New Aspects of Hadron Spectroscopy with Heavy Flavor

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EXA2014

Vienna, Sep. 15, 2014

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Introduction
New Hadron Spectroscopy

Quark Model / Charmonium

- **50 year anniversary of the Quark Model (1964)**

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

Quark Model / Charmonium

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- The quark model gives a very good guideline to classify and interpret the low-lying hadrons in QCD.

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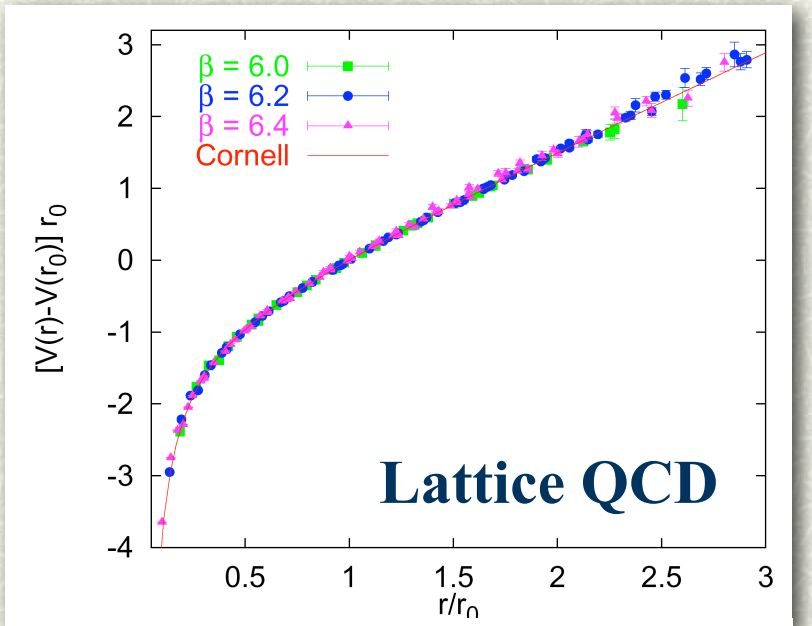
- The quark model gives a very good guideline to classify and interpret the low-lying hadrons in QCD.
- The charmonium spectrum gives a textbook example of the quark model.

Linear + Coulomb potential

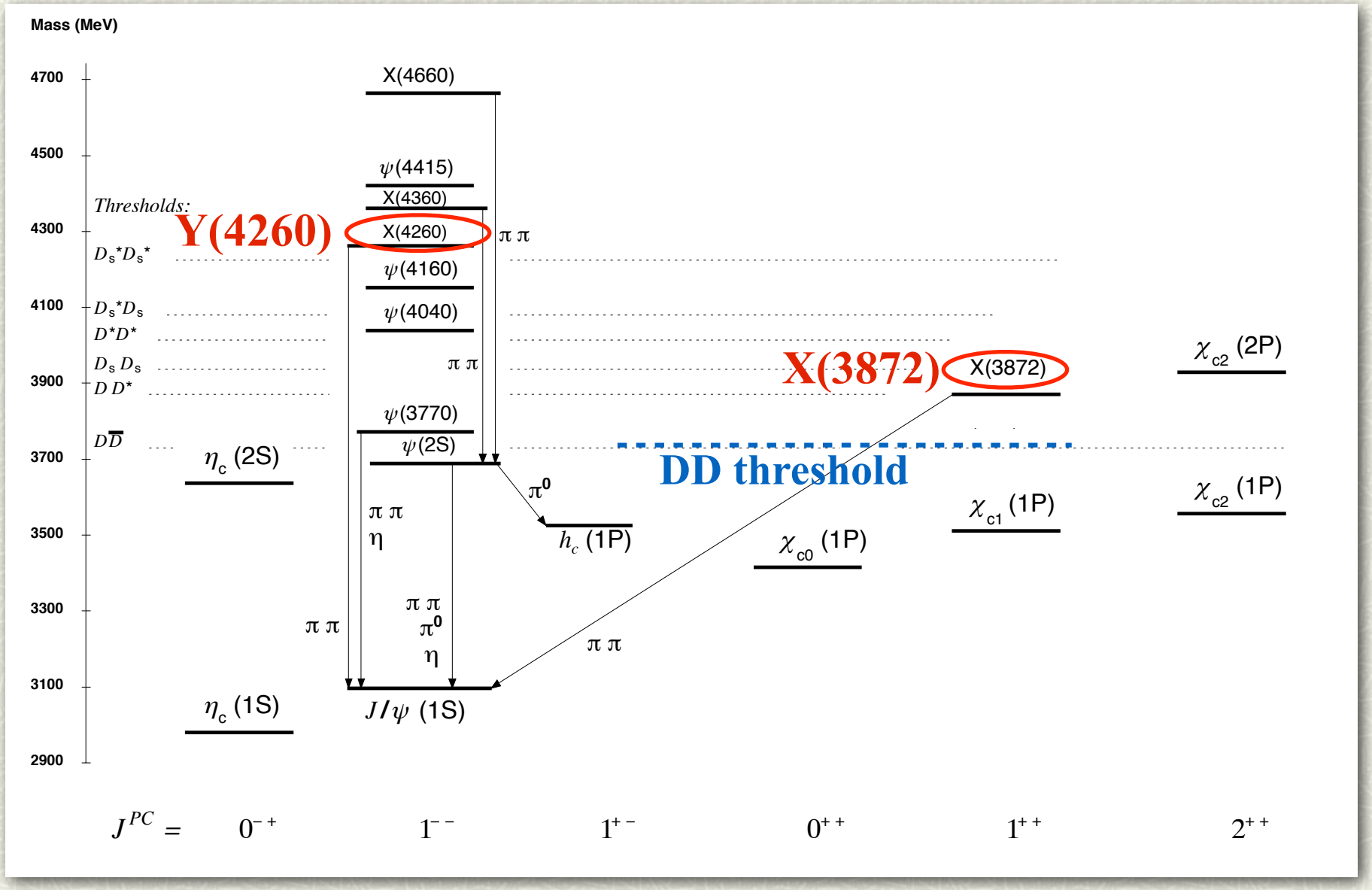
$$V(r) = -\frac{e}{r} + \sigma r$$

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

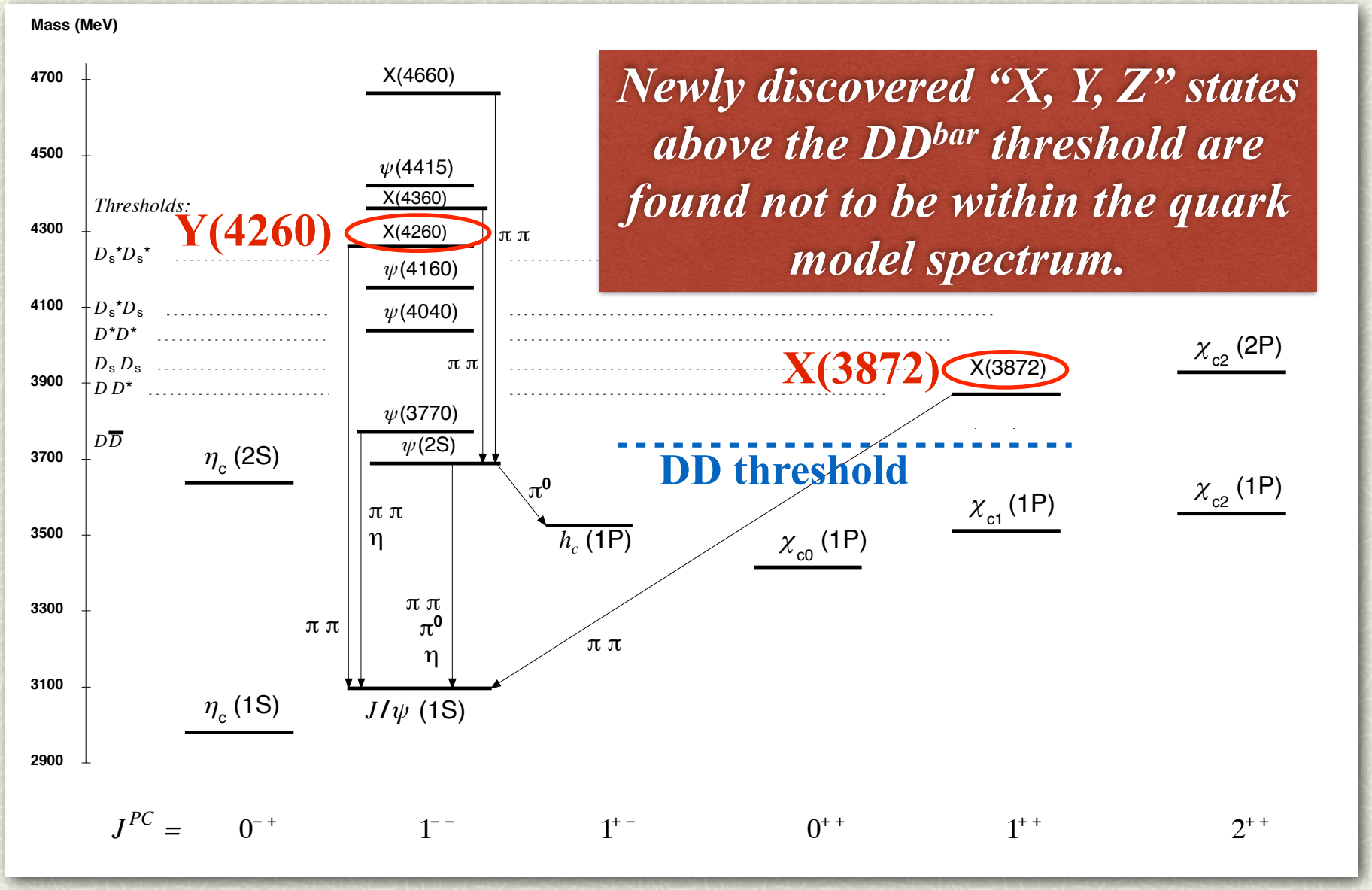


G.S. Bali, Phys. Rept. 343 (2001) 1

Quark Model / Charmonium



Quark Model / Charmonium

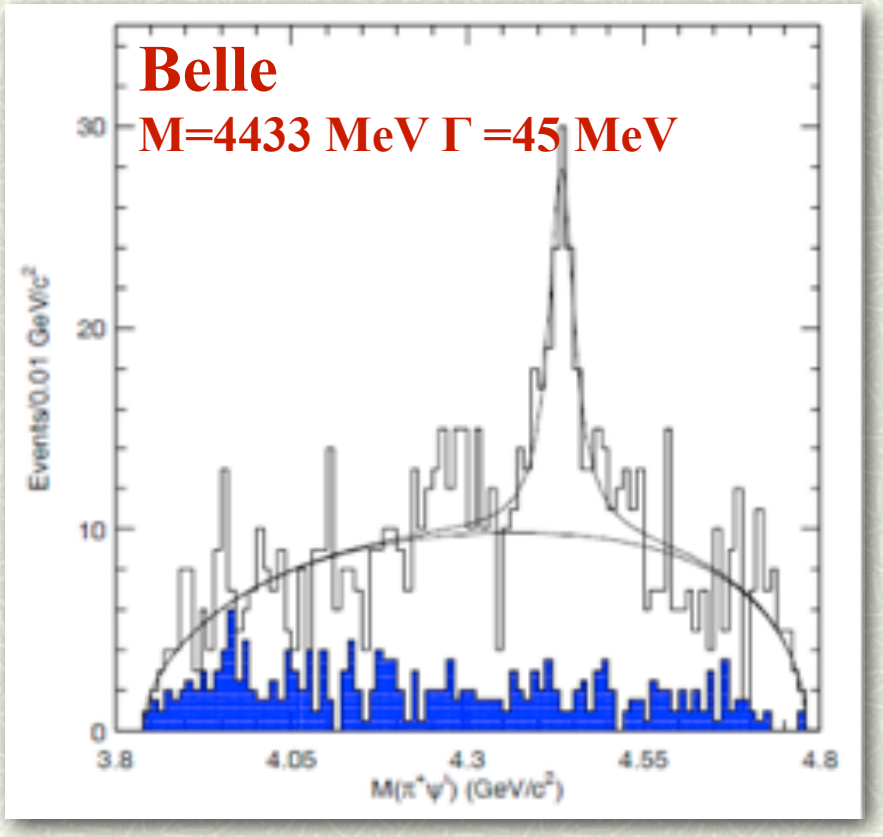


Newly discovered "X, Y, Z" states above the DD^bar threshold are found not to be within the quark model spectrum.

“Charged” Quarkonia?

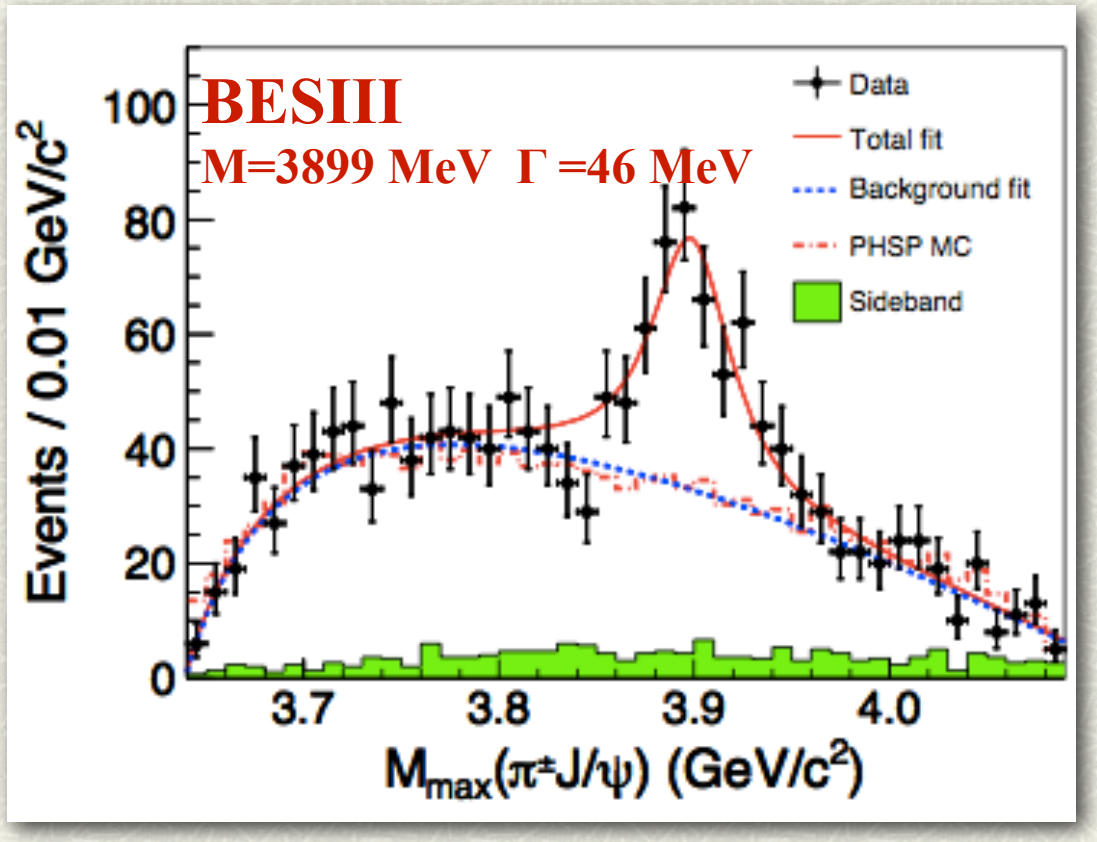
- Hidden charm states which decay into $cc^{bar}+\pi^{\pm}$.

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



PRL 100 (2008) 142001

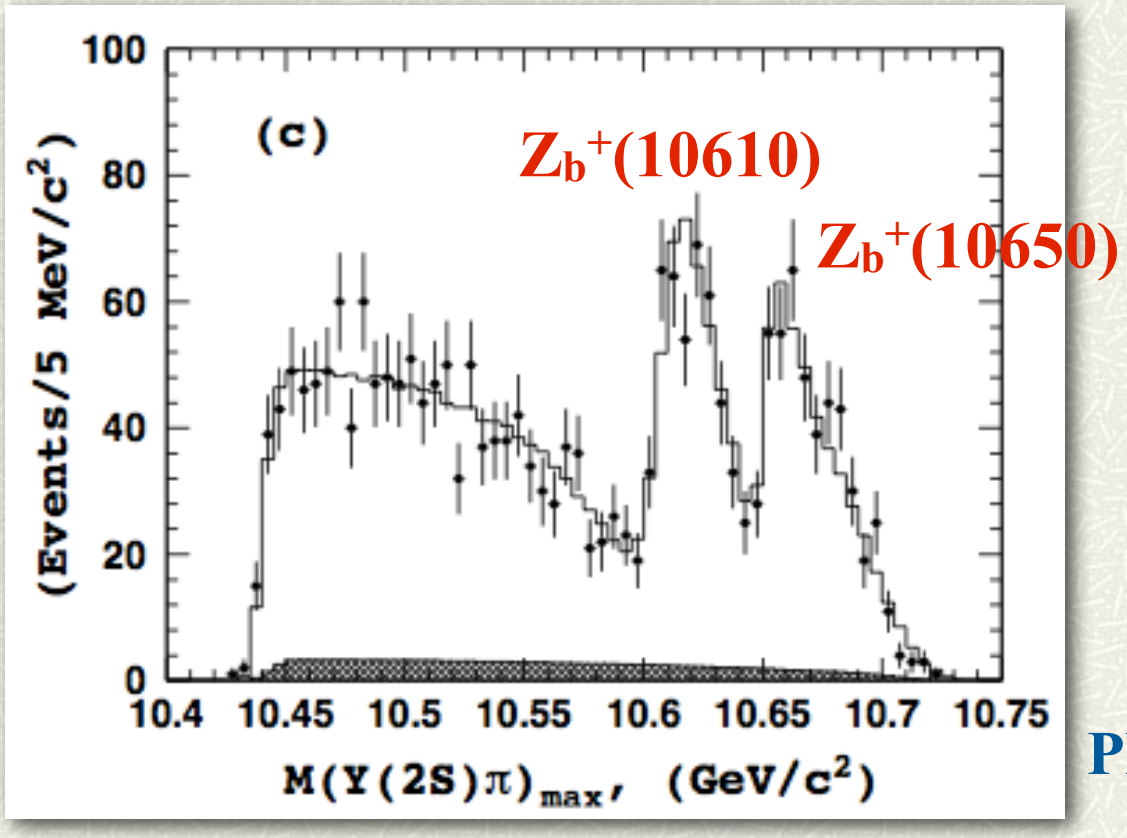
$Z_c^+(3900)$



PRL 110 (2013) 252001

"Charged" Quarkonia?

- $Z_b^{\pm}$ at Belle and LHCb (confirmed)



PRL 108 (2012) 122001

They require at least 4 quarks (~$QQ^{bar}+ud^{bar}$), i.e., tetra-quarks or hadron molecules.

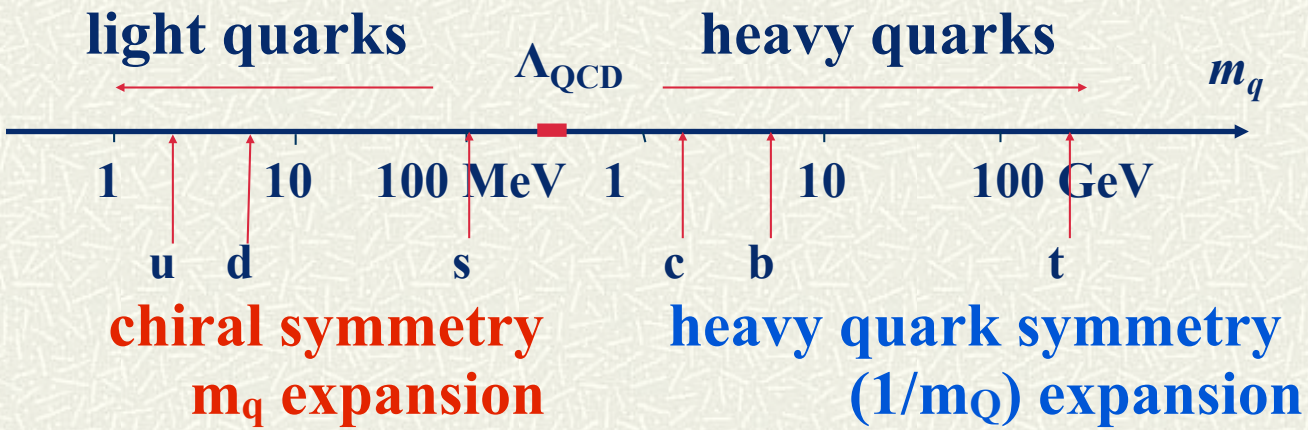
Why Heavy Quarks are interesting ?

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

  $m(\rho/\omega) : m(K^*) : m(D^*) : m(B^*)$

  $= 1 : 1.15 : 2.59 : 6.87$

- $\Lambda_{QCD}(\sim 300\ \text{MeV}) \ll m_c(\sim 1.3\ \text{GeV}) \ll m_b(\sim 4.2\ \text{GeV})$



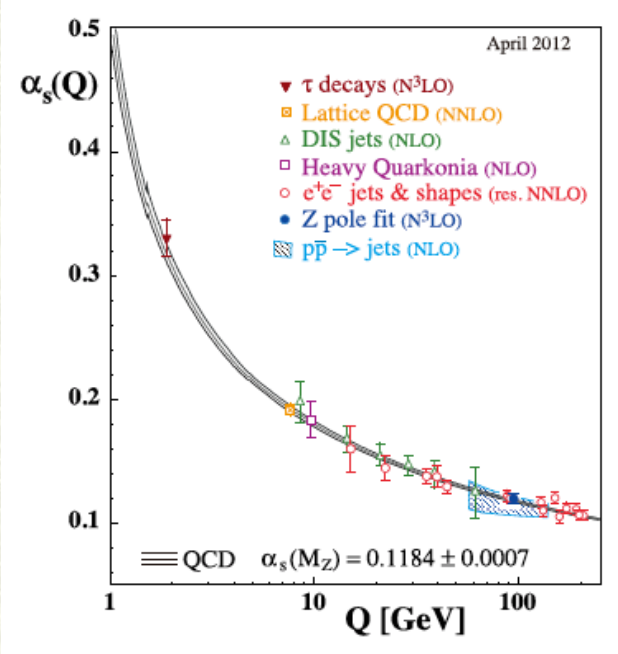
Why Heavy Quarks are interesting ?

- **Dynamics of Heavy Quarks**

  Asymptotic free

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

  → Heavy Quark Spin Symmetry



  Non-relativistic

  QQ^{bar} mixing is suppressed.

  Heavy quarks provide color sources for light quarks.

  Can focus on the dynamics of light quarks.

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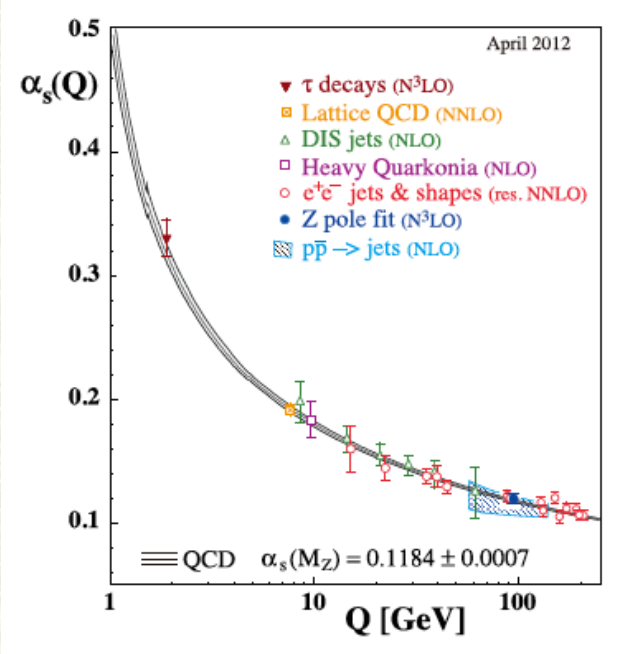

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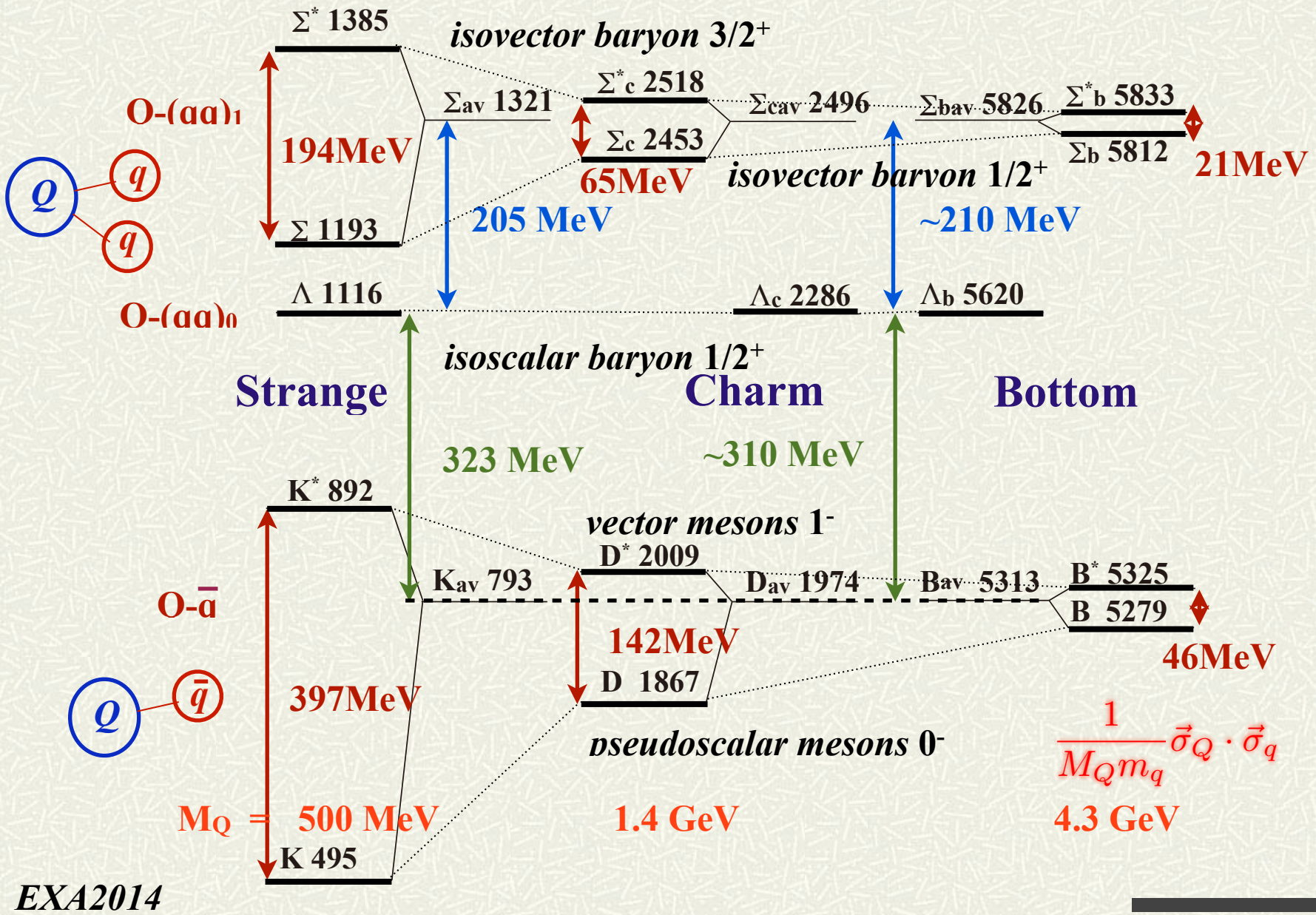
- **Are *Strange* quarks light or heavy? Or both?**

  $SU(3)_f$ symmetry vs HQ symmetry

From Strangeness to Heavy Quarks



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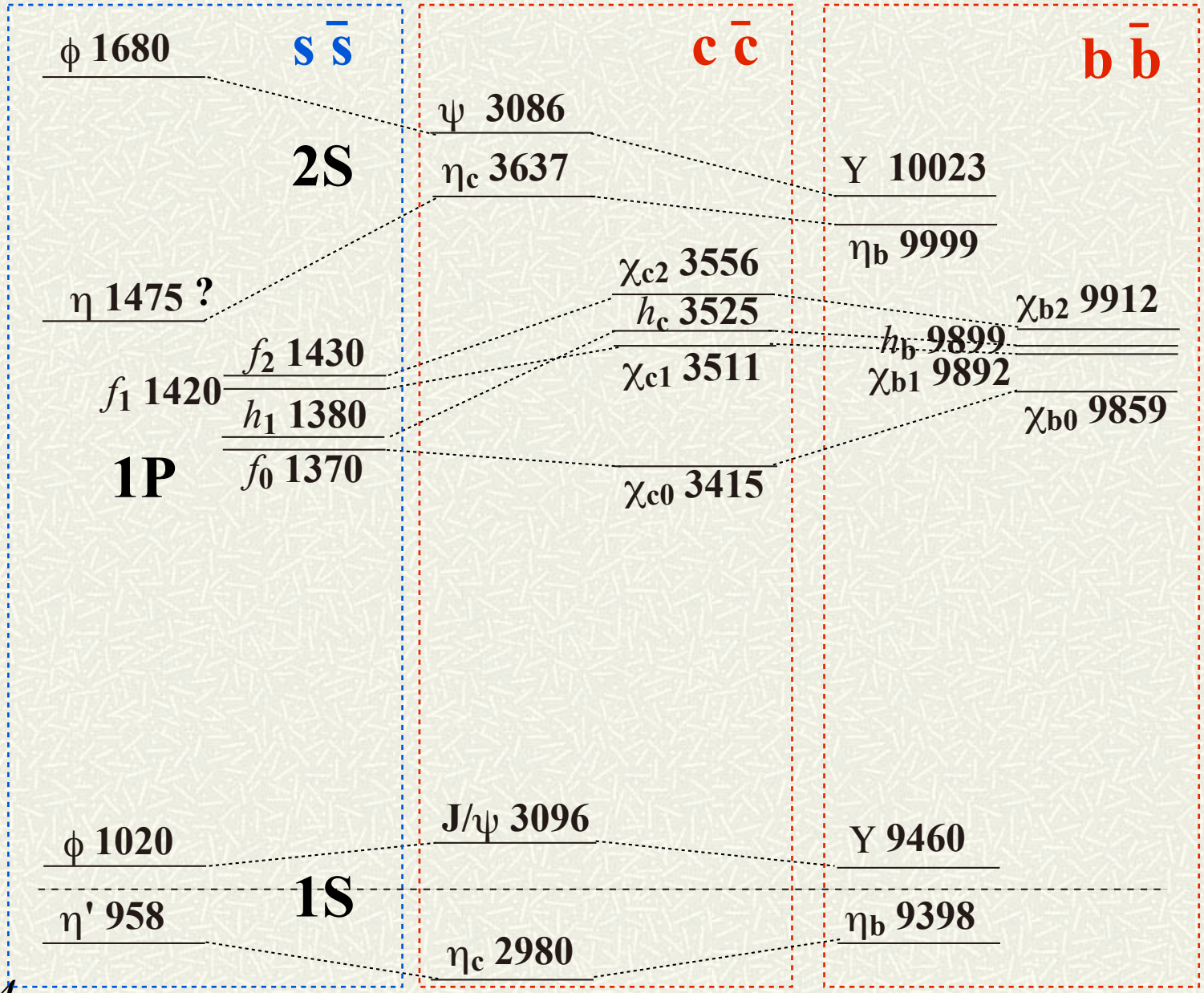
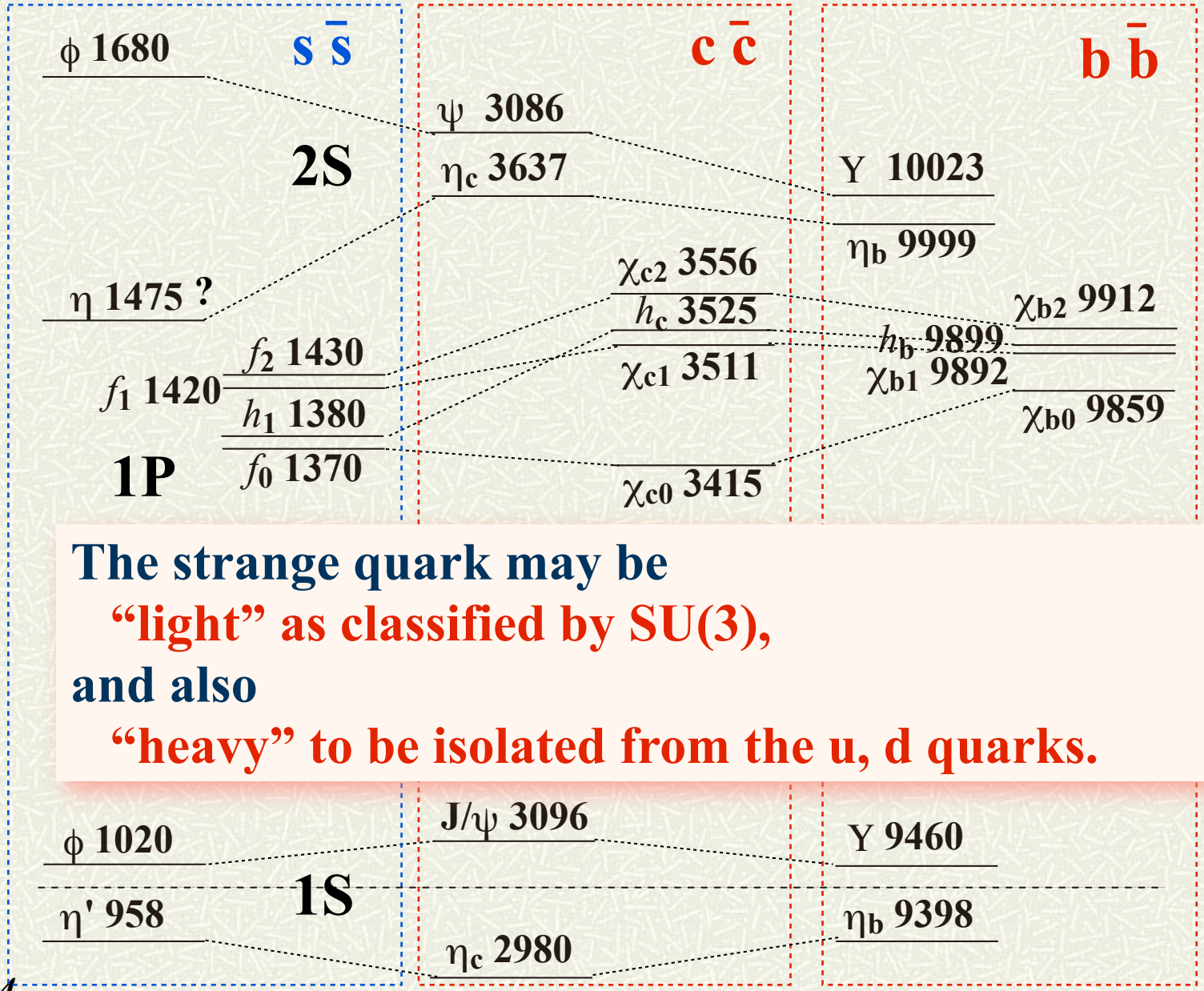
From Strangeness to Heavy Quarks



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

- **$\Lambda(1405)$ 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 $\Lambda\Lambda$-$N\Xi$-$\Sigma\Sigma$ 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.

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Hadron molecule

Multi-quark hadron

Exotic hadron

Multi-flavor hadron

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Exotic hadron

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Multi-flavor hadron

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

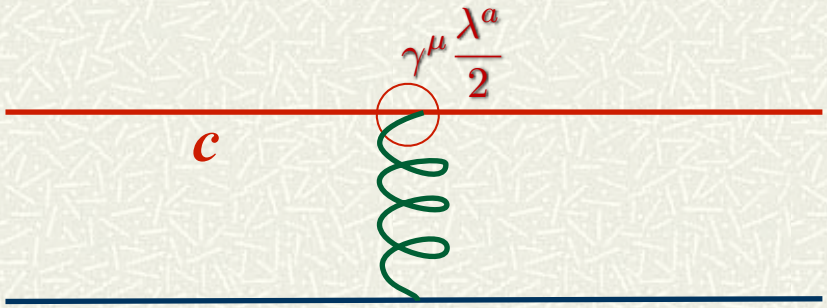
Key Dynamics

Heavy Quark Spin Symmetry

Diquark correlation

Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



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

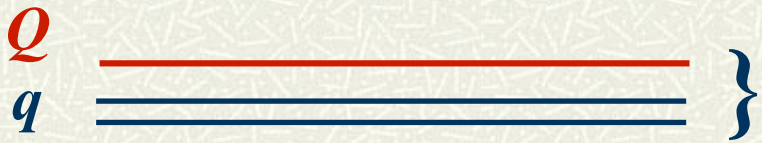
(Color Electric coupling) ≫ (Color Magnetic coupling)

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

⇨ **Heavy Quark Spin Symmetry**

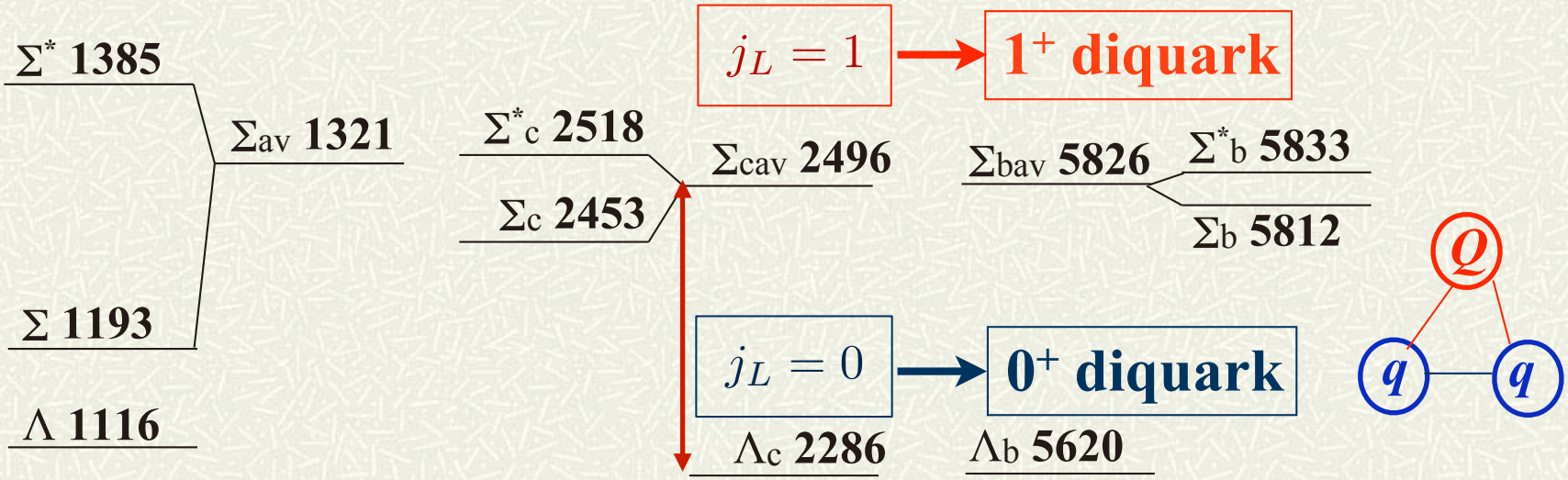
Heavy Quark Spin Symmetry

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.**



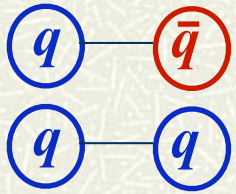
Diquark

- 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

- **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 is sensitive to 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

- **Scalar diquark**

  as a new building block of the Quark Model

  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)

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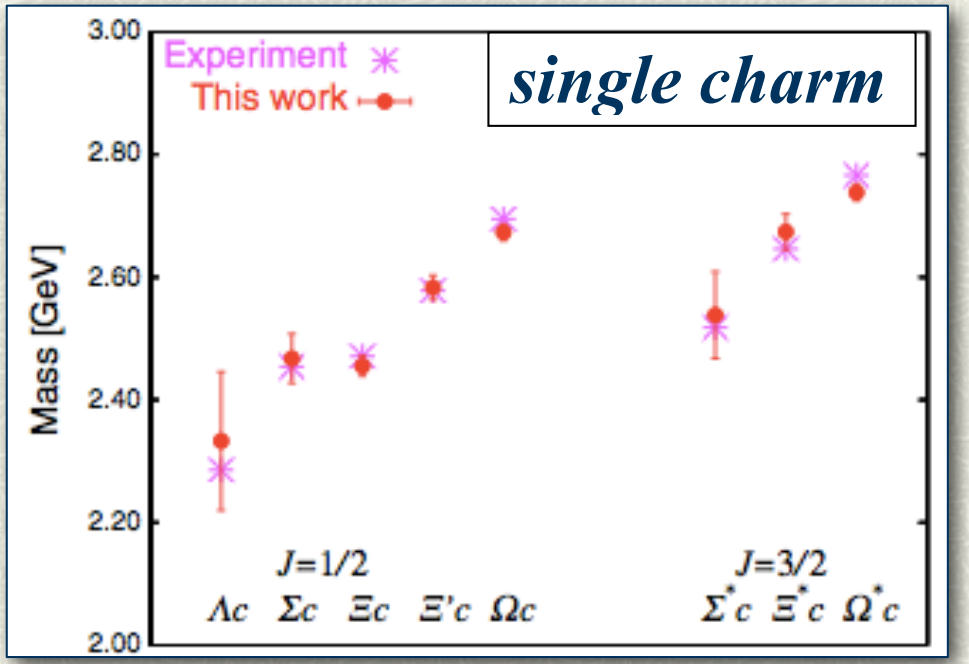
  S^{bar}: 2SC (U^{bar}: uSC D^{bar}: dSC)

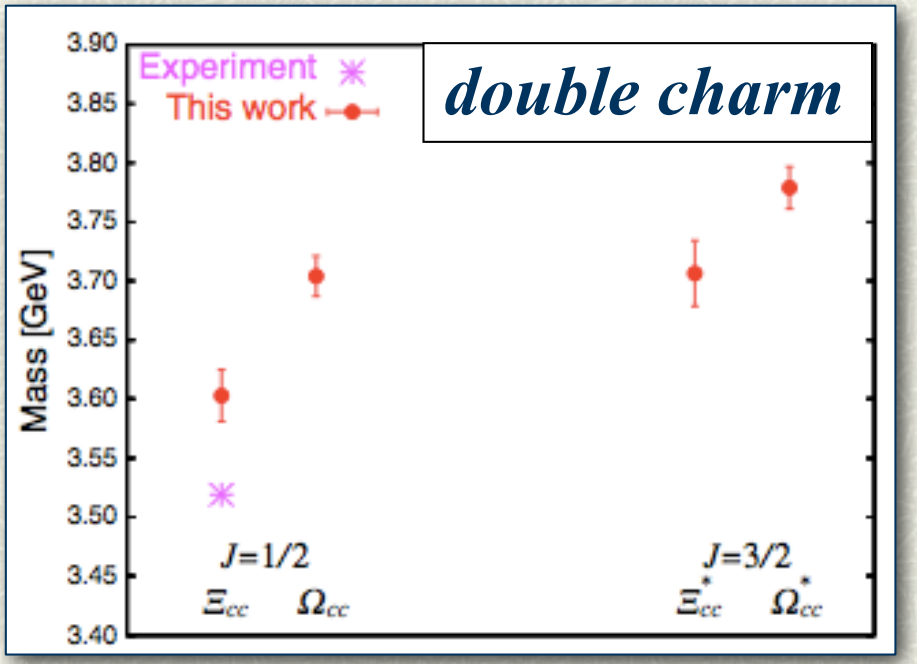
Exotic

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)





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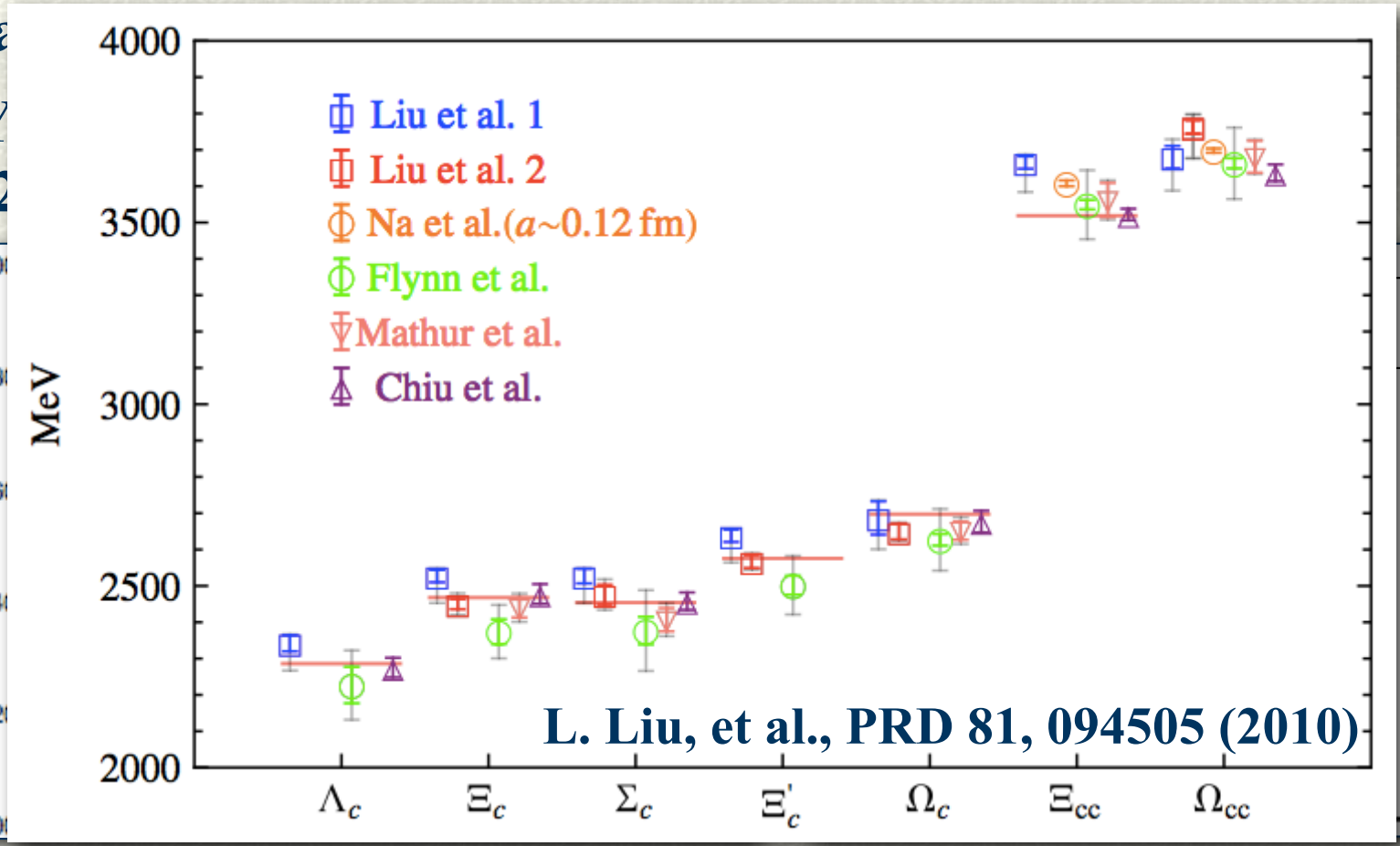
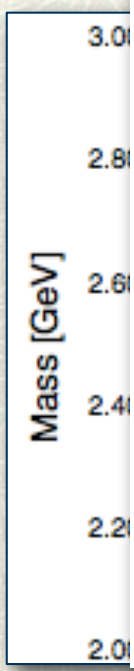
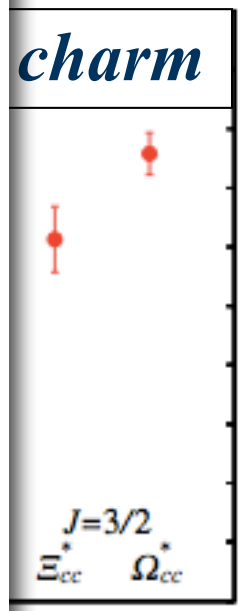
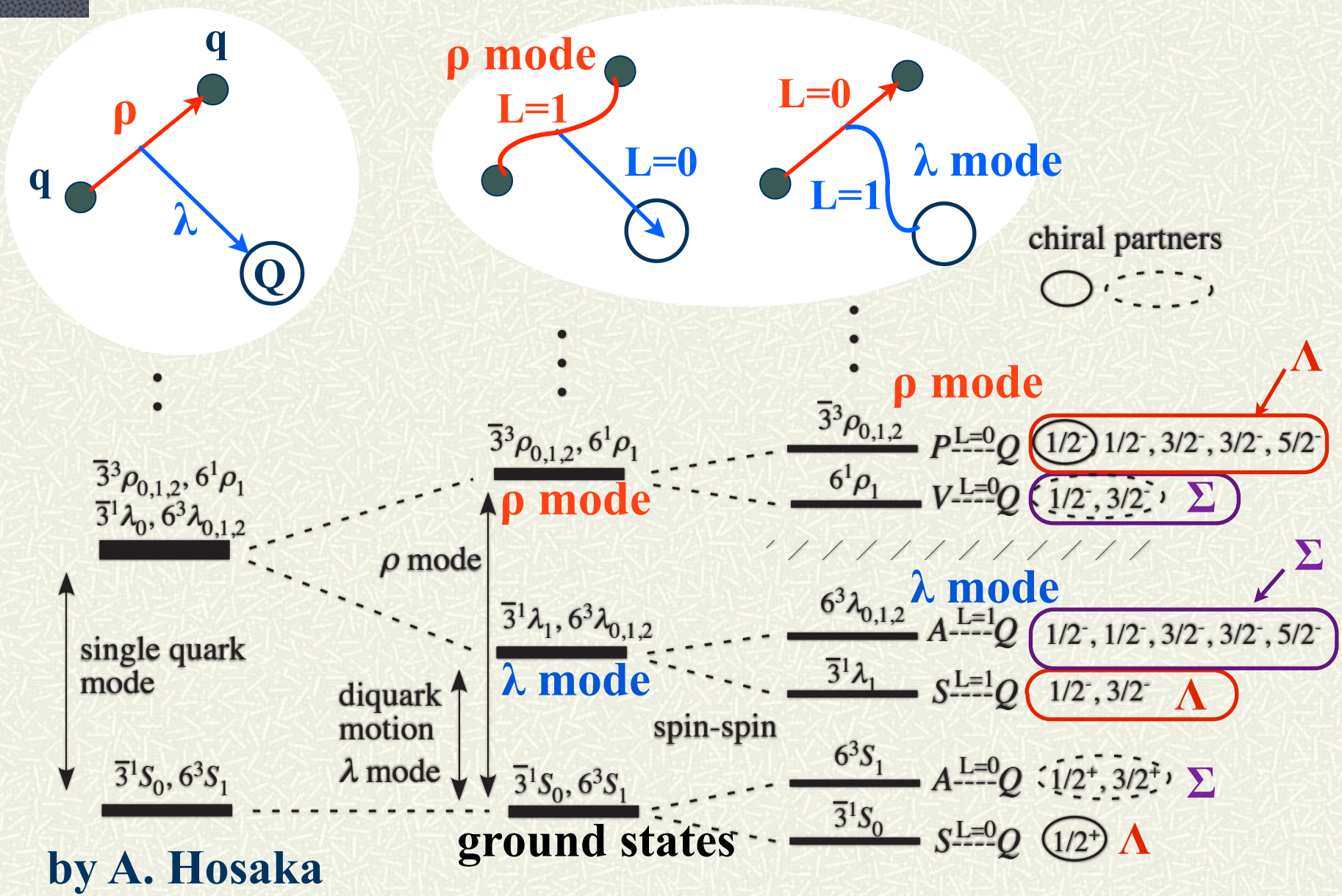
(2 (2013)







Excited States



by A. Hosaka

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Excited States

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

Excited States

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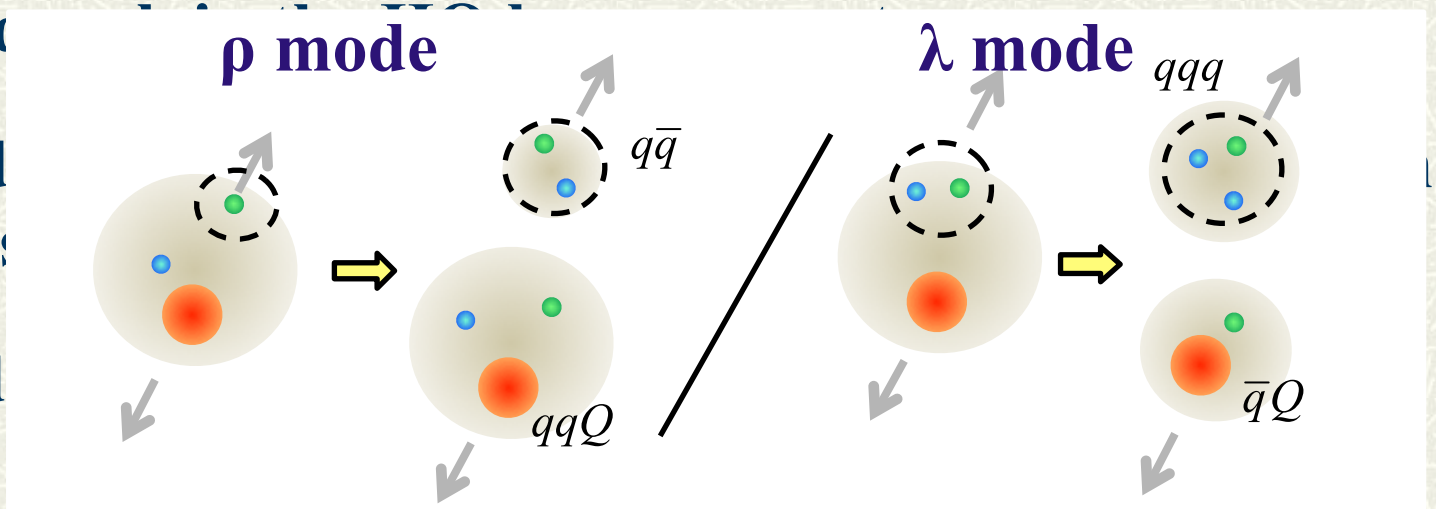
- The ρ mod a diquark s
- The λ mod diquarks.



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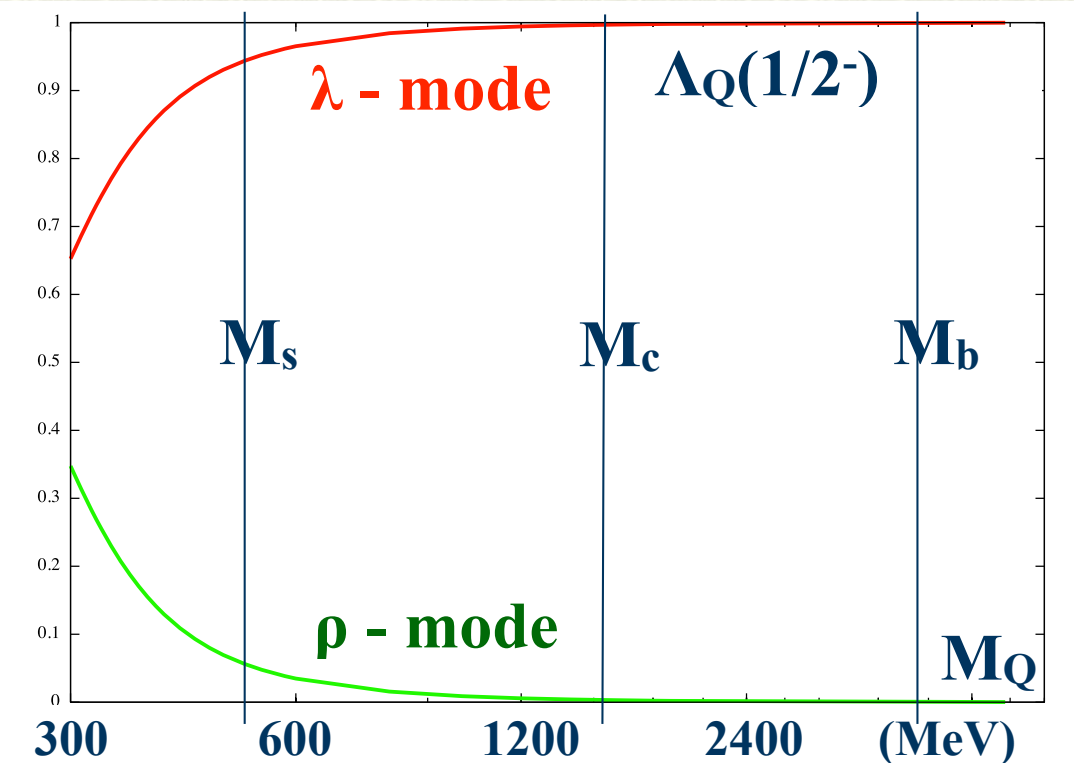
  ρ-mode → Heavy baryon (Qqq) + light mesons (qq^{bar})
  λ-mode → Heavy meson (Qq^{bar}) + light baryon (qqq)

Excited States

- 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.

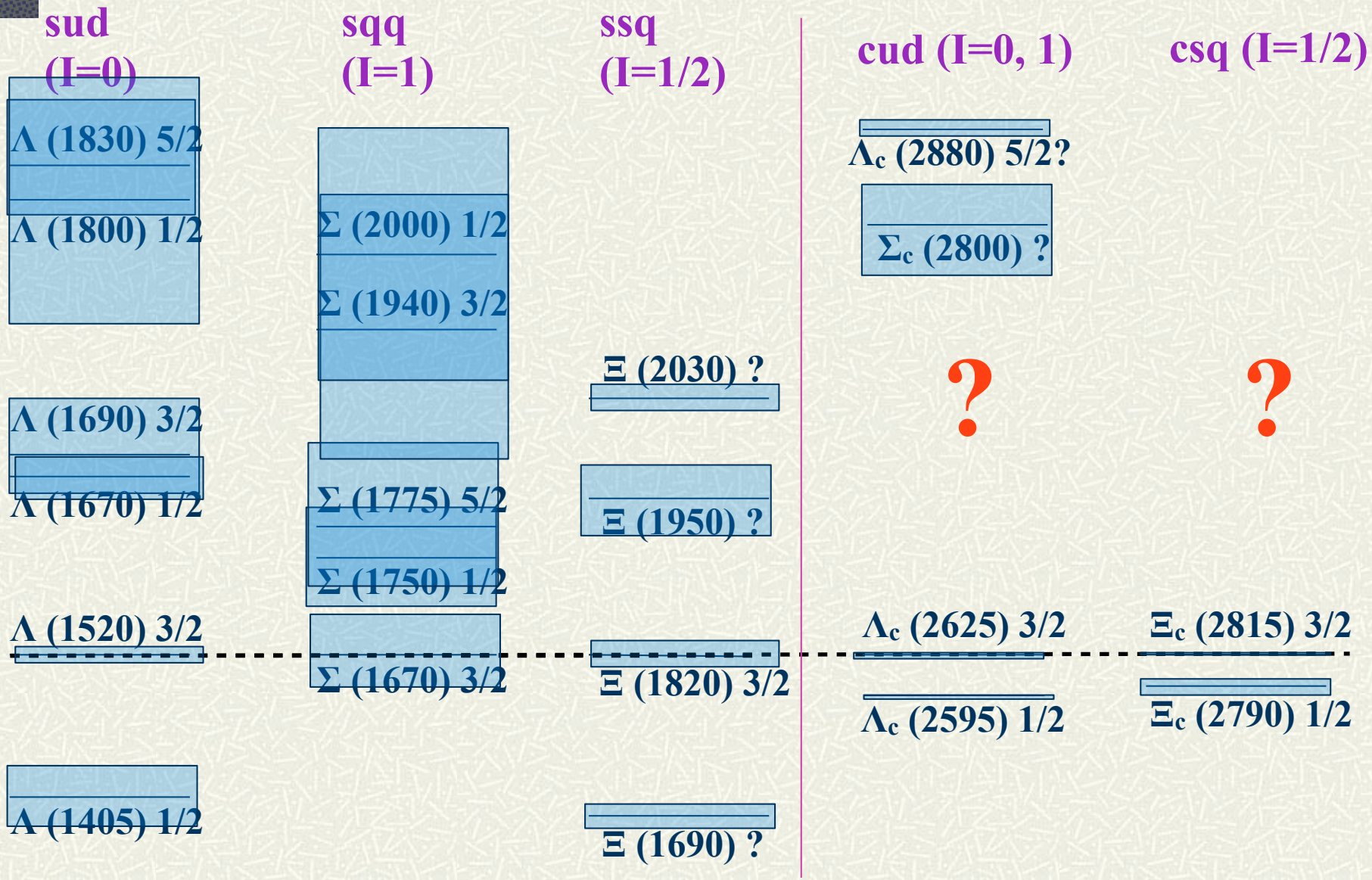
Negative-parity states

sud (I=0)	sqq (I=1)	ssq (I=1/2)
Λ (1830) 5/2	$(S=1/2)_\rho$	
Λ (1800) 1/2	Σ (2000) 1/2	
$(S=3/2)_\rho$	Σ (1940) 3/2	
		Ξ (2030) ?
Λ (1690) 3/2	$(S=3/2)_\lambda$	
Λ (1670) 1/2	Σ (1775) 5/2	Ξ (1950) ?
$(S=1/2)_\rho$	Σ (1750) 1/2	
Λ (1520) 3/2		
	Σ (1670) 3/2	Ξ (1820) 3/2
$(S=1/2)_\lambda$	$(S=1/2)_\lambda$	
Λ (1405) 1/2		Ξ (1690) ?

Negative-parity states

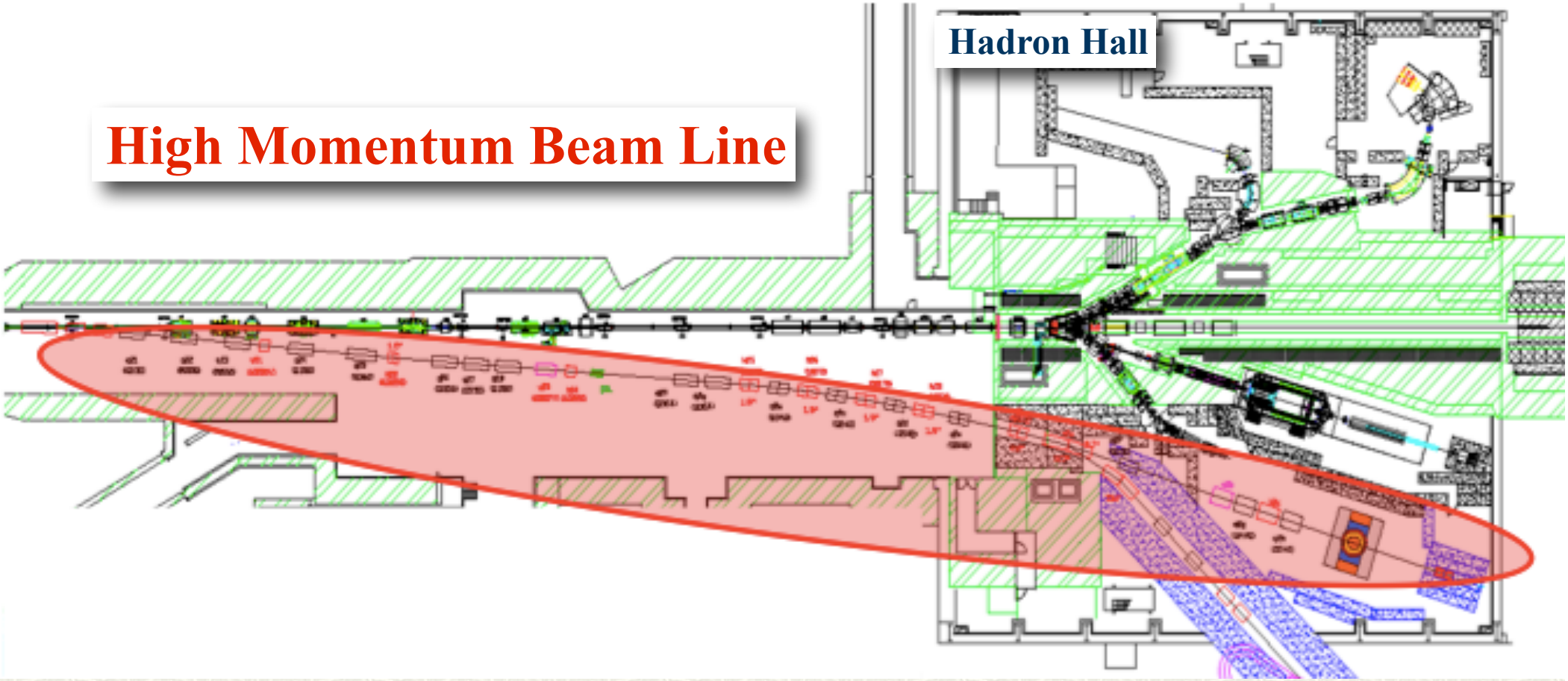
sud (I=0)	sqq (I=1)	ssq (I=1/2)	cud (I=0, 1)	csq (I=1/2)
Λ (1830) 5/2	$(S=1/2)_\rho$		Λ_c (2880) 5/2?	
Λ (1800) 1/2	Σ (2000) 1/2		Σ_c (2800) ?	
$(S=3/2)_\rho$	Σ (1940) 3/2	Ξ (2030) ?	?	?
Λ (1690) 3/2	$(S=3/2)_\lambda$			
Λ (1670) 1/2	Σ (1775) 5/2	Ξ (1950) ?		
$(S=1/2)_\rho$	Σ (1750) 1/2			
Λ (1520) 3/2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

Negative-parity states



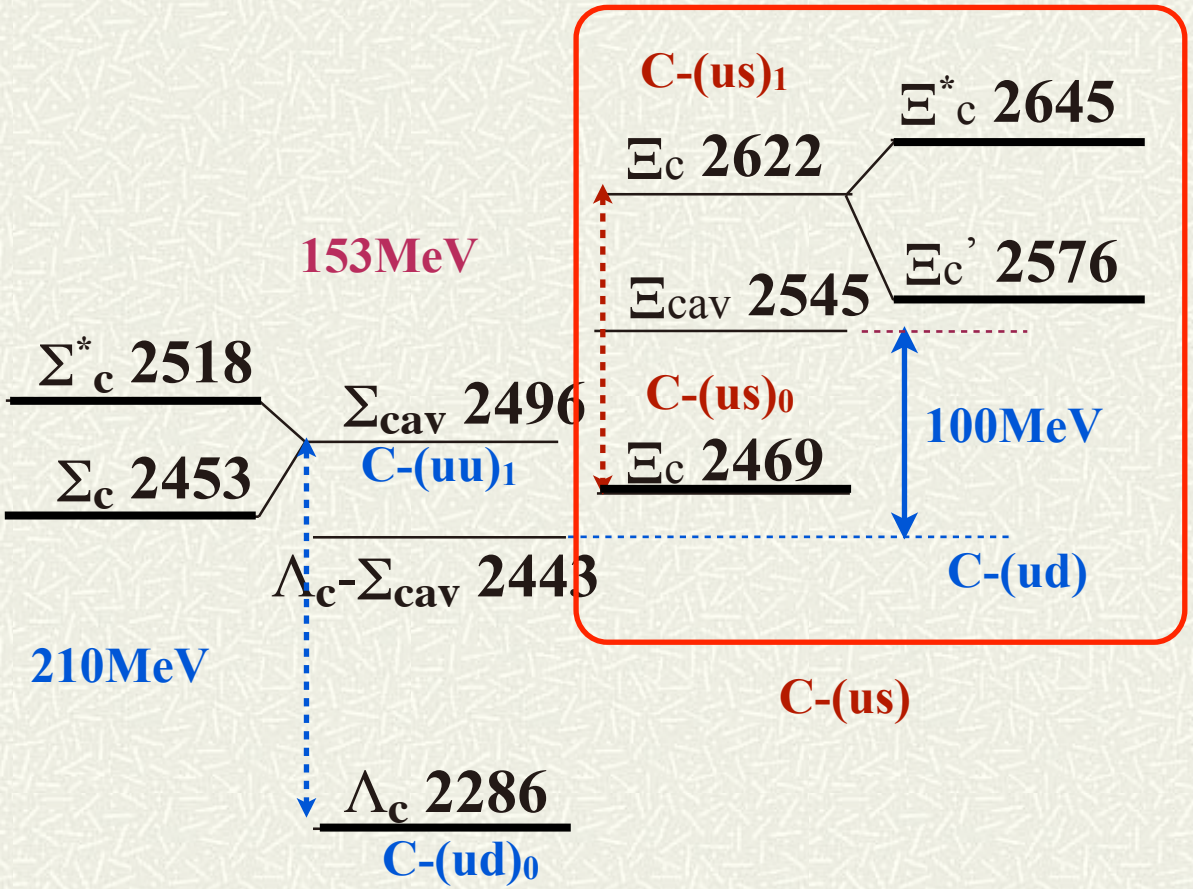
Hadron Hall, J-PARC, @Tokai

Primary Proton Beam (30GeV), $10^{10\text{-}12}$ per spill
High Momentum un-separated secondary beam (≤20GeV/*c*), 10^{7} per spill
Primary Proton Beam (8GeV) for COMET



Ξ_c = csu, csd, SU(3) diquarks

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



Exotic Charmed States

Charm in Nuclei

- **Possible charmed 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**

    Charmed hypernuclei: $\Lambda_c pn$ bound state

    Yan-rui Liu, M.O., "$\Lambda_c N$ bound states revisited", PR D85 (2012) 014015

    W. Meguro, Y.R. 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:**

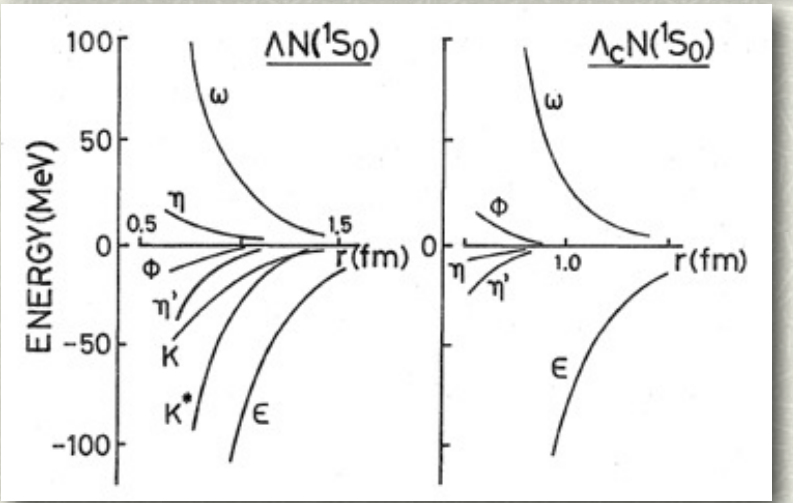
    bound $(J/\psi, \eta_c)$ - ^{4}He nuclei.

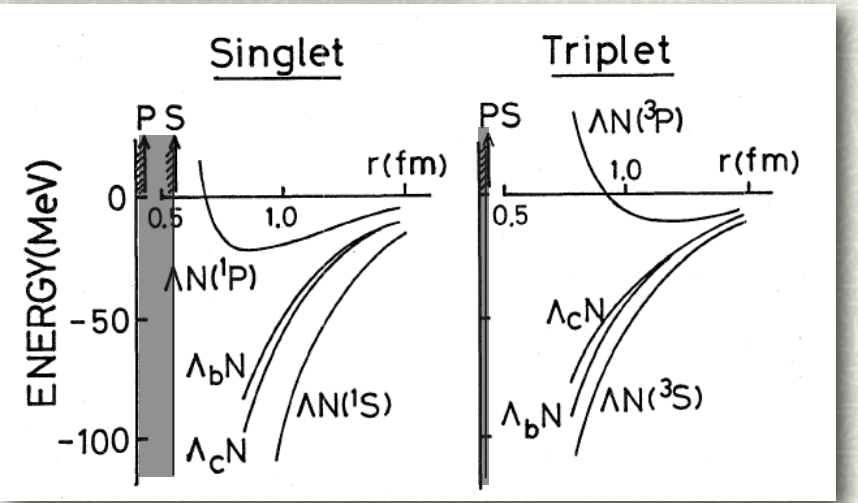
    A. Yokota, E. Hiyama, M.O., "Possible existence of charmonium–nucleus bound states", PTEP (2013) 113D01.

Y_c-N charmed deuteron

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

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
  $\Lambda_c N$-$\Sigma_c N$-$\Sigma^*_c N$ (0^+: $^1S_0$-$^5D_0$)
  $\Lambda_c N$-$\Sigma_c N$-$\Sigma^*_c N$ (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 Σ^*_cN (S=1, 2) states, whose thresholds are degenerate in the large m_Q limit.

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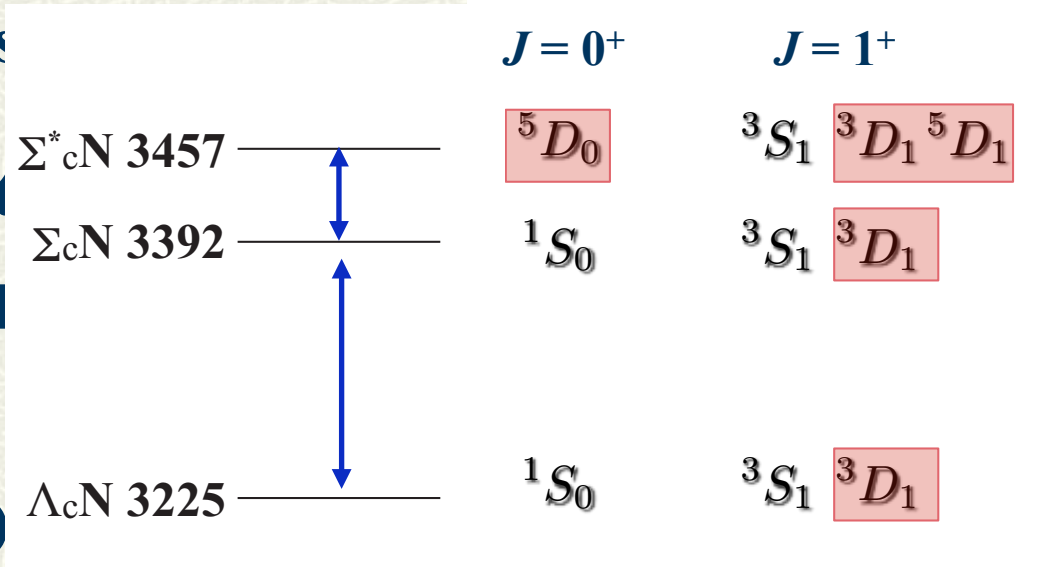

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Y_c-N charmed deuteron

- 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

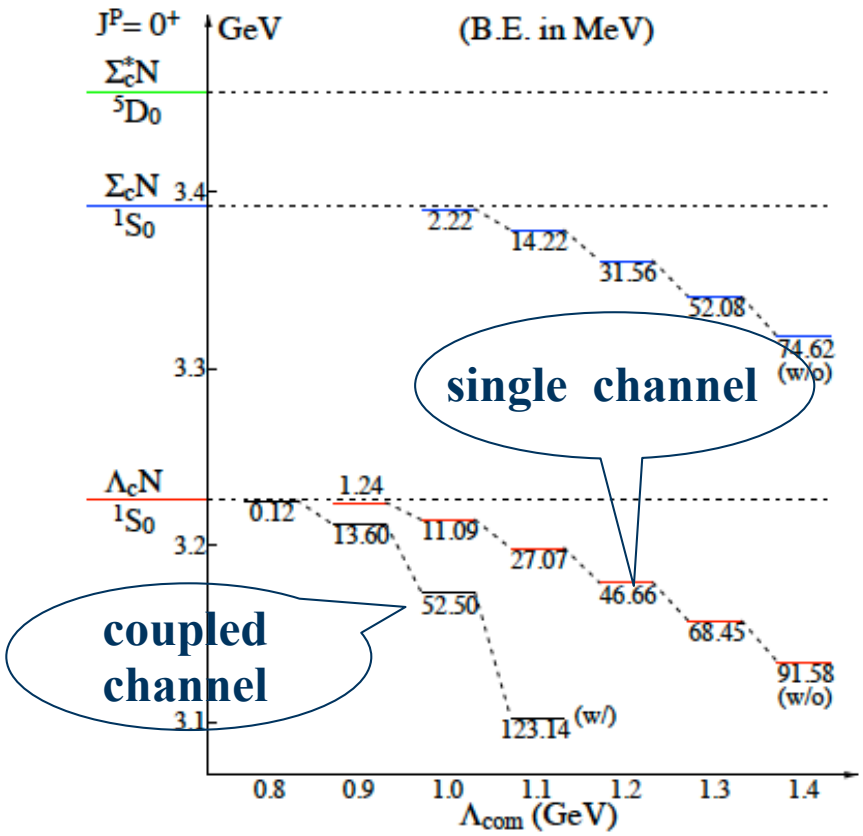
$$F(q) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$$

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

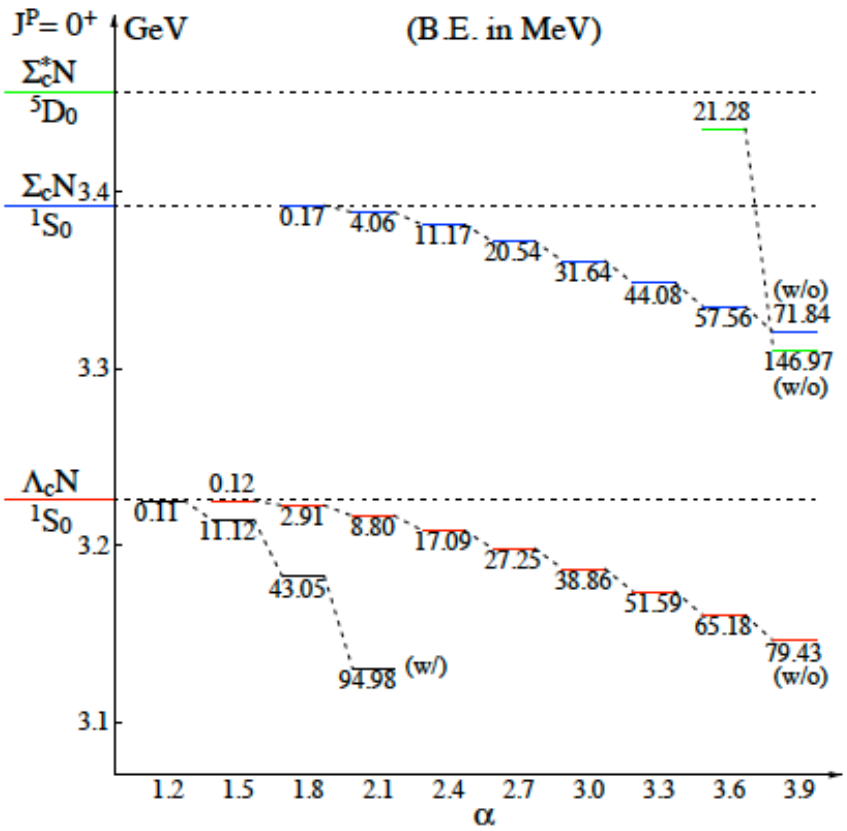
$\Lambda_c N$: 0^+ $\quad \Lambda_c N(^1S_0) - \Sigma_c N(^1S_0) - \Sigma_c^* N(^5D_0)$

OMEP model ($\Lambda_{\rm com}$ & α)

Yan-Rui Liu, M.O., Phys. Rev. D85 (2012) 014015



Λ independent of meson mass



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

Y_c-N charmed deuteron

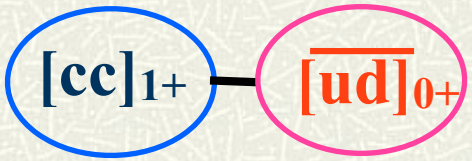
- **Further studies are going on to include the short range part of the potential in a dynamical model.**
  The color-magnetic interaction in the quark cluster model gives
  $$V(\Lambda_c\text{-}N) \sim 300 \text{ MeV}, \quad V(\Sigma_c\text{-}N) \sim 100 \text{ MeV at } R=0$$
  compared with $V(N\text{-}N;\ ^1S_0) \sim 450$ **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, and there will be some Λ_c-Nucleus bound states, such as Λ_c-p-n (charmed triton).**
  S. Maeda, Y.R. Liu, E. Hiyama, M.O.

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).

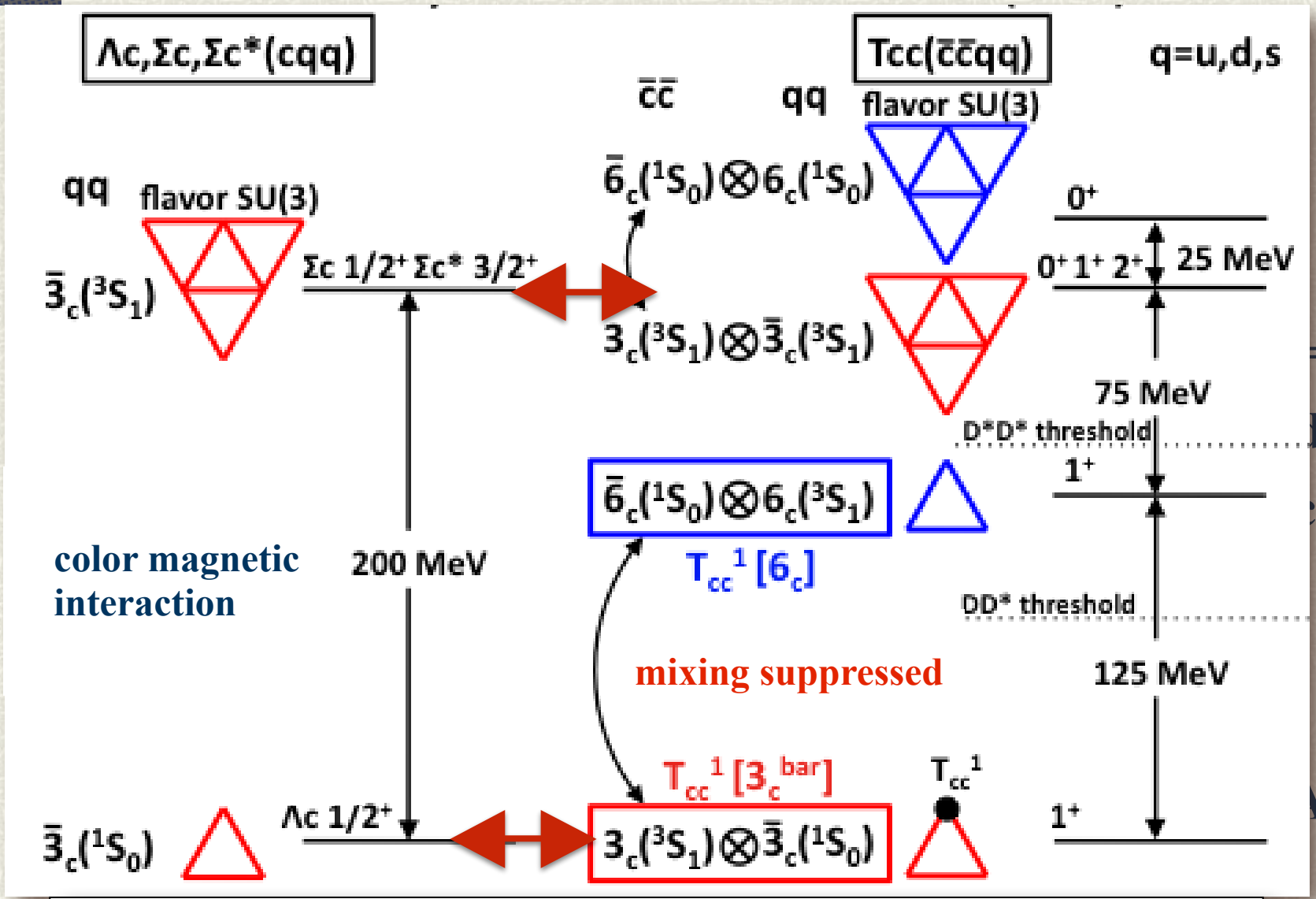
- If the scalar diquark is light enough to make T_{cc} bound below DD* threshold, T_{cc} will be a stable tetra-quark resonance.

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



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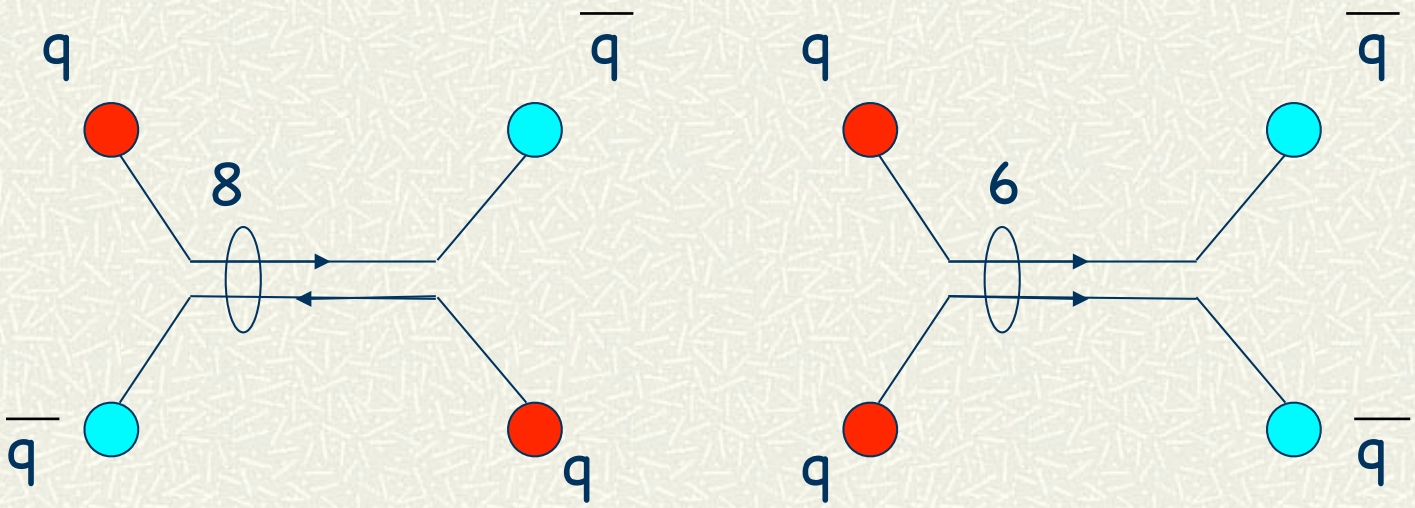
ArXiv

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

Exotic Hadrons

Exotic Hadrons are "Colorful" ! (Lipkin@YKIS06)

$(qq)_{\bar{8}}$ or $(qq)_6$ are allowed only in the multi-quarks.

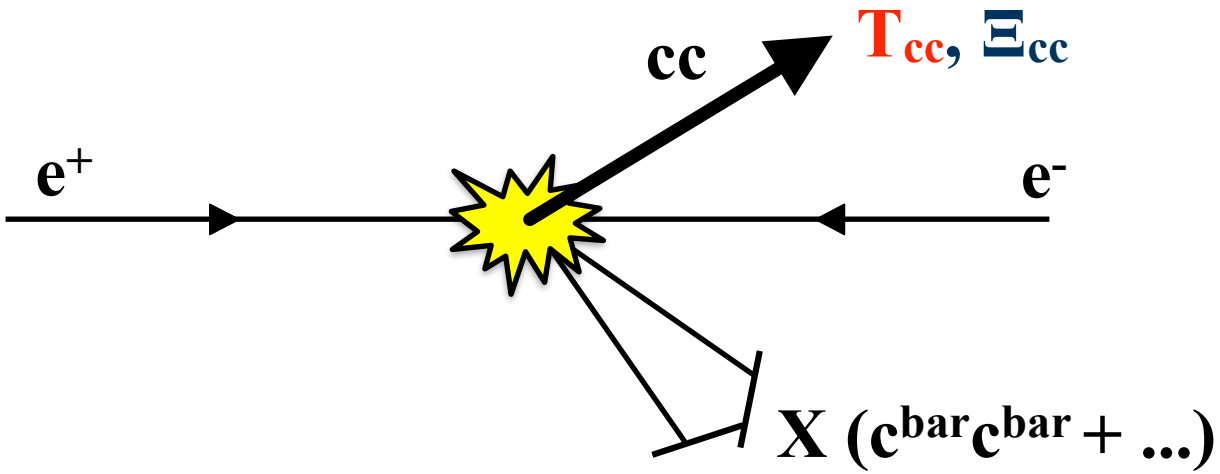


Production in $e^+ e^-$ collisions

- 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)

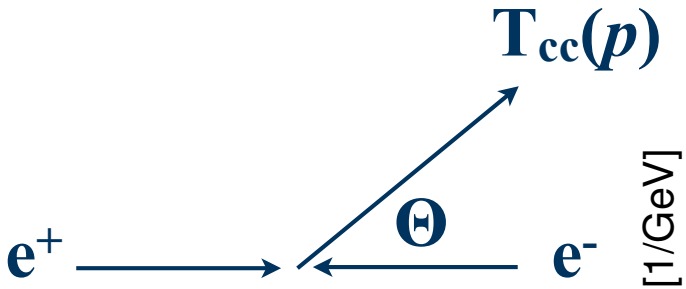
- Recombination of the charm quarks and antiquarks will produce double charmed mesons (T_{cc}'s) and baryons (Ξ_{cc}).



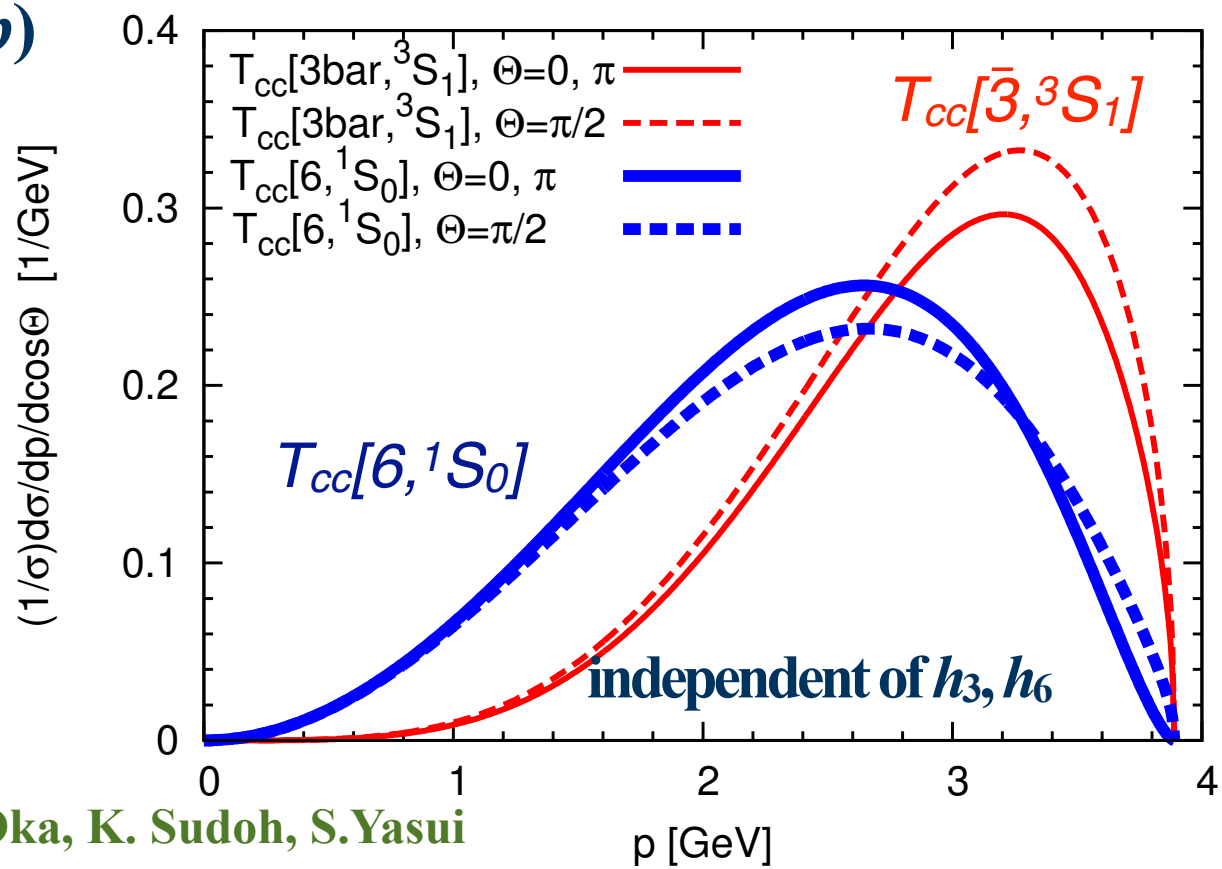
- "Production of doubly charmed tetraquarks with exotic color configurations in electron-positron collisions", T. Hyodo, Y.-R. Liu, M. O., K. Sudoh, S. Yasui, PL B721 (2013) 56-60.

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.**

Conclusion

- Spectroscopy of HQ hadrons open a new era of the HADRON SPECTROSCOPY. Experimental data are precious.
- QCD is the first principle. Yet, we need to choose *proper degrees of freedom* to characterize hadron structures.
- Diquark is a new building block. The charmed baryons are useful for diquark spectroscopy.
- Various bound systems with charm hadrons may be possible. J/ψ-nuclei, D-nuclei and charmed hypernuclei.
- New accelerators for heavy hadron spectroscopy are coming *ex*, charmed mesons, exotics, baryons, charmed nuclei.

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Thank you very much!