Quark mass dependence of H-dibaryon in $\Lambda\Lambda$ scattering

Yasuhiro Yamaguchi[1,2,3], Tetsuo Hyodo[3]

[1]RIKEN Nishina Center, Japan,

[2]INFN Genova, Italy,

[3]YITP Kyoto University, Japan

Y. Yamaguchi and T. Hyodo, PRC94,065207(2016)

Strangeness Nuclear Physics 2017

3/12-14 2017, Osaka Electro-communication University, Japan

Outline

Quark mass dependence of the H-dibaryon

1. Introduction
    - Exotic hadron
    - H-dibaryon
2. Model setup
    - Coupled-channel scattering amplitude
    - Quark mass dependence
3. Numerical results
    - Result in the SU(3) limit
    - Result at the Phys point
    - Interpolation of SU(3) limit and the Phys point
4. Summary

Outline

Quark mass dependence of the H-dibaryon

1. Introduction

- Exotic hadron
- H-dibaryon

2. Model setup

- Coupled-channel scattering amplitude
- Quark mass dependence

3. Numerical results

- Result in the SU(3) limit
- Result at the Phys point
- Interpolation of SU(3) limit and the Phys point

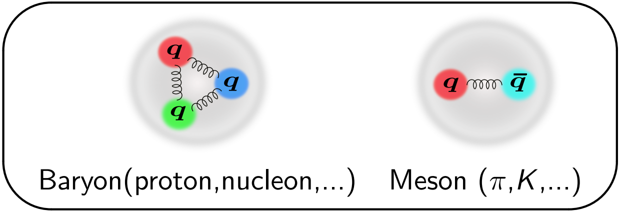
4. Summary

Exotic Hadrons

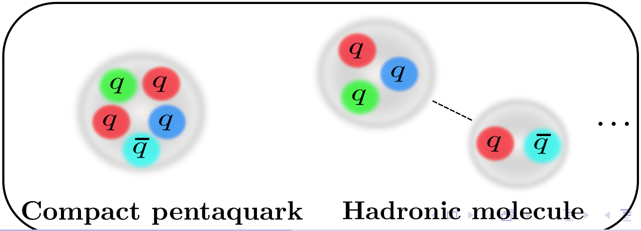
- Hadron: Composite particle of **Quarks** and **Gluons**
- Constituent quark model (Baryon(qqq) and Meson $q\bar{q}$) has been successfully applied to the hadron spectra!

Baryon(proton,nucleon,...) Meson (π,K,...)

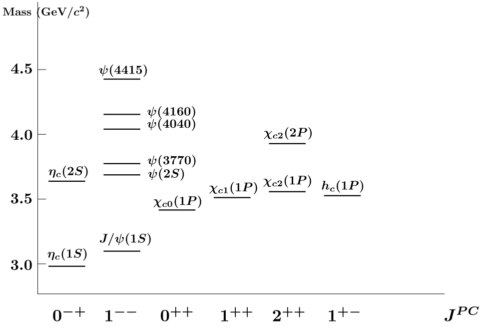
- Hadron: Composite particle of **Quarks** and **Gluons**
- Constituent quark model (Baryon(qqq) and Meson $q\bar{q}$) has been successfully applied to the hadron spectra!



- **Exotic hadrons?** $\rightarrow$ Multiquark state



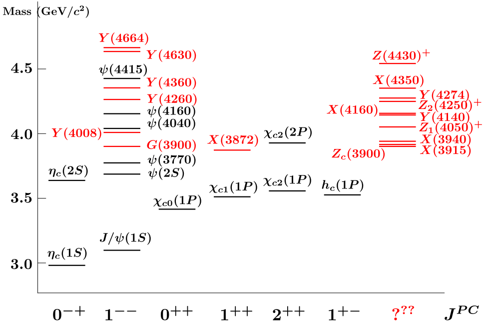
▷ e.g. Charmonium ($c\bar{c}$)



Charmonium $c\bar{c}$

N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534
S. Godfrey and N. Isgur, PRD**32**(1985)189

▷ e.g. Charmonium ($c\bar{c}$) and **New Exotic hadrons** ***X, Y, Z***



Charmonium $c\bar{c}$

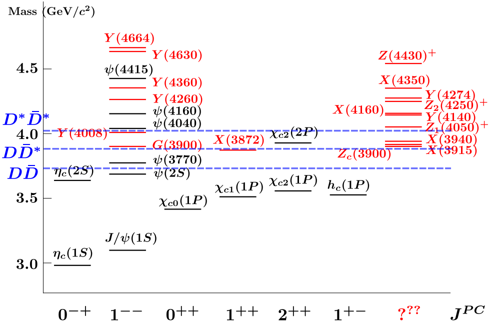
and

Exotic hadrons ($\neq c\bar{c}$)

X, Y, Z

N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534
S. Godfrey and N. Isgur, PRD**32**(1985)189

▷ e.g. Charmonium ($c\bar{c}$) and **New Exotic hadrons *X*, *Y*, *Z***

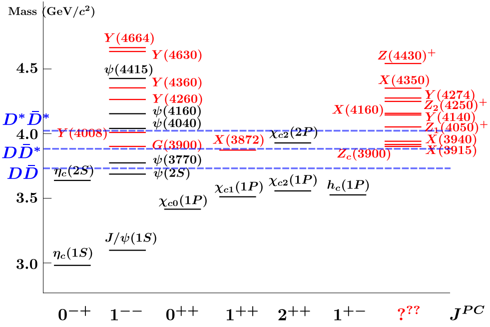


Charmonium $c\bar{c}$
and
Exotic hadrons ($\neq c\bar{c}$)
X*, *Y*, *Z

N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534
S. Godfrey and N. Isgur, PRD**32**(1985)189

▷ **What is the structure of exotic hadrons?**

▷ e.g. Charmonium ($c\bar{c}$) and **New Exotic hadrons *X*, *Y*, *Z***



Charmonium $c\bar{c}$

and

Exotic hadrons ($\neq c\bar{c}$)

X*, *Y*, *Z

N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534
S. Godfrey and N. Isgur, PRD**32**(1985)189

▷ **What is the structure of exotic hadrons?**

Light $\Lambda(1405)$: $\bar{K}N - \pi\Sigma$? T. Hyodo *et al.* Prog.Part.Nucl.Phys. **67** (2012) 55-98.

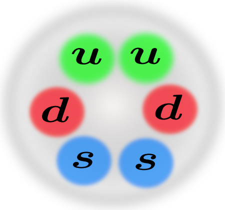
Charm $X(3872)$: $D\bar{D}^*$? P_c: Hidden-charm Pentaquark?

Belle PRL **91** (2003) 262001. LHCb PRL**115**(2015)072001.

Bottom $Z_b^{(\prime)}$: $B^{(*)}\bar{B}^*$? Belle PRL **108** (2012) 122001

- R.L.Jaffe (Bag model) PRL**38**(1977)195
  - ▷ $J^P = 0^+$: $M_H = 2150$ MeV ($\sim$80 MeV below $\Lambda\Lambda$)

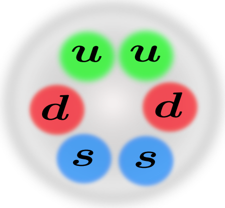
Flavor singlet bound state



***H*-dibaryon?**

- R.L.Jaffe (Bag model) PRL**38**(1977)195
  - ▷ $J^P = 0^+$: $M_H = 2150$ MeV (∼80 MeV below ΛΛ)

Flavor singlet bound state



$\boldsymbol{H}$-dibaryon?

However...

- R.L.Jaffe (Bag model) PRL**38**(1977)195
  - ▷ $J^P = 0^+$: $M_H = 2150$ MeV ($\sim$80 MeV below $\Lambda\Lambda$)
- **Experiments**

- R.L.Jaffe (Bag model) PRL**38**(1977)195
  ▷ $J^P = 0^+$: $M_H = 2150$ MeV ($\sim$80 MeV below $\Lambda\Lambda$)

- **Experiments**
  - ▷ NAGARA event: ${}^{6}_{\Lambda\Lambda}\mathrm{He} \not\rightarrow {}^{4}\mathrm{He} + H$
    H.Takahashi *et al.*,PRL**87**(2001)212502

H-dibaryon bound state?

Introduction:H-dibaryon

- R.L.Jaffe (Bag model) PRL**38**(1977)195
  ▷ $J^P = 0^+$: $M_H = 2150$ MeV ($\sim$80 MeV below $\Lambda\Lambda$)

- **Experiments**
  - ▷ NAGARA event: ${}^{\ 6}_{\Lambda\Lambda}\mathrm{He} \not\to {}^4\mathrm{He} + H$

    H.Takahashi *et al.*,PRL**87**(2001)212502

    $\Rightarrow$ Constraint $\boldsymbol{B_H < 6.93}$ **MeV** $(= B_{\Lambda\Lambda}({}^{\ 6}_{\Lambda\Lambda}\mathrm{He}))$.

- R.L.Jaffe (Bag model) PRL**38**(1977)195
  ▷ $J^P = 0^+$: $M_H = 2150$ MeV (∼80 MeV below ΛΛ)

- **Experiments**
  ▷ NAGARA event: ${}^{6}_{\Lambda\Lambda}\mathrm{He} \not\to {}^{4}\mathrm{He} + H$
  H.Takahashi *et al.*,PRL**87**(2001)212502
  ⇒ Constraint $\boldsymbol{B_H < 6.93}$ **MeV** $(= B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}))$.
  ▷ Belle: $\Upsilon(1S)$ and $\Upsilon(2S)$ decays
  B. H. Kim *et al.*,PRL**110**(2013)222002
  ⇒ **No peak** near the $2m_\Lambda$ threshold.

H-dibaryon bound state?

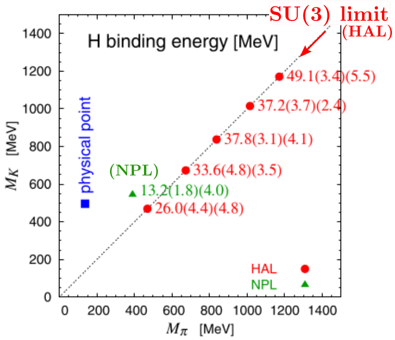
Introduction:H-dibaryon

- R.L.Jaffe (Bag model) PRL**38**(1977)195
  ▷ $J^P = 0^+$: $M_H = 2150$ MeV ($\sim$80 MeV below $\Lambda\Lambda$)

- **Experiments**
  ▷ NAGARA event: ${}^{6}_{\Lambda\Lambda}\mathrm{He} \not\rightarrow {}^{4}\mathrm{He} + H$
  H.Takahashi *et al.*,PRL**87**(2001)212502
  $\Rightarrow$ Constraint $\boldsymbol{B_H < 6.93}$ **MeV** $(= B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}))$.
  ▷ Belle: $\Upsilon(1S)$ and $\Upsilon(2S)$ decays
  B. H. Kim *et al.*,PRL**110**(2013)222002
  $\Rightarrow$ **No peak** near the $2m_\Lambda$ threshold.
  ▷ RHIC-STAR: $\Lambda\Lambda$ correlation
  L.Adamczyk *et al.*,PRL**114**(2015)022301, K.Morita,*et al.*,PRC**91**(2015)024916
  $\Rightarrow$ **Attractive scattering length** of $\Lambda\Lambda$ ($\rightarrow$**No Bound state?**)

Experiments $\Rightarrow$ No (deeply) bound state?

- H-dibaryon from Lattice QCD **(Large quark mass region)**

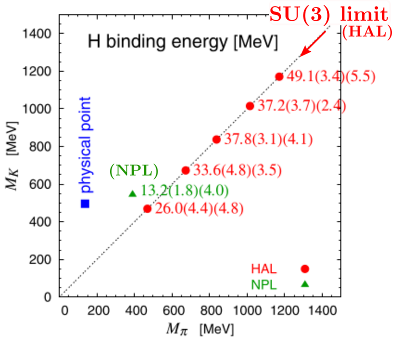


- HAL (SU(3)$_f$ **limit**)
  NPA**881**(2012)28
- NPL (SU(3)$_f$ **breaking**)
  $\Lambda\Lambda - N\Xi - \Sigma\Sigma$
  PRD**85**(2012)054511

Bound at large m_q regions!

T. Inoue *et al.*, (HALQCD) NPA**881**(2012)28.

- H-dibaryon from Lattice QCD **(Large quark mass region)**



T. Inoue *et al.*, (HALQCD) NPA**881**(2012)28.

- HAL ($SU(3)_f$ **limit**)
  NPA**881**(2012)28
- NPL ($SU(3)_f$ **breaking**)
  $\Lambda\Lambda - N\Xi - \Sigma\Sigma$
  PRD**85**(2012)054511

Bound at large m_q regions!

$\Downarrow$

(Un)Bound at **Physical point**?

Extrapolation: Large $m_q \to$ Phys point

- Lattice QCD: T. Inoue, *et al.*, (HAL QCD), NPA**881**(2012)28.
  At Large m_q (SU(3) limit) $\Rightarrow$ Bound state below $\Lambda\Lambda$

Extrapolation: Large $m_q \to$ Phys point

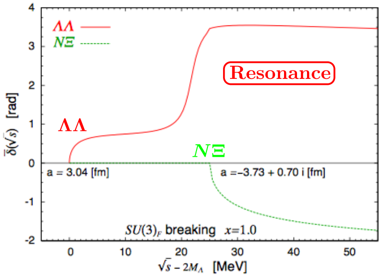
Introduction: H-dibaryon

- Lattice QCD: T. Inoue, *et al.*, (HAL QCD), NPA**881**(2012)28.
  At Large m_q (SU(3) limit) $\Rightarrow$ Bound state below $\Lambda\Lambda$

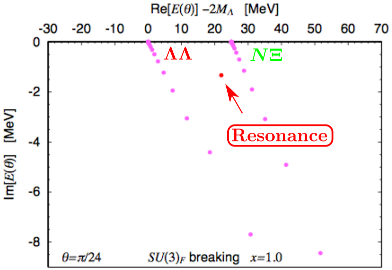
  $\Downarrow$ Extrapolation

At Physical point: No bound state, but... Resonance

(i) Phase shift



(ii) Complex energy-plane



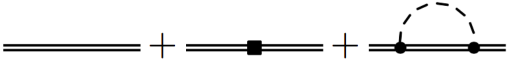
Resonance below the $N\Xi$ threshold?

- Quark mass dependence by EFT

▷ Quark mass dependence by EFT

- Bare H-state ($6q$ state) by evaluating the NG boson loop

  P. E. Shanahan *et al.*, PRL**107**(2011)092004, JPS Conf.Proc.**1**(2014)013028

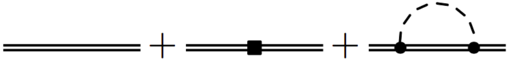


Results: Unbound at phys point

▷ Quark mass dependence by EFT

- Bare H-state ($6q$ state) by evaluating the NG boson loop

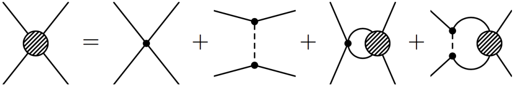
  P. E. Shanahan *et al.*, PRL**107**(2011)092004, JPS Conf.Proc.**1**(2014)013028



Results: **Unbound** at phys point

- Chiral effective field theory $\cdots$ BB scattering

  J. Haidenbauer and U. G. Meissner, PLB**706**(2011)100, NPA**881**(2012)44

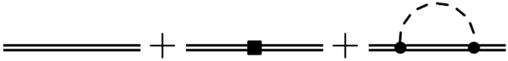


Results: **Unbound** at phys point, but **Resonance** below $N\Xi$

▷ Quark mass dependence by EFT

- Bare H-state ($6q$ state) by evaluating the NG boson loop

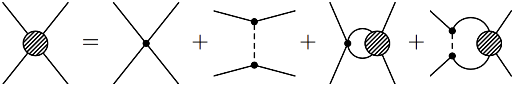
  P. E. Shanahan *et al.*, PRL**107**(2011)092004, JPS Conf.Proc.**1**(2014)013028



Results: **Unbound** at phys point
$\to$ Couplings to ***BB*** **channels** is absent.

- Chiral effective field theory $\cdots$ BB scattering

  J. Haidenbauer and U. G. Meissner, PLB**706**(2011)100, NPA**881**(2012)44



Results: **Unbound** at phys point, but **Resonance** below $N\Xi$
$\to$ **Compact** $6q$ **state** is absent.

Quark mass dependence of the H-dibaryon

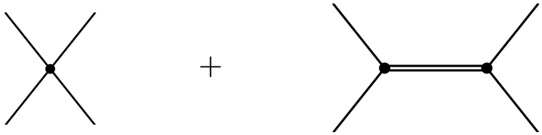
1. Introduction
   - Exotic hadron
   - H-dibaryon
2. **Model setup**
   - Coupled-channel scattering amplitude
   - Quark mass dependence
3. Numerical results
   - Result in the SU(3) limit
   - Result at the Phys point
   - Interpolation of SU(3) limit and the Phys point
4. Summary

Our work

Purpose: Quark mass dependence of H-dibaryon is studied.

Method: EFT with

Contact term and **Bare H-dibaryon field**.



D. B. Kaplan, NPB **494**(1997)471,E.Braaten,*et al.*,Annals,Phys.**323**(2008)1770

⇒ Comparing
(i) **Contact term** and
(ii) **Contact term + Bare H-dibaryon field**

- Coupled-channel analysis $(1, 8_s, 27) = (\Lambda\Lambda, N\Xi, \Sigma\Sigma)$
- Parameters are fitted by the Lattice QCD (HALQCD).

- HALQCD results in SU(3) limit are used.

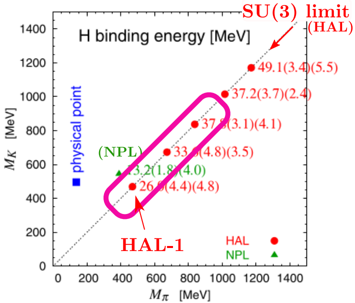
T.Inoue *et al.*, (HALQCD) NPA**881**(2012)28.

	Data	B [MeV]	M_Λ [MeV]	M_{NG} [MeV]
$SU(3)_f$ limit	HAL-1	26.0	1161	469
	HAL-2	33.6	1484	672
	HAL-3	37.8	1749	837
Physical point		???	1116	m_π : 140, m_K : 500

- HALQCD results in SU(3) limit are used.

  T.Inoue *et al.*, (HALQCD) NPA**881**(2012)28.

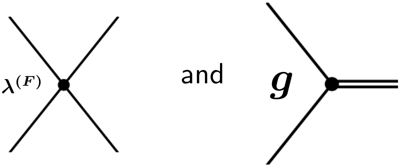
	Data	B [MeV]	M_Λ [MeV]	M_{NG} [MeV]
SU(3)$_f$ limit	HAL-1	26.0	1161	469
	HAL-2	33.6	1484	672
	HAL-3	37.8	1749	837
Physical point		???	1116	m_π : 140, m_K : 500



- **Contact term** and **Bare H-dibaryon field (singlet)**

$$\mathcal{L}_{int} = -\sum_{\mathbf{F}=1,8,27} \lambda^{(\mathbf{F})} \mathbf{D}^{(\mathbf{F})\dagger} \mathbf{D}^{(\mathbf{F})} - \mathbf{g}\left[\mathbf{D}^{(1)\dagger}\mathbf{H} + \mathbf{H}^{\dagger}\mathbf{D}^{(1)}\right]$$

1,8,27 1



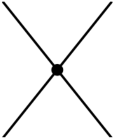
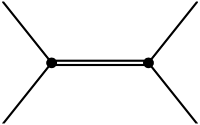
$$\begin{pmatrix} D^{(1)} \\ D^{(8)} \\ D^{(27)} \end{pmatrix} = \begin{pmatrix} -\sqrt{1/8} & \sqrt{1/2} & \sqrt{3/8} \\ -\sqrt{1/5} & \sqrt{1/5} & -\sqrt{3/5} \\ \sqrt{27/40} & \sqrt{3/10} & -\sqrt{1/40} \end{pmatrix} \begin{pmatrix} \Lambda\Lambda \\ N\Xi \\ \Sigma\Sigma \end{pmatrix}$$

SU(3) basis Isospin basis

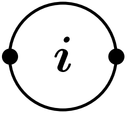
Coupled-channel Scattering amplitude
Model setup

- Scattering amplitude of (1,8,27) $\Leftrightarrow$ $(\Lambda\Lambda, N\Xi, \Sigma\Sigma)$

$$\mathcal{A}(E) = \left[\left(\mathcal{A}^{\text{tree}}(E)\right)^{-1} + I(E)\right]^{-1}$$

$\mathcal{A}^{\text{tree}}_{ij}(E) =$ i  j $+$ i  j

$\lambda^{(F)}$ g, Bare mass ν

$I_i(E) =$ 

with $\Lambda = 300$ MeV

- Couplings $\lambda^{(F)}, g$ and Bare mass ν are fixed by the Lattice data (HALQCD)

$\Rightarrow$ We obtain Scattering lengths, poles.

Quark mass dependence 1

Model setup

- Quark masses: $B_0 m_l = \frac{m_\pi^2}{2}, \quad B_0 m_s = m_K^2 - \frac{m_\pi^2}{2}$
- Baryon masses $(N, \Lambda, \Sigma, \Xi)$

$$
\begin{aligned}
M_N &= M_0 - (2\alpha + 2\beta + 4\sigma)\mathbf{B_0 m_l} - 2\sigma \mathbf{B_0 m_s} \\
M_\Lambda &= M_0 - (\alpha + 2\beta + 4\sigma)\mathbf{B_0 m_l} - (\alpha + 2\sigma)\mathbf{B_0 m_s} \\
M_\Sigma &= M_0 - (\tfrac{5}{3}\alpha + \tfrac{2}{3}\beta + 4\sigma)\mathbf{B_0 m_l} - (\tfrac{1}{3}\alpha + \tfrac{4}{3}\beta + 2\sigma)\mathbf{B_0 m_s} \\
M_\Xi &= M_0 - (\tfrac{1}{3}\alpha + \tfrac{4}{3}\beta + 4\sigma)\mathbf{B_0 m_l} - (\tfrac{5}{3}\alpha + \tfrac{2}{3}\beta + 2\sigma)\mathbf{B_0 m_s}
\end{aligned}
$$

Quark mass dependence 1
Model setup

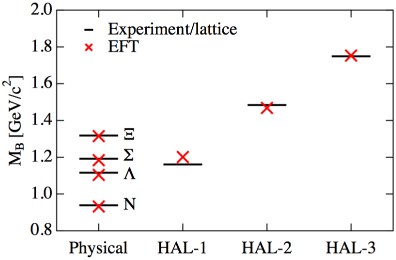
- Quark masses: $B_0 m_l = \frac{m_\pi^2}{2}, \quad B_0 m_s = m_K^2 - \frac{m_\pi^2}{2}$
- Baryon masses (N, Λ, Σ, Ξ)

$$M_N = M_0 - (2\alpha + 2\beta + 4\sigma)\mathbf{B_0 m_l} - 2\sigma \mathbf{B_0 m_s}$$

$$M_\Lambda = M_0 - (\alpha + 2\beta + 4\sigma)\mathbf{B_0 m_l} - (\alpha + 2\sigma)\mathbf{B_0 m_s}$$

$$M_\Sigma = M_0 - (\tfrac{5}{3}\alpha + \tfrac{2}{3}\beta + 4\sigma)\mathbf{B_0 m_l} - (\tfrac{1}{3}\alpha + \tfrac{4}{3}\beta + 2\sigma)\mathbf{B_0 m_s}$$

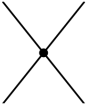
$$M_\Xi = M_0 - (\tfrac{1}{3}\alpha + \tfrac{4}{3}\beta + 4\sigma)\mathbf{B_0 m_l} - (\tfrac{5}{3}\alpha + \tfrac{2}{3}\beta + 2\sigma)\mathbf{B_0 m_s}$$



- Parameters $M_0, \alpha, \beta, \sigma$
  $\rightarrow$ Fitted to reproduce the masses at **the phys point** and in **HALQCD** simulations
  T.Inoue, *et al.*, NPA**881**(2012)28

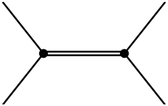
- $M_0 = 0.95$ GeV, $\alpha = -0.75$ GeV^{-1}, $\beta = -0.64$ GeV^{-1}, $\sigma = 0.083$ GeV^{-1}

- Coupling constants and Bare mass



$$\lambda^{(F)}(m_l, m_s) = \lambda_0^{(F)} + \lambda_1^{(F)} B_0(2m_i + m_s)$$

F=1,8,27



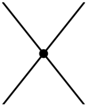
$$g(m_l, m_s) = g \text{ (Const.)}$$

$$\nu(m_l, m_s) = M_{H,0} - \sigma_H B_0(2m_l + m_s) - 2M_\Lambda$$

Quark mass dependence 2

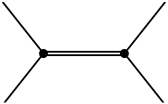
Model setup

- Coupling constants and Bare mass



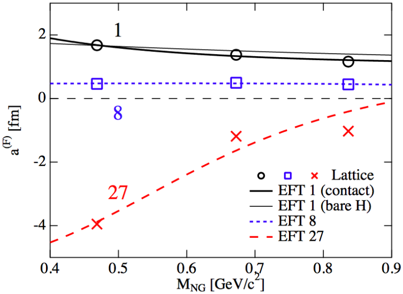
$$\lambda^{(F)}(m_l, m_s) = \lambda_0^{(F)} + \lambda_1^{(F)} B_0(2m_i + m_s)$$

F=1,8,27



$$g(m_l, m_s) = g \text{ (Const.)}$$

$$\nu(m_l, m_s) = M_{H,0} - \sigma_H B_0(2m_l + m_s) - 2M_\Lambda$$



- Parameters $\lambda_0^{(F)}, \lambda_1^{(F)}, g, M_{H,0}, \sigma_H$ $\rightarrow$ Fitted to reproduce **the scattering lengths** in HALQCD simulations

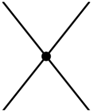
T.Inoue, *et al.*, NPA**881**(2012)28

Obtained parameters

Model setup

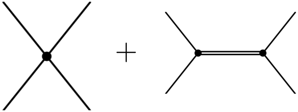
- For 1 channel: (i) **Contact** and (ii) **Contact** + **Bare H**

(i)



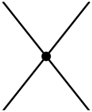
▷ $\lambda_0^{(1)} = -88.5\ \text{GeV}^{-2},\ \lambda_1^{(1)} = -163\ \text{GeV}^{-4}$

(ii)



▷ $\lambda_0^{(1)} = -12.8\ \text{GeV}^{-2},$
$g^2 = 2350\ \text{GeV}^{-1},\ M_{H,0} = 19.8\ \text{GeV}$
$\sigma_H = -1.53\ \text{GeV}^{-1}$

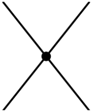
- For 8 and 27 channels



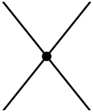
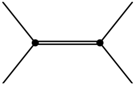
▷ $\lambda_0^{(8)} = 54.2\ \text{GeV}^{-2},\ \lambda_1^{(8)} = -23.7\ \text{GeV}^{-4}$
$\lambda_0^{(27)} = -58.2\ \text{GeV}^{-2},\ \lambda_1^{(27)} = 45.3\ \text{GeV}^{-4}$

Obtained parameters
Model setup

- For 1 channel: (i) **Contact** and (ii) **Contact + Bare H**

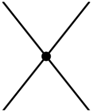
(i) 

▷ $\lambda_0^{(1)} = -88.5\ \mathrm{GeV}^{-2}$, $\lambda_1^{(1)} = -163\ \mathrm{GeV}^{-4}$

(ii)  + 

▷ $\lambda_0^{(1)} = -12.8\ \mathrm{GeV}^{-2}$,
$g^2 = 2350\ \mathrm{GeV}^{-1}$, $\boldsymbol{M_{H,0} = 19.8\ \mathrm{GeV}}$
$\sigma_H = -1.53\ \mathrm{GeV}^{-1}$

- For 8 and 27 channels



▷ $\lambda_0^{(8)} = 54.2\ \mathrm{GeV}^{-2}$, $\lambda_1^{(8)} = -23.7\ \mathrm{GeV}^{-4}$
$\lambda_0^{(27)} = -58.2\ \mathrm{GeV}^{-2}$, $\lambda_1^{(27)} = 45.3\ \mathrm{GeV}^{-4}$

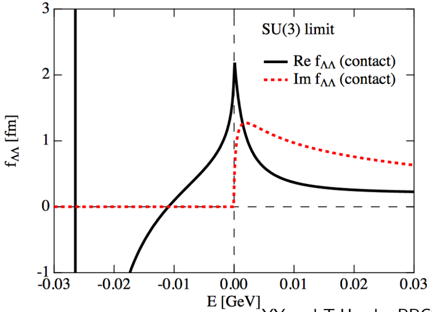
⇒ **Massive bare field** → Bare-H term is a higher-order correction to the contact term.

Quark mass dependence of the H-dibaryon

1. Introduction
   - Exotic hadron
   - H-dibaryon
2. Model setup
   - Coupled-channel scattering amplitude
   - Quark mass dependence
3. **Numerical results**
   - Result in the SU(3) limit
   - Result at the Phys point
   - Interpolation of SU(3) limit and the Phys point
4. Summary

Numerical results: SU(3) limit (Large m_q)

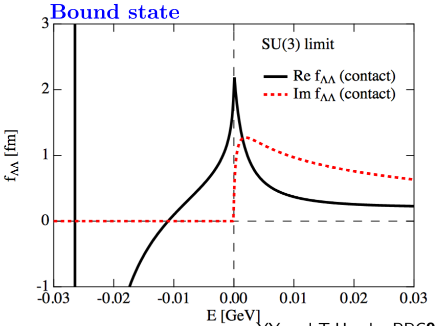
- Scattering amplitude of $\Lambda\Lambda$ in the SU(3) limit (HAL-1)



YY and T.Hyodo, PRC**94**(2016)065207.

Numerical results: SU(3) limit (Large m_q)

- Scattering amplitude of $\Lambda\Lambda$ in the SU(3) limit (HAL-1)

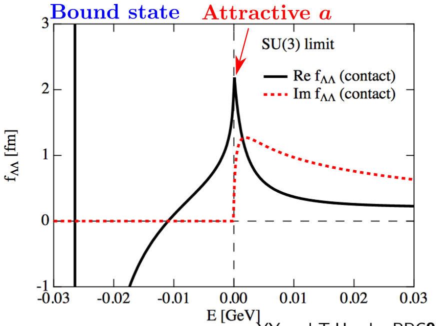


YY and T.Hyodo, PRC**94**(2016)065207.

- **Bound state** of **the 1 channel**

Numerical results: SU(3) limit (Large m_q)

- Scattering amplitude of ΛΛ in the SU(3) limit (HAL-1)

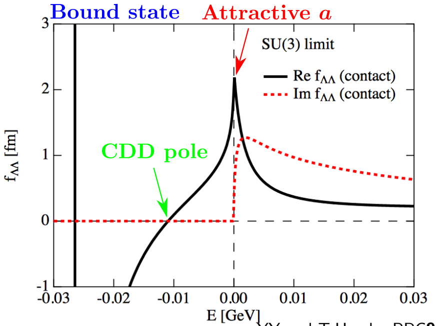


YY and T.Hyodo, PRC**94**(2016)065207.

- **Bound state** of **the 1 channel**
- **Attractive** scattering length of ΛΛ ← given by **27**

$$f_{\Lambda\Lambda}(E) = \frac{1}{8}f^{(1)}(E) + \frac{1}{5}f^{(8)}(E) + \underline{\frac{\mathbf{27}}{\mathbf{40}}\mathbf{f}^{(\mathbf{27})}(\mathbf{E})}$$

- Scattering amplitude of ΛΛ in the SU(3) limit (HAL-1)



YY and T.Hyodo, PRC**94**(2016)065207.

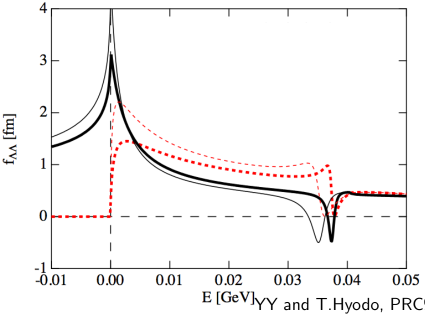
- **Bound state** of **the 1 channel**
- **Attractive** scattering length of ΛΛ ← given by **27**

$$f_{\Lambda\Lambda}(E) = \frac{1}{8}f^{(1)}(E) + \frac{1}{5}f^{(8)}(E) + \underline{\boldsymbol{\frac{27}{40}\mathbf{f}^{(27)}(\mathbf{E})}}$$

- **CDD pole**: coupled-channel effect

Numerical results: Extrapolation to the phys point

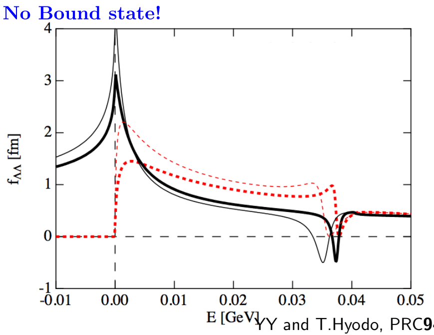
- Scattering amplitude of ΛΛ at the phys point



YY and T.Hyodo, PRC**94**(2016)065207.

Numerical results: Extrapolation to the phys point

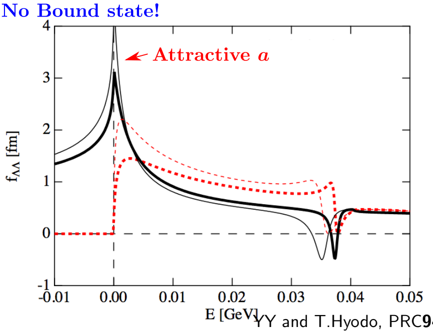
- Scattering amplitude of ΛΛ at the phys point



YY and T.Hyodo, PRC**94**(2016)065207.

- **No Bound state!**

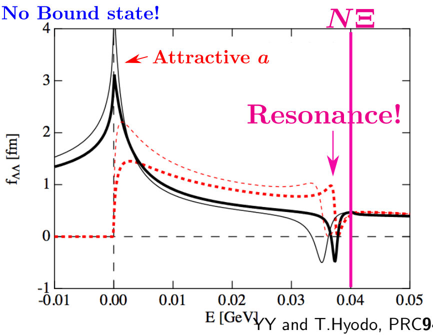
- Scattering amplitude of ΛΛ at the phys point



YY and T.Hyodo, PRC**94**(2016)065207.

- **No Bound state!**
- **Attractive** scattering length of ΛΛ: -3.2 fm

- Scattering amplitude of ΛΛ at the phys point



YY and T.Hyodo, PRC**94**(2016)065207.

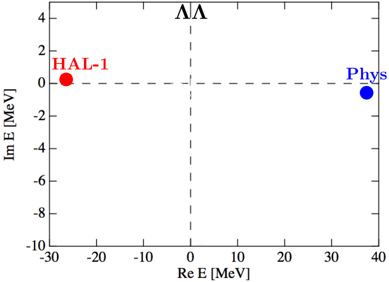
- **No Bound state!**
- **Attractive** scattering length of ΛΛ: -3.2 fm
- **Resonance!**: $E = 37 - i0.6$ MeV (below $N\Xi$ threshold)

Bound state (SU(3) limit) → Resonance (at phys point)?

- Interpolation of SU(3) limit and Phys point

$$m_{\pi,K}(x) = x m_{\pi,K}^{\text{phys}} + (1-x) m_{\pi,K}^{\text{HAL}-1}$$

Fig. Pole trajectory from $x = 0$ (HAL-1) to $x = 1$ (Phys)

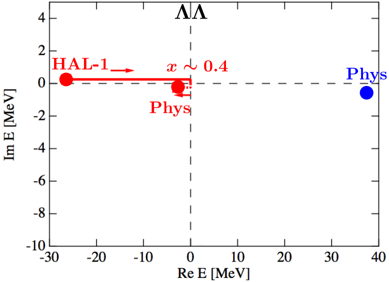


Numerical results: SU(3) limit $\Leftrightarrow$ Phys point

- Interpolation of SU(3) limit and Phys point

$$m_{\pi,K}(x) = x m_{\pi,K}^{\rm phys} + (1-x) m_{\pi,K}^{\rm HAL-1}$$

Fig. Pole trajectory from $x = 0$ (HAL-1) to $x = 1$ (Phys)



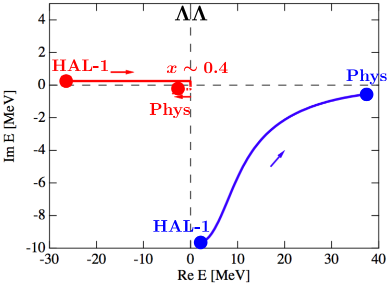
- **Bound state** becomes a virtual state at $x \sim 0.4$
  $(m_\pi, m_K) = (340, 480)$ MeV.
  $\Rightarrow$ It is NOT the origin of **the resonance!**

Numerical results: SU(3) limit ⇔ Phys point

- Interpolation of SU(3) limit and Phys point

$$m_{\pi,K}(x) = x m_{\pi,K}^{\rm phys} + (1-x) m_{\pi,K}^{\rm HAL-1}$$

Fig. Pole trajectory from $x = 0$ (HAL-1) to $x = 1$ (Phys)



- **Bound state** becomes a virtual state at $x \sim 0.4$
  $(m_\pi, m_K) = (340, 480)$ MeV.
  ⇒ It is NOT the origin of **the resonance!**
- **Another pole** above the thresholds in the SU(3) limit
  ⇐ Non-resonance pole on the II-I-I sheet

Summary

Subject: Quark mass dependence of the H-dibaryon

$\Downarrow$

- Coupled-channel baryon-baryon scattering $(1, 8, 27) = (\Lambda\Lambda, N\Xi, \Sigma\Sigma)$ is discussed.
- The scattering amplitude is described by **Contact term** and **Bare H field**.
- The coupling constants of the EFT is fitted by the Lattice QCD results (HALQCD).
- **Bound state** in the SU(3) limit vanishes at the physical point.
- At the physical point, **the resonance** below the $N\Xi$ threshold is obtained, which is originated by the non-resonance pole in the SU(3) limit.

Y. Yamaguchi and T. Hyodo, PRC**94**(2016)065207

Thank you for your kind attention.

Back up

- Scattering amplitude

$$f_{ii}(E) = \frac{\mu_i}{2\pi}\left[(\mathcal{A}^{\rm tree})^{-1} + I(E)\right]^{-1}_{ii}$$

$$\mathcal{A}^{\rm tree}_{ij}(E) = -\left(V_{ij} + \frac{g^2 d_i^\dagger d_j}{E-\nu+i0^+}\right)$$

$$I_i(E) = \frac{\mu_i}{\pi^2}\left(-\Lambda + k_i \mathrm{artanh}\frac{\Lambda}{k_i}\right)$$

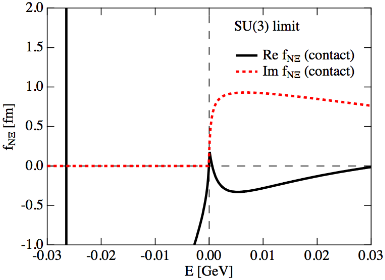
- Loop func. in the first and second Riemann sheet

$$I_{i,\mathrm{I}}(E) = \frac{\mu_i}{\pi^2}\left[-\Lambda + [2\mu_i(E-\Delta_i)]^{1/2}\mathrm{artanh}\frac{\Lambda}{[2\mu_i(E-\Delta_i)]^{1/2}}\right]$$

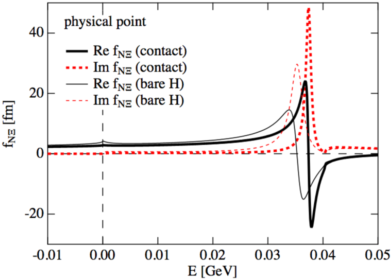
$$I_{i,\mathrm{II}}(E) = \frac{\mu_i}{\pi^2}\left[-\Lambda + [2\mu_i(E-\Delta_i)]^{1/2} \times\left(\mathrm{artanh}\frac{\Lambda}{[2\mu_i(E-\Delta_i)]^{1/2}} + i\pi\right)\right]$$

- Scattering amplitudes of $N\Xi$

SU(3) limit (HAL-1)



Phys point



- Unitary limit