a^{(\pi\{\Lambda N\}-)}\left(\mathbf{x}_1^{(3)}, \mathbf{x}_2^{(3)}\right) \left|S_{\Lambda N}=0\right\rangle \left|\left[[\pi\Lambda]_1 N\right]_{T=1/2,\,Tz=1/2}, \{\Lambda N\}_A\right\rangle
\end{aligned}
$$

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

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

Ch. 3: $\pi\Sigma N$, $[\pi\Sigma]_{I=0}$, $\{\Sigma N\}_{Sym.}$

Ch. 4: $\pi\Sigma N$, $[\pi\Sigma]_{I=0}$, $\{\Sigma N\}_{Asym.}$

Ch. 5: $\pi\Sigma N$, $[\pi\Sigma]_{I=1}$, $\{\Sigma N\}_{Sym.}$

Ch. 6: $\pi\Sigma N$, $[\pi\Sigma]_{I=1}$, $\{\Sigma N\}_{Asym.}$

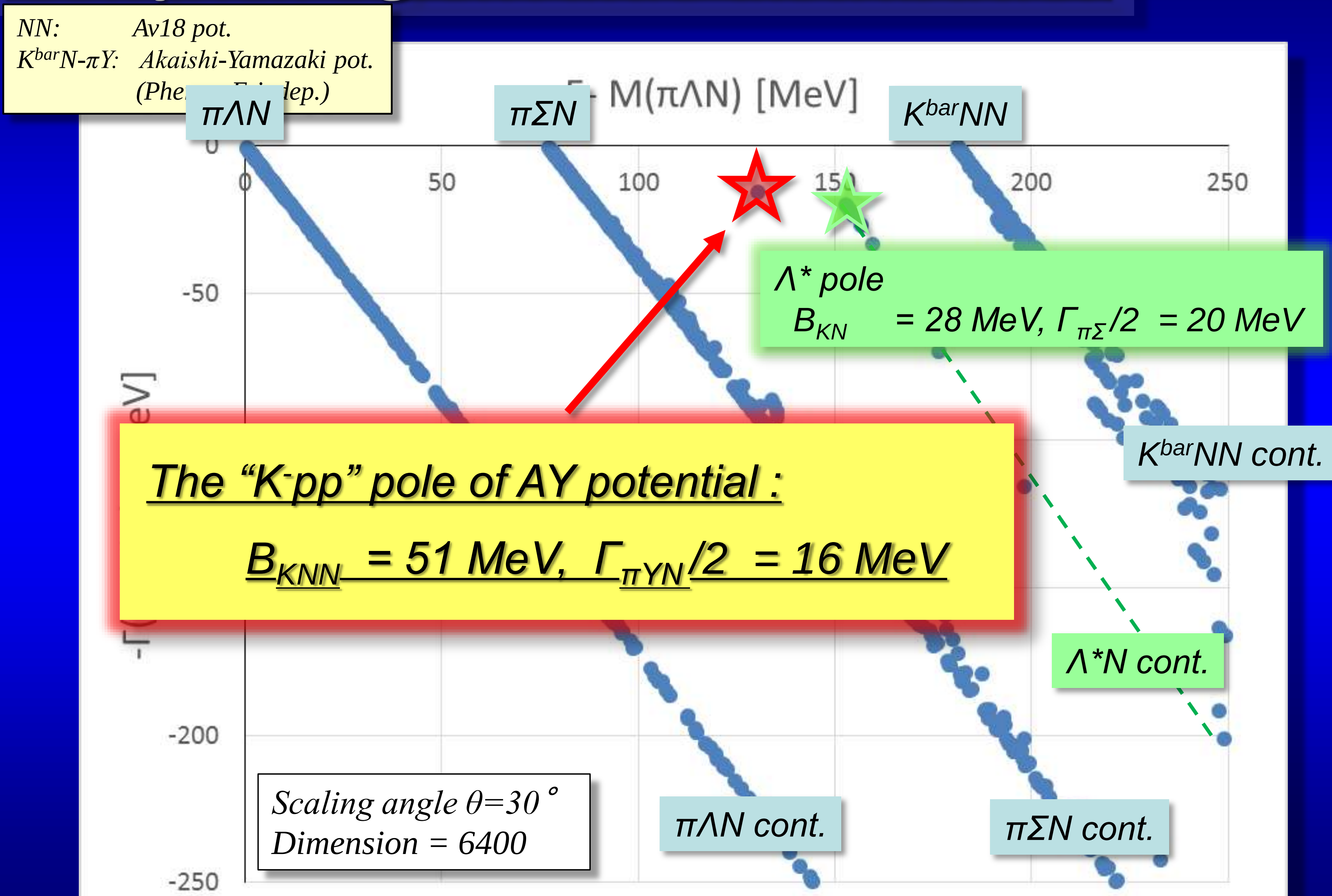
Ch. 7: $\pi\Lambda N$, $[\pi\Lambda]_{I=1}$, $\{\Lambda N\}_{Sym.}$

Ch. 8: $\pi\Lambda N$, $[\pi\Lambda]_{I=1}$, $\{\Lambda N\}_{Asym.}$

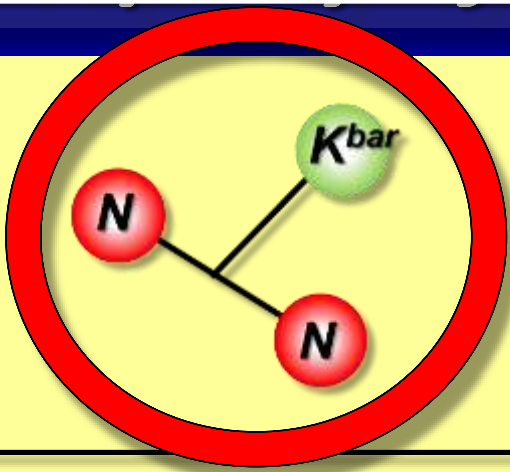
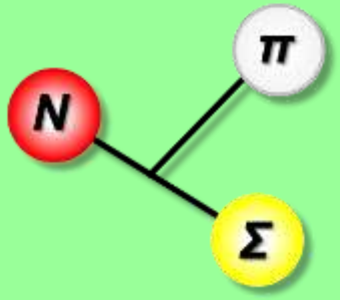
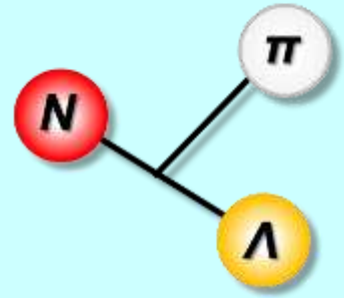
Spatial part: Correlated Gaussian projected onto a parity eigenstate of B_1B_2, including 3 types of Jacobi coordinates

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

Complex eigenvalue distribution



Property of the “K⁻pp” pole

		
Norm 1.004 - i 0.286	-0.002 + i 0.276	-0.002 + i 0.010
$K^{bar}N$	πΣ	πΛ
(I=0) 0.726 - i 0.213	(I=0) -0.009 + i 0.261	(I=0) ---
(I=1) 0.278 - i 0.073	(I=1) 0.007 + i 0.015	(I=1) -0.002 + i 0.010
BB distance [fm]		
1.86 + i 0.14	1.50 + i 0.48	1.10 + i 0.23
MB distance [fm]		
(I=0) 1.40 - i 0.01	(I=0) 0.52 + i 1.31	(I=0) ---
(I=1) 1.95 + i 0.14	(I=1) 0.80 + i 1.22	(I=1) 0.74 + i 0.74

5. Summary, future plans and remarks

5. Summary

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

"$K^{-}pp$" is theoretically investigated in various ways:

Chiral SU(3)-based potential (E-dep.) → Shallow binding … $B(K^{-}pp)$ = 10~25 MeV
Phenomenological potential (E-indep.) → Deep binding … $B(K^{-}pp)$ = 50~90 MeV

All theoretical studies predict $B(K^{-}pp) < 100$ MeV.

$K^{-}pp$ studied with "coupled-channel Complex Scaling Method + Feshbach projection"

- *A chiral SU(3)-based $K^{bar}N$ potential constrained with the latest $K^{bar}N$ scattering length data*

  $K^{-}pp$ ($J^{\pi}=0^{-}$, T=1/2) … (B, Γ/2) = (15~22, 10~25) MeV *(SIDDHARTA constraint)*

- *A candidate of self-consistent solution is found. … Deeper binding and larger decay width*

  $K^{-}pp$ ($J^{\pi}=0^{-}$, T=1/2) …. (B, Γ/2) = (60~80, 75~105) MeV *(Martin constraint, Particle pict.)*

  "$K^{-}pp$" has a double-pole structure similarly to Λ(1405)?

- *The signal observed in J-PARC E27 corresponds to the lower pole of "$K^{-}pp$"??*
  J-PARC E15 may pick up the higher pole of "$K^{-}pp$"???

- *NN mean distance of "$K^{-}pp$" system = 2.1 fm (Chiral pot.), 1.9 fm (AY pot.)*
  → *If $K^{bar}N$ potential is so attractive as AY potential,*
  kaonic nuclei could be a gateway to dense matter.

5. Future plans and remarks

Future plans:

- Fully coupled-channel calculation of K^-pp (on-going)
  … E-dep. Chiral SU(3) pot. case, Detail study for the double pole structure, etc
- Application to resonances of other hadronic systems

Remaining issues:

1. **Spectrum calculations with reaction mechanism, for the comparison with experimental result**

   Earlier works on ^{3}He(in-flight K^-, n) reaction: -->> *T. Sekihara, E. Oset and A. Ramos, arXiv: 1607.02058 (PTEP in press)*
   T. Koike and T. Harada, PRC80, 055208 (2009)
   J. Yamagata-Sekihara, D. Jido, H. Nagahiro and S. Hirenzaki, Phys. Rev. C 80, 045204 (2009)

   Poles obtained in theoretical study = **on the complex energy plane**
   Observables measured in experiments = **on the real energy axis**

2. **Non-mesic decay of "K^-pp" (two nucleon absorption, "K^-pp" --> YN)?**

   Most of theoretical calculations of the "K^-pp" pole position consider only mesic-decay mode, not non-mesic decay mode. Need to be careful when comparing with experimental results.

3. **Nature of Λ(1405) and $K^{bar}N$ interaction**
   How strongly attractive is the $K^{bar}N$ interaction? "Λ(1405) vs Λ(1420)"

Thank you for your attention!

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3. A. D., T. Inoue, T. Myo,
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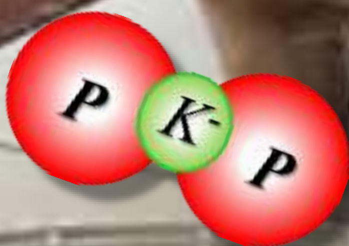
   JPS Conf. Proc. (Proc. of HYP2015)
   (to be published)



Cats in KEK