Hadron Spectroscopy
from Strange to Charm/Bottom
- Effective theories or Lattice ? -

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Hadrons and Hadron Interactions in QCD
- Effective theories and Lattice -
Yukawa Institute Theoretical Physics

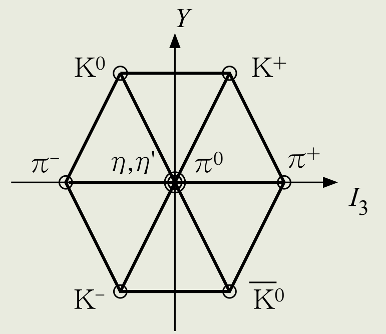
Introduction

Nuclear Physics vs Hadron Physics

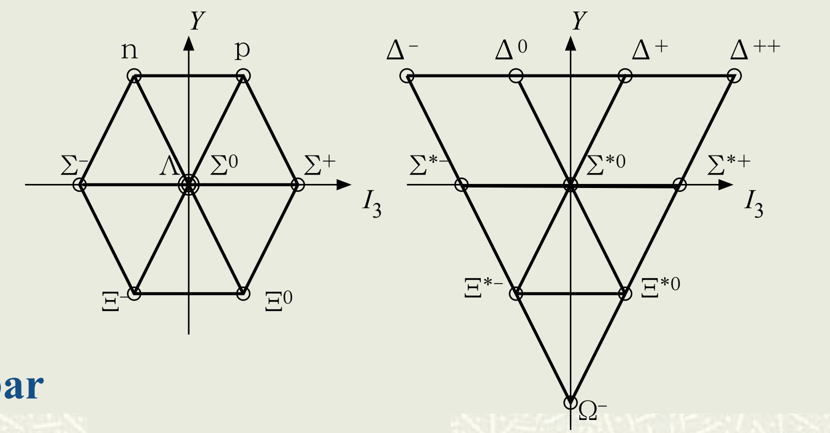
Nuclear Dynamics	*Hadron Dynamics*
single particle motions **shell structure**	**valence quark motions** **quark model, symmetries**
collective motions **rotations and vibrations**	**collective motions in field theory** **NG bosons, Skyrmion**
cluster **alpha, di-neutron**	**di-quark** **color-non-singlet clusters**
exotic nuclei **neutron rich nuclei, halo**	**exotic hadrons** **multi-quark, hybrid hadrons**
large amplitude motions, **deformation, fission**	**molecular bound states** **resonance states**
superfluidity/dense matter	**hot/dense hadronic matter**

From QCD to Hadron Spectrum

- QCD = colored quarks + colored gluons with $SU(3)_c$ gauge symmetry
- Quarks have flavor quantum numbers: u, d, s, c, b, t.
  QCD Lagrangian is flavor independent, but the coupling constant runs.
- The lowest-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

From QCD to Hadron Spectrum

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

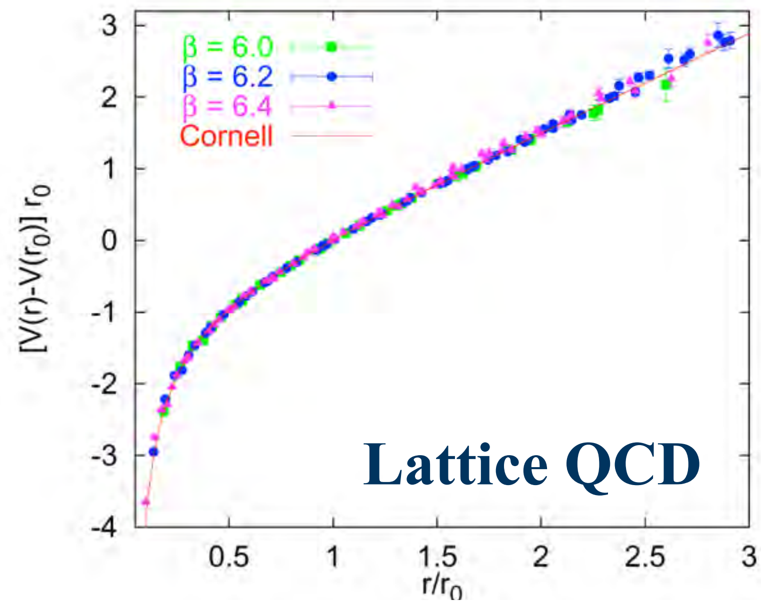
- **The charmonium spectrum is a textbook example.**
  "hydrogen atom" in QCD

- **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

From QCD to Hadron Spectrum

- The color is confined. Effective dynamical degrees of freedom at low energy are color-singlet hadrons.
- In the variety of excited hadrons, can we identify
  - constituent quark excitations?
  - hadron molecule states?
  - di-quark or other clusters of quarks and gluons?
- QCD is the judge.
  The lattice QCD will be able to help us to understand the (most) effective DOF in the hadron spectrum.
- It is important to “derive” effective theories from QCD.
  - inter-quark potential from lattice QCD or PQCD
  - comparison of effective theories in a box with LQCD

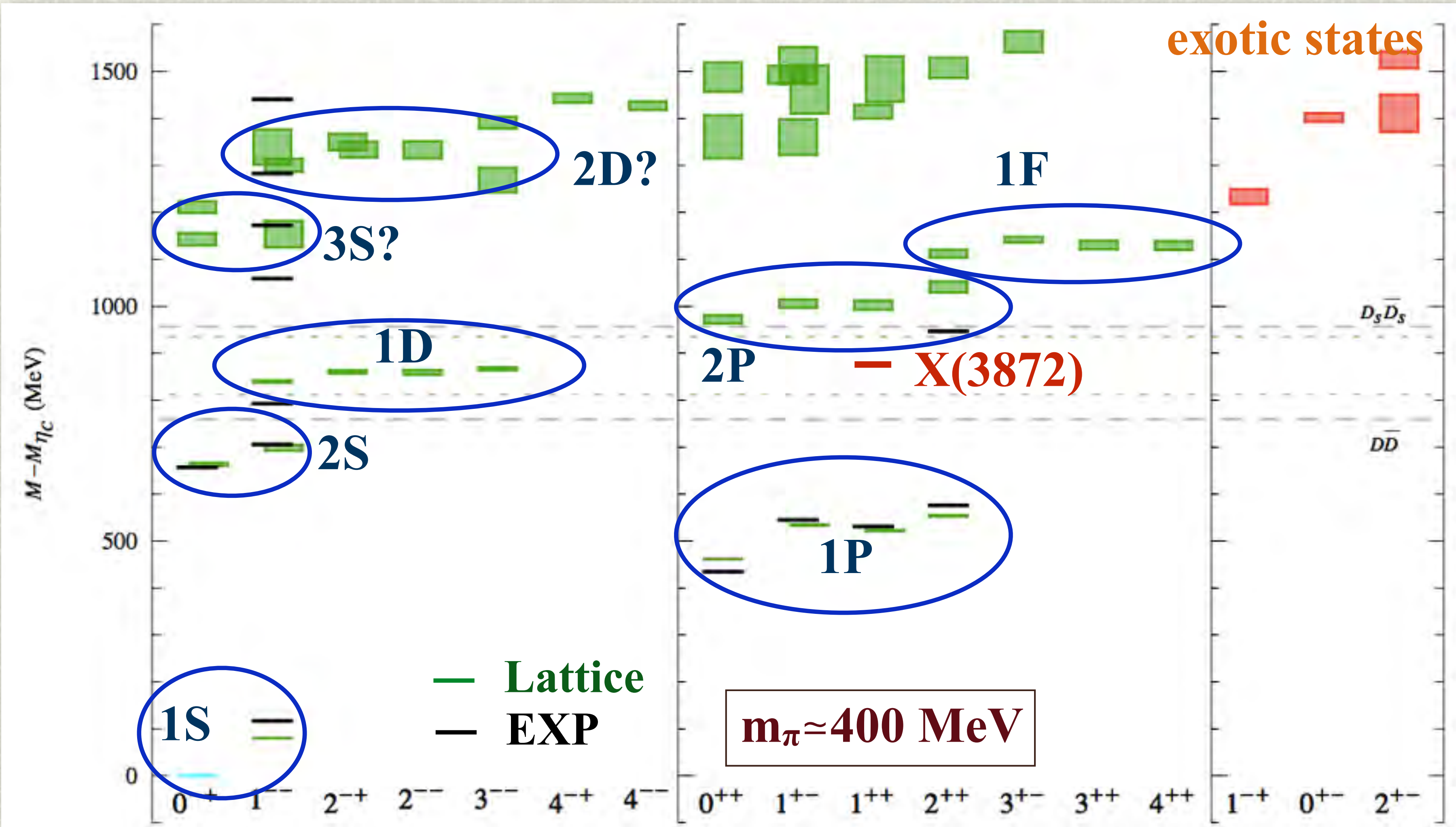
Lattice QCD calculations is reaching state-of-the-art stage.

It is very successful for the ground-state hadrons.

For excited states, $q\text{-}q^{bar}$ or qqq operators may not be good enough.

Charmonium spectra on Lattice

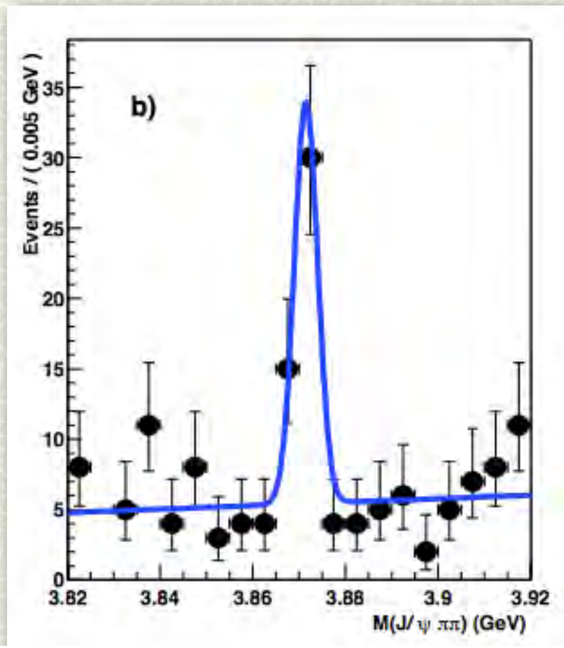
Liuming Liu, et al. (Hadron Spectrum Collaboration)
JHEP 07, 126 (2012)



New Charmonium-like States

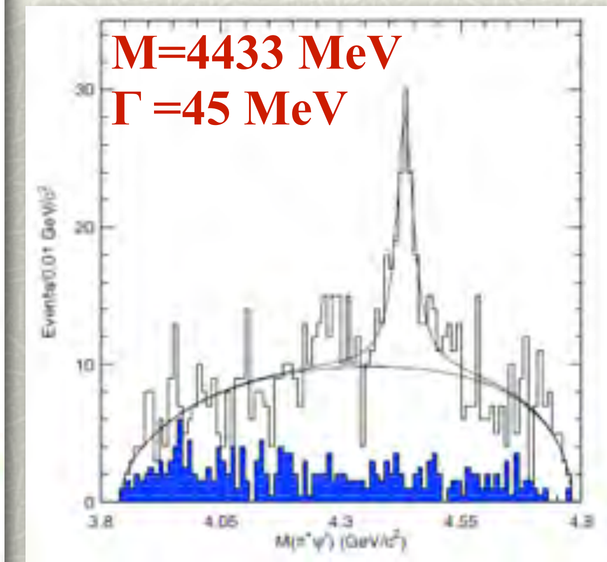
- X(3872) found in 2003 by Belle (KEK)
- Z(3900), Z(4430) etc. : charged hidden charm states

X(3872)



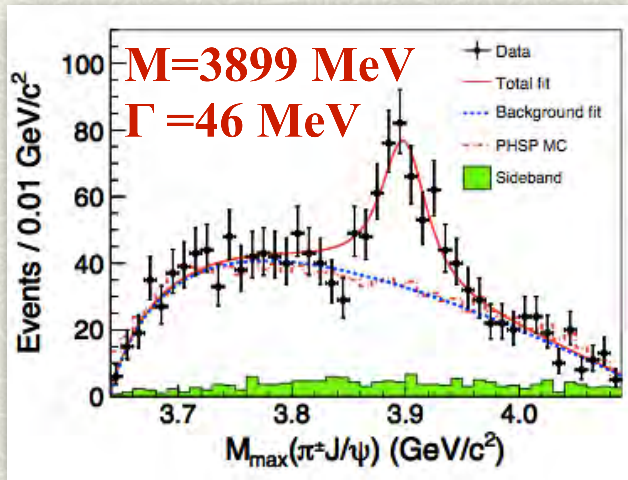
PRL 91 (2003) 262001

$Z_c^+(4430)$



PRL 100 (2008) 142001

$Z_c^+(3900)$

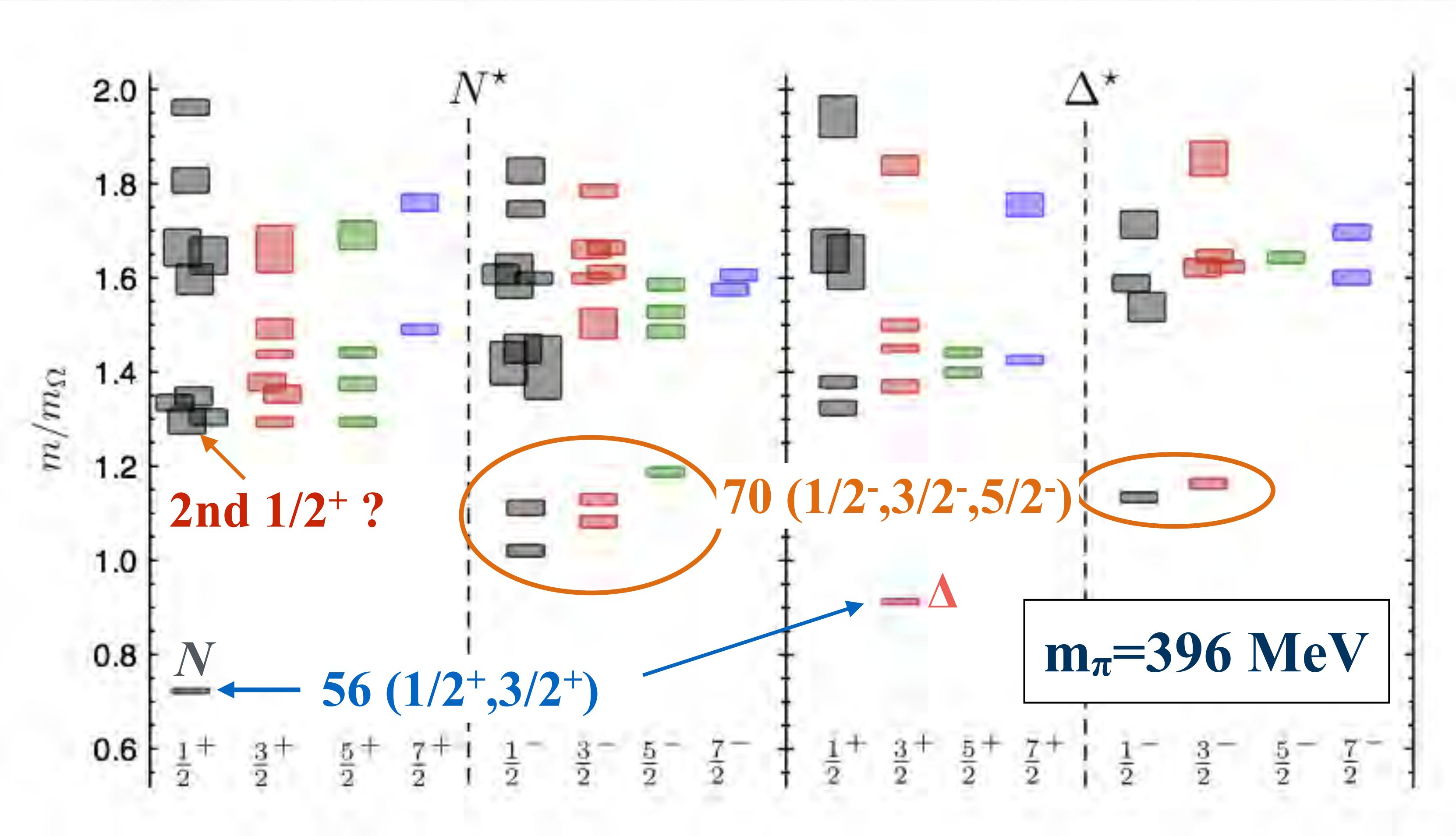


PRL 110 (2013) 252001

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

Baryons in LQCD

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



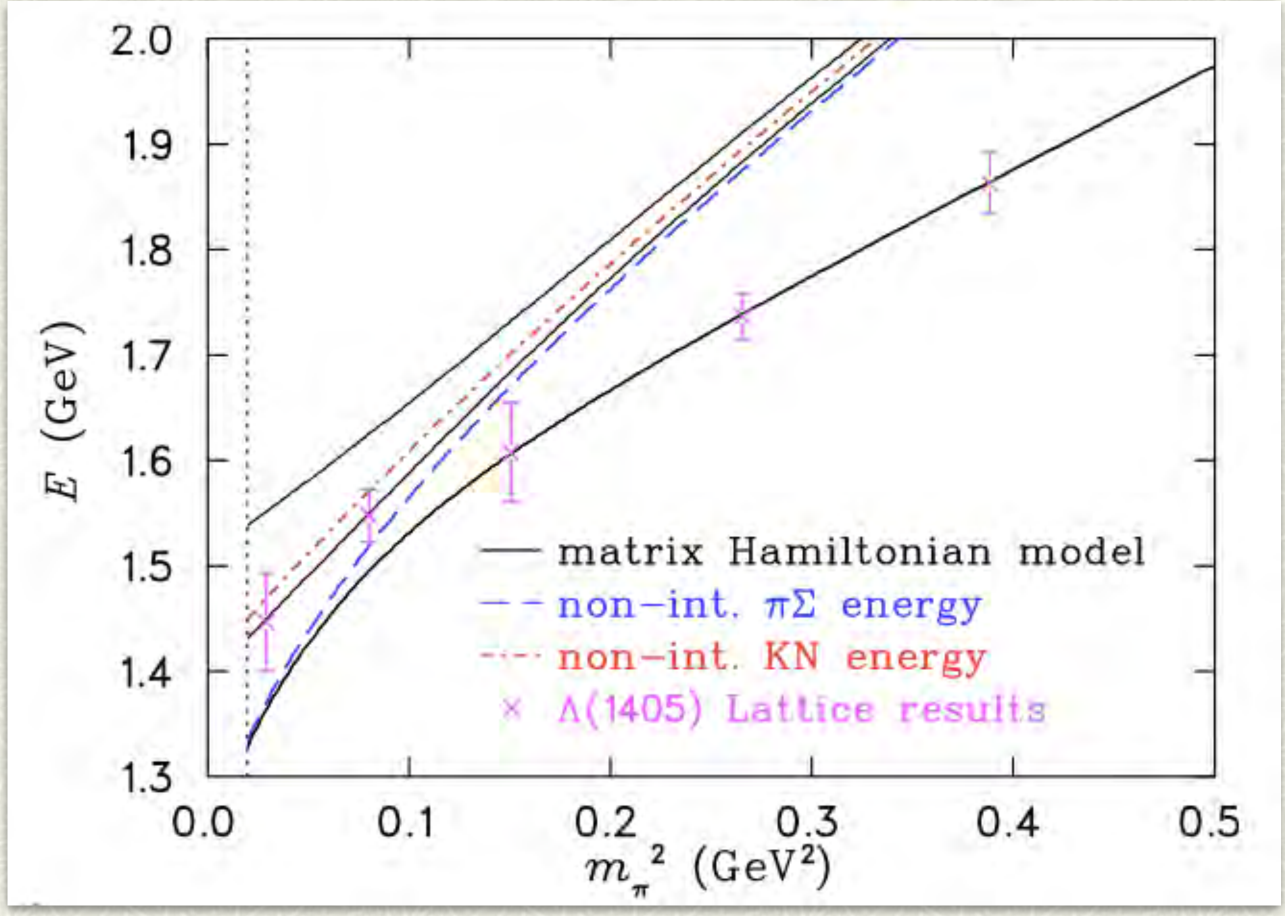
Lattice QCD has confirmed that the overall features of the low-lying hadron spectrum are given by the constituent quark model.

Some (exotic) hadrons are not reproduced by the simple qq^{bar} or qqq operators. They may be given by multi-quark or multi-hadron operators.

Which are exotic?
Recent development of analyses of Λ(1405)

Λ(1405)

- **Recent analysis of the lattice QCD data by J.M.M. Hall et al. ArXiv:1411.3402, claims K^bar^N dominance.**



Λ(1405)

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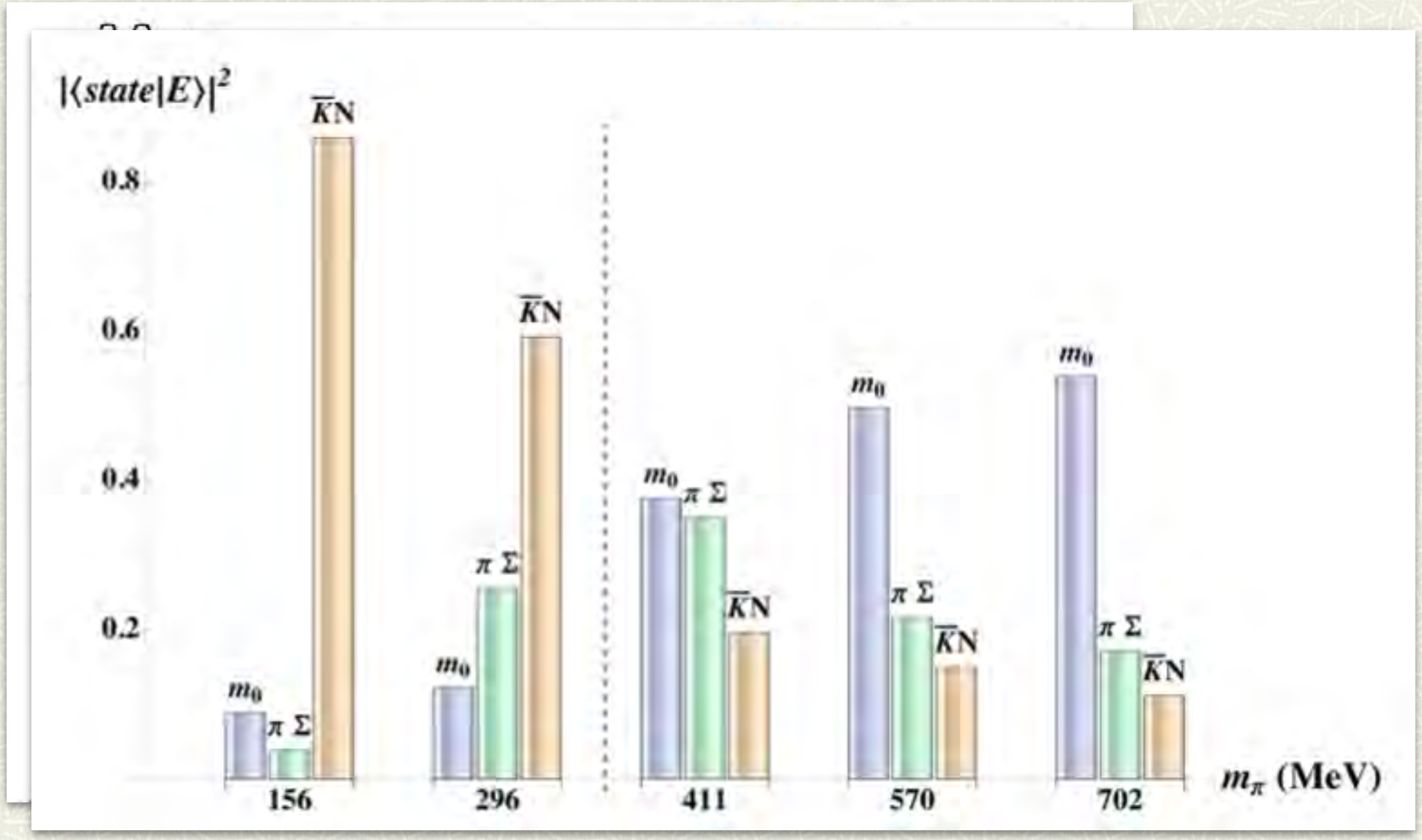
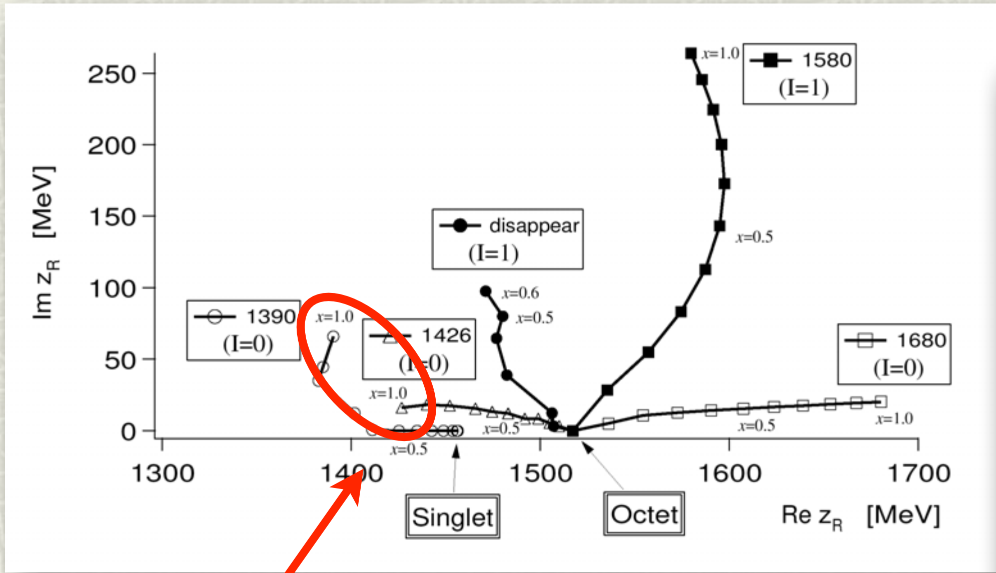
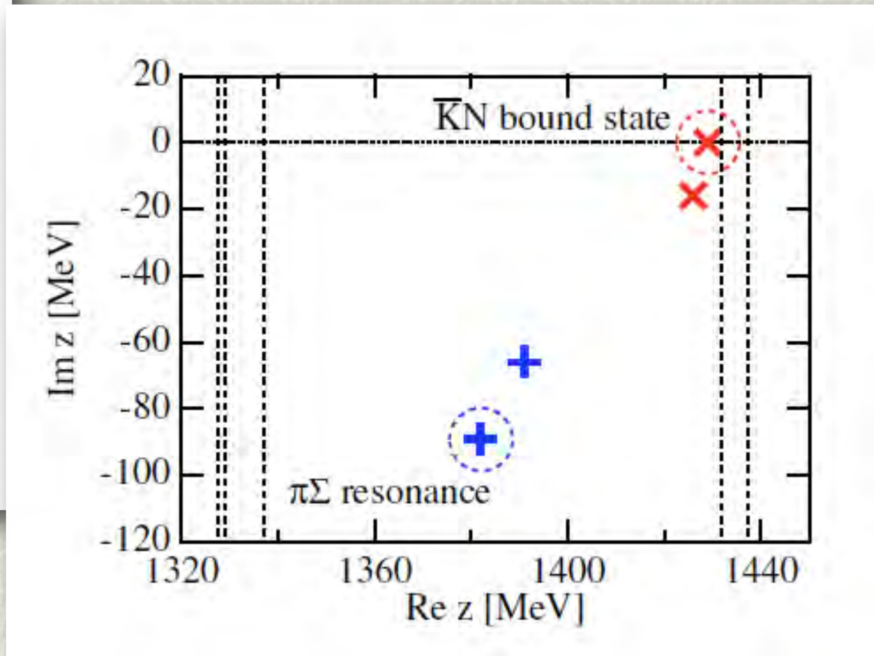


Λ(1405) as a hadron molecule

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

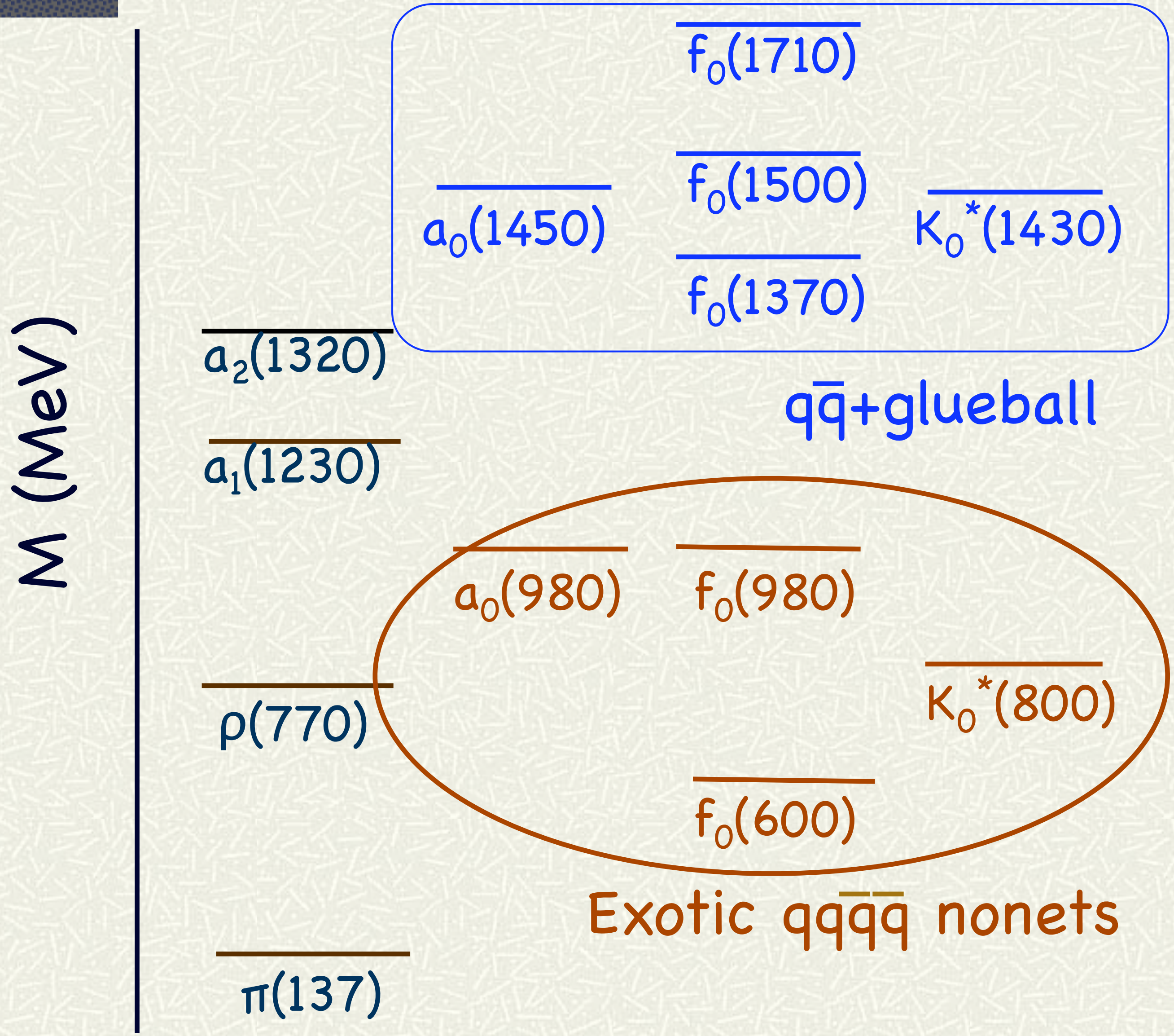


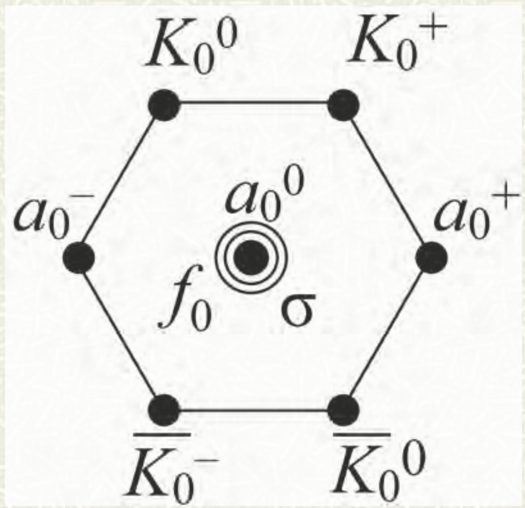


Chiral unitary approaches predict *two resonance poles for Λ(1405)*. (Jido et al., 2003)
They originate from a K^{bar}N bound state and a πΣ resonance. (Hyodo, Weise)

Multi-quark states

Multi-quark exotic hadrons





scalar nonets

Multi-quark exotic hadrons

Why is Λ(1405) likely to be a 5-quark state (in the quark model)?

Λ(1405) $J^{\pi}= 1/2^{-}$, flavor singlet

☆ uds L=1 orbital excited state with spin 1/2

=> $J=1/2^{-}$ and $3/2^{-}$: spin-orbit partner Λ(1520) $3/2^{-}$

☆ udsuū, . . L= 0 state, *i.e.* NO orbital excitation required

$(ud)_{s=0}$ $(su)_{s=0}$ ū (= two di-quarks + an anti-quark)

The total quark spin is S=1/2 so that only a $J=1/2^{-}$ state exists, *i.e.* no spin-orbit partner.

The competition between the kinetic energy (L=1) and the extra quark masses (qq^{bar}) indicates possible mixing of the two Fock components.

QCD sum rule approach

- **How can we directly determine the Fock components of hadrons from QCD?**
- **In order to identify 5-quark components, one may use overlaps of local operators to the hadron states.**
  Choose two local operators, 3-quark *J*$_3$ and 5-quark *J*$_5$

$$\langle 0|J_{3q}(x)|\Lambda\rangle = \lambda \cos\theta\, u(x)$$
$$\langle 0|J_{5q}(x)|\Lambda\rangle = \lambda \sin\theta\, u(x)$$

- **Then one can determine the "mixing angle" ?**

$$\langle J_{3q}(x)\bar{J}_{3q}(0)\rangle = \lambda^2 \cos^2\theta$$
$$\langle J_{5q}(x)\bar{J}_{5q}(0)\rangle = \lambda^2 \sin^2\theta$$
$$\langle J_{3q}(x)\bar{J}_{5q}(0)\rangle = \lambda^2 \sin\theta\cos\theta$$

QCD sum rule approach

- **Choose some operators for Λ(1/2⁻)**

$$
\begin{aligned}
J_3 &= \epsilon_{abc}\Big[\left(u_a^T C\gamma_5 d_b\right) s_c - \left(u_a^T C d_b\right)\gamma_5 s_c - \left(u_a^T C\gamma_5\gamma^\mu d_b\right)\gamma_\mu s_c\Big] \\
&= 2\epsilon_{abc}\Big[\left(u_a^T C\gamma_5 d_b\right) s_c + \left(d_a^T C\gamma_5 s_b\right) u_c + \left(s_a^T C\gamma_5 u_b\right) d_c\Big] \\
J_5 &= \epsilon_{abc}\epsilon_{def}\epsilon_{cfg}\Big[\left(d_a^T C\gamma_5 s_b\right)\left(s_d^T C\gamma_5 u_e\right)\gamma_5 C\bar{s}_g^T \\
&\qquad + \left(s_a^T C\gamma_5 u_b\right)\left(u_d^T C\gamma_5 d_e\right)\gamma_5 C\bar{u}_g^T \\
&\qquad + \left(u_a^T C\gamma_5 d_b\right)\left(d_d^T C\gamma_5 s_e\right)\gamma_5 C\bar{d}_g^T\Big]
\end{aligned}
$$

- **However, it does not work, as these operators are not normalized properly (ex. their dimensions are different).**
- **We need to normalize the operators. Two methods were proposed.**

T. Nakamura, J. Sugiyama, T. Nishikawa, N. Ishii, MO, PRD78 (2008) 014010

QCD sum rule approach

Choose a J_5 and define a genuine 5-quark operator J_5' so that 3-quark component of J_5 is subtracted.

$$J_5 = J_5' + \underbrace{\left(-\frac{1}{18}(\langle \bar{u}u\rangle + \langle \bar{d}d\rangle + \langle \bar{s}s\rangle)J_3\right)}_{J_3'}$$

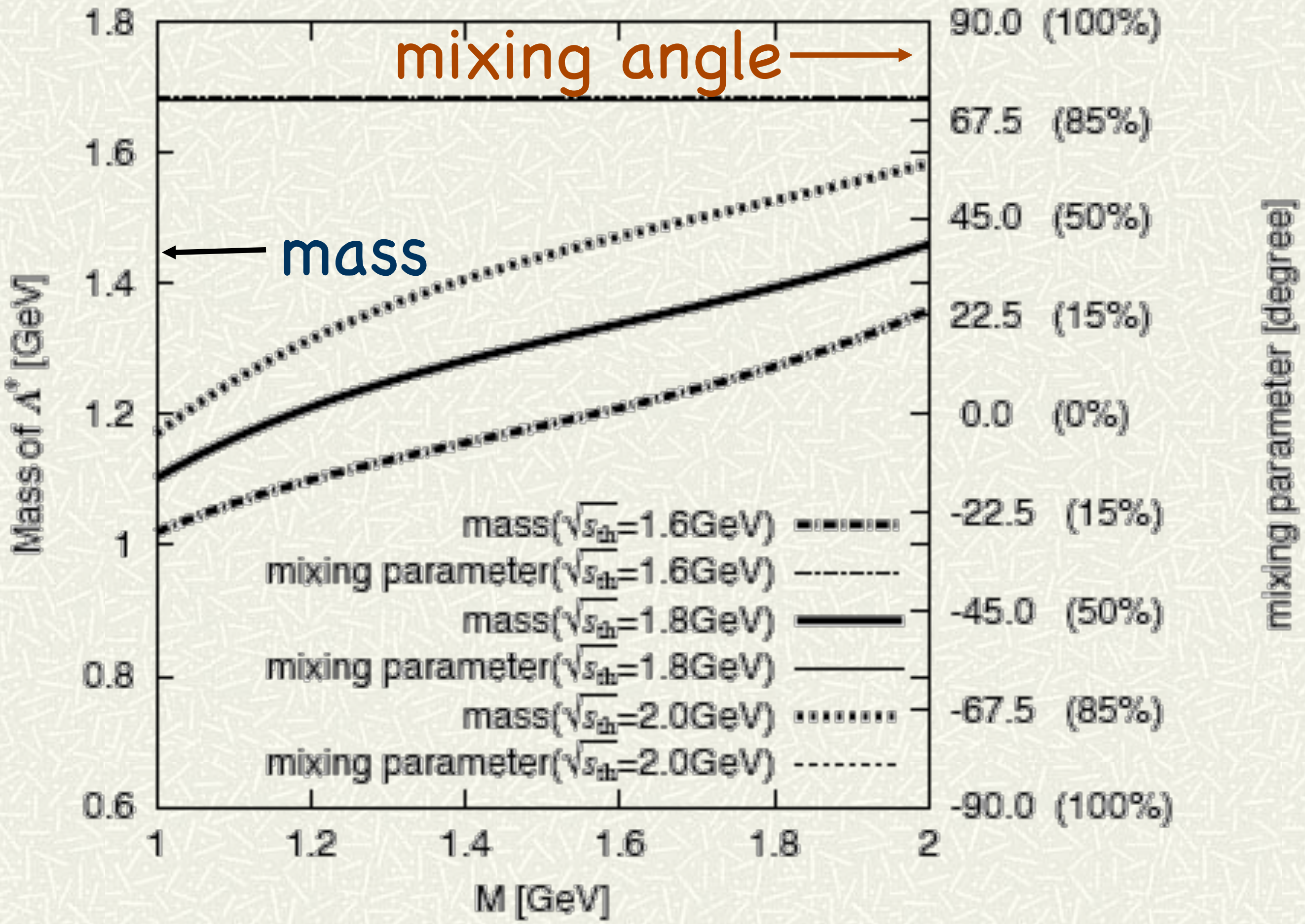
then one may determine the operator which couples most strongly to the physical state,

$$J_\Lambda(x) = \cos\theta J_3'(x) + \sin\theta J_5'(x)$$

This method is "model independent", but it depends on the choice of the operators.

Λ(singlet, 1/2⁻)

- **Mass and mixing angle *v.s.* the Borel mass**



T. Nakamura, et al, PRD78 (2008) 014010

Number of quarks in QCD

"Counting" the number of quarks?

There is no conserved current corresponding to the # of quarks: $N(q)+N(\bar{q})$.

It may depend on choices of the quark operator.

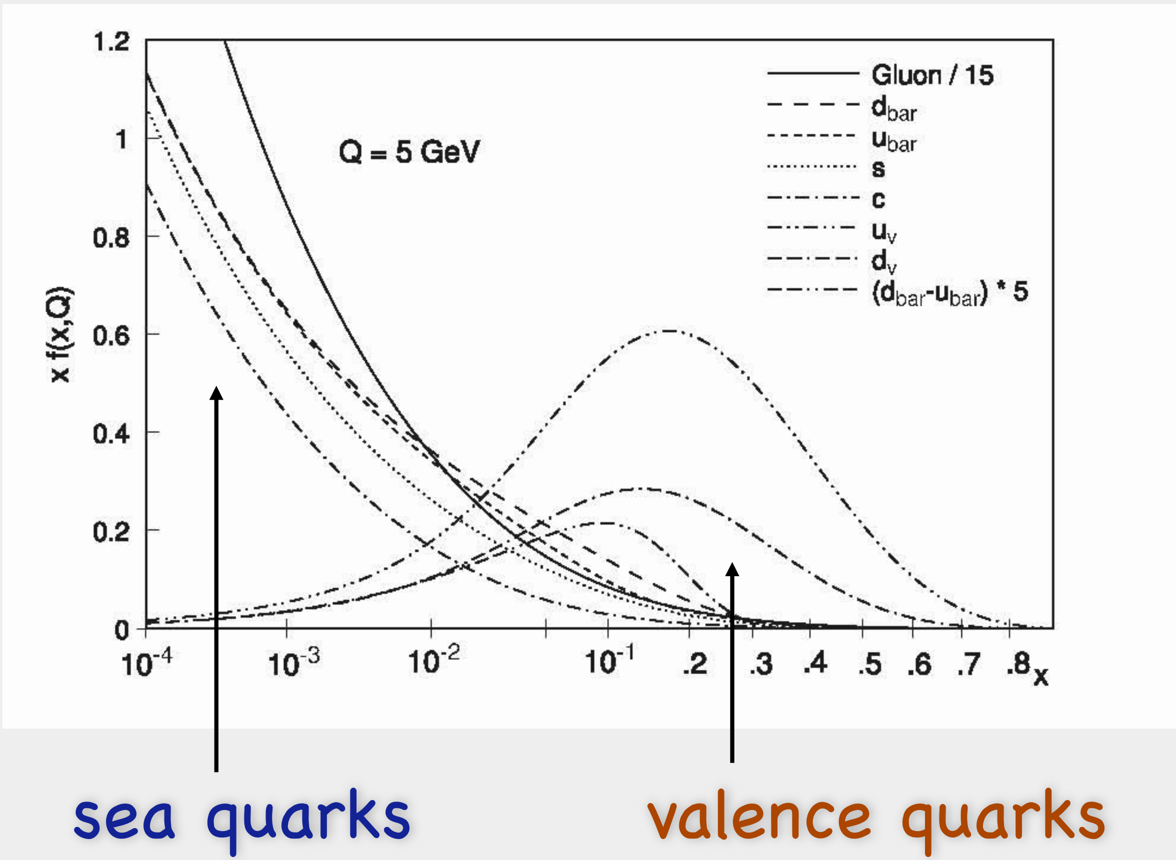
Ex. Bogoliubov transformation may change the # of quarks in a hadron.

Any observables which can distinguish valence and sea quarks?

Parton distribution in the light-cone frame?

Number of quarks in QCD

In DIS and other high energy processes, one may distinguish and count "valence" quarks.



Number of quarks in QCD

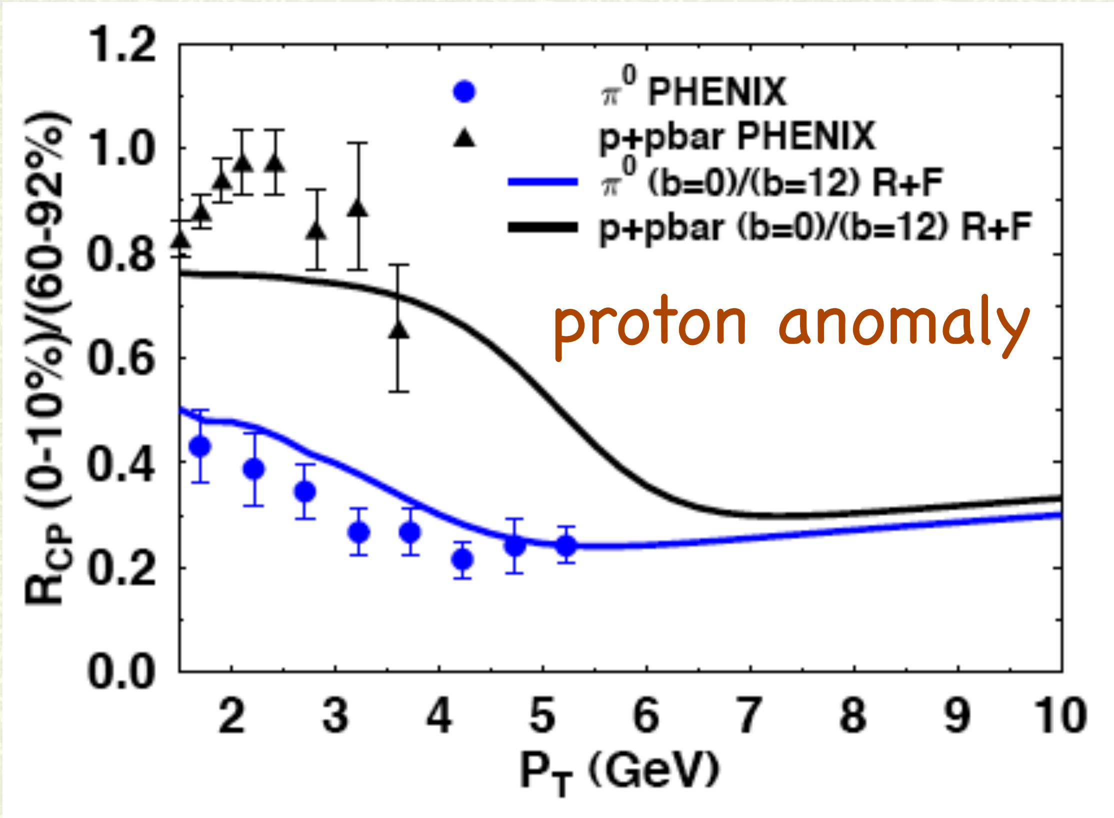
Hadronization in heavy ion collisions:
Recombination and fragmentation of partons

R. J. Fries, S. A. Bass, B. Muller, C. Nonaka, PRL 90 (2003) 202303

meson vs baryon

qq → 2 <p$_T$>

qqq → 3 <p$_T$>

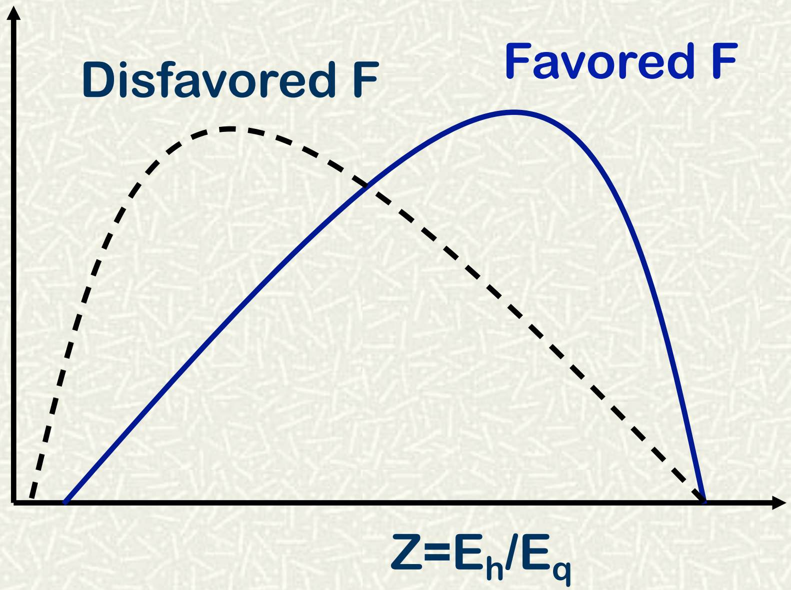


Then
how do 4 or 5 quark states behave?

Number of quarks in QCD

M. Hirai, S. Kumano, MO, K. Sudoh, PR D77 (2008) 017504

- **We proposed to apply to the fragmentation functions of resonances.**
  - **determined by a global analysis of $e^+ + e^- \rightarrow h + X$ experimental data**
- **Favored vs Disfavored FF**
  - **Favored FF → valence quarks**
    - **constituents of produced hadrons**
    - **peaked at medium to large z**
  - **Disfavored FF → sea quarks**
    - **peaked at small z**



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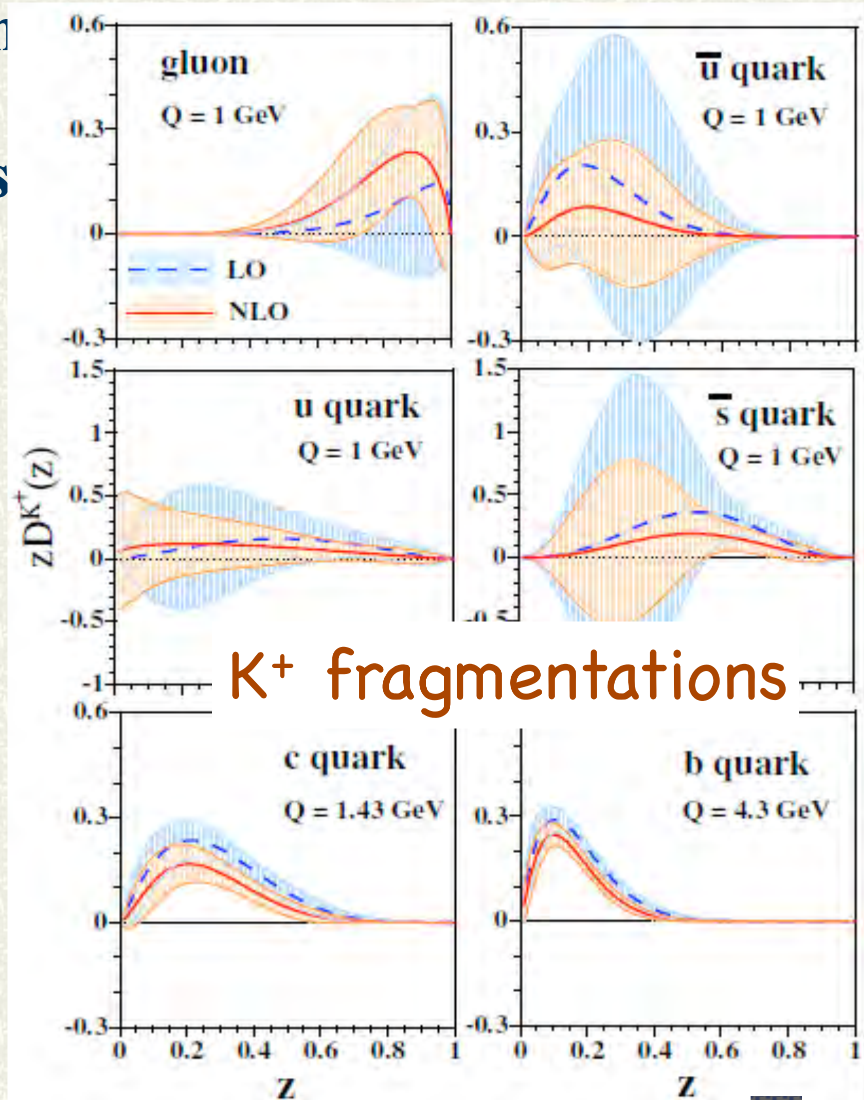


Number of quarks in QCD

Applied to $f_0(980)$ (0^+, I=0)

- Tetra-quark configuration

  favored FF: u and s quarks

  Peak at large-z (z~0.85)

  $z_u^{max} \sim z_s^{max}$

OR

- $S\bar{S}$ configuration

  $M_u < M_s$

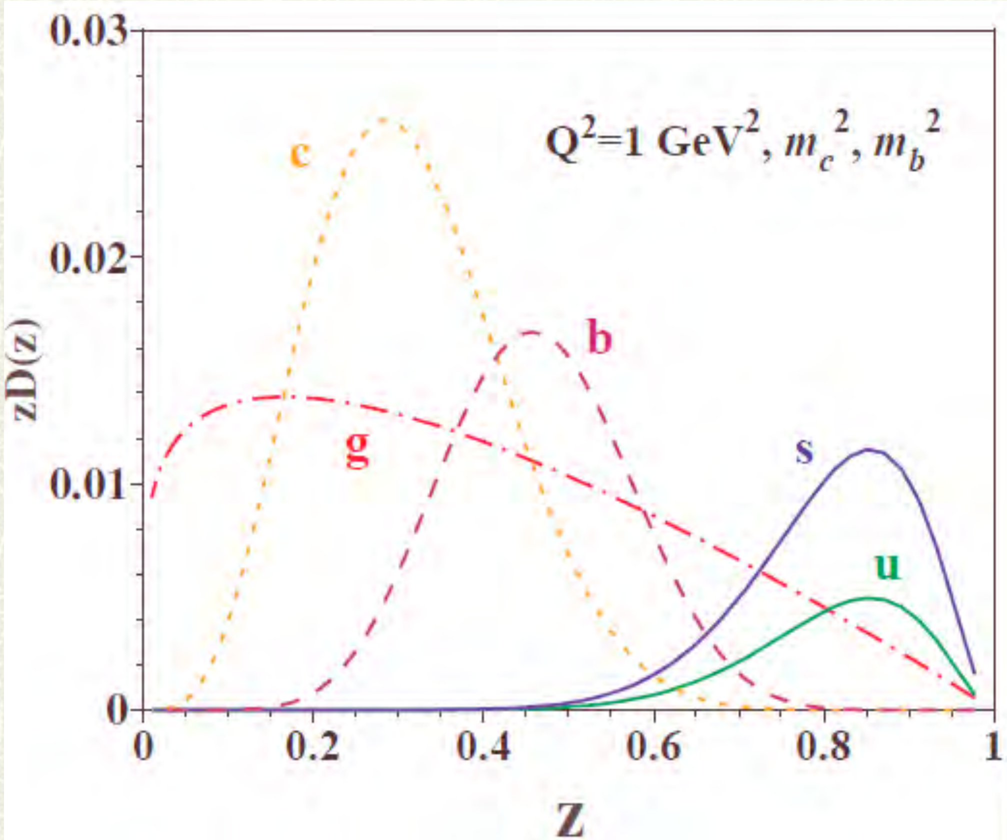
  (M_u/M_s=0.43 ± 6.73)

Large uncertainty

  Need further precise data

  χ^2/d.o.f. = 0.907

  Total Number of data: 23



2^{nd} moments

- M_u=0.0012 ± 0.0107
- M_s=0.0027 ± 0.0183
- M_g=0.0090 ± 0.0046

Heavy Quark Hadrons

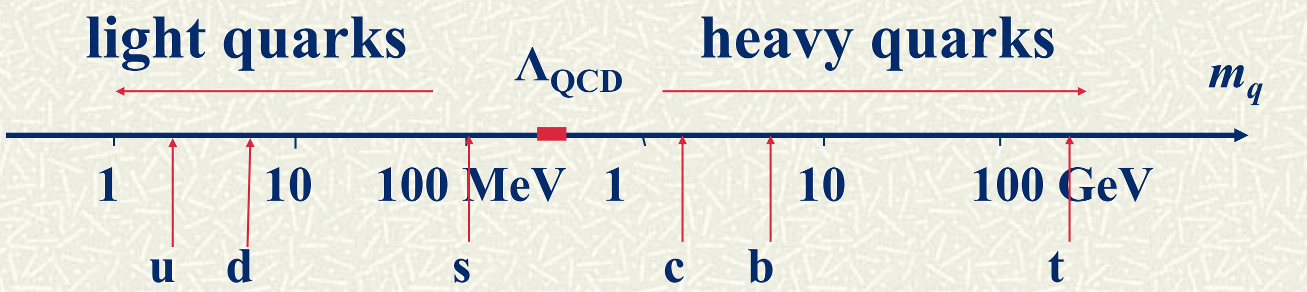
Why Heavy Quarks are interesting ?

- The c, b, (t) quarks have large masses.

  m(ρ/ω): m(K*): m(D*): m(B*)

  = 1 : 1.15 : 2.59 : 6.87

- Λ_{QCD}(~ 300 MeV) ≪ m_c(~ 1.3 GeV) ≪ m_b(~ 4.2 GeV)



chiral symmetry
m_q expansion

heavy quark symmetry
($1/m_Q$) expansion

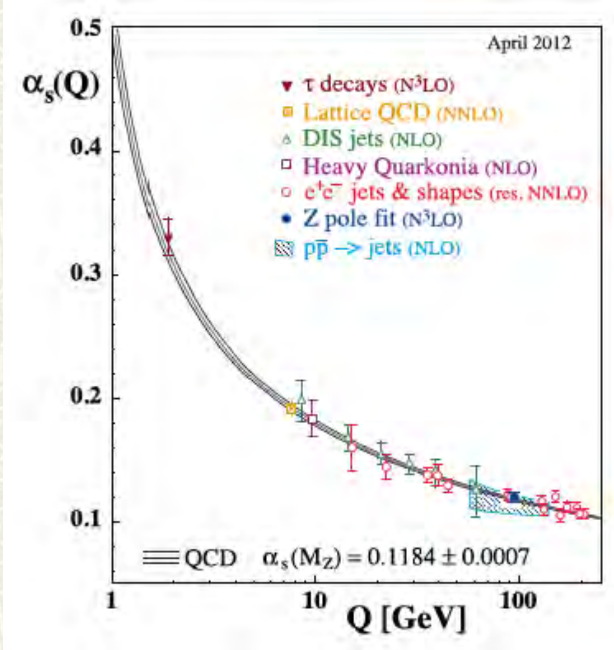
Why Heavy Quarks are interesting ?

- **Dynamics of Heavy Quarks**

  Asymptotic free

  small $\alpha_s \sim v/c$ (~ 0.25 for charm)

  → Heavy Quark Spin Symmetry



  Non-relativistic

  $Q\bar{Q}$ mixing is suppressed.

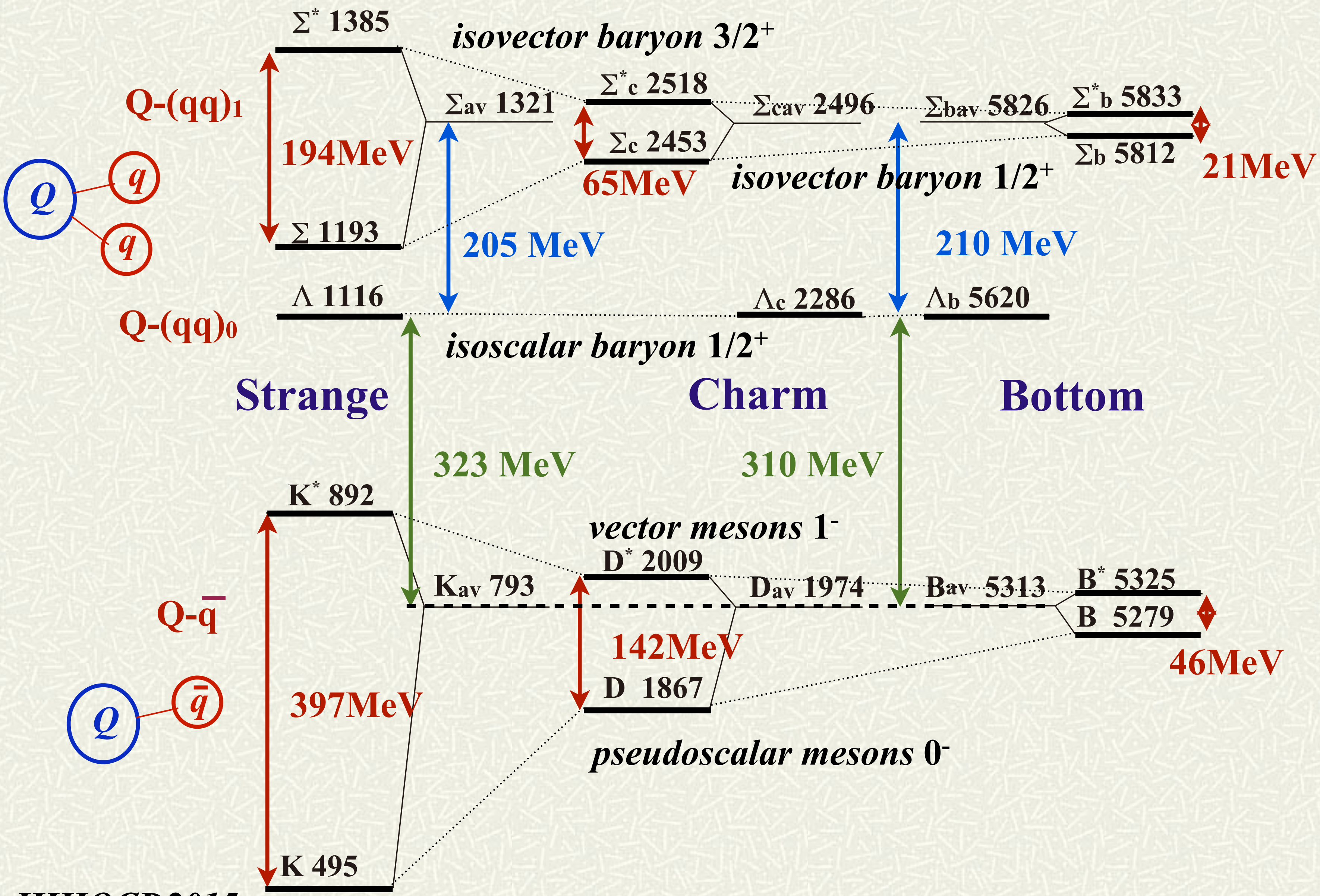
  Heavy quarks provide color sources for light quarks.

  We can extract the dynamics of light quarks.

- **Are *Strange* quarks light or heavy? Or both?**

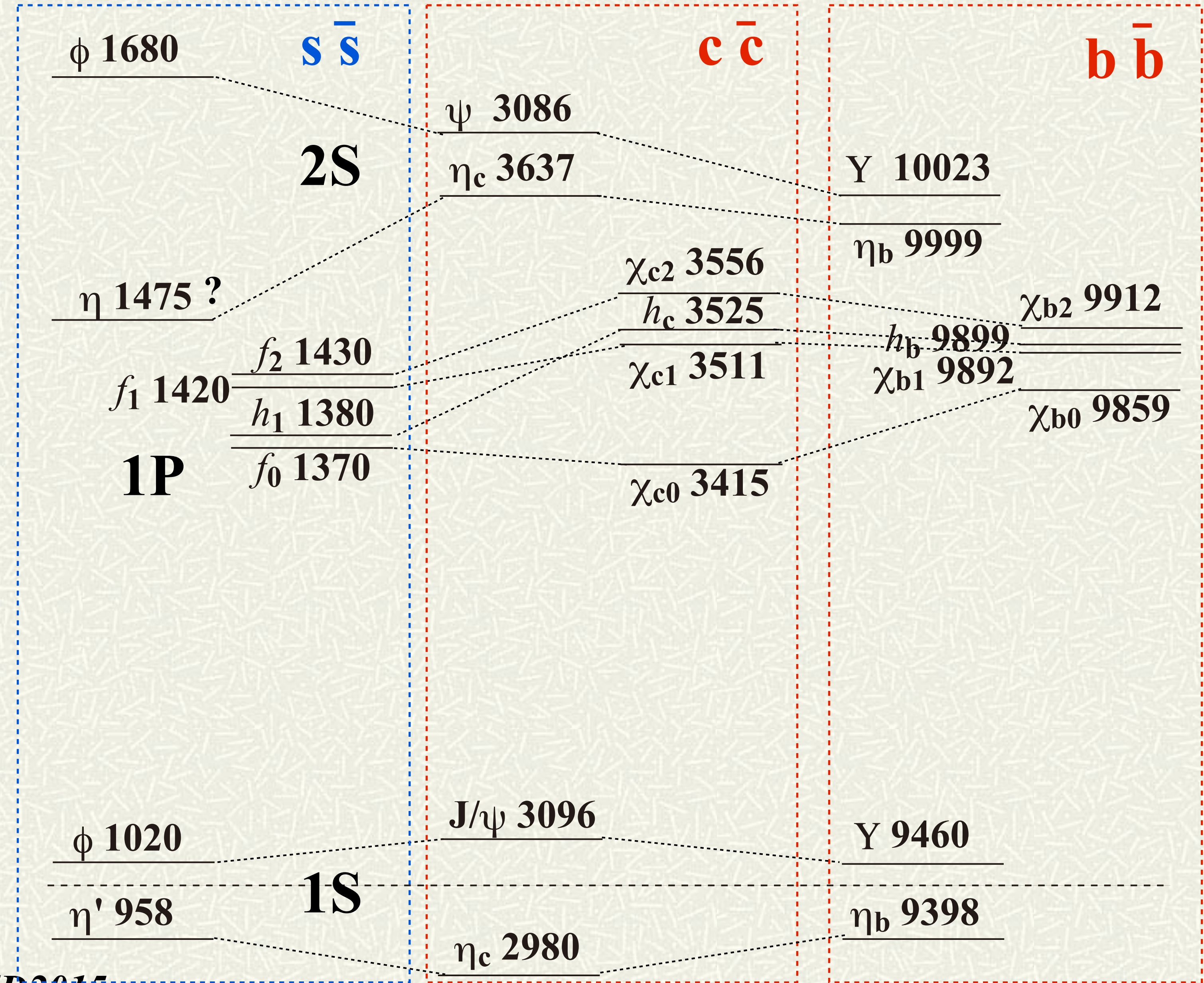
  $SU(3)_f$ symmetry vs HQ symmetry

From Strangeness to Heavy Quarks

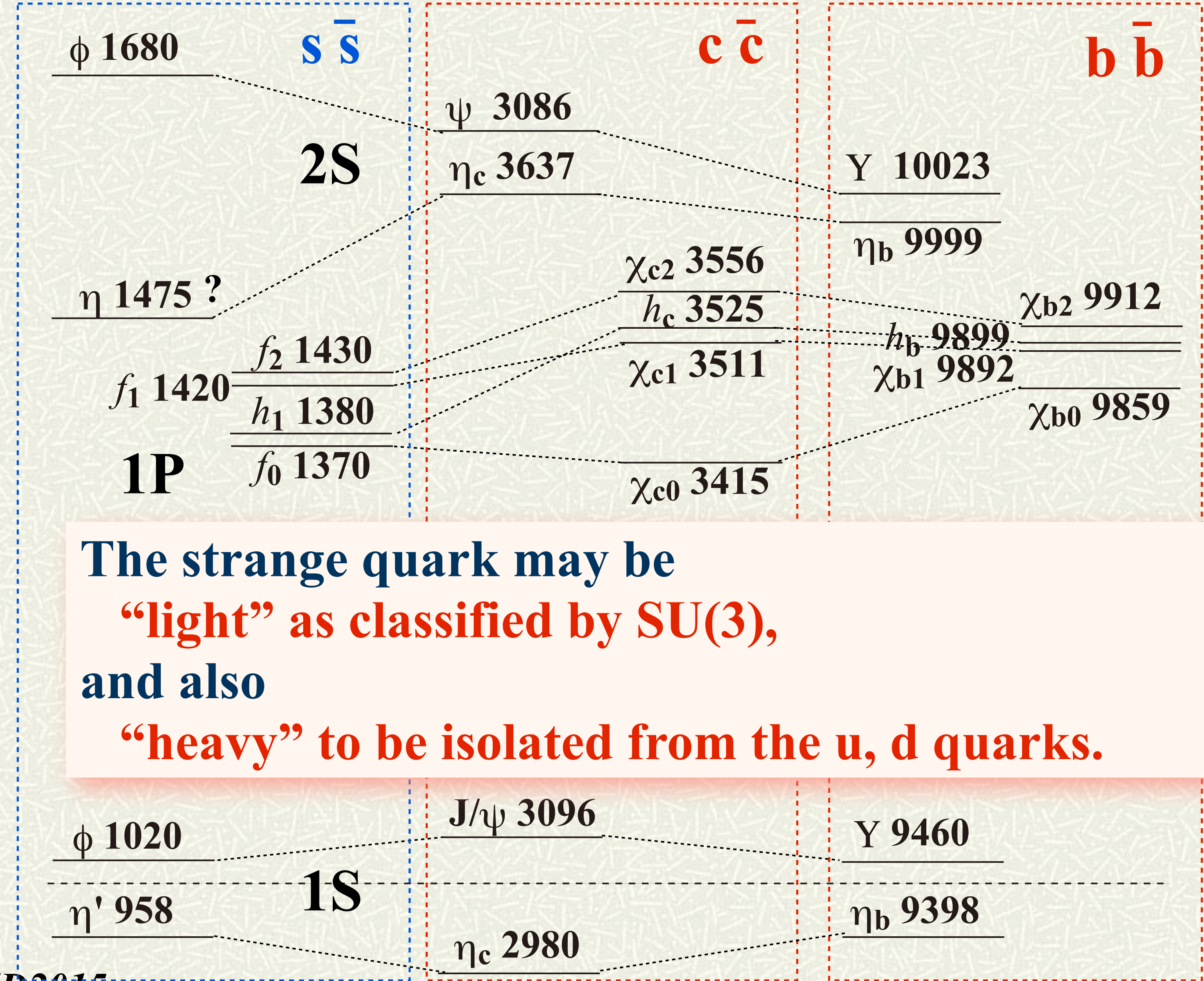


HHIQCD2015

From Strangeness to Heavy Quarks



From Strangeness to Heavy Quarks



The strange quark may be
"light" as classified by SU(3),
and also
"heavy" to be isolated from the u, d quarks.

From Strangeness to Heavy Quarks

- Λ(1405) as a (K^{bar}N) molecule
  - the lowest negative parity baryon resonance
  - significantly lower than the other P-wave baryons
- H dibaryon
  - B=2, Str = -2, $J=0^+$, I=0 resonance predicted by Jaffe (1977)
  - Also predicted by the LQCD calculation (HALQCD, etc)
  - (strongly) coupled to ΛΛ-NΞ-ΣΣ two-baryon channels
- Θ^+ pentaquark
  - Str = +1 baryon resonance, classified as SU(3) 10^{bar} predicted in the chiral quark model by Diakonov
- S= -2, -3 baryons
  - The available data are very limited.

Hadron molecule

Multi-quark hadron

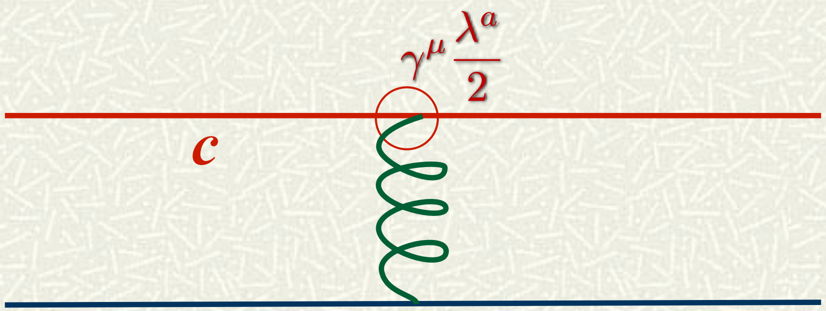
Exotic hadron

Multi-flavor hadron

Are these "novel" features unique to the Strangeness?
Do they persist in the charm/bottom sectors?

Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



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

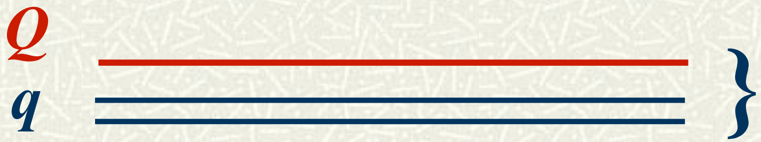
(Color Electric coupling) ≫ (Color Magnetic coupling)

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

⇨ Heavy Quark Spin Symmetry

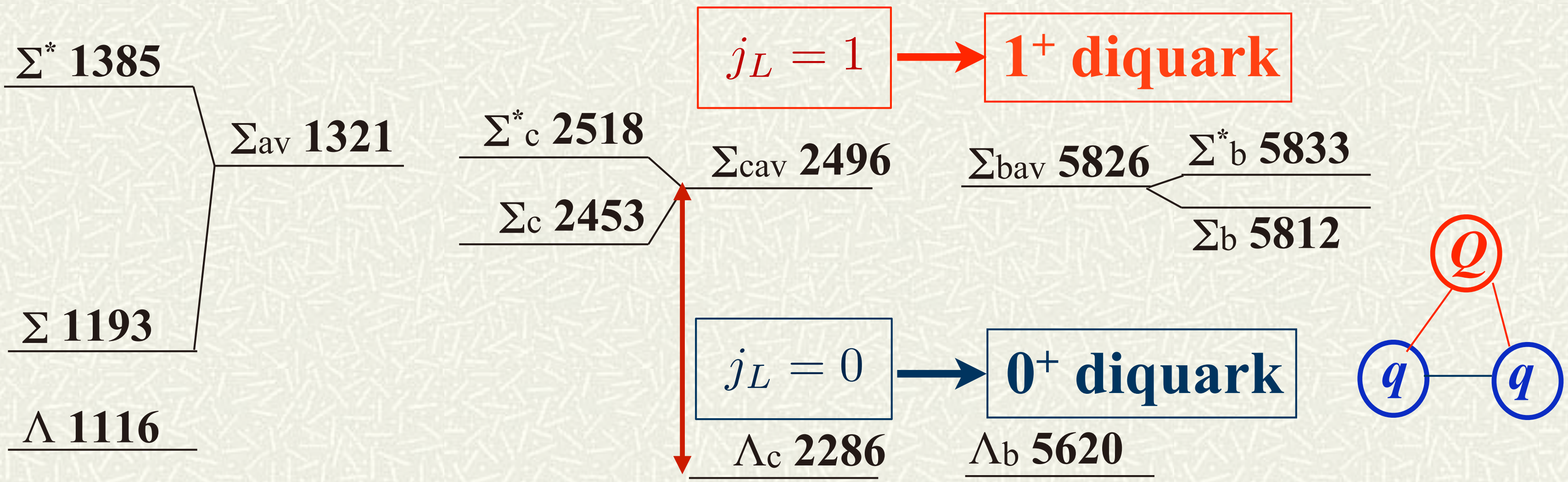
Heavy Quark Spin Symmetry

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



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

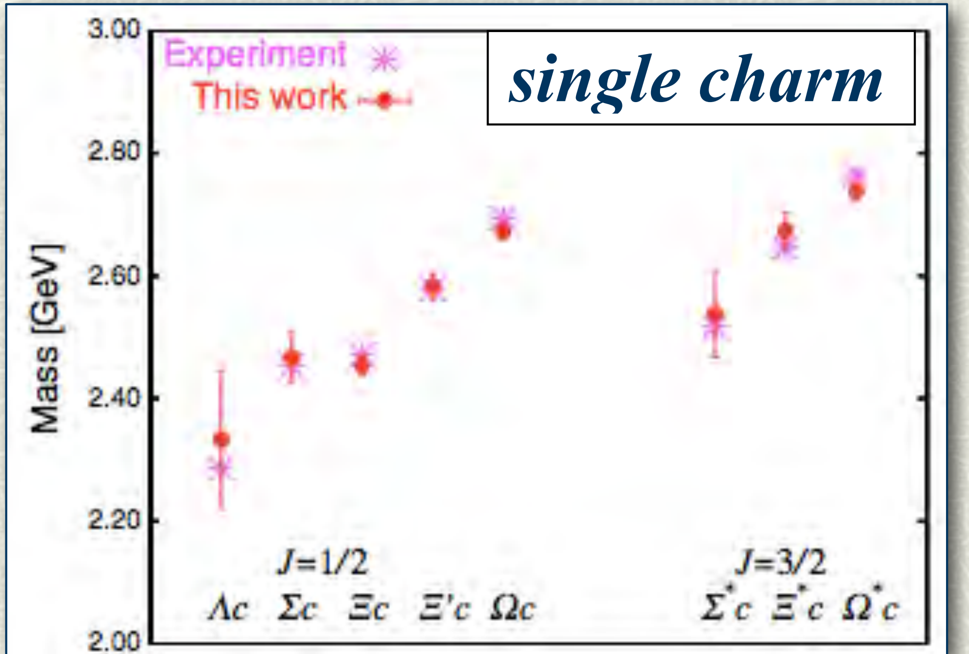
$J = j_L \pm \frac{1}{2}$ **states are degenerate in the HQ limit.**

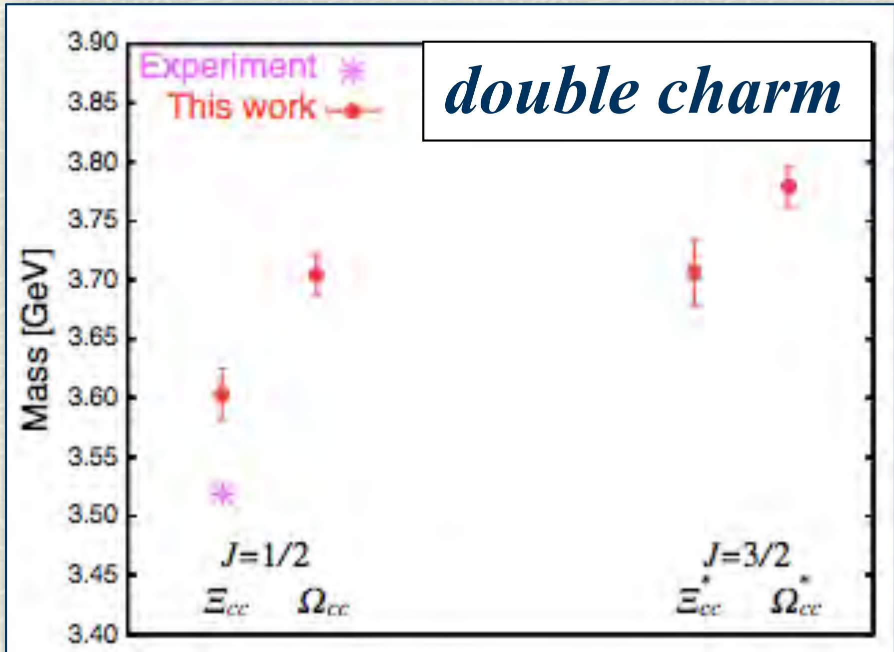


Spectroscopy of Light Diquarks

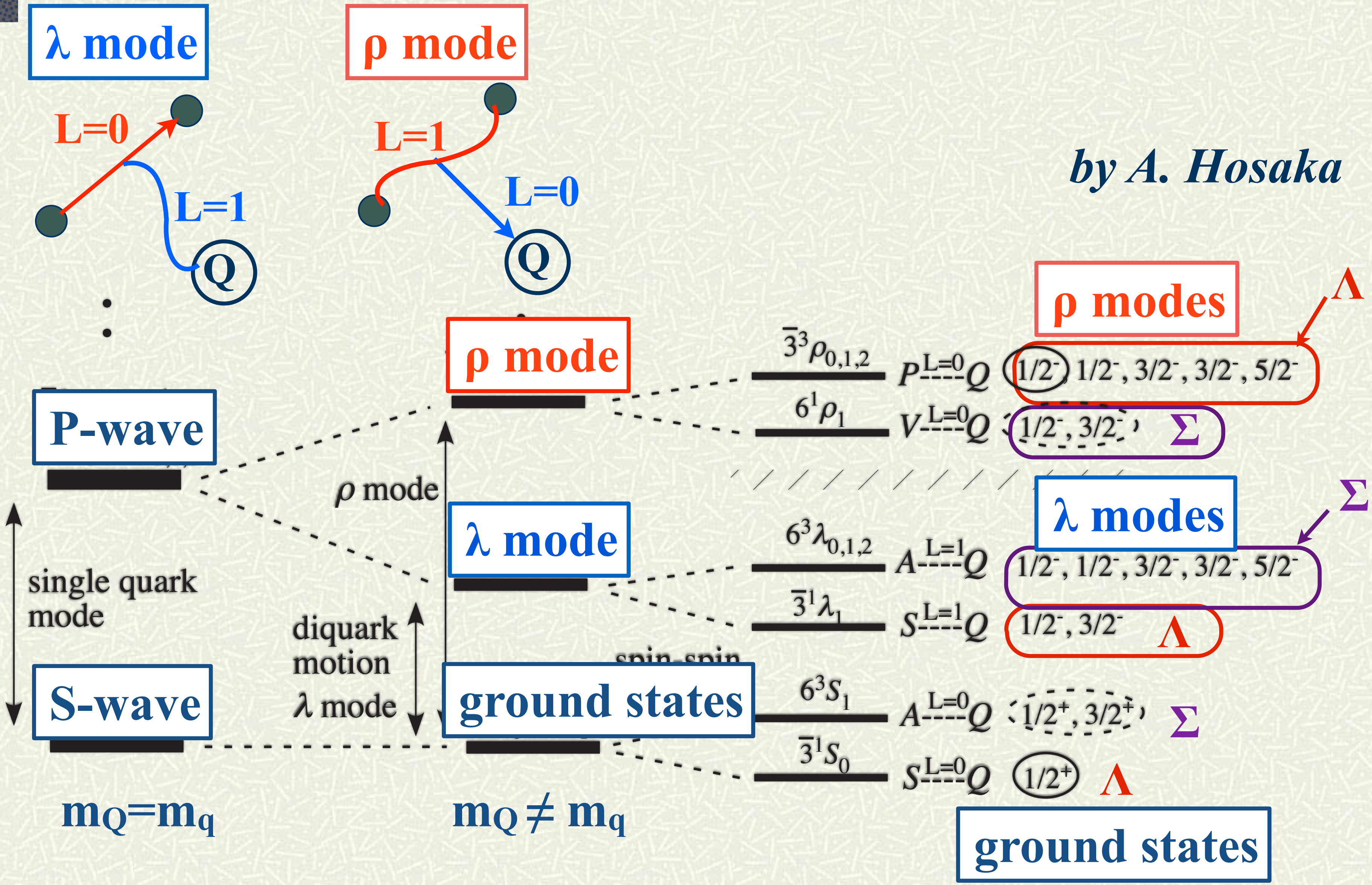
Charmed Baryons: Ground states

- **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)





P-wave excited states



P-wave excited states

- The "diquark clusters" 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 → Heavy baryon (Qqq) + light mesons (qq^{bar})
  λ-mode → Heavy meson (Qq^{bar}) + light baryon (qqq)

P-wave excited states

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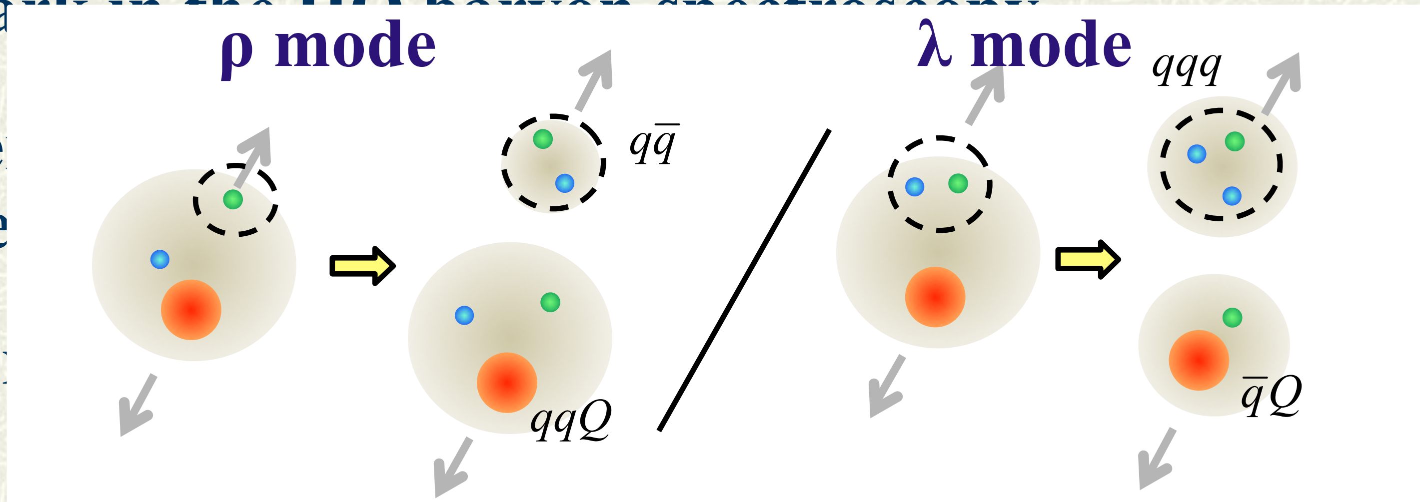

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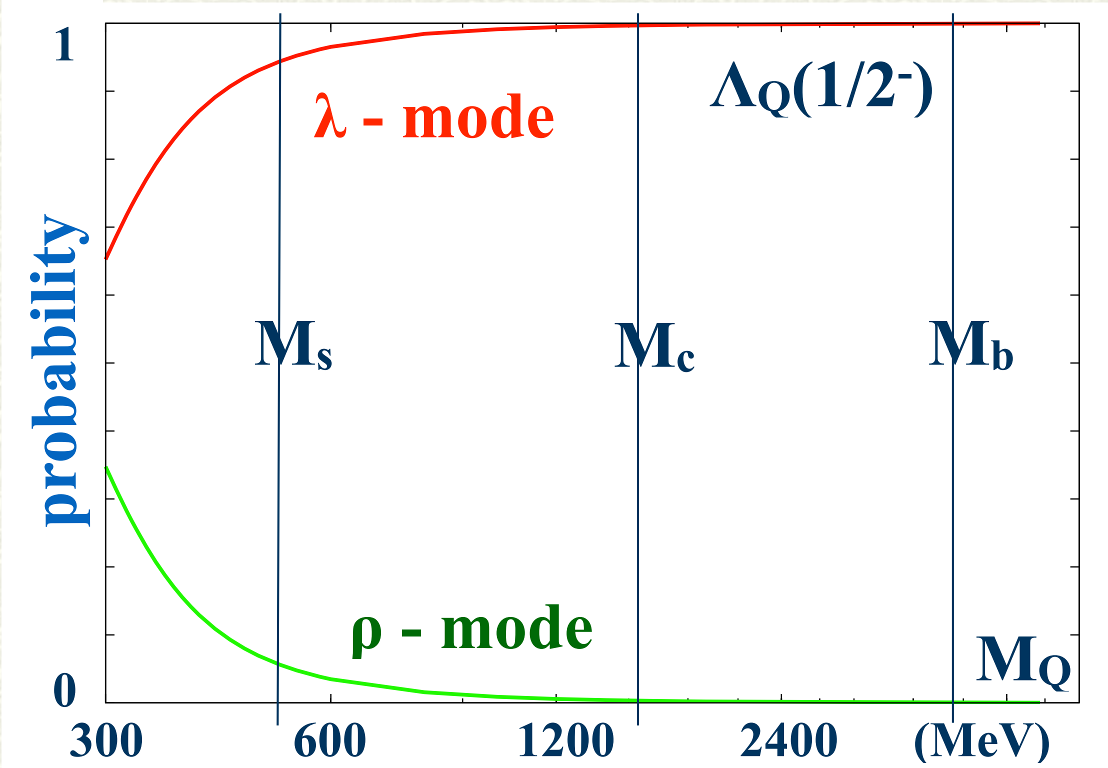
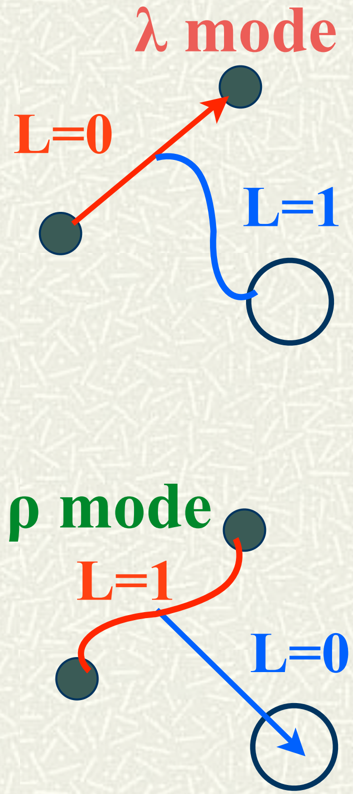
P-wave excited states: from s to c

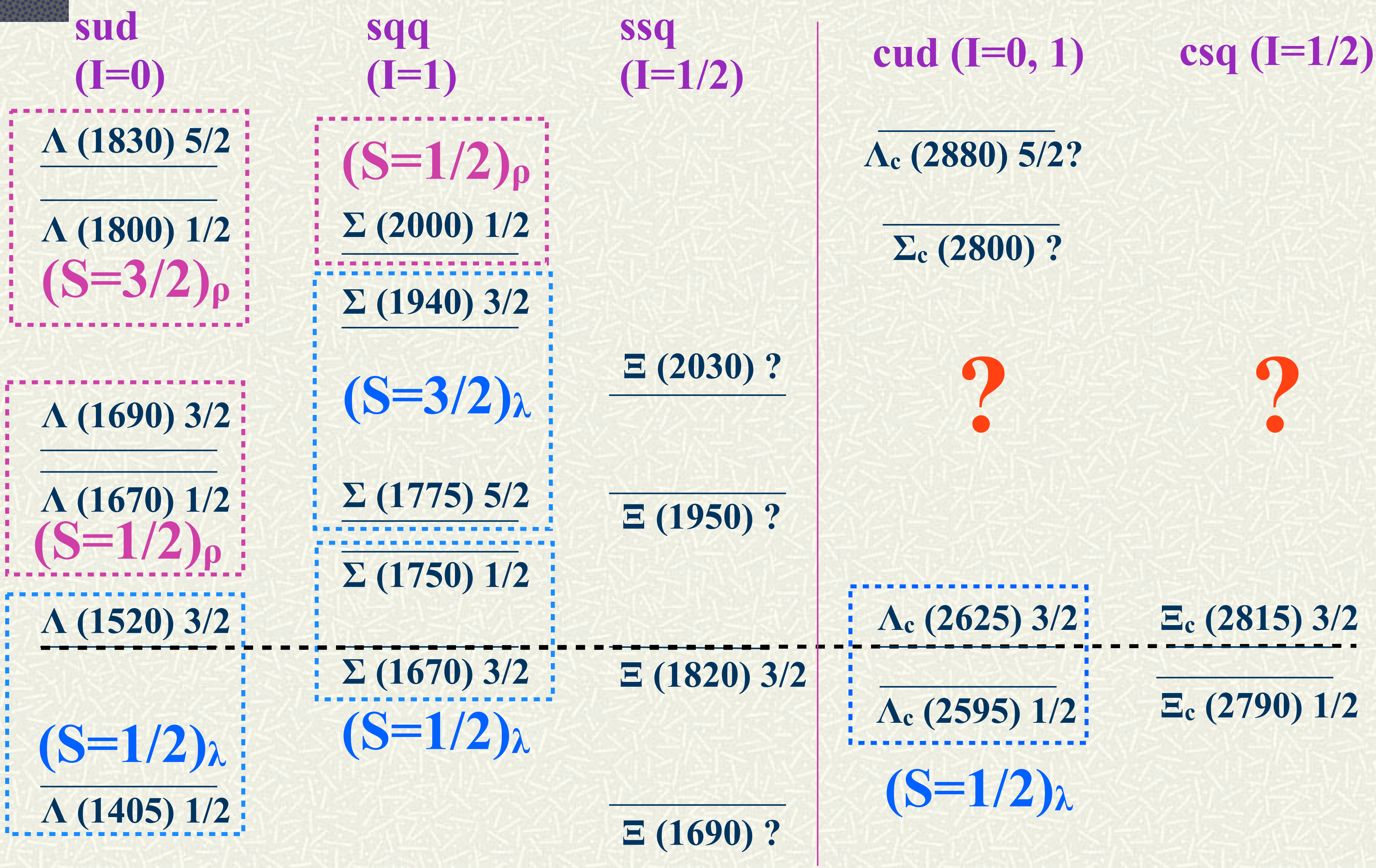
- Probabilities of λ and ρ modes *v.s.* heavy quark mass by a Hamiltonian quark model with spin-spin, spin-orbit and tensor forces



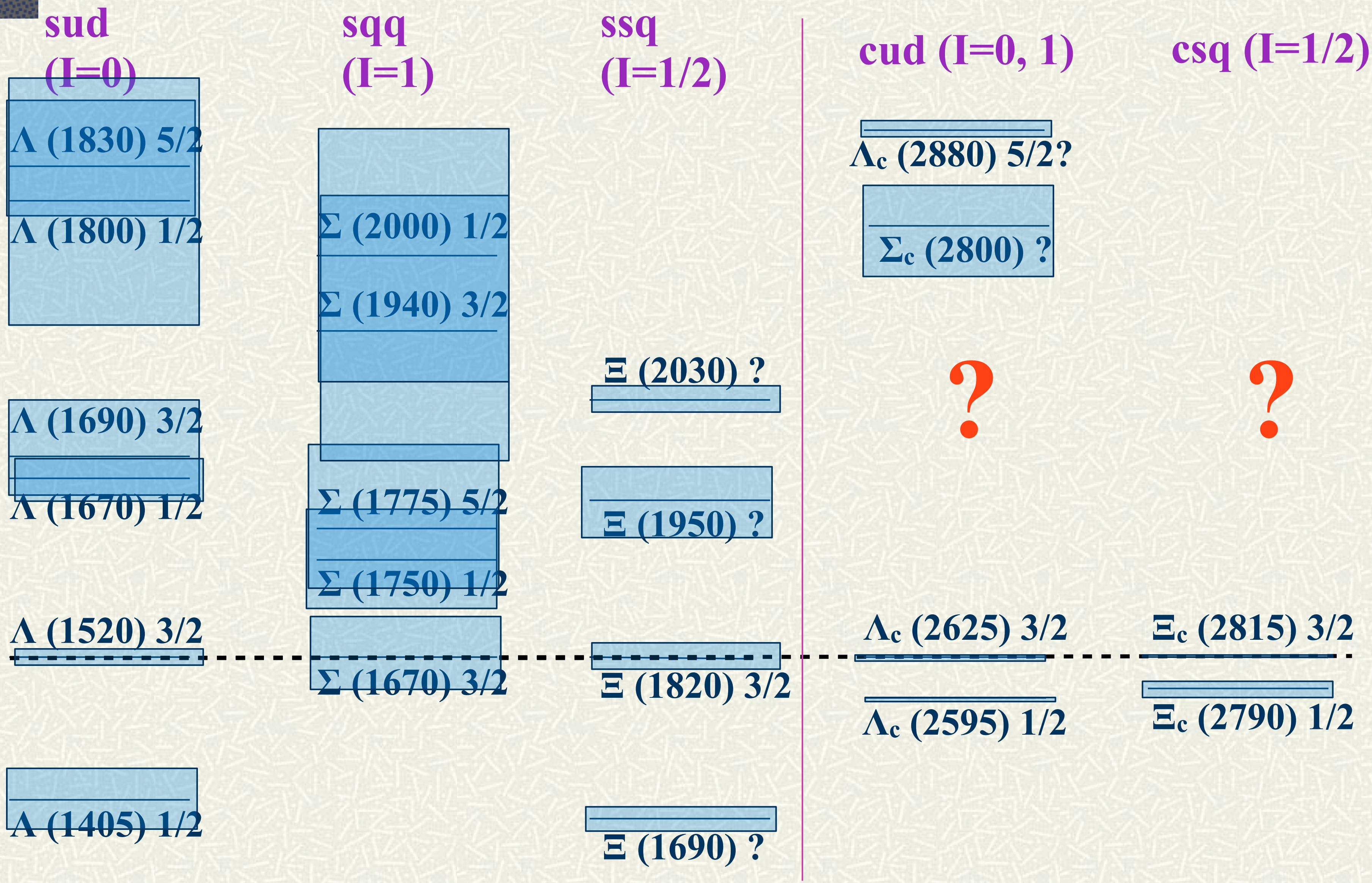


Yoshida, Sadato, Hosaka, Hiyama, MO, in preparation.

P-wave excited states: from s to c



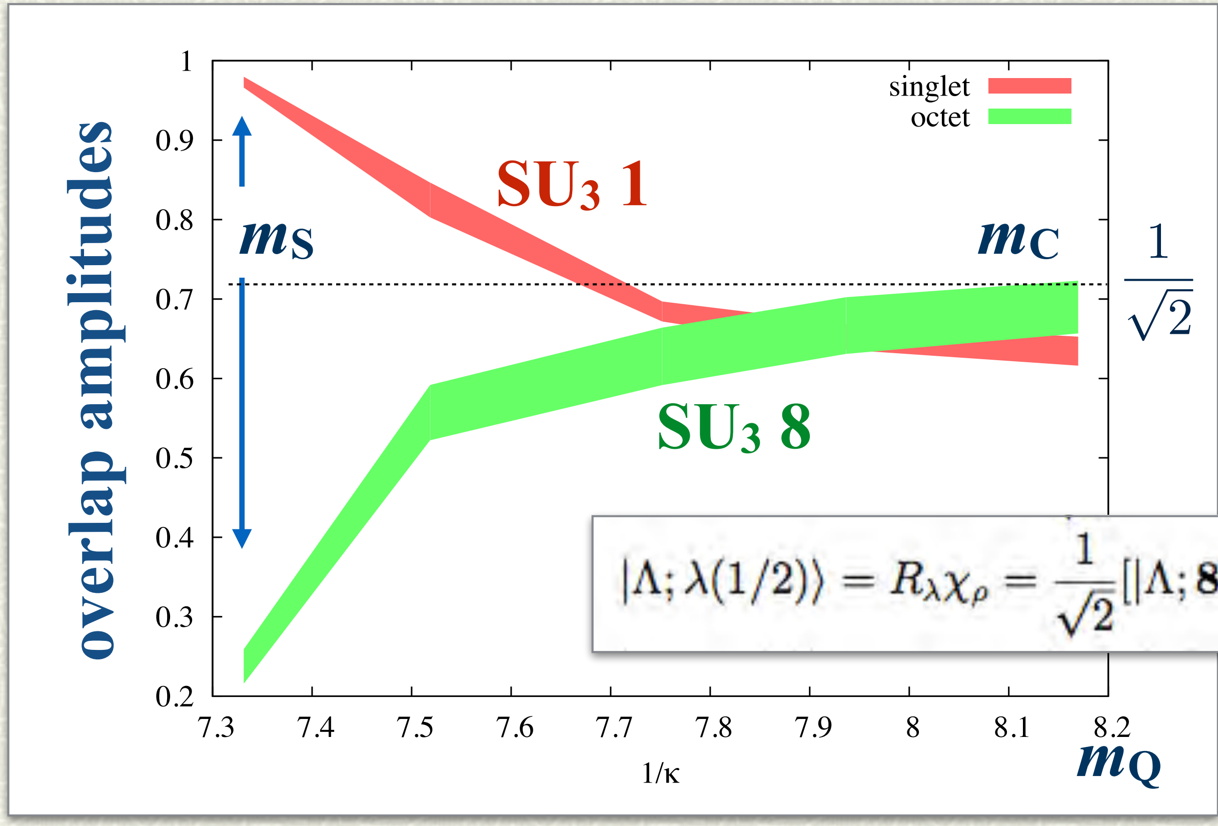
P-wave excited states: from s to c



P-wave excited states: from s to c

- **Transition from the SU(3)$_f$ to HQ.**

Lattice QCD for $m_Q = m_S \to m_C$ with $m_\pi^2 = 410$ MeV



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

P. Gubler, T.T. Takahashi, M.O., preliminary

Conclusion and Further possibilities

- Going from strange to charm/bottom, we may isolate light degrees freedom by using the heavy quark spin symmetry. This may help extracting inter-quark and di-quark interactions in hadrons.
- Hadrons and Hadronic Interactions of charmed (heavy) quarks may show more exotic features than strangeness.
- A few interesting problems are:
  Where are Ξcc ground and excited states?
  Do exotic double charm mesons exist?
  Are there any bound states of D mesons to nucleon/nuclei?
  How strong are the interactions of charmed baryons with nucleon? Are there charmed hyper-nuclei?
- Many interesting physics subjects are waiting for the new heavy quark projects in J-PARC, GSI and others.