Quark Structure of Hadrons

Makoto Oka

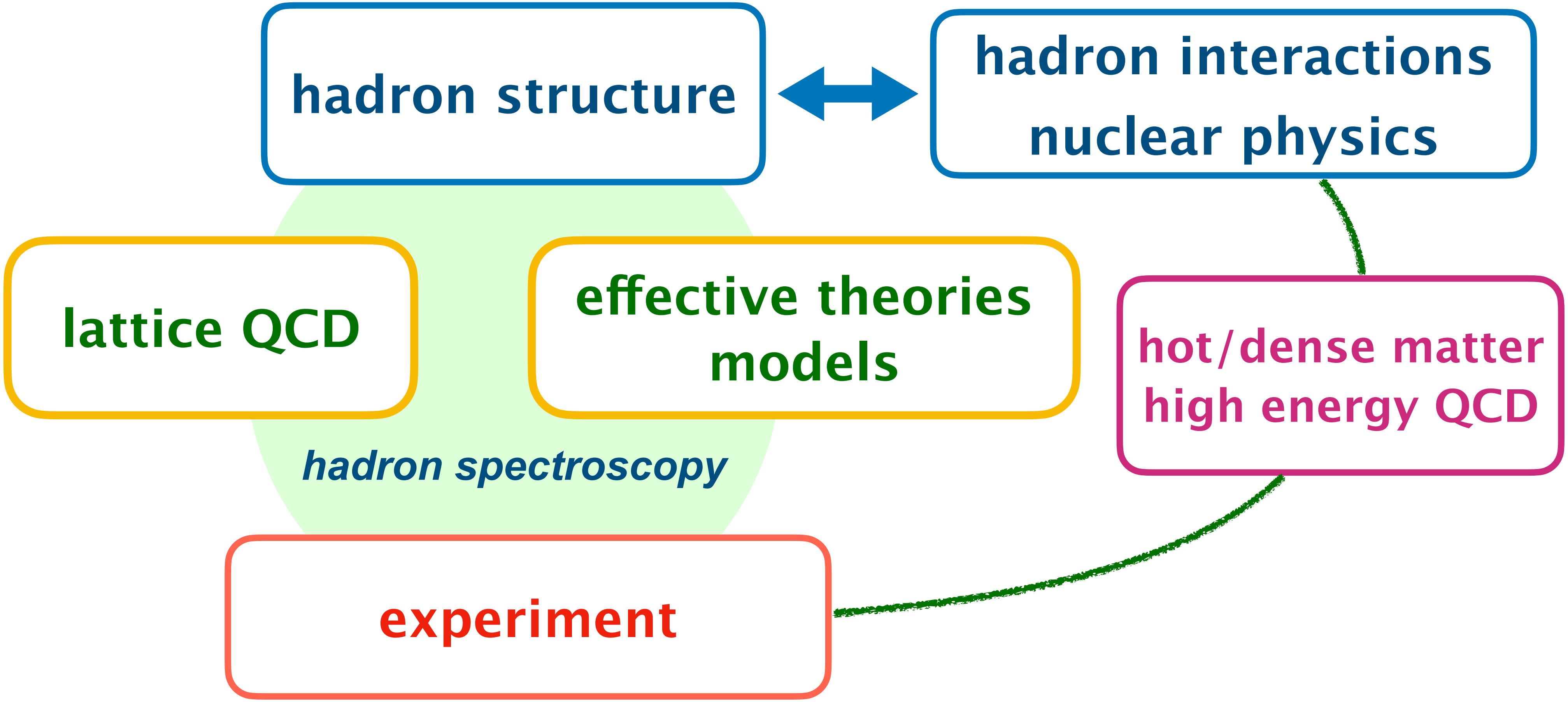
RIKEN Nishina Center for Accelerator Based Science, RIKEN

and

Advanced Science Research Center, JAEA

International Workshop on Quark Structure of Hadrons
August 09, 2024 @ RIKEN

to explore recent progress in understanding “the quark structure of hadrons”, addressing topics such as hadron spectroscopy, reaction, structure, interaction, and their modification in the nuclear medium



hadron structure

hadron interactions
nuclear physics

lattice QCD

effective theories
models

hot/dense matter
high energy QCD

hadron spectroscopy

experiment

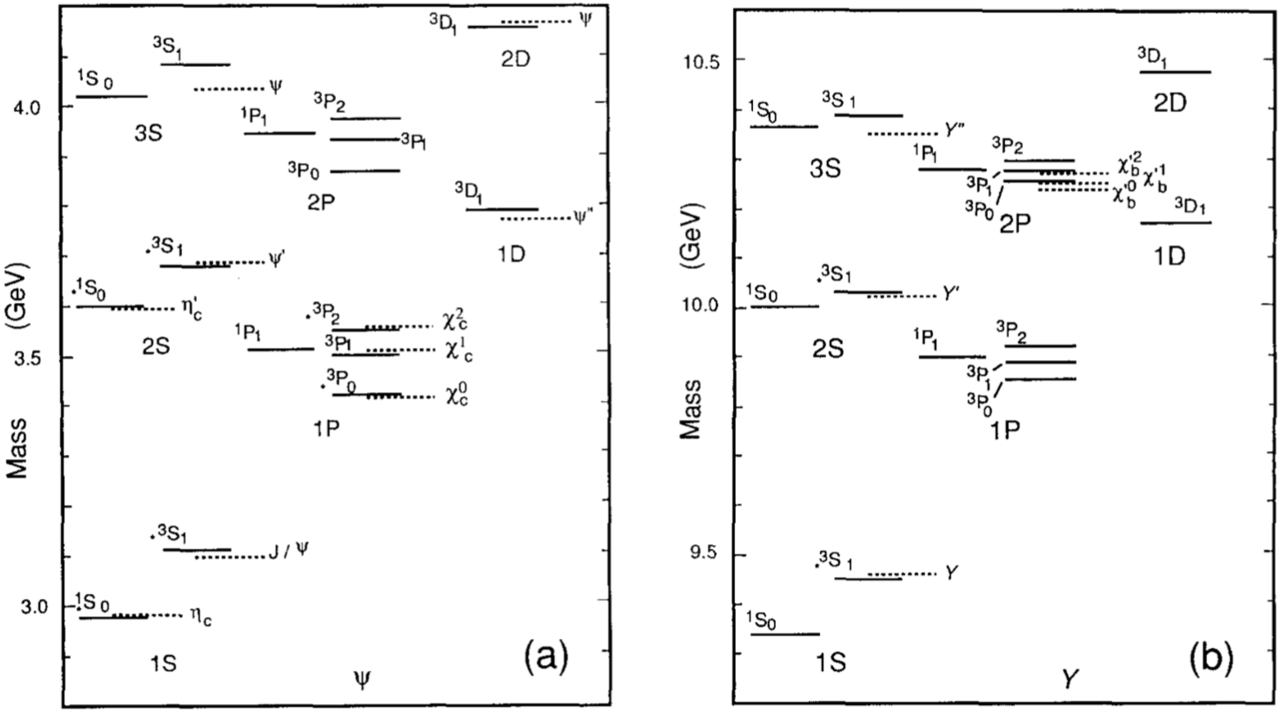
Quark Model viewpoints of Hadron Spectrum

Quark model

- **After 70 years since it was born, the Quark Model gives reliable guidelines to classify and interpret the hadron spectrum.**
- **The quarkonium ($c\bar{c}$, $b\bar{b}$) spectrum is *"hydrogen atom" in QCD.* A Linear + Coulomb potential fits 1S, 1P, 2S, . . $c\bar{c}$ and $b\bar{b}$ states.**

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

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

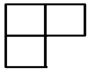


**S.N. Mukherjee et al.
Phys. Rep. 231 (1993)**

Ground-State Hadrons

- **"Ground state" = no orbital excitation ($0\hbar\omega$, L=0)**
- **Quark model predicts 30 GS mesons and 75 GS baryons.**

30 Mesons PS+V	q=(u,d,s)	c	b
$\bar{q}=(\bar{u},\bar{d},\bar{s})$	9+9	3+3	3+3
$\bar{c}$	3+3	1+1	1+1 $\bar{B}_c^*$
$\bar{b}$	3+3	1+1 B_c^*	1+1

75 Baryons **flavor spin**	qqq	Qqq	QQq	QQQ
 S=3/2	10	12 Ω_b^*	9 Ξ_{cc}	4
 S=1/2	8	18	12	2

not yet observed

- **29 mesons and 48 baryons were discovered.**
  The observed masses and quantum numbers are all consistent with the quark model predictions and lattice QCD calculations.

Quark Model Hamiltonian

- **Non-relativistic (NR) quarks with constituent masses**
  Linear + Color Coulomb + Color Magnetic interactions
- **"AL1" potential by Silvestre-Brac, Few-Body Syst. 20, 1 (1996)**

$$H = \sum_i \left(m_i + \frac{\boldsymbol{p}_i^2}{2m_i} \right) - K_G + \sum_{i<j} \frac{(\lambda_i \cdot \lambda_j)}{4} V_{ij}$$

$$V_{ij} = -\frac{3}{4} \left(\sigma r_{ij} - \frac{\alpha}{r_{ij}} + \frac{2\pi\alpha'}{3m_i m_j} f(r_{ij}, r_{0ij}) (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) - \Lambda \right)$$

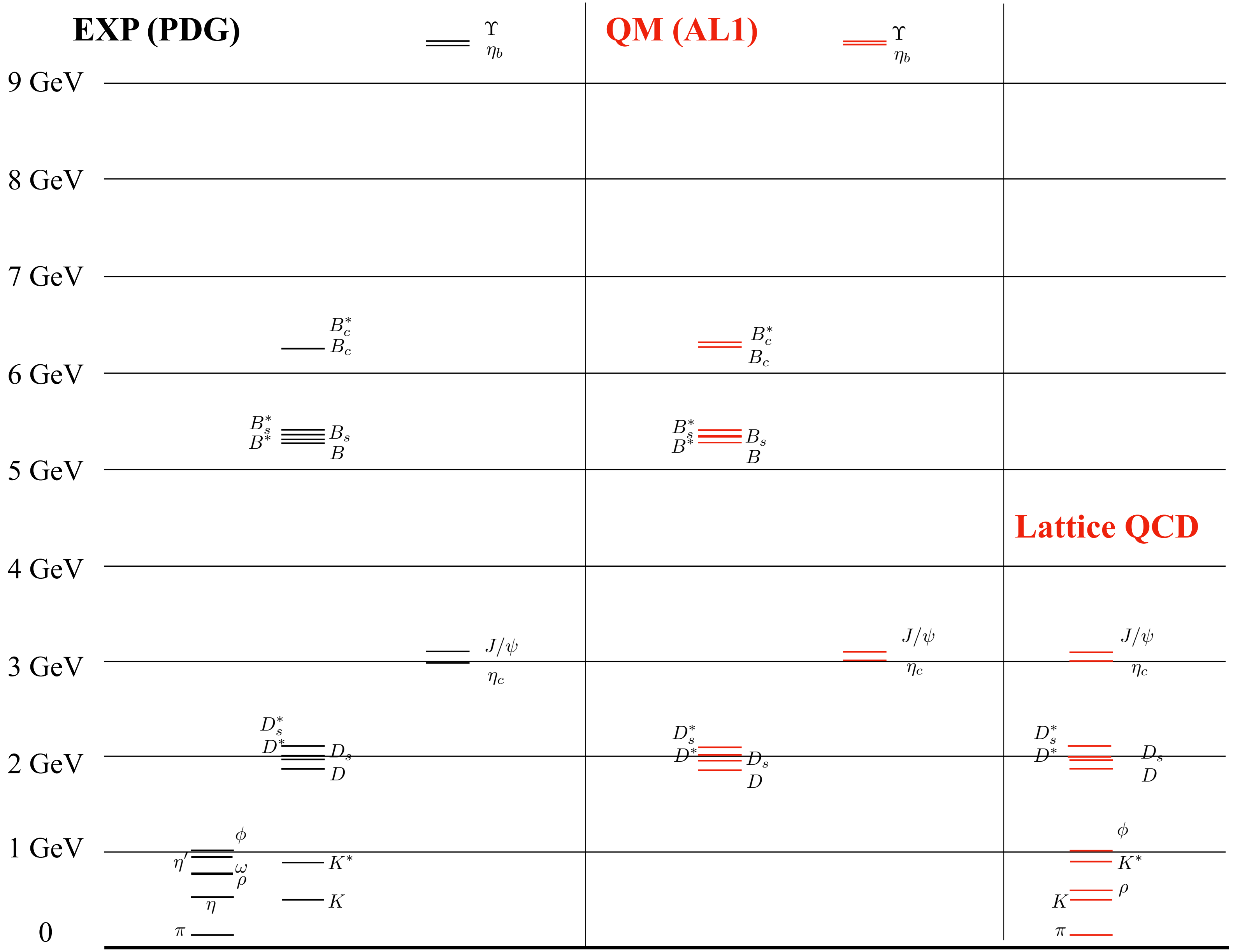
$$f(r, r_0) = \frac{\exp(-r^2/r_0^2)}{\pi^{3/2} r_0^3} \qquad r_{0ij} = A \left(\frac{2m_i m_j}{m_i + m_j} \right)^{-B}$$

$$m_{u/d} = 0.315\text{GeV}, m_s = 0.577\text{GeV}, m_c = 1.836\text{GeV}, m_b = 5.227\text{GeV}$$

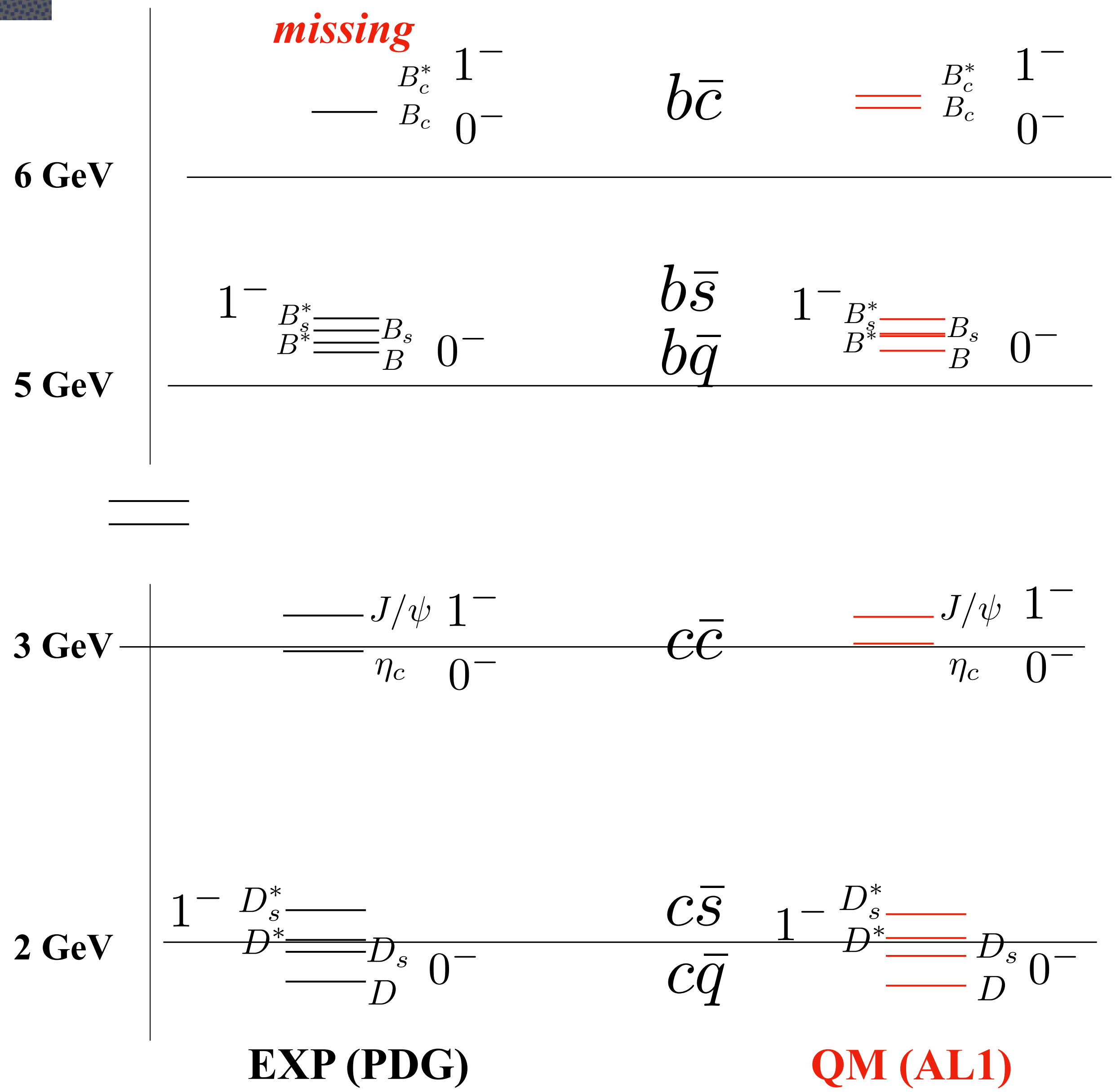
$$\sigma = 0.1653\text{GeV}^2, \alpha = 0.5069, \alpha' = 1.8609$$

$$B = 0.2204\text{GeV}, A = 1.6553\text{GeV}^{B-1}, \Lambda = 0.8321\text{GeV}$$

GS Meson Spectrum



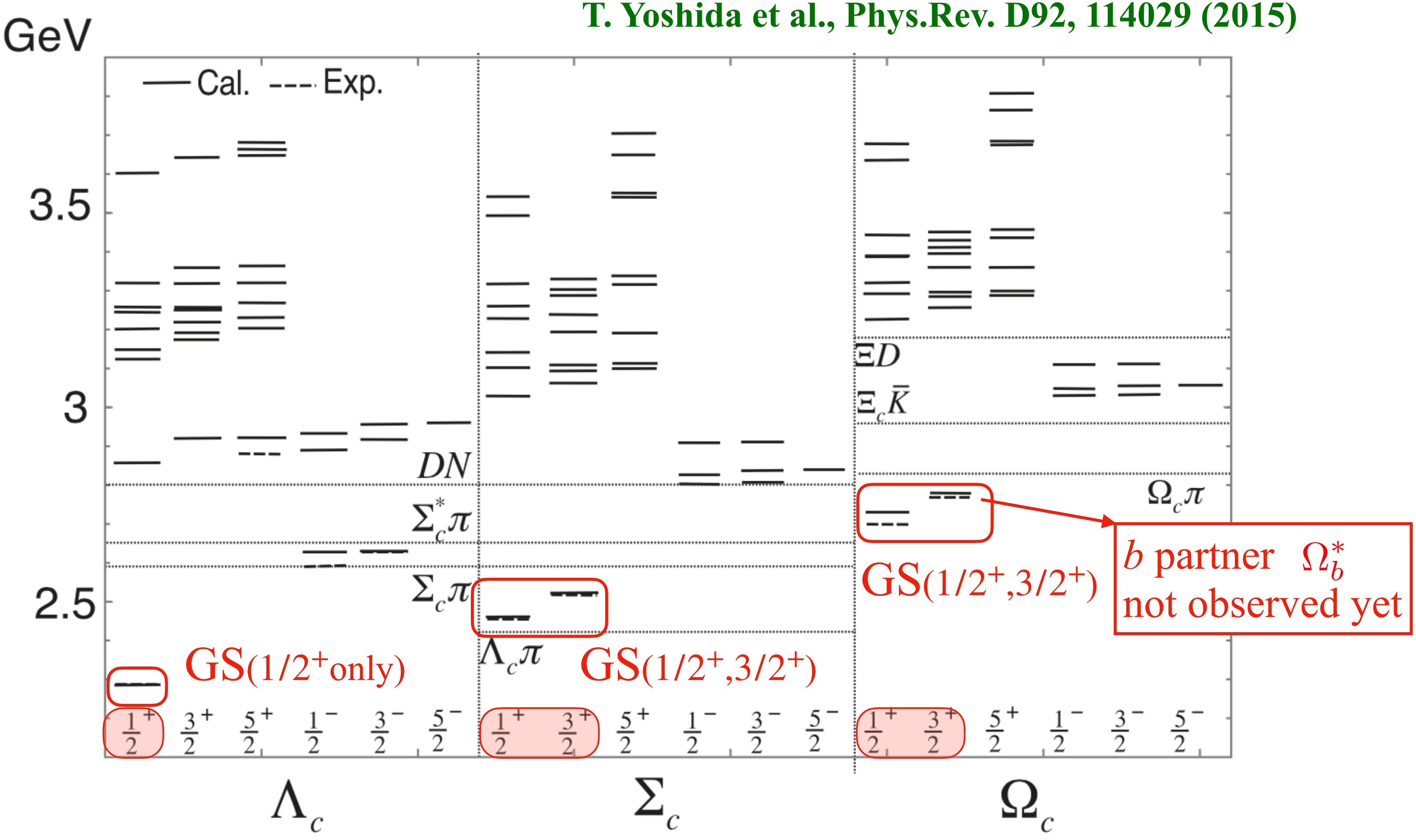
GS Heavy Meson Spectrum



Heavy Baryon Spectrum

Quark model

T. Yoshida et al., Phys.Rev. D92, 114029 (2015)



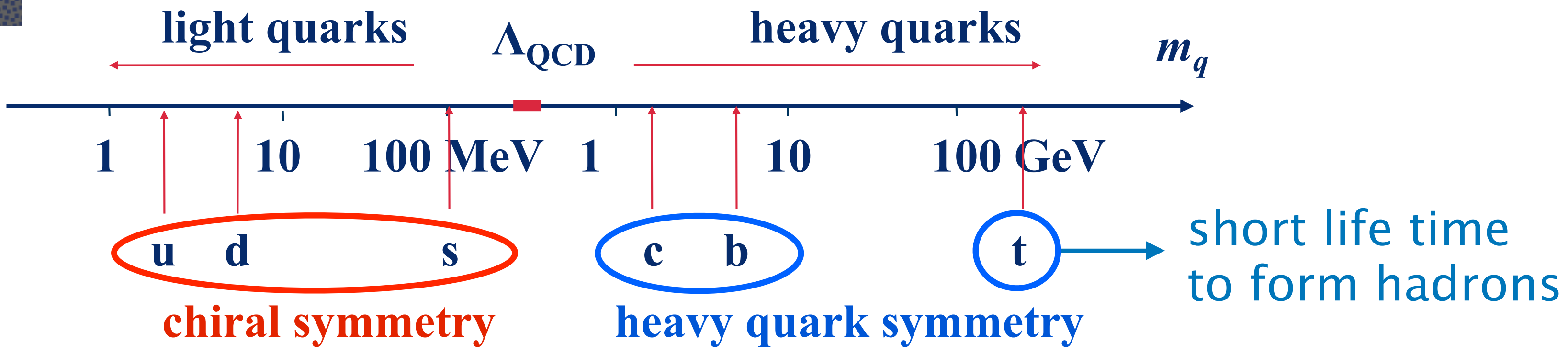
GS($1/2^+$only)

GS($1/2^+$,$3/2^+$)

GS($1/2^+$,$3/2^+$)

b partner Ω_b^*
not observed yet

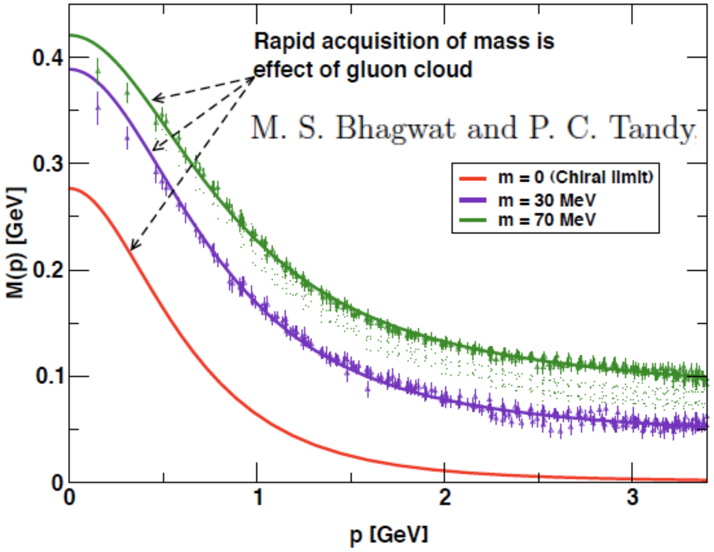
Flavors



short life time
to form hadrons

- **Light quarks**
  chiral symmetry breaking
  $SU(3)_R \times SU(3)_L \rightarrow SU(3)_V$
  ⇒
  ***Nambu-Goldstone bosons* (π, K, η)**
  ***Effective quark masses ~ 300* MeV**

Effective quark masses in LQCD

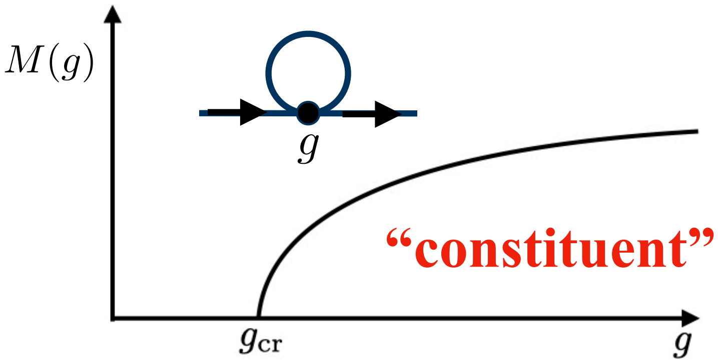


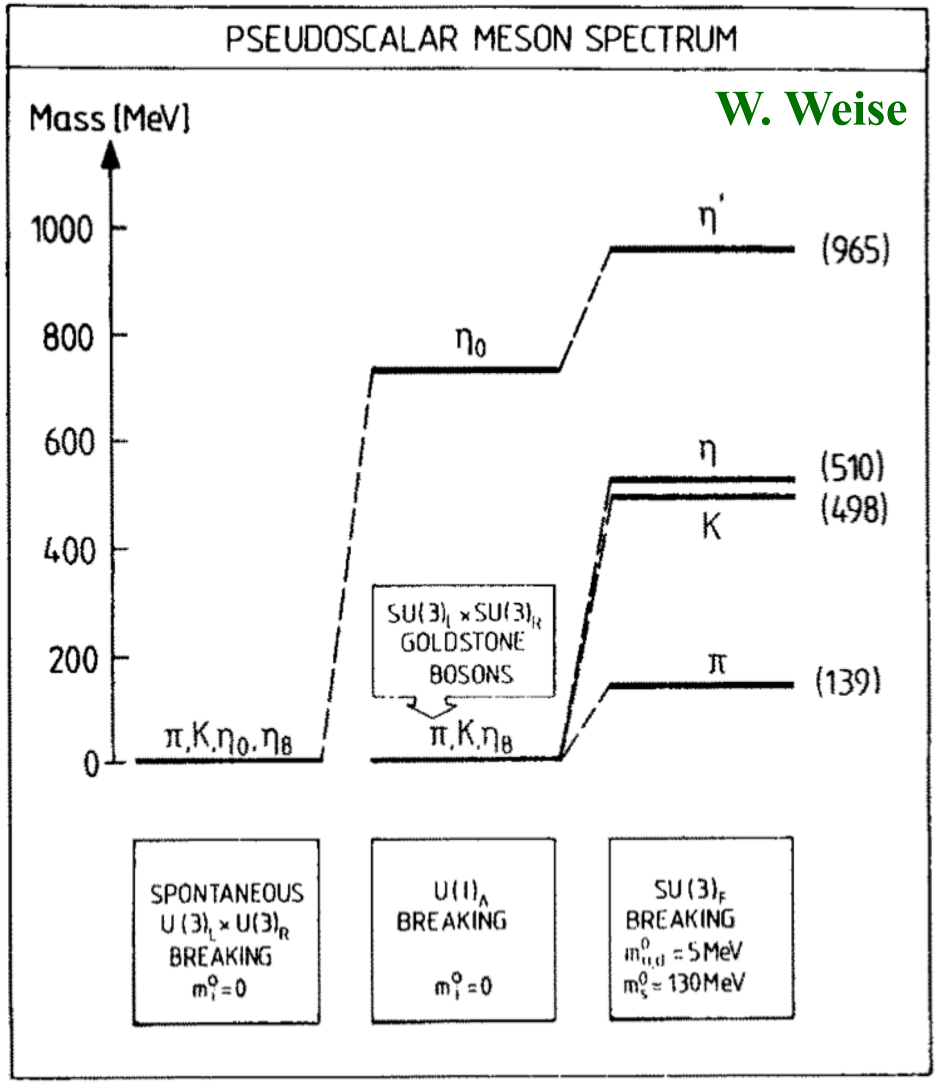
- **Heavy quark symmetry**
  suppression of the QCD running coupling and the magnetic gluons

Chiral Symmetry Breaking

NG bosons and Effective quark mass

Effective quark mass
vs 4q coupling strength in NJL model





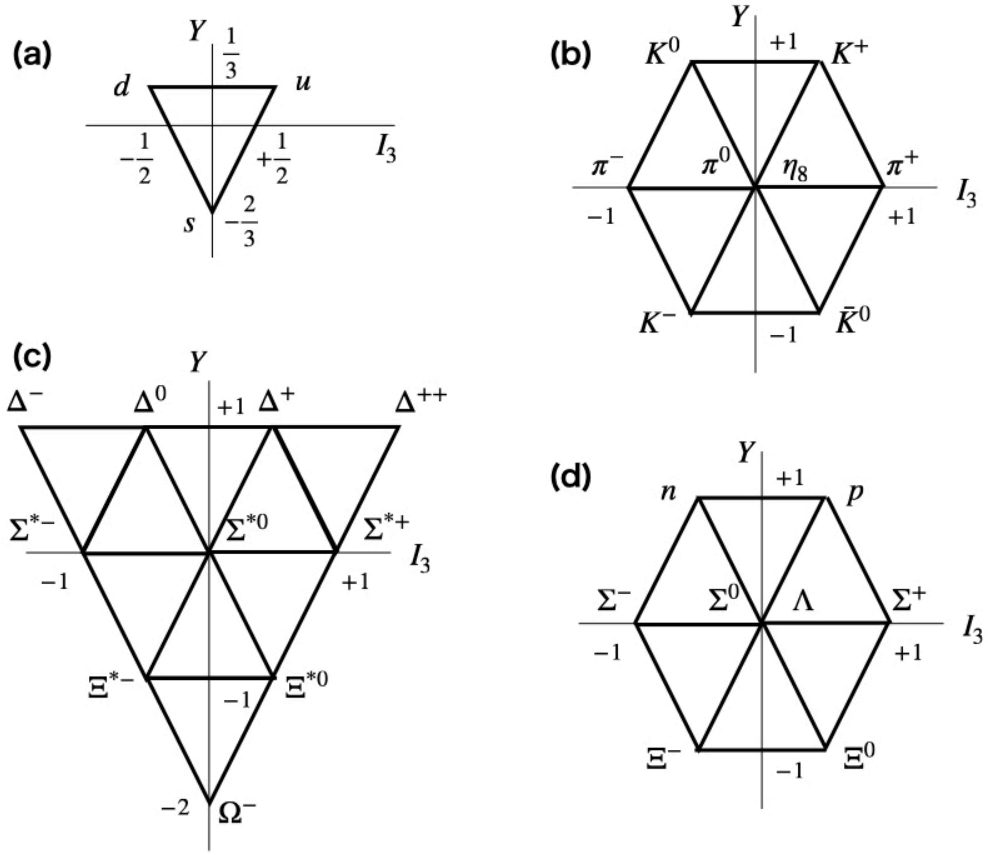
W. Weise

Axial U(1) anomaly

$$\partial_\mu J_A^{0\mu} = \frac{\alpha_s}{2\pi} N_f \mathrm{Tr}[G^{\mu\nu}\tilde{G}_{\mu\nu}] \neq 0$$

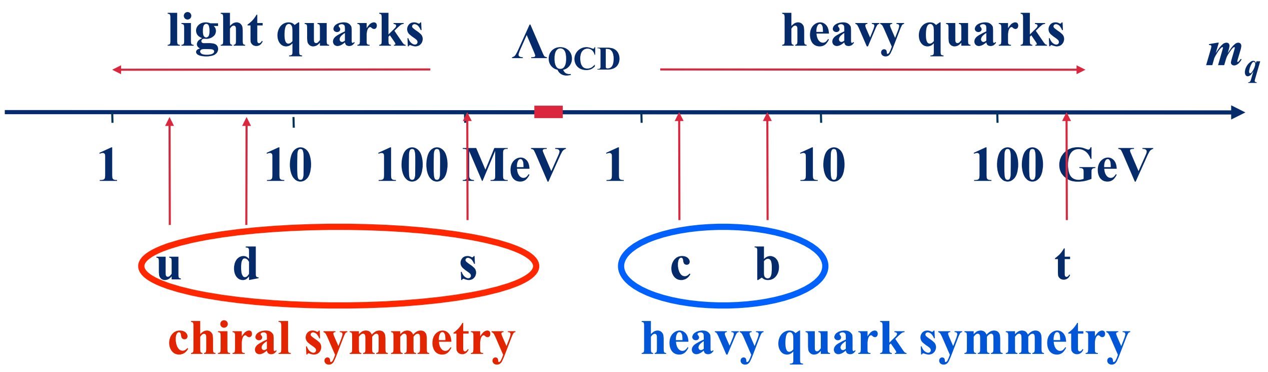
Symmetries of NRQM

- **Symmetries of the *Non-Relativistic* Quark Model (NRQM)**
  $SU(3)_c \times SU(3)_f \times SU(2)_s \times O(3)$
- **quantum numbers of "constituent" quarks**
  color 3 $SU(3)_c$
  spin 1/2 $SU(2)_s$
- **Light hadrons**
  flavor $SU(3)_f$ (u,d,s)
- **Orbital motion**
  non-relativistic O(3)
  radial + angular excitations



Heavy Quark Dynamics

- **Dynamics of heavy quarks (c, b) is perturbative and nonrelativistic. It decouples from light quarks.**

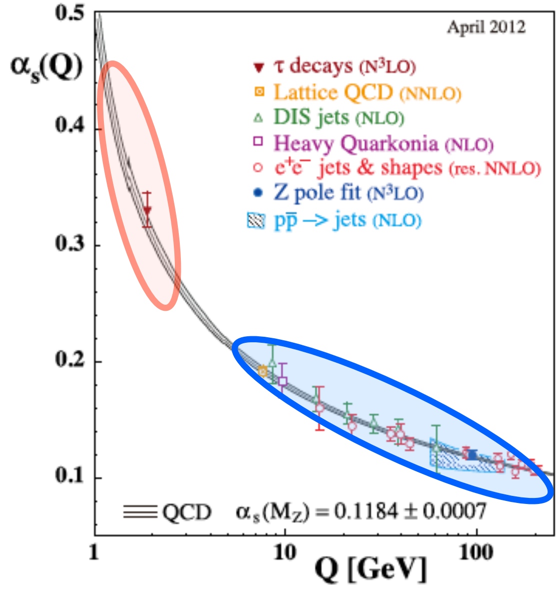


light quarks Λ_{QCD} **heavy quarks** m_q

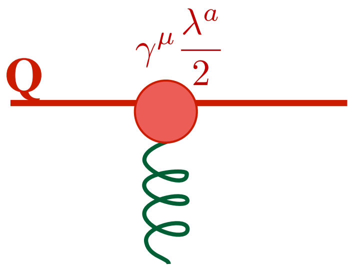
1 10 100 MeV 1 10 100 GeV

u d s **c b** **t**

chiral symmetry **heavy quark symmetry**



- **Magnetic gluon coupling is suppressed.**



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

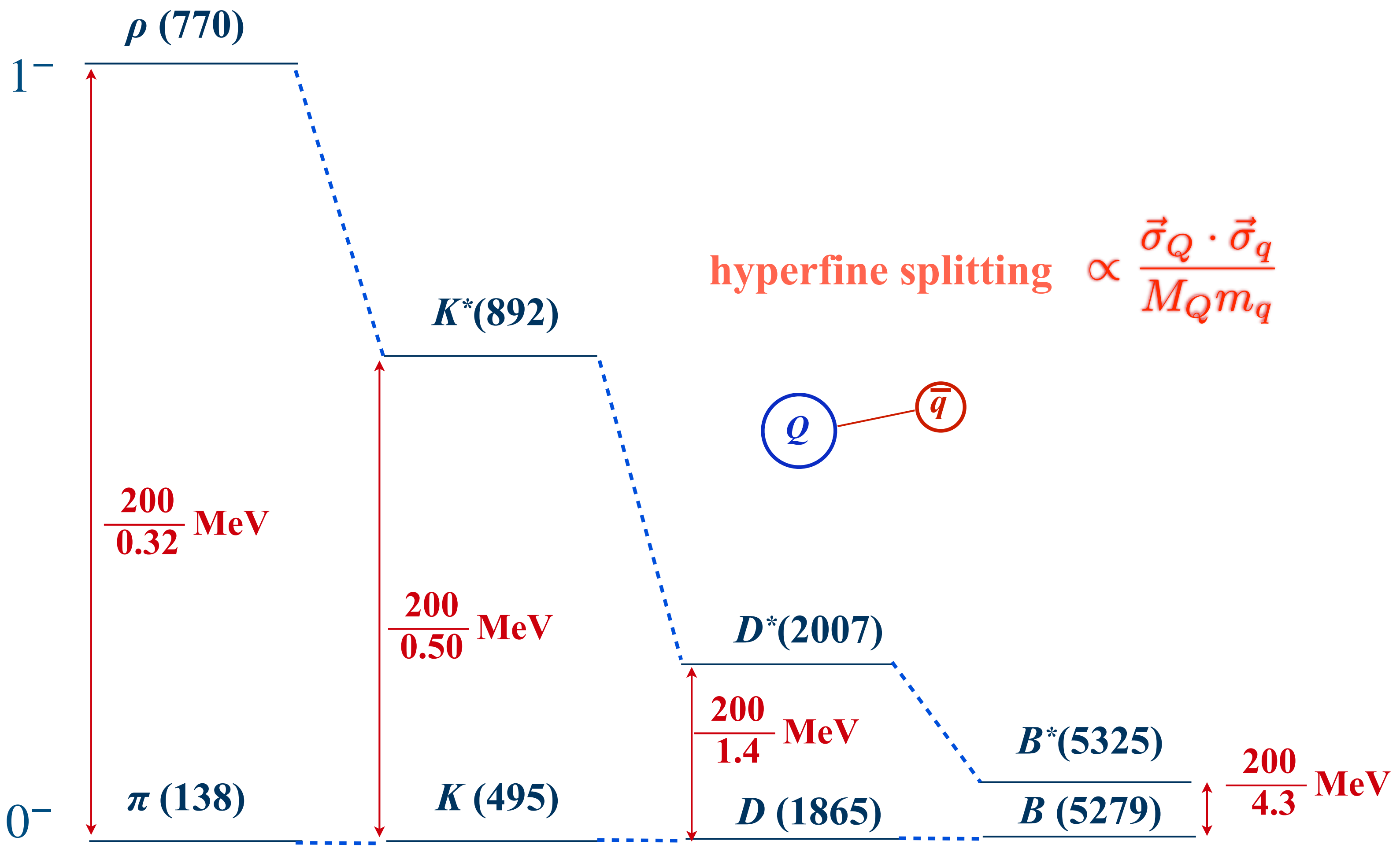
(Color Electric coupling) ≫ (Color Magnetic coupling)

⇒ *Heavy quark symmetry* : Light quarks do not feel the mass and spin of the heavy quark (in the limit $m_Q \rightarrow \infty$).

Heavy Quark Spin Symmetry

- **Hyperfine splitting of mesons**

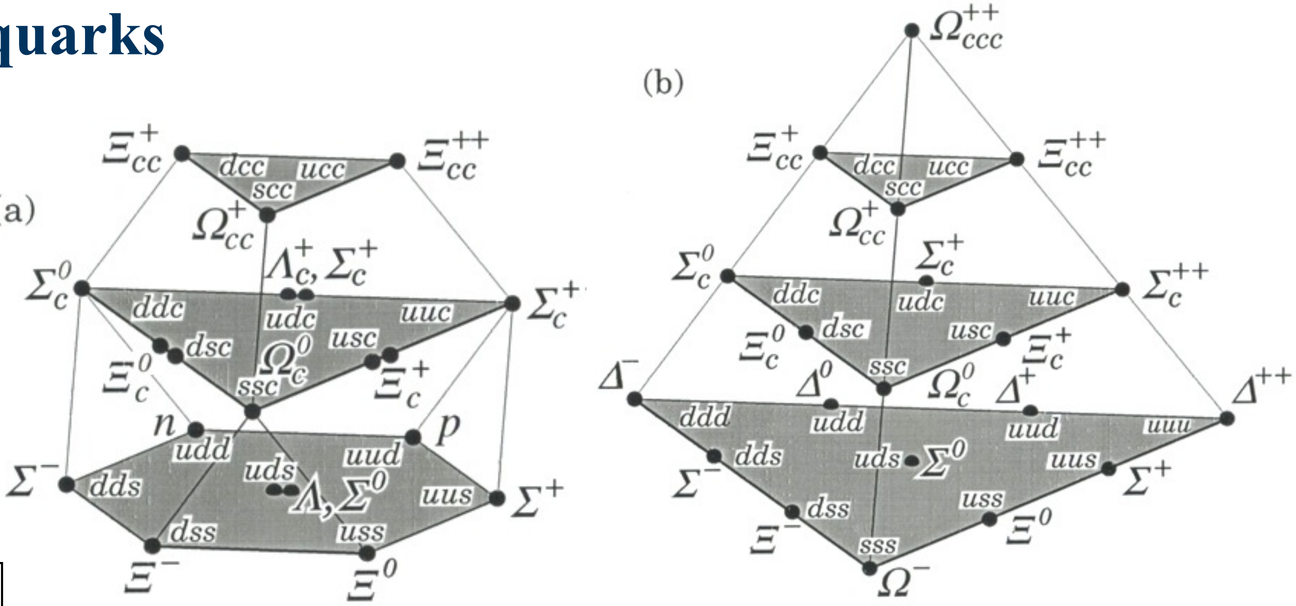
PS ($0^-, L = 0, S = 0$) and V($1^-, L = 0, S = 1$)

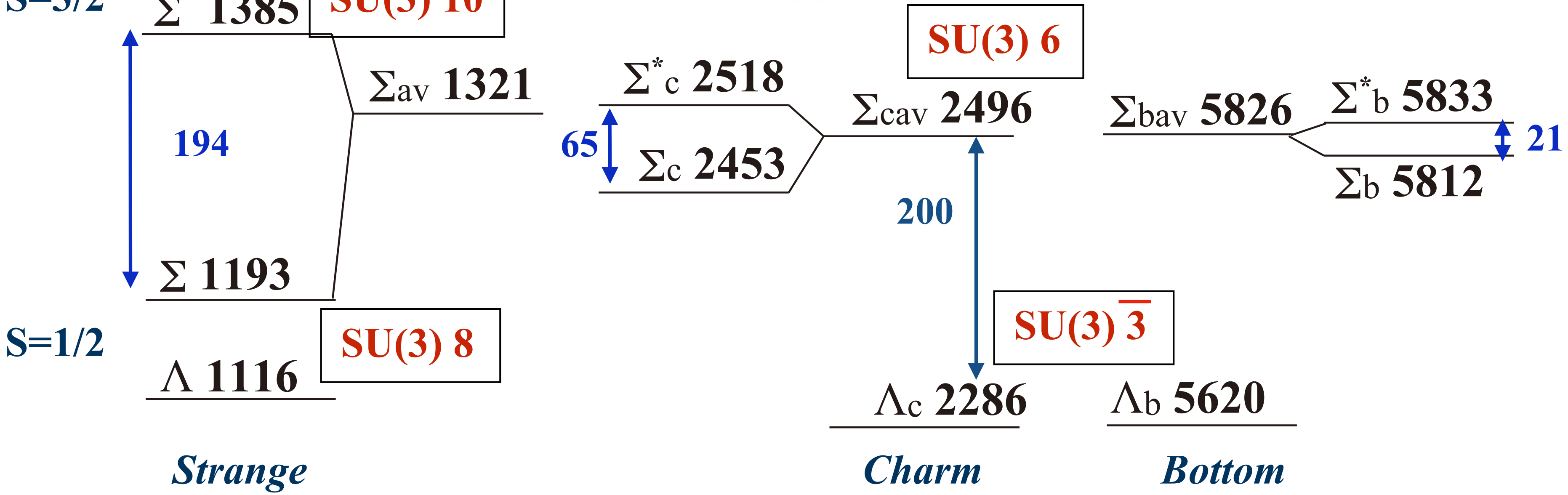


hyperfine splitting $\propto \dfrac{\vec{\sigma}_Q \cdot \vec{\sigma}_q}{M_Q m_q}$

Heavy Quark Spin Symmetry

- **Baryons with heavy quarks**





S=3/2

Σ^* 1385

SU(3) 10

Σ_{av} 1321

194

Σ 1193

S=1/2

SU(3) 8

Λ 1116

Σ^*_c 2518

65

Σ_c 2453

SU(3) 6

Σ_{cav} 2496

200

SU(3) $\overline{3}$

Λ_c 2286

Σ_{bav} 5826

Σ^*_b 5833

21

Σ_b 5812

Λ_b 5620

Strange

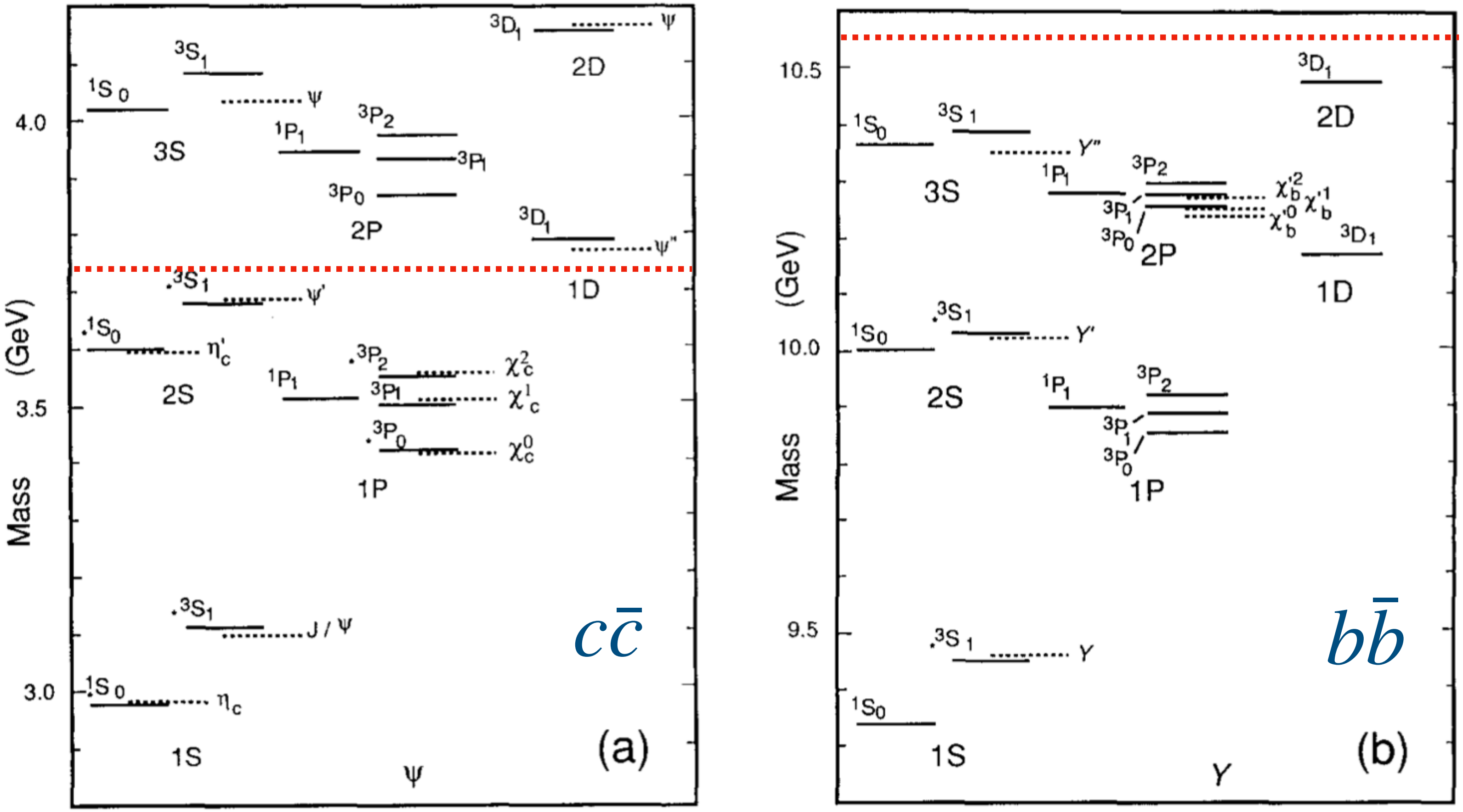
Charm

Bottom

Difficulties in Excited states

Excited states

- So far, so good! How about excited states?
- The quark model works well for excited heavy mesons *below the two-hadron threshold*

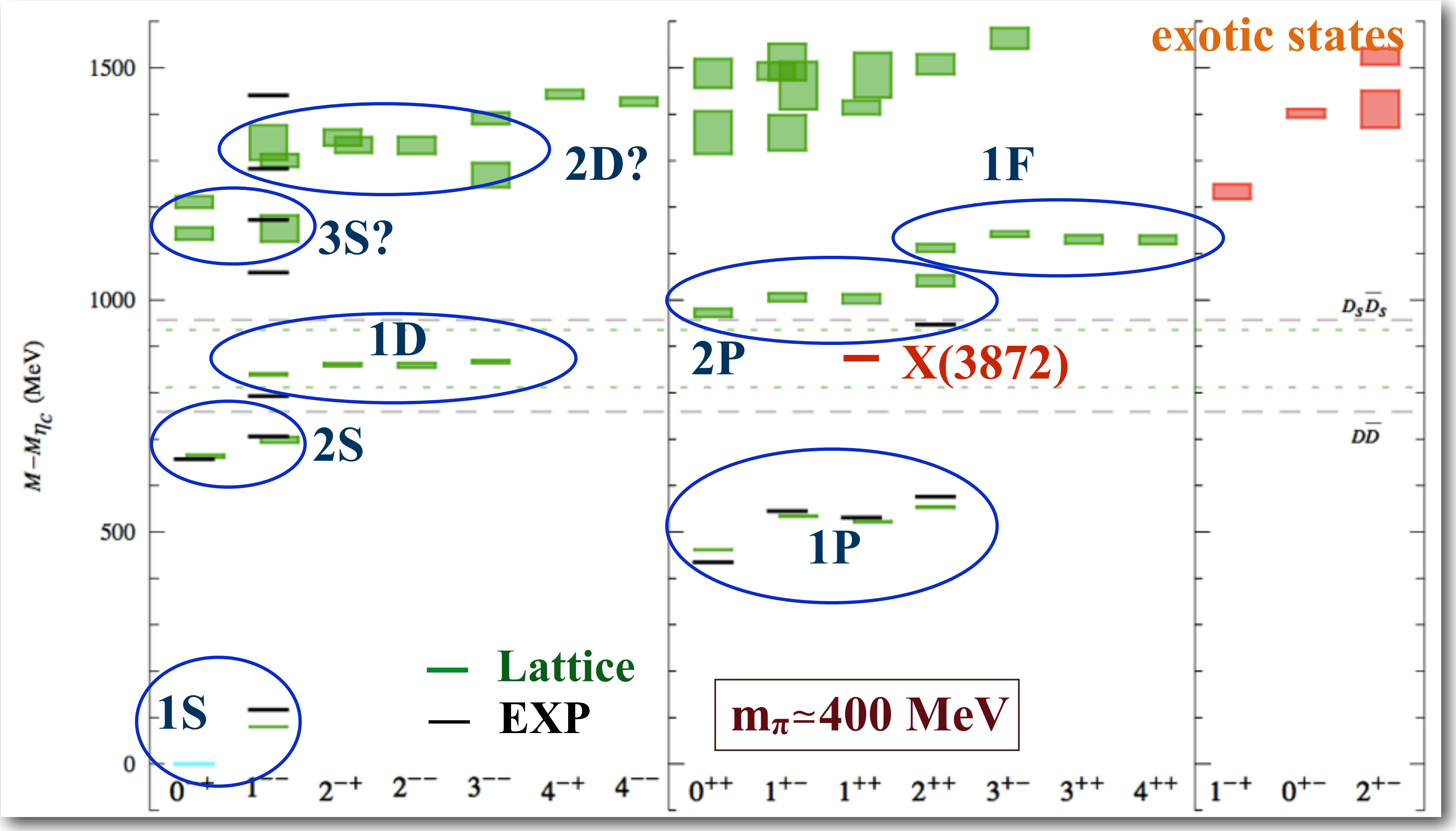


S.N. Mukherjee et al., Phys. Rep. 231 (1993)

Lattice QCD

Charmonium spectrum on Lattice

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



Excited states (scalar nonet)

NRQM faces difficulties in explaining the excited states

Scalar (0^{++}) nonets as P-wave $q\bar{q}$ ($^3P_0$) excited states

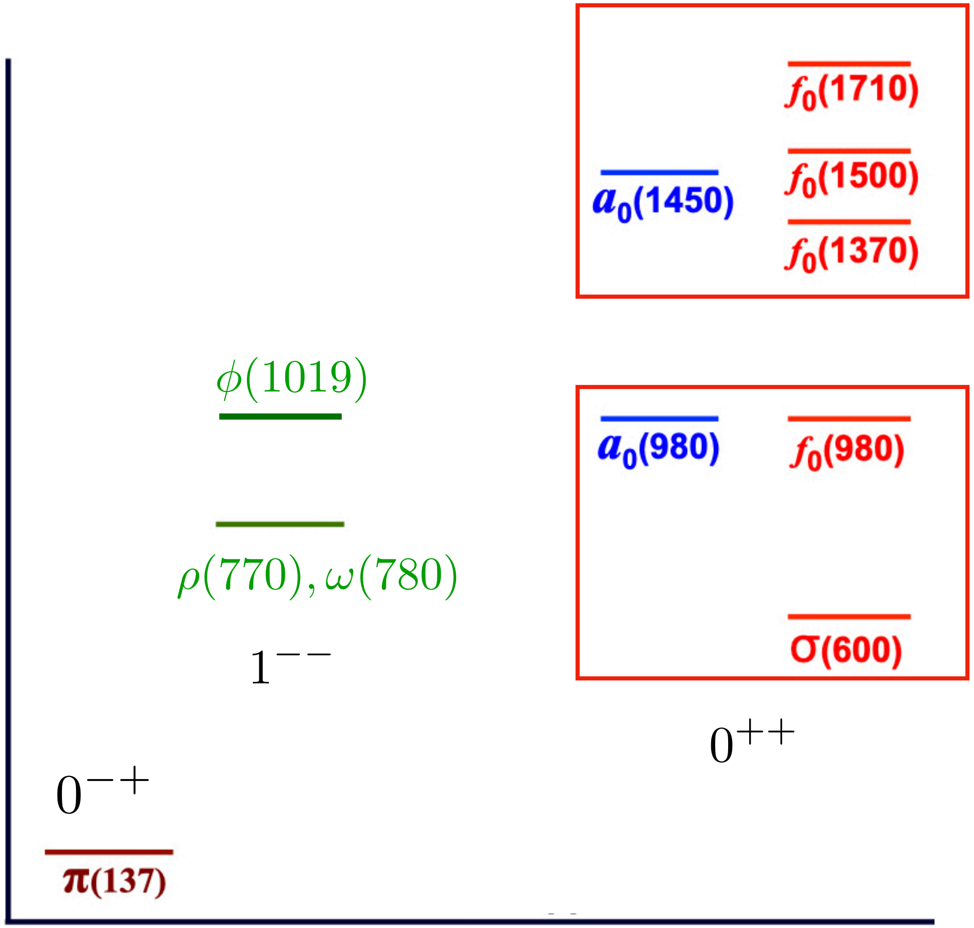
$$f_0 = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

$$f_0' = s\bar{s}$$

$$a_0^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

$$a_0^+ = u\bar{d}, \quad a_0^- = d\bar{u}$$

$$\boxed{m(f_0) \sim m(a_0) < m(f_0')}$$



Excited states (scalar nonet)

The hierarchy problem can be solved by

Jaffe's tetra-quark picture, R.L. Jaffe, PRD15, 267 (1977)

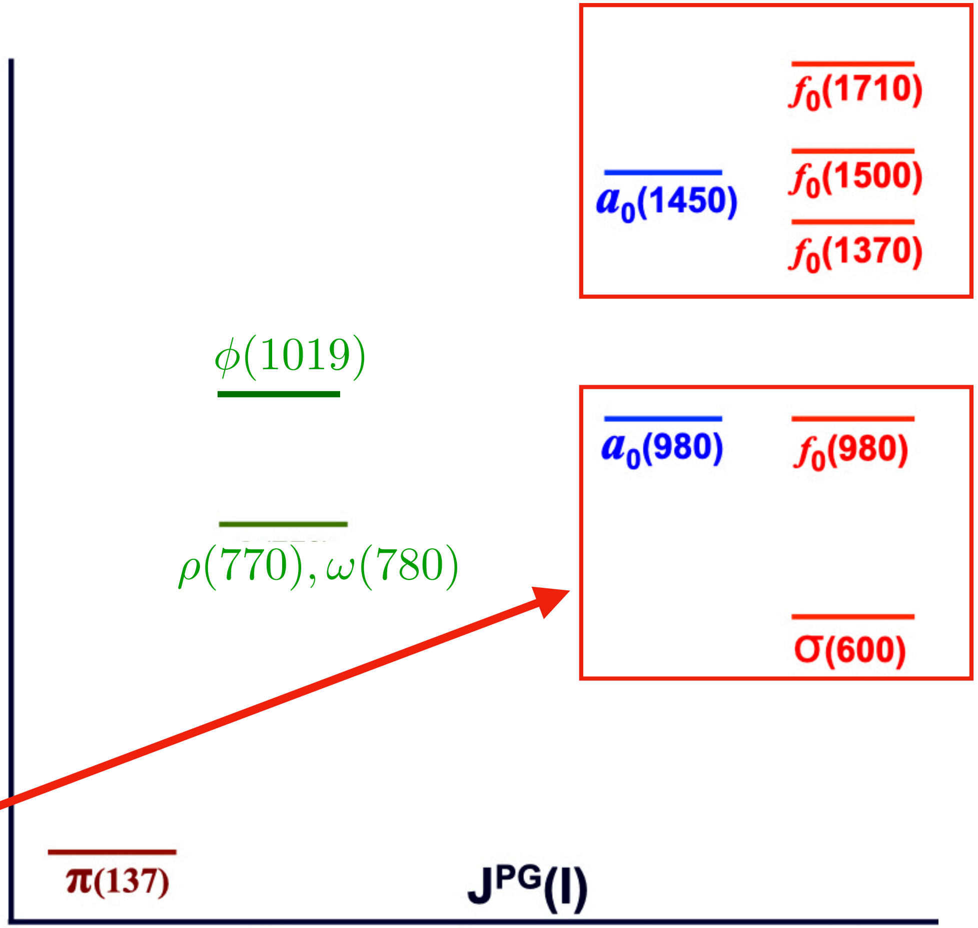
$$f_0 = ud\bar{u}\bar{d}$$

$$f_0' = \frac{1}{\sqrt{2}}(us\bar{u}\bar{s} + ds\bar{d}\bar{s})$$

$$a_0^0 = \frac{1}{\sqrt{2}}(us\bar{u}\bar{s} - ds\bar{d}\bar{s})$$

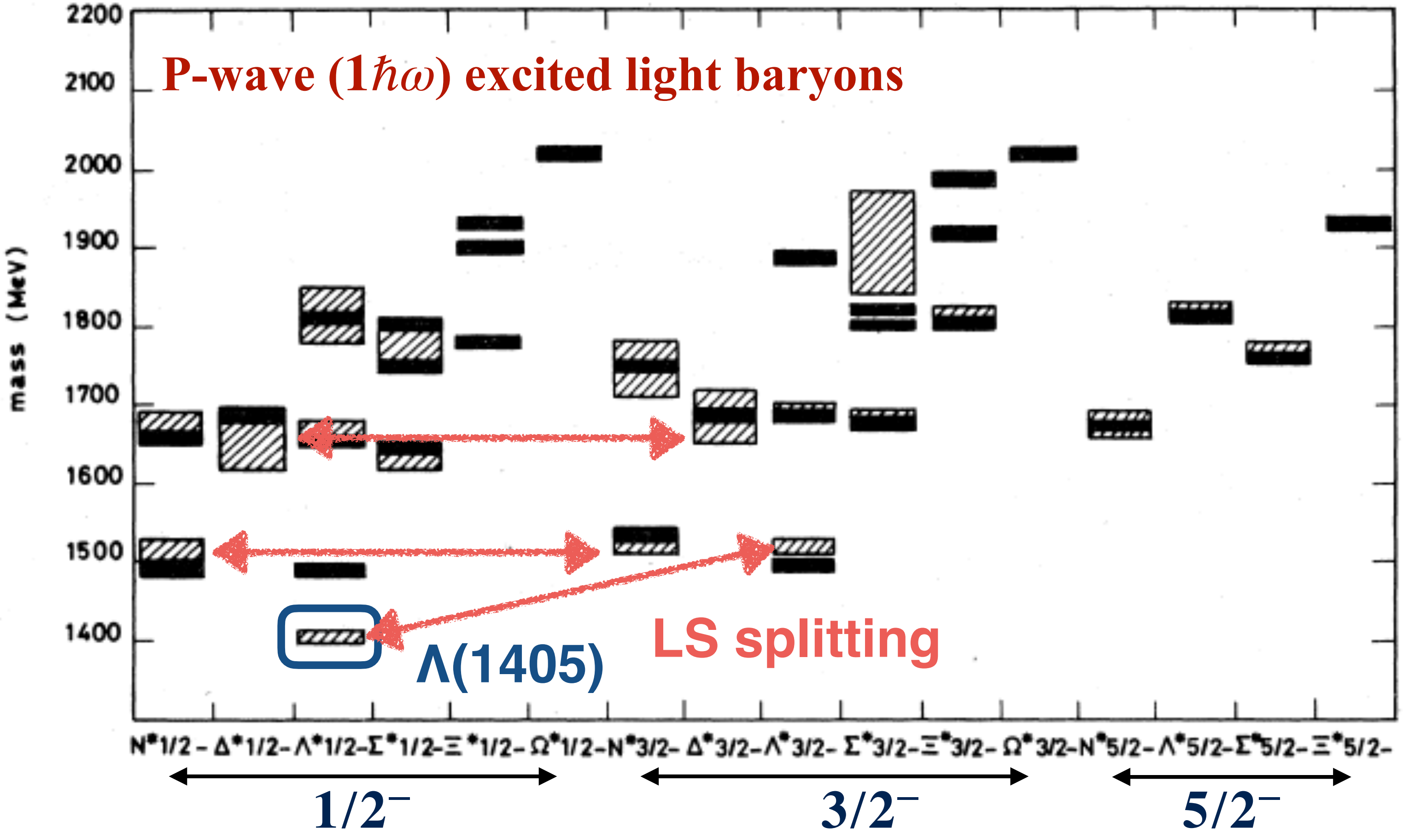
$$a_0^+ = us\bar{d}\bar{s}, a_0^- = ds\bar{u}\bar{s}$$

$$\boxed{m(f_0) < m(a_0) \sim m(f_0')}$$



Excited states (light baryons)

- Isgur-Karl potential model for baryons “*Shell model of hadrons*”



P-wave ($1\hbar\omega$) excited light baryons

Λ(1405)

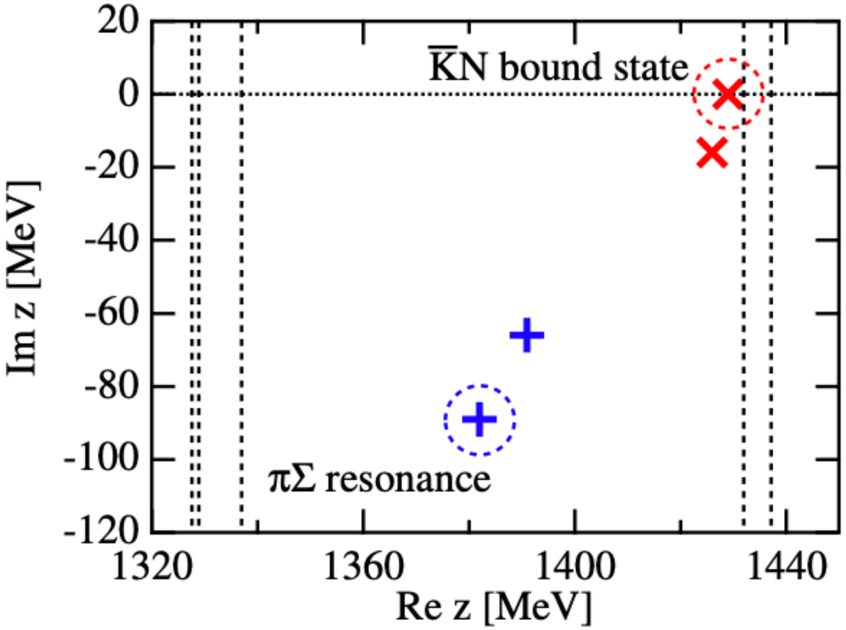
LS splitting

- The lowest negative parity baryon is $\Lambda(1405)$ ($1/2^-$).
  The LS splitting ($1/2^- \leftrightarrow 3/2^-$) is abnormally large.

Excited states

- **Intense researches on the nature of $\Lambda(1405)$ conclude $\Lambda(1405) \sim N\bar{K}\,(I=0, L=0)$ bound state.**

R.H. Dalitz, S.F. Tuan, PRL 2, 425 (1959)
T. Hyodo, D. Jido, PPNP 67, 55 (2012)



- **A *common origin* of difficulties**

competition: orbital L=1 excitation *v.s.* extra $q\bar{q}$

Scalar meson nonet $q\bar{q}\,(L=1, 0^+)$ ***v.s.*** $qq\bar{q}\bar{q}\,(L=0, 0^+)$

Negative parity baryon $qqq\,(L=1, 1/2^-)$ ***v.s.*** $qqqq\bar{q}\,(L=0, 1/2^-)$

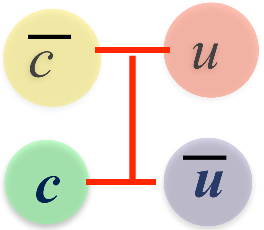
- ***Many resonances are likely to couple with extra $q\bar{q}$ or meson.***

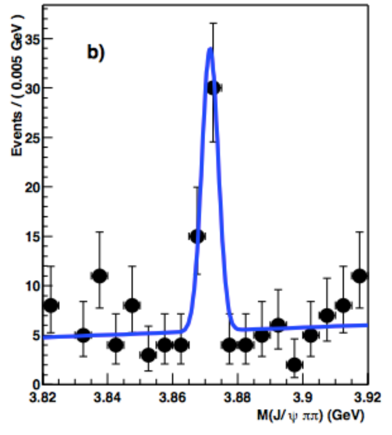
Exotic Multiquark Hadrons

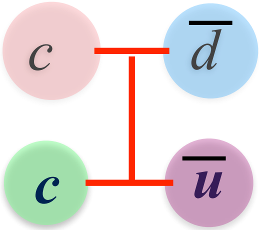
- **Hadrons that do not fit the simple quark model picture**

X(3872) ***Belle***

PRL 91 (2003)

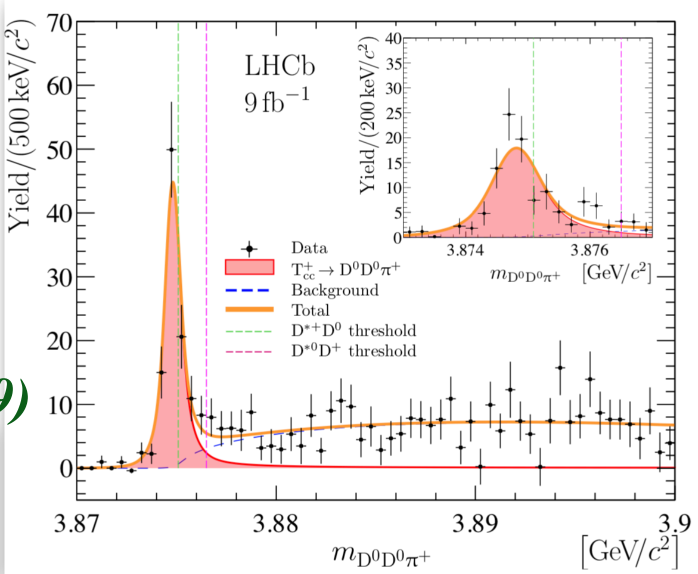






T_{cc} ***LHCb***

Nature Phys. 18 (2022)751

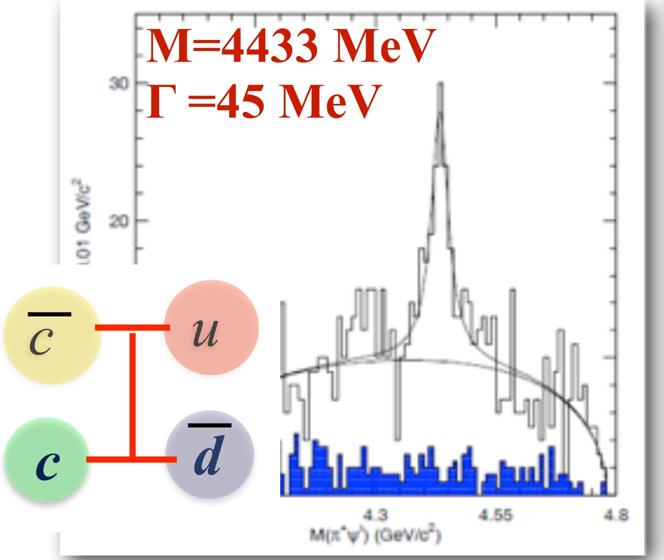


Z_c^+(4430) ***Belle***

PRL 100 (2008) 142001

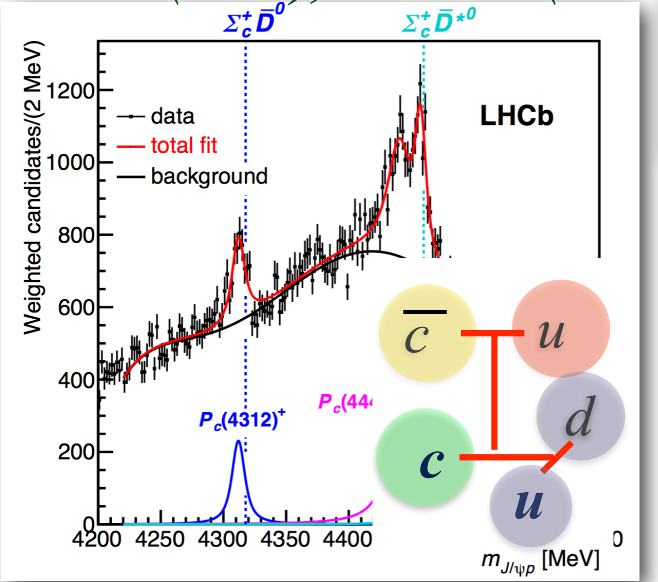
P_c (4312) (4440) (4457) ***LHCb***

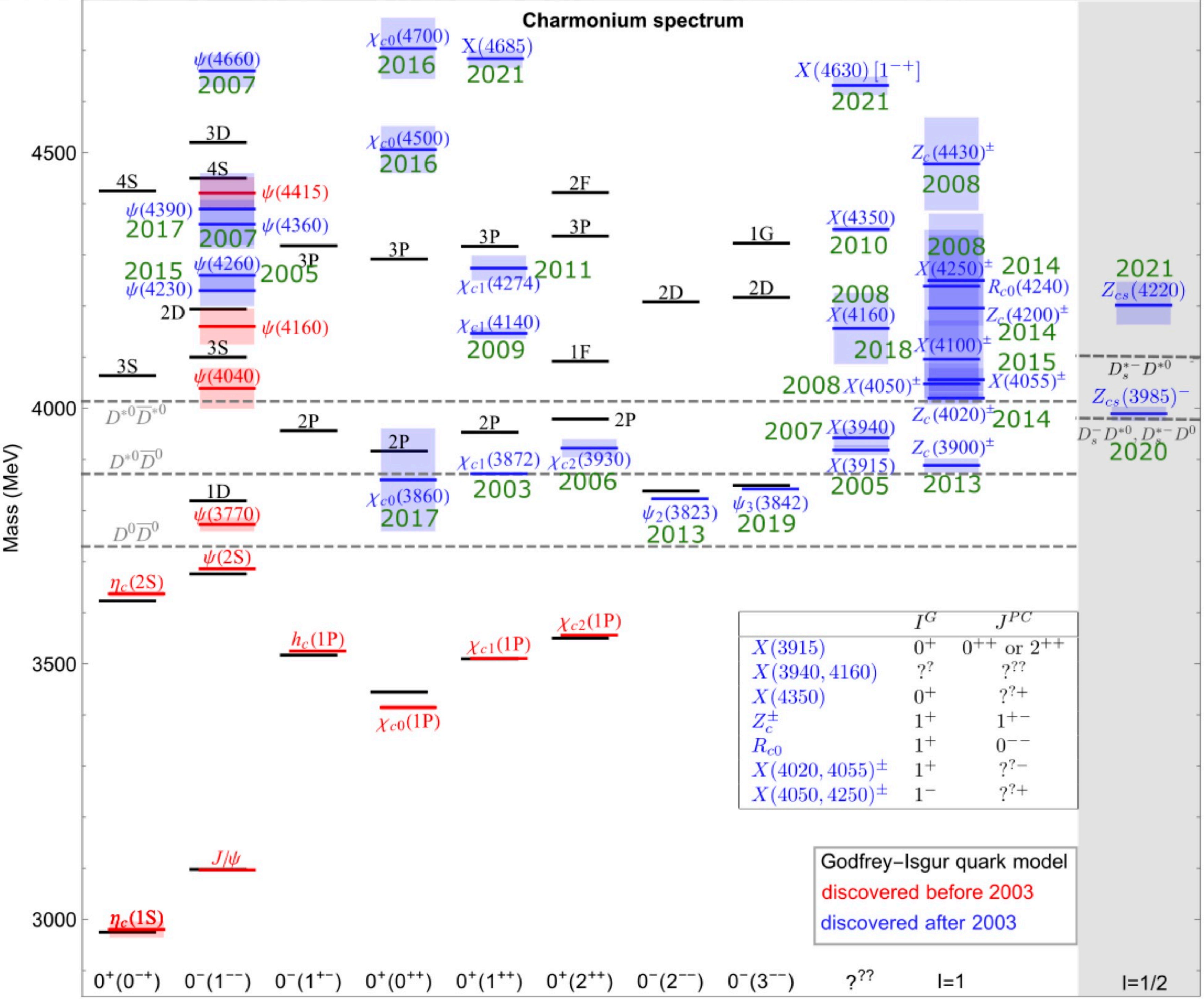
PRL 115 (2015), PRL 122 (2019)



M=4433 MeV

Γ =45 MeV





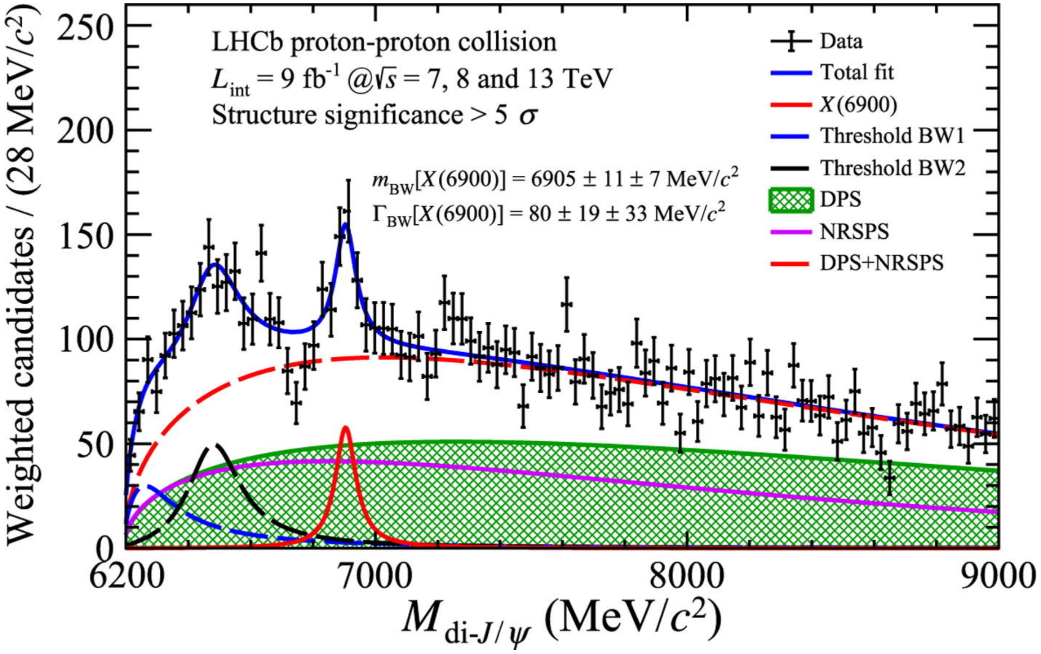
	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^\pm$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^\pm$	1^+	$?^{?-}$
$X(4050, 4250)^\pm$	1^-	$?^{?+}$

Exotic Multiquark Hadrons

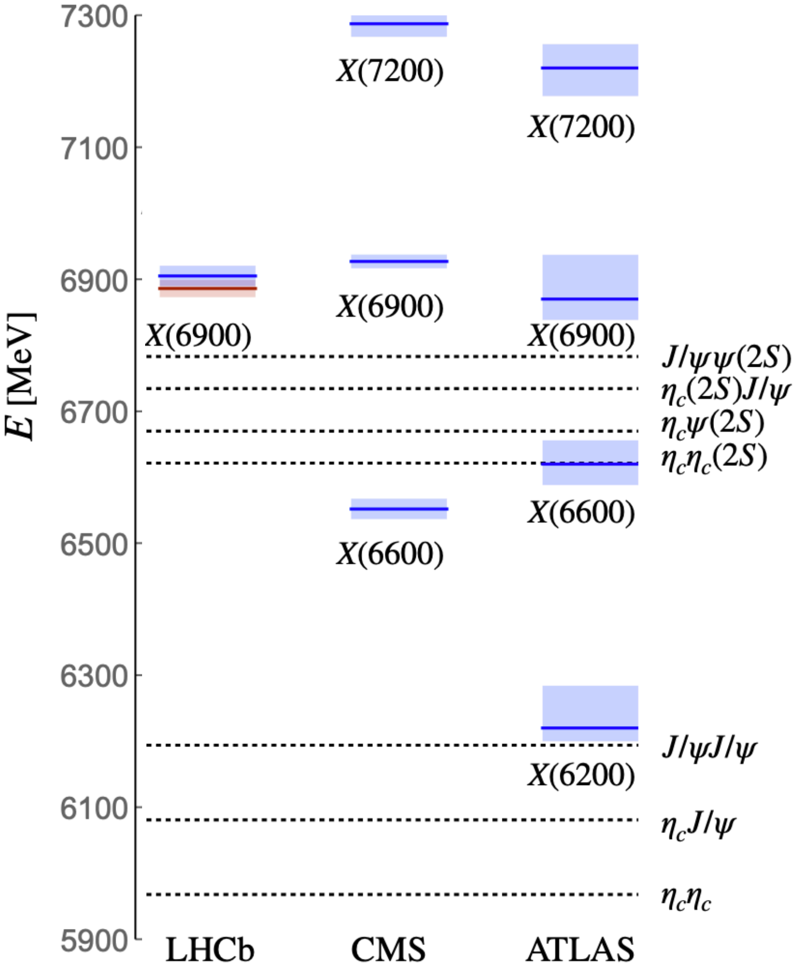
- ***Fully charmed tetra-quark resonances*** $X(cc\bar{c}\bar{c}) \rightarrow J/\psi + J/\psi$

observed at LHC (quantum numbers unknown)

$$m_{\mathrm{BW}}[X(6900)] = 6905 \pm 11 \pm 7\ \mathrm{MeV}/c^2$$
$$\Gamma_{\mathrm{BW}}[X(6900)] = 80 \pm 19 \pm 33\ \mathrm{MeV}/c^2$$

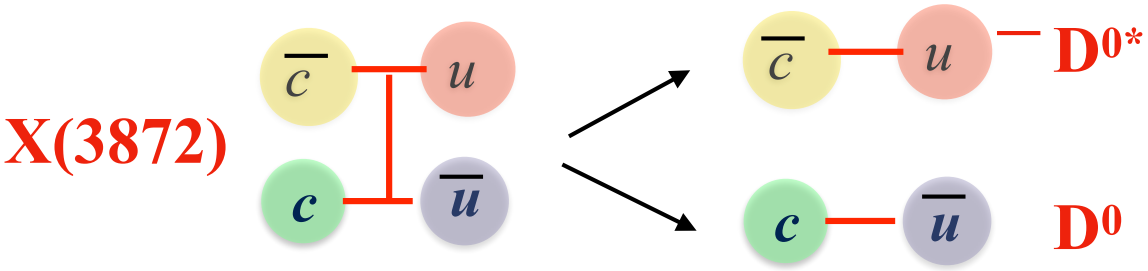


Two *J/ψ* spectrum



Current status summary

- Quark model works excellently for the ground states.
- Multi-quark or hadronic components may play important roles for the excited/exotic states. There may also be other ingredients (constituent gluon, diquark, . .) in the hadron structure.
- Couplings to two- (or more-) hadron (S-wave) thresholds are critically important in understanding hadron spectra and structures.
- We focus on the *Confinement Mechanism of Multi-Quark System* and the couplings to two-hadron scattering states.

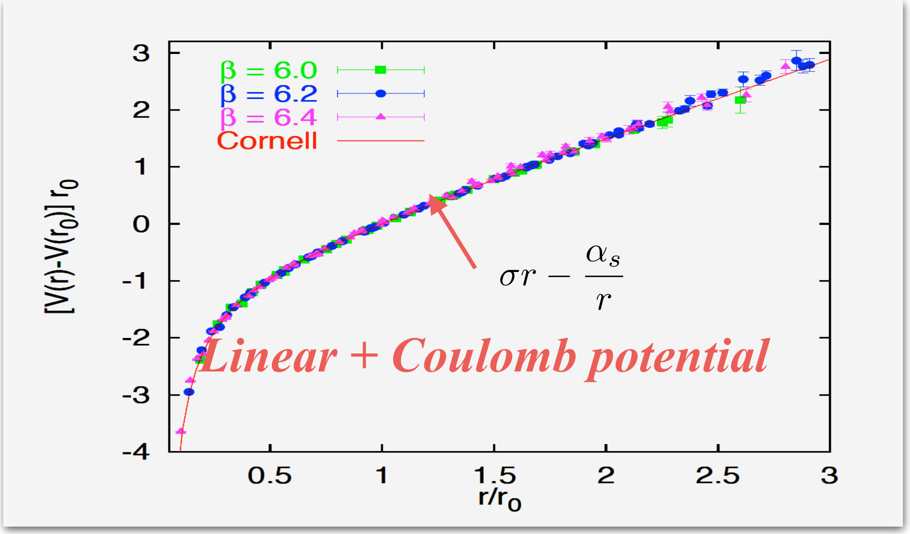


Confinement of Quarks
in Multi-Quark States

Quark Confinement

- **Heavy $Q\bar{Q}$ potential**
  Linear confinement
  + Coulomb potential

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

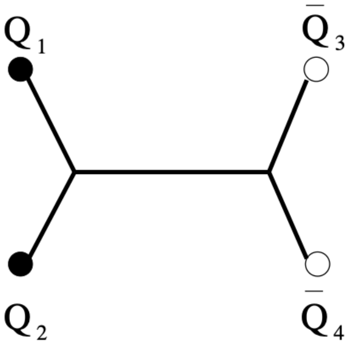


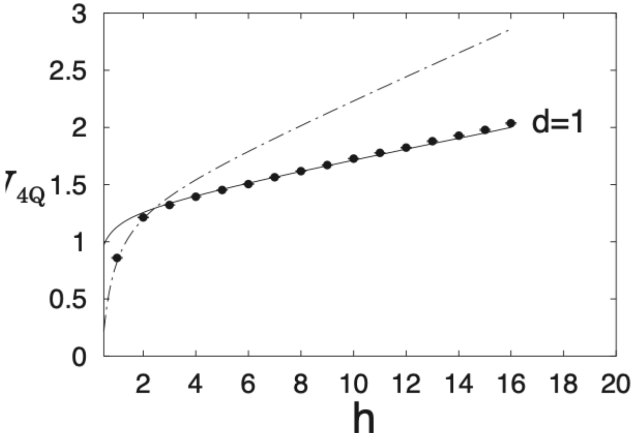
G.S. Bali / Phys. Rep. 343 (2001) 1

- **Confinement for tetraquarks on the lattice**

Strings with the minimal length connect quarks into color singlet hadron.

It should allow two color singlet hadrons fly away.





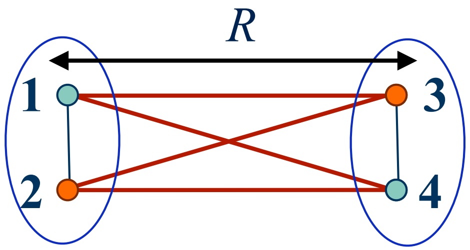
Lattice QCD Wilson loop for tetra quarks
F. Okiharu, et al., J. Mod. Phys. 7 ,774–789 (2016)

Conventional model of confinement

- **Two-body linear potential with color saturation**

$$V = \sum_{i<j} (\lambda_i \cdot \lambda_j)(-a r_{ij}) \qquad (\lambda_i \cdot \lambda_j) = \sum_{\alpha} \lambda_i^{\alpha} \lambda_j^{\alpha}$$

***string tension*:** $\sigma = \frac{16}{3} a \sim 1 \text{ GeV/fm}$



color-singlet **color-singlet**

- **No confinement between two color-singlet systems.**

$$V(R) = \left\langle \sum_{i\in(1,2), j\in(3,4)} (\lambda_i \cdot \lambda_j)(-a r_{ij}) \right\rangle \sim -\langle(\lambda_1 + \lambda_2)(\lambda_3 + \lambda_4)\rangle a R = 0$$

- **It, however, induces long-range color van der Waals force** $\propto -\frac{1}{R^3}$

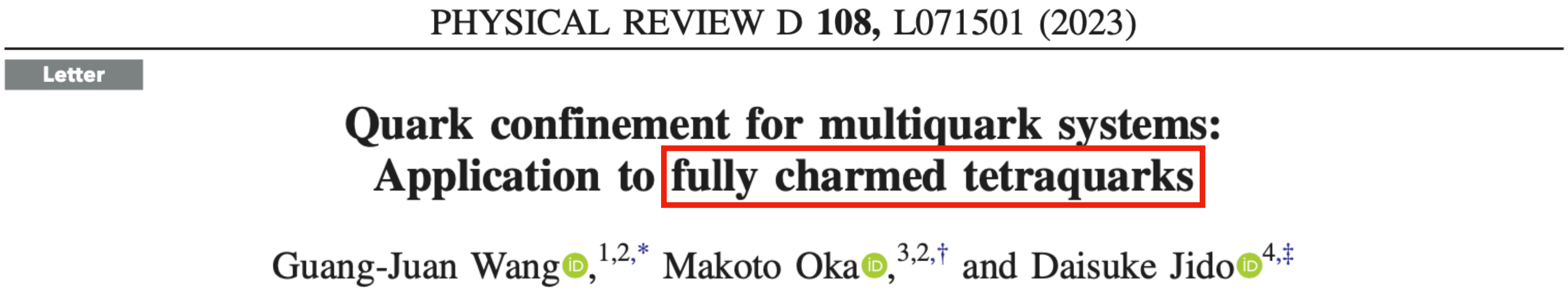
T. Appelquist, W. Fischler, Phys. Lett. B77, 405 (1978)

R.S. Willey, Phys. Rev. D18, 270 (1978)

S. Matsuyama, H. Miyazawa, Prog. Theor. Phys. 61, 942 (1979)

Quark confinement for tetraquarks

- Reconsider the quark confinement potential for the quark model from the QCD viewpoints.
- Conventional potential models assume a combination of two-body confinements, while QCD indicates a string-like confinement potential. How can we take into account the string potential in the quark model?
- We propose to extend the color configuration space of the conventional quark model with a compact hidden-color $|\mathrm{hc}\rangle\rangle$ state, whose mixing induces extra attraction among the multi-quark systems. The model is applied to the fully charmed tetraquarks.



PHYSICAL REVIEW D **108,** L071501 (2023)

Letter

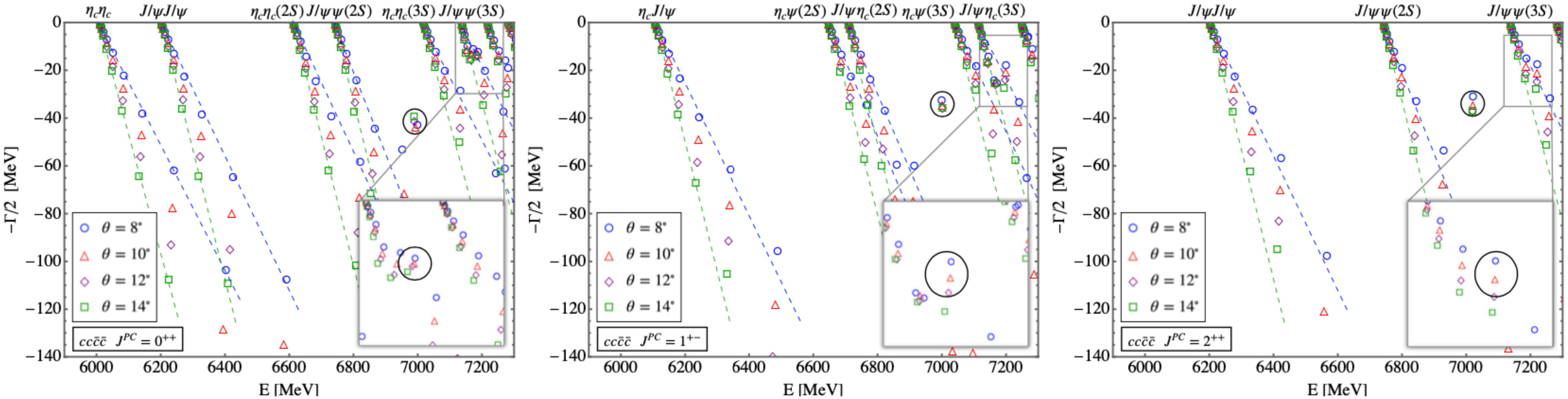
Quark confinement for multiquark systems:
Application to fully charmed tetraquarks

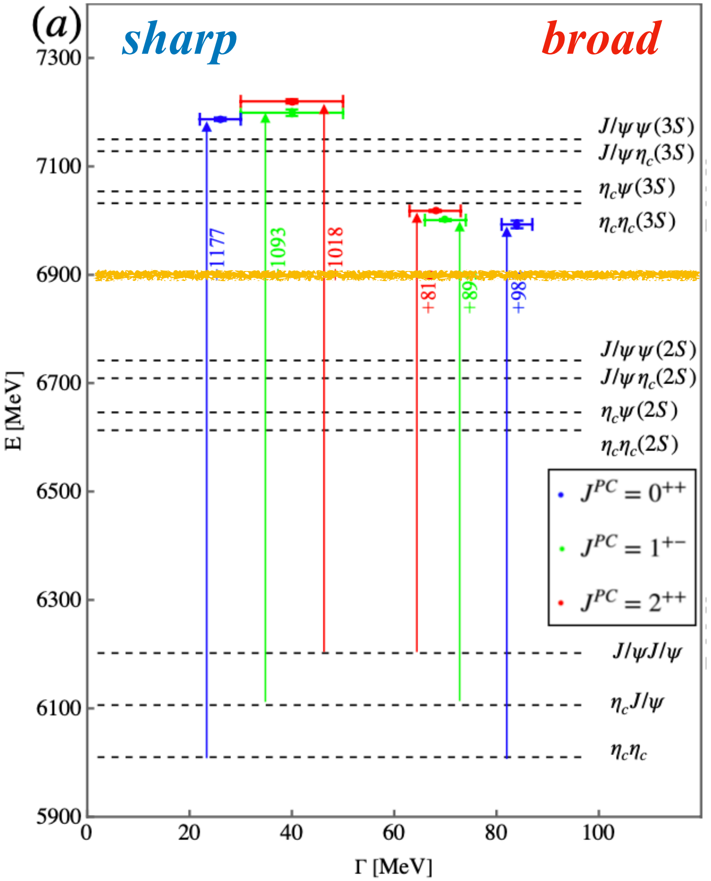
Guang-Juan Wang,[1,2,*] Makoto Oka,[3,2,†] and Daisuke Jido[4,‡]

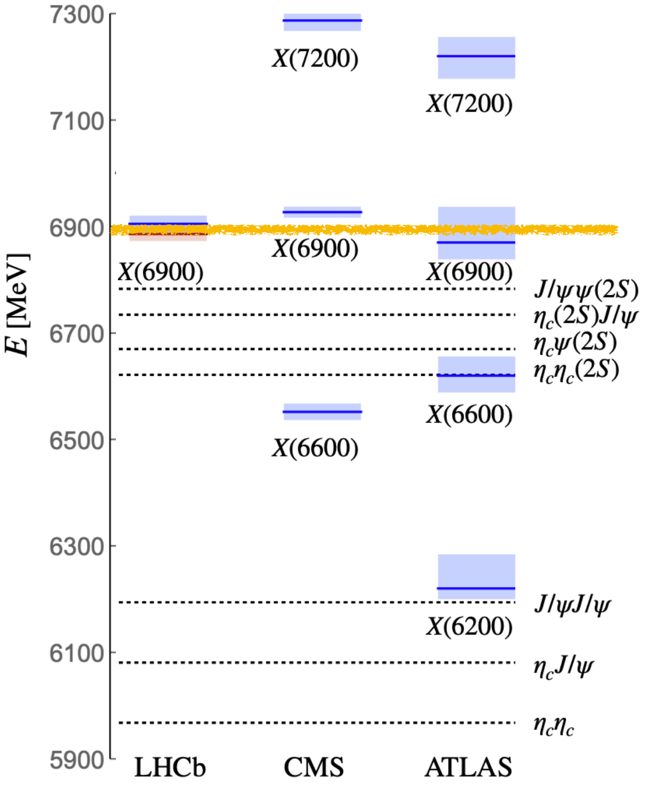
“Check” the confinement potentials

- **Fully heavy tetraquarks are ideal objects to check the validity of the quark model and confinement mechanism of multiquarks.**
- **Possible J^{PC} quantum numbers for the S-wave $cc\bar{c}\bar{c}$ or $bb\bar{b}\bar{b}$ states are $0^{++}, 1^{+-}, 2^{++}$. Their two-hadron S-wave thresholds are $\eta_c\eta_c\,(0^{++})$, $J/\psi J/\psi\,(0^{++}, 2^{++})$, and $\eta_c J/\psi\,(1^{+-})$ and the other excited states.**
- **We apply the Gaussian expansion method (GEM) to the full 4-quark calculation. The AL1 potential model is emplyed.**
- **We use the complex scaling method to distinguish resonance states from scattering states in the finite size basis calculation, *i.e.*, rotating the variables into complex plane as** $\boldsymbol{r} \to \boldsymbol{r}e^{i\theta}, \boldsymbol{p} \to \boldsymbol{p}e^{-i\theta}$

Qi Meng, Guang-Juan Wang, MO, ArXiv:2404.01238
G.J. Wang, Qi Meng, MO, Phys. Rev. D106, 096005 (2022)
Qi Meng, et al., Phys. Lett. B 846, 138221 (2023)
Qi Meng et al., Phys. Lett. B814, 136095 (2021)







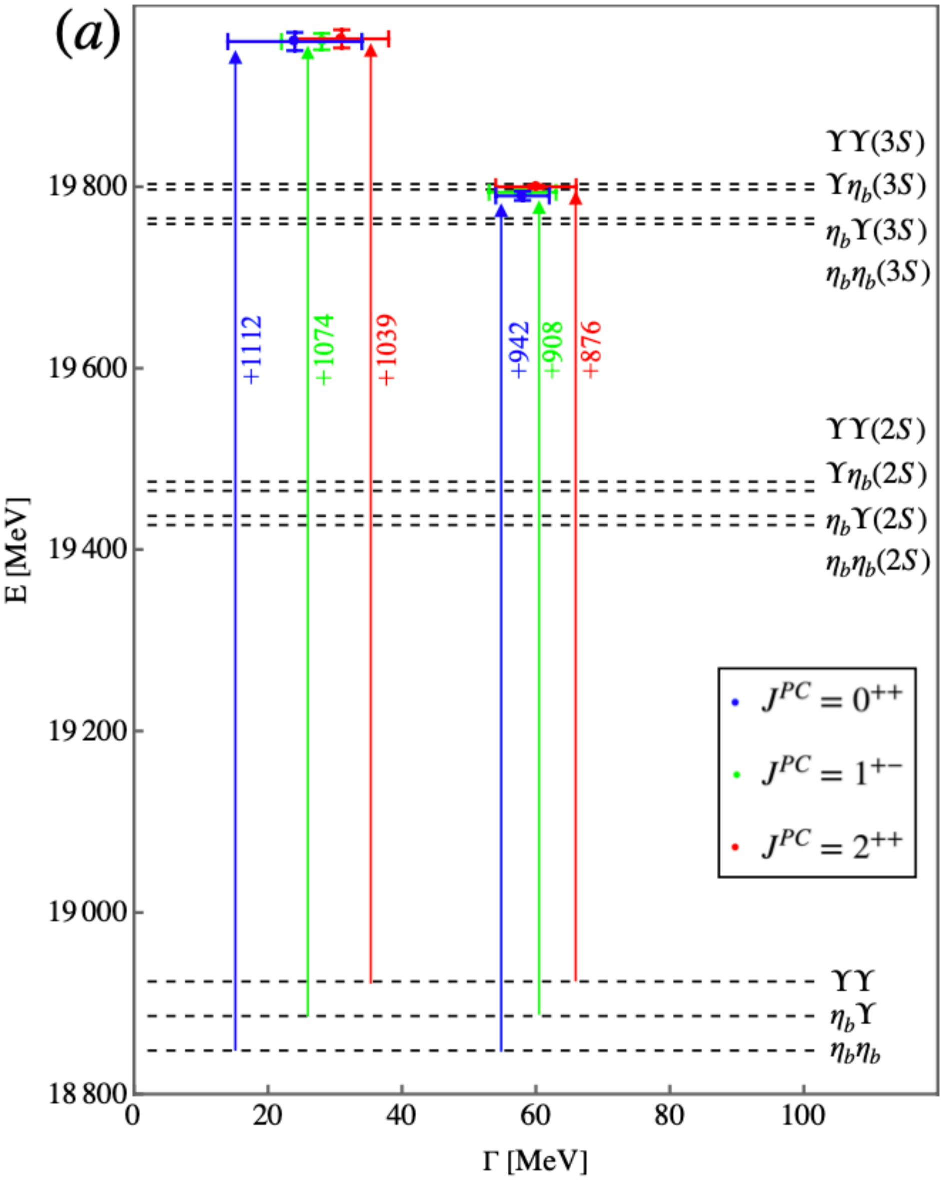
$cc\bar{c}\bar{c}$ spectrum

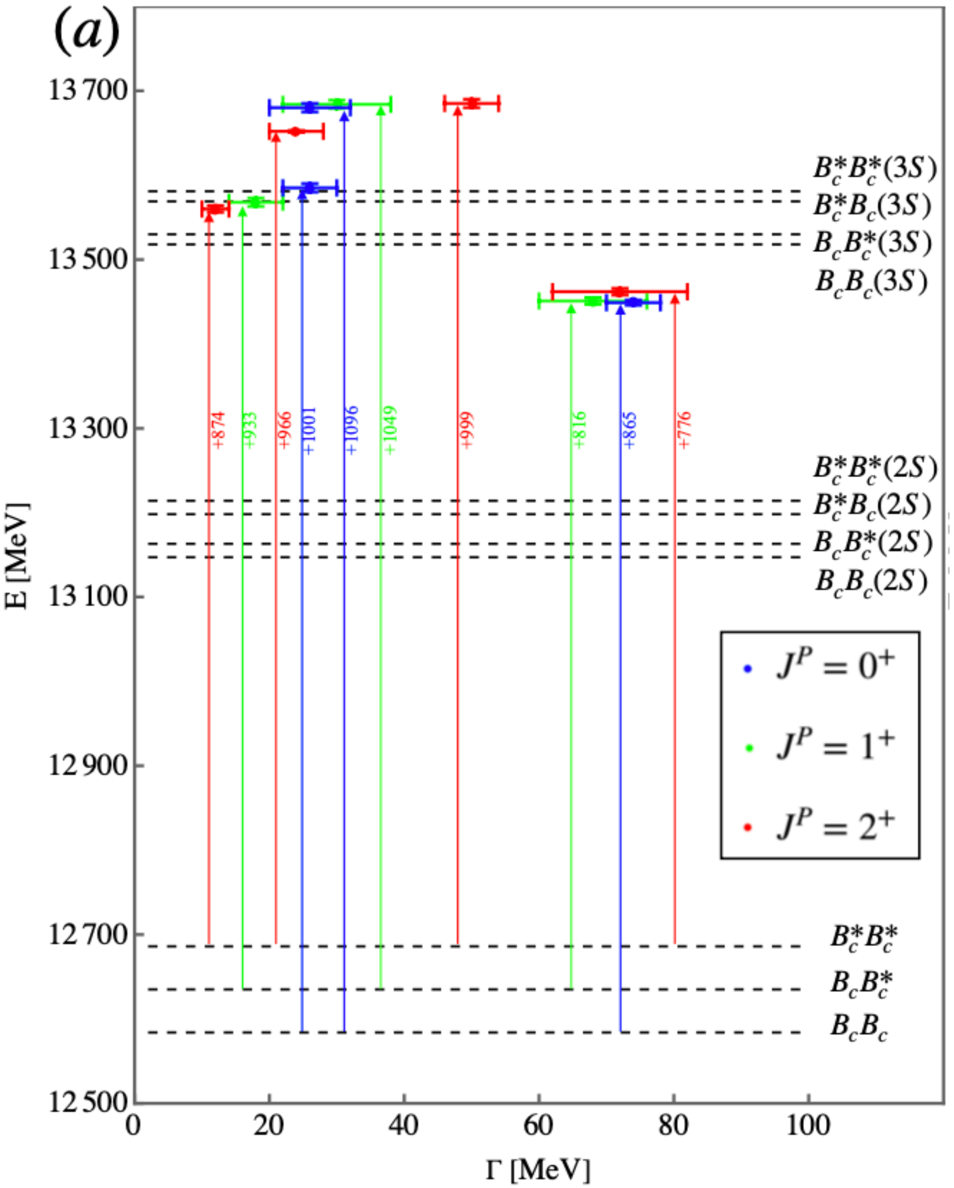
- **no bound state**
- **Six resonances are found around 7-7.2 GeV**
- **They are more than 100 MeV above the observed resonances.**

Qi Meng, Guang-Juan Wang, MO, ArXiv:2404.01238

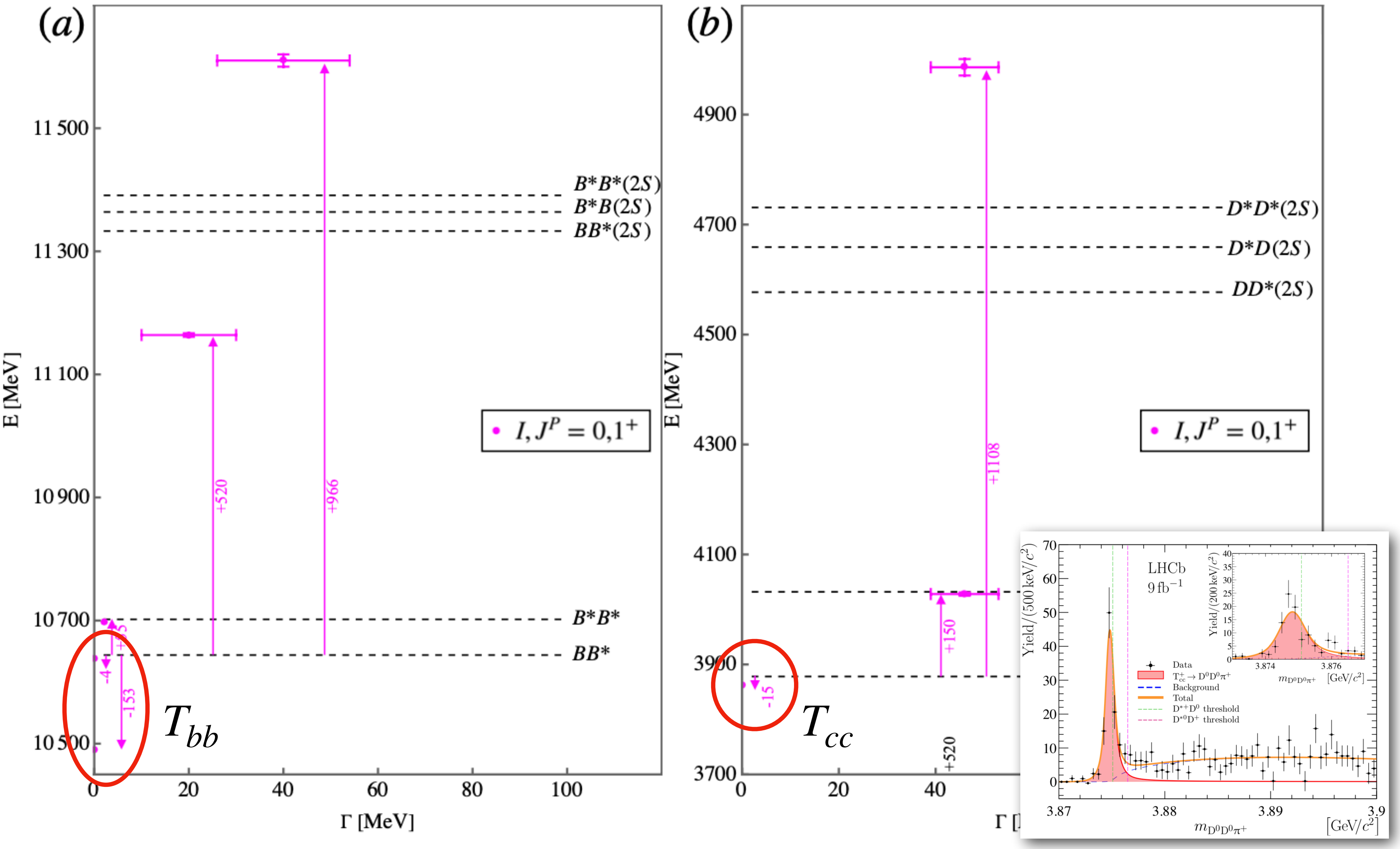
$bb\bar{b}\bar{b}$, $bb\bar{c}\bar{c}$ spectrum (no exp. data)

Similar resonance structures are seen but not low-lying resonances.





The same Hamiltonian applied to the doubly heavy tetraquarks, $T_{QQ} = QQ\bar{q}\bar{q}$ (I=0, 1+), and gives 2 $bb\bar{u}\bar{d}$ and 1 $cc\bar{u}\bar{d}$ bound states.

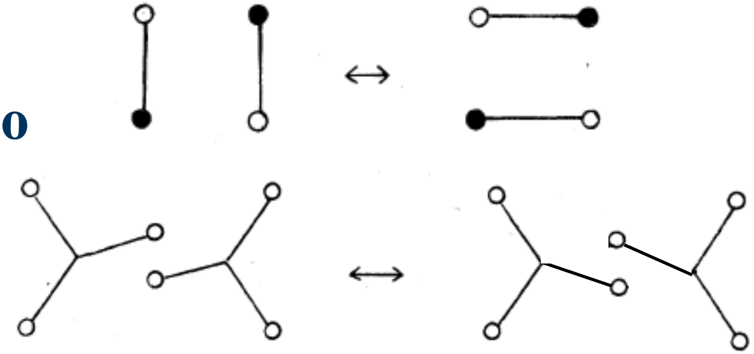


String confinement model

- “Reconnection of strings and quark matter”,
  H. Miyazawa, Phys. Rev. D20, 2953 (1979)

  “String Flip-Flop” model
  with reconnections of strings according to
  the spatial configuration of the quarks

  $$V_{\text{string}} = \sigma \times \min_{\text{links}} \sum r_{\text{link}}$$

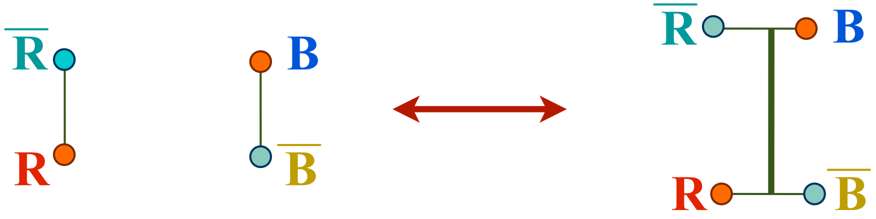


- Similar “string-type” confinement potential models for multi-quark systems were discussed by

  O.W. Greenberg, J. Hietarinta, Phys. Lett. B 86, 309 (1979)
  N. Isgur, J. E. Paton, Phys. Lett. B 124, 247 (1983)
  M. Oka, Phys. Rev. D 31, 2274 (1985).
  F. Lenz, et al., Annals Phys. 170, 65 (1986).
  Y. Koike et al., Nucl. Phys. A449, 635 (1986), PTP S137, 21 (2000).
  G.A. Miller, Phys. Rev D37, 2431 (1998).
  J. Vijande, A. Valcarce, J.M. Richard, Phys. Rev. D 85, 014019 (2012).

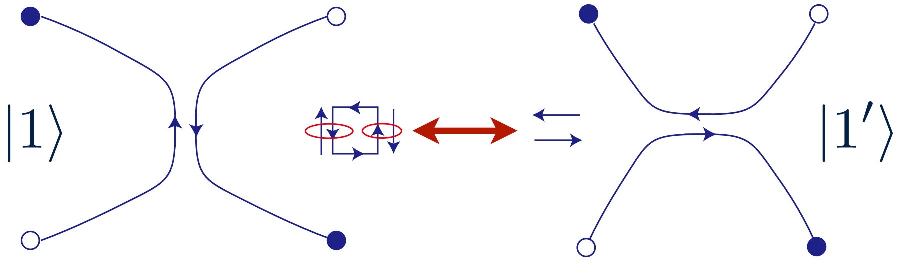
String flip-flop model

- **The string FF model works well for the U(1) charge, but for the color SU(3) theory, color recombination becomes nontrivial. Coupling of hidden color channels is unavoidable.**



Hidden Color channel

- **QCD predicts flip-flop in the *strong coupling expansion***



- **Two states are independent and transferred dynamically. This “string dynamics” can *not* be implemented in the conventional quark model.**

Quark model - color configurations

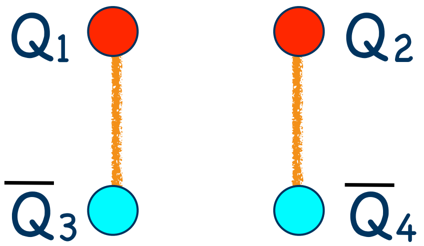
- **Only two independent color states are allowed in Quark Model.**

$$\mathbf{3}\otimes\mathbf{3}\otimes\bar{\mathbf{3}}\otimes\bar{\mathbf{3}}=\boxed{2\times\mathbf{1}}\oplus 4\times\mathbf{8}\oplus\mathbf{10}\oplus\overline{\mathbf{10}}\oplus\mathbf{27}$$

- **Color singlet Q_1 Q_2 Q_3^{bar} Q_4^{bar} system is described by**

Two singlets (mesons) states:

$$|1\rangle=|(Q_1\bar{Q}_3)_{\mathbf{1}}(Q_2\bar{Q}_4)_{\mathbf{1}}\rangle\quad|1'\rangle=|(Q_1\bar{Q}_4)_{\mathbf{1}}(Q_2\bar{Q}_3)_{\mathbf{1}}\rangle$$

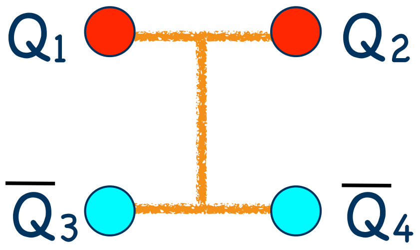


Singlet + hidden color states:

$$|1\rangle=|(Q_1\bar{Q}_3)_{\mathbf{1}}(Q_2\bar{Q}_4)_{\mathbf{1}}\rangle\quad|8\rangle=|(Q_1\bar{Q}_3)_{\mathbf{8}}(Q_2\bar{Q}_3)_{\mathbf{8}}\rangle$$

Diquarks with color 3^{bar} and 6:

$$|3\rangle=|(Q_1Q_2)_{\bar{\mathbf{3}}}(\bar{Q}_3\bar{Q}_4)_{\mathbf{3}}\rangle\quad|6\rangle=|(Q_1Q_2)_{\mathbf{6}}(\bar{Q}_3\bar{Q}_4)_{\bar{\mathbf{6}}}\rangle$$



- ***These bases are all equivalent.***

$$|1\rangle=\sqrt{\frac{1}{3}}|3\rangle+\sqrt{\frac{2}{3}}|6\rangle\qquad|8\rangle=-\sqrt{\frac{2}{3}}|3\rangle+\sqrt{\frac{1}{3}}|6\rangle$$

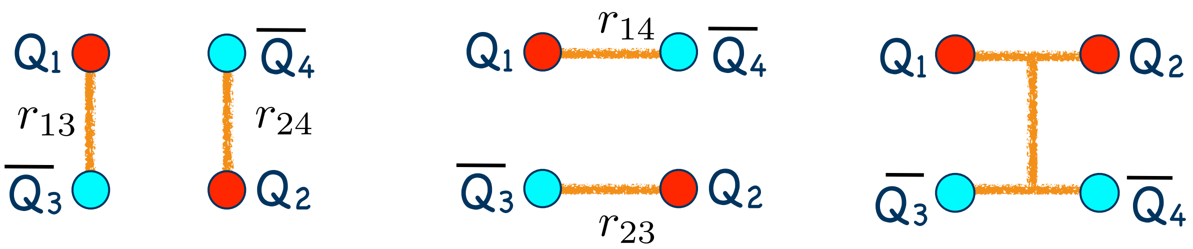
- **Two-meson states are not orthogonal.** $\langle 1|1'\rangle=\frac{1}{3}$

Novel string-like potential

- **If the quarks are the only carriers of color charges, the quark model does not have enough *freedom for color configurations*.**
- **We propose to extend the color Hilbert space of the quark model that can incorporate the color dynamics for multiquark systems.**

G.J. Wang, MO, D. Jido, Phys. Rev. D 108, L071501 (2023)

- **For a tetra-quark systems, we choose 3 color basis states:**



$$|\mathbf{1}\rangle\!\rangle \equiv |(Q_1 \to \bar{Q}_3)_1 (Q_2 \to \bar{Q}_4)_1\rangle$$
$$|\mathbf{1}'\rangle\!\rangle \equiv |(Q_1 \to \bar{Q}_4)_1 (Q_2 \to \bar{Q}_3)_1\rangle$$
$$|\mathbf{hc}\rangle\!\rangle \equiv |(Q_1 \leftrightarrow Q_2)_{\bar{3}} \leftarrow (\bar{Q}_3 \leftrightarrow \bar{Q}_4)_3\rangle$$

orthogonal bases

Novel string-like potential

- **The string confinement potential**

$$\langle\langle \mathbf{1}|V_{\mathrm{ST}}|\mathbf{1}\rangle\rangle = \sigma(r_{13}+r_{24}),$$

$$\langle\langle \mathbf{1}'|V_{\mathrm{ST}}|\mathbf{1}'\rangle\rangle = \sigma(r_{14}+r_{23}).$$

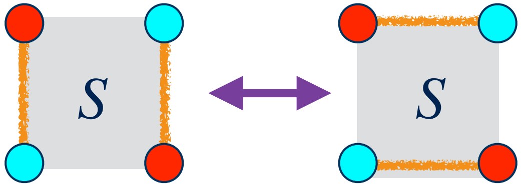
σ: string tension

- **Transitions by quantum tunneling filled the area by gauge field**

$$\langle\langle \mathbf{1}|V_{\mathrm{ST}}|\mathbf{1}'\rangle\rangle = \kappa e^{-\sigma S}$$

S: Minimal surface area

Y. Koike, O. Morimatsu, K. Yazaki, PTP S137, 21 (2000)

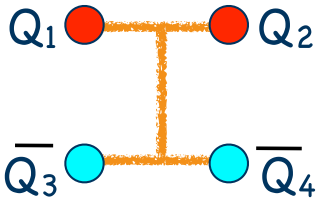


- **Confinement in $|\mathbf{hc}\rangle\rangle$ channel**

$$\langle\langle \mathbf{hc}|V_{\mathrm{ST}}|\mathbf{hc}\rangle\rangle = \sigma\left[\frac{r_{13}+r_{24}+r_{14}+r_{23}}{4}+\frac{r_{12}+r_{34}}{2}\right]$$

$$\langle\langle \mathbf{1}|V_{\mathrm{ST}}|\mathbf{hc}\rangle\rangle = \langle\langle \mathbf{1}'|V_{\mathrm{ST}}|\mathbf{hc}\rangle\rangle = \pm\kappa'\exp\left(-\sigma S\right)$$

$$\kappa' = \sqrt{8}\kappa$$

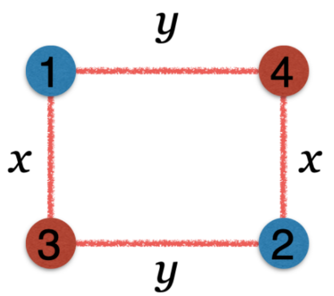


- **3-channel confinement potential (full 4-body potential)**

$$V_{\mathrm{ST}} = \begin{array}{c} \left(\begin{array}{ccc} \sigma(r_{13}+r_{24}) & \kappa e^{-\sigma S} & \kappa' e^{-\sigma S} \\ \kappa e^{-\sigma S} & \sigma(r_{14}+r_{23}) & -\kappa' e^{-\sigma S} \\ \kappa' e^{-\sigma S} & -\kappa' e^{-\sigma S} & \frac{\sigma}{4}[r_{13}+r_{24}+r_{14}+r_{23}+2(r_{12}+r_{34})] \end{array}\right) \end{array} \begin{array}{l} |\mathbf{1}\rangle\rangle \\ |\mathbf{1}'\rangle\rangle \\ |\mathbf{hc}\rangle\rangle \end{array}$$

Born-Oppenheimer effective potential

- **A rectangle configuration of $QQ\bar{Q}\bar{Q}$**



- **QM confinement for the non-orthogonal $|\mathbf{1}\rangle, |\mathbf{1}'\rangle$ bases**

$$V = \begin{pmatrix} 2\sigma x & (2/3)\sigma(x+y-\sqrt{x^2+y^2}) \\ (2/3)\sigma(x+y-\sqrt{x^2+y^2}) & 2\sigma y \end{pmatrix}$$

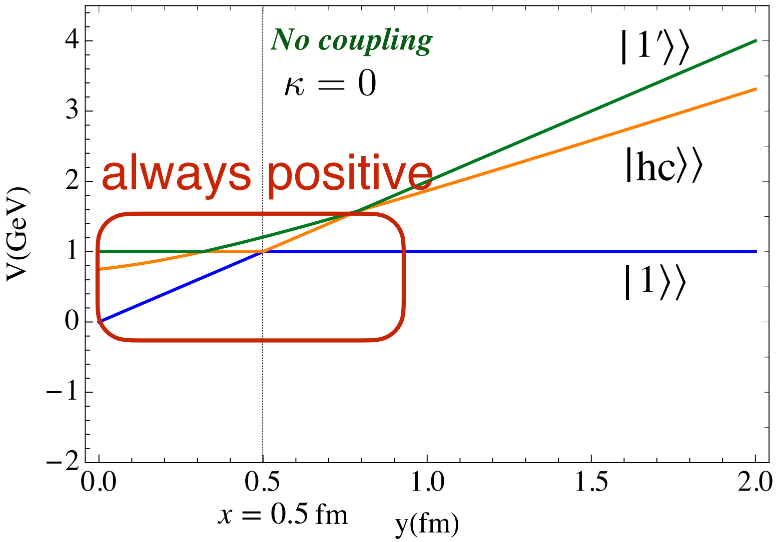
- **String confinement for the orthogonal $|\mathbf{1}\rangle\rangle, |\mathbf{1}'\rangle\rangle, |\mathbf{hc}\rangle\rangle$ bases**

$$V_{\mathrm{ST}}(x,y) = \begin{pmatrix} 2\sigma x & \kappa e^{-\sigma xy} & \kappa' e^{-\sigma xy} \\ \kappa e^{-\sigma xy} & 2\sigma y & -\kappa' e^{-\sigma xy} \\ \kappa' e^{-\sigma xy} & -\kappa' e^{-\sigma xy} & \sigma(\frac{x+y}{2}+\sqrt{x^2+y^2}) \end{pmatrix}$$

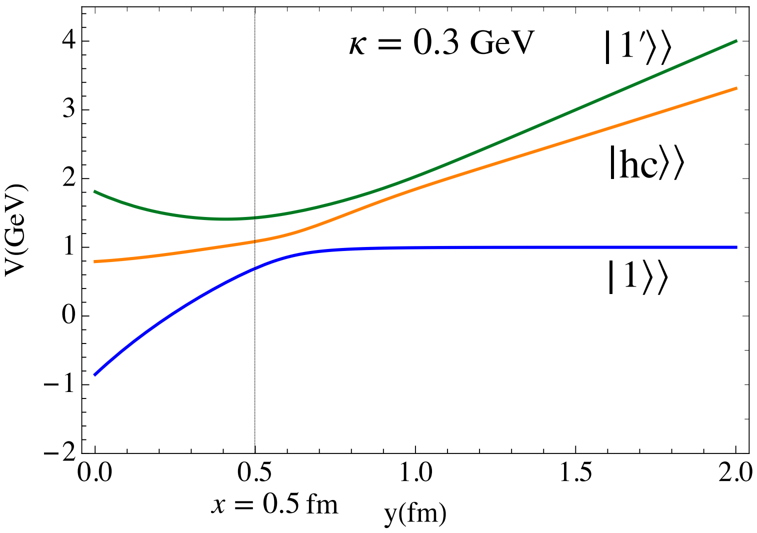
One free parameter κ $(\kappa' = \sqrt{8}\kappa)$

Born-Oppenheimer effective potential

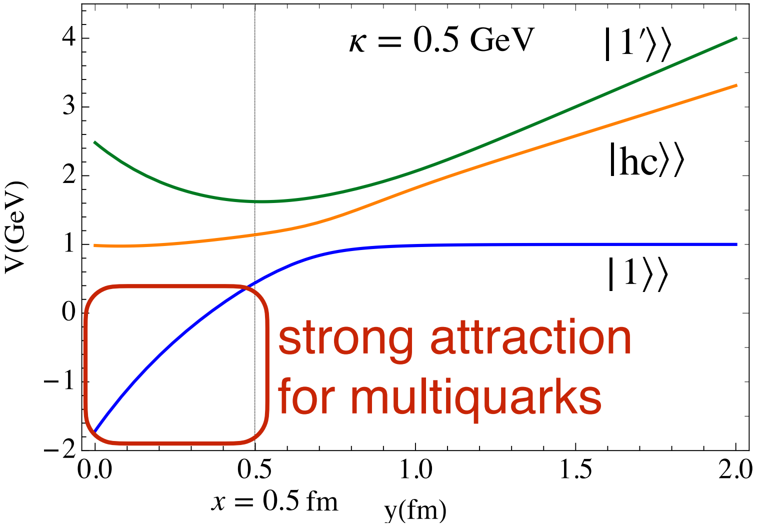
- **Novel String-like confinement: adiabatic potential at fixed *x***



always positive



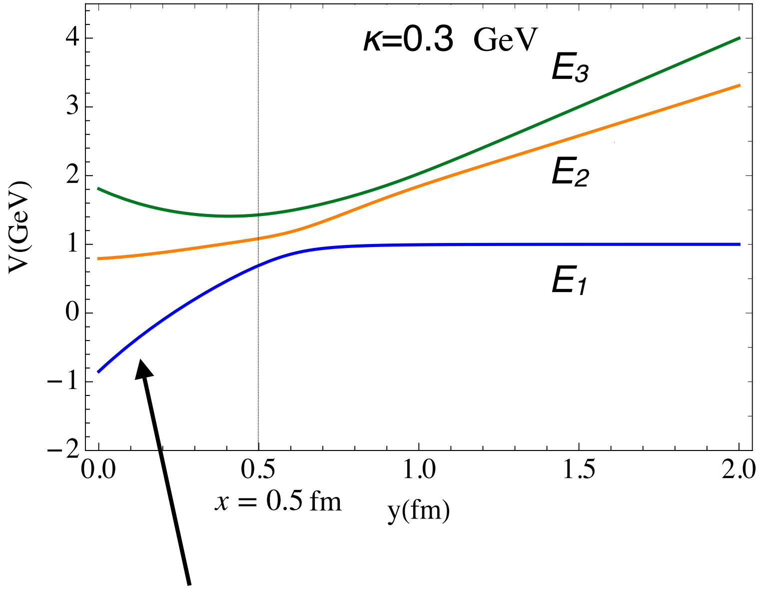
$$V_{\rm ST}(x,y) = \begin{pmatrix} 2\sigma x & \kappa e^{-\sigma xy} & \kappa' e^{-\sigma xy} \\ \kappa e^{-\sigma xy} & 2\sigma y & -\kappa' e^{-\sigma xy} \\ \kappa' e^{-\sigma xy} & -\kappa' e^{-\sigma xy} & \sigma(\frac{x+y}{2} + \sqrt{x^2+y^2}) \end{pmatrix}$$

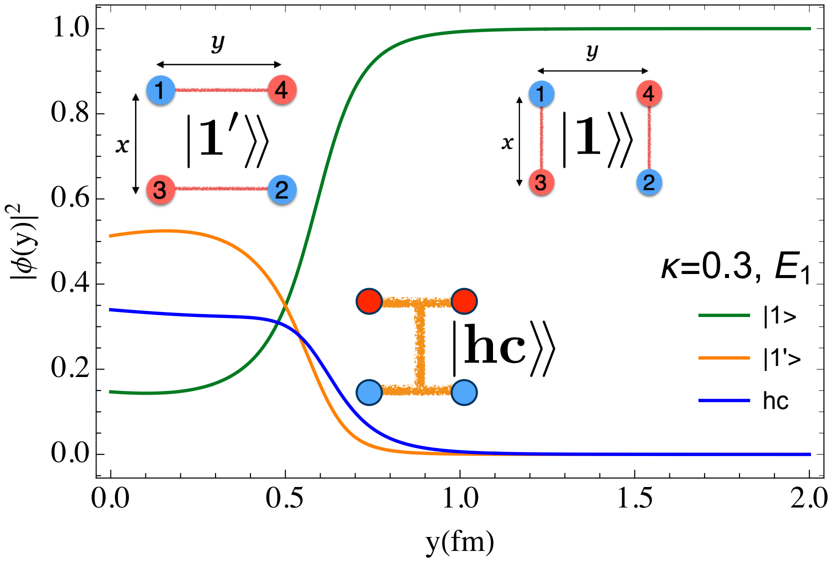


strong attraction
for multiquarks

Born-Oppenheimer effective potential

- **Novel String-like confinement: adiabatic potential at fixed *x***



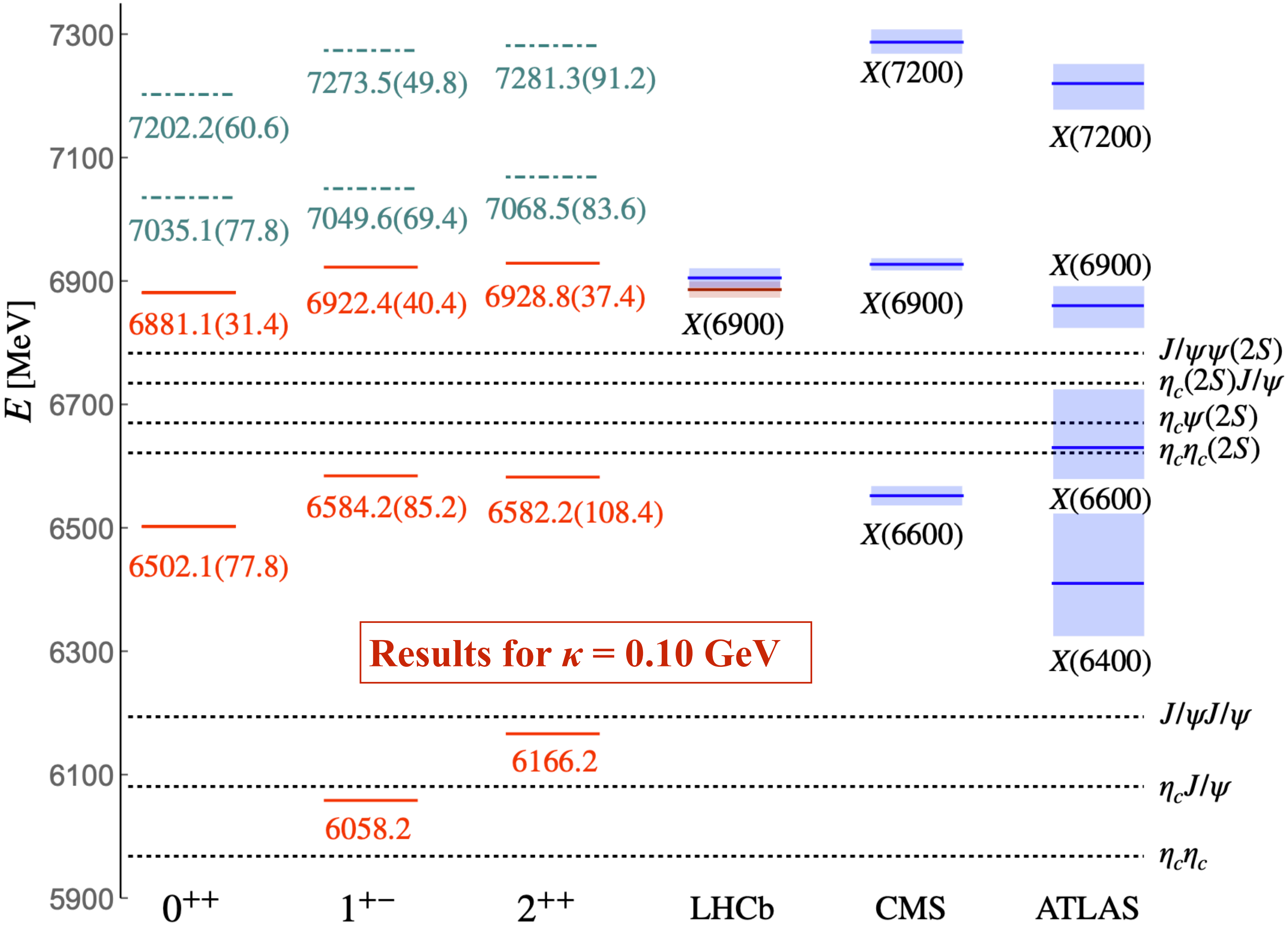


- **A short-range attraction due to the large mixing of the hidden color (hc) state. Compact tetra-quark configurations become important at short distances.**
- **The only free parameter *κ* will take a value in**

$$0 \leq \kappa' = \sqrt{8}\kappa \leq 2\sigma a \sim 2\sqrt{\sigma} \sim 1\text{GeV} \longrightarrow \quad \kappa \leq 0.3\text{GeV}$$

Tetra-charms with novel confinement

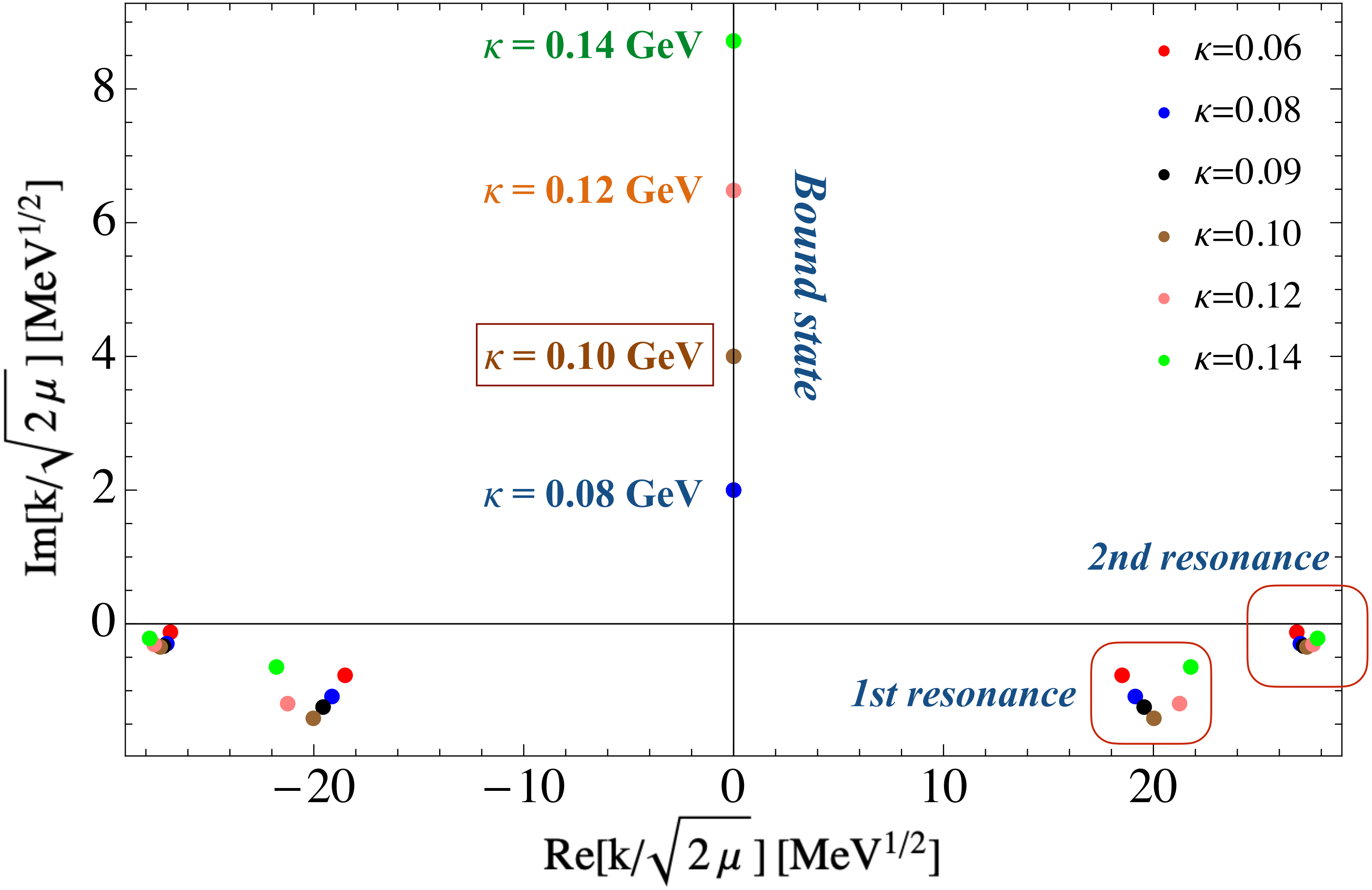
G.J. Wang, MO, D. Jido, Phys. Rev. D 108, L071501 (2023)



Results for $\kappa = 0.10$ GeV

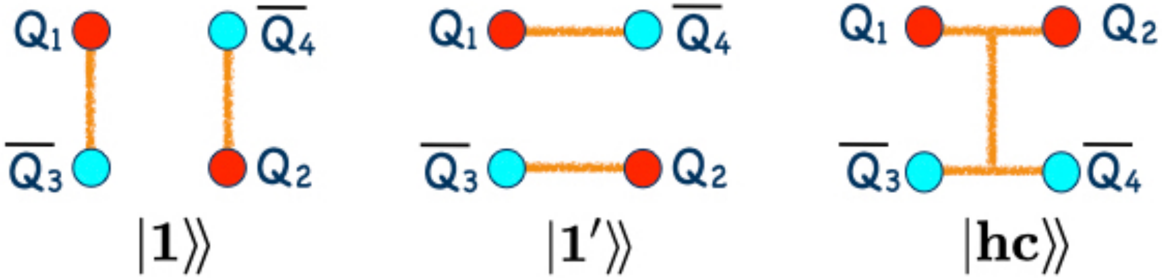
Tetra-charms with novel confinement

- **Pole positions of the 2^{++} charmed tetraquark in complex *k* plane**



Summary

- Confinement in the tetra(multi)-quark system is not trivial nor well established from the quark model viewpoints.
- String-like confinement potential is proposed by extending the color configuration space of the conventional quark model with a compact hidden-color state.



- Mixing of the $|\mathrm{hc}\rangle\!\rangle$ state induces strong attraction among the multi-quark systems.
- The model is applied to the fully-charmed tetra-quark system. A bound state appears due to the attraction of HC. Complex scaling method provides us with two or more resonances that seem consistent with experiment.