Variational calculation of K^-pp system

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T. Hyodo (TITech), W. Weise (TU Munich)

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1. Introduction
2. Model wave function
3. Effective $K^{bar}N$ potential and self-consistency on kaon's energy
4. Result of systematic study with effective *s*-wave $K^{bar}N$ potential
5. Other effects
   - Dispersive effect, *P*-wave interaction, Two nucleons absorption
6. Summary and Comments

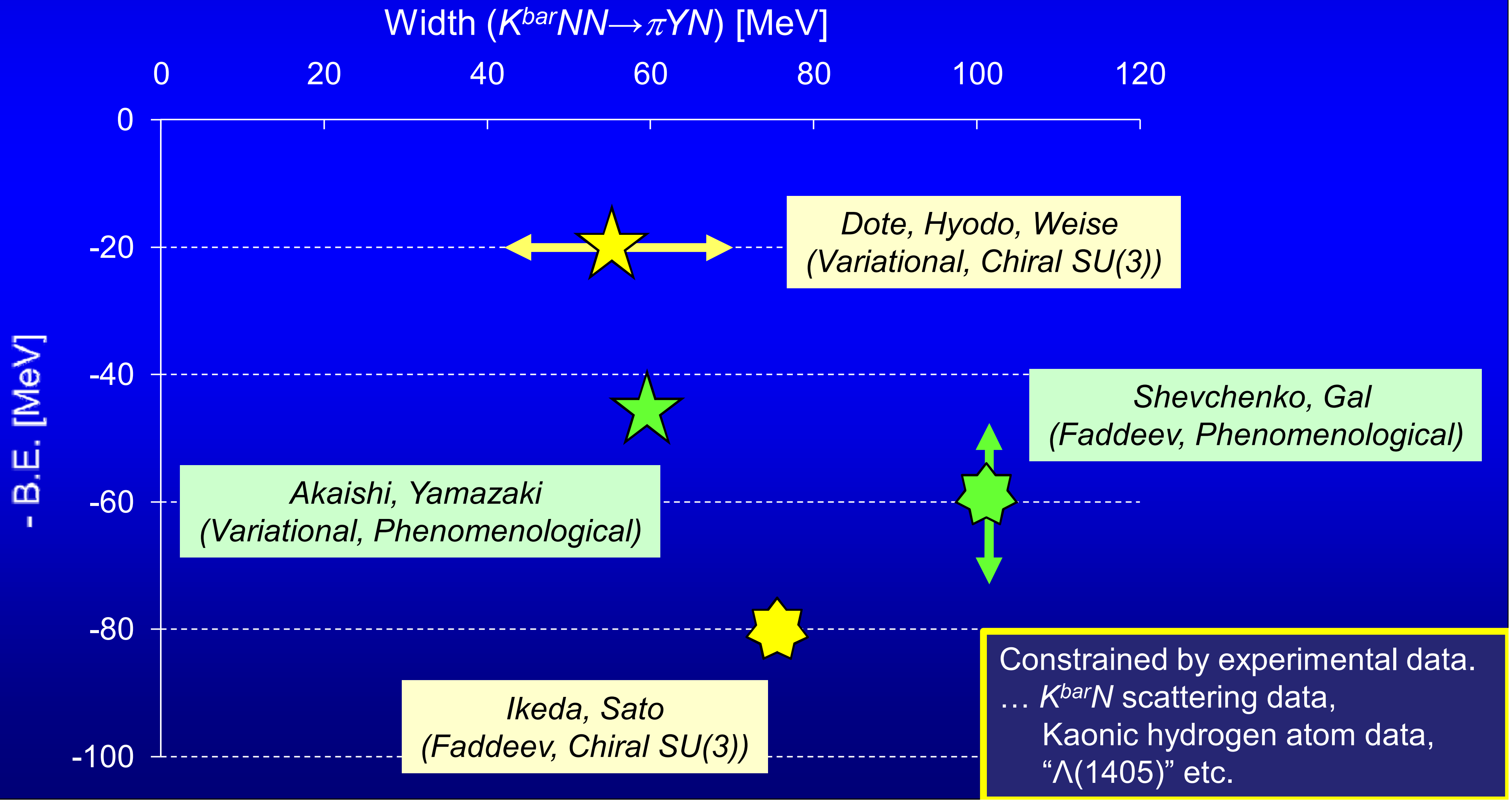
「少数粒子系物理の現状と今後の展望」研究会
08.12.25 @ RCNP

1. Introduction

People have focused on

K^-pp, "a prototype of K^{bar} nuclei"

But, different theoretical studies give different results from each other…



Dote, Hyodo, Weise
(Variational, Chiral SU(3))

Shevchenko, Gal
(Faddeev, Phenomenological)

Akaishi, Yamazaki
(Variational, Phenomenological)

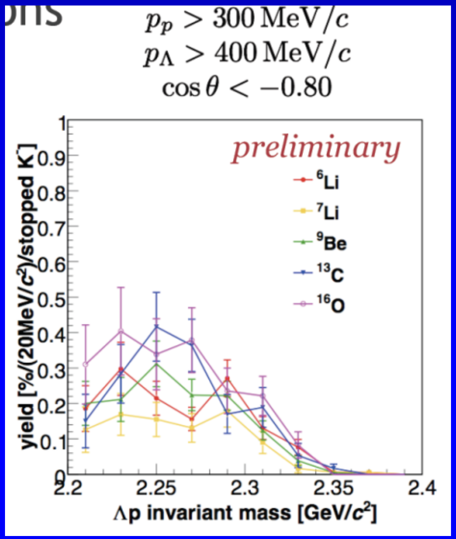
Ikeda, Sato
(Faddeev, Chiral SU(3))

Constrained by experimental data.
… $K^{bar}N$ scattering data,
Kaonic hydrogen atom data,
"Λ(1405)" etc.

1. Introduction

Experiments concerned to this subject…

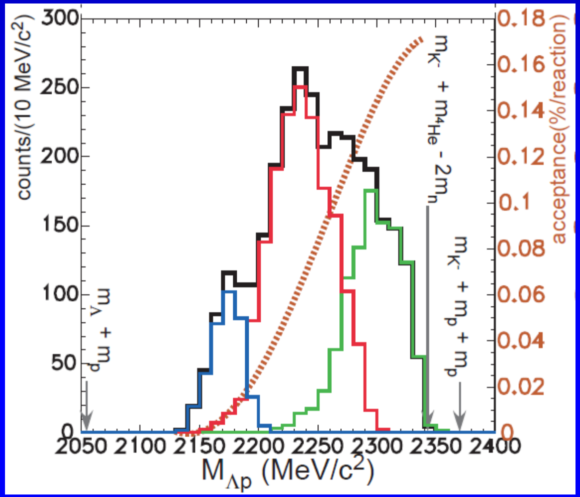
- FINUDA (Run 2)



- K^- absorption on various targets
- Λp invariant mass

H. Fujioka's talk
(FINUDA collaboration)
at PANIC'08

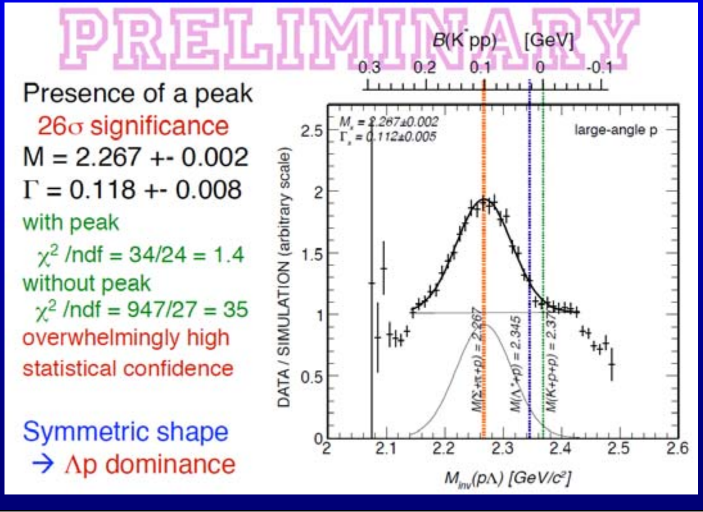
- Re-analysis of KEK E549



- K^- stopped on ^{4}He target
- Λp invariant mass

T. Suzuki et al
(KEK-PS E549 collaboration),
arXiv:0711.4943v1[nucl-ex]

- DISTO collaboration



Presence of a peak
26σ significance
M = 2.267 +- 0.002
Γ = 0.118 +- 0.008
with peak
χ^2 /ndf = 34/24 = 1.4
without peak
χ^2 /ndf = 947/27 = 35
overwhelmingly high
statistical confidence

Symmetric shape
→ Λp dominance

- $p + p \to K^+ + \Lambda + p$ @ 2.85GeV
- Λp invariant mass

T. Yamazaki's talk at EXA'08

1. Introduction

✓ *Variational method*

… Investigate various properties
with the obtained wave function.

✓ *Av18 NN potential*

… a realistic NN potential
with strong repulsive core.

✓ *K^{bar}N potential based on Chiral SU(3) theory*

… Well describe S=-1 meson-baryon scattering
and dynamical generation of Λ(1405)

2. Model wave fucntion

Thanks,
Akaishi-san!

Model wave function — *Simple Correlated Model (Revised)* —

$$\left|\Psi_{SCM2}\right\rangle = N^{-1/2}\left[\ \left|\Phi_1\right\rangle + C_{mix}\left|\Phi_0\right\rangle\ \right]$$

$$J^{\pi} = 0^{-}, T = \frac{1}{2}$$

$$\left|\Phi_1\right\rangle = \Phi_1\left(\vec{r}_1, \vec{r}_2, \vec{r}_K\right)\left|S_N = 0\right\rangle \left|\left[\left[NN\right]_{T_N=1} \overline{K}\right]_{1/2,1/2}\right\rangle$$

$$\left|\Phi_0\right\rangle = \Phi_0\left(\vec{r}_1, \vec{r}_2, \vec{r}_K\right)\left|S_N = 0\right\rangle \left|\left[\left[NN\right]_{T_N=0} \overline{K}\right]_{1/2,1/2}\right\rangle$$

$$\Phi_1\left(\vec{r}_1, \vec{r}_2, \vec{r}_K\right) = G\left(\vec{r}_1\right)G\left(\vec{r}_2\right)G'\left(\vec{r}_K\right) \cdot F\left(\vec{r}_1, \vec{r}_2\right)\left\{F_1'\left(\vec{r}_1, \vec{r}_K\right)F_2'\left(\vec{r}_2, \vec{r}_K\right) + F_1'\left(\vec{r}_2, \vec{r}_K\right)F_2'\left(\vec{r}_1, \vec{r}_K\right)\right\}$$

$$\Phi_0\left(\vec{r}_1, \vec{r}_2, \vec{r}_K\right) = G\left(\vec{r}_1\right)G\left(\vec{r}_2\right)G'\left(\vec{r}_K\right) \cdot F\left(\vec{r}_1, \vec{r}_2\right)\left\{F_1'\left(\vec{r}_1, \vec{r}_K\right)F_2'\left(\vec{r}_2, \vec{r}_K\right) - F_1'\left(\vec{r}_2, \vec{r}_K\right)F_2'\left(\vec{r}_1, \vec{r}_K\right)\right\}$$

Single-particle motion

$$G\left(\vec{r}_i\right) = \exp\left[-\mu\, \vec{r}_i^{\,2}\right]$$

Nucleon

$$G'\left(\vec{r}_K\right) = \exp\left[-\gamma\, \vec{r}_K^{\,2}\right]$$

Kaon

NN correlation function

$$F\left(\vec{r}_1, \vec{r}_2\right) = 1 - \sum_n f_n^{NN} \exp\left[-\lambda_n^{NN}\left(\vec{r}_1 - \vec{r}_2\right)^2\right]$$

K^bar^N correlation function

$$F_a'\left(\vec{r}_i, \vec{r}_K\right) = 1 + \sum_n f_n^{KN,a} \exp\left[-\lambda_n^{KN}\left(\vec{r}_K - \vec{r}_i\right)^2\right]$$

2. Model wave fucntion

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$$\left|\Phi_1\right\rangle = \Phi_1\left(\vec{r}_1, \vec{r}_2 \right.$$

$$\left|\Phi_0\right\rangle = \Phi_0\left(\vec{r}_1, \right.$$

NN in $\left|\Phi_1\right\rangle$: ${}^1E,\ T_N=1$ ⇨ K^-pp

NN in $\left|\Phi_0\right\rangle$: ${}^1O,\ \boxed{T_N=0}$

$$\Phi_1\left(\vec{r}_1, \vec{r}_2, \right.$$

$$\Phi_0\left(\vec{r}_1, \vec{r}_2, \vec{r}_K\right) = G\left(\vec{r}_1\right)G\left(\vec{r}_2\right)G'\left(\vec{r}_K\right) \cdot F\left(\vec{r}_1, \vec{r}_2\right)\left\{F_1'\left(\vec{r}_1, \vec{r}_K\right)F_2'\left(\vec{r}_2, \vec{r}_K\right) - F_1'\left(\vec{r}_2, \vec{r}_K\right)F_2'\left(\vec{r}_1, \vec{r}_K\right)\right\}$$

Singl

$$G\left(\vec{r}_i\right)$$

$$G'\left(\vec{r}_K\right)$$

NN correlation
is directly treated.

NN correlation function

$$F\left(\vec{r}_1, \vec{r}_2\right) = 1 - \sum_n f_n^{NN} \exp\left[-\lambda_n^{NN}\left(\vec{r}_1 - \vec{r}_2\right)^2\right]$$

K^bar N correlation function

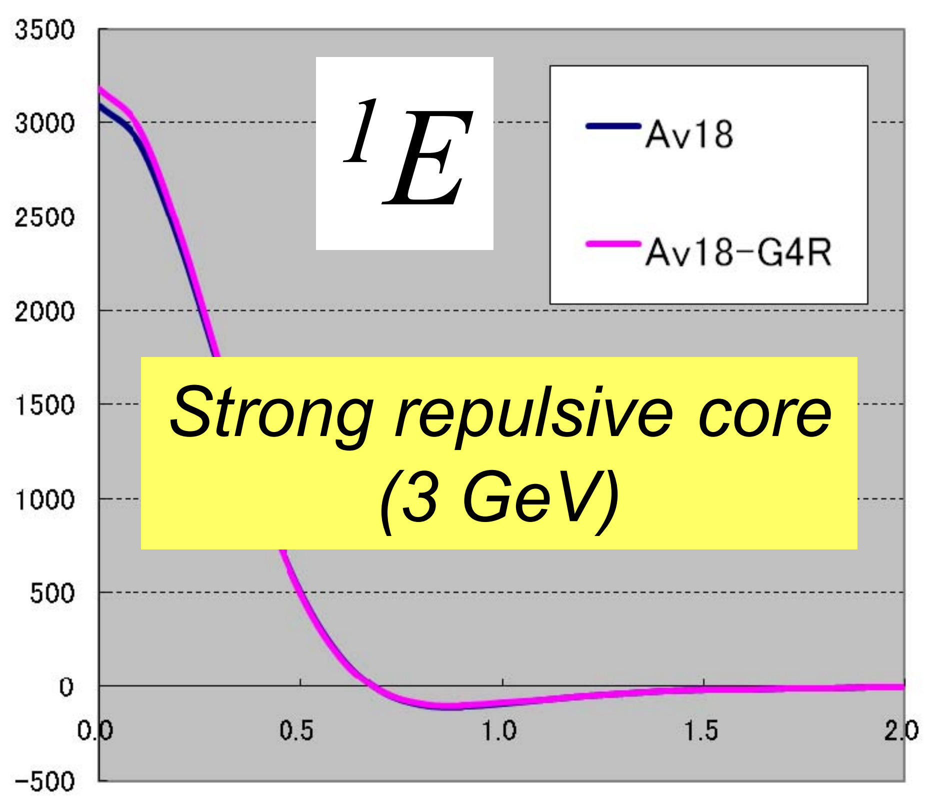
$$F_a'\left(\vec{r}_i, \vec{r}_K\right) = 1 + \sum_n f_n^{KN,a} \exp\left[-\lambda_n^{KN}\left(\vec{r}_K - \vec{r}_i\right)^2\right]$$

2. *NN* potential

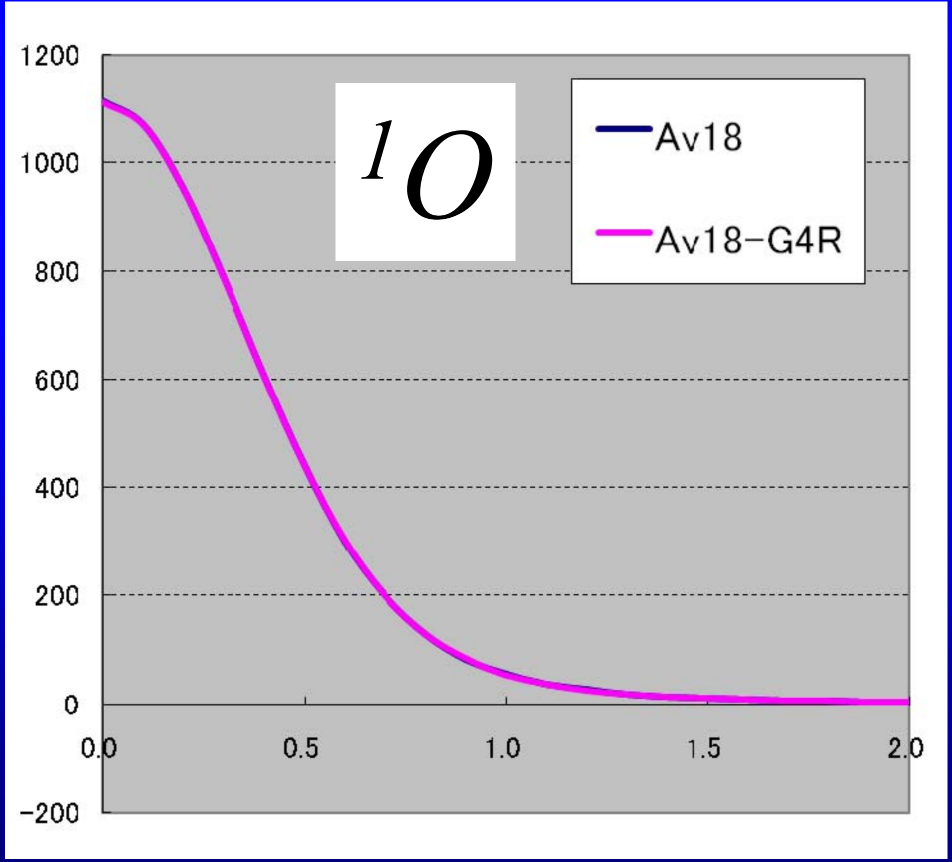
A realistic NN potential … Av18 potential

- Use one-pion-exchange potential (Central and Spin-Spin) and L^2 potentials in addition to phenomenological central term (= repulsive core).

<u>Central potential</u>



Strong repulsive core (3 GeV)



2. Model

Influence of the improvement

T_N=1 + T_N=0

T_N=1 only

	SCM ver2	SCM ver1	ATMS
C_{mix}	Finite	Zero	---
B. E.	51.4	39.0	48
$\Gamma(K^{bar}N \to \pi Y)$	61.0	60.0	61
B(K)	80.0	65.8	68
Nucl. E	28.7	26.8	20
Kinetic	162.4	147.0	167
NN pot	-19.2	-19.8	-19
K^{bar}N pot	-194.6	-166.2	-196
Rel (NN)	1.83	1.75	1.90
Rel (KN)	1.55	1.54	1.57
Mixing ratio	5.9%	0.0%	

NN potential … Tamagaki potential

Effective $K^{bar}N$ potential … Akaishi-Yamazaki potential

3. Model

Influence of the improvement

$T_N=1$

$$\langle \Phi_1 | \hat{V}_{\bar{K}N} | \Phi_1 \rangle = \frac{3}{4} V^{\bar{K}N}_{I=0} + \frac{1}{4} V^{\bar{K}N}_{I=1}$$

$$\langle \Phi_0 | \hat{V}_{\bar{K}N} | \Phi_0 \rangle = \frac{1}{4} V^{\bar{K}N}_{I=0} + \frac{3}{4} V^{\bar{K}N}_{I=1}$$

$$\langle \Phi_0 | \hat{V}_{\bar{K}N} | \Phi_1 \rangle = \frac{\sqrt{3}}{4} \left[V^{\bar{K}N}_{I=0} - V^{\bar{K}N}_{I=1} \right]$$

Additional $K^{bar}N$ attraction

C_{mix}	SC		
B. E.			
$\Gamma(K^{bar}N \to \pi Y)$			
		.8	68
Nucl. E	28.7	26.8	20
Kinetic	162.4	147.0	167
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NN potential … Tamagaki potential

Effective $K^{bar}N$ potential … Akaishi-Yamazaki potential

3. Local $K^{bar}N$ potential based on Chiral SU(3)

T. Hyodo and W. Weise, PRC77, 035204(2008)

Effective K

Effective K^{bar}N potential …

reproduce the scattering $K^{bar}N$ amplitude obtained with Chiral unitary model

$$U_I^{Eff}\left(r,\sqrt{s}\right) = V_I^{Eff}\left(\sqrt{s}\right)\cdot g_a\left(r\right)$$

$$g_a\left(r\right)=\left(\frac{1}{\pi a^2}\right)^{3/2}\exp\left[-\left(r/a\right)^2\right]$$

- *Single channel*
  … only $K^{bar}N$ channel, $\pi\Sigma$ is eliminated.
- *Energy dependent and Complex potential*
- *Local, Gaussian form*

$$T_{ij}^{Ch.U.} = V_{ij} + V_{ik}\,G_k\,T_{kj}^{Ch.U.}$$

: Chiral unitary

Relativistic / Coupled Channel

$T_{11}^{Ch.U.}$ ⋯ T−matrix for $K^{bar}N$ channel

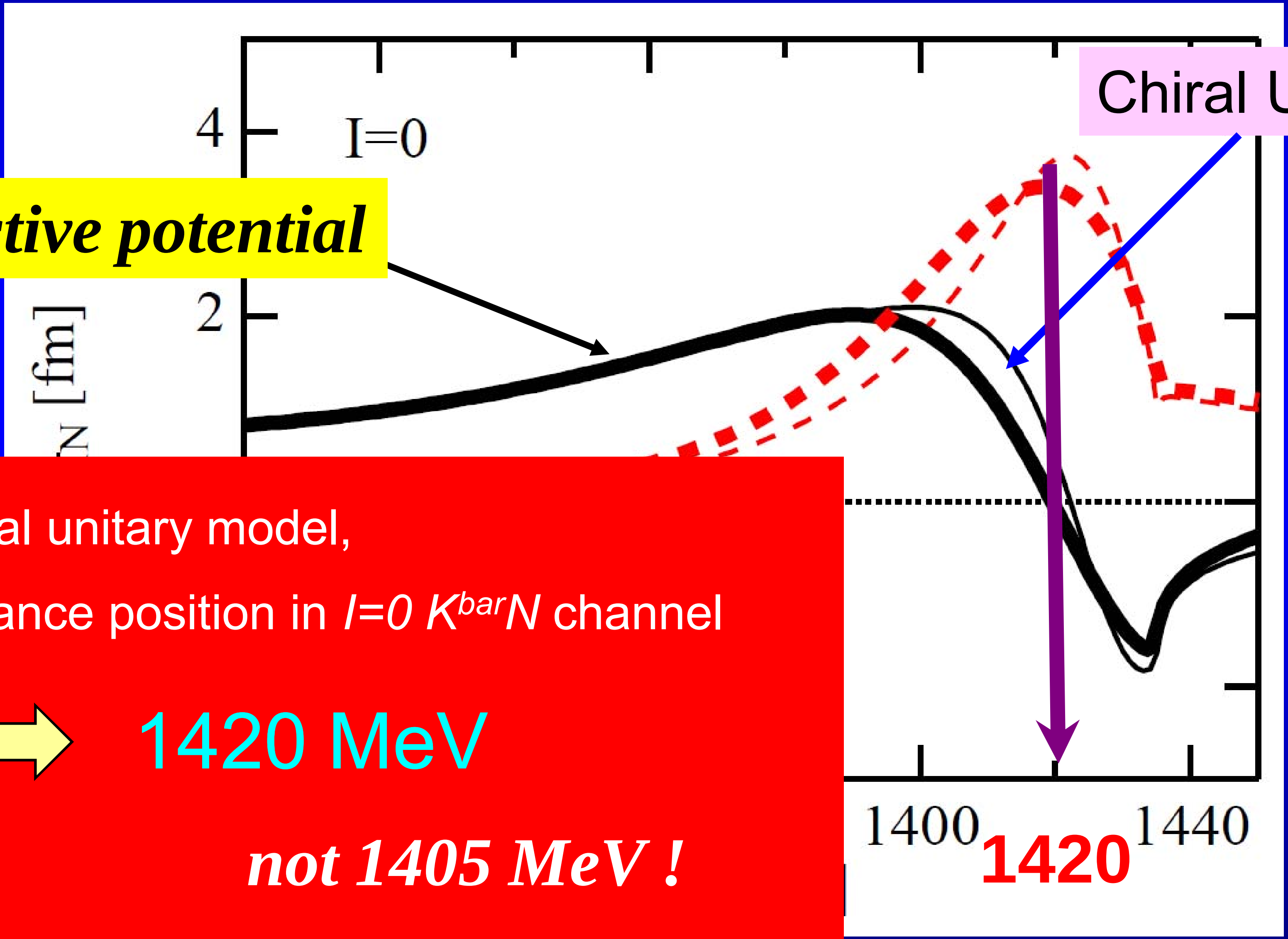
$$T_{11} = U^{Eff} + U^{Eff}\,G_1\,T_{11}$$

: Effective local potential

Non−relativistic / Single Channel

3. Local *$K^{bar}N$* potential based on Chiral SU(3)

$I=0$ $K^{bar}N$ scatteing amplitude



Chiral Unitary

Effective potential

1420

In Chiral unitary model,

Resonance position in *$I=0$ $K^{bar}N$* channel

⇨ 1420 MeV

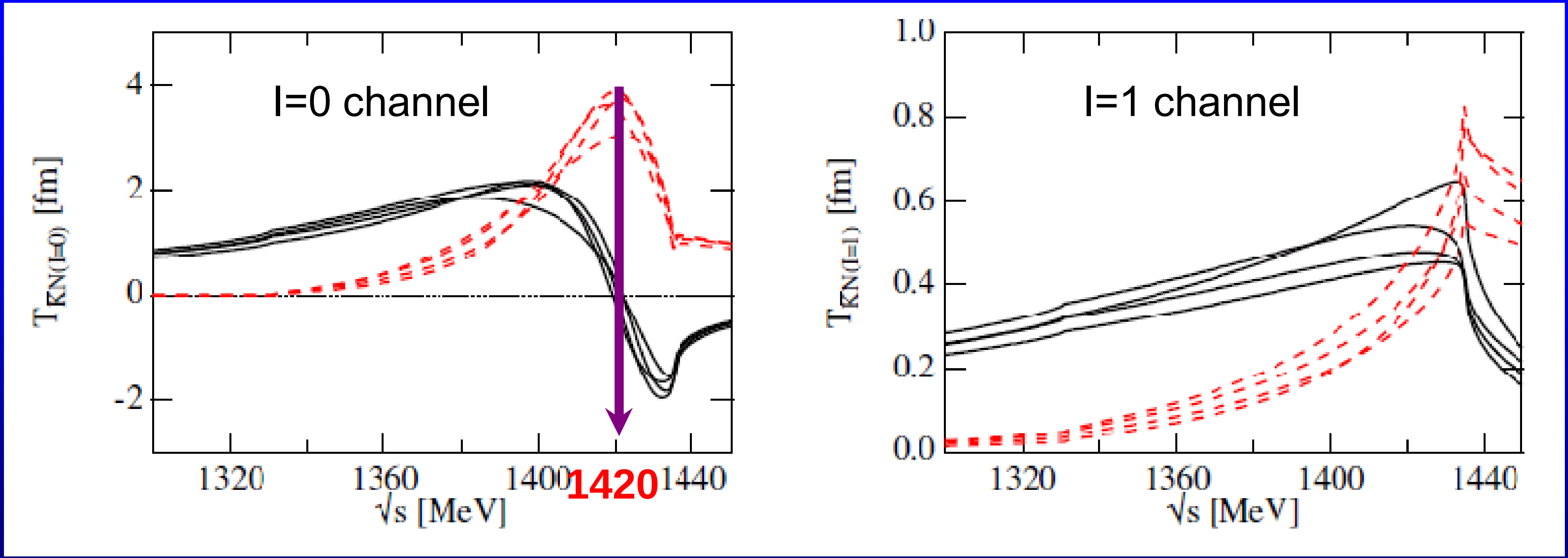
not 1405 MeV !

Chiral unitary; T. Hyodo, S. I. Nam, D. Jido, and A. Hosaka, Phys. Rev. C68, 018201 (2003)

3. Local $K^{bar}N$ potential based on Chiral SU(3)

➢ Four Chiral unitary models:

- “ORB” E. Oset, A. Ramos, and C. Bennhold, Phys. Lett. B527, 99 (2002)
- “HNJH” T.Hyodo, S. I. Nam, D. Jido, and A. Hosaka, Phys. Rev. C68, 018201 (2003)
- “BNW” B. Borasoy, R. Nissler, and W. Weise, Eur. Phys. J. A25, 79 (2005)
- “BMN” B. Borasoy, U. G. Meissner, and R. Nissler, Phys. Rev. C74, 055201 (2006)



3. Self-consistency of kaon's energy

- Hamiltonian $\hat{H} = \hat{T} + \hat{V}_{NN} + \mathrm{Re}\left[\hat{V}_{KN-S}\left(\sqrt{s}\right)\right] - \hat{T}_{CM}$

$$\hat{V}_{NN} = V_C(r) + V_{ss}(r)\,\hat{\sigma}_1 \cdot \hat{\sigma}_2 + V_{L2}(r)\,\hat{\mathbf{L}}^2$$

$\mathrm{Im}\left[\hat{V}_{KN-S}\left(\sqrt{s}\right)\right]$ treated perturbatively.

✓ *Self-consistency for anti-kaon's energy* ⇐ $\hat{V}_{KN-S}\left(\sqrt{s}\right)$

Controlled by "***Anti-kaon's binding energy***"

$$B(K) \equiv -\left\{ \left\langle \hat{H} \right\rangle - \left\langle \hat{H}_{Nucl} \right\rangle \right\}$$

$\hat{H}_{Nucl}$: Hamiltonian of nuclear part

- Try two ansatz for $\sqrt{s}$.

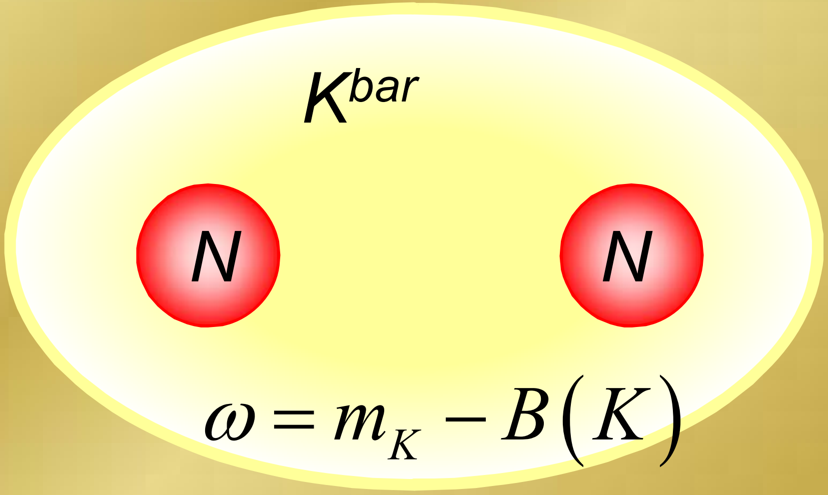
$$\sqrt{s} = M_N + \omega = \begin{cases} M_N + m_K - B(K) \\ M_N + m_K - B(K)/2 \end{cases}$$

# of kaon’s energy

$s\big)\big]-\hat{T}_{CM}$

$$\hat{V}_{NN}=V_C(r)+V_{ss}(r)\,\hat{\sigma}_1\cdot\hat{\sigma}_2+V_{L2}(r)\,\hat{\mathbf{L}}^2$$

perturbatively.



K^{bar} field surrounds two nucleons which are almost static.

’s energy ⇐ $\hat{V}_{KN-S}\left(\sqrt{s}\right)$

Controlled by “***Anti-kaon’s binding energy***”

$$B(K)\equiv-\left\{\left\langle\hat{H}\right\rangle-\left\langle\hat{H}_{Nucl}\right\rangle\right\}$$

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- Try two ansatz for $\sqrt{s}$.

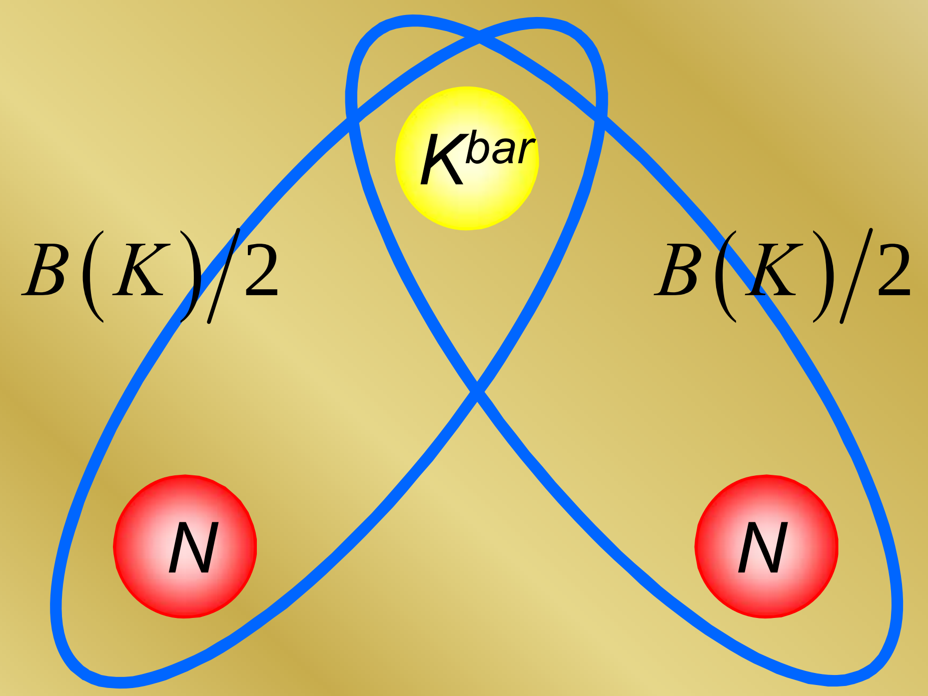
$$\sqrt{s}=M_N+\omega=\begin{cases}\boxed{M_N+m_K-B(K)}\\ M_N+m_K-B(K)/2\end{cases}$$

3. Self-consistenc

- Hamiltonian $\widehat{H} = \widehat{T} + \widehat{V}_{NN} + \mathrm{Re}\Big[\widehat{V}_{KN-S}\Big($

$\mathrm{Im}\left[\widehat{V}_{KN-S}\left(\sqrt{s}\right)\right]$ treate

✓ *Self-consistency for anti-kac*



K^{bar} is bound by each nucleon with B(K)/2 binding energy.

Controlled by “***Anti-kaon’s binding energy***”

$$B(K) \equiv -\left\{\left\langle \widehat{H} \right\rangle - \left\langle \widehat{H}_{Nucl} \right\rangle\right\}$$

$\widehat{H}_{Nucl}$: Hamiltonian of nuclear part

- Try two ansatz for $\sqrt{s}$.

$$\sqrt{s} = M_N + \omega = \begin{cases} M_N + m_K - B(K) \\ \boxed{M_N + m_K - B(K)/2} \end{cases}$$

4. Result with effective *s*-wave $K^{bar}N$ potential

ORB, HNJH
BNW, BMN

×

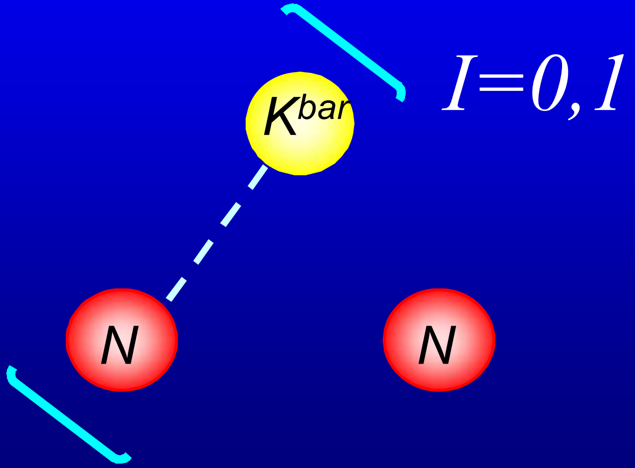
$$\sqrt{s} = \begin{cases} M_N + m_K - B(K) \\ M_N + m_K - B(K)/2 \end{cases}$$

Total B. E. : 20 ± 3 MeV
$\Gamma(K^{bar}N \to \pi Y)$: 40 ∼ 70 MeV

… Shallow binding
… Not so dependent on chiral unitary models

NN distance = 2.2 fm
$K^{bar}N$ distance = 2.0 fm

∼ *NN* distance in normal nuclei



$I=0$ $K^{bar}N$ distance = 1.82 fm
$I=1$ $K^{bar}N$ distance = 2.33 fm

… $I=0$ $K^{bar}N$ potential is more attractive than $I=1$ one.

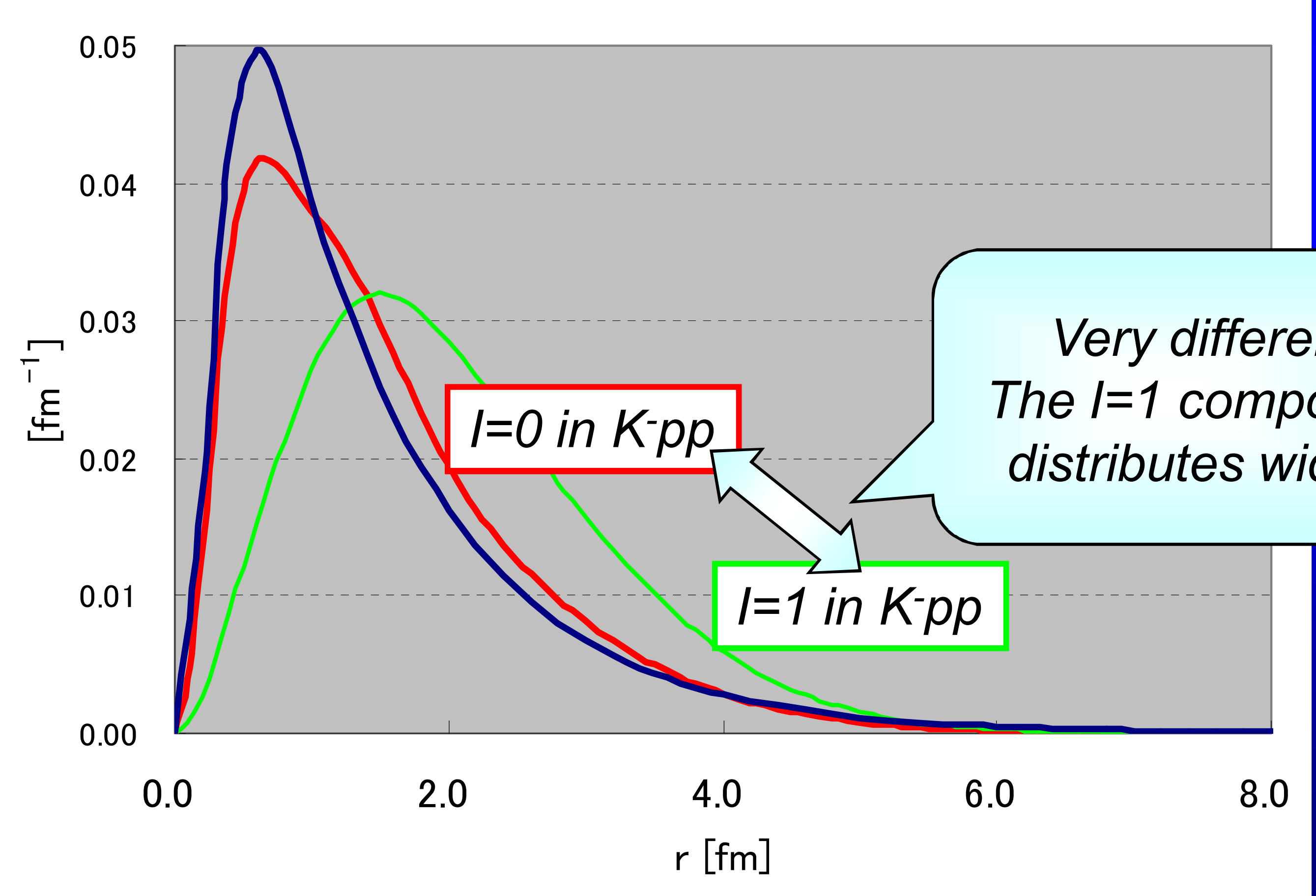
Structure of K⁻pp

K^bar^N potential based on “HNJH”
“Corrected”, $\sqrt{s} = M_N + m_K - B(K)$

Density distribution
$K^{bar}N$ pair in K^-pp vs $\Lambda(1405)$

$$r^2 \rho_{\bar{K}N}^{Normalized}(r)$$

For comparison,
All densities are normalized to 1.



Very different.
The I=1 component distributes widely.

Structure of $K^{-}pp$

$K^{bar}N$ potential based on "HNJH"

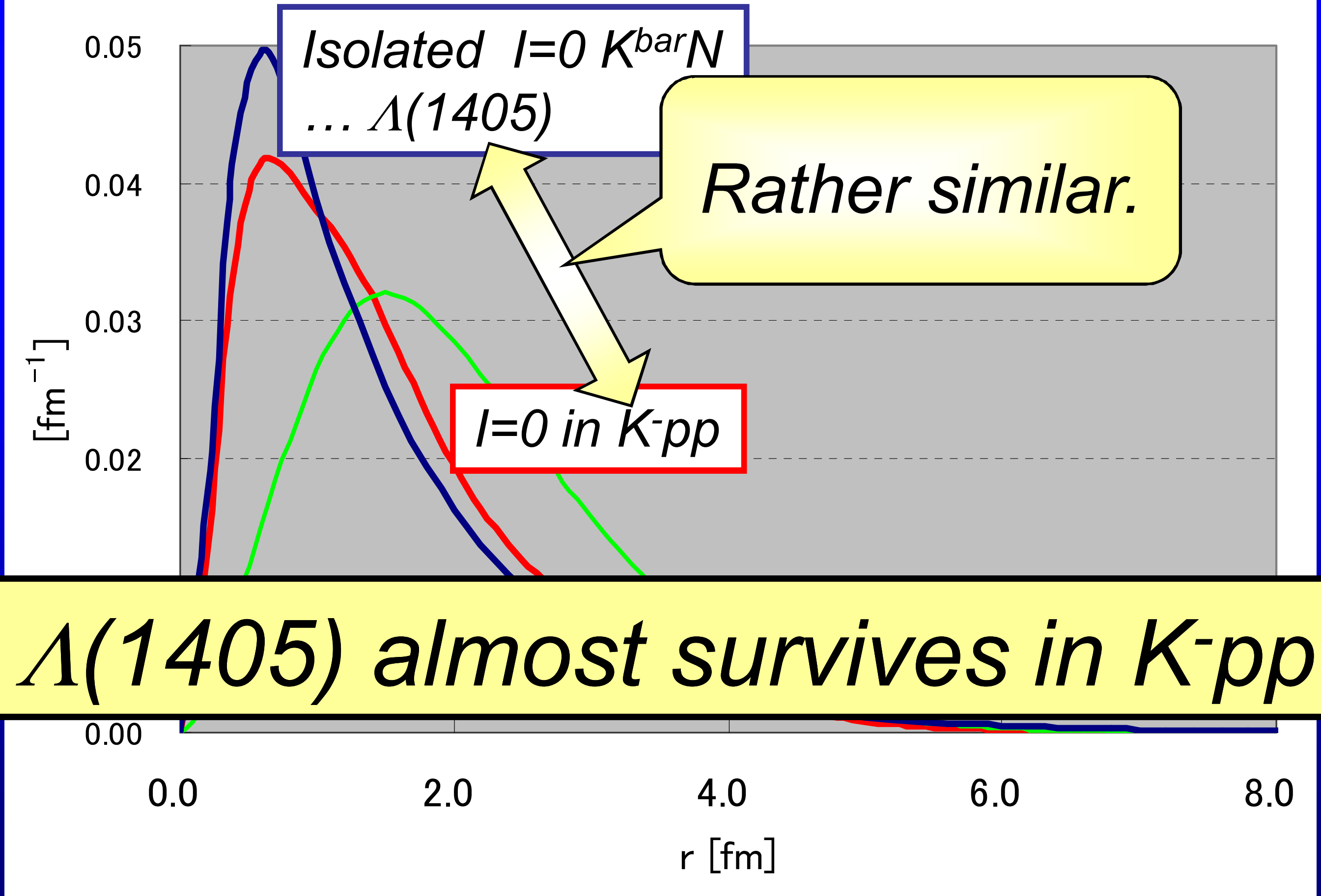
"Corrected", $\sqrt{s} = M_N + m_K - B(K)$

Density distribution

$K^{bar}N$ pair in $K^{-}pp$ vs $\Lambda(1405)$

$r^2 \rho_{\bar{K}N}^{Normalized}(r)$

For comparison,
All densities are normalized to 1.



Isolated I=0 $K^{bar}N$
… $\Lambda(1405)$

Rather similar.

I=0 in $K^{-}pp$

$\Lambda(1405)$ almost survives in $K^{-}pp$!

5. Other effects

Estimate other possible effects, perturbatively…

I. Dispersive correction

(Effect of imaginary part)

II. p-wave $K^{bar}N$ *potential*

III. Two nucleon absorption

I. Dispersive correction

(Effect of imaginary potential)

Two-body system ($I=0\ K^{bar}N$) case

Complex

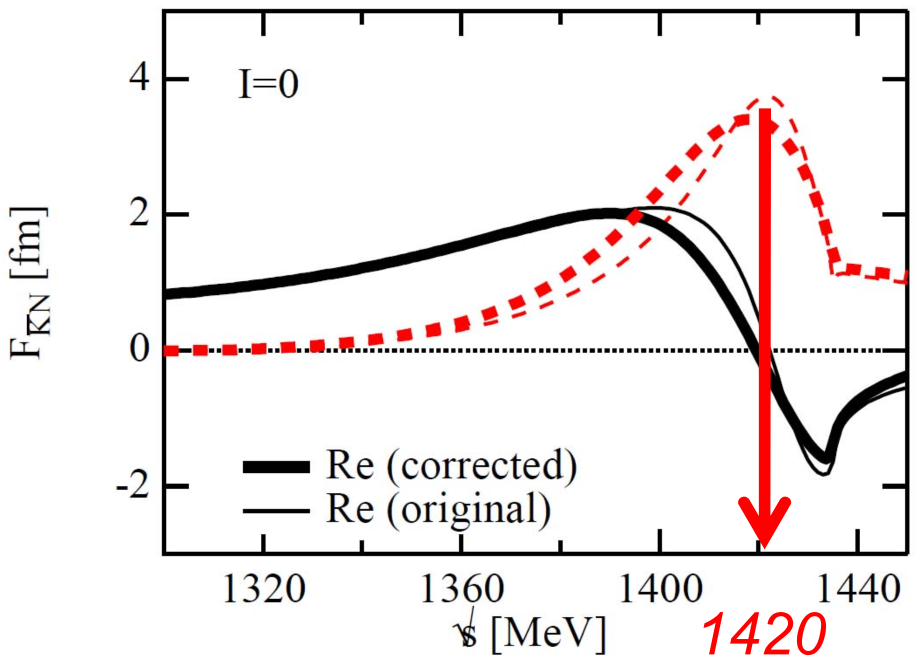
$$U_{I=0}^{Eff}\left(r,\sqrt{s}\right)$$

Lippmann-Schwinger eq.
with
the complex potential

B. E. ∼ 15 MeV

Schroedinger eq.
with
only the real part

B. E. ∼ 10 MeV



I. Dispersive correction

(Effect of imaginary potential)

Two-body system ($I=0$ $K^{bar}N$) case

Lippmann-Schwinger eq.
with
the complex potential

$$U^{Eff}_{I=0}\left(r,\sqrt{s}\right)$$

Schroedinger eq.
with
only the real part

B. E. ～ 15 MeV

B. E. ～ 10 MeV

Dispersive correction for $K^{bar}N$ system
～ +5 MeV to B. E.

×2

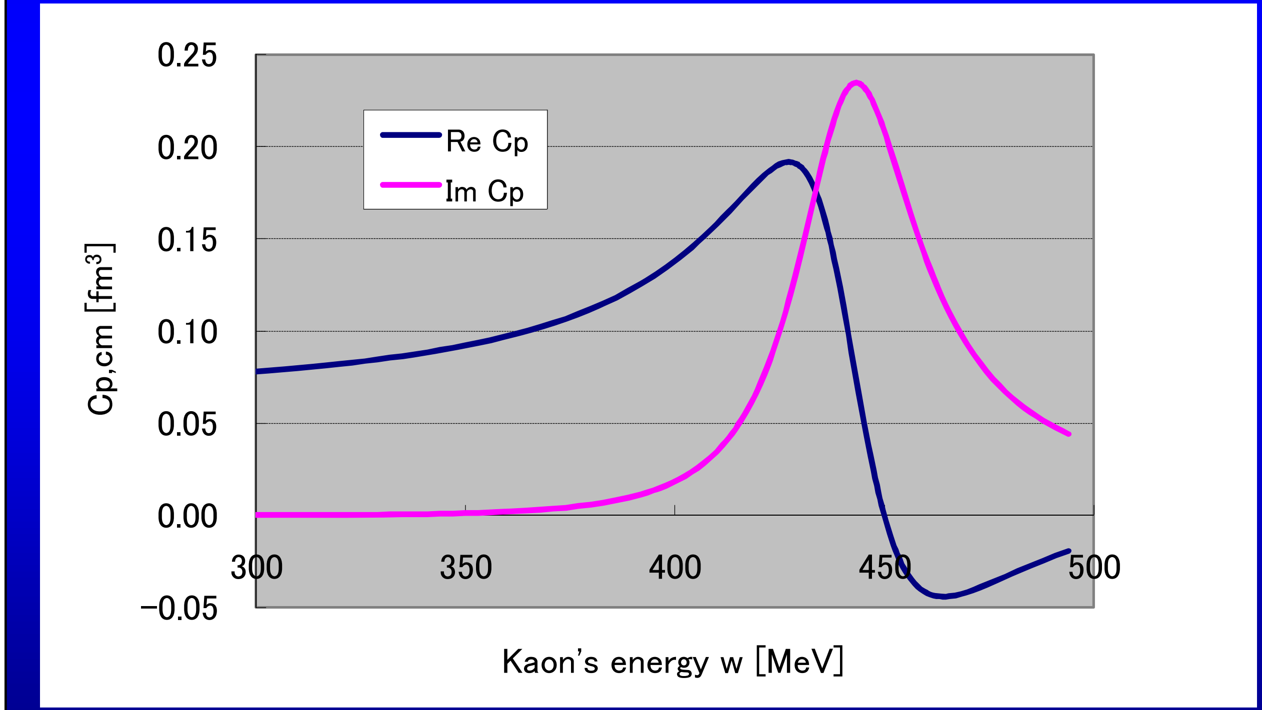
Dispersive correction for $K^{bar}NN$
+6 ～ +18 MeV

Considering
Four variants of models…

II. P-wave $K^{bar}N$ potential

- Estimate its contribution *perturbatively.*
- Derived from *“Full”* scattering volume.

$$v_{KN,P-wave}(\mathbf{r}_K-\mathbf{r}_N,\omega)=-\frac{1}{2\omega}\cdot\frac{4\pi\sqrt{s}}{M_N}C_{KN}(\omega)\cdot\vec{\nabla}\frac{1}{\pi^{3/2}a_P^3}\exp\left[-(\mathbf{r}_K-\mathbf{r}_N)^2\Big/a_P^2\right]\vec{\nabla}$$



For a_p= 0.4～0.9 fm,

✓ *Re* $V_{KN,P}$ ～ *+3 MeV*

…small and repulsive

✓ $\Gamma_{p\text{-}wave}$ = *-2 Im* $V_{KN,P}$ = *10 ～ 35 MeV*

R. Brockmann, W. Weise and L. Tauscher,
Nucl. Phys. A 308, 365 (1978)

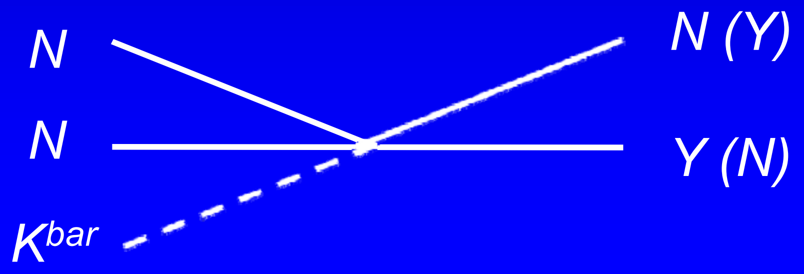
III. Two nucleon absorption

$$\Delta\Gamma_{abs} = \frac{2\pi\tilde{B}_0}{\omega}\beta_{pp}(\omega)\int d^3\boldsymbol{r}\,\rho_{\bar{K}}(\boldsymbol{r})\,\rho_N^2(\boldsymbol{r}),$$

J. Mares, E. Friedman and A. Gal,
Nucl. Phys. A 770, 84 (2006)

- *For mean-field model*
  … no correlation between two nucleons

- *Contact interaction*



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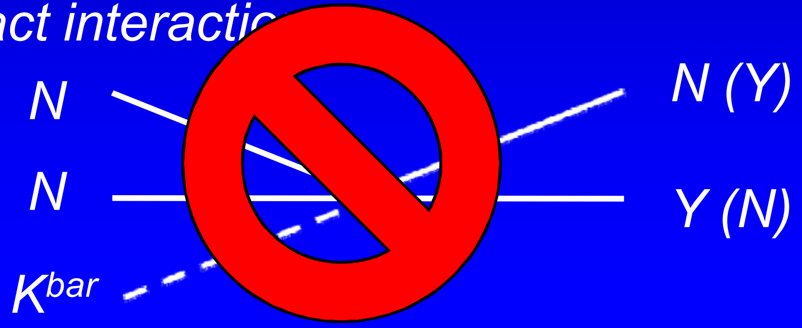

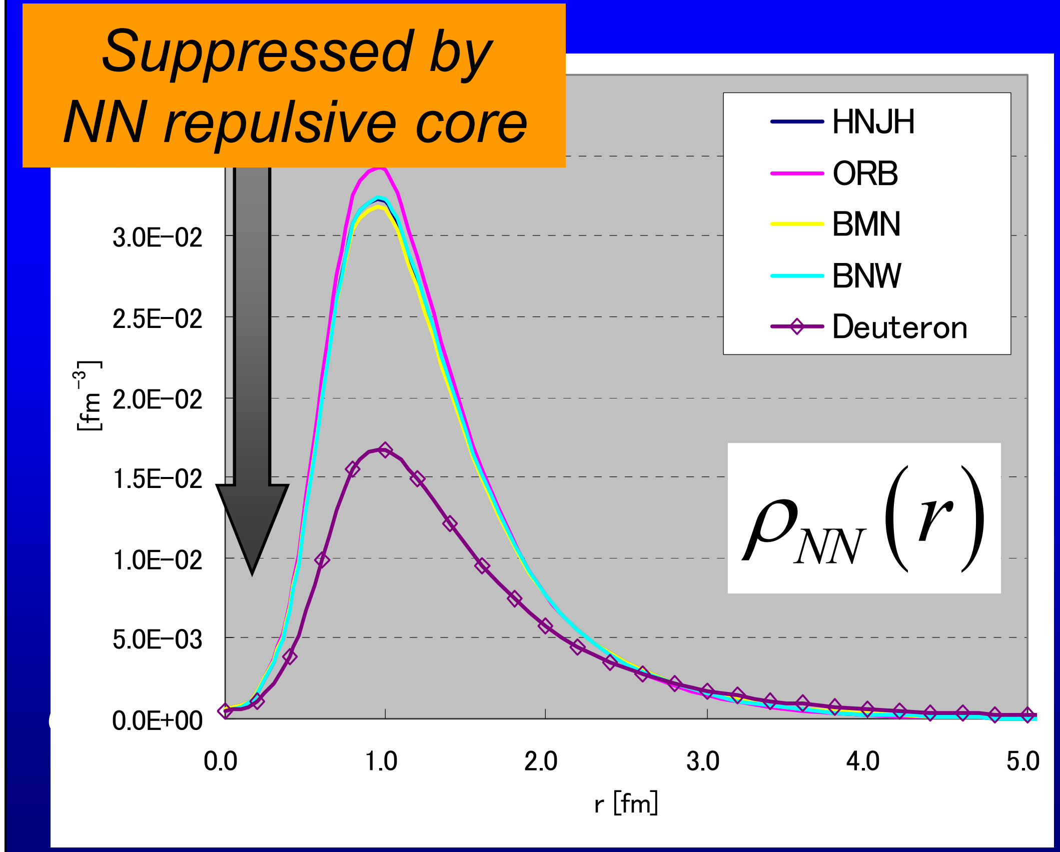
Suppressed by NN repulsive core

III. Two nucleon absorption

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J. Mares, E. Friedman and A. Gal,
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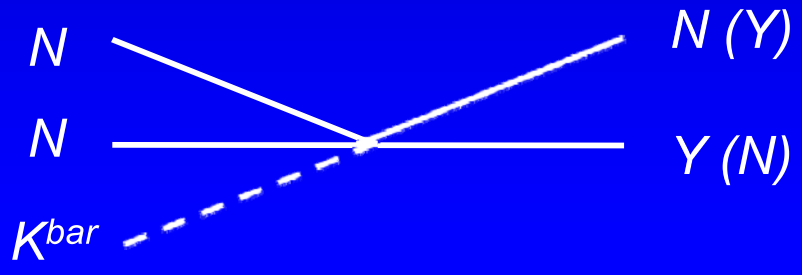
In our model, particles are strongly correlated.
The NN can't touch each other, due to the strong NN repulsion!!

$$\Delta\Gamma_{abs}(K^- pp \to YN) = \frac{2\pi B_0}{\omega}\beta_{pp}(\omega) \times \int d^3\boldsymbol{r}\int d^3\boldsymbol{x}\,\rho^{(3)}(\boldsymbol{r},\boldsymbol{r},\boldsymbol{x})\,G(\boldsymbol{x}-\boldsymbol{r};a)$$

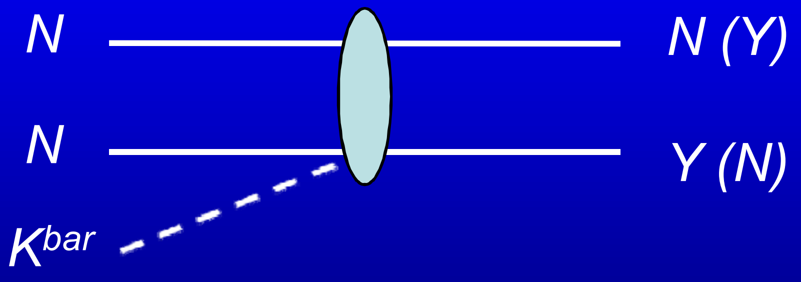
Three-body correlation density

Gaussian-type Interaction for NN

- *For mean-field model*
  … no correlation between two nucleons
- *Contact interaction*



- *Finite range interaction (between NN)*



III. Two nucleon absorption

$$\Delta\Gamma_{abs} = \frac{2\pi\tilde{B}_0}{\omega}\beta_{pp}(\omega)\int d^3\boldsymbol{r}\,\rho_{\bar{K}}(\boldsymbol{r})\,\rho_N^2(\boldsymbol{r}),$$

J. Mares, E. Friedman and A. Gal,
Nucl. Phys. A 770, 84 (2006)

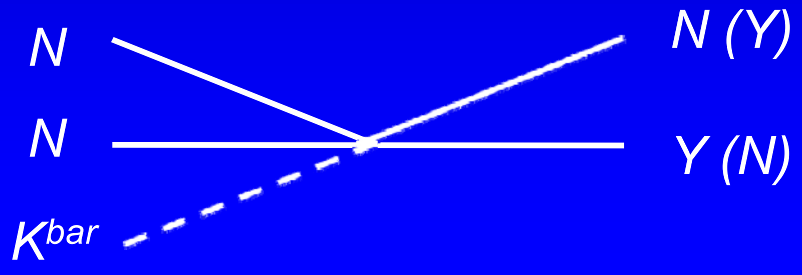
In our model, particles are strongly correlated.
The NN can't touch each other, due to the strong NN repulsion!!

$$\Delta\Gamma_{abs}(K^-pp \to YN) = \frac{2\pi B_0}{\omega}\beta_{pp}(\omega) \times \int d^3\boldsymbol{r}\int d^3\boldsymbol{x}\,\rho^{(3)}(\boldsymbol{r},\boldsymbol{r},\boldsymbol{x})\,G(\boldsymbol{x}-\boldsymbol{r};a)$$

Three-body correlation density

Gaussian-type Interaction for NN

- *For mean-field model*
  … no correlation between two nucleons
- *Contact interaction*



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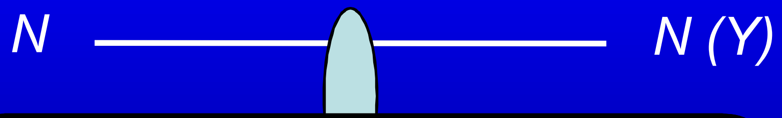

$$\Delta\Gamma_{abs} = 4 \sim 12\ \mathrm{MeV}$$

for a = 0.6 fm,
B_0 = 0.85 ∼ 1.5 fm^4

6. Summary

- *We studied K^-pp with a variational method, using a realistic NN potential (Av18) and a Chiral SU(3)-based $K^{bar}N$ potential.*
- *We tried four variants of Chiral unitary models and two ansatz of $K^{bar}N$ energy in the three-body system. However, the result doesn't depend so much on them. Total binding energy and mesonic decay width are in the small window:*

Binding energy and mesonic decay width of K^-pp

- *Total binding energy and mesonic decay width are in the small window:*

Total Binding energy = 20 ± 3 MeV
$\Gamma(K^{bar}N \to \pi Y)$ = 40 ∼ 70 MeV
… *Very shallow binding*

Structure of K^-pp

- *NN distance in K^-pp is smaller than that of deuteron, rather comparable to that in normal nuclei.*

NN distance = ∼2.2 fm
$K^{bar}N$ distance = ∼2.0 fm

- *The I=0 $K^{bar}N$ component in K^-pp is found to be very similar to $\Lambda(1405)$.*

Contribution of *other effects*

- *Dispersive correction:* +6 ∼ +18MeV to B.E.
- *p-wave $K^{bar}N$ potential:* ∼ -3MeV to B.E. , 10 ∼ 35MeV to width
- *Two nucleon absorption:* 4 ∼ 12MeV to width

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Structure of *K^-pp*

- *NN distance in* … distance = ∼2.2 fm
  rather compara … *N* distance = ∼2.0 fm
- *The I=0 $K^{bar}N$*

$\Lambda(1405)$ almost survives in *K^-pp*.
But, such a state is very short-lived.

Contribution of *other effects*

- *Disp*
- *p-w* … *width*
- *Two* … *width*

By rough estimation,
Total Binding energy = 20 ∼ 40 MeV
Γ (*total*) = 55 ∼ 120 MeV

6. Comment

- *Difference from Faddeev calculation with a separable $K^{bar}N$ potential constrained with Chiral SU(3) theory*

Total B. E. = 79 MeV,
Decay width = 74 MeV

by Dr. Ikeda and Prof. Sato

Separable potential?

Non-relativistic (semi-relativistic) vs relativistic?

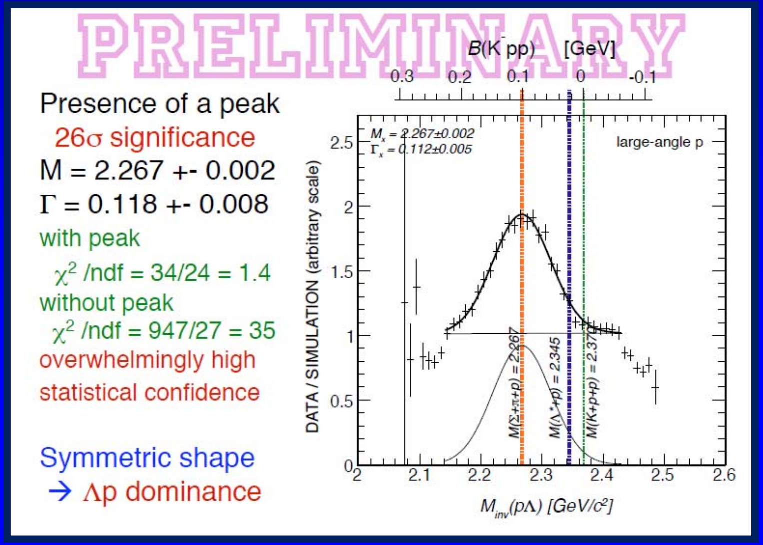
Energy dependence of two-body system ($K^{bar}N$) in the three-body system ($K^{bar}NN$)?

Important role of πΣN thee-body dynamics? ⇐ *Y. Ikeda and T. Sato, arXiv:0809.1285*

…???

6. Comment

- *What is the object measured experimentally?*



Presence of a peak
26σ significance
M = 2.267 +- 0.002
Γ = 0.118 +- 0.008
with peak
χ^2 /ndf = 34/24 = 1.4
without peak
χ^2 /ndf = 947/27 = 35
overwhelmingly high
statistical confidence

Symmetric shape
→ Λp dominance

Just a bound state of K^-pp,
should πΣN be included???

Even if the experimental result is not an artifact, only what we can say at the moment from this is
"There is some object with B=2, S=-1, charge=+1"…

- *How to distinguish which is the dominant component, K^-pp or πΣN experimentally?*
- *Since the signal position is very close to π+Σ+N threshold,*
  it is more natural that the observed state is mainly the bound state of πΣN?

→ *Coupled channel calculation of K^{bar}NN-πΣN , using a realistic NN potential and a K^{bar}N and πY potential derived from Chiral SU(3) theory. (NOT separable type)*

Thank you very much!!