Y_cN dibaryon resonances in the phenomenological potential model

Makoto Oka

Advanced Science Research Center, JAEA

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$Y_c N$ dibaryon resonances in the phenomenological potential model

1. Introduction for charm hadron physics

   strangeness → charm/bottom

2. Heavy quark dynamics

   heavy quark spin symmetry

3. Y_c (charmed baryon) – N interaction

4. Y_c N potential and Λ_c N bound states

5. $\Sigma_c^{(*)}$ N resonance states

6. Conclusion

Introduction

- **Strangeness Nuclear Physics has a long, successful history (~ 50 years) of excellent performance. Recent developments in technology both in theory and experiments allow us to go forward. → *heavy flavors***
- **Among the 3 generations of quark flavors,**

u	***c***	***t***
d	***s***	***b***

we consider *c* and *b* (as "*t*" is too short-lived.)

- **B-factories, HI colliders, and Hadron beam facilities will provide us with great possibility of developing HQ hadron physics. Belle, BES, LHCb, J-PARC, PANDA, . .**

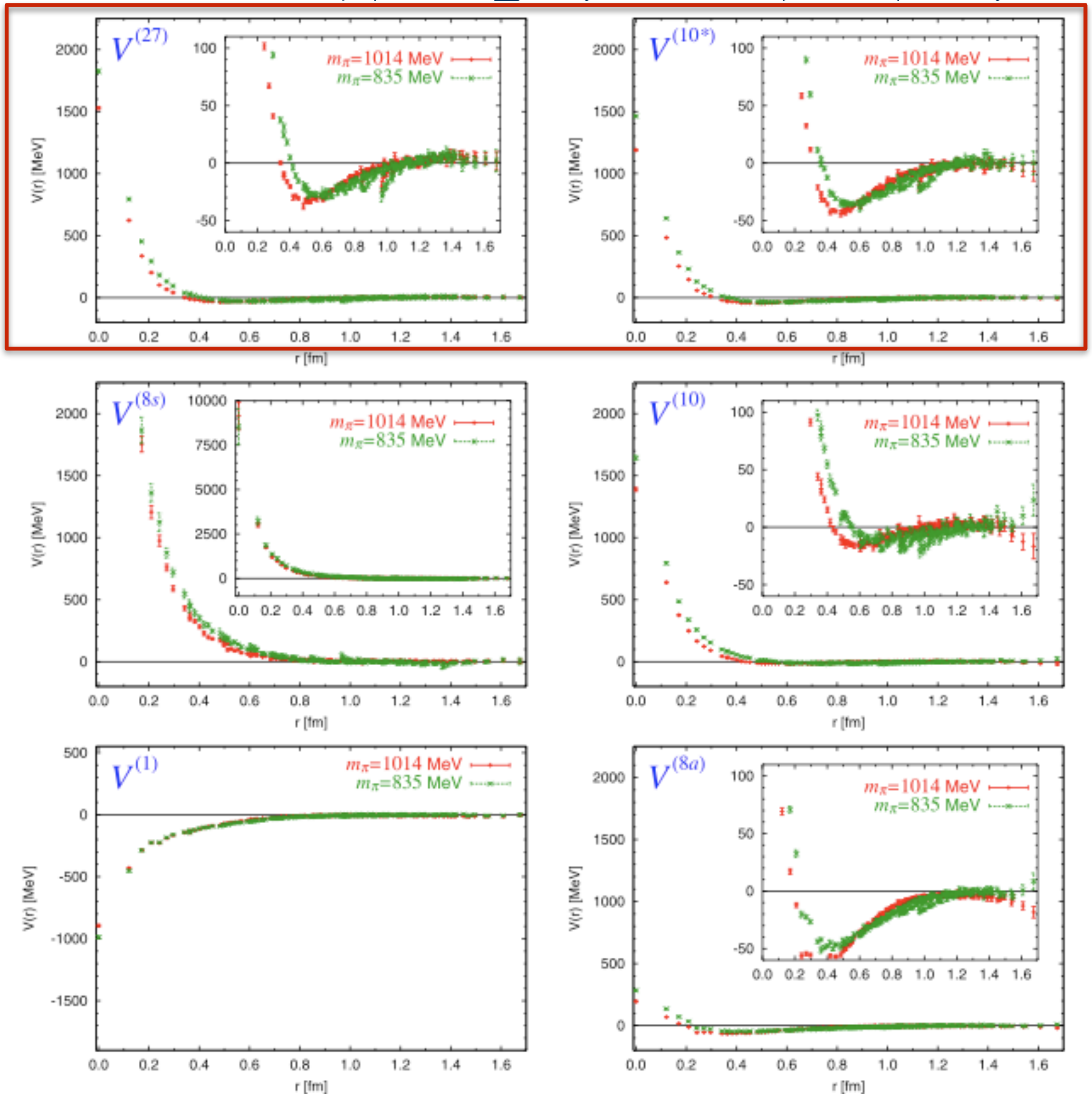
Introduction

- **What have we learned in Hypernuclear Physics?**
  Hyperons do not melt in nuclei as the nucleons do not.
  <= single particle motions in nuclei

  YN and YY interactions are generalized nuclear force.
  => SU(3) *symmetry, meson exchange interactions*
  quark structure at short distances

HAL QCD Lattice calculation of the BB potentials (in SU(3) scheme) shows that the potentials have long-range meson exchange part plus short-range part consistent with the quark Pauli effects.

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



NN interactions

YN and YY interactions

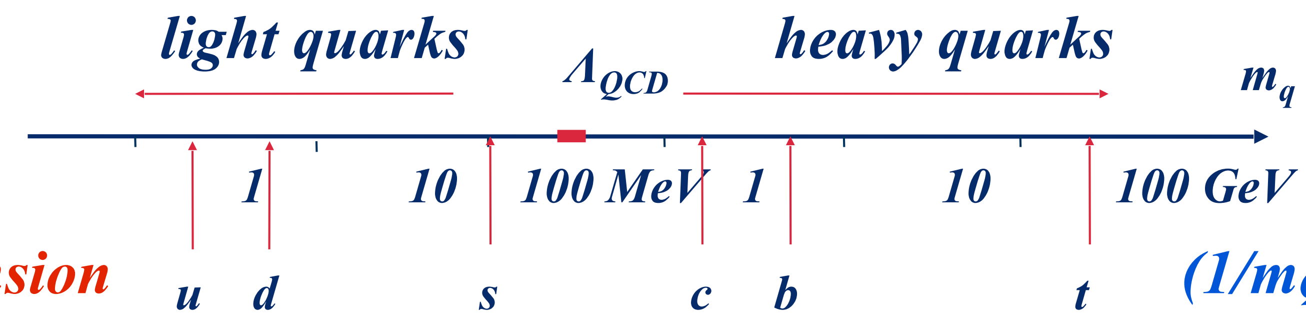
Introduction

- **Most hadrons are protected from being dissociated into multi-quark compound in medium.**
  => Thanks to short-range repulsion due to the quark structure of hadrons
- **There are exceptions, which are very interesting.**
  K^{bar} *feels a strong attraction to* N, *forming a molecular bound state* Λ(1405).
  The flavor singlet BB interaction is attrative, giving H-dibaryon ($u^2d^2s^2$) which couples to* ΛΛ, NΞ, ΣΣ *channels.
- **The strange hadron physics is mature now, and why do we need heavier hadrons?**

Heavy Quarks

QCD dynamics is *flavor-dependent* as the coupling constant runs.

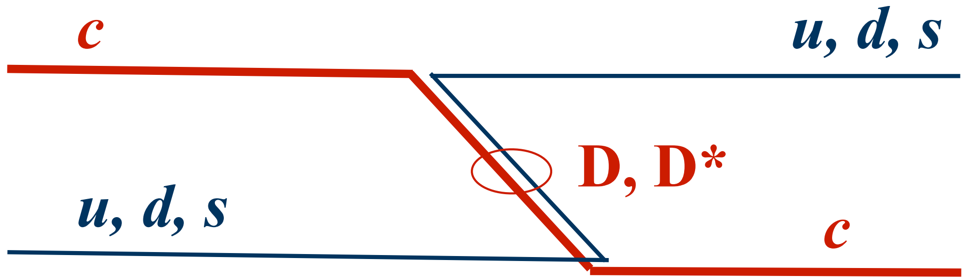
m_s (~0.1GeV) < Λ_{QCD} (~0.2GeV) ≪ m_c (~1.2GeV) ≪ m_b (~4.5GeV)



m_q expansion *(1/m_Q) expansion*

chiral symmetry *heavy quark symmetry*

1. **<u>Heavy flavor exchanges are suppressed.</u>**



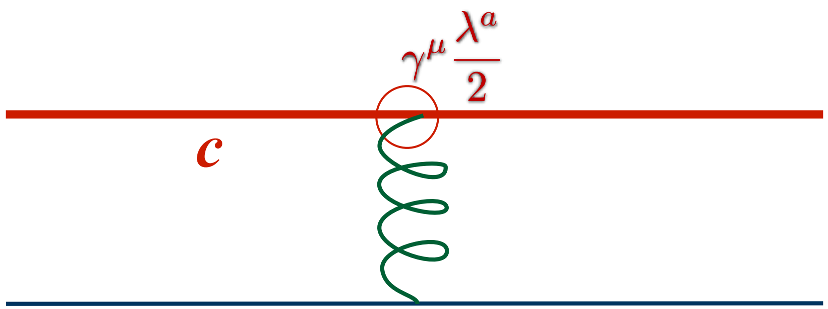
m(D, B) ≫ m(π, K, ρ)

Heavy meson exchange forces are $O(1/m_Q)^2$.

Heavy Quarks

2. <u>Magnetic gluon coupling is suppressed</u>

Relativistic effects in $1/m_Q$ expansion



$$\bar{\Psi}\gamma^\mu \frac{\lambda^a}{2}\Psi A^a_\mu \sim \Psi^\dagger \frac{\lambda^a}{2}\Psi A^a_0 - \Psi^\dagger \sigma \frac{\lambda^a}{2}\Psi \cdot \frac{1}{m_Q}(\nabla \times A^a)$$

(Color Electric coupling) ≫ (Color Magnetic coupling)

HQ spin-flip amplitudes are suppressed by $(1/m_Q)$.

⇨ **Heavy Quark Spin Symmetry**

Heavy Quarks

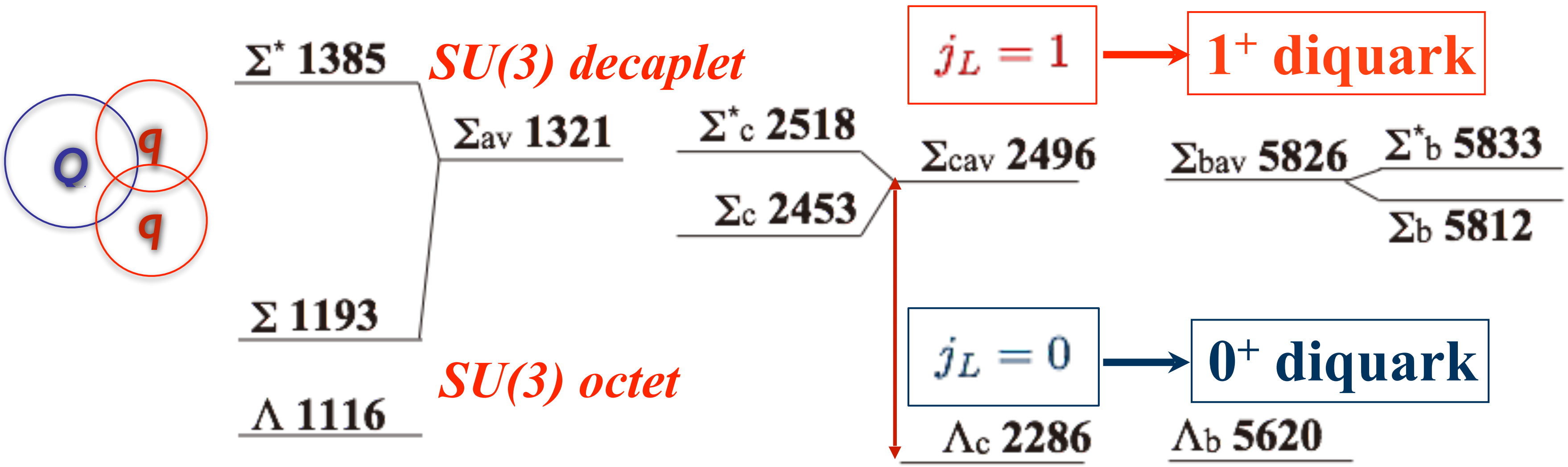
HQ spin symmetry $$[S_Q, H] = O\left(\frac{1}{m_Q}\right)$$

Q

qq

$$\vec{J} = \vec{S}_Q + \vec{j}_L \qquad \vec{j}_L = \vec{S}_q + \vec{L}_q$$

$J = j_L \pm \frac{1}{2}$ ***states are degenerate in the HQ limit.***

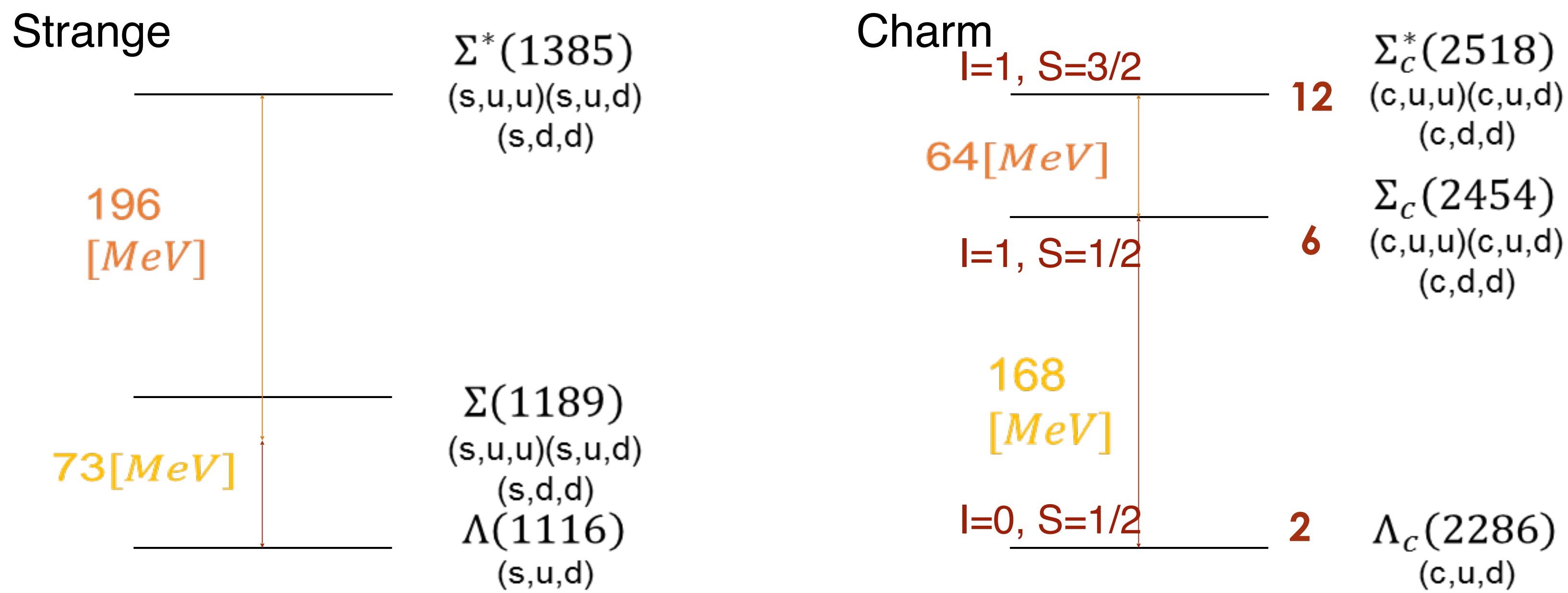


m_s (~0.1 GeV) $\ll m_c$ (~1.2 GeV) $\ll m_b$ (~4.5 GeV)

Diquark spectroscopy

Heavy Dibaryon $Y_c N$ systems

- **Couplings among $\Lambda_c N$, $\Sigma_c N$ and $\Sigma_c^* N$ are important.**



Coupled channels of $\Lambda_c N$ - $\Sigma_c N$ - $\Sigma_c^* N$ systems

Y.R. Liu, M.O., Phys. Rev. D85 (2012) 014015

S. Maeda, M.O., A. Yokota, E. Hiyama, Y.R. Liu, PTEP (2016) 023D02

S. Maeda, M.O., Y.R. Liu, Phys. Rev. C98 (2018) 035203

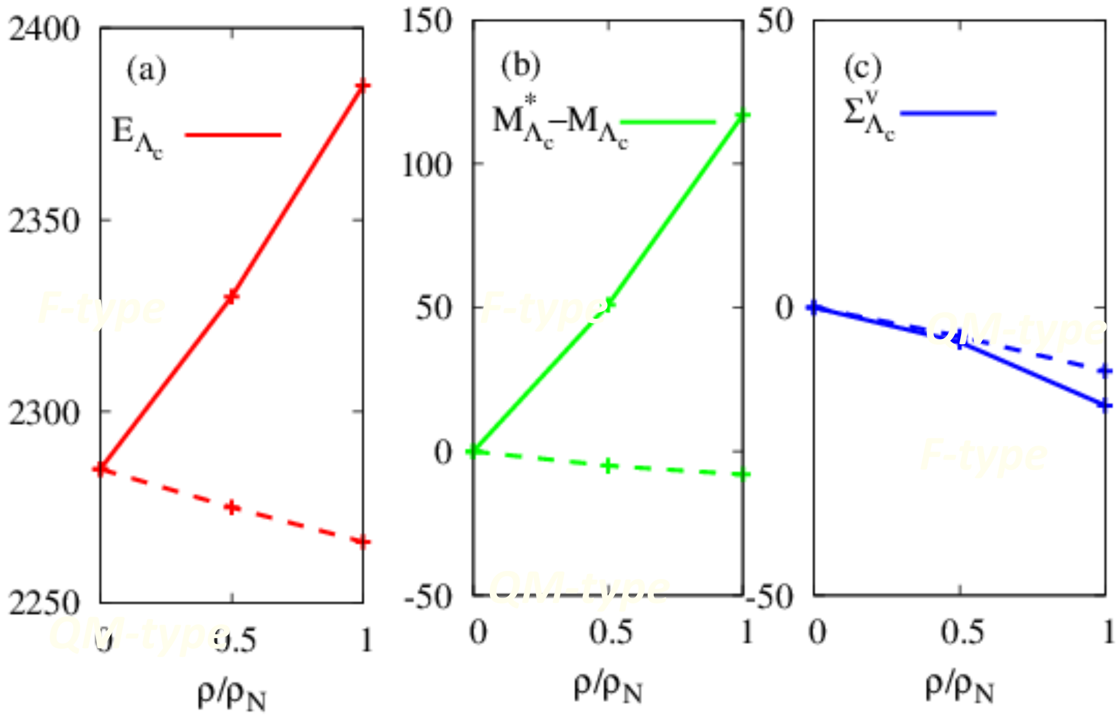
Y_cN interaction

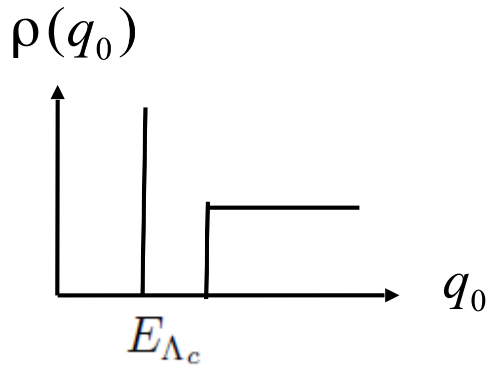
Various approaches for Λ_cN interaction/Λ_c in matter

- **Lattice QCD**
  T. Miyamoto (HAL-QCD) (2016)
  chiral extrapolation by J. Haidenbauer, G. Krein (2017)
- **QCD sum rule (@ finite density) K. Ohtani et al. (2017)**
  Λ_c bound in nuclear matter
- **SU(4) based Meson Exchange Model**
  Tyapkin (1975), Dover, Kahana (1977), Bando, Nagata (1983)
  The interaction is weaker as the $D^{(*)}$ meson, instead of $K^{(*)}$, exchanges are suppressed.

Λ_c in medium from QCD sum rules

K. Ohtani, K-J. Araki, MO, PRC 96 (2017) 055208





$$E_{\Lambda_c} = \Sigma_v + \sqrt{M^{*2}_{\Lambda_c} + \vec{q}^2}$$

Density dependence of the 4-quark condensate in the factorization scheme is too strong.

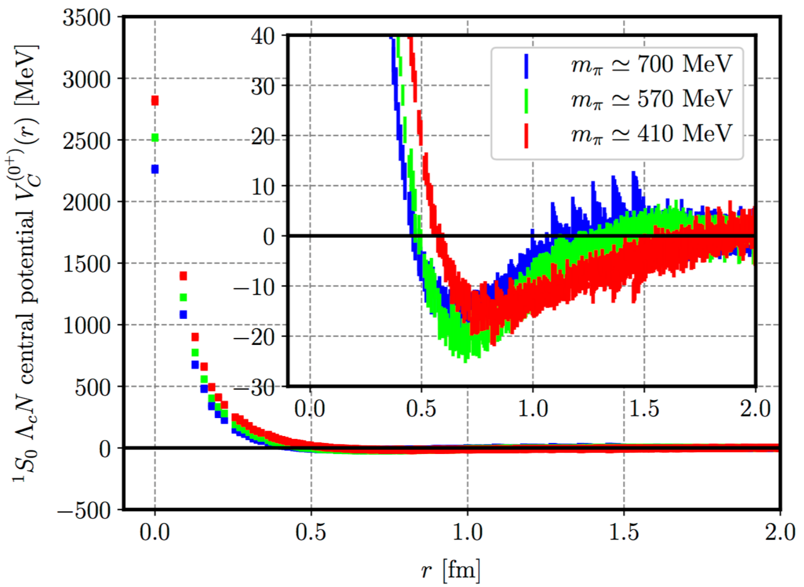
The perturbative chiral quark model (PCQM) gives milder dependence. $\Delta E_{\Lambda c} \sim -20$ MeV @ normal nuclear density

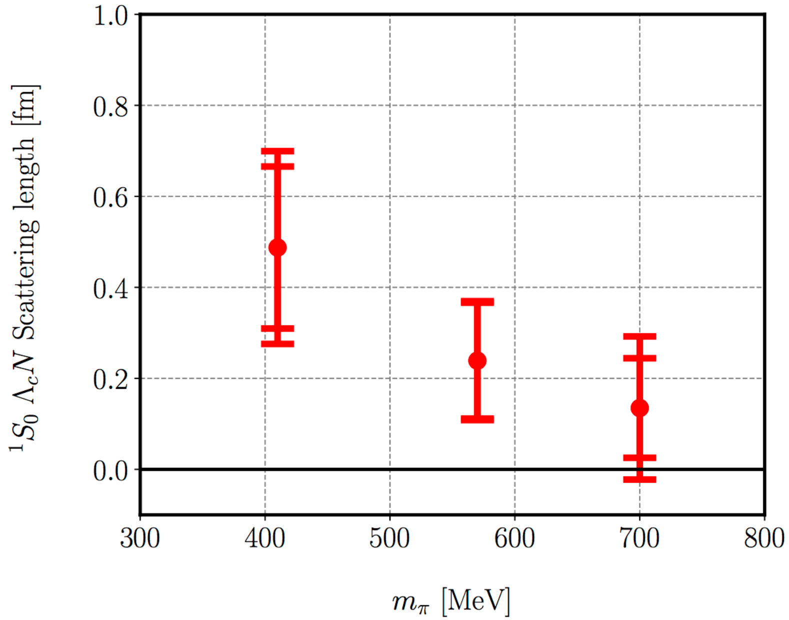
R. Thomas, et al., NPA 795, 19 (2007)

E. G. Drukarev, et al., PRD 68, 054021 (2003)

Λ_cN potential in Lattice QCD

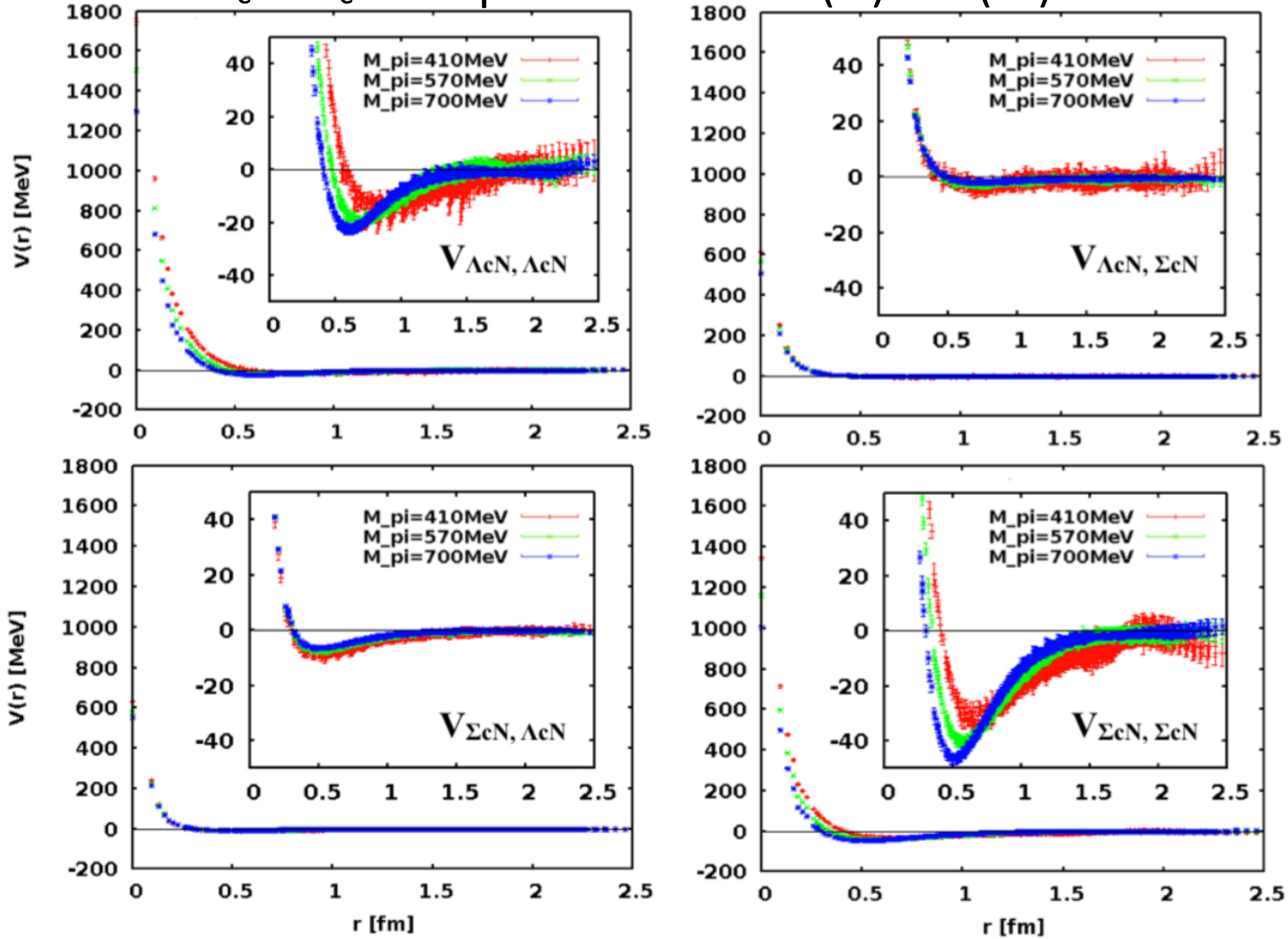
- **T. Miyamoto et al., HAL-QCD, Nucl. Phys. A971 (2018) 113.**
  The Λ_c-N interaction looks similar to the ΛN interaction: the short-range repulsion plus long-range attraction, almost spin independent, with negligible tensor force.
  Λ_c-hypernuclei may exist for large A, although two-body bound state is unlikely.





T. Miyamoto (HAL QCD), PoS (LATTICE2016) 117

$\Lambda_c N$ -$\Sigma_c N$ coupled channel : I (J^P) = 1 (1^+)

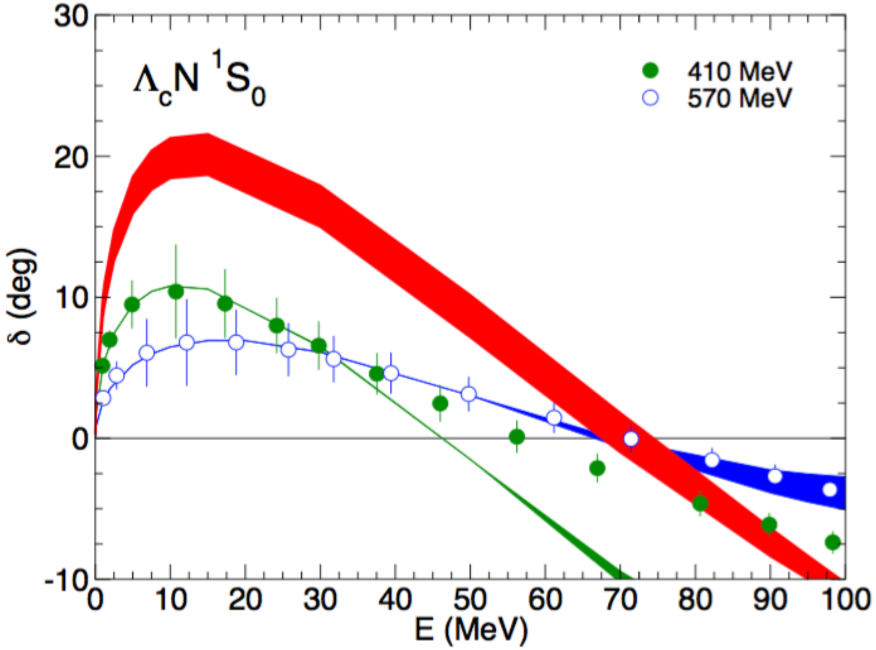


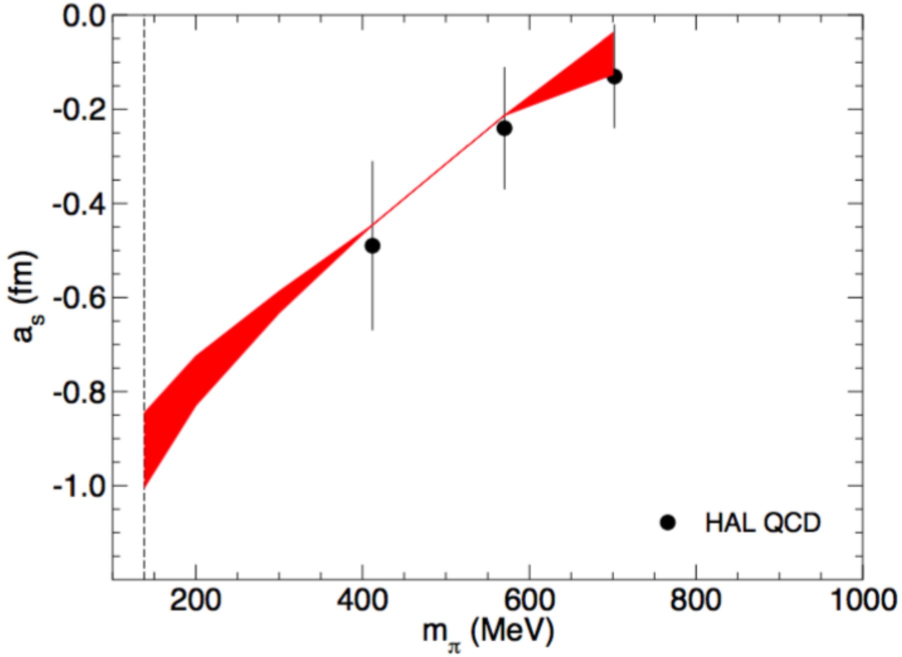
Pion exchanges are still not fully included with large quark masses.

$\Lambda_c N$ potential in Lattice QCD

- **J. Haidenbauer, G. Krein, arXiv:1711.06470**
  Chiral extrapolation of the lattice data to the physical pion mass

$$V(^1S_0) = \tilde{C}_{^1S_0} + \tilde{D}_{^1S_0} m_\pi^2 + (C_{^1S_0} + D_{^1S_0} m_\pi^2)(p^2 + p'^2)$$





Is this extrapolation form justified for strong $\Sigma_c^* N$ coupling?

Meson exchange picture

- Based on the effective Lagrangian
  for light hadrons : chiral SU(3) + hidden local symmetry
  for heavy hadrons : HQ symmetry

Heavy baryon Q+(qq)

$(S, f) = (1/2\ \ 3^{\mathrm{bar}})$ $\qquad$ $(1/2\ \ 6)$

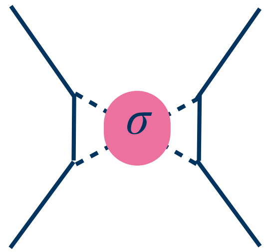
$$B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c^{\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} & \Omega_c^0 \end{pmatrix}$$

$(3/2\ \ 6)$

$$B_6^* = \begin{pmatrix} \Sigma_c^{*++} & \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \Sigma_c^{*0} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} & \Omega_c^{*0} \end{pmatrix}$$

$$S_\mu = B_{6\,\mu}^* + \frac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma_5 B_6$$

- We introduce a flavor singlet (I=0) scalar σ meson (m_σ = 600 MeV), simulating two pion exchanges in the I=0, J=0 channel. We assume that the σ meson couples to *u* and *d* quarks, but not to charm.



Y.R. Liu and MO, Phys. Rev. D85 (2012) 014015

Meson exchange picture

⌗ Heavy-Quark-Chiral Effective Lagrangian

Pseudoscalar (π)
Vector (ρ, ω)
Scalar (σ)

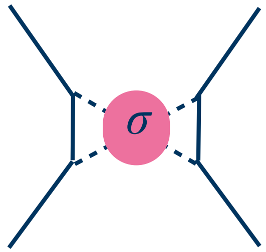
$$\mathcal{L}_{B_{\bar{3}}} = \frac{1}{2}\mathrm{tr}[\bar{B}_{\bar{3}}(iv\cdot D)B_{\bar{3}}] + i\beta_B \mathrm{tr}[\bar{B}_{\bar{3}} v^\mu (\Gamma_\mu - V_\mu) B_{\bar{3}}] + \ell_B \mathrm{tr}[\bar{B}_{\bar{3}}\sigma B_{\bar{3}}]$$

$$\mathcal{L}_S = -\mathrm{tr}[\bar{S}^\alpha(iv\cdot D - \Delta_B)S_\alpha] + \frac{3}{2}g_1(iv_\kappa)\epsilon^{\mu\nu\lambda\kappa}\mathrm{tr}[\bar{S}_\mu A_\nu S_\lambda] + i\beta_S \mathrm{tr}[\bar{S}_\mu v_\alpha(\Gamma^\alpha - V^\alpha)S^\mu] + \lambda_S \mathrm{tr}[\bar{S}_\mu F^{\mu\nu} S_\nu] + \ell_S \mathrm{tr}[\bar{S}_\mu \sigma S^\mu]$$

$$\mathcal{L}_{int} = g_4 \mathrm{tr}[\bar{S}^\mu A_\mu B_{\bar{3}}] + i\lambda_I \epsilon^{\mu\nu\lambda\kappa} v_\mu \mathrm{tr}[\bar{S}_\nu F_{\lambda\kappa} B_{\bar{3}}] + h.c.,$$

$$D_\mu B_{\bar{3}} = \partial_\mu B_{\bar{3}} + \Gamma_\mu B_{\bar{3}} + B_{\bar{3}}\Gamma_\mu^T,$$
$$D_\mu S_\nu = \partial_\mu S_\nu + \Gamma_\mu S_\nu + S_\nu \Gamma_\mu^T.$$

$$\Delta_B = M(B_6) - M(B_{\bar{3}})$$



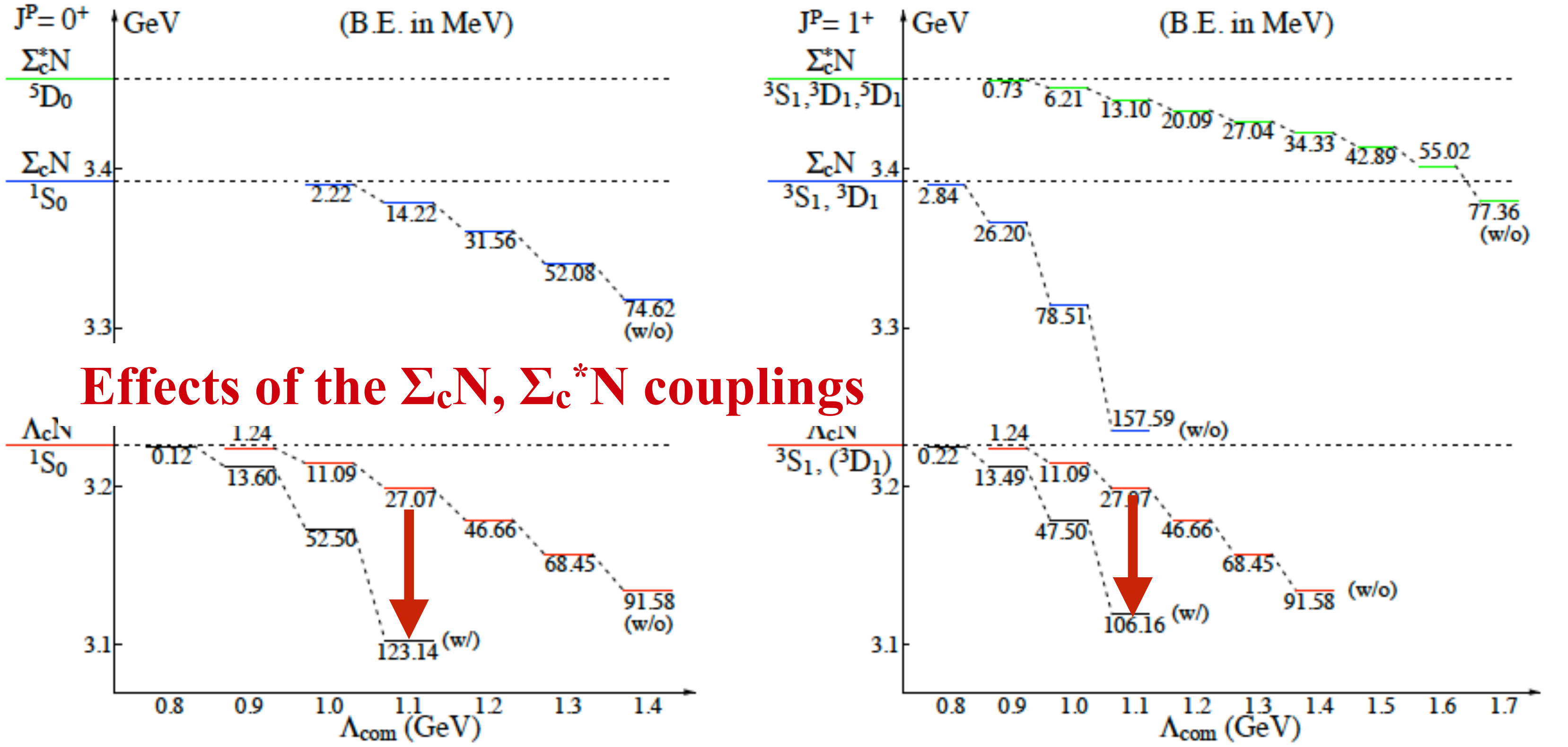
$$\mathcal{L}_N = -\frac{g_A}{2f}\bar{N}\gamma^\mu\gamma^5\partial_\mu(\pi^i\tau^i)N - h_\sigma \bar{N}\sigma N - h_V \bar{N}\gamma^\mu(\tau^i\rho^i_\mu + \omega_\mu)N - h_T \bar{N}\sigma^{\mu\nu}\partial_\mu(\tau^i\rho^i_\nu + \omega_\nu)N.$$

Y.R. Liu and MO, Phys. Rev. D85 (2012) 014015

Meson exchange picture

- **The attractive force (via σ exchange) gives the 0^+ and 1^+ two-body $\Lambda_c N$ bound states.**

All the S-wave states have a bound state for large cutoff parameters.



Effects of the $\Sigma_c N$, $\Sigma_c^* N$ couplings

$J^P = 0^+$ $\qquad$ $J^P = 1^+$

Y.R. Liu and MO, Phys. Rev. D85 (2012) 014015

Quark exchange interactions

- **Microscopic view of the short-range B-B interactions can be understood by the quark exchange mechanism.**
- **The Color Magnetic Interaction gives estimates of the short-range potentials at the origin R=0.**
  We find weaker repulsions for
  $V(\Lambda_c\text{-}N) \sim 300$ MeV
  $V(\Sigma_c\text{-}N) \sim 100$ MeV
  in the heavy quark limit, compared with
  $V(N\text{-}N; {}^1S_0) \sim 450$ MeV, $V(\Lambda\text{-}N; {}^1S_0) \sim 400$ MeV

$$H = -\alpha \sum_{a,i<j} (\lambda_i^a \lambda_j^a)(\vec{\sigma}_i \cdot \vec{\sigma}_j) = \alpha \left[8n - 2C_6 + \frac{4}{3} S(S+1) + C_2 \right]$$

Quadratic Casimir $C_6 \equiv C_2[SU(6)_{\rm cs}]$ $C_2 \equiv C_2[SU(3)_c]$

Color magnetic interaction

- **Spin Independent Force**

$$H = C \sum_{a,i<j} (\lambda_i^a \lambda_j^a) = \frac{C}{2} \sum_a \left[(\sum_i \lambda_i^a)^2 - \sum_i (\lambda_i^a)^2 \right] = C \left[C_2 - \frac{8}{3} n \right]$$

$C_2 \equiv C_2[SU(3)_c]$ **Quadratic Casimir, C_2=0 for singlet**

- **Color Magnetic Interaction**

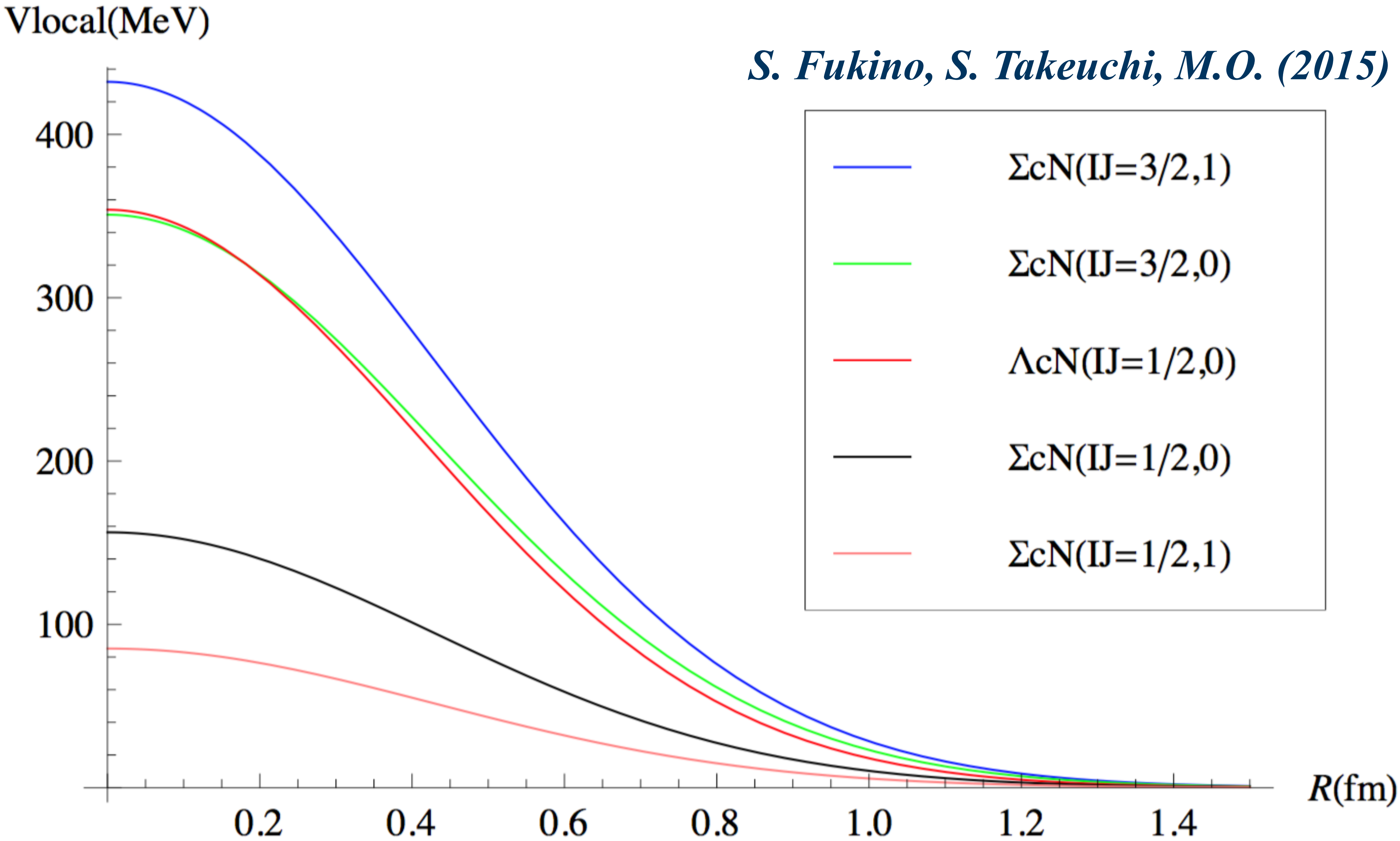
$$H = -\alpha \sum_{a,i<j} (\lambda_i^a \lambda_j^a)(\vec{\sigma}_i \cdot \vec{\sigma}_j)$$

$$= \alpha \left[8n - 2C_6 + \frac{4}{3} S(S+1) + C_2 \right]$$

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

Y_c-N local potentials
given by the *Quark Cluster Model*

S. Fukino, S. Takeuchi, M.O. (2015)



CTNN potential model(s)

- **pi + sigma + QCM repulsion adjusted to NN interaction**

S. Maeda M.O., A. Yokota, E. Hiyama, Y.R. Liu, PTEP 2016, 023D02 (2016)

$$V_\pi(i,j) = C_\pi(i,j)\frac{m_\pi^3}{24\pi f_\pi^2}\left\{\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_2 Y_1(m_\pi,\Lambda,r) + \mathcal{O}_{ten}H_3(m_\pi,\Lambda,r)\right\},$$

$$V_\sigma(i) = C_\sigma(i)\frac{m_\sigma}{16\pi}\left\{4Y_1(m_\sigma,\Lambda,r) + \vec{L}\cdot\vec{\sigma}_2\left(\frac{m_\sigma}{M_N}\right)^2 Z_3(m_\sigma,\Lambda,r)\right\},$$

$\mathcal{O}_i$: spin operators

$\mathcal{O}_{ten}$: tensor operator

$$Y(x) = \frac{e^{-x}}{x},\quad Z(x) = \left(\frac{1}{x}+\frac{1}{x^2}\right)Y(x),\quad H(x) = \left(1+\frac{3}{x}+\frac{3}{x^2}\right)Y(x),$$

$$Y_1(m,\Lambda,r) = Y(mr) - \left(\frac{\Lambda}{m}\right)Y(\Lambda r) - \frac{\Lambda^2-m^2}{2m\Lambda}e^{-\Lambda r},$$

$$V_{\rm QCM} = V_0 e^{-\left(r^2/b^2\right)}$$

	C_σ	b [fm]
a	−67.58	0.6
b	−77.5	0.6
c	−60.76	0.5
d	−70.68	0.5

$$\Lambda_\pi = 750\text{MeV},\ \Lambda_\sigma = 1000\text{MeV}$$

S. Maeda M.O., A. Yokota, E. Hiyama, Y.R. Liu, PTEP (2016) 023D02

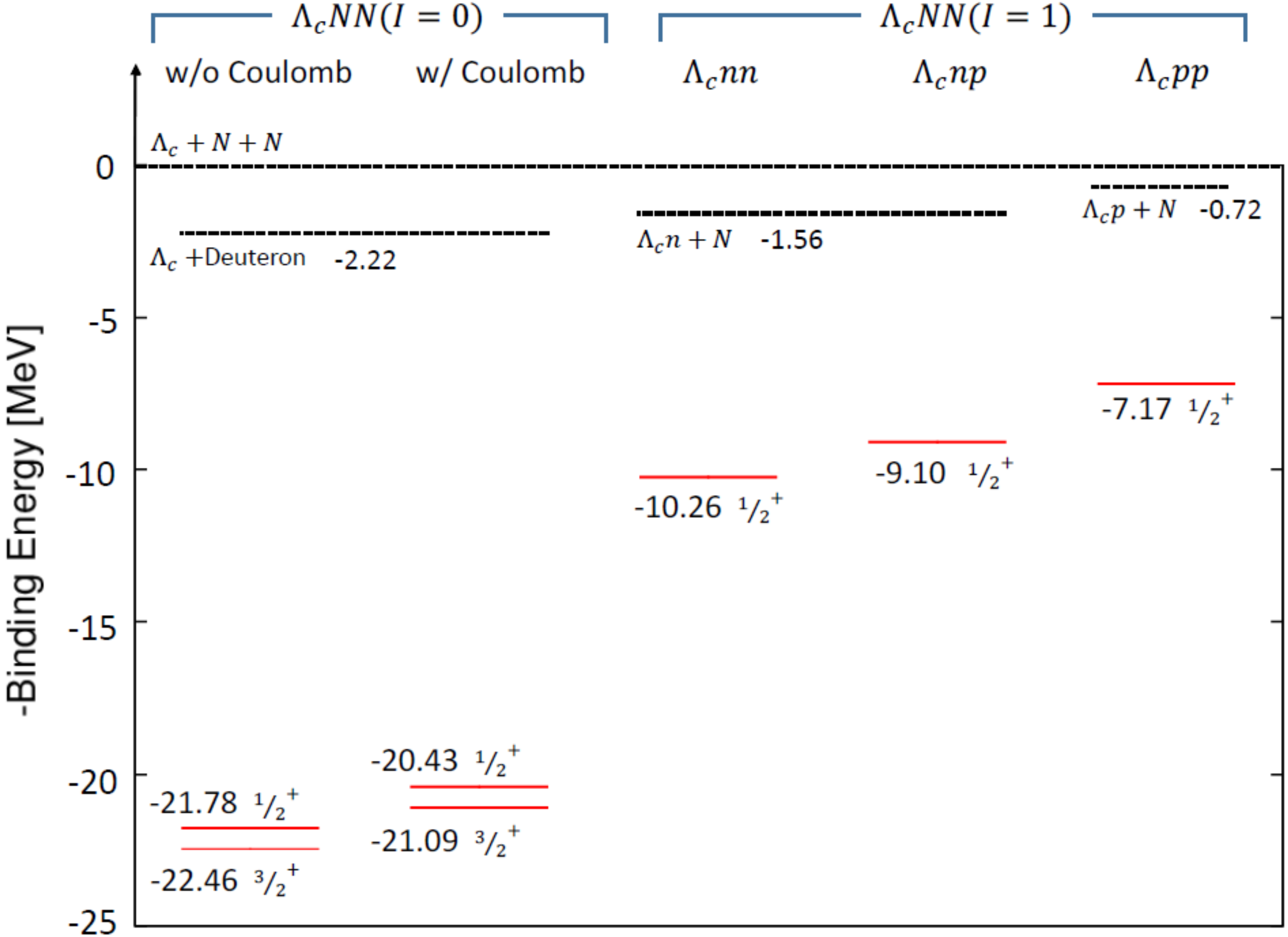
S. Maeda, M. Oka, Y.R. Liu, Phys. Rev. C98 (2018) 035203

	CTNN-a	CTNN-b	CTNN-c	CTNN-d
B.E. [MeV] $J^\pi = 0^+$	*unbound*	—	1.72×10^{-3}	1.37
(+Coulomb)			*barely bound*	(0.56)
Scattering length [fm]	−3.64	−65.15	130.93	5.31
B.E. [MeV] $J^\pi = 1^+$	—	2.62×10^{-4}	1.97×10^{-2}	1.57
(+Coulomb)				(0.72)
Scattering length [fm]	−4.11	337.53	39.27	5.01

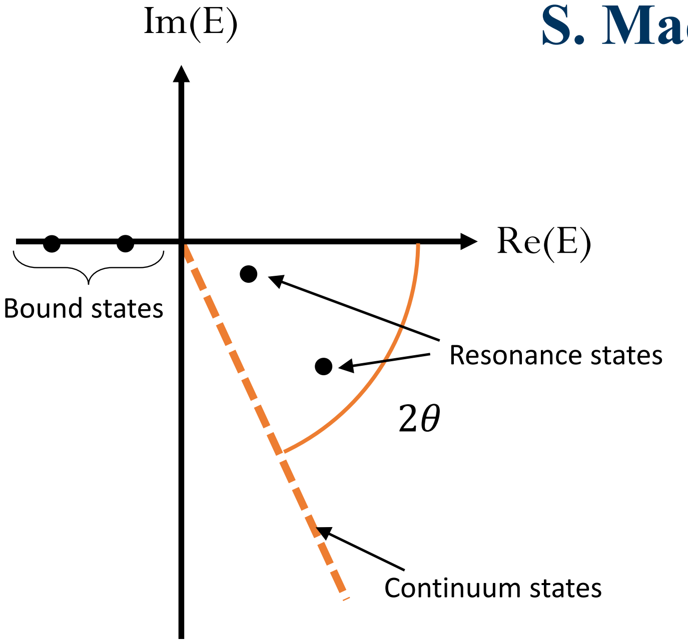
bound

Threshold	J^π	Energy	(From threshold)
$\Sigma_c N$	$J^\pi = 0^+$	165	(−2)
	$J^\pi = 1^+$	153	(−14)
$\Sigma_c^* N$	$J^\pi = 1^+$	224	(−8)
	$J^\pi = 2^+$	214	(−18)

Λ_cNN bound states

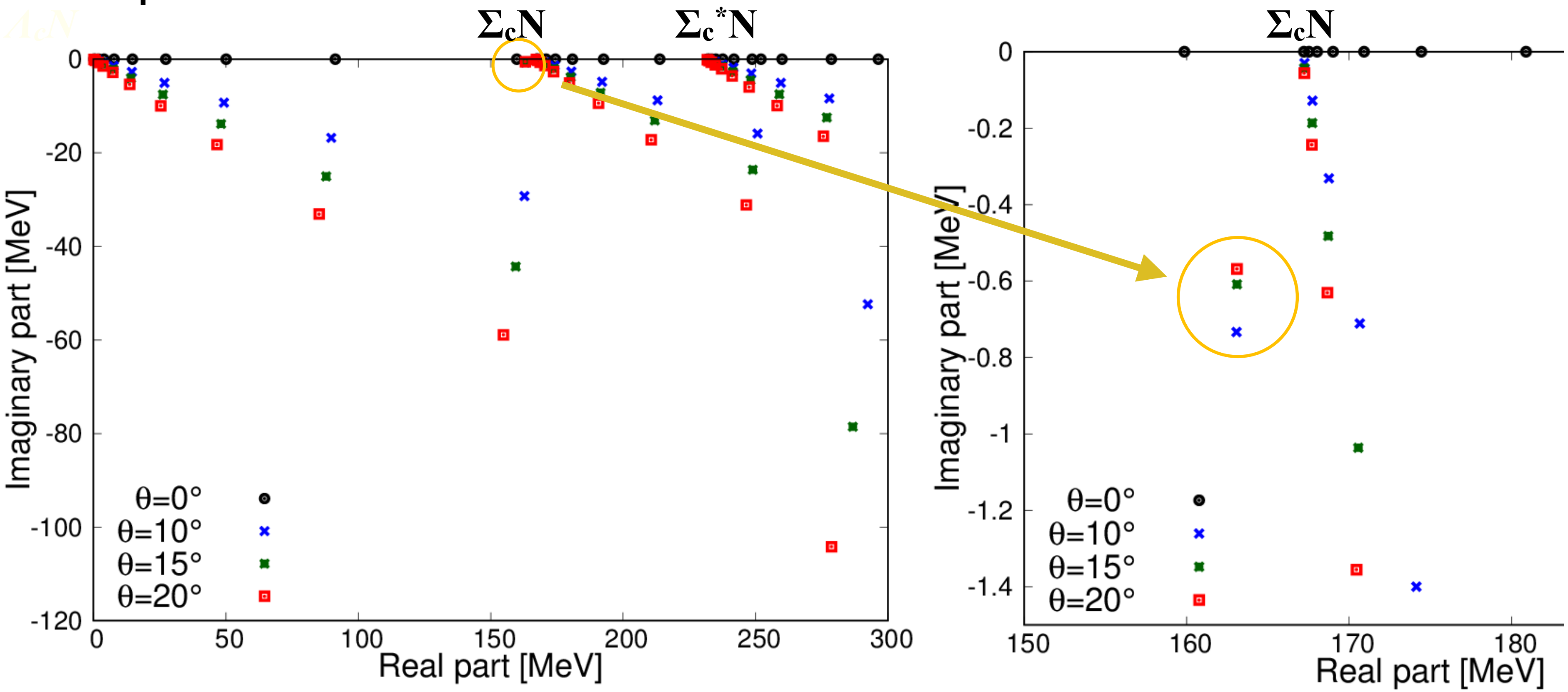


S. Maeda, M. Oka, Y.R. Liu, Phys. Rev. C98 (2018) 035203

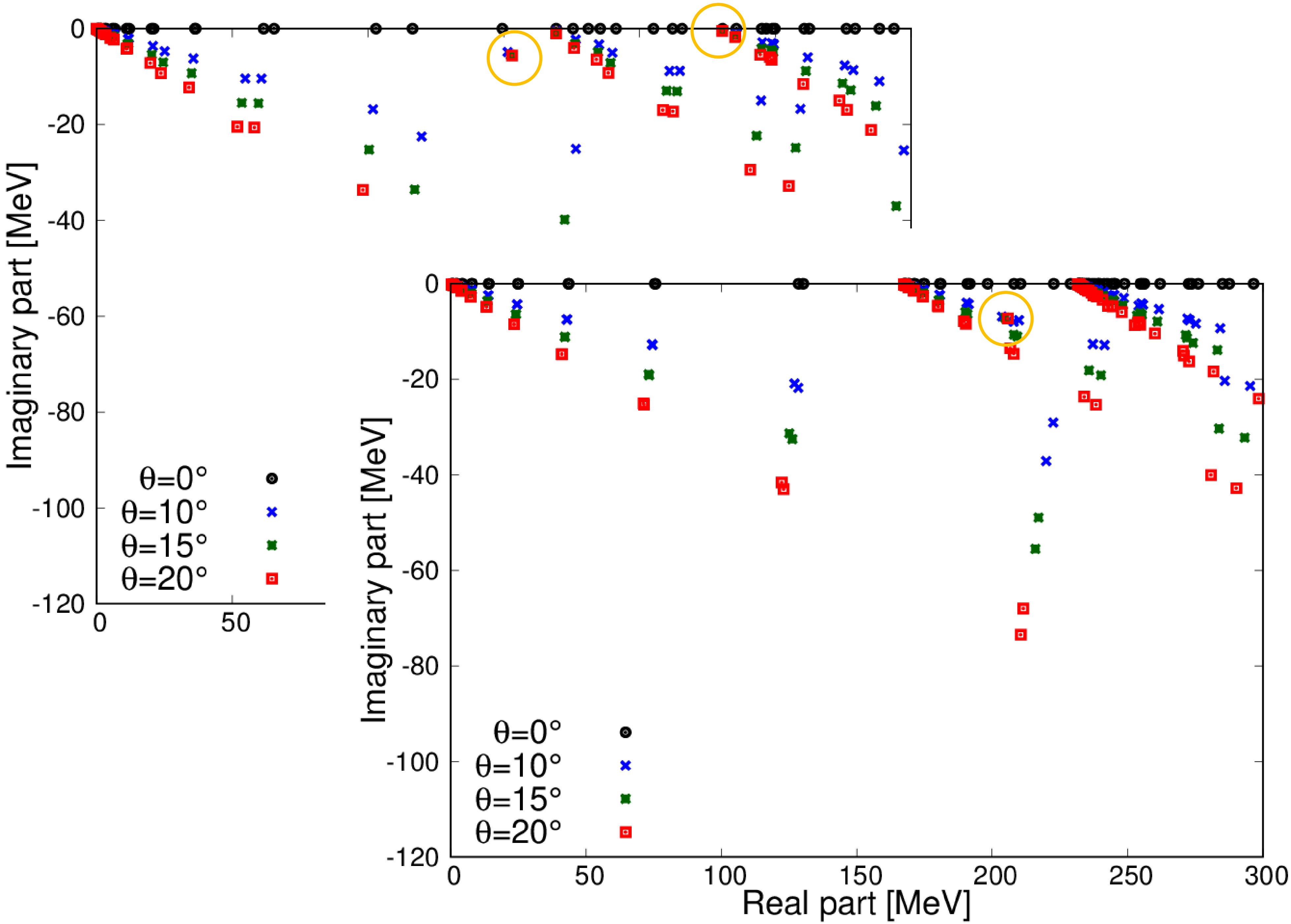


Complex scaling method is employed to obtain the complex pole positions corresponding to bound Σ_c N and Σ_c^* N states coupled to the Λ_c N scattering states.

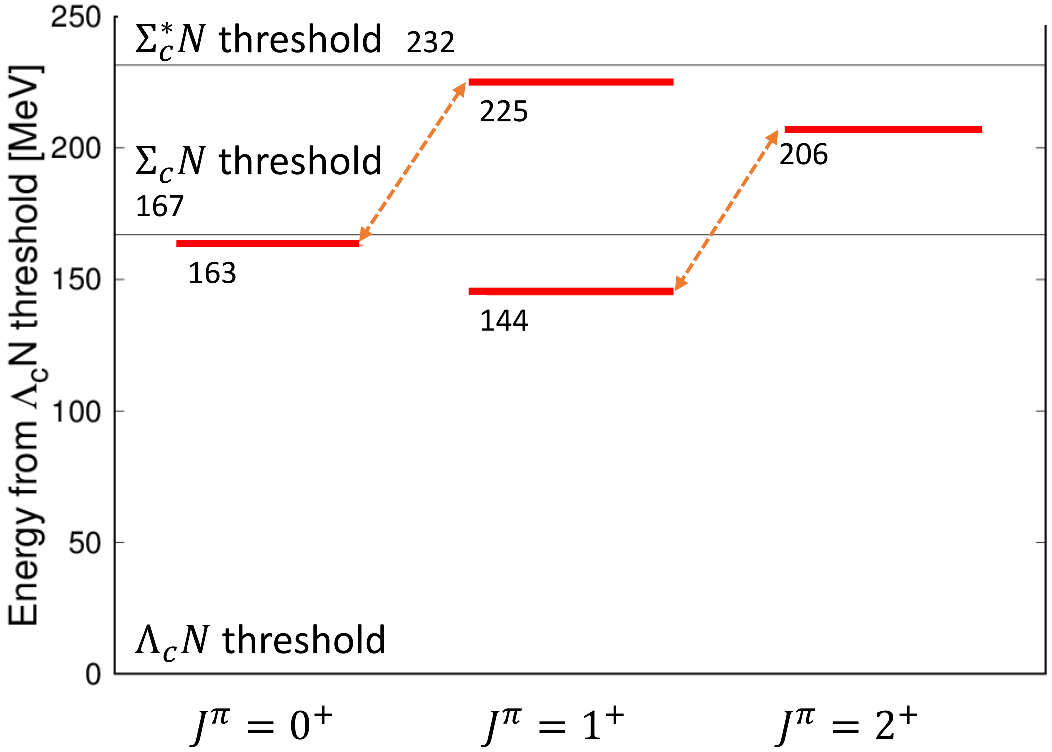
$$U(\theta) : \begin{cases} r \to re^{i\theta}, \\ k \to ke^{-i\theta}, \end{cases}$$



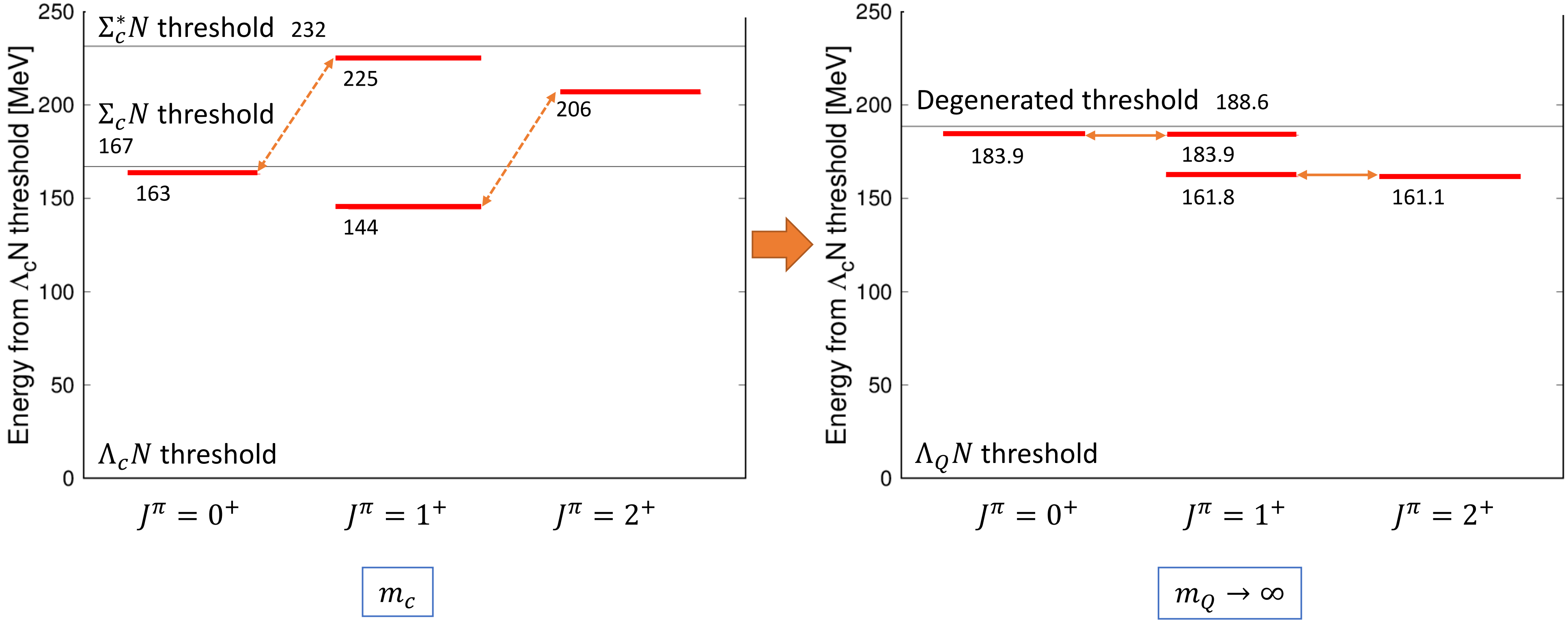
S. Maeda, M. Oka, Y.R. Liu, Phys. Rev. C98 (2018) 035203



State	Energy (MeV)		Width (MeV)
$J^\pi = 0^+ \ (\Sigma_c N)$	163	(-4)	1
$J^\pi = 1^+ \ (\Sigma_c N)$	144	(-23)	12
$J^\pi = 1^+ \ (\Sigma_c^* N)$	225	(-7)	2
$J^\pi = 2^+ \ (\Sigma_c^* N)$	206	(-25)	14



In the HQ spin symmetry limit ($m_Q \to \infty$), we find two sets of resonance states, i.e., a shallow (j=1/2) and a deep bound (j=3/2) state.



Summary

- **Sharp Feshbach resonances may exist if the $\Sigma_c N$-$\Sigma_c^* N$ coupling is strong enough.**
- **We predict one 0^+, two 1^+ and one 2^+ states, which are all S-wave bound states of $\Sigma_c N$ or $\Sigma_c^* N$. They may show good examples of the HQ spin symmetry.**
- ***Big challenge to search such dibaryon states at B-factories, HI colliders, and Hadron beam facilities.***
  $\Lambda_c N$ bound states: through HI reactions, weak decay
  $\Sigma_c^{(*)} N$ sharp resonances: cusp region of $\Lambda_c N$ amplitude
  $\Lambda_c NN$ charm hypernucleus: through weak decay