Spectroscopy of Heavy Quark Hadrons from QCD

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Introduction:

From QCD to Hadron Spectrum

From QCD to Hadron Spectrum

- **QCD = quarks + gluons with color $SU(3)_c$ gauge symmetry**

$$\mathcal{L} = \bar{q}(i\not{D} - m_q)q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

expected low energy modes

massless gluons

light quarks ($m_q < 10$ MeV)

From QCD to Hadron Spectrum

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$$\mathcal{L} = \bar{q}(i\not{D} - m_q)q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

expected low energy modes
massless gluons
light quarks ($m_q < 10$ MeV)

- **In reality,**

massless gluons => glueballs ($m_{GB} \sim 1.4$ GeV or larger)

light quarks

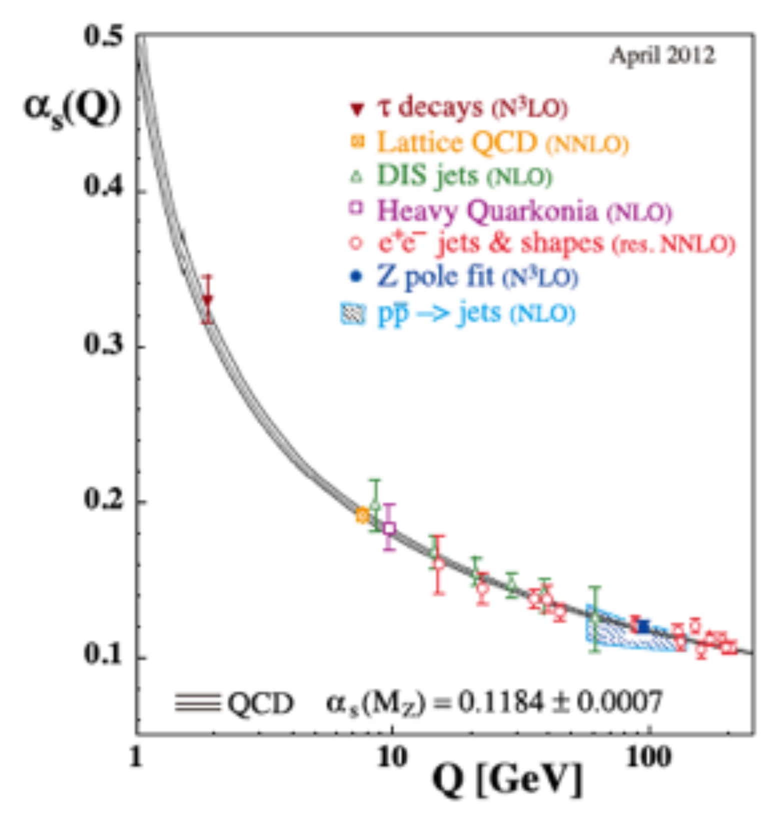
=> mesons (500~800 MeV) except for pion, Kaon
baryons (900 MeV ~)

From QCD to Hadron Spectrum

- **QCD @ low energy is strongly correlated.**

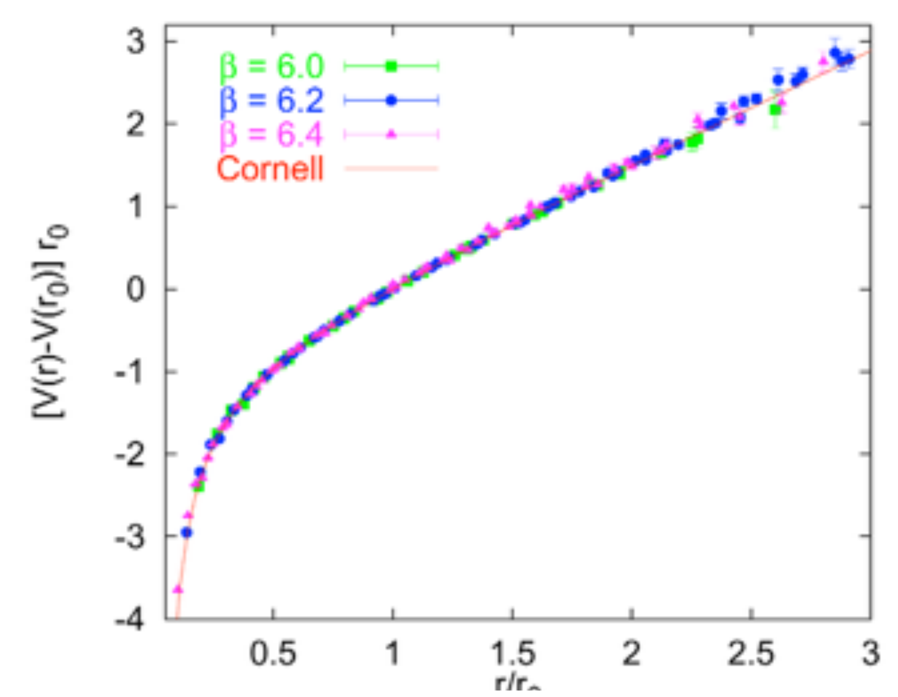
1. coupling constant runs

$$\Lambda_{\mathrm{QCD}}^{(4)} \sim 300\ \mathrm{MeV}$$



2. color confinement

mass gap : color singlet = hadrons



G.S. Bali, P. Rep. 343 (2001) 1

From QCD to Hadron Spectrum

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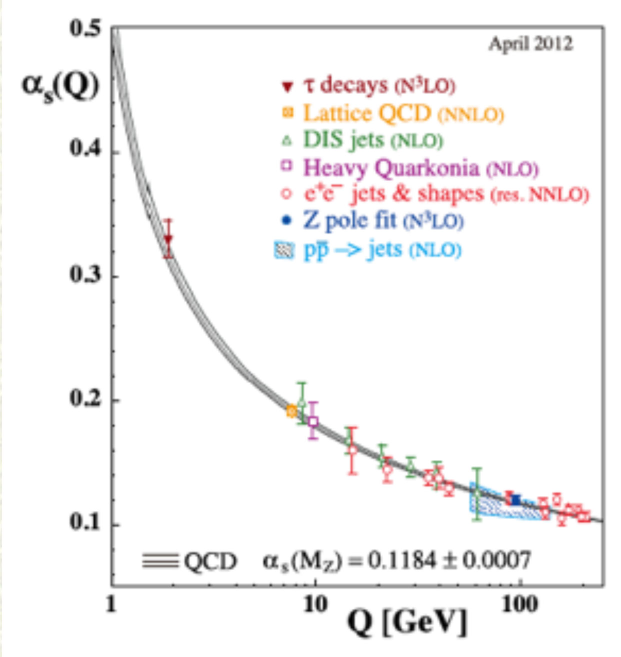


2. color confinement

mass gap : color singlet = hadrons

3. non-trivial vacuum

requires non-perturbative solution

quark condensate breaks chiral symmetry

gluon condensate breaks scale invariance

From QCD to Hadron Spectrum

- **Scale anomaly ← gluon condensate**

$$\partial_\mu j_D^\mu = \sum_q m_q \bar{q} q + \frac{\beta(\alpha_s)}{\alpha_s} \mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}]$$

$$\langle (\alpha_s/\pi) G^{\mu\nu} G_{\mu\nu} \rangle \sim (350 \mathrm{MeV})^4 \sim \Lambda^4$$

- **Chiral symmetry breaking ← quark condensates**

$$SU(N_f)_R \times SU(N_f)_L \to SU(N_f)_V$$

$$\langle \bar{q} q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$$

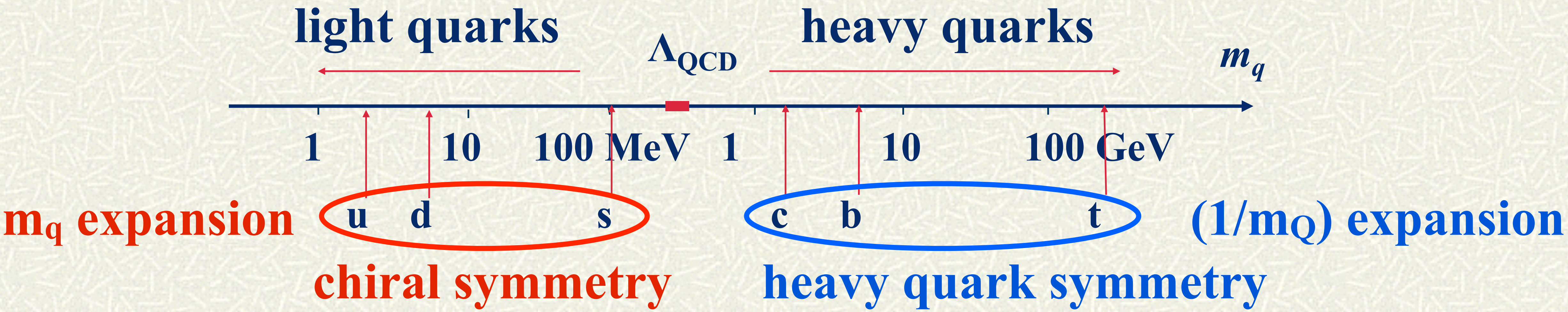
$$\langle \bar{u} u \rangle \simeq \langle \bar{d} d \rangle \sim -(250\,\mathrm{MeV})^3 \sim \mathrm{O}(\Lambda^3)$$

- **Low energy dof: "constituent quark" with mass**

$$M_q \sim m_q - G_\chi \langle \bar{q} q \rangle \sim 300 \mathrm{MeV} \sim \mathrm{O}(\Lambda)$$

From QCD to Hadron Spectrum

- QCD Lagrangian is flavor independent, but the coupling constant runs.



light quarks

Λ_{QCD}

heavy quarks

m_q

1 10 100 MeV 1 10 100 GeV

m_q expansion

u d s

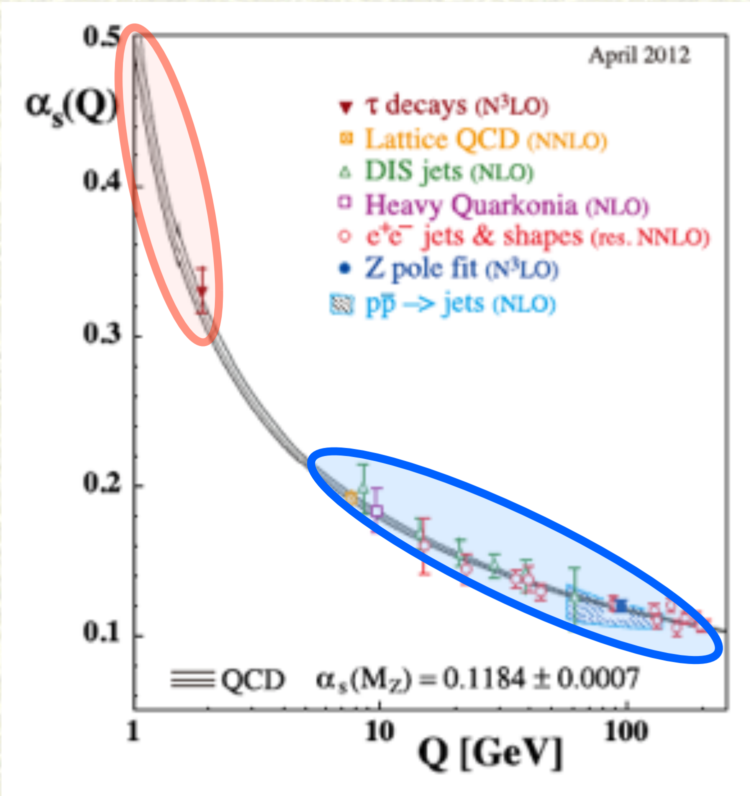
c b t

$(1/m_Q)$ expansion

chiral symmetry

heavy quark symmetry

- Light quarks are nonperturbative/ relativistic.
- Heavy quarks are perturbative/ non-relativistic.



From QCD to Hadron Spectrum

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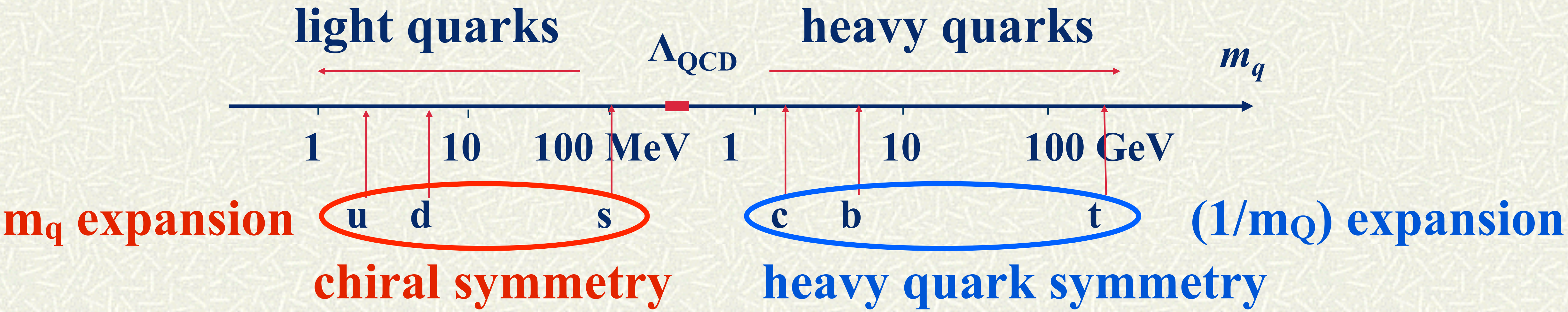

light quarks

Λ_{QCD}

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m_q

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m_q expansion

u d s

c b t

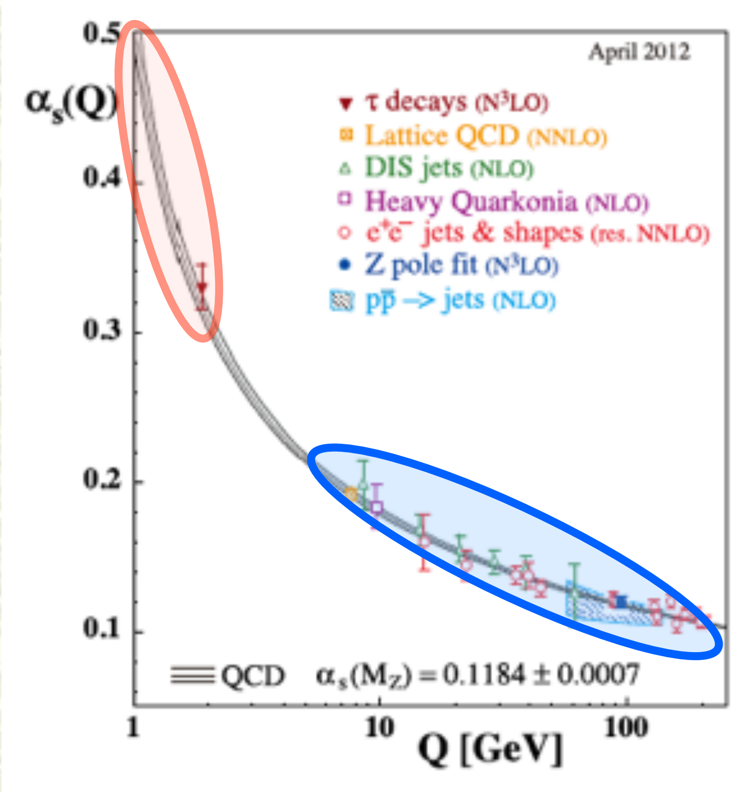
$(1/m_Q)$ expansion

chiral symmetry

heavy quark symmetry

- **Light quarks are nonperturbative/ relativistic.**
- **Heavy quarks are perturbative/ non-relativistic.**

Light and Heavy quarks look different in QCD



Quarkonium

Quarkonium

- **After 50 years since it was born, the quark model gives very good guidelines to classify and interpret the hadron spectrum.**

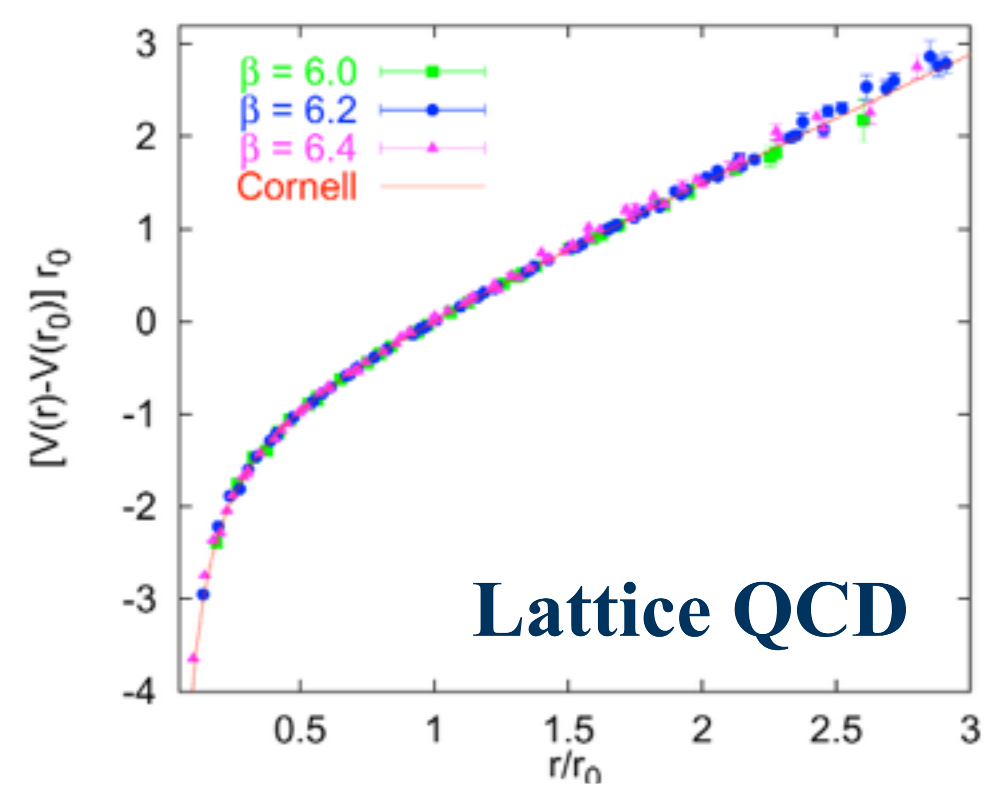
- **The charmonium spectrum is a textbook example.**
  "hydrogen atom" in QCD

- **The Hamiltonian with a Linear + Coulomb potential**

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

E. Eichten, et al., PRL 34 (1975) 369

gives a good fit to the 1S, 1P, 2S, . . charmonium (and bottomonium) states.

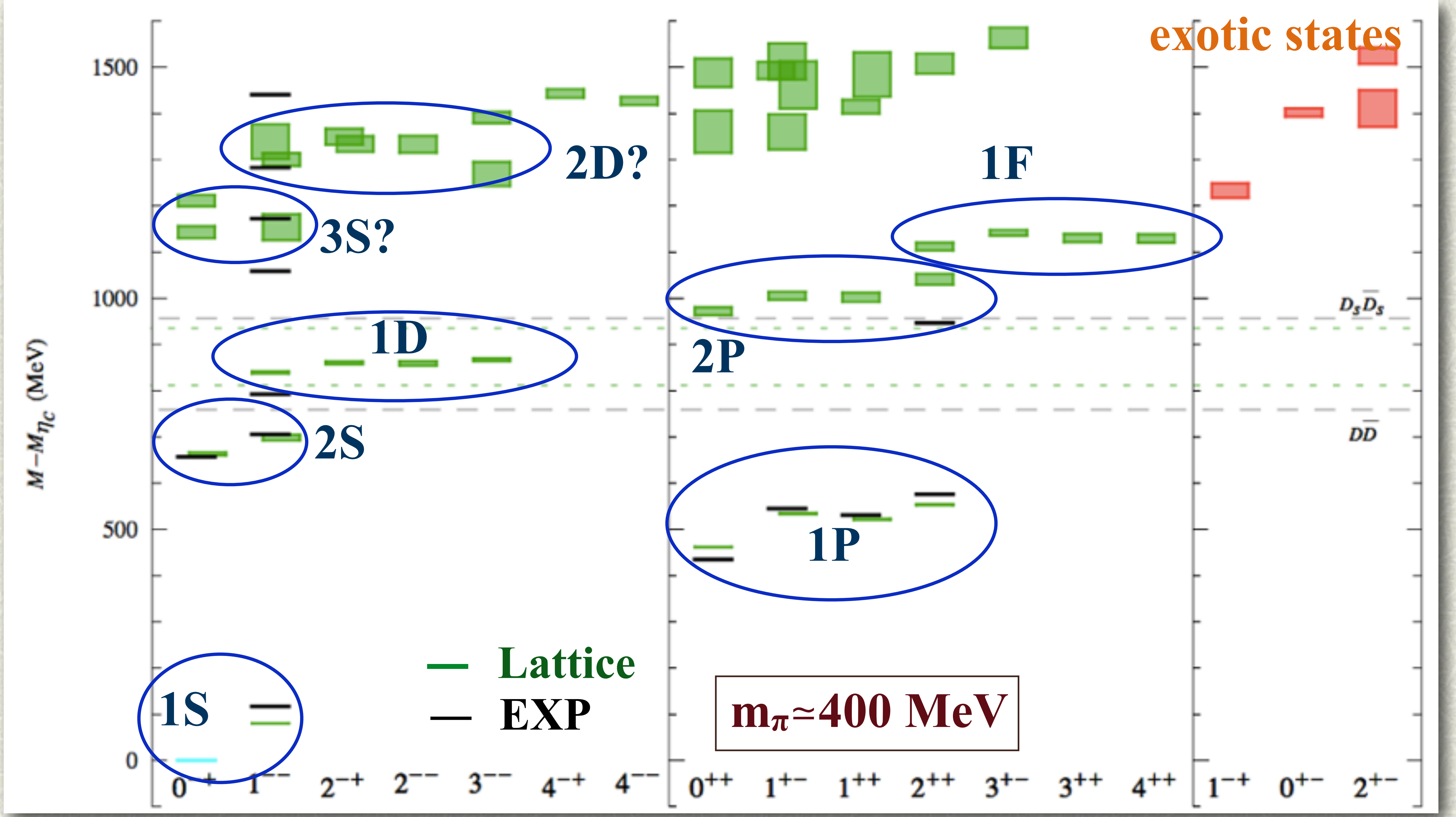


Lattice QCD

G.S. Bali, Phys. Rept. 343 (2001) 1

Charmonium spectra on Lattice

Liuming Liu, et al. (Hadron Spectrum Collaboration)
JHEP 07, 126 (2012)



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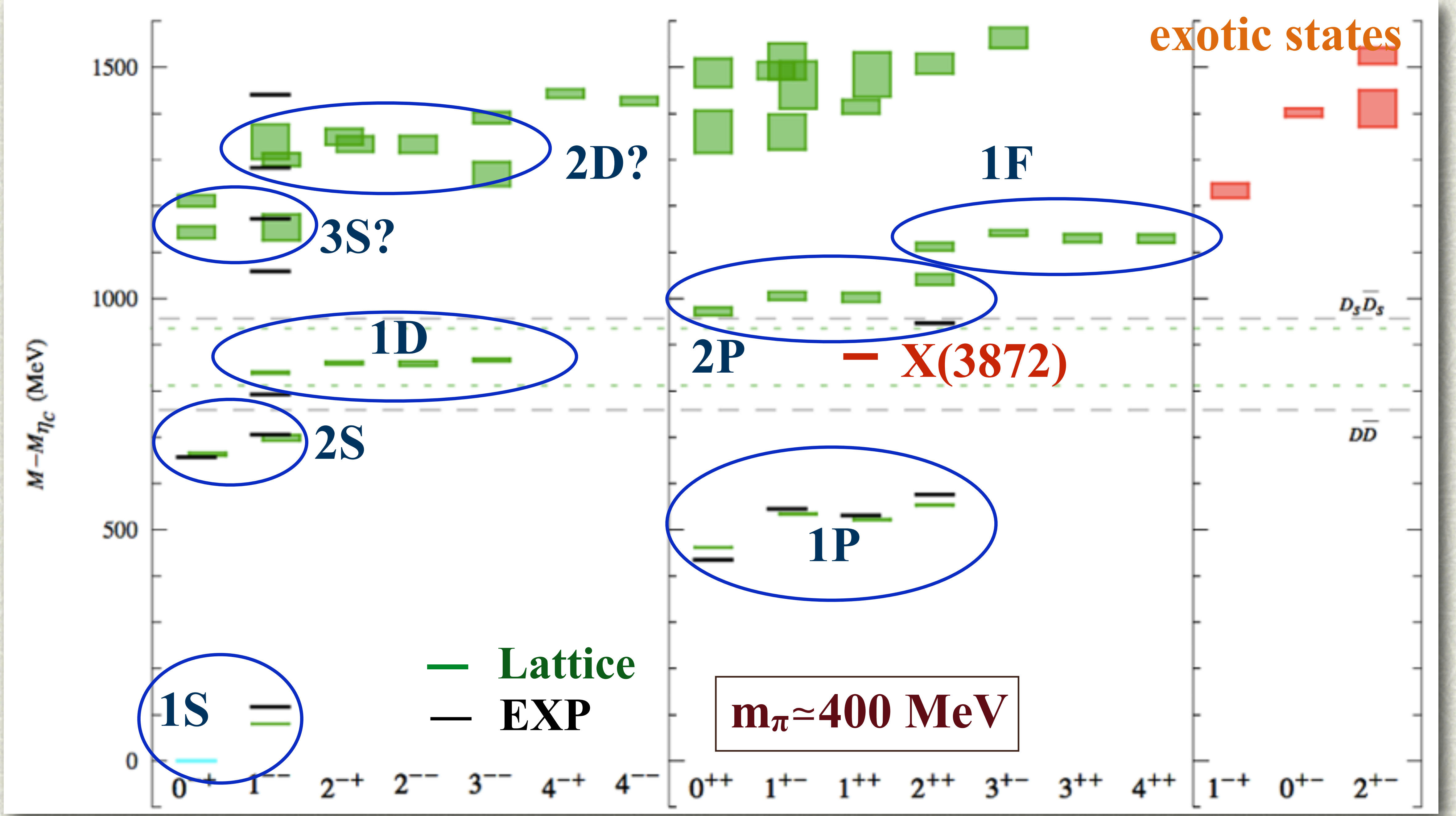
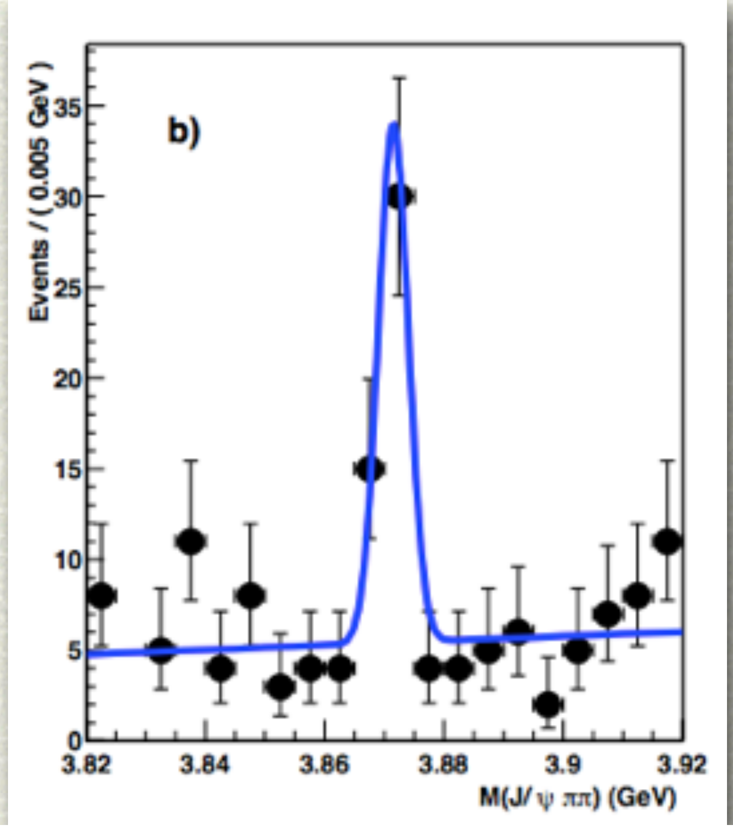


New Charmonium-like States

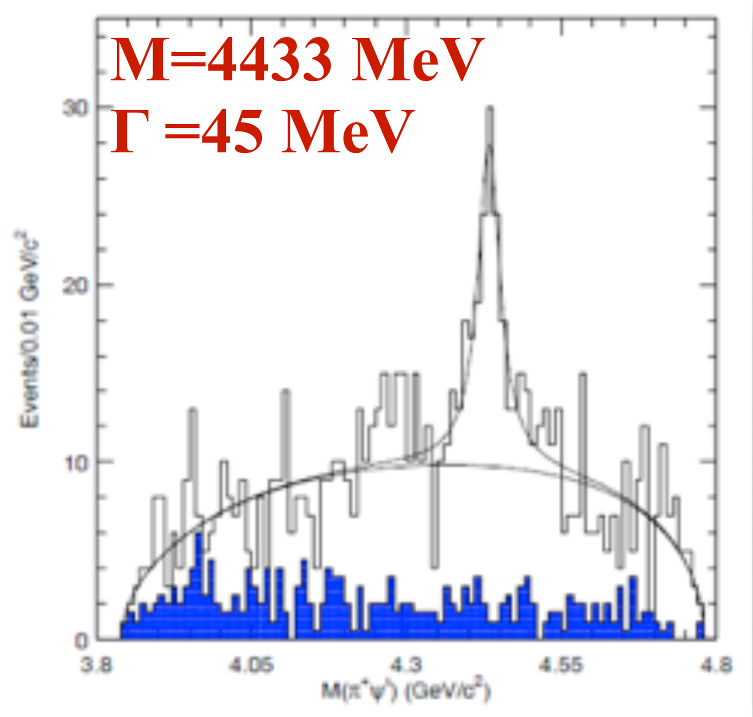
- X(3872) found in 2003 by Belle (KEK)
- Z(3900), Z(4430) etc. : Charged hidden charm states

X(3872)



PRL 91 (2003) 262001

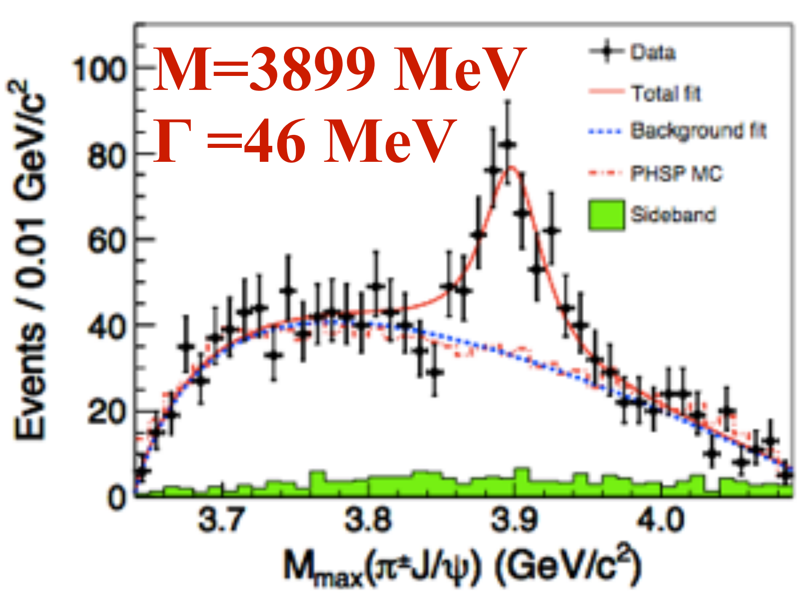
$Z_c^+(4430)$



M=4433 MeV
Γ =45 MeV

PRL 100 (2008) 142001

$Z_c^+(3900)$



M=3899 MeV
Γ =46 MeV

PRL 110 (2013) 252001

These states require at least 4 quarks,
i.e., tetra-quarks or hadron molecules.

New Charmonium-like States

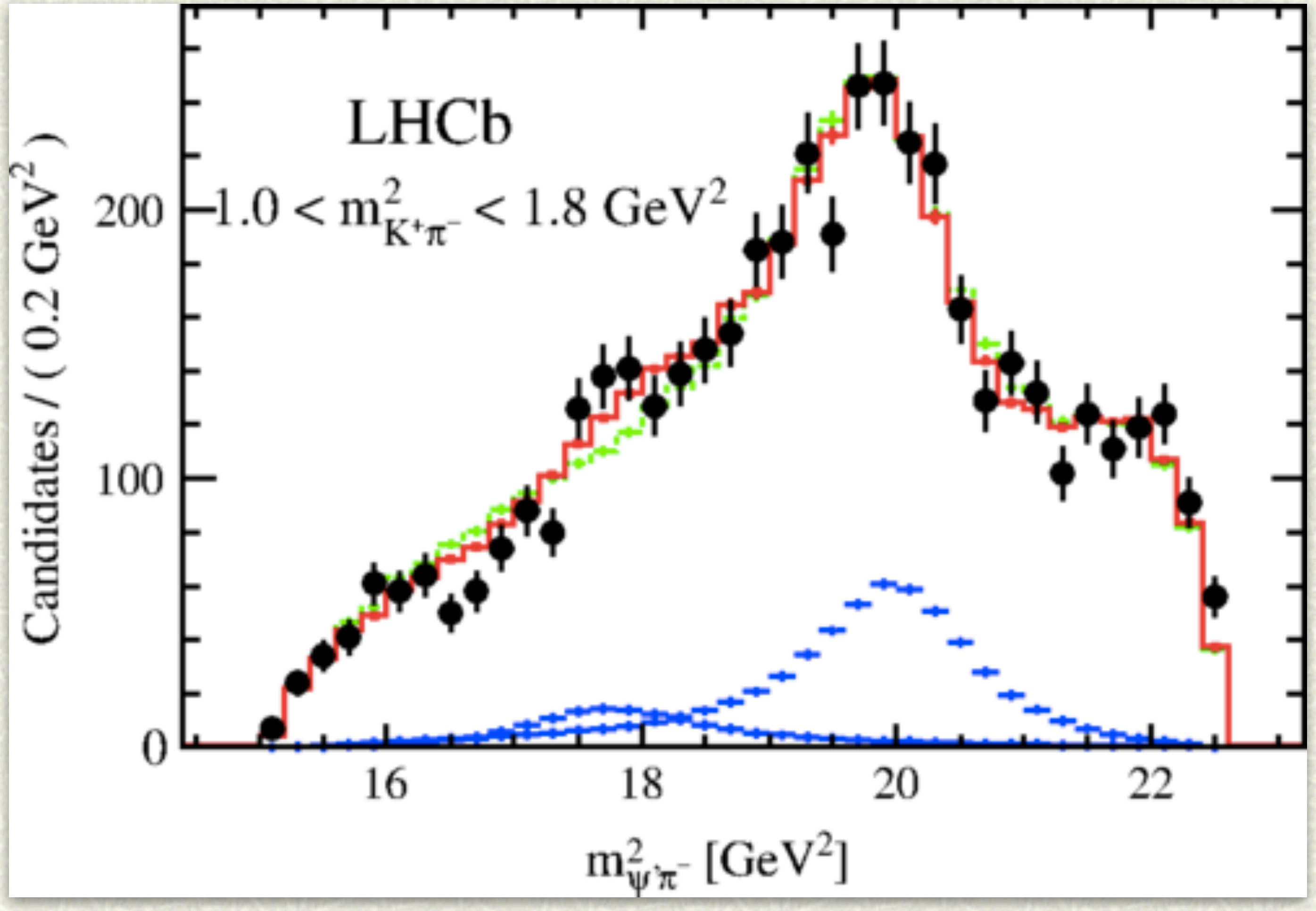
- X(3872) @ Belle, $J^{PC}=1^{++}$, confirmed @ LHCb, *PRL 110 (2013)*
- X(3872) is NOT a cc^{bar} state, because . .
  - Its mass, just at the DD^* threshold, is significantly lower than $\chi_{c1}(2P)$ prediction. (cf. $\chi_{c2}(2P)$=3930MeV)
  - Decay → $\gamma\psi(2S)$ is suppressed.
  - The isospin violation observed in the decays

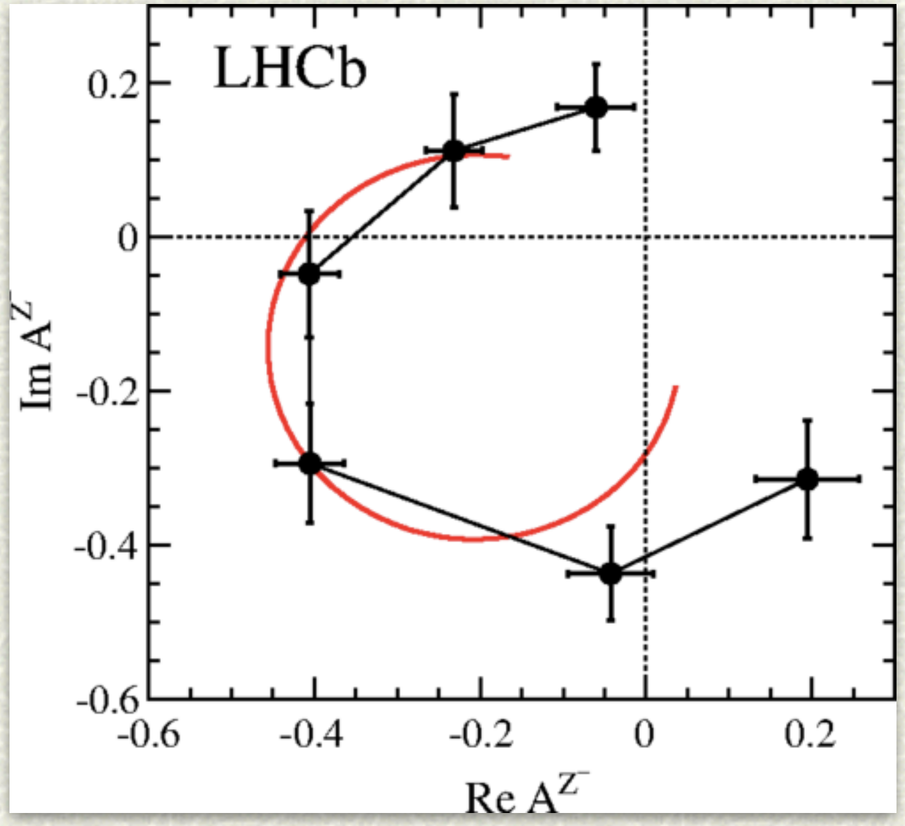
    $$X(3872) \rightarrow J/\psi + \rho \quad (I=1)$$
    $$\rightarrow J/\psi + \omega \quad (I=0)$$

    indicates a strong coupling to D^0D^{0*}(3872).

New Charmonium-like States

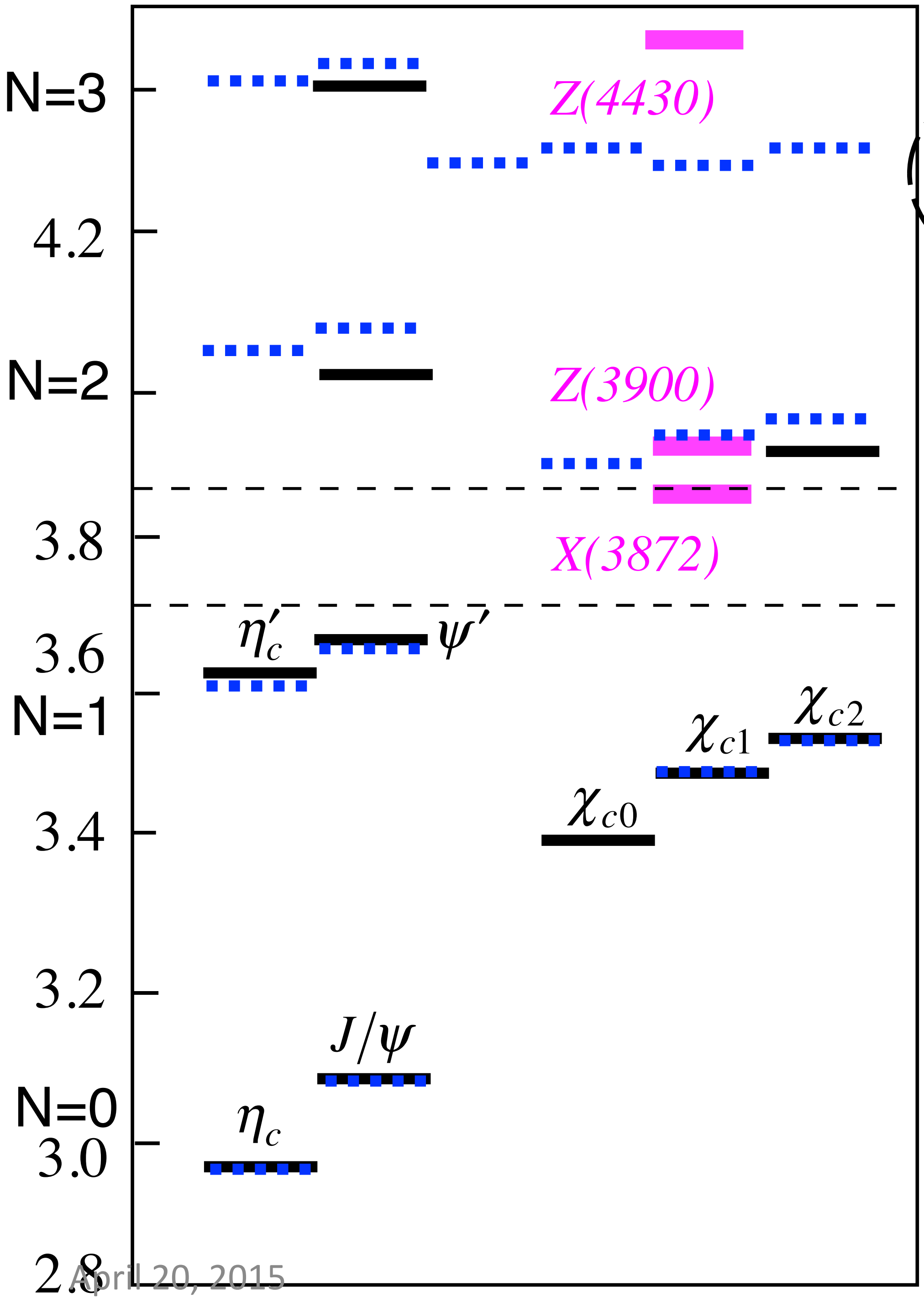
- **Z(4430) confirmed at LHCb, PRL 112, 222002 (2015) in $B^0 \to \psi' \pi^- K^+$ decay spectrum**

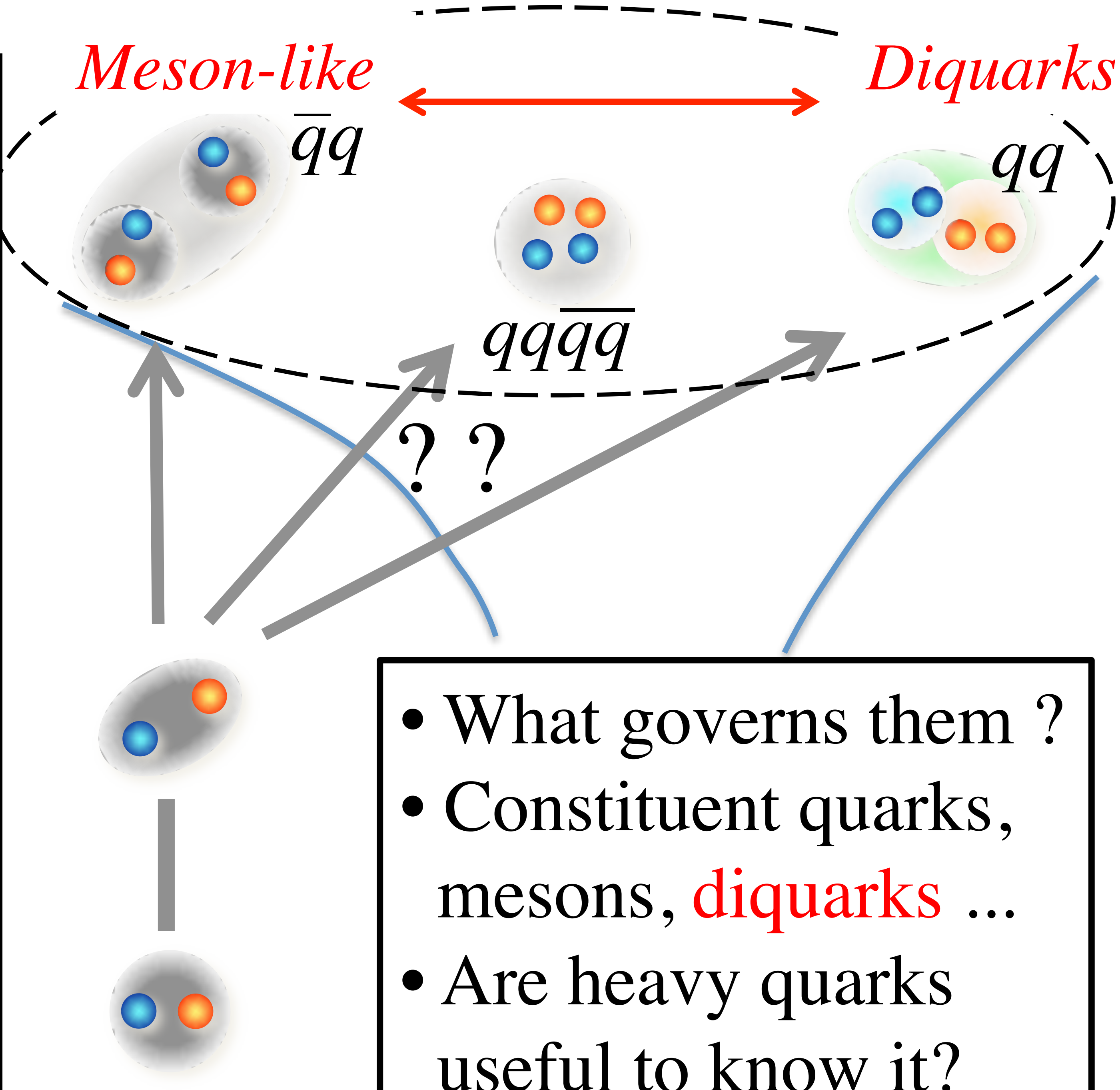




Above the threshold

$q\bar{q}$ creation and rearrangement of multiquarks



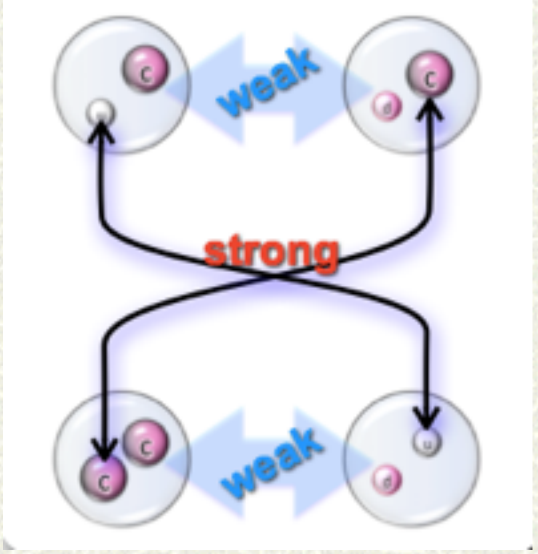


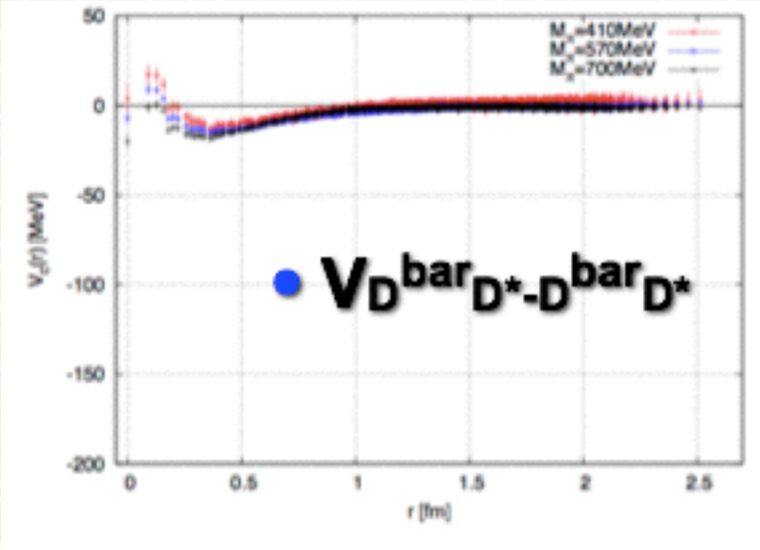
- What governs them ?
- Constituent quarks, mesons, diquarks ...
- Are heavy quarks useful to know it?

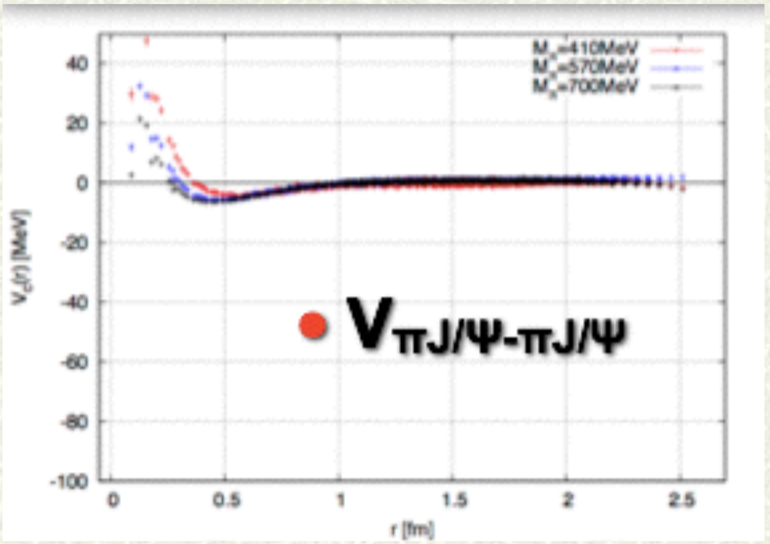
by A. Hosaka

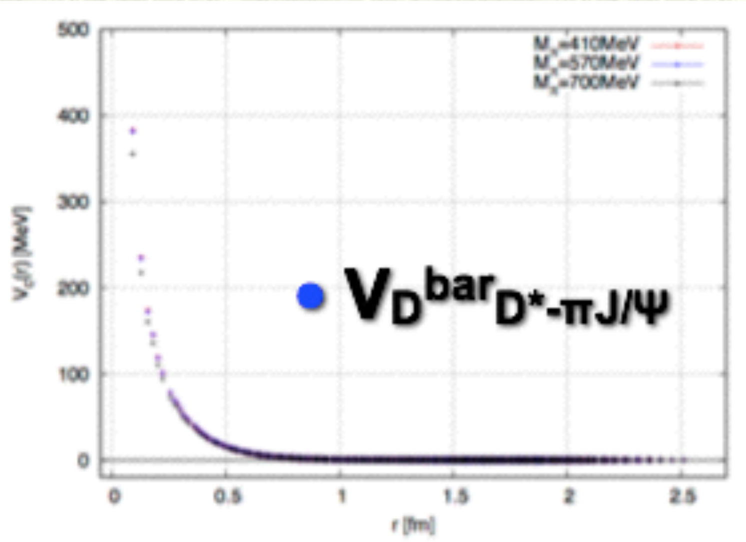
Exotic States on Lattice

- **$Z_c(3900)$ v.s. ($D^{bar}D^*$) + (π J/ψ) using the HAL QCD method**
  Y. Ikeda for HALQCD @ NSTAR2015 (in preparation)









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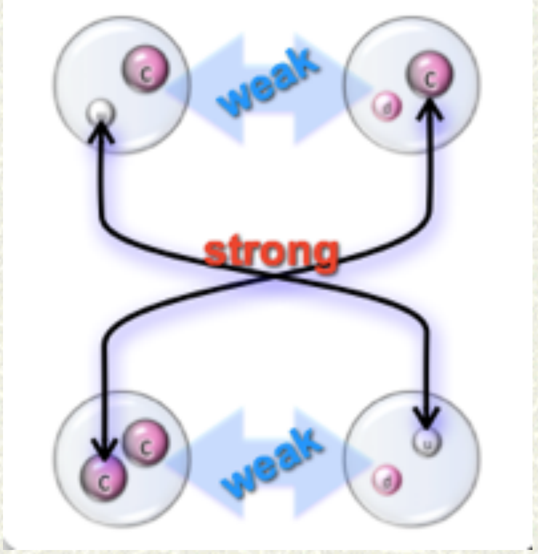
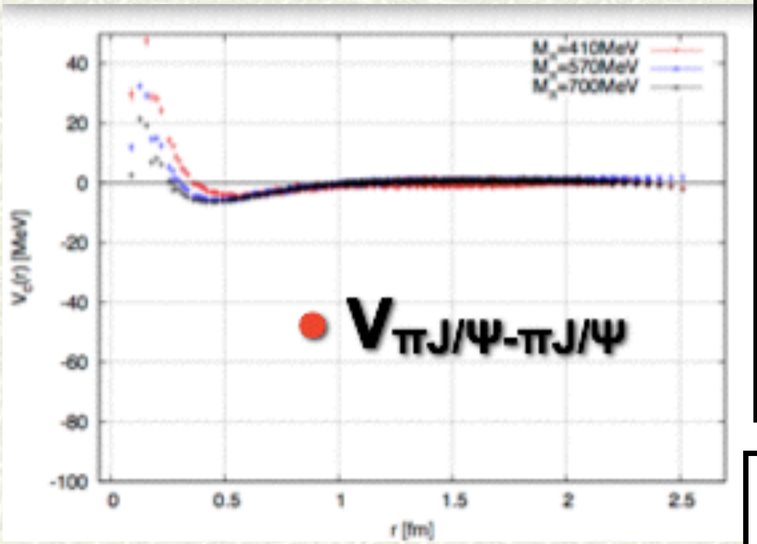
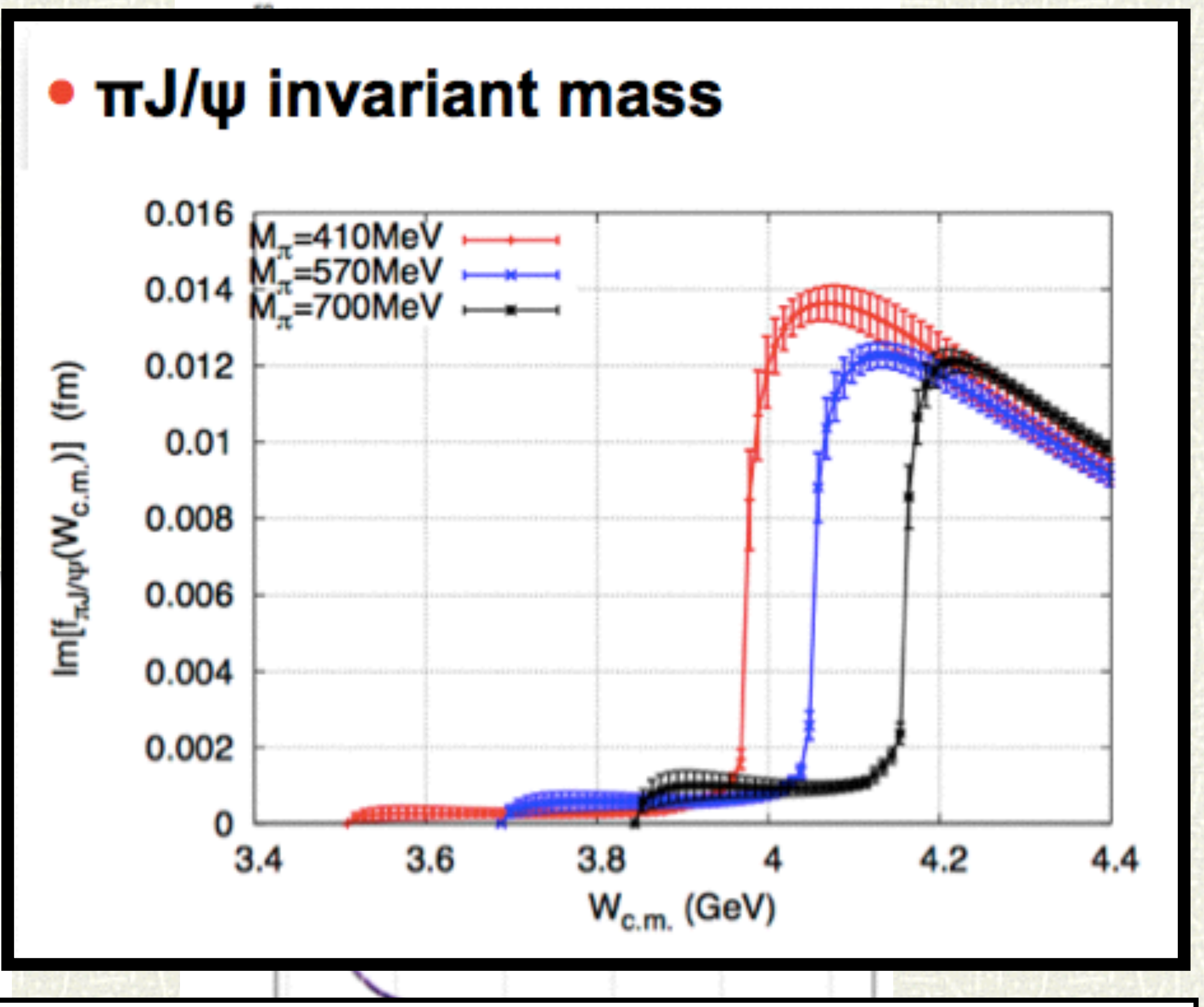




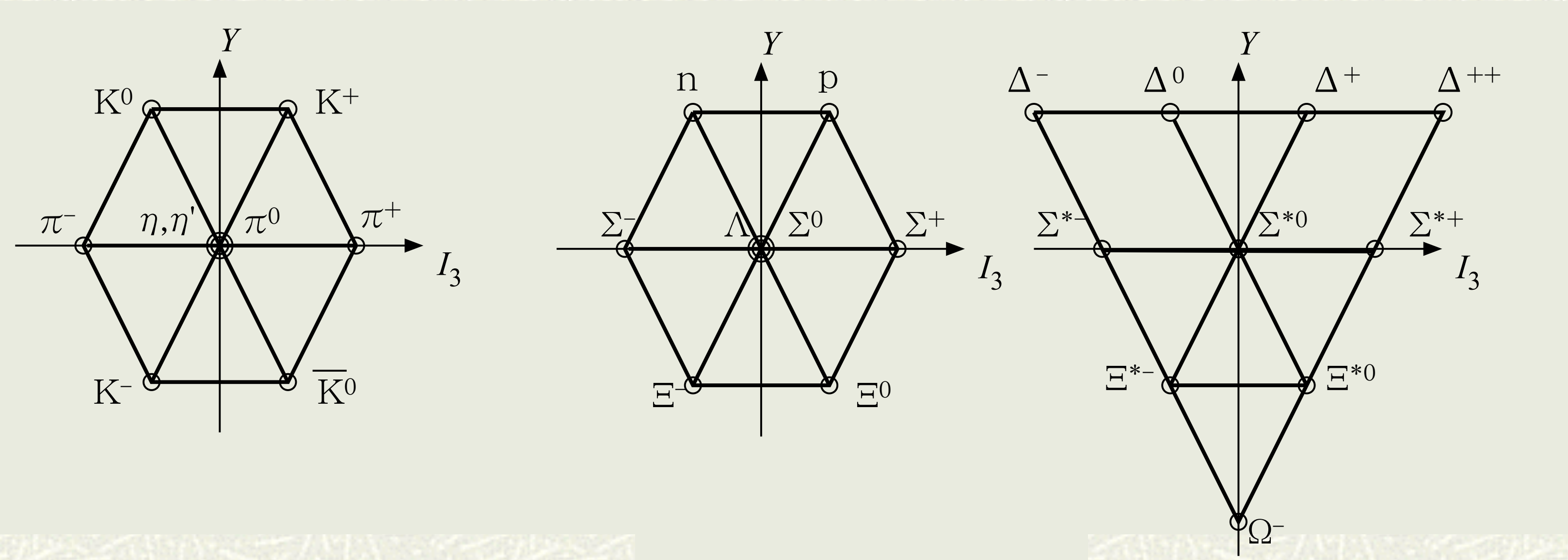


Strong (cusp) enhancement above the $D^{bar}D^*$ threshold

Light Exotic Hadrons

Light Hadrons

- **Light hadrons**
  The low-lying hadrons with u, d, s quarks form complete patterns of the SU(3)$_f$ representations.
- **SU(3)$_f$ symmetry is the basis of the constituent quark model.**

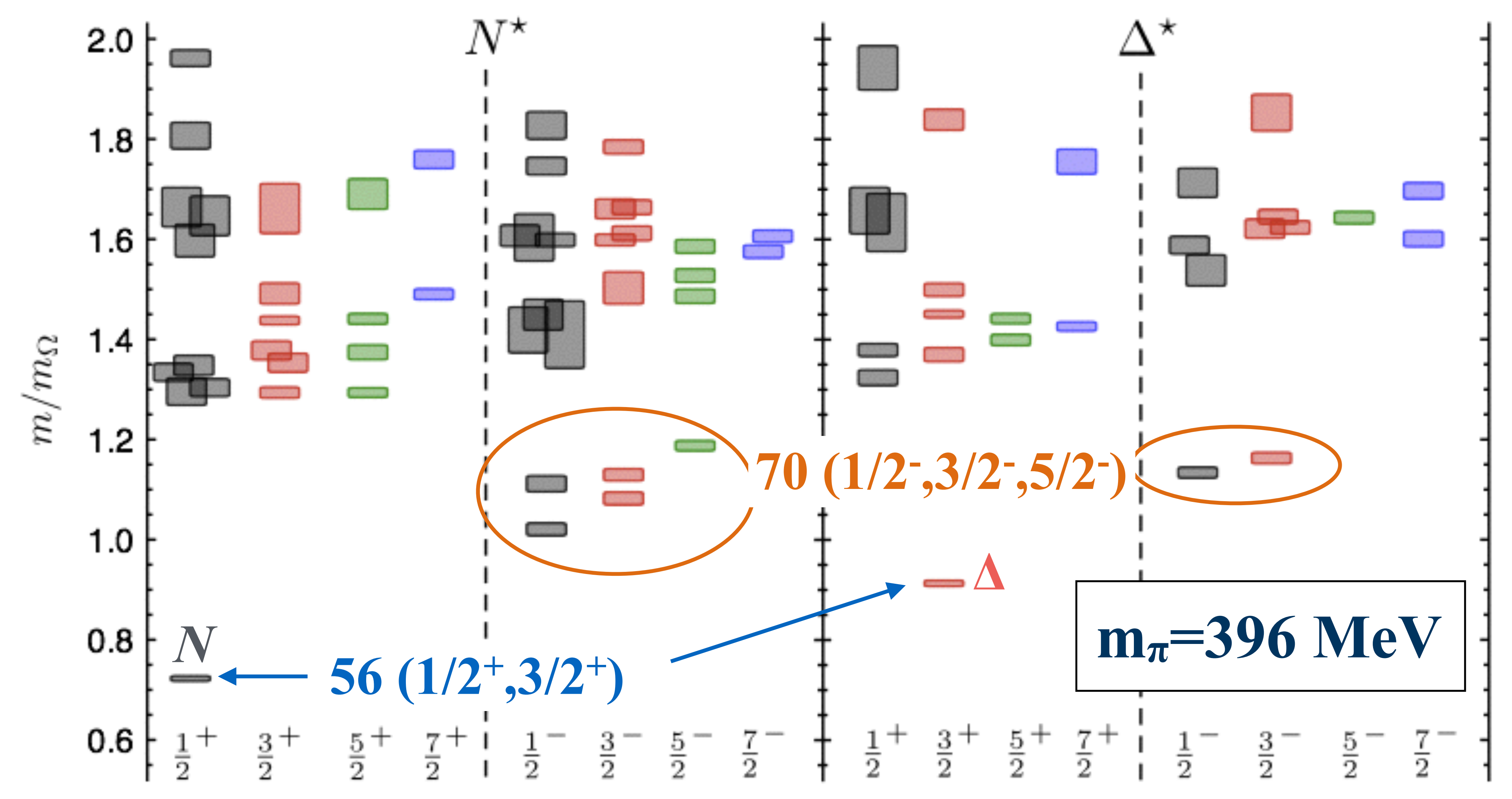


mesons with qq^{bar}

baryons with qqq

Light Hadrons

- **Light baryon spectra by R.G. Edwards et al., PRD84 (2011) 074508, are consistent with the SU(6)×O(3) quark model.**



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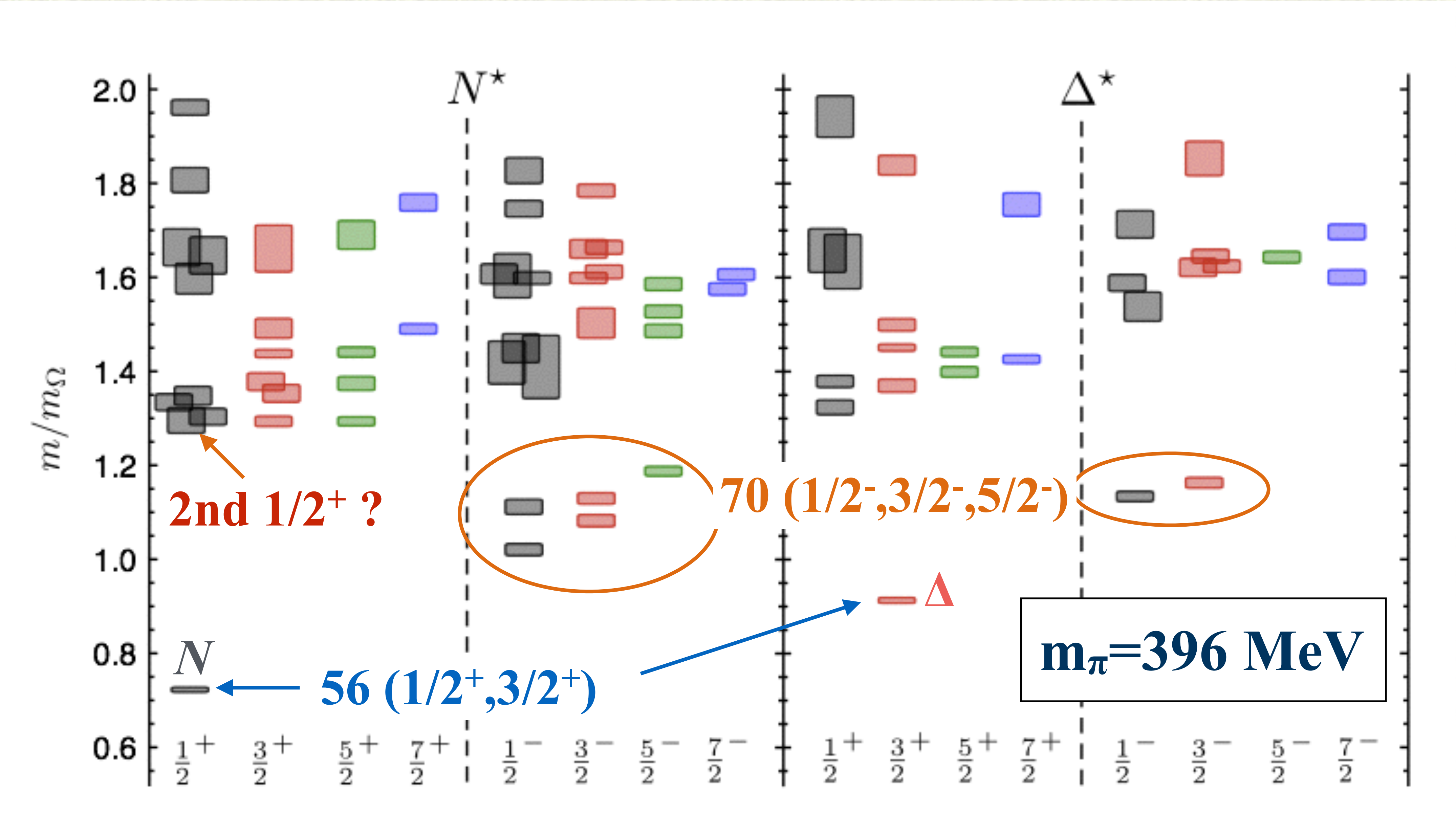


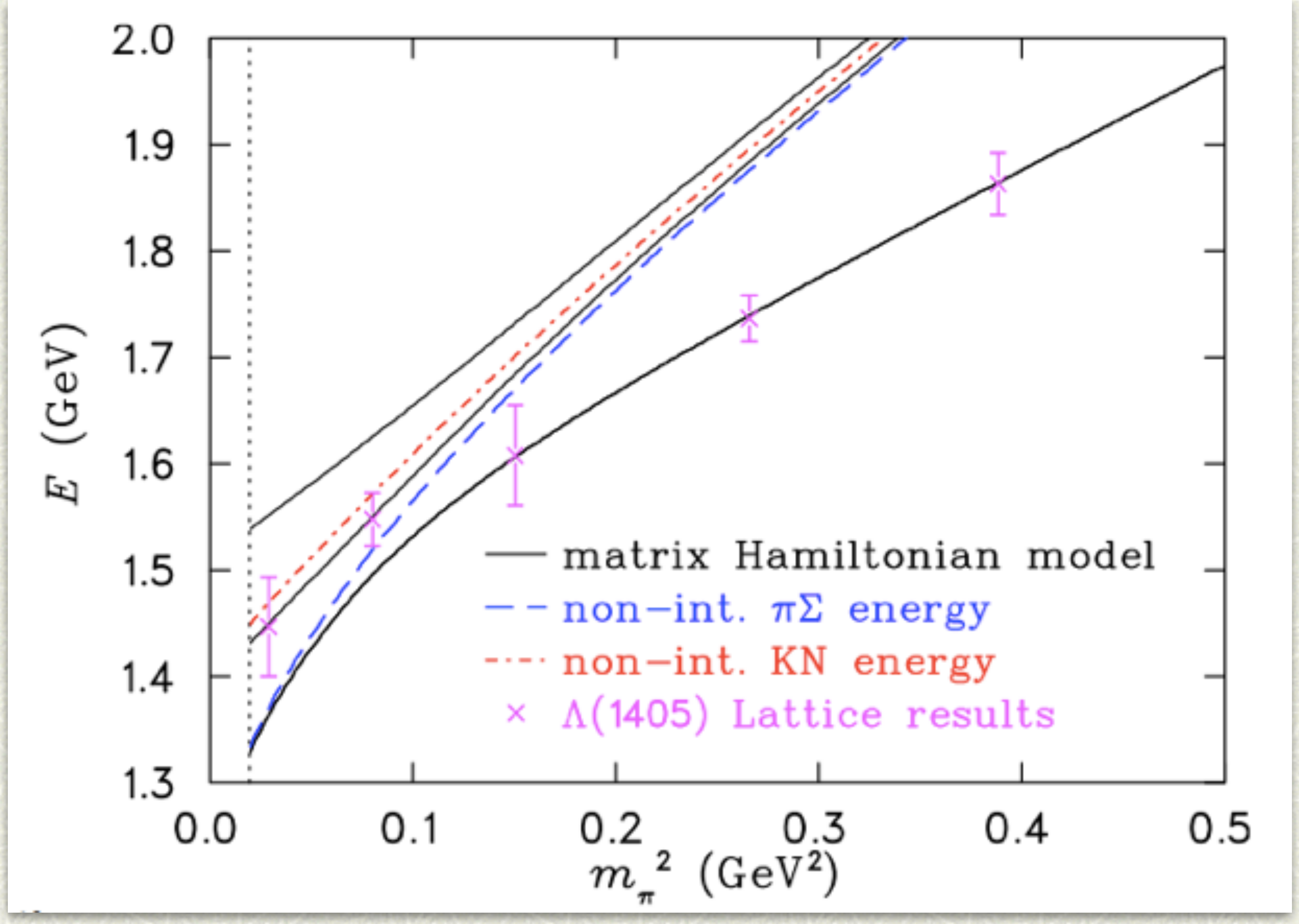
m_π=396 MeV

Light Hadrons

- **Lattice QCD has confirmed that the overall features of the low-lying hadron spectrum are given consistently as the constituent quark model.**
- **Yet, there are some (exotic) hadrons which are not reproduced in LQCD by simple qq^{bar} or qqq operators.**
- **A few prominent examples:**
  Light scalar mesons, Roper resonance(s), Λ(1405), . .
- **Recent analyses have “confirmed” the exotic properties of Λ(1405).**

Λ(1405)

- **Recent LQCD analysis by J.M.M. Hall et al. *PRL 114, 132002 (2015) (ArXiv:1411.3402)*, claims $K^{bar}N$ dominance.**



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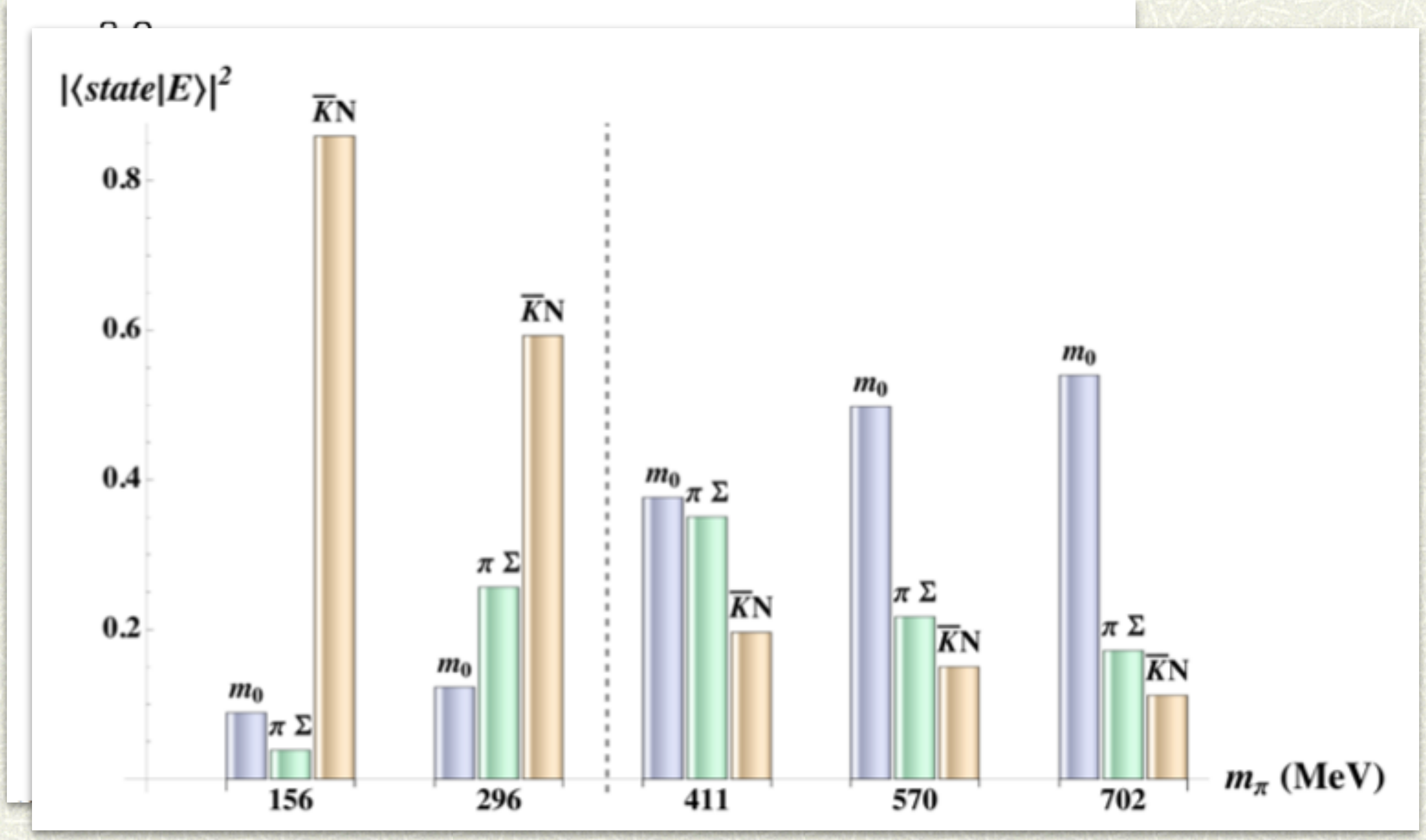
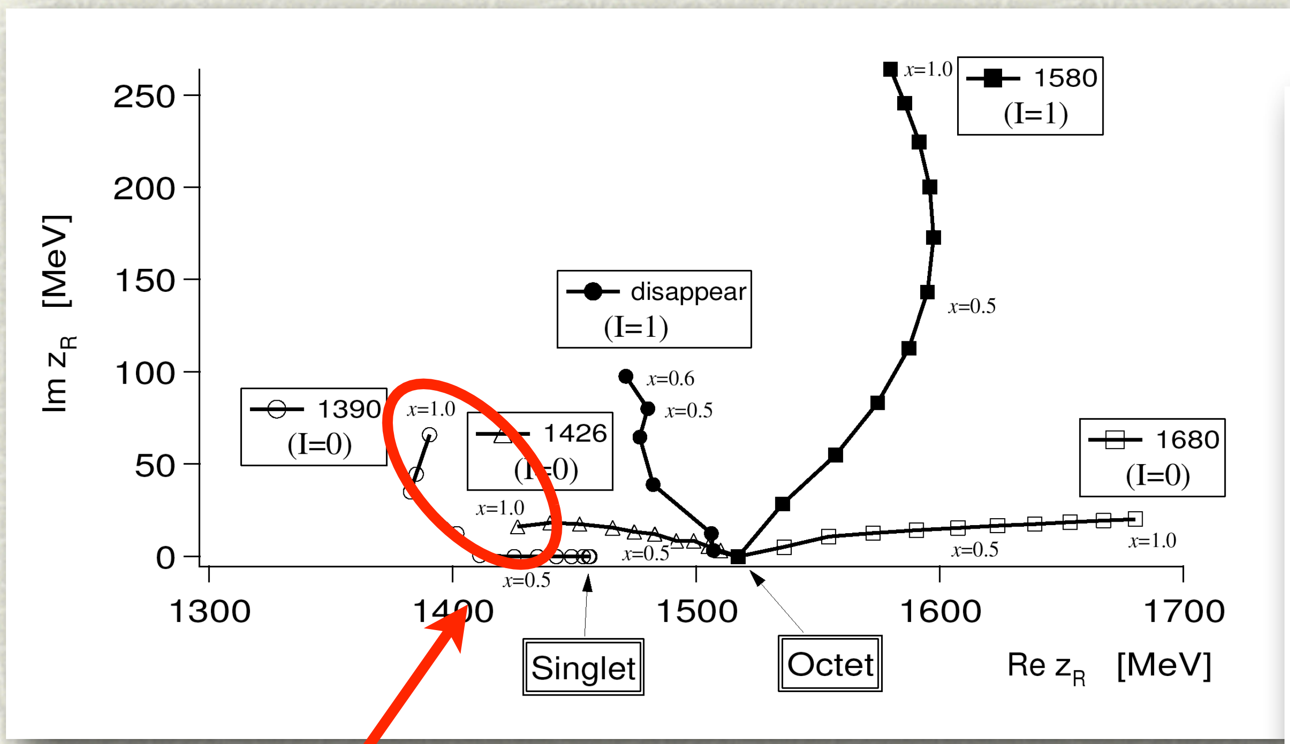
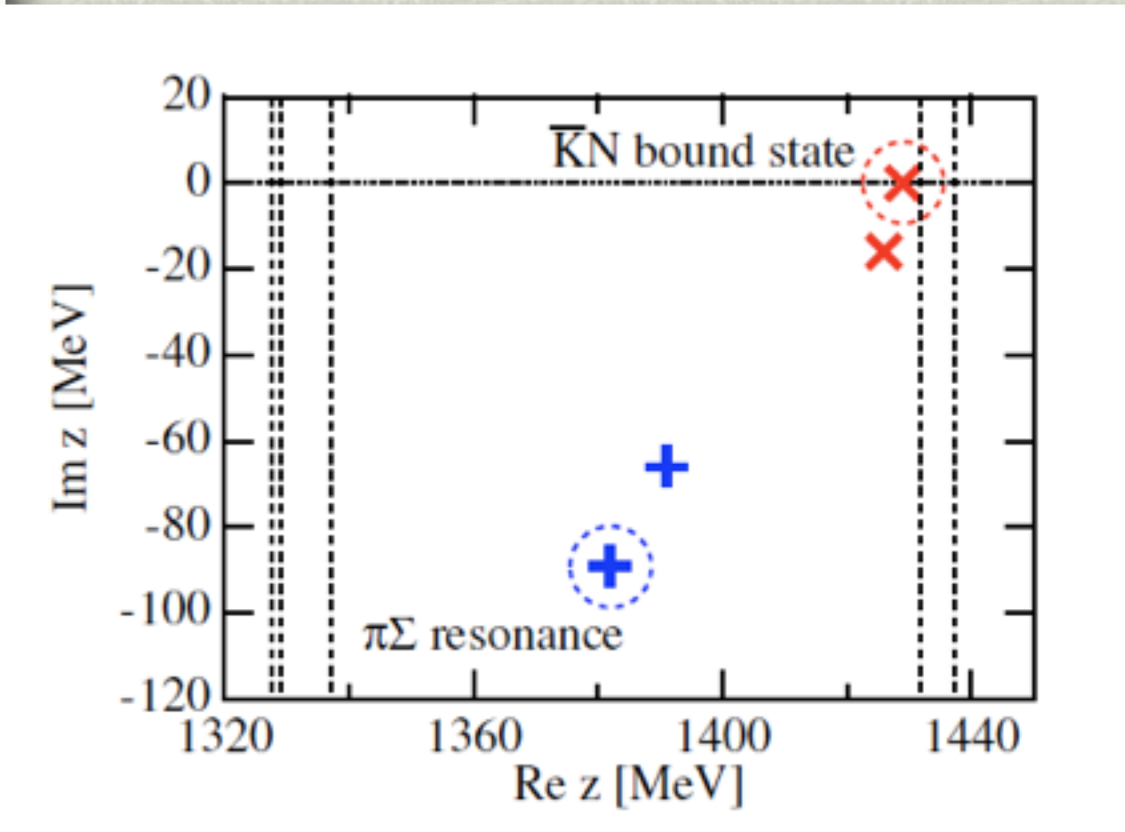


Λ(1405)

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



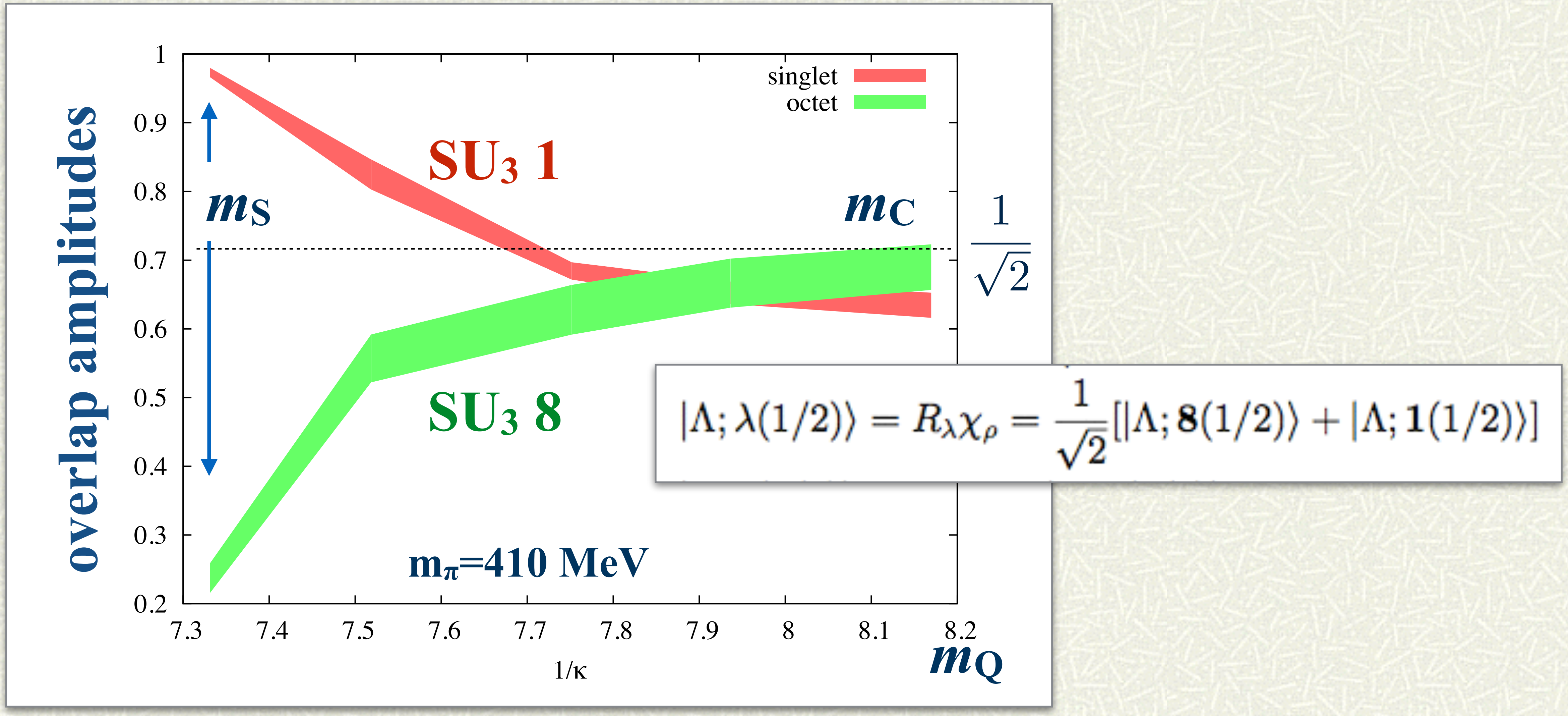


Chiral unitary approaches predict *two resonance poles for* Λ(1405). (Jido et al., 2003)
They originate from a K^{bar}N bound state and a πΣ resonance. (Hyodo, Weise)

Λ(1405)

- **HQ mass dependence: $m_Q = m_S \rightarrow m_C$ transition from SU(3) to HQ symmetry**

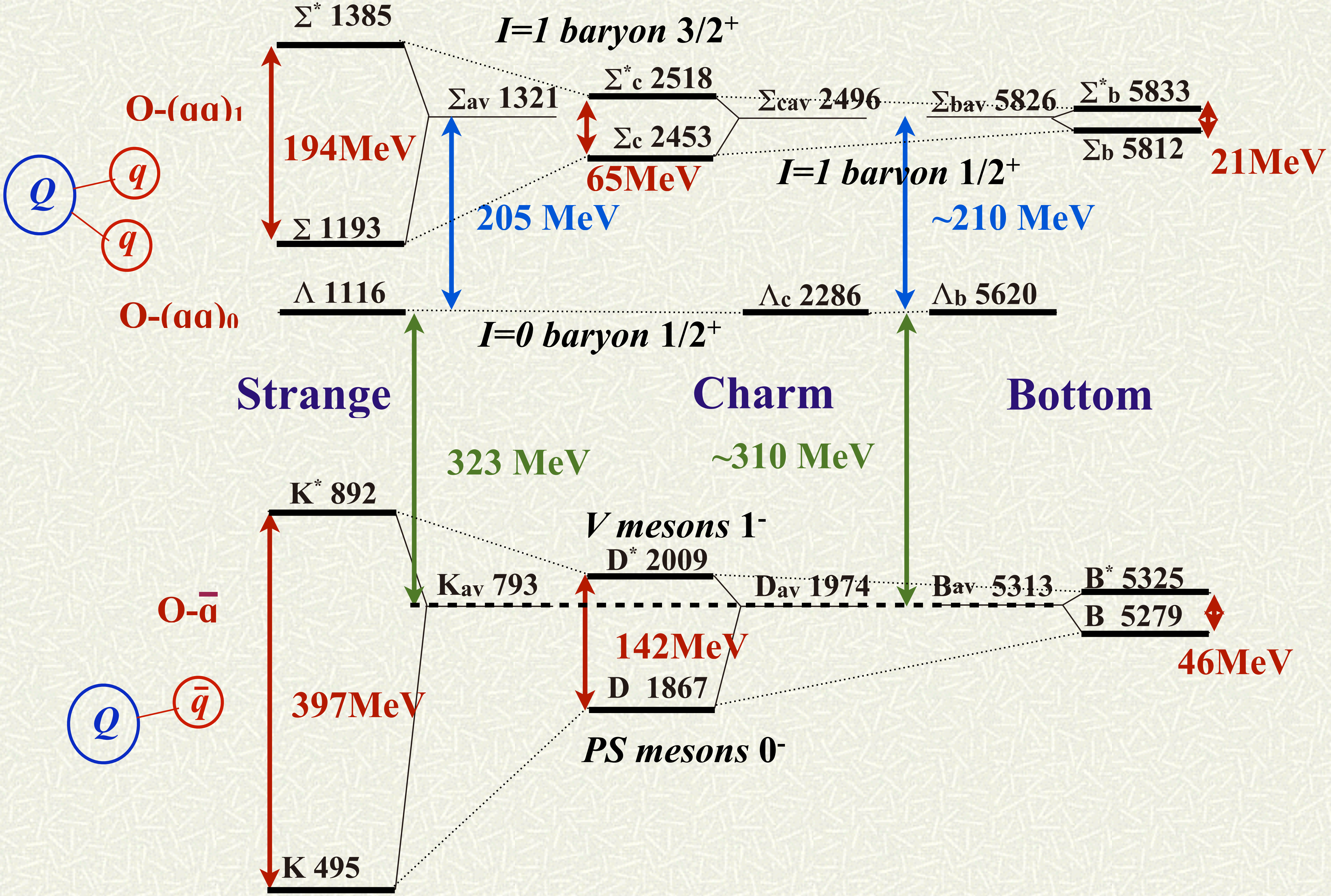
P. Gubler, T.T. Takahashi, M.O., in preparation



$$|\Lambda;\lambda(1/2)\rangle = R_\lambda \chi_\rho = \frac{1}{\sqrt{2}}[|\Lambda;\mathbf{8}(1/2)\rangle + |\Lambda;\mathbf{1}(1/2)\rangle]$$

Diquarks in Heavy Baryons

Strange *v.s.* Charm/Bottom



Σ^* 1385

I=1 baryon $3/2^+$

Σ^*_c 2518

Σ_{av} 1321

Σ_{cav} 2496

Σ_{bav} 5826

Σ^*_b 5833

O-$(qq)_1$

194MeV

Σ_c 2453

Σ_b 5812

21MeV

65MeV

I=1 baryon $1/2^+$

Q

q

q

205 MeV

~210 MeV

Σ 1193

Λ 1116

Λ_c 2286

Λ_b 5620

O-$(qq)_0$

I=0 baryon $1/2^+$

Strange

Charm

Bottom

323 MeV

~310 MeV

K^* 892

V mesons 1^-

D^* 2009

K_{av} 793

D_{av} 1974

B_{av} 5313

B^* 5325

O-$\bar{q}$

B 5279

142MeV

46MeV

D 1867

Q

$\bar{q}$

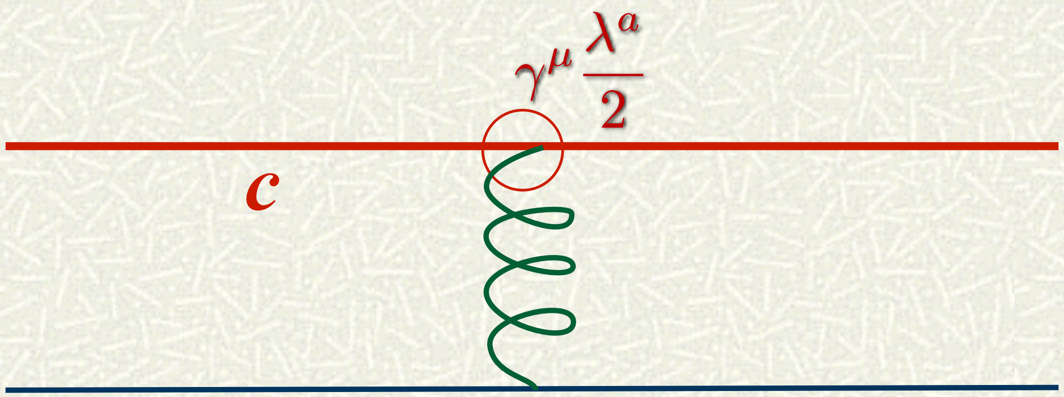
397MeV

PS mesons 0^-

K 495

Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



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

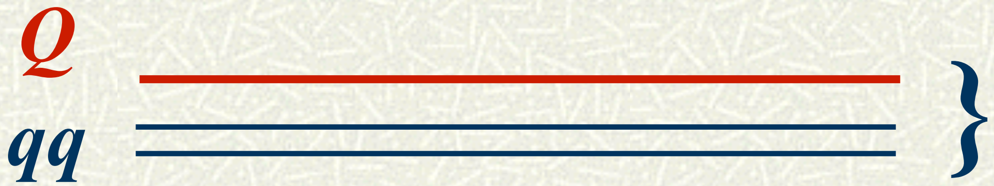
(Color Electric coupling) ≫ (Color Magnetic coupling)

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

⇨ Heavy Quark Spin Symmetry

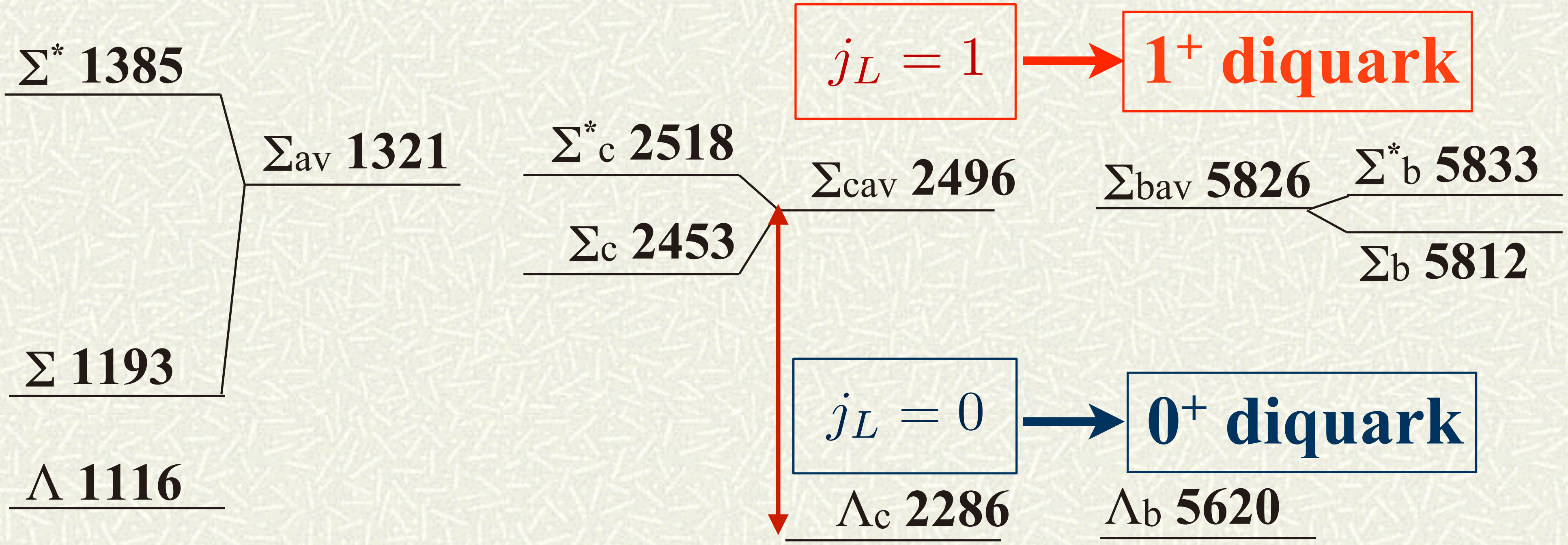
Heavy Quark Spin Symmetry

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



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

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



$j_L = 1$ → **1^+ diquark**

$j_L = 0$ → **0^+ diquark**

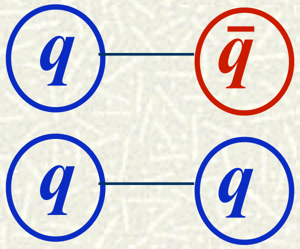
Diquark

- **The Scalar (0^+) diquark is an analogue of the PS meson:**

  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} : $[ud]_0$, $[ds]_0$, $[sd]_0$

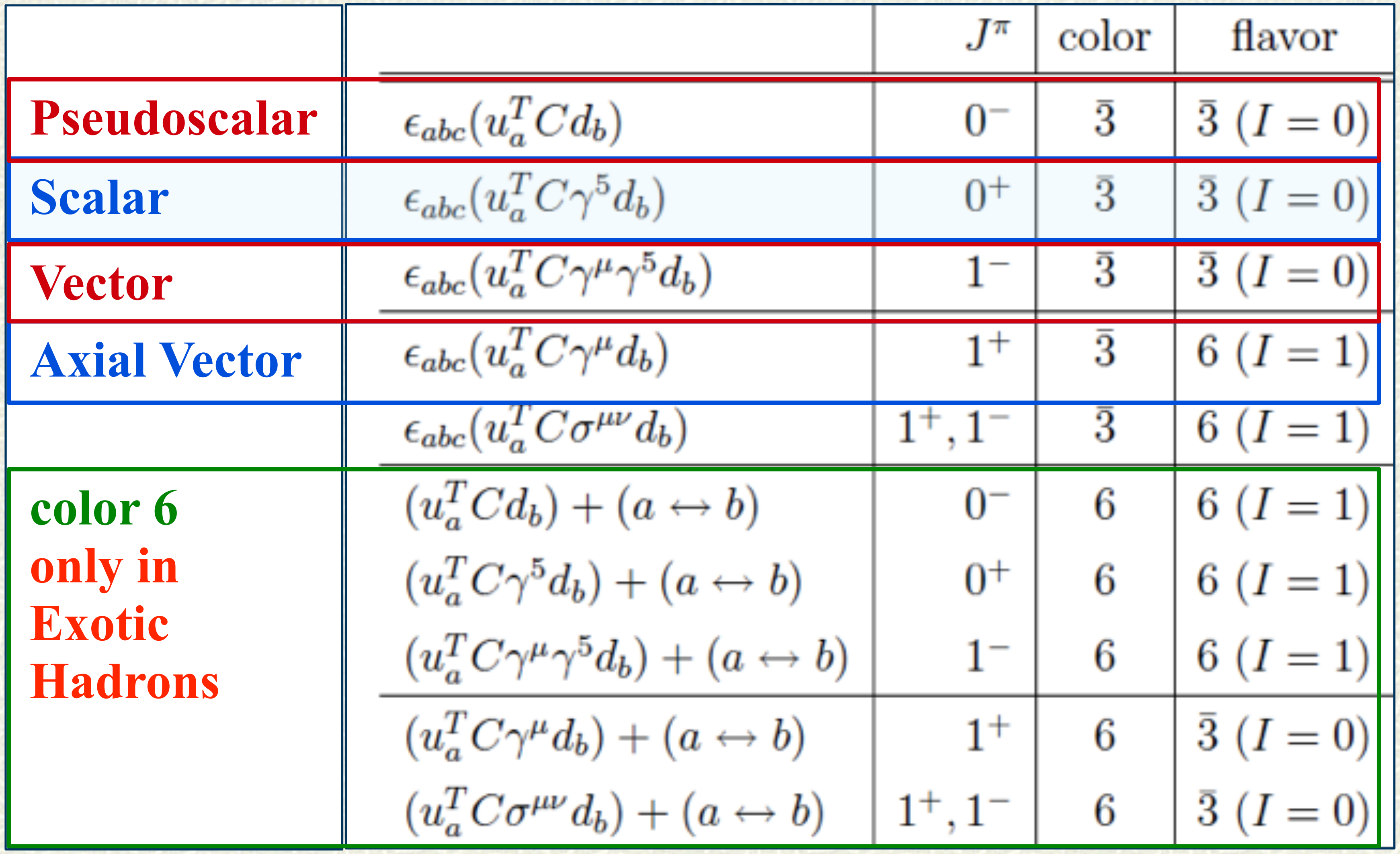


  - **Color magnetic interaction (CMI) of the OgE is attractive for the scalar diquark.**
  - **Instanton Induced Interaction (III) is attractive in the flavor antisymmetric states**
  - **Rough estimate: $S(0^+)$ *v.s.* $A(1^+)$**

    $M(1^+)-M(0^+) = (2/3)\,[M(\Delta)- M(N)] \sim 200$ MeV

Diquark

- **Heavy Baryons, Λ_Q, Σ_Q = Q + (qq)**
  Because the spin dependent interaction is suppressed between the heavy Q and light quarks, the heavy baryon spectrum will reflect the light diquark (qq) *spin-dependent* correlation.



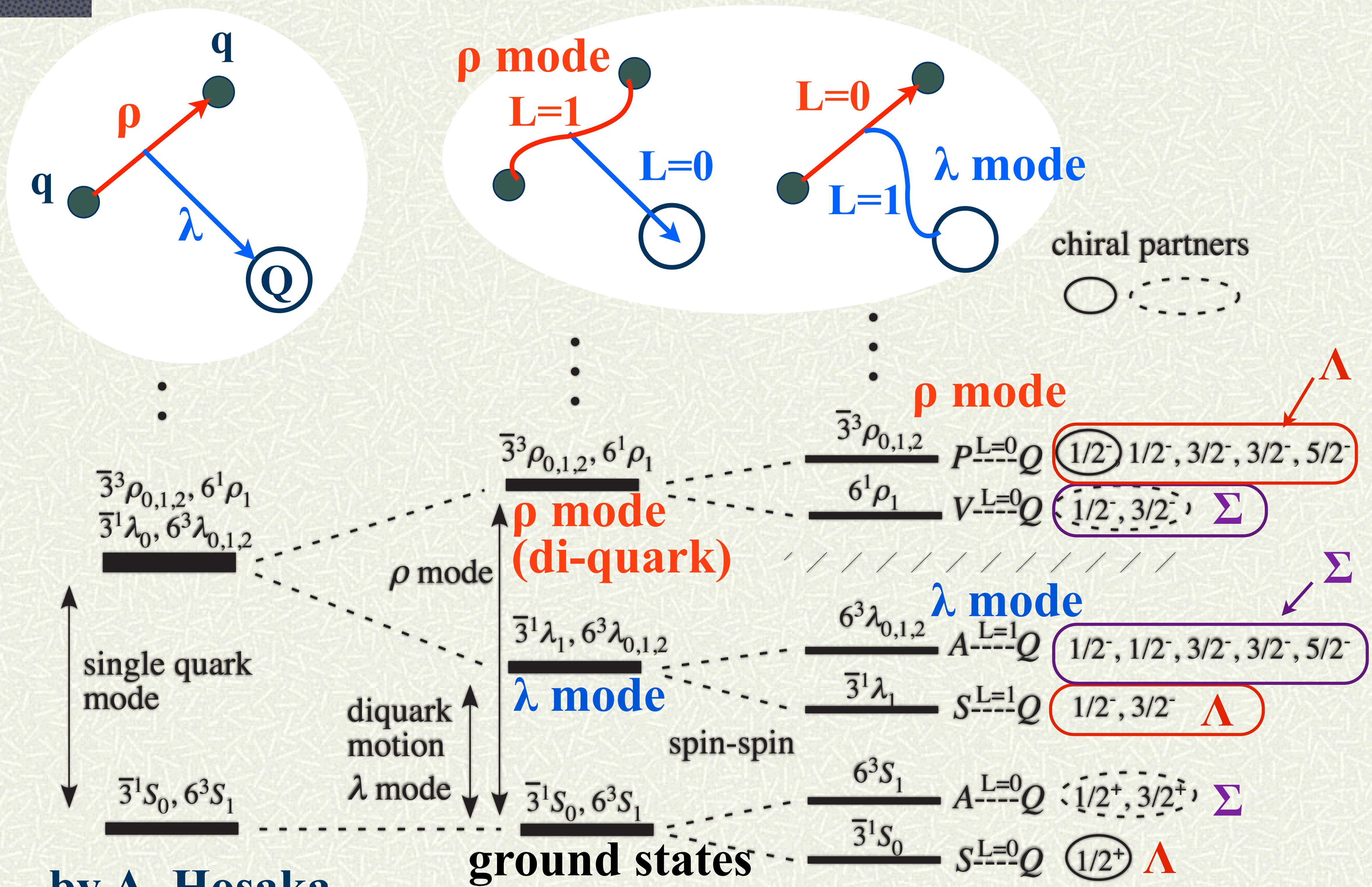
		J^π	color	flavor
Pseudoscalar	$\epsilon_{abc}(u_a^T C d_b)$	0^-	$\bar{3}$	$\bar{3}\ (I=0)$
Scalar	$\epsilon_{abc}(u_a^T C\gamma^5 d_b)$	0^+	$\bar{3}$	$\bar{3}\ (I=0)$
Vector	$\epsilon_{abc}(u_a^T C\gamma^\mu\gamma^5 d_b)$	1^-	$\bar{3}$	$\bar{3}\ (I=0)$
Axial Vector	$\epsilon_{abc}(u_a^T C\gamma^\mu d_b)$	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	$\bar{3}\ (I=0)$

Diquark

- **Diquarks in (quenched) lattice calculations**
  - **Hess, Karsch, Laermann, Wetzorke, PR D58, 111502 (1998)**
    $M(0^+) \sim 694$ MeV, $M(1^+) \sim 810$ MeV (Landau gauge)
  - **Alexandrou, de Forcrand, Lucini, PRL 97, 222002 (2006)**
    gauge invariant calculation in *a Qqq system*
    $M(1^+) - M(0^+) \sim 100\text{-}150$ MeV
  - **Babich, et al., PR D76, 074021 (2007)**
    $M(1^+) - M(0^+) \sim 162$ MeV (Landau gauge)
  - **DeGrand, Liu, Schaefer, PR D77, 034505 (2008)**
    S: strongly attractive, PS: attractive for small m_q

- **The scalar 0^+ diquark has a strong attractive correlation.**

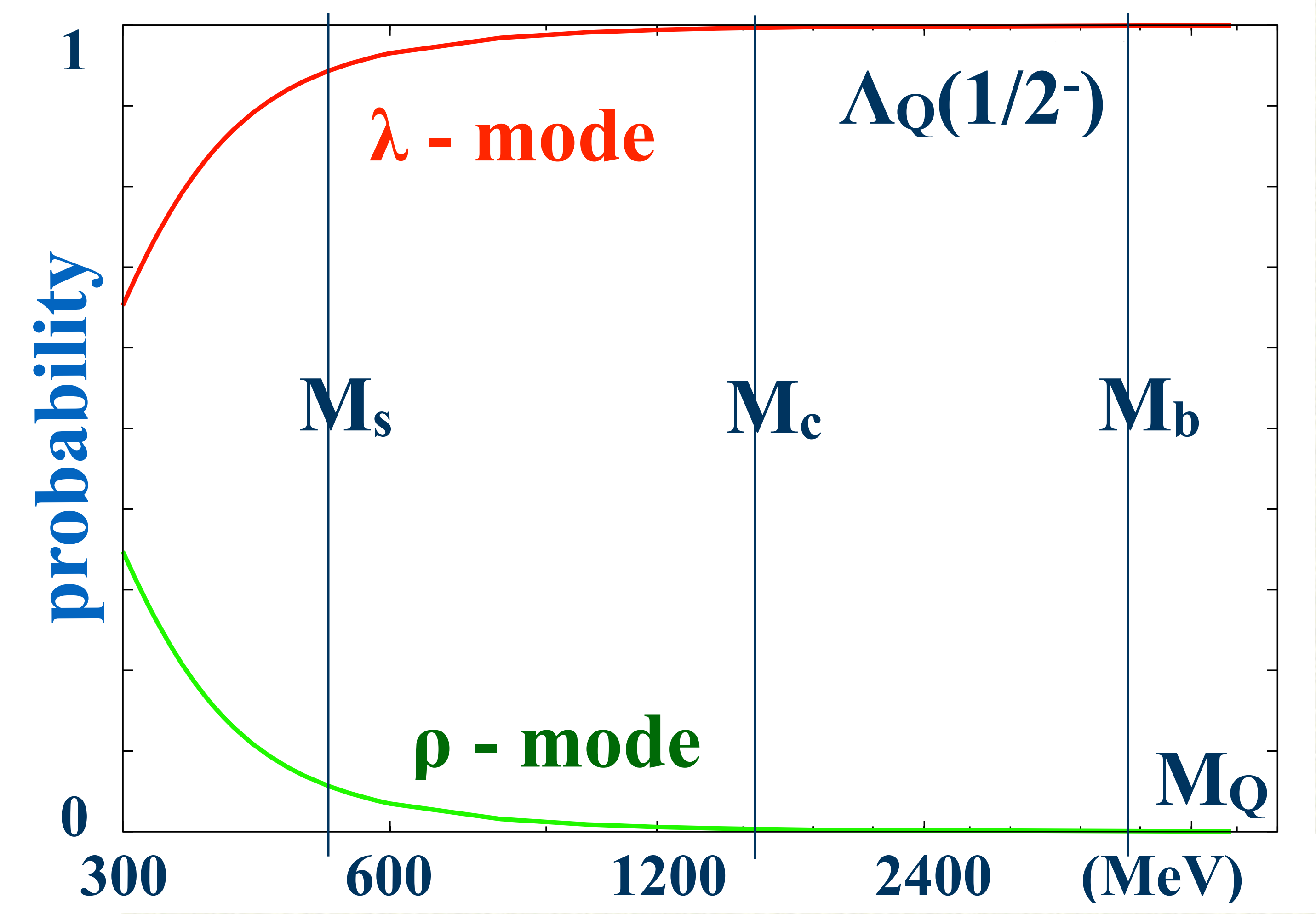
Diquarks in P-wave Baryons

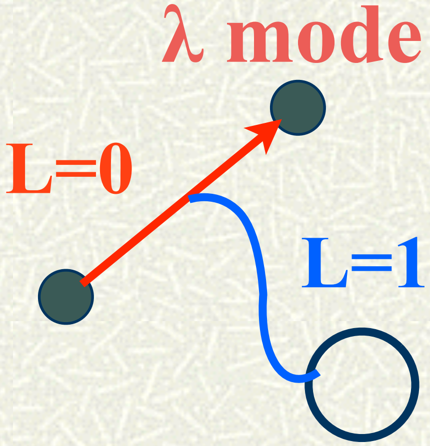


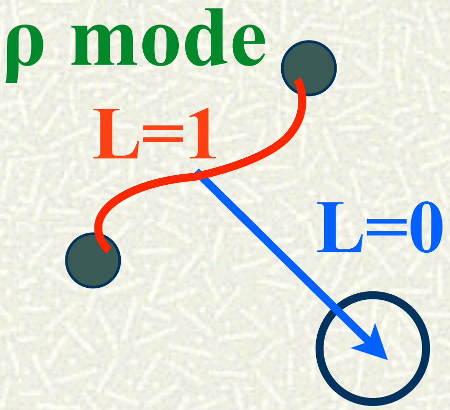
by A. Hosaka

Diquarks in 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**

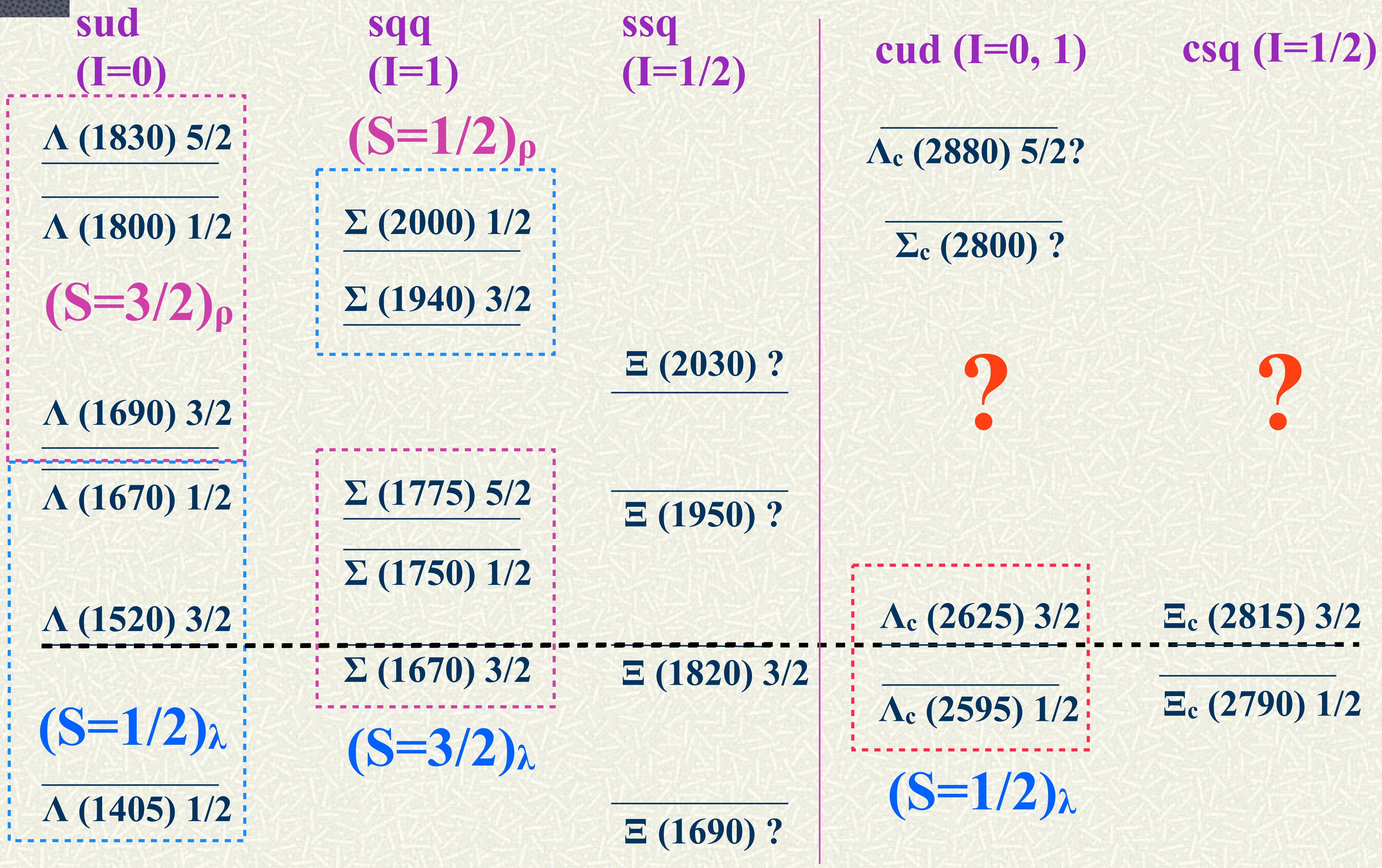






Yoshida, Sadato, Hosaka, Hiyama, MO, in preparation.

Diquarks in P-wave Baryons



sud (I=0)

Λ (1830) 5/2

Λ (1800) 1/2

$(S=3/2)_\rho$

Λ (1690) 3/2

Λ (1670) 1/2

Λ (1520) 3/2

$(S=1/2)_\lambda$

Λ (1405) 1/2

sqq (I=1)

$(S=1/2)_\rho$

Σ (2000) 1/2

Σ (1940) 3/2

Σ (1775) 5/2

Σ (1750) 1/2

Σ (1670) 3/2

$(S=3/2)_\lambda$

ssq (I=1/2)

Ξ (2030) ?

Ξ (1950) ?

Ξ (1820) 3/2

Ξ (1690) ?

cud (I=0, 1)

Λ_c (2880) 5/2?

Σ_c (2800) ?

?

Λ_c (2625) 3/2

Λ_c (2595) 1/2

$(S=1/2)_\lambda$

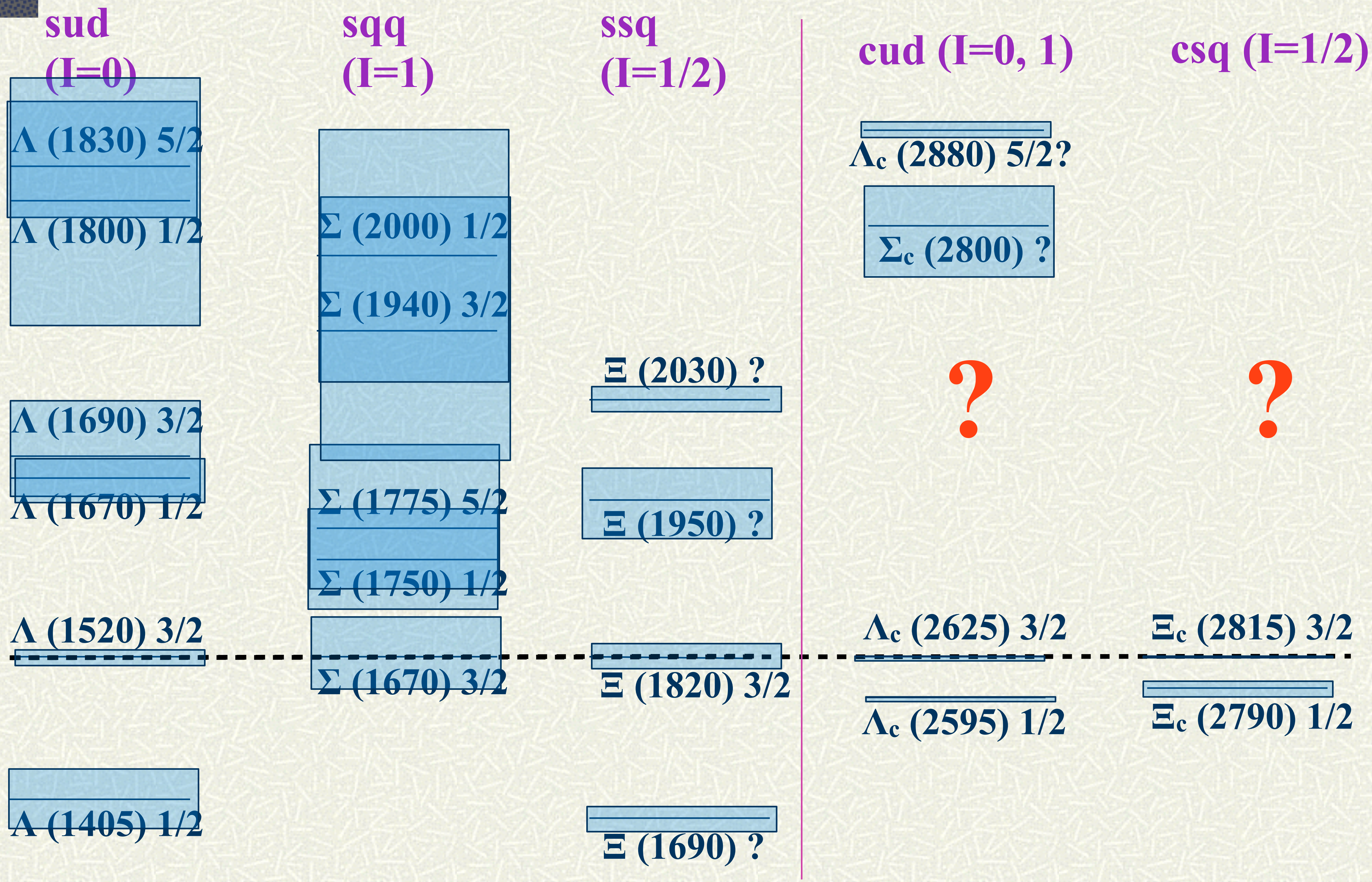
csq (I=1/2)

?

Ξ_c (2815) 3/2

Ξ_c (2790) 1/2

Diquarks in P-wave Baryons



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Λ (1800) 1/2

Λ (1690) 3/2

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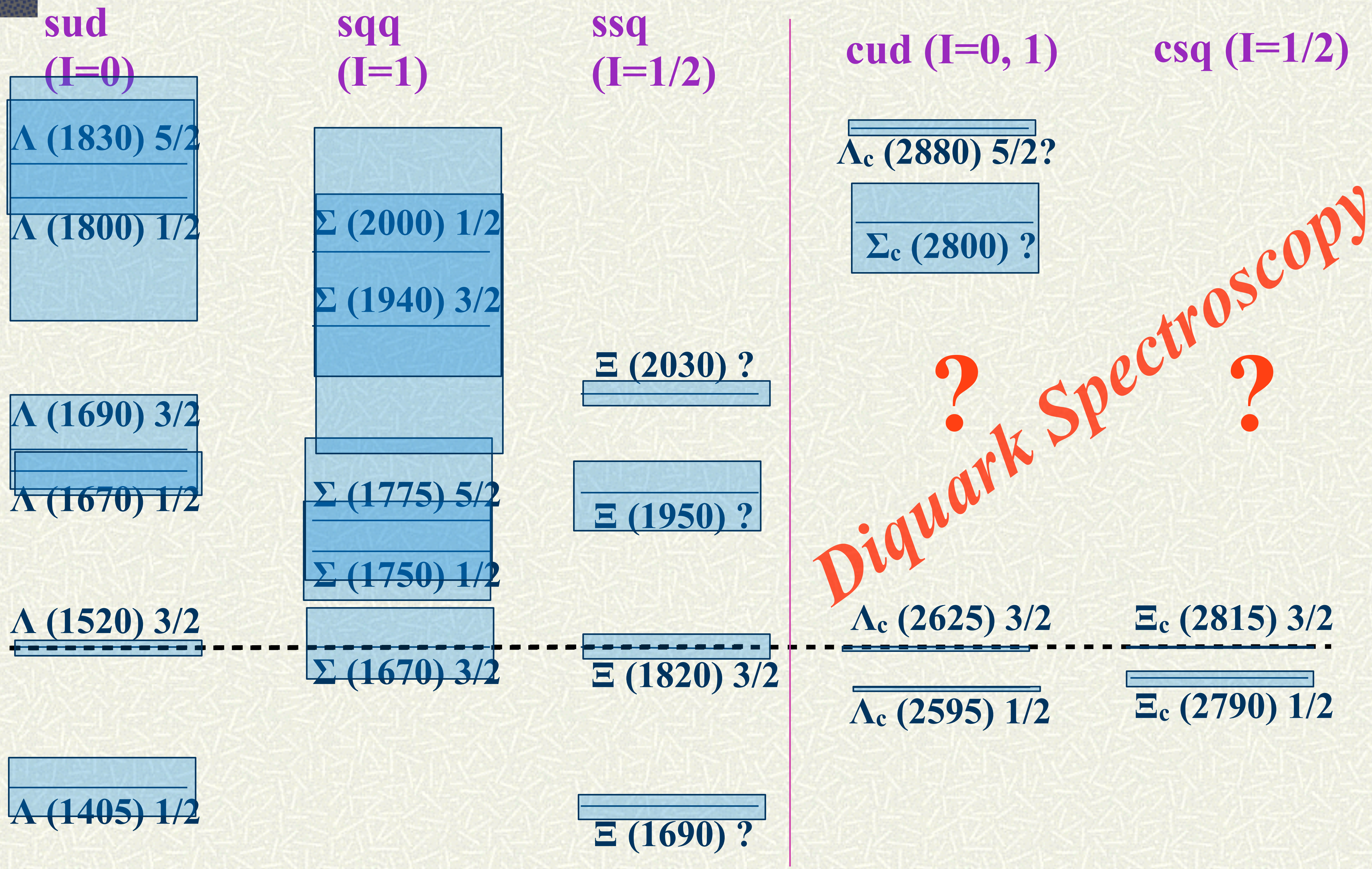
Diquarks in P-wave Baryons



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Λ (1800) 1/2

Λ (1690) 3/2

Λ (1670) 1/2

Λ (1520) 3/2

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Λ_c (2880) 5/2?

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csq (I=1/2)

?

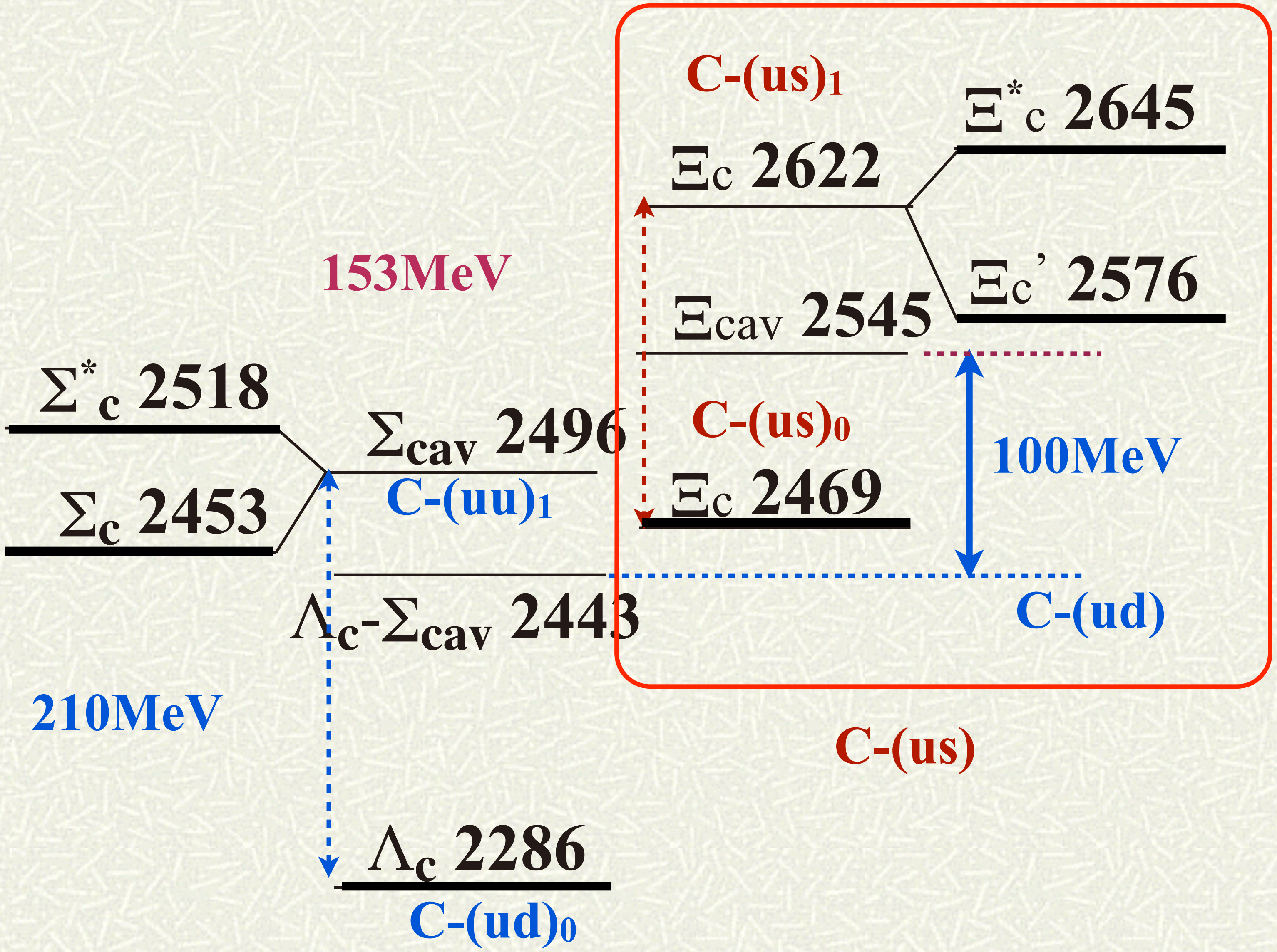
Ξ_c (2815) 3/2

Ξ_c (2790) 1/2

Diquark Spectroscopy

Ξ_c = csu, csd, strange diquarks

- $[us]_J$, $[ds]_J$ diquarks are probed by the Ξ_c spectrum



C-$(us)_1$

Ξ^*_c 2645

Ξ_c 2622

153MeV

Ξ_c' 2576

Ξ_{cav} 2545

Σ^*_c 2518

Σ_{cav} 2496

C-$(us)_0$

100MeV

C-$(uu)_1$

Ξ_c 2469

Σ_c 2453

Λ_c-Σ_{cav} 2443

C-(ud)

210MeV

C-(us)

Λ_c 2286

C-$(ud)_0$

Diquark

- **Scalar diquark as a new building block.**

  D^bar=qq: color 3^bar, spin-parity 0^+, flavor 3^bar in SU(3)

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

- diquark "meson" D D^bar → tetra-quark

- di-diquark "baryon" D-D-q → pentaquark

- tri-diquark "dibaryon" D^3 → dibaryon

color 1, flavor 1, 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)

Diquark

- **Scalar diquark as a new building block.**

  D^{bar}=qq: color 3^{bar}, spin-parity 0^{+}, flavor 3^{bar} in SU(3)

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

- diquark "meson" D D^{bar} → tetra-quark

- di-diquark "baryon" D-D-q → pentaquark

- tri-diquark "dibaryon" D^{3} → dibaryon

color 1, flavor 1, 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)

Exotic

Conclusion

- Spectroscopy of heavy quark hadrons requires new concepts, i.e., multi-quark states, hadron molecules, heavy quark spin symmetry, diquark correlations, etc.
- Heavy baryon spectroscopy is used for the di-quark spectroscopy.
- In order to draw the complete picture of the heavy hadron spectrum, further experimental data are essential, both in quantity and in quality.
- It is important to carry out various experimental methods using the facilities, such as Belle, BES (e^+e^- collider), JLab (e), LHCb (hadron collider), J-PARC (p, π, K), PANDA (p^{bar}).