Structure of 5-quark Systems in Chiral Quark Model

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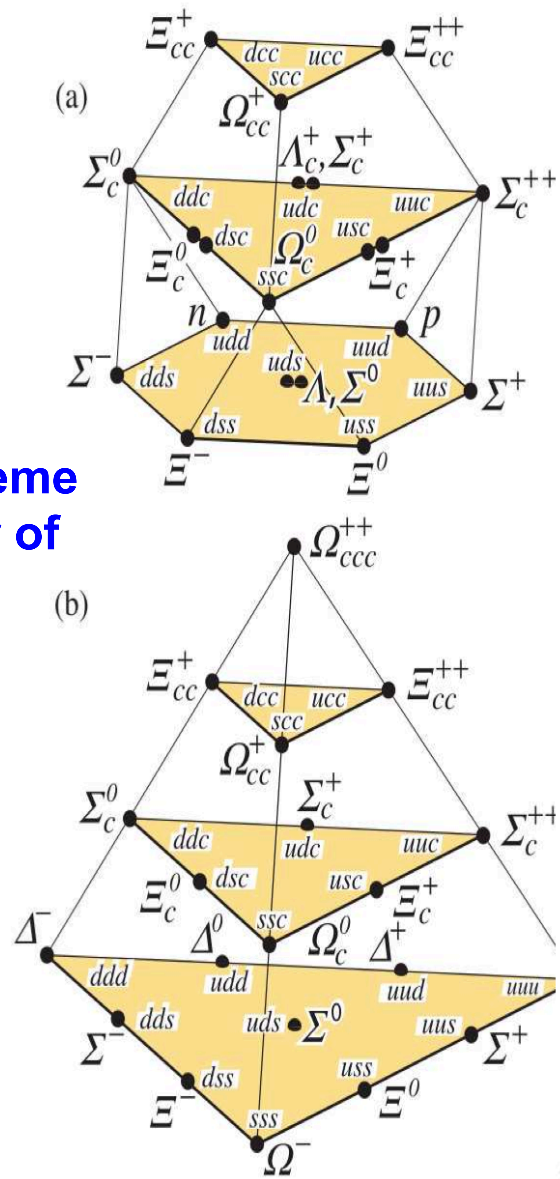
Outline:

- Introductions
- ChQM and calculation methods
- Review on P_c^+ and Ω_c^0 from the LHCb collaboration
- 5-quark study in nucleon sector
- Summary

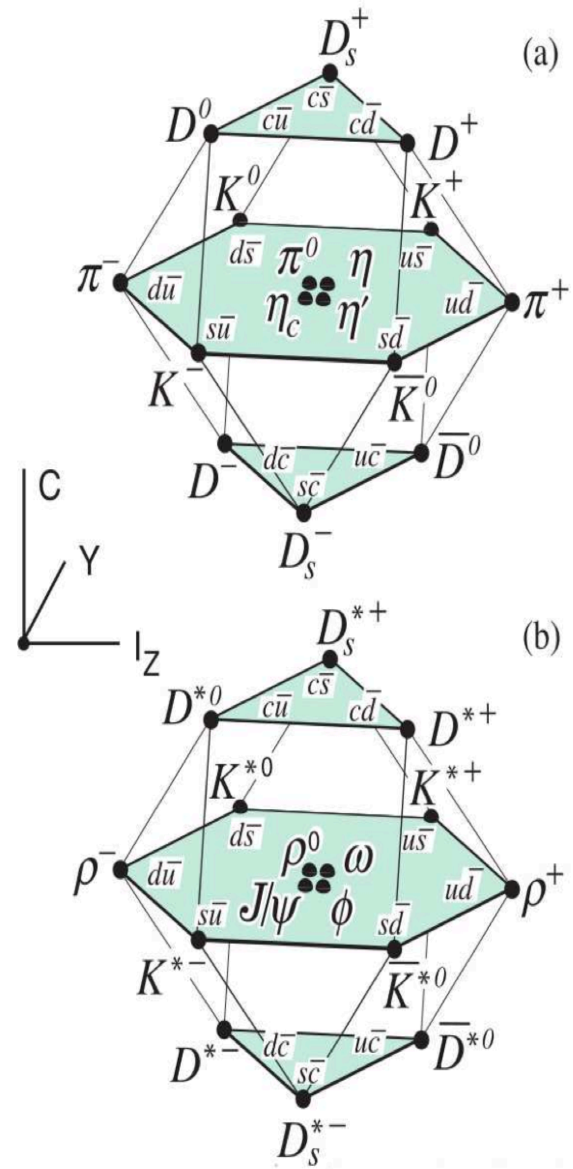
Introduction

Successful classification scheme organizing the large number of conventional hadrons

Baryons



Mesons



$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$

$$3 \otimes \bar{3} = 8 \oplus 1$$

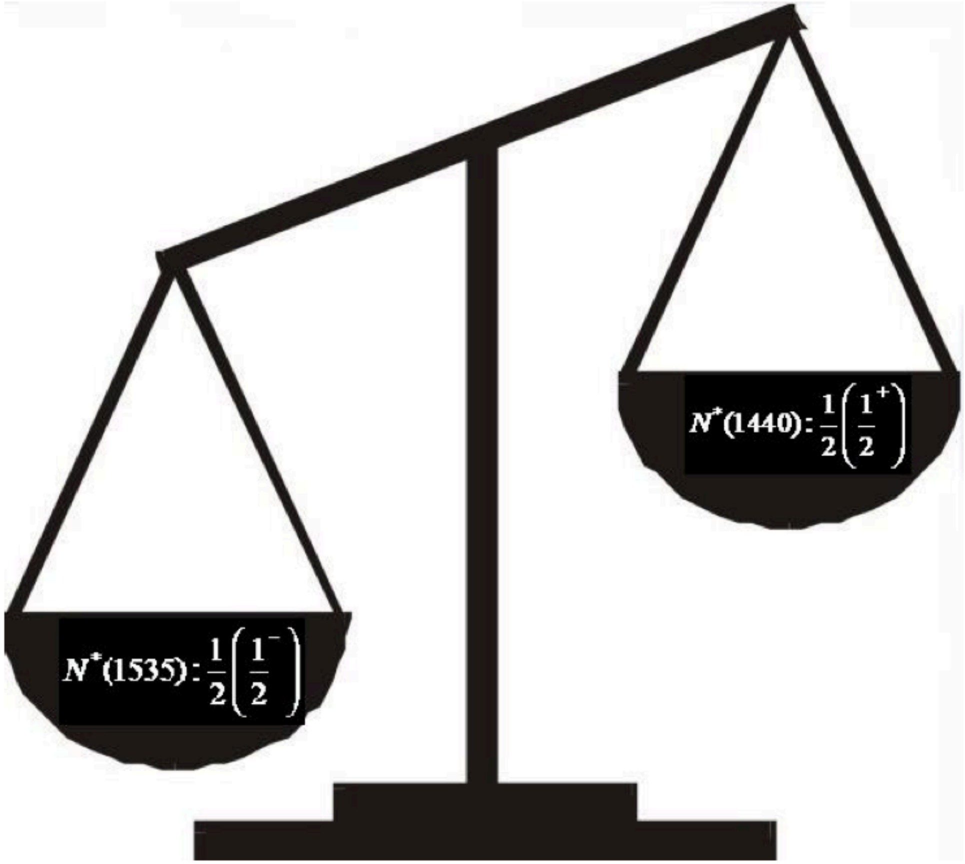
- **Mass order reverse**

V. D. Burkert, C. D. Roberts,
arXiv: 1710.02549 [nucl-ex]

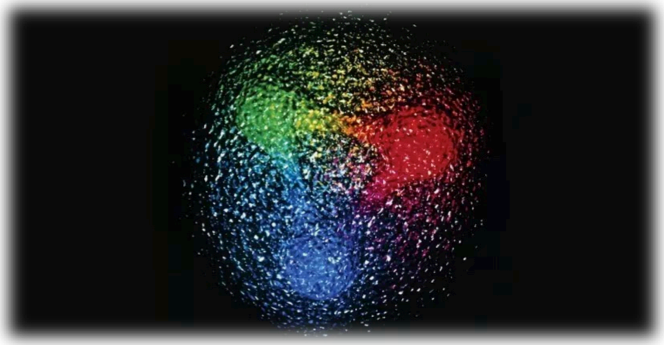
$$E_{SHO} = \left(2n + L + \frac{3}{2}\right)\hbar\omega$$

$$E_{n=0,\, L=1} < E_{n=1,\, L=0}$$

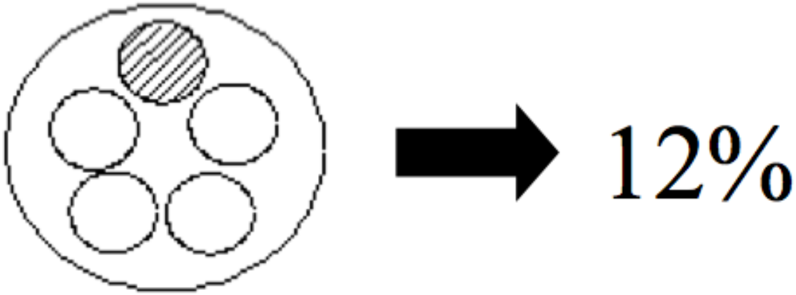
Roper resonance puzzle



- $\bar{u}$ **and** $\bar{d}$ **asymmetry**



$$\bar{d} - \bar{u} \approx 0.12$$



Garvey G T, Peng J C., Prog. Part. Nucl. Phys., 2001, 47: 203.

- **More exotic states**

$\Lambda(1405)$ uds (Pwave) ; [ud][su] $\bar{u}$

$\Lambda(1670)$ uds (Pwave) ; [us][ds] $\bar{s}$

Zou *et al*, NPA835 (2010) 199 ; CLAS, PRC 87(2013) 035206

Dibaryon: H, d*, $N-\Omega$, $\Omega-\Omega$ ...

J. L. Ping *et al,* PRC 79(2009) 024001 ; PRC 83(2011) 015202
R. L. Jaffe, PRL 38(1977) 195

- **Pentaquark:** $\Theta^+, \Xi^-, P_c^+ \ldots$

T. Nakano *et al*, PRL 91(2003) 012002
R. Aaij *et al*, PRL 115(2015) 072001

Theoretical interpretation:

- **Couple-channel unitary approach:**
  B. S. Zou *et al*, PRL 105(2010) 232001; PRC 84(2011) 015202

- **One-boson-exchange model:**
  X. Liu , S. L. Zhu *et al*, CPC 36(2012) 6
  R. Chen, X. Liu, X. Q. Li and S. L. Zhu, PRL 115(2015) 132002

- **Bethe-Salpeter equation method:**
  J. He , PLB 753(2016) 547

- **QCD sum rule approach:**
  H. X. Chen, X. Liu and S. L. Zhu *et al*, PRL 115(2015) 172001
  Z. G. Wang, EPJC 76(2016) 70

- **Diquark-triquark model:**

  R. L. Zhu, C. F. Qiao, PLB 756(2016) 259

- **Non-resonance explanations:**

  Q. Zhao *et al*, PLB 757(2016) 231

  F. K. Guo *et al*, PRD 92(2015) 071502

- **Tetraquark:** X(3872), Y(3940), Z(3900)…

The stage of multi-quark systems may coming!

ChQM and calculation methods

- ChQM has acquired great achievement both in describing the hadron spectra and hadron-hadron interaction.

A. Valcarce *et al*, Rep. Prog. Phys. 68(2005) 965-1041

A. Valcarce *et al*, J. Phys. G: Nucl. Part. Phys. 31(2005) 481-506

- General form of Hamiltonian

$$H=\sum_{i=1}^{5}\left(m_i+\frac{p_i^2}{2m_i}\right)-T_{CM}+\sum_{j>i=1}^{5}V_{ij}^{C}\left(\vec{r}_{ij}\right)$$

- # The central part of potential
  - *Screened potential:*

$$V_{CON}(\mathbf{r}_{ij}) = \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c \left[-a_c(1-e^{-\mu_c r_{ij}}) + \Delta\right],$$

  - *OGE:*

$$V_{OGE}(\mathbf{r}_{ij}) = \frac{1}{4}\alpha_s \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c \left[\frac{1}{r_{ij}} - \frac{1}{6m_i m_j}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \frac{e^{-r_{ij}/r_0(\mu)}}{r_{ij} r_0^2(\mu)}\right], \quad r_0(\mu) = \hat{r}_0/\mu,$$

  - *Quark-quark interaction:*

$$V_\chi(\mathbf{r}_{ij}) = v_\pi(\mathbf{r}_{ij}) \sum_{a=1}^{3} \boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a + v_K(\mathbf{r}_{ij}) \sum_{a=4}^{7} \boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a + v_\eta(\mathbf{r}_{ij})[\boldsymbol{\lambda}_i^8 \cdot \boldsymbol{\lambda}_j^8 \cos\theta_P - \boldsymbol{\lambda}_i^0 \cdot \boldsymbol{\lambda}_j^0 \sin\theta_P],$$

$$v_\chi(\mathbf{r}_{ij}) = \frac{g_{ch}^2}{4\pi} \frac{m_\chi^2}{12 m_i m_j} \frac{\Lambda_\chi^2}{\Lambda_\chi^2 - m_\chi^2} m_\chi \left[Y(m_\chi r_{ij}) - \frac{\Lambda_\chi^3}{m_\chi^3} Y(\Lambda_\chi r_{ij})\right] \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, \qquad \chi = \pi, K, \eta,$$

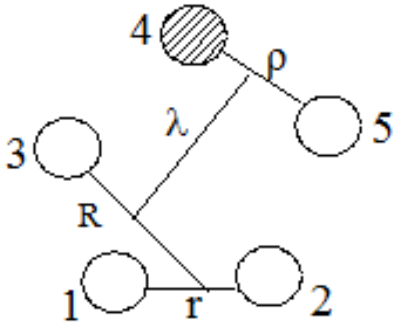
$$V_s(\mathbf{r}_{ij}) = v_\sigma(\mathbf{r}_{ij})(\boldsymbol{\lambda}_i^0 \cdot \boldsymbol{\lambda}_j^0) + v_{a_0}(\mathbf{r}_{ij}) \sum_{a=1}^{3} \boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a + v_\kappa(\mathbf{r}_{ij}) \sum_{a=4}^{7} \boldsymbol{\lambda}_i^a \cdot \boldsymbol{\lambda}_j^a + v_{f_0}(\mathbf{r}_{ij})(\boldsymbol{\lambda}_i^8 \cdot \boldsymbol{\lambda}_j^8),$$

$$v_s(\mathbf{r}_{ij}) = -\frac{g_{ch}^2}{4\pi} \frac{\Lambda_s^2}{\Lambda_s^2 - m_s^2} m_s \left[Y(m_s r_{ij}) - \frac{\Lambda_s}{m_s} Y(\Lambda_s r_{ij})\right], \qquad s = \sigma, a_0, \kappa, f_0.$$

Calculation method

In solving the Schrodinger equation by variation method

$$\langle \Psi | H - E | \Psi \rangle = 0$$



The complete wave function for 5-body

$$\Psi = \sum_{g=1}^{N_{total}} C_g \mathrm{A} \phi_{n_1 l_1 m_1}(\vec{r}) \psi_{n_2 l_2 m_2}(\vec{R}) \omega_{n_3 l_3 m_3}(\vec{\rho}) \eta_{n_4 l_4 m_4}(\vec{\lambda}) \chi_i^{\sigma} \chi_j^{f} \chi_k^{c}$$

$$g = \{n_1, l_1, n_2, l_2, n_3, l_3, n_4, l_4, i, j, k\}$$

Antisymmetry operator:

$$A = 1 - (1\,3) - (1\,5) - (2\,3) - (2\,5) - (3\,5)$$
$$+ (1\,3\,5) + (1\,5\,3) + (2\,3\,5) + (2\,5\,3) + (1\,3)(2\,5) + (1\,5)(2\,3)$$

- **Gaussian basis function**

E. Hiyama et al., Prog. Part. Nucl. Phys. 51(2003) 223-307

The spatial part is constructed by an expansion of a series of different size of Gaussian basis.

$$\phi_{nlm}(\vec{r}) = \phi^{G}_{nl}(r) Y_{lm}(\hat{r})$$
$$= N_{nl} r^{l} e^{-\nu_n r^2} Y_{lm}(\hat{r})$$
$$= \sqrt{\frac{2^{l+2}(2\nu_n)^{l+\frac{3}{2}}}{\sqrt{\pi}(2l+1)!!}} r^{l} e^{-\nu_n r^2} Y_{lm}(\hat{r})$$

Transform into the ISG form,

$$\phi_{nlm}(\vec{r}) = N_{nl} \lim_{\varepsilon \to 0} \left(\frac{l}{4\nu_n \varepsilon} \right)^{l} \sum_{j=0}^{\left| \frac{l-m}{2} \right|} A_{lm,j} \sum_{s=0}^{p} \sum_{t=0}^{q} \sum_{u=0}^{j} C^{s}_{p} C^{t}_{q} C^{u}_{j} e^{-\nu_n (\vec{r} - \varepsilon \vec{D})^2}$$

$$A_{lm,j} = \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}} \frac{(l+m)!}{2^m} \frac{(-1)^j}{4^j j!(m+j)!(l-m-2j)!}$$

$$p = l - m - 2j$$
$$q = m + j$$

The parameter of Gaussian is taken as the geometric progression numbers.

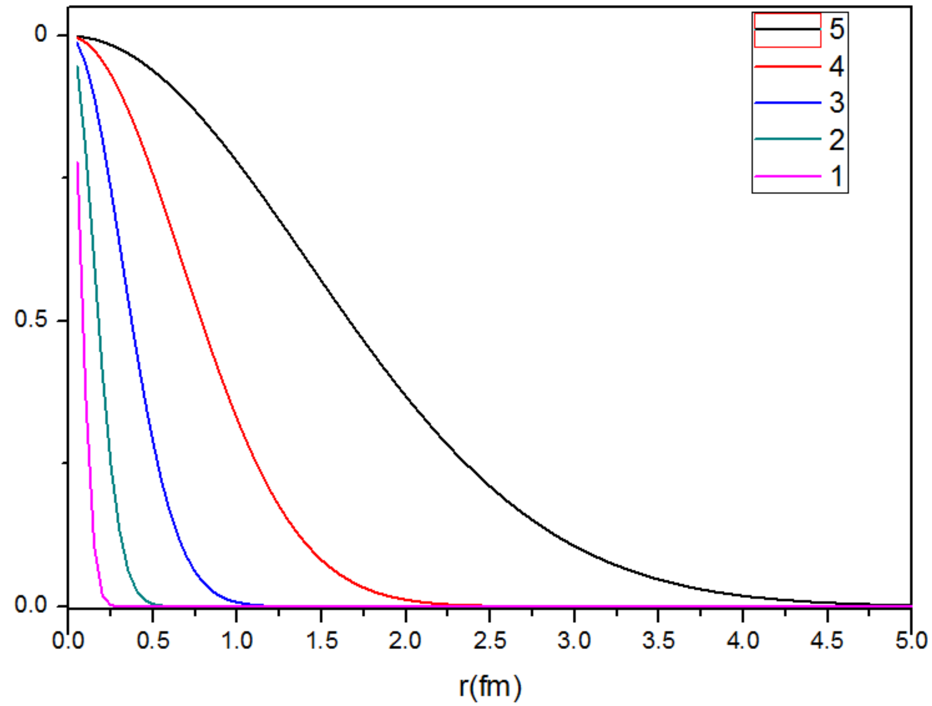
$$v_n = [r_{max}^{\frac{n-1}{N-1}} \cdot r_{min}^{\frac{(n-1)(N-2)}{N-1}}]^{-2}$$

e.g.

$$r_{min} = 0.1\,fm; r_{max} = 2.0\,fm; N=5.$$

$$v_1 = 100; v_2 = 22.4; v_3 = 5; v_4 = 1.1; v_5 = 0.3;$$

$$\varphi_n = e^{-v_n \cdot r^2}$$

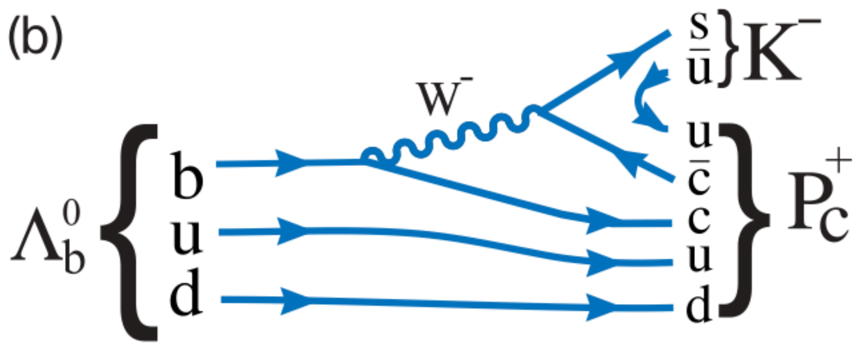


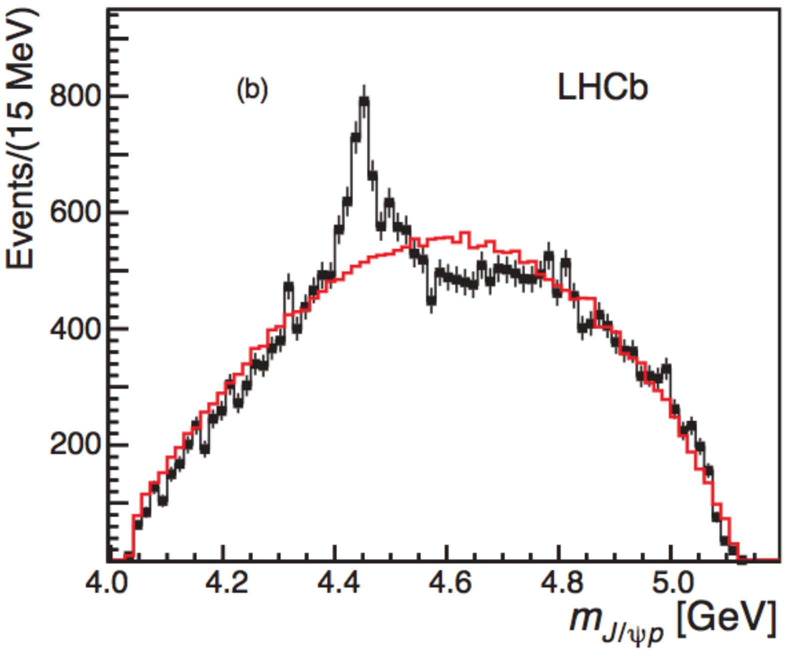
The results on P_c^+ and Ω_c^0 from LHCb data

- **Two pentaquark states have been discovered in the $J/\psi p$ invariant mass spectrum.**

$$P_c^+(4380): 4380 \pm 8 \pm 29\ MeV; \Gamma = 205 \pm 18 \pm 86\ MeV.$$

$$P_c^+(4450): 4449.8 \pm 1.7 \pm 2.5\ MeV; \Gamma = 39 \pm 5 \pm 19\ MeV.$$





R. Aaij *et al*, PRL 115(2015) 072001

- **Flavor wave-function of P_c^+ in *I=1/2*.**

$$\chi_1^f = \sqrt{\frac{2}{3}} B_{11} M_{\frac{1}{2},-\frac{1}{2}} - \sqrt{\frac{1}{3}} B_{10} M_{\frac{1}{2},\frac{1}{2}},$$
$$\chi_2^f = B_{00} M_{\frac{1}{2},\frac{1}{2}},$$
$$\chi_3^f = B^1_{\frac{1}{2},\frac{1}{2}} M_{00},$$
$$\chi_4^f = B^2_{\frac{1}{2},\frac{1}{2}} M_{00}.$$

5q

Sub-cluster

$$B_{11} = uuc, \qquad B_{10} = \frac{1}{\sqrt{2}}(ud + du)c, \qquad B_{1-1} = ddc,$$
$$B_{00} = \frac{1}{\sqrt{2}}(ud - du)c,$$
$$B^1_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{6}}(2uud - udu - duu),$$
$$B^2_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{2}}(ud - du)u,$$
$$M_{\frac{1}{2},\frac{1}{2}} = \bar{c}u, \qquad M_{\frac{1}{2},-\frac{1}{2}} = \bar{c}d, \qquad M_{00} = \bar{c}c. \qquad (4)$$

- **Spin wave-function of P_c^+.**

$$\chi^{\sigma1}_{\frac{1}{2},\frac{1}{2}}(5) = \sqrt{\frac{1}{6}}\chi^{\sigma}_{\frac{3}{2},-\frac{1}{2}}(3)\chi^{\sigma}_{11} - \sqrt{\frac{1}{3}}\chi^{\sigma}_{\frac{3}{2},\frac{1}{2}}(3)\chi^{\sigma}_{10} + \sqrt{\frac{1}{2}}\chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{1-1}$$

$$\chi^{\sigma2}_{\frac{1}{2},\frac{1}{2}}(5) = \sqrt{\frac{1}{3}}\chi^{\sigma1}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{10} - \sqrt{\frac{2}{3}}\chi^{\sigma1}_{\frac{1}{2},-\frac{1}{2}}(3)\chi^{\sigma}_{11}$$

$$\chi^{\sigma3}_{\frac{1}{2},\frac{1}{2}}(5) = \sqrt{\frac{1}{3}}\chi^{\sigma2}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{10} - \sqrt{\frac{2}{3}}\chi^{\sigma2}_{\frac{1}{2},-\frac{1}{2}}(3)\chi^{\sigma}_{11}$$

$$\chi^{\sigma4}_{\frac{1}{2},\frac{1}{2}}(5) = \chi^{\sigma1}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{00}$$

$$\chi^{\sigma5}_{\frac{1}{2},\frac{1}{2}}(5) = \chi^{\sigma2}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{00}$$

$$\chi^{\sigma1}_{\frac{3}{2},\frac{3}{2}}(5) = \sqrt{\frac{3}{5}}\chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{10} - \sqrt{\frac{2}{5}}\chi^{\sigma}_{\frac{3}{2},\frac{1}{2}}(3)\chi^{\sigma}_{11}$$

$$\chi^{\sigma2}_{\frac{3}{2},\frac{3}{2}}(5) = \chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{00}$$

$$\chi^{\sigma3}_{\frac{3}{2},\frac{3}{2}}(5) = \chi^{\sigma1}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{11}$$

$$\chi^{\sigma4}_{\frac{3}{2},\frac{3}{2}}(5) = \chi^{\sigma2}_{\frac{1}{2},\frac{1}{2}}(3)\chi^{\sigma}_{11}$$

$$\chi^{\sigma1}_{\frac{5}{2},\frac{5}{2}}(5) = \chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3)\chi^{\sigma}_{11}$$

Total part

Sub-cluster

$$\chi^{\sigma}_{\frac{3}{2},\frac{3}{2}}(3) = \alpha\alpha\alpha,$$

$$\chi^{\sigma}_{\frac{3}{2},\frac{1}{2}}(3) = \frac{1}{\sqrt{3}}(\alpha\alpha\beta + \alpha\beta\alpha + \beta\alpha\alpha),$$

$$\chi^{\sigma}_{\frac{3}{2},-\frac{1}{2}}(3) = \frac{1}{\sqrt{3}}(\alpha\beta\beta + \beta\alpha\beta + \beta\beta\alpha),$$

$$\chi^{\sigma1}_{\frac{1}{2},\frac{1}{2}}(3) = \frac{1}{\sqrt{6}}(2\alpha\alpha\beta - \alpha\beta\alpha - \beta\alpha\alpha),$$

$$\chi^{\sigma2}_{\frac{1}{2},\frac{1}{2}}(3) = \frac{1}{\sqrt{2}}(\alpha\beta\alpha - \beta\alpha\alpha),$$

$$\chi^{\sigma1}_{\frac{1}{2},-\frac{1}{2}}(3) = \frac{1}{\sqrt{6}}(\alpha\beta\beta - \alpha\beta\beta - 2\beta\beta\alpha),$$

$$\chi^{\sigma2}_{\frac{1}{2},-\frac{1}{2}}(3) = \frac{1}{\sqrt{2}}(\alpha\beta\beta - \beta\alpha\beta),$$

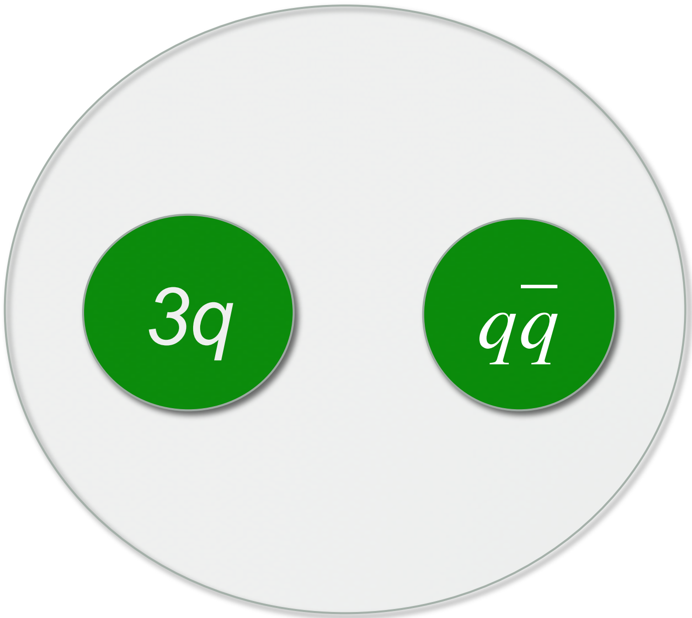
$$\chi^{\sigma}_{11} = \alpha\alpha, \qquad \chi^{\sigma}_{10} = \frac{1}{\sqrt{2}}(\alpha\beta + \beta\alpha), \qquad \chi^{\sigma}_{1-1} = \beta\beta,$$

$$\chi^{\sigma}_{00} = \frac{1}{\sqrt{2}}(\alpha\beta - \beta\alpha).$$

- **Color wave-function of P_c^+ .**

I. Color singlet channel

$$\chi_1^c = \frac{1}{\sqrt{18}}(rgb - rbg + gbr - grb + brg - bgr) \times (\bar{r}r + \bar{g}g + \bar{b}b),$$



$[1] \otimes [1]$

II. *Hidden color channel*

$$[8] \otimes [8]$$

$$\chi_k^c = \frac{1}{\sqrt{8}}\left(\chi^k_{3,1}\chi^k_{2,8} - \chi^k_{3,2}\chi^k_{2,7} - \chi^k_{3,3}\chi^k_{2,6} + \chi^k_{3,4}\chi^k_{2,5} + \chi^k_{3,5}\chi^k_{2,4} - \chi^k_{3,6}\chi^k_{2,3} - \chi^k_{3,7}\chi^k_{2,2} + \chi^k_{3,8}\chi^k_{2,1}\right)$$

$$\chi^2_{3,1} = \frac{1}{\sqrt{6}}(2rrg - rgr - grr), \qquad \chi^3_{3,1} = \frac{1}{\sqrt{2}}(rgr - grr),$$

$$\chi^2_{3,2} = \frac{1}{\sqrt{6}}(rgg + grg - 2ggr), \qquad \chi^3_{3,2} = \frac{1}{\sqrt{2}}(rgg - grg),$$

$$\chi^2_{3,3} = \frac{1}{\sqrt{6}}(2rrb - rbr - brr), \qquad \chi^3_{3,3} = \frac{1}{\sqrt{2}}(rbr - brr),$$

$$\chi^2_{3,4} = \frac{1}{\sqrt{12}}(2rgb - rbg + 2grb - gbr - brg - bgr),$$

$$\chi^3_{3,4} = \frac{1}{\sqrt{4}}(rbg + gbr - brg - bgr),$$

Sub-cluster

$$\chi_{2,1} = \bar{b}r, \qquad \chi_{2,2} = \bar{b}g$$

$$\chi_{2,3} = -\bar{g}r, \qquad \chi_{2,4} = \frac{1}{\sqrt{2}}(\bar{r}r - \bar{g}g),$$

$$\chi_{2,5} = \frac{1}{\sqrt{6}}(2\bar{b}b - \bar{r}r - \bar{g}g), \qquad \chi_{2,6} = \bar{r}g$$

$$\chi_{2,7} = -\bar{g}b, \qquad \chi_{2,8} = \bar{r}b.$$

$$\chi^2_{3,5} = \frac{1}{\sqrt{4}}(rbg - gbr + brg - bgr),$$

$$\chi^3_{3,5} = \frac{1}{\sqrt{12}}(2rgb + rbg - 2grb - gbr - brg + bgr),$$

$$\chi^2_{3,6} = \frac{1}{\sqrt{6}}(2ggb - gbg - bgg), \qquad \chi^3_{3,6} = \frac{1}{\sqrt{2}}(gbg - bgg),$$

$$\chi^2_{3,7} = \frac{1}{\sqrt{6}}(rbb + brb - 2bbr), \qquad \chi^3_{3,7} = \frac{1}{\sqrt{2}}(rbb - brb),$$

$$\chi^2_{3,8} = \frac{1}{\sqrt{6}}(gbb + bgb - 2bbg), \qquad \chi^3_{3,8} = \frac{1}{\sqrt{2}}(gbb - bgb),$$

TABLE IV: The lowest eigen-energies of the $udc\bar{c}u$ system with $J^P = \frac{3}{2}^-$ (unit: MeV).

Channel	E	E_{th}^{Theo}	E_B	E_{th}^{Exp}	E'
$J^P = 3/2^-$					
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 3,4,$ $j = 3,4,$ $k = 1$	3841	3841	0	$4036(NJ/\psi)$	4036
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 3,4,$ $j = 3,4,$ $k = 2,3$	4722				
color-singlet+hidden color	3841				
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 3,4,$ $j = 2,$ $k = 1$	4115	4115	0	$4293(\Lambda_c\bar{D}^*)$	4293
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 3,4,$ $j = 2,$ $k = 2,3$	4680				
color-singlet+hidden color	4115				
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 3,4,$ $j = 1,$ $k = 1$	4518	4520	−2	$4462(\Sigma_c\bar{D}^*)$	4460
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 3,4,$ $j = 1,$ $k = 2,3$	4961				
color-singlet+hidden color	4517	4520	−3	4462	4459
		percentage(S;H): 96.3%; 3.7%			
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 2,$ $j = 1,$ $k = 1$	4444	4447	−3	$4385(\Sigma^*_c\bar{D})$	4382
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 2,$ $j = 1,$ $k = 2,3$	4754				
color-singlet+hidden color	4432	4447	−15	4385	4370
		percentage(S;H): 82.6%; 17.4%			
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 1,$ $j = 1,$ $k = 1$	4564	4566	−2	$4527(\Sigma^*_c\bar{D}^*)$	4525
$\chi^{\sigma i}_{3/2}\chi^f_j\chi^c_k$ $i = 1,$ $j = 1,$ $k = 2,3$	4623				
color-singlet+hidden color	4549	4566	−17	4527	4510
		percentage(S;H): 61.1%; 38.9%			
mixed (only color-singlet)	3841				
mixed (color-singlet+hidden color)	3841				

$P_c^+(4380)$

unbound

JP=1/2-

Channel	E	E_{th}^{Theo}	E_B	E_{th}^{Exp}	E'
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=4,5,$ $j=3,4,$ $k=1$	3745	3745	0	3919($N\eta_c$)	3919
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=4,5,$ $j=3,4,$ $k=2,3$	4714				
color-singlet+hidden color	3745				
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=2,3,$ $j=3,4,$ $k=1$	3841	3841	0	4036(NJ/ψ)	4036
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=2,3,$ $j=3,4,$ $k=2,3$	4964				
color-singlet+hidden color	3841				
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=4,5,$ $j=2,$ $k=1$	3996	3996	0	4151($\Lambda_c\bar{D}$)	4151
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=4,5,$ $j=2,$ $k=2,3$	4663				
color-singlet+hidden color	3996				
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=2,3,$ $j=2,$ $k=1$	4115	4115	0	4293($\Lambda_c\bar{D}^*$)	4293
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=2,3,$ $j=2,$ $k=2,3$	4599				
color-singlet+hidden color	4115				
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=4,5,$ $j=1,$ $k=1$	4398	4402	−4	4320($\Sigma_c\bar{D}$)	4316
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=4,5,$ $j=1,$ $k=2,3$	4835				
color-singlet+hidden color	4394	4402	−8	4320	4312
		percentage(S;H): 91.0%; 7.0%			
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=2,3,$ $j=1,$ $k=1$	4518	4520	−2	4462($\Sigma_c\bar{D}^*$)	4460
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=2,3,$ $j=1,$ $k=2,3$	4728				
color-singlet+hidden color	4479	4520	−41	4462	4421
		percentage(S;H): 67.4%; 32.6%			
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=1,$ $j=1,$ $k=1$	4563	4566	−3	4527($\Sigma_c^*\bar{D}^*$)	4524
$\chi_{1/2}^{\sigma i}\chi_j^f\chi_k^c$ $i=1,$ $j=1,$ $k=2,3$	4476				
color-singlet+hidden color	4461	4566	−105	4527	4422
		percentage(S;H): 23.0%; 77.0%			
mixed (only color singlet)	3745				
mixed (color singlet+hidden color)	3745				

Scattering state

$J^P = 5/2^-$					
$\chi^{\sigma i}_{5/2}\chi^f_j\chi^c_k$ $i=1,\ j=1,\ k=1$	4563	4566	-3	$4527(\Sigma_c^*\bar{D}^*)$	4524
$\chi^{\sigma i}_{5/2}\chi^f_j\chi^c_k$ $i=1,\ j=1,\ k=2,3$	5002				
color-singlet+hidden color	4477	4566	-89	4527	4438
	percentage(S;H): 66.2%; 33.8%				

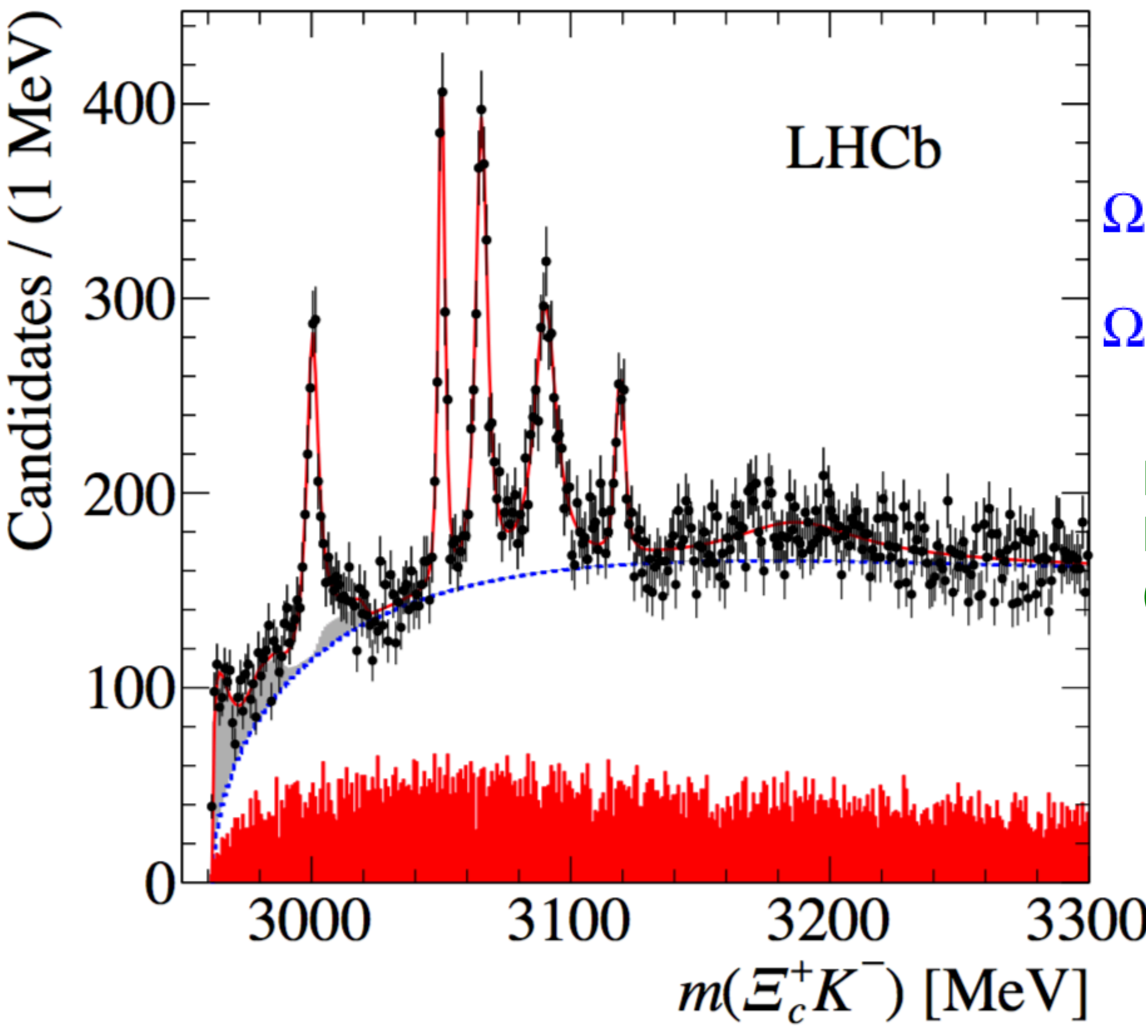
TABLE V: Distances between any two quarks (unit: fm).

J^P	Channel	r_{12}	r_{13}	r_{14}	r_{34}
$\frac{1}{2}^-$	$\chi^{\sigma i}_{1/2}\chi^f_j$ $i=4,5, j=1, k=1$ $(\Sigma_c\bar{D})$	0.8	0.7	2.1	2.1
	$\chi^{\sigma i}_{1/2}\chi^f_j$ $i=4,5, j=1, k=2,3$	1.0	0.8	0.8	0.4
	$\chi^{\sigma i}_{1/2}\chi^f_j$ $i=2,3, j=1, k=1$ $(\Sigma_c\bar{D}^*)$	0.8	0.7	2.2	2.1
	$\chi^{\sigma i}_{1/2}\chi^f_j$ $i=2,3, j=1, k=2,3$	0.9	0.8	0.8	0.4
	$\chi^{\sigma i}_{1/2}\chi^f_j$ $i=1, j=1, k=1$ $(\Sigma_c^*\bar{D}^*)$	0.9	0.8	2.1	2.0
	$\chi^{\sigma i}_{1/2}\chi^f_j$ $i=1, j=1, k=2,3$	0.9	0.8	0.8	0.4
$\frac{3}{2}^-$	$\chi^{\sigma i}_{3/2}\chi^f_j$ $i=3,4, j=1, k=1$ $(\Sigma_c\bar{D}^*)$	0.8	0.7	2.4	2.3
	$\chi^{\sigma i}_{3/2}\chi^f_j$ $i=3,4, j=1, k=2,3$	1.1	0.9	0.9	0.5
	$\chi^{\sigma i}_{3/2}\chi^f_j$ $i=2, j=1, k=1$ $(\Sigma_c^*\bar{D})$	0.9	0.8	2.2	2.2
	$\chi^{\sigma i}_{3/2}\chi^f_j$ $i=2, j=1, k=2,3$	1.0	0.9	0.9	0.5
	$\chi^{\sigma i}_{3/2}\chi^f_j$ $i=1, j=1, k=1$ $(\Sigma_c^*\bar{D}^*)$	0.9	0.8	2.6	2.4
	$\chi^{\sigma i}_{3/2}\chi^f_j$ $i=1, j=1, k=2,3$	0.9	0.9	0.8	0.4
$\frac{5}{2}^-$	$\chi^{\sigma i}_{5/2}\chi^f_j$ $i=1, j=1, k=1$ $(\Sigma_c^*\bar{D}^*)$	0.9	0.8	2.4	2.3
	$\chi^{\sigma i}_{5/2}\chi^f_j$ $i=1, j=1, k=2,3$	1.3	1.4	1.3	0.8

$udc\bar{c}u$

$\sim P_c^+(4380)$

- **Five new Ω_c^0 states are discovered in the $\Xi_c^+ K^-$ mass spectrum of pp collision.**



$\Omega_c^0(3000)$, $\Omega_c^0(3050)$, $\Omega_c^0(3066)$
$\Omega_c^0(3090)$, $\Omega_c^0(3119)$

R. Aaij *et al.*
Phys. Rev. Lett. 118, 182001 (2017)

- **Theoretical interpretation**

H. X. Chen, X. Liu, S. L. Zhu *et al.* Phys. Rev. D 95, 094008 (2017)

Q. Zhao, X. H. Zhong *et al.* Phys. Rev. D 95, 116010 (2017)

Z. G. Wang Eur. Phys. J. C77 (2017) 325

X. Liu *et al.* arXiv: 1704.02583 [hep-ph]

H. X. Huang, J. L. Ping *et al.* arXiv: 1704.01421 [hep-ph]

…

- **Attempt in the *3q* configuration**

Masses of baryons and mesons in ChQM with two sets of parameters.

P	$N(939)$	$\Delta(1232)$	$\Omega(1672)$	$\Lambda(1116)$	$\Sigma(1189)$	$\Xi(1315)$
			set I			
+	936	1208	1643	1154	1173	1362
−	1575	1625	2203	1772	1777	1981
			set II			
+	939	1231	1671	1187	1209	1408
−	1661	1716	2301	1889	1895	2098
	$\Sigma^*(1383)$	$\Xi^*(1532)$	$\Omega_c(2695)$	$\Omega_c(2765)$	$\Xi_c(2467)$	$\Xi_c^*(2645)$
			set I			
+	1342	1488	2675	2748	2541	2603
−	1805	1999	3257	3282	3086	3093
			set II			
+	1393	1539	2748	2818	2629	2727
−	1928	2119	3378	3389	3145	3166
			set I			
P	$\pi(140)$	$\rho(775)$	$\eta(548)$	$\omega(782)$	$K(495)$	$K^*(892)$
−	93	800	611	705	326	965
	$\eta'(958)$	$\phi(1019)$	$D^0(1865)$	$D^*(2007)$		
−	914	1056	1842	2043		

Too heavy

A test on our results with E. Hiyama *et al.* PRD 92(2015) 114029.

TABLE XVI: P-wave results. (unit: MeV)

$J^P=\frac{1}{2}^-$	Λ_c	Σ_c	Ω_c	Ξ_{cc}
I	2632	2813	3037	3952
HIYAMA	2628	2802	3030	3947

- **The calculated masses of Ω_c^0 in ground states and low-lying excited states**

nL	$\Omega_c(2695)$	$\Omega_c(2765)$
	set I	
$1S$	2675	2748
$2S$	3074	3112
$1P$	3257	3282
	set II	
$1S$	2748	2818
$2S$	3167	3201
$1P$	3378	3389

- **Flavor wave-function of 5-quark systems.**

$$B^1_{00} = ssc, \quad B^2_{00} = sss,$$

$$B^1_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{6}}(sus + uss - 2ssu),$$

$$B^1_{\frac{1}{2},-\frac{1}{2}} = \frac{1}{\sqrt{6}}(sds + dss - 2ssd),$$

$$B^2_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{2}}(us - su)s, \quad B^2_{\frac{1}{2},-\frac{1}{2}} = \frac{1}{\sqrt{2}}(ds - sd)s,$$

$$B^3_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{3}}(ssu + sus + uss),$$

$$B^3_{\frac{1}{2},-\frac{1}{2}} = \frac{1}{\sqrt{3}}(ssd + sds + dss),$$

$$B^4_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{2}}(us + su)c, \quad B^4_{\frac{1}{2},-\frac{1}{2}} = \frac{1}{\sqrt{2}}(ds + sd)c,$$

$$B^5_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{2}}(us - su)c, \quad B^5_{\frac{1}{2},-\frac{1}{2}} = \frac{1}{\sqrt{2}}(ds - sd)c.$$

$$M^1_{\frac{1}{2},\frac{1}{2}} = \bar{d}c, \quad M^1_{\frac{1}{2},-\frac{1}{2}} = -\bar{u}c,$$

$$M^2_{\frac{1}{2},\frac{1}{2}} = \bar{d}s, \quad M^2_{\frac{1}{2},-\frac{1}{2}} = -\bar{u}s,$$

$$M^1_{00} = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d), \quad M^2_{00} = \bar{s}s, \quad M^3_{00} = \bar{s}c.$$

Sub-cluster

$$\chi^f_1 = \sqrt{\frac{1}{2}}(B^1_{\frac{1}{2},\frac{1}{2}} M^1_{\frac{1}{2},-\frac{1}{2}} - B^1_{\frac{1}{2},-\frac{1}{2}} M^1_{\frac{1}{2},\frac{1}{2}}),$$

$$\chi^f_2 = \sqrt{\frac{1}{2}}(B^2_{\frac{1}{2},\frac{1}{2}} M^1_{\frac{1}{2},-\frac{1}{2}} - B^2_{\frac{1}{2},-\frac{1}{2}} M^1_{\frac{1}{2},\frac{1}{2}}),$$

$$\chi^f_3 = \sqrt{\frac{1}{2}}(B^3_{\frac{1}{2},\frac{1}{2}} M^1_{\frac{1}{2},-\frac{1}{2}} - B^3_{\frac{1}{2},-\frac{1}{2}} M^1_{\frac{1}{2},\frac{1}{2}}),$$

$$\chi^f_4 = \sqrt{\frac{1}{2}}(B^4_{\frac{1}{2},\frac{1}{2}} M^2_{\frac{1}{2},-\frac{1}{2}} - B^4_{\frac{1}{2},-\frac{1}{2}} M^2_{\frac{1}{2},\frac{1}{2}}),$$

$$\chi^f_5 = \sqrt{\frac{1}{2}}(B^5_{\frac{1}{2},\frac{1}{2}} M^2_{\frac{1}{2},-\frac{1}{2}} - B^5_{\frac{1}{2},-\frac{1}{2}} M^2_{\frac{1}{2},\frac{1}{2}}),$$

$$\chi^f_6 = B^1_{00} M^1_{00}, \quad \chi^f_7 = B^1_{00} M^2_{00}, \quad \chi^f_8 = B^2_{00} M^3_{00}.$$

5q part

- **Possible channels**

TABLE III: The channels with $IJ^P = 0\frac{1}{2}^-$.

index	$\chi^{\sigma_i}_{1/2}$	χ^f_j	χ^c_k	physical channel
1	$i=1$	$j=3$	$k=1$	$\Xi^*\bar{D}^*$
2	$i=1$	$j=3$	$k=3$	
3	$i=1$	$j=4$	$k=1$	$\Xi^*_c\bar{K}^*$
4	$i=1$	$j=4,5$	$k=2,3$	
5	$i=1$	$j=6$	$k=1$	$\Omega^*_c\omega$
6	$i=1$	$j=6$	$k=3$	
7	$i=2,3$	$j=1,2$	$k=1$	$\Xi\bar{D}^*$
8	$i=2,3$	$j=1,2$	$k=2,3$	
9	$i=2,3$	$j=4,5$	$k=1$	$\Xi_c\bar{K}^*$
10	$i=2,3$	$j=4,5$	$k=2,3$	
11	$i=2$	$j=6$	$k=1$	$\Omega_c\omega$
12	$i=2,3$	$j=6$	$k=2,3$	
13	$i=4,5$	$j=1,2$	$k=1$	$\Xi\bar{D}$
14	$i=4,5$	$j=1,2$	$k=2,3$	
15	$i=4,5$	$j=4,5$	$k=1$	$\Xi_c\bar{K}$
16	$i=4,5$	$j=4,5$	$k=2,3$	
17	$i=4$	$j=6$	$k=1$	$\Omega_c\eta$
18	$i=4,5$	$j=6$	$k=2,3$	

TABLE IV: The channels with $IJ^P = 0\frac{3}{2}^-$.

index	$\chi^{\sigma_i}_{3/2}$	χ^f_j	χ^c_k	physical channel
1	$i=1$	$j=3$	$k=1$	$\Xi^*\bar{D}^*$
2	$i=1$	$j=3$	$k=3$	
3	$i=1$	$j=4$	$k=1$	$\Xi^*_c\bar{K}^*$
4	$i=1$	$j=4,5$	$k=2,3$	
5	$i=1$	$j=6$	$k=1$	$\Omega^*_c\omega$
6	$i=1$	$j=6$	$k=3$	
7	$i=2$	$j=3$	$k=1$	$\Xi^*\bar{D}$
8	$i=2$	$j=3$	$k=3$	
9	$i=2$	$j=4$	$k=1$	$\Xi^*_c\bar{K}$
10	$i=2$	$j=4,5$	$k=2,3$	
11	$i=2$	$j=6$	$k=1$	$\Omega^*_c\eta$
12	$i=2$	$j=6$	$k=3$	
13	$i=3,4$	$j=1,2$	$k=1$	$\Xi\bar{D}^*$
14	$i=3,4$	$j=1,2$	$k=2,3$	
15	$i=3,4$	$j=4,5$	$k=1$	$\Xi_c\bar{K}^*$
16	$i=3,4$	$j=4,5$	$k=2,3$	
17	$i=3$	$j=6$	$k=1$	$\Omega_c\omega$
18	$i=3,4$	$j=6$	$k=2,3$	

TABLE V: The channels with $IJ^P = 0\frac{5}{2}^-$.

index	$\chi^{\sigma_i}_{5/2}$	χ^f_j	χ^c_k	physical channel
1	$i=1$	$j=3$	$k=1$	$\Xi^*\bar{D}^*$
2	$i=1$	$j=3$	$k=3$	
3	$i=1$	$j=4$	$k=1$	$\Xi^*_c\bar{K}^*$
4	$i=1$	$j=4,5$	$k=2,3$	
5	$i=1$	$j=6$	$k=1$	$\Omega^*_c\omega$
6	$i=1$	$j=6$	$k=3$	

- **Calculation in the 5-quark configuration**

$ssc\bar{u}u; ssc\bar{d}d$

TABLE VII: The lowest eigen-energies of the $ssc\bar{u}u+ssc\bar{d}d$ system with $J^P=\frac{1}{2}^-$ (unit: MeV). The percentages of color-singlet (S) and hidden-color (H) channels are also given.

Channel	E	E_{th}^{Theo}	E_B	E_{th}^{Exp}	E'
1	3526	3531	-5	$3539(\Xi^*\bar{D}^*)$	3534
2	4016				
1+2	3525		-6		3533
		percentage(S;H): 99.8%; 0.2%			
3	3566	3568	-2	$3537(\Xi_c^*\bar{K}^*)$	3535
4	3616				
3+4	3564		-4		3533
		percentage(S;H): 96.3%; 3.7%			
5	3453	3453	0	$3548(\Omega_c^*\omega)$	3548
6	3404				
5+6	3402		-51		3497
		percentage(S;H): 0.2%; 99.8%			
7	3374	3405	-31	$3322(\Xi\bar{D}^*)$	3291
8	3672				
7+8	3373		-32		3290
		percentage(S;H): 99.8%; 0.2%			
9	3495	3506	-11	$3359(\Xi_c\bar{K}^*)$	3348
10	3613				
9+10	3472		-34		3325
		percentage(S;H): 85.2%; 14.8%			
11	3380	3380	0	$3477(\Omega_c\omega)$	3477
12	3608				
11+12	3380				
13	3175	3204	-29	$3185(\Xi\bar{D})$	3156
14	3811				
13+14	3175		-29		3156
		percentage(S;H): 100.0%; 0.0%			
15	2867	2867	0	$2961(\Xi_c\bar{K})$	2961
16	3807				
15+16	2855		-12		2949
		percentage(S;H): 96.7%; 3.3%			
17	3286	3286	0	$3243(\Omega_c\eta)$	3243
18	3828				
17+18	3286				
mixed (singlet)	2771	2867	-96	$2961(\Xi_c\bar{K})$	2865
mixed (full)	2675	2867	-192	$2961(\Xi_c\bar{K})$	2769

TABLE IX: The lowest eigen-energies of the $ssc\bar{u}u+ssc\bar{d}d$ system with $\frac{3}{2}^-$(unit: MeV).

Channel	E	E_{th}^{Theo}	E_B	E_{th}^{Exp}	E'
1	3521	3531	-10	$3539(\Xi^*\bar{D}^*)$	3529
2	4026				
1+2	3521		-10		3529
		percentage(S;H): 100.0%; 0.0%			
3	3565	3568	-3	$3537(\Xi_c^*\bar{K}^*)$	3534
4	3617				
3+4	3562		-6		3531
		percentage(S;H): 94.0%; 6.0%			
5	3453	3453	0	$3548(\Omega_c^*\omega)$	3548
6	3477				
5+6	3453				
7	3309	3330	-21	$3397(\Xi^*\bar{D})$	3376
8	4145				
7+8	3309		-21		3376
		percentage(S;H): 100.0%; 0.0%			
9	2929	2929	0	$3139(\Xi_c^*\bar{K})$	3139
10	3782				
9+10	2928		-1		3138
		percentage(S;H): 99.7%; 0.3%			
11	3359	3359	0	$3314(\Omega_c^*\eta)$	3314
12	3763				
11+12	3359				
13	3388	3405	-17	$3322(\Xi\bar{D}^*)$	3305
14	3705				
13+14	3388		-17		3305
		percentage(S;H): 100.0%; 0.0%			
15	3506	3506	0	$3359(\Xi_c\bar{K}^*)$	3359
16	3656				
15+16	3348		-158		3201
		percentage(S;H): 57.7%; 42.3%			
17	3380	3380	0	$3477(\Omega_c\omega)$	3477
18	3588				
17+18	3380				
mixed (singlet)	2928	2929	-1	$3139(\Xi_c^*\bar{K})$	3138
mixed (full)	2857	2929	-72	$3139(\Xi_c^*\bar{K})$	3067

$\sim\Omega_c^0(3066)$

TABLE X: The lowest eigen-energies of the $ssc\bar{u}u$+$ssc\bar{d}d$ system with $\frac{5}{2}^-$(unit: MeV).

Channel	E	E_{th}^{Theo}	E_B	E_{th}^{Exp}	E'
1	3508	3531	−23	3539($\Xi^* \bar{D}^*$)	3516
2	4042				
1+2	3507		−24		3515
		percentage(S;H): 99.8%; 0.2%			
3	3568	3568	0	3537($\Xi_c^* \bar{K}^*$)	3537
4	3646				
3+4	3532		−36		3501
		percentage(S;H): 80.0%; 20.0%			
5	3453	3453	0	3548($\Omega_c^* \omega$)	3548
6	3563				
5+6	3453				
mixed (singlet)	3453				
mixed (full)	3453				

unbound

TABLE XI: Distances between quarks, q is for u, d quark and Q is for c quark (unit: fm).

J^P	Channel	r_{qq}	r_{qQ}	$r_{q\bar{q}}$	$r_{Q\bar{q}}$
$\frac{1}{2}^-$	$\Omega_c^0(2769)$	1.3	1.1	1.4	1.2
$\frac{3}{2}^-$	$\Omega_c^0(3067)$	1.4	1.1	1.2	1.4

compact

5-quark study in *N,P* sector

- **Flavor wave-function of 5-quark systems.**

$$B^1_{\frac{3}{2},\frac{3}{2}} = uuu, \quad B^1_{\frac{3}{2},-\frac{3}{2}} = ddd,$$
$$B^1_{\frac{3}{2},\frac{1}{2}} = \frac{1}{\sqrt{3}}(uud+udu+duu), \quad B^1_{\frac{3}{2},-\frac{1}{2}} = \frac{1}{\sqrt{3}}(udd+dud+ddu),$$
$$B^1_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{6}}(2uud-udu-duu), \quad B^2_{\frac{1}{2},\frac{1}{2}} = \frac{1}{\sqrt{2}}(ud-du)u,$$
$$B^1_{\frac{1}{2},-\frac{1}{2}} = \frac{1}{\sqrt{6}}(udd+dud-2ddu), \quad B^2_{\frac{1}{2},-\frac{1}{2}} = \frac{1}{\sqrt{2}}(ud-du)d,$$
$$M^1_{1,1} = \bar{d}u, \quad M^1_{1,-1} = -\bar{u}d,$$
$$M^1_{10} = \frac{1}{\sqrt{2}}(\bar{d}d-\bar{u}u), \quad M^1_{00} = -\frac{1}{\sqrt{2}}(\bar{u}u+\bar{d}d).$$

$$\chi^{f1}_{\frac{1}{2},\frac{1}{2}} = \sqrt{\frac{1}{6}}B_{\frac{3}{2},-\frac{1}{2}}M_{11} - \sqrt{\frac{1}{3}}B_{\frac{3}{2},\frac{1}{2}}M_{10} + \sqrt{\frac{1}{2}}B_{\frac{3}{2},\frac{3}{2}}M_{1-1}$$
$$\chi^{f2}_{\frac{1}{2},\frac{1}{2}} = \sqrt{\frac{1}{3}}B^1_{\frac{1}{2},\frac{1}{2}}M_{10} - \sqrt{\frac{2}{3}}B^1_{\frac{1}{2},-\frac{1}{2}}M_{11}$$
$$\chi^{f3}_{\frac{1}{2},\frac{1}{2}} = \sqrt{\frac{1}{3}}B^2_{\frac{1}{2},\frac{1}{2}}M_{10} - \sqrt{\frac{2}{3}}B^2_{\frac{1}{2},-\frac{1}{2}}M_{11}$$
$$\chi^{f4}_{\frac{1}{2},\frac{1}{2}} = B^1_{\frac{1}{2},\frac{1}{2}}M_{00}$$
$$\chi^{f5}_{\frac{1}{2},\frac{1}{2}} = B^2_{\frac{1}{2},\frac{1}{2}}M_{00}$$

$$\chi^{f1}_{\frac{3}{2},\frac{3}{2}} = \sqrt{\frac{3}{5}}B_{\frac{3}{2},\frac{3}{2}}M_{10} - \sqrt{\frac{2}{5}}B_{\frac{3}{2},\frac{1}{2}}M_{11}$$
$$\chi^{f2}_{\frac{3}{2},\frac{3}{2}} = B_{\frac{3}{2},\frac{3}{2}}M_{00}$$
$$\chi^{f3}_{\frac{3}{2},\frac{3}{2}} = B^1_{\frac{1}{2},\frac{1}{2}}M_{11}$$
$$\chi^{f4}_{\frac{3}{2},\frac{3}{2}} = B^2_{\frac{1}{2},\frac{1}{2}}M_{11}$$
$$\chi^{f1}_{\frac{5}{2},\frac{5}{2}} = B_{\frac{3}{2},\frac{3}{2}}M_{11}.$$

- **Possible channels in negative parity.**

		$I=\frac{1}{2}$		$I=\frac{3}{2}$		$I=\frac{5}{2}$	
J^P	index	$\chi_J^{\sigma_i};\ \chi_I^{f_j};\ \chi_k^c$ $[i;\ j;\ k]$	phys. channel	$\chi_J^{\sigma_i};\ \chi_I^{f_j};\ \chi_k^c$ $[i;\ j;\ k]$	phys. channel	$\chi_J^{\sigma_i};\ \chi_I^{f_j};\ \chi_k^c$ $[i;\ j;\ k]$	phys. channel
$\frac{1}{2}^-$	1	$[4,5;\ 4,5;\ 1]$	$P\eta$	$[4,5;\ 3,4;\ 1]$	$P\pi$	$[1;\ 1;\ 1]$	$\Delta\rho$
	2	$[4,5;\ 4,5;\ 2,3]$		$[4,5;\ 3,4;\ 2,3]$		$[1;\ 1;\ 3]$	
	3	$[4,5;\ 2,3;\ 1]$	$P\pi$	$[2,3;\ 3,4;\ 1]$	$P\rho$		
	4	$[4,5;\ 2,3;\ 2,3]$		$[2,3;\ 3,4;\ 2,3]$			
	5	$[2,3;\ 4,5;\ 1]$	$P\omega$	$[1;\ 2;\ 1]$	$\Delta\omega$		
	6	$[2,3;\ 4,5;\ 2,3]$		$[1;\ 2;\ 3]$			
	7	$[2,3;\ 2,3;\ 1]$	$P\rho$	$[1;\ 1;\ 1]$	$\Delta\rho$		
	8	$[2,3;\ 2,3;\ 2,3]$		$[1;\ 1;\ 3]$			
	9	$[1;\ 1;\ 1]$	$\Delta\rho$				
	10	$[1;\ 1;\ 3]$					
$\frac{3}{2}^-$	1	$[3,4;\ 4,5;\ 1]$	$P\omega$	$[3,4;\ 3,4;\ 1]$	$P\rho$	$[2;\ 1;\ 1]$	$\Delta\pi$
	2	$[3,4;\ 4,5;\ 2,3]$		$[3,4;\ 3,4;\ 2,3]$		$[2;\ 1;\ 3]$	
	3	$[3,4;\ 2,3;\ 1]$	$P\rho$	$[2;\ 2;\ 1]$	$\Delta\eta$	$[1;\ 1;\ 1]$	$\Delta\rho$
	4	$[3,4;\ 2,3;\ 2,3]$		$[2;\ 2;\ 3]$		$[1;\ 1;\ 3]$	
	5	$[2;\ 1;\ 1]$	$\Delta\pi$	$[2;\ 1;\ 1]$	$\Delta\pi$		
	6	$[2;\ 1;\ 3]$		$[2;\ 1;\ 3]$			
	7	$[1;\ 1;\ 1]$	$\Delta\rho$	$[1;\ 2;\ 1]$	$\Delta\omega$		
	8	$[1;\ 1;\ 3]$		$[1;\ 2;\ 3]$			
	9			$[1;\ 1;\ 1]$	$\Delta\rho$		
	10			$[1;\ 1;\ 3]$			
$\frac{5}{2}^-$	1	$[1;\ 1;\ 1]$	$\Delta\rho$	$[1;\ 2;\ 1]$	$\Delta\omega$	$[1;\ 1;\ 1]$	$\Delta\rho$
	2	$[1;\ 1;\ 3]$		$[1;\ 2;\ 3]$		$[1;\ 1;\ 3]$	
	3			$[1;\ 1;\ 1]$	$\Delta\rho$		
	4			$[1;\ 1;\ 3]$			

- **Dynamic study in ChQM for the light quark sector(u,d) with three sets of parameters.**

qqq systems

TABLE II: Masses of baryon and meson in ChQM with the three sets of parameters (unit: MeV).

set	$N(939)$	$\Delta(1232)$	$\Omega(1672)$	$\Lambda(1116)$
I	939	1231	1671	1178
II	749	1116	1623	1033
III	833	1178	1704	1124
	$\Sigma(1189)$	$\Xi(1315)$	$\Sigma^*(1383)$	$\Xi^*(1532)$
I	1201	1408	1381	1527
II	1058	1260	1341	1428
III	1147	1406	1350	1525
	$\pi(140)$	$\rho(775)$	$\eta(548)$	$\omega(782)$
I	305	817	646	693
II	139	742	551	573
III	145	783	561	653
	$K(495)$	$K^*(892)$	$\eta'(958)$	$\phi(1019)$
I	517	968	771	1070
II	483	886	958	1027
III	483	955	857	1093

Total mass error for baryons and mesons in 3 sets of parameters.

set	ΔE_b	ΔE_m
I	176	632
II	770	272
III	373	405

TABLE V: The lowest eigen-energies of system with $IJ^P = \frac{1}{2}\frac{3}{2}^-$ in three sets of parameters (unit: MeV). The percentages of color-singlet (S) and hidden-color (H) channels are also given.

		set I				set II				set III			
Channel	E_{th}^{Exp}	E	E_{th}^{Theo}	E_B	E'	E	E_{th}^{Theo}	E_B	E'	E	E_{th}^{Theo}	E_B	E'
1	1722($P\omega$)	1632	1632	0	1722	1322	1322	0	1722	1486	1486	0	1722
2		2063				1878				1964			
1+2		1632		0	1722	1322		0	1722	1486		0	1722
percentage (S; H):			100%; 0.0%				100%; 0.0%				100%; 0.0%		
3	1714($P\rho$)	1756	1756	0	1714	1491	1491	0	1714	1616	1616	0	1714
4		2143				1991				2049			
3+4		1756		0	1714	1491		0	1714	1616		0	1714
percentage (S; H):			100%; 0.0%				100%; 0.0%				100%; 0.0%		
5	1371($\Delta\pi$)	1533	1536	-3	1368	1252	1255	−3	1368	1321	1323	−2	1369
6		2556				2568				2478			
5+6		1533		−3	1368	1252		−3	1368	1320		−3	1368
percentage (S; H):			100%; 0.0%				100%; 0.0%				100%; 0.0%		
7	2007($\Delta\rho$)	2048	2048	0	2007	1858	1858	0	2007	1961	1961	0	2007
8		2516				2517				2431			
7+8		2048		0	2007	1858		0	2007	1961		0	2007
percentage (S; H):			100%; 0.0%				100%; 0.0%				100%; 0.0%		
mixed (singlet)	1371($\Delta\pi$)	1514	1536	−22	1349	1223	1255	−32	1339	1301	1323	−22	1349
mixed (full)	1371($\Delta\pi$)	1497	1536	−39	1332	1201	1255	−54	1317	1283	1323	−40	1331

TABLE VII: The percentage of each component within the full channel-coupling of the lowest energy for $IJ^P = \frac{1}{2}\frac{3}{2}^-$ state in three set of parameters.

components (*set* I)	$(P\omega)^1$	$(P\omega)^8$	$(P\rho)^1$	$(P\rho)^8$
	27.1%	1.5%	11.1%	0.7%
	$(\Delta\pi)^1$	$(\Delta\pi)^8$	$(\Delta\rho)^1$	$(\Delta\rho)^8$
	51.7%	1.5%	4.7%	1.7%
components (*set* II)	$(P\omega)^1$	$(P\omega)^8$	$(P\rho)^1$	$(P\rho)^8$
	26.9%	0.7%	8.4%	0.8%
	$(\Delta\pi)^1$	$(\Delta\pi)^8$	$(\Delta\rho)^1$	$(\Delta\rho)^8$
	57.6%	1.9%	1.5%	2.2%
components (*set* III)	$(P\omega)^1$	$(P\omega)^8$	$(P\rho)^1$	$(P\rho)^8$
	23.1%	1.1%	9.5%	0.2%
	$(\Delta\pi)^1$	$(\Delta\pi)^8$	$(\Delta\rho)^1$	$(\Delta\rho)^8$
	59.3%	1.5%	3.7%	1.6%

TABLE VI: The lowest eigen-energies of system with $IJ^P = \frac{1}{2}\frac{5}{2}^-$ (unit: MeV) in three sets of parameters. The percentages of color-singlet (S) and hidden-color (H) channels are also given.

Channel	E	E_{th}^{Theo}	E_B	E_{th}^{Exp}	E'
		set I			
1	2043	2048	-5	2007($\Delta\rho$)	2002
2	2633				
1+2	2042		-6		2001
		percentage (S; H): 99.3%; 0.7%			
		set II			
1	1849	1858	-9	2007($\Delta\rho$)	1998
2	2674				
1+2	1847		-11		1996
		percentage (S; H): 99.3%; 0.7%			
		set III			
1	1954	1961	-7	2007($\Delta\rho$)	2000
2	2563				
1+2	1953		-8		1999
		percentage (S; H): 99.3%; 0.7%			

TABLE VIII: Distances between quarks and quark-antiquark in three sets of parameters (unit: fm).

	set I		set II		set III	
IJ^P	r_{qq}	$r_{q\bar{q}}$	r_{qq}	$r_{q\bar{q}}$	r_{qq}	$r_{q\bar{q}}$
$\frac{1}{2}\frac{3}{2}^-$	1.18	1.22	1.01	1.06	1.15	1.18
$\frac{1}{2}\frac{5}{2}^-$	1.99	2.33	1.60	1.87	1.94	2.27

compact

molecular

- **May be a model-independent results for the nature of pentaquark states of $\Delta\pi$, $\Delta\rho$ with the spin-parity of 3/2- and 5/2-,respectively, and *I*=1/2.**

$$\frac{1}{2}\left(\frac{3}{2}\right)^{-}$$: ***N*(1331)***

$$\frac{1}{2}\left(\frac{5}{2}\right)^{-}$$: ***N*(2000)***

Conclusions and prospects

- **The pentaquark state $P_c^+(4380)$ can be interpreted as the molecular baryons of $\Sigma_c^* D$.**
- **One of the newly discovered Ω_c^0 excited states may be the pentaquark state of $\Xi_c^* K$.**
- **Two higher excited states of Ω_c^0 can be explained as the 2S states.**
- **The high spin N* states may exist the tightly bound states of pentaquark.**
- ***The coupling between 3q and 5q in unquenched quark model should be developed in future.***
- ***The spin-orbit, tensor force may be considered in future.***

Thanks!