Spectroscopy of Heavy Quark Hadrons

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Chiral Symmetry in Hadrons and Nuclei
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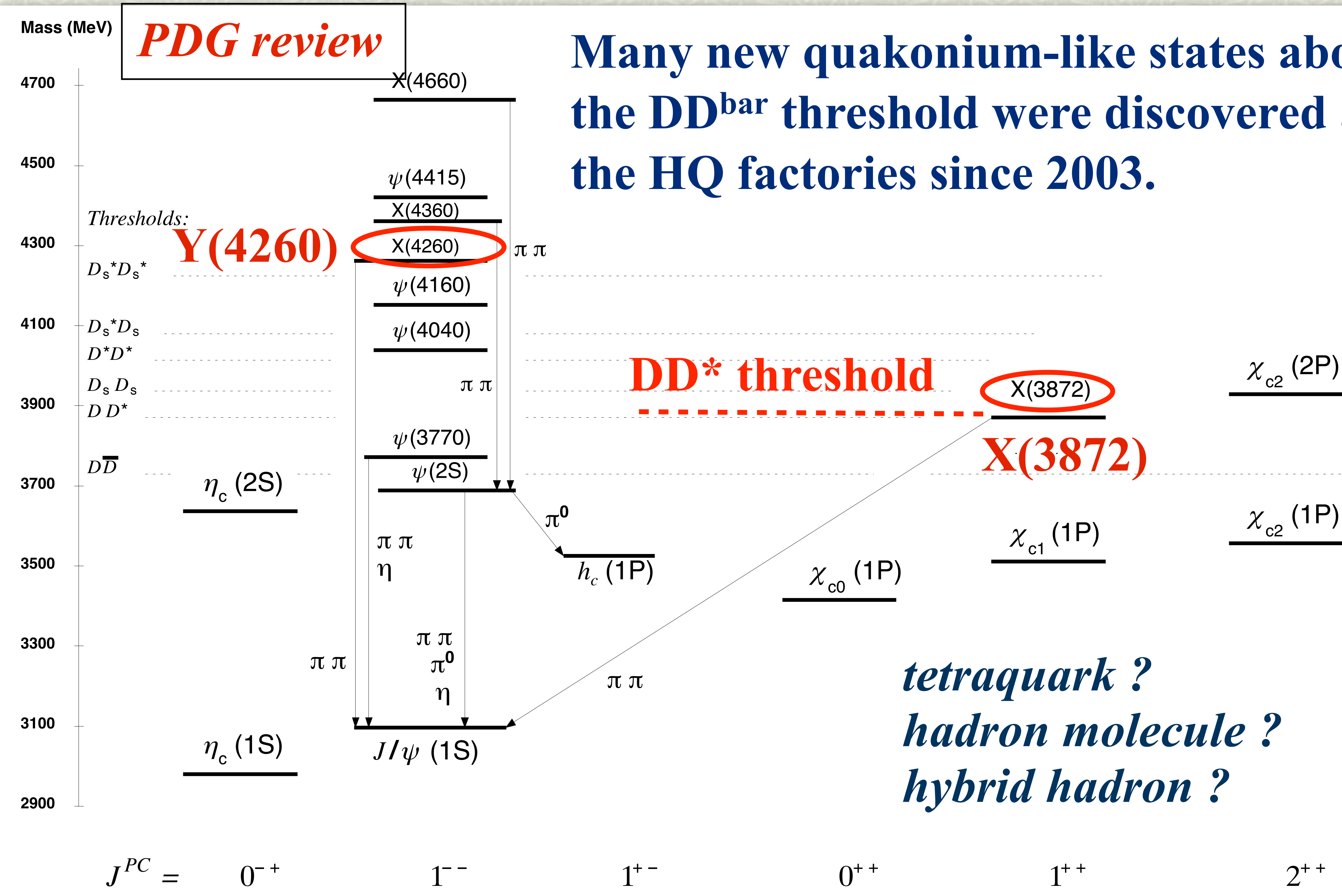
Heavy Quark Physics
Key Dynamics

Quarkonium(-like) mesons



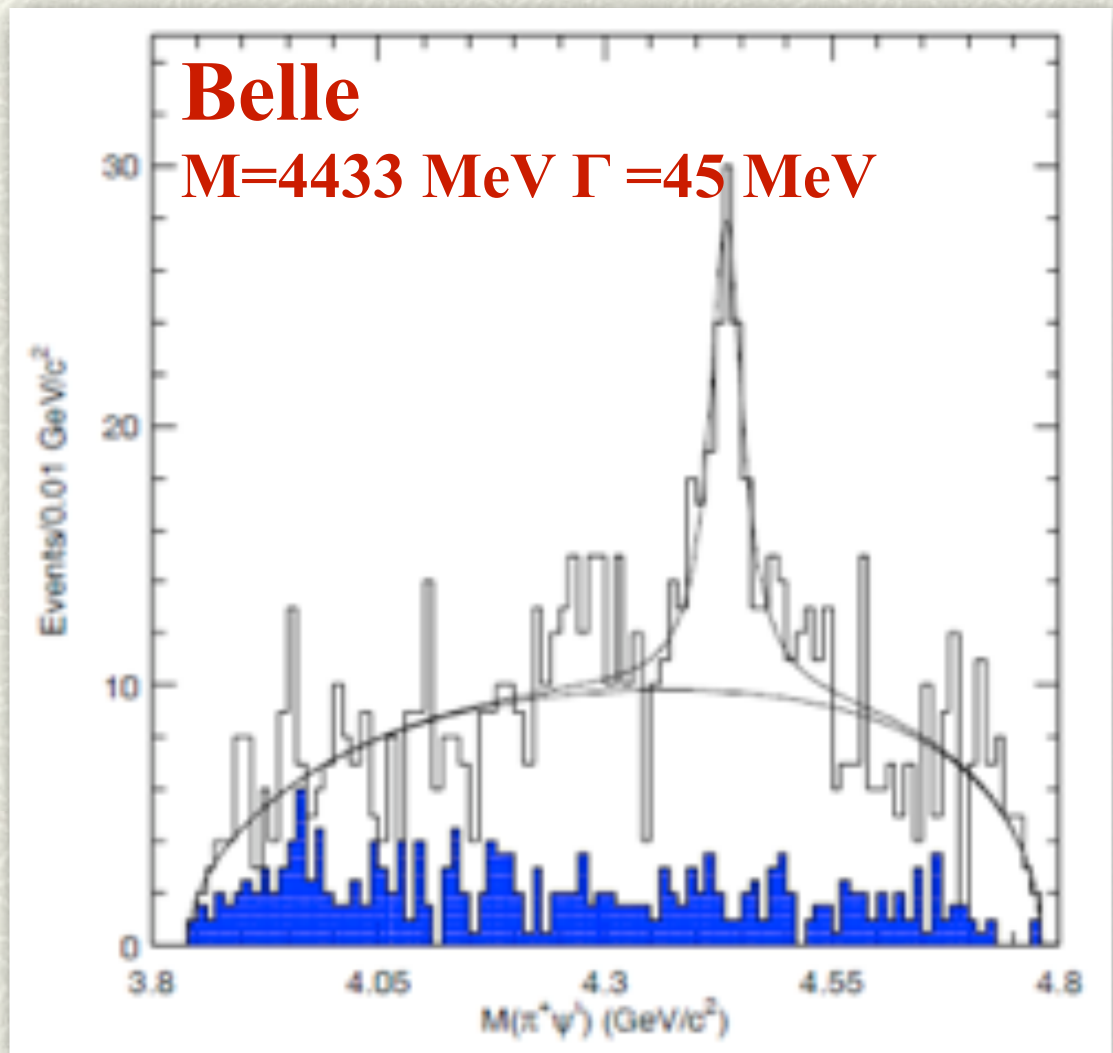
Many new quakonium-like states above the DD^{bar} threshold were discovered at the HQ factories since 2003.

tetraquark ?
hadron molecule ?
hybrid hadron ?

Quarkonium(-like) mesons

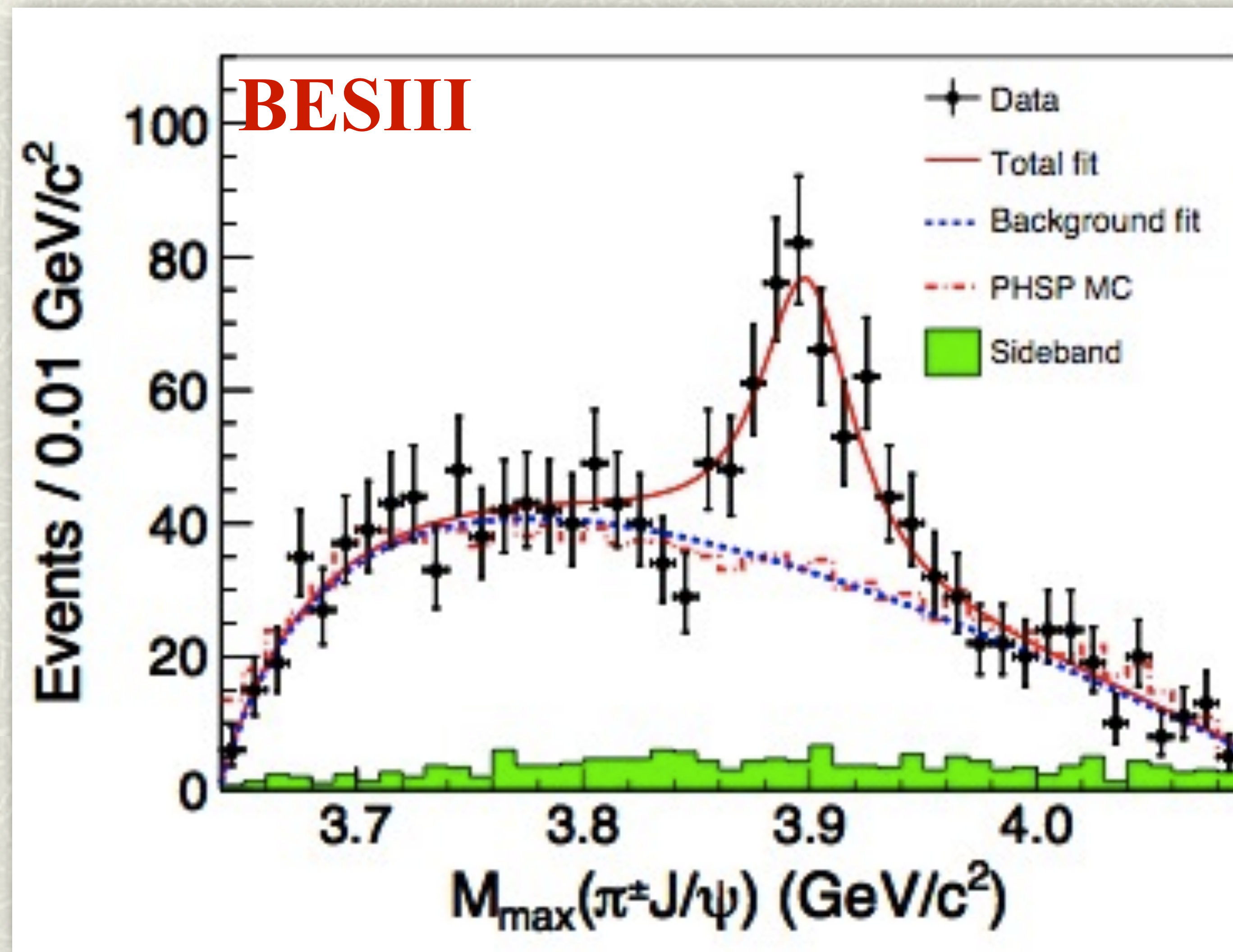
- Charged "Charmonium" at Belle and BESIII

$Z_c^+(4430)$, $Z_{c1}(4050)$, $Z_{c2}(4250)$



PRL 100 (2008) 142001

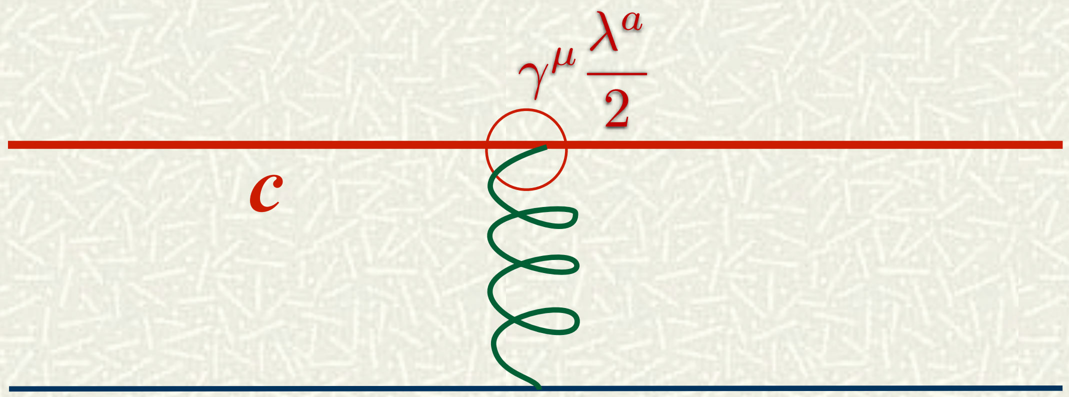
$Z_c(3900)$, $Z_c(4020)$



PRL 110 (2013) 252001

Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



$$\bar{\Psi}\gamma^\mu \frac{\lambda^a}{2}\Psi A_\mu^a \sim \Psi^\dagger \frac{\lambda^a}{2}\Psi A_0^a - \Psi^\dagger \sigma \frac{\lambda^a}{2}\Psi \cdot \frac{1}{m_Q}(\nabla \times A^a)$$

(Color Electric coupling) ≫ (Color Magnetic coupling)

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

⇨ **Heavy Quark Spin Symmetry**

Heavy Quark Spin Symmetry

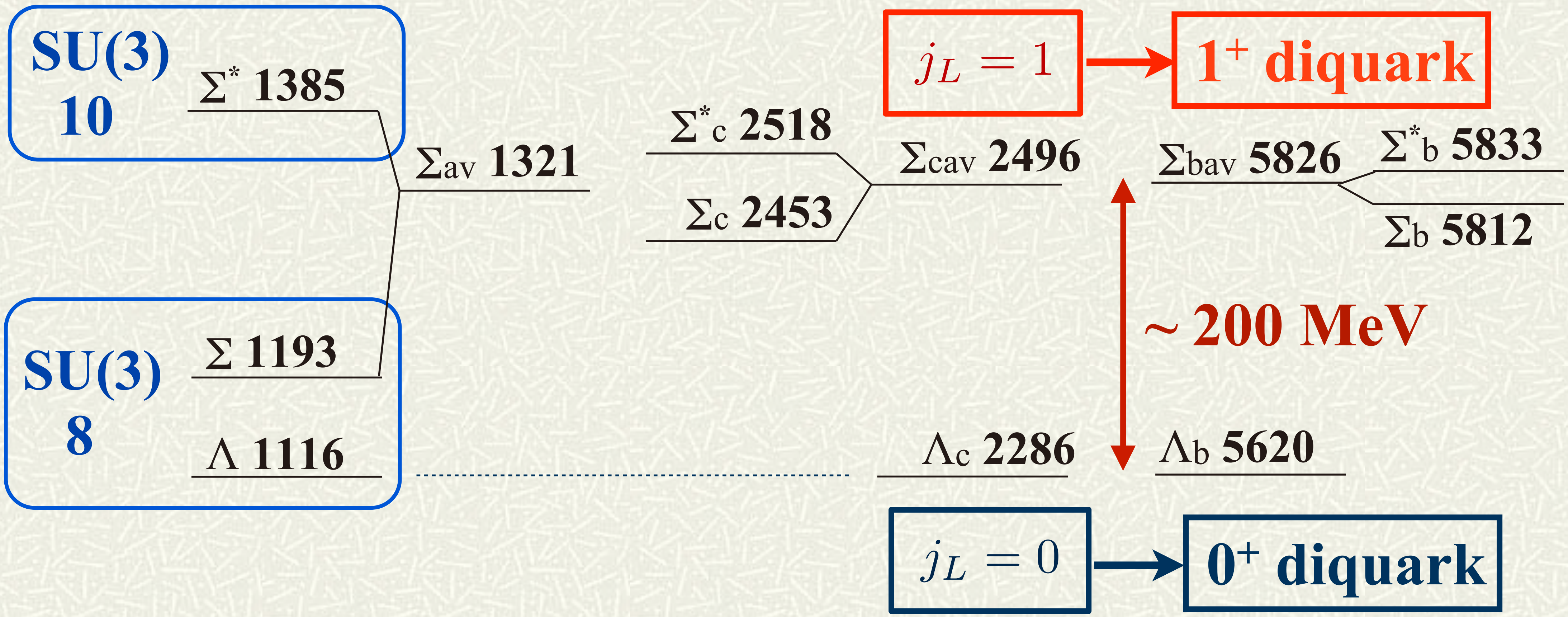
HQ spin symmetry $[S_Q, H] = O\left(\frac{1}{m_Q}\right)$

Q

q

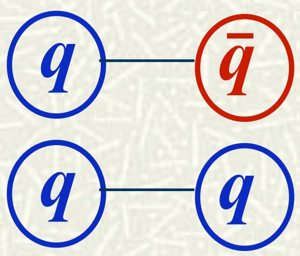
$$\vec{J} = \vec{S}_Q + \vec{j}_L \qquad \vec{j}_L = \vec{S}_q + \vec{L}_q$$

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



Diquark

- QCD predicts attraction in the PS and S channels:
  PS meson qq^{bar} : color 1, $J^{\pi}=0^{-}$, flavor 1+8
  S diquark $[qq]_0$: color 3^{bar}, $J^{\pi}=0^{+}$,
  flavor SU(3) 3^{bar} : $[ud]_0$, $[ds]_0$, $[sd]_0$



- perturbative one gluon exchange - *Color Magnetic Interaction*
  CMI = $(-\alpha)\,\Sigma_{ij}\,(\lambda_i\cdot\lambda_j)\,(\sigma_i\cdot\sigma_j) = -16\,\alpha$ for PS qq^{bar} meson
  $= -8\,\alpha$ for S qq diquark

- non-perturbative *Instanton Induced Interaction* (III)
  attraction in the flavor antisymmetric states

- These quark-model interactions yield
  $M(A)-M(S) = (2/3)\,[M(\Delta)- M(N)] \sim 200$ MeV
  $(32/3)\alpha$ $\quad +8\,\alpha - (-8\,\alpha) = 16\,\alpha$

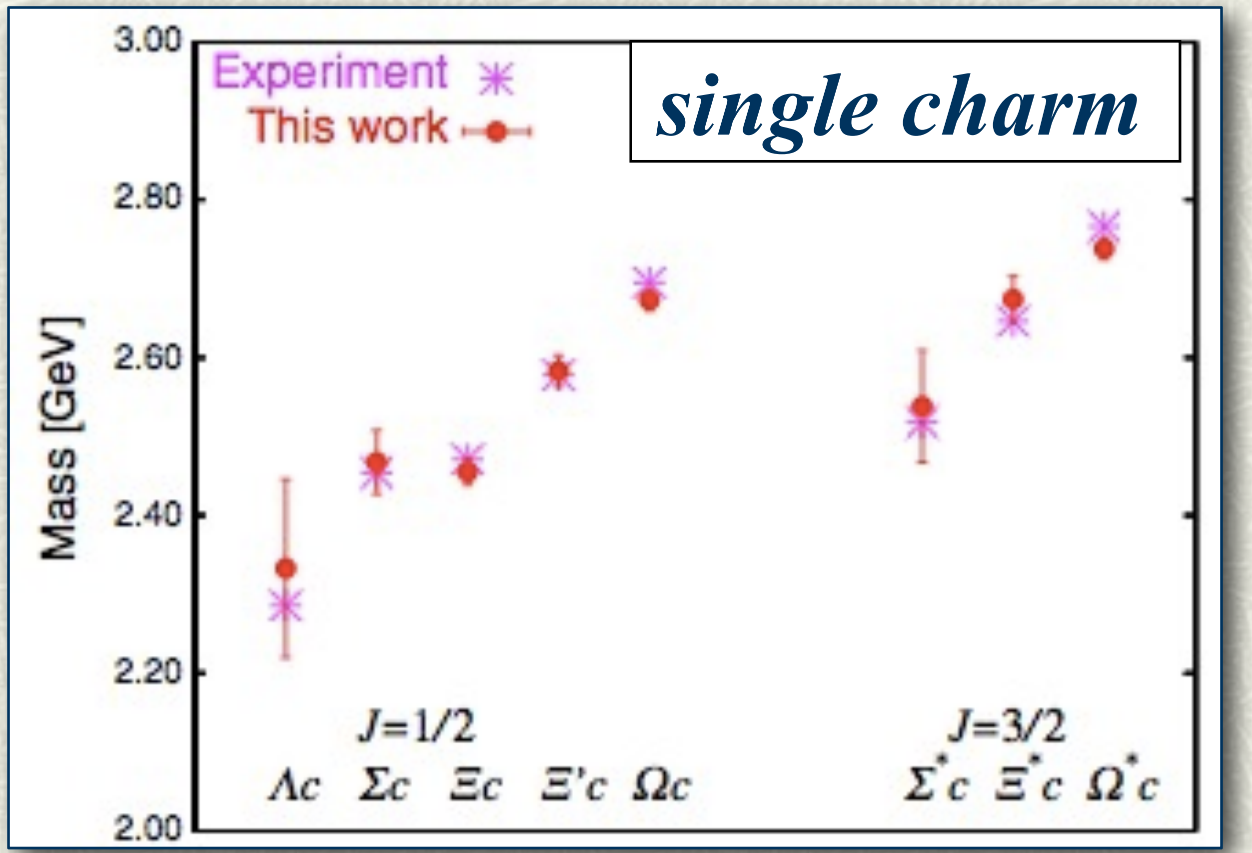
Diquark

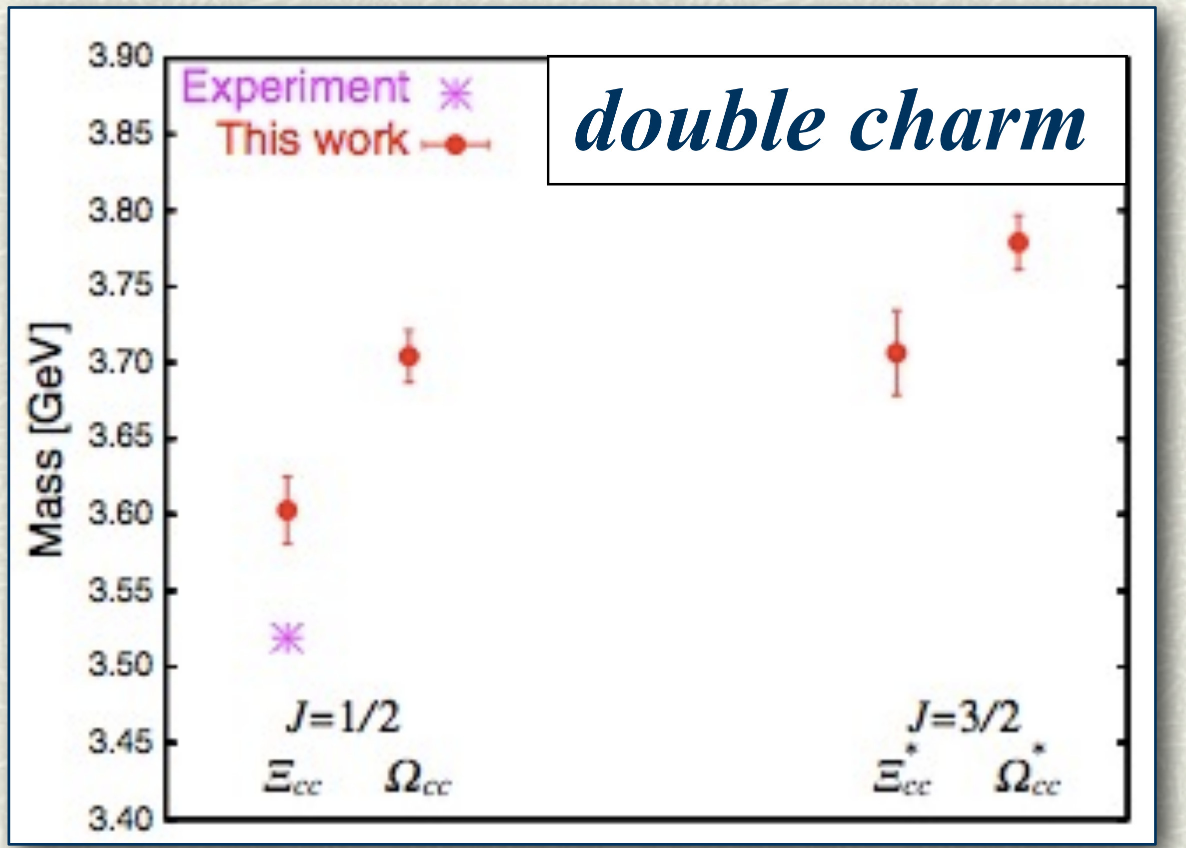
- Diquarks in (quenched) lattice calculations
  - Hess, Karsch, Laermann, Wetzorke, PR D58, 111502 (1998)
    from the correlators in the Landau gauge
    m_q ~ 342 MeV, M(S) ~ 694 MeV, M(A) ~ 810 MeV
  - Alexandrou, de Forcrand, Lucini, PRL 97, 222002 (2006)
    gauge invariant calculation inside a 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

Charmed Baryon Spectroscopy

Ground states

- All the ground-state (S-wave) single charm baryons have been observed, and are consistent with the quark model.
- Lattice QCD reproduces the ground state baryon spectrum fairly well.
- Y. Namekawa, et al., (PACS-CS Collaboration)
(2+1) flavor with physical quark mass, PRD 87, 094512 (2013)





Ground states

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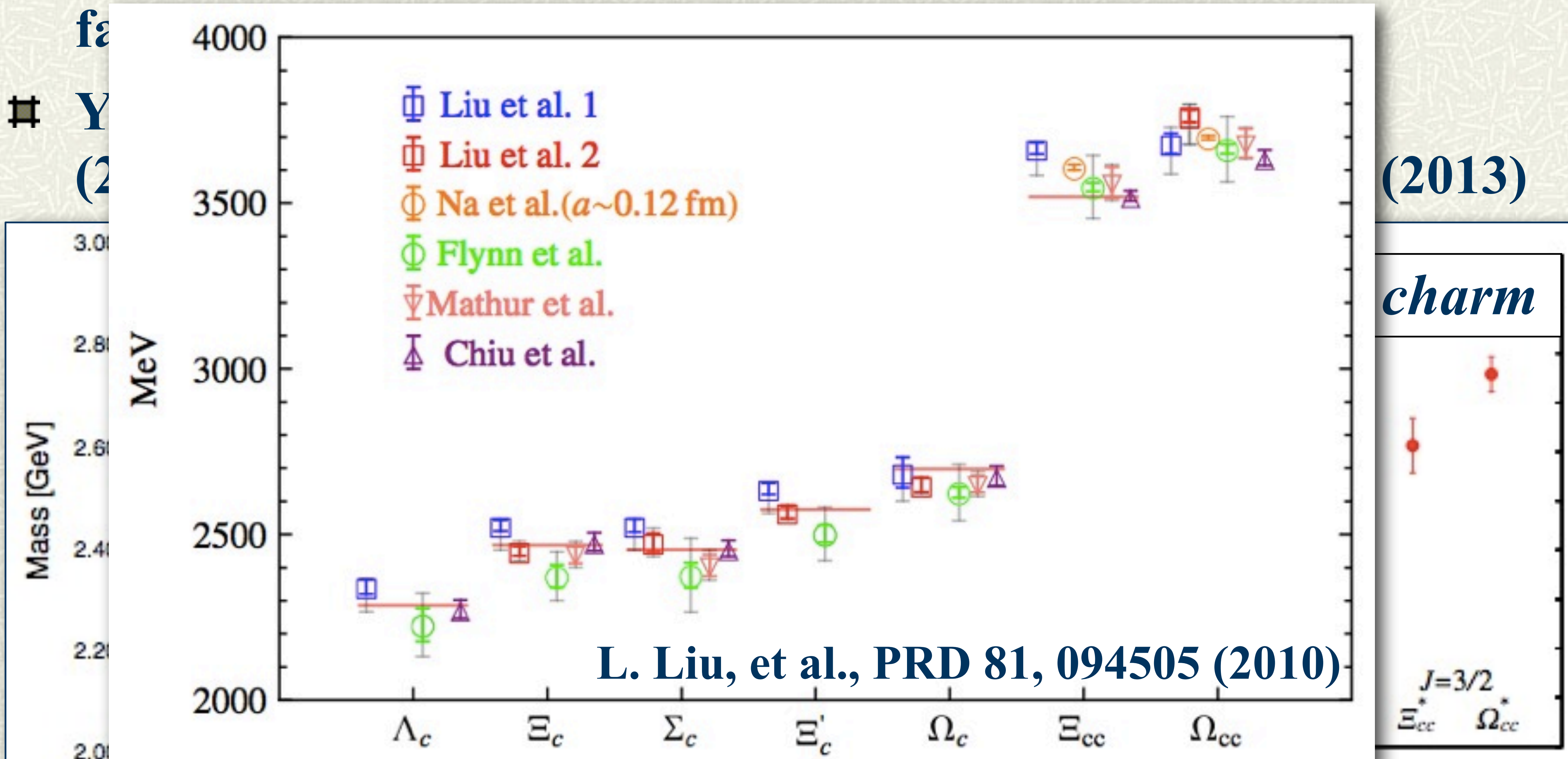
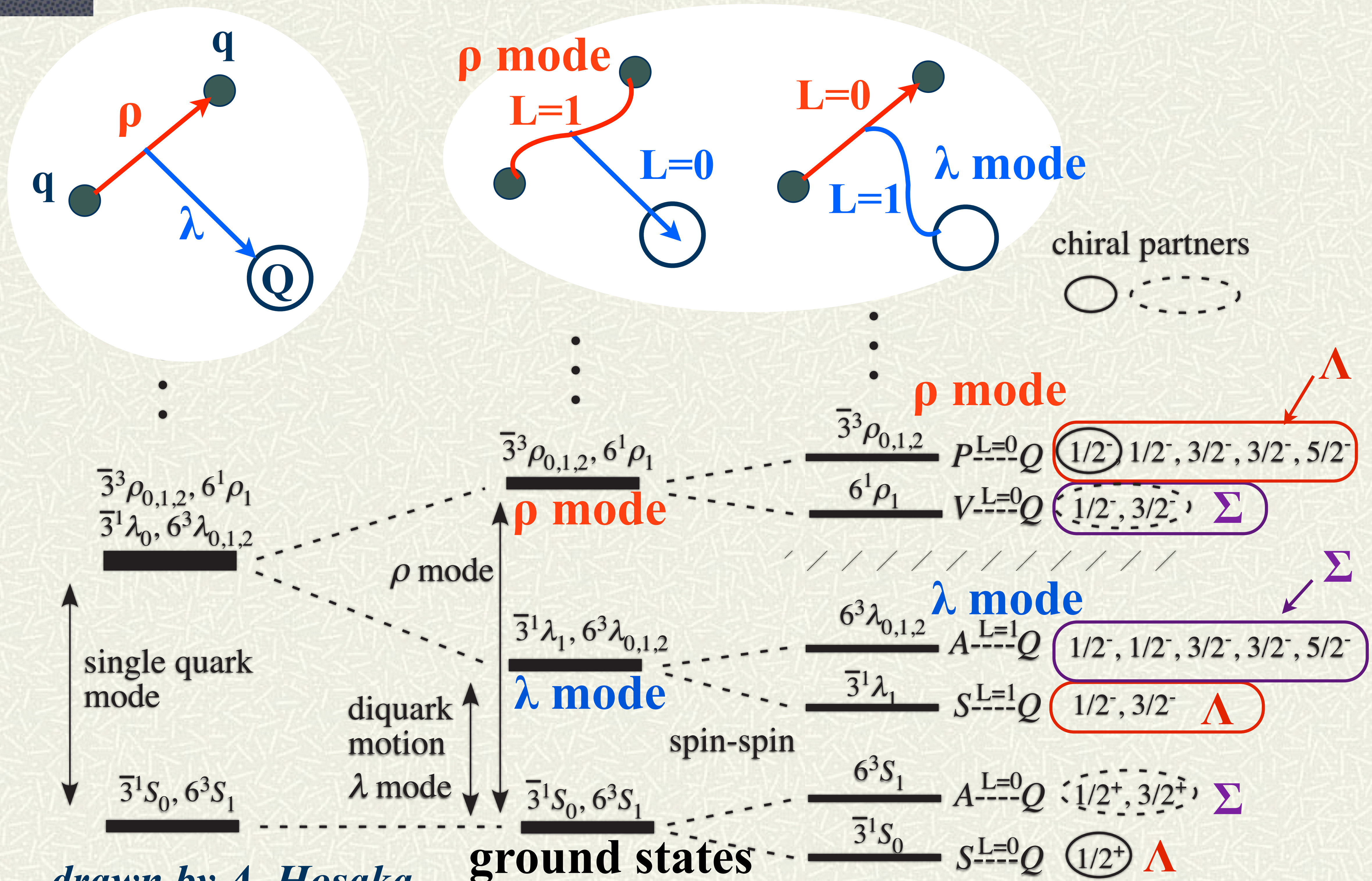
  (2 (2013)



L. Liu, et al., PRD 81, 094505 (2010)

Negative-parity (P-wave) Baryons



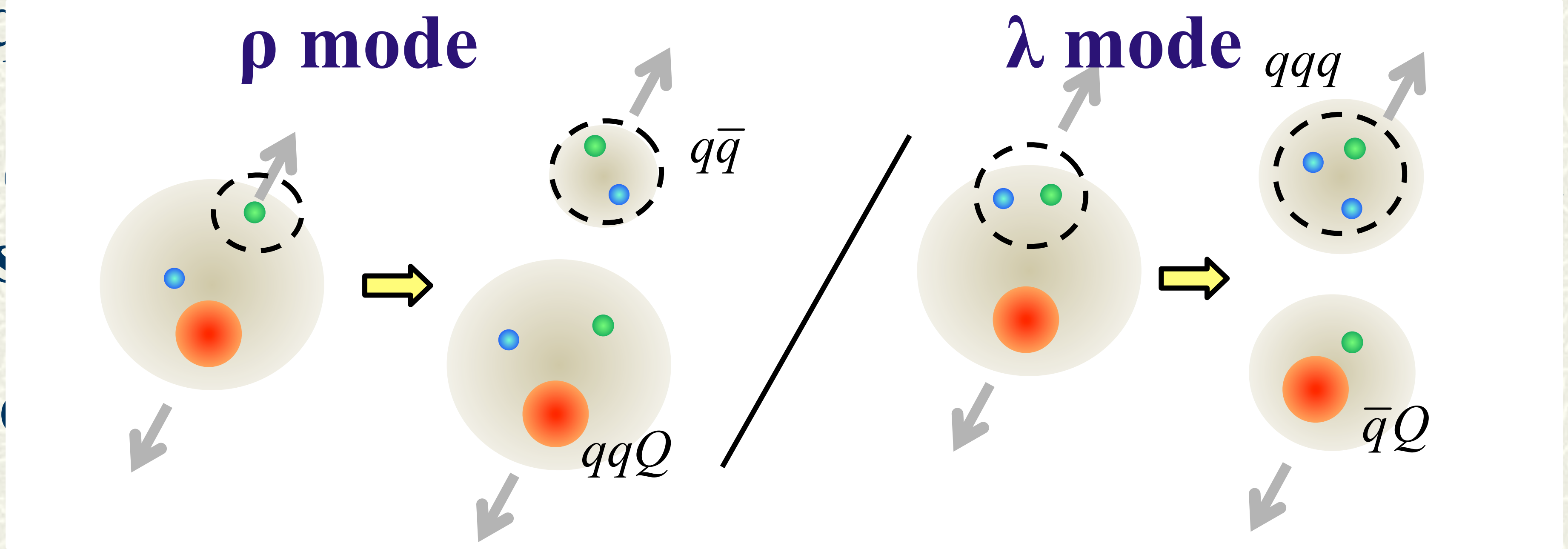
drawn by A. Hosaka

Negative-parity (P-wave) Baryons

- The **Diquark** "cluster" can be identified with the help of the heavy quark in the HQ baryon spectroscopy.
- The ρ mode excitations of the HQ baryons provide us with a diquark spectrum.
- The λ mode excitations reveal the interaction of the diquarks.
- The decays of the ρ and λ modes have different properties.
  ρ-mode $\rightarrow$ Heavy baryon (Qqq) + light mesons (qq^{bar})
  λ-mode $\rightarrow$ Heavy meson (Qq^{bar}) + light baryon (qqq)

Negative-parity (P-wave) Baryons

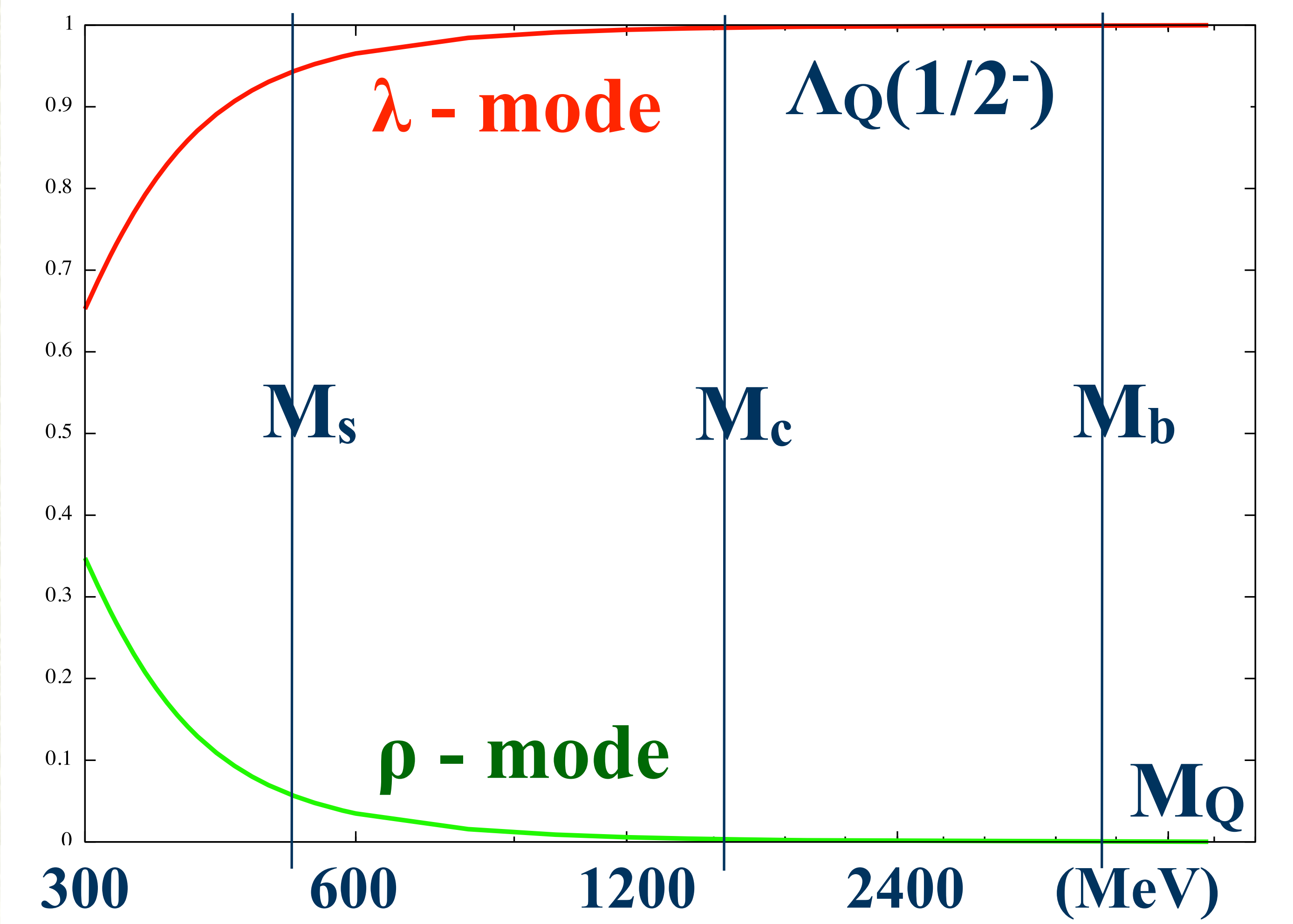
- The Diquark “cluster” can be identified with the help of the heavy q



- The ρ mod
  a diquark s
- The λ mod
  diquarks.
- The decays of the ρ and λ modes have different properties.
  ρ-mode → Heavy baryon (Qqq) + light mesons (qq^{bar})
  λ-mode → Heavy meson (Qq^{bar}) + light baryon (qqq)

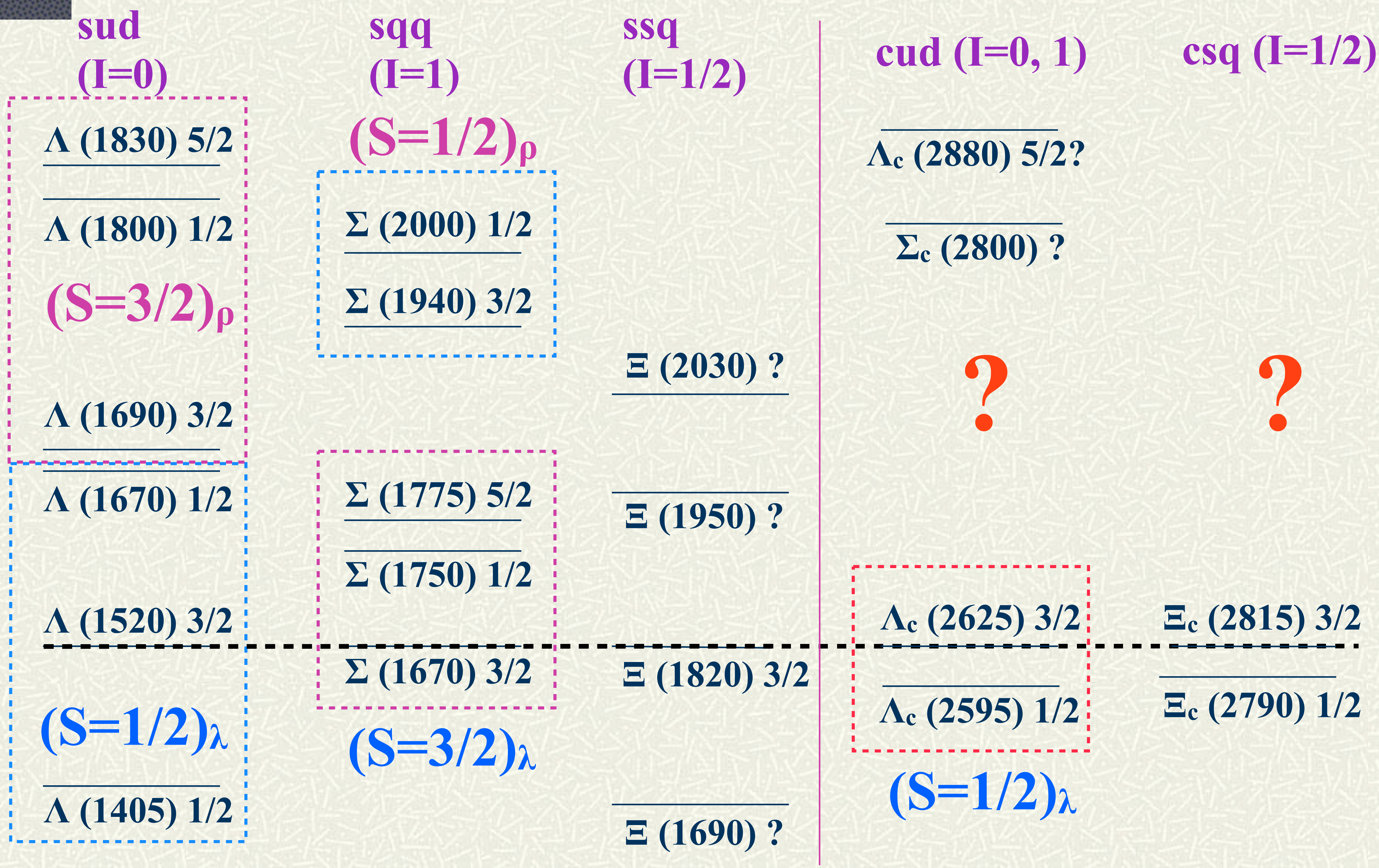
Negative-parity (P-wave) Baryons

- **Probabilities of λ and ρ modes *v.s.* heavy quark mass by a Hamiltonian quark model with spin-spin, spin-orbit and tensor forces**

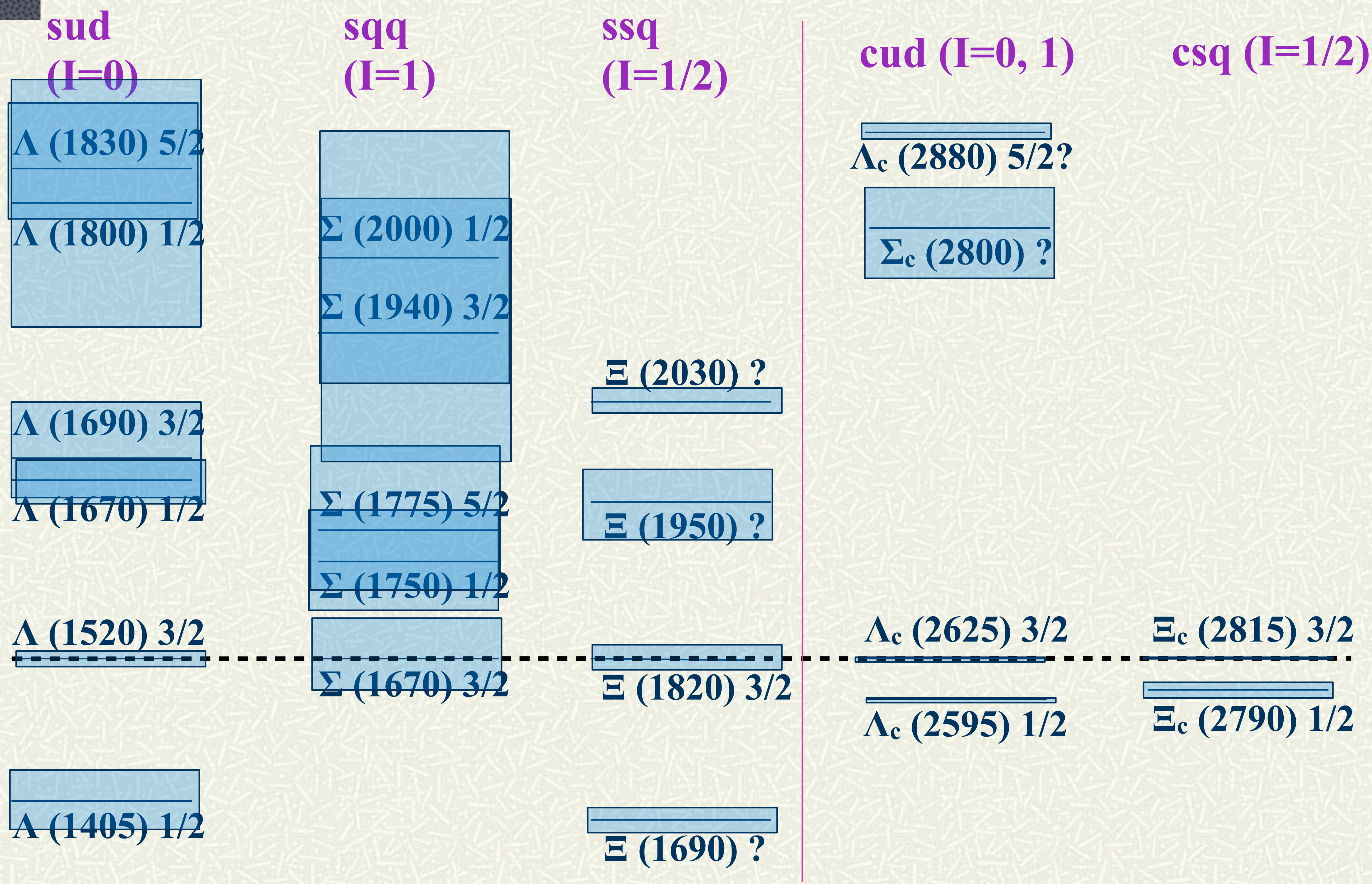


T. Yoshida,, A. Hosaka, E. Hiyama, MO

Negative-parity (P-wave) Baryons



Negative-parity (P-wave) Baryons

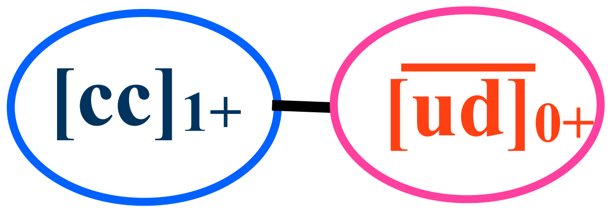


Double Charm Exotics
Tetraquark T_{cc}

Double Charm Tetraquark

- **Double charm meson**

  $T_{cc}\ (ccu^{bar}d^{bar},\ 1^{+},\ I=0) = [cc]_{1+}\ [u^{bar}d^{bar}]_{0+}$



  - The lowest strong-decay threshold is $D(0^{-}) – D^{*}(1^{-})$ (L=0).

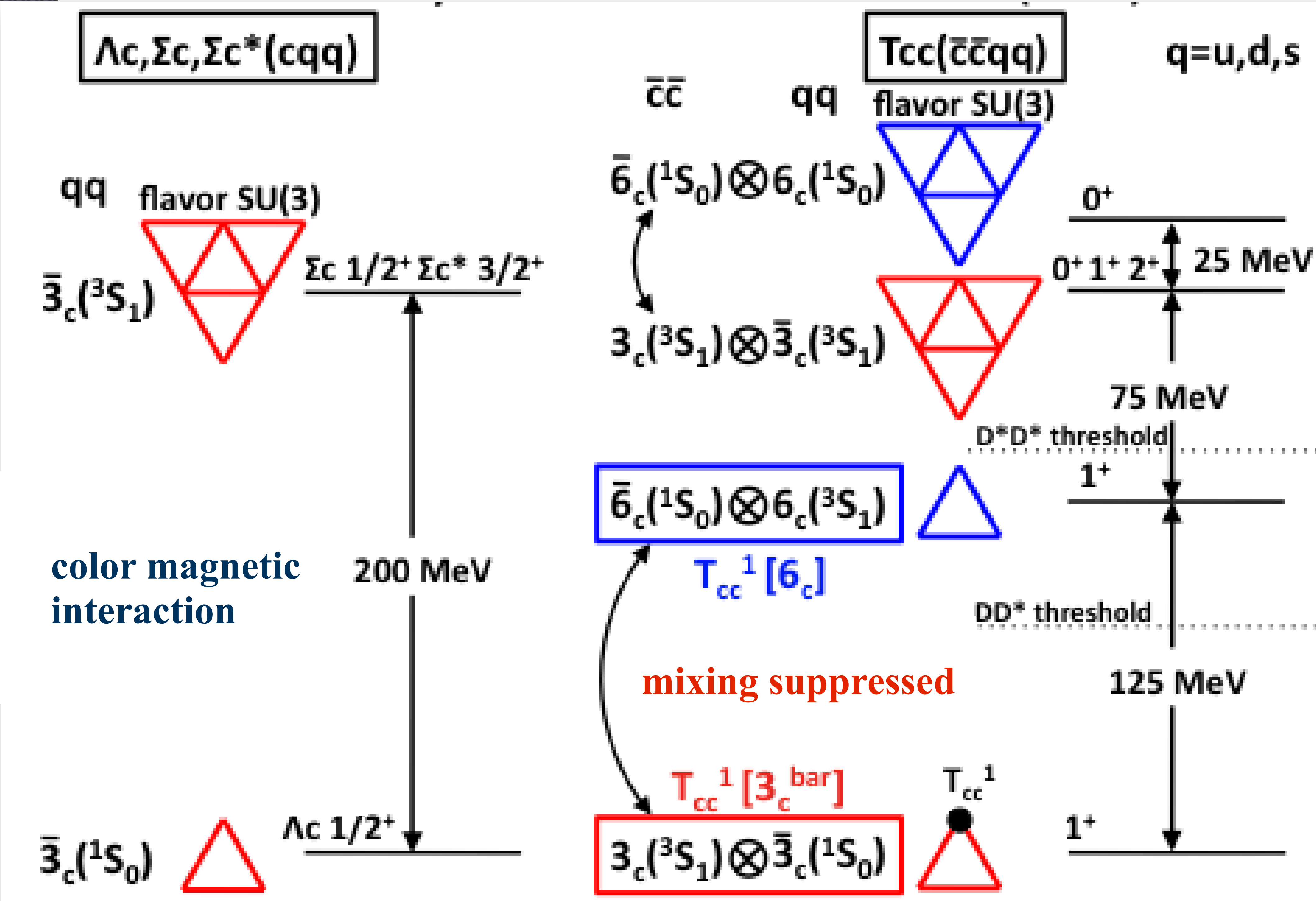
  - If the scalar diquark is light enough to make T_{cc} bound below DD* threshold, T_{cc} will be a stable tetra-quark resonance.

  S. Zouzou, et al., Z. Phys. C30 (1986)457
  H.J. Lipkin, Phys. Lett. B172 (1986) 242

- **New possible color correlations**

  Hyodo, Liu, Oka, Sudoh, Yasui, PLB721 (2013) 56-60, ArXiv 1209.6207

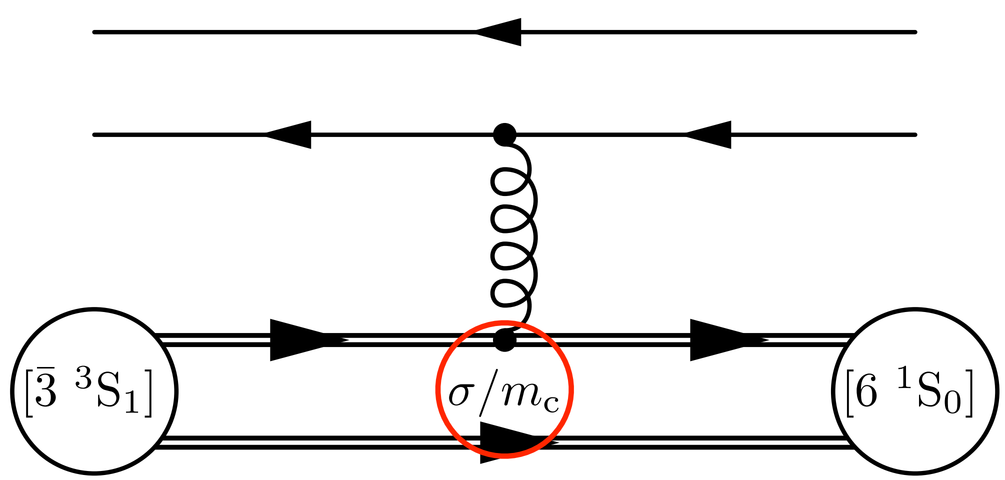
Double Charm Tetraquark



Hyodo, Liu, Oka, Sudoh, Yasui, PL B721 (2013) 56-60, ArXiv 1209.6207

T_{cc} spectrum

- The lowest two states, $T_{cc}[3, {}^3S_1]$, $T_{cc}[6, {}^1S_0]$, have $I(J^P) = 0(1^+)$, and in principle mix with each other.
  However, the mixing is suppressed in the HQ limit as ~ $1/m_Q$.

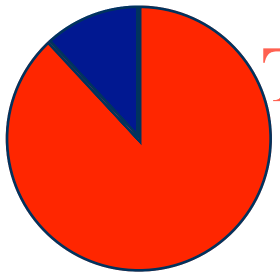


charm spin flip
mixing probability ~ $1/m_c^2$

- Dynamical 4-quark calculation:

J. Vijande, A. Valcarce, PRC80, 035204 (2009)

- Fraction: $\bar{3}$ (0.881) ***v.s.*** 6 (0.119) for the ground state.



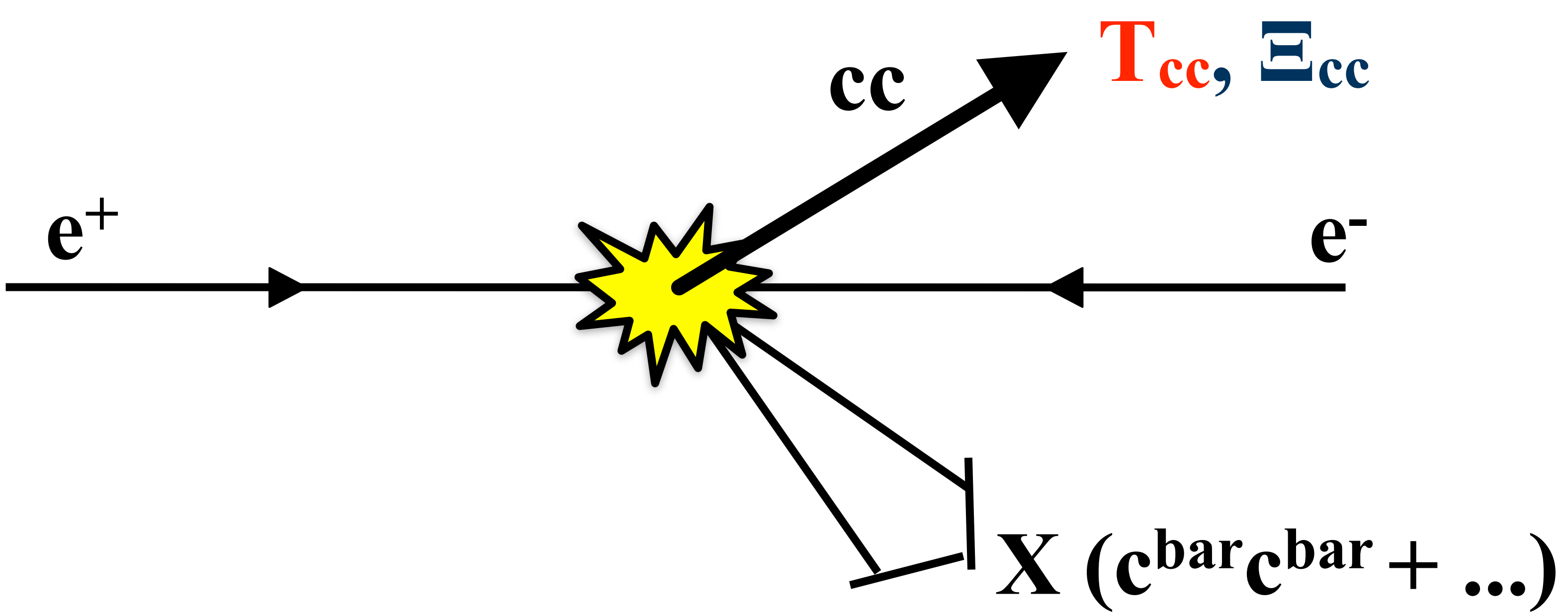
$T_{cc}[3, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$ are well separated.

Production in $e^+ e^-$ collisions

- e+ e- collisions at Belle (KEKB; B-factory)
  Double-charm productions ($J/\psi+\eta_c$, ...) have been observed.

  K. Abe, et al, Belle Collaboration, Phys. Rev. Lett. 89, 142001 (2002)

- Recombination of the charm quarks and antiquarks will produce double charmed mesons (T_{cc}'s) and baryons (Ξ_{cc}).



- Calculate the cross sections of double charmed hadrons.

Cross section

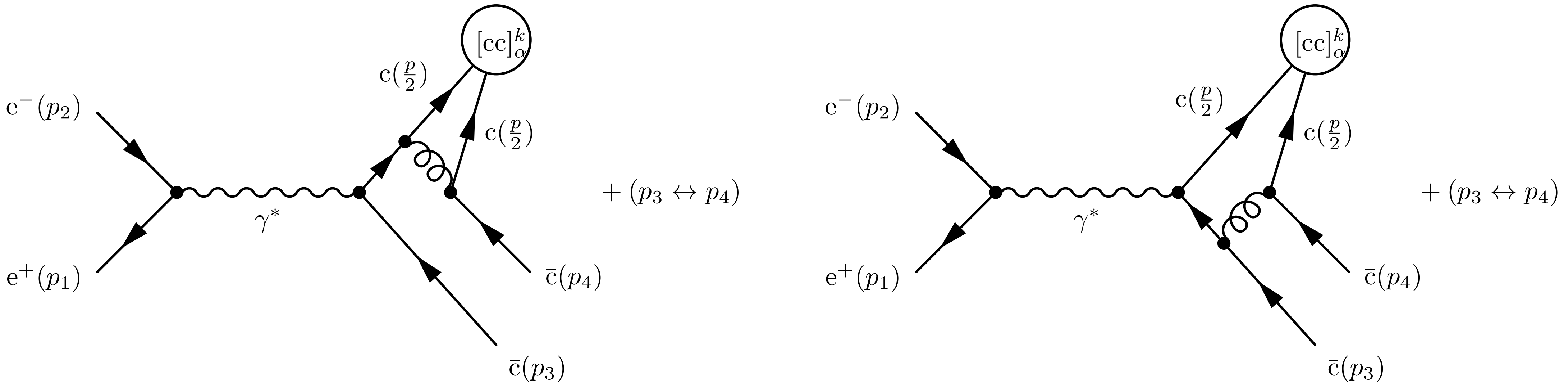
- Production of doubly charmed tetraquarks with exotic color configurations in electron-positron collisions,
  T. Hyodo, Y.-R. Liu, M. Oka, K. Sudoh, S. Yasui
  Physics Letters B721 (2013) 56-60,
  and in preparation.
- Formalism: NRQCD (factorization and expansion in v_Q)
  hard process
  $e^+e^- \to cc\ [J^P]$ calculated perturbatively
  soft process
  representing the formation of T_{cc} as a matrix element

Cross section

- **Cross section**

$$d\sigma_\alpha(e^+e^- \to T_{cc}[\alpha] + X) = \sum_k d\hat{\sigma}(e^+e^- \to [cc]^k_\alpha + \bar{c} + \bar{c}) \left|\langle T_{cc} + X|[cc]^k_\alpha|0\rangle\right|^2$$

Hard part: leading order in α_s by pQCD calculation
cc with color-spin projection



Soft part can be factorized: leading order in v → a number.

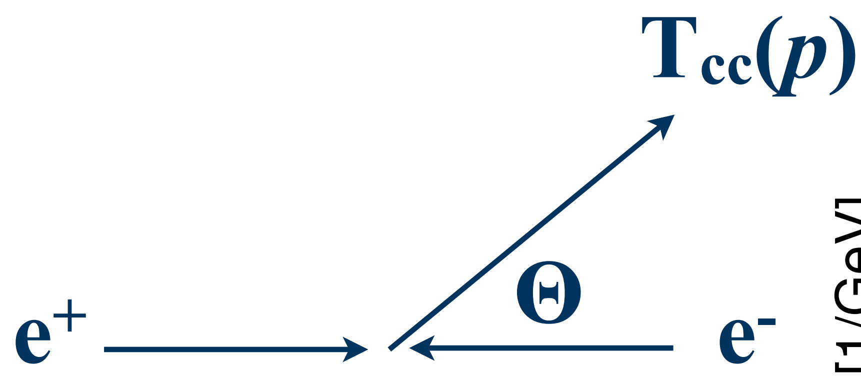
$$\left|\langle T_{cc} + X|[cc]^k_\alpha|0\rangle\right|^2\Big|_{k=\mathrm{LO}} = \begin{cases} h_3 & \text{for } \alpha = [\bar{\mathbf{3}}, {}^3S_1] \\ h_6 & \text{for } \alpha = [\mathbf{6}, {}^1S_0] \end{cases}$$

→ cancel when normalized by the total cross section dσ/σ

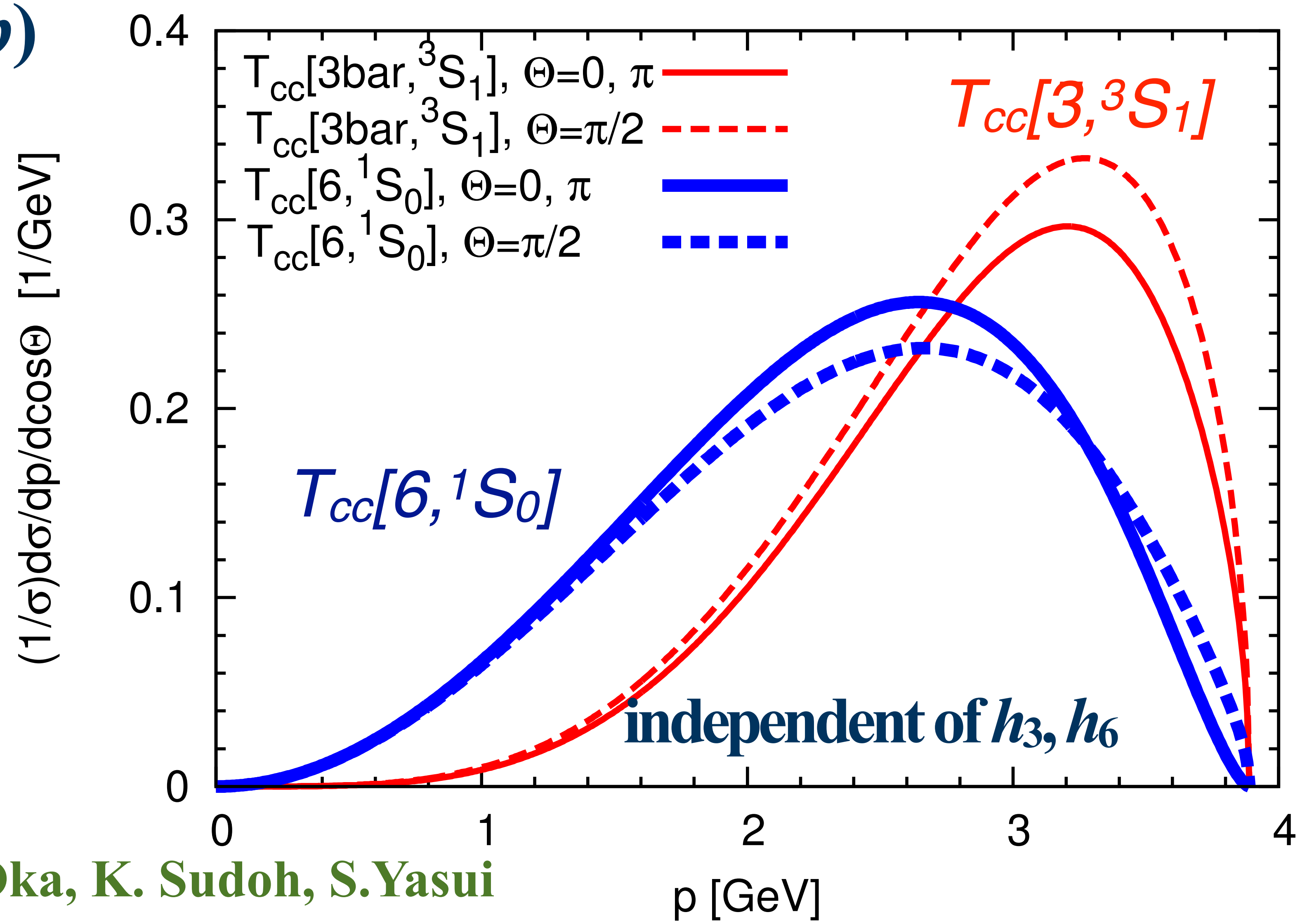
Cross section

- **Normalized differential cross sections**

$$\frac{1}{\sigma}\frac{d\sigma_\alpha}{dp\, d\cos\Theta}$$



$m_c = 1.8$ GeV
$\alpha_s = 0.212$
$s^{1/2} = 10.6$ GeV



T. Hyodo, Y.R. Liu, M. Oka, K. Sudoh, S.Yasui

- **Momentum distribution depends on the color configurations.**

Cross section

- **For absolute value, we need nonperturbative matrix elements.**

  Charmonium case: $c\bar{c}$ wave function at origin.

  G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. D51, 1125 (1995)
  A. Petrelli, *et al*, Nucl. Phys. B514, 245 (1998)

$$\left|\langle J/\psi|\bar{c}c|0\rangle\right|^2 \sim \frac{1}{4\pi}|R_{\bar{c}c}(x=0)|^2$$

- **Constituent quark model for T_{cc} with harmonic confinement.**

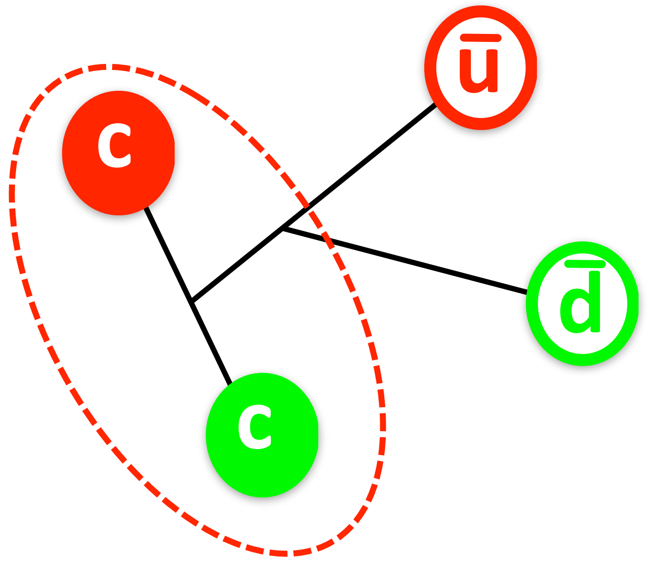
$$V = \sum_{i<j}\left(-\frac{3}{16}\right)\vec{\lambda}_i\cdot\vec{\lambda}_j\frac{k}{2}|\vec{r}_i - \vec{r}_j|^2$$

$T_{cc}[\bar{3}]$

$$h_3 = \frac{1}{4\pi}|R_{cc}^{\bar{\mathbf{3}}_c({}^3S_1)}(0)|^2$$

$$\sim 0.089 \text{ GeV}^3$$

$$\sigma(T_{cc}[\bar{3}]) = 13.8 \text{ fb}$$



ref: Ξ_{cc} production with NRQCD formalism
- Ma, Si, PLB568, 135 (2003), - Jian, et al., arXiv:1208.3051

Cross section

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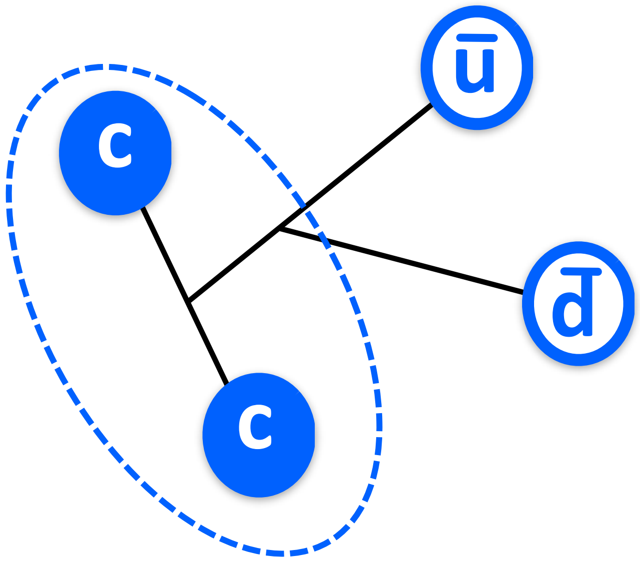
$$V=\sum_{i<j}\left(-\frac{3}{16}\right)\vec{\lambda}_i\cdot\vec{\lambda}_j\frac{k}{2}|\vec{r}_i-\vec{r}_j|^2$$

$T_{cc}[6]$

$$h_6=\frac{1}{4\pi}|R_{cc}^{\mathbf{6}_c(^1S_0)}(0)|^2 \sim 0.053\ \mathrm{GeV}^3$$

$\sigma(T_{cc}[6]) =$ 4.1 fb



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- Ma, Si, PLB568, 135 (2003), - Jian, et al., arXiv:1208.3051

Cross section

- **The present treatment assumes that the light quarks are supplied by the vacuum to form T_{cc} without a further factor. The ratio of Ξ_{cc}/T_{cc} productions is about unity.**
- **HARD processes $e^+ + e^- \rightarrow QQ^{bar}, Q^2Q^{bar2}, \ldots$ are followed by SOFT hadronization. In high energy processes, the hard vertex with heavy quarks and the soft hadronization processes are "factorized".**
- **Productions with the common hard parts:**
  D/B (Qq^{bar}) *vs* Λ_Q, Σ_Q (Qqq)
  Ξ_{QQ} (QQq) *vs* T_{QQ} $(QQq^{bar}q^{bar})$
- **High energy production of *b* quark fragmented into B mesons and b-Baryons, eventually decaying via the weak interaction. Fragmentation probabilities of B_u, B_d, B_s, Λ_b productions are measured at LEP (Z decay), CDF (pp^{bar}), and LHCb (pp).**

expts: LEP, CDF and LHCb

- Lifetime and production rate of beauty baryons from Z decays, DELPHI Collaboration, Z. Phys. C68 (1995) 375.
- Measurement of the b baryon lifetime and branching fractions in Z decays, The ALEPH Collaboration, Eur. Phys. J C2 (1998) 197.
  $f_B = 0.101 \pm 0.040$
- Measurement of b-Quark Fragmentation Fractions in pp^bar collisions at s^1/2 = 1.8 TeV,
  CDF Collaboration, Phys. Rev. Lett. 84 (2000) 1663.
  $f_B / (f_u + f_d) = (0.090 \pm 0.029)/(0.750 \pm 0.046) = 0.118 \pm 0.042$
- Measurement of ratios of fragmentation functions for bottom hadrons in pp^bar collisions at s^1/2 = 1.96 TeV,
  CDF Collaboration, Phys. Rev. D77 (2008) 072003.
  $f_B/(f_u+f_d) = 0.281 \pm 0.10$
- Measurement of b hadron production in 7 TeV pp collisions,
  The LHCb Collaboration, Phys. Rev. D85 (2012) 032008.
  $f_B/(f_u+f_d) = (0.40 \pm 0.10) \times (1 - 0.031\, p_T(\mathrm{GeV}))$

Estimate the ratio by counting

- **Probability of creating a qq^{bar} pair : η_q.**

  The ratio of (Baryon)/(Meson) = (5/12) η_q = 0.42 η_q

- **Exp data ~ 0.3-0.4 $\Rightarrow$ $\eta_q = 0.7 \sim 1.0$**

- **T_{QQ} and Ξ_{QQ}**

  Ξ_{QQ} (1/2) $\to$ (1/3)(2/3)(1/6) η_q = (1/27) η_q

  Ξ^*_{QQ} (3/2) $\to$ (1/3)(4/3)(1/6) η_q = (2/27) η_q

  T_{QQ} (1^+, 3^{bar}) $\to$ (1/108) $(\eta_q)^2$

  T_{QQ} (1^+, 6) $\to$ (1/72) $(\eta_q)^2$

- **$(T_{QQ})/(\Xi_{QQ})$**

  3^{bar} 1/2 = (1/4) η_q = 0.15 ~ 0.25

  6 1/2 = (3/8) η_q = 0.2 ~ 0.38

- **$T_{QQ}(6)/T_{QQ}(3^{bar})$ = 1.5 (indep. of η_q)**

Charmed Hadrons in Nuclei

Charmed Hadrons in Nuclei

- **Possible heavy hadron nuclei**
  - **DNN bound state**

    M. Bayar, C.W. Xiao, T. Hyodo, A. Dote, M.O., E. Oset, PR C86 (2012) 044004

  - **Charmed deuteron: $\Lambda_c N$-$\Sigma_c N$-$\Sigma^*_c N$ bound states (Liu, Oka)**
    charmed hypernuclei:
    $\Lambda_c pn$ bound state (Maeda, Yokota, Hiyama, Fukukawa, Oka)

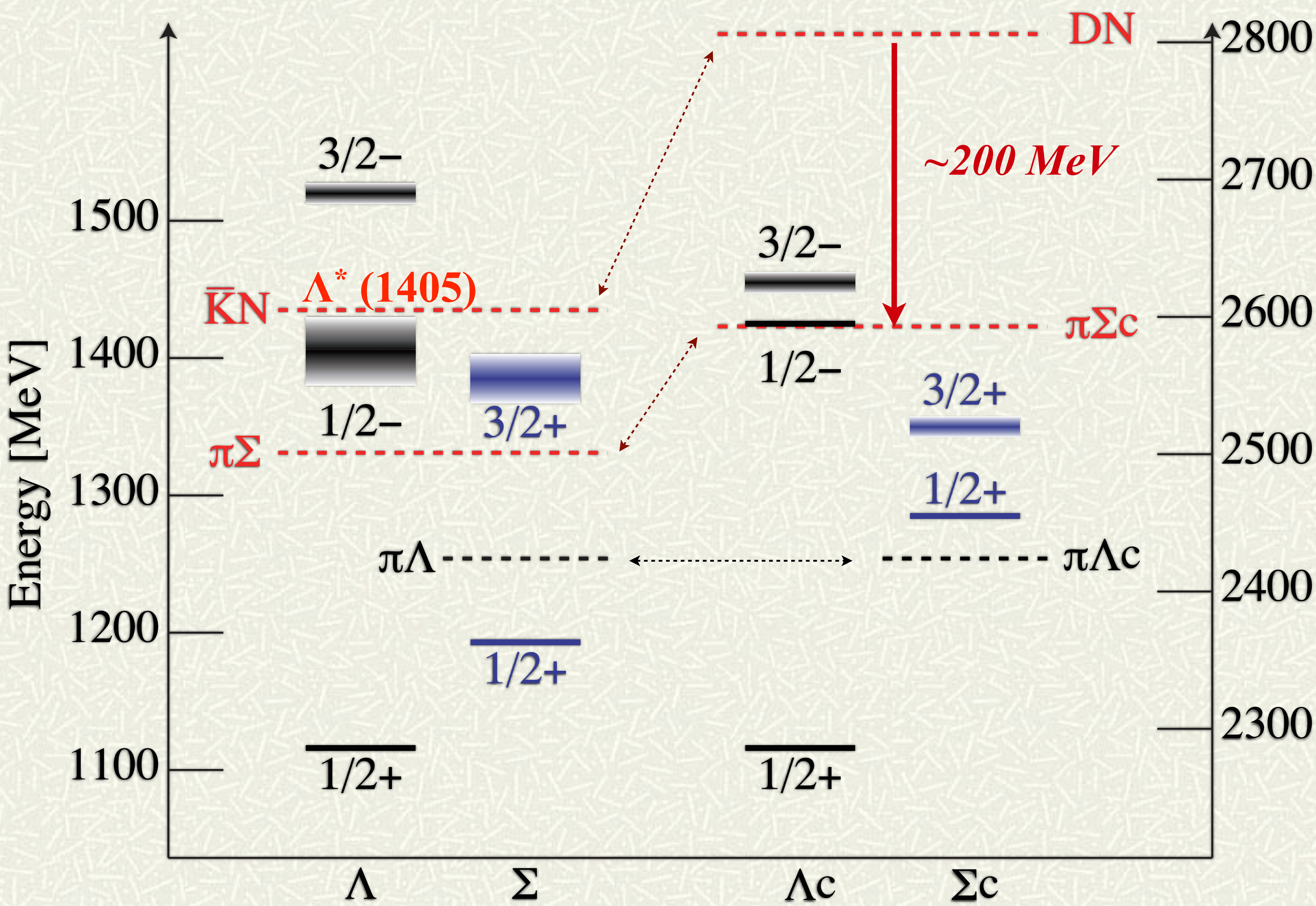
    Yan-rui Liu, M.O., "$\Lambda_c N$ bound states revisited", PR D85 (2012) 014015
    Wakafumi Meguro, Yan-rui Liu, M.O., "Possible $\Lambda_c \Lambda_c$ molecular bound state", Phys. Lett. B704 (2011) 547.

  - **Hidden-charm nuclei, *i.e.*, J/ψ, η_c nuclei:**
    bound (J/ψ, η_c) - ^{4}He nuclei. (Yokota, Hiyama, Oka)

    A. Yokota, E. Hiyama, M.O., "Possible Existence of Charmonium-Nucleus Bound States", arXiv:1308.6102, PTEP in print.

DN → DNN

- **Negative-parity charmed baryon as DN ← Λ(1405) as K^{bar}N**

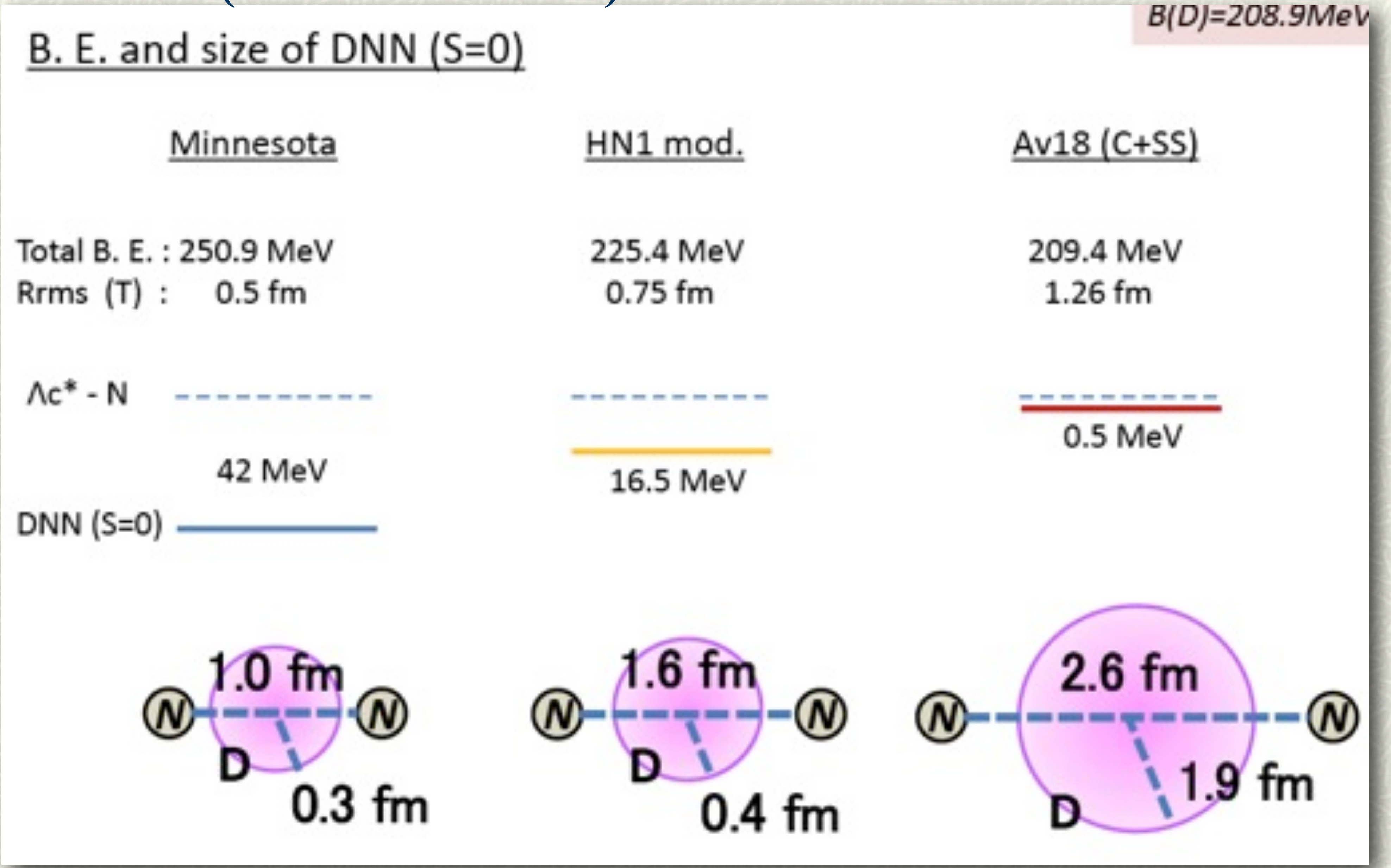


T. Mizutani, A. Ramos, PRC74(2006)

DN → DNN

- **A narrow DNN bound state is predicted.**

M. Bayar, C.W. Xiao, T. Hyodo, A. Dote, M.O., E. Oset, **PR C86 (2012) 044004 (arXiv:1205.2275)**



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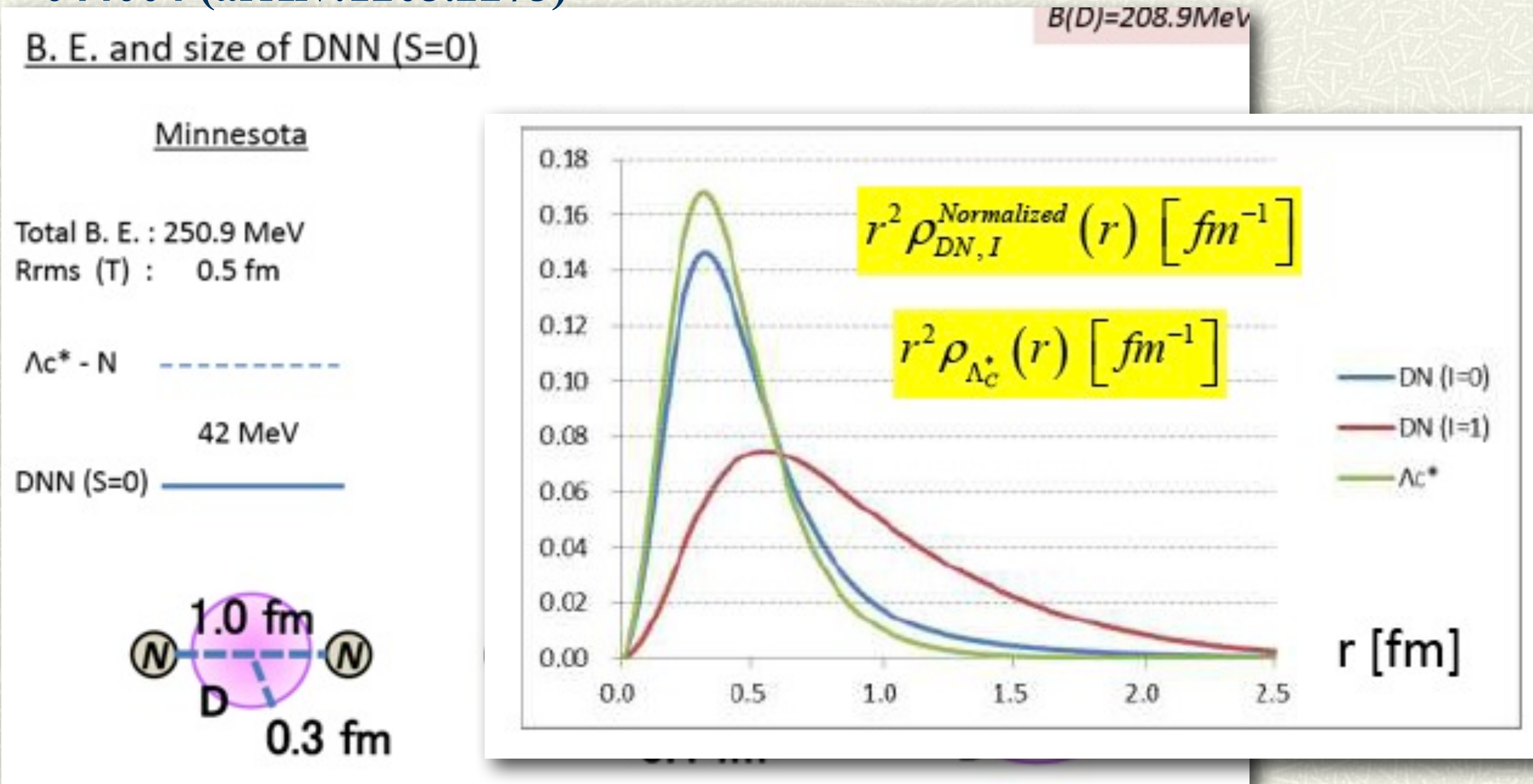
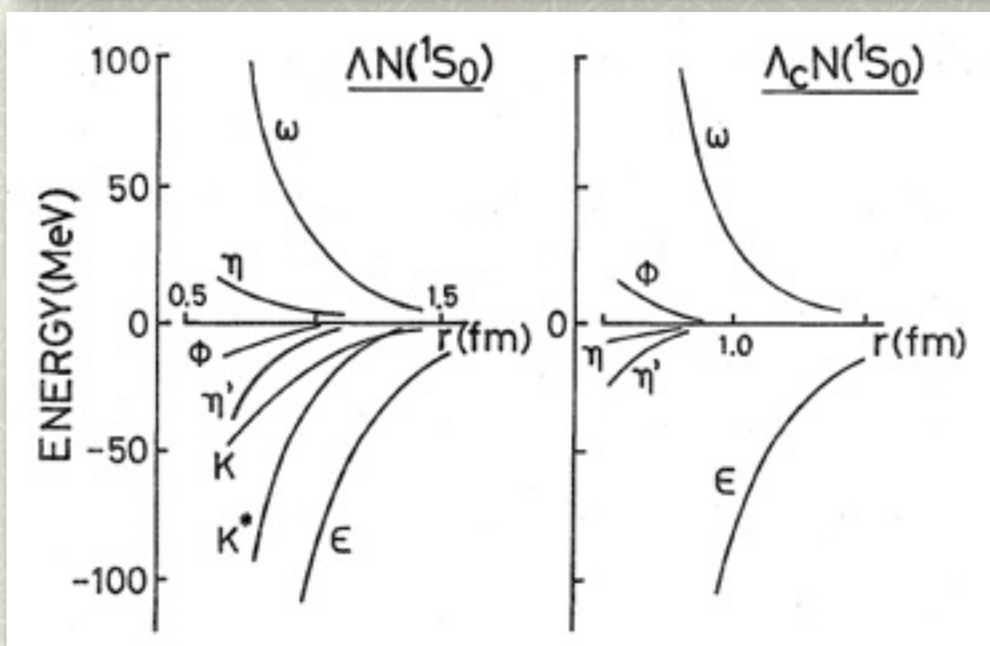
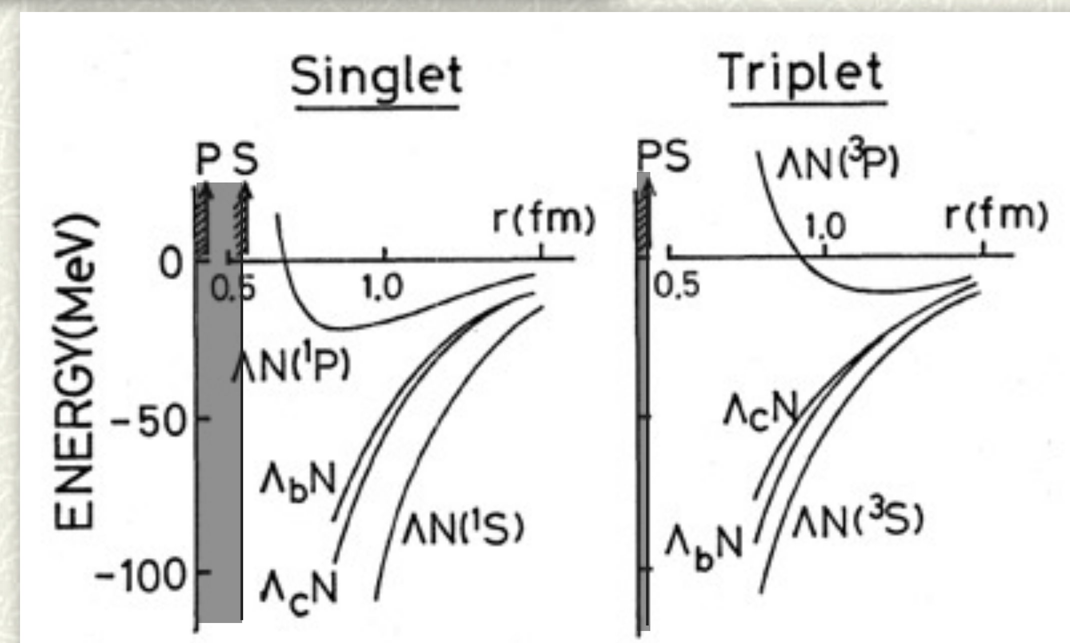


Y_c-N charmed deuteron

- *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.**

Y_c-N charmed deuteron

- We have reexamined 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.
- One-boson-exchange (OBE) potential model for the Y_cN system is constructed and
  Λ_cN-Σ_cN-$\Sigma^*{}_cN$ (0^+: ${}^1S_0$-${}^5D_0$)
  Λ_cN-Σ_cN-$\Sigma^*{}_cN$ (1^+: ${}^3S_1$-${}^{3,5}D_1$)
  coupled channel systems are considered.
- The OPE tensor force induces strong mixings of the D-wave Σ_cN (S=1) and $\Sigma^*{}_cN$ (S=1, 2) states, whose thresholds are degenerate in the large m_Q limit.

Y_c-N charmed deuteron

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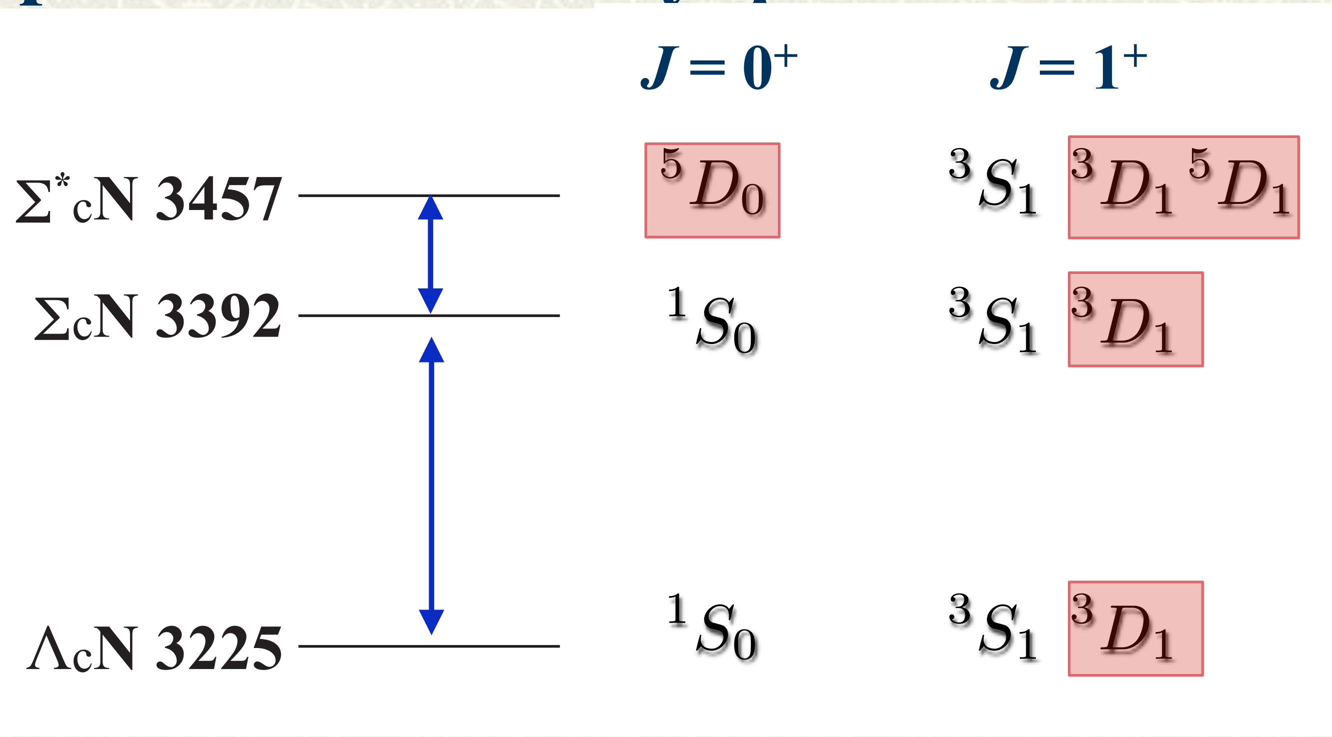

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Y_c-N charmed deuteron

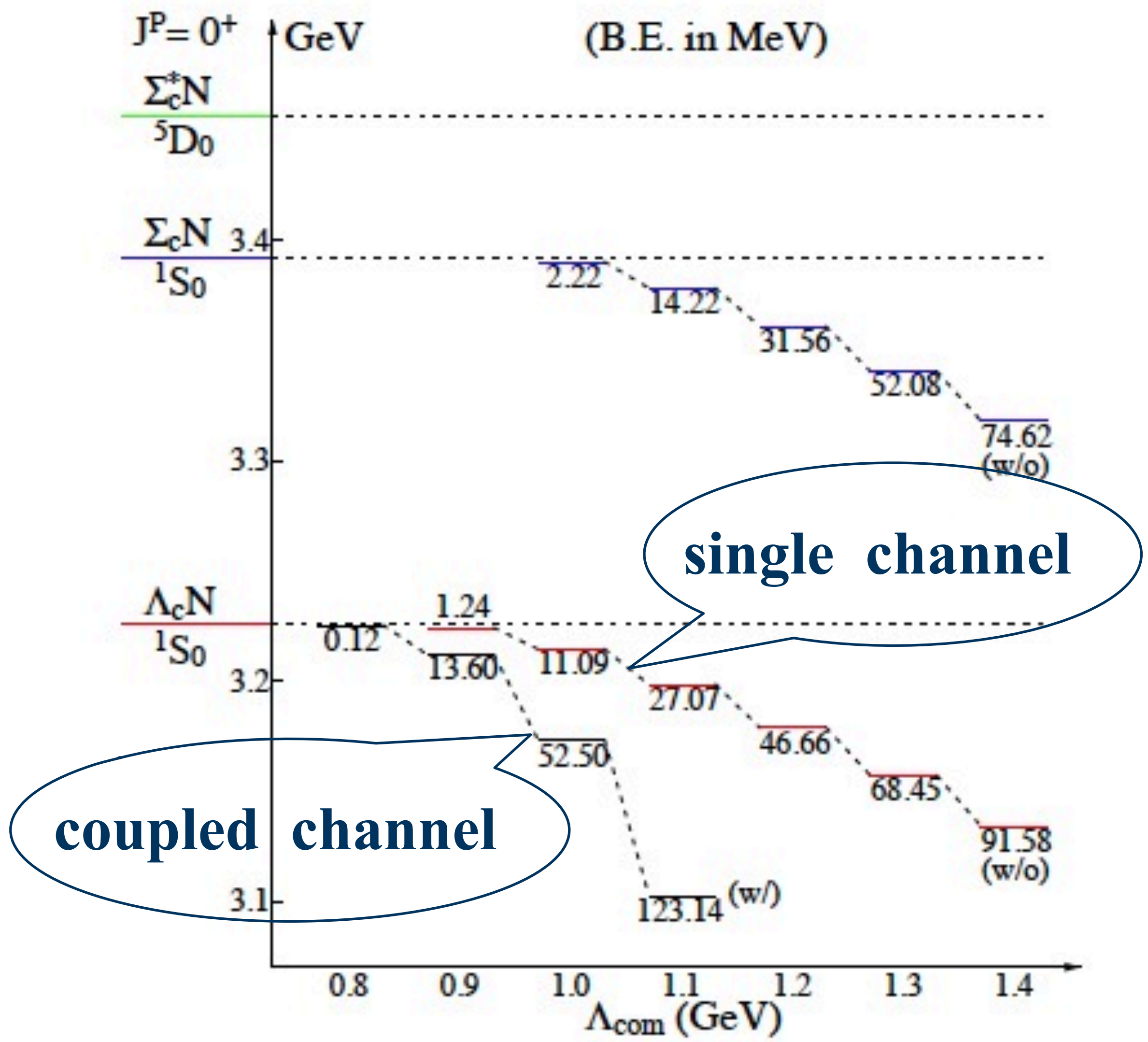
- **Heavy-quark spin symmetry, chiral symmetry, and hidden local symmetry are used to determine the meson-baryon couplings.**
- **Short range part of the potential**
  by the monopole form factor for each vertex

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

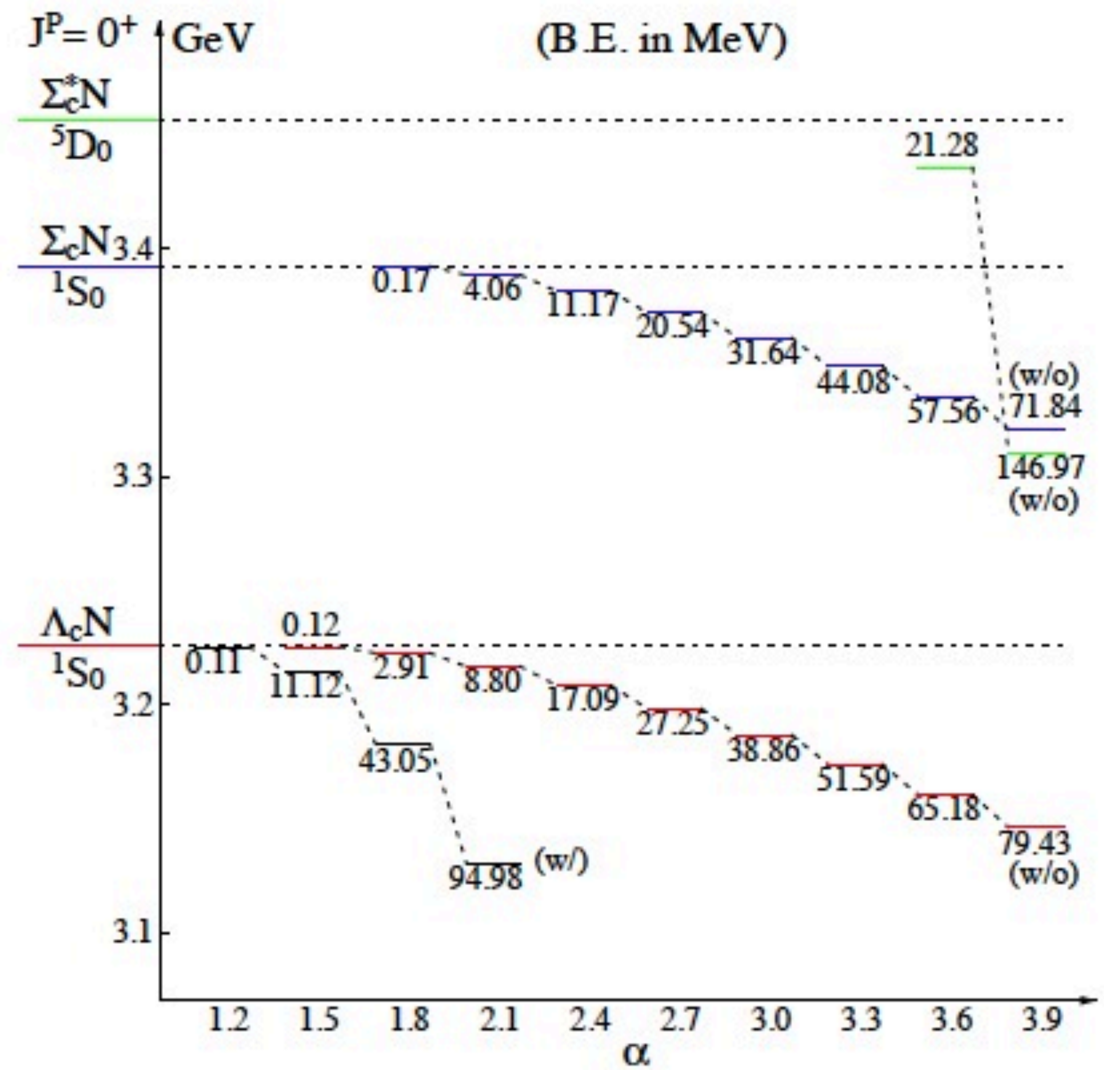
- **We found bound states in both $J^\pi = 0^+$ and 1^+ states.**
- **The binding energies depend on the choice of Λ.**

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

OMEP model ($\Lambda_{\rm com}$ & α)



Λ independent of meson mass



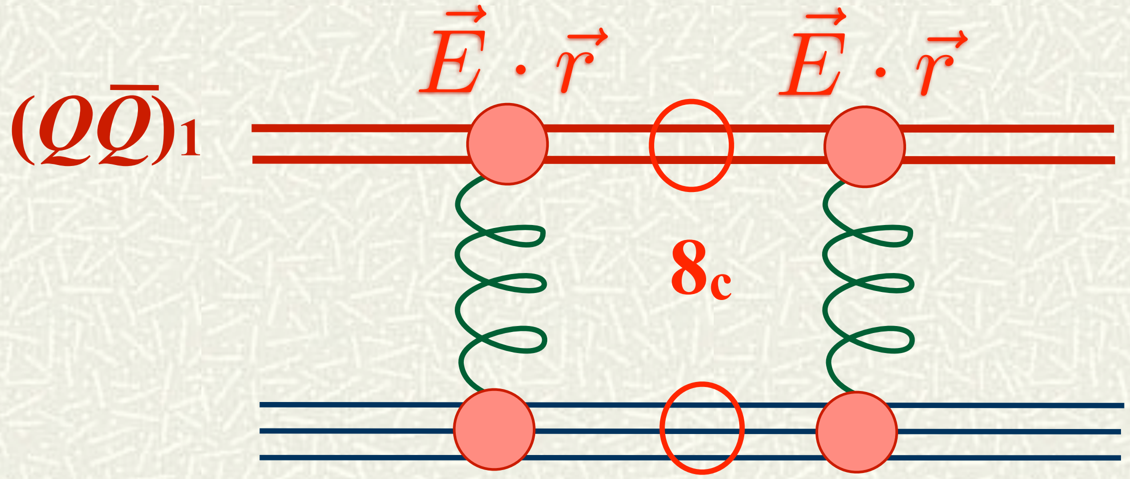
$\Lambda = m(\text{meson}) + \alpha \times 0.22\text{GeV}$

Y_c-N charmed deuteron and more

- Further studies are going on to include the short range part of the potential in a dynamical model.
  The color-magnetic interaction in the quark cluster model gives
  $V(\Lambda_c\text{-}N) \sim 300$ MeV, $V(\Sigma_c\text{-}N) \sim 100$ MeV at R=0
  compared with $V(N\text{-}N; {}^1S_0) \sim 450$ MeV, $V(\Lambda\text{-}N; {}^1S_0) \sim 400$ MeV
- Preliminary results show that the Λ_c-N interaction is strong enough so that Λ_c-N system is barely bound, but there will be Λ_c-Nucleus (few-body) bound states, such as Λ_c-p-n (charmed triton).
- It is extremely interesting to look for a new kind of nucleus with charmed baryon(s).

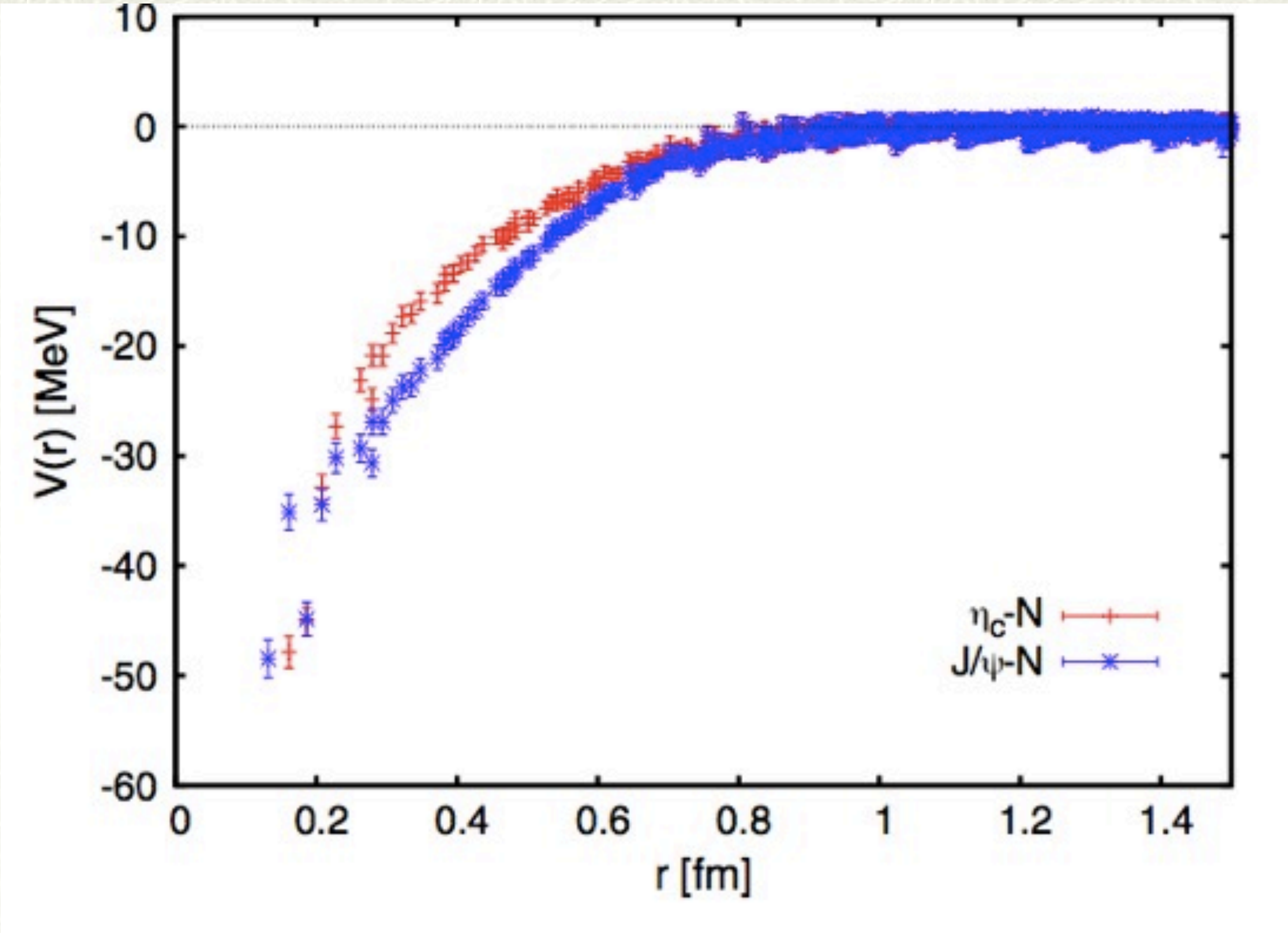
Charmonium bound in Nuclei

Pure HQ hadrons have attractive interaction with matter.



Color-van-der-Waals force (second order perturbation) is (weakly) attractive.

Charmonium bound in Nuclei

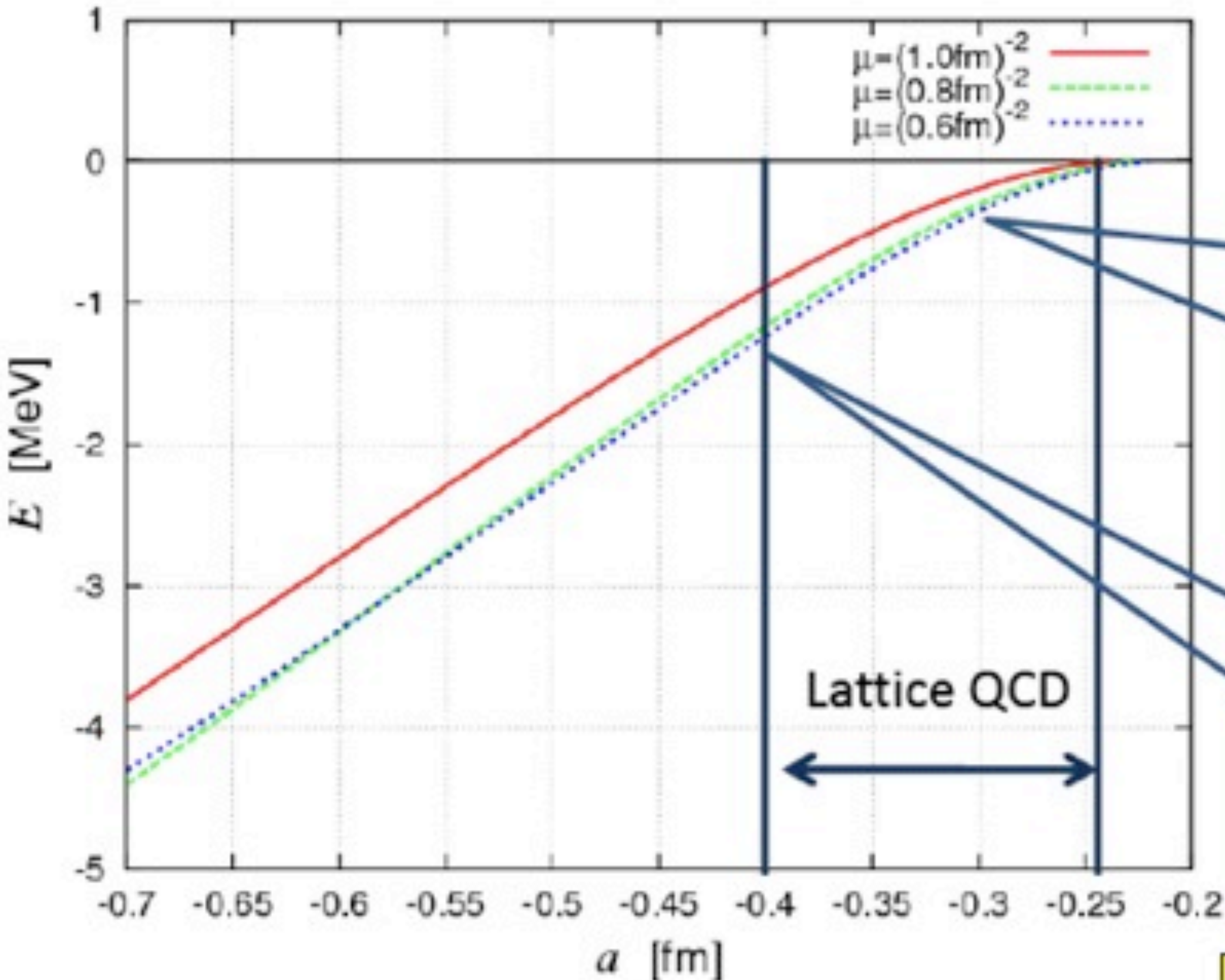


Lattice QCD (quenched) calculation by T. Kawanai, S. Sasaki, PoS LATTICE2010 (2010) 156, PRD82, 091501 (2010), shows weakly attractive potential at short distances and screened at large distances.

This results favors J/ψ bound states in light nuclei.

Charmonium bound in Nuclei

J/ψ in ^{4}He



Yokota, Hiyama, M.O., PTEP (2013)

$J/\psi -{}^4He$ bound state is made when

$a_{J/\psi N} \leq -0.24\text{fm} \quad (\mu = (1.0\text{fm})^{-2})$

$a_{J/\psi N} \leq -0.23\text{fm} \quad (\mu = (0.8\text{fm})^{-2})$

$a_{J/\psi N} \leq -0.22\text{fm} \quad (\mu = (0.6\text{fm})^{-2})$

If $a_{J/\psi N} = -0.3\text{fm}$

$E = -0.22\text{MeV} \ (\mu = (1.0\text{fm})^{-2})$

$E = -0.36\text{MeV} \ (\mu = (0.8\text{fm})^{-2})$

$E = -0.44\text{MeV} \ (\mu = (0.6\text{fm})^{-2})$

If $a_{J/\psi N} \sim -0.4\text{fm}$

$E = -1.03\text{MeV} \ (\mu = (1.0\text{fm})^{-2})$

$E = -1.18\text{MeV} \ (\mu = (0.8\text{fm})^{-2})$

$E = -1.29\text{MeV} \ (\mu = (0.6\text{fm})^{-2})$

There should be bound state!

Conclusion

- Key dynamics of heavy quarks in the spectroscopy is the weak spin dependent interaction.
- The HQ baryon spectroscopy may sort out the diquark correlations and their spectrum.
- Diquarks are new building blocks of the constituent quark model.
- Many exotic HQ bound/resonance states (T_{cc}, DN...) are possible, and interesting to find them in experiments.
- Bound charmed deuterons ($\Lambda_c N$, or $\Lambda_c\Lambda_c$) may exist via the strong tensor couplings of the $\Sigma_c^{(*)}N$ and $\Sigma_c^{(*)}\Sigma_c^{(*)}$ channels. Such interactions will generate further charmed (bottomed) hypernuclear bound states.