Di-baryons with and without Strangeness

Makoto Oka

Tokyo Institute of Technology
and
ASRC, JAEA

Valencia, June 16, 2015

Japan Atomic Energy Agency (JAEA) @ Tokai
J-PARC (High Intensity Proton Accelerator)

Tokyo Institute of Technology
The largest National University in Science and Technology

Contents

Pauli principles and Spin dependence

Baryon-Baryon Interaction

- Recent Lattice QCD calculations have confirmed that the short-range baryon-baryon interactions follow the quark model symmetry and dynamics. => HALQCD
- Two important effects are given by
  - Fermi-Dirac statistics among quarks (Pauli effect)
  - Spin dependent force: Color-magnetic interaction (CMI)
- Symmetries of internal degrees of freedom

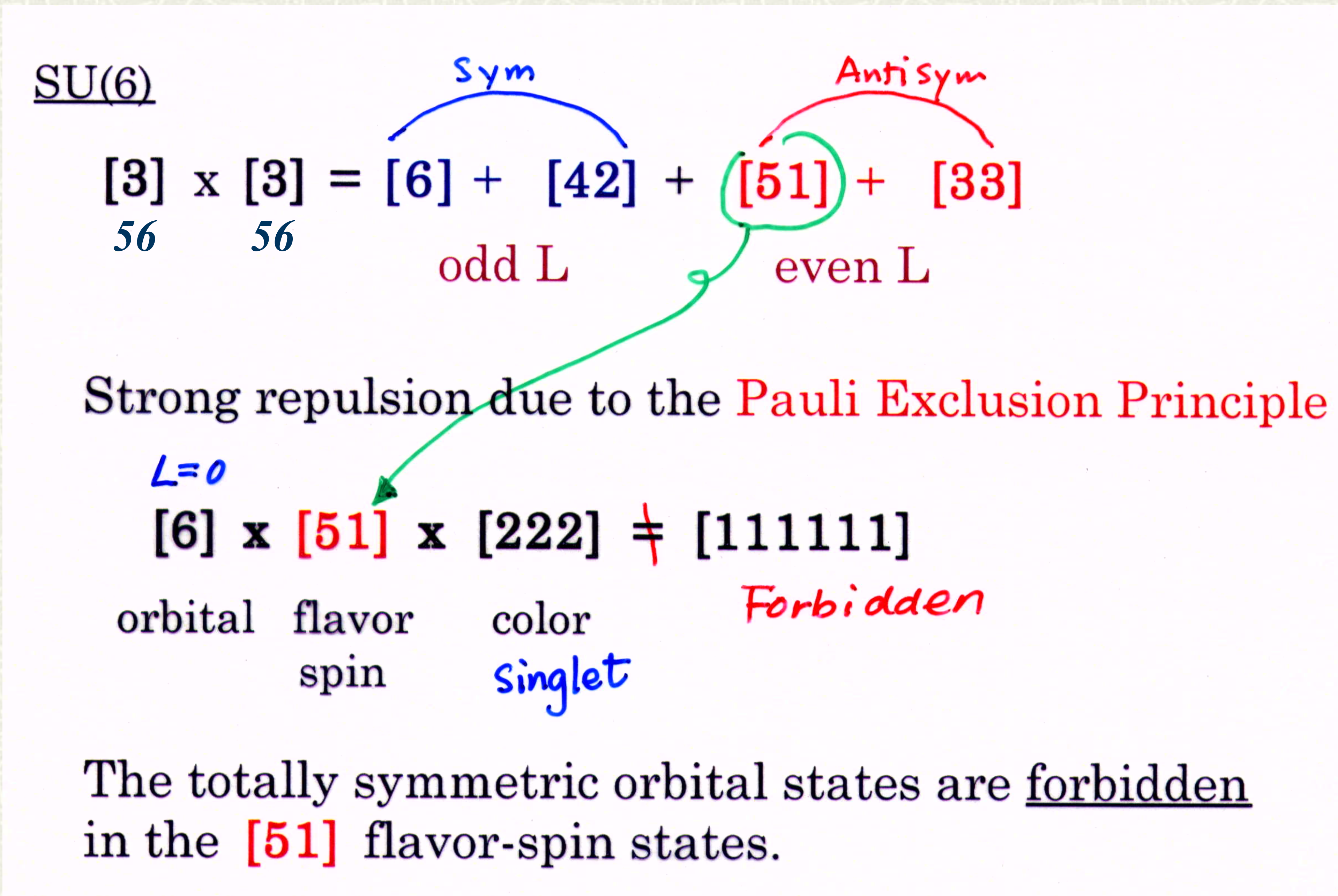
  spin × flavor × color × orbital motion

  $SU(2) \times SU(N_f) \times SU(3) \times O(3)$

  $SU(2N_f) \times SU(3) \times O(3)$

Pauli effect

- **SU(6) ⊃ $SU(2)_S \times SU(3)_f$ symmetry of two-baryon states: *56* [3] = (*8*, 1/2) + (*10*, 3/2) baryons.**



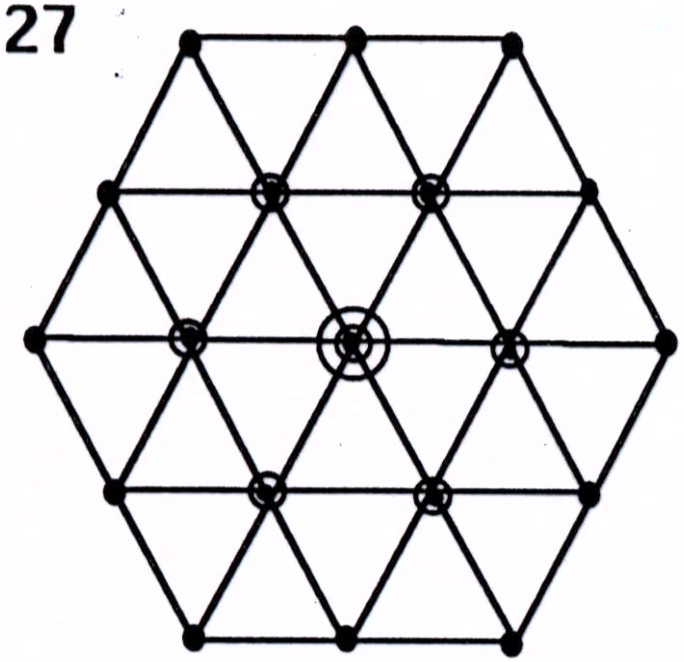
Strong short-range repulsion appears when the [6] symmetric orbital state is forbidden by the Pauli principle.

L	SU(4)		BB' (S,I)
even	{33}		ΔΔ (3,0), ΔΔ (0,3)
even	{51}	forbidden	ΔΔ (3,2), ΔΔ (2,3), NΔ(2,2), NΔ(1,1)
even	{33}+{51}		ΔΔ+NΔ (2,1), ΔΔ+NΔ(1,2) NN+ΔΔ (1,0), NN+ΔΔ(0,1)
odd	{6}	forbidden	ΔΔ(3,3)
odd	{42}		ΔΔ(3,1), ΔΔ(1,3), ΔΔ(2,0), ΔΔ(0,2) NΔ(2,1), NΔ(1,2)
odd	{6} + {42}		NΔ+ΔΔ(2,2), NN+ΔΔ(0,0)
odd	$\{6\} + \{42\}^2$		NN+NΔ+ΔΔ (1,1)

taken from D. Sc Thesis by M.O. (1980)

B_8B_8 Flavor Symmetric → singlet even/triplet odd

27



NN(I=1)

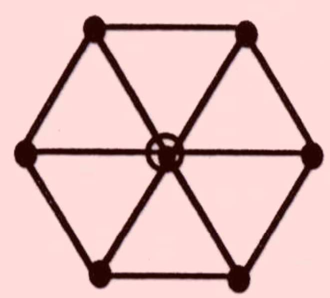
ΣN(I=3/2), ΣN−ΛN(I=1/2)

ΣΣ(I=2), ΞN−ΣΣ−ΣΛ(I=1), ΞN−ΣΣ−ΛΛ(I=0)

ΞΣ(I=3/2), ΞΣ−ΞΛ(I=1/2)

ΞΞ(I=1)

8_s



ΣN−ΛN(I=1/2)

ΞN−ΣΛ(I=1), ΞN−ΣΣ−ΛΛ(I=0)

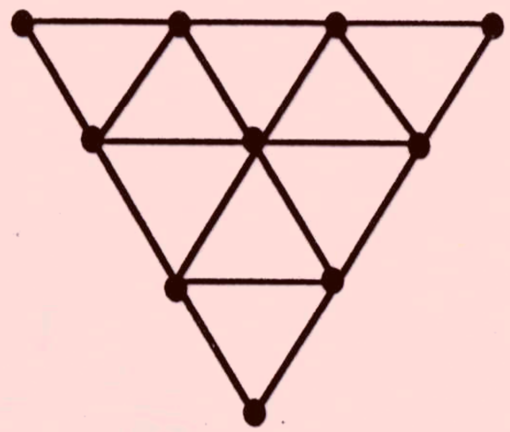
ΞΣ−ΞΛ(I=1/2)

1

ΞN−ΣΣ−ΛΛ(I=0)

B_8B_8 Flavor Antisymmetric → triplet even/singlet odd

10



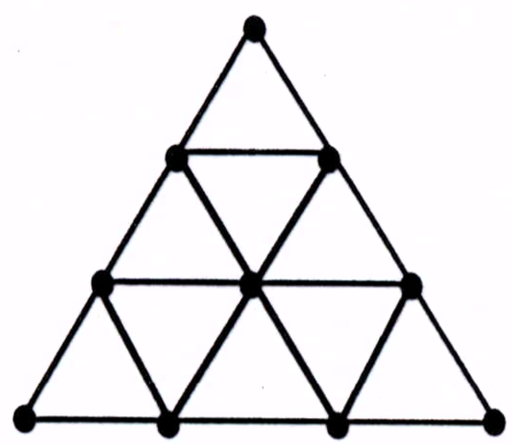
ΣN(I=3/2)

ΞN−ΣΣ−ΣΛ(I=1)

ΞΣ−ΞΛ(I=1/2)

ΞΞ(I=0)

$\overline{10}$



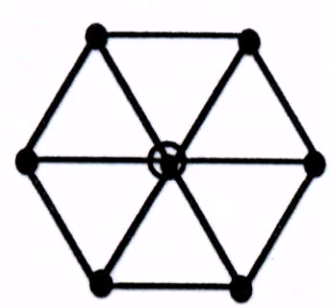
NN(I=0)

ΣN−ΛN(I=1/2)

ΞN−ΣΛ(I=1)

ΞΣ(I=3/2)

8_A



ΣN−ΛN(I=1/2)

ΞN−ΣΣ−ΣΛ(I=1), ΞN(I=0)

ΞΣ−ΞΛ(I=1/2)

Pauli effect

- **HAL QCD data are consistent with the quark Pauli effects.**

S=0

1	[33]	Allowed, ΛΛ+NΞ+ΣΣ → H
8_s	[51]	Pauli forbidden, ΣN (I=1/2, S=0)
27	[33], [51]	55% Allowed, NN $^1S_0$

S=1

8_a	[33], [51]	
10	[33], [51]	Almost forbidden, ΣN (I=3/2, S=1)
10*	[33], [51]	NN $^3S_1$

Pauli effect

- HAL QCD data are c

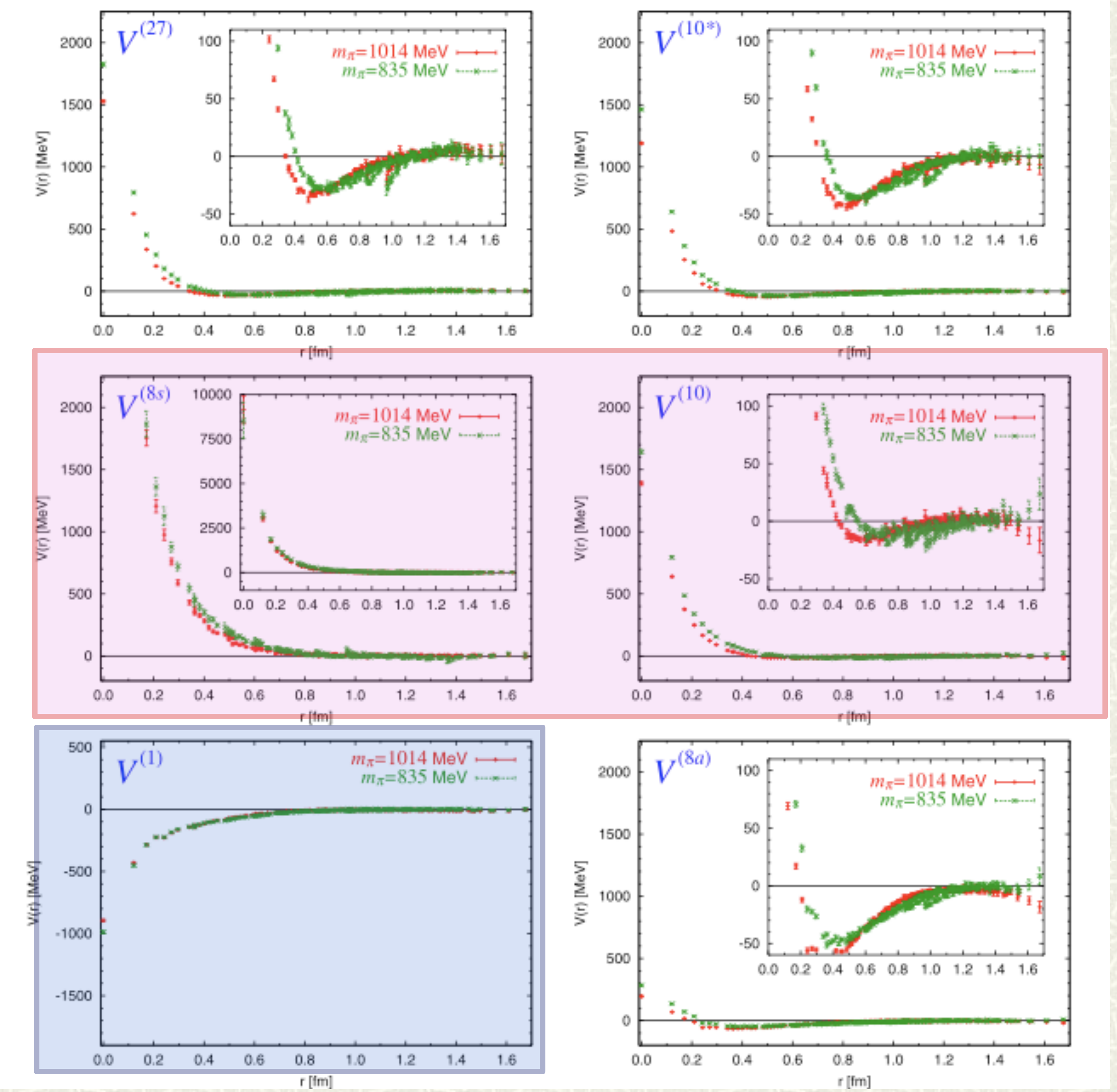
S=0

1	[33]	All
8_s	[51]	Pa
27	[33], [51]	55

S=1

8_a	[33], [51]	
10	[33], [51]	Alr
10*	[33], [51]	NN

T. Inoue et al., (HAL QCD) PTP 124, 591 (2010)



Spin dependence

- **Spin-spin interaction aka Color-Magnetic Interaction (CMI)**

$$V_{\rm CMI} = -\alpha \sum_{i<j} (\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) f(r_{ij}) \qquad f(r_{ij}) \sim \delta(r_{ij})$$

prefers symmetric color-spin states

$$\langle V_{\rm CMI} \rangle_{(0s)^N} = \alpha \langle f(r) \rangle_{0s} \Delta_{\rm CM} = V_0 \Delta_{\rm CM}$$

$$\Delta_{\rm CM} \equiv \langle - \sum_{i<j} (\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) \rangle$$

$$\Delta_{\rm CM} = 8N - 2C_2[SU(6)_{cs}] + \frac{4}{3} S(S+1) + C_2[SU(3)_c]$$

$$C_2[SU(g)]([f_1, f_2, \ldots, f_g]) = \sum_i f_i(f_i - 2i + g + 1) - \frac{N^2}{g}$$

$$C_2[\text{singlet}] = 0$$

Spin dependence

- **CMI prefers color-spin symmetric states, i.e. flavor antisymmetric states.**

$$\Delta_{\rm CM} = 8N - 2C_2[SU(6)_{cs}] + \frac{4}{3}S(S+1) + C_2[SU(3)_c]$$

$$\Delta_{\rm CM}(\mathbf{10}) - \Delta_{\rm CM}(\mathbf{8}) = 8 - (-8) = 16$$

$$M(\Delta) - M(N) = 16V_0 \sim 300\,\mathrm{MeV}$$

$$V_0 \sim 300/16 \sim 19\,\mathrm{MeV}$$

$$\Delta_{\rm CM}(H) - 2\Delta_{\rm CM}(\Lambda) = -24 - 2(-8) = -8$$

H (ΛΛ+NΞ+ΣΣ, S=0)

$$\Delta_{\rm CM}(D_\Delta) - 2\Delta_{\rm CM}(\Delta) = 16 - 2\times 8 = 0$$

D_Δ (ΔΔ, I=0, S=3)

H di-baryon

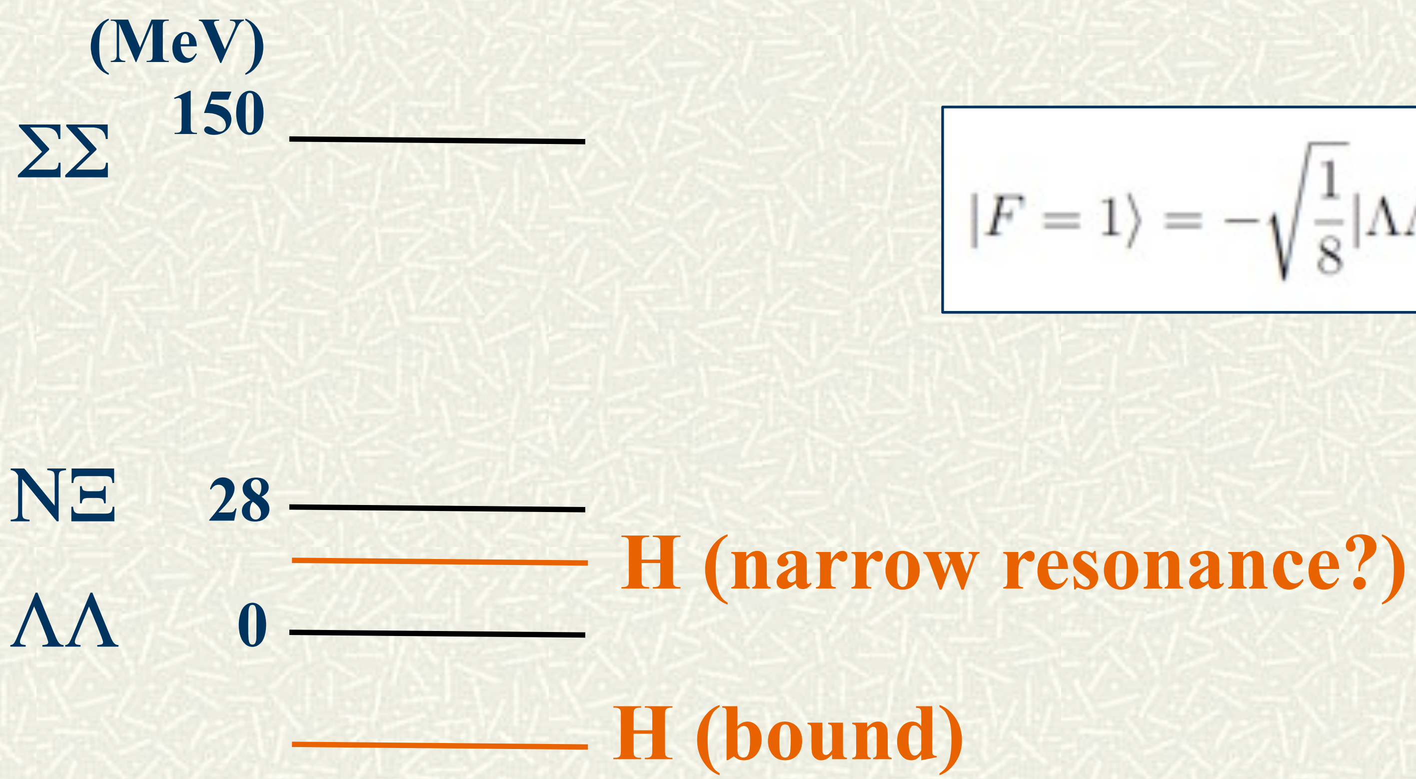
H di-baryon

H = $u^2d^2s^2$ (S= -2, J=0^+ I=0) predicted by Jaffe (1977)

CMI prefers

symmetric color-spin state ⇔ antisymmetric flavor state

Most favored state is the flavor singlet state.



$$|F=1\rangle = -\sqrt{\frac{1}{8}}|\Lambda\Lambda\rangle + \sqrt{\frac{4}{8}}|N\Xi\rangle + \sqrt{\frac{3}{8}}|\Sigma\Sigma\rangle$$

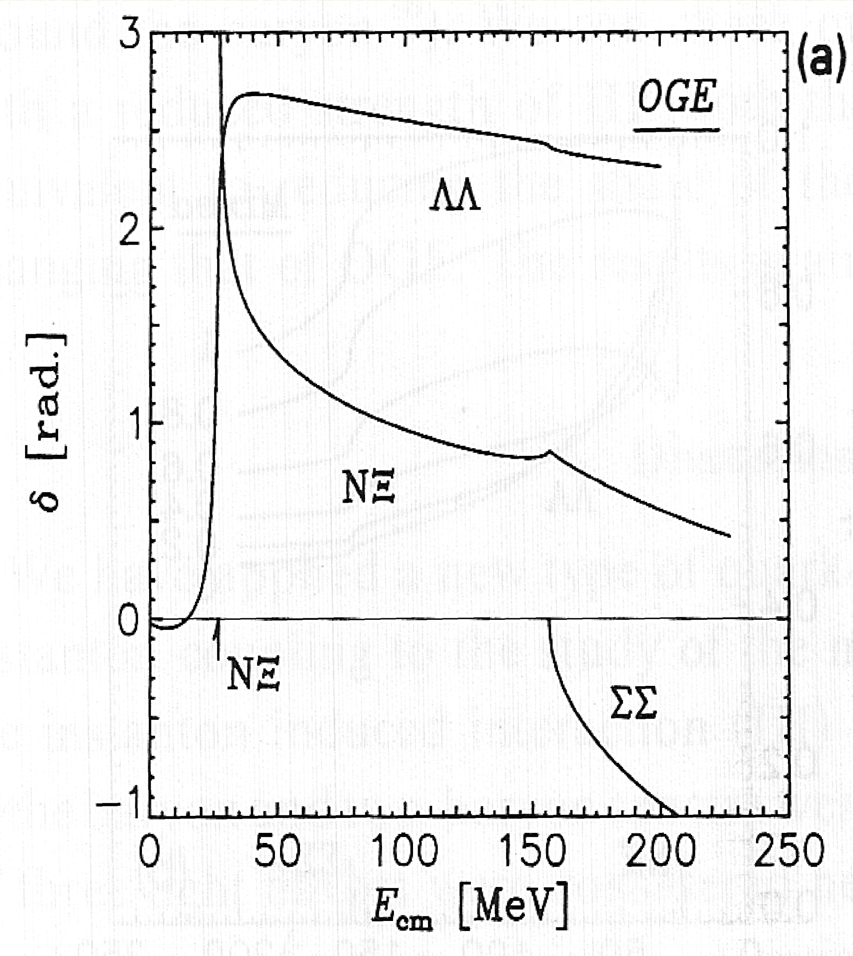
H di-baryon

Quark cluster model approach to the coupled channel ΛΛ, NΞ, ΣΣ system, with the linear + OgE potential for quarks.

MO, K. Shimizu, K. Yazaki (1983)
- The BB(F=1) channel is PAULI allowed.

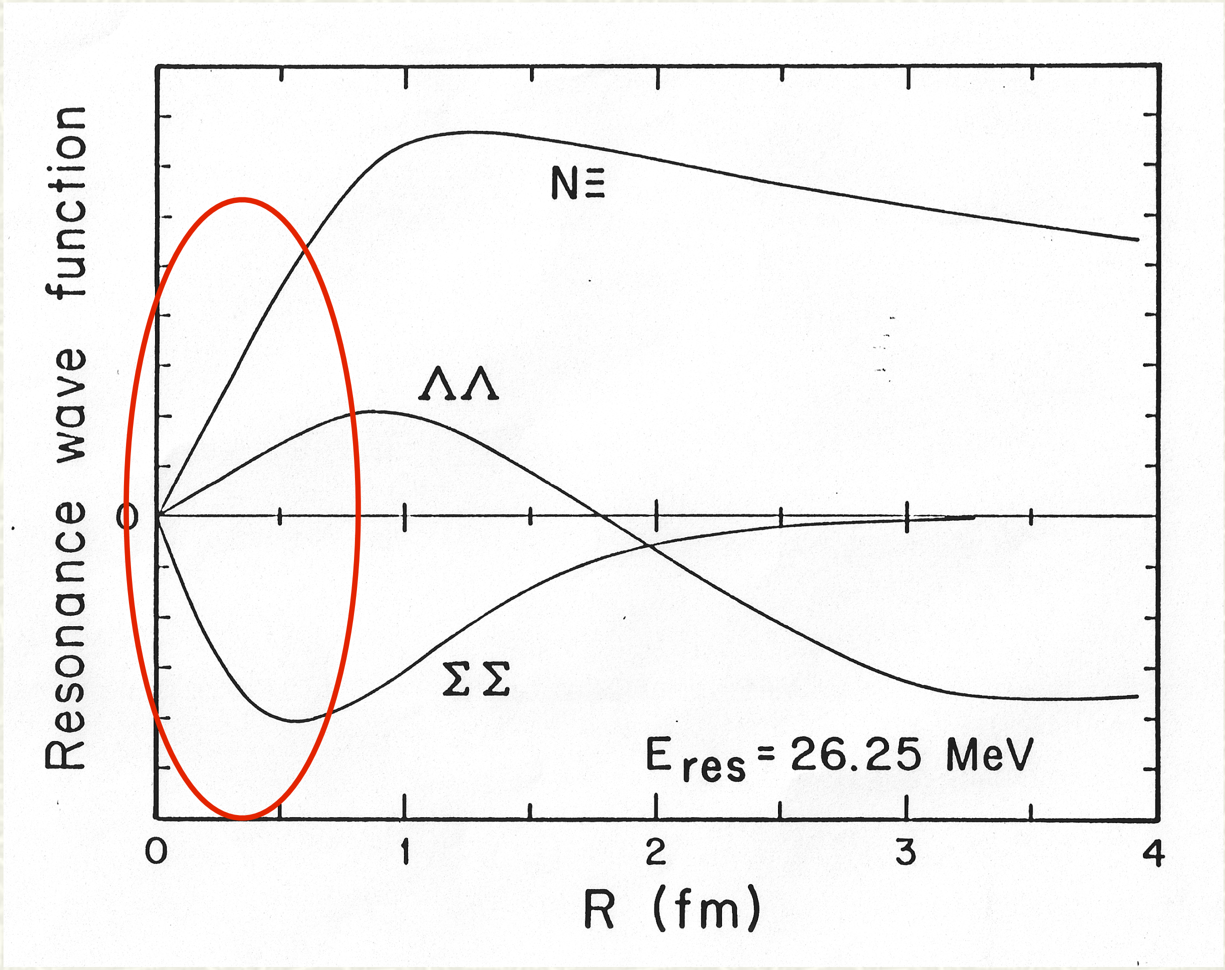
- There appears a very sharp resonance just below the NΞ threshold.
- Additional long range attraction will form a bound state below the ΛΛ threshold.

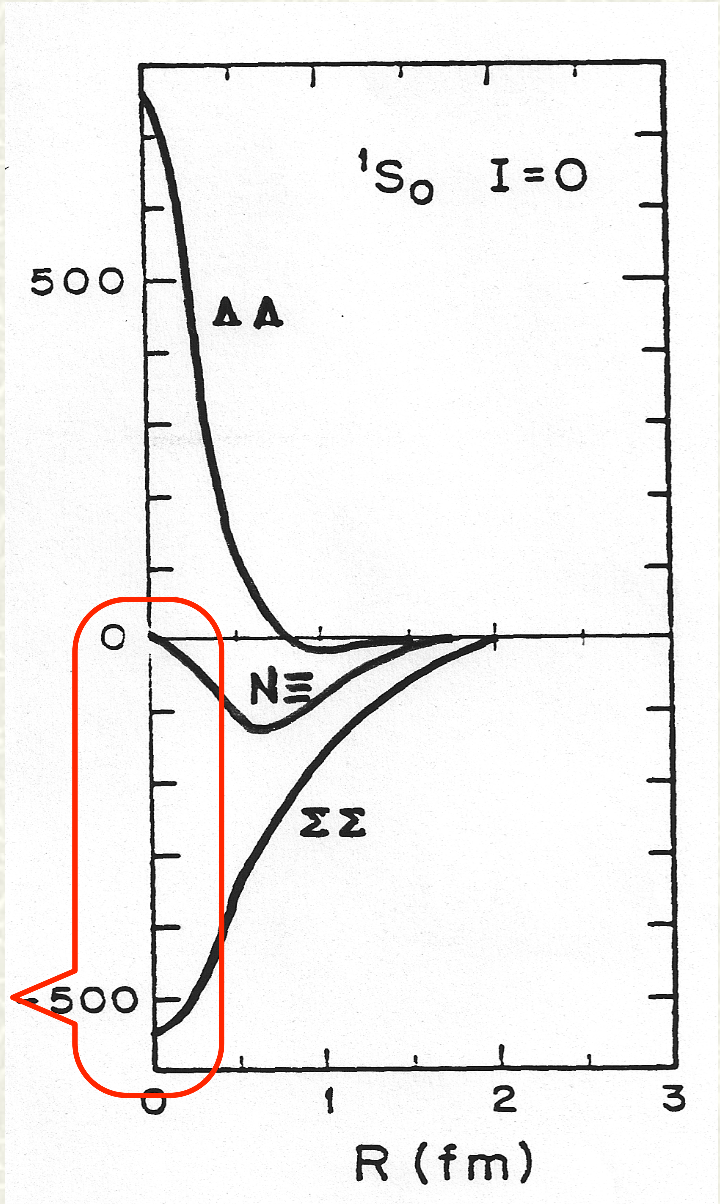
S. Takeuchi and MO (1991)
- The instanton induced interaction yields 3-body repulsive force to H, resulting no bound state.



H di-baryon

- **The resonance H looks as a "bound state" of NΞ, but the wave function (@ the resonance peak) reveals its flavor singlet-ness.**





$$|\text{Singlet}\rangle = \sqrt{\tfrac{1}{8}}|\Lambda\Lambda\rangle + \sqrt{\tfrac{4}{8}}|N\Xi\rangle - \sqrt{\tfrac{3}{8}}|\Sigma\Sigma\rangle$$

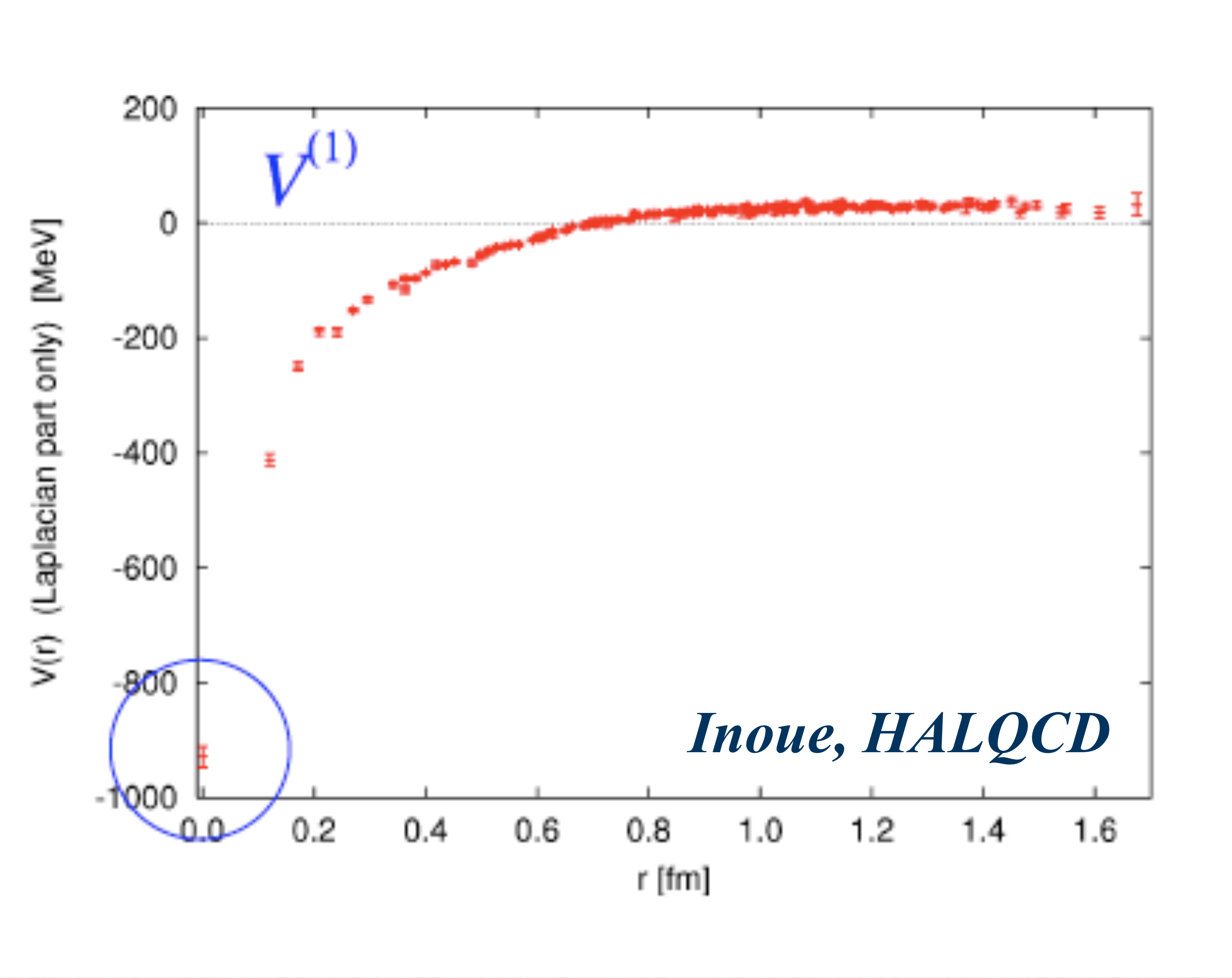
No strong repulsion at short distances

H di-baryon on Lattice

- A compact 6-quark bound/resonance state is expected.
- New Lattice QCD calculations of H di-baryon
  - Bound H di-baryon in Flavor SU(3) Limit of Lattice QCD
    Takashi Inoue (HAL QCD Collaboration)
    PRL 106, 162002 (2011)
  - Evidence for a Bound H di-baryon from Lattice QCD
    S. R. Beane et al. (NPLQCD Collaboration)
    PRL 106, 162001 (2011)

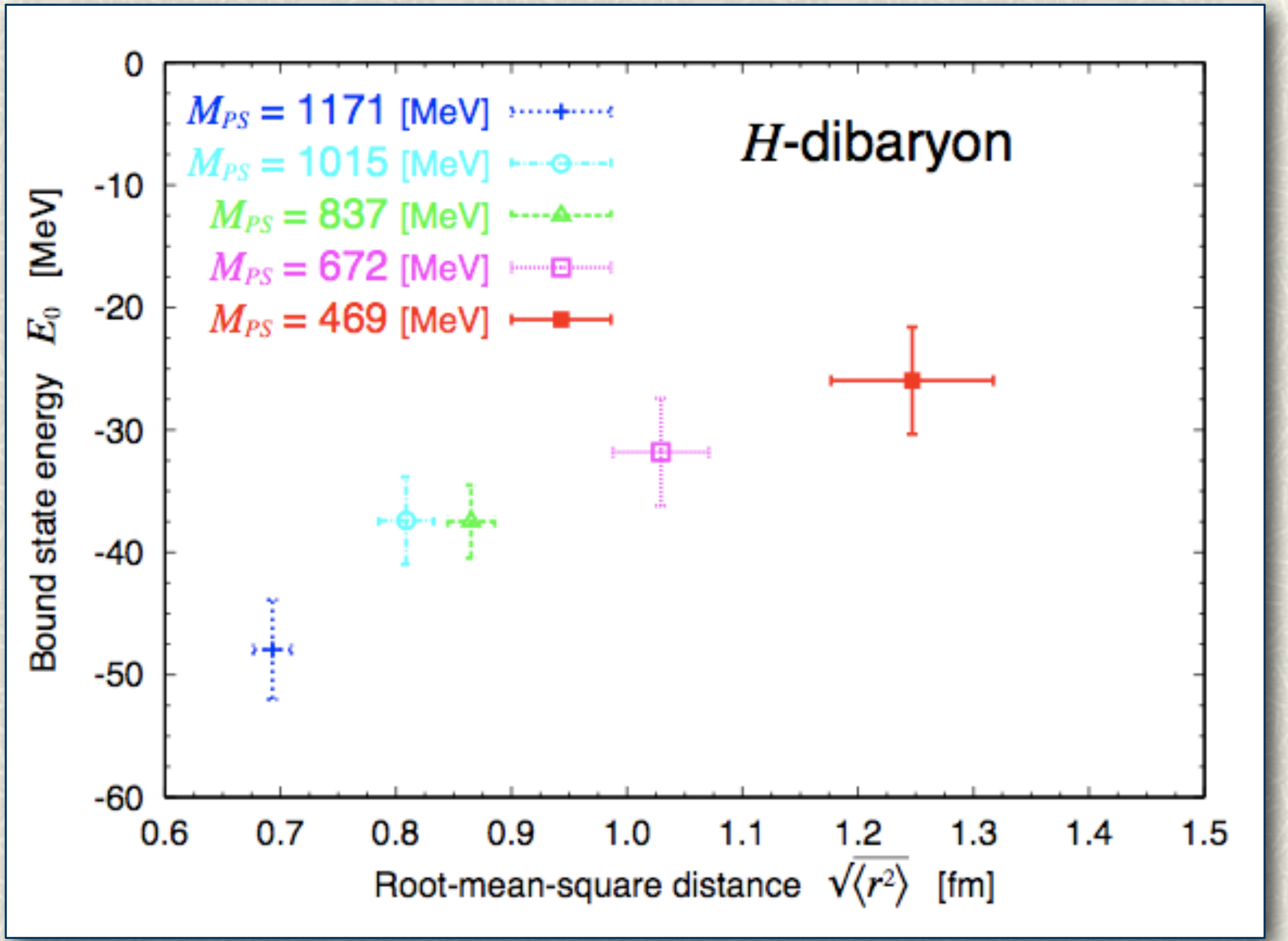
H di-baryon on Lattice

- A compact 6-quark bound/resonance state is expected.
- New Lattice QC
  - Bound H di-bar
    Takashi Inoue (
    PRL 106, 16200
  - Evidence for a B
    S. R. Beane et al
    PRL 106, 16200



H di-baryon on Lattice

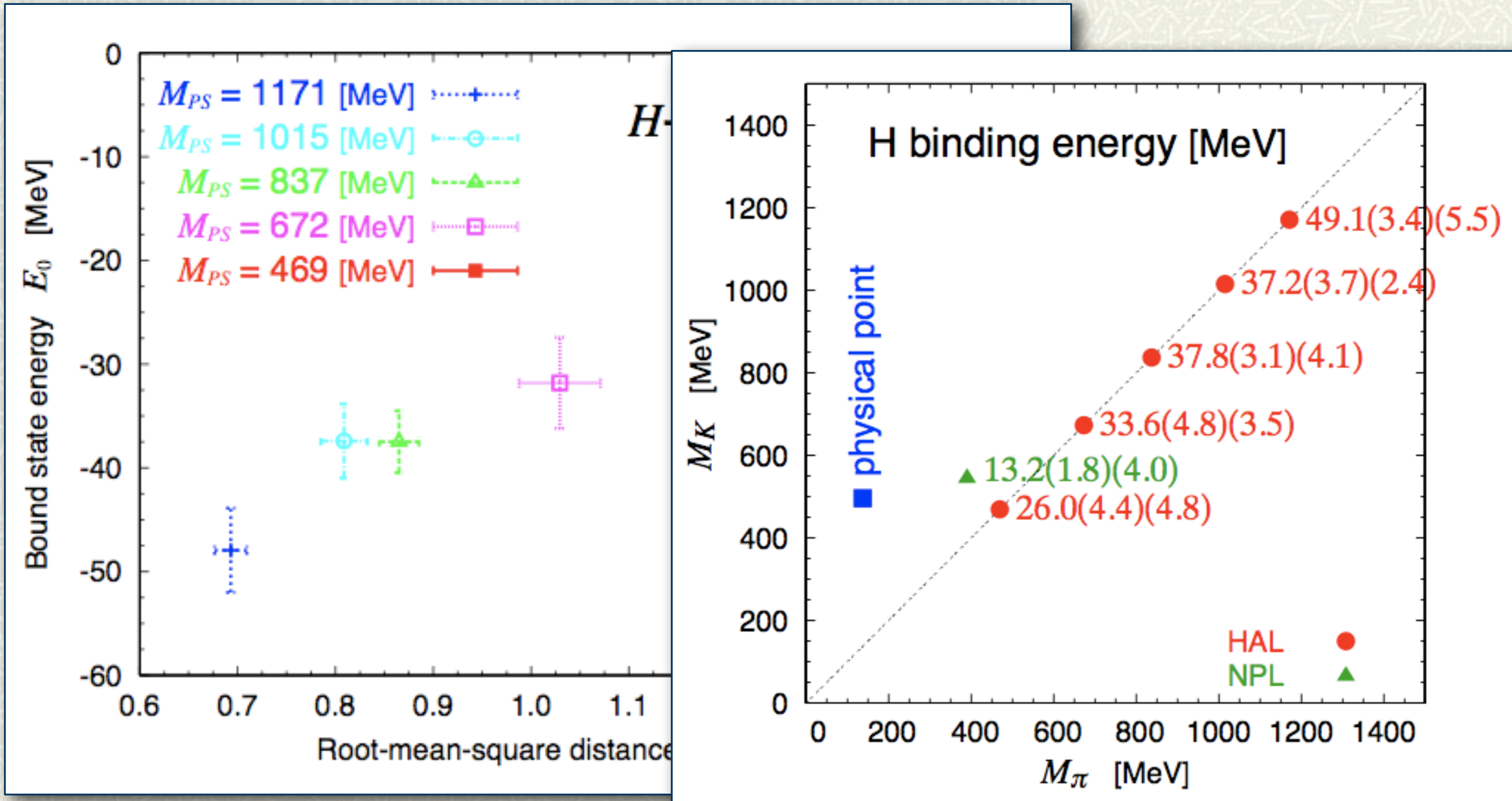
- Lattice QCD predicts H di-baryon



T. Inoue et al., (HAL-QCD) NP A881 (2012) 28.

H di-baryon on Lattice

- Lattice QCD predicts H di-baryon



T. Inoue et al., (HAL-QCD) NP A881 (2012) 28.

From ABC to d*

ABC effect

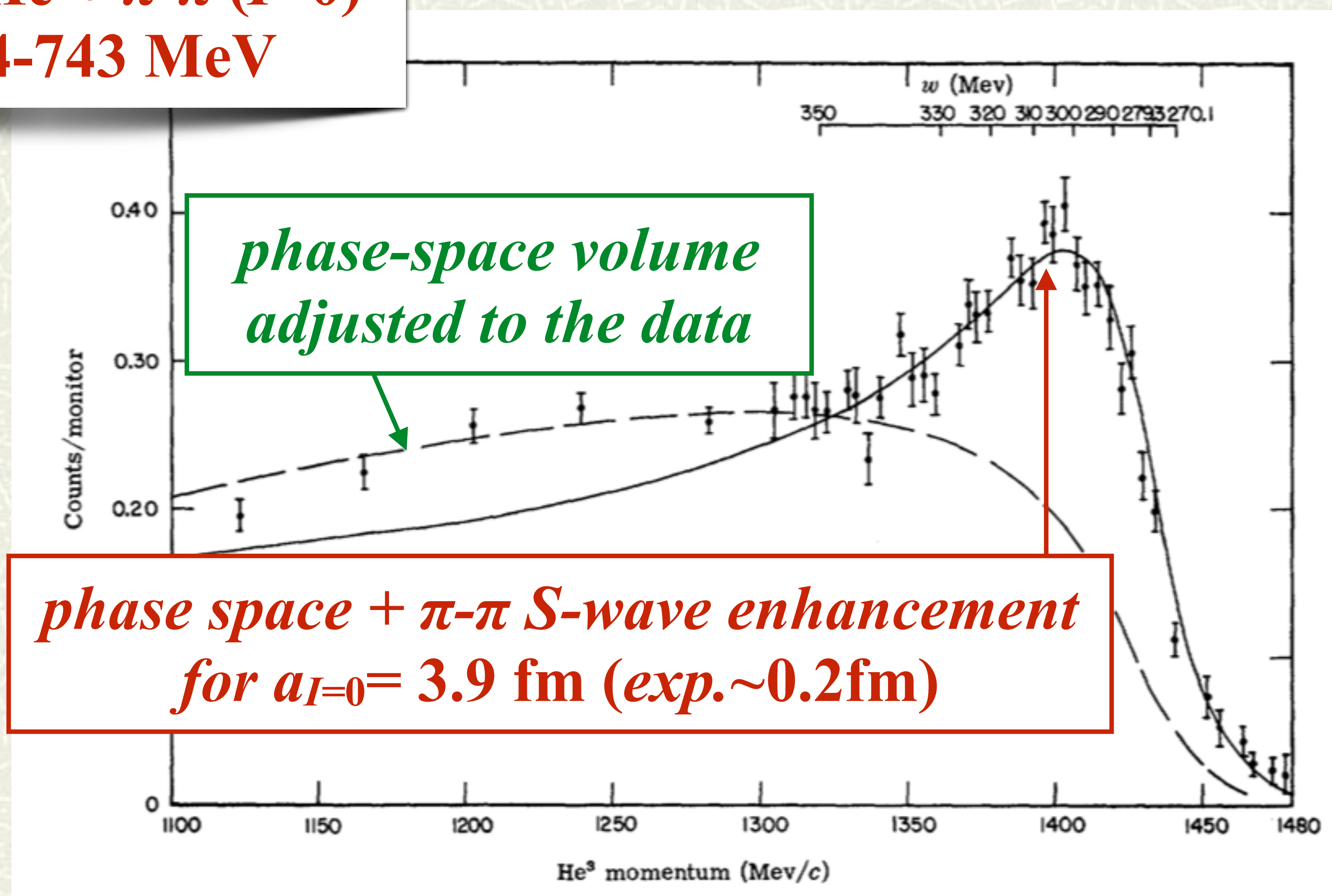
- **A. Abashian, N.E. Booth, K.M. Crowe**
  ***Possible anomaly in meson production in p+d collisions*, *PRL* 5, 258 (1960)**
  ***Anomaly in meson production in p+d collisions*, *PRL* 7, 35 (1961)**

- **Low mass ππ enhancement observed in the inclusive production,**
  $p + d \rightarrow {}^3\mathrm{He} + \mathrm{X}, {}^3\mathrm{H} + X$ (E_p=624-743 MeV, Berkeley)
  $X = \pi$ or
  ππ (I=0) for ^{3}He
  ππ (I=1) for ^{3}He and ^{3}H
  Using the data of ^{3}H production, one can determine the ππ (I=0) production cross section.

ABC effect

- **A. Abashian, N.E. Booth, K.M. Crowe**
  Possible anomaly in meson production in p+d collisions, ***PRL*** **5, 258 (1960)**
  Anomaly in meson production in p+d collisions, ***PRL*** **7, 35 (1961)**

$p + d \rightarrow {}^3He + \pi\text{-}\pi$ (I=0)
E_p=624-743 MeV



phase-space volume adjusted to the data

phase space + π-π S-wave enhancement for $a_{I=0}$= 3.9 fm (exp.~0.2fm)

ABC effect

- **A. Abashian, N.E. Booth, K.M. Crowe**
  ***Possible anomaly in meson production in p+d collisions*, *PRL* 5, 258 (1960)**
  ***Anomaly in meson production in p+d collisions*, *PRL* 7, 35 (1961)**

- **Low mass ππ enhancement observed in the inclusive production,**
  $p + d \rightarrow {}^3\mathrm{He} + \mathrm{X}$, ${}^3\mathrm{H} + X$ (E_p=624-743 MeV, Berkeley)
  X = π or
  ππ (I=0) for ^{3}He
  ππ (I=1) for ^{3}He and ^{3}H
  Using the data of ^{3}H production, one can determine the ππ (I=0) production cross section.

- **As the beam energies correspond to ΔΔ excitation in nucleus, the ππ enhancement is attributed to the ΔΔ excitations.**
  → precise measurements by WASA group (Bashkanov).
  WASA@CELSIUS, PRL 102, 052301 (2009)
  WASA@COSY, PRL 106, 242302 (2011)

ABC effect → d* resonance

- **Double-pionic fusion of nuclear systems and the "ABC" effect**
  WASA@CELSIUS, PRL 102, 052301 (2009)
  $p+d \rightarrow d+\pi^0+\pi^0+p_{spectator}$ at T_p=1.03, 1.35 GeV

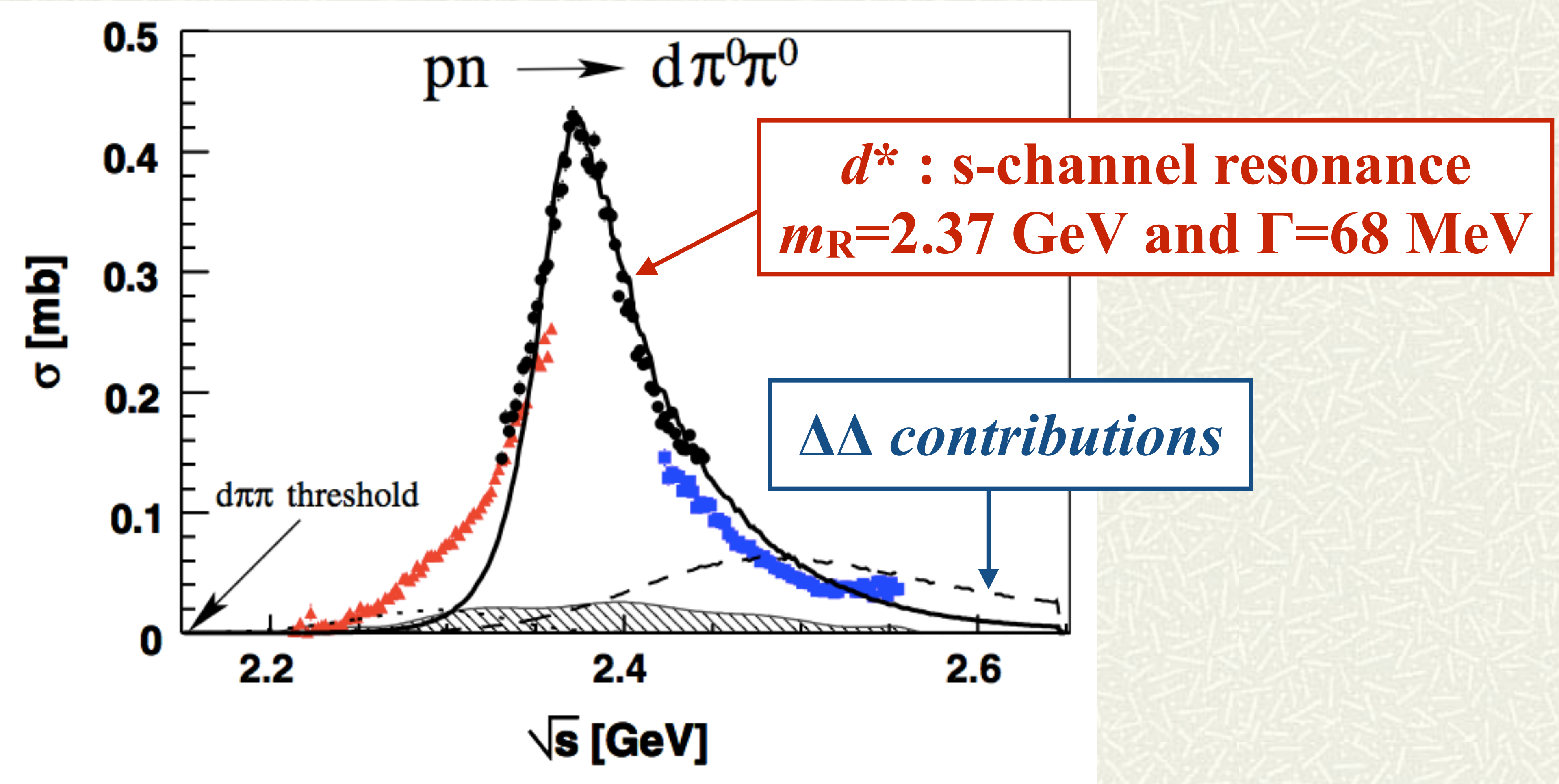
  The $\pi^0\pi^0$ enhancement is much larger than estimate in ΔΔ production
  by Alvarez-Ruso, Oset, Hernandez, NPA 633 (1998) 519.
  A s-channel resonance at m_R~2.36 GeV may explain the results.

- **ABC effect in basic double-pionic fusion: A new resonance?**
  WASA@COSY, PRL 106, 242302 (2011)
  $p+d \rightarrow d+\pi^0+\pi^0+p_{spectator}$ at T_p=1.0, 1.2, 1.4 GeV

ABC effect → d* resonance

WASA@COSY, PRL 106, 242302 (2011)

$p + n(d) \rightarrow d + \pi^0 + \pi^0$ $(+p_{spectator})$ at T_p=1.0, 1.2, 1.4 GeV

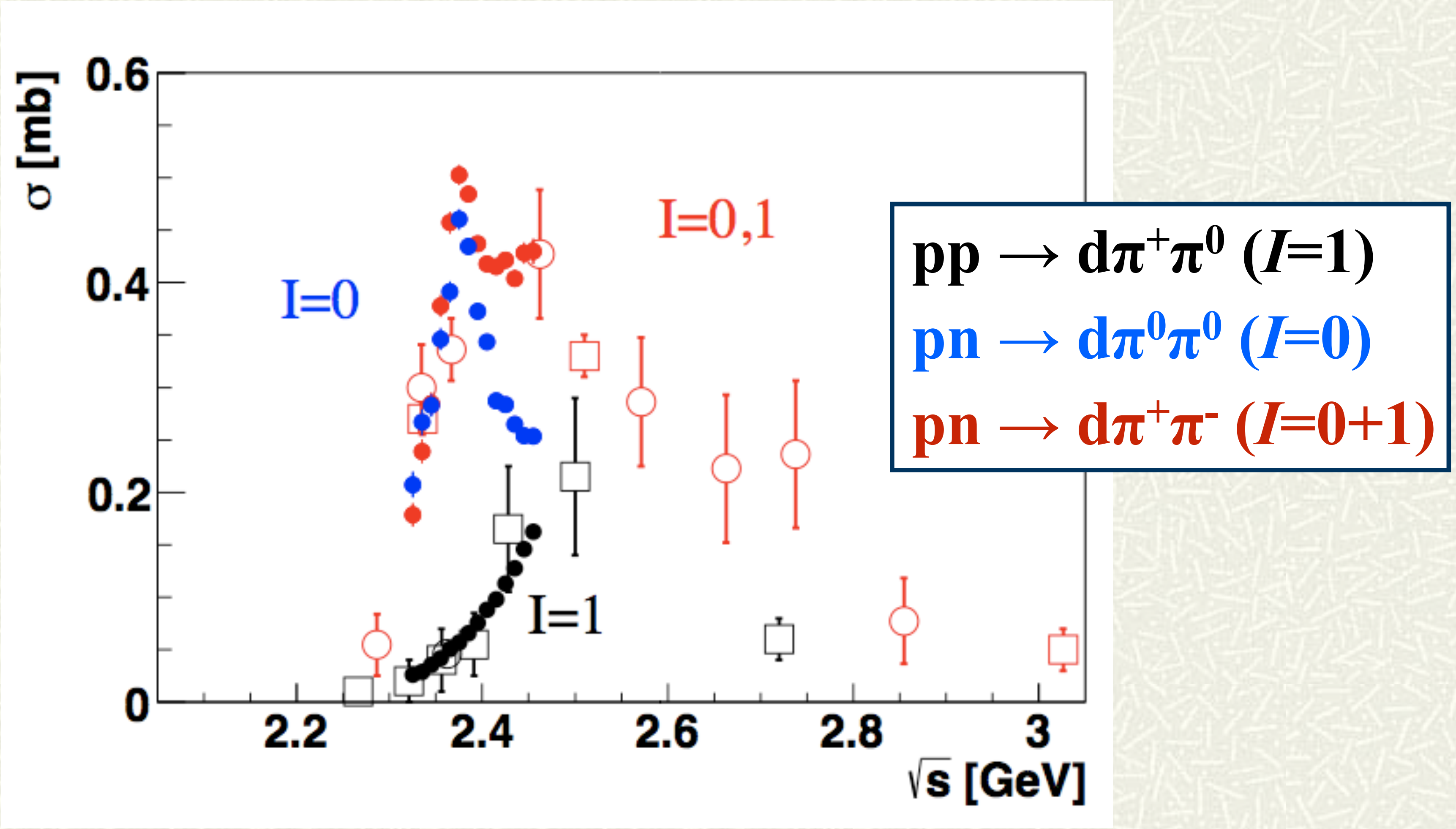


A di-baryon resonance, *d (*I*=0, J^π=3$^+$) (in pn and ΔΔ) is confirmed.**

ABC effect → d* resonance

WASA@COSY, PLB 721 (2013) 229

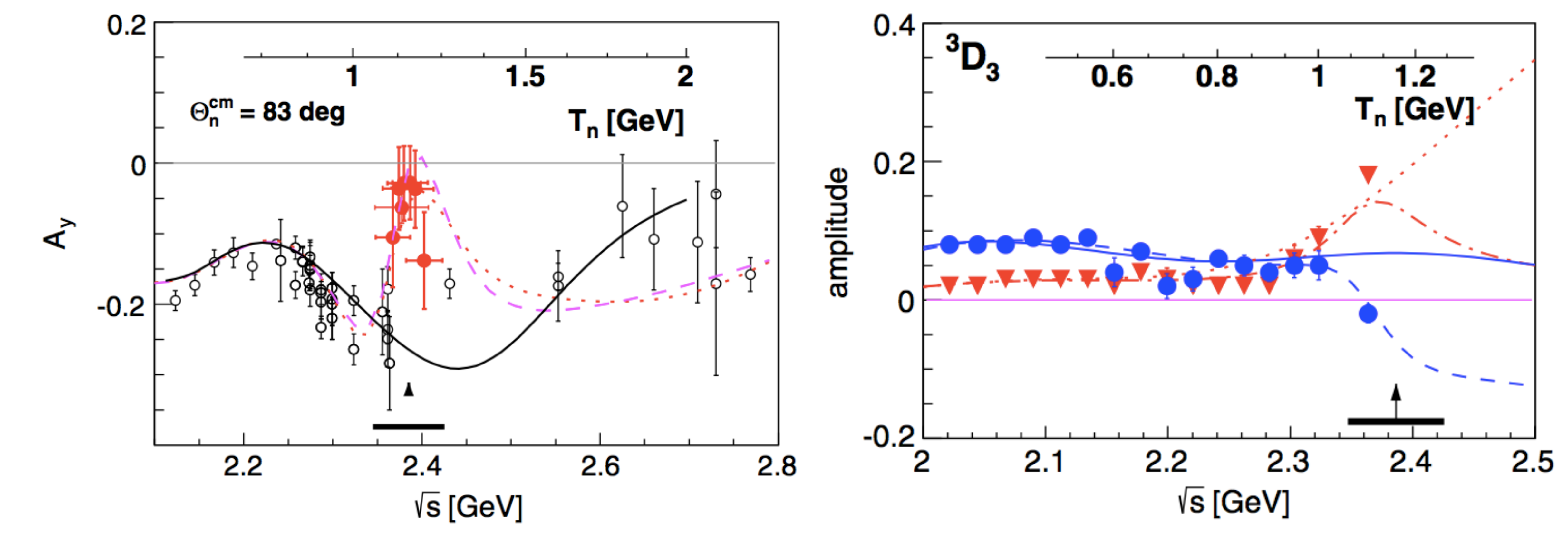
Isospin decomposition of the basic double-pionic fusion in the region of the ABC effect



The (I=1) production is consistent with the ΔΔ production.

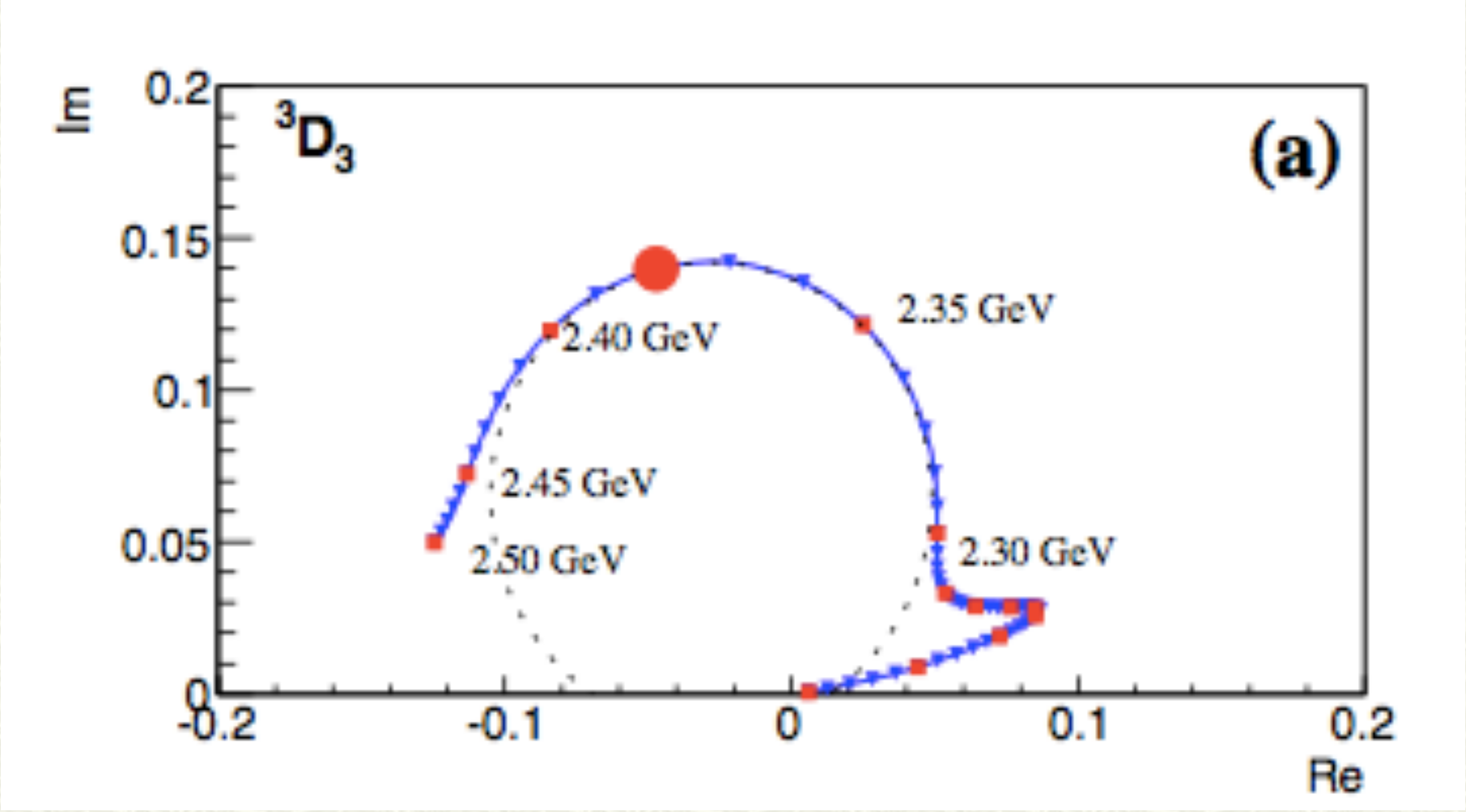
ABC effect → d* resonance

- **WASA@COSY+SAID, PRL 112, 202301 (2014)**
  Evidence for a new resonance from polarized n-p scattering
  d(↑) + p → np + $p_{spectator}$
  np analyzing power, $A_y(\theta)$, at T_n=1.108-1.197 GeV
  A phase shift analysis of $^3D_3$ (3^+) amplitudes shows a narrow resonance at M=2380 MeV and Γ~70 MeV.



ABC effect → d* resonance

- **WASA@COSY+SAID, PRL 112, 202301 (2014)**
  Evidence for a new resonance from polarized n-p scattering
  d(↑) + p → np + $p_{spectator}$
  np analyzing power, $A_y(\theta)$, at T_n=1.108-1.197 GeV
  A phase shift analysis of $^3D_3$ (3^+) amplitudes shows a narrow resonance at M=2380 MeV and Γ~70 MeV.



D_{Δ} $(\Delta\Delta)_{I=0}$ di-baryon

D_Δ $(\Delta\Delta)_{I=0}$ di-baryon

- **S=3, I=0 (Δ^2) bound state**
  → relatively narrow NNππ (I=0) resonance

Volume 90B, number 1, 2 PHYSICS LETTERS 11 February 1980

NUCLEAR FORCE IN A QUARK MODEL

M. OKA and K. YAZAKI
Department of Physics, Faculty of Science, University of Tokyo, Bunkyō-ku, Tokyo 113, Japan

The problem of the nuclear force in a nonrelativistic quark model is studied by the resonating group method which has been extensively used in treating the interaction between composite particles. The calculated phase shifts for the $^3S_1$ and $^1S_0$ states of two nucleons indicate the presence of a strong repulsive force at short distance, while an attractive force is predicted for the $^7S_3((S, T) = (3, 0))$ state of two Δ's. These features are due to an interplay between the Pauli principle and the spin–spin interaction between quarks.

D. Sc Thesis by M.O. (1980)

Classification of two baryon systems without strangeness.

The spin-flavor SU(6) is reduced to the spin-isospin SU(4).

S(I) denotes the total spin (isospin) of the system.

L	SU(4)		BB' (S,I)
even	{33}		ΔΔ (3,0), ΔΔ (0,3)
even	{51}	forbidden	ΔΔ (3,2), ΔΔ (2,3), NΔ(2,2), NΔ(1,1)
even	{33}+{51}		ΔΔ+NΔ (2,1), ΔΔ+NΔ(1,2) NN+ΔΔ (1,0), NN+ΔΔ(0,1)
odd	{6}	forbidden	ΔΔ(3,3)
odd	{42}		ΔΔ(3,1), ΔΔ(1,3), ΔΔ(2,0), ΔΔ(0,2) NΔ(2,1), NΔ(1,2)
odd	{6} + {42}		NΔ+ΔΔ(2,2), NN+ΔΔ(0,0)
odd	$\{6\} + \{42\}^2$		NN+NΔ+ΔΔ (1,1)

$$\Gamma_{\rm CM} \equiv -\sum_{i<j}(\lambda_i^a\lambda_j^a)(\sigma_i^k\sigma_j^k) = 8n - 2C_6 + \frac{4}{3}S(S+1)$$

$$C_6 \equiv C_2[SU(6)_{\rm cs}] = \sum_i f_i(f_i - 2i + 7) - \frac{n^2}{6}$$

$$\Gamma_{\rm CM}(\Delta) = +8$$
$$\Gamma_{\rm CM}(N) = -8$$

$SU(6)_{cs}$ representation	$4C_6$	$SU(3)_f$ representation		
490	144	$\underline{1}$	$H = \Lambda\Lambda(I = S = 0)$	$V = V_0 \times (-8)$
896	120	$\underline{8}$		
280	96	10		
175	96	$\underline{10^*}$	$\Delta\Delta(I = 0, S = 3)$	$V = V_0 \times 0$
189	80	$\underline{27}$		
35	48	$\underline{35}$		
1	0	$\underline{28}$	$\Delta\Delta(I = 3, S = 0)$	$V = V_0 \times 32$

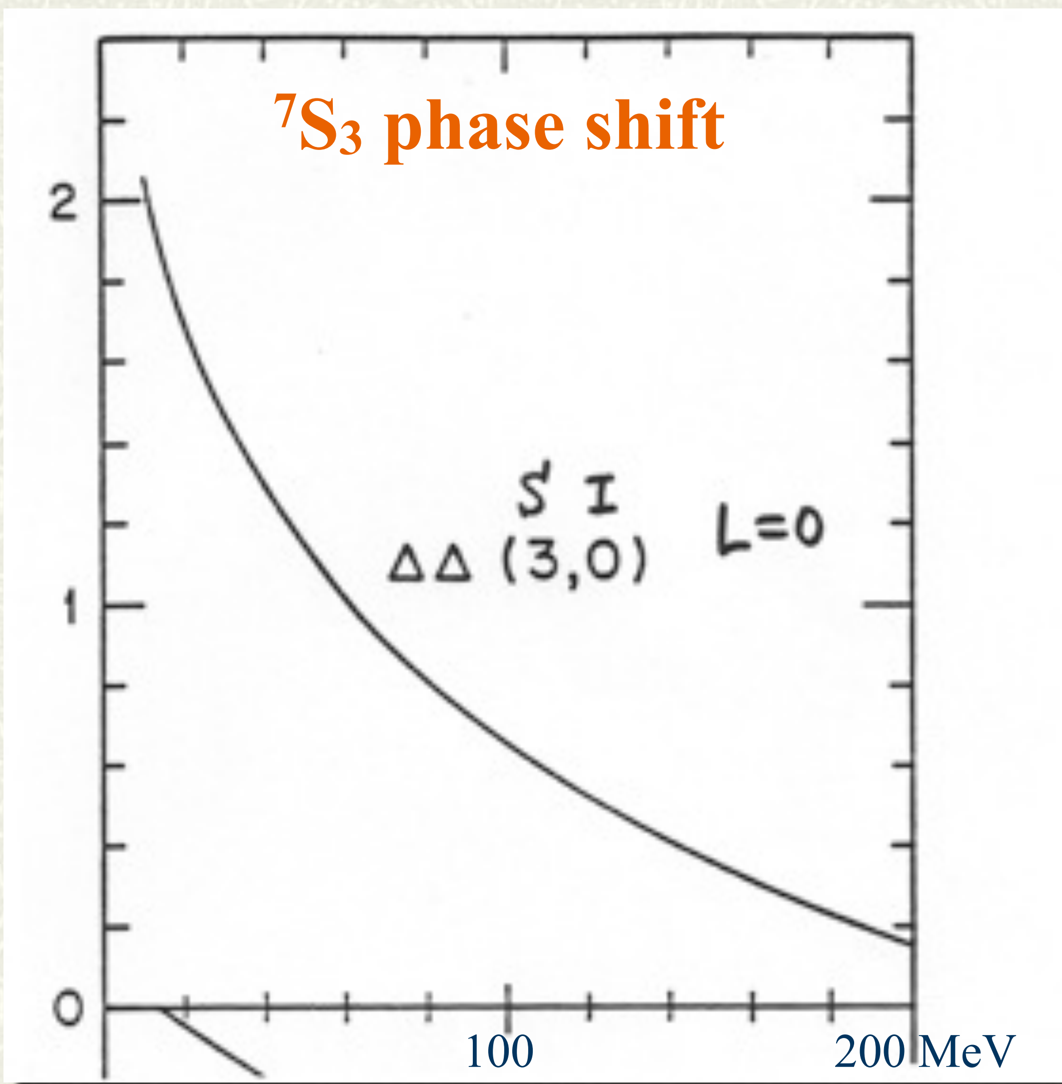
Perhaps a Stable Dihyperon*

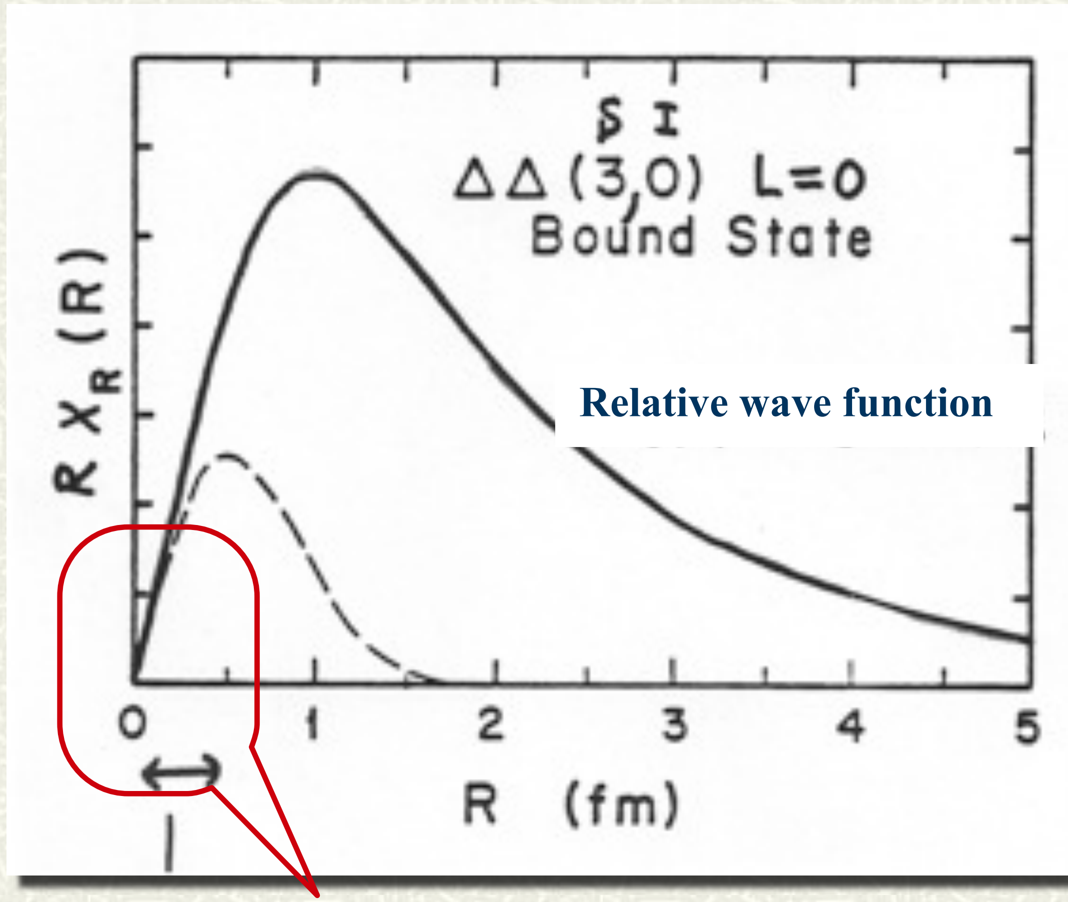
R.L. Jaffe, PRL 38 (1977) 195

$$V_0 = 300/16 \sim 18(\rm MeV)$$

D_Δ $(\Delta\Delta)_{I=0}$ di-baryon

- **S=3, I=0 (Δ^2) bound state**





No repulsive core

Conclusion

- Simple quark model description of the di-baryon interaction seems to work very well.
- Di-baryon is supposed to be a compact six-quark like state, or at least it contains six-quark component predominantly.
- LQCD has confirmed the Pauli effect as well as the CMI that favors flavor anti-symmetric states.
- H (F=1) is the most-likely di-baryon.
- D_{Δ} =(ΔΔ) (I=0, S=3) is another favorable state.
- The d* resonance at WASA-COSY is a strong candidate of a “compact” di-baryon.