Short-range BB interactions

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Introduction

- Long time ago, a quark model study of the baryon-baryon interactions showed that the short-range part of the BB interaction is accounted in terms of
  the quark Pauli exclusion principle effect and
  the quark exchange interaction induced by the color-magnetic interaction (CMI).
- Recent Lattice QCD calculation of the baryon-baryon potentials has proved that the short-range part of the BB interactions follow the quark model predictions.
- There are indications of di-baryon resonances in the channels with no repulsive core, H and D_{Δ}.

Baryon-baryon interaction

SU(6)

Sym / Antisym

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

odd L / even L

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.

Baryon-baryon interaction

- SU(3) × SU(2)spin ⇒ SU(6) classification

MO, K. Shimizu, K. Yazaki, PLB130 (1983), NPA464 (1987)

S=0

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

S=1

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

- The SU(6) symmetry predicts a strong spin-isospin dependence of the ΣN interaction.
- It also predicts state dependences of the spin-orbit interaction.

Baryon-

- SU(3) × SU(

MC

S=0

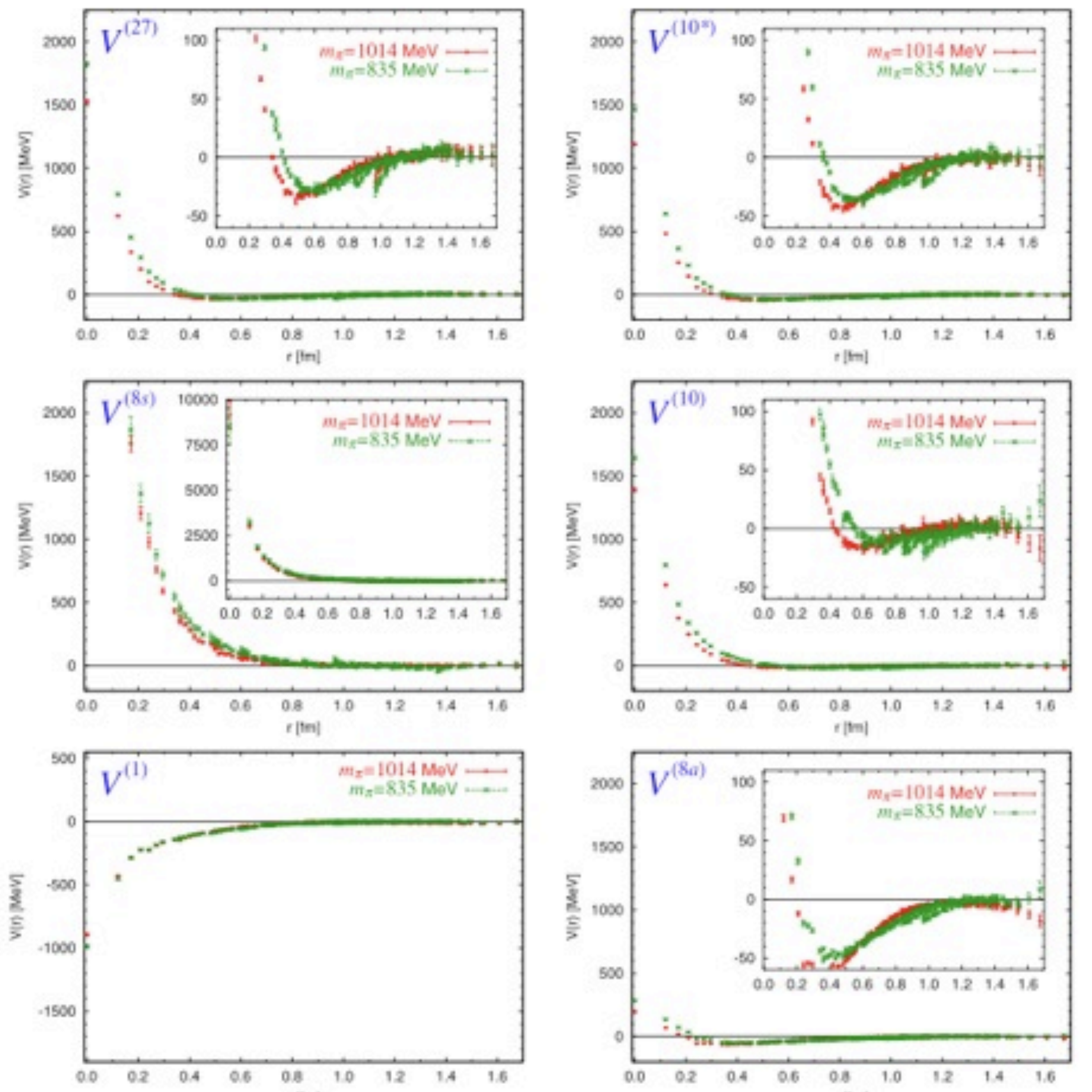
1	×	(
8_s	×	(
27	×	(

S=1

8_a	×	
10	×	1
10*	×	1

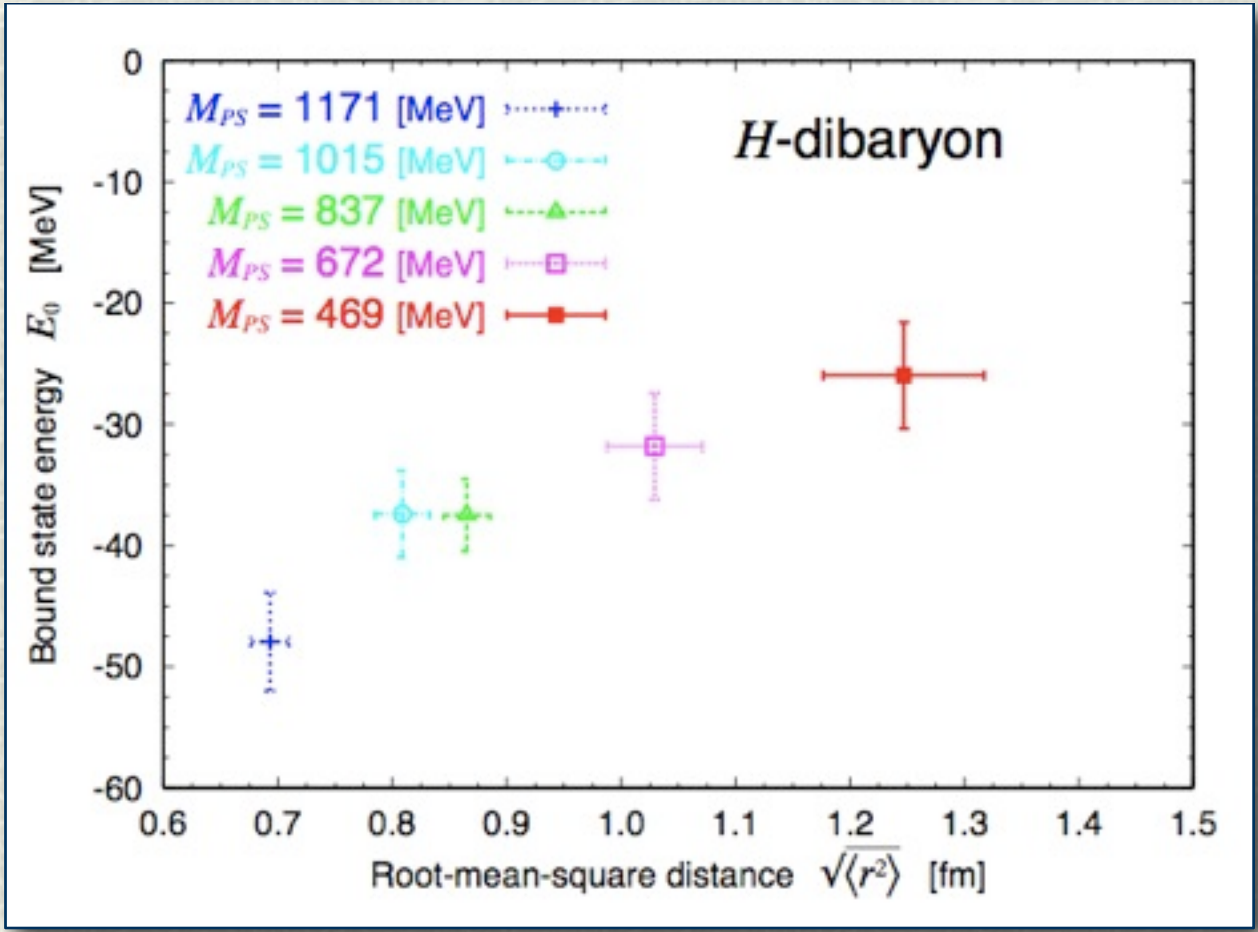
- The SU(6) sy
  of the ΣN inte
- It also predict

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



H dibaryon on the Lattice

T. Inoue et al., (HAL-QCD) arXiv:1112.5926 [hep-lat]



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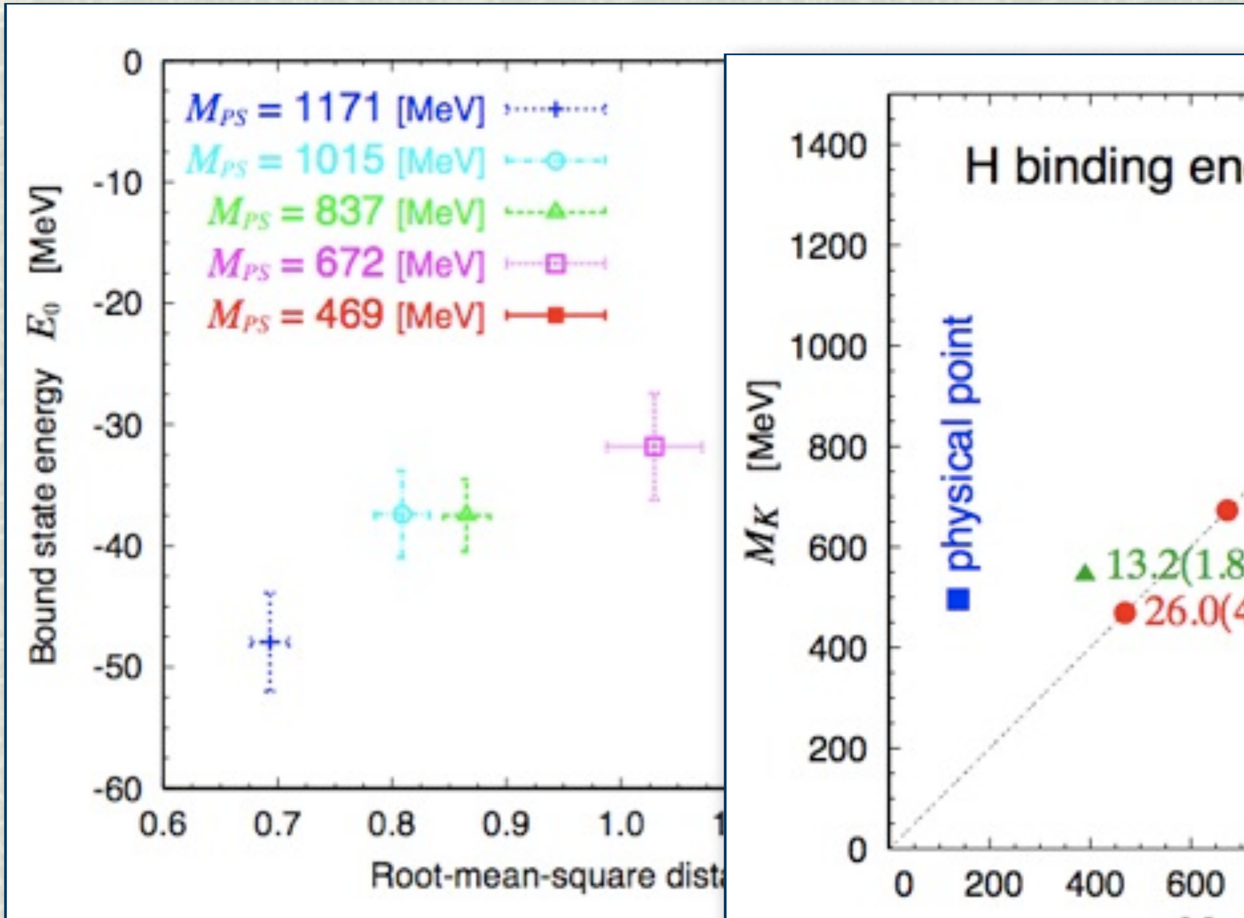
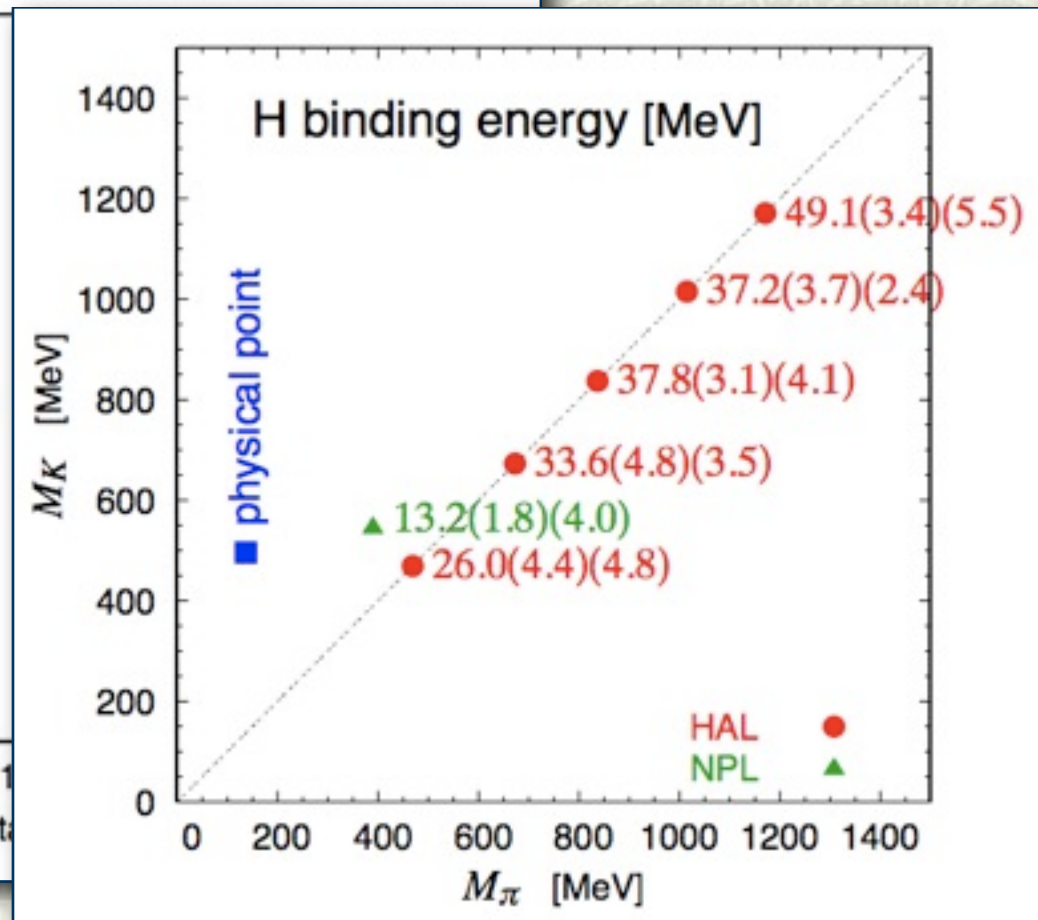




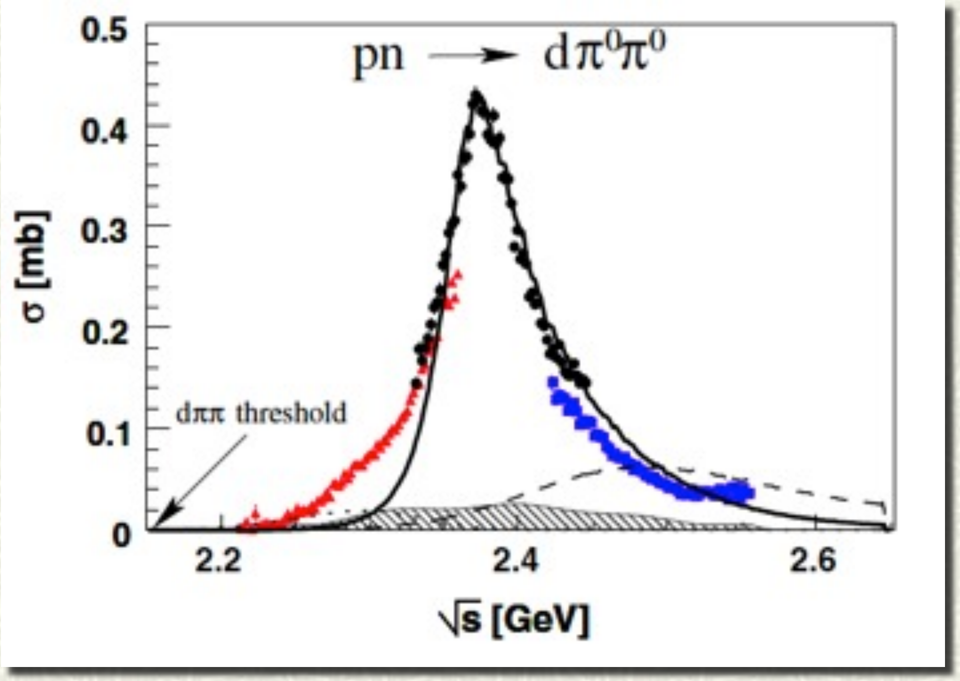
ABC Effect

WASA@COSY PRL 106, 242302 (2011) June

PRL 106, 242302 (2011) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2011

Abashian-Booth-Crowe Effect in Basic Double-Pionic Fusion: A New Resonance?

$m = 2.37$ GeV, $\Gamma \approx 70$ MeV and $I(J^P) = 0(3^+)$ in both pn and $\Delta\Delta$ systems.



D_Δ $(\Delta\Delta)_{I=0}$ Dibaryon

- **S=3, I=0 (Δ^2) bound state**

  → relatively narrow NNππ (I=0) resonance

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NUCLEAR FORCE IN A QUARK MODEL

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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.

BB interaction in quark models

- **Color-Magnetic Interaction**

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

prefers color-spin symmetric states

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

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

$$= 8N - 2C_2[SU(6)] + \frac{4}{3} S(S+1)$$

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

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

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

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

BB interaction in quark models

- Possible structures of inter-quark potential
  - restrict to two-body central forces
  - Force without color-cluster saturation is no good.

$$V = \sum_{i<j} f(r_{ij}) \longrightarrow \langle V \rangle \sim \langle f \rangle \frac{N(N-1)}{2}$$ ~ universal gravity

  - Spin-independent color-saturated force is trivial.

$$V = -\sum_{i<j} f(r_{ij})(\vec{\lambda}_i \cdot \vec{\lambda}_j) \longrightarrow \langle V \rangle \sim \frac{8}{3} N \langle f \rangle$$

  - Spin dependent force leads to CMI.

$$V = -\sum_{i<j} f(r_{ij})(\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) \longrightarrow \langle V \rangle \sim \langle f \rangle \Delta_{\mathrm{CM}}$$

  - Similarly for color-flavor force. → Tubingen model

HQ Baryons

- **HQ spin symmetry suppresses the color-spin force for the heavy quark, and then the potential for light quarks is relevant.**
  → color non-singlet system

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

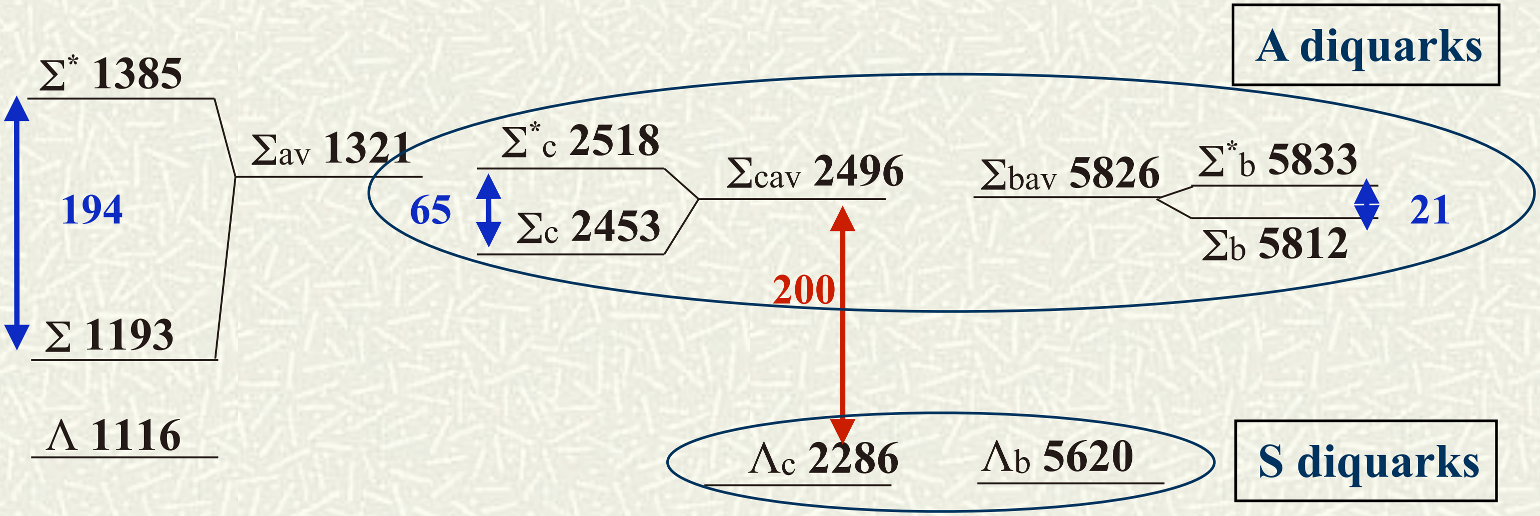
$$\langle \Delta_{\rm CM} \rangle(\Lambda_Q) = -8 \qquad \langle \Delta_{\rm CM} \rangle(\Sigma_Q) = \frac{8}{3}$$

$$M(\Sigma_Q - \Lambda_Q) = \frac{32}{3} \times \frac{300\,{\rm MeV}}{16} = 200\,{\rm MeV}$$

$$\langle \Delta_{\rm CM} \rangle(N) = -8 \qquad \langle \Delta_{\rm CM} \rangle(\Delta) = 8$$

Heavy-Quark Hadrons

- **Heavy quark spectroscopy ⇔ Diquark spectroscopy**
  Λ_Q (Σ_Q) contains only the S (A) diquark.



- **What are the roles of (other) diquarks in the excited states?**
  – PS diquark for the negative-parity excited states
  – Novel diquark for the Roper-like states

HQ Baryons

- **Evaluate the short range parts of the $\Lambda_c N$ and $\Sigma_c^{(*)} N$ potentials.**

$$V = V_0 \exp[-(r/b)^2] \qquad : b \sim 0.5 \text{ fm}$$

V_0 is determined from the CMI for $(0s)^N$ configuration.

$\Lambda_c N$ or $\Sigma_c N(S=0, I=1/2) \qquad \langle \Delta_{\rm CM} \rangle = \langle \Delta_{\rm CM} \rangle_{1/2} = 0$

$$\to V_{\Lambda_c N(S=0,I=1/2)}(R=0) = (0 - (-8 \times 2)) \times \frac{300}{16} = 300\,\text{MeV}$$

$$\to V_{\Sigma_c N(S=0,I=1/2)}(R=0) = (0 - (-8 + 8/3)) \times \frac{300}{16} = 100\,\text{MeV}$$

$$\to V_{\Lambda_c N(S=0,I=1/2) \leftrightarrow \Sigma_c N(S=0,I=1/2)} = 0$$

$\Lambda_c N(S=1, I=1/2) \qquad \langle \Delta_{\rm CM} \rangle = \langle \Delta_{\rm CM} \rangle_{1/2} = 0$

$$\to V_{\Lambda_c N(S=1,I=1/2)}(R=0) = V_{\Lambda_c N(S=0,I=1/2)}(R=0) = 300\,\text{MeV}$$

$$\Sigma_c N(S=1, I=1/2) = -\frac{1}{3}|S_{ud} = 1/2\rangle + \frac{2\sqrt{2}}{3}|S_{ud} = 3/2\rangle$$

$$\langle \Delta_{\rm CM} \rangle = (1/9)\langle \Delta_{\rm CM} \rangle_{1/2} + (8/9)\langle \Delta_{\rm CM} \rangle_{3/2} = 32/9$$

$$\to V_{\Sigma_c N(S=1,I=1/2)}(R=0) = (32/9 - (-8 + 8/3)) \times \frac{300}{16} = 167\,\text{MeV}$$

HQ Baryons

$$\Lambda_c N \text{ or } \Sigma_c N(S=0, I=1/2) \qquad \langle \Delta_{\rm CM} \rangle = \langle \Delta_{\rm CM} \rangle_{1/2} = 0$$

$$\to V_{\Lambda_c N(S=0,I=1/2)}(R=0) = (0-(-8\times 2)) \times \frac{300}{16} = 300\,\text{MeV}$$

$$\to V_{\Sigma_c N(S=0,I=1/2)}(R=0) = (0-(-8+8/3)) \times \frac{300}{16} = 100\,\text{MeV}$$

$$\to V_{\Lambda_c N(S=0,I=1/2)\leftrightarrow \Sigma_c N(S=0,I=1/2)} = 0$$

$$\Lambda_c N(S=1, I=1/2) \qquad \langle \Delta_{\rm CM} \rangle = \langle \Delta_{\rm CM} \rangle_{1/2} = 0$$

$$\to V_{\Lambda_c N(S=1,I=1/2)}(R=0) = V_{\Lambda_c N(S=0,I=1/2)}(R=0) = 300\,\text{MeV}$$

$$\Sigma_c N(S=1, I=1/2) = -\frac{1}{3}|S_{ud}=1/2\rangle + \frac{2\sqrt{2}}{3}|S_{ud}=3/2\rangle$$

$$\langle \Delta_{\rm CM} \rangle = (1/9)\langle \Delta_{\rm CM} \rangle_{1/2} + (8/9)\langle \Delta_{\rm CM} \rangle_{3/2} = 32/9$$

$$\to V_{\Sigma_c N(S=1,I=1/2)}(R=0) = (32/9-(-8+8/3)) \times \frac{300}{16} = 167\,\text{MeV}$$

HQ Baryons

$$\Sigma_c^* N(S=1, I=1/2) = \frac{2\sqrt{2}}{3}|S_{ud}=1/2\rangle + \frac{1}{3}|S_{ud}=3/2\rangle$$

$$\langle \Delta_{\mathrm{CM}} \rangle = (8/9)\langle \Delta_{\mathrm{CM}} \rangle_{1/2} + (1/9)\langle \Delta_{\mathrm{CM}} \rangle_{3/2} = 4/9$$

$$\rightarrow V_{\Sigma_c^* N(S=1,I=1/2)}(R=0) = (4/9 - (-8 + 8/3)) \times \frac{300}{16} = 108\,\mathrm{MeV}$$

$$\rightarrow V_{\Lambda_c N(S=1,I=1/2) \leftrightarrow \Sigma_c^{(*)} N(S=1,I=1/2)} = 0$$

$$\rightarrow V_{\Sigma_c N(S=1,I=1/2) \leftrightarrow \Sigma_c^{(*)}(S=1,I=1/2)} = \frac{2\sqrt{2}}{9}\langle \Delta_{\mathrm{CM}} \rangle_{3/2} \times \frac{300}{16} = \frac{8\sqrt{2}}{9} \times \frac{300}{16} = 24\,\mathrm{MeV}$$

$$\Sigma_c^* N(S=2, I=1/2) \qquad \langle \Delta_{\mathrm{CM}} \rangle = \langle \Delta_{\mathrm{CM}} \rangle_{3/2} = 4$$

$$\rightarrow V_{\Sigma_c^* N(S=2,I=1/2)}(R=0) = (4 - (-8 + 8/3)) \times \frac{300}{16} = 175\,\mathrm{MeV}$$

$$\Lambda_c \Lambda_c(S=0, I=0) \qquad \langle \Delta_{\mathrm{CM}} \rangle = \langle \Delta_{\mathrm{CM}} \rangle_{1/2} = -4$$

$$\rightarrow V_{\Lambda_c \Lambda_c(S=0,I=0)}(R=0) = (-4 - (-8 \times 2)) \times \frac{300}{16} = 225\,\mathrm{MeV}$$

HQ Baryons

- The quark Pauli effects for Λ_c-N, Σ_c-N, Λ_c-Λ_c, do not produce strong repulsion at short distances.
- The color-magnetic interaction (CMI) will give some repulsion in these channels. A simple evaluation of the CMI assuming the heavy-quark limit (charm spin decoupled) gives

  $V(\Lambda_c\text{-}N) \sim 300$ MeV at R=0

  $V(\Sigma_c\text{-}N) \sim 100 \sim 170$ MeV

  $V(\Lambda_c\text{-}\Lambda_c) \sim 220$ MeV

  compared with

  $V(N\text{-}N;\ {}^1S_0) \sim 450$ MeV

  $V(\Lambda\text{-}N;\ {}^1S_0) \sim 400$ MeV