Theory overview of YN interactions and scatterings

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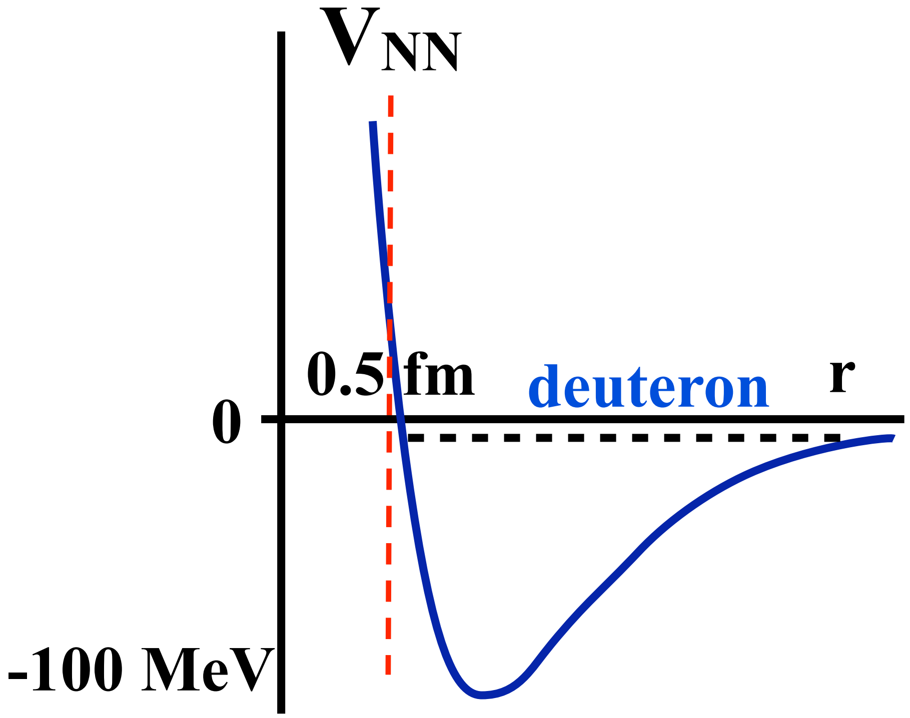
Nuclear force



The Nuclear Force is composed of
LR (OPE)− MR (TPE/OBE)− SR(PHE)

OPE: spin-isospin dependence + tensor force
TPE: σ (ππ, I=0) strong attraction
ρ (ππ, I=1) LS + tensor force
SR: repulsive core of radius $r \sim 0.5$ fm

The energy scale of QCD (hadron excitation) ~ Λ_{QCD} = 300 MeV
⇔ Nuclear binding energies ~ 10 MeV

The deuteron's binding energy, 2.2 MeV, is a result of large cancellation.

⇒ *Fine-tuning* problem

Do the interactions between other baryons, Λ, Σ, . . . , or Δ, Ω, . . . , or Λ_c, Λ_b, . . have the same property (cancellation)?

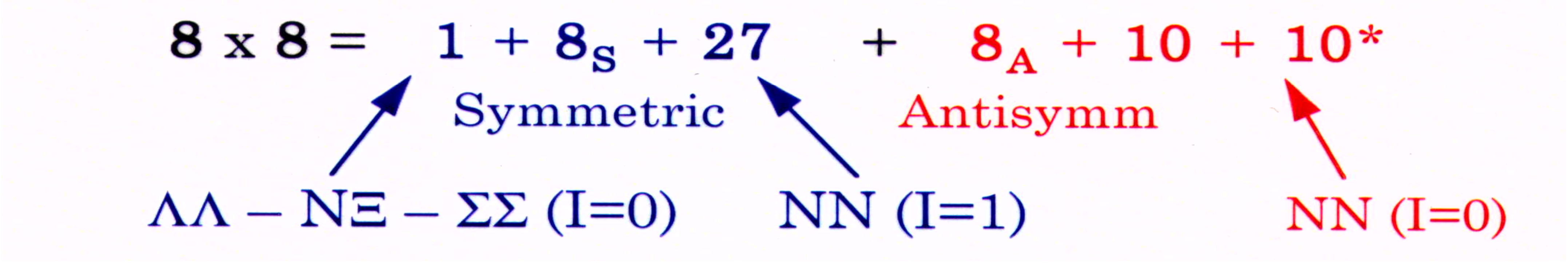
From QCD to Generalized Nuclear Forces

Three major approaches:

- Phenomenological Potentials (Nijmegen, Bonn/Julich)
(→ Rijken)
OBE(PS, V, S, A) + TBE + SR
SU(3+) symmetry to generalize to YN/YY, and Y_cN . .

- Chiral Effective Field Theories (→ Haidenbauer)
PS (NG) bosons + 4-B vertex (SR)
LO 4 new parameters + NLO (to break SU(3))

- Lattice QCD a la HAL QCD (→ Ishii, Doi, Sasaki)
Derivative expansion of non-local potentials ⇒ C, T, LS forces
6 independent potentials in the SU(3) limit of 8×8 baryons



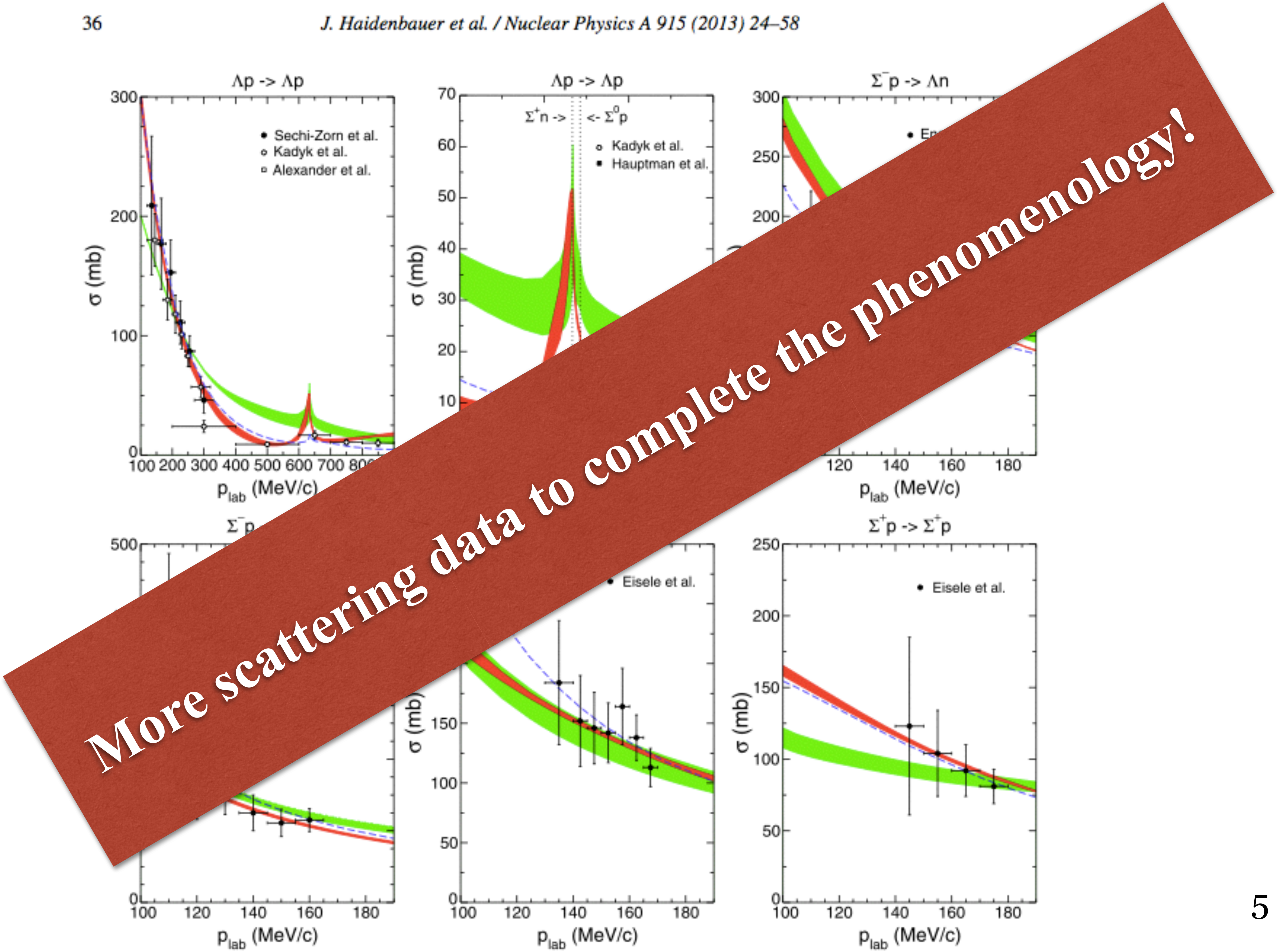
$$8 \times 8 = \underbrace{1 + 8_S + 27}_{\text{Symmetric}} + \underbrace{8_A + 10 + 10^*}_{\text{Antisymm}}$$

ΛΛ – NΞ – ΣΣ (I=0)

NN (I=1)

NN (I=0)

From QCD to Generalized Nuclear Forces



36 J. Haidenbauer et al. / Nuclear Physics A 915 (2013) 24–58

More scattering data to complete the phenomenology!

Generalized Nuclear Force

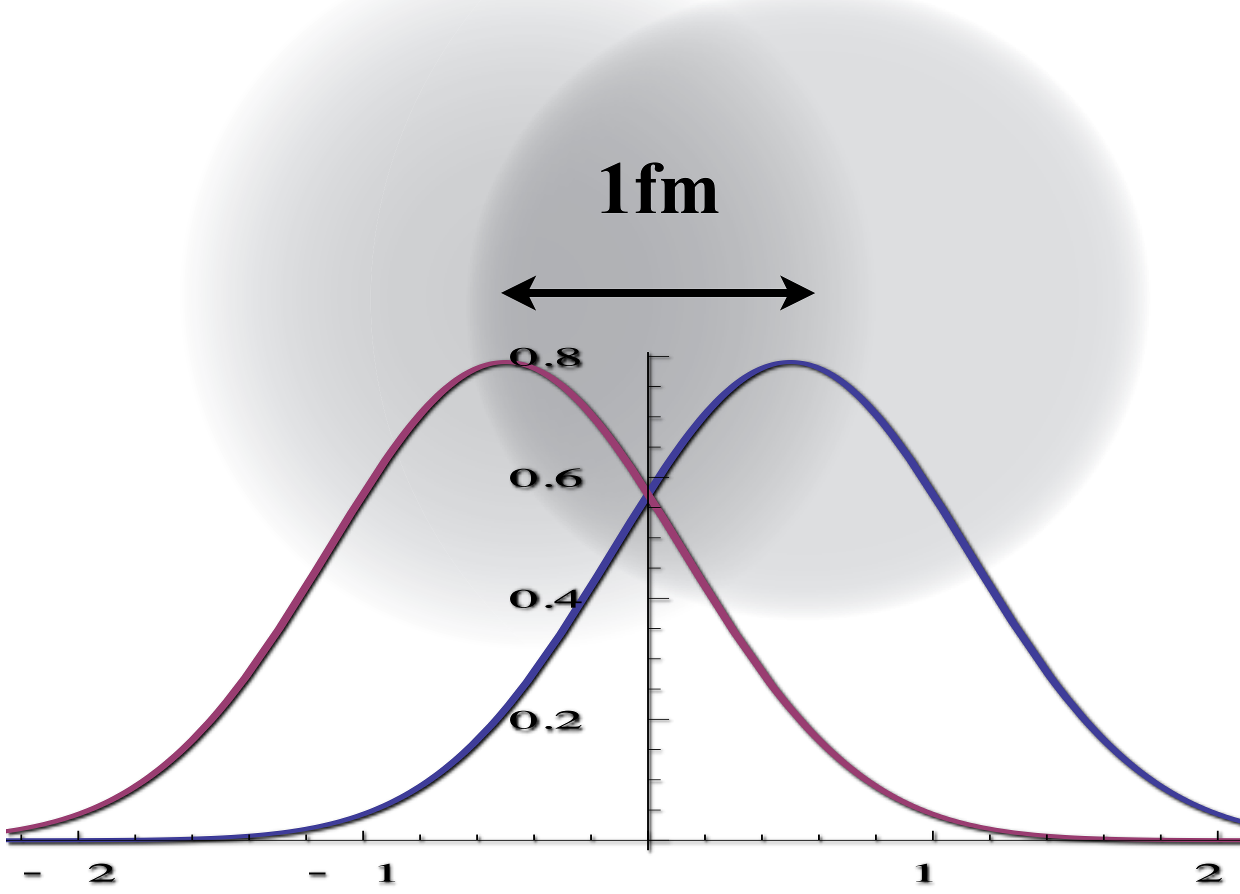
SR repulsion

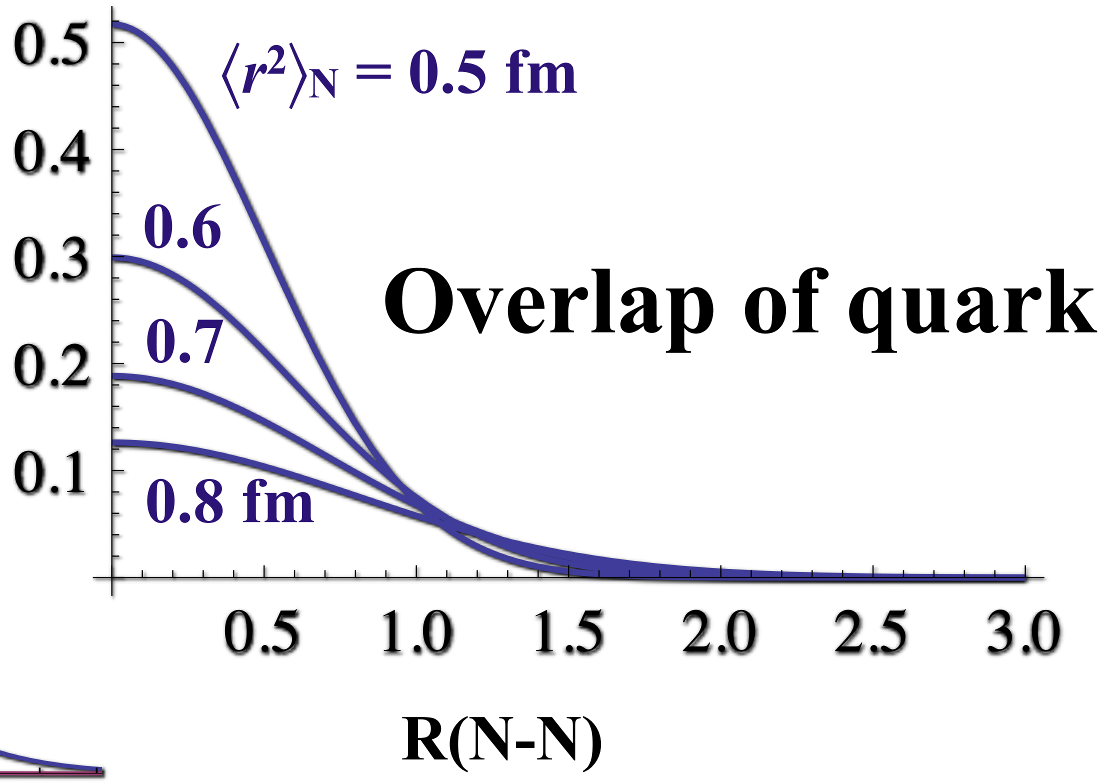
ESC08: pomeron + quark model phenomenology

EFT: parameters of the four baryon vertices

The overlap of the baryons is significant at short distances.

proton charge radius ~ 0.8 fm





Overlap of quarks

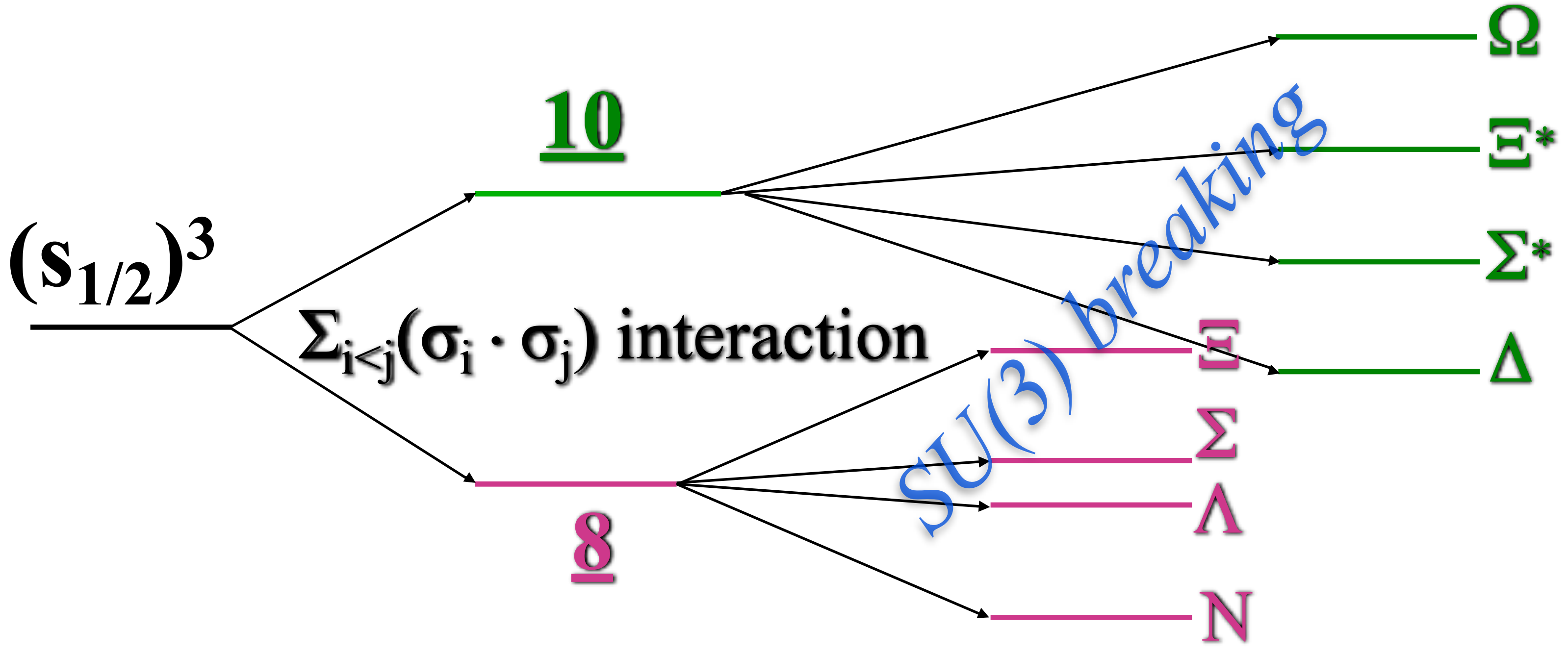
Origin of the SR repulsion

Symmetry of quarks in the ground-state baryons

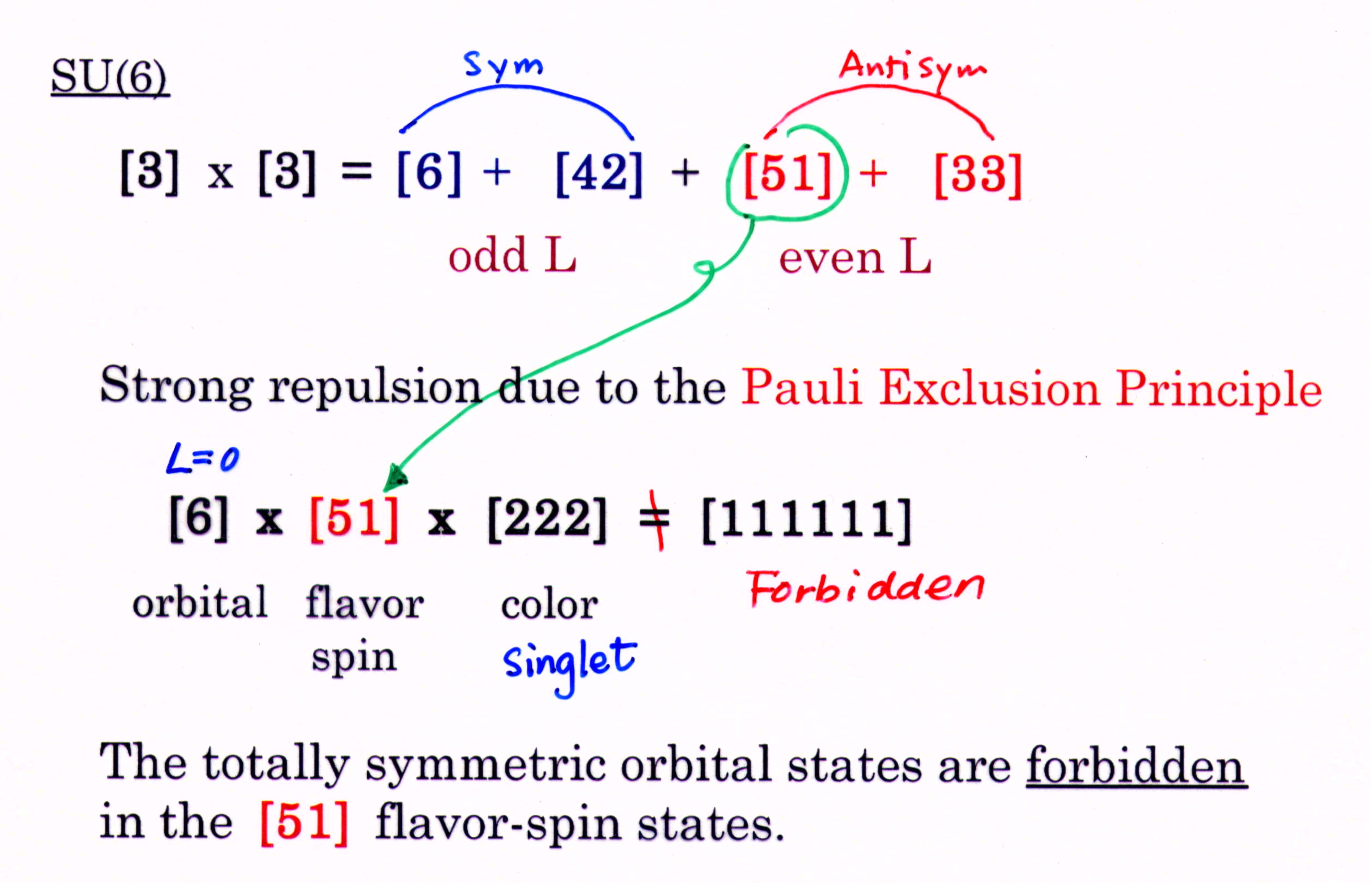
$SU(3)_c$ → color singlet

$SU(6) \supset SU(3)_{\text{flavor}} \times SU(2)_{\text{spin}}$

$$[3]\ \underline{56} \left\langle \begin{array}{l} 8\ (S=1/2):\ N\ \Lambda\ \Sigma\ \Xi \\ 10\ (S=3/2):\ \Delta\ \Sigma^*\ \Xi^*\ \Omega \end{array}\right.$$



Origin of the SR repulsion



SU(6)

Sym Antisym

$$[3] \times [3] = \underbrace{[6] + [42]}_{\text{odd } L} + \underbrace{[51] + [33]}_{\text{even } L}$$

Strong repulsion due to the Pauli Exclusion Principle

L=0

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

orbital flavor spin color singlet

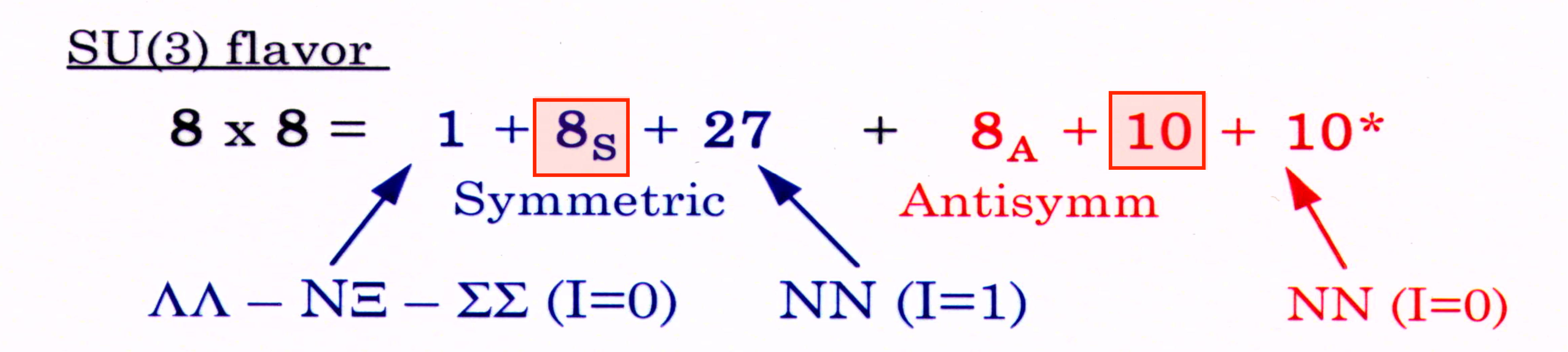
Forbidden

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

Quark Pauli effect : Tamagaki, Neudachin, Smirnov (1977)

Quark Cluster Model (+CMI) : MO, Yazaki (1980)

Origin of the SR repulsion



SU(3) flavor

$$8 \times 8 = \underbrace{1 + \boxed{8_S} + 27}_{\text{Symmetric}} + \underbrace{8_A + \boxed{10} + 10^*}_{\text{Antisymm}}$$

ΛΛ – NΞ – ΣΣ (I=0)

NN (I=1)

NN (I=0)

$$|8 \times 8 = 1\rangle = |[33]1\rangle$$

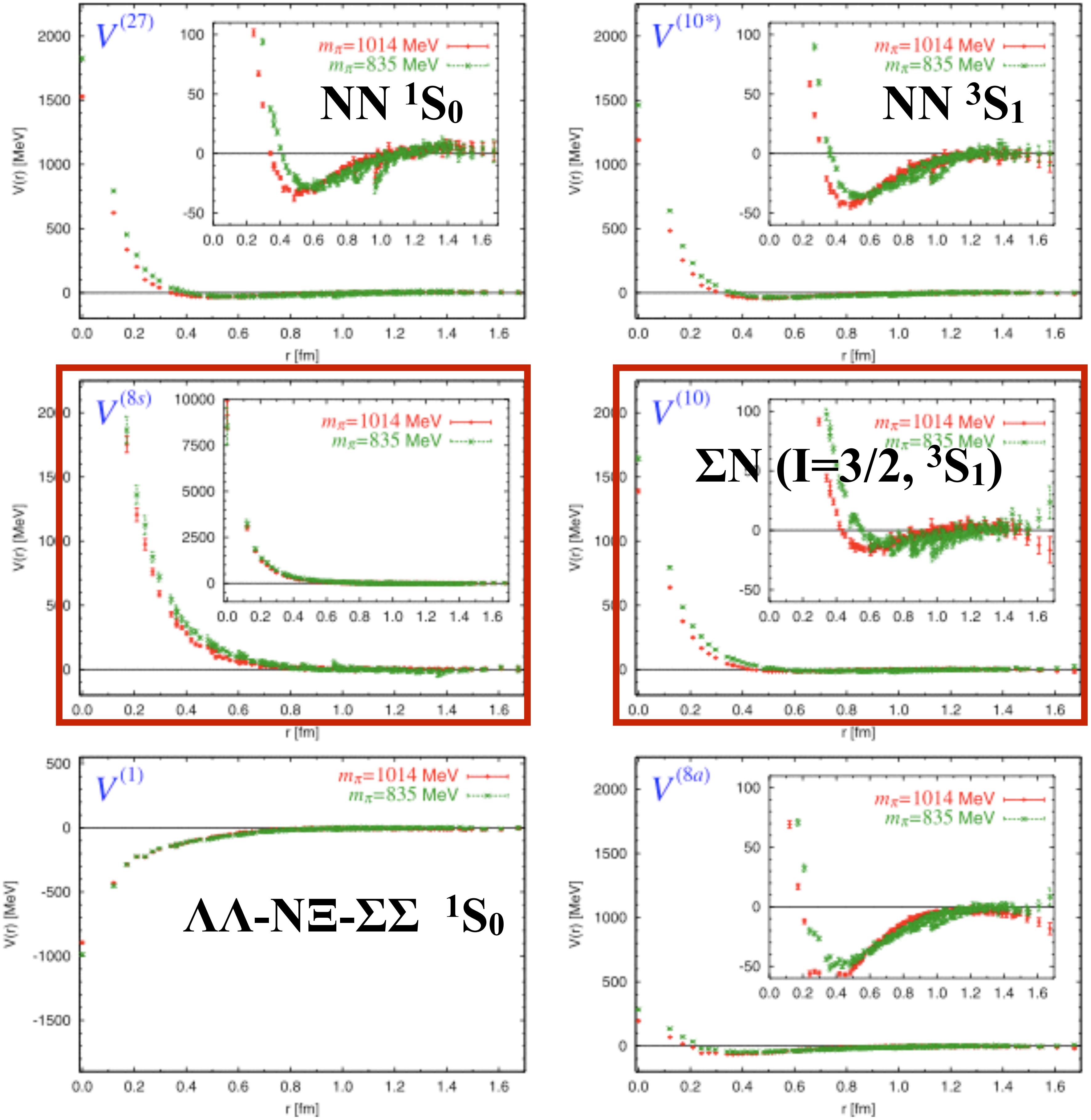
$$\boxed{|8 \times 8 = 8_s\rangle = |[51]8_s\rangle}$$

$$|8 \times 8 = 27\rangle = \sqrt{\frac{4}{9}}|[51]27\rangle - \sqrt{\frac{5}{9}}|[33]27\rangle$$

$$|8 \times 8 = 10\rangle = \boxed{\sqrt{\frac{8}{9}}|[51]10\rangle} + \sqrt{\frac{1}{9}}|[33]10\rangle$$

Recent LQCD calculations of the BB potential (HAL QCD) have confirmed the quark Pauli effects.

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



CMI breaks SU(6)

Why is the NN SR force repulsive?

Quark Pauli effect? Partly, but not fully.

What else? Color-magnetic gluon exchanges (CMI)

$$V_{CMI} \propto -\frac{\alpha_s}{m_i m_j}\sum_{i<j}(\lambda_i\cdot\lambda_j)(\vec{\sigma}_i\cdot\vec{\sigma}_j)$$

motivated by OgE interaction by De Rujula, Georgi, Glashow, PRD12

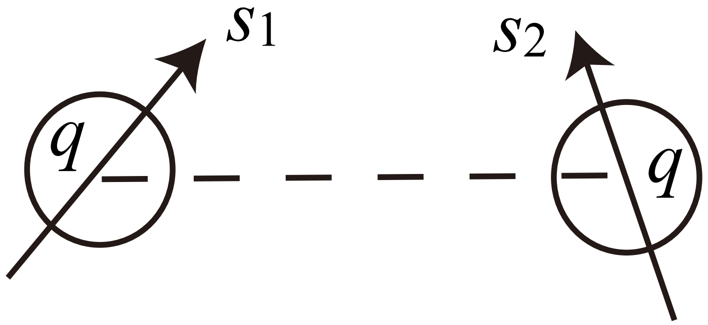
$$S_{ij} = \frac{1}{|\vec{r}|} - \frac{1}{2m_i m_j}\left(\frac{\vec{p}_i\cdot\vec{p}_j}{|\vec{r}|} + \frac{\vec{r}\cdot(\vec{r}\cdot\vec{p}_i)\vec{p}_j}{|\vec{r}|^3}\right) - \frac{\pi}{2}\delta^3(\vec{r})\left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \boxed{\frac{16\vec{s}_i\cdot\vec{s}_j}{3m_i m_j}}\right)$$

Color-Magnetic Interaction (CMI)

$$-\frac{1}{2|\vec{r}|^3}\left\{\boxed{\frac{1}{m_i^2}\vec{r}\times\vec{p}_i\cdot\vec{s}_i - \frac{1}{m_j^2}\vec{r}\times\vec{p}_j\cdot\vec{s}_j + \frac{1}{m_i m_j}[2\vec{r}\times\vec{p}_i\cdot\vec{s}_j - 2\vec{r}\times\vec{p}_j\cdot\vec{s}_i} - \boxed{2\vec{s}_i\cdot\vec{s}_j + 6\frac{(\vec{s}_i\cdot\vec{r})(\vec{s}_j\cdot\vec{r})}{|\vec{r}|^2}}]\right\} + \cdots$$

LS interaction

Tensor force



vector part of gluon exchange

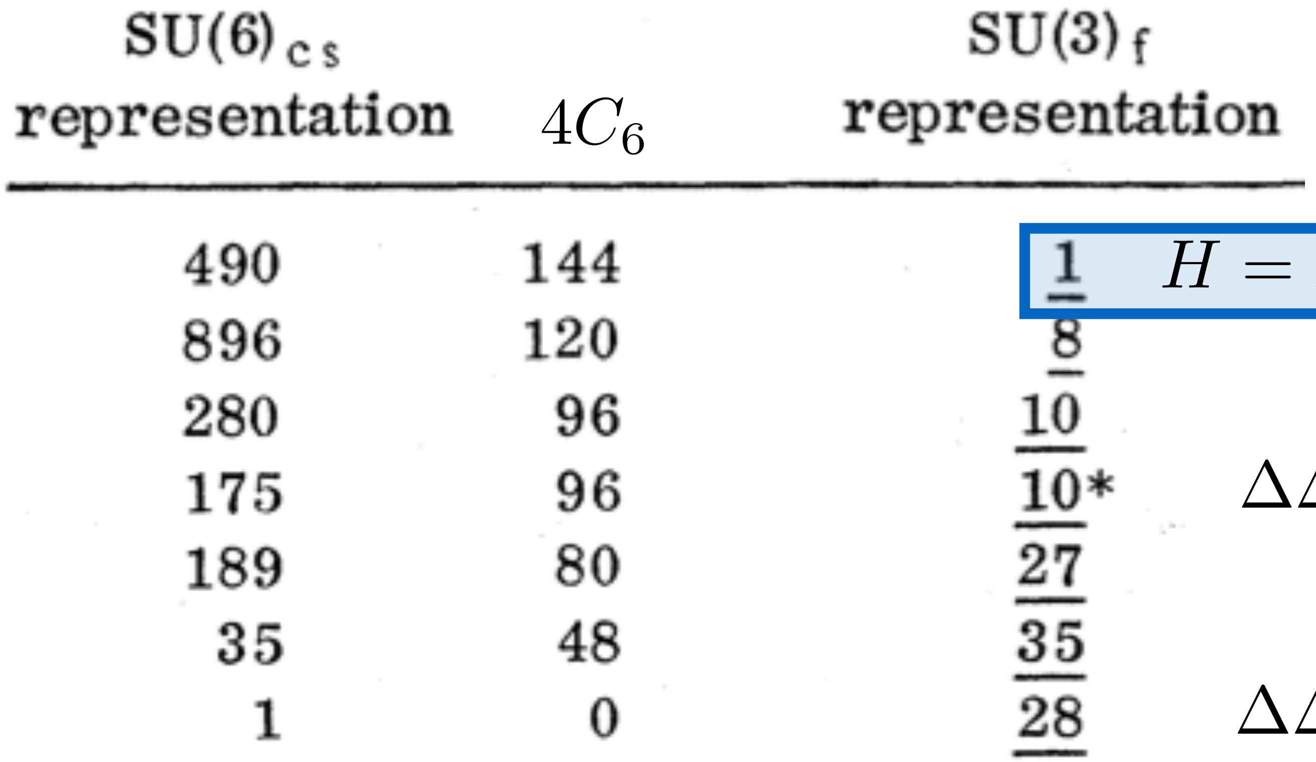
$$\frac{\vec{\gamma}_1\cdot\vec{\gamma}_2}{q^2} \sim \frac{(\vec{s}_1\cdot\vec{q})}{m_1}\frac{(\vec{s}_2\cdot\vec{q})}{m_2}\frac{1}{q^2} \to \frac{1}{3}\frac{(\vec{s}_1\cdot\vec{s}_2)}{m_1 m_2}$$

CMI breaks SU(6)

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

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

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

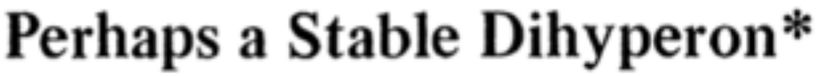


$SU(6)_{cs}$ representation	$4C_6$	$SU(3)_f$ representation
490	144	1
896	120	8
280	96	10
175	96	10*
189	80	27
35	48	35
1	0	28

$\boxed{\underline{1} \quad H = \Lambda\Lambda(I=S=0)}$ $\quad V = V_0 \times (-8)$

$\Delta\Delta(I=0, S=3) \quad V = V_0 \times 0$

$\Delta\Delta(I=3, S=0) \quad V = V_0 \times 32$



Perhaps a Stable Dihyperon*

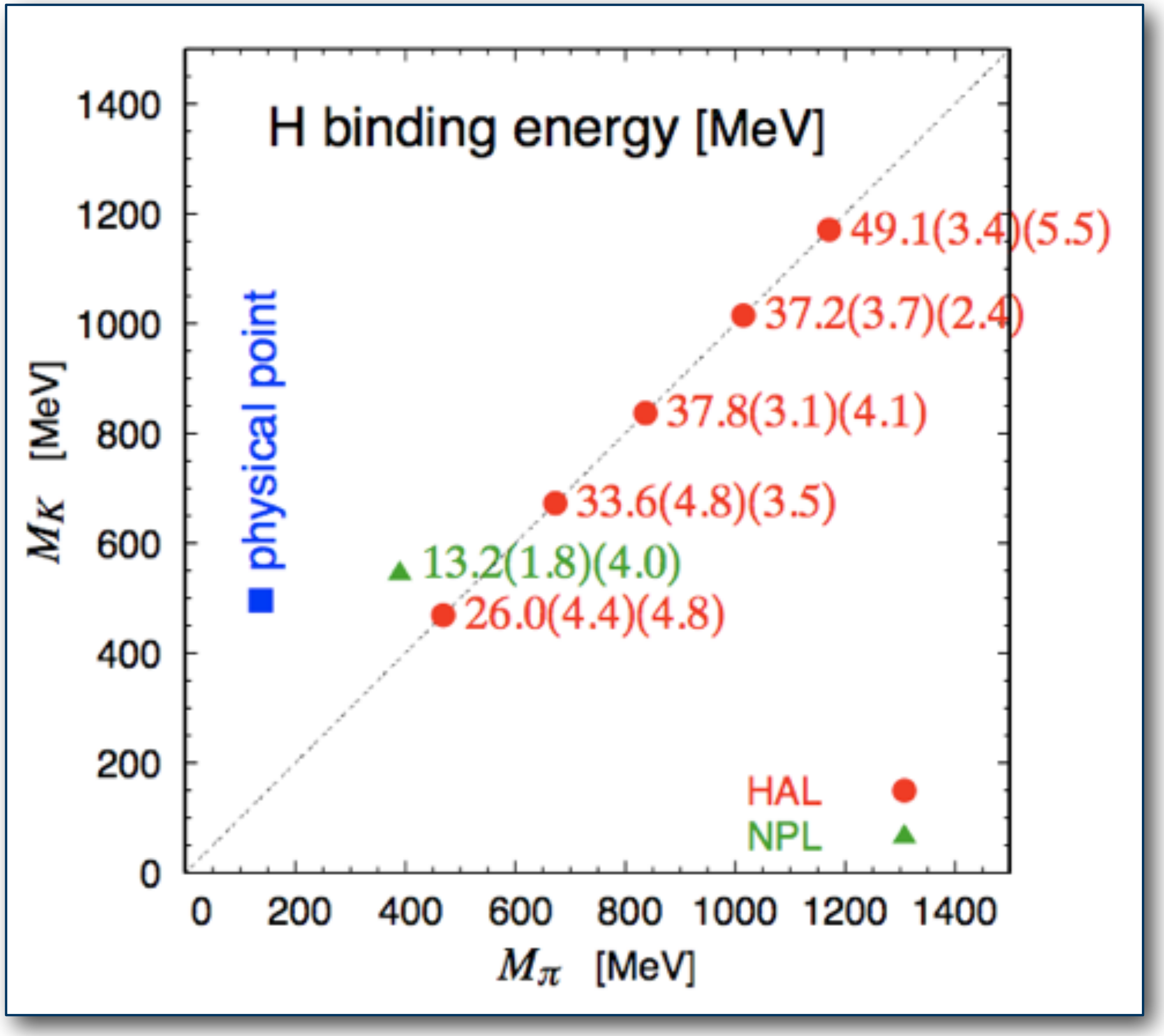
R.L. Jaffe, PRL 38 (1977) 195

$V_0 = 300/16 \sim 18(\mathrm{MeV})$

H dibaryon

H dibaryon in the SU(3) limit

T. Inoue et al. (HAL QCD Coll.), Phys. Rev. Lett. 106 (2011) 162002



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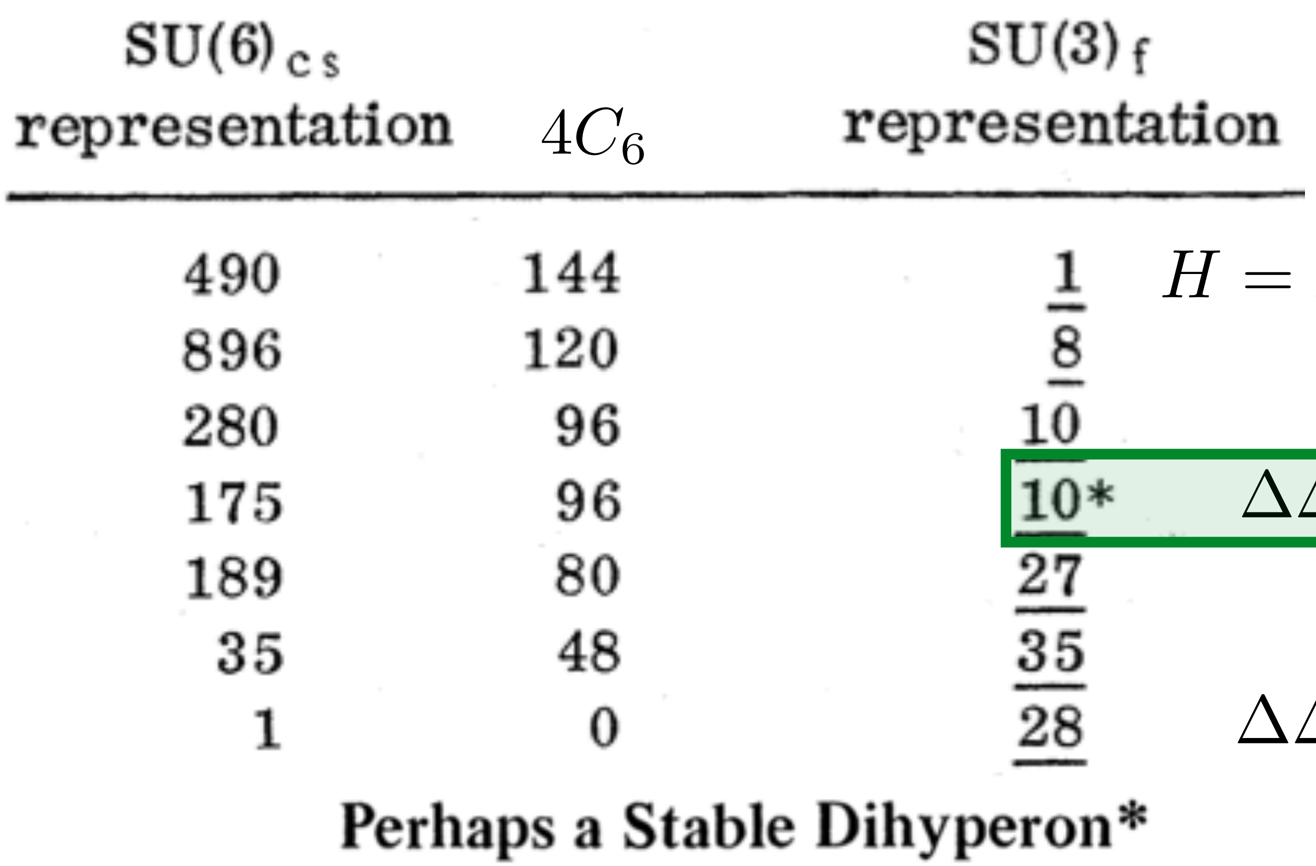

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$\Delta\Delta(I = 0, S = 3)$ $\quad V = V_0 \times 0$

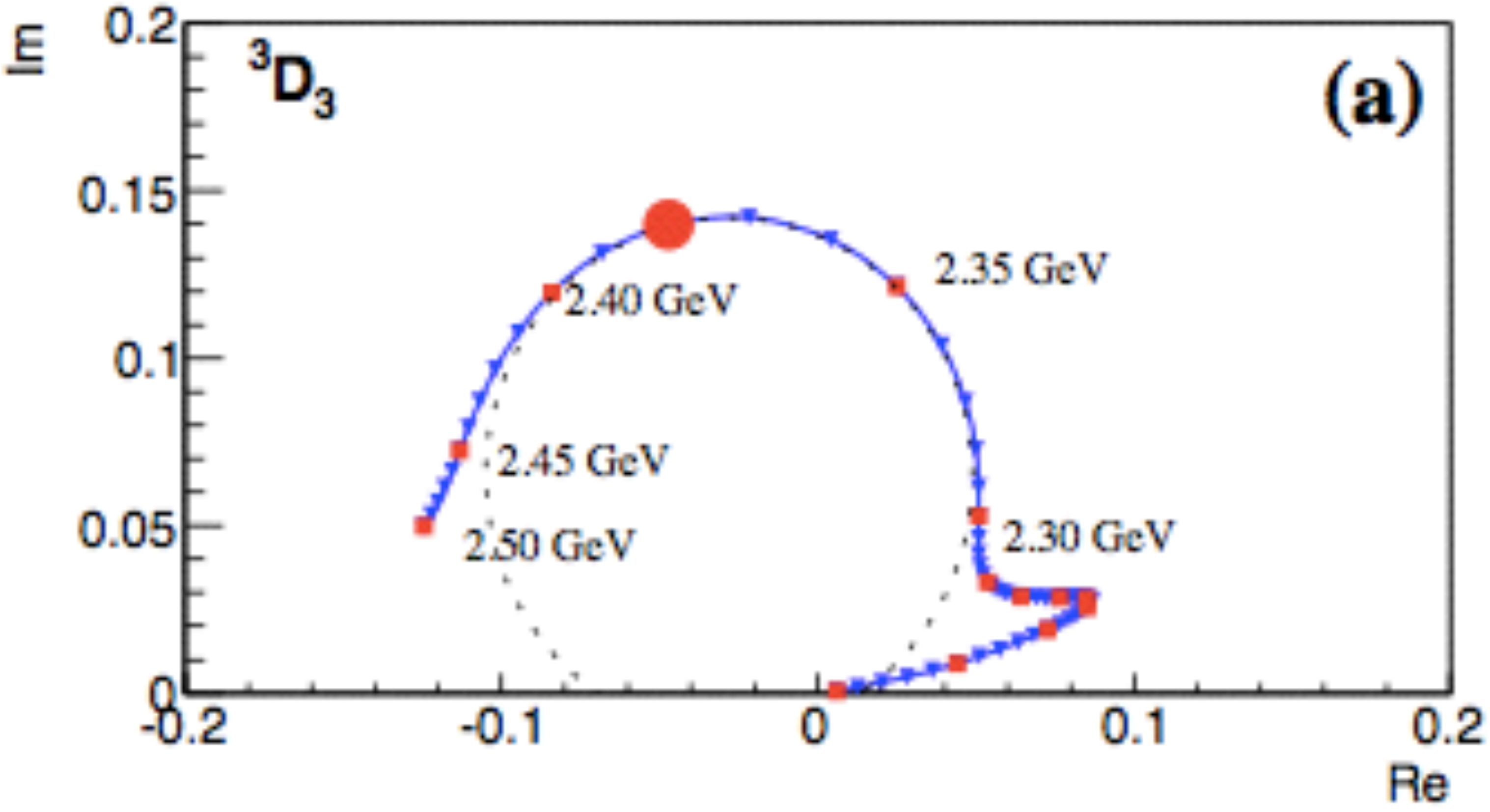
$\Delta\Delta(I = 3, S = 0)$ $\quad V = V_0 \times 32$

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

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

d* resonance

WASA@COSY+SAID, *PRL 112, 202301 (2014)*
A phase shift analysis of $^3D_3$ (3^+) amplitudes shows a narrow resonance at M=2380 MeV and Γ~70 MeV.



Antisymmetric LS forces between unlike baryons (Λ, N)

antisymmetric LS force $(\vec{\sigma}_\Lambda - \vec{\sigma}_N)\cdot\vec{L}$

induces $^3P_1 \leftrightarrow {}^1P_1$ mixing

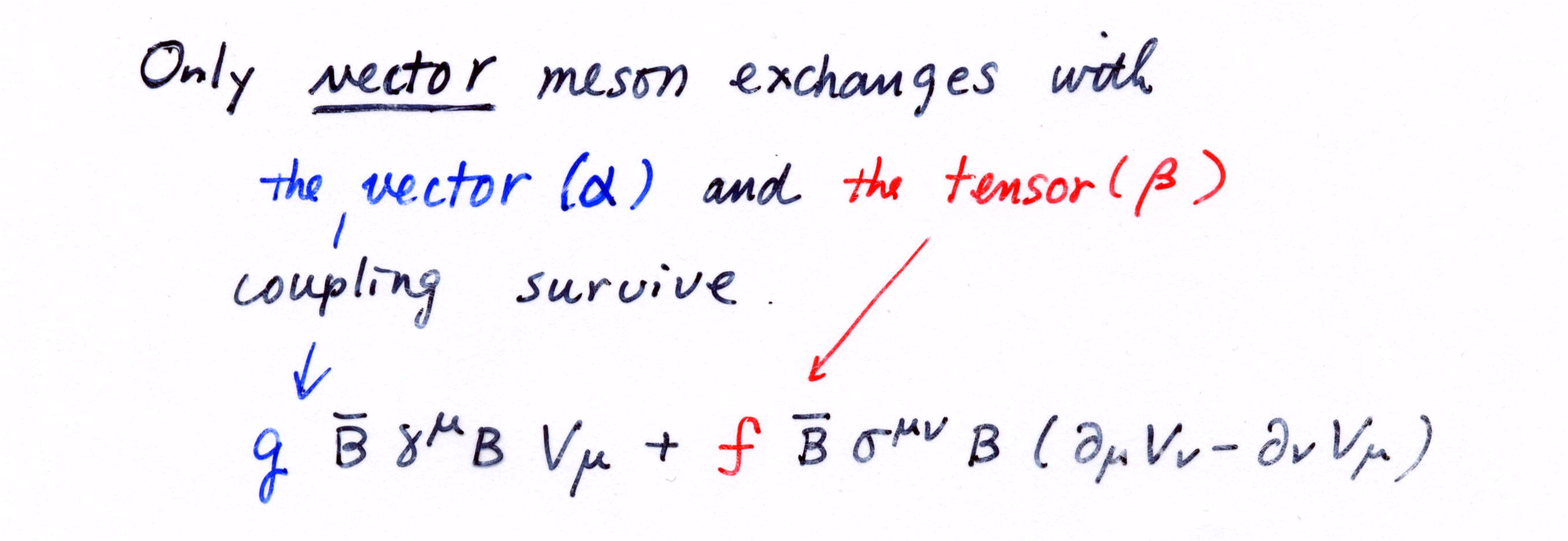
$$
\begin{aligned}
V_{SO} &= V_{SLS}(\vec{\sigma}_\Lambda + \vec{\sigma}_N)\cdot\vec{L} + V_{ALS}(\vec{\sigma}_\Lambda - \vec{\sigma}_N)\cdot\vec{L} \\
&= (V_{SLS} + V_{ALS})\,\vec{\sigma}_\Lambda\cdot\vec{L} + (V_{SLS} - V_{ALS})\,\vec{\sigma}_N\cdot\vec{L}
\end{aligned}
$$

ALS changes the flavor symmetry

8 × 8 = 1(S) + 8(S) + 27(S) + 8(A) + 10(A)+ 10*(A)

The coefficient V_{ALS} must be antisymmetric in flavor.
Only one matrix element ($8_{\mathrm{S}} \Leftrightarrow 8_{\mathrm{A}}$) survives the SU(3) limit.
The NN ALS force breaks the isospin symmetry (I=0 ⇔ I=1).

ALS is weak in the one-boson exchange SU(3) potentials.
ALS may be strong in the quark exchange process.



Only vector meson exchanges with

the vector (α) and the tensor (β)

coupling survive.

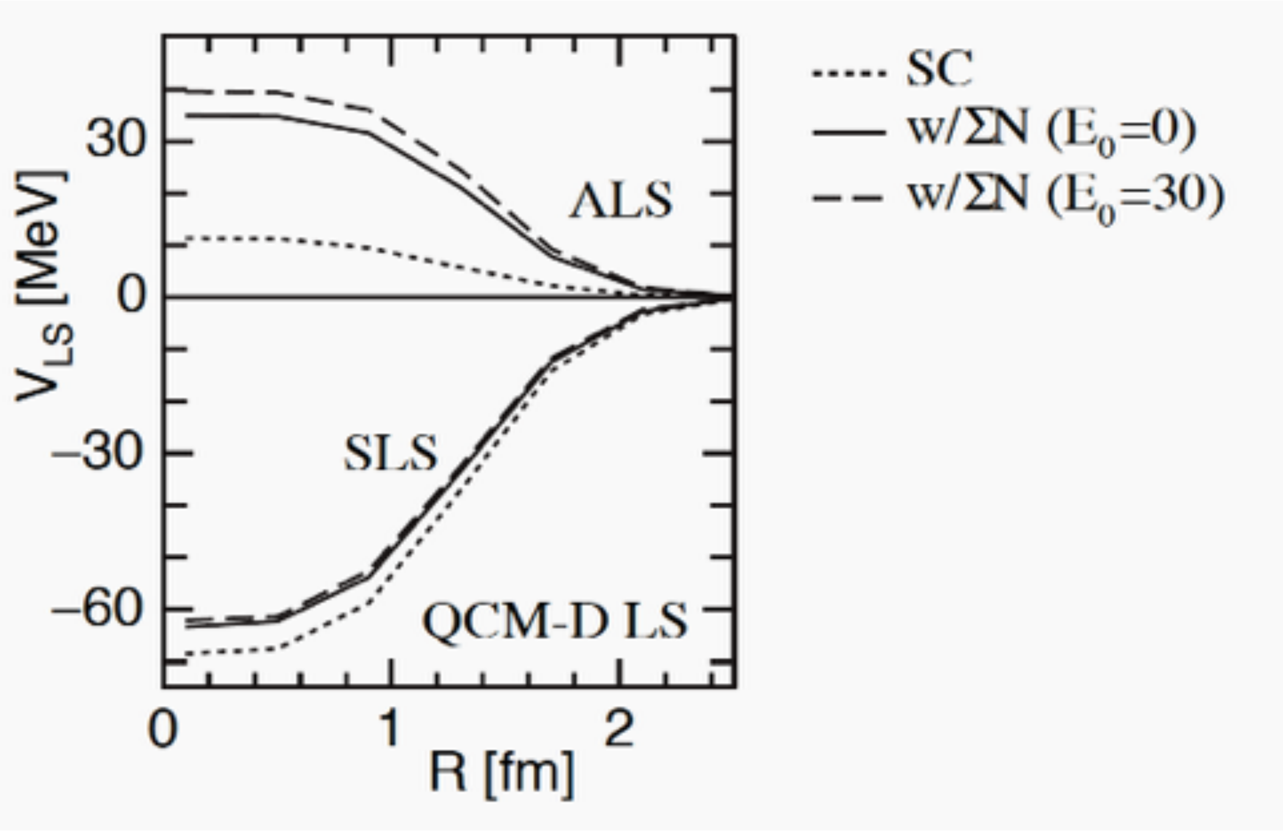
$$g \, \bar{B} \gamma^{\mu} B \, V_{\mu} + f \, \bar{B} \sigma^{\mu\nu} B \, (\partial_{\mu} V_{\nu} - \partial_{\nu} V_{\mu})$$

ALS $\sim (f_1 g_2 - g_1 f_2) \sim (\alpha - \beta)$

ρNN : $g >> f$

ωNN : $f >> g$

Strong antisymmetric LS force between ΛN and ΛN-ΣN predicted in the quark cluster model



Takeuchi, Tani, Oka, NPA684 (2001)

- **The ALS potentials extracted from Lattice QCD have confirmed the strong mixing effects of *ΣN* channels.**
  (→ Ishii, Murano, (HAL QCD))

Isospin dependences of the ΛN-ΣN ALS forces

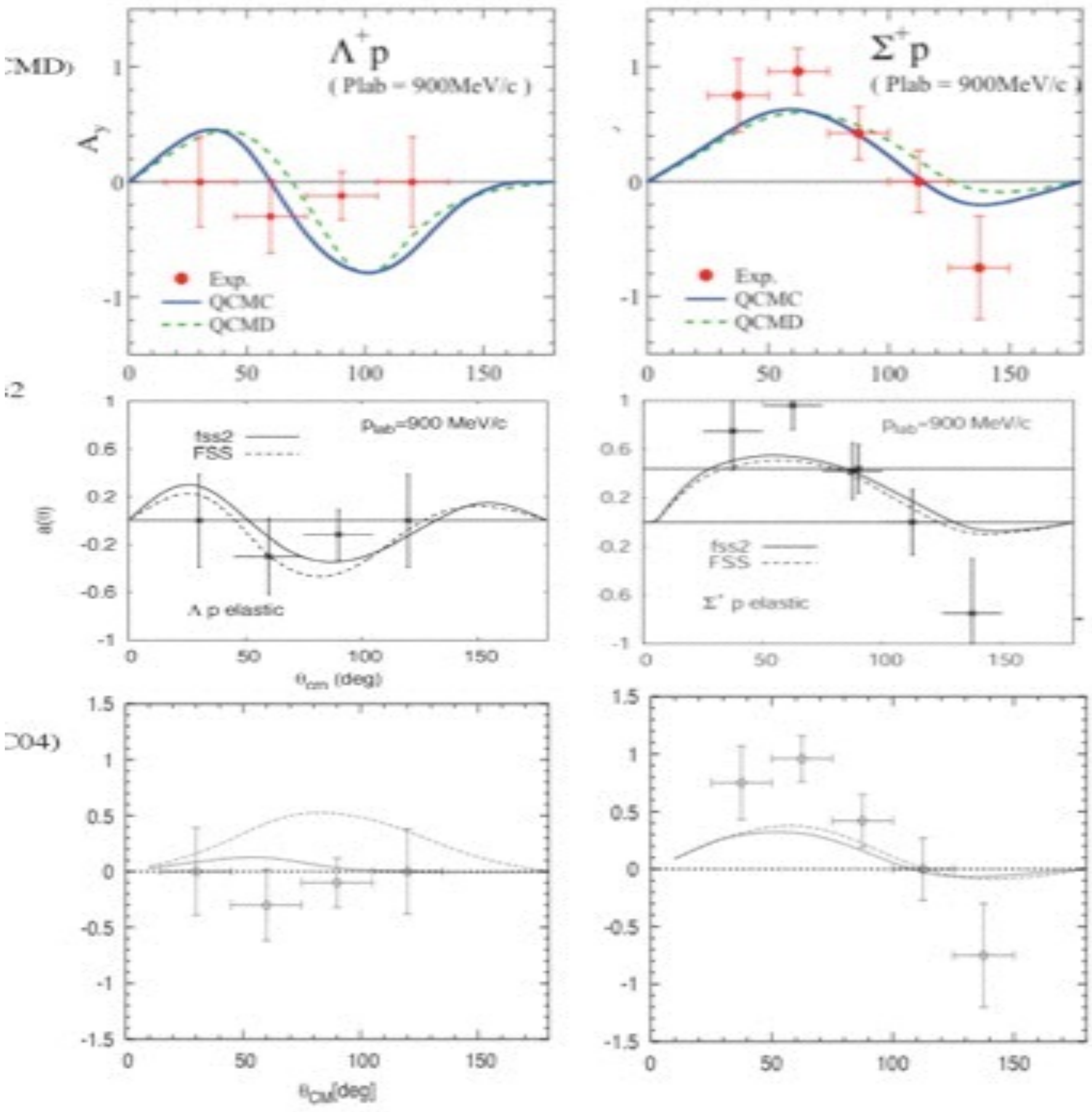
The SU(3) symmetry fixes the ratios of the ALS matrix elements.

- SU(3) predicts the strong *ΛN−ΣN* (I=1/2) conversion.

$$
\begin{aligned}
\langle \Lambda N\, {}^1P_1 | V | \Lambda N\, {}^3P_1 \rangle &= V_0 \\
\langle \Sigma N\, {}^1P_1 | V | \Lambda N\, {}^3P_1 \rangle &= -V_0 \\
\langle \Lambda N\, {}^1P_1 | V | \Sigma N\, {}^3P_1 \rangle &= 3V_0 \\
\langle \Sigma N\, {}^1P_1 | V | \Sigma N\, {}^3P_1 \rangle &= -3V_0
\end{aligned}
$$

- No ALS in *ΣN* (I=3/2) in the SU(3) limit

Analyzing powers of Λ, Σ N scatterings



Tokyo
Takeuchi

Kyoto-Niigata
Fujiwara

Nijmegen
Rijken

Conclusion

1. To understand the mechanism of the (SR part of) generalized BB force is one of the main goals of the strangeness nuclear physics.

2. Lattice QCD predicts strong flavor dependences of the (SR) BB interactions, which can be explained naturally by symmetries of the constituent quark model.

3. The antisymmetric LS force is another key quantity of the generalized BB force. SU(3) symmetry is powerful in determining the ALS, and predicts a strong mixing of ΣN(I=1/2) to ΛN, but no ALS for ΣN(I=3/2).

Remarks

4. Generalization to the Charm sector is interesting, because the SU(3) flavor representations for the light quarks are different and simpler.

5. Three body forces are also important.
can measure Λ(Σ) - d scattering?