Theoretical study of "K^-pp"

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   - SIDDHARTA constraint for K^-p scattering length
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   - Double pole of "K^-pp"?
5. Summary and future plan

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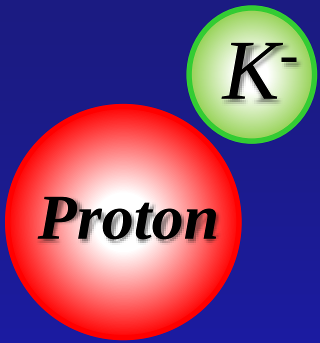
The 31st Reimei Workshop on Hadron Physics in Extreme Conditions at J-PARC
18. Jan. '16 @ Advanced Science Research Center (ASRC), JAEA Tokai Campus

1. Introduction



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

Low energy scattering data, 1s level shift of kaonic hydrogen atom

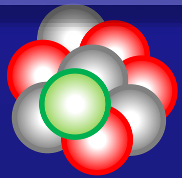
*"Excited hyperon **Λ(1405)** = K^- proton quasi-bound state"*

Strongly attractive $K^{bar}N$ potential

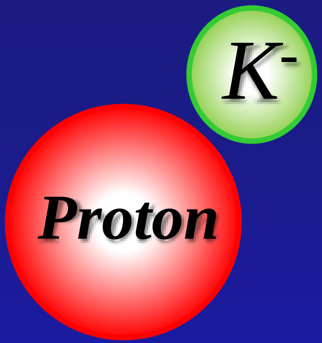
- *Doorway to **dense matter**†*
  → Chiral symmetry restoration in dense matter
- *Interesting structure†*
- *Neutron star*

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

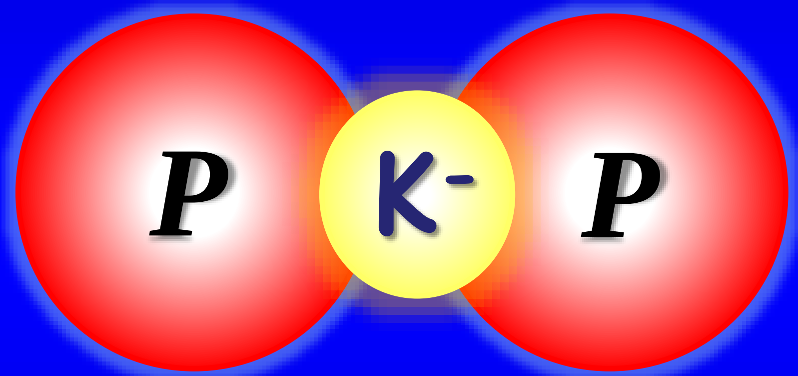
Kaonic nuclei



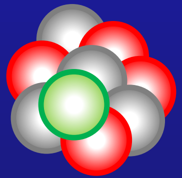
$^3HeK^-$, $pppK^-$,
$^4HeK^-$, $pppnK^-$,
…, $^8BeK^-$, …



$K^{bar}N$ two-body system = $\Lambda(1405)$



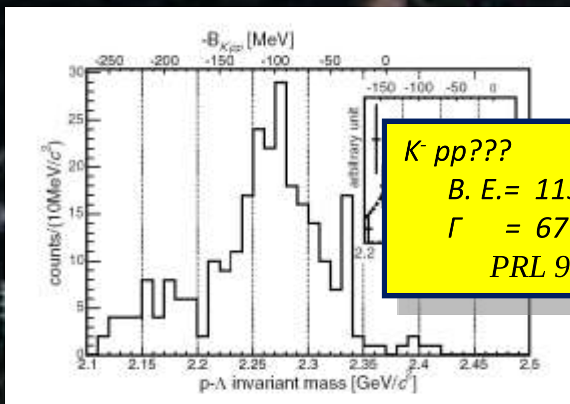
Prototype system = K^- pp



Kaonic nuclei
= Nuclear many-body system with antikaons

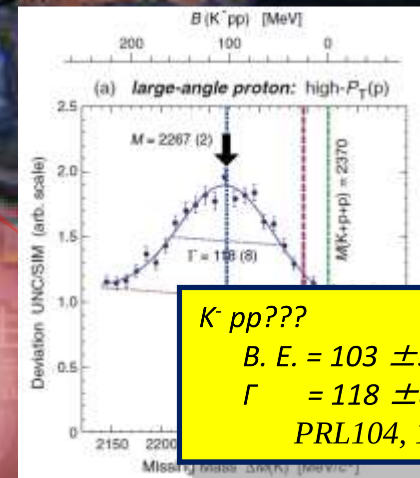
Experiments of K⁻pp search

FINUDA



K⁻ pp???
B. E.= 115 MeV
Γ = 67 MeV
PRL 94, 212303 (2005)

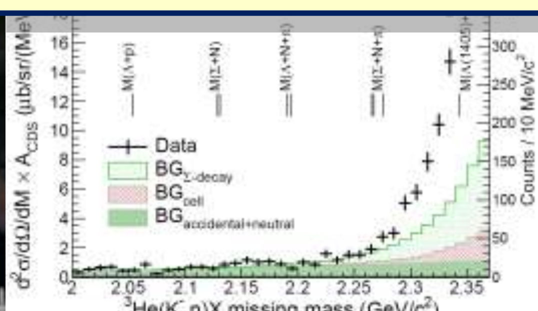
DISTO



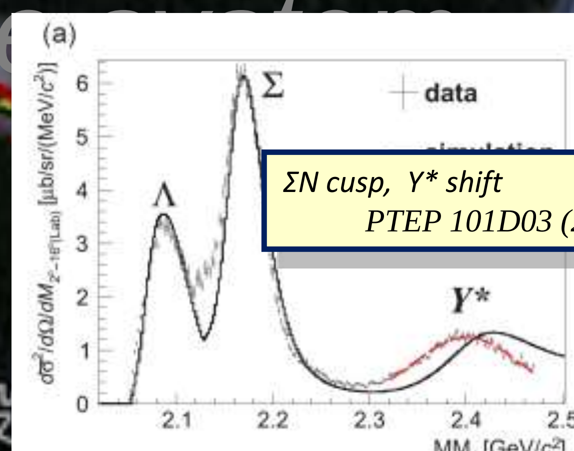
K⁻ pp???
B. E. = 103 ±3 ±5 MeV
Γ = 118 ±8 ±10 MeV
PRL104, 132502 (2010)

J-PARC E15

Attraction in K⁻pp subthreshold region
arXiv:1408.5637 [nucl-ex]

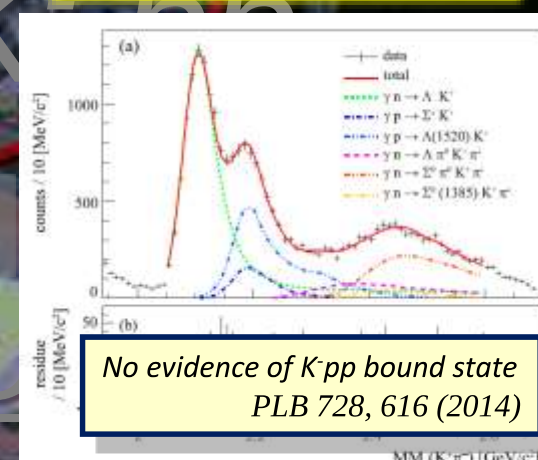


J-PARC E27



ΣN cusp, Y shift*
PTEP 101D03 (2014)

SPring8/LEPS



No evidence of K⁻pp bound state
PLB 728, 616 (2014)

$K^{-}pp$ at J-PARC

- J-PARC E27

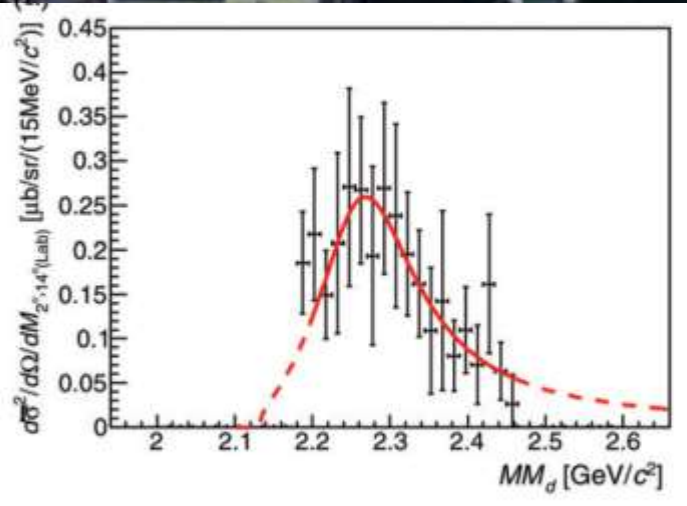
  $d(\pi^{+}, K^{+})$ P_{π}=1.7GeV/c

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

  (B_{Kpp} ~ 95 MeV)

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

  Y. Ichkawa et al. PTEP 2015, 021D01

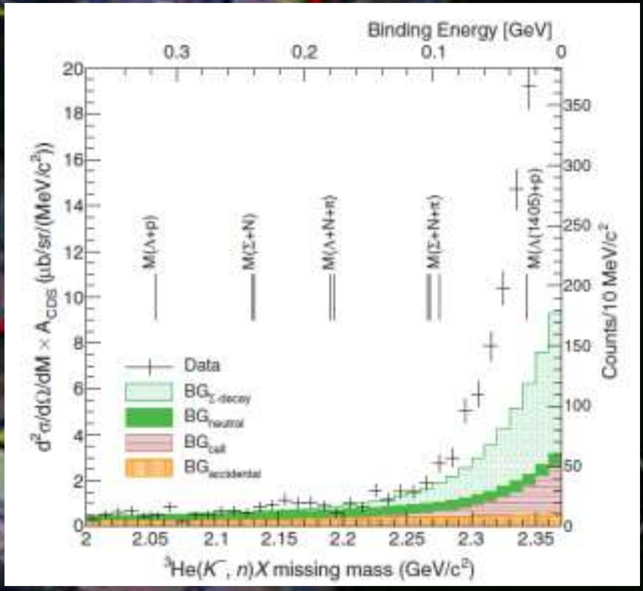


- J-PARC E15 (1st run)

  ^{3}He(inflight K^{-}, n)X P_{K}=1.0GeV/c

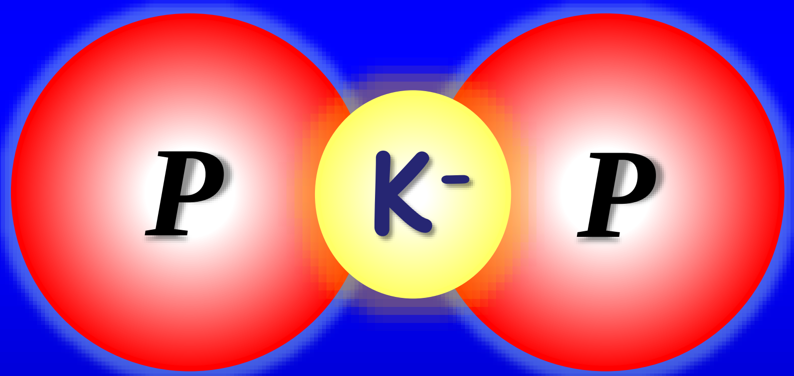
  $X \rightarrow \Lambda + p$

  Attraction in $K^{-}pp$ subthreshold region



T. Hashimoto et al. PTEP 2015, 061D01

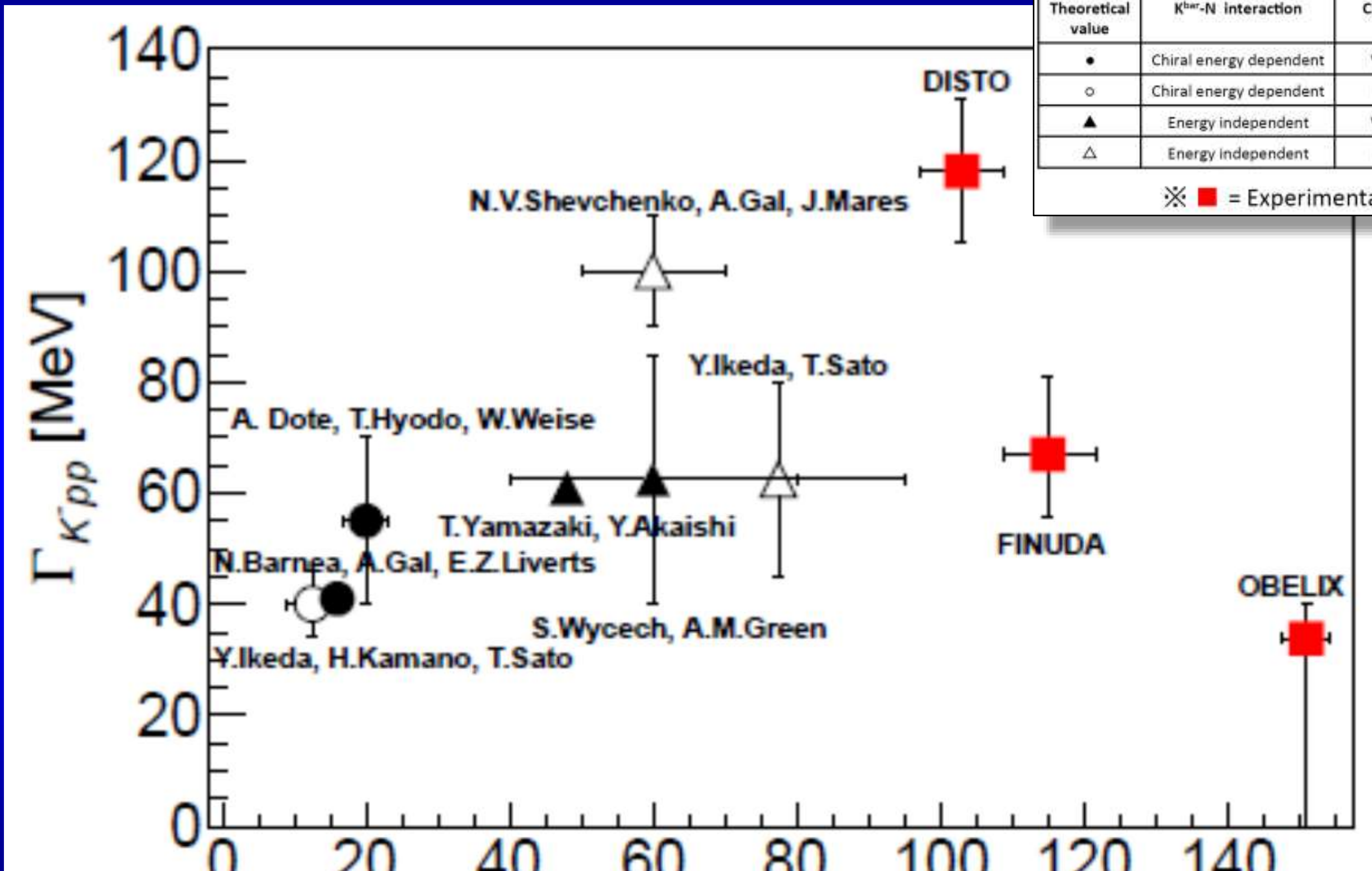
2. Situation of theoretical studies



"K⁻pp" $=$

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

Theoretical studies of "K⁻pp"



Theoretical value	K^{bar}-N interaction	Calculation method
●	Chiral energy dependent	Variation
○	Chiral energy dependent	Faddeev
▲	Energy independent	Variation
△	Energy independent	Faddeev

※ ■ = Experimental value.

Y. Ichikawa
J-PARC hadron salon (May 18, 2015)

Theoretical studies of "K^-pp"

	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.*

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

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

K^-pp should be a resonance between $K^{bar}NN$ and πΣN thresholds.

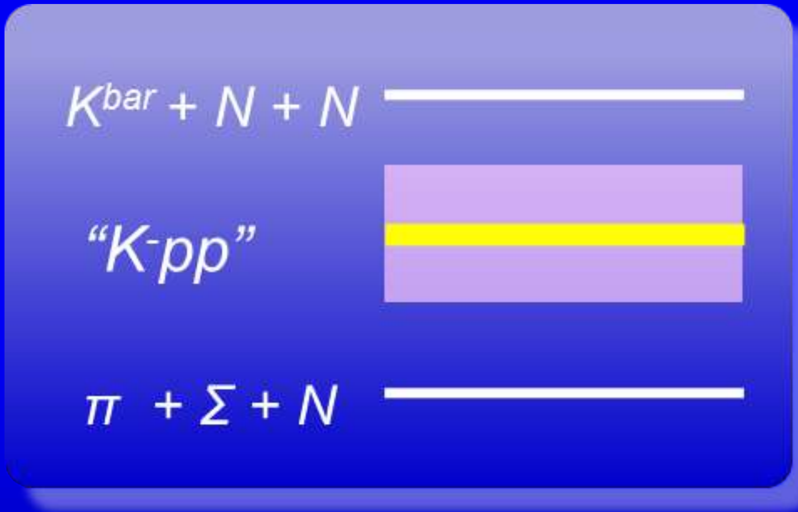
3. "K^-pp" investigated with ccCSM+Feshbach method

- ***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"

Complex Scaling Method

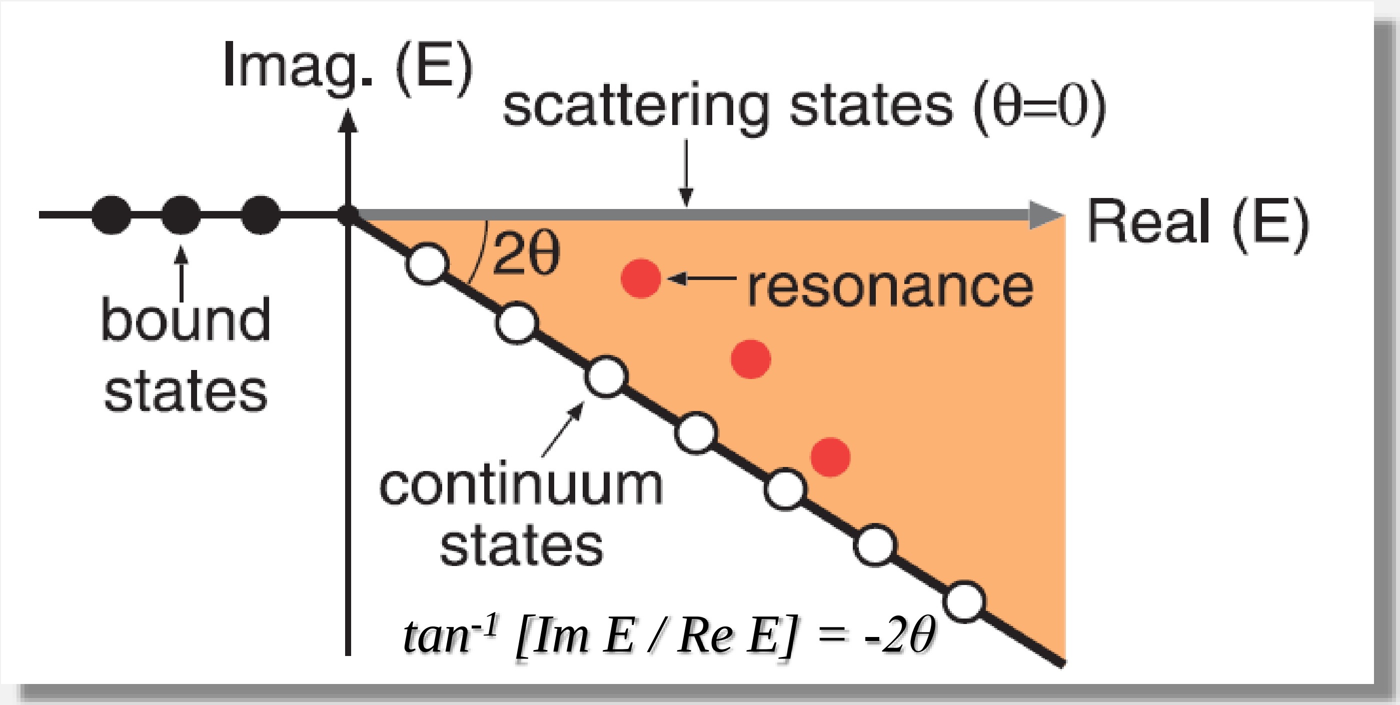
S. Aoyama, T. Myo, K. Kato, K. Ikeda, PTP116, 1 (2006)
T. Myo, Y. Kikuchi, H. Masui, K. Kato, PPNP79, 1 (2014)

… 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)

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

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

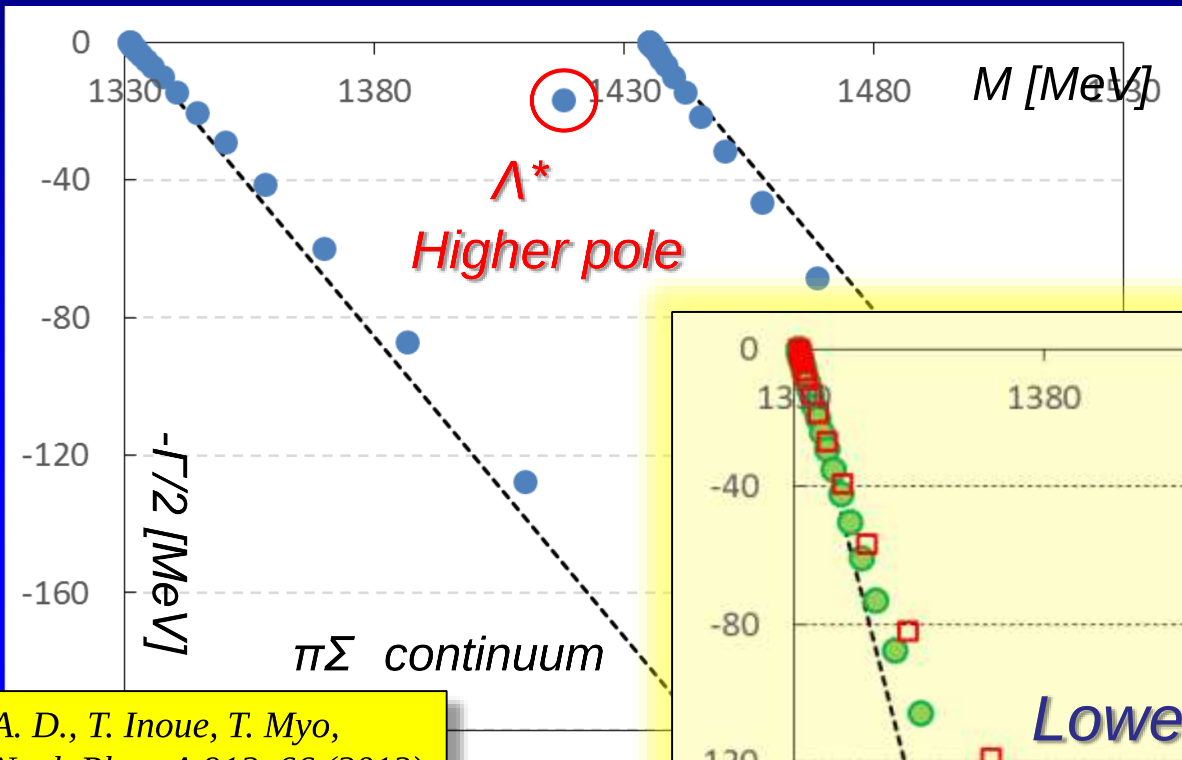
ω_i: meson energy

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

$a_{KN(I=0)}$ = -1.70+i0.67fm, $a_{KN(I=1)}$ = 0.37+i0.60fm

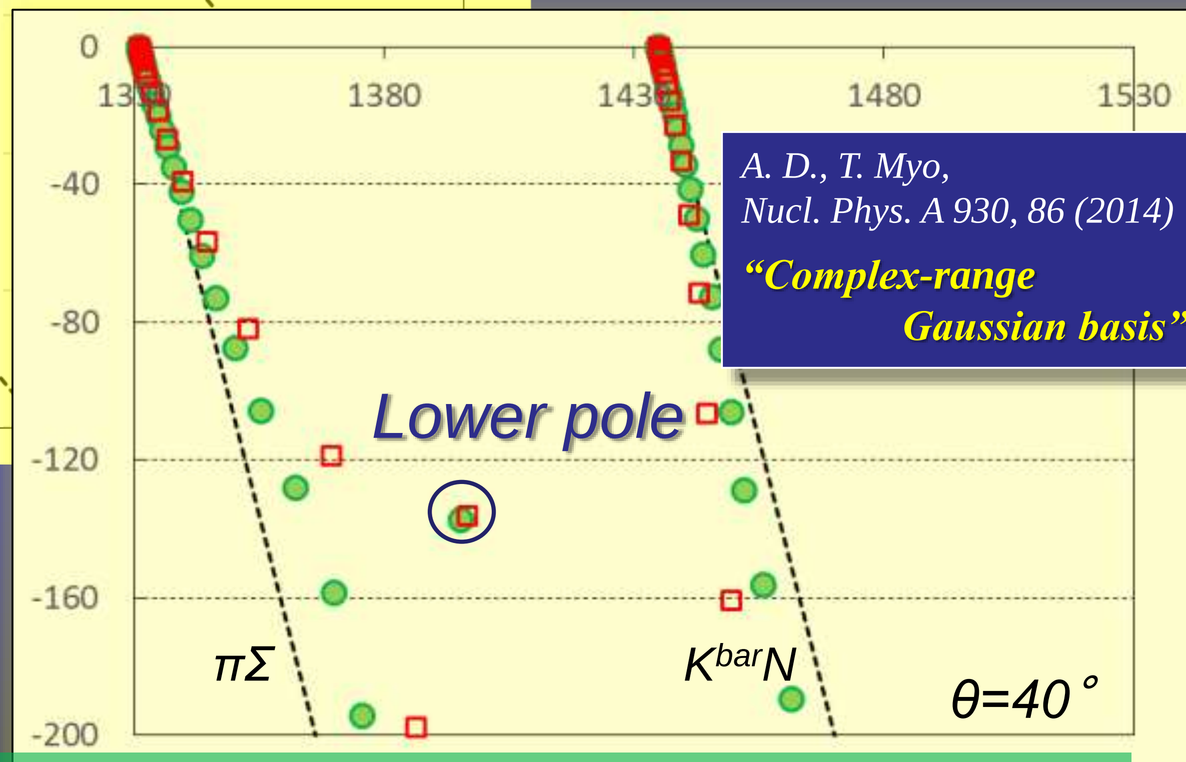
A. D. Martin, NPB179, 33(1979)

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)



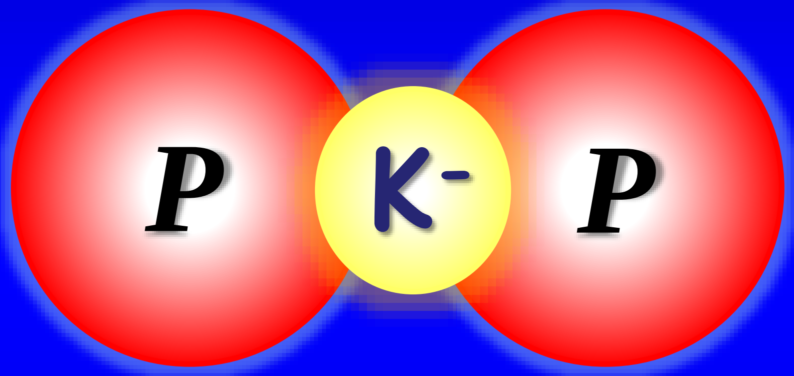
A. D., T. Myo,
Nucl. Phys. A 930, 86 (2014)
"Complex-range Gaussian basis"

Double-pole structure of Λ(1405)

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

“$K^- pp$” =

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



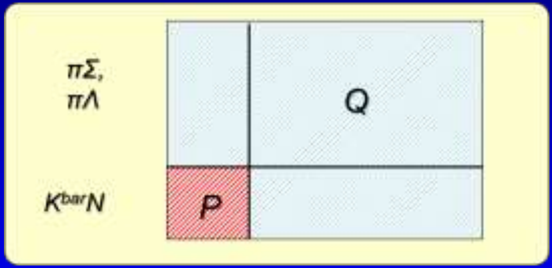
Feshbach projection on coupled-channel Complex Scaling Method

“ccCSM+Feshbach method”

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

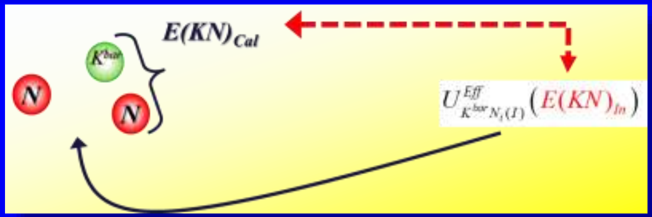
Remarks on "K⁻pp" calculation

1. For economical treatment of a three-body system of "K⁻pp", an effective $K^{bar}N$ single-channel potential is derived by means of Feshbach projection on CSM.



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

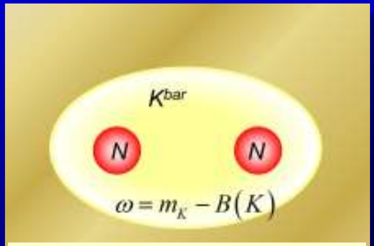
2. Self-consistency for complex $K^{bar}N$ energy is taken into account.



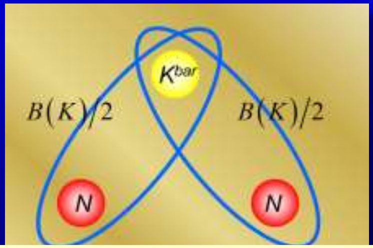
- $E(KN)_{In}$: assumed in the $K^{bar}N$ potential
- $E(KN)_{Cal}$: calculated with the obtained $K^{-}pp$

$$\Rightarrow \quad E(KN)_{In} = E(KN)_{Cal}$$

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



Field picture



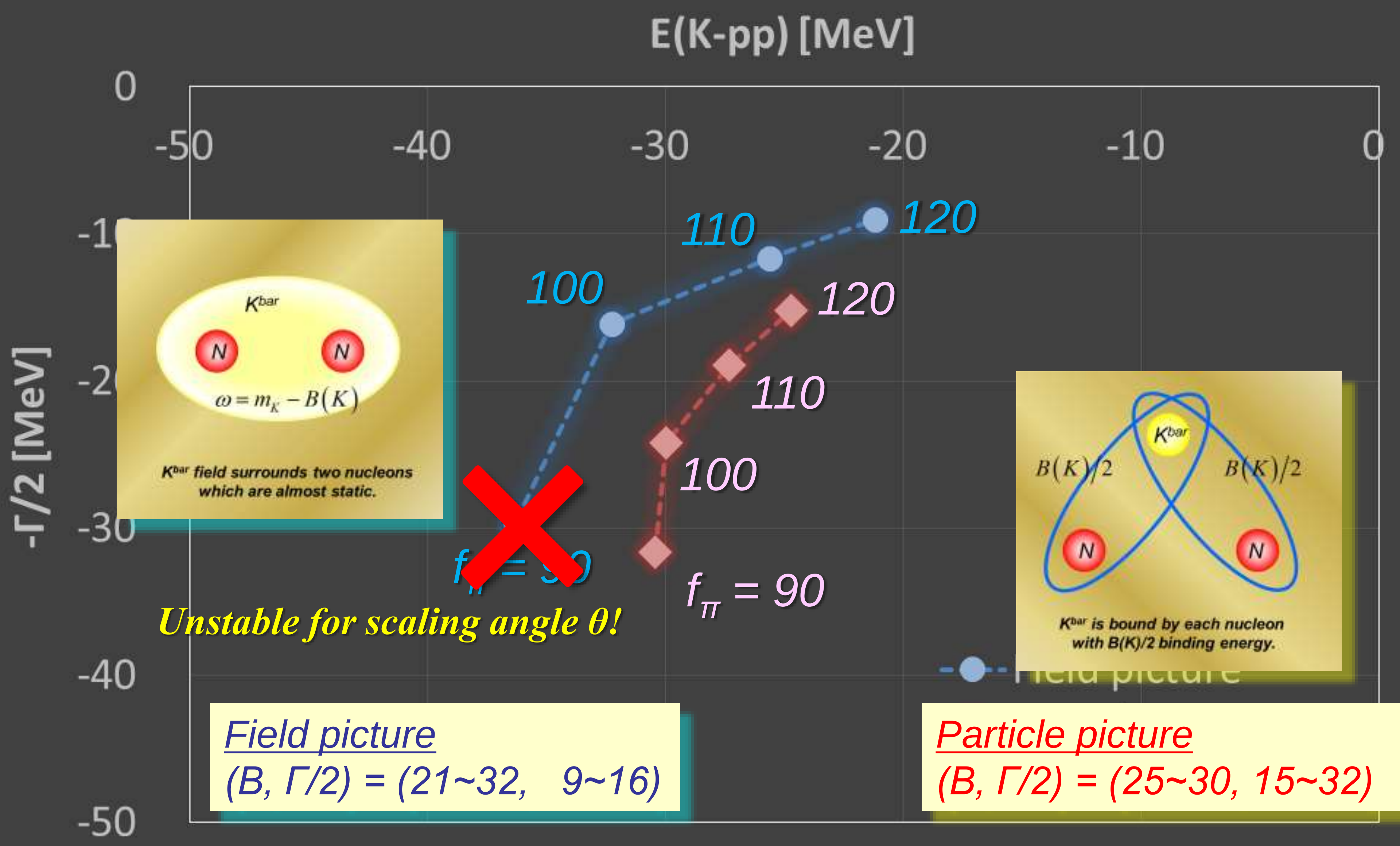
Particle picture

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

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

Self-consistent results
f_π=90~120MeV

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



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

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

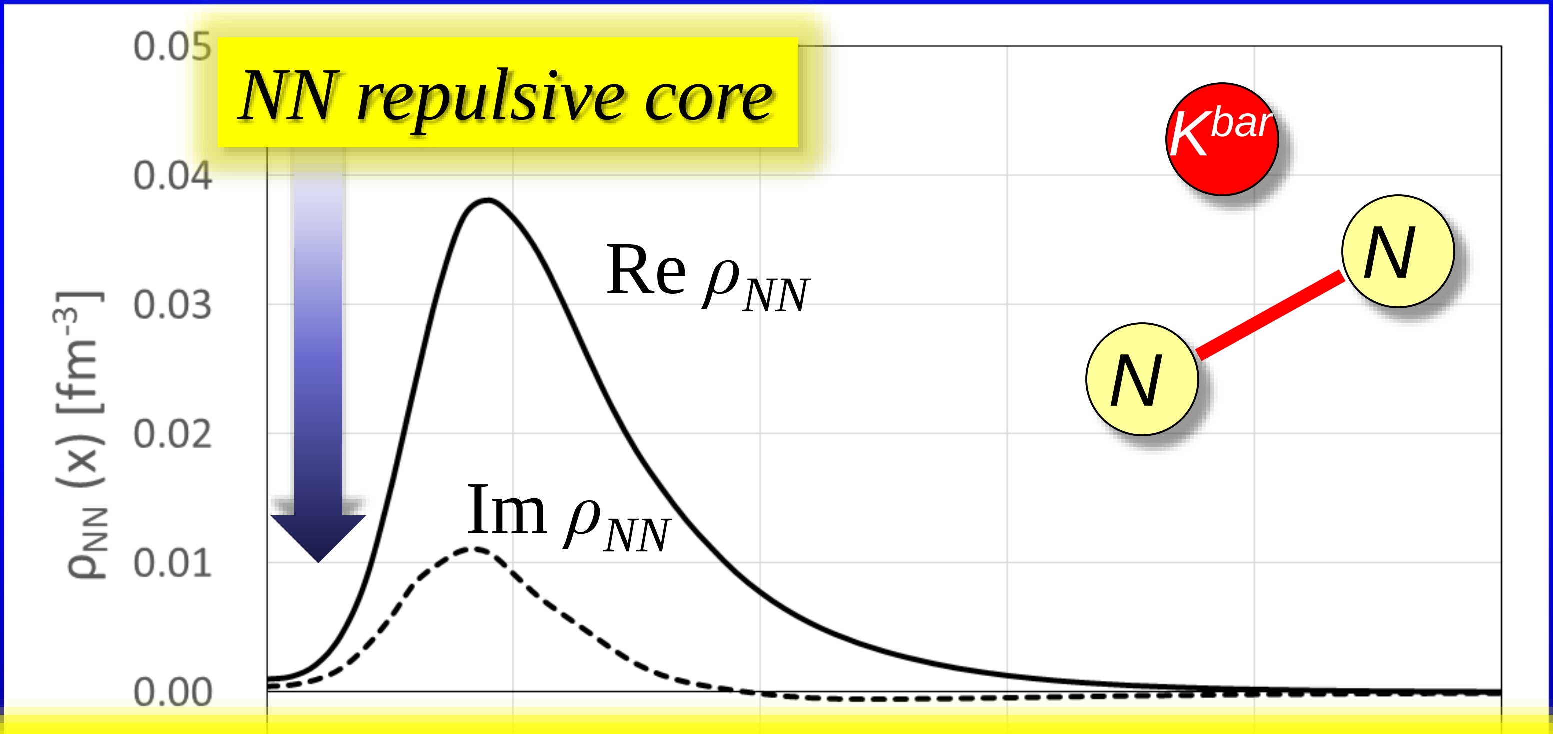
NN correlation density

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

Correlation density in Complex Scaling Method

$$\rho_{NN,\theta}(\mathbf{x}) = \delta^3\left(\hat{\mathbf{r}}_{NN,\theta} - \mathbf{x}\right) \qquad \hat{\mathbf{r}}_{XN,\theta} = \hat{\mathbf{r}}_{XN}\, e^{i\theta}$$

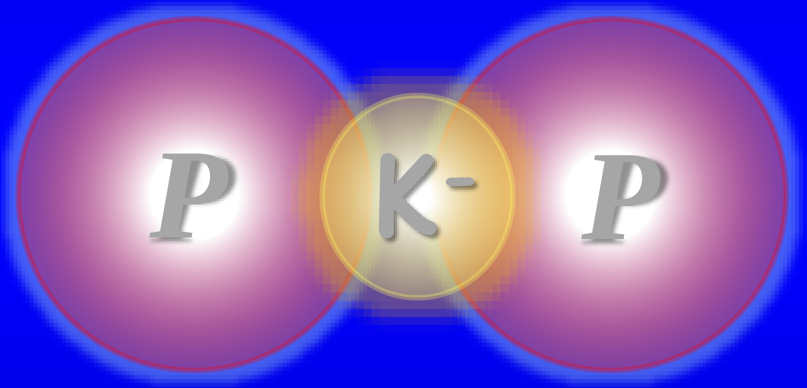
$$\rho_{NN}(\mathbf{x}) \equiv \left\langle \Phi_\theta \middle| \rho_{XN,\theta}(\mathbf{x}) \middle| \Phi_\theta \right\rangle = e^{-3i\theta} \int d^3\mathbf{R}\, \Phi_\theta^2\left(\mathbf{x}e^{-i\theta}, \mathbf{R}\right)$$



NN distance = 2.1 - i 0.3 fm

~ Mean distance of 2N in nuclear matter at normal density!

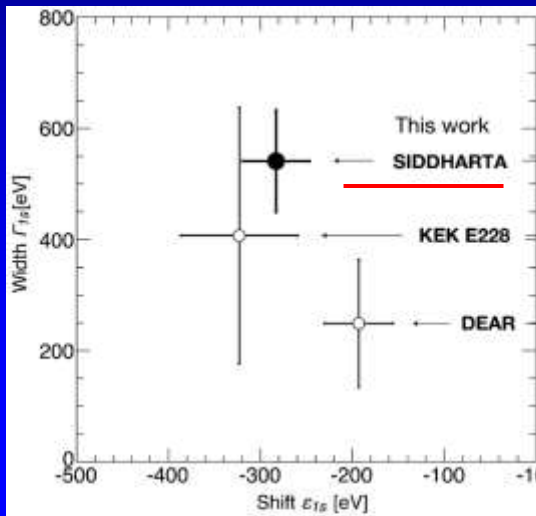
4. Further analysis of "K⁻pp"



- SIDDHARTA constraint for $K^{-}p$ scattering length
- Another way of $K^{bar}N$ energy self-consistency

K^-pp with SIDDHARTA data

Precise measurement of 1s level shift of kaonic hydrogen



Strong constraint for the $K^{bar}N$ interaction!

$$\epsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$
$$\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV},$$

M. Bazzi et al. (SIDDHARTA collaboration), NPA 881, 88 (2012)

- *K^-p scattering length (with improved Deser-Truman formula)*

U. -G. Meissner, U. Raha and A. Rusetsky, Eur. Phys. J. C 35, 349 (2004)

$$\text{Re}\, a(K^- p) = -0.65 \pm 0.10\ \text{fm}, \qquad \text{Im}\, a(K^- p) = 0.81 \pm 0.15\ \text{fm}$$

- *K^-n scattering length (with coupled-channel chiral dynamics)*

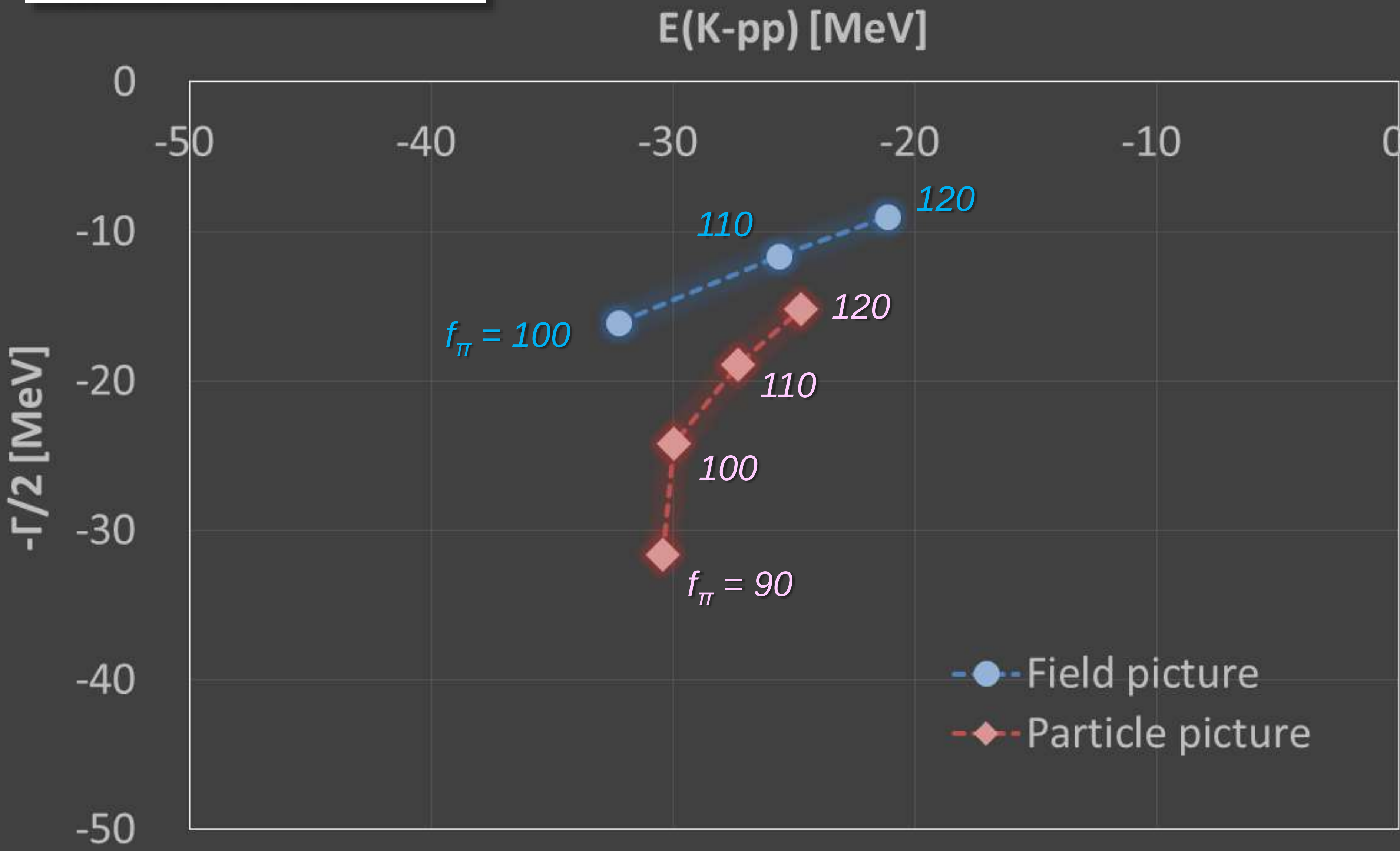
$$a(K^- n) = 0.57^{+0.04}_{-0.21} + i0.72^{+0.26}_{-0.41}\ \text{fm}.$$

Y. Ikeda, T. Hyodo and W. Weise, NPA 881, 98 (2012)

"$K^{-}pp$" with Martine value

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

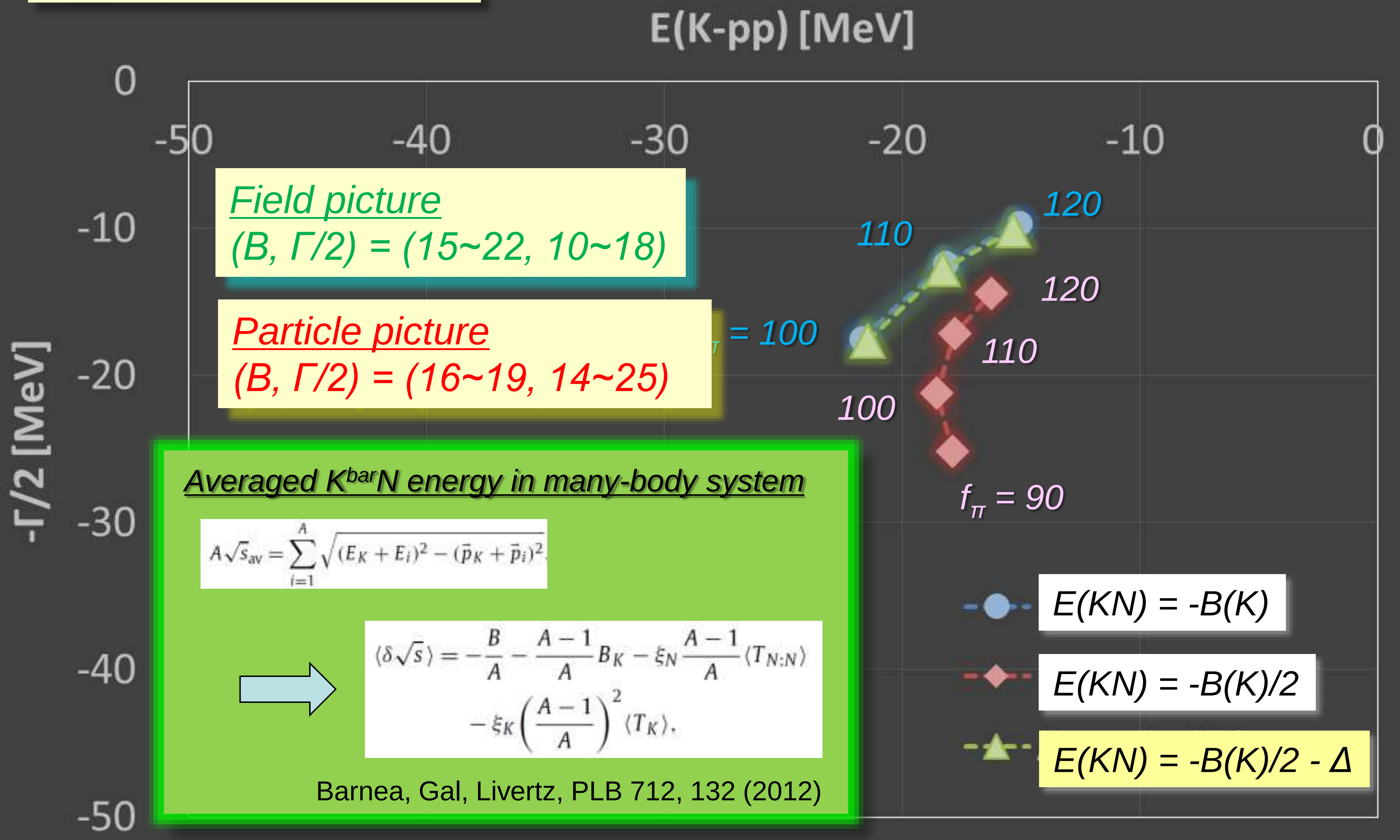
$a_{KN}(I=0) = -1.7 + i0.68$ fm
$a_{KN}(I=1) = (0.37) + i0.60$ fm



"K⁻pp" with SIDDHARTA value

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

$a_{KN}(I=0)$ = -1.97 + i1.05 fm
$a_{KN}(I=1)$ = 0.57 + i0.73 fm



Field picture
(B, Γ/2) = (15~22, 10~18)

Particle picture
(B, Γ/2) = (16~19, 14~25)

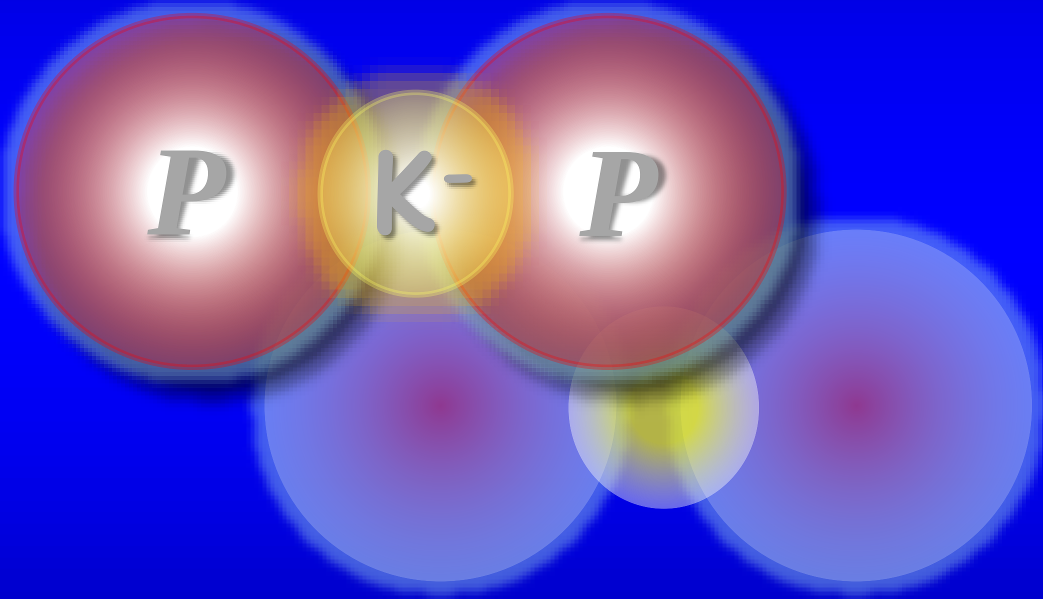
Averaged $K^{bar}N$ energy in many-body system

$$A\sqrt{s}_{av} = \sum_{i=1}^{A} \sqrt{(E_K + E_i)^2 - (\vec{p}_K + \vec{p}_i)^2}$$

$$\Rightarrow \langle \delta\sqrt{s} \rangle = -\frac{B}{A} - \frac{A-1}{A} B_K - \xi_N \frac{A-1}{A} \langle T_{N:N} \rangle - \xi_K \left(\frac{A-1}{A}\right)^2 \langle T_K \rangle,$$

Barnea, Gal, Livertz, PLB 712, 132 (2012)

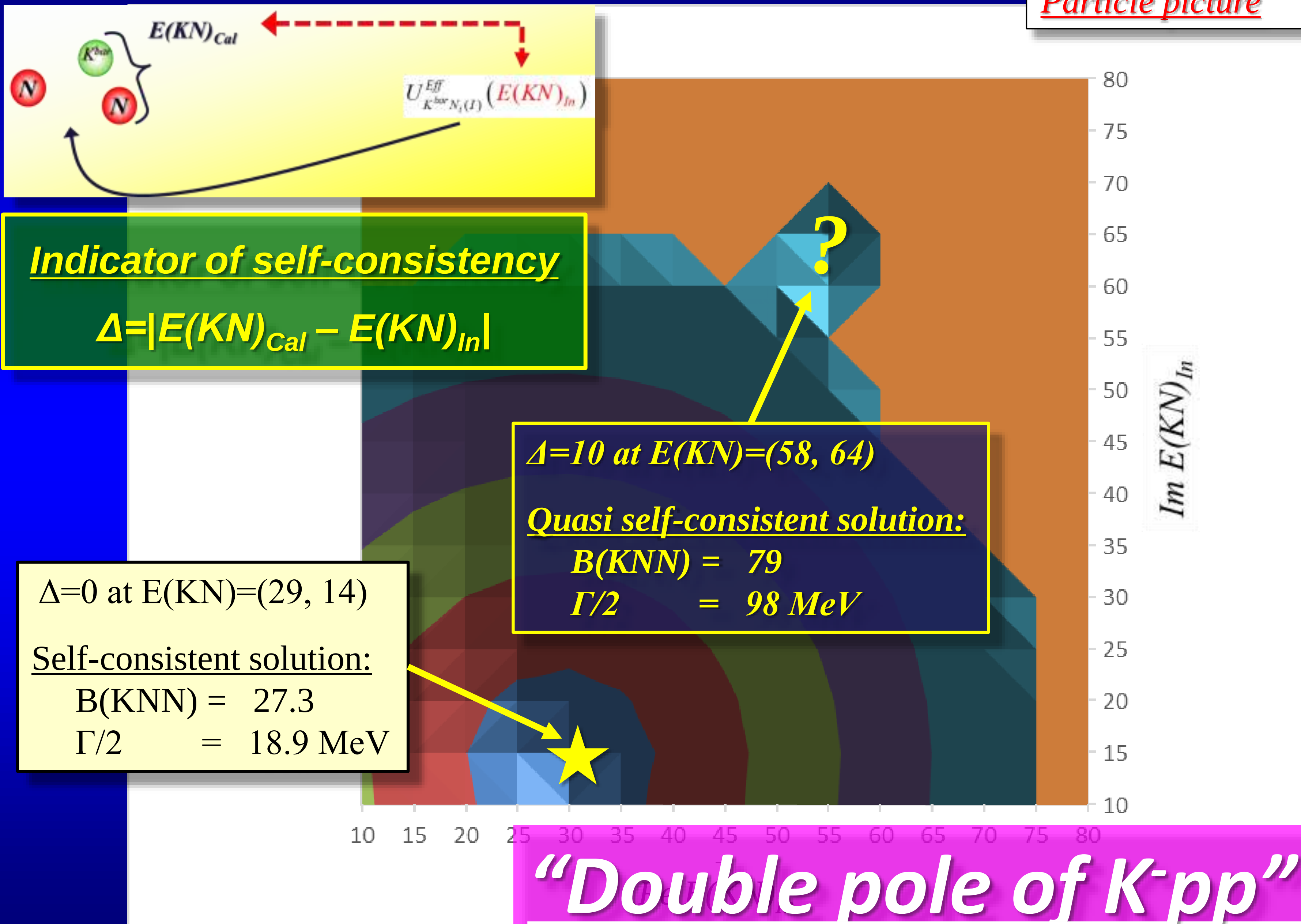
4. Further analysis of "K⁻pp"



- **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"?

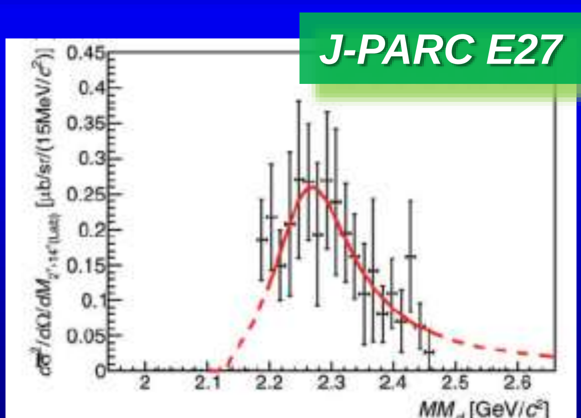
- ✓ *Quasi self-consistent solution is obtained …*
  (B(KNN), Γ/2) = (62～79, 74～104) MeV for f_π=90～120 MeV
  with Particle picture
- ✓ *Such solutions are not obtained with Field picture.*

- *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?*



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

Lower pole of "K⁻pp" (J^π=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^π=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

"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"

- 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 (Martin constraint)
(15~22, 10~25) MeV (SIDDHATA constraint)

- Quasi self-consistent solution with Particle picture
  … Deeper binding and larger decay width

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

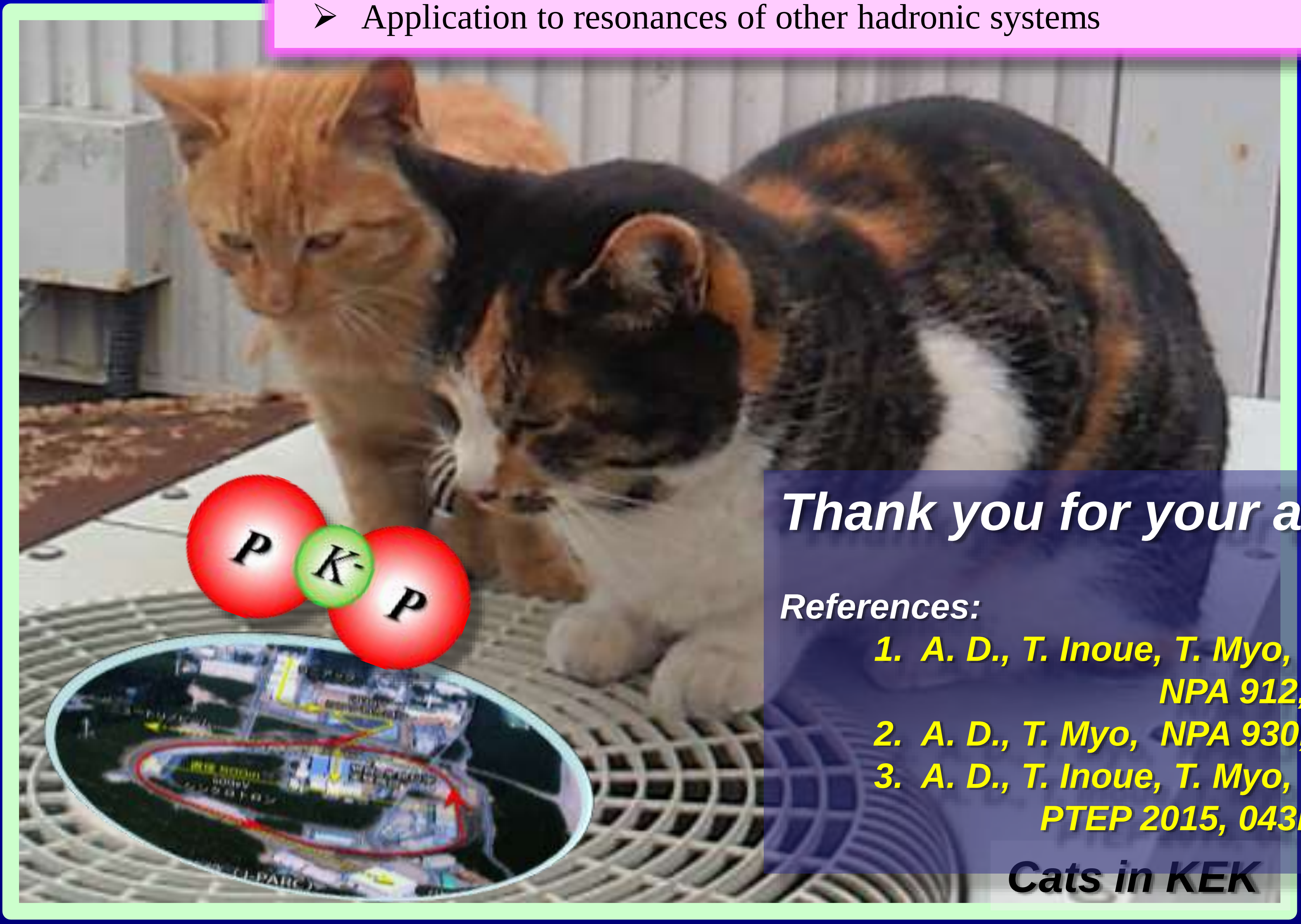
"K^-pp" has a double-pole structure similarly to $\Lambda(1405)$?

- 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 $K^{-}pp$
  ... *Deailed 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)***

Cats in KEK