Spectroscopy of Heavy Hadrons

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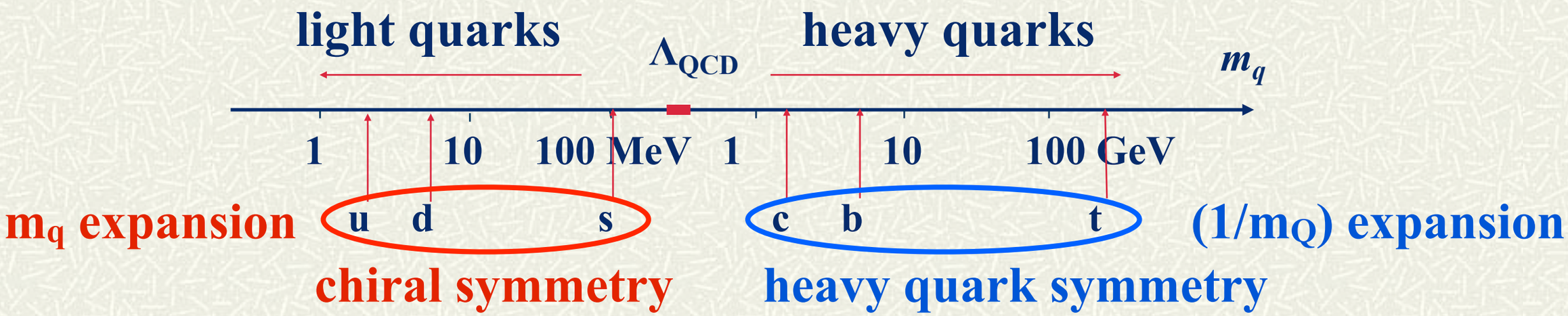
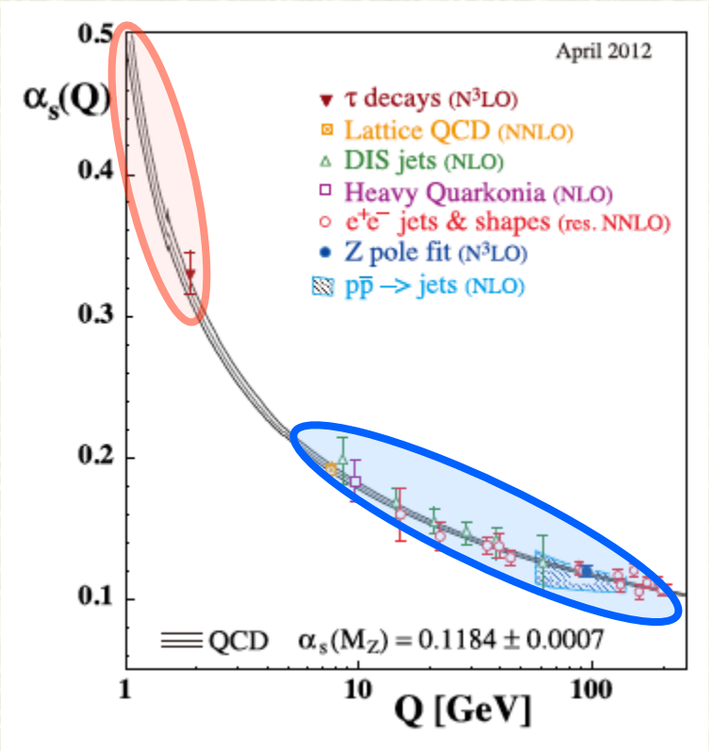
Mass dependence of QCD

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



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



Light and Heavy quarks look different in QCD

Quarkonium

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

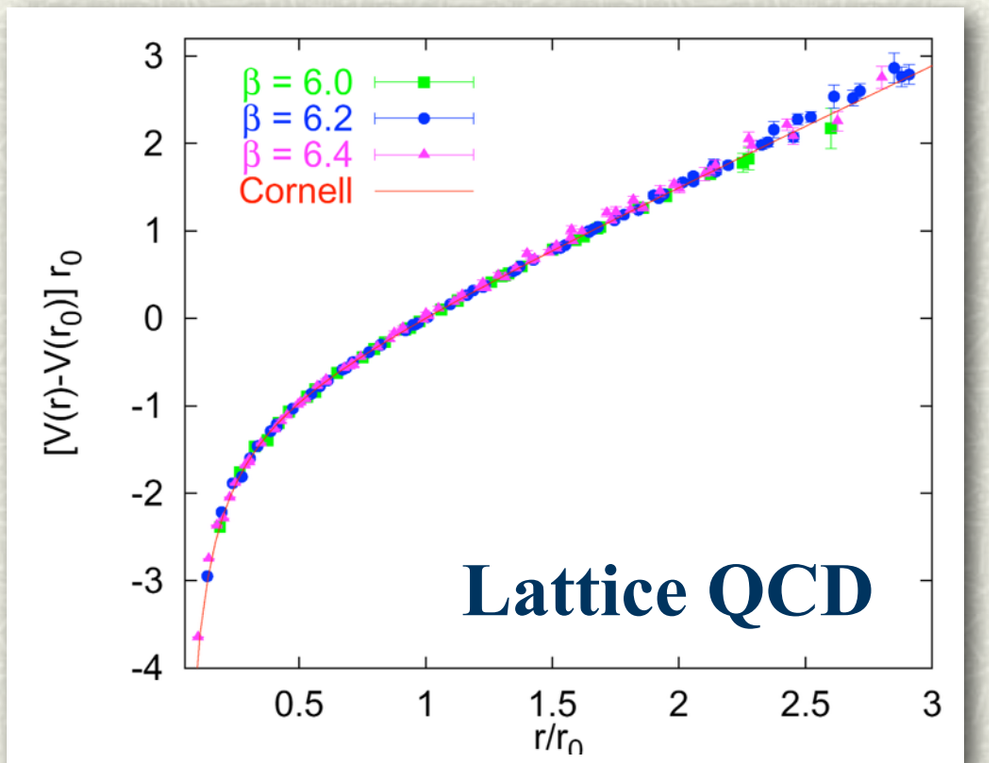
- The charmonium spectrum is a textbook example.
  "hydrogen atom" in QCD

- The Hamiltonian with a Linear + Coulomb potential

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

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

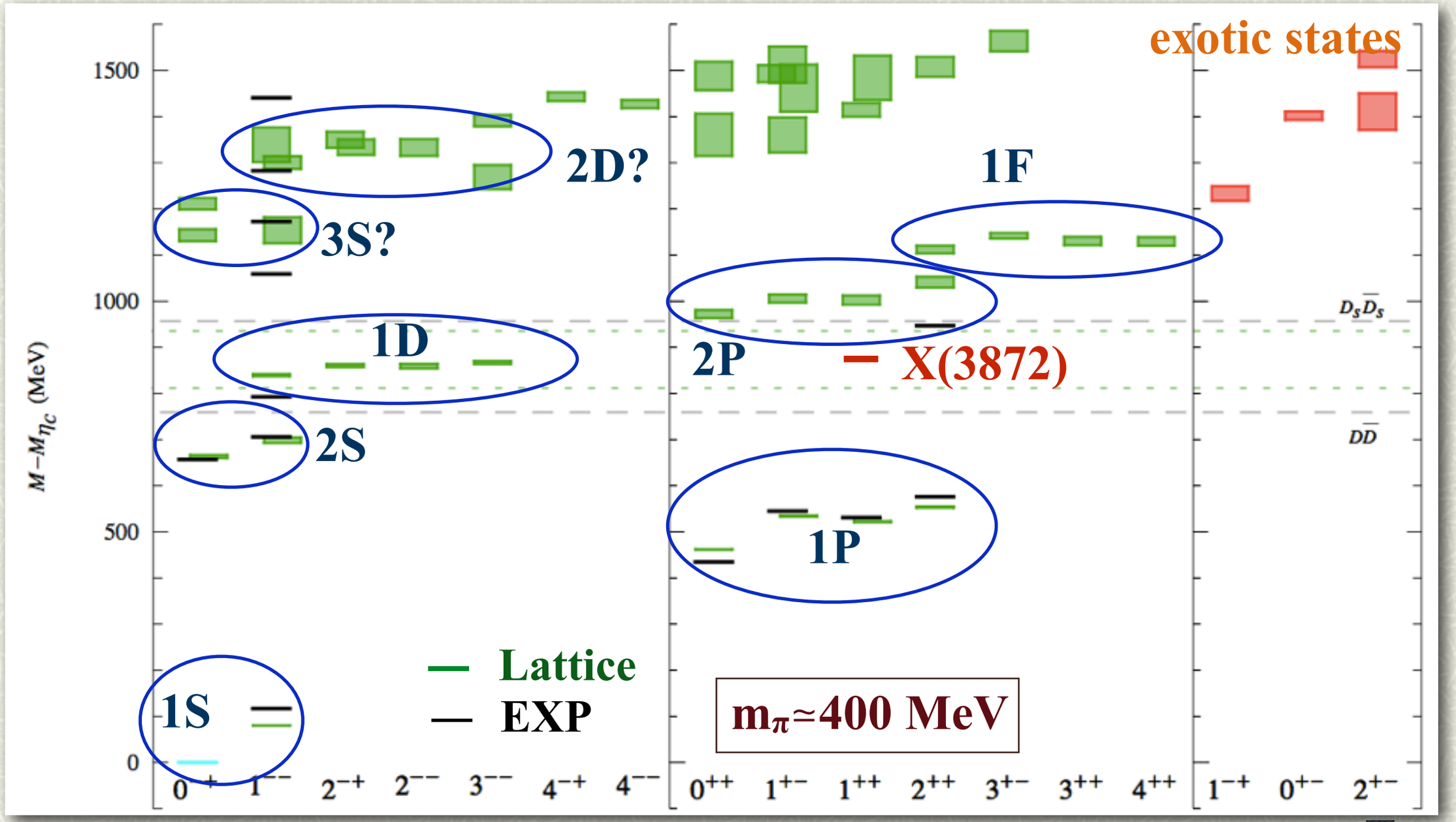
gives a good fit to the 1S, 1P, 2S, . . charmonium (and bottomonium) states.



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

Charmonium spectra on Lattice

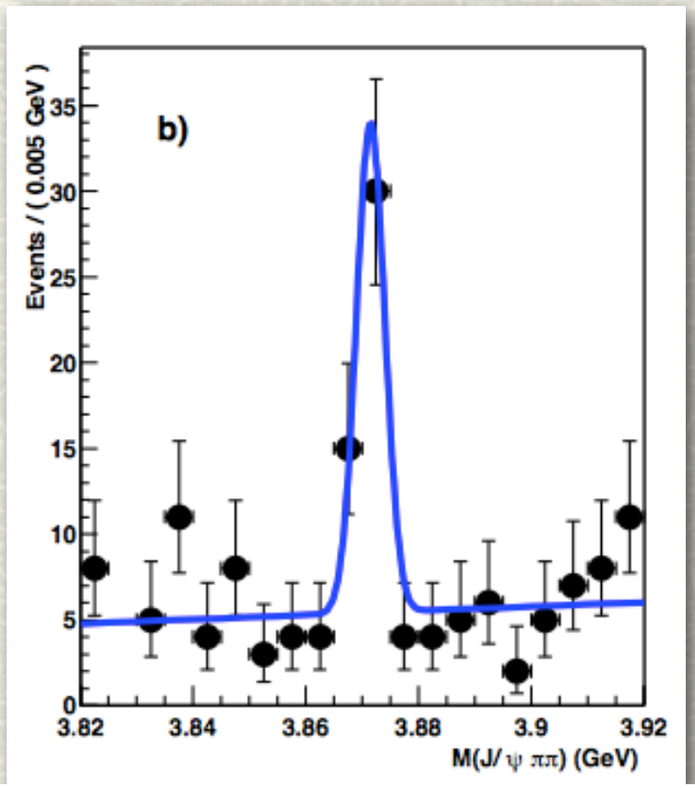
Liuming Liu, et al. (Hadron Spectrum Collaboration)
JHEP 07, 126 (2012)



New Charmonium-like States

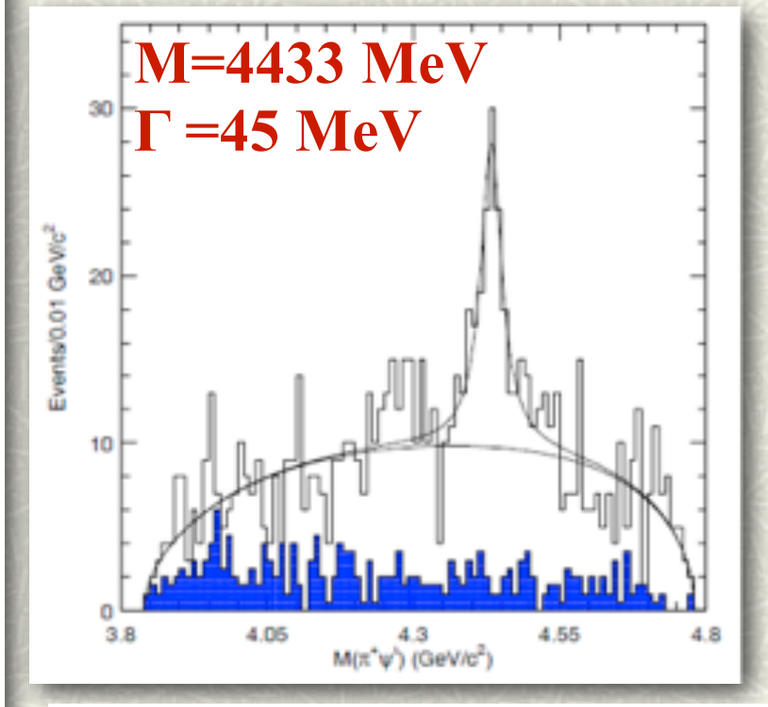
- X(3872) found in 2003 by Belle (KEK)
- Z(3900), Z(4430) etc. : Charged hidden charm states

X(3872)



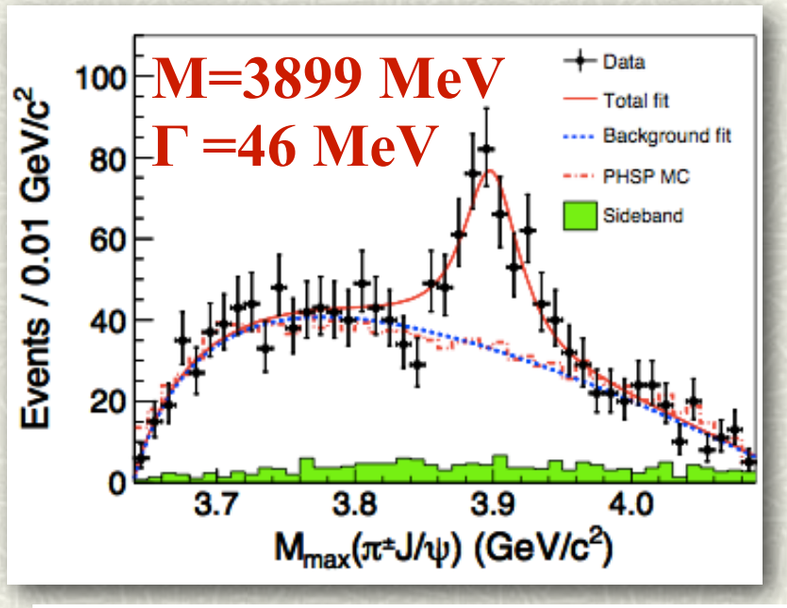
PRL 91 (2003) 262001

$Z_c^+(4430)$



PRL 100 (2008) 142001

$Z_c^+(3900)$



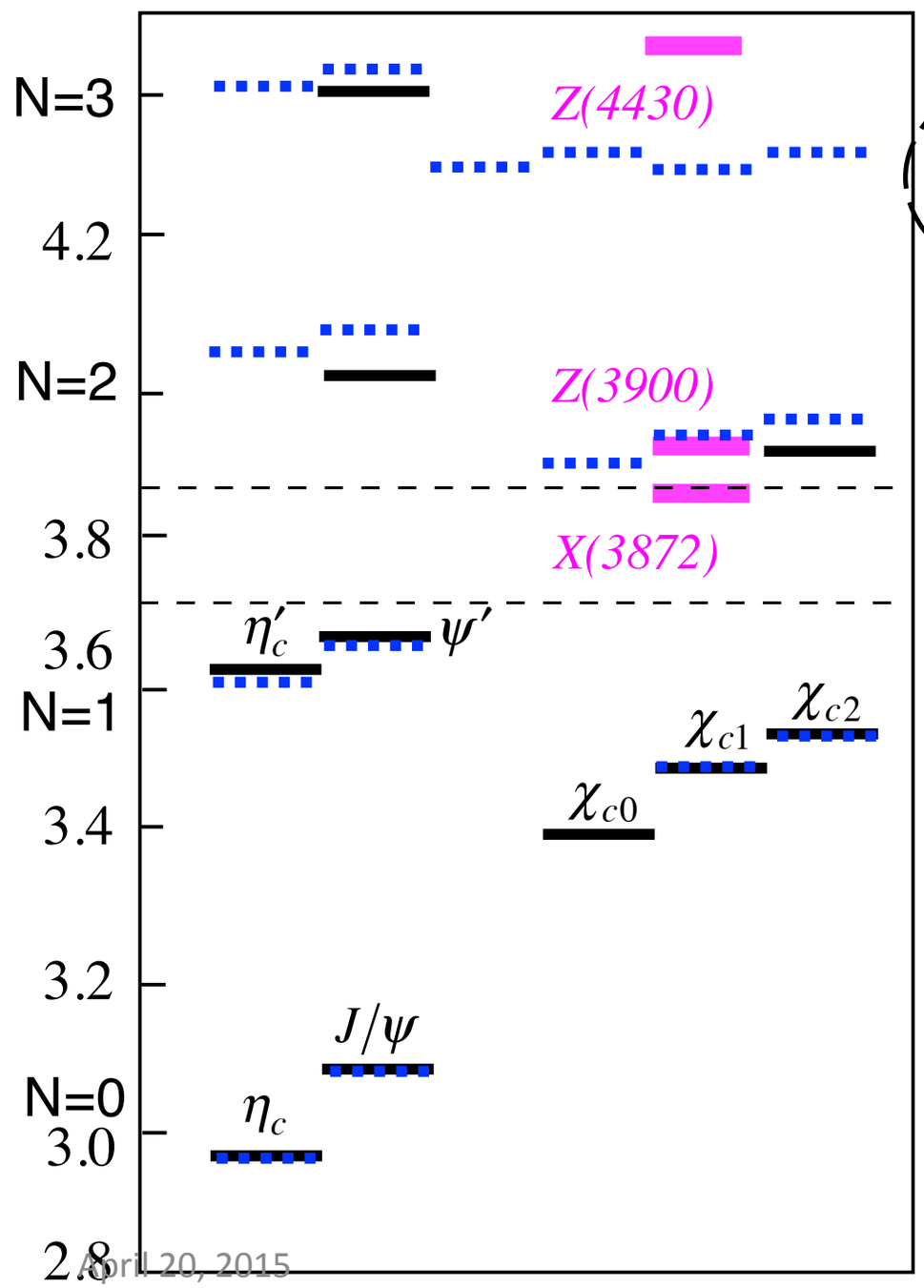
PRL 110 (2013) 252001

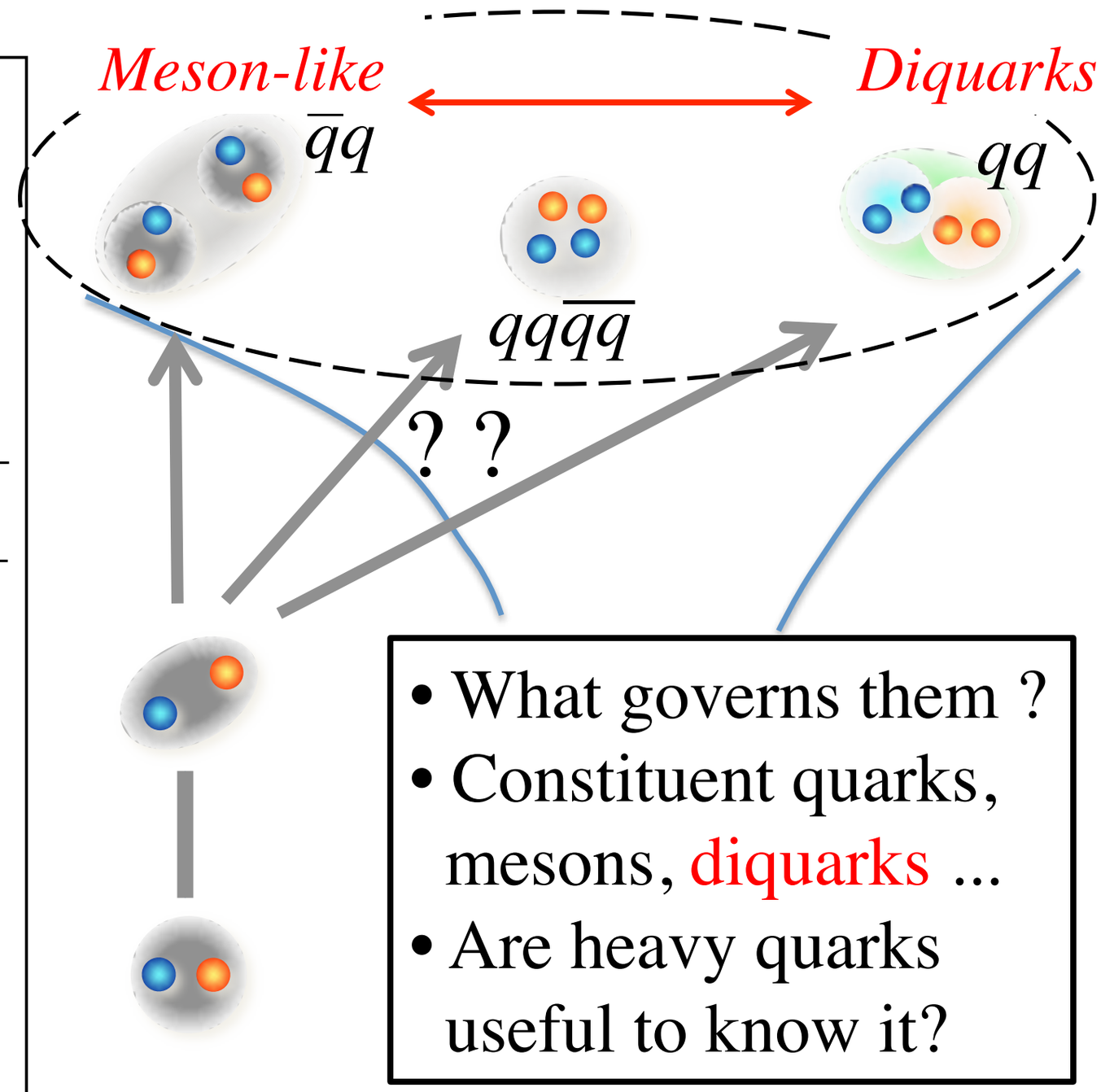
These states require at least 4 quarks,

i.e., tetra-quarks or hadron molecules.

Above the threshold

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



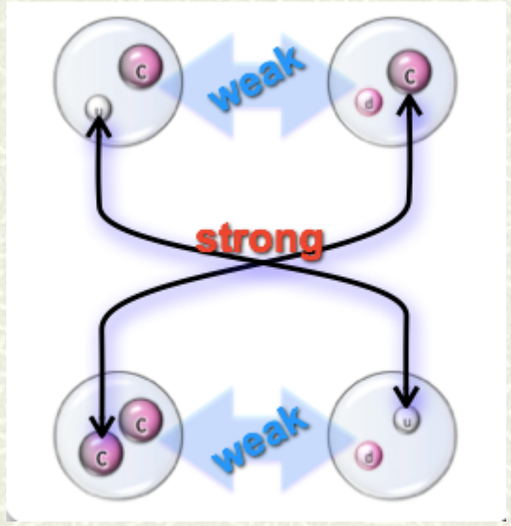


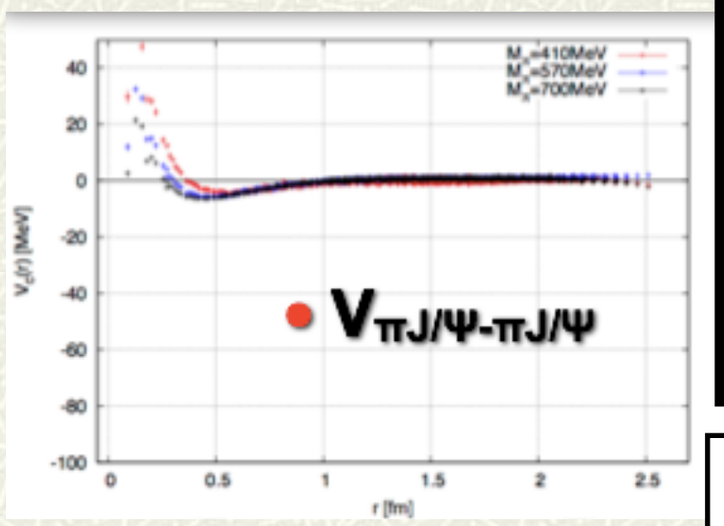
- What governs them ?
- Constituent quarks, mesons, diquarks ...
- Are heavy quarks useful to know it?

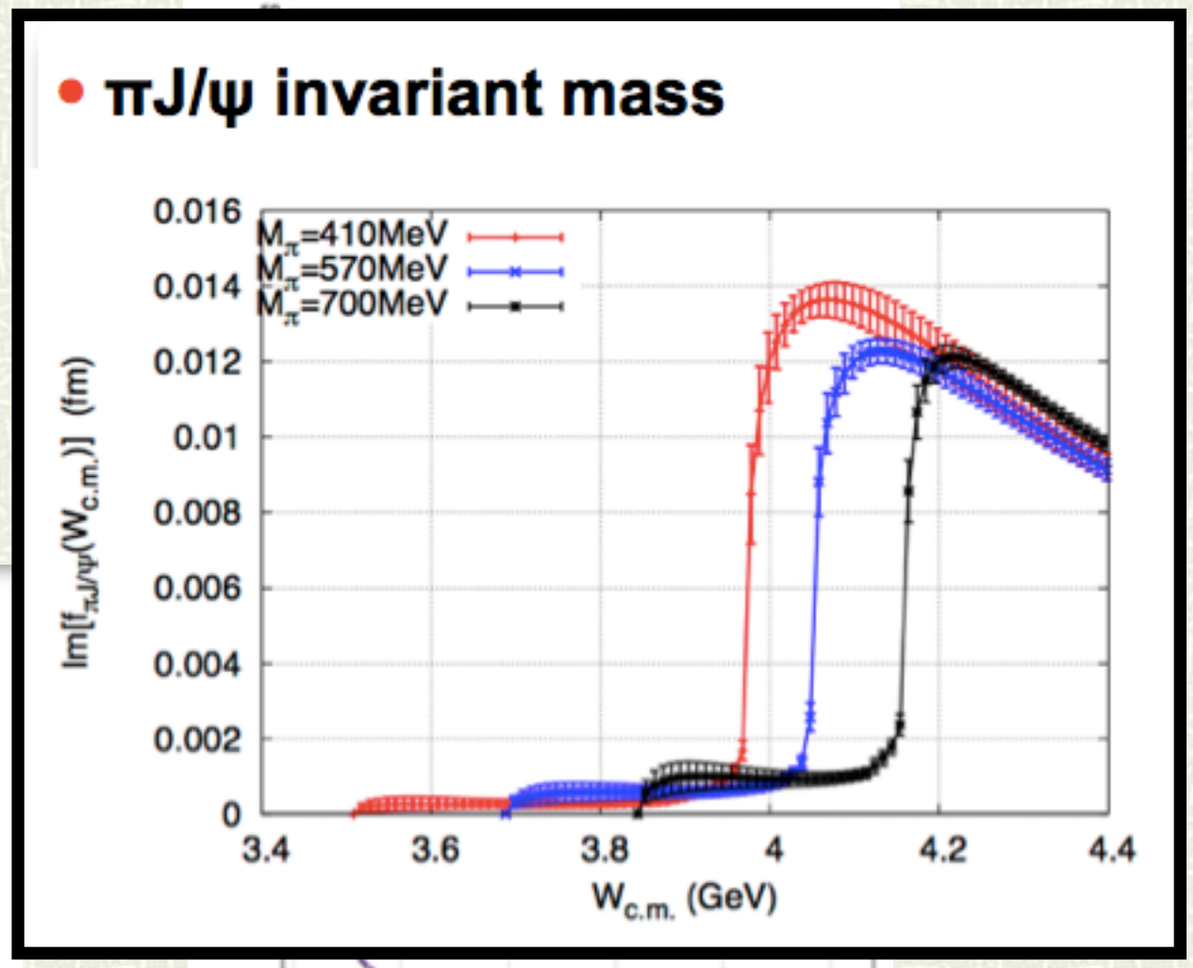
by A. Hosaka

Exotic States on Lattice

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



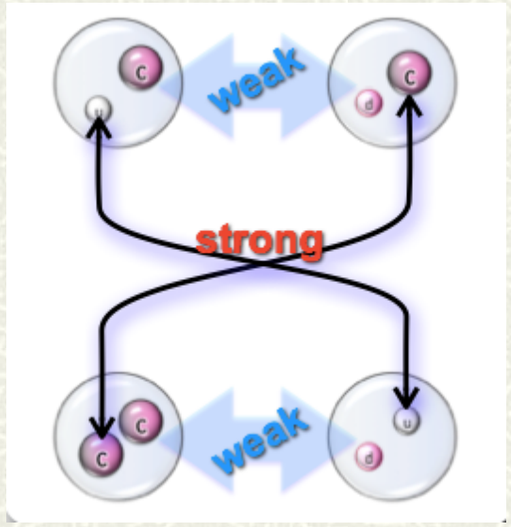


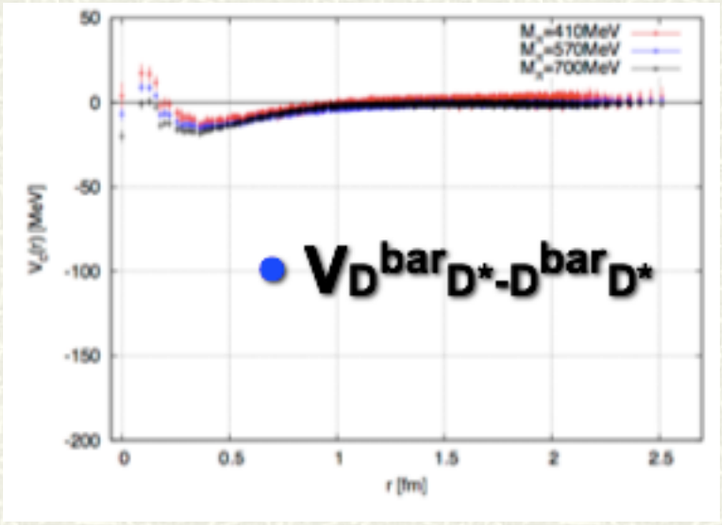


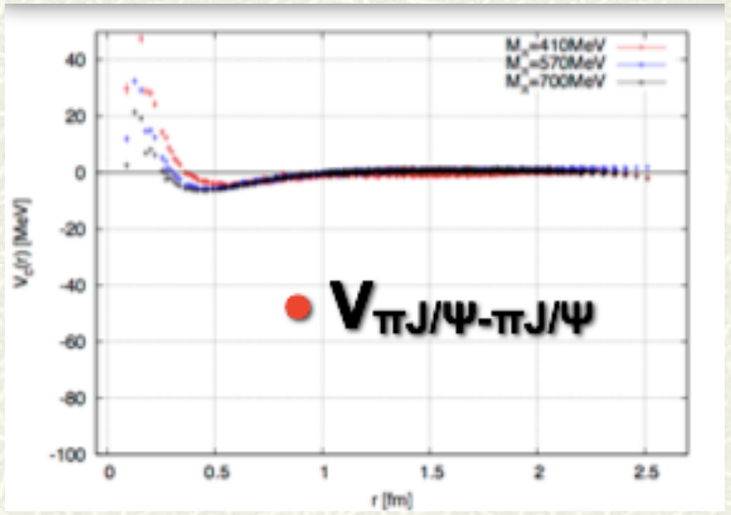
Strong (cusp) enhancement above the $D^{bar}D^*$ threshold

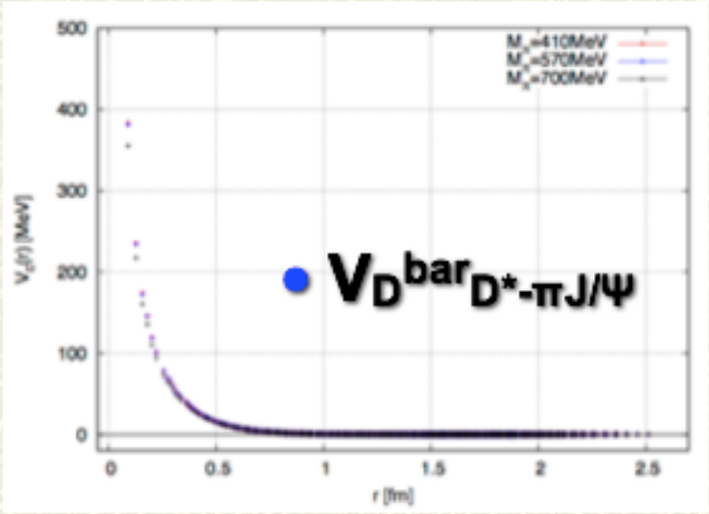
Exotic States on Lattice

- **If the couplings of pi+J/psi and D D* are strong, then is the resonance more like a tetera-quark?**

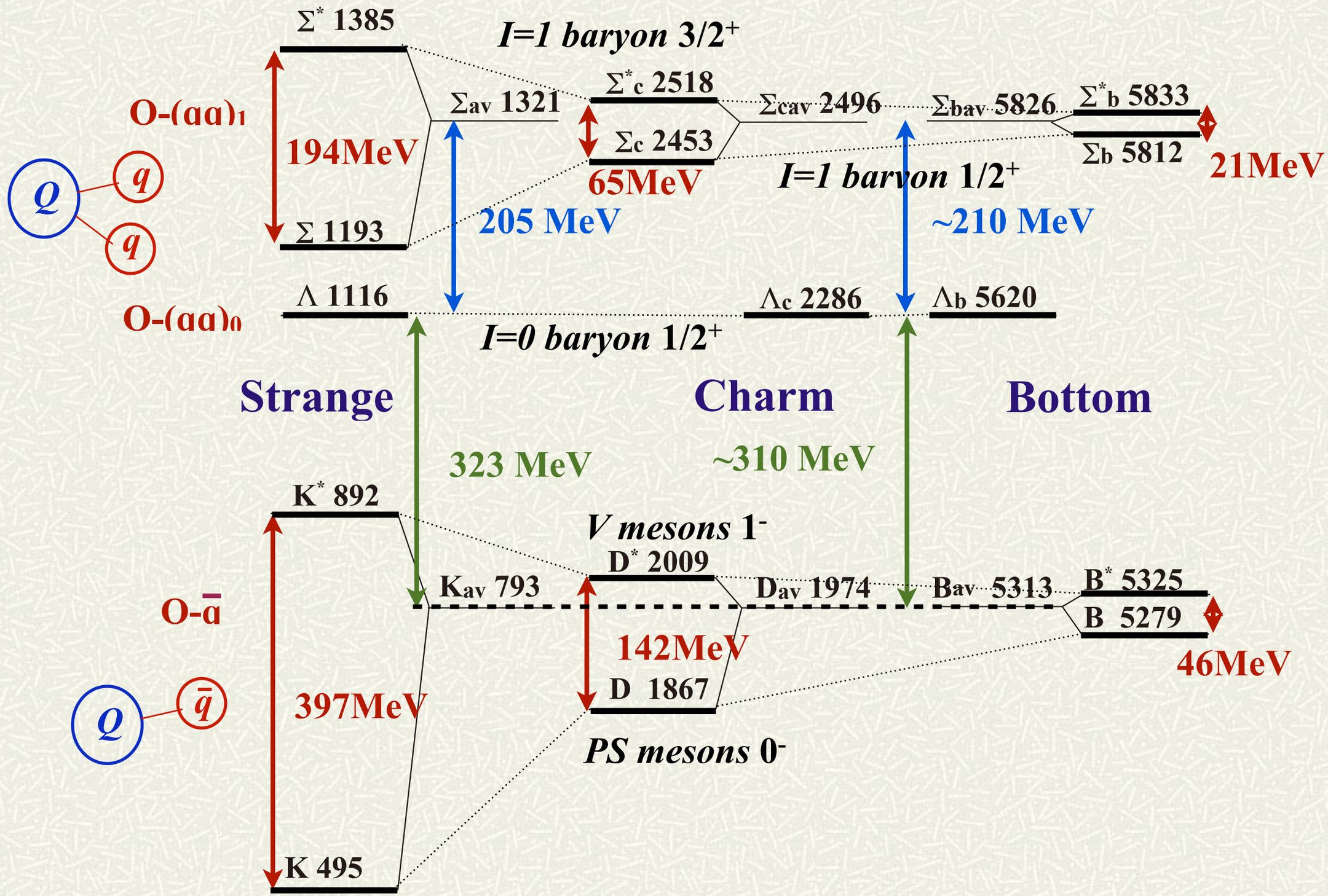






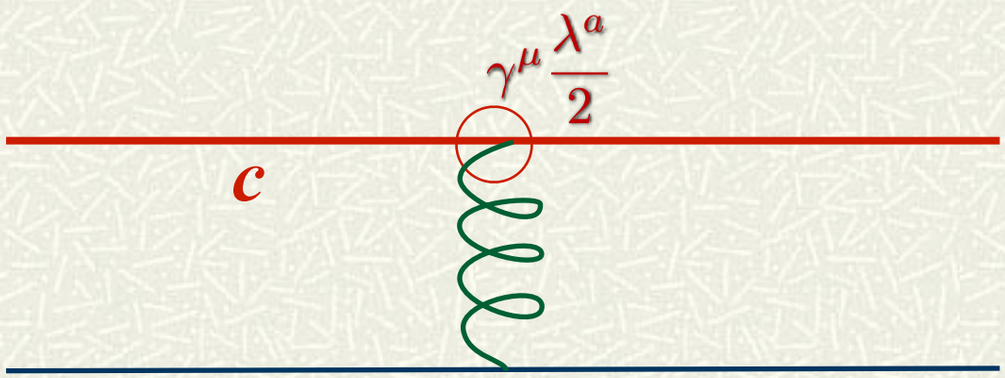


Strange *v.s.* Charm/Bottom



Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



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

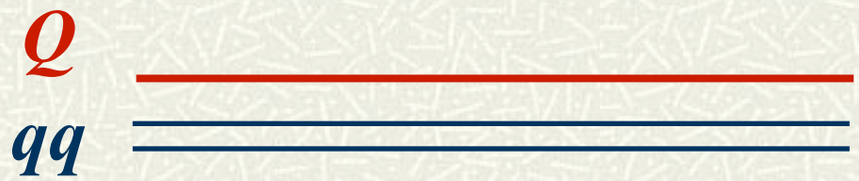
(Color Electric coupling) ≫ (Color Magnetic coupling)

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

⇨ Heavy Quark Spin Symmetry

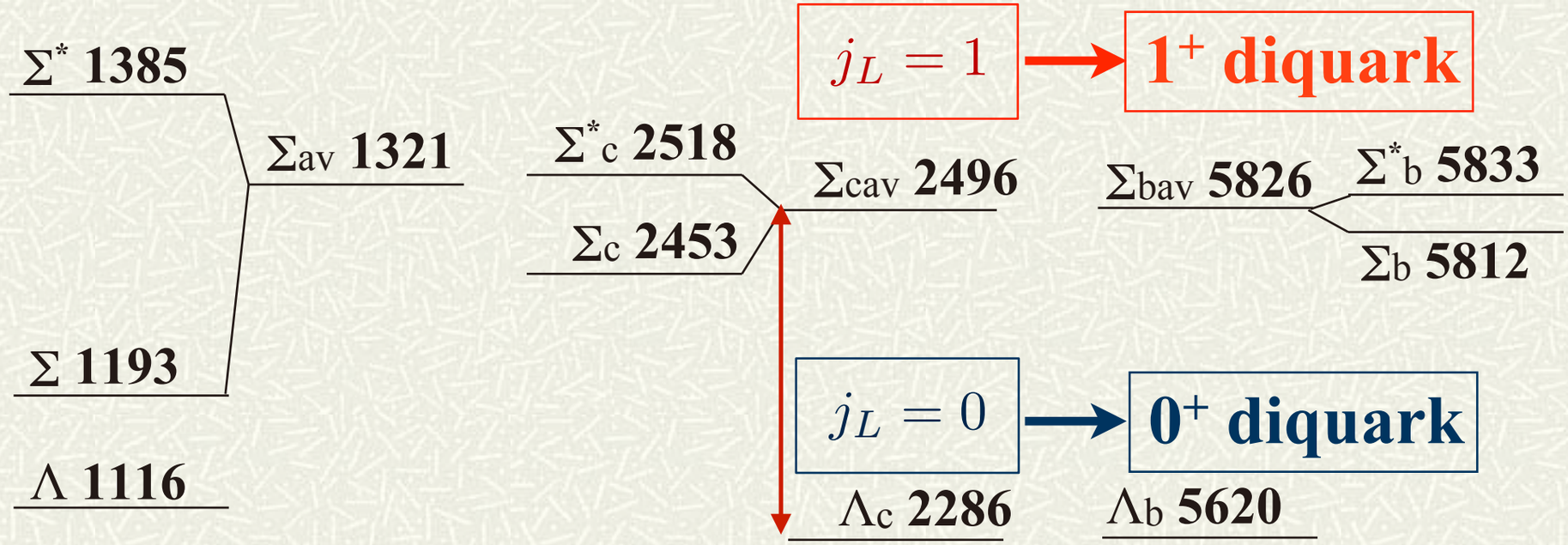
Heavy Quark Spin Symmetry

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



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

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

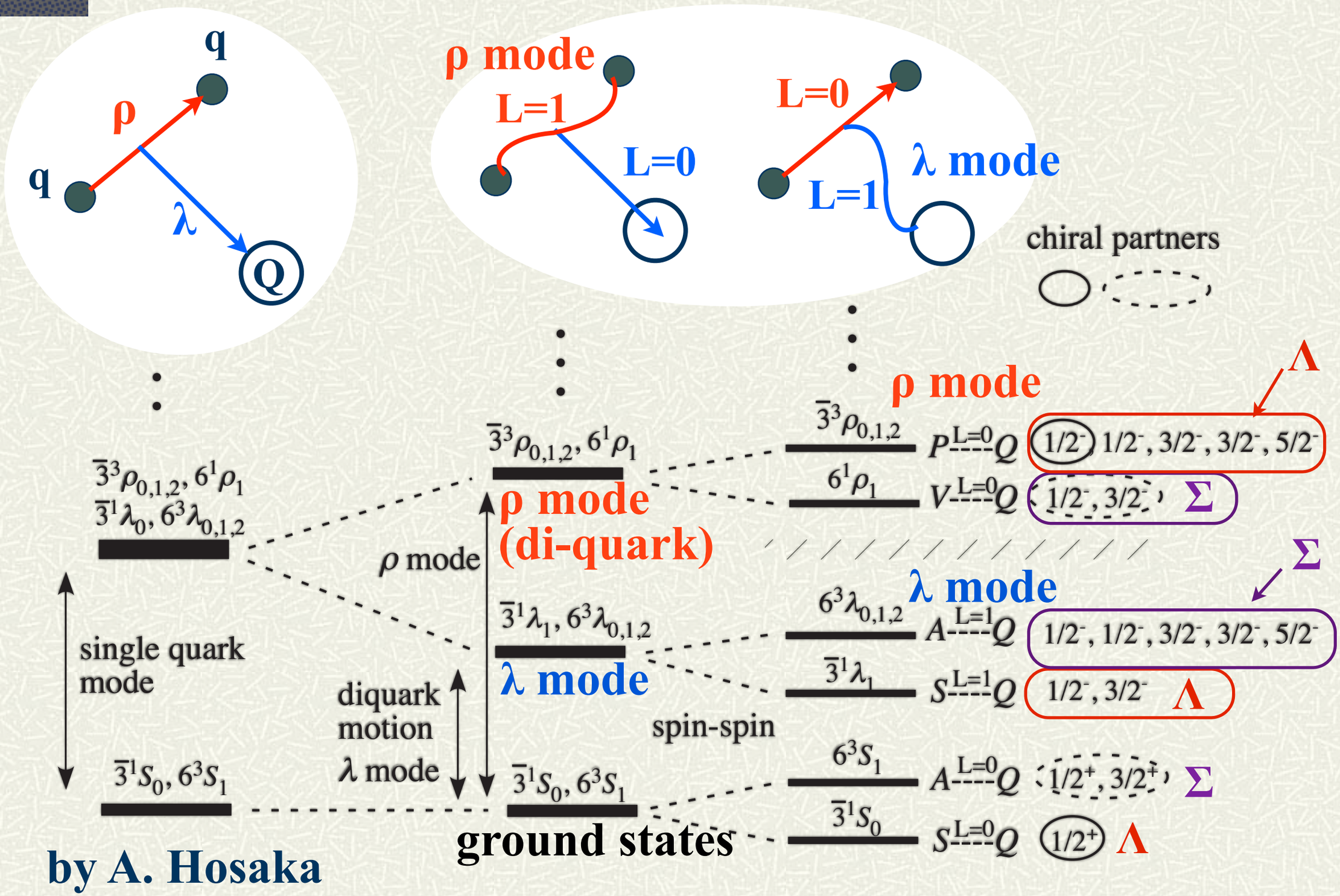


Diquark

- **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	$\bar{3}$ $(I=0)$

Diquarks in P-wave Baryons



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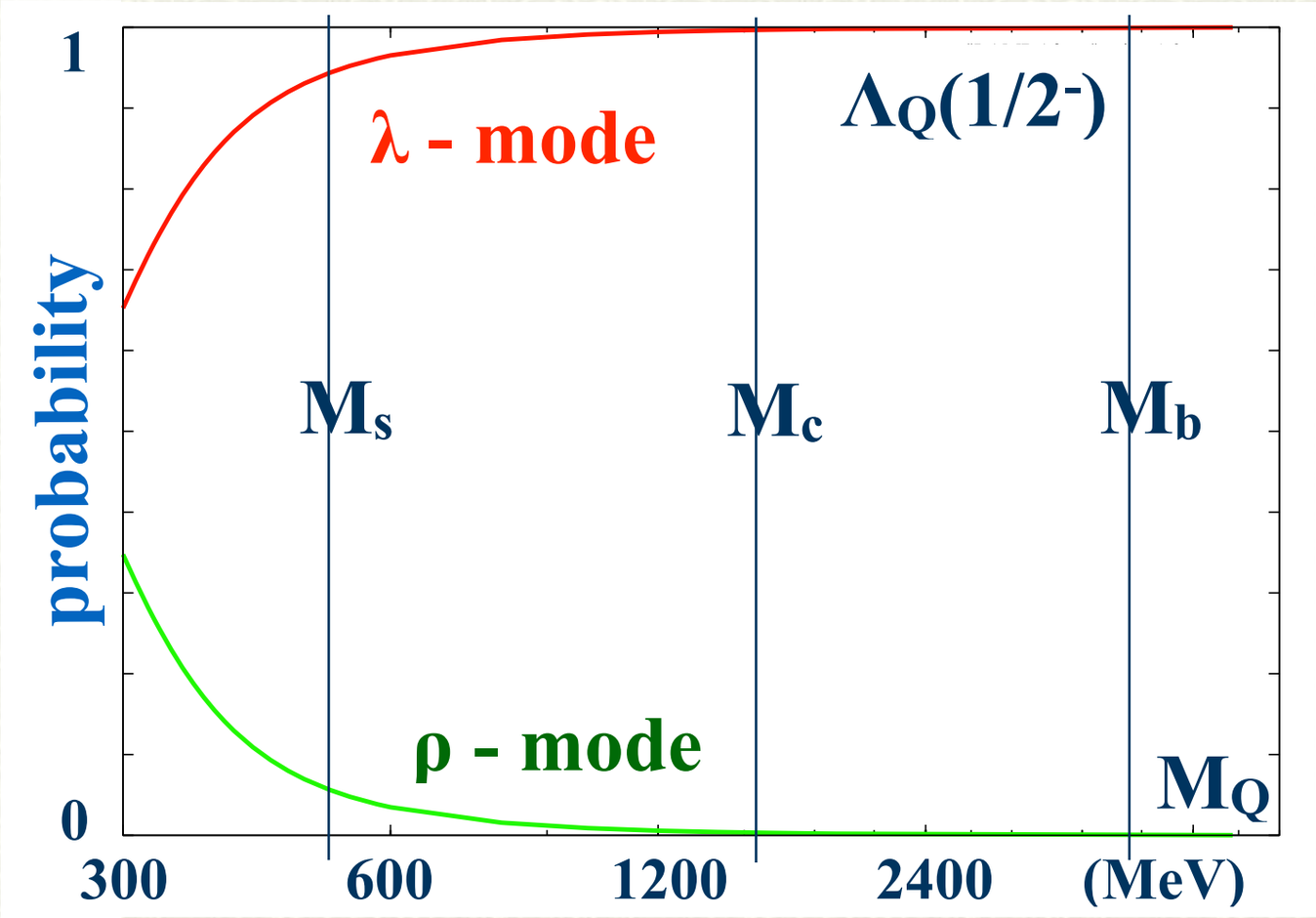
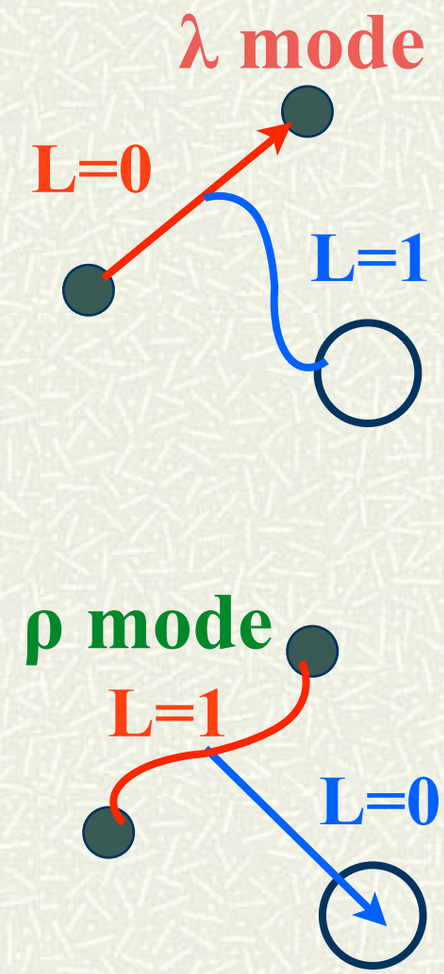
Diquarks in P-wave Baryons

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



T. Yoshida



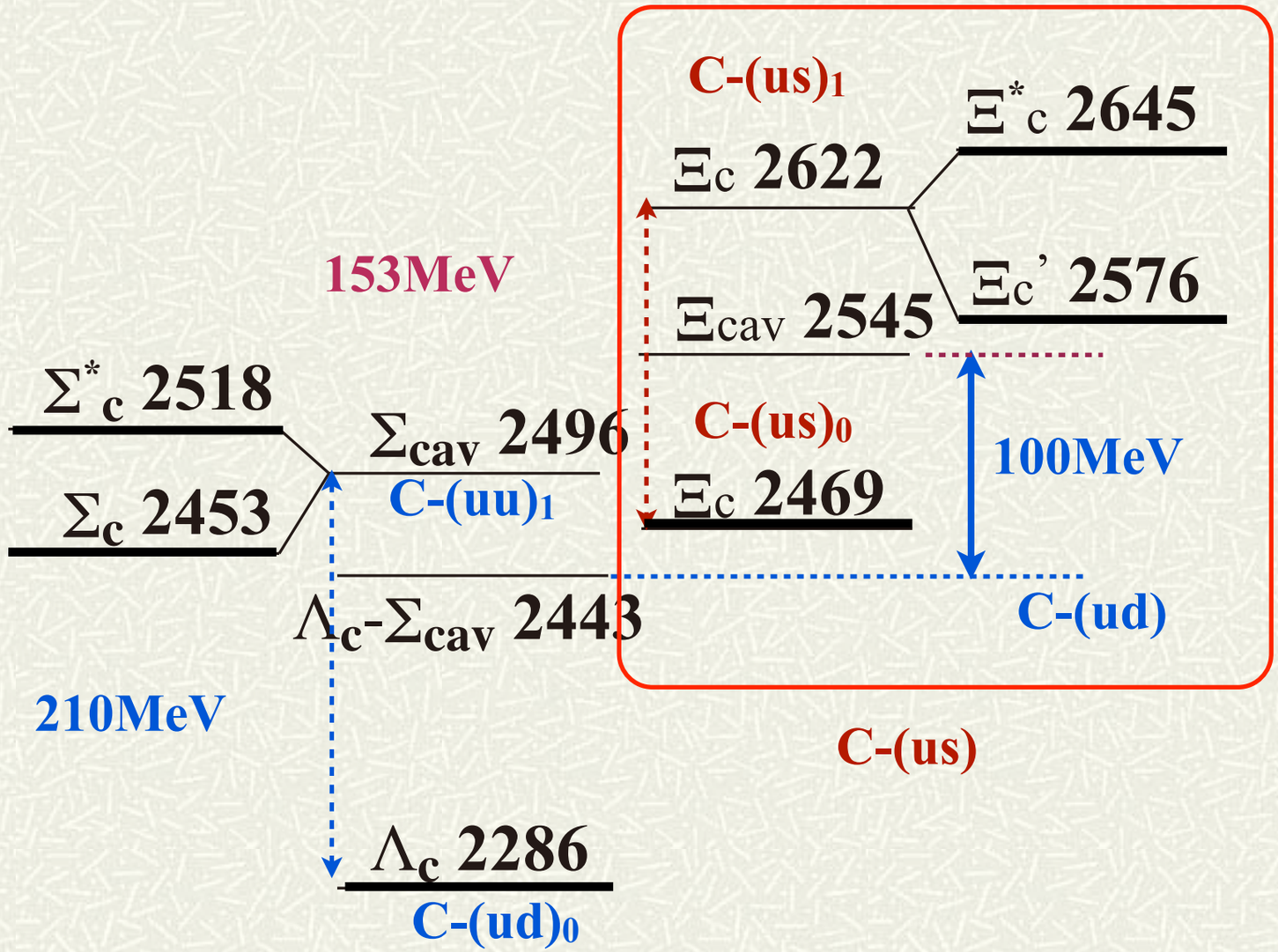
Diquarks in P-wave Baryons

sud (I=0)	sqq (I=1)	ssq (I=1/2)	cud (I=0, 1)	csq (I=1/2)
Λ (1830) 5/2	$(S=1/2)_\rho$		Λ_c (2880) 5/2?	
Λ (1800) 1/2	Σ (2000) 1/2		Σ_c (2800) ?	
$(S=3/2)_\rho$	Σ (1940) 3/2		?	?
Λ (1690) 3/2		Ξ (2030) ?		
Λ (1670) 1/2	Σ (1775) 5/2	Ξ (1950) ?		
Λ (1520) 3/2	Σ (1750) 1/2		Λ_c (2625) 3/2	Ξ_c (2815) 3/2
$(S=1/2)_\lambda$	Σ (1670) 3/2	Ξ (1820) 3/2	Λ_c (2595) 1/2	Ξ_c (2790) 1/2
Λ (1405) 1/2	$(S=3/2)_\lambda$	Ξ (1690) ?	$(S=1/2)_\lambda$	

Diquark Spectroscopy

Ξ_c = csu, csd, strange diquarks

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

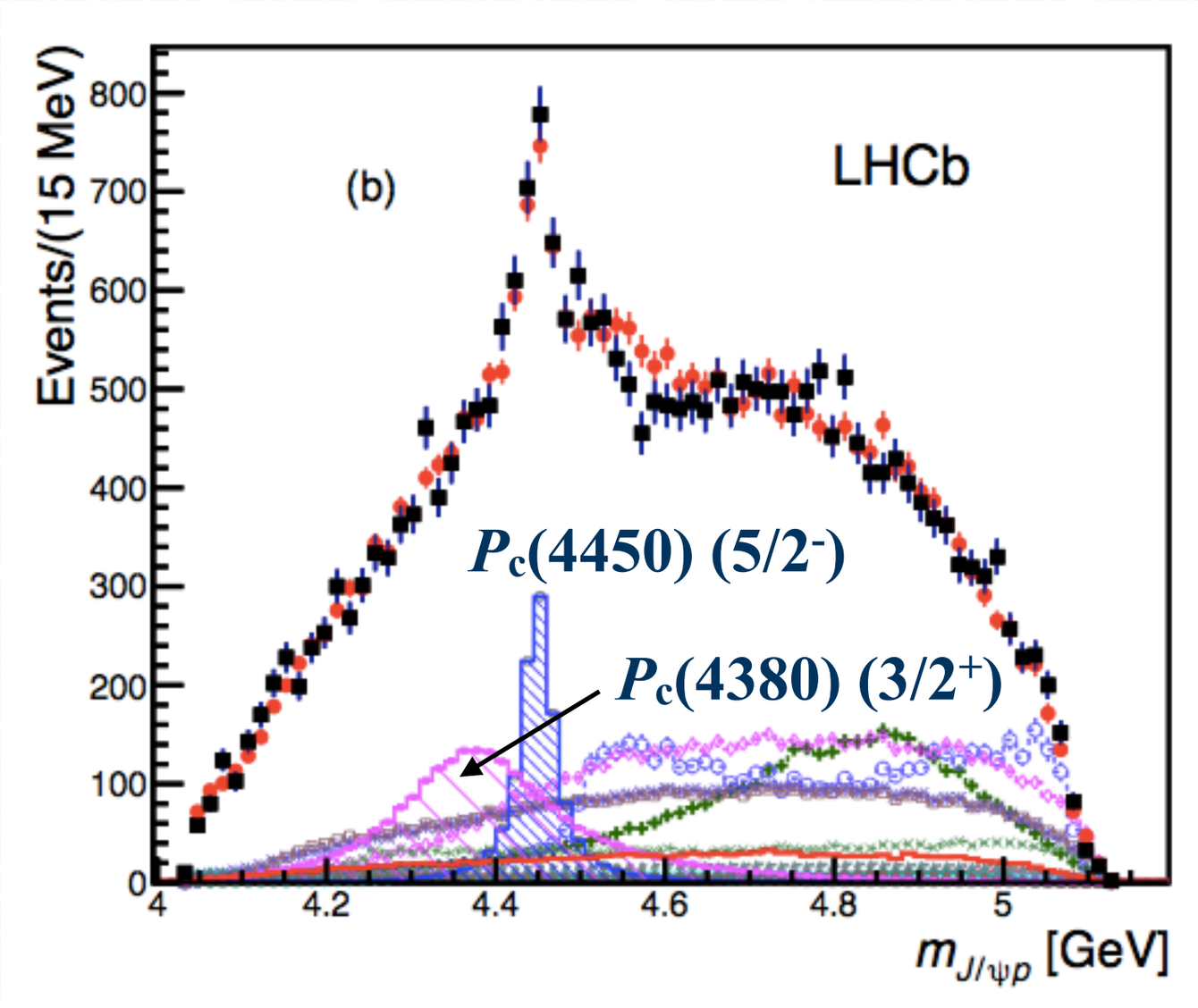


P_c Pentaquark

- P_c ($cc^{bar}uud$) → J/ψ+p

  P_c(4380) ($3/2^+$?)

  P_c(4450) ($5/2^-$?)



P_c Pentaquark

- **SU(3) classification**

  c-c^{bar} **spin 0 or 1** η_c J/ψ

  color 1 or 8 η_c^8 ψ^8

  qqq (uud, . .)

  color 1 or 8

  SU(6): even L → 56 [3] or 70 [21]

  odd L → 70 [21] or 56[3]+70[21]+20[1^3]

- **This is B_8 spectroscopy.**

Spin dependence

- **Spin-spin interaction aka Color-Magnetic Interaction (CMI)**

$$V_{\rm CMI} = -\alpha \sum_{i<j} (\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) f(r_{ij}) \qquad f(r_{ij}) \sim \delta(r_{ij})$$

$$\langle V_{\rm CMI} \rangle_{(0s)^N} = \alpha \, \langle f(r) \rangle_{0s} \, \Delta_{\rm CM} = V_0 \Delta_{\rm CM}$$

$$\Delta_{\rm CM} \equiv \langle - \sum_{i<j} (\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) \rangle$$

$$\boxed{\Delta_{\rm CM} = 8N - 2C_2[SU(6)_{cs}] + \frac{4}{3} S(S+1) + C_2[SU(3)_c]}$$

$$C_2[SU(g)]([f_1, f_2, \ldots, f_g]) = \sum_i f_i (f_i - 2i + g + 1) - \frac{N^2}{g}$$

prefers symmetric color-spin states ⇔ flavor antisymmetric states

Spin dependence

$$\Delta_{\rm CM} = 8N - 2C_2[SU(6)_{cs}] + \frac{4}{3}S(S+1) + C_2[SU(3)_c]$$

$$\Delta_{\rm CM}(\mathbf{10}) - \Delta_{\rm CM}(\mathbf{8}) = 8 - (-8) = 16$$

$$M(\Delta) - M(N) = 16V_0 \sim 300\,{\rm MeV} \qquad V_0 \sim 300/16 \sim 19\,{\rm MeV}$$

$$\Delta_{\rm CM}(H) - 2\Delta_{\rm CM}(\Lambda) = -24 - 2(-8) = -8$$ **H (ΛΛ+NΞ+ΣΣ, S=0)**

$$\Delta_{\rm CM}(D_\Delta) - 2\Delta_{\rm CM}(\Delta) = 16 - 2\times 8 = 0$$ **D_Δ (ΔΔ, I=0, S=3)**

octet : 70 = (1, 1/2) + (8, 1/2) + (8, 3/2) + (10, 1/2)

(1,1/2) = uds Δ= -14~ -270MeV
(8,1/2) Δ=0, (8,3/2) Δ=4
(10,1/2) Δ=10

Conclusion

- Spectroscopy of heavy (s, c, b) 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}).