Spectroscopy and Interactions of Heavy Hadrons

Makoto Oka
Tokyo Institute of Technology

Particle and nuclear physics seminar at J-PARC

Workshop on
"Heavy-Quark Hadrons at J-PARC 2012"

06/27/12, J-PARC Branch, KEK

Heavy-Quark Hadrons at J-PARC 2012

- Workshop

  6/18-22 at Tokyo Tech

  6/22 One-day Symposium

  6/25-29 at Tokai Branch, KEK Theory Center

- Organized by

  A. Dote, S. Hashimoto, A. Hosaka, T. Hyodo, D. Jido,
  M. Oka, K. Ozawa, M. Takizawa, S. Yasui

- Sponsored by

  KEK, Theory Center, JPARC Branch
  JPARC Project
  HPCI Strategic Program Field 5
  RCNP, YITP, Tokyo Tech groups

Heavy-Quark Hadrons at J-PARC

- **The 1st week: 9 Seminars + Symposium**

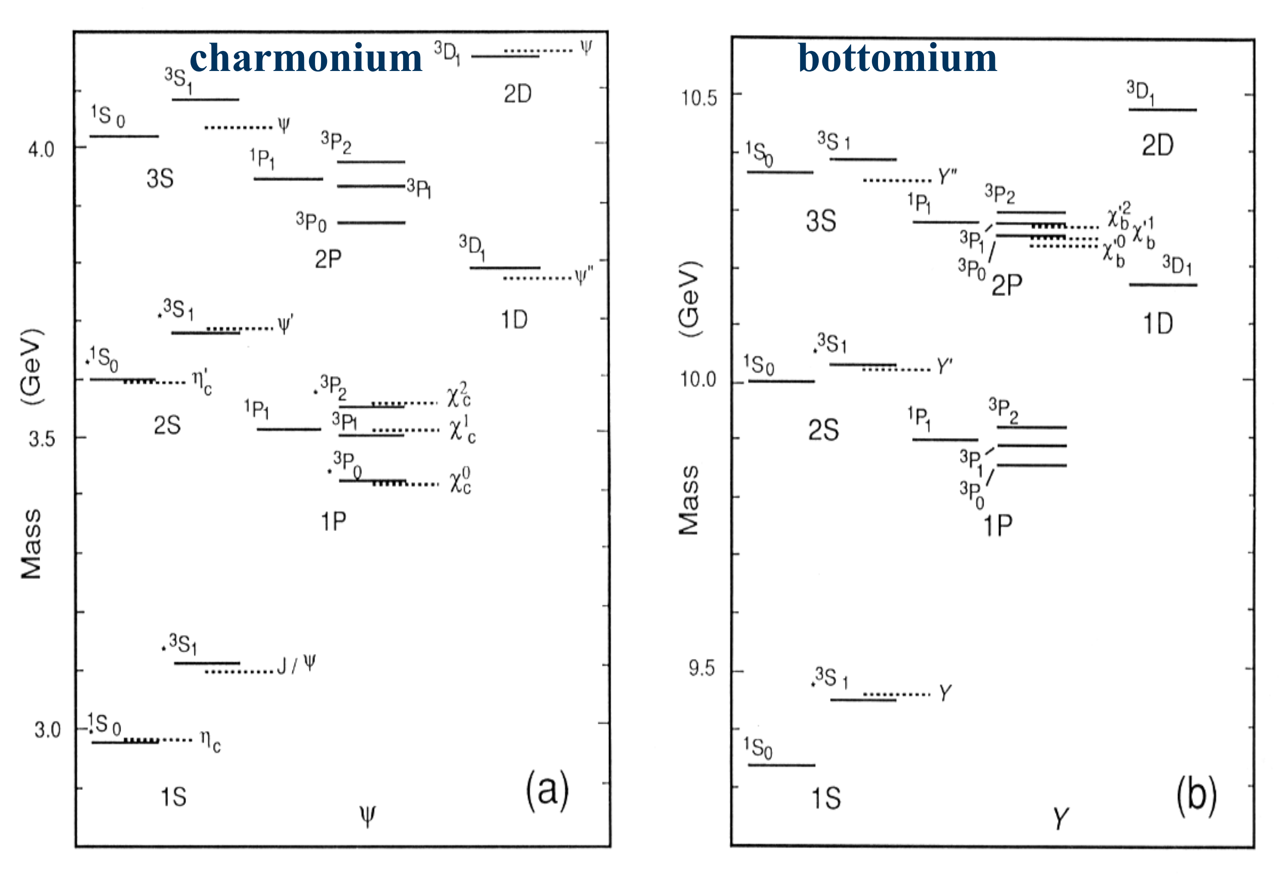
Olsen, ***Spectroscopy at BES and Belle***
Ozawa, ***Heavy quarks at J-PARC***
Takeuchi, Takizawa, ***X(3872)***
Molina, Ohkoda, ***D-D* D*-D* bound/resonances***
Hyodo, Yamaguchi, ***D-N bound state***
Namekawa, Takahashi, ***LQCD for charmed hadrons***
Lee, ***Heavy quark and QCD correlators***
Kim, ***QCD sum rule and diquarks***
Harada, ***Chiral effective theories for heavy hadrons***
Sudo, Kiyo, ***Charm production***
Suzuki, Fujii, ***Heavy hadrons in medium***
Sasaki, Koma, ***Heavy quark interactions***

Contents

Heavy Hadron Spectra

Quarkonium

- **Hydrogen atom in QCD**



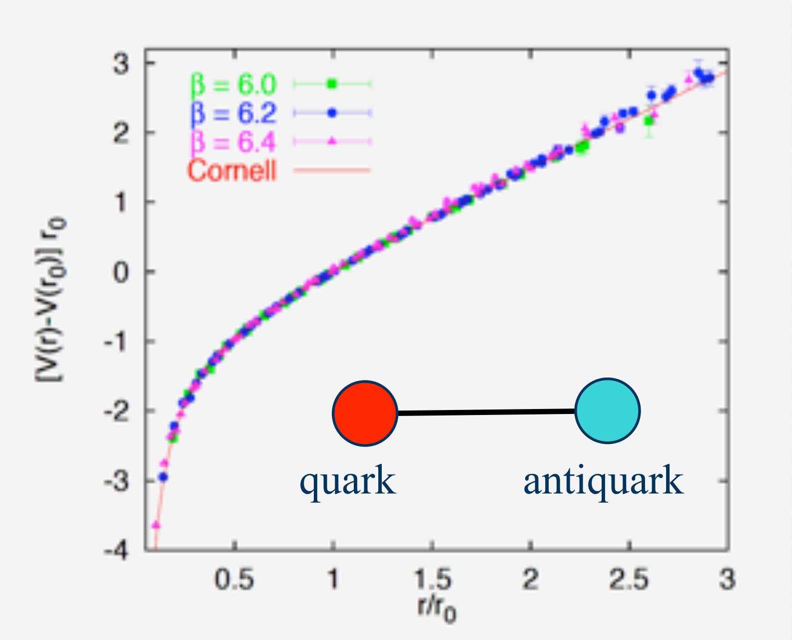
S.N. Mukherjee, et al., Phys. Rep. 231 (1993)

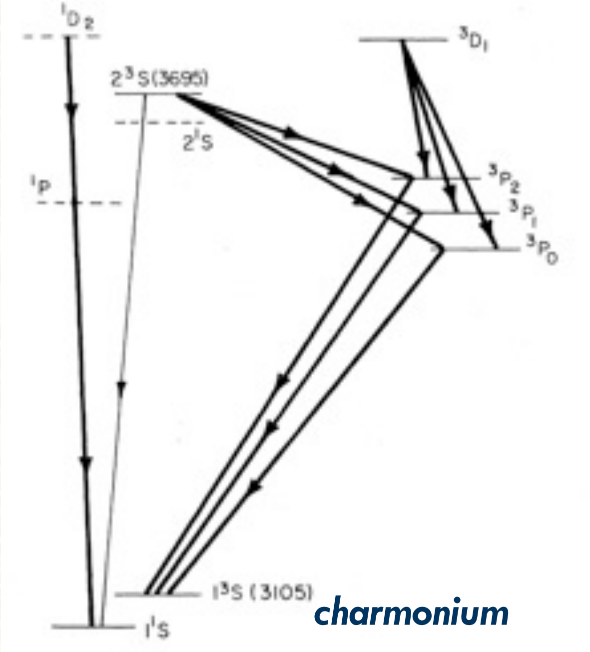
Quarkonium

- **Linear + Coulomb (Cornell) potential (Eichten et al.)**

$$V(r) = -\frac{e}{r} + \sigma r$$

- **Heavy quark potential from LQCD**



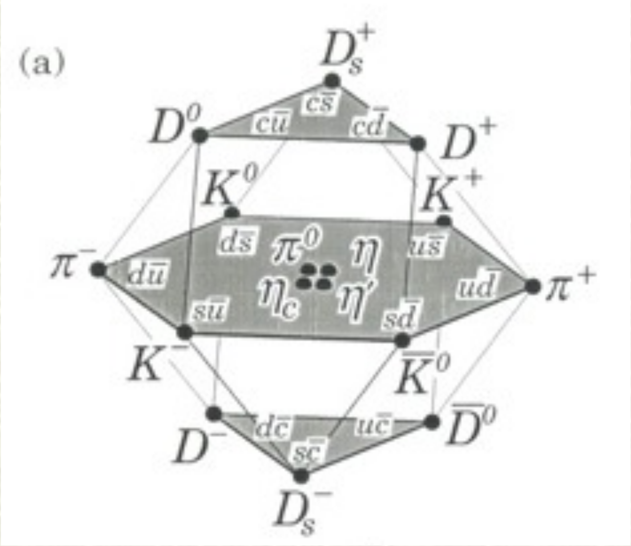


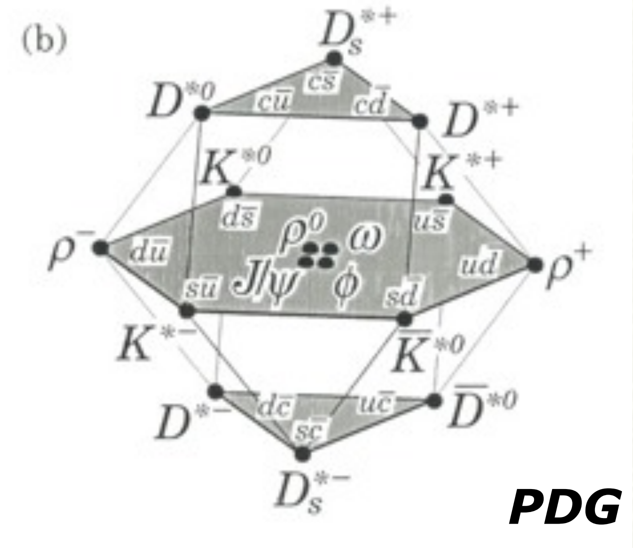
quenched **r_0: Sommer scale**

G.S. Bali / Phys. Rep. 343 (2001) 1

Heavy-Quark Hadrons

- **Heavy mesons and baryons**
  The SU(4) classification for the ground states works.
  They follow the quark model assignments (as the light sector)





PDG

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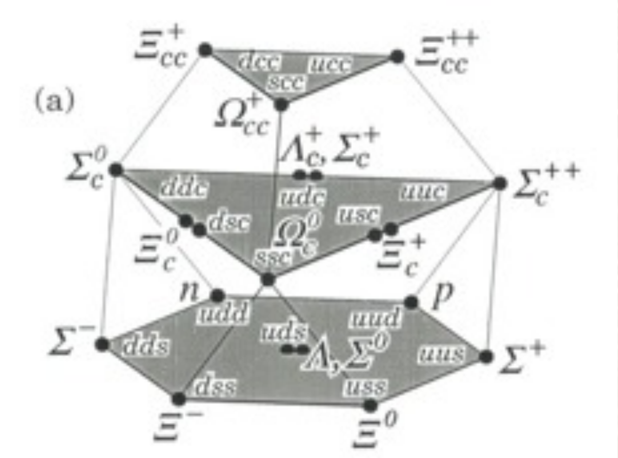
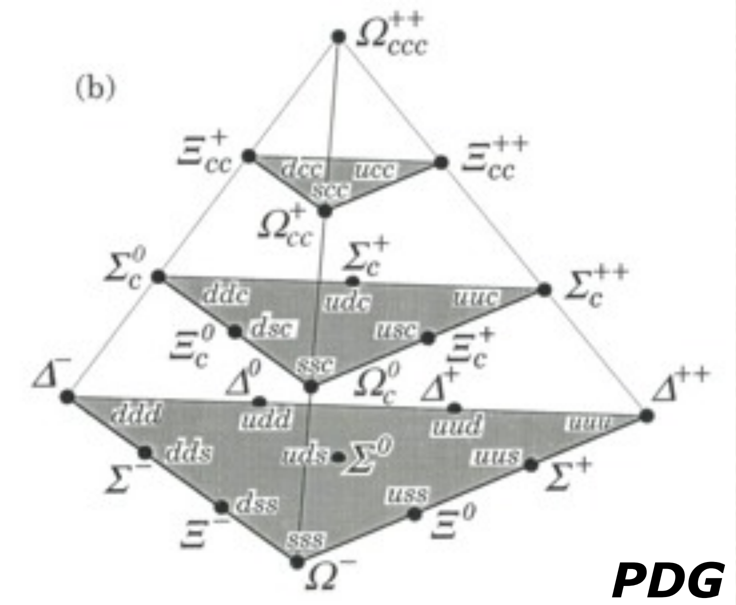




PDG

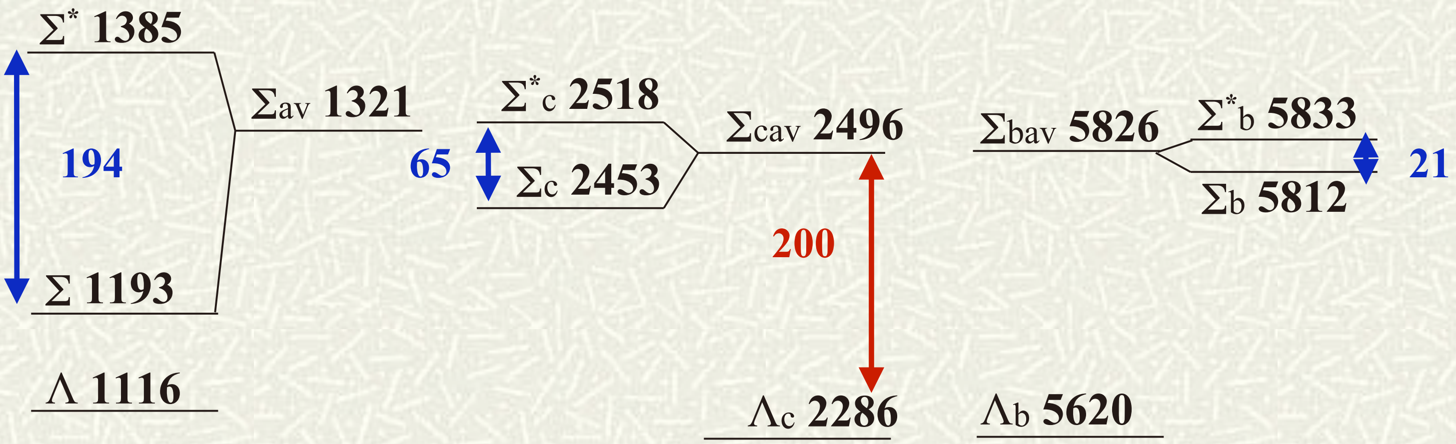
Heavy-Quark Hadrons

- **New dynamics for heavy quarks**

Λ_{QCD}(~250 MeV) < m_c(~1.2 GeV) << m_b(~4.5 GeV)

– Heavy quark decouples and the system is simpler.

– New symmetries are realized. ***ex.*** **HQ spin symmetry**

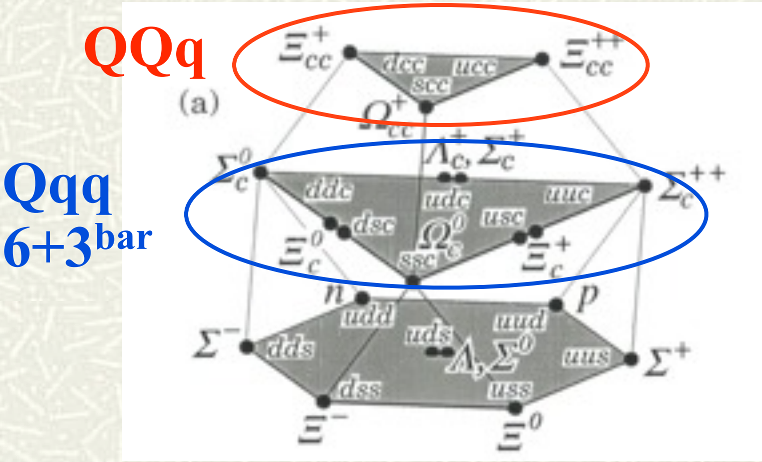


Heavy-Quark Hadrons

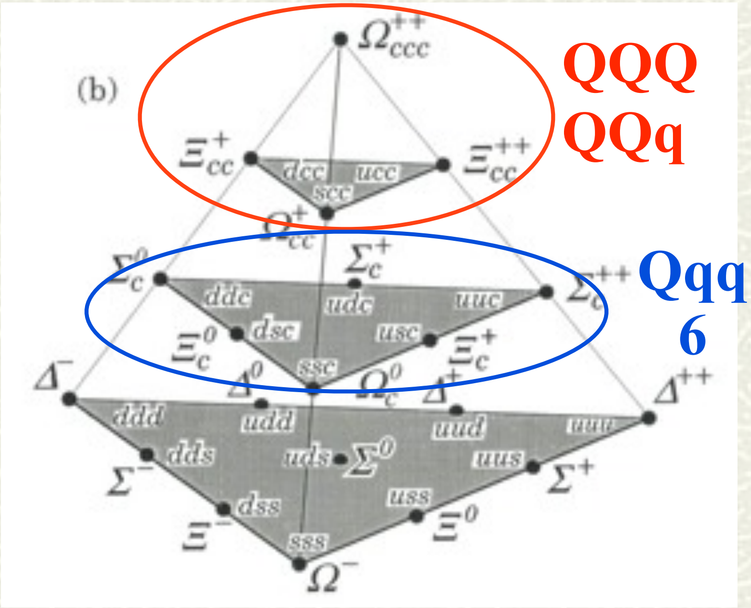
- **Light Baryons: qqq color singlet (color antisymmetric)**
  SU(6) 56 dim. L=0, (8, S=1/2) + (10, S=3/2)
- **Heavy Baryons:**
  Qqq ⇒ (3$^{\text{bar}}$, J=1/2) + $\boxed{(6, J=1/2) + (6, J=3/2)}$

HQ spin symmetry

J=1/2



J=3/2



Heavy-Quark Hadrons

- **New dynamics for heavy quarks**

  Λ_{QCD}(~250 MeV) < m_c(~1.2 GeV) ≪ m_b(~4.5 GeV)

  – Heavy quark decouples and the system is simpler.

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- **New interesting dynamical contents in Heavy Baryons**

  – Di-quark spectroscopy Q-(qq)

  – Chiral partners

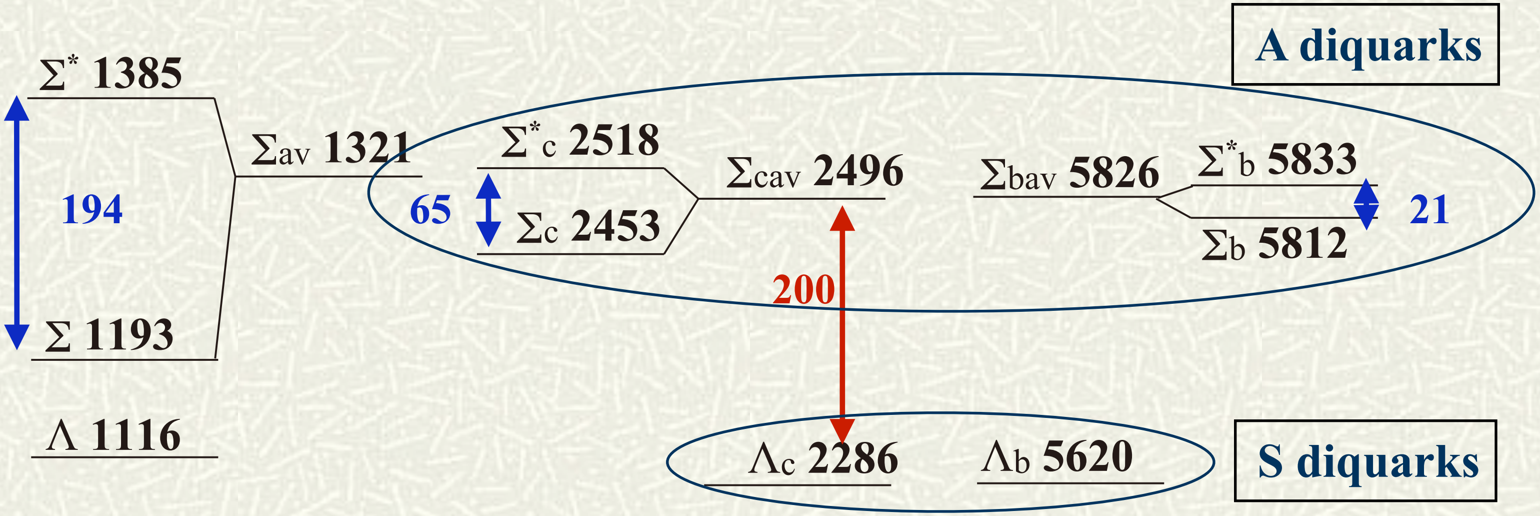
  diquark $Q(qq)^+$ v.s. $Q(qq)^-$

  quark QQq^+ v.s. QQq^-

  – Appearance of the Roper-like states

Heavy-Quark Hadrons

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



A diquarks

Σ^* 1385

194

Σ 1193

Λ 1116

Σ_{av} 1321

$\Sigma^*{}_c$ 2518

65

Σ_c 2453

Σ_{cav} 2496

200

Λ_c 2286

Σ_{bav} 5826

$\Sigma^*{}_b$ 5833

21

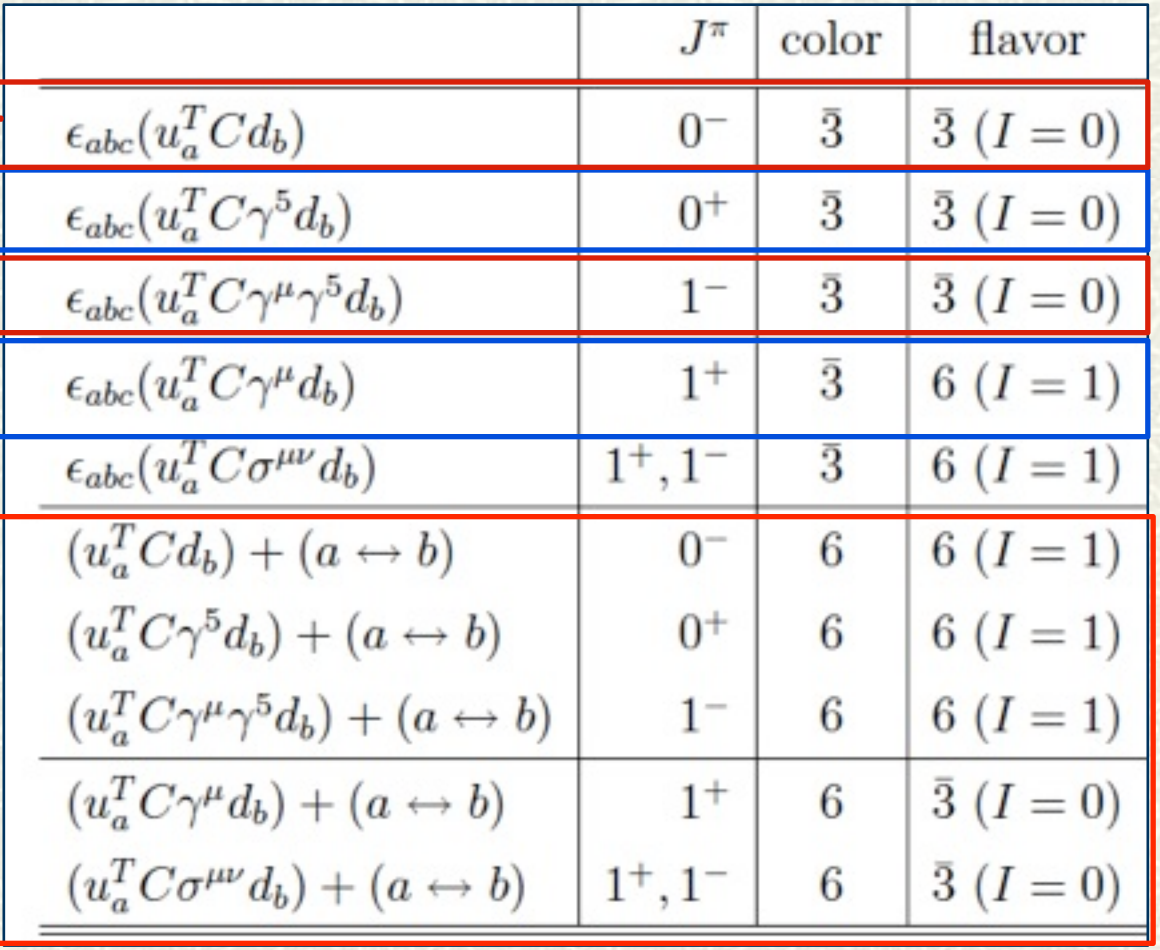
Σ_b 5812

Λ_b 5620

S diquarks

- 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

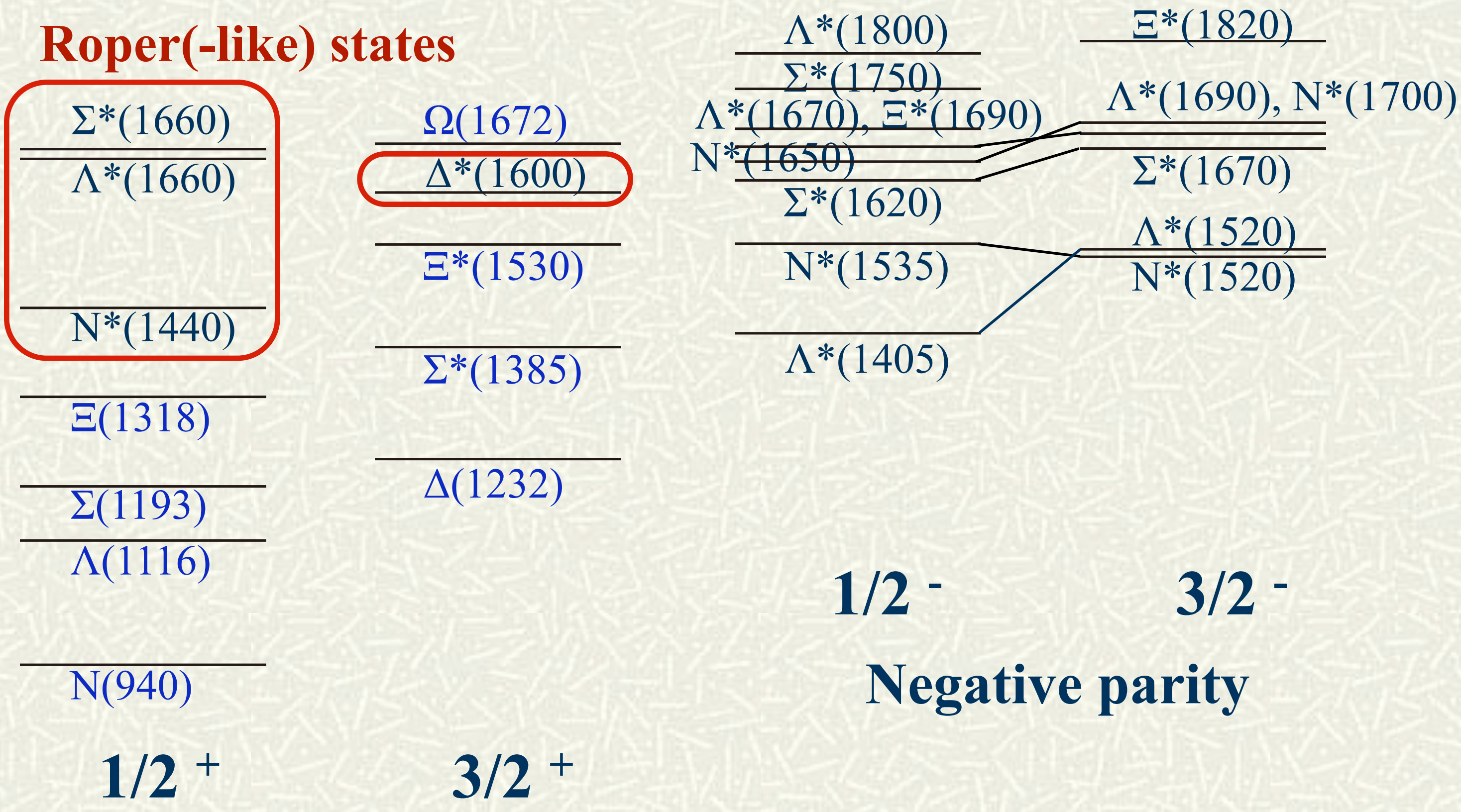
Diquarks in QCD



		J^π	color	flavor
Pseudoscalar	$\epsilon_{abc}(u_a^T C d_b)$	0^-	$\bar{3}$	$\bar{3}\ (I=0)$
Scalar (S)	$\epsilon_{abc}(u_a^T C \gamma^5 d_b)$	0^+	$\bar{3}$	$\bar{3}\ (I=0)$
Vector	$\epsilon_{abc}(u_a^T C \gamma^\mu \gamma^5 d_b)$	1^-	$\bar{3}$	$\bar{3}\ (I=0)$
Axial V. (A)	$\epsilon_{abc}(u_a^T C \gamma^\mu d_b)$	1^+	$\bar{3}$	$6\ (I=1)$
	$\epsilon_{abc}(u_a^T C \sigma^{\mu\nu} d_b)$	$1^+, 1^-$	$\bar{3}$	$6\ (I=1)$
Color 6 only in Exotic Hadrons	$(u_a^T C d_b) + (a \leftrightarrow b)$	0^-	6	$6\ (I=1)$
	$(u_a^T C \gamma^5 d_b) + (a \leftrightarrow b)$	0^+	6	$6\ (I=1)$
	$(u_a^T C \gamma^\mu \gamma^5 d_b) + (a \leftrightarrow b)$	1^-	6	$6\ (I=1)$
	$(u_a^T C \gamma^\mu d_b) + (a \leftrightarrow b)$	1^+	6	$\bar{3}\ (I=0)$
	$(u_a^T C \sigma^{\mu\nu} d_b) + (a \leftrightarrow b)$	$1^+, 1^-$	6	$\bar{3}\ (I=0)$

Baryon Spectrum

- **Light baryon spectrum**



Roper(-like) states

Σ*(1660)
Λ*(1660)
N*(1440)
Ξ(1318)
Σ(1193)
Λ(1116)
N(940)

Ω(1672)
Δ*(1600)
Ξ*(1530)
Σ*(1385)
Δ(1232)

Λ*(1800)
Σ*(1750)
Λ*(1670), Ξ*(1690)
N*(1650)
Σ*(1620)
N*(1535)
Λ*(1405)

Ξ*(1820)
Λ*(1690), N*(1700)
Σ*(1670)
Λ*(1520)
N*(1520)

$1/2^+$ **$3/2^+$**

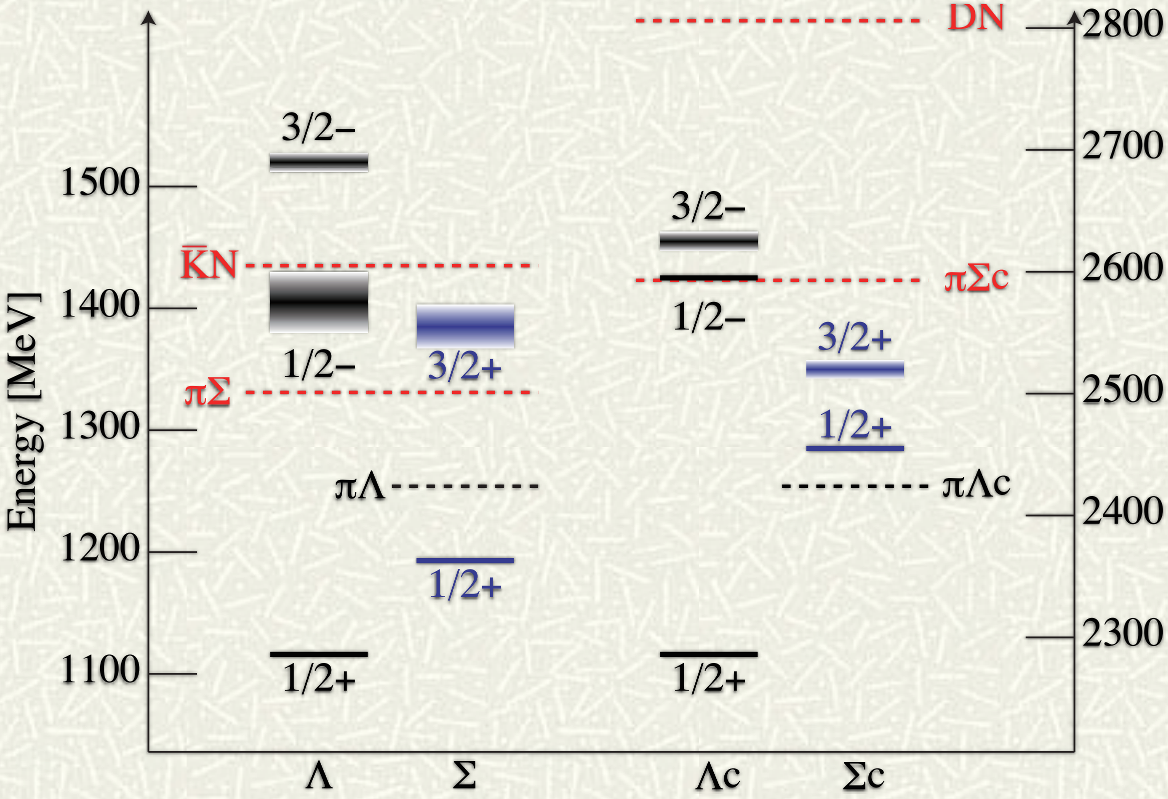
Positive Parity

$1/2^-$ **$3/2^-$**

Negative parity

Baryon Spectrum

- **Heavy baryon spectrum looks simpler. They may reveal the nature of the light baryon excited states.**
  The higher thresholds make the heavy baryon excited states narrower.



Diquarks in QCD

- **QCD predicts attraction in the channels:**
  PS meson q-q^{bar} : color 1, spin-parity 0^-, flavor 1+8
  S diquark q-q : color 3^{bar}, spin-parity 0^+, flavor 3^{bar}

$$U = [d\bar{s}]_{C=3,J=0,F=3}, \quad D = [\bar{s}\bar{u}]_{3,0,3}, \quad S = [\bar{u}d]_{3,0,3}$$

- **diquark "meson" d d^{bar} (tetra-quark)**
- **di-diquark "baryon" d-d-q (pentaquark)**
- **tri-diquark "dibaryon" d^3 (6 quarks)**
  color 1, flavor 1, 0^{++} H dibaryon

$$H = [\bar{U}\bar{D}\bar{S}]_A = [uuddss]$$

- **diquark matter: color superconductivity**
  U^{bar}+D^{bar}+S^{bar} condensates: color-flavor locking (CFL)
  S^{bar}: 2SC (U^{bar}: uSC D^{bar}: dSC)

Diquarks in QCD

- Diquarks in quench lattice calculations
  - Hess, Karsch, Laermann, Wetzorke, PR D58, 111502 (1998)
    from the correlators in the Landau gauge
    m_q~342 MeV, M(S)~694 MeV, M(A) ~ 810 MeV
  - Alexandrou, de Forcrand, Lucini, PRL 97, 222002 (2006)
    gauge invariant calculation inside a Qqq system
    M(A)- M(S) ~ 100-150 MeV, R(S) ~ 1 fm
    M(PS)- M(S) ~ 600 MeV
  - Babich, et al., PR D76, 074021 (2007)
    diquark correlation and effective mass in the Landau gauge
    M(S)- 2m_q ~ -200 MeV, M(A)-M(S) ~162 MeV
  - DeGrand, Liu, Schaefer, PR D77, 034505 (2008)
    diquark correlation in the light baryon
    S: strongly attractive, PS: attractive for small m_q

Diquarks in QCD

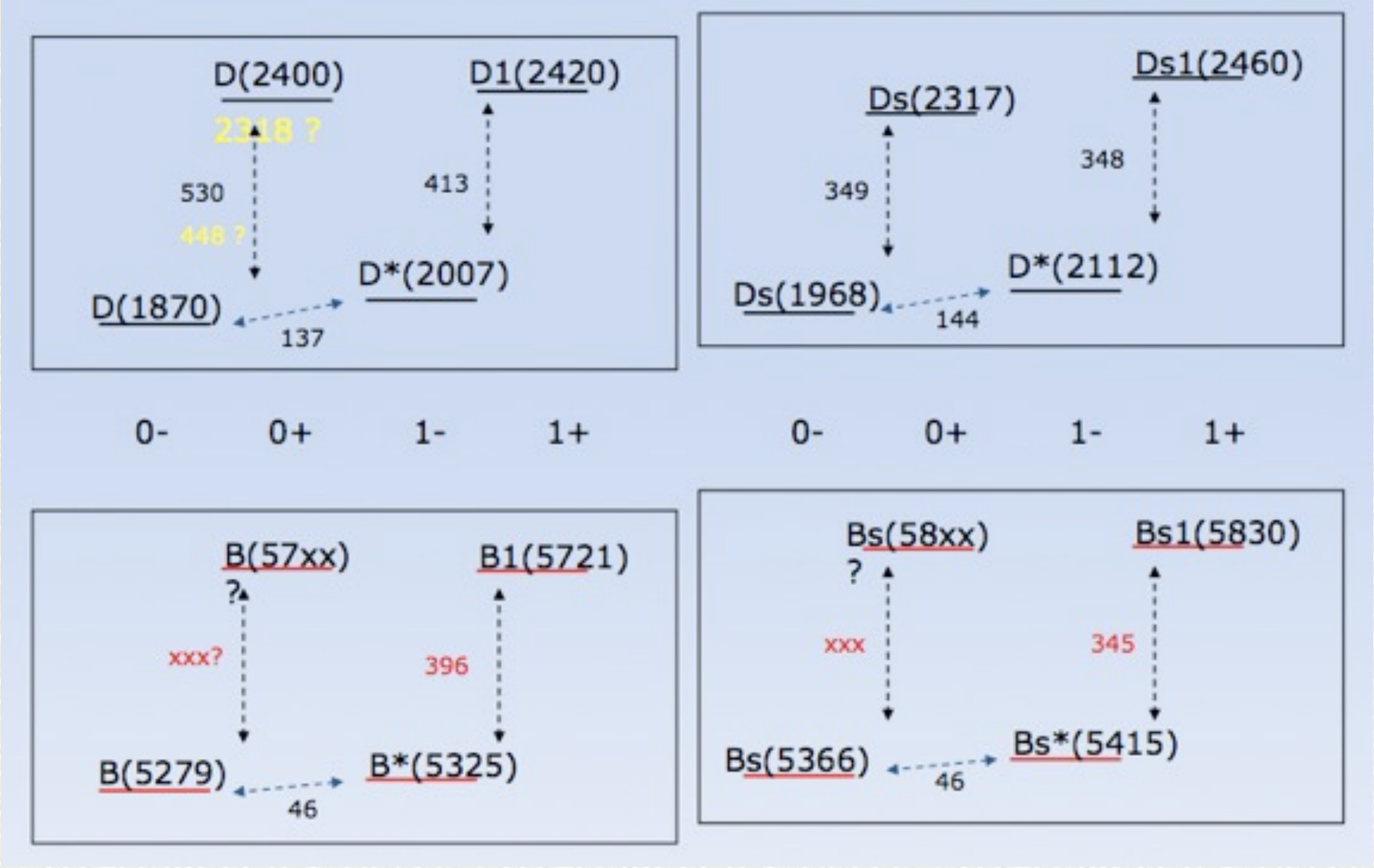
- **There are two independent local operators for the octet baryons, i.e.**
  $J_1 = (q^T C\gamma^5 q)_S \; q$
  $J_2 = (q^T C q)_{PS} \; \gamma^5 q$
- **It is found by both the LQCD and QCDSR calculations that the ground state nucleon couples mainly to J_1 while J_2 couples to the negative parity nucleon.**
- **Is the mysterious Roper resonance (the 1st excited state of the nucleon with $J^\pi=1/2^+$) related to the second baryonic current J_2?**
- **The local operator is unique for the decuplet baryons.**

Diquarks

- The Diquark "cluster" may play major roles in the baryon excitations.
- How can we quantify the Diquark correlation in QCD?
  How heavy are the Diquarks?
  How large is the SU(3) breaking mass splitting?
  m(U) = m(D) > m(S)
  What are the interaction of color-non-singlet Diquarks?
- How can we measure the Diquark correlation in hadrons?
  Colored correlations in hadrons and nuclei.
  => Exotic Hadrons

Chiral Symmetry in Heavy Hadrons

- **Mesons (SH Lee, Harada)**



Chiral Symmetry in Heavy Hadrons

- **Baryons**

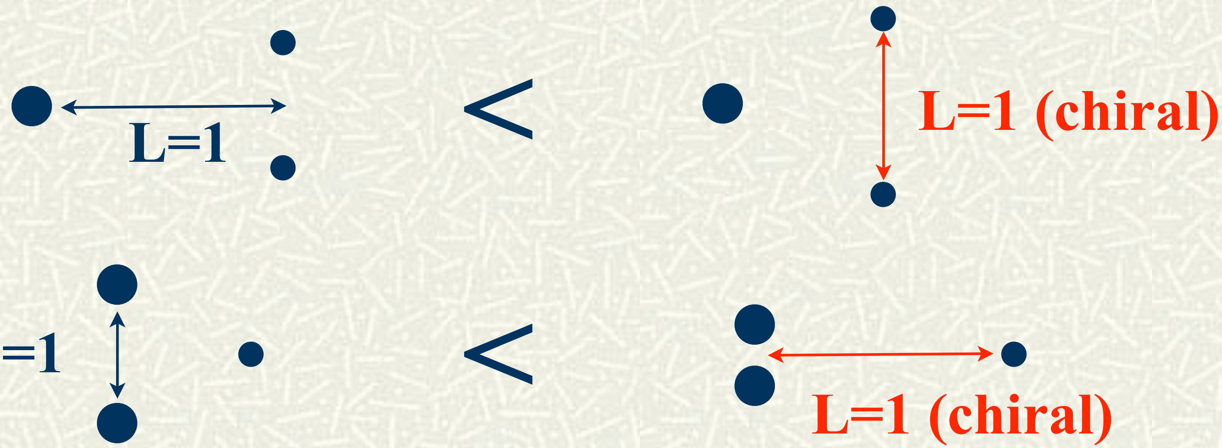
  Chiral symmetry of

  $q^3 = (8,1)+(1,8)$, $(3,3^{\mathrm{bar}})+(3^{\mathrm{bar}},3)$, . . .

  $Qq^2 = (3^{\mathrm{bar}},1)+(1,3^{\mathrm{bar}})$, $(3,3)$, $(6,1)+(1,6)$

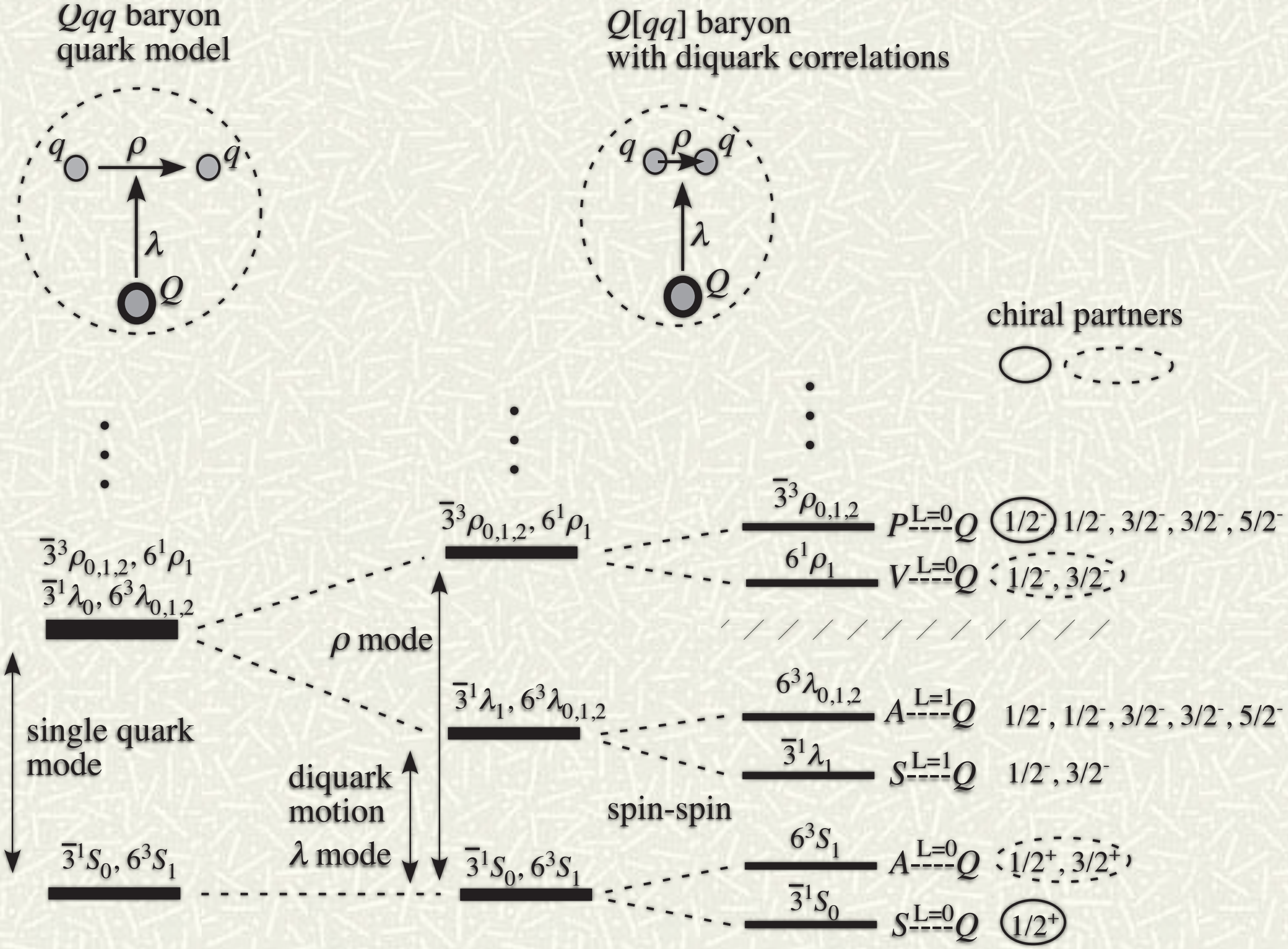
  $QQq = (3,1)+(1,3)$

- **P-wave Heavy Baryons have two excitation modes.**



Chiral Symmetry in Heavy Hadrons

- **Two excitation modes of the P-wave Heavy Baryons**



New “Exotic” Resonances

Exotic Hadrons: Candidates

- Mesons

  Scalar meson nonets: f_0, a_0 vs KK^{bar}

  Baryonium-like state X(1835)

  Charmonium-like resonances:

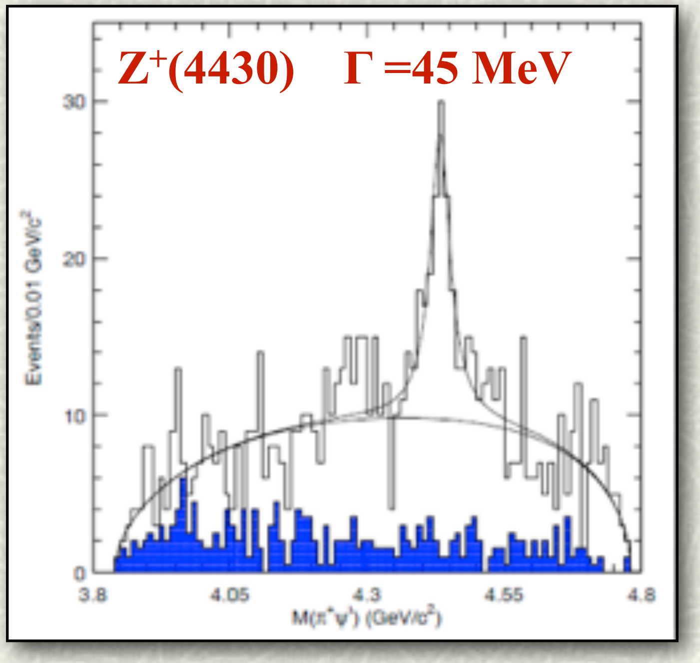
  X(3872)

  X, Y(3940), Z(3930)

  Charged (I=1) resonances:

  $Z^+(4430)$, $Z_1(4050)$, $Z_2(4250)$

  $Z_b(10610)$, $Z_b(10650)$ (bb^{bar}-like)

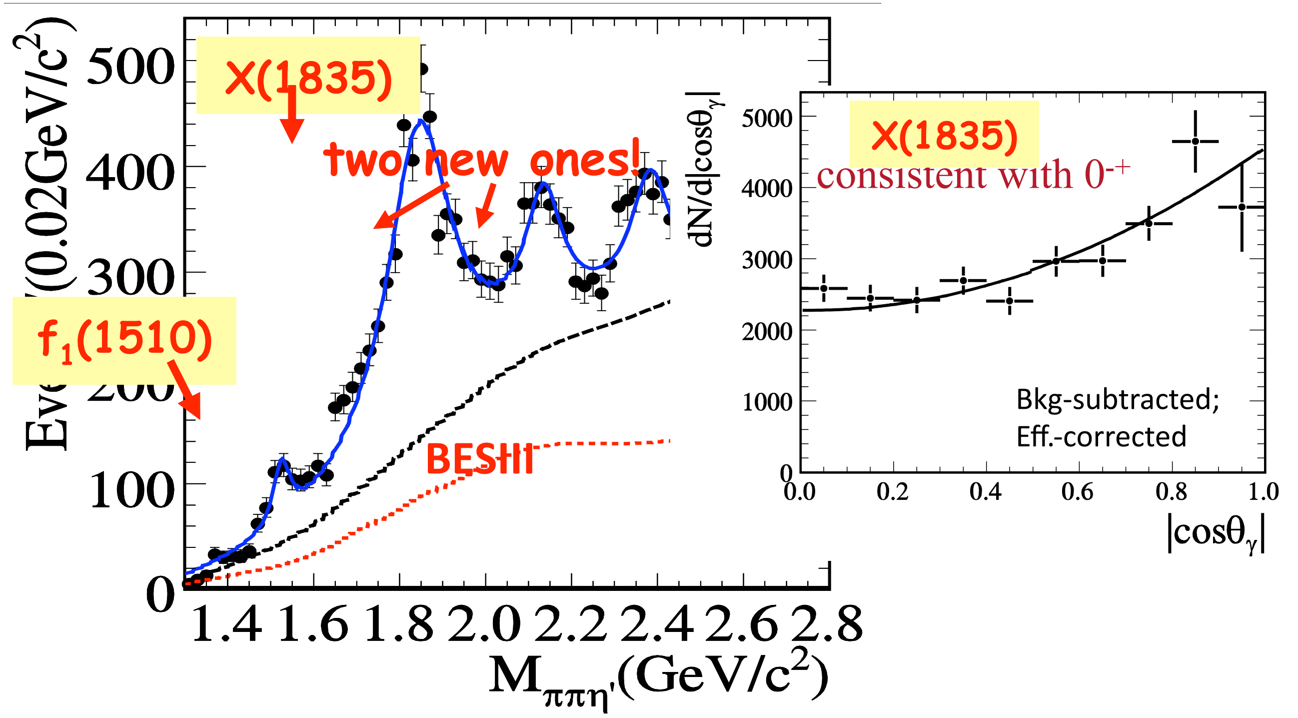


BESIII: X(1835) confirmed + 2 new structures

$J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$

$\eta' \rightarrow \eta\pi^+\pi^-$

$\eta' \rightarrow \gamma\pi^+\pi^-$



BESIII PRL 106, 072002 (2011)

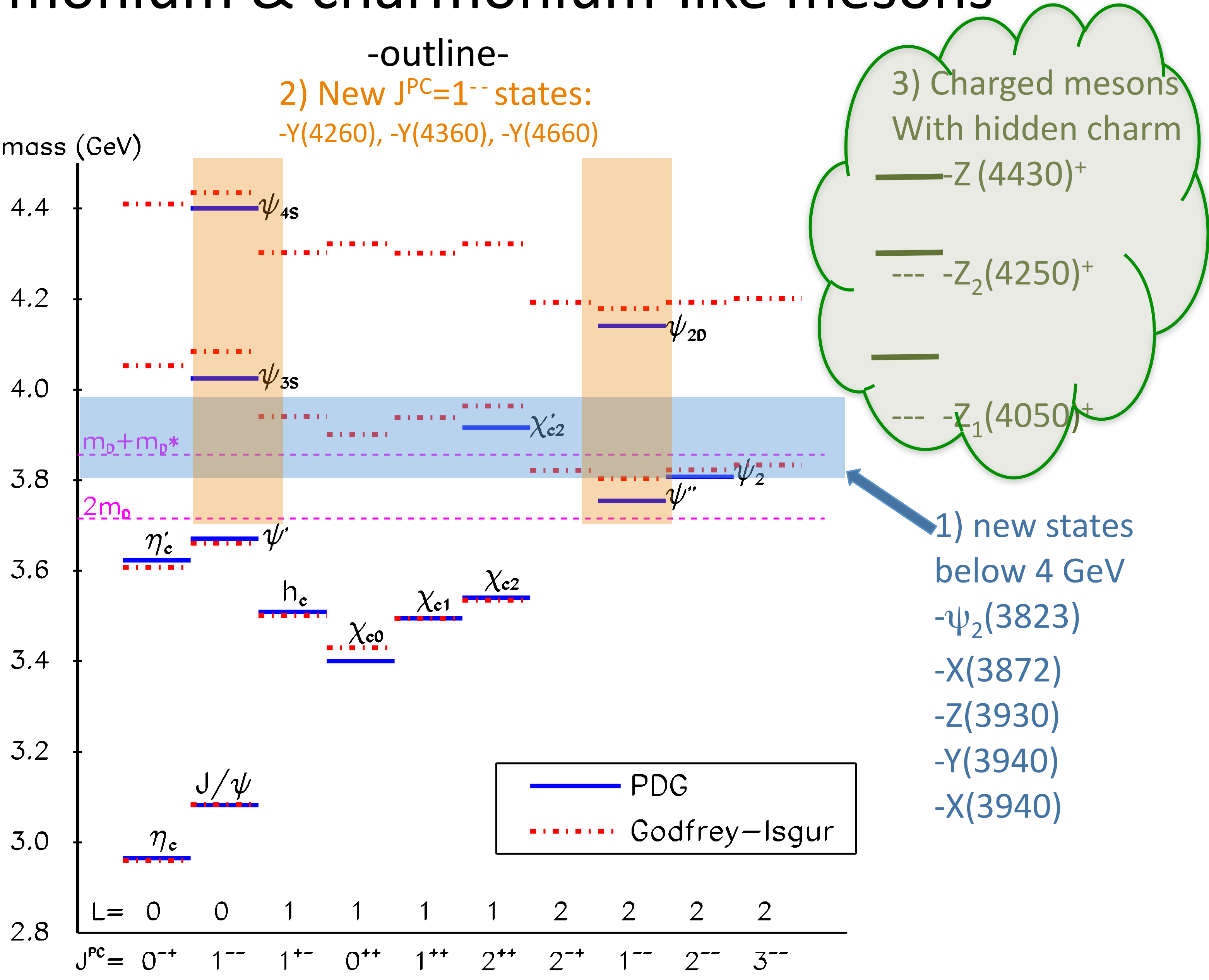
X(1835): same mass and J^{PC} as the $p\bar{p}$ peak, but larger width

Resonance	M(MeV/c²)	Γ(MeV/c²)	Stat.Sig.
X(1835)	$1836.5 \pm 3.0^{+5.6}_{-2.1}$	$190.1 \pm 9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4 \pm 6.7^{+4.7}_{-2.7}$	$83 \pm 16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3 \pm 8.7^{+3.2}_{-4.3}$	$83 \pm 17^{+44}_{-6}$	6.4σ

narrow!!

S. OLSEN, HEAVY QUARK HADRON 2012

Charmonium & charmonium-like mesons



-outline-

2) New $J^{PC}=1^{--}$ states:

-Y(4260), -Y(4360), -Y(4660)

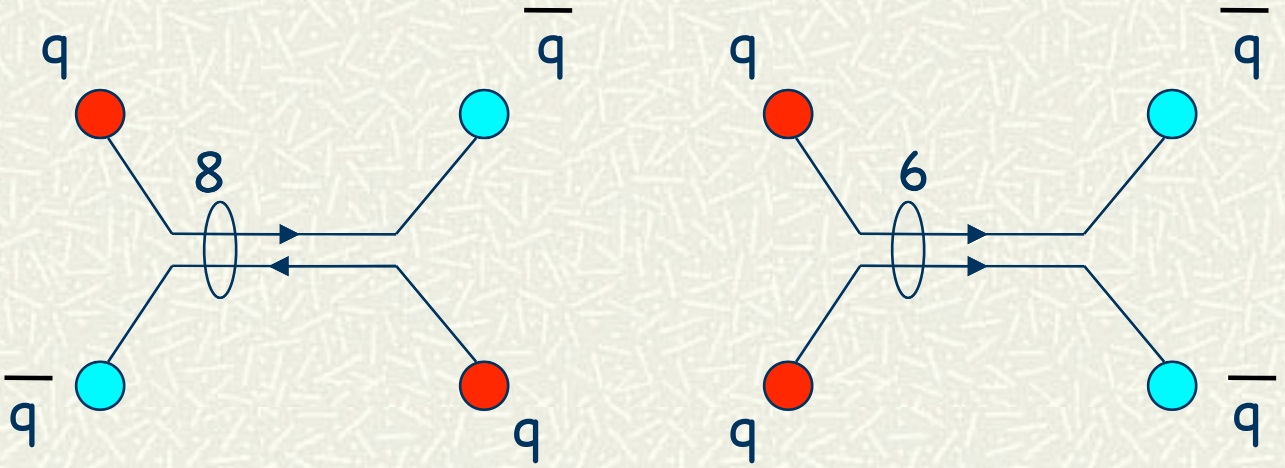
3) Charged mesons
With hidden charm
-Z (4430)$^+$
--- -Z_2(4250)$^+$
--- -Z_1(4050)$^+$

1) new states
below 4 GeV
-ψ_2(3823)
-X(3872)
-Z(3930)
-Y(3940)
-X(3940)

Exotic Hadrons

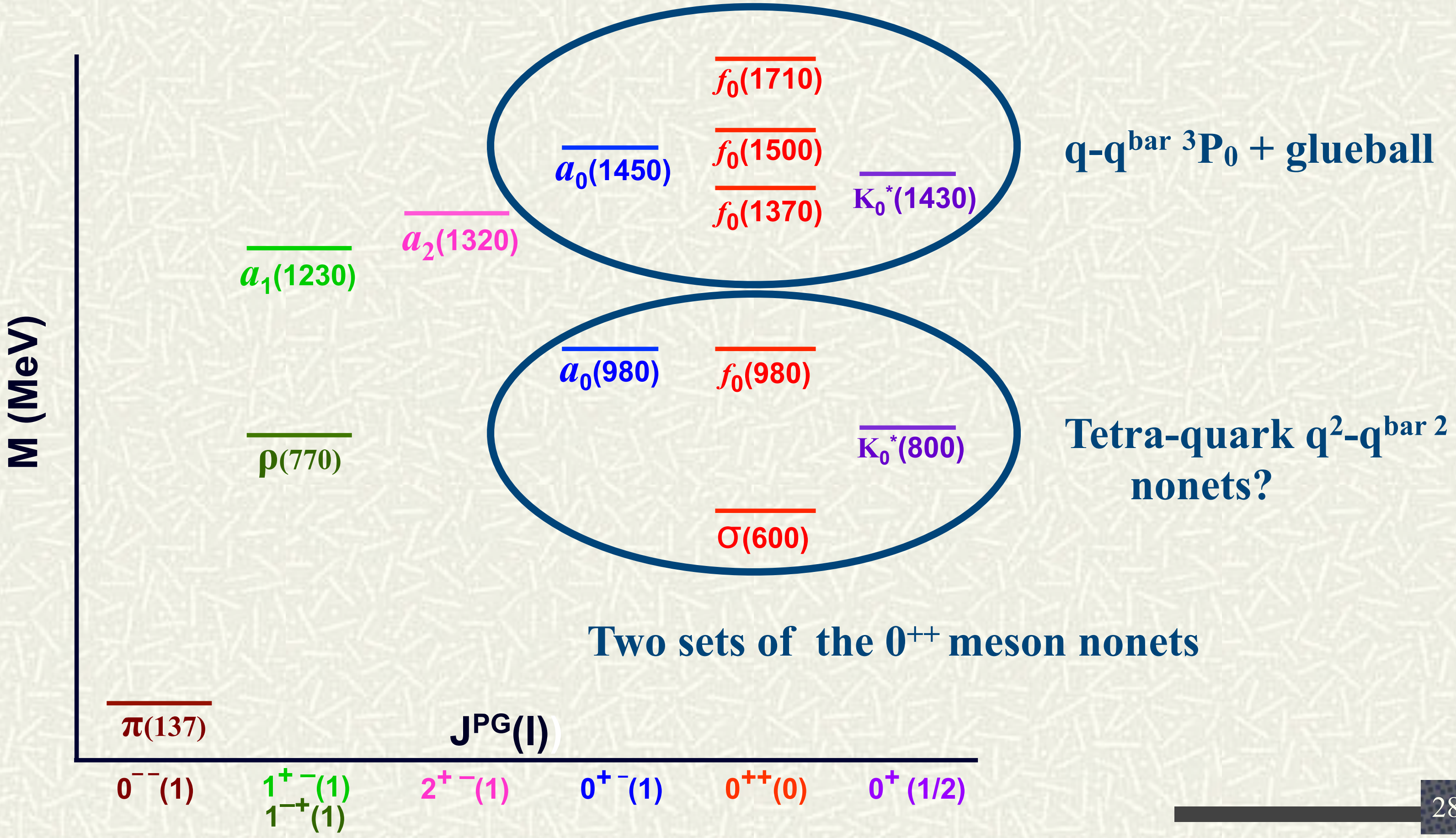
Exotics are "Colorful" ! (Lipkin@YKIS07)

$(q\bar{q})_8$ or $(qq)_6$ are allowed only in the multi-quarks.



Scalar mesons

- The lowest lying scalar nonets, f_0(600, 980), a_0(980), K^0(800), have wrong ordering and do not fit the qq^{bar} spectrum.



q-q^{bar} $^3P_0$ + glueball

Tetra-quark q^2-$q^{bar\ 2}$ nonets?

Two sets of the 0^{++} meson nonets

Scalar mesons

Tetra-quark conjecture (Jaffe, Shechter)

$$f_0(600) \sim S\bar{S} = (ud)(\bar{u}\bar{d})$$

no strange quark

$$a_0(980) \sim \frac{U\bar{U} - D\bar{D}}{\sqrt{2}} = \frac{(ds)(\bar{d}\bar{s}) - (su)(\bar{s}\bar{u})}{\sqrt{2}}$$

$$f_0(980) \sim \frac{U\bar{U} + D\bar{D}}{\sqrt{2}} = \frac{(ds)(\bar{d}\bar{s}) + (su)(\bar{s}\bar{u})}{\sqrt{2}}$$

two strange quarks

composed of Di(anti-)quarks in flavor 3

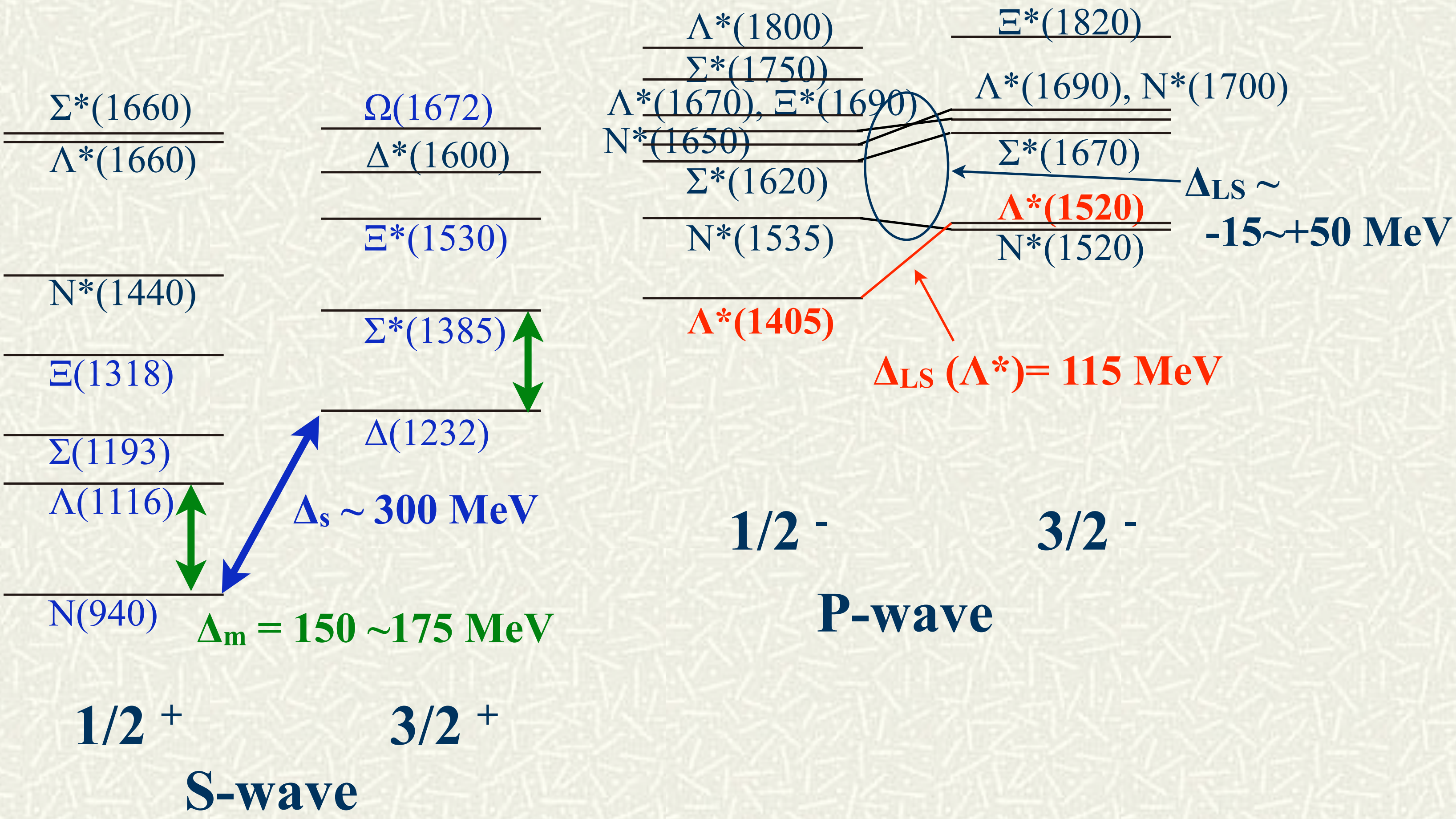
$$U = (\bar{d}\bar{s})_{S=0,C=3} \qquad D = (\bar{s}\bar{u})_{S=0,C=3} \qquad S = (\bar{u}\bar{d})_{S=0,C=3}$$

Now the observed mass ordering can be explained by the numbers of the strange quarks.

All the quarks are in S-wave, so that no extra excitation energy is necessary.

Λ(1405)

- **Why is Λ(1405) the lowest negative-parity baryon?**



Λ*(1800)

Ξ*(1820)

Σ*(1750)

Λ*(1690), N*(1700)

Σ*(1660)

Ω(1672)

Λ*(1670), Ξ*(1690)

N*(1650)

Λ*(1660)

Δ*(1600)

Σ*(1670)

Σ*(1620)

Δ_{LS} ~

Λ*(1520)

-15~+50 MeV

Ξ*(1530)

N*(1535)

N*(1520)

N*(1440)

Σ*(1385)

Λ*(1405)

Δ_{LS} (Λ*)= 115 MeV

Ξ(1318)

Δ(1232)

Σ(1193)

Λ(1116)

Δ_s ~ 300 MeV

1/2 $^-$

3/2 $^-$

N(940)

Δ_m = 150 ~175 MeV

P-wave

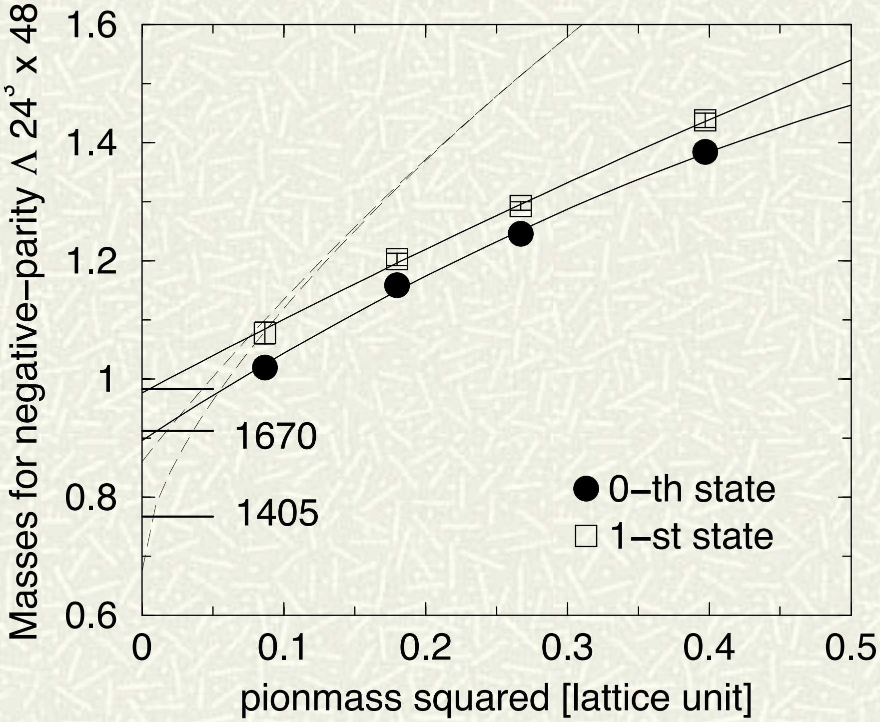
1/2 $^+$

3/2 $^+$

S-wave

Λ(1405)

- **Lattice QCD calculation by T. Takahashi**
  Two Lambda states are observed, whose masses are much higher than Λ(1405).
  The result indicates that Λ(1405) may not be a 3-quark state.



T.T. Takahashi, M.O.

PRD81, 034505 (2010)

Λ(1405)

- **Penta-quark picture of Λ*(1405)**

$$\Lambda^* = \frac{1}{\sqrt{2}}(\bar{S}\bar{D}\bar{u} + \bar{S}\bar{U}\bar{d}) = \frac{1}{\sqrt{2}}uds(u\bar{u} + d\bar{d})$$

The orbital angular momenta are all zero : $J^{\pi}=1/2^{-}$

Need no spin $3/2^{-}$ partner

Flavor 1+8, ideal mixing

- **New Σ* partner? (B.S. Zou, Σ*(1385) ($1/2^{-}$))**

$$\Sigma^* = \frac{1}{\sqrt{2}}(\bar{S}\bar{D}\bar{u} - \bar{S}\bar{U}\bar{d}) = \frac{1}{\sqrt{2}}uds(u\bar{u} - d\bar{d}), \bar{S}\bar{D}\bar{d}, \bar{S}\bar{U}\bar{u}$$

- **Are many of the “P-wave” hadrons all in S-wave?**

ΔM (qq^{bar}-pair) *v.s.* ΔM (L=1)

However, . . .

Quark core v.s. Hadron molecule

- Most of these multi-quark-like resonances lie close to two-hadron threshold(s)

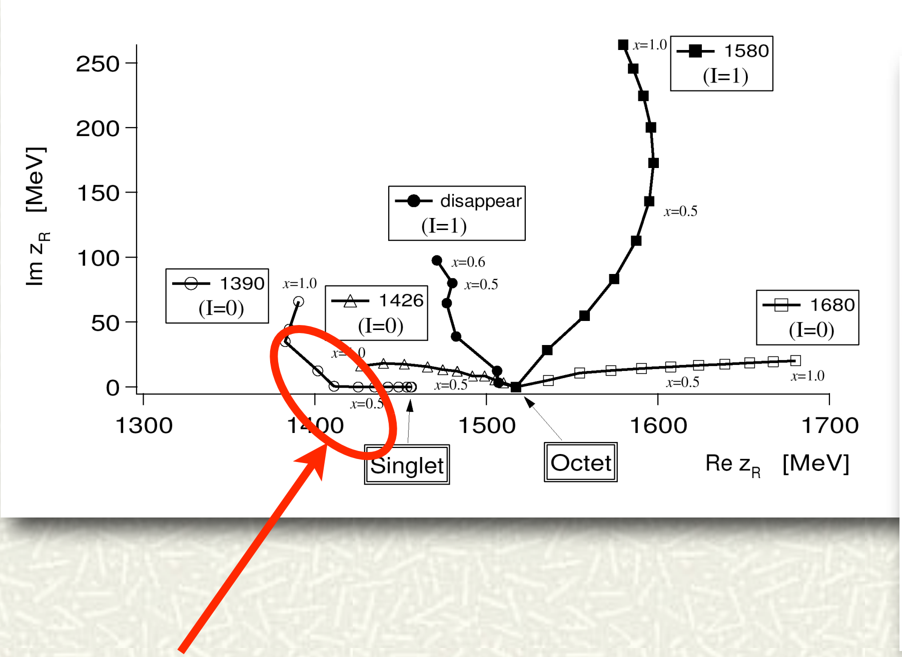
  $f_0(980)$ and $a_0(980)$ *v.s.* KK^{bar}

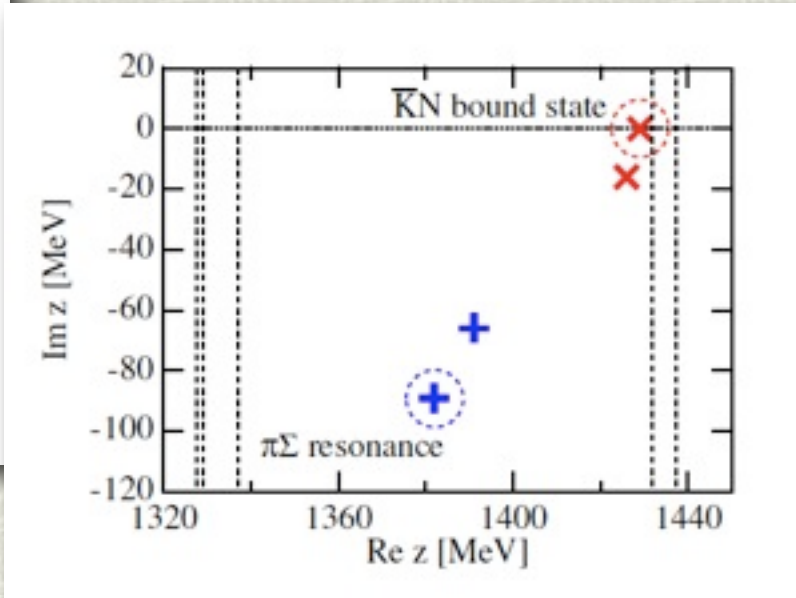
  Λ(1405) *v.s.* NK^{bar}

  X(3872) *v.s.* DD^{*bar}
- Couplings of the "core" quark state with two hadron bound and/or continuum states are important.
- Some resonances are dominated by two-hadron components with significant fraction (sometimes 100%).
  "Hadron Molecules" or color-singlet "Hadron Cluster" states
- "Clustering" is strongly developed at the hadronic thresholds.
- Are there Λ(1405)-like baryons with heavy quark(s)?

Λ(1405) as a molecule

- **Λ(1405) as a K^{bar} N “bound” state.**

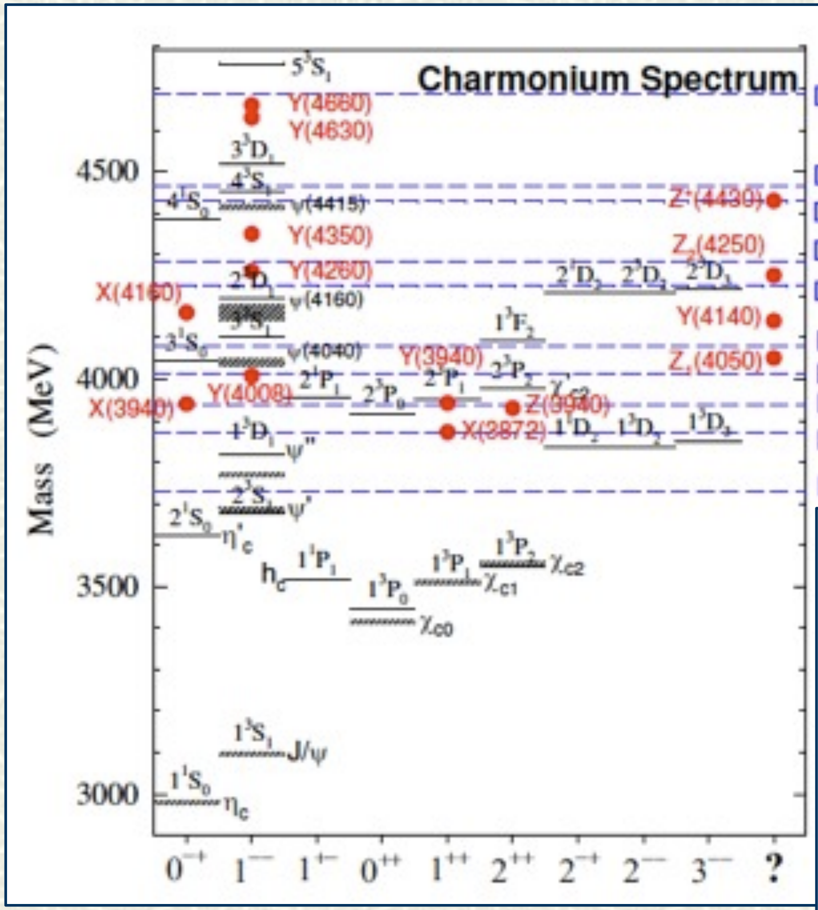




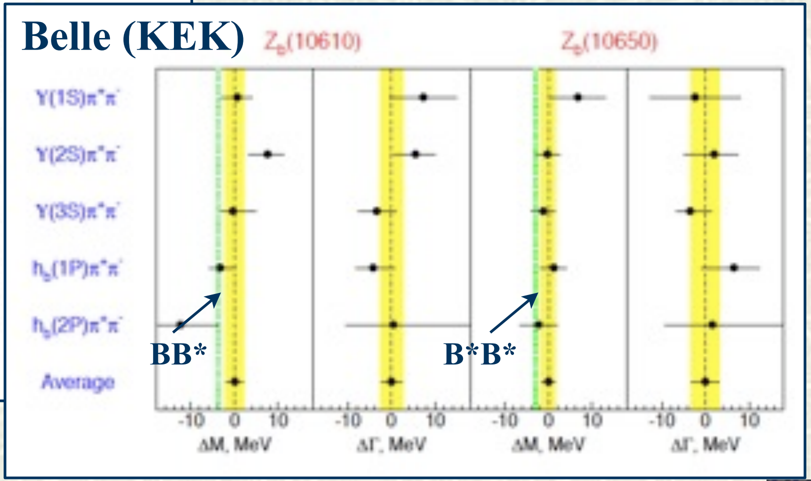
Chiral unitary approaches predict *two resonance poles for Λ(1405)*. (Jido et al., 2003)
They are “generated” by a K^{bar}N bound state and a πΣ resonance. (Hyodo, Weise)

Heavy Exotic Hadrons

- **New quarkonium-like resonances v.s. open charm thresholds**

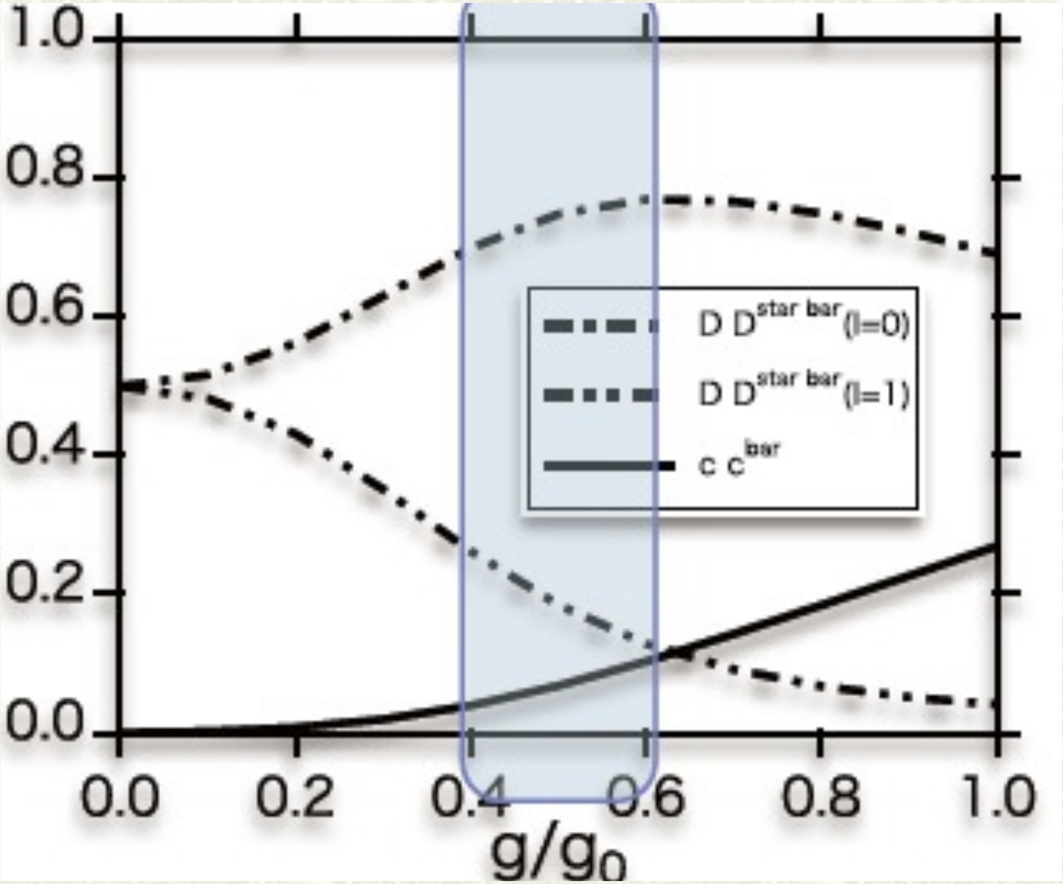


Coincidences of the new quarkonium-like resonances and the open charm (bottom) thresholds motivate interpretations of those states as hadronic molecules.



Exotic Hadrons - Mesons

- **X(3872) Takeuchi, Takizawa**



Exotic Hadrons - Mesons

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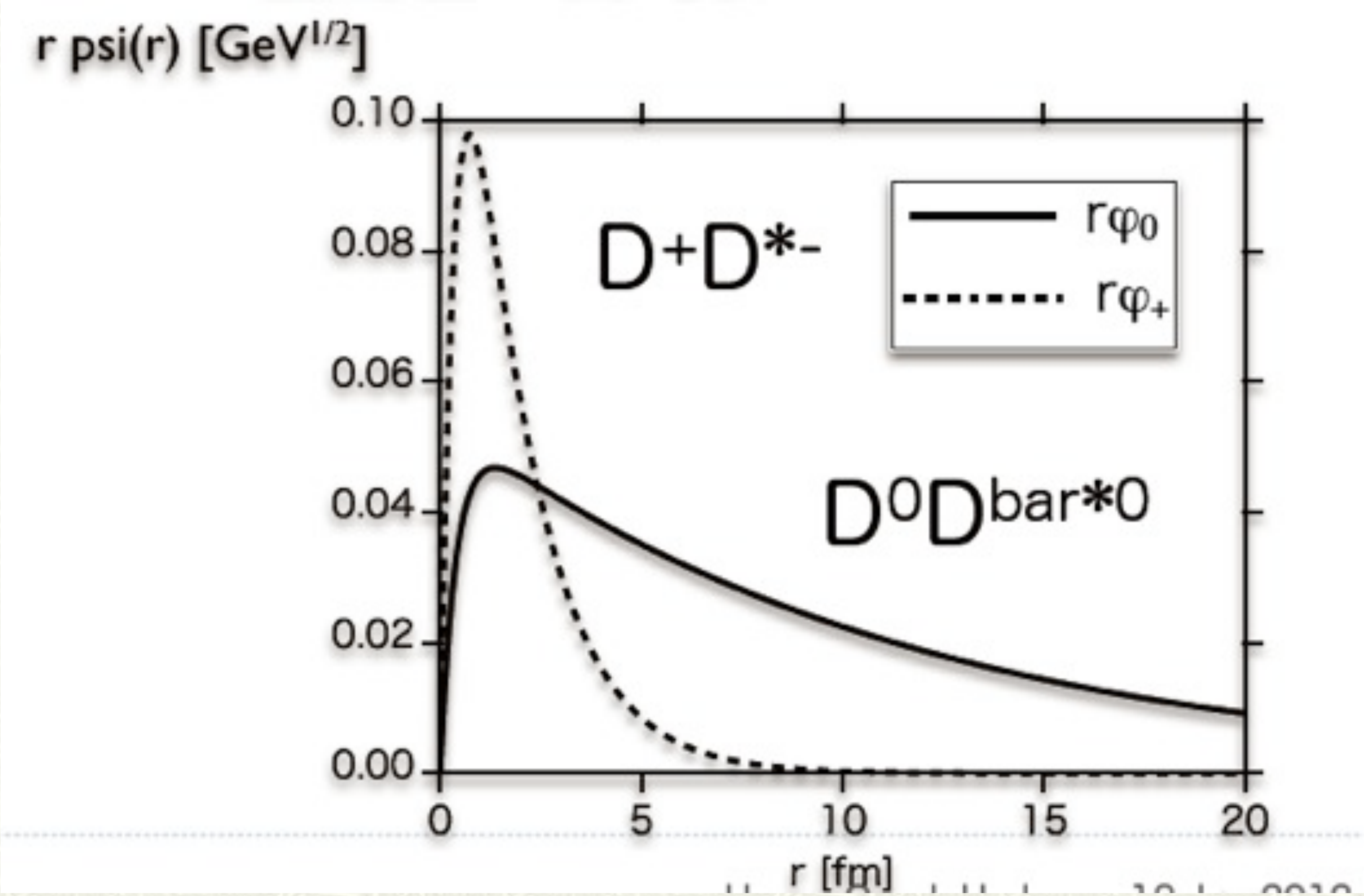

Exotic Hadrons - Mesons

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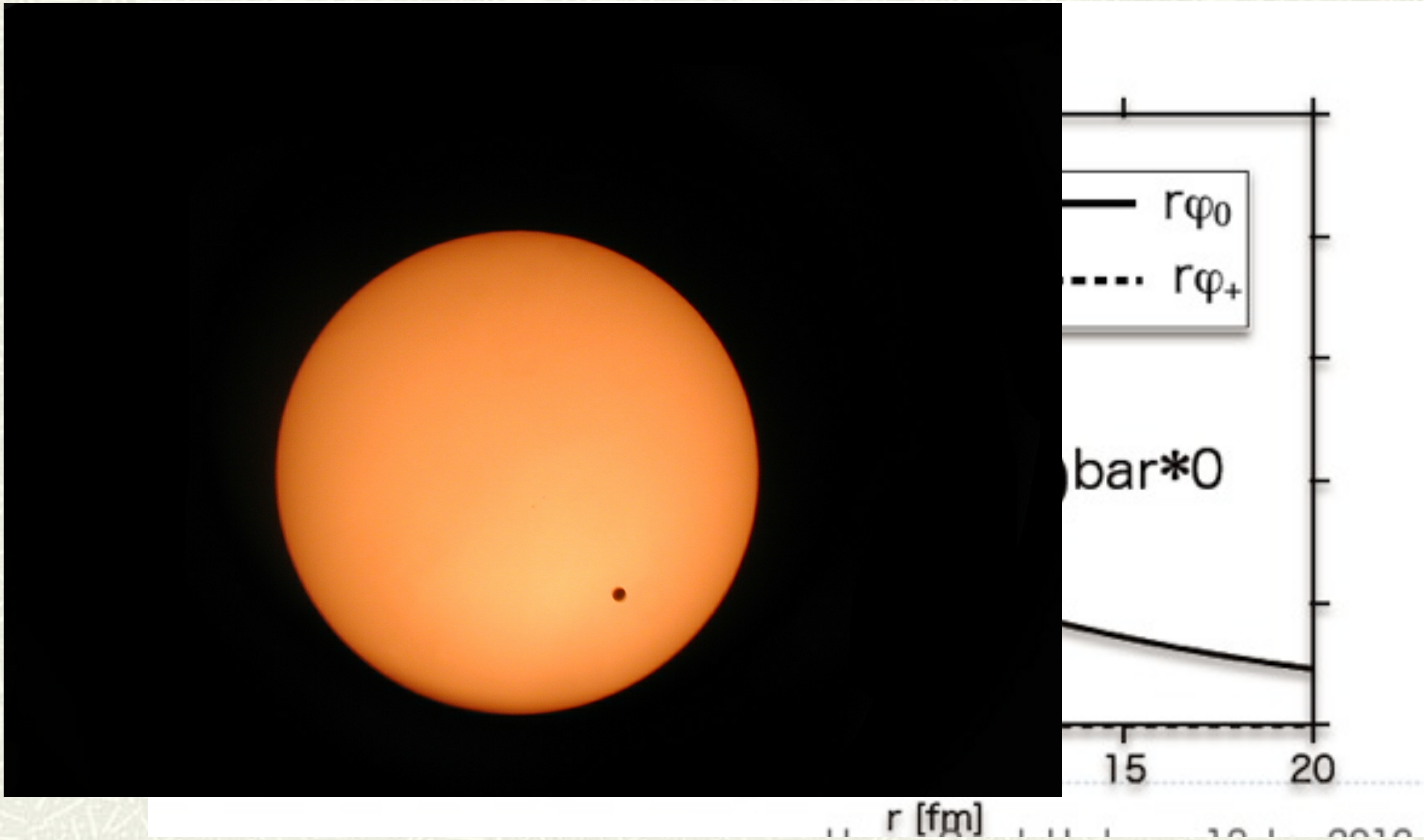


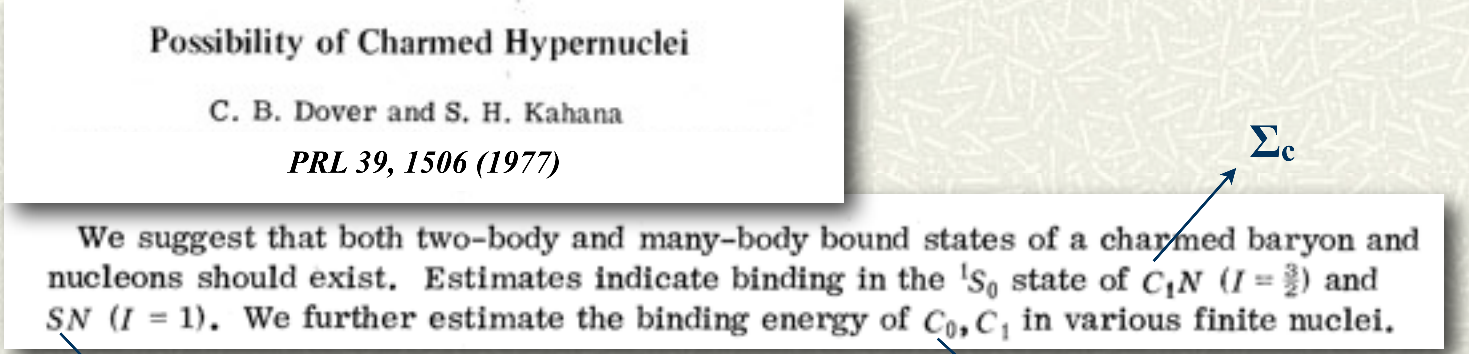
A few questions on Heavy exotics

- **Many mesonic "exotic" resonances have been found at Belle and the other heavy-quark factories.**
  What can J-PARC do? Different production processes are important to reveal exotic natures of resonances.
  Are there Λ(1405)-like baryons with heavy quark(s)?
- **How can we distinguish "exotic" hadrons from the "ordinary" hadrons?**

Charmed Deuteron

Charm in Medium

- **Di-baryon and Nuclei with Heavy Quark(s)**
  Λ_cN, Σ_cN, . . . , (charmed deuteron)
  Ξ_cN, $\Lambda_c\Lambda_c$, $\Lambda_c\Sigma_c$, . . (doubly charmed deuteron)
  Charmed hypernucleus (super-nucleus??)
- **D$^{(*)}$, B$^{(*)}$, J/ψ bound states in nucleus**
  HQ version of the K$^{\mathrm{bar}}$-nucleus
- ***Not a new idea***



Possibility of Charmed Hypernuclei

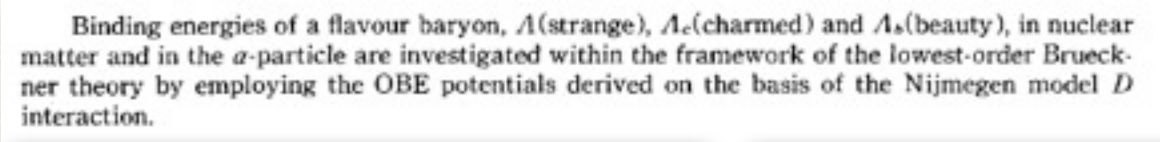
C. B. Dover and S. H. Kahana

PRL 39, 1506 (1977)

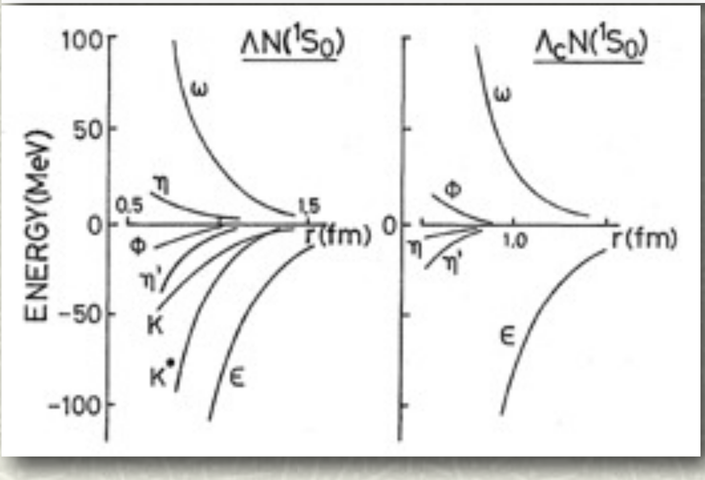
We suggest that both two-body and many-body bound states of a charmed baryon and nucleons should exist. Estimates indicate binding in the $^1S_0$ state of C_1N $(I=\frac{3}{2})$ and SN $(I=1)$. We further estimate the binding energy of C_0, C_1 in various finite nuclei.

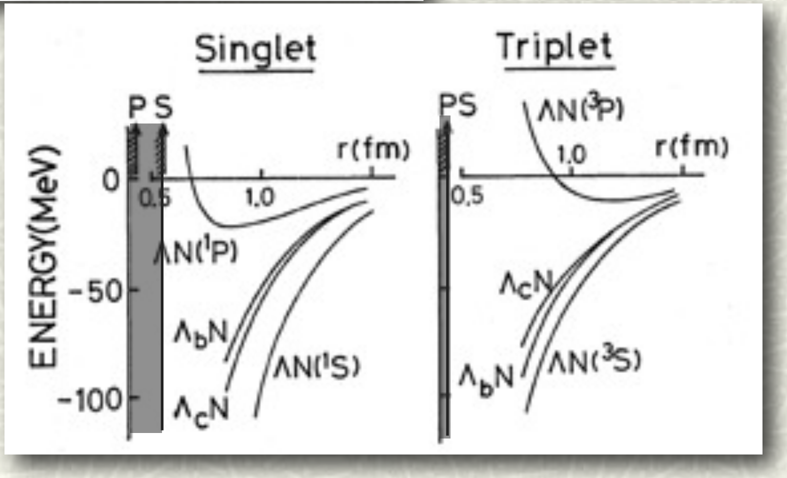
Charmed deuteron

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



Binding energies of a flavour baryon, Λ(strange), Λc(charmed) and Λb(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 D (HC) model potential is employed.**
- **No K, K* exchanges are allowed for the Λ_cN, which results in a weaker Y_cN potential compared with ΛN.**
- **No 2-body bound state is found.**

Charmed deuteron

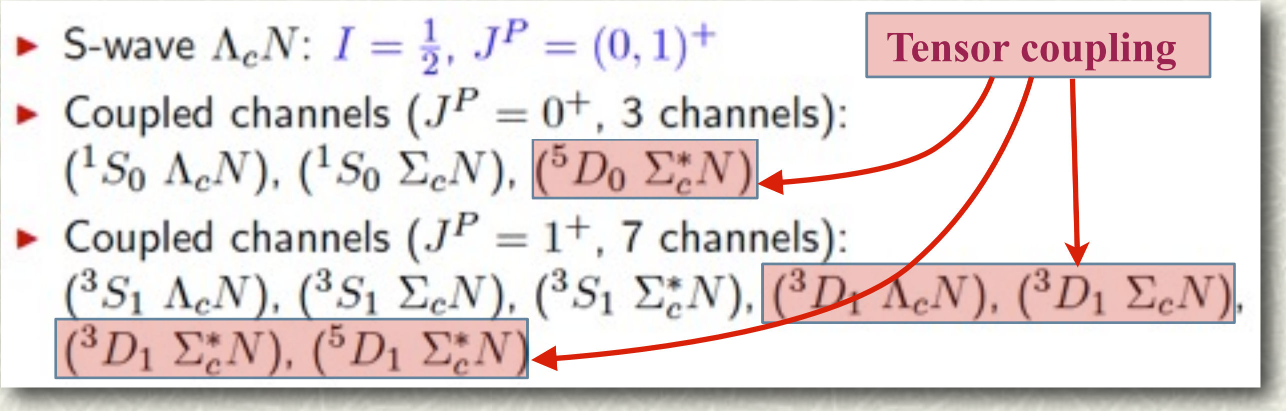
- We reexamine the possibility of the Y_cN and Y_cY_c bound states from the modern view points of the heavy quark symmetry and chiral symmetry.
- Advantages of the heavy baryon systems:
  - The large mass of Y_c suppresses the kinetic energy.
  - Strong Y_c - Y^*_c channel couplings give extra attractions.
- 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.

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

Charmed deuteron

⌗ **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):
  $(^1S_0\ \Lambda_c N)$, $(^1S_0\ \Sigma_c N)$, $(^5D_0\ \Sigma_c^* N)$
- Coupled channels ($J^P = 1^+$, 7 channels):
  $(^3S_1\ \Lambda_c N)$, $(^3S_1\ \Sigma_c N)$, $(^3S_1\ \Sigma_c^* N)$, $(^3D_1\ \Lambda_c N)$, $(^3D_1\ \Sigma_c N)$,
  $(^3D_1\ \Sigma_c^* N)$, $(^5D_1\ \Sigma_c^* N)$

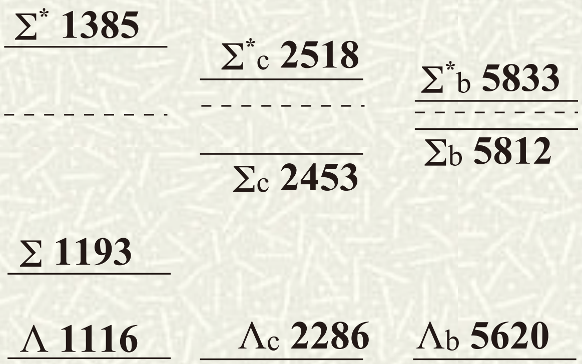
Heavy quark symmetry

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

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

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

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



Σ^* 1385

Σ 1193

Λ 1116

Σ^*_c 2518

Σ_c 2453

Λ_c 2286

Σ^*_b 5833

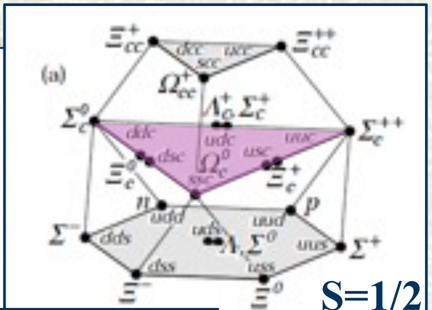
Σ_b 5812

Λ_b 5620

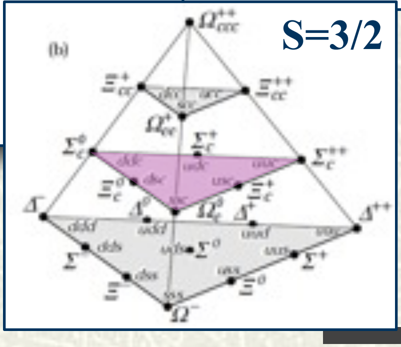
(S, f) = (1/2 3$^{\text{bar}}$) **(1/2 6)**

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

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



S=1/2



S=3/2

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 $k^\mu = O(\Lambda_{\mathrm{QCD}}) \ll m_Q v^\mu$, 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) $(S, f)= (0^+, 3^{\mathrm{bar}})$ or $(1^+, 6)$
    → $(S, f) = (1/2, 3^{\mathrm{bar}}) \oplus [(1/2, 6) \oplus (3/2, 6)]$ degenerate in the HQ limit

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

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

(3/2 6)

$$B_{6\,\mu}^* = \begin{pmatrix} \Sigma_c^{*++} & \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \Sigma_c^{*0} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{*\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime 0} & \Omega_c^{*0} \end{pmatrix}_{\mu} \longrightarrow \boxed{S_\mu = B_{6\,\mu}^* + \frac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma_5 B_6}$$

Georgi

  - 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**

G bosons

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

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

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

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

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

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

Heavy quark symmetry

⌗ Heavy-Quark-Chiral Effective Lagrangian

🟢 **Pseudoscalar (π)**

🔵 **Vector (ρ, ω)**

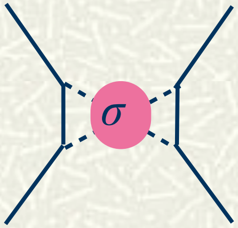
🔴

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

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

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

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



⌗ A flavor singlet (I=0) scalar σ meson (m_σ = 600 MeV) is introduced. It “simulates” exchanges of two pions correlated in the I=0, J=0 channel. We assume that the σ meson couples to *u* and *d* quarks, but not to charm.

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

$\Sigma_c \longrightarrow \Lambda_c + \pi$

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**

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

$\mathcal{O}_i$: spin operators

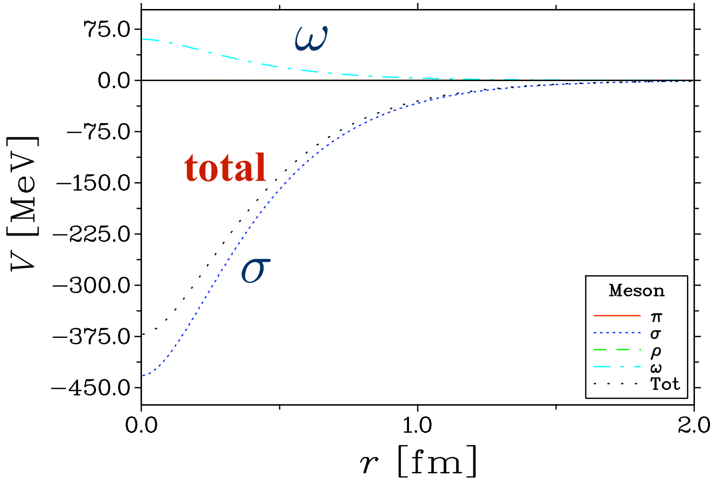
$\mathcal{O}_{ten}$: tensor operator

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

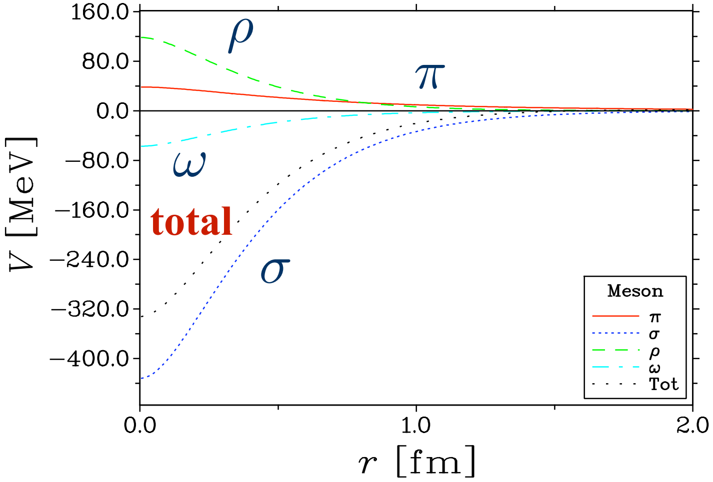
and so on

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

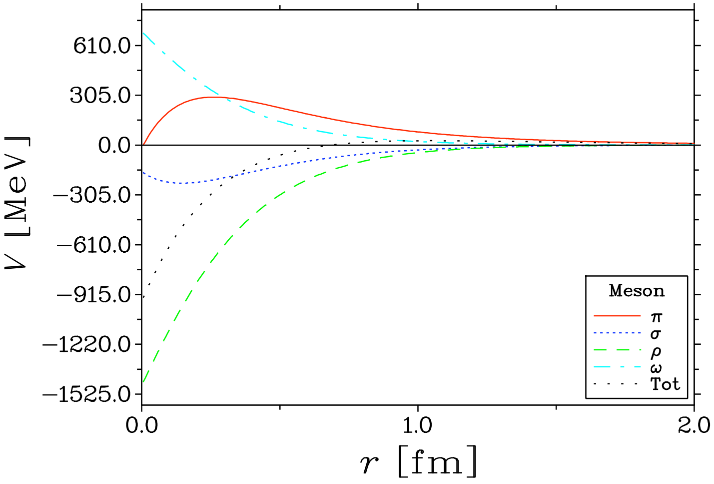
Diagonal potentials with $\Lambda_\pi = \Lambda_\sigma = \Lambda_{\text{vec}} = 1$ GeV



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



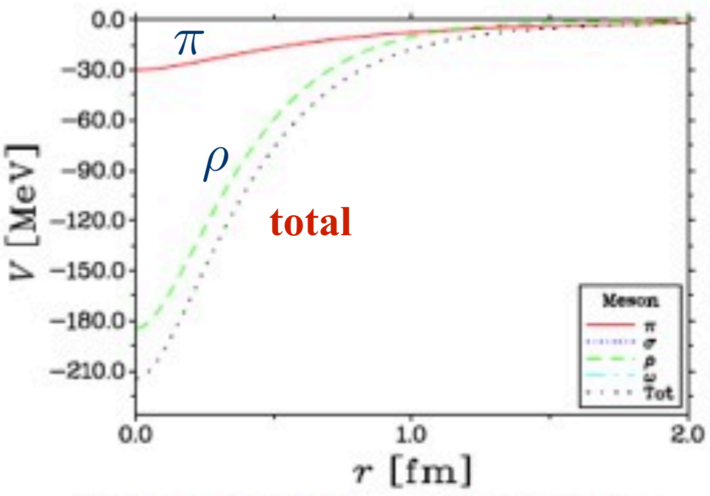
(22): $\Sigma_c N(^1S_0) \leftrightarrow \Sigma_c N(^1S_0)$



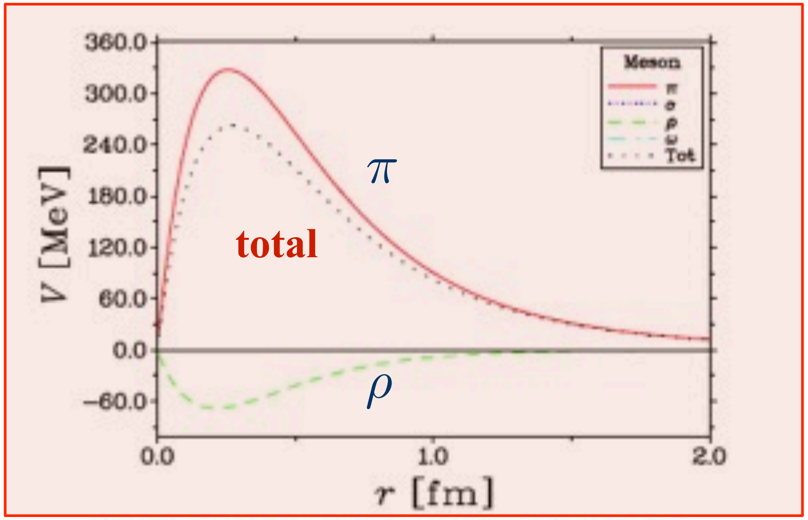
$\Leftarrow$ (33): $\Sigma_c^* N(^5D_0) \leftrightarrow \Sigma_c^* N(^5D_0)$

$\Lambda_c N$: 0^+

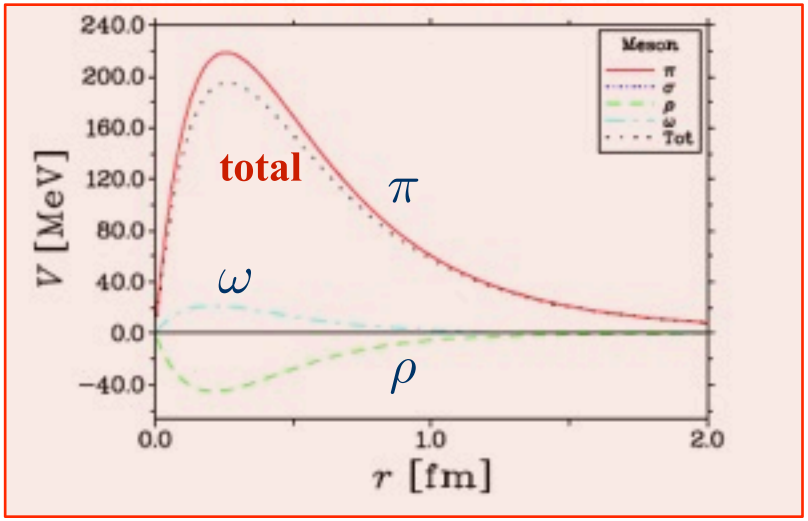
Transition potentials with $\Lambda_\pi = \Lambda_\sigma = \Lambda_{\mathrm{vec}} = 1$ GeV



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



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



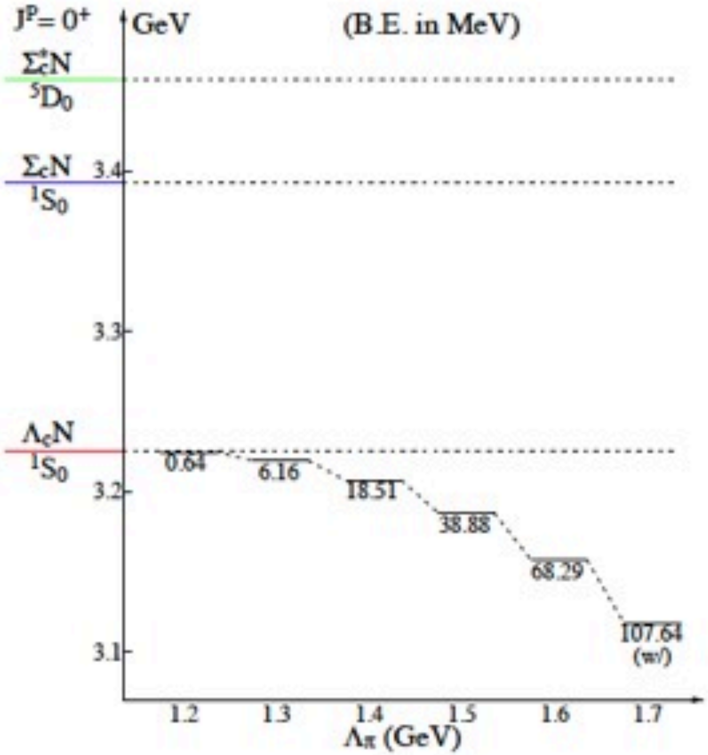
Strong tensor mixings due to the pion exchange potential

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

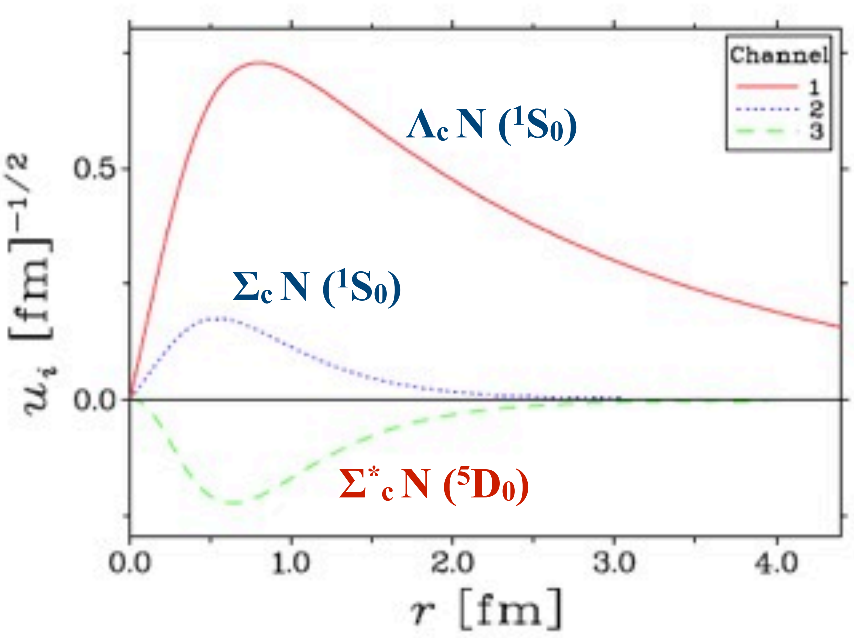
$\Lambda_c N$: 0^+ OPEP model:

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

One Pion Exchange Only



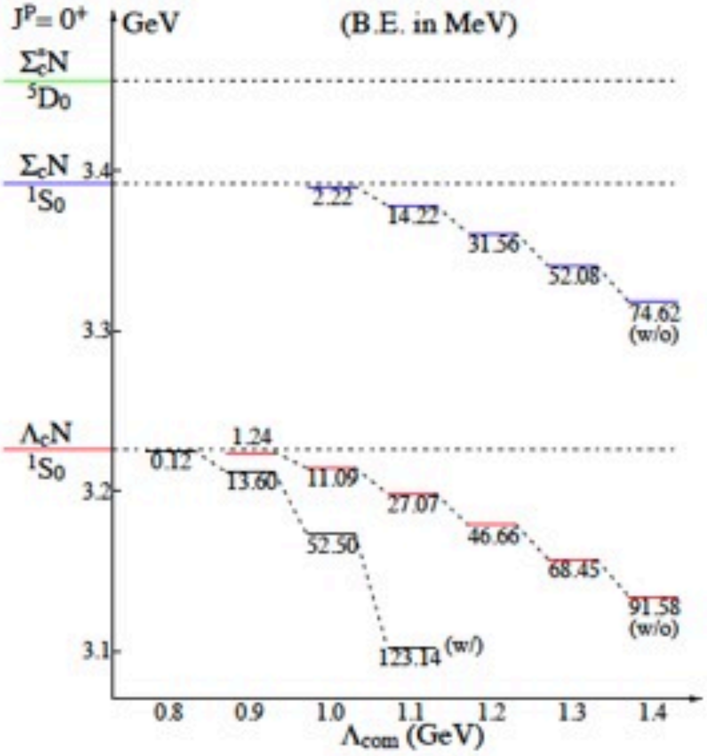
Binding energies (B.E.)

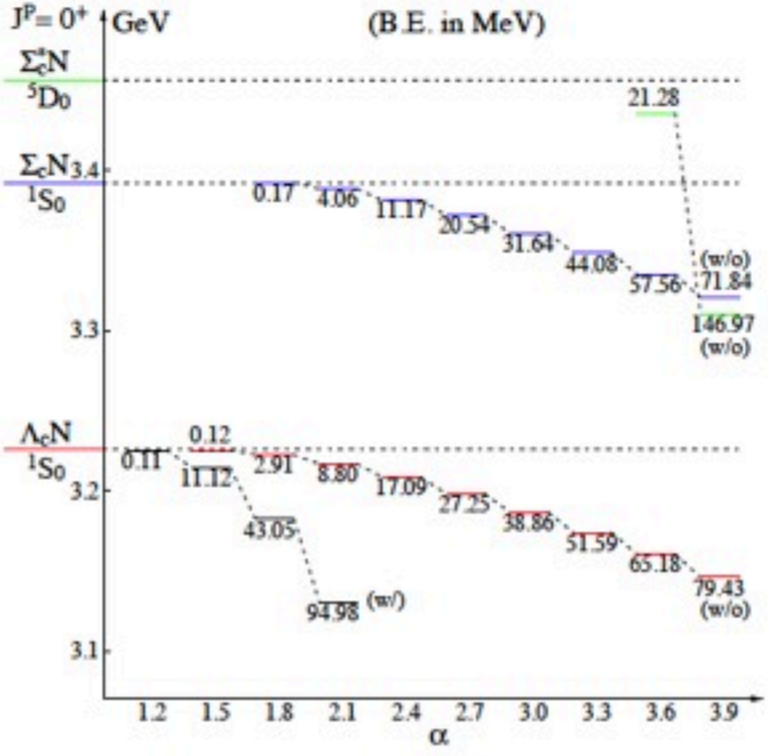


Wave functions with $\Lambda_\pi = 1.3$ GeV

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

OMEP model ($\Lambda_{\rm com}$ & α)



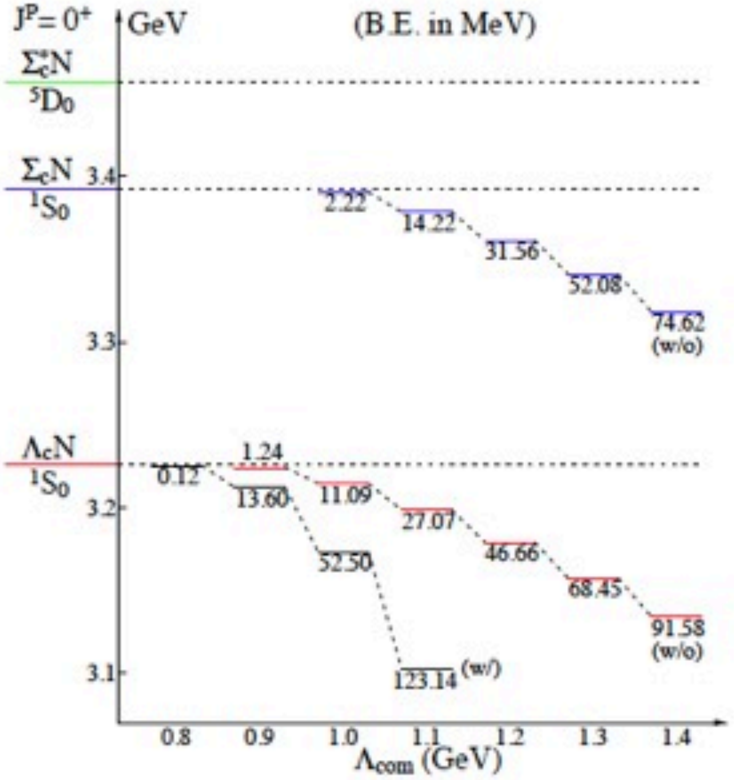


$\Lambda_c N$: 0^+ & 1^+

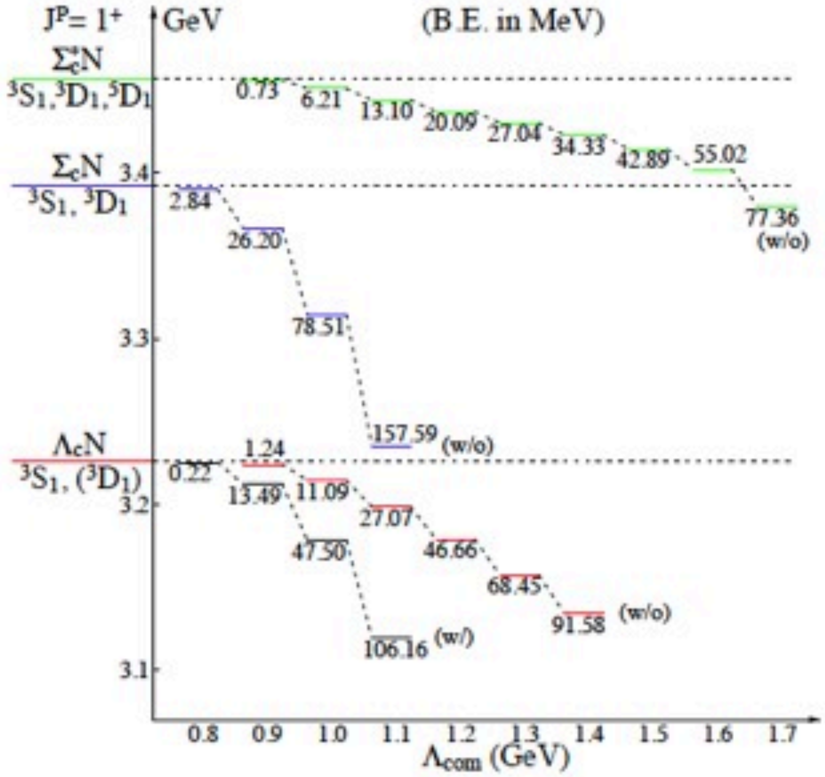
OMEP model ($\Lambda_{\rm com}$)

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

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



$J^P = 0^+$



$J^P = 1^+$

$\Lambda_c N$: comparison

J^P		$\Lambda_c N$ (S-wave)	$\Lambda_c N - \Sigma_c N - \Sigma_c^* N$
0^+	OPEP (Λ)	×	[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)	×	[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 Λ_{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.

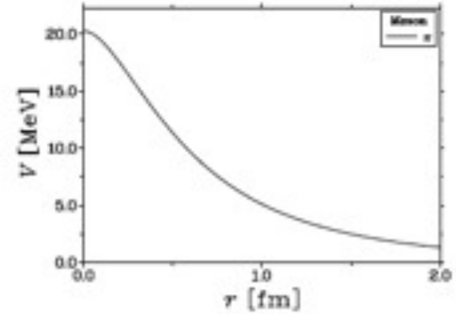
$\Lambda_c\Lambda_c$ ($J^P = 0^+$): Only OPEP model

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

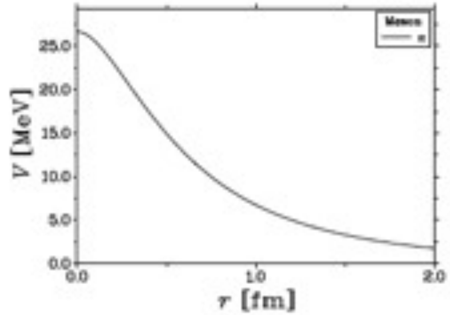
For the $\Lambda_c\Lambda_c$ systems, we take only the one-pion exchange interaction.

Note that there is no $\pi\Lambda_c\Lambda_c$ coupling, and thus the binding comes only from the channel coupling effect.

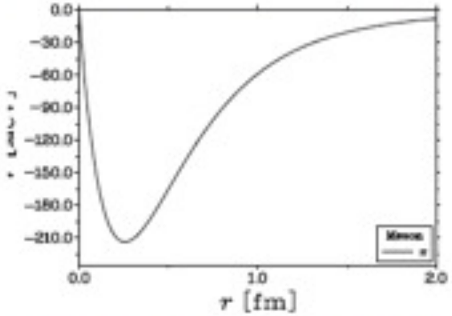
Again the tensor coupling strength is very strong so that the $\Sigma^*_c\Sigma^*_c$ channel contribution is large.



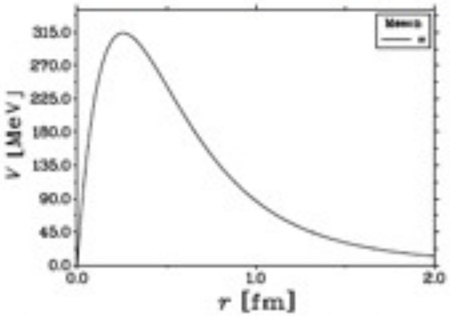
(12): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c\Sigma_c(^1S_0)$



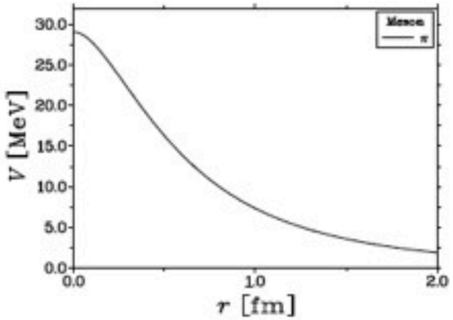
(13): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma^*_c\Sigma^*_c(^1S_0)$



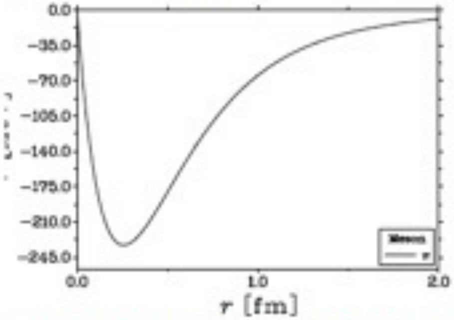
(14): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma^*_c\Sigma^*_c(^5D_0)$



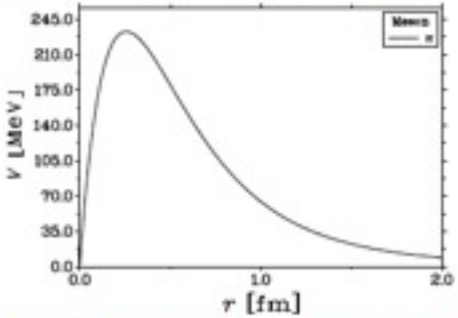
(15): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c\Sigma^*_c(^5D_0)$



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



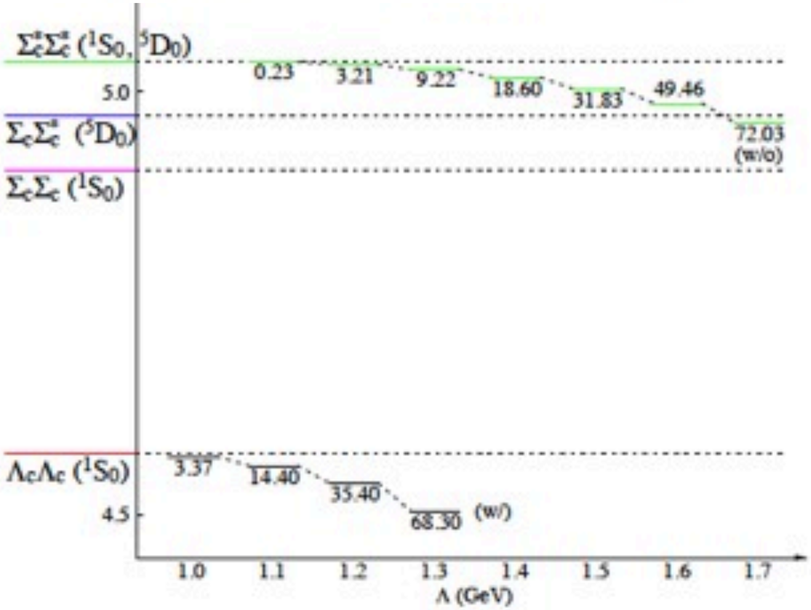
(25): $\Sigma_c\Sigma_c(^1S_0) \to \Sigma_c\Sigma^*_c(^5D_0)$



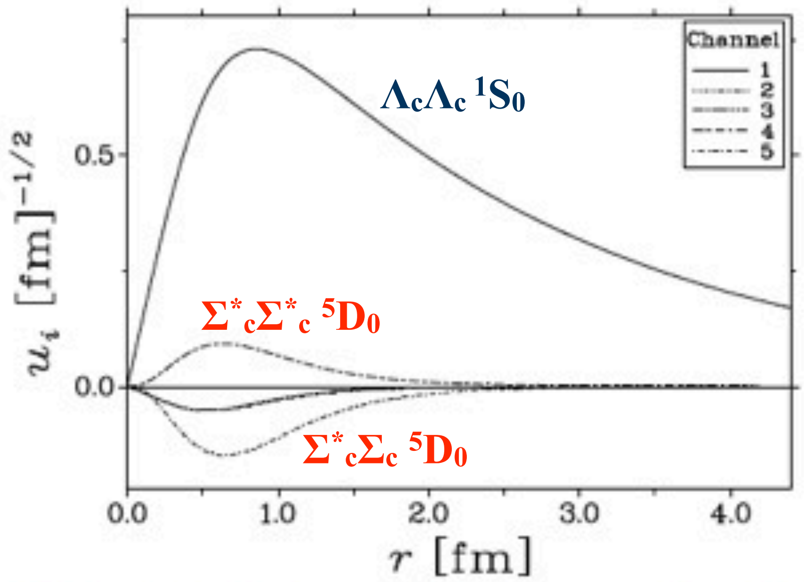
(34): $\Sigma^*_c\Sigma^*_c(^1S_0) \to \Sigma^*_c\Sigma^*_c(^5D_0)$

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

Summary for Charmed Deuteron

- 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.

Short-range repulsion

- **Microscopic view of the short-range B-B interactions can be provided by the quark substructure of the baryons.**
- **The quark Pauli effects for Λ_c-N, Σ_c-N, Λ_c-Λ_c, do not produce strong repulsion at short distances.**
- **On the other hand, the color-magnetic interaction (CMI) will give some repulsion to 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
  $V(\Sigma_c\text{-}N) \sim 100$ 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

Work in progress

Further interests

- Other predictions of heavy-quark bound states
  - DN bound state → Λ^*_c ($1/2^-$) by Mizutani, Ramos.
    DNN may also be bound (Dote, Hyodo, MO).
  - D^{bar} N: exotic (pentaquark) bound state by Yamaguchi, Yasui *et al*.
  - J/ψ, η_c bound nuclei:
    Weak attraction to N with *a* (J/ψ, η_c - N) ~ 0.2-0.4 fm
    in lattice QCD calculation by Kawanai, Sasaki.
    Such an attraction may produce a bound (J/ψ, η_c) - ^{4}He nuclei. (Yokota, Hiyama, MO)

Goals of the Workshop

Questions to be answered

- What are the most valuable observables in HQ physics?
  @ J-PARC?
- What new information does HQ physics give to QCD?
  How are HQs different from q?

Personal answer

- Heavy baryon spectroscopy → excited states
- Exotic heavy meson/baryon states → molecules
- Heavy quark in medium → heavy quark/hadron bound nuclei