Hidden-charm Pentaquarks in Constituent Quark Models

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Exotic Hadrons

- **Hadron is a color-singlet composite of quarks and gluons.**

  q-qbar (meson): $3 \otimes \bar{3} = 1 \oplus 8$

  q-q-q (baryon) : $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$

- **and *MORE* . . .**

  g-g (glueball) : $8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus \overline{10} \oplus 27$

  q-qbar-g (hybrid): $3 \otimes \bar{3} \otimes 8 = 1 \oplus (3 \times 8) \oplus 10 \oplus \overline{10} \oplus 27$

  q^2-$qbar^2$ (tetra-quark):

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

  q^4-qbar (penta-quark): $3^4 \otimes \bar{3} = (3 \times 1) \oplus \ldots$

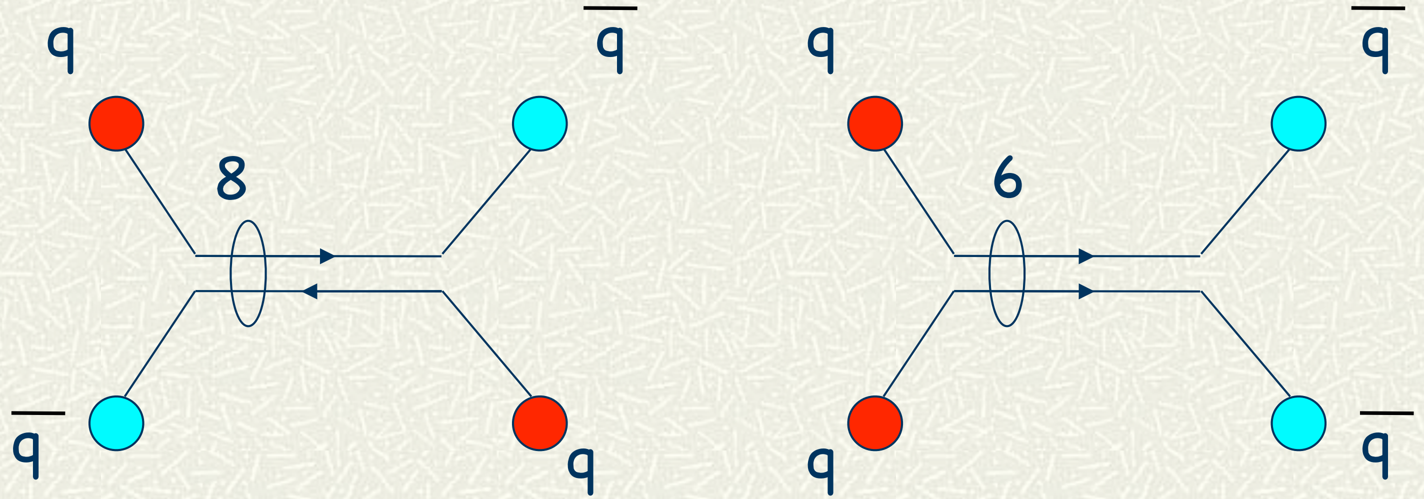
  q^6 (di-baryon) : $3^6 = (5 \times 1) \oplus \ldots$

Multi-Quark (MQ) dynamics

- **“Extrapolation” to MQ hadrons is not trivial.**
- **“Color Confinement” is a key in the MQ dynamics.**

Exotic Hadrons are “Colorful” ! (Lipkin@YKIS06)

$(qq^{bar})_8$ or $(qq)_6$ are allowed only in the MQ hadrons.



Novel Dynamics

What we learn from MQ hadrons?

- ***CONFINEMENT*** **of Quarks**

  What is the Mechanism and Dynamics of quark confinement?

  Modeling of confinement

  Bag model *v.s.* Potential model

- ***COUPLINGS*** **of Resonances to Hadronic states**

  How decay channels and widths are determined?

  Mechanisms of the strong decays

  Possibility of narrow resonances

Bag Model

- **MIT Bag Model:**
  Quarks (and gluons) are confined (and, in total, color-singlet) in a "Bag". The bag is self-sustained by the "bag energy".

- **Two conditions at the bag surface**

  \- ***No outflow of color from the surface*** $n \cdot j_c^\alpha|_{\text{surface}} = 0$

$$j_c^{\alpha\mu} = \bar{q}\gamma^\mu \frac{\lambda^\alpha}{2} q + (\text{gluon color current})$$

  \- ***Pressure balance of two phases*** $P_{\text{in}} = P_{\text{out}}$

$$P_{\text{in}} = (\text{pressure by quarks and gluons})$$

$$P_{\text{out}} = (\text{pressure by the bag energy})$$

$$E_{\text{bag}} = BV$$

Bag Model

- **Energy of the hadron containing massless quarks**

$$E(R) = B\frac{4\pi R^3}{3} + \sum_i E_i = \frac{4\pi B R^3}{3} + \sum_i \frac{\omega_i}{R}$$

$$\frac{dE(R)}{dR} = B4\pi R^2 - \frac{\sum_i \omega_i}{R^2} = 0 \longrightarrow R(n) = \left(\frac{n\omega}{4\pi B}\right)^{1/4}$$

$$E_n = E(R(n)) = (\mathrm{const}) \times B^{1/4} n^{3/4}$$

- **E_n is a convex function of n, that is $E_{2n} < 2E_n$. If there is no other interaction, the binding energy is larger as the size of the system gets larger.**
- **The energy scale is $B^{1/4} \sim 200$ MeV. It is not surprising to have a bound state of binding energy ~ 100-200 MeV.**

Potential Model

- **Two-body confinement forces**
  - **Force without color-cluster saturation is *no good*.**

$$V = \sum_{i<j} v(r_{ij}) \longrightarrow \langle V \rangle \sim \frac{n(n-1)}{2} \langle v \rangle \quad \text{~ gravity}$$

  - **Spin-independent color-saturated force is linear in *n*.**

$$V = -\sum_{i<j} (\lambda_i^c \cdot \lambda_j^c) v(r_{ij}) \longrightarrow \langle V \rangle \sim \frac{8}{3} n \langle v \rangle$$

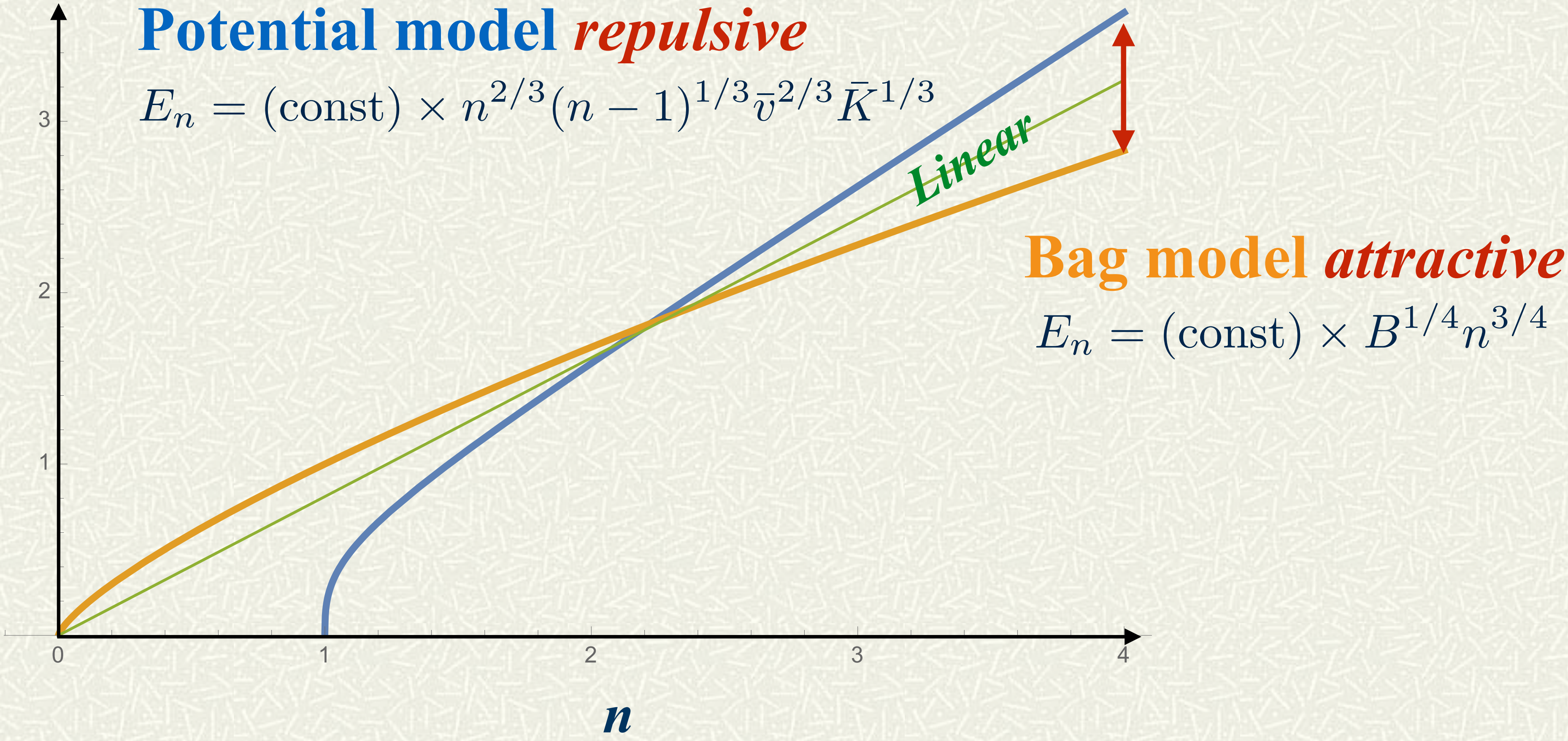
  - ***R* determined by the energy minimum**

$$E(R) = \langle K + V \rangle \sim \frac{n-1}{R^2} \bar{K} + n\bar{v}R$$

$$E_n = (\text{const}) n^{2/3} (n-1)^{1/3} \bar{v}^{2/3} \bar{K}^{1/3}$$

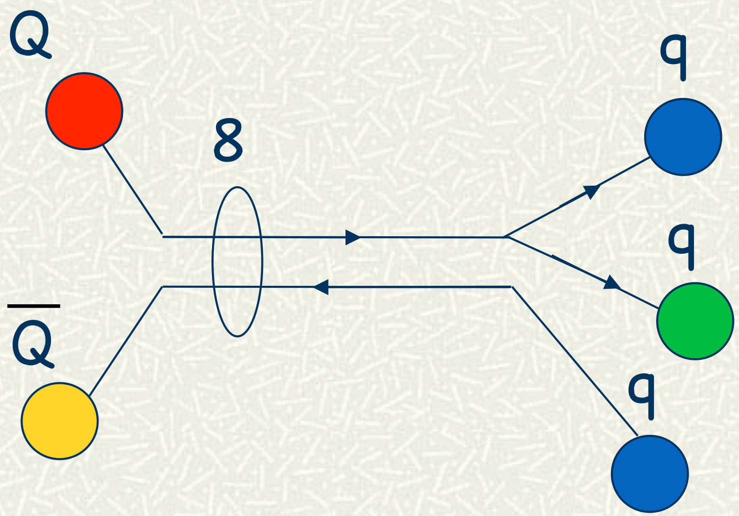
Bag model *v.s.* Potential model

- ***n*** **dependences**



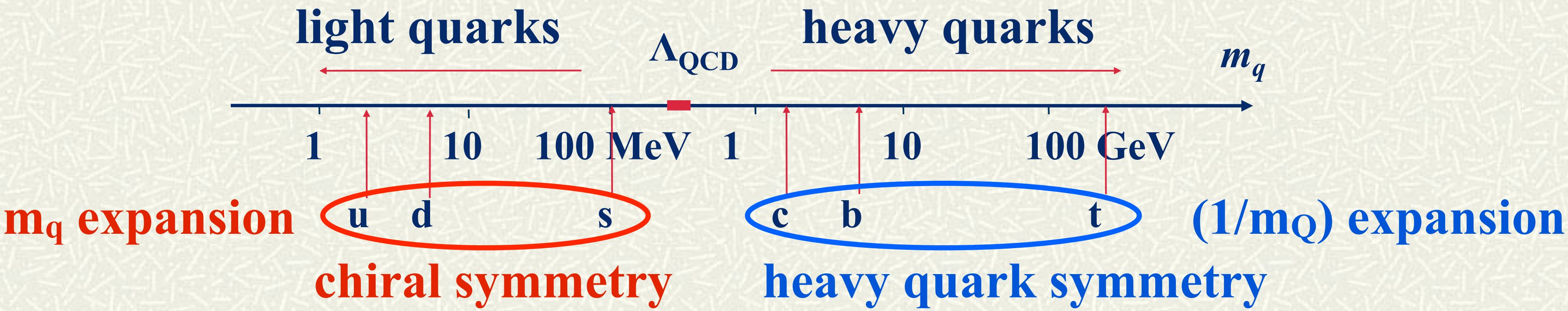
Exotic MQ states

- To look for "stable" (or narrow) multi-quark states, we consider "colorful" configurations.
- ***Hidden Charm Pentaquarks*** **are cases in which the** ***color-octet*** **"baryon" might be stabilized with the help of** ***color-octet*** **heavy "quarkonium".**



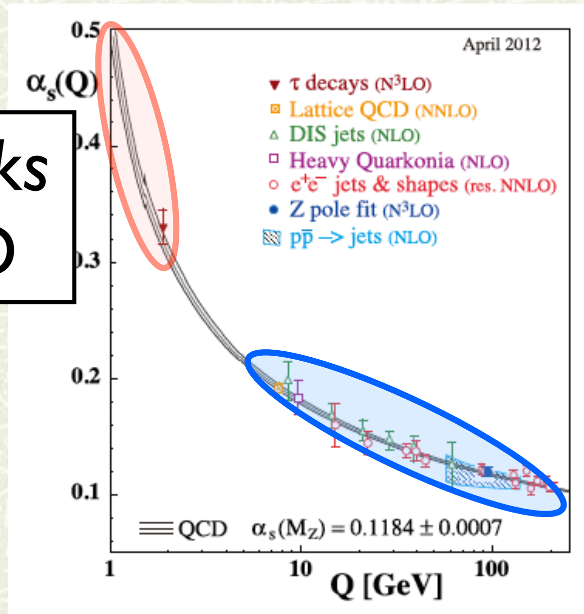
Heavy Quark

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



- Light quarks are nonperturba
- Heavy quar
perturbative/ non-relativistic.

Light and Heavy quarks look different in QCD



Charmonium

- The quark model gives very good guidelines to classify and interpret the hadron spectrum.

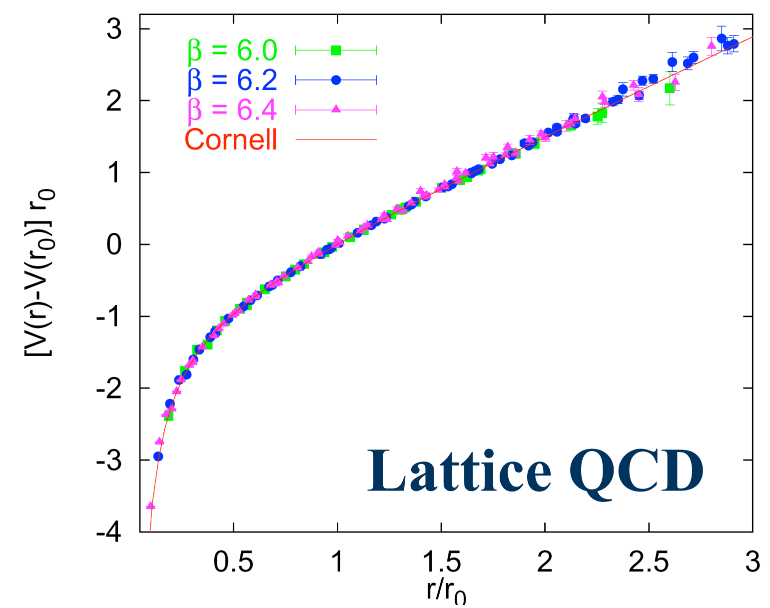
  The charmonium spectrum is a textbook example.
  "hydrogen atom" in QCD

- The Hamiltonian with a Linear + Coulomb potential

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

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

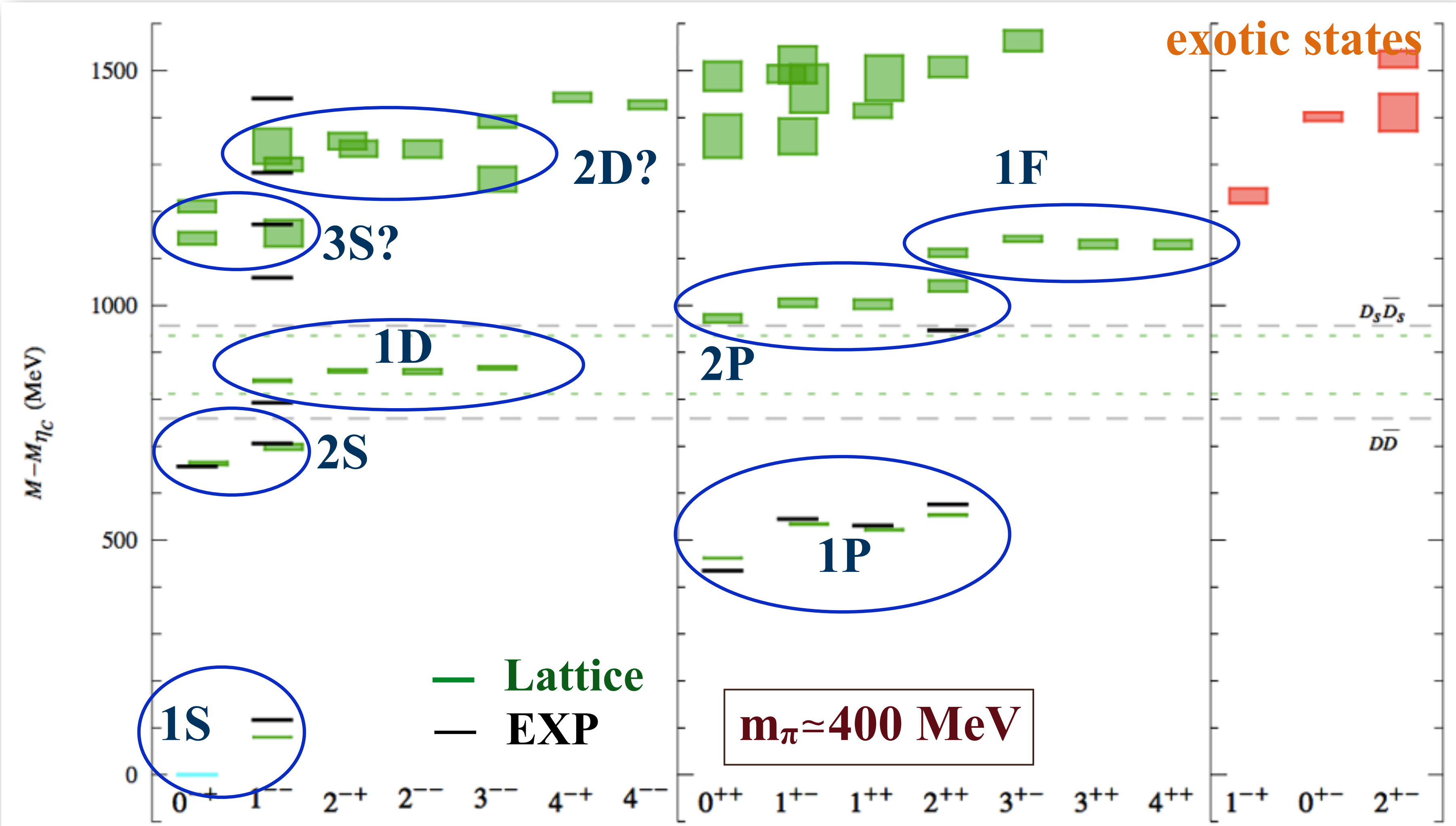
gives a good fit to the 1S, 1P, 2S, . . charmonium (and bottomonium) states.



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

Charmonium

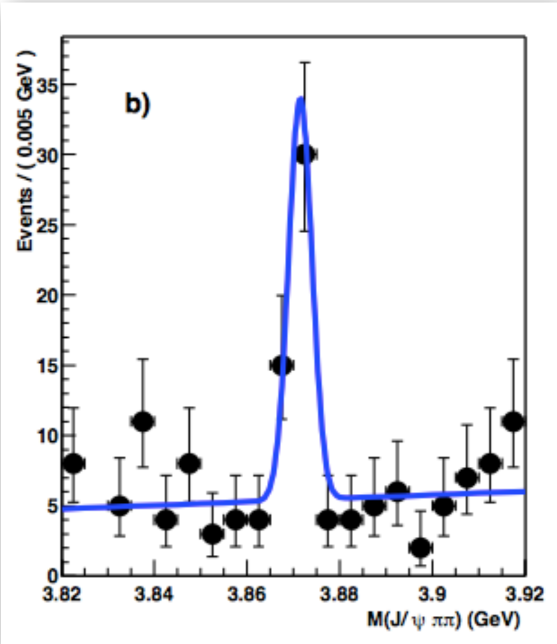
Liuming Liu, et al. (Hadron Spectrum Collaboration)
JHEP 07, 126 (2012)



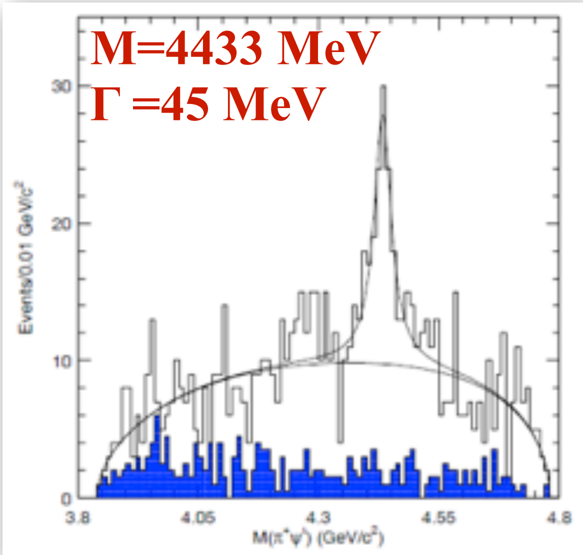
HQ Exotic Hadrons

- X(3872) found in 2003 by Belle (KEK)
  → *not reproduced by lattice QCD using only q-q^{bar} operators.*
- Z(3900), Z(4430) etc. : charged hidden charm states

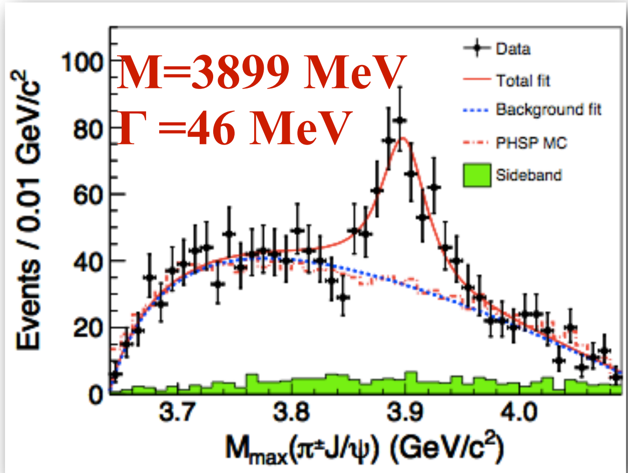
X(3872)	Z_c^+(4430)	Z_c^+(3900)
Belle	*Belle*	*BES III*



PRL 91 (2003) 262001



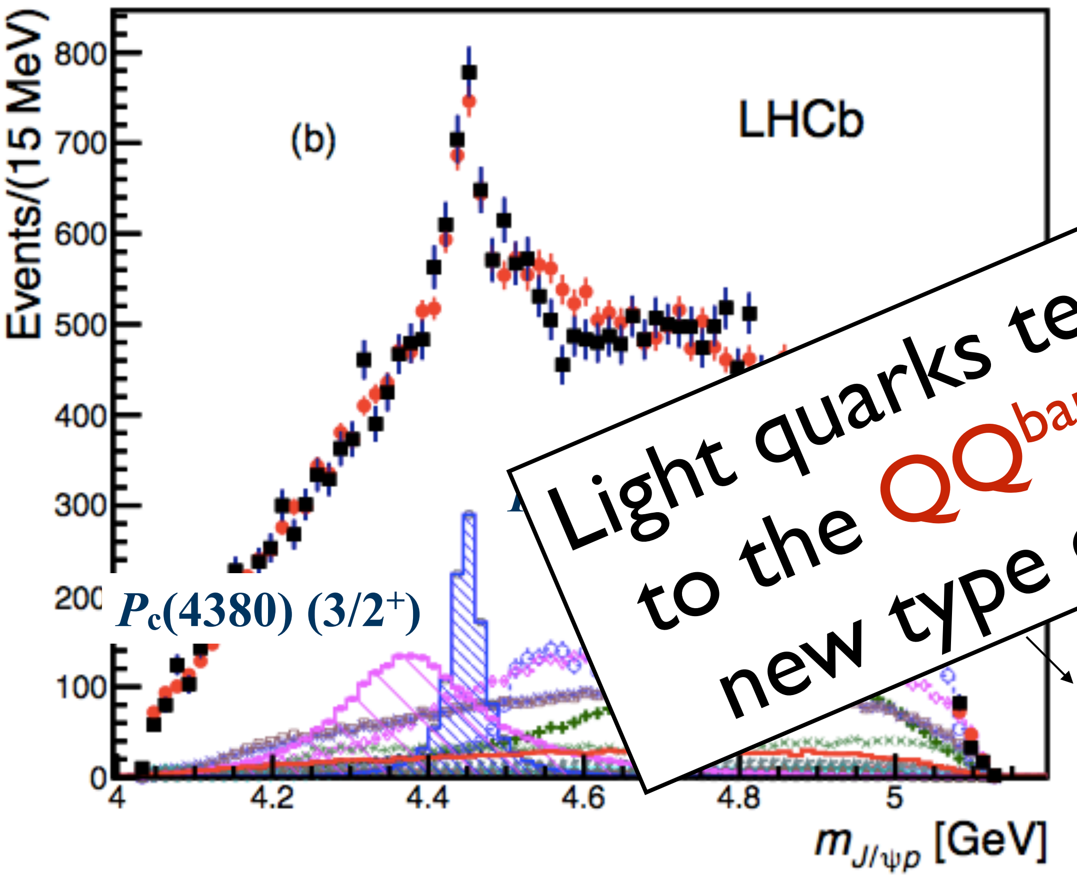
PRL 100 (2008) 142001



PRL 110 (2013) 252001

Hidden Charm Pentaquark P_c

- $P_c \rightarrow J/\psi + p$ ($cc\bar{u}ud$)
  LHCb (*PRL 115 (2015) 07201*) found two penta-quark states with hidden $c\bar{c}$.



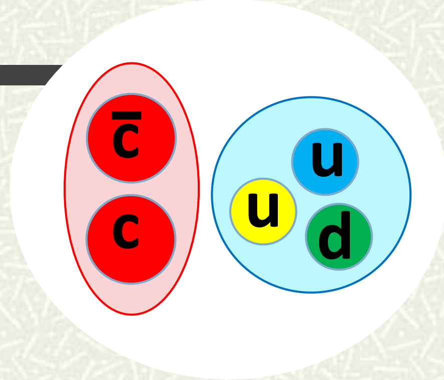
Light quarks tend to stick to the QQ^{bar} forming a new type of hadrons.

Hidden Charm Pentaquark P_c

Constituent quark model analyses

- **Study of qqq cbar c five quark system with three kinds of quark-quark hyperfine interaction,**
  S.G. Yuan, K.W. Wei, J. He, H.S. Xu, and B.S. Zou,
  Eur. Phys. J. A 48 (2012) 61
- **The hidden charm pentaquarks are the hidden color-octet uud baryons?**
  Sachiko Takeuchi, Makoto Takizawa,
  Physics Letters B 764 (2017) 254–259
- **Flavor-singlet charm pentaquark**
  Yoya Irie, Makoto Oka and Shigehiro Yasui,
  in preparation
- **Hidden-charm pentaquark with strangeness**
  Sachiko Takeuchi, Makoto Oka
  in preparation

Hidden Charm Pentaquark P_c



- **color 1 $c\bar{c}$**

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

  56 = (8, 1/2) + (10, 3/2)

  (8,1/2) Δ_{CM} = -8 $c\bar{c}$ uud (udd) = η_c/J/ψ+p

  (10,3/2) Δ_{CM} = 8

- **color 8 $c\bar{c}$**

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

  (1,1/2) Δ_{CM} = -14 P_{cs}= $c\bar{c}$ uds = η_8/ψ_8+ Λ_8(singlet)

  (8,1/2) Δ_{CM} = -2 η_8/ψ_8+ N_8

  The most favored state with $c\bar{c}$ by CMI may not be J/ψ + p.

- **P_{cs} family (I=0, Str= -1)**

  $(c\bar{c})_{8,J=1}$ + $(uds)_{8,\,J=1/2}$ $J^\pi = 1/2^-, 3/2^-$

  $(c\bar{c})_{8,J=0}$ + $(uds)_{8,\,J=1/2}$ $J^\pi = 1/2^-$

Flavor Singlet Pentaquark P_{cs}

- **Potential Quark Model**

Linear confinement with color Casimir dependence

$$V_{\rm conf} = \sum_{i<j} -\sigma(\lambda_i \cdot \lambda_j) r_{ij}$$

Coulomb electric interaction from one-gluon-exchange

$$V_{\rm Coulomb} = \sum_{i<j} \frac{\alpha_s}{4 r_{ij}} (\lambda_i \cdot \lambda_j)$$

Color magnetic spin-spin interaction from OGE

$$V_{\rm CMI} = -\frac{\alpha_s}{4} \sum_{i<j} \frac{\pi}{m_i m_j} (\lambda_i \cdot \lambda_j) \left[1 + \tfrac{2}{3} \sigma_i \cdot \sigma_j\right] \delta(r_{ij})$$

Non-relativistic quarks with

$$m(u,d) = 313\,{\rm MeV} \quad m(s) = 522\,{\rm MeV}$$

Instanton Induced Interaction

Instanton： **Classical solution of 4-dim. Euclidian QCD**

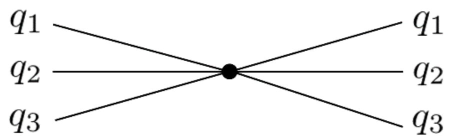
Light quarks couple with instanton → **Effective point-like interaction of light quarks (KMT)**

3-body interaction

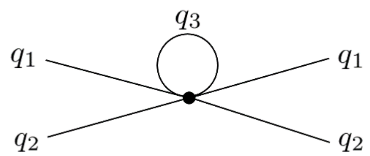
$$V_{\mathrm{III3}} = V_0 \frac{189}{40} \sum_{(ijk)} \mathcal{A}_3^f \left[1 - \frac{1}{7} (\sigma_i \cdot \sigma_j + \sigma_j \cdot \sigma_k + \sigma_k \cdot \sigma_i) \right] \delta(r_{ij}) \delta(r_j k)$$

2-body interaction

$$V_{\mathrm{III2}} = U_0^{(2)} \frac{15}{8} \sum_{i<j} \mathcal{A}_2^f \frac{1}{m_i m_j} \left[1 - \frac{1}{5} \sigma_i \cdot \sigma_j \right] \delta(r_{ij})$$



The 3-body III is *repulsive* for flavor singlet u-d-s systems

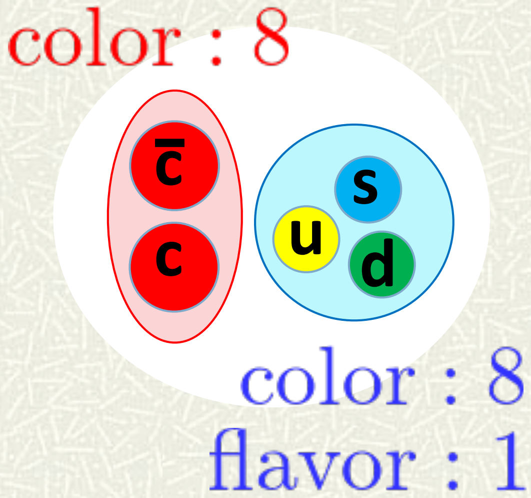


2-body III

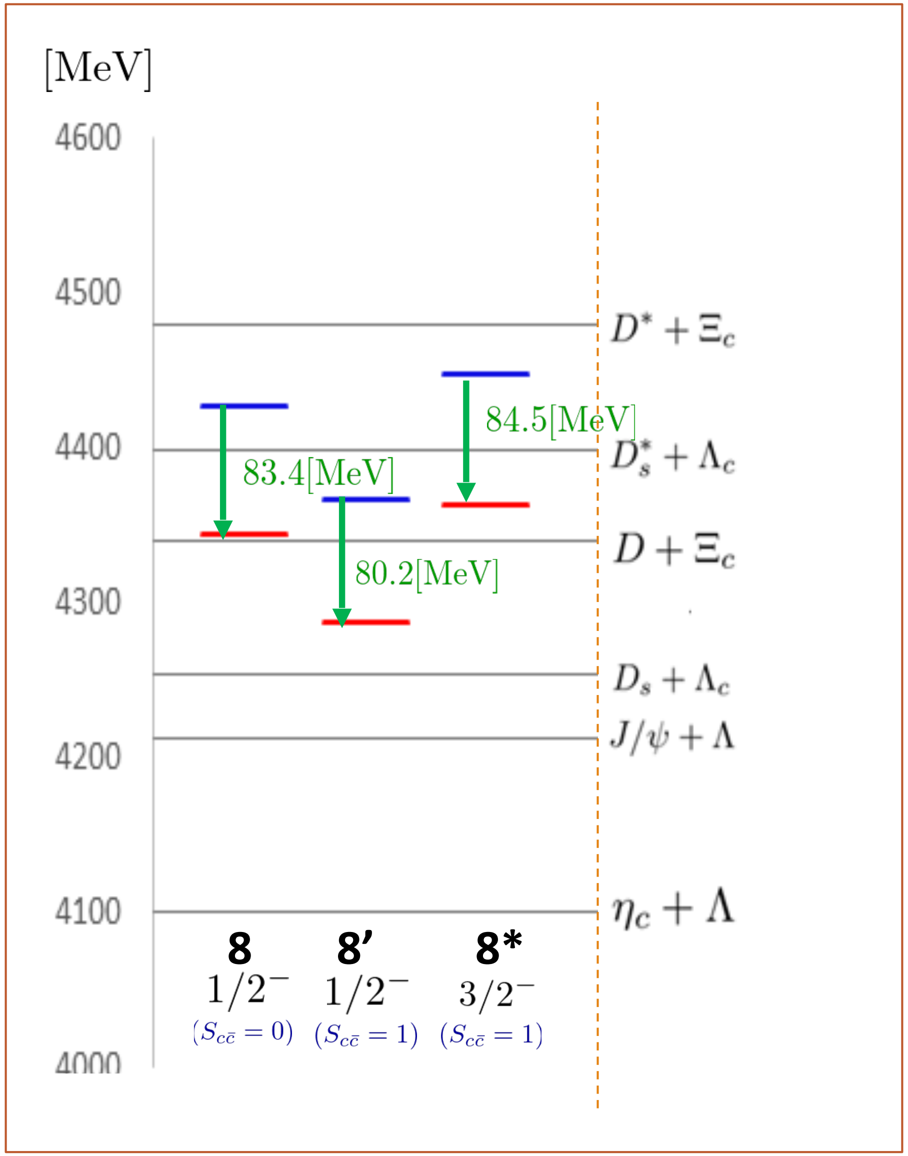
Flavor Singlet Pentaquark P_{cs}

- **P_{cs} family (I=0, Str= -1)**

(I, J^P)	octet type ($\mathbf{8}$)					
		component	color	spin	flavor	isospin
$(0, 1/2^-)$	$\mathbf{8}$	$c\bar{c}$	$\mathbf{8}$	0	—	—
		uds	$\mathbf{8}$	1/2	$\mathbf{1}$	0
$(0, 1/2^-)$	$\mathbf{8}'$	$c\bar{c}$	$\mathbf{8}$	1	—	—
		uds	$\mathbf{8}$	1/2	$\mathbf{1}$	0
$(0, 3/2^-)$	$\mathbf{8}^*$	$c\bar{c}$	$\mathbf{8}$	1	—	—
		uds	$\mathbf{8}$	1/2	$\mathbf{1}$	0



Energy Spectrum (Preliminary)



Y. Irie, S. Yasui. M. Oka

A variational method is used for a qualitative evaluation of the spectrum.

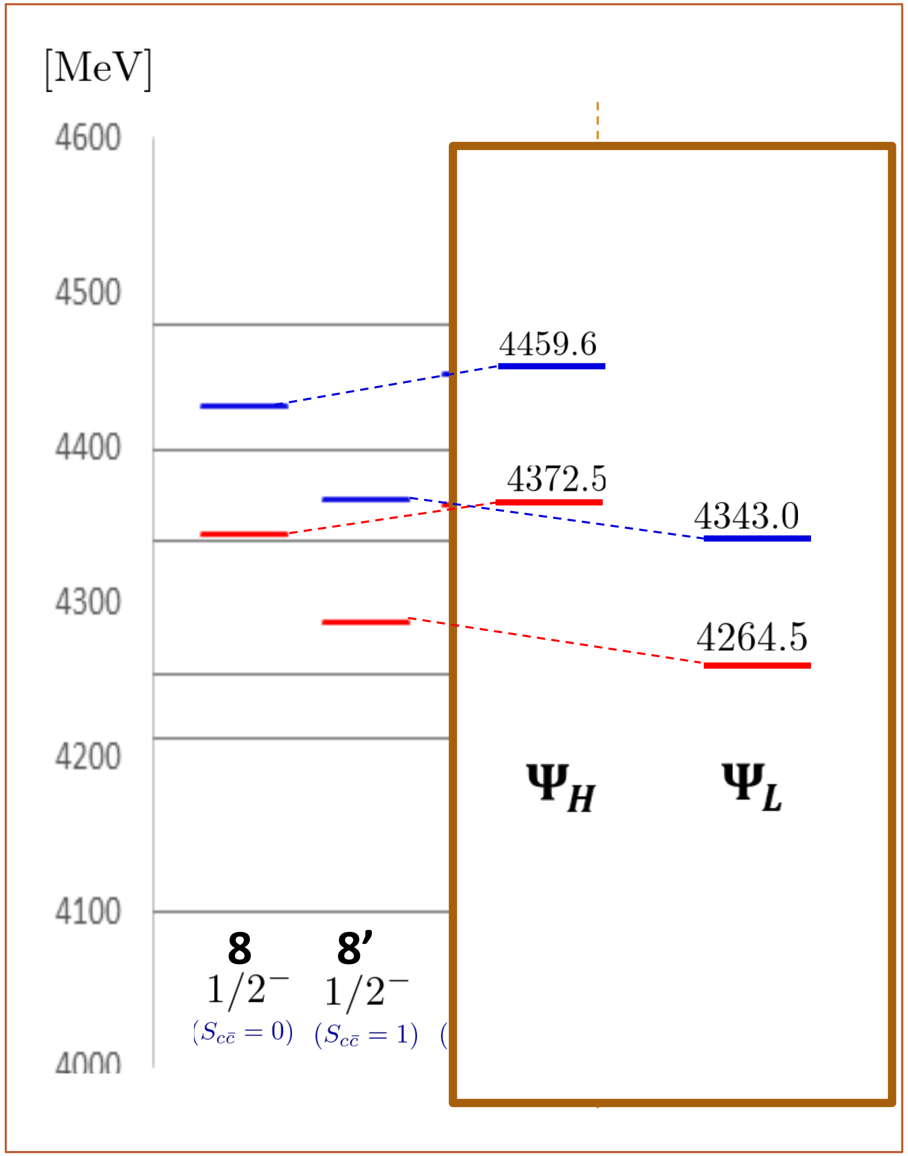
The lowest energy state is **8'**.

$$(1/2^-, S_{c\bar{c}} = 1)$$

The instanton induced interaction lowers the masses by about 80 MeV.

Two $1/2^-$ states mix by the CMI.

Energy Spectrum (Preliminary)



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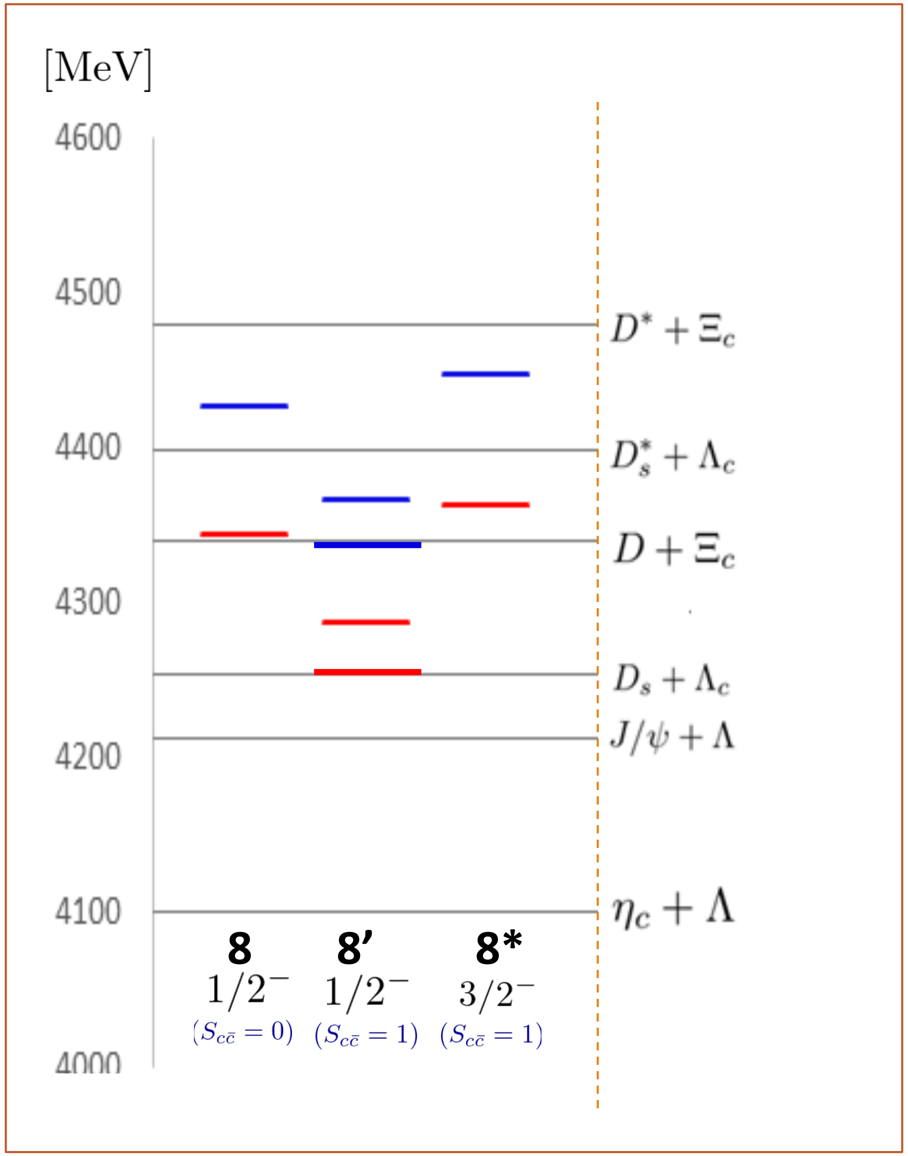
Decays



Y. Irie, S. Yasui. M. Oka

$\eta_c(J/\psi) + \Lambda$

Flavor SU(3) : suppressed

$D_s + \Lambda_c$

(barely) allowed

8* : D-wave decay

$D_s^* + \Lambda_c$

8* : S-wave decay

With Instantons

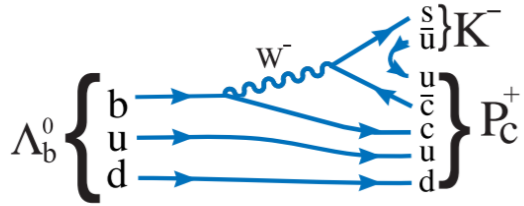
→ forbidden

Production

$Pc(4380), Pc(4450)$

$\Lambda_b^0(bud) \rightarrow Pc^+ + K^-$

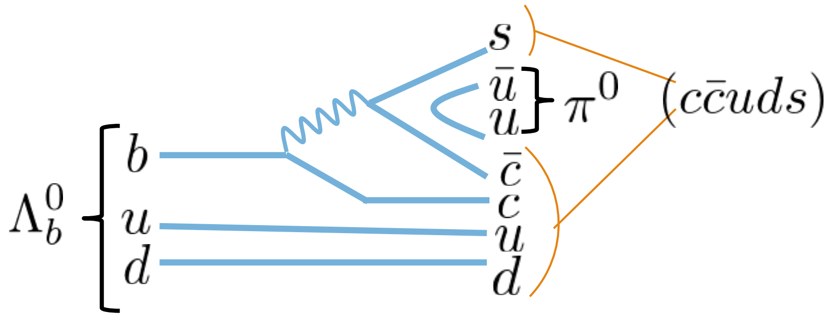
$Pc^+ \rightarrow J/\Psi + p$



R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. 115, 072001 – Published 12 August 2015

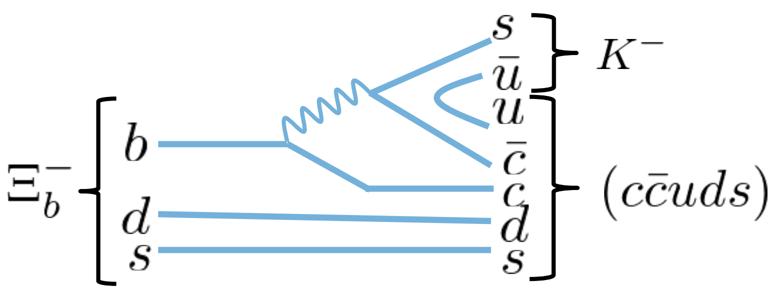
$\Lambda_b^0(bud) \rightarrow (c\bar{c}uds) + \underline{\pi^0}$

no charge



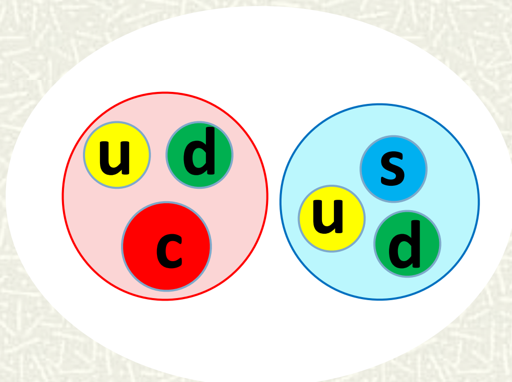
$\Xi_b^-(bds) \rightarrow (c\bar{c}uds) + \underline{K^-}$

minus charge!

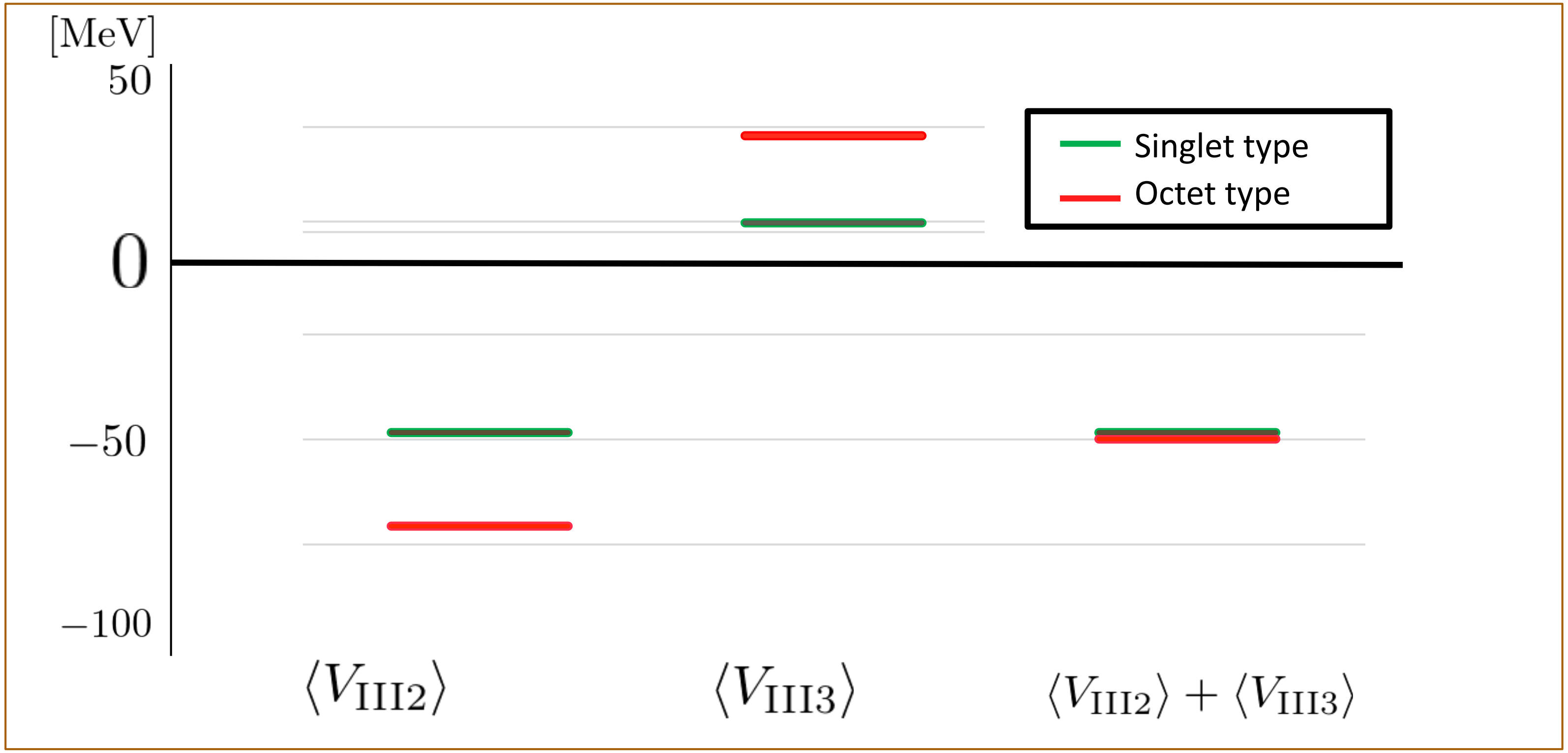


Conclusion+

- Exotic (MQ) hadrons can be keys for understanding the mechanisms of
  - CONFINEMENT – novel color configurations
  - HADRON COUPLINGS/ INTERACTIONS
- Pentaquarks
  Hidden-charm pentaquarks
  $P_c = c\bar{c}qqq$ (flavor octet),
  $P_{cs} = c\bar{c}uds$ (flavor singlet)
- Other possibilities
  $P_{c\bar{s}} = c\bar{s}qqq$ (Diakonov)
- Hexaquarks (aka Dibaryon)
  $H=q^6=(uuddss)$ (flavor singlet)
  $H_c=(cuudds)=(cud\ uds)$ (flavor 3bar)



Contributions of III



Two-Body III

more attractive in color octet

Three-Body III

repulsive in color octet

Total

Net effects are almost the same

Contributions of CMI

$$V_{\rm CMI} = -\frac{\alpha_s}{4}\sum_{i<j}\frac{\pi}{m_i m_j}(\lambda_i\cdot\lambda_j)\left[1+\tfrac{2}{3}\sigma_i\cdot\sigma_j\right]\delta(r_{ij})$$

The CMI between the HQ and LQ modifies the masses.