EXA 2017 @ Wien, 2017, Sep.

$\bar{\mathrm{K}}$N-$\pi\Sigma$ coupled-channel potential derived from Chiral SU(3) dynamics

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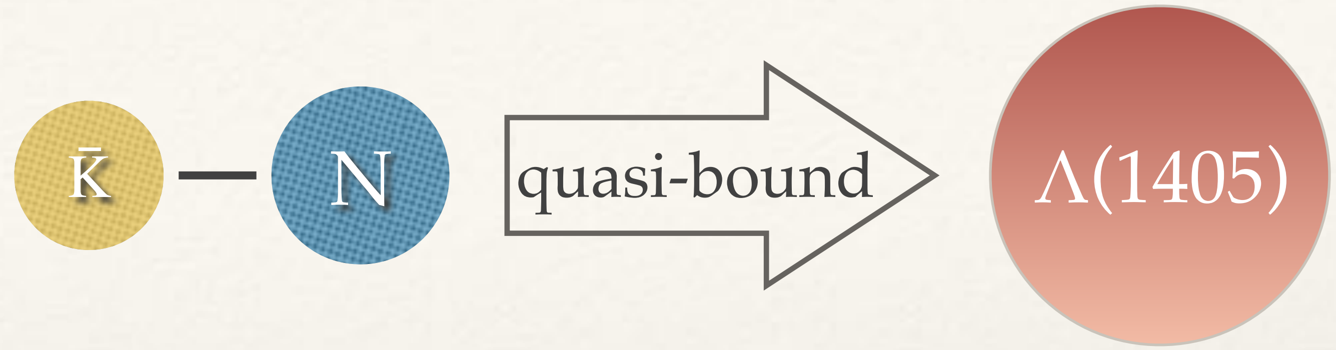
Contents

- Motivation
- Formulation
- $\bar{\mathrm{K}}$N single-channel potential
  - Potential with SIDDHARTA constraint
  - Application to $\Lambda(1405)$ and $\bar{\mathrm{K}}$-nuclei
- $\bar{\mathrm{K}}$N-$\pi\Sigma$ coupled-channel potential
- Summary

Motivation

- **$\bar{K}N$ interaction**
  - strongly attractive



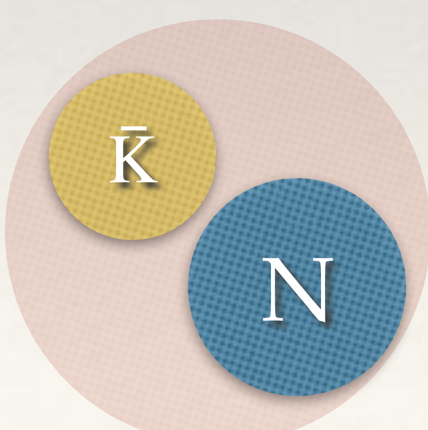
  - without repulsive core

$\bar{K}N$ < $K^{-}p$: $(s\bar{u})$ (uud) ; $\bar{K}^{0}n$: $(s\bar{d})$ (udd)

<u>Interesting states with $\bar{K}$ and N's are expected.</u>

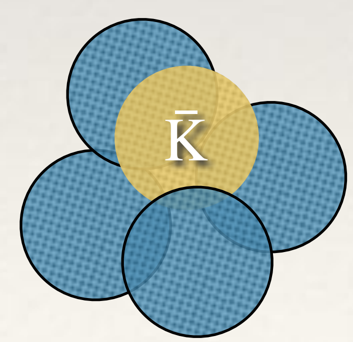
Akaishi, Yamazaki, Phys. Rev. C 65 (2002) 044005
Hyodo, Jido, Prog. Part. Nucl. Phys. 67 (2012) 55

"molecule picture" of Λ(1405)



- exotic state ?
- double pole ?

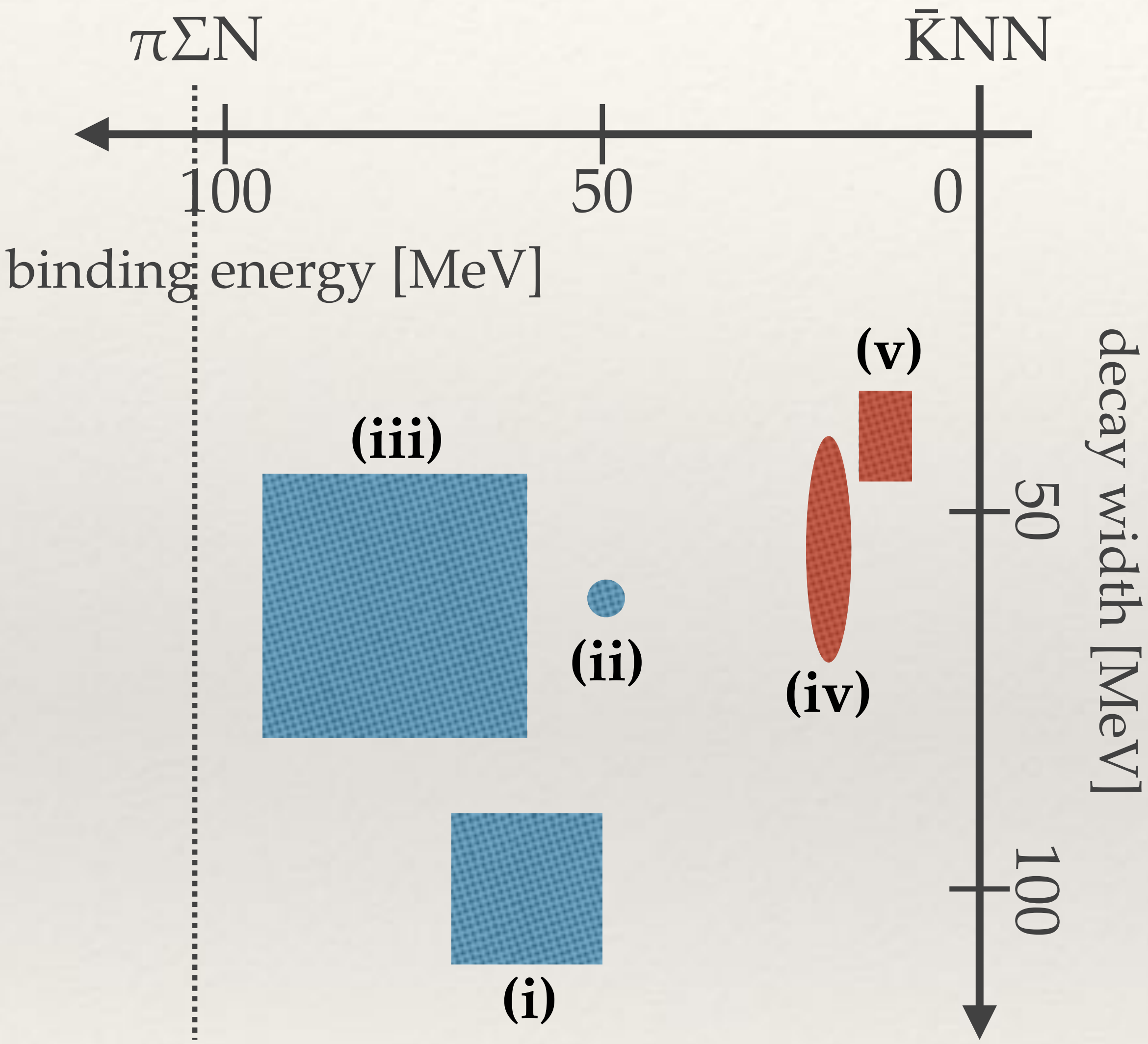
$\bar{K}$ nuclei



- deeply bound ?
- compact state ?
(high density)

Motivation

- $\bar{K}NN$ state ($I=1/2$, $J^P=0^-$)



- 3-body calculation
  - variational
  - Faddeev

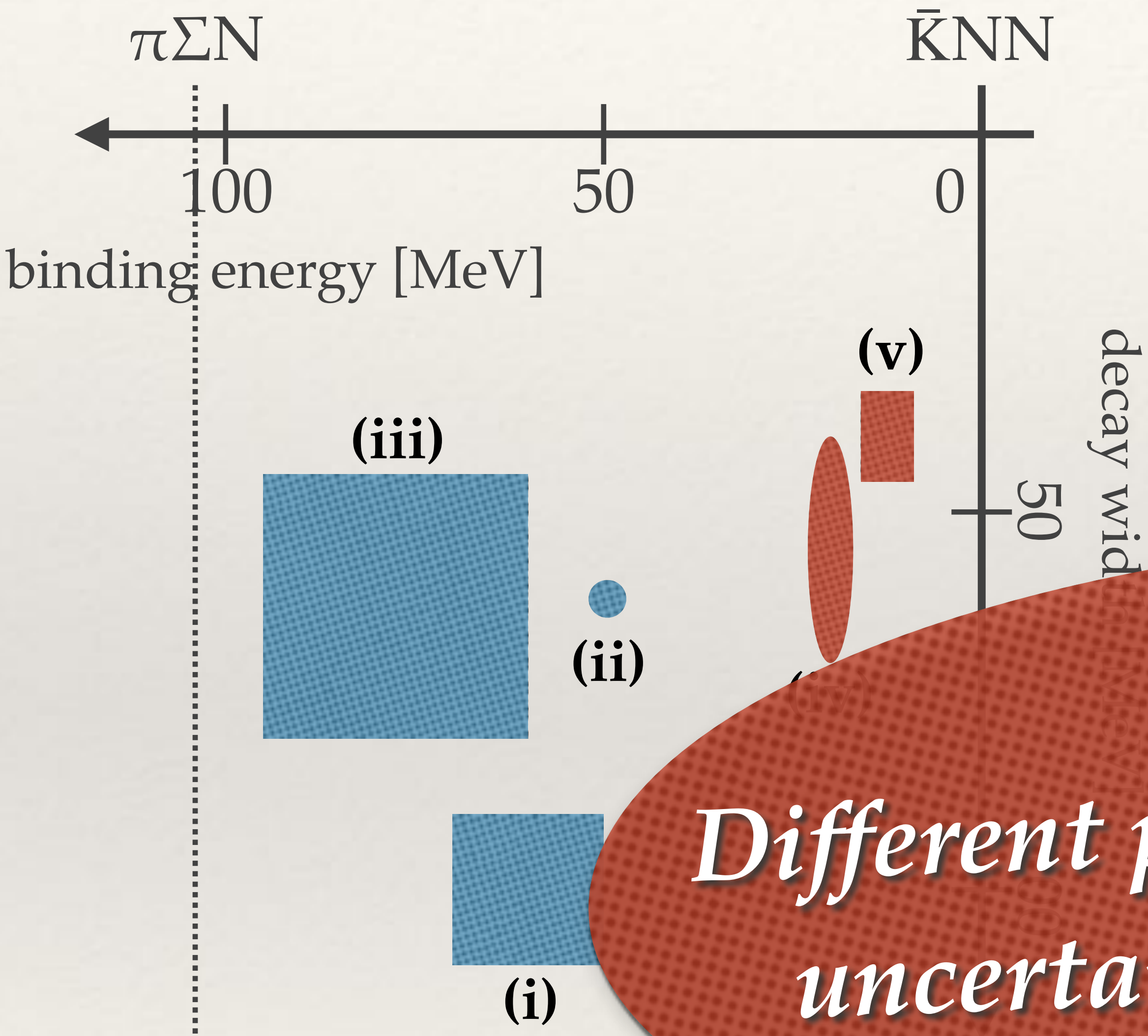
<u>theory</u>

(i) Shevchenko, Gal, Mares, PRC 76 (2007) 044004
(ii) Yamazaki, Akaishi, PRC 76 (2007) 045201
(iii) Ikeda, Sato, PRC 76 (2007) 035203
(iv) Dote, Hyodo, Weise, PRC 79 (2009) 014003
(v) Ikeda, Kamano, Sato, PTP 124 (2010) 533

<u>Conclusive result has not been achieved.</u>

Motivation

- **$\bar{K}NN$ state (I=1/2, $J^P=0^-$)**



- **3-body calculation**
  - **variational**
  - **Faddeev**

theory

(i) Shevchenko, Gal, Mares, PRC 76 (2007) 044004
(ii) Yamazaki, Akaishi, PRC 76 (2007) 045201
(iii) Ikeda, Sato, PRC 76 (2007) 035203
PRC 79 (2009) 014003
010) 533

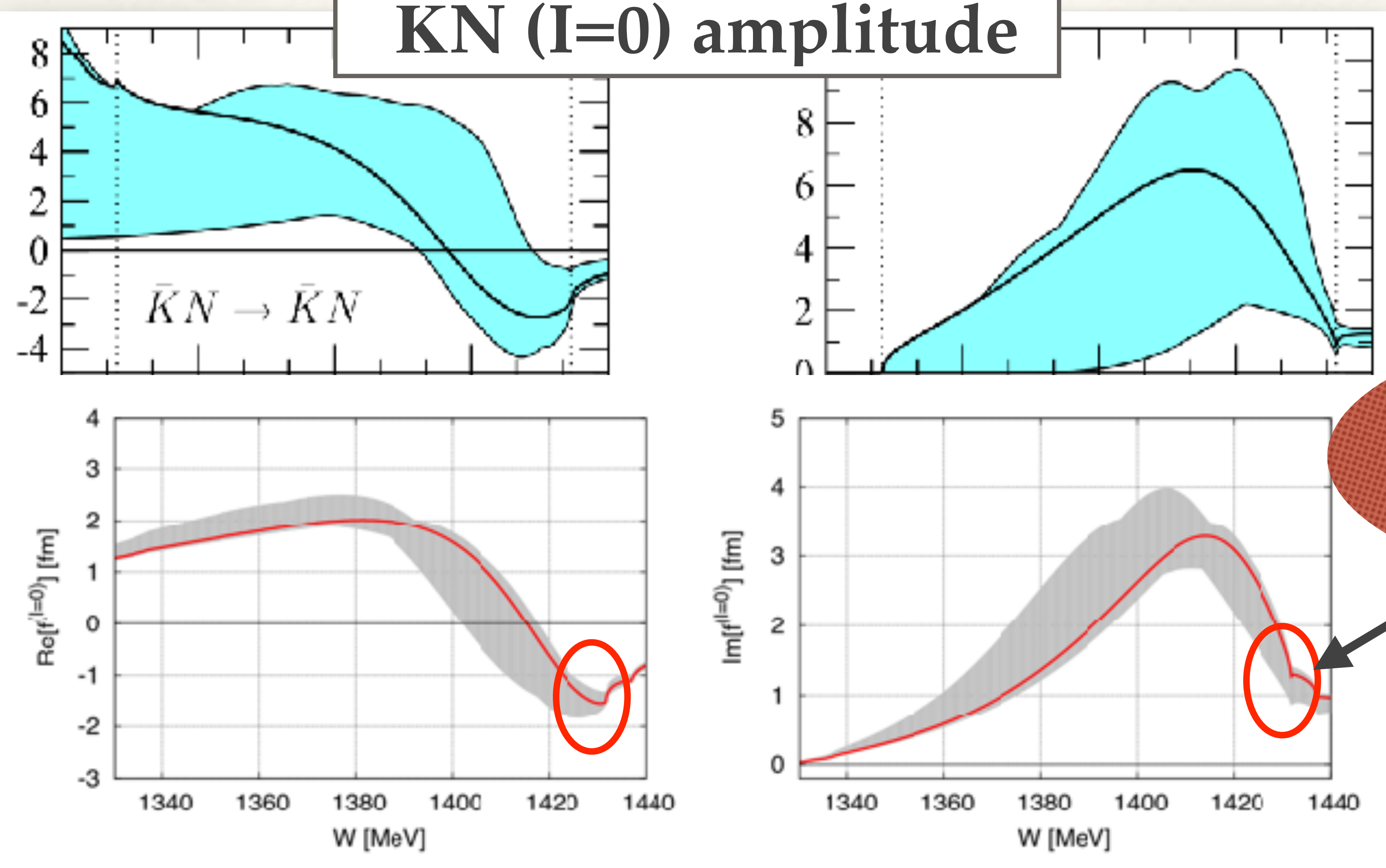
Different predictions are caused by uncertainty of $\bar{K}N$ interaction.

Conclusive result has not been achieved.

Motivation

- New constraint from precise exp.

K̄N (I=0) amplitude



- Borasoy et al. PRC 74 (2006) 055201
- R.Nissler, Ph.D thesis (2007)

Bazzi et al. PLB 704, 113 (2011)

SIDDHARTA

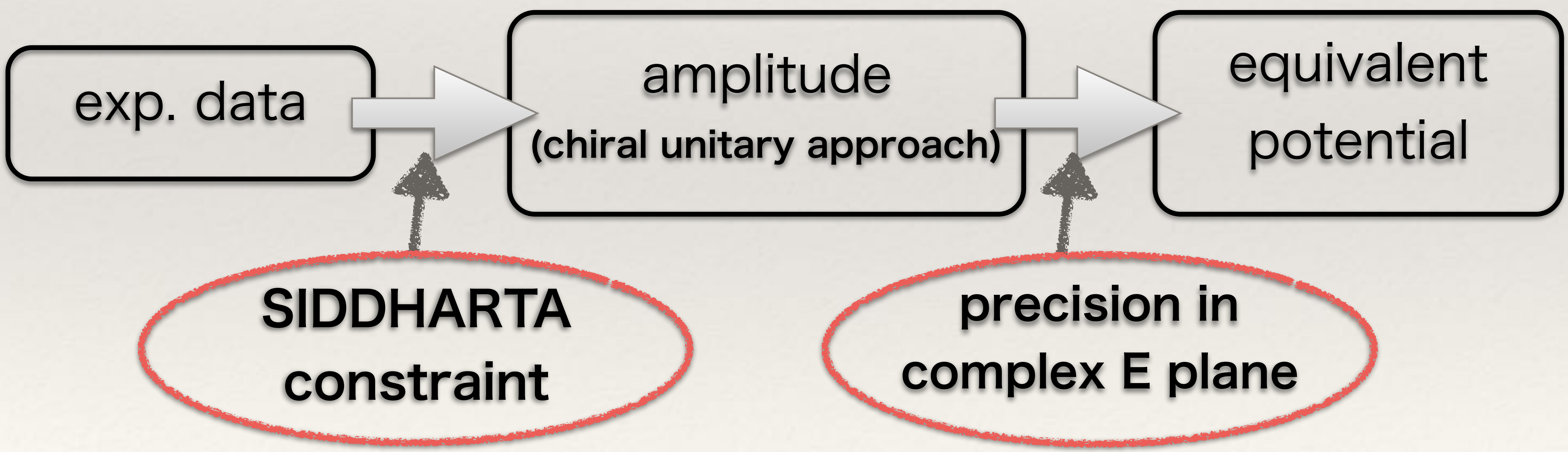
- Ikeda, Hyodo, Weise, NPA 881 (2012) 98
- Kamiya, et al., NPA 954 (2016) 41

SIDDHARTA exp. has enabled quantitative discussion.

Motivation

Construct *r*-dep. realistic potential with SIDDHARTA constraint.

→
- Λ(1405) analysis
- few-body calculation

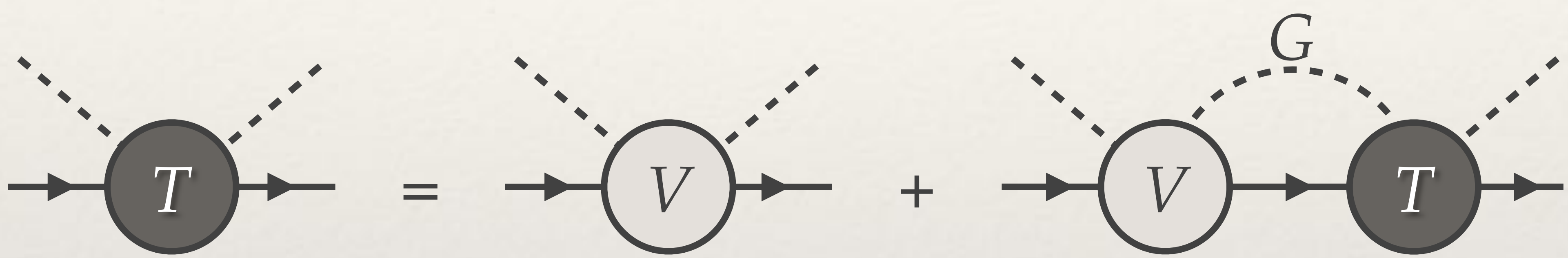


Formulation

cf.) Hyodo, Weise, PRC77 (2008) 035204

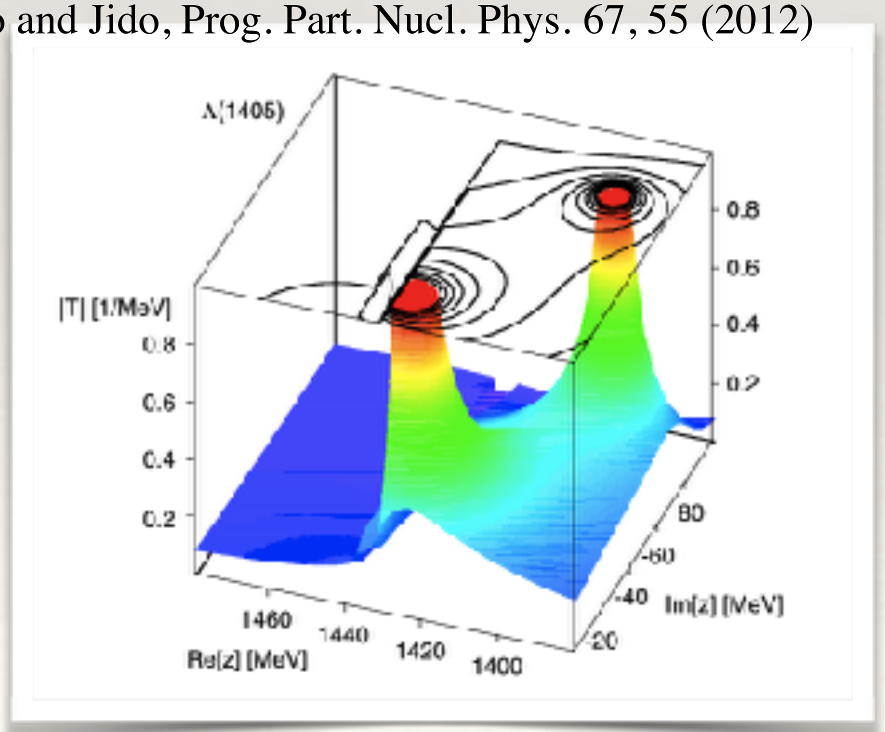
exp. data → amplitude : $F^{Ch.}$ → potential

- **chiral unitary approach**



chiral perturbation theory

Hyodo and Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)



channel coupling

attraction in $\bar{\mathrm{K}}\mathrm{N}$ and $\pi\Sigma$ channels

⟶ double pole structure of $\Lambda(1405)$

Formulation

cf.) Hyodo, Weise,
PRC77 (2008) 035204

exp. data → amplitude : $F^{Ch.}$ → potential

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2} + V^{\text{equiv}}(r,E)u(r) = Eu(r)$$

$$\Rightarrow \boxed{F^{\text{equiv}} = F^{\text{Ch}}}$$

$$V^{\text{equiv}}(r,E) = g(r)N(E)\left[V^{\text{eff}}(E) + \Delta V\right]$$

assume Gauusian *r*-dependence

$$g(r) = \frac{1}{\pi^{3/2}b^3}e^{-r^2/b^2}$$

(b : range parameter)

Formulation

cf.) Hyodo, Weise, PRC77 (2008) 035204

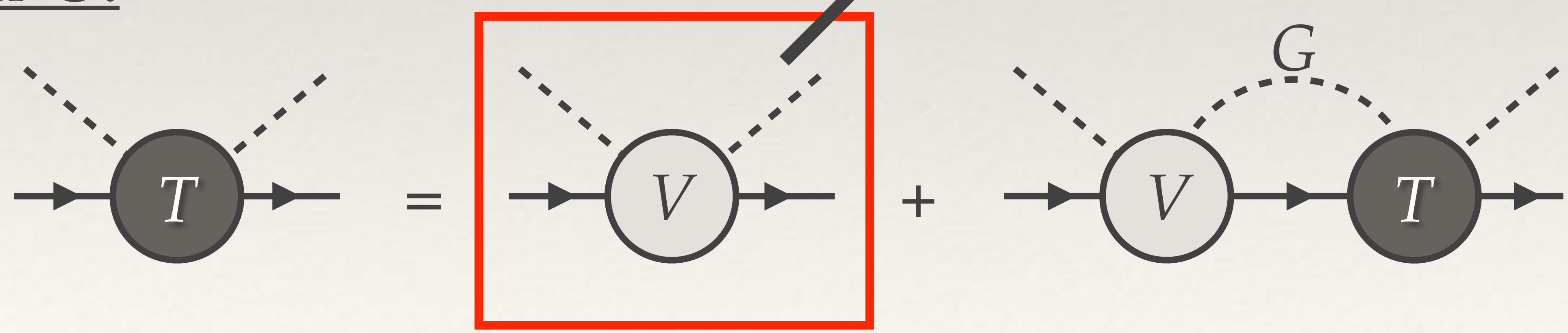
exp. data → amplitude : $F^{\mathrm{Ch.}}$ → potential

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2} + V^{\mathrm{equiv}}(r,E)u(r) = Eu(r)$$

$$\Rightarrow \boxed{F^{\mathrm{equiv}} = F^{\mathrm{Ch}}}$$

$$V^{\mathrm{equiv}}(r,E) = g(r)N(E)\left[V^{\mathrm{eff}}(E) + \Delta V\right]$$

Ch-U.



Formulation

cf.) Hyodo, Weise, PRC77 (2008) 035204

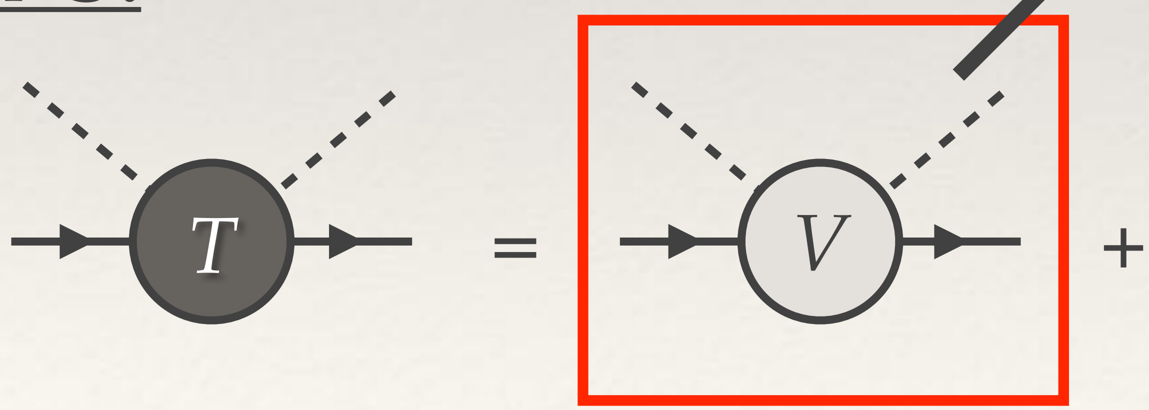
exp. data → amplitude : $F^{\mathrm{Ch.}}$ → potential

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\underline{V^{\mathrm{equiv}}(r,E)}u(r)=Eu(r)$$

$$\Rightarrow \boxed{F^{\mathrm{equiv}}=F^{\mathrm{Ch}}}$$

$$V^{\mathrm{equiv}}(r,E)=g(r)N(E)\left[\underline{V^{\mathrm{eff}}(E)}+\Delta V\right]$$

Ch-U.



channel coupling

Ch-U. : πΣ, K̄N, ηΛ, KΞ

Schrödinger : (πΣ), K̄N

→ **Feshbach projection**

Formulation

cf.) Hyodo, Weise, PRC77 (2008) 035204

exp. data → amplitude : $F^{\text{Ch.}}$ → potential

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\underline{V^{\text{equiv}}(r,E)}u(r)=Eu(r)$$

$$\Rightarrow \boxed{F^{\text{equiv}}=F^{\text{Ch}}}$$

$$V^{\text{equiv}}(r,E)=g(r)N(E)\left[V^{\text{eff}}(E)+\underline{\Delta V}\right]$$

correction for model difference

Ch-U. ⟷ Schrödinger eq.

Formulation

cf.) Hyodo, Weise, PRC77 (2008) 035204

exp. data → amplitude : $F^{Ch.}$ → potential

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2} + \underline{V^{\text{equiv}}(r,E)}u(r) = Eu(r)$$

$$\Rightarrow \boxed{F^{\text{equiv}} = F^{\text{Ch}}}$$

$$V^{\text{equiv}}(r,E) = g(r)N(E)\left[V^{\text{eff}}(E) + \Delta V\right]$$

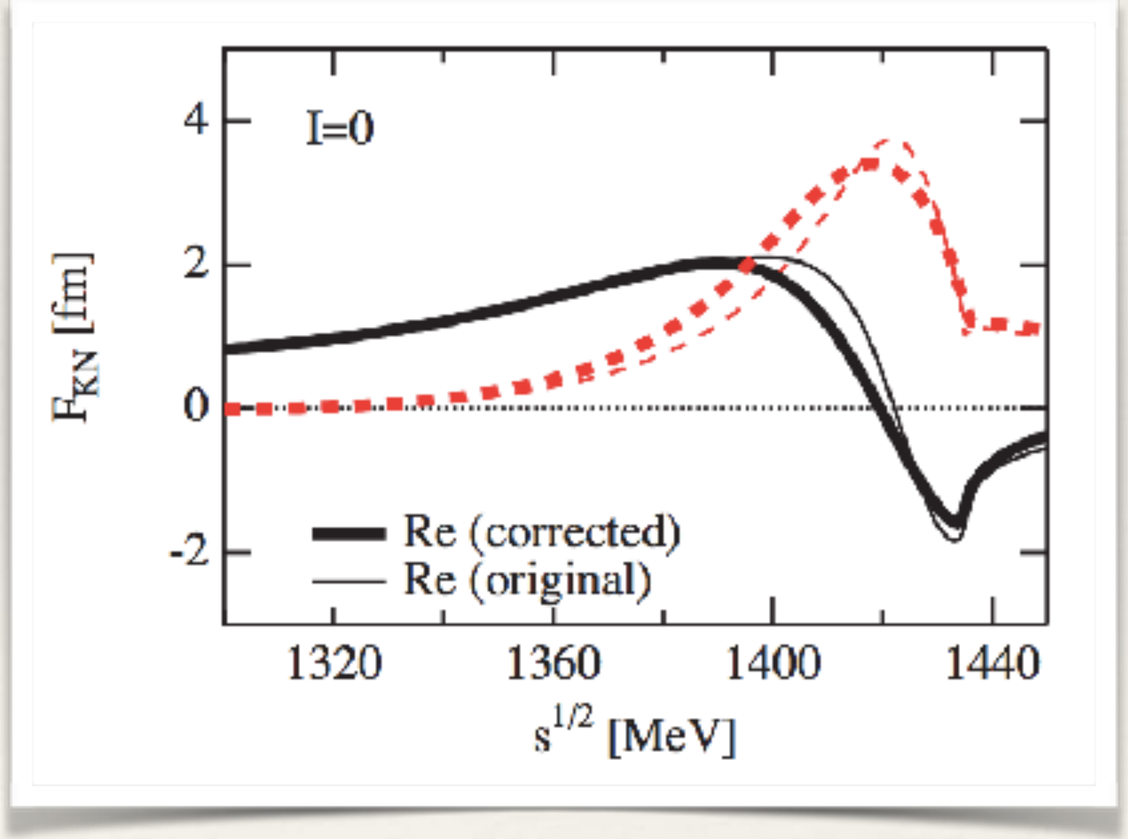
⇒ **fit by polynomial**

$$V^{\text{equiv}} = g(r)N(E)\left[\sum_i c_i E^i\right]$$

for convenience and analytical continuation

single-channel $\bar{K}N$ potential

- **Previous work : Hyodo, Weise, PRC77 (2008) 035204)**
  - ΔV : real
  - fit range : 1300-1400 MeV
  - polynomial type : 3rd order in E

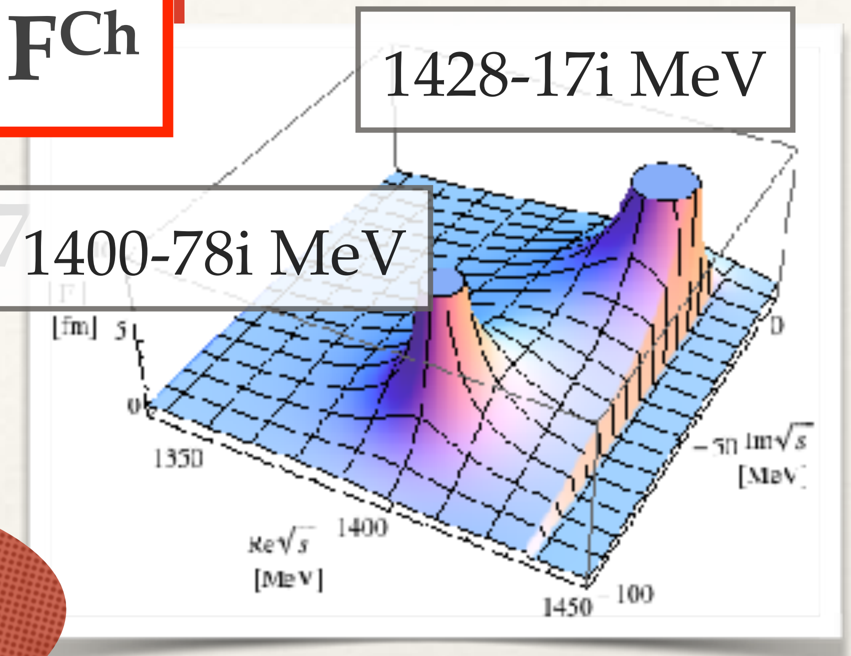


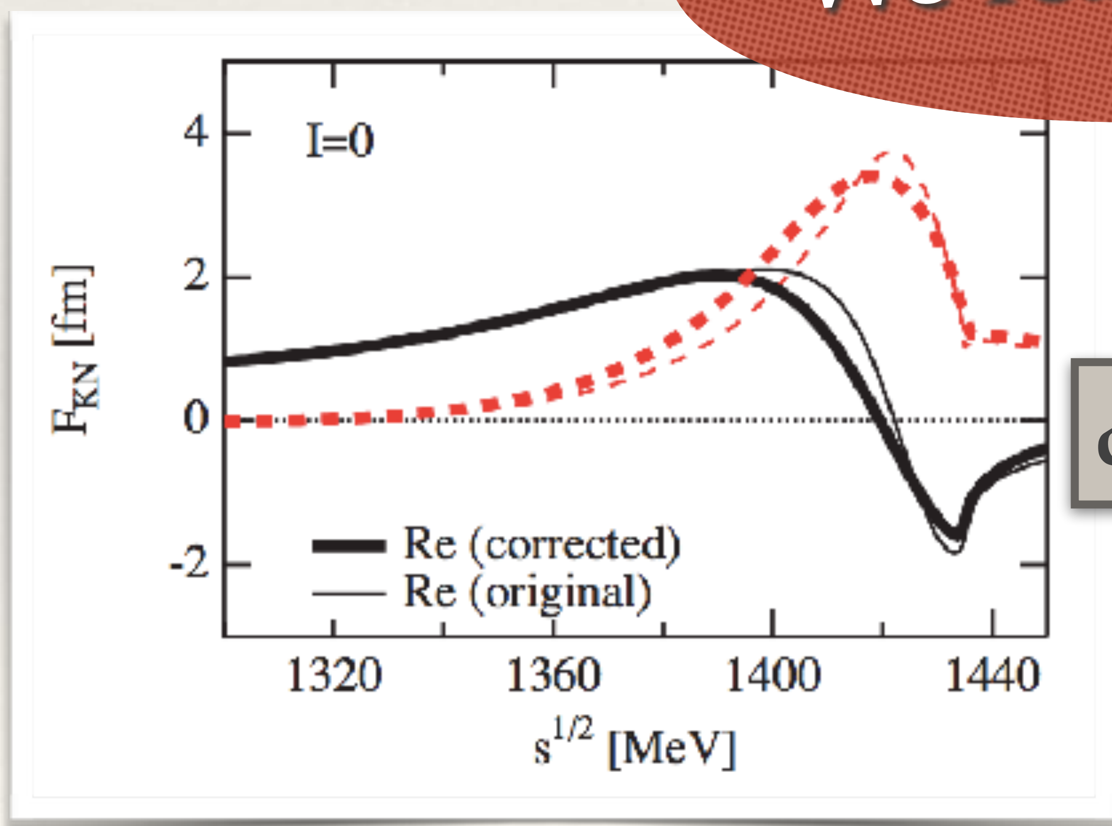
<u>F^{Ch} was almost reproduced on real *E* axis.</u>

single-channel $\bar{K}N$ pote

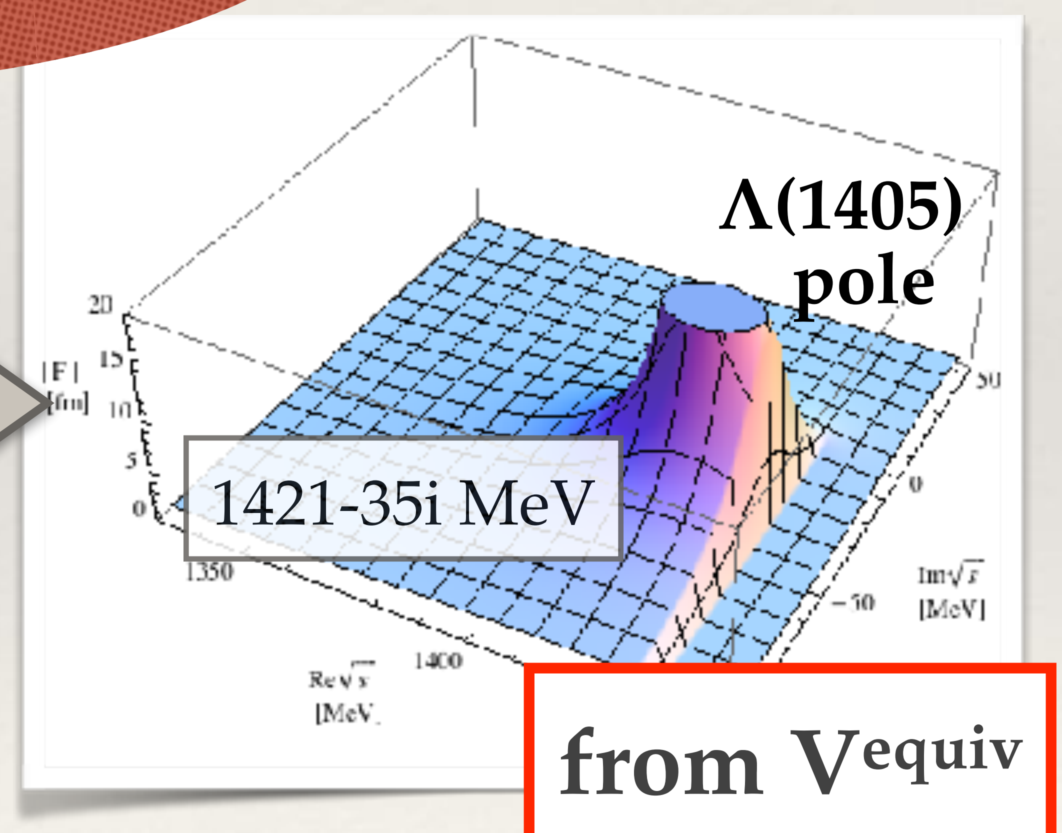
- **Previous work : Hyodo, Weise, PRC7**
  - ΔV : real
  - fit range : 1300-1400 MeV
  - polynomial

We reanalyzed …





comp E



V^{equiv} does not reproduce pole structure of F^{Ch}.

single-channel K̄N potential

- **Our work : Miyahara, Hyodo, PRC93 (2016) 015201**
  - ΔV : ~~real~~ ⟶ complex
  - fit range : ~~1300-1400~~ MeV ⟶ 1332-1450
  - polynomial type : 3rd order in E

$$V^{\mathrm{equiv}}(r,E) = g(r)N(E)\left[\underline{V^{\mathrm{eff}}(E)} + \Delta V\right]$$

$$V^{\mathrm{Ch}}_{ij} \in \mathbb{R} \quad \Longrightarrow \quad V^{\mathrm{eff}}_{\bar{K}N,\bar{K}N} \in \mathbb{C}$$

Feshbach projection

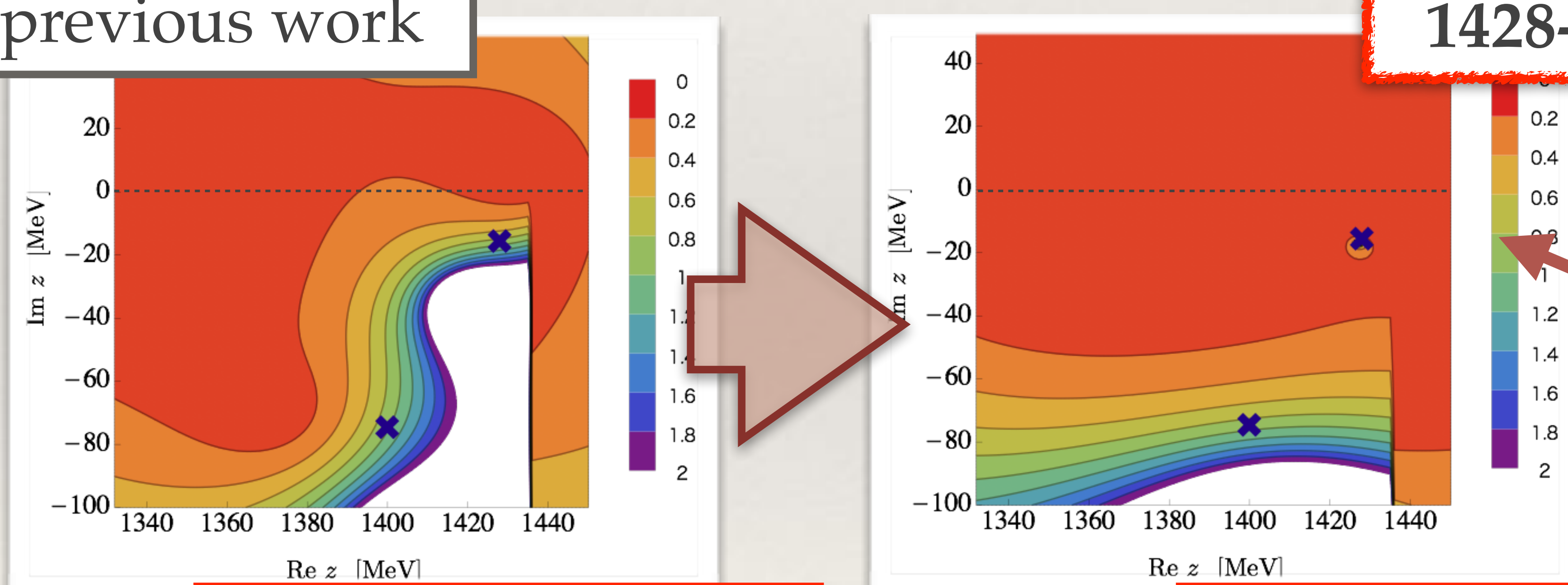
eliminate πΣ decay channel

single-channel $\bar{K}$N potential

- **Our work : Miyahara, Hyodo, PRC93 (2016) 015201**
  - ΔV : ~~real~~ → complex
  - fit range : ~~1300-1400~~ MeV → 1332-1450
  - polynomial type : 3rd order in E

previous work

original pole (Ch-U.) :
1428-17i MeV, 1400-76i MeV



"deviation" in complex *E*

$$\Delta F = \left| \frac{F^{\mathrm{Ch}} - F^{\mathrm{equiv}}}{F^{Ch}} \right|$$

pole : 1421-35i MeV

1427-17i MeV

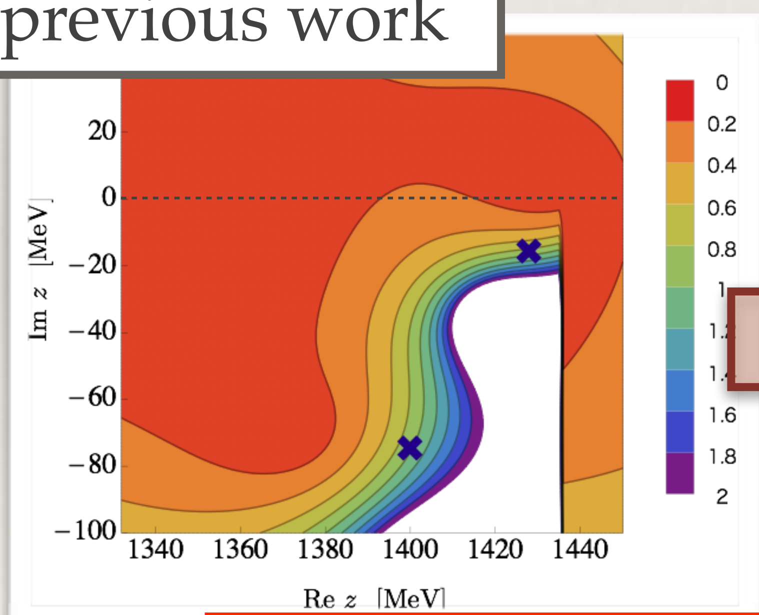
Precision on real *E* and higher pole are improved.

single-channel $\bar{K}N$ potential

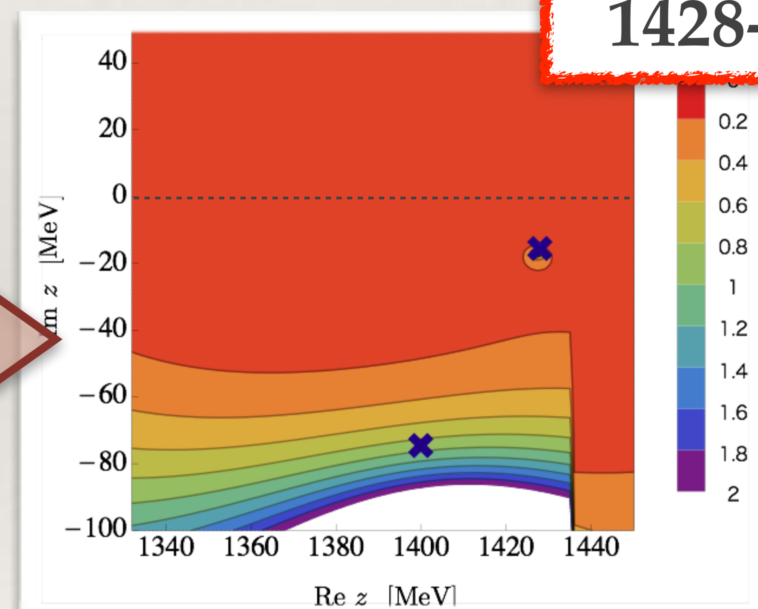
- **Our work : Miyahara, Hyodo, PRC93 (2016) 015201**
  - ΔV : ~~real~~ → complex
  - fit range : ~~1300-1400~~ MeV → 1332-1450
  - polynomial type : 3rd order in E

original pole (Ch-U.) :
1428-17i MeV, 1400-76i MeV

previous work



pole : 1421-35i MeV



1427-17i MeV

no lower pole

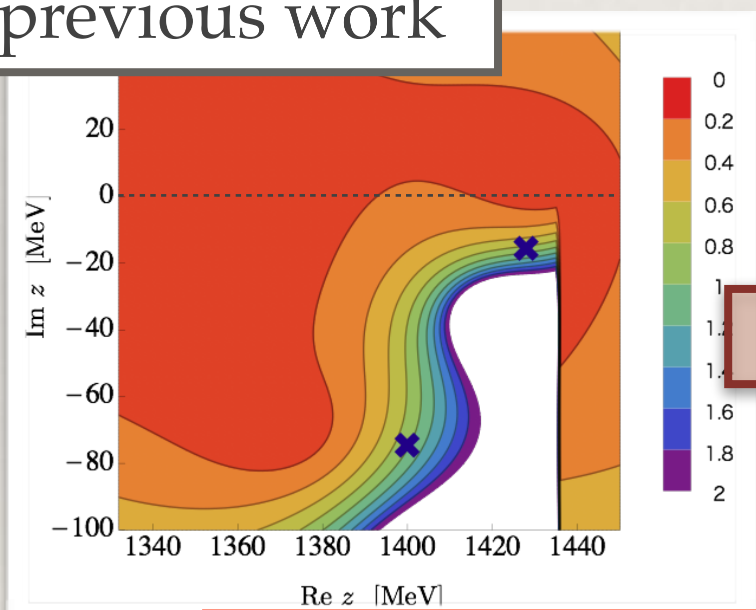
<u>Precision on real *E* and higher pole are improved.</u>

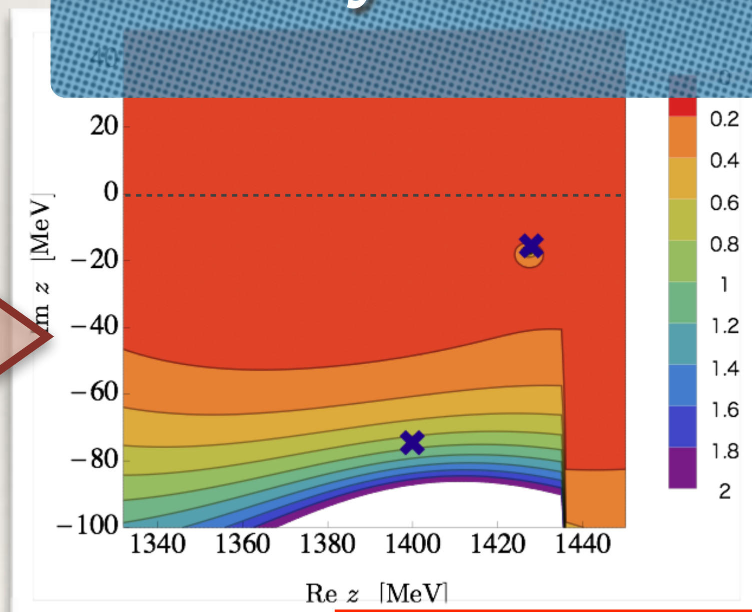
single-channel $\bar{K}N$ potential

- **Our work : Miyahara, Hyodo, PRC93 (2016) 015201**
  - ΔV : ~~real~~ → complex
  - fit range : ~~1300-1400~~ MeV → ~~1332-1450~~ → **1332-1520**
  - polynomial type : 3rd order in E

Analytic continuation is unique

previous work





pole : 1421-35i MeV

1427-17i MeV

no lower pole

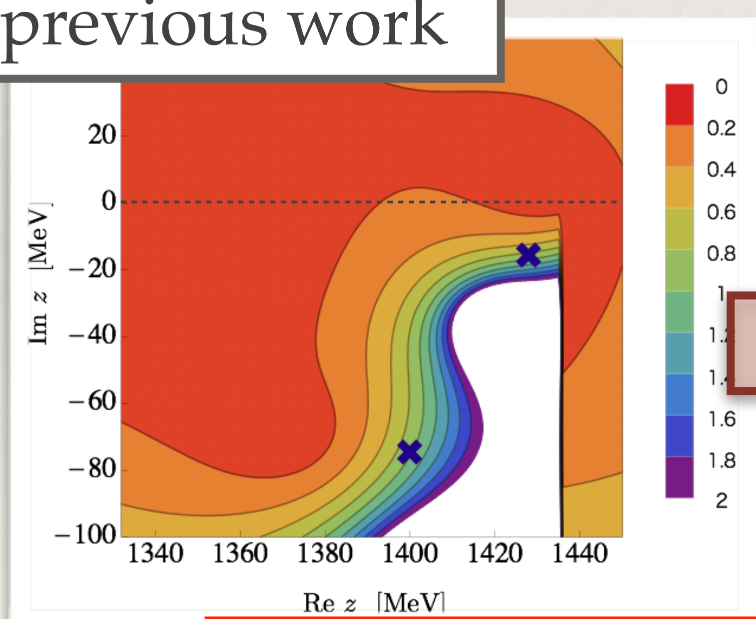
<u>Precision on real *E* and higher pole are improved.</u>

single-channel $\bar{K}N$ potential

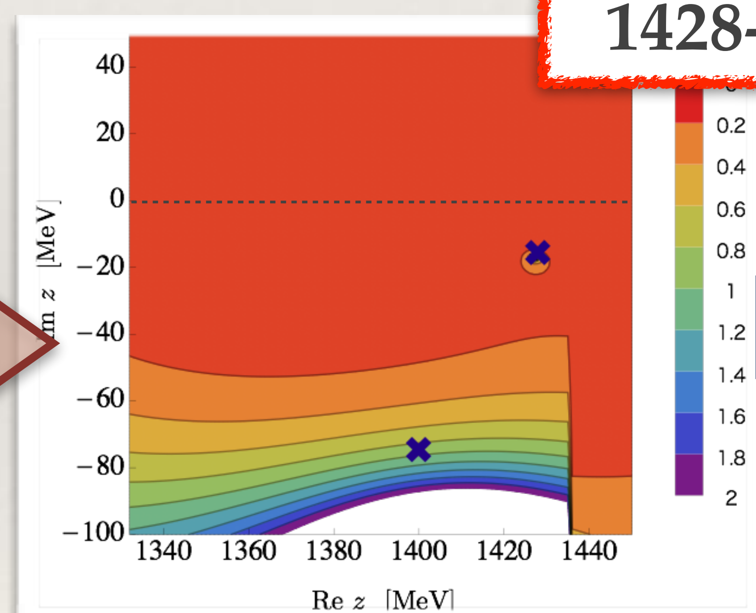
- **Our work : Miyahara, Hyodo, PRC93 (2016) 015201**
  - ΔV : ~~real~~ → complex
  - fit range : ~~1300-1400~~ MeV → ~~1332-1450~~ → **1332-1520**
  - polynomial type : ~~3rd order~~ in E → **10th order**

original pole (Ch-U.) :
1428-17i MeV, 1400-76i MeV

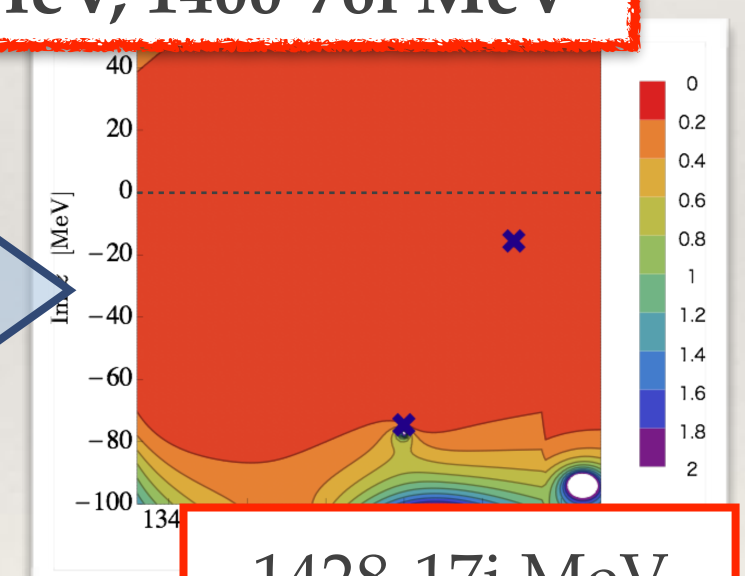
previous work



pole : 1421-35i MeV



1427-17i MeV



1428-17i MeV
1400-77i MeV

<u>**Two poles are well reproduced.**</u>

single-channel $\bar{K}N$ potential

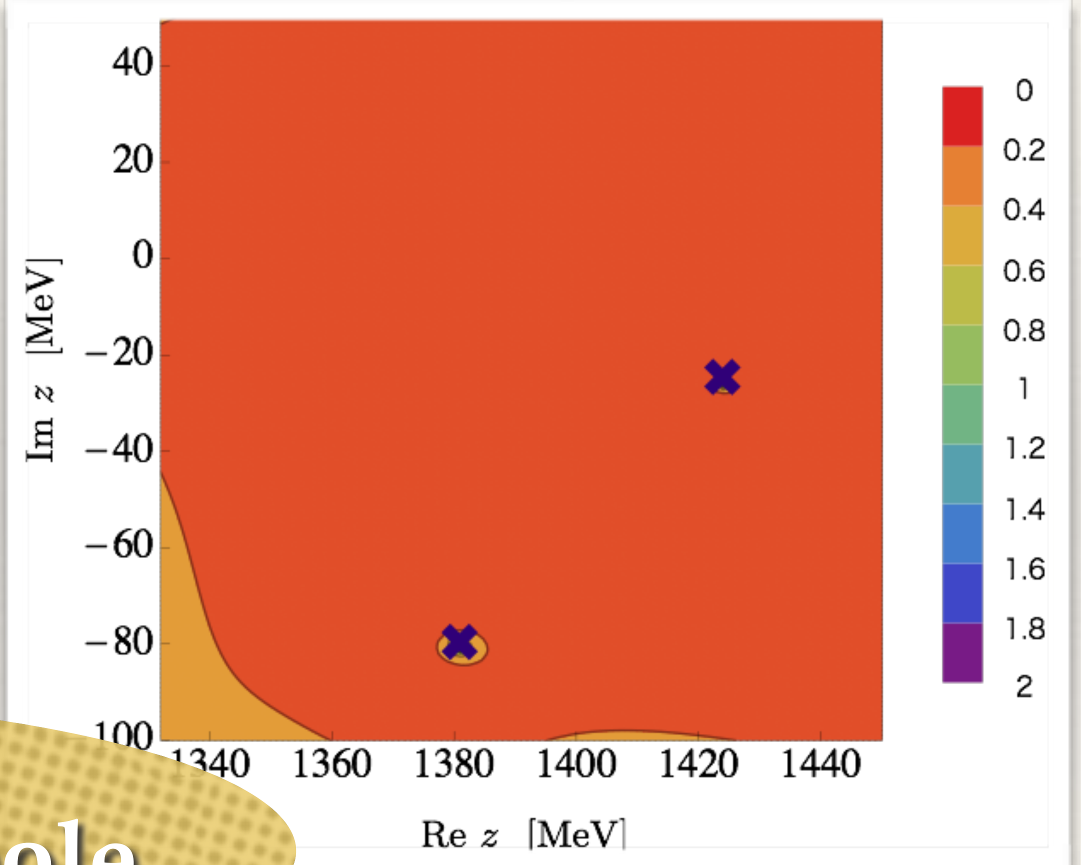
with SIDDHARTA constraint

- **Our work : Miyahara, Hy**

Ch-U. with SIDDHARTA : Ikeda, Hyodo, Weise, NPA881 (2012) 98

- ΔV : complex
- fit range : 1332-1657 MeV
- polynomial type : 10th order

pole :
1424-26i MeV
1381-81i MeV



same as original pole

Reliable $\bar{K}N$ potential is obtained.

single-channel $\bar{\text{K}}$N potential

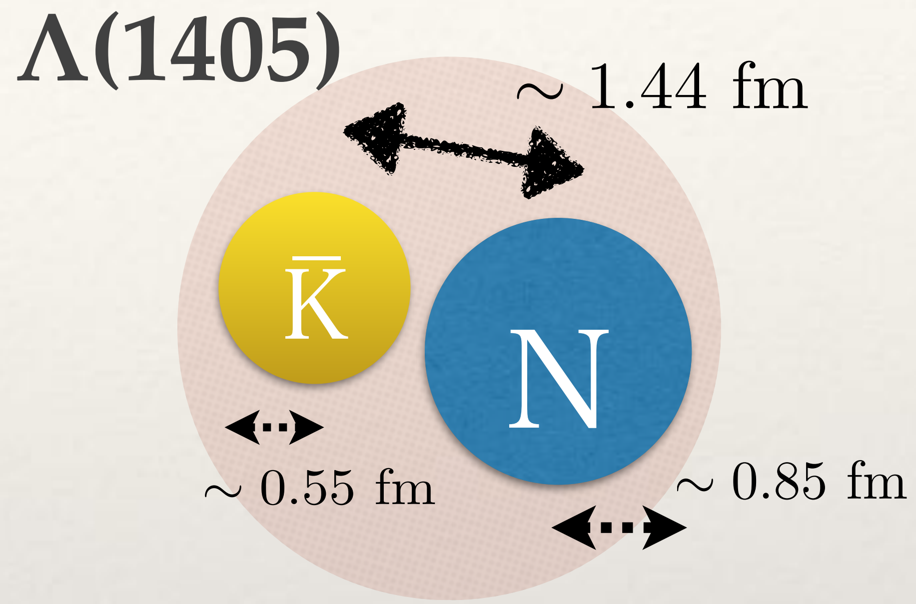
- **Application**

1. spatial size of Λ(1405)

Miyahara, Hyodo, PRC93 (2016) 015201

$$\boxed{\sqrt{\langle r^2 \rangle} \sim 1.44\text{fm}}$$

→ **"molecular picture"**



2. $\bar{\text{K}}$-nuclei Ohnishi et al., PRC95 (2017) 065202

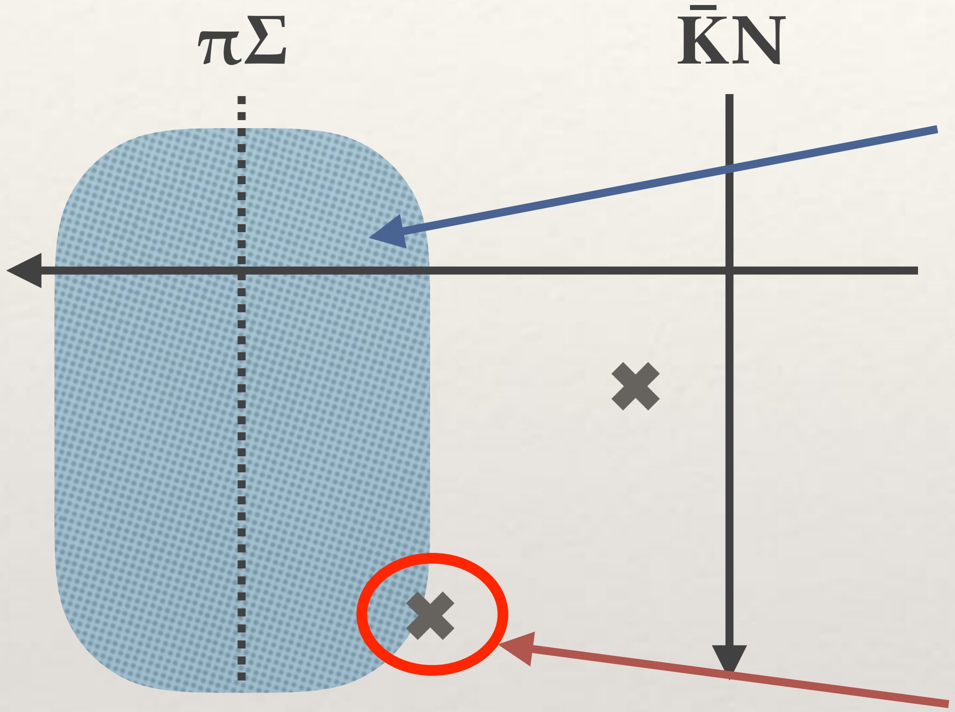
- variational method → $\bar{\text{K}}$NN, … , $\bar{\text{K}}$NNNNNN

$\bar{\text{K}}$NN : (B, Γ) = (26.1-27.9, 30.9-59.3) MeV

cf.) with AY potential : (48.7, 61.9) MeV

coupled-channel $\bar{K}N$-$\pi\Sigma$ potential

- **explicit treatment of $\pi\Sigma$**



- reliability in lower E region

  cf.) B.E. of some $\bar{K}$-nuclei

  ~ 70 MeV

  Ohnishi et al., PRC95 (2017) 065202

- dynamically generated by $\pi\Sigma$

  This may affect the $\bar{K}$-nuclei result.

We construct $\bar{K}N$-$\pi\Sigma$ potential.

coupled-channel K̄N-πΣ potential

- **explicit treatment of $\pi\Sigma$**
  - ΔV : real
  - fit range : 1300-1500 MeV
  - polynomial type : 3rd order in E

$$V^{\text{equiv}}(r,E) = g(r)N(E)\left[V^{\text{eff}}(E) + \Delta V\right]$$

$$V_{ij}^{\text{Ch}} \in \mathbb{R} \Longrightarrow V_{ij}^{\text{eff}} \in \mathbb{R}$$

Feshbach projection

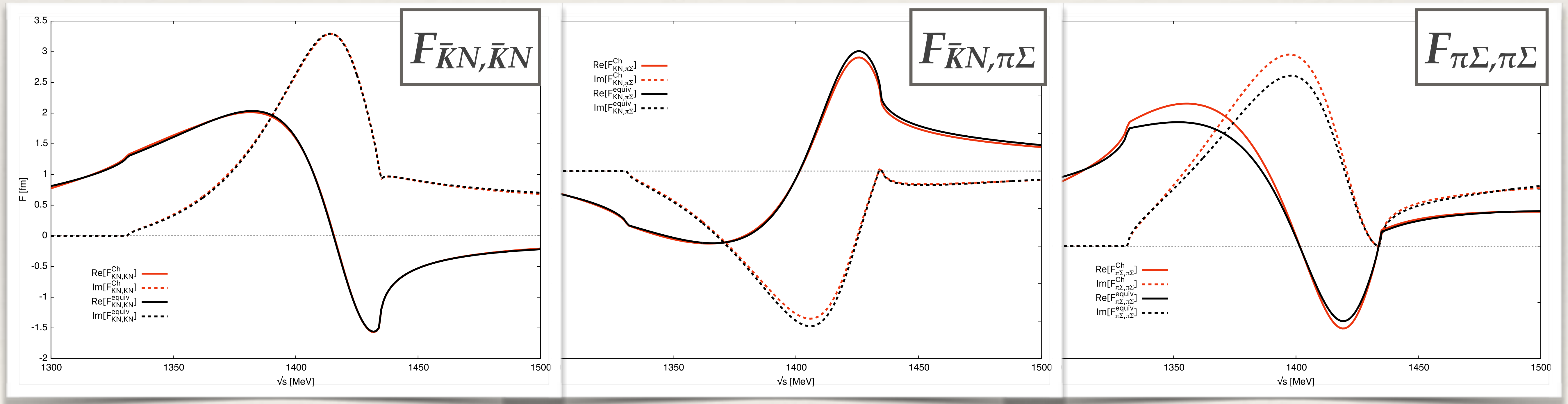
πΣ, K̄N, ~~ηΛ, KΞ~~

coupled-channel $\bar{K}N$-$\pi\Sigma$ potential

- **explicit treatment of $\pi\Sigma$**
  - ΔV : real
  - fit range : 1300-1500 MeV
  - polynomial type : 3rd order in E

original pole (Ch-U.) :
1424-26i MeV, 1381-81i MeV

pole from equiv. potential :
1424-28i MeV, 1401-85i MeV



V^{equiv} almost reproduces F^{Ch} including poles.

coupled-channel $\bar{K}N$-$\pi\Sigma$ potential

- **explicit treatment of $\pi\Sigma$**
  - ΔV : real
  - fit range : 1300-1500 MeV
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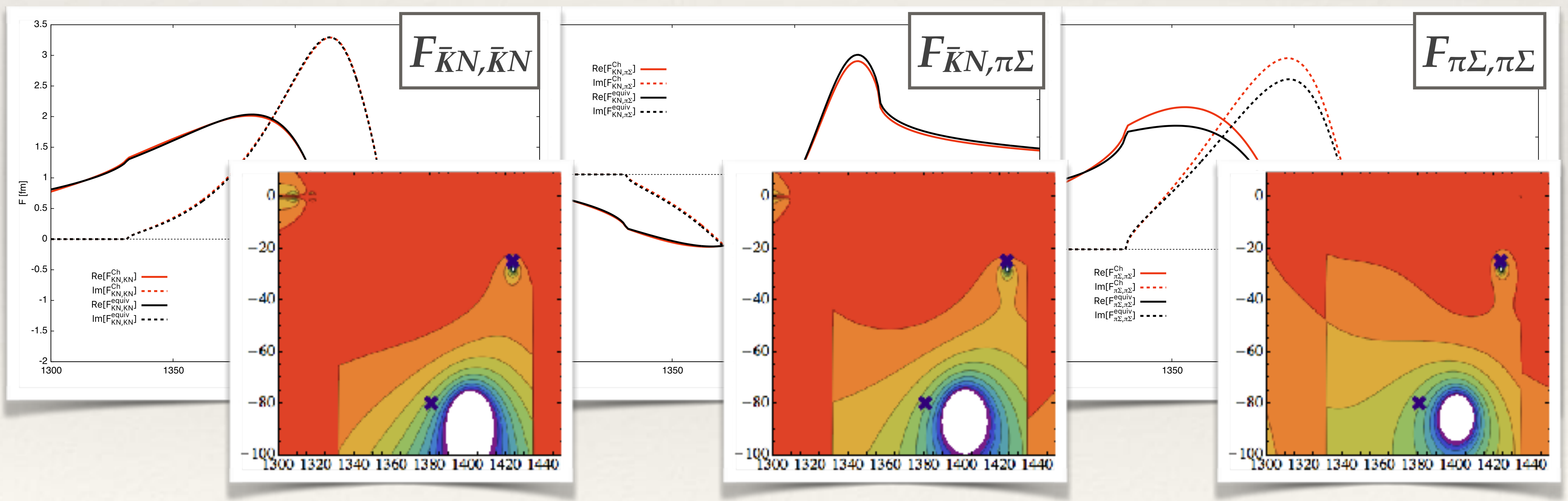
1424-28i MeV, 1401-85i MeV



<u>V^{equiv} almost reproduces F^{Ch} including poles.</u>

Summary

- We have improved the potential construction procedure paying attention to *F* in complex *E*.

- Realistic $\bar{K}N$ potential has been obtained with SIDDHARTA constraint.
  - Application $\Lambda(1405)$: $\sqrt{\langle r^2 \rangle} = 1.44$ fm

    Miyahara, Hyodo, PRC93 (2016) 015201

    $\bar{K}NN$: $(B, \Gamma) = (26.1\text{-}27.9,\ 30.9\text{-}59.3)$ MeV

    Ohnishi et al., PRC95 (2017) 065202

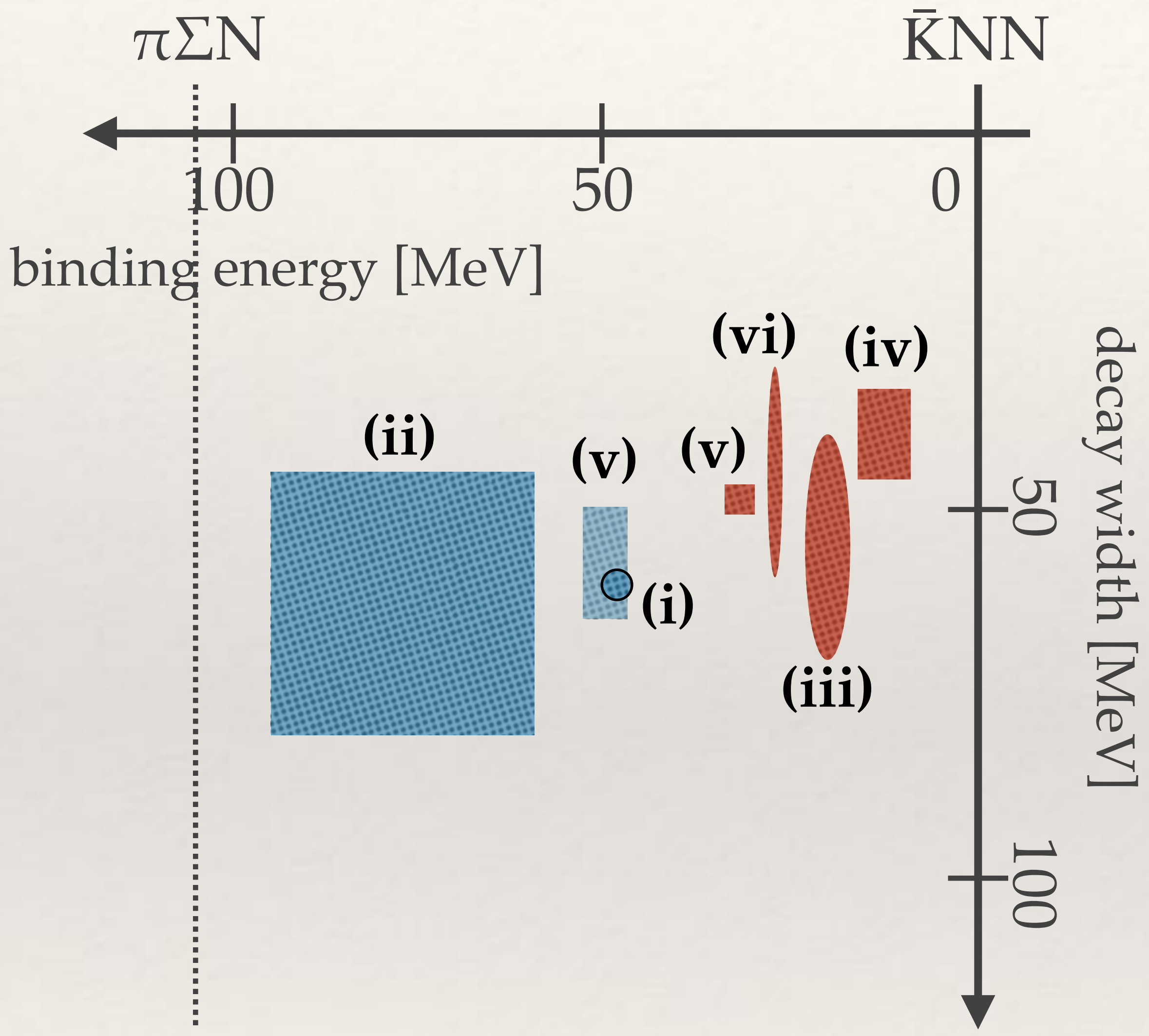
- Similarly, we have constructed reliable $\bar{K}N$-$\pi\Sigma$ coupled-channel potential.

  Miyahara, Hyodo, Weise, in preparation

Backup slides

Motivation

- **$\bar{K}NN$ state (I=1/2, $J^P=0^-$)**



- **3-body calculation**
  - **variational**
  - **Faddeev**

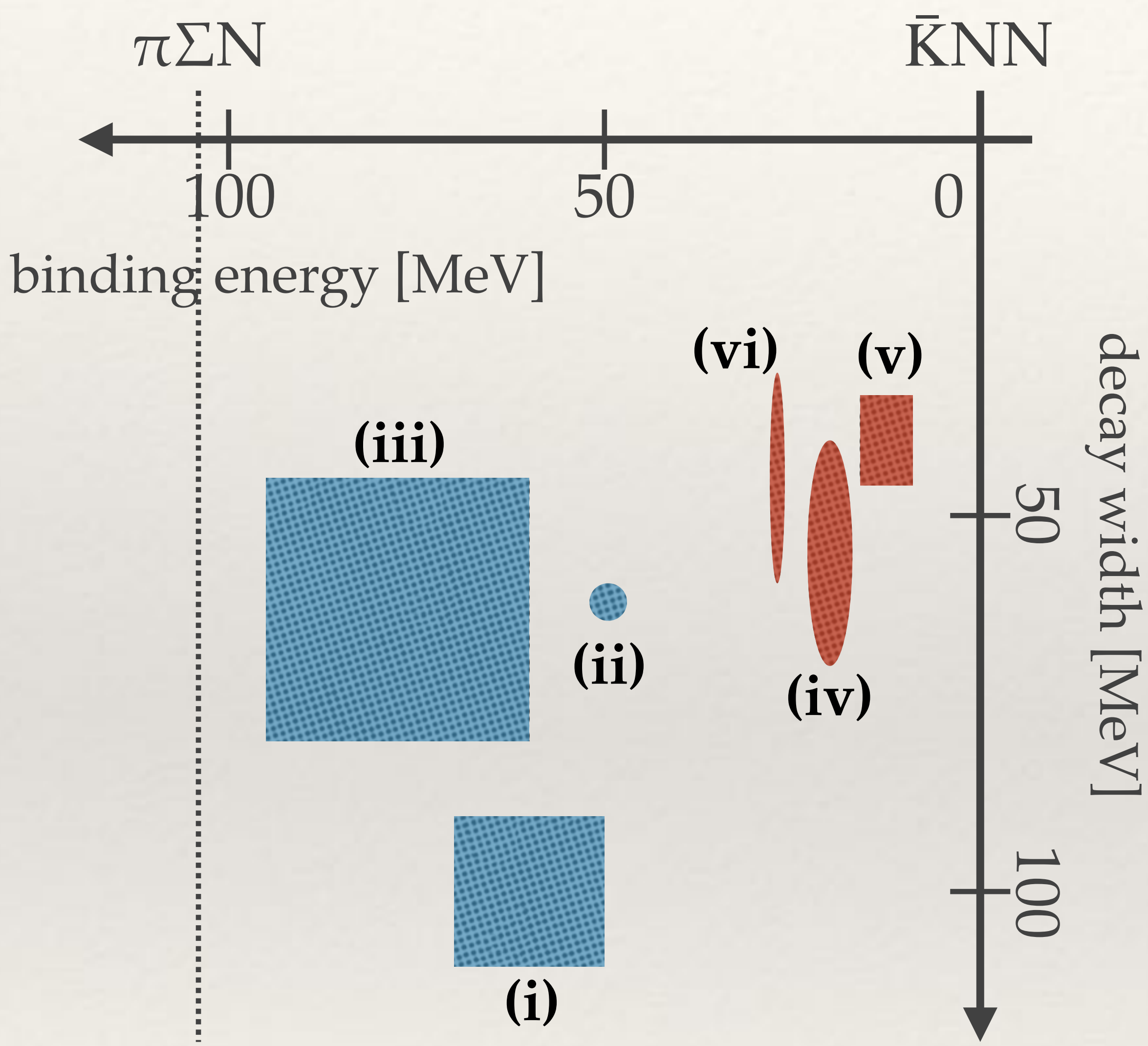
<u>theory</u>

(i) Yamazaki, Akaishi, PRC 76 (2007) 045201
(ii) Ikeda, Sato, PRC 76 (2007) 035203
(iii) Dote, Hyodo, Weise, PRC 79 (2009) 014003
Barnea, Gal, Liverts, PLB 712 (2012) 132
(iv) Ikeda, Kamano, Sato, PTP 124 (2010) 533
(v) Revai, Shevchenko, PRC 90 (2014) 034004
(vi) Ohnishi et al. PRC 95 (2017) 065202

<u>Conclusive result has not been achieved.</u>

Motivation

- **K̄NN state (I=1/2, $J^P=0^-$)**



- **3-body calculation**
  - **variational**
  - **Faddeev**

- **K̄N interaction**
  - **E-indep. (↔ sigle pole)**
  - **E-dep. (↔ double pole)**

(i) Shevchenko, Gal, Mares, PRC 76 (2007) 044004
(ii) Yamazaki, Akaishi, PRC 76 (2007) 045201
(iii) Ikeda, Sato, PRC 76 (2007) 035203
(iv) Dote, Hyodo, Weise, PRC 79 (2009) 014003
(v) Ikeda, Kamano, Sato, PTP 124 (2010) 533
(vi) Ohnishi et al. PRC 95 (2017) 065202

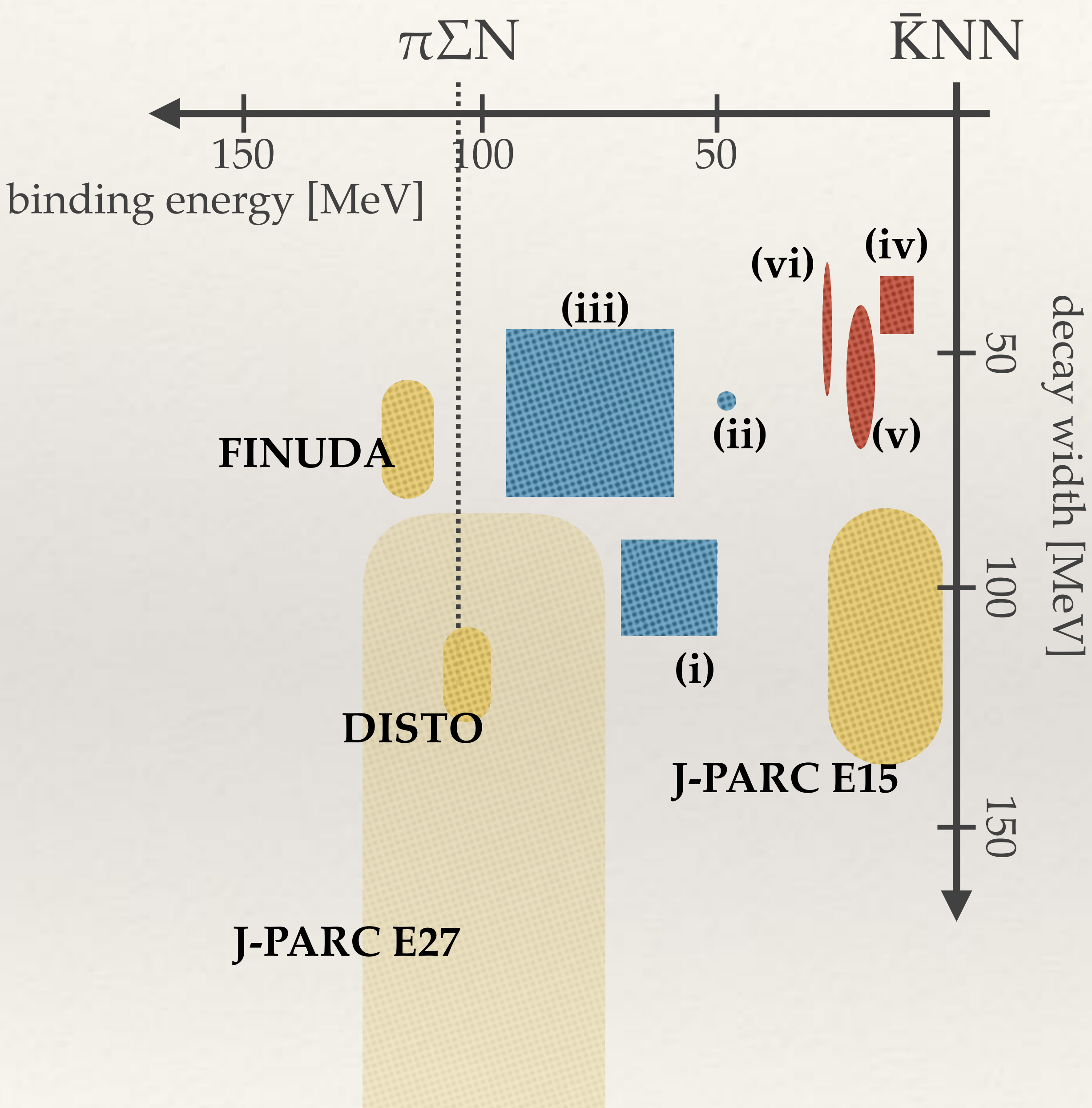
exp. situation

	Group	Reaction	($B_{\bar{K}NN}$, $\Gamma_{\bar{K}NN}$) [MeV]
2005年	FINUDA	$K^- A \to A'(\Lambda p)$	(115, 67) Angello et al., PRL 94 (2005) 212303
2010年	DISTO	$pp \to K^+(\Lambda p)$	(103, 118) Yamazaki et al., PRL 104 (2010) 132502
2014年	LEPS	$\gamma d \to K^+ \pi^- X$	no peak Tokiyasu et al., PLB728 (2014) 616
2015年	J-PARC E27	$\pi^+ d \to K^+ X$	(95, 162) Ichikawa et al., PTEP 2015, 021D01
2015年	HADES	$pp \to K^+(\Lambda p)$	no peak Agakishiev et al., PLB742 (2015) 242
2015年	J-PARC E15	$K^- \, {}^3He \to nX$	no peak Hashimoto et al., PTEP 2015, 061D01

We do not have conclusive results.

Motivation

- **$\bar{K}NN$ state ($I=1/2$, $J^P=0^-$)**



- **3-body calculation**
  - **variational**
  - **Faddeev**

theory

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(v) Ikeda, Kamano, Sato, PTP 124 (2010) 533
(vi) Ohnishi et al. PRC 95 (2017) 065202

exp.

- [FINUDA] Angello et al., PRL 94 (2005) 212303
- [DISTO] Yamazaki et al,. PRL 104 (2010) 132502
- [J-PARC E27] Ichikawa et al., PTEP 2015, 021D01
- [J-PARC E15] Sada et al., PTEP 2016, 051D01

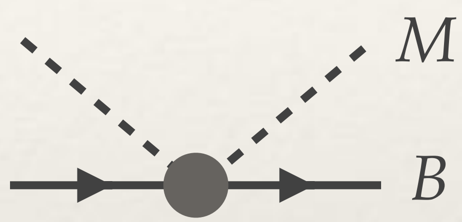
Conclusive result has not been achieved.

Chiral unitary approach

- **Ch-EFT**
  - nonlinear sigma model based on SU(3) chiral sym.
  - expand in terms of small energy, momentum, and mass

on-shell
s wave

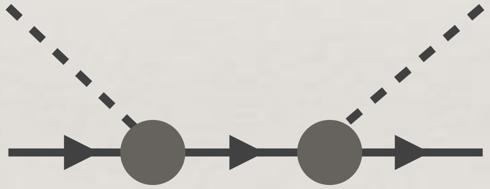
$$\mathcal{L}^{(1)}_{\mathrm{WT}} = \frac{1}{4f^2}\mathrm{Tr}\left(\bar{B}i\gamma^{\mu}[\Phi\partial_{\mu}\Phi - (\partial_{\mu}\Phi)\Phi, B]\right)$$



WT term

$\mathcal{O}(p)$

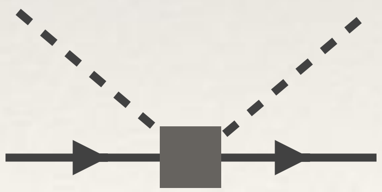
$$\mathcal{L}^{(1)}_{\mathrm{Yukawa}} = -\frac{1}{\sqrt{2}f}\mathrm{Tr}\Big(D(\bar{B}\gamma^{\mu}\gamma_5\{\partial_{\mu}\Phi, B\}) + F(\bar{B}\gamma^{\mu}\gamma_5[\partial_{\mu}\Phi, B])\Big)$$



Born term

$\mathcal{O}(p^2)$

$\mathcal{L}^{(2)}$: including $\underbrace{\text{other low energy constants}}_{\text{free parameter}}$

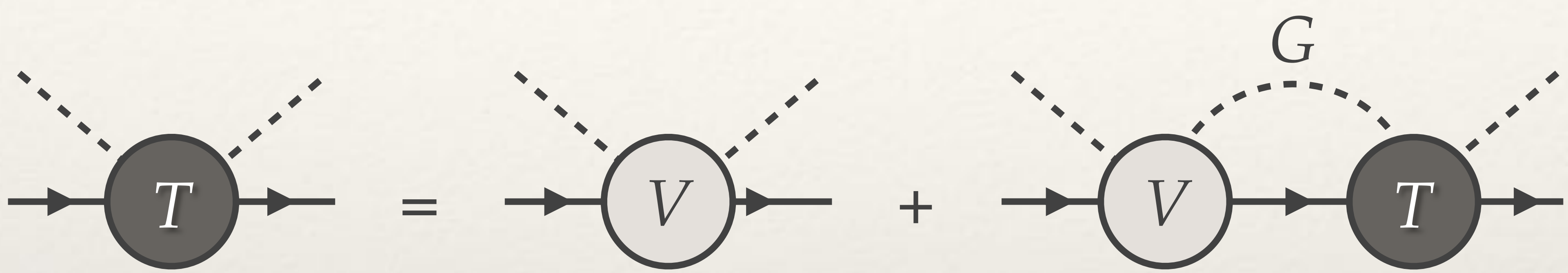


$\mathcal{O}(p^2)$

$\left(\begin{array}{l} B \;:\; \text{baryon octet} \\ \Phi \;:\; \text{meson octet} \end{array} \right.$

Chiral unitary approach

- **chiral unitary approach**
  - non-perturbative treatment (bound state, resonance state)



$$T = V + VGT = V + VGV + VGVGV + \cdots$$

$$= (V^{-1} - G)^{-1}$$: pole ⟷ **resonance state**

$$G(W) = i\int \frac{d^4q}{(2\pi)^4} \frac{2M}{(P-q)^2 - M^2 + i\epsilon} \frac{1}{q^2 - m^2 + i\epsilon}$$

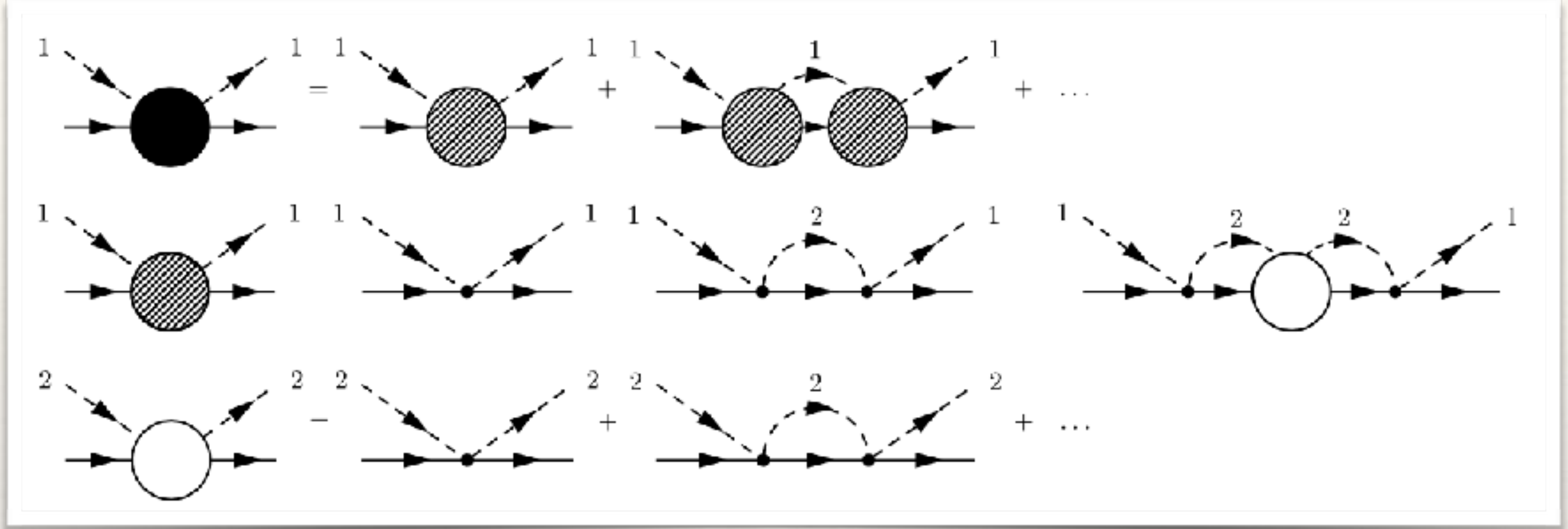
dimensional regularization ⇒ **subtraction constant**

free parameter

fit scattering data

→ **well describe resonance**

Feshbach projection

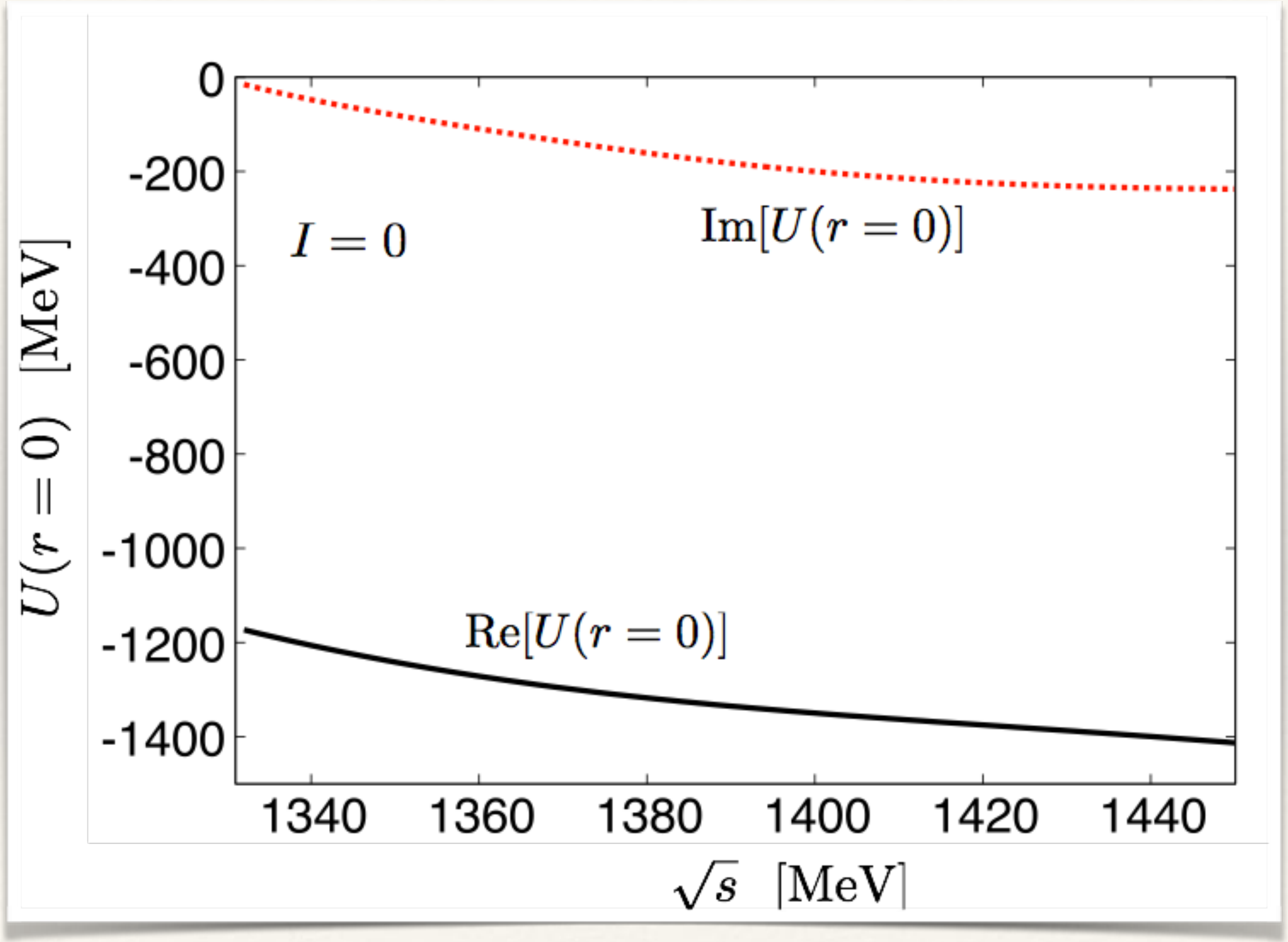


$$T_{\bar{K}N,\bar{K}N} = V^{\text{eff}}_{\bar{K},\bar{K}N} + V^{\text{eff}}_{\bar{K},\bar{K}N} G_{\bar{K}N} T_{\bar{K},\bar{K}N}$$

$$V^{\text{eff}}_{\bar{K}N} = \sum_{m\neq\bar{K}N} V_{\bar{K}N,m} G_m V_{m,\bar{K}N} + \sum_{m,l\neq\bar{K}N} V_{\bar{K}N,m} G_m \tilde{T}_{m,l} G_l V_{l,\bar{K}N}$$

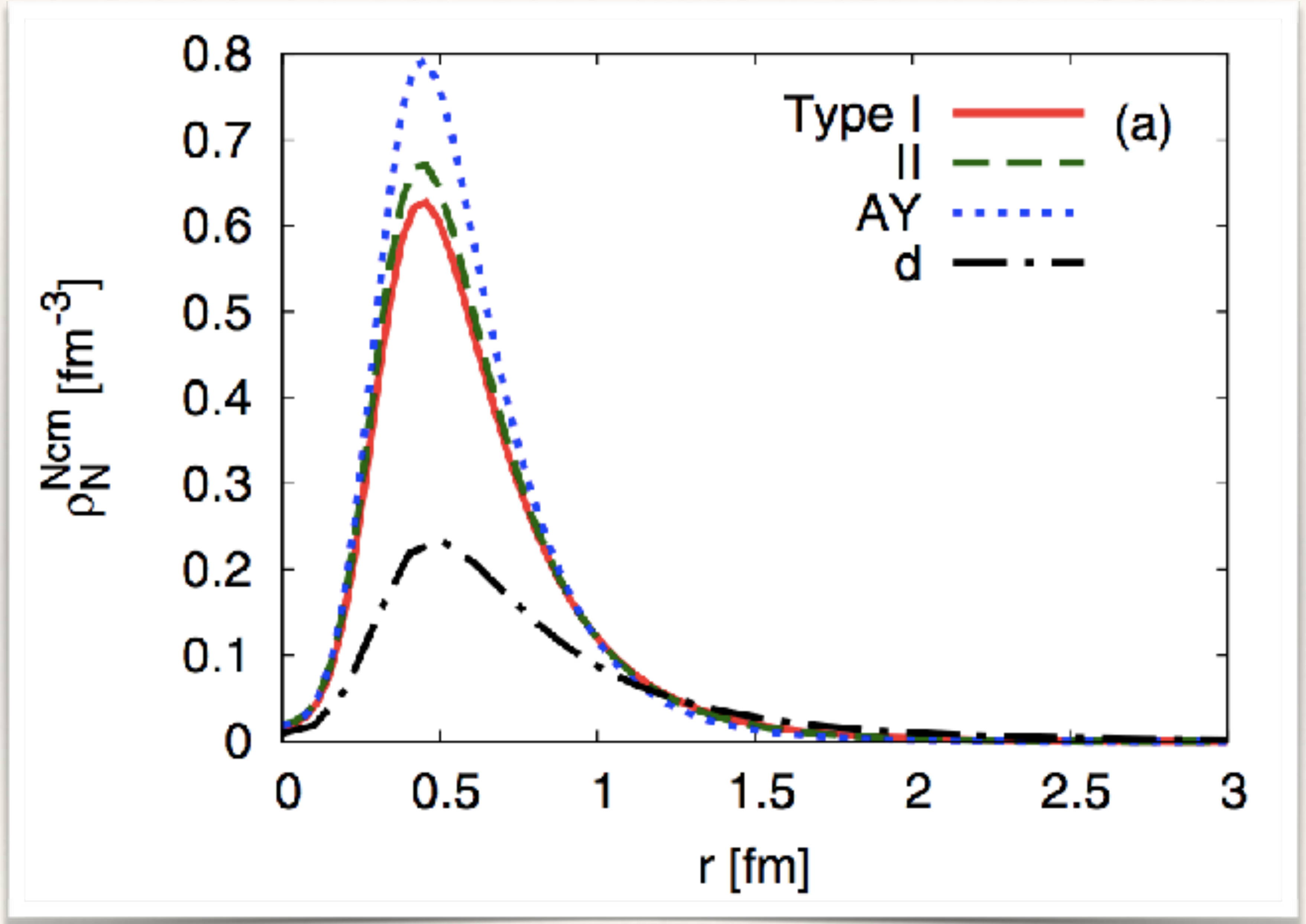
$$\tilde{T}_{m,l} = V_{m,l} + \sum_{k\neq\bar{K}N} V_{m,k} G_k \tilde{T}_{k,l}$$

Kyoto $\bar{\mathrm{K}}$N potential



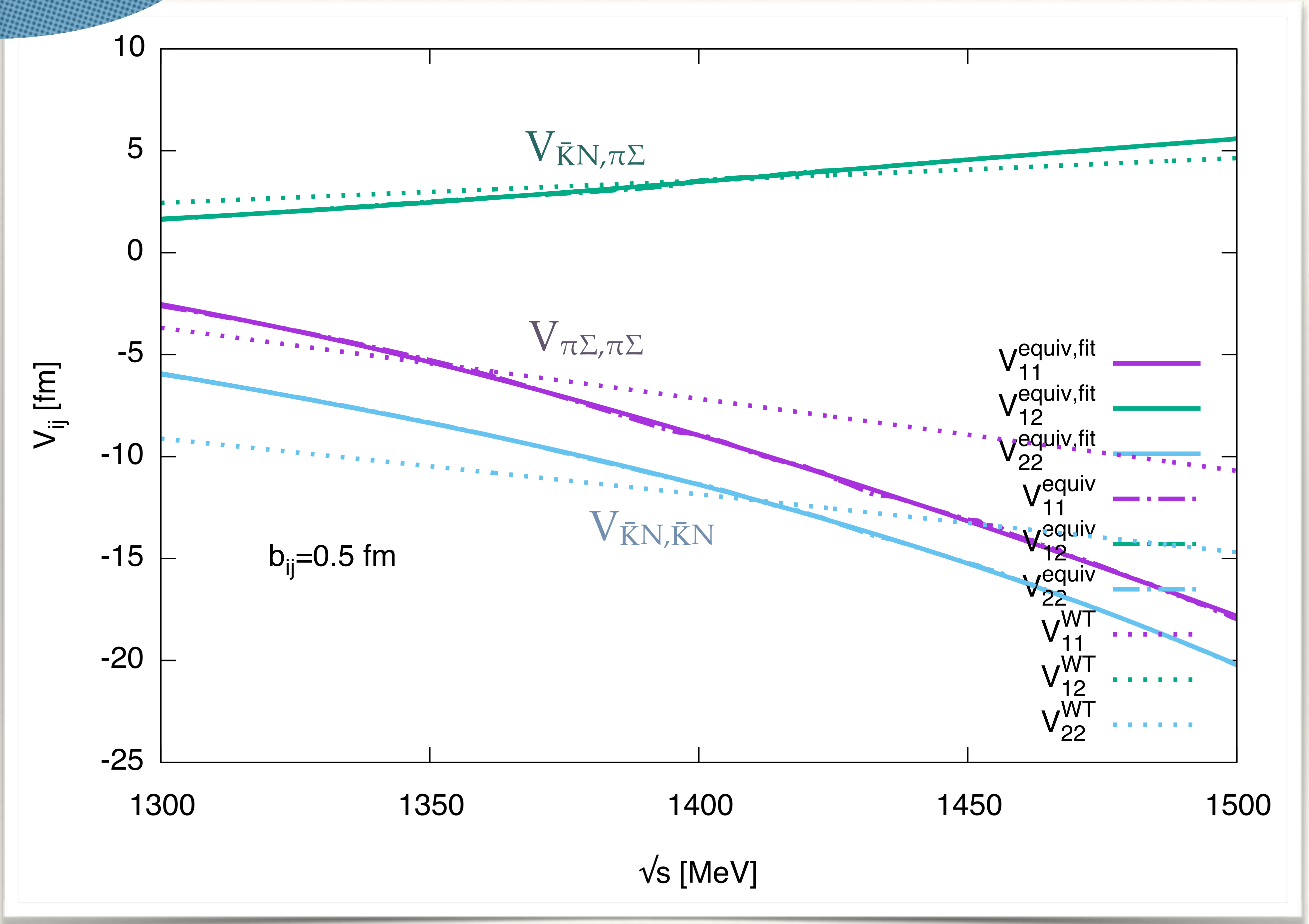
nucleon distribution in $\bar{K}NN$

Ohnishi et al., PRC95 (2017) 065202



$\bar{K}N$-$\pi\Sigma$ potential

HNJH model



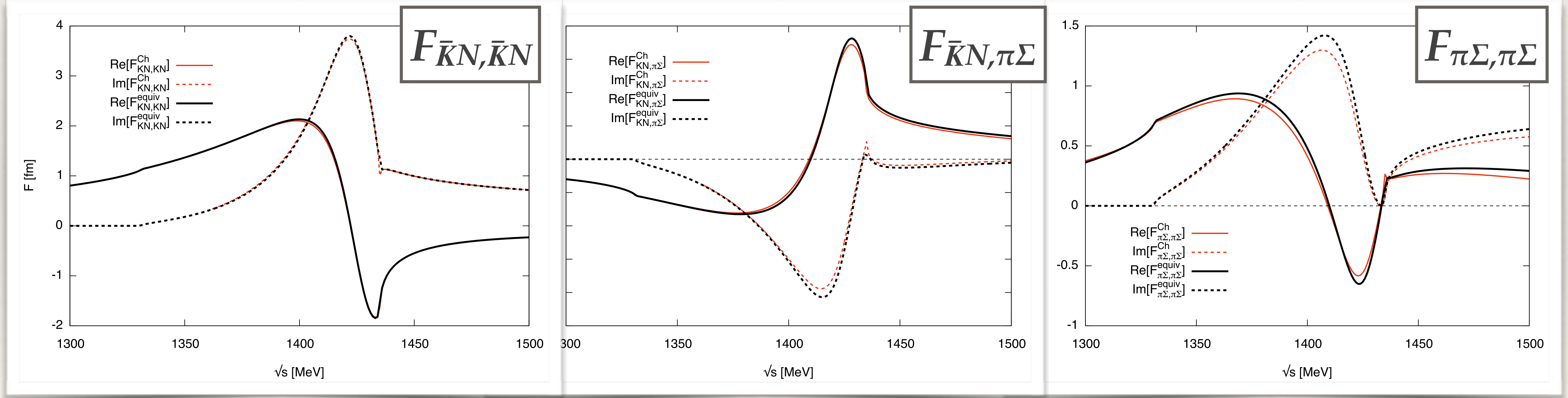
coupled-channel $\bar{K}N$-$\pi\Sigma$ potential

HNJH model

- explicit treatment of $\pi\Sigma$
  - ΔV : real
  - fit range : 1300-1500 MeV
  - polynomial type : 3rd order in E

original pole (Ch-U.) :
1428-17i MeV, 1400-76i MeV

pole from equiv. potential :
1427-17i MeV, 1397-83i MeV



V^{equiv} almost reproduces F^{Ch} including poles.