Charmed Deuteron

Makoto Oka

Tokyo Institute of Technology

11/11/11 @ JAEA/ASRC/ Hadron Group

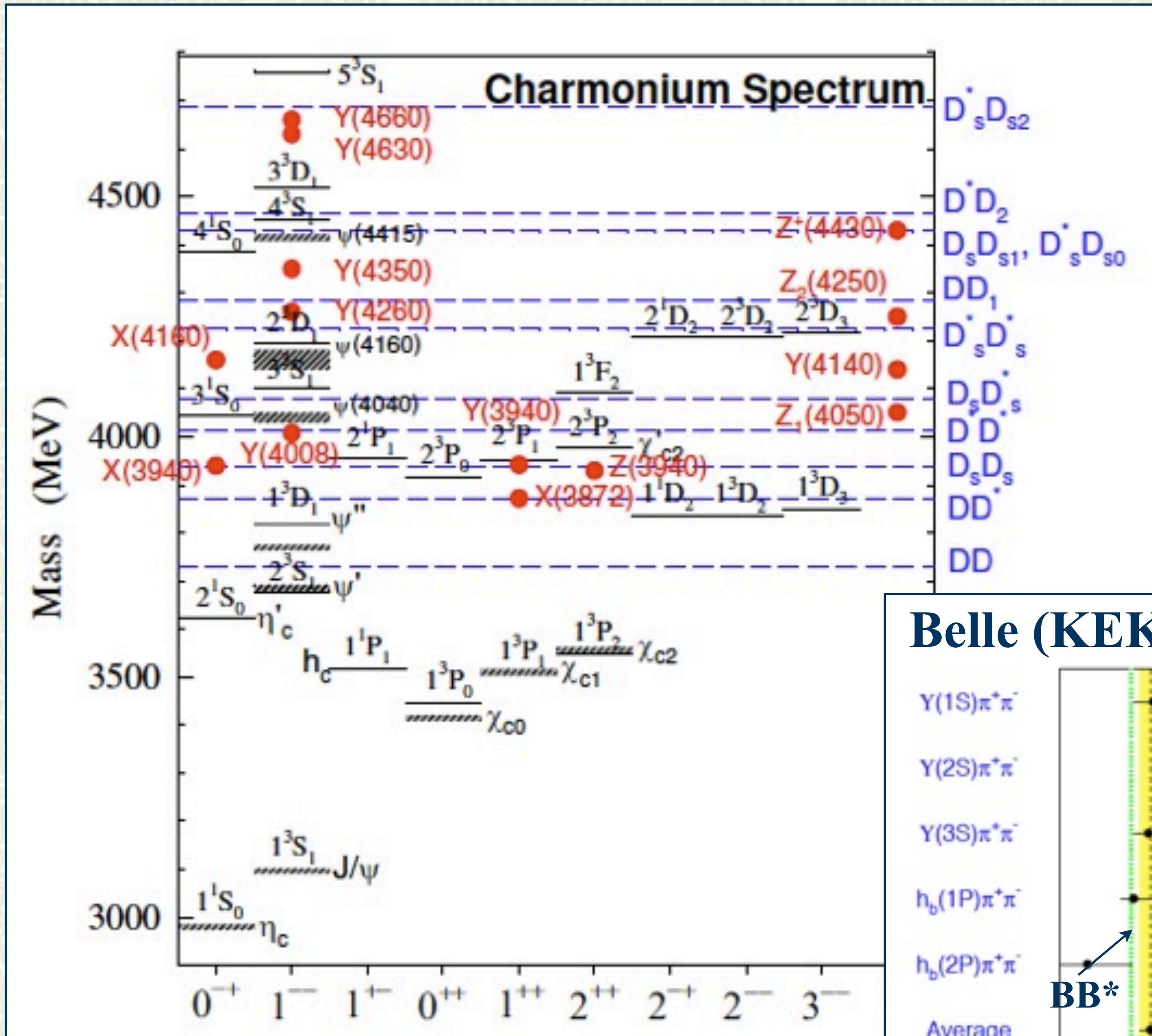
Contents

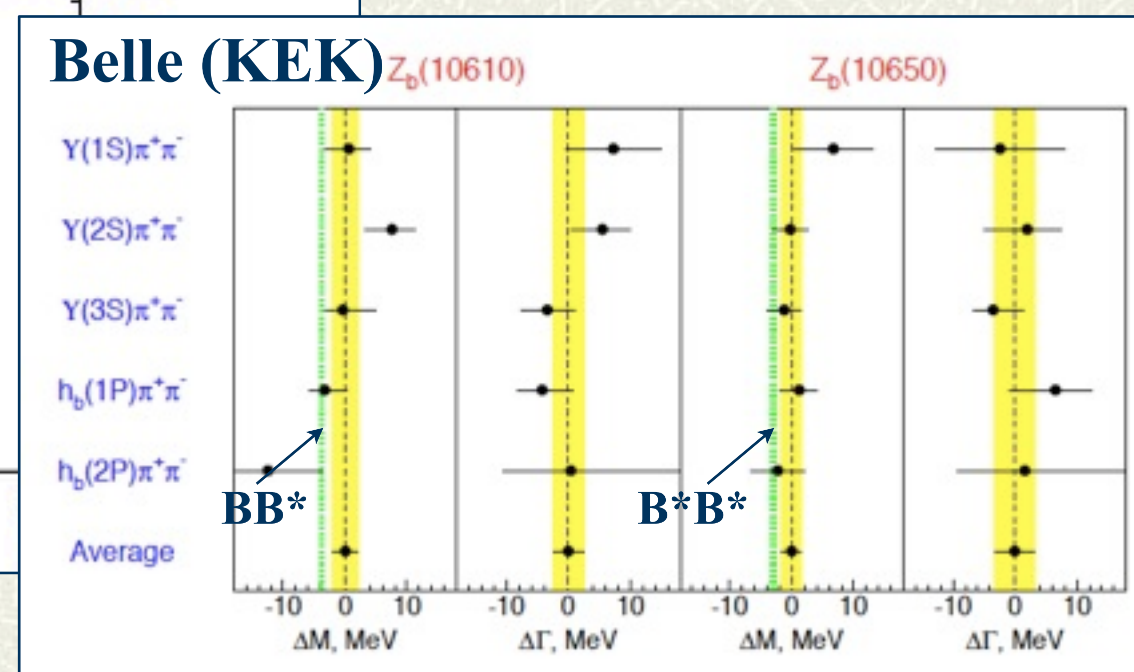
References

- Yan-rui Liu, M.O., "$\Lambda_c N$ bound states revisited", arXiv:1103.4624
- Wakafumi Meguro, Yan-rui Liu, M.O., "Possible $\Lambda_c\Lambda_c$ molecular bound state", Phys. Lett. B704 (2011) 547, arXiv:1105.3693

Introduction

- **Discoveries of New Quarkonium-like Mesons**





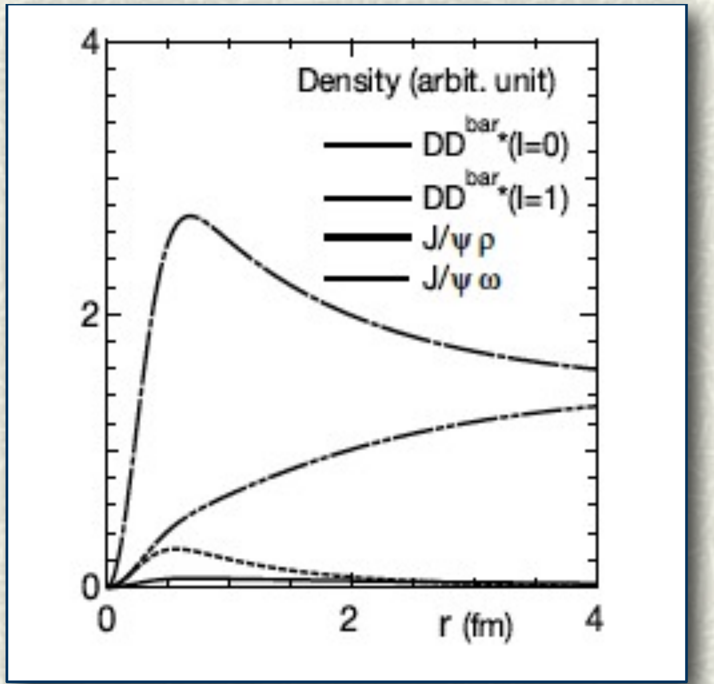
Coincidences of the quarkonium-like meson states with the open charm (bottom) thresholds motivate interpretations of those states as hadronic molecules.

Introduction

X (3872): The new charmonium-like resonance (1^{++}) just at the DD* threshold may not be a simple $c\bar{c}$, but possibly a ($c\bar{c}q\bar{q}$) tetra-quark, or ($D\bar{D}^* + D^*\bar{D}$) molecule.

Note: At around the threshold, hadron molecular states are necessarily mixed.

Takeuchi, Shimizu, Takizawa, (arXiv:1110.3694)
A quark-model QQ^{bar} state is coupled to the two hadron bound/continuum states.



This is not new, but has been seen in the strange sector;

$\Lambda^*(1405)$ coupled to the NK^{bar}
f_0, and a_0 scalar mesons to KK^{bar}
H dibaryon to ΛΛ, NΞ, ΣΣ

May have more hadron molecules with heavy quark(s).

Introduction

- **Do dibaryons (baryon molecules) with heavy quarks exist?**
  Λ_cN, Σ_cN, . . . , (charmed deuteron)
  Ξ_cN, $\Lambda_c\Lambda_c$, $\Lambda_c\Sigma_c$, . . (doubly charmed deuteron)
- **Do the charmed baryons, Λ_c, Σ_c, Ξ_c, . . . , form nuclear bound states?**
  Charmed hypernucleus
- **Do the charmed mesons, D, D*, . . . , form mesonic nuclear bound states?**
  ***i.e.*, HQ version of the K^{bar}-nucleus**

- **Not a new idea:**

Possibility of Charmed Hypernuclei

C. B. Dover and S. H. Kahana

PRL 39, 1506 (1977)

Σ_c

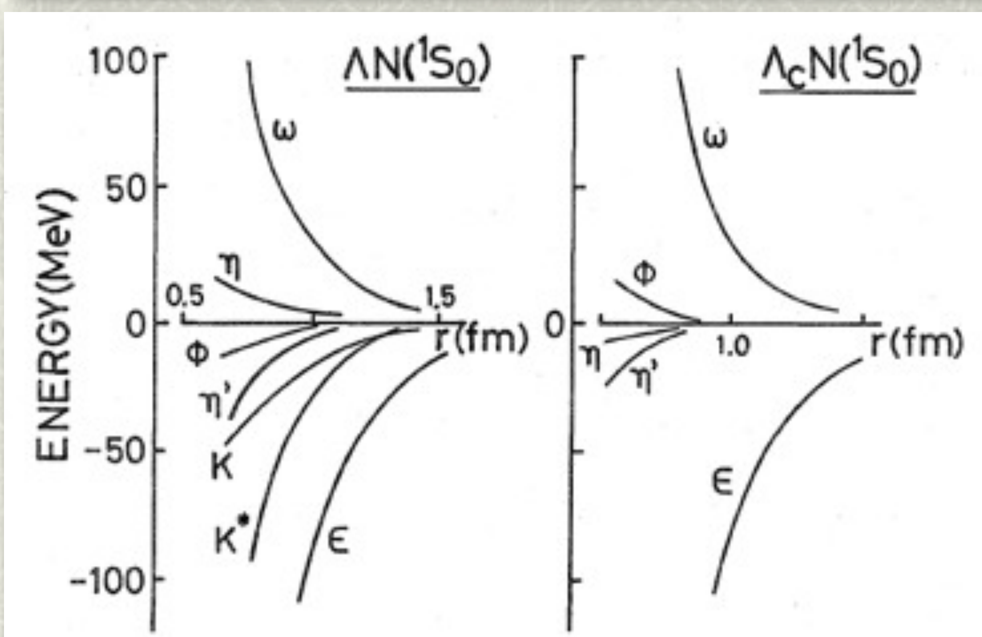
We suggest that both two-body and many-body bound states of a charmed baryon and nucleons should exist. Estimates indicate binding in the $^1S_0$ state of C_1N $(I=\frac{3}{2})$ and SN $(I=1)$. We further estimate the binding energy of C_0, C_1 in various finite nuclei.

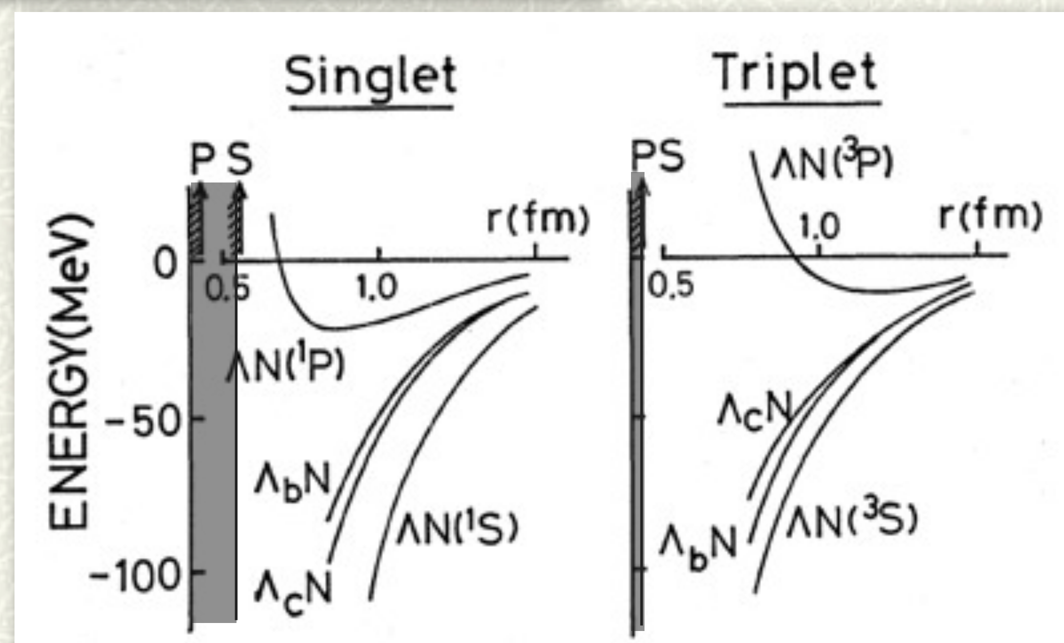
Ξ'_c Λ_c

Introduction

- *H. Bando, S. Nagata,* PTP 69, 557 (1983), *H. Bando,* PTP S81, 197 (1984)

Binding energies of a flavour baryon, Λ(strange), Λ_c(charmed) and Λ_b(beauty), in nuclear matter and in the α-particle are investigated within the framework of the lowest-order Brueckner theory by employing the OBE potentials derived on the basis of the Nijmegen model D interaction.





- SU(4) extension of the Nijmegen HC model potential is employed.
- No K, K* exchanges are allowed for the Λ_cN, which results in the weaker Y_cN potential compared with ΛN.
- No 2-body bound state is found.

Introduction

- We reexamine the possibility of the Y_cN and Y_cY_c bound states from the modern view points of the heavy quark symmetry and chiral symmetry.
- Advantages of the heavy baryon systems:
  - The large mass of Y_c suppresses the kinetic energy.
  - Strong Y_c-Y^*_c channel couplings give extra attractions.
- We emphasize the importance of the Σ_c - Σ_c^* degeneracy under the heavy quark spin symmetry and the couplings of the Σ_cN, Σ_c^*N virtual states to the Λ_cN states through the central and tensor forces.

NN ($^1S_0$, I=1)	×	NN ($^3S_1$-$^3D_1$, I=0)	deuteron
ΛN-ΣN ($^1S_0$)	×	ΛN-ΣN ($^3S_1$-$^3D_1$)	×
Λ_cN-Σ_cN-$\Sigma^*{}_cN$ ($^1S_0$-$^5D_0$)	?	Λ_cN-Σ_cN-$\Sigma^*{}_cN$ ($^3S_1$-$^{3,5}D_1$)	?
$\Lambda\Lambda$-$N\Xi$-$\Sigma\Sigma$ ($^1S_0$)	H dibaryon △		
$\Lambda_c\Lambda_c$-$\Sigma_c\Sigma_c$-$\Sigma^*{}_c\Sigma^*{}_c$ (0^+)	?		

Introduction

- **Our framework:**
  - **The Y_c-N and Y_c-Y_c interactions are composed of one-pion or one-boson (π, σ, ρ, ω) exchange potentials.**
  - **Heavy-quark spin symmetry, chiral symmetry, and hidden local symmetry are used to determine the meson-baryon couplings.**
  - **The OPE tensor force induces strong mixings of the D-wave Σ_cN (*S*=1) and Σ^*_cN (*S*=1, 2) states, whose thresholds are degenerate in the large m_Q limit.**

- S-wave $\Lambda_c N$: $I = \frac{1}{2}$, $J^P = (0,1)^+$
- Coupled channels ($J^P = 0^+$, 3 channels):
  $(^1S_0\ \Lambda_c N)$, $(^1S_0\ \Sigma_c N)$, $\boxed{(^5D_0\ \Sigma_c^* N)}$
- Coupled channels ($J^P = 1^+$, 7 channels):
  $(^3S_1\ \Lambda_c N)$, $(^3S_1\ \Sigma_c N)$, $(^3S_1\ \Sigma_c^* N)$, $\boxed{(^3D_1\ \Lambda_c N), (^3D_1\ \Sigma_c N)}$,
  $\boxed{(^3D_1\ \Sigma_c^* N), (^5D_1\ \Sigma_c^* N)}$

Tensor coupling

Heavy quark symmetry

- The heavy quark (c, b) is "inactive" in the heavy-light hadron systems.

$$\Lambda_Q = \left[Q \oplus [\,ud\,]^{S=0}_{f=\bar{3}} \right]^{J=1/2}$$

$$\Sigma_Q = \left[Q \oplus \{ud\}^{S=1}_{f=6} \right]^{J=1/2}$$

$$\Sigma^*_Q = \left[Q \oplus \{ud\}^{S=1}_{f=6} \right]^{J=3/2}$$

Σ^* 1385

Σ^*_c 2518

Σ^*_b 5833

Σ_b 5812

Σ_c 2453

Σ 1193

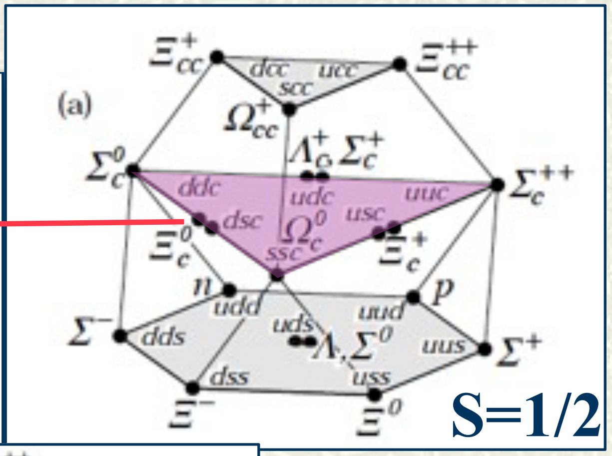
Λ 1116 $\quad$ Λ_c 2286 $\quad$ Λ_b 5620

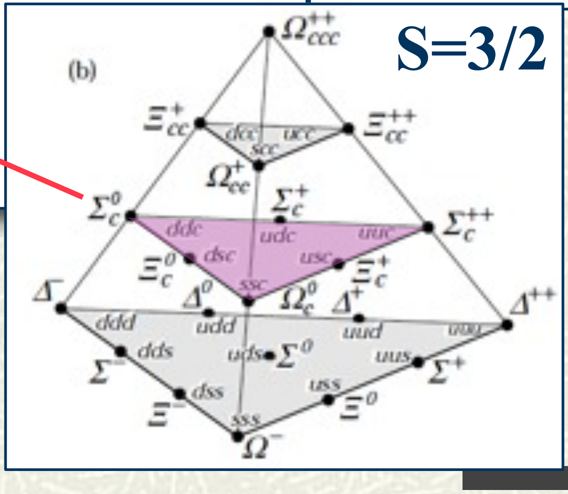
$(S, f) = (1/2\ \ 3^{\text{bar}})$ $\qquad$ $(1/2\ \ 6)$

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

$(3/2\ \ 6)$

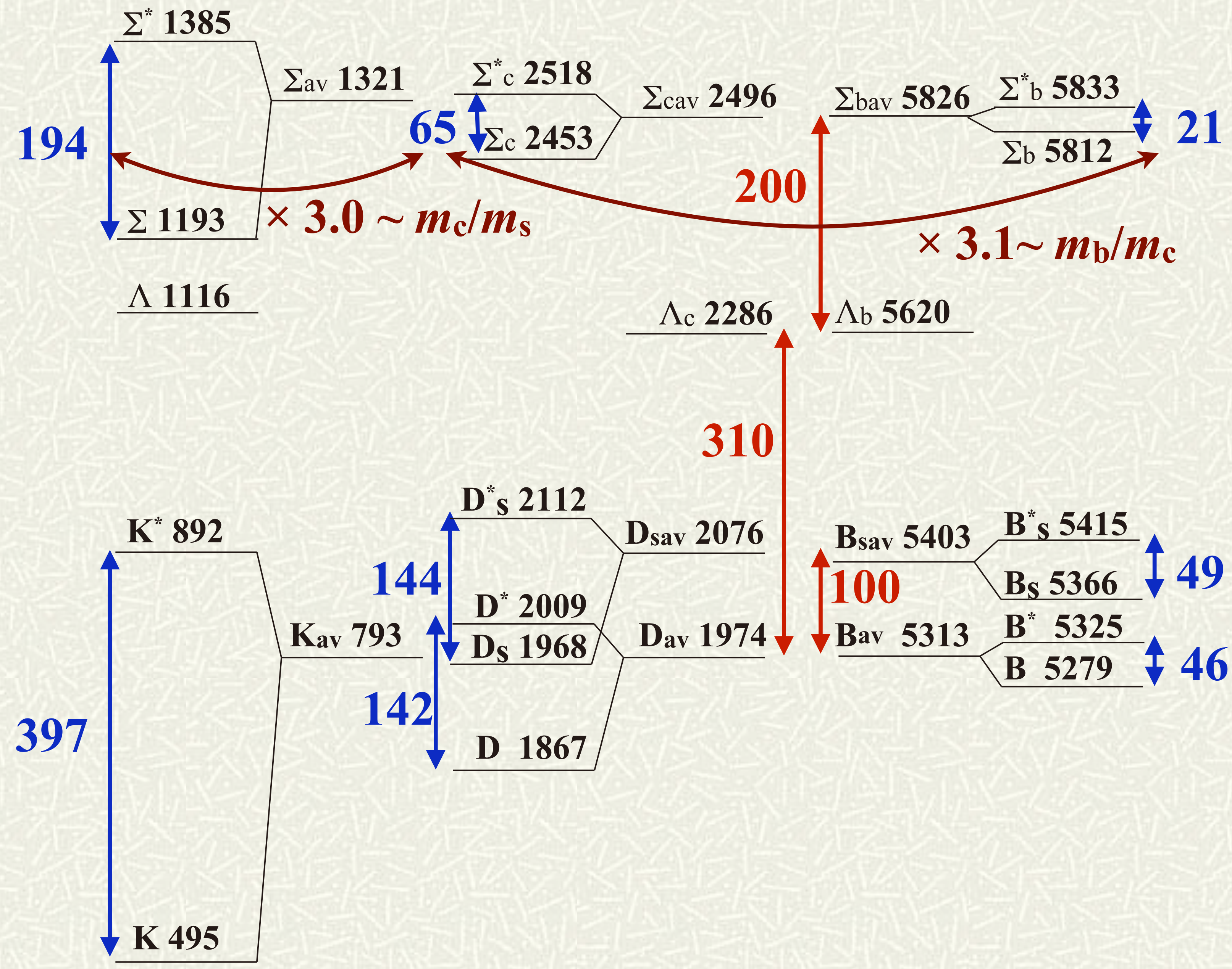
$$B_6^* = \begin{pmatrix} \Sigma_c^{*++} & \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \Sigma_c^{*0} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} & \Omega_c^{*0} \end{pmatrix}$$





Heavy quark symmetry

- Spectra of the heavy-light hadrons are insensitive to m_Q.
- The spin-dependent interactions are $O(1/m_Q)$ for the heavy quarks.



Heavy quark symmetry

- Physics of heavy quark systems is simplified for $m_Q \gg \Lambda_{QCD}$
- Light quarks do not feel the mass and spin of the heavy quark in the $m_Q \to \infty$ limit.
  - asymptotic freedom
  - suppressed magnetic-gluon coupling
- Effective field theory based on the $1/m_Q$ expansion, which leads to a *super-selection* rule of the heavy quark velocity.

  $$p^\mu = m_Q v^\mu + k^\mu$$

  For small $k^\mu = O(\Lambda_{\rm QCD}) \ll m_Q v^\mu$, the velocity of the heavy quark is preserved. Then, we can remove the large momentum component by defining a new effective heavy quark field $Q_v(x) = e^{im_Q v\cdot x} Q(x)$.
- This is a symmetry of QCD in the large m_Q regime.
- The heavy quark spin is conserved at each velocity. (HQ spin symmetry)

Heavy quark symmetry

- **Effective Lagrangian with the heavy-baryon and light mesons**
  - **Heavy baryon Q(qq): qq (di-quark) $(S, f) = (0^+, 3^{bar})$ or $(1^+, 6)$**

  $\rightarrow (S, f) = (1/2, 3^{bar}) \oplus \boxed{[(1/2, 6) \oplus (3/2, 6)]}$ degenerate in the HQ limit

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

$$B_3 = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c'^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c'^0 \\ \frac{1}{\sqrt{2}}\Xi_c'^+ & \frac{1}{\sqrt{2}}\Xi_c'^0 & \Omega_c^0 \end{pmatrix}$$

(3/2 6)

$$B^*_{6\,\mu} = \begin{pmatrix} \Sigma_c^{*++} & \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \Sigma_c^{*0} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} & \Omega_c^{*0} \end{pmatrix}_\mu$$

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

  - **Pseudoscalar and vector nonet mesons**

Pseudoscalar nonet mesons

$$\Pi = \frac{\sqrt{2}}{f}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

Vector nonet mesons

$$V^\mu = i\frac{g_V}{\sqrt{2}}\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}^\mu$$

Heavy quark symmetry

- Chiral and Hidden-Gauge symmetries for light quarks/hadrons
  - Chiral transform $SU(3)_L \times SU(3)_R$

$$\Sigma = e^{i\Pi(x)} = \xi^2(x) \qquad \Sigma \to g_L \Sigma g_R^\dagger$$

  - Hidden Local Gauge Symmetry: $h(x) \in SU(3)$

$$\Sigma = LR^\dagger \qquad L \to g_L L h^\dagger(x) \qquad R \to g_R R h^\dagger(x) \qquad B_f \to h B_f h^\dagger$$

$$\Gamma_\mu = \frac{1}{2}(L^\dagger \partial_\mu L + R^\dagger \partial_\mu R) \qquad A_\mu = \frac{1}{2}(L^\dagger \partial_\mu L - R^\dagger \partial_\mu R)$$

$$\Gamma_\mu \to h \Gamma_\mu h^\dagger + h \partial_\mu h^\dagger \qquad A_\mu \to h A h^\dagger$$

  - Light Vector mesons

$$V_\mu \to h V_\mu h^\dagger + h \partial_\mu h^\dagger \qquad F^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu + [V^\mu, V^\nu]$$

$$\mathcal{L} = -\frac{f^2}{2}\left\{\mathrm{Tr}[A_\mu A^\mu + a\mathrm{Tr}[(\Gamma_\mu - V_\mu)^2]\right\} + \frac{1}{2g_V^2}\mathrm{Tr}[F_{\mu\nu}F^{\mu\nu}]$$

Heavy quark symmetry

- **Heavy-Quark-Chiral Effective Lagrangian**

$$
\begin{aligned}
\mathcal{L}_{B_{\bar{3}}} &= \frac{1}{2}\mathrm{tr}[\bar{B}_{\bar{3}}(iv\cdot D)B_{\bar{3}}] + i\beta_B \mathrm{tr}[\bar{B}_{\bar{3}} v^\mu (\Gamma_\mu - V_\mu) B_{\bar{3}}] \\
&\quad + \ell_B \mathrm{tr}[\bar{B}_{\bar{3}} \sigma B_{\bar{3}}] \\
\mathcal{L}_S &= -\mathrm{tr}[\bar{S}^\alpha (iv\cdot D - \Delta_B) S_\alpha] + \frac{3}{2} g_1 (iv_\kappa) \epsilon^{\mu\nu\lambda\kappa} \mathrm{tr}[\bar{S}_\mu A_\nu S_\lambda] \\
&\quad + i\beta_S \mathrm{tr}[\bar{S}_\mu v_\alpha (\Gamma^\alpha - V^\alpha) S^\mu] + \lambda_S \mathrm{tr}[\bar{S}_\mu F^{\mu\nu} S_\nu] \\
&\quad + \ell_S \mathrm{tr}[\bar{S}_\mu \sigma S^\mu] \\
\mathcal{L}_{int} &= g_4 \mathrm{tr}[\bar{S}^\mu A_\mu B_{\bar{3}}] + i\lambda_I \epsilon^{\mu\nu\lambda\kappa} v_\mu \mathrm{tr}[\bar{S}_\nu F_{\lambda\kappa} B_{\bar{3}}] + h.c.,
\end{aligned}
$$

Pseudoscalar (π)

Vector (ρ, ω)

Scalar (σ)

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

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

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

- **A flavor singlet (I=0) scalar σ meson is introduced.**

Coupling constants

- π: g_1, g_4
  σ: ℓ_B, ℓ_S
  ρ, ω: β_B, β_S, λ_S, λ_I

linear sigma model

$\Sigma_c \to \Lambda_c + \pi$

Couping	Quark Model	Chiral Multiplet	VMD	QSR	Decay
g_1	1.00				
g_4	1.06			0.94	0.999
ℓ_B	-3.65	$-\frac{\Delta M}{2f_\pi} \approx -3.1$			
ℓ_S	7.30	$\frac{\Delta M}{f_\pi} \approx 6.2$			
$(\beta_B g_V)$	-6.0		≈ -5.04		
$(\beta_S g_V)$	12.0		≈ 10.08		
$(\lambda_S g_V)$	19.2 GeV^{-1}			21.0, 13.5 GeV^{-1}	
$(\lambda_I g_V)$	-6.8 GeV^{-1}				
g_A	1.25				
h_σ	10.95			14.6	
h_V	3.0				
h_T	6.4 GeV^{-1}				

Table: The coupling constants in different methods. For the quark model estimation, we use $g_A^q = 0.75$, $g_\sigma^q = 3.65$, $g_\rho^q = 3.0$, and $f_\rho^q = 0.0$.

The mesons couple to the light quarks only.

OBEP

- The Λ_c-N, Σ_c-N and Σ^*_c-N diagonal and transition potentials are composed of one-pion and/or one-boson (π, σ, ρ, ω) exchange model. Note that the Λ_c (in general the 3^{bar} baryon) does not couple to the pion (pseudoscalar meson) directly. The other possible mesons, η and ϕ, are neglected because they give little contribution.
- Short range part of the potential is implemented by the cutoff parameters in the form factors.
  - The monopole form factor for each vertex is taken into account.

$$F(q) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$$

  - The cutoff parameters are chosen in two ways:
    (1) The *universal* cutoff for all the mesons
    (2) The *scaled* cutoff $\Lambda = m + \alpha \Lambda_{QCD}$ (Λ_{QCD}=220 MeV)

OBEP

- **Standard meson exchange potential with monopole form factors**
  - **Neglect $O(1/M_Q)$ corrections and the contact terms.**

$$
\begin{aligned}
V_\pi &= C_\pi(i,j)\frac{m_\pi^3}{24\pi f_\pi^2}\left\{\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_2 Y_1(m_\pi,\Lambda,r)+\mathcal{O}_{ten}H_3(m_\pi,\Lambda,r)\right\},\\
V_\sigma &= C_\sigma(i)\frac{m_\sigma}{16\pi}\left\{4Y_1(m_\sigma,\Lambda,r)+\vec{L}\cdot\vec{\sigma}_2\left(\frac{m_\sigma}{M_N}\right)^2 Z_3(m_\sigma,\Lambda,r)\right\},\\
V_\rho &= C_{\rho 1}(i,j)\frac{m_\rho}{32\pi}\left\{8Y_1(m_\rho,r)+(1+\frac{4M_N h_T}{h_V})\frac{m_\rho^2}{M_N^2}\left[Y_1(m_\rho,r)-2\vec{L}\cdot\vec{\sigma}_2 Z_3(m_\rho,r)\right]\right.\\
&+ C_{\rho 2}(i,j)\frac{m_\rho^3}{36\pi M_N}\left\{(1+\frac{2M_N h_T}{h_V})\left[2\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_2 Y_1(m_\rho,r)-\mathcal{O}_{ten}H_3(m_\rho,\Lambda,r)\right]\right.\\
&\left.-6\vec{L}\cdot\vec{\mathcal{O}}_1 Z_3(m_\rho,r)\right\},
\end{aligned}
$$

$\mathcal{O}_i$: spin operators

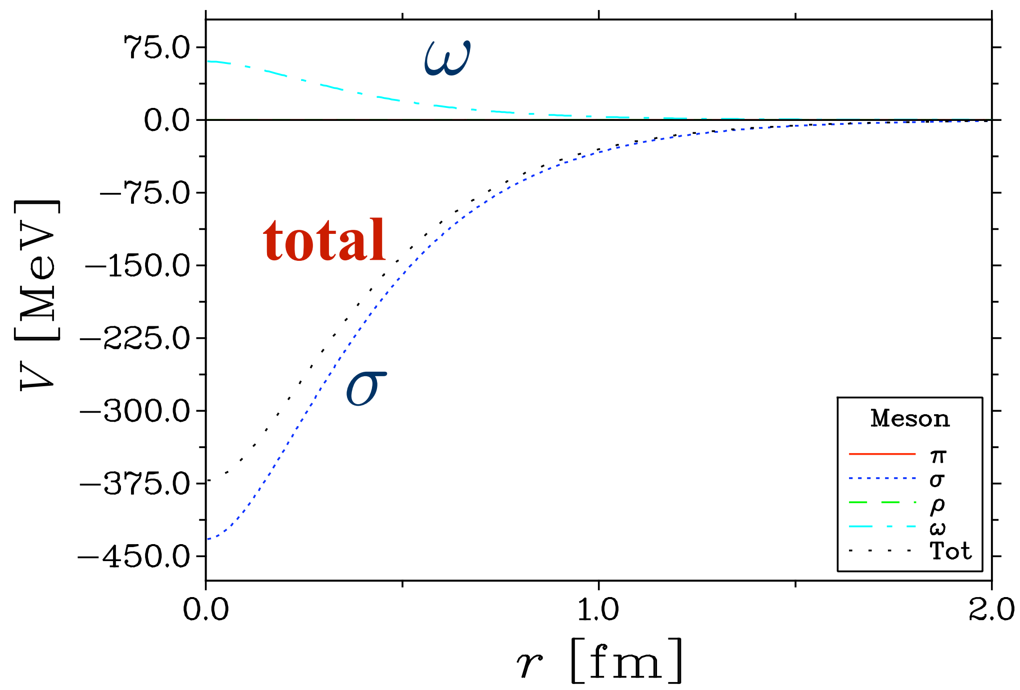
$\mathcal{O}_{ten}$: tensor operator

$$
\begin{aligned}
Y(x) &= \frac{e^{-x}}{x},\quad Z(x)=(\frac{1}{x}+\frac{1}{x^2})Y(x),\quad H(x)=(1+\frac{3}{x}+\frac{3}{x^2})Y(x),\\
Y_1(m,\Lambda,r) &= Y(mr)-\left(\frac{\Lambda}{m}\right)Y(\Lambda r)-\frac{\Lambda^2-m^2}{2m\Lambda}e^{-\Lambda r},
\end{aligned}
$$

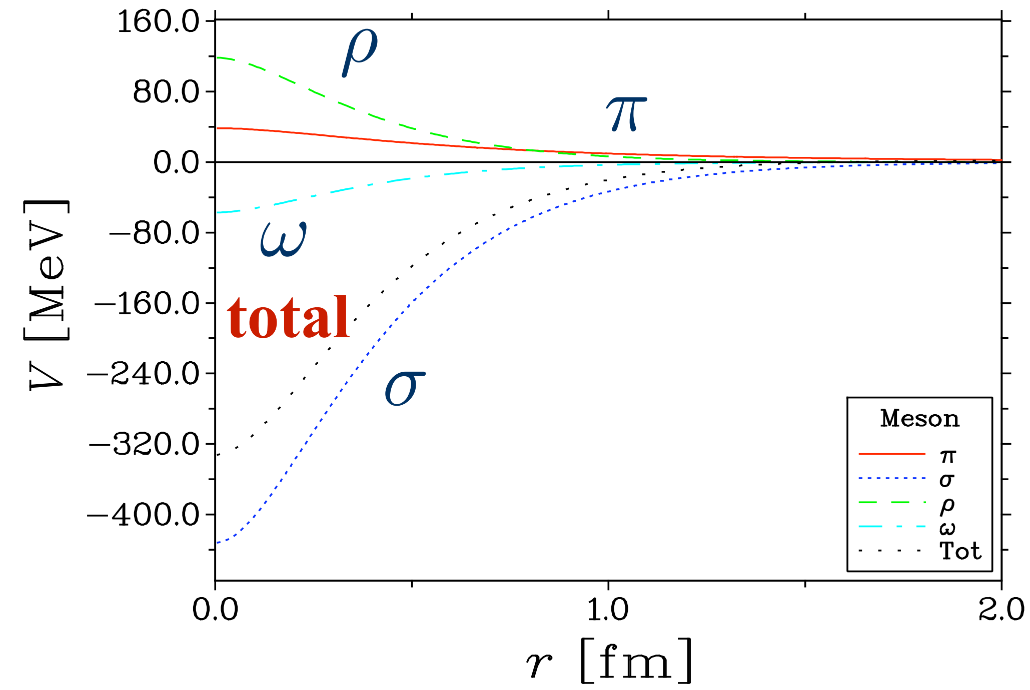
and so on

$\Lambda_c N$: 0^+ $\quad \Lambda_c N(^1S_0) - \Sigma_c N(^1S_0) - \Sigma_c^* N(^5D_0)$

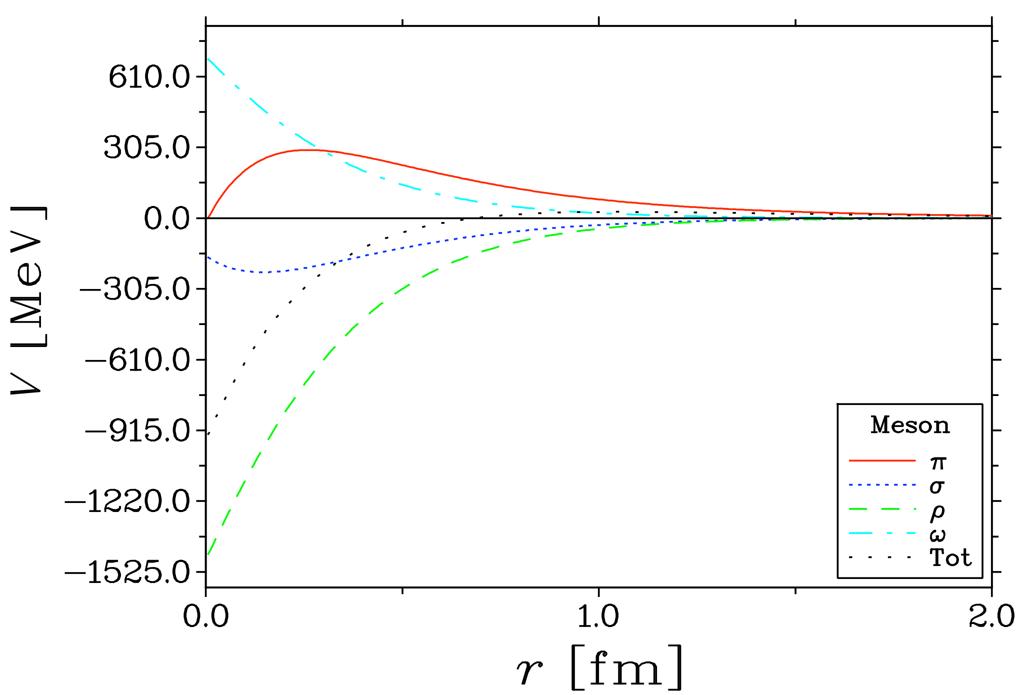
Diagonal potentials with $\Lambda_\pi = \Lambda_\sigma = \Lambda_{\rm vec} = 1$ GeV



(11): $\Lambda_c N(^1S_0) \leftrightarrow \Lambda_c N(^1S_0)$



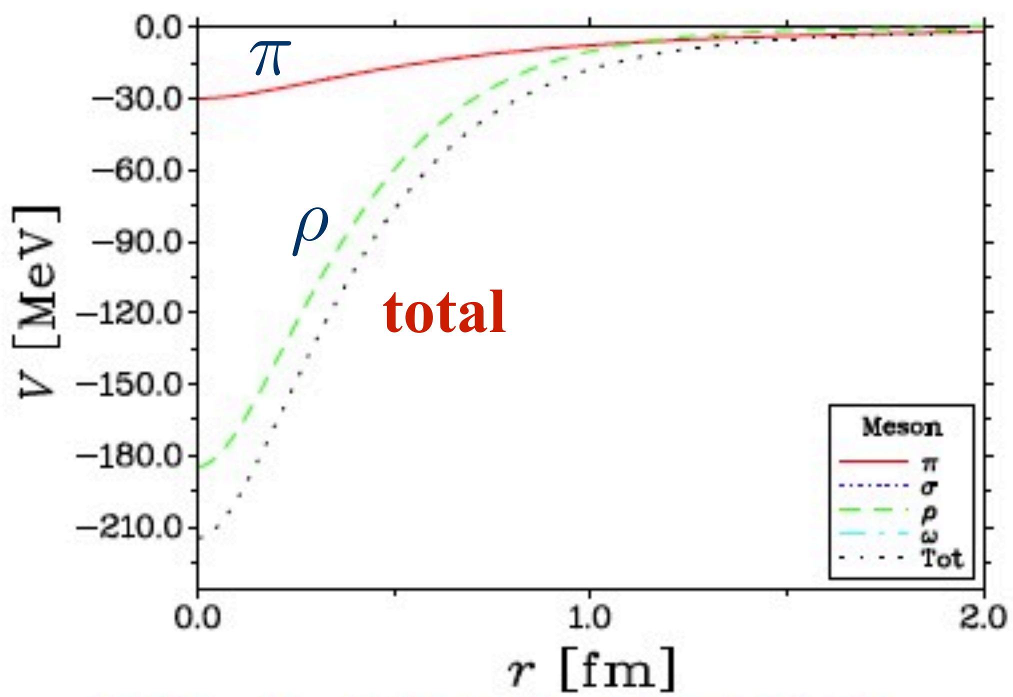
(22): $\Sigma_c N(^1S_0) \leftrightarrow \Sigma_c N(^1S_0)$



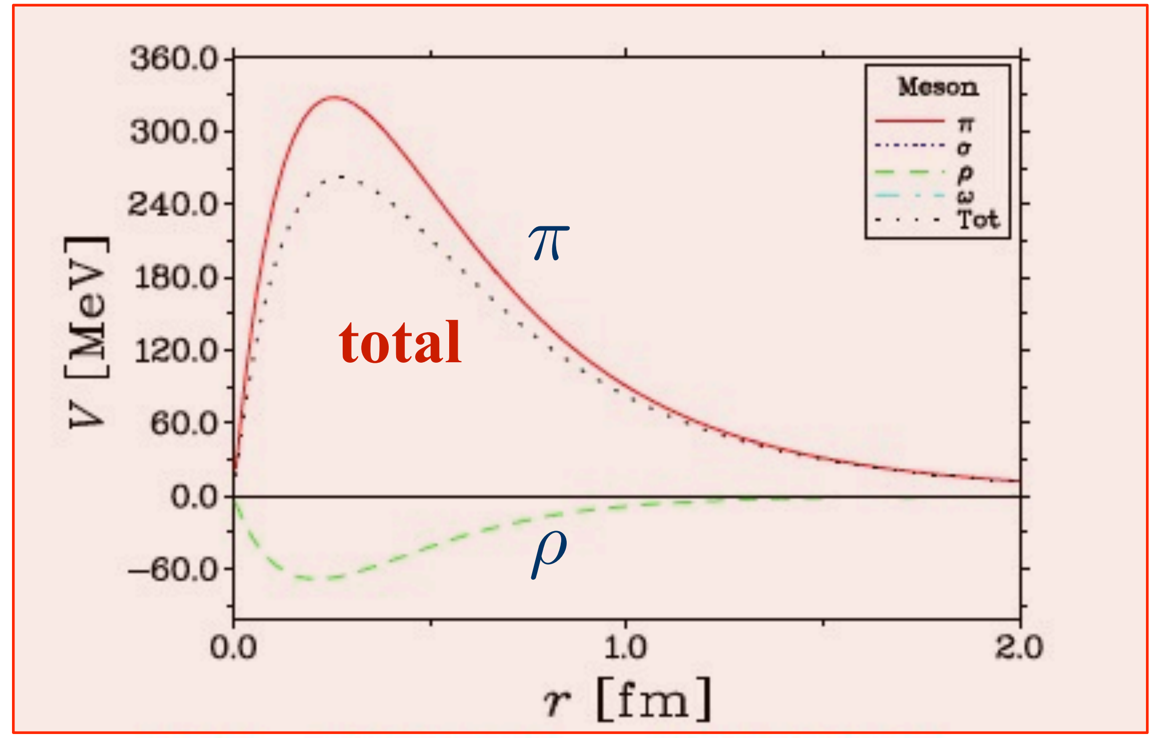
$\Leftarrow$ (33): $\Sigma_c^* N(^5D_0) \leftrightarrow \Sigma_c^* N(^5D_0)$

$\Lambda_c N$: 0^+

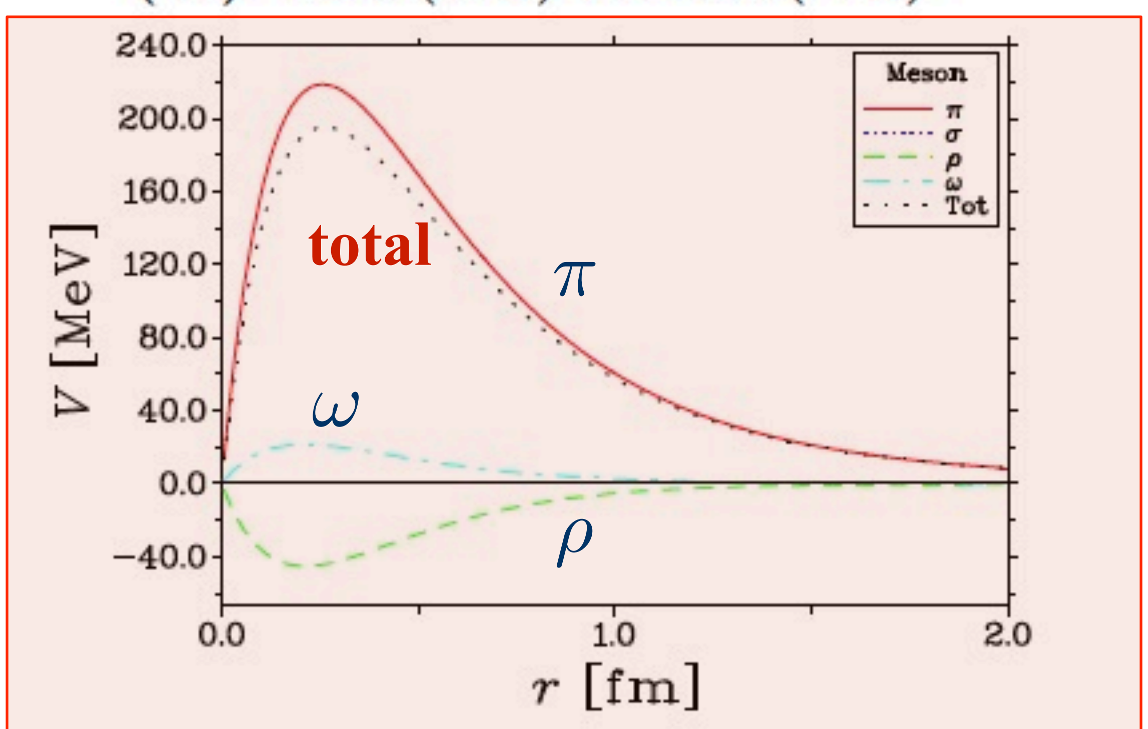
Transition potentials with $\Lambda_\pi = \Lambda_\sigma = \Lambda_{\mathrm{vec}} = 1$ GeV



(12): $\Lambda_c N(^1S_0) \leftrightarrow \Sigma_c N(^1S_0)$



(13): $\Lambda_c N(^1S_0) \leftrightarrow \Sigma_c^* N(^5D_0)$



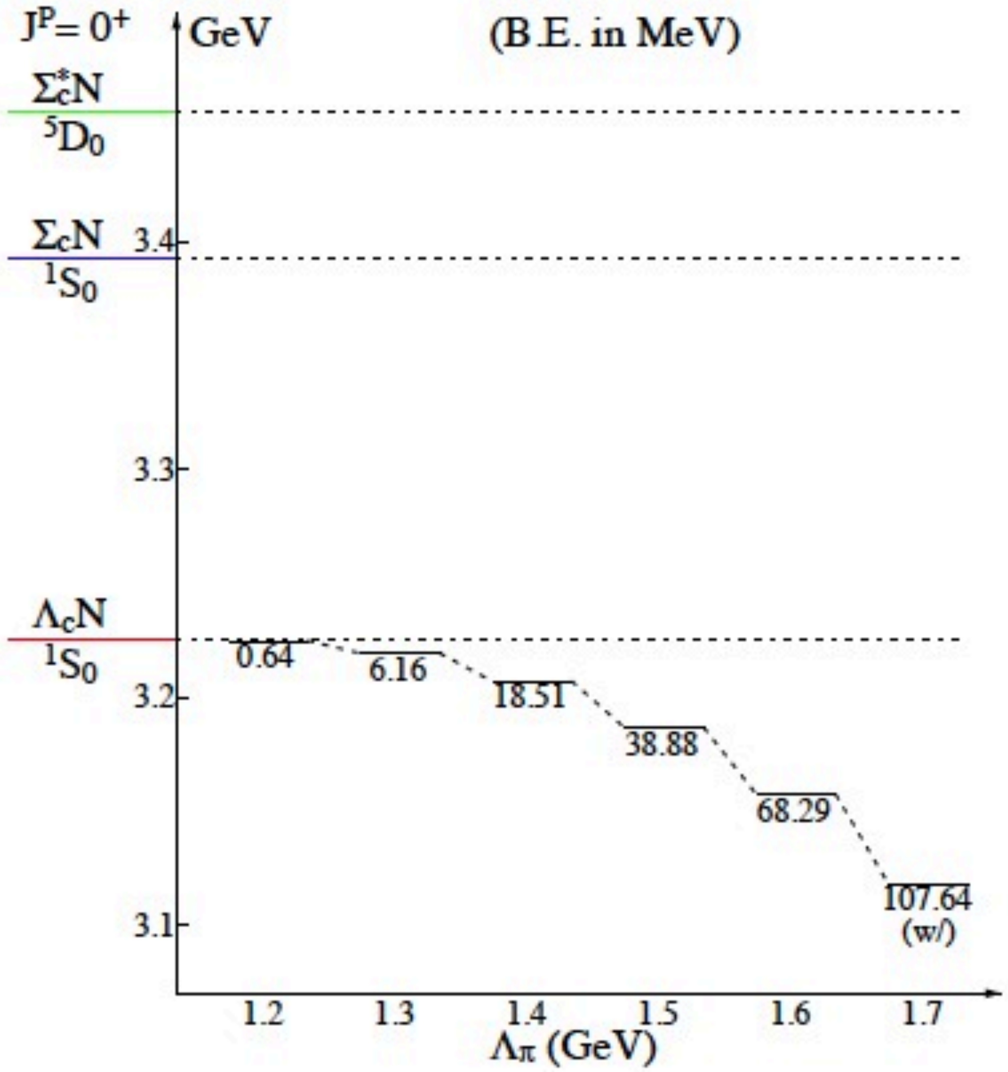
Strong tensor mixings due to the pion exchange potential

$\Leftarrow$ (23): $\Sigma_c N(^1S_0) \leftrightarrow \Sigma_c^* N(^5D_0)$

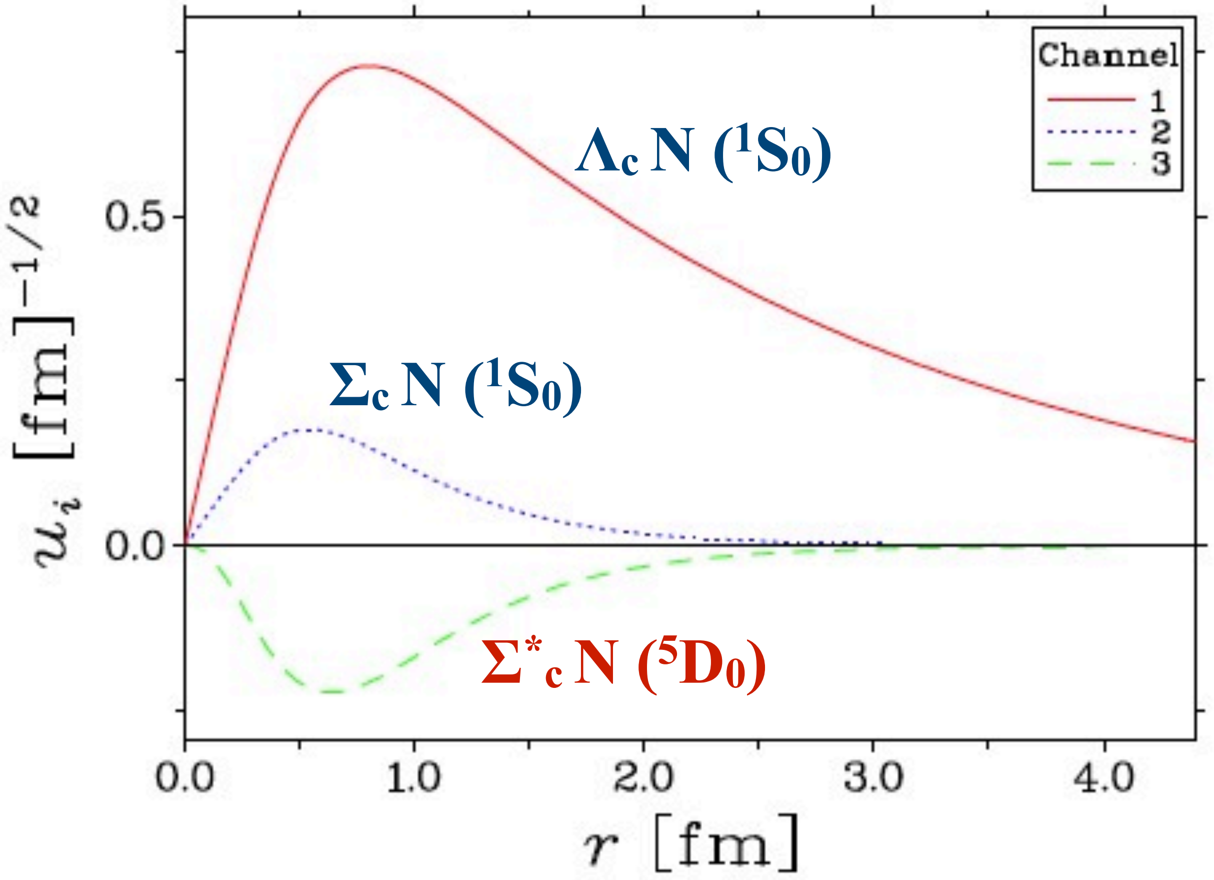
$\Lambda_c N$: 0^+ $\qquad \Lambda_c N(^1S_0) - \Sigma_c N(^1S_0) - \Sigma_c^* N(^5D_0)$

OPEP model:

One Pion Exchange Only



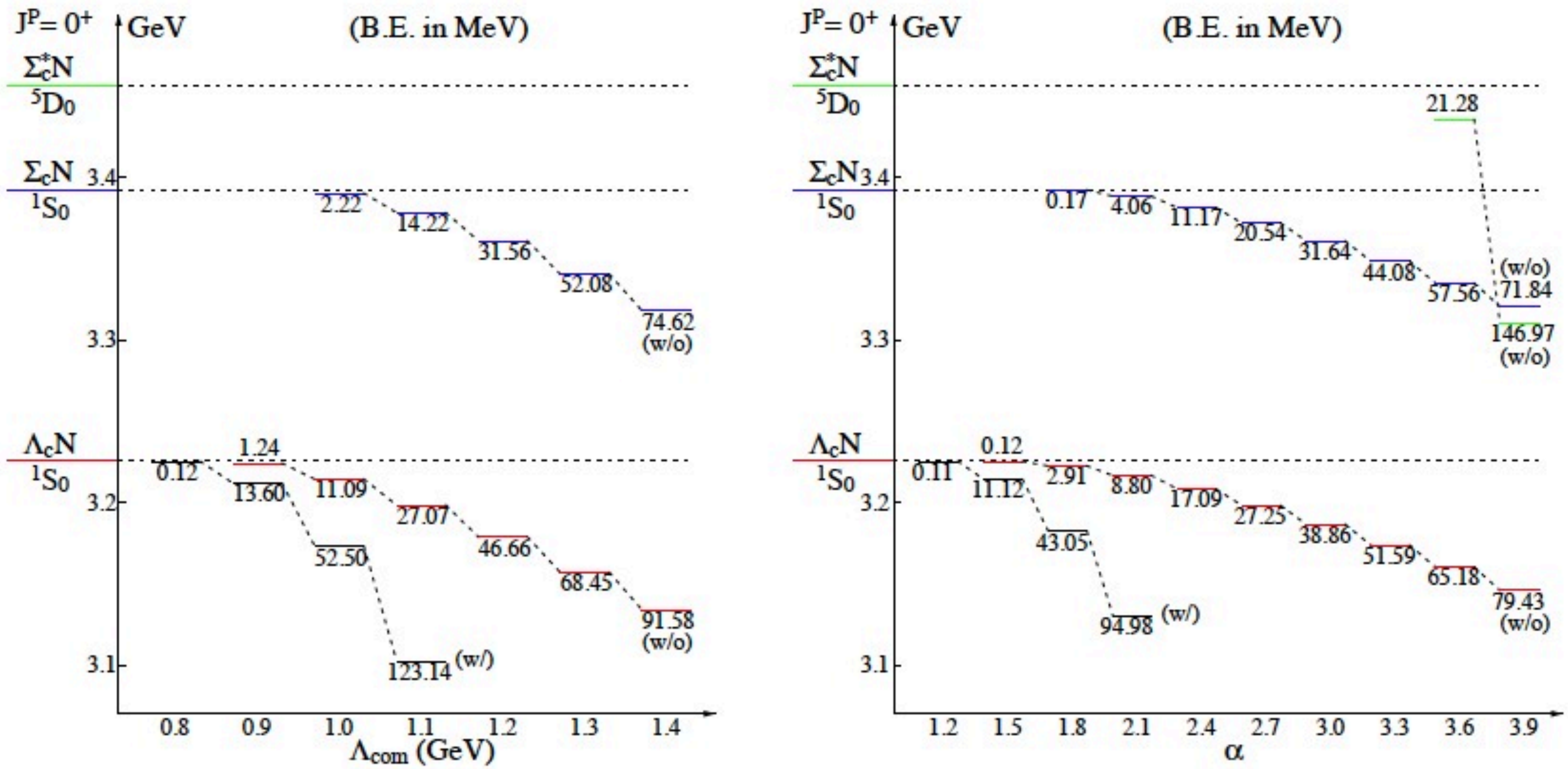
Binding energies (B.E.)



Wave functions with $\Lambda_\pi = 1.3$ GeV

$\Lambda_c N$: 0^+ $\quad \Lambda_c N(^1S_0) - \Sigma_c N(^1S_0) - \Sigma_c^* N(^5D_0)$

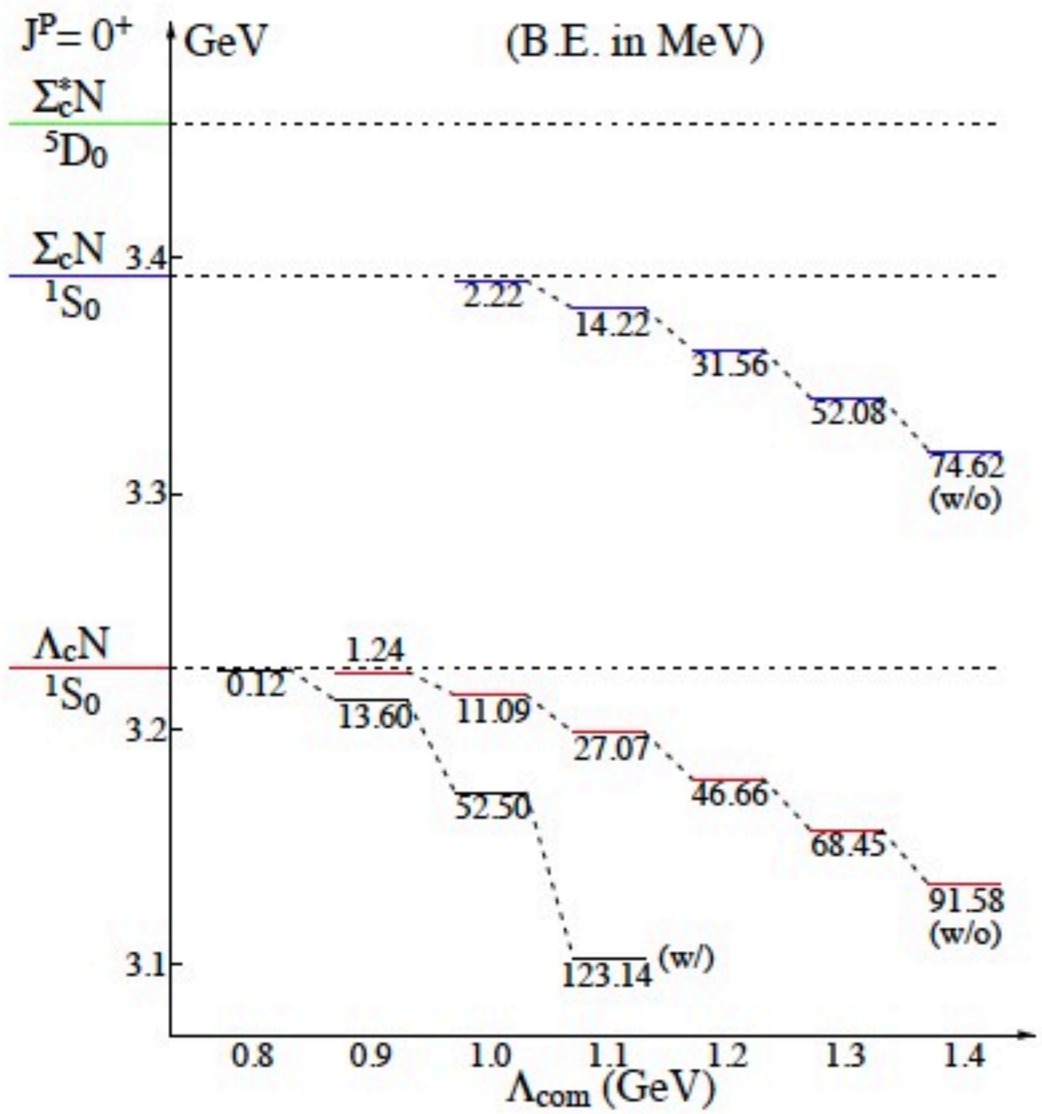
OMEP model (Λ_{com} & α)



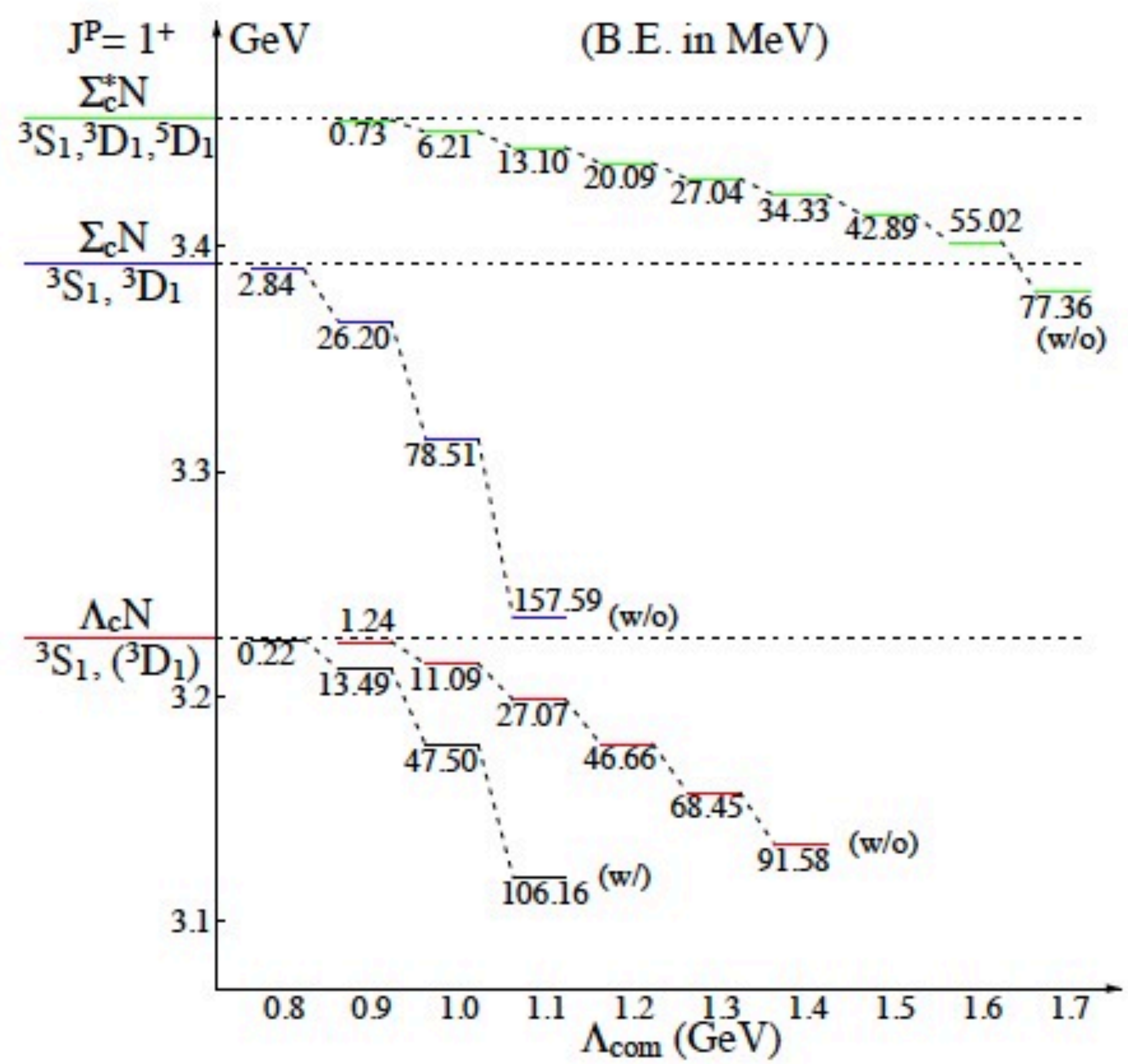
$\Lambda_c N$: 0^+ & 1^+
OMEP model ($\Lambda_{\rm com}$)

$$\Lambda_c N(^1S_0) - \Sigma_c N(^1S_0) - \Sigma_c^* N(^5D_0)$$

$$\Lambda_c N(^3S_1 - {}^3D_1) - \Sigma_c N(^3S_1 - {}^3D_1) - \Sigma_c^* N(^3S_1 - {}^3D_1 - {}^5D_1)$$



$J^P = 0^+$



$J^P = 1^+$

$\Lambda_c N$: comparison

J^P		$\Lambda_c N$ (S-wave)	$\Lambda_c N - \Sigma_c N - \Sigma_c^* N$
0^+	OPEP (Λ)	$\times$	[1.367: 13.60, 1.38]
	OMEP (Λ)	[0.900: -1.24, 3.86]	[0.900: 13.60, 1.46]
	OMEP (α)	[1.533: -0.25, 8.13]	[1.533: 13.57, 1.37]
1^+	OPEP (Λ)	$\times$	[1.353: 13.54, 1.40]
	OMEP (Λ)	[0.900: -1.24, 3.86]	[0.900: 13.49, 1.47]
	OMEP (α)	[1.618: -0.80, 4.72]	[1.618: 13.47, 1.39]

Table: Comparison among different cases. The meaning of the numbers are [cutoff $\Lambda_{\rm com}$ in GeV or dimensionless α: B.E. in MeV, RMS radius in fm]. $(\Lambda = m_{meson} + \alpha\Lambda_{QCD})$

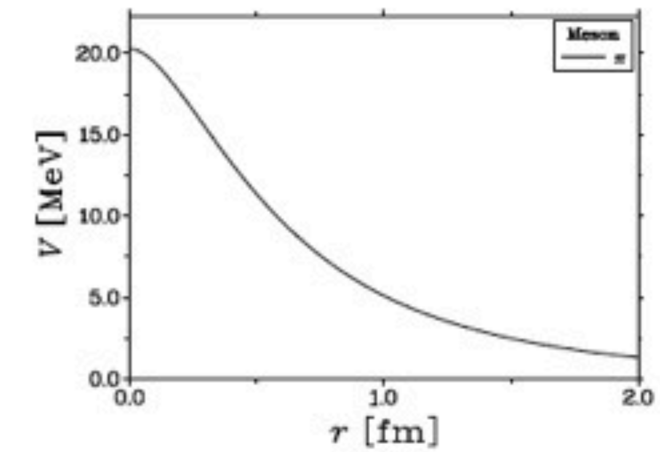
For the coupled channel calculation, one may get similar binding energies (and the corresponding RMS radiuses) in the OMEP model and in the OPEP model.

$\Lambda_c\Lambda_c$ ($J^P = 0^+$): Only OPEP model

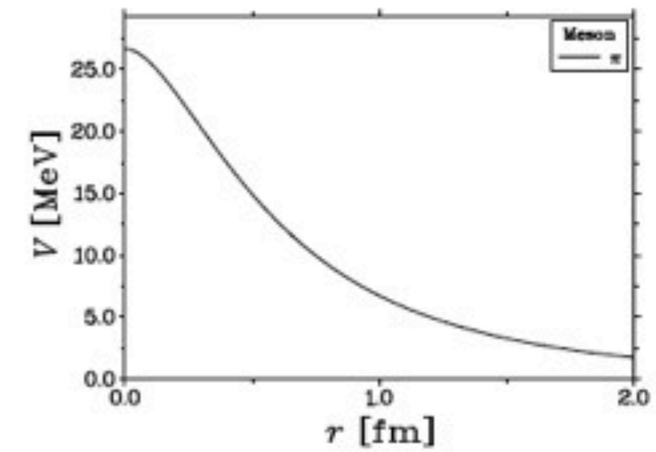
Diagonal potentials ($\Lambda_\pi = 1$ GeV)

For the $\Lambda_c\Lambda_c$ systems, we take only the one-pion exchange interaction.
Note that there is no $\pi\Lambda_c\Lambda_c$ coupling, and thus the binding comes only from the channel coupling effect.

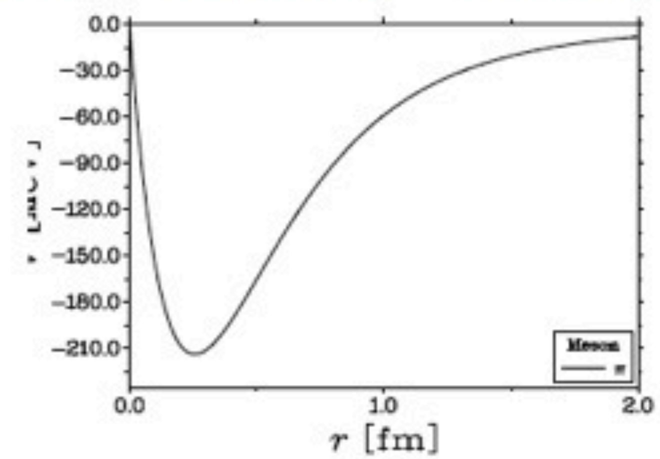
Again the tensor coupling strength is very strong so that the $\Sigma^*_c\Sigma^*_c$ channel contribution is large.



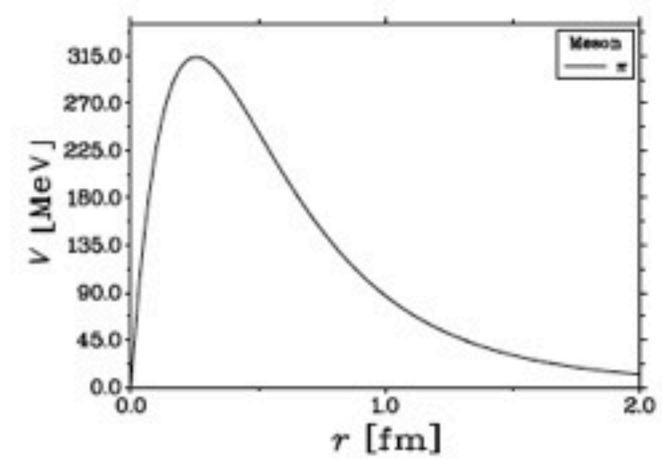
(12): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c\Sigma_c(^1S_0)$



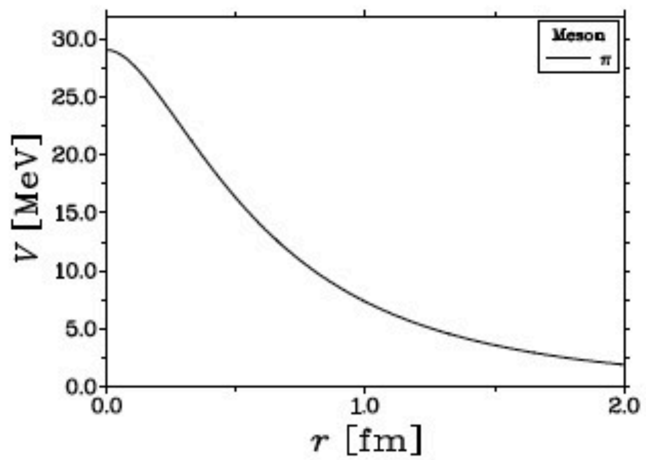
(13): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma^*_c\Sigma^*_c(^1S_0)$



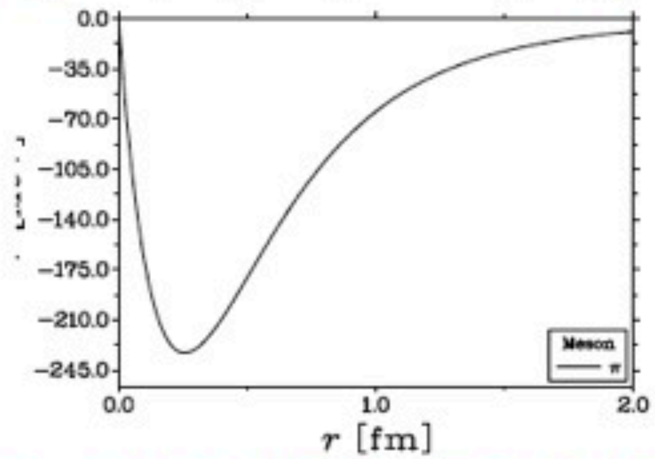
(14): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma^*_c\Sigma^*_c(^5D_0)$



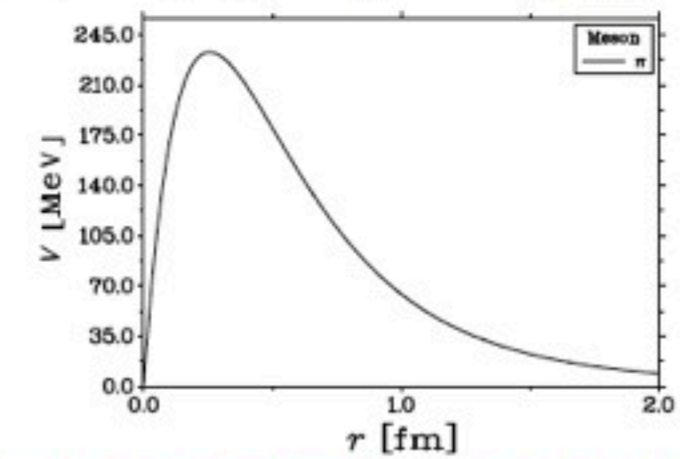
(15): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c\Sigma^*_c(^5D_0)$



(22): $\Sigma_c\Sigma_c(^1S_0) \to \Sigma_c\Sigma_c(^1S_0)$



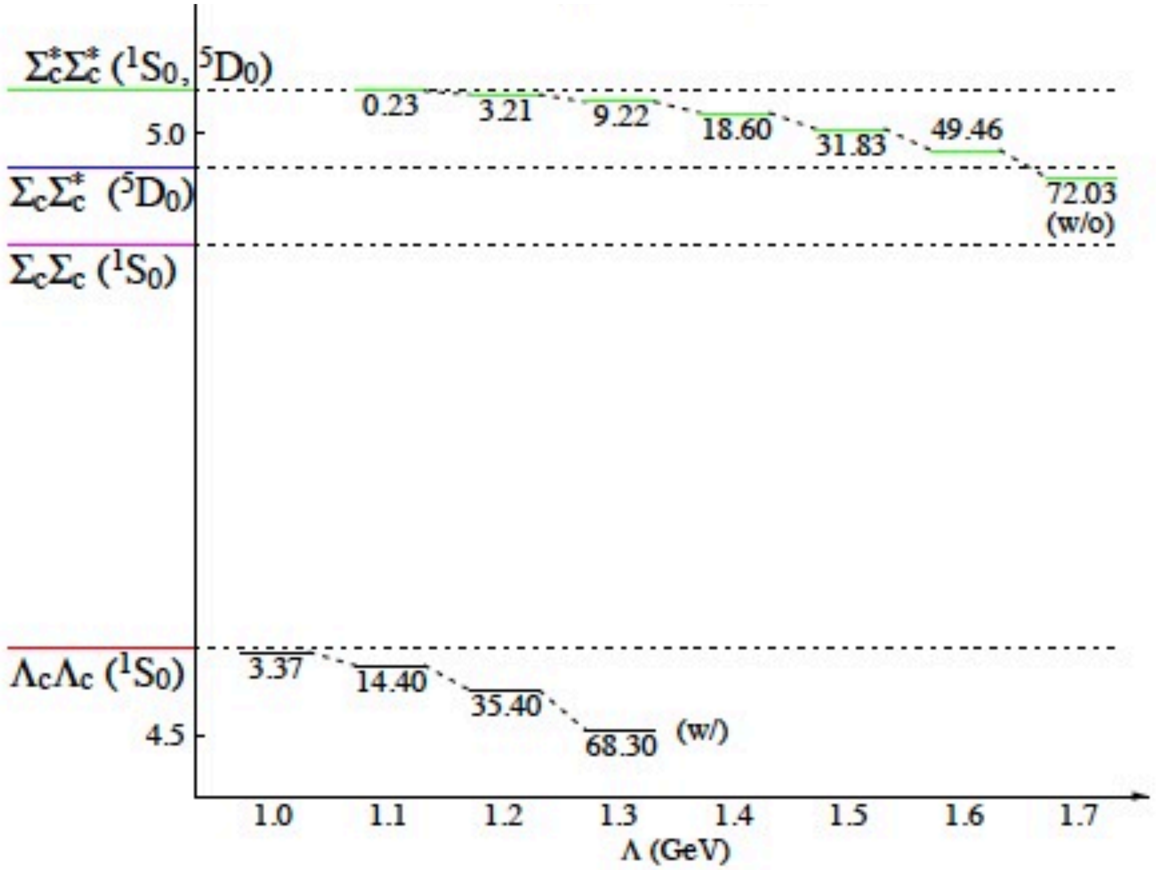
(25): $\Sigma_c\Sigma_c(^1S_0) \to \Sigma_c\Sigma^*_c(^5D_0)$



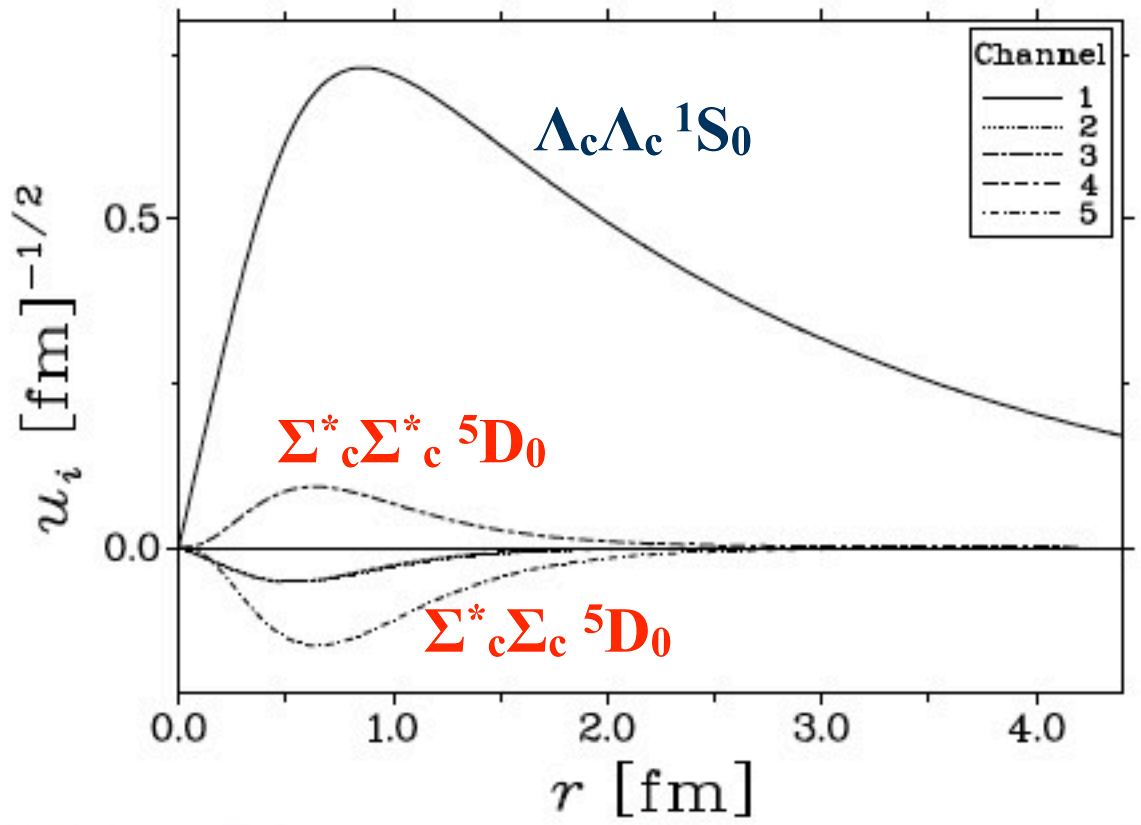
(34): $\Sigma^*_c\Sigma^*_c(^1S_0) \to \Sigma^*_c\Sigma^*_c(^5D_0)$

$\Lambda_c\Lambda_c$ ($J^P = 0^+$): Only OPEP model

Λ (GeV)	1.0	1.1	1.2	1.3
B.E. (MeV)	3.39	14.45	35.44	68.37
$\sqrt{\langle r^2 \rangle}$ (fm)	2.0	1.2	0.9	0.7
Prob. (%)	(97.4,0.2,0.2, 0.6,1.6)	(94.3,0.5,0.5, 1.3,3.4)	(90.7,1.1,1.0, 2.0,5.2)	(86.8,1.8,1.8, 2.6,7.0)
D-wave prob.	2.2%	4.7%	7.2%	9.6%



Binding energies (B.E.)

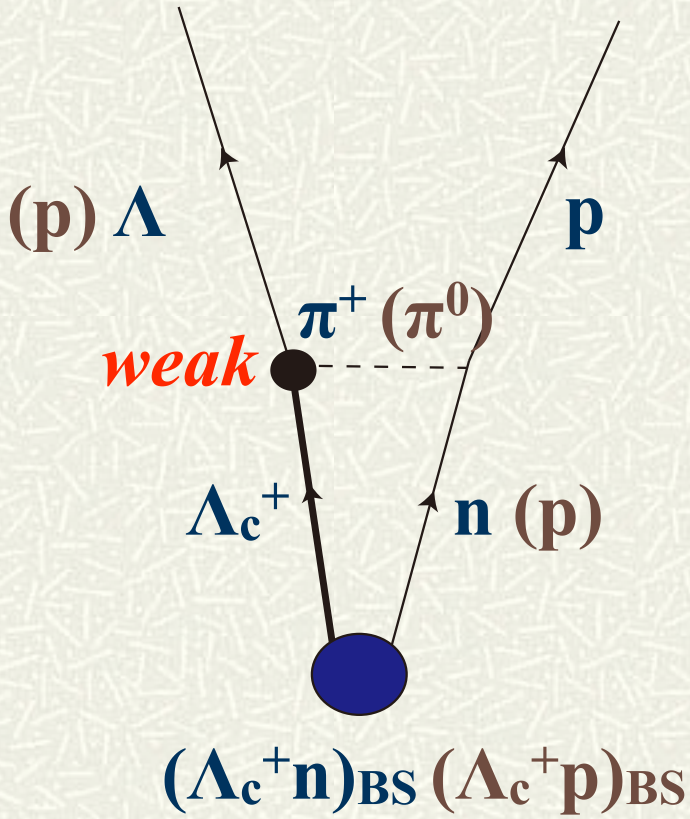


Wave functions with $\Lambda_\pi = 1.0$ GeV

Charmed deuteron

- How to find it
  - Production
    Heavy ion collision + coalescence
    High energy collision + fragmentation
    $D^+ + {}^3He \Rightarrow (\Lambda_c\, p) + p$?
  - Decay
    nonmesonic weak decays
    via pion exchange

    $(\Lambda_c^+ n)_{BS} \rightarrow \Lambda p \rightarrow pp\pi^-$
    $(\Lambda_c^+ p)_{BS} \rightarrow pp$ (Cabibbo suppressed)



Conclusion

- **Possibility of bound Charmed deuteron ($\Lambda_c N$, or $\Lambda_c \Lambda_c$ bound states) has been studied in the one-boson exchange potential approach.**
- **The effective Lagrangian is derived from the *heavy-quark spin symmetry* for charm quarks as well as *chiral symmetry* and *hidden local symmetry* for the light quark sector in order to determine the couplings of pseudo-scalar and vector mesons to the heavy baryons.**
- **The short-range part of the potential is parameterized by the cut-off parameters. The results are sensitive to the choice of the cutoff. It is an important and interesting future problem to evaluate the short range part of the BB interaction.**
- **The couplings of the $\Sigma_c N$ and $\Sigma_c^* N$ ($\Sigma_c \Sigma_c$, $\Sigma_c^* \Sigma_c$ and $\Sigma_c^* \Sigma_c^*$) channels are taken into account and we have found that the tensor couplings to the D wave $\Sigma_c^* N$ ($^5D_0$ etc) states are very important.**

Further interests

- **Heavy quark baryons have a rich spectrum, which are not yet explored. Many "predictions", Few data.**

Baryon	J^P	I	S^π	Quark content	Mass [MeV] Quark model [25, 34]	Mass [MeV] Experiment [6]
Ξ_{cc}	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	ccn	3613	3518.9
Ω_{cc}	$\frac{1}{2}^+$	0	1^+	ccs	3712	–
Λ_c	$\frac{1}{2}^+$	0	0^+	udc	2295	2286.5
Σ_c	$\frac{1}{2}^+$	1	1^+	nnc	2469	2453.6
Σ_c^*	$\frac{3}{2}^+$	1	1^+	nnc	2548	2518.0
Ξ_c	$\frac{1}{2}^+$	$\frac{1}{2}$	0^+	nsc	2474	2469.3
Ξ_c'	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	nsc	2578	2576.8
Ξ_c^*	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	nsc	2655	2645.9
Ω_c	$\frac{1}{2}^+$	0	1^+	ssc	2681	2695.2
Ω_c^*	$\frac{3}{2}^+$	0	1^+	ssc	2755	2765.9

Single, Double, Triple

	This work Variational	[3] Faddeev	[10] LQCD	[1] Bag Model	[2]	[4] NRCQM	[5] Coulomb	[6] NRCQM	[7] RTQM	[8] Regge	[9] QCDSR
$m_{\Omega_{bbb}^*}$	14398	14398	14371 ± 12	14300	14760 ± 180	–	14370 ± 80	14834	14569	–	13280 ± 100
$m_{\Xi_{bbc}^*}$	11245	–	–	11200	11480 ± 120	–	11190 ± 80	11554	11287	–	10540 ± 110
$m_{\Xi_{bbc}}$	11214	11217	–	–	–	–	11190 ± 80	11535	11280	–	10300 ± 100
$m_{\Xi_{ccb}^*}$	8046	–	–	8030	8200 ± 90	–	7980 ± 70	8265	8025	–	7450 ± 160
$m_{\Xi_{ccb}}$	8018	8019	–	–	–	–	7980 ± 70	8245	8018	–	7410 ± 130
$m_{\Omega_{ccc}^*}$	4799	4799	–	4790	4925 ± 90	4632	4760 ± 60	4965	4803	4819 ± 7	4670 ± 150

Further interests

- **Mass of Triply-Heavy Baryon in LQCD**

PHYSICAL REVIEW D **82**, 114514 (2010)

Prediction of the Ω_{bbb} mass from lattice QCD

Stefan Meinel

Department of Physics, College of William & Mary, Williamsburg, Virginia 23187-8795, USA

(Received 28 October 2010; published 29 December 2010)

The mass of the triply-heavy baryon Ω_{bbb} is calculated in lattice QCD with 2 + 1 flavors of light sea quarks. The b quark is implemented with improved lattice nonrelativistic QCD. Gauge field ensembles from both the RBC/UKQCD and MILC collaborations with lattice spacings in the range from 0.08 fm to 0.12 fm are used. The final result for the Ω_{bbb} mass, which includes an electrostatic correction, is $14.371 \pm 0.004_{\mathrm{stat}} \pm 0.011_{\mathrm{syst}} \pm 0.001_{\mathrm{exp}}$ GeV. The hyperfine splitting between the physical $J = 3/2$ state and a fictitious $J = 1/2$ state is also calculated.

Further interests

- **Mass of Triply-Heavy Baryon in LQCD**

PHYSICAL REVIEW D **82**, 114514 (2010)

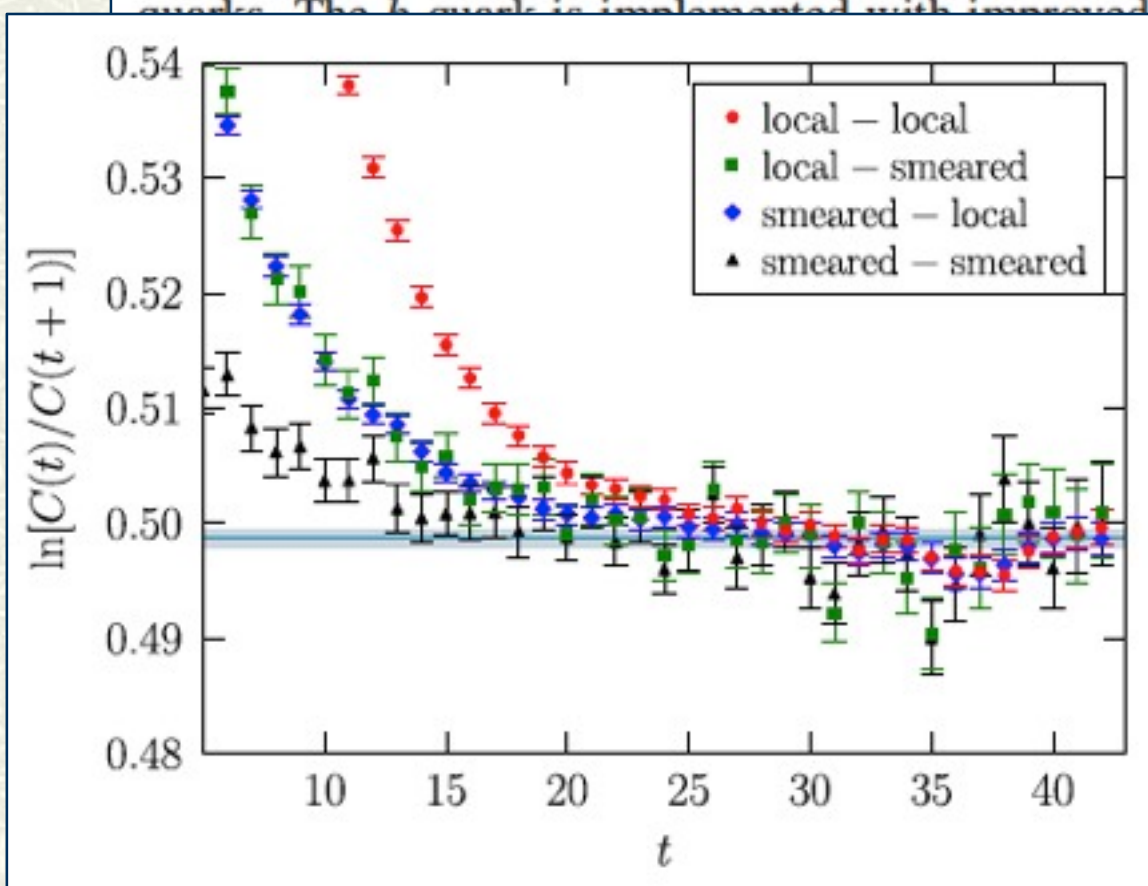
Prediction of the Ω_{bbb} mass from lattice QCD

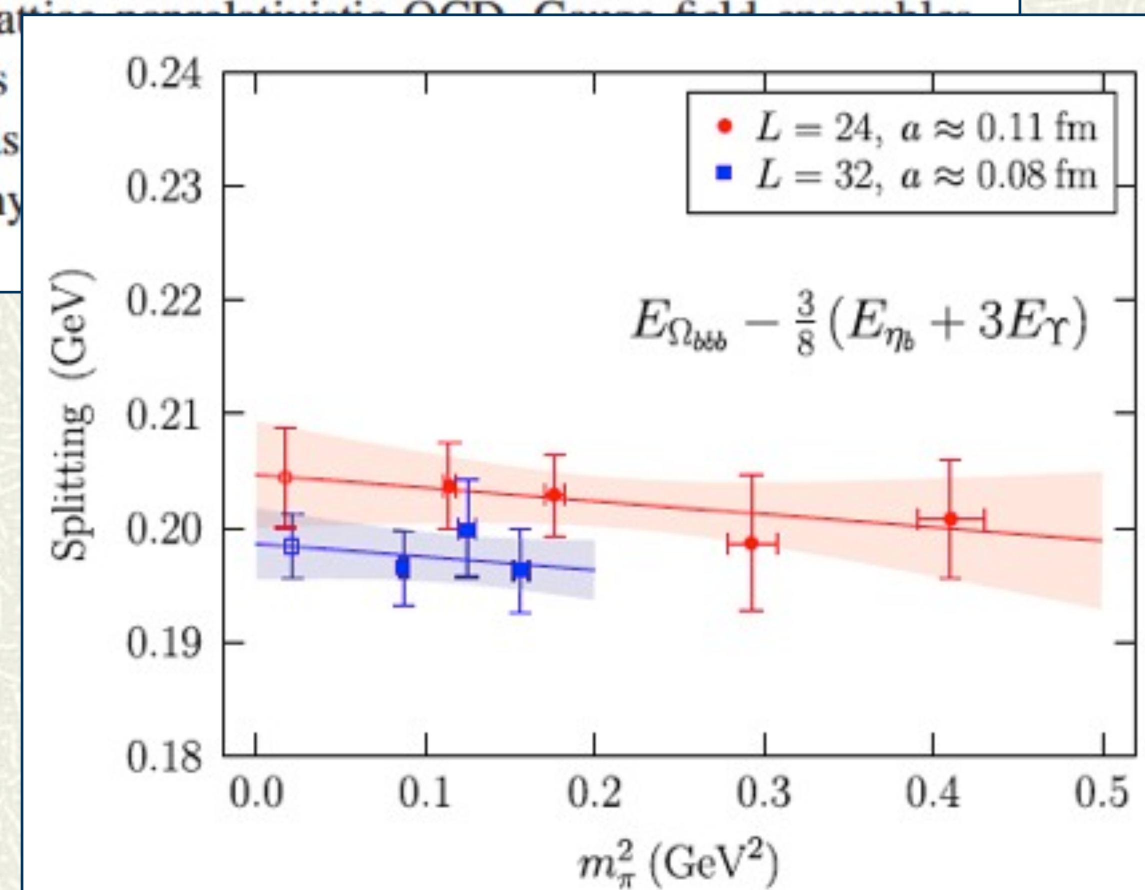
Stefan Meinel

Department of Physics, College of William & Mary, Williamsburg, Virginia 23187-8795, USA

(Received 28 October 2010; published 29 December 2010)

The mass of the triply-heavy baryon Ω_{bbb} is calculated in lattice QCD with 2 + 1 flavors of light sea





Further interests

- **Mass of Triply-Heavy Baryon in LQCD**

PHYSICAL REVIEW D **82**, 114514 (2010)

Prediction of the Ω_{bbb} mass from lattice QCD

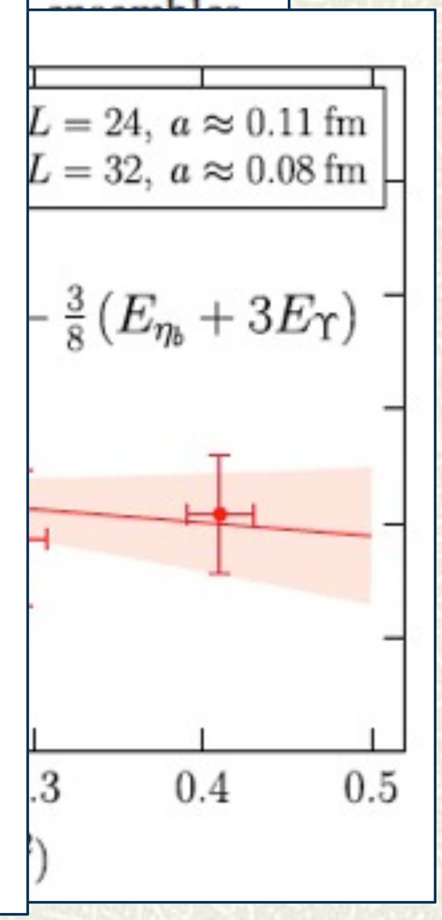
Stefan Meinel

Department of Physics, College of William & Mary, Williamsburg, Virginia 23187-8795, USA
(Received 28 October 2010; published 29 December 2010)

The mass of the triply-heavy baryon Ω_{bbb} is calculated in lattice QCD with 2 + 1 flavors of light sea

TABLE IV. Comparison of results for the Ω_{bbb} mass.

Reference	$M_{\Omega_{bbb}}$ (GeV)
Ponce [3]	14.248
Hasenfratz *et al.* [4]	14.30
Bjorken [5]	14.76 ± 0.18
Tsuge *et al.* [6]	13.823
Silvestre-Brac [9]	14.348–14.398
Jia [14]	14.37 ± 0.08
Martynenko [15]	14.569
Roberts and Pervin [17]	14.834
Bernotas and Simonis [18]	14.276
Zhang and Huang [19] **QCDSR violates M(Ω_{bbb})>1.5 M(Υ)**	13.28 ± 0.10
This work	$14.371 \pm 0.004_{\rm stat} \pm 0.011_{\rm syst} \pm 0.001_{\rm exp}$



Further interests

- **Other possibilities of heavy-quark nuclei**
  - **DN bound state (BE~200 MeV) will give Λ^*_c (1/2$^-$).**
    A prediction in the coupled channel calculation by Mizutani, Ramos.
    DNN and other D-Nuclear states are expected.
  - **D^{bar} N: exotic (pentaquark) bound state is predicted in OPE by Yasui and Sudo.**
  - **Hidden-charm baryons and nuclei, *i.e.*, J/ψ, η_c bound nuclei:**
    Attractive force with *a* (J/ψ, η_c) ~ 0.2-0.3 fm
    predicted in lattice QCD calculation by Kawanai, Sasaki.
    Such an attraction may produce a bound (J/ψ, η_c) - ^{4}He nuclei.