Dibaryons with and without Heavy Flavor

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International Workshop on Progress on J-PARC Hadron Physics
March 03, 2016

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Why dibaryons?

- Dibaryon = (Baryon+ Baryon) = (6 quarks)
- A "loosely bound" dibaryon (ex. deuteron) is a hadron molecule, which provides important information on the (long-range) baryon-baryon interaction.
- A compact dibaryon could be a 6-quark state, which is related to the short-distance baryon-baryon interaction.
- The dibaryon is a "good" resonance because there is no annihilation channel. The only outgoing channels are two baryons (neglecting meson emissions).
- The quark model symmetries give simple and robust guidelines on the existence of compact dibaryons.

Pauli principles and Spin dependence

Symmetries

- **Recent Lattice QCD calculations (HALQCD) have confirmed that the short-range baryon-baryon interactions follow the quark model symmetry and dynamics.**
- **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
  $\underline{SU(2)_s \times SU(N_f)_f} \times SU(3)_c \times O(3)$
  $SU(2N_f)_{\underline{sf}} \times SU(3)_c \times O(3)$

Pauli effect

- $SU_{sf}(6) \supset SU(2)_s \times SU(3)_f$ symmetry of two-baryon states:
  two *56* [3] = (*8*, 1/2) + (*10*, 3/2) baryons.

SU(6)

Sym / Antisym

$$[3] \times [3] = [6] + [42] + [51] + [33]$$

56 56

odd L (for [6] + [42]) / even L (for [51] + [33])

Strong repulsion due to the Pauli Exclusion Principle

L=0

$$[6] \times [51] \times [222] \neq [111111]$$

orbital, flavor spin, color singlet — Forbidden

The totally symmetric orbital states are forbidden in the [51] flavor-spin states.

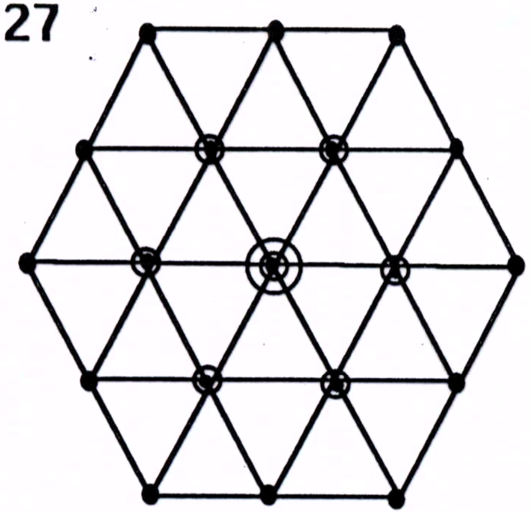
Strong short-range repulsion appears when the [6] symmetric orbital state is forbidden by the Pauli principle.

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

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

B_8B_8 Flavor Symmetric → singlet even/triplet odd

27



NN(I=1)

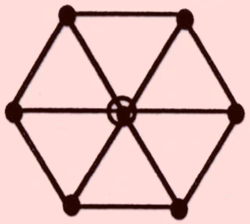
ΣN(I=3/2), ΣN−ΛN(I=1/2)

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)

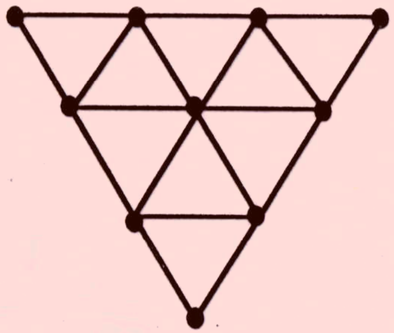
ΞΣ−ΞΛ(I=1/2)

1

ΞN−ΣΣ−ΛΛ(I=0)

B_8B_8 Flavor Antisymmetric → triplet even/singlet odd

10



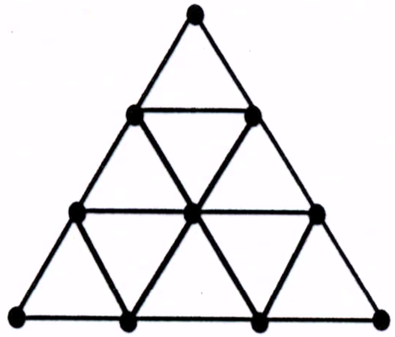
ΣN(I=3/2)

ΞN−ΣΣ−ΣΛ(I=1)

ΞΣ−ΞΛ(I=1/2)

ΞΞ(I=0)

$\overline{10}$



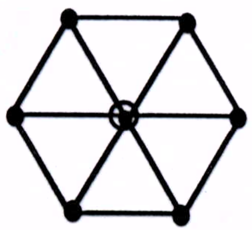
NN(I=0)

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

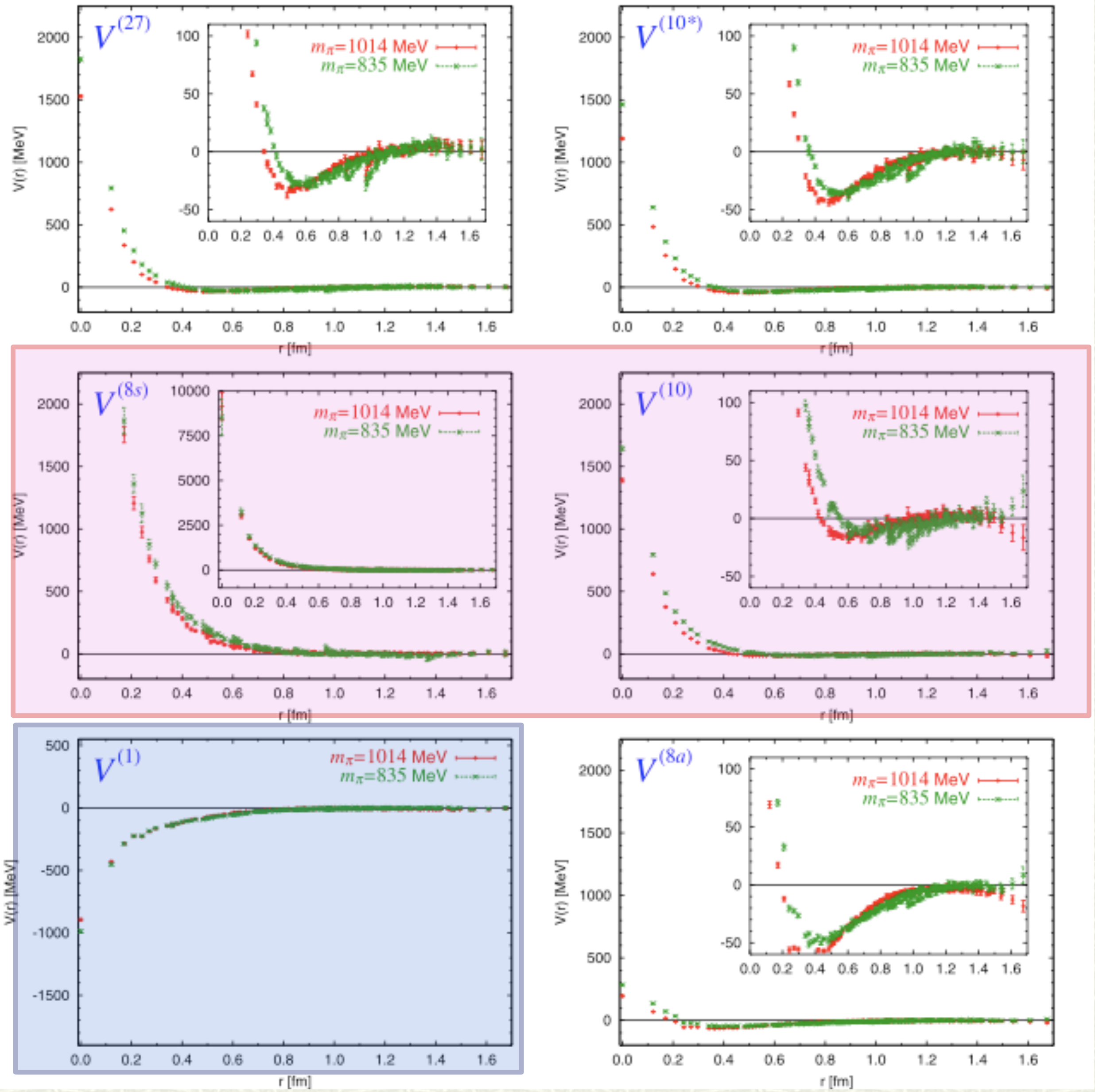
S=0

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

S=1

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

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



Spin dependence

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

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

prefers symmetric color-spin states

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

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

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

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

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

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 dibaryon

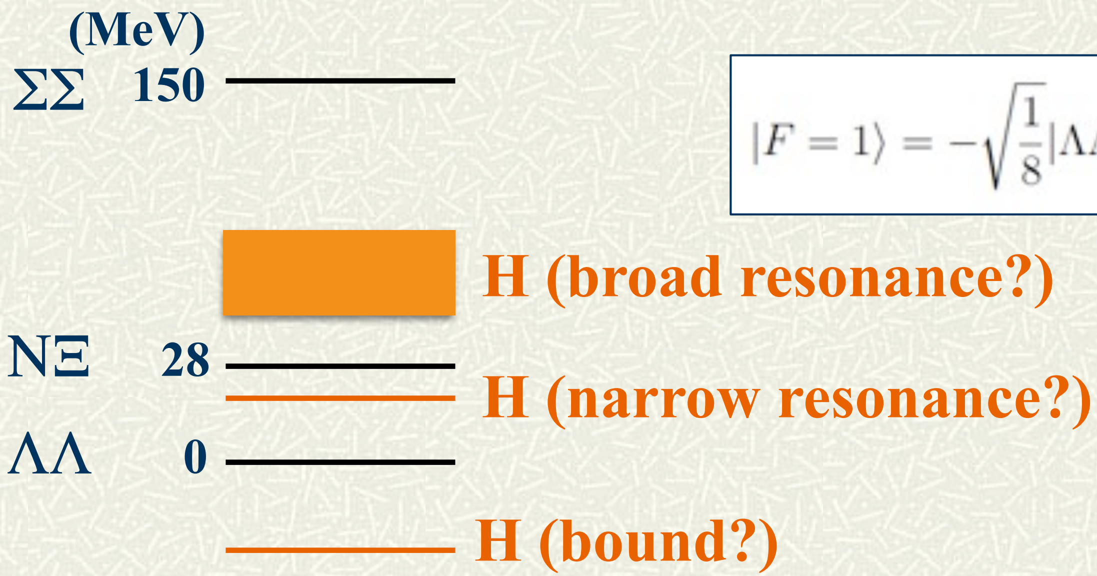
H dibaryon

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.

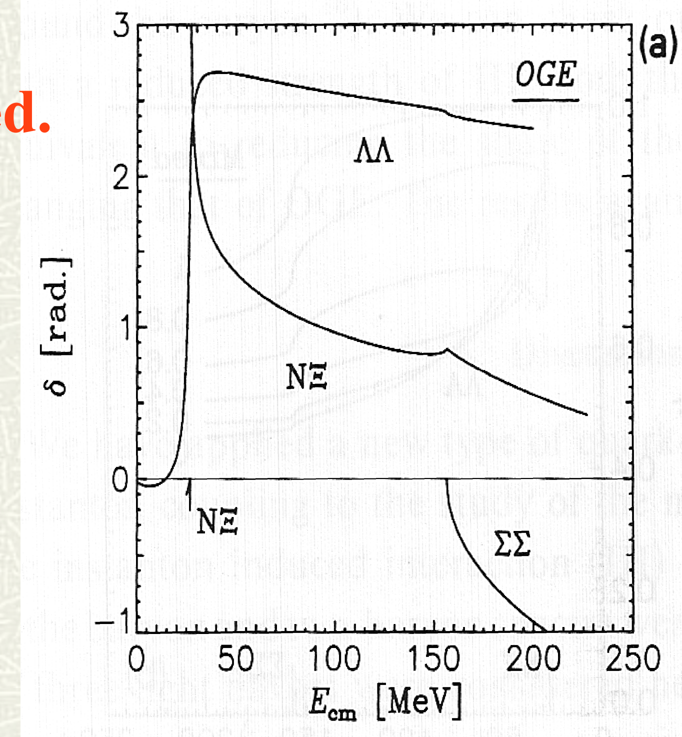


$$|F=1\rangle = -\sqrt{\frac{1}{8}}|\Lambda\Lambda\rangle + \sqrt{\frac{4}{8}}|N\Xi\rangle + \sqrt{\frac{3}{8}}|\Sigma\Sigma\rangle$$

H dibaryon

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 B_8B_8 (F=1) channel is Pauli super-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.**

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

H dibaryon on Lattice

- New Lattice QCD calculations of H dibaryon
  - 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)

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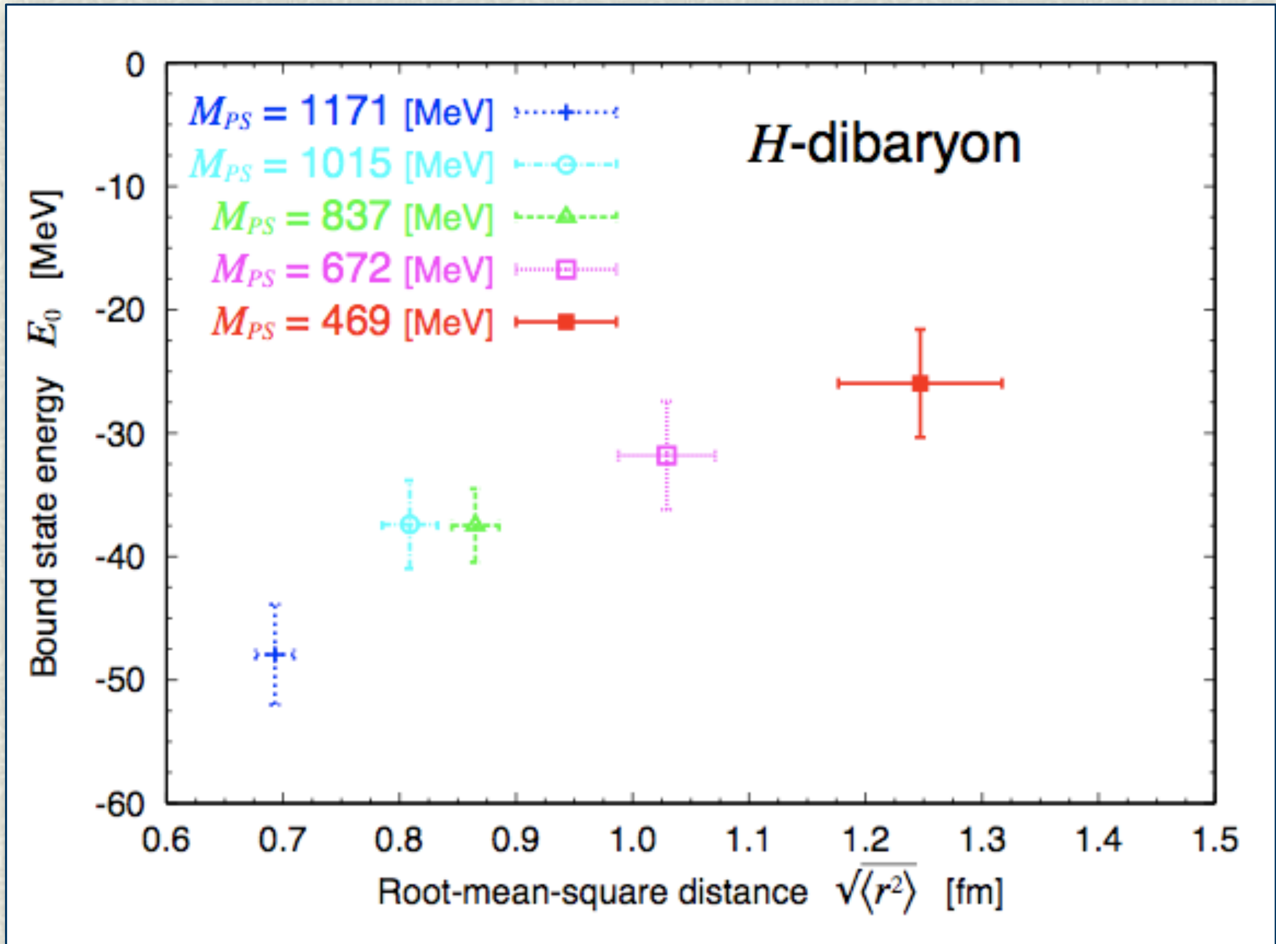
- **tice QCD**



H dibaryon on Lattice

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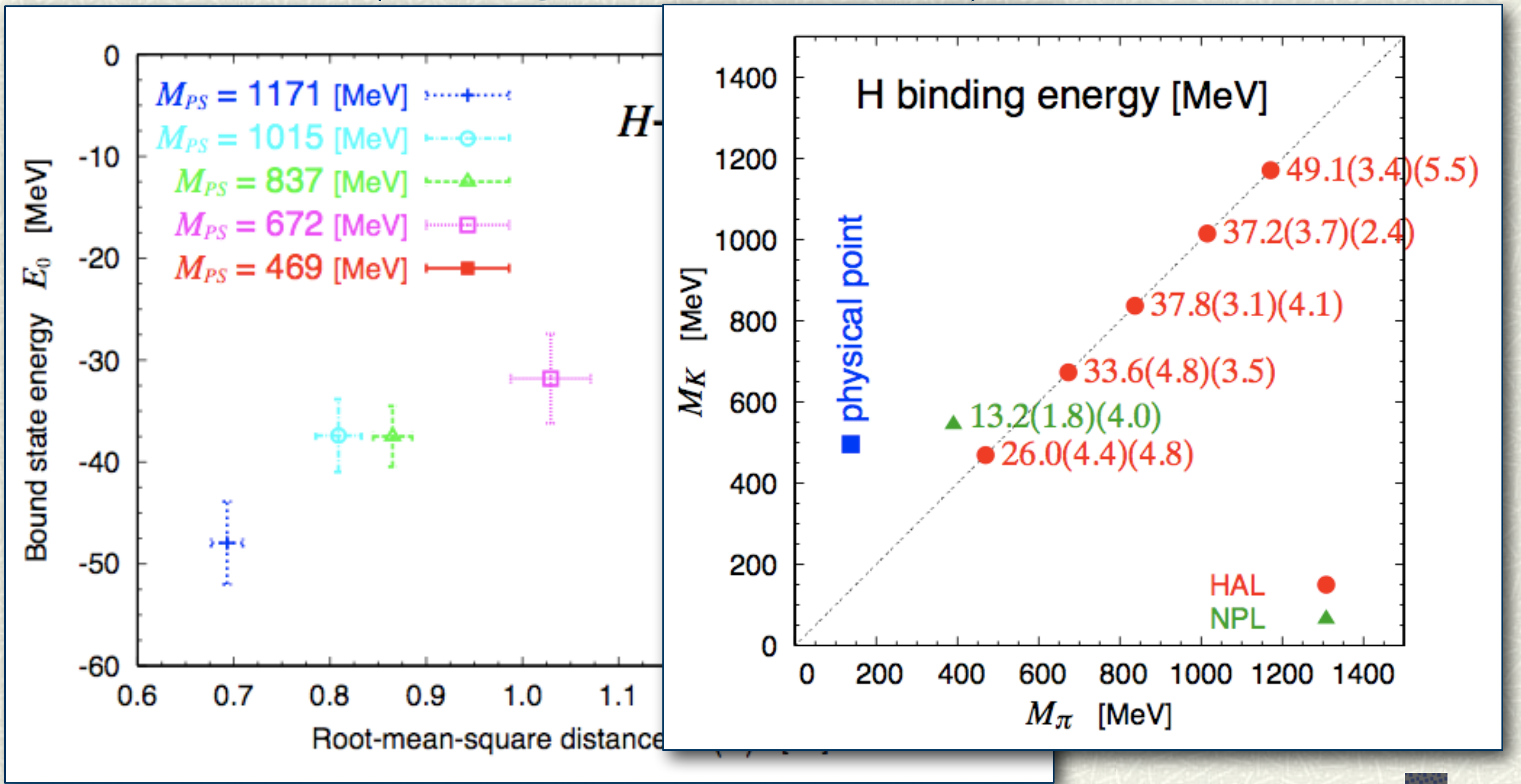
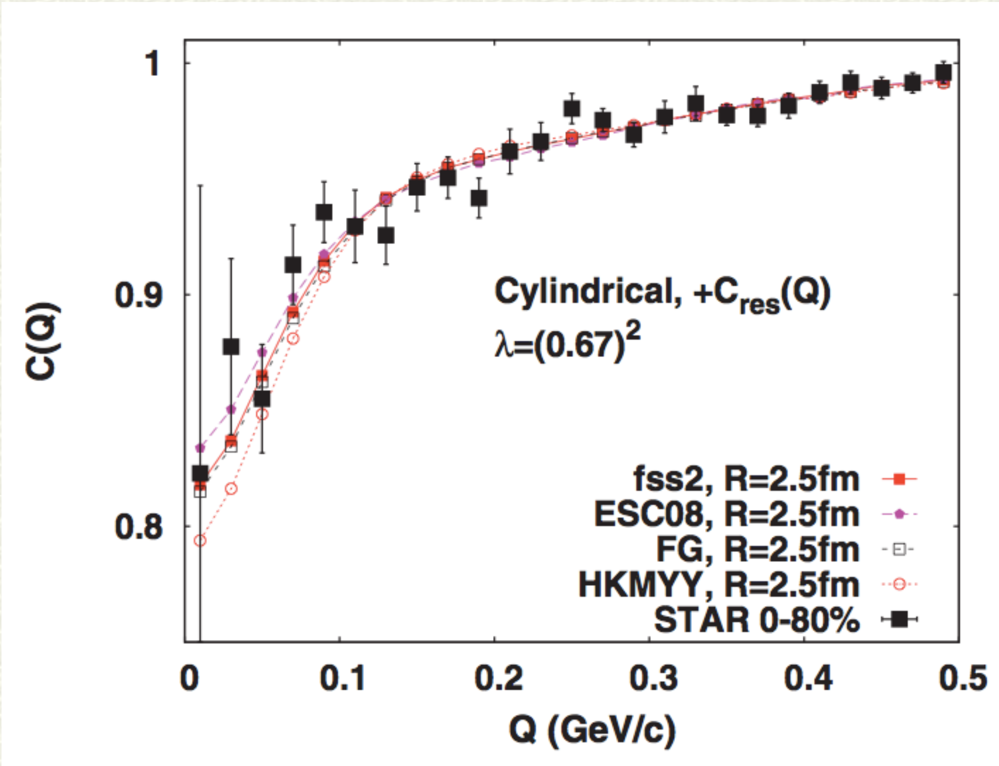
- ○



ΛΛ correlation in Heavy Ion Collisions

- **STAR collaboration, PRL 114, 022301 (2015)**
  ΛΛ correlation function in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
- **K. Morita, T. Furumoto, A. Ohnishi, PRC 91, 024916 (2015)**
  ΛΛ interaction from relativistic heavy-ion collisions



ΛΛ correlation in Heavy Ion Collisions

- **K. Morita, T. Furumoto, A. Ohnishi, PRC 91, 024916 (2015) The STAR data prefer small negative scattering length (attractive) and effective range ~ 4 fm. The recent new potentials, fss2 and ESC08, are favored.**

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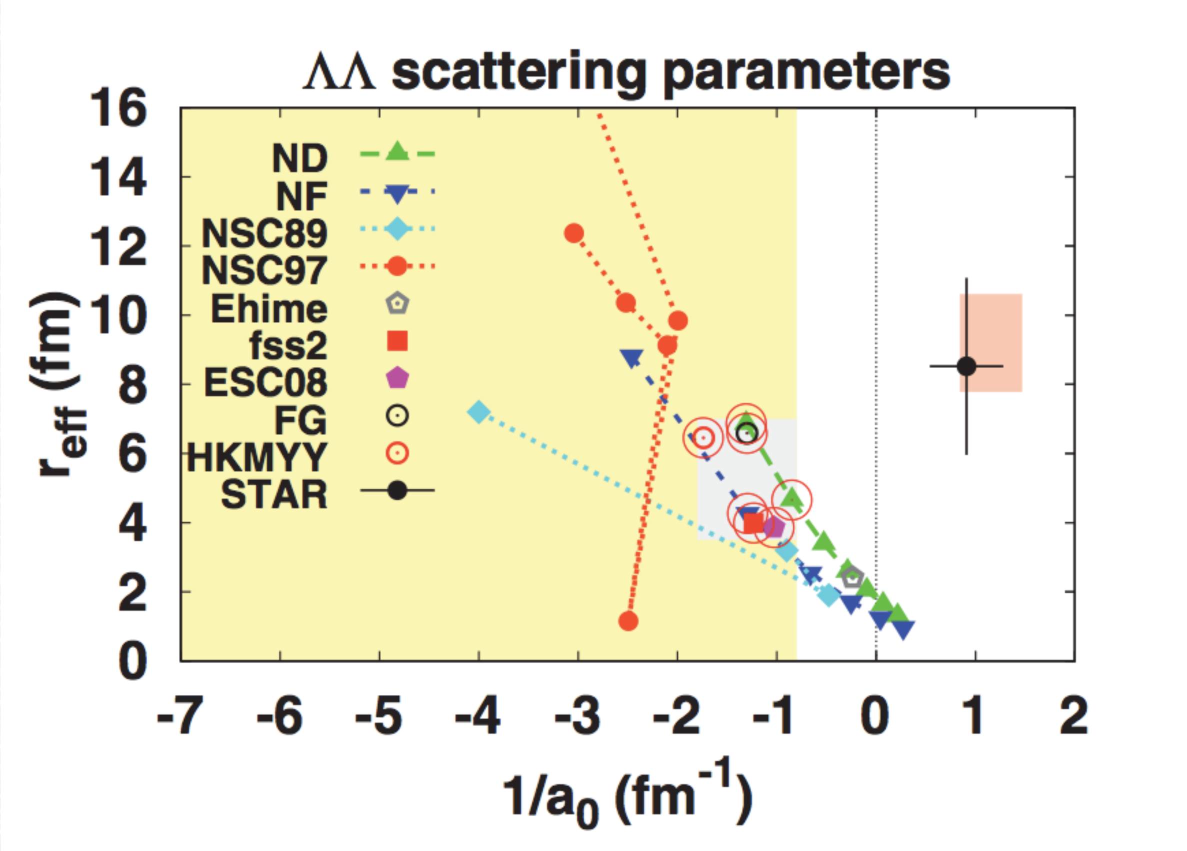


D_{Δ} $(\Delta\Delta)_{I=0}$ dibaryon

D_Δ $(\Delta\Delta)_{I=0}$ dibaryon

- S=3, I=0 (Δ^2) bound state

  → relatively narrow $NN\pi\pi$ (I=0) resonance

NUCLEAR FORCE IN A QUARK MODEL

Phys. Lett. 90B (1980) 41

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

Received 24 July 1979

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.

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.

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

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

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

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

CMI strength: $V_0 = 300/16 \sim 18(\mathrm{MeV})$ from $\Gamma_{\rm CM}(\Delta) = +8$, $\Gamma_{\rm CM}(N) = -8$

$SU(6)_{cs}$ 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	$\underline{10}$		
175	96	$\underline{10}$*	$\Delta\Delta(I = 0, S = 3)$ *favored*	$V = V_0 \times 0$
189	80	$\underline{27}$		
35	48	$\underline{35}$		
1	0	$\underline{28}$	$\Delta\Delta(I = 3, S = 0)$ *less favored*	$V = V_0 \times 32$

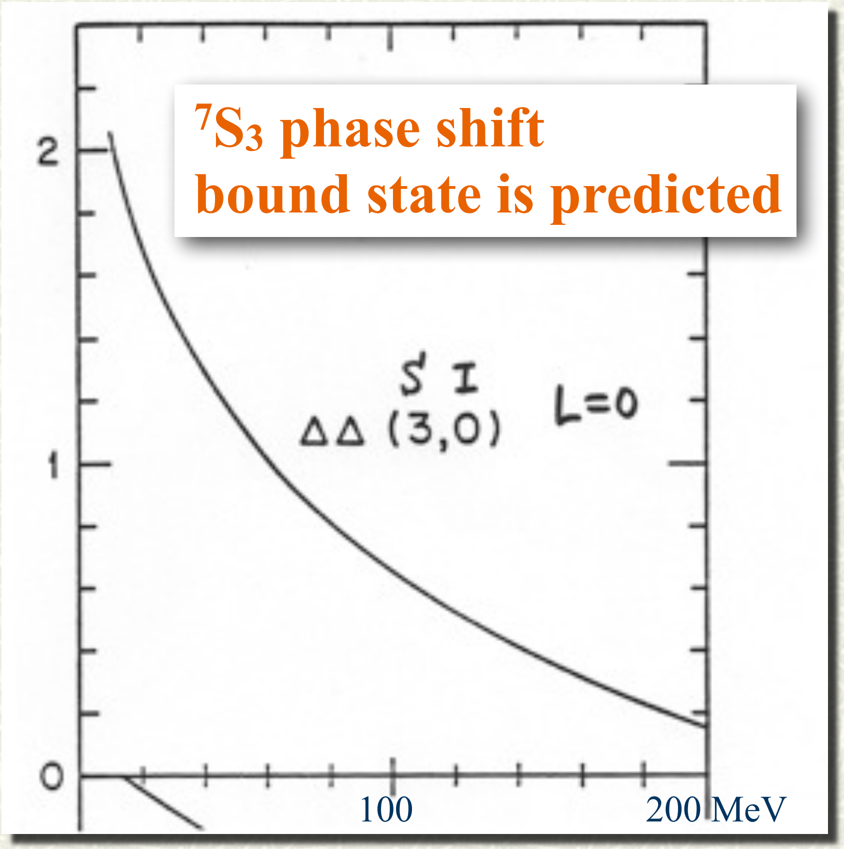
Perhaps a Stable Dihyperon*

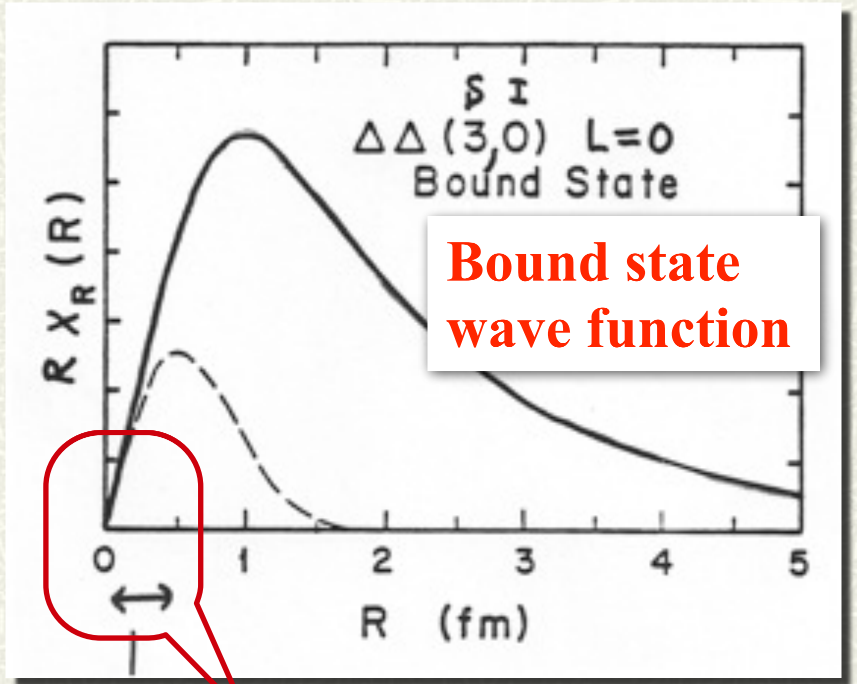
R.L. Jaffe, PRL 38 (1977) 195

D_Δ $(\Delta\Delta)_{I=0}$ dibaryon

- **Quark Cluster Model: S=3, I=0 (Δ^2) bound state**

MO, K. Yazaki, Phys. Lett. 90B (1980) 41



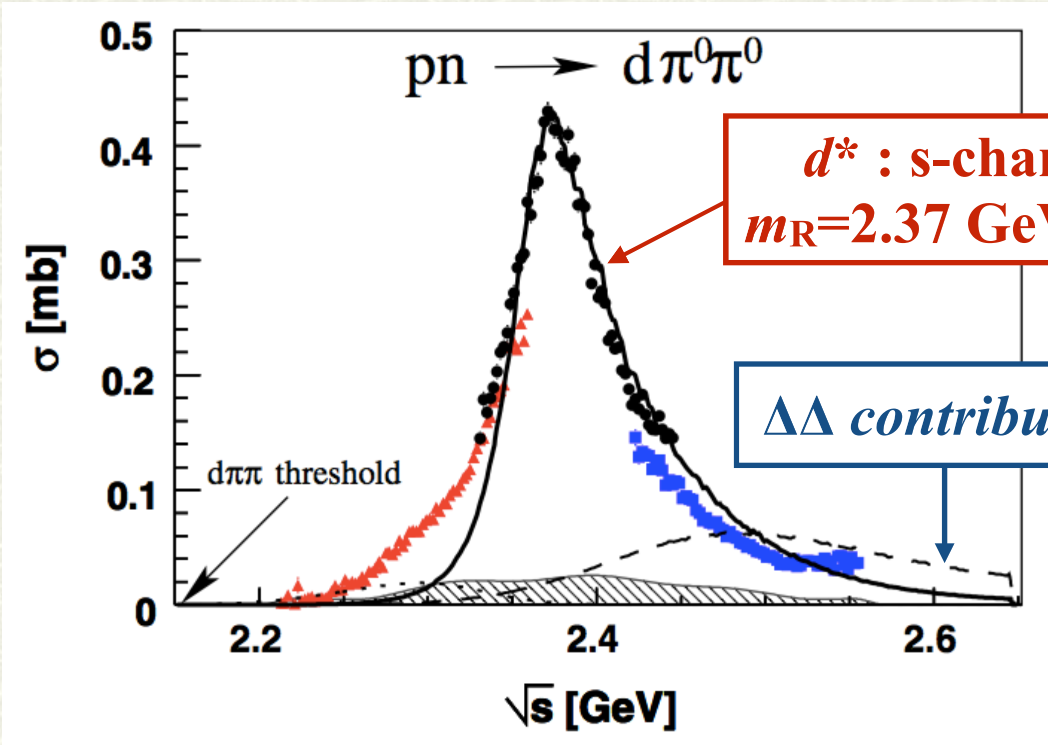


No repulsive core

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



d* **: s-channel resonance**
m_R=2.37 GeV and Γ=68 MeV

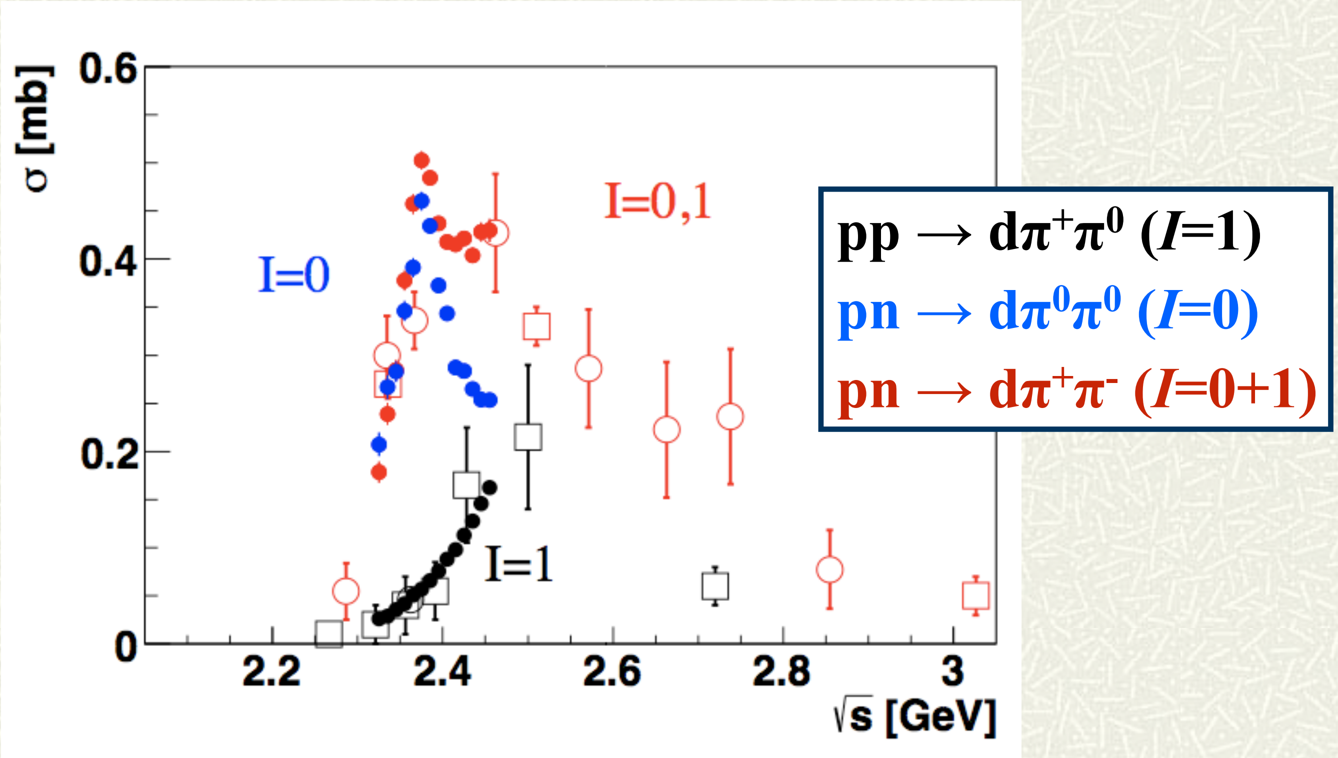
ΔΔ contributions

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

d* resonance

WASA@COSY, PLB 721 (2013) 229

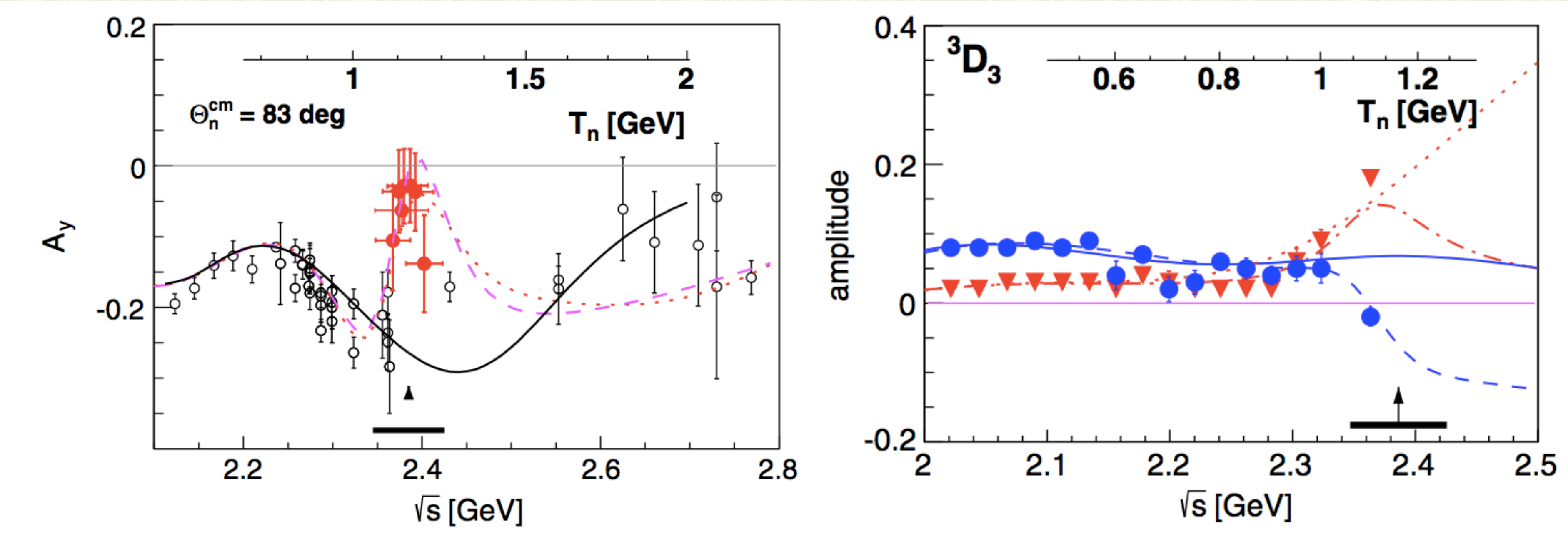
Isospin decomposition of the basic double-pionic fusion in the region of the ABC effect



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

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.



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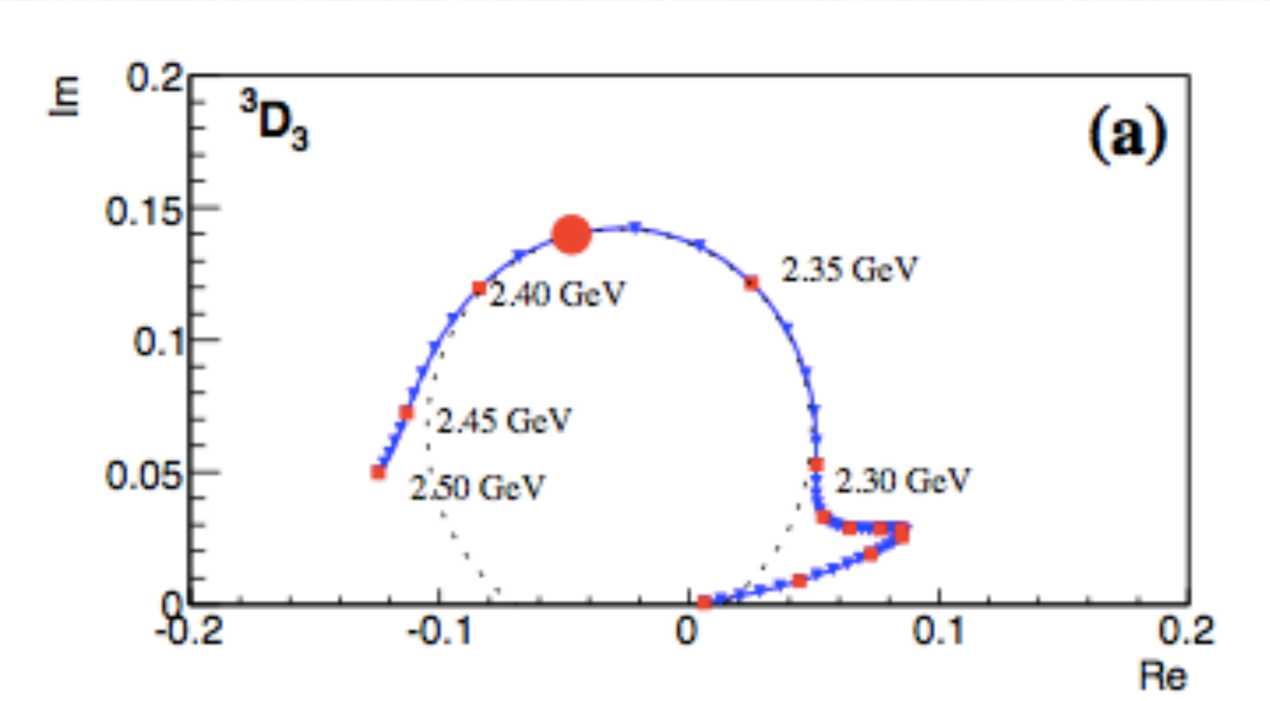

Conclusion

- **"Dibaryon" is a long-standing but still exciting subject. Its existence should be correlated to the short-range baryonic interactions.**
- **LQCD has confirmed the Pauli effect and the CMI for the short-range baryon-baryon interactions.**
- **The quark model symmetries, $SU(6)_{sf}$ for the Pauli effect and $SU(3)_f$ for the CMI, give guideline for possible compact dibaryons.**
- **H (F=1) is the most-likely dibaryon.**
- **D_Δ =($\Delta\Delta$) (I=0, S=3) is another favorable state.**
  The d* resonance at WASA-COSY is a strong candidate of a "compact" dibaryon.