Color magnetic interaction and multiquark states

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Content

- Introduction
- The CMI model
- Selected systems
    1. Hidden-charm pentaquarks
    2. Triply-heavy mesons
    3. Tcc and partner states
- Summary

In collaboration with

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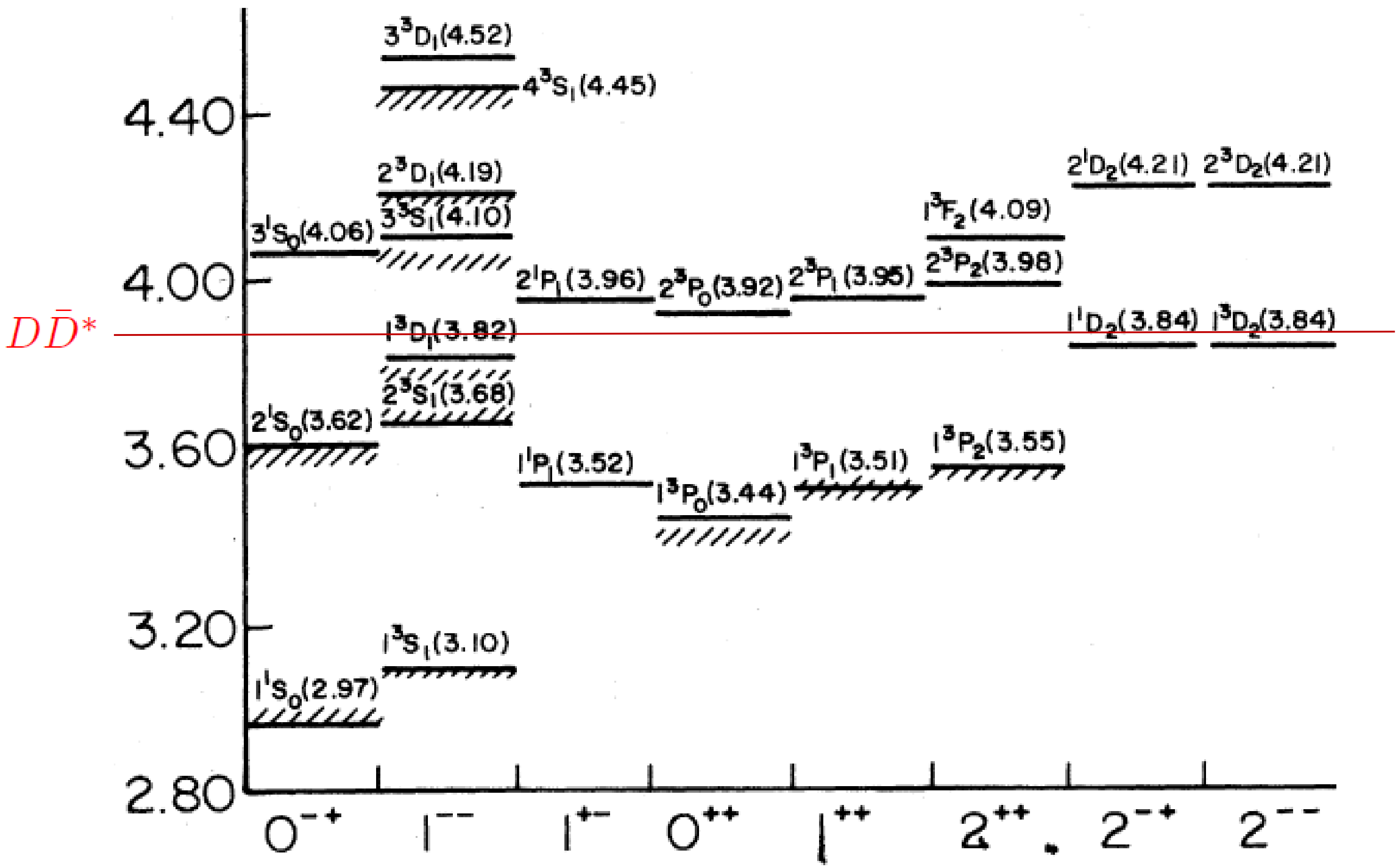
Kazutaka Sudoh, Shigehiro Yasui, Shi-Lin Zhu,

Kan Chen, Si-Qiang Luo, Jing Wu

Introduction

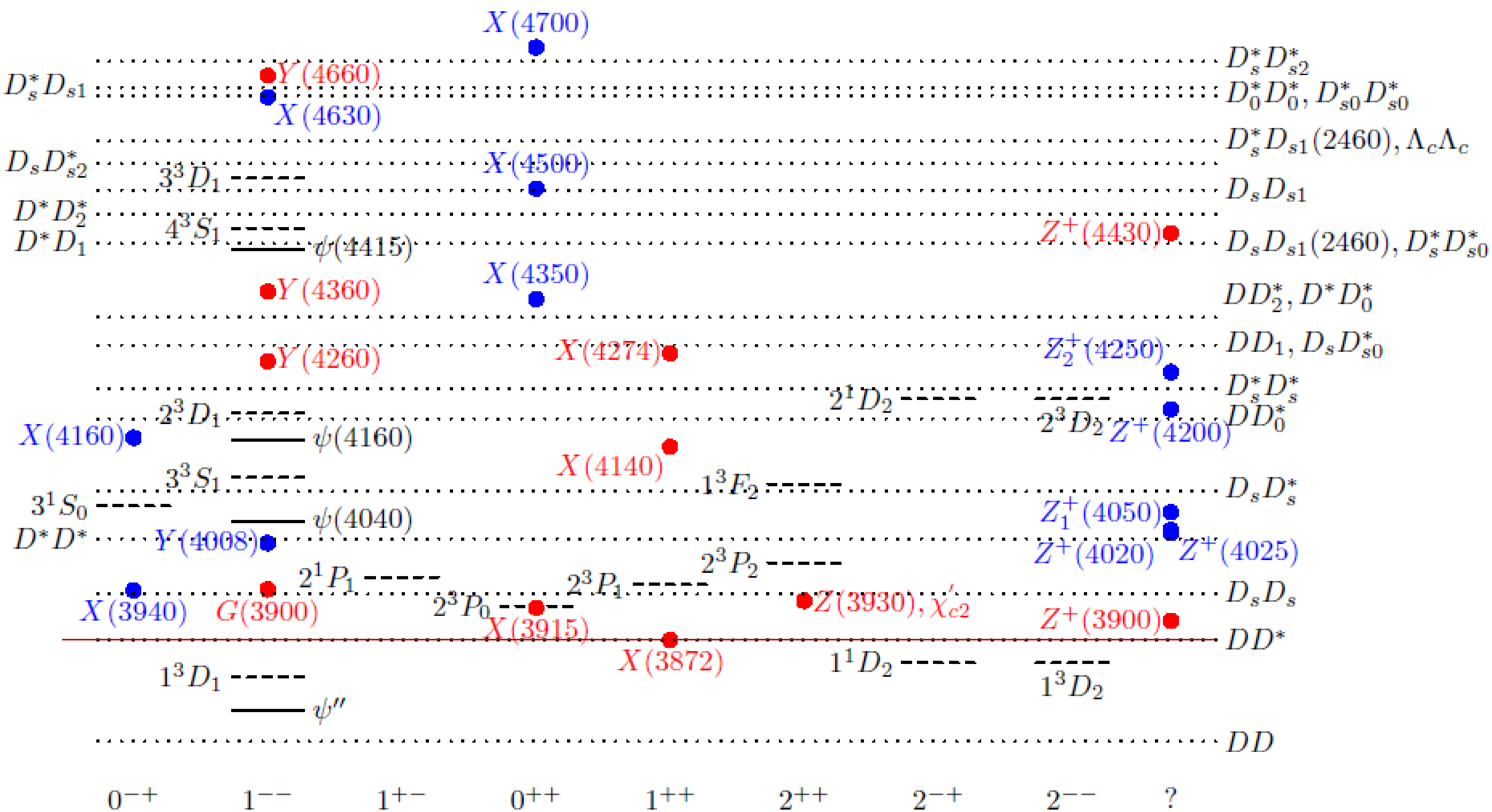
- Charmonia and XYZ states



Godfrey, Isgur, PRD 32,189 (1985)

Introduction

- Charmonia and XYZ states



Introduction

- Charmonium
- Molecular or tetraquark states
- Hybrid
- Non-resonant interpretations

- More states with exotic structures?

  Here discuss with a simple model

The color-magnetic-interaction(CMI) model

- Mass splittings for S-wave states:

$$H = \sum_i m_i + \sum_i T_i + V_{eff},$$

$$V_{eff} = \sum_{i<j} \left[A(r_{ij}) \lambda_i \cdot \lambda_j + B \frac{\delta^3(r_{ij})}{m_i m_j} \lambda_i \cdot \lambda_j \sigma_i \cdot \sigma_j \right].$$

$$\Rightarrow \quad H = \sum_i m_i^{eff} + H_{eff}, \qquad H_{eff} = -\sum_{i<j} C_{ij} \lambda_i \cdot \lambda_j \sigma_i \cdot \sigma_j.$$

$$\langle \lambda_i \cdot \lambda_j \rangle = \begin{cases} -\frac{16}{3}, & (q\bar{q}) \\ -\frac{8}{3}, & (qq) \end{cases}$$

$$M_\Delta - M_N \sim 300 \text{ MeV}$$

The CMI model

- Drawbacks:

  No Dynamics;

  Effective quark masses;

  Effective coupling constants;

  Estimated masses and other problems

- Few-body problem complicated
- Simple for estimation of rough positions of multiquark states
- CMI model can catch basic features of spectra

The CMI model

$$\langle H_{CM}\rangle = -\sum_{i<j} C_{ij}\langle \lambda_i \cdot \lambda_j \sigma_i \cdot \sigma_j \rangle$$

$$w.f. = (color) \otimes (spin)\delta$$

$$\langle H_{C}\rangle = \sum_{i<j} C_{ij}\langle \lambda_i \cdot \lambda_j \rangle$$

$$\delta : \text{Pauli principle}$$

$$\langle H_{S}\rangle = -\sum_{i<j} C_{ij}\langle \sigma_i \cdot \sigma_j \rangle$$

Hogaasen, Sorba,MPLA19,2403(2004).

- For (qqq...): M.Oka, NPA881,6(2012)

$$\left\langle \sum_{i<j} (\lambda_i \cdot \lambda_j)(\sigma_i \cdot \sigma_j) \right\rangle = -\left[8N + \frac{4}{3}S(S+1) + 2C_2[SU(3)_c] - 4C_2[SU(6)_{cs}] \right]$$

- For ($q\underline{q}$):

$$\langle (\lambda_4 \cdot \lambda_5)(\sigma_4 \cdot \sigma_5) \rangle = 4\left[C_2[SU(3)_c] - \frac{8}{3} \right]\left[S_{c\bar{c}}(S_{c\bar{c}}+1) - \frac{3}{2} \right]$$

The CMI model

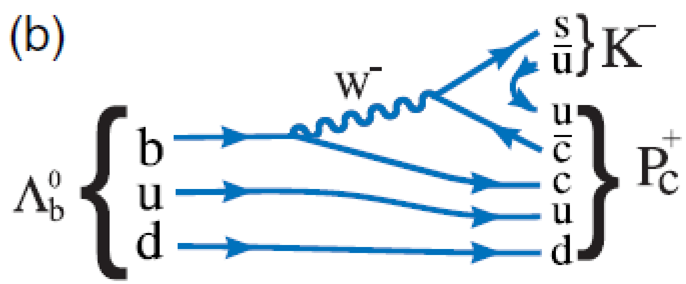
- Two schemes of estimation:

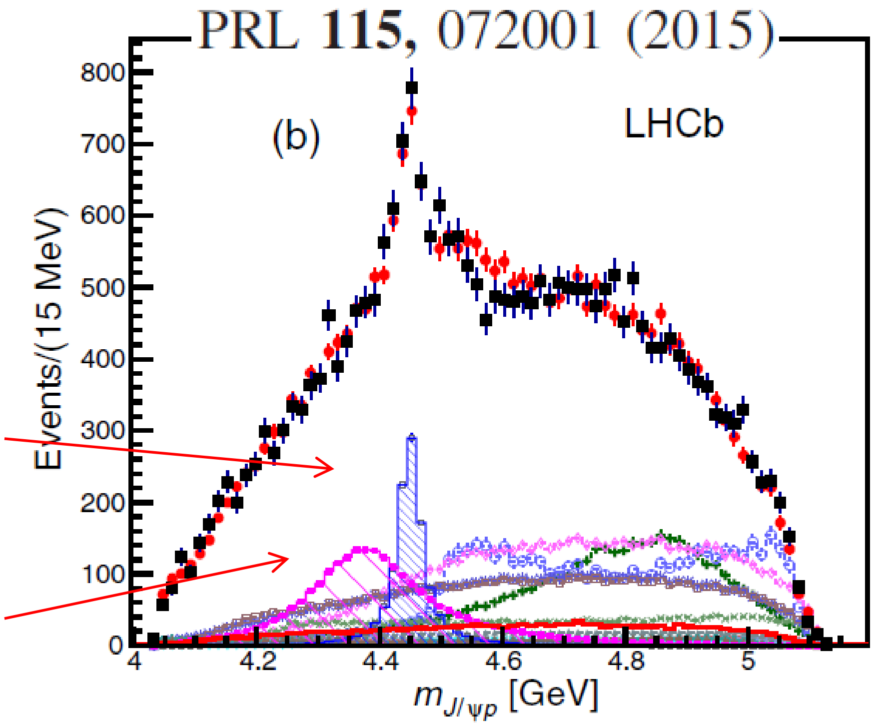
$$M = \sum_i m_i + \langle H_{CM} \rangle$$ ←Upper limit

$$M = M_{ref} - \langle H_{CM} \rangle_{ref} + \langle H_{CM} \rangle$$

Hadron	CMI	Hadron	CMI	Parameter(MeV)
N	$-8C_{nn}$	Δ	$8C_{nn}$	$C_{nn} = 18.4$
Σ	$\frac{8}{3}C_{nn} - \frac{32}{3}C_{ns}$	Σ^*	$\frac{8}{3}C_{nn} + \frac{16}{3}C_{ns}$	$C_{ns} = 12.4$
Ξ^0	$\frac{8}{3}(C_{ss} - 4C_{ns})$	Ξ^{*0}	$\frac{8}{3}(C_{ss} + C_{ns})$	
Ω	$8C_{ss}$			$C_{ss} = 6.5$
Λ	$-8C_{nn}$			
D	$-16C_{c\bar{n}}$	D^*	$\frac{16}{3}C_{c\bar{n}}$	$C_{c\bar{n}} = 6.7$
D_s	$-16C_{c\bar{s}}$	D_s^*	$\frac{16}{3}C_{c\bar{s}}$	$C_{c\bar{s}} = 6.7$
B	$-16C_{b\bar{n}}$	B^*	$\frac{16}{3}C_{b\bar{n}}$	$C_{b\bar{n}} = 2.1$
B_s	$-16C_{b\bar{s}}$	B^*	$\frac{16}{3}C_{b\bar{s}}$	$C_{b\bar{s}} = 2.3$
η_c	$-16C_{c\bar{c}}$	J/ψ	$\frac{16}{3}C_{c\bar{c}}$	$C_{c\bar{c}} = 5.3$
η_b	$-16C_{b\bar{b}}$	Υ	$\frac{16}{3}C_{b\bar{b}}$	$C_{b\bar{b}} = 2.9$
Σ_c	$\frac{8}{3}C_{nn} - \frac{32}{3}C_{cn}$	Σ_c^*	$\frac{8}{3}C_{nn} + \frac{16}{3}C_{cn}$	$C_{cn} = 4.0$
Ξ_c'	$\frac{8}{3}C_{ns} - \frac{16}{3}C_{cn} - \frac{16}{3}C_{cs}$	Ξ_c^*	$\frac{8}{3}C_{ns} + \frac{8}{3}C_{cn} + \frac{8}{3}C_{cs}$	$C_{cs} = 4.8$
Σ_b	$\frac{8}{3}C_{nn} - \frac{32}{3}C_{bn}$	Σ_b^*	$\frac{8}{3}C_{nn} + \frac{16}{3}C_{bn}$	$C_{bn} = 1.3$
Ξ_b'	$\frac{8}{3}C_{ns} - \frac{16}{3}C_{bn} - \frac{16}{3}C_{bs}$	Ξ_b^*	$\frac{8}{3}C_{ns} + \frac{8}{3}C_{bn} + \frac{8}{3}C_{bs}$	$C_{bs} = 1.2$

Hidden-charm pentaquarks





$$M_{P_c(4450)} = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV},$$
$$\Gamma_{P_c(4450)} = 39 \pm 5 \pm 19 \text{ MeV}.$$

$$M_{P_c(4380)} = 4380 \pm 8 \pm 29 \text{ MeV},$$
$$\Gamma_{P_c(4380)} = 205 \pm 18 \pm 86 \text{ MeV}.$$

- Wu, Molina, Oset, Zou,PRL105,232001(2010)

In summary, we find two $N^*_{c\bar{c}}$ states and four $\Lambda^*_{c\bar{c}}$ states from PB and VB channels. All of these states have large $c\bar{c}$ components, so their masses are all larger than 4200 MeV. The widths of these states decaying to light meson and baryon channels without $c\bar{c}$ components are all very small.

Hidden-charm pentaquarks

[1] J. J. Wu, R. Molina, E. Oset and B. S. Zou, Dynamically generated N^* and Λ^* resonances in the hidden charm sector around 4.3 GeV, Phys. Rev. C **84**, 015202 (2011), [arXiv:1011.2399 [nucl-th]].

[2] Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, The possible hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon, Chin. Phys. C **36**, 6 (2012), [arXiv:1105.2901 [hep-ph]].

[3] W. L. Wang, F. Huang, Z. Y. Zhang and B. S. Zou, $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ states in a chiral quark model, Phys. Rev. C **84**, 015203 (2011), [arXiv:1101.0453 [nucl-th]].

[4] S. G. Yuan, K. W. Wei, J. He, H. S. Xu and B. S. Zou, Study of $qqqc\bar{c}$ five quark system with three kinds of quark-quark hyperfine interaction, Eur. Phys. J. A **48**, 61 (2012), [arXiv:1201.0807 [nucl-th]].

[5] J. J. Wu, T.-S. H. Lee and B. S. Zou, Nucleon Resonances with Hidden Charm in Coupled-Channel Models, Phys. Rev. C **85**, 044002 (2012), [arXiv:1202.1036 [nucl-th]].

Hidden-charm pentaquarks

- Interpretations: molecules, pentaquarks, kinematical effects, triangle singularity, ...

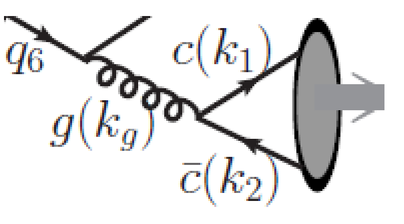
- J/ψ N resonance?

  4380-4035=345 MeV

  (a=0.71 fm [Yokokawa et al, PRD74, 034504(2006)])

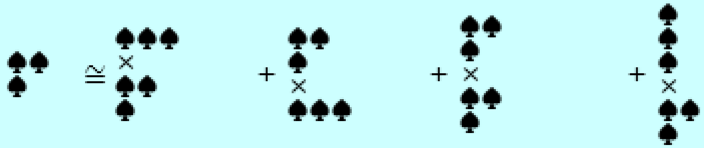
- Colored charm-anticharm pair?

$$(qqq)_{8_c}(c\bar{c})_{8_c}$$



Dynamical calculation: Takeuchi, Takizawa, PLB 764, 254 (2017).

Hidden-charm pentaquarks

SU(6)≅SU(3)×SU(2): 

Representation:	[2,1]	[3]×[2,1]	[2,1]×[3]	[2,1]×[2,1]	[1^3]×[2,1]
Coefficient:		1	1	1	1
Dimension:	70	(10,2)	+ (8,4)	+ (8,2)	+ (1,2)

SU(6): flavor-spin of qqq

TABLE I. Flavor multiplets and wave functions of the colored qqq in different spaces. Young diagrams for the color-spin $SU(6)_{cs}$ are also given in the first column.

Multiplet	Space	Wave function	Wave function
10_f	Color	ϕ^{MS}	ϕ^{MA}
	Spin	χ^{MA}	χ^{MS}
$[111]_{cs}$	Flavor	F^S	F^S
1_f	Color	ϕ^{MS}	ϕ^{MA}
	Spin	χ^{MS}	χ^{MA}
$[3]_{cs}$	Flavor	F^A	F^A
$8_f(1)$	Color	ϕ^{MS}	ϕ^{MA}
	Spin	χ^S	χ^S
$[21]_{cs}$	Flavor	F^{MA}	F^{MS}
$8_f(2)$	Color	ϕ^{MS}	ϕ^{MA}
	Spin	χ^{MS} χ^{MA}	χ^{MS} χ^{MA}
$[21]_{cs}$	Flavor	F^{MA} F^{MS}	F^{MS} F^{MA}

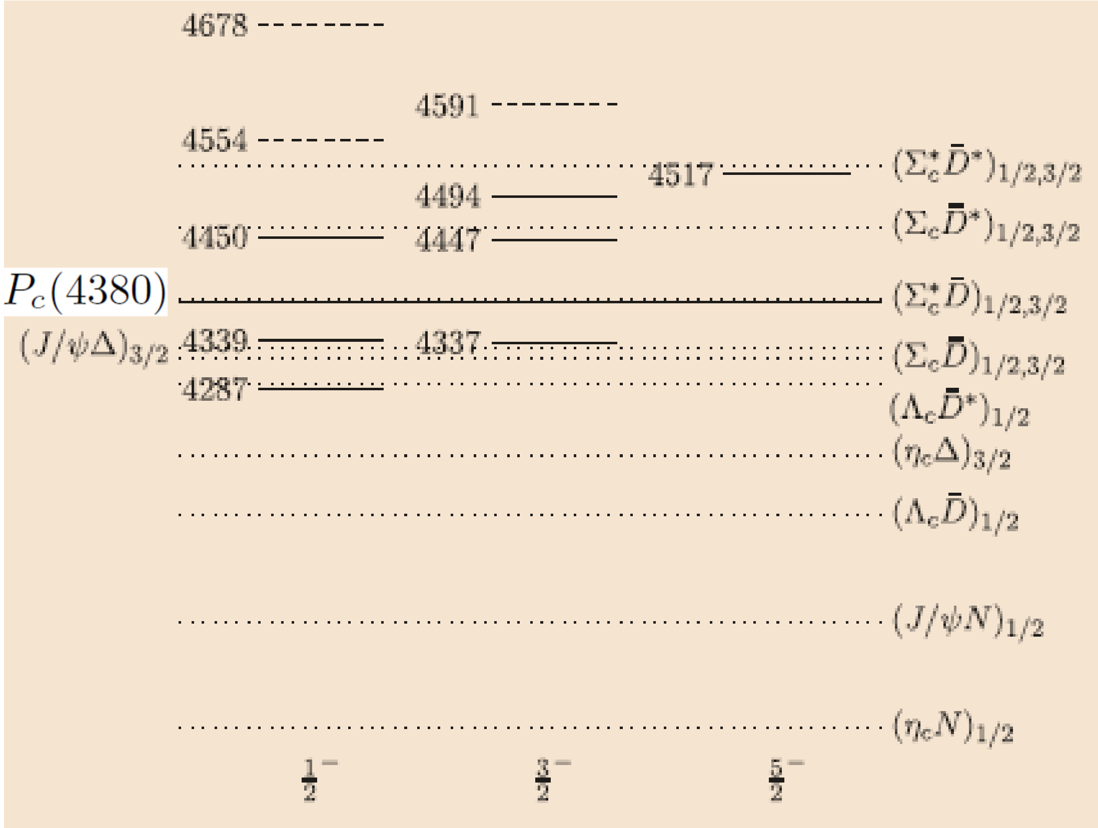
TABLE II. Antisymmetric wave function for a color-octet qqq state.

Multiplet	Flavor-color-spin wave function
10_f	$\frac{1}{\sqrt{2}}[F^S \otimes (\phi^{MS} \otimes \chi^{MA} - \phi^{MA} \otimes \chi^{MS})]$
1_f	$\frac{1}{\sqrt{2}}[F^A \otimes (\phi^{MS} \otimes \chi^{MS} + \phi^{MA} \otimes \chi^{MA})]$
$8_f(1)$	$\frac{1}{\sqrt{2}}[(F^{MS} \otimes \phi^{MA} - F^{MA} \otimes \phi^{MS}) \otimes \chi^S]$
$8_f(2)$	$\frac{1}{2}[(F^{MS} \otimes \chi^{MA} + F^{MA} \otimes \chi^{MS}) \otimes \phi^{MS}$ $+(F^{MS} \otimes \chi^{MS} - F^{MA} \otimes \chi^{MA}) \otimes \phi^{MA}]$

$$\phi_{\text{penta}}^{MS,MA} = \frac{1}{2\sqrt{2}}\Big[-p_C^{MS,MA}(b\bar{r}) - n_C^{MS,MA}(b\bar{g}) - \Sigma_C^{+MS,MA}(g\bar{r}) + \Sigma_C^{-MS,MA}(r\bar{g}) - \Xi_C^{0MS,MA}(g\bar{b}) + \Xi_C^{-MS,MA}(r\bar{b}) - \frac{1}{\sqrt{2}}\Sigma_C^{0MS,MA}(g\bar{g} - r\bar{r}) + \frac{1}{\sqrt{6}}\Lambda_C^{MS,MA}(r\bar{r} + g\bar{g} - 2b\bar{b})\Big],$$

J. Wu, Y.R. Liu, K. Chen, Xiang Liu, Shi-Lin Zhu, PRD, 95, 034002 (2017), “Hidden-charm pentaquarks and their hidden-bottom and Bc-like partner states”

Hidden-charm pentaquarks



(a) $I = \frac{3}{2}$ (dashed) and $I = \frac{1}{2}$ (solid) $nnnc\bar{c}$ states

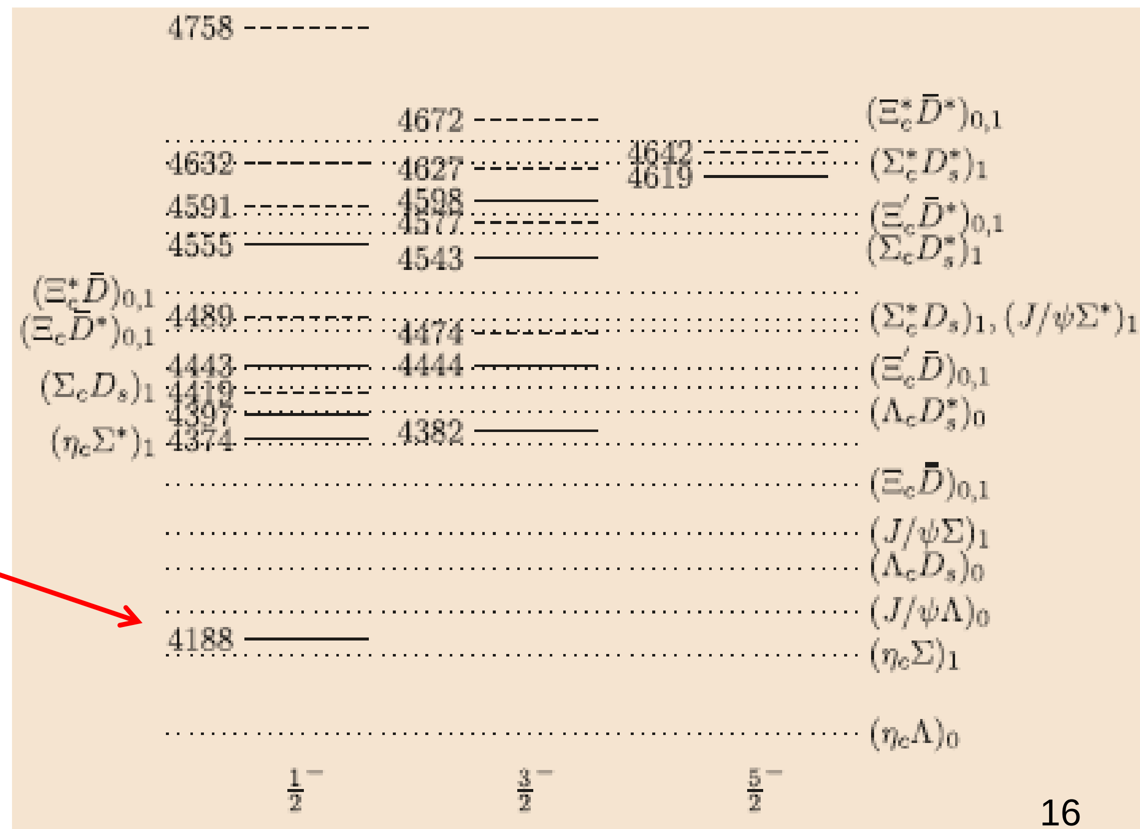
- $J^P = \frac{5}{2}^-$: D-wave decay, not so broad
- Others: open-charm decays, broad

Hidden-charm pentaquarks

- SU(3) breaking:

  Buccella, Hogaasen, Richard, Sorba, EPJC49,743 (2007).

- Narrow state lower than possible molecules



(b) $I = 1$ (dashed) and $I = 0$ (solid) $nnsc\bar{c}$ states

Hidden-charm pentaquarks

- Why low state possible?

(1) SU(3)_f symmetric case:

$$10_f:\ \langle H_{CM}\rangle = 10C_{qq} + 2C_{c\bar{c}}, \quad \text{for } \left(S_{c\bar{c}}=0, J=\frac{1}{2}\right)$$

$$\langle H_{CM}\rangle = 10C_{qq} - \frac{2}{3}C_{c\bar{c}} - \frac{20}{3}(C_{qc} - C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{1}{2}\right)$$

$$\langle H_{CM}\rangle = 10C_{qq} - \frac{2}{3}C_{c\bar{c}} + \frac{10}{3}(C_{qc} - C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{3}{2}\right),$$

$$8_f(1):\ \langle H_{CM}\rangle = 2C_{qq} + 2C_{c\bar{c}}, \quad \text{for } \left(S_{c\bar{c}}=0, J=\frac{3}{2}\right)$$

$$\langle H_{CM}\rangle = 2C_{qq} - \frac{2}{3}C_{c\bar{c}} - 10(C_{qc} + C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{1}{2}\right)$$

$$\langle H_{CM}\rangle = 2C_{qq} - \frac{2}{3}C_{c\bar{c}} - 4(C_{qc} + C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{3}{2}\right)$$

$$\langle H_{CM}\rangle = 2C_{qq} - \frac{2}{3}C_{c\bar{c}} + 6(C_{qc} + C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{5}{2}\right),$$

$$1_f:\ \langle H_{CM}\rangle = -14C_{qq} + 2C_{c\bar{c}}, \quad \text{for } \left(S_{c\bar{c}}=0, J=\frac{1}{2}\right)$$

$$\langle H_{CM}\rangle = -14C_{qq} - \frac{2}{3}C_{c\bar{c}} - \frac{4}{3}(C_{qc} + 11C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{1}{2}\right)$$

$$\langle H_{CM}\rangle = -14C_{qq} - \frac{2}{3}C_{c\bar{c}} + \frac{2}{3}(C_{qc} + 11C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{3}{2}\right),$$

$$8_f(2):\ \langle H_{CM}\rangle = -2C_{qq} + 2C_{c\bar{c}}, \quad \text{for } \left(S_{c\bar{c}}=0, J=\frac{1}{2}\right)$$

$$\langle H_{CM}\rangle = -2C_{qq} - \frac{2}{3}C_{c\bar{c}} - 4(C_{qc} + C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{1}{2}\right)$$

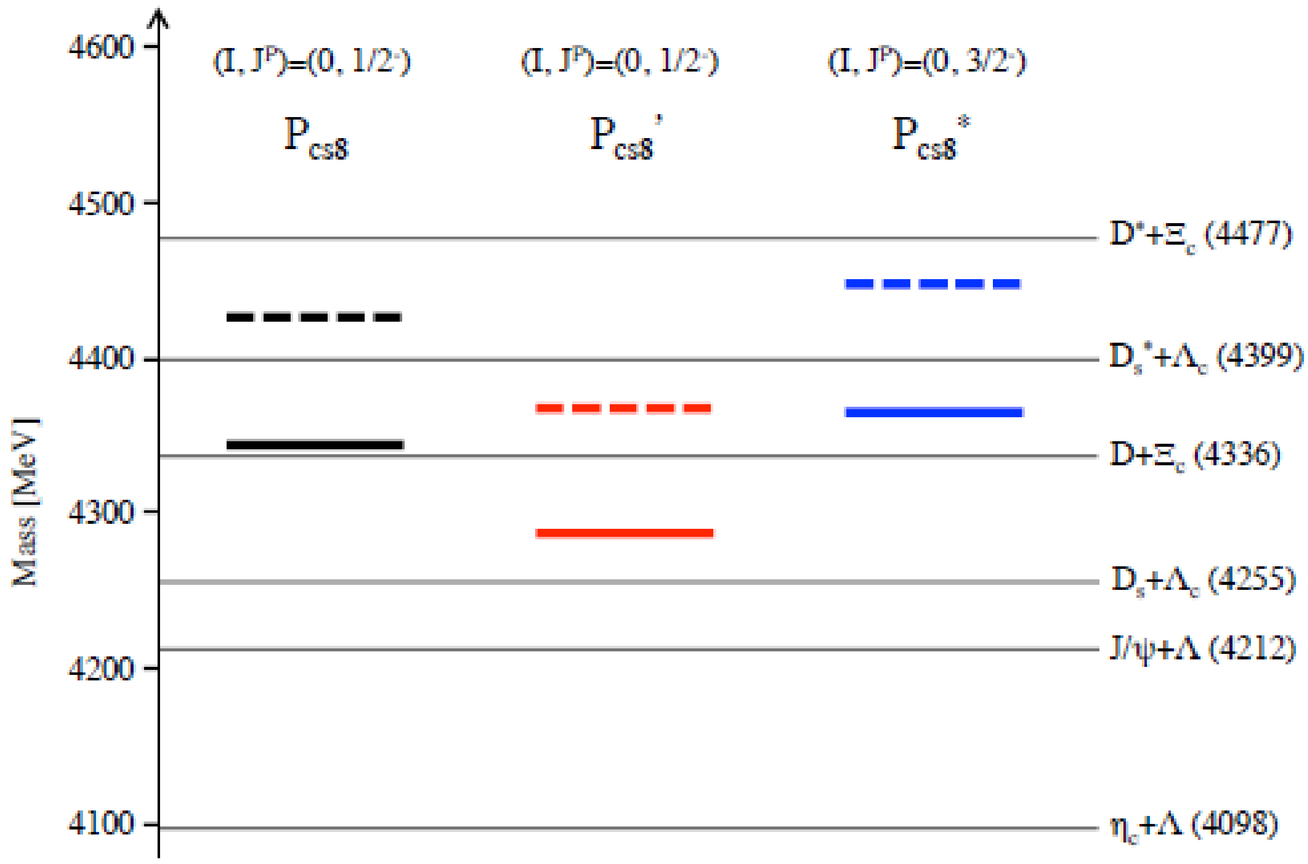
$$\langle H_{CM}\rangle = -2C_{qq} - \frac{2}{3}C_{c\bar{c}} + 2(C_{qc} + C_{q\bar{c}}), \quad \text{for } \left(S_{c\bar{c}}=1, J=\frac{3}{2}\right).$$

(2) Channel coupling → low mass

More elaborate study

- Y. Irie, M. Oka, S. Yasui, “Flavor-singlet charm pentaquark”, arXiv:1707.04544 [hep-ph].

- OGE interaction and instanton-induced interaction



A comparison for quark level and hadron level calculations

- In PRL105,232001(2010) [Wu et al]:

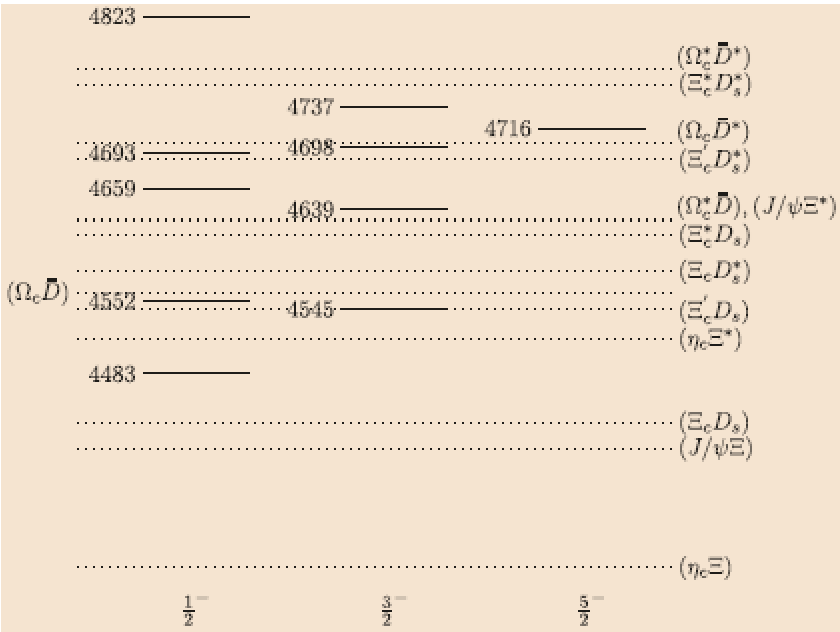
  lowest $N_{c\underline{c}}$ is around 4261 MeV [here ~4287 MeV];

  lowest $\Lambda_{c\underline{c}}$ is around 4209 MeV [here ~4190 MeV].

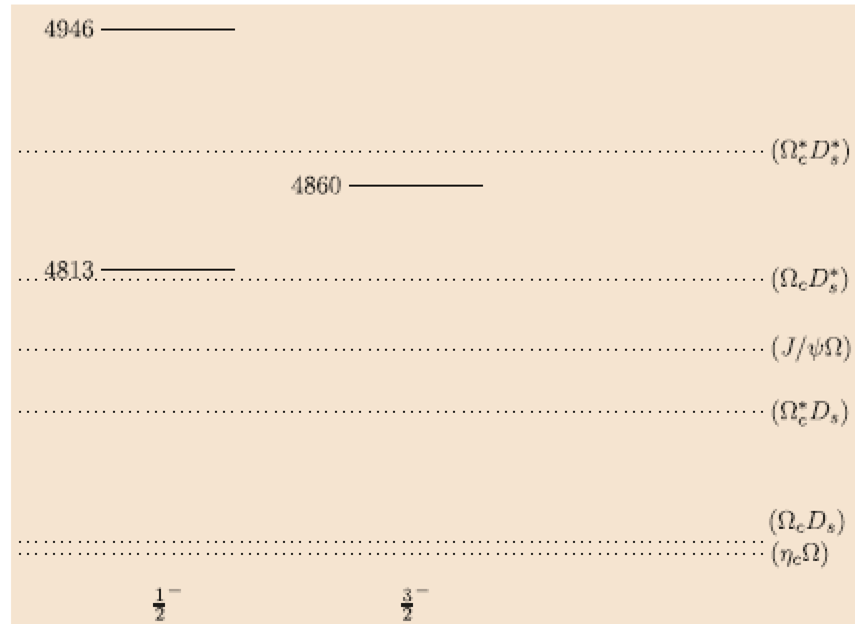
$$(qqq)_{8_c}(c\bar{c})_{8_c} \approx [\bar{D}\Lambda_c - \bar{D}^*\Lambda - \bar{D}\Sigma_c - \bar{D}^*\Sigma_c - \bar{D}\Sigma_c^* - \bar{D}^*\Sigma_c^*]?$$

Y. Yamaguchi, E. Santopinto, PRD96, 014018 (2017) ?

Hidden-charm pentaquarks



(c) $I = \frac{1}{2}$ (solid) $ssnc\bar{c}$ states



(d) $I = 0$ (solid) $sssc\bar{c}$ system

- Hidden-bottom and Bc-like partner states

Triply-heavy mesons

- Can we distinguish compact tetraquarks from molecules?

  e.g. X(5568), states in $J/\psi\phi$

- A system without light meson exchange?

  e.g. long history $QQ\underline{QQ}$,

  Y. Iwasaki, Prog. Theor. Phys. **54**, 492 (1975).
  K.T. Chao, Z. Phys. C **7**, 317 (1981).

  & not widely discussed $QQ\underline{Qq}$

  Y. Cui, X.L. Chen, W.Z. Deng, S.L. Zhu, HEPNP 31, 7 (2007).

Triply-heavy mesons

- In the prediction of hidden-charm pentaquarks, an excited N around 4.3 GeV should contain a charm-anticharm pair.
- Similarly, is it possible that an excited D, Ds, or other heavy-light meson also contains a charm-anticharm pair?

1. $bb\bar{b}\bar{q}$, $bb\bar{c}\bar{q}$, $cc\bar{c}\bar{q}$, $cc\bar{b}\bar{q}$,
2. $bc\bar{b}\bar{q}$, $bc\bar{c}\bar{q}$.

K. Chen, X. Liu, Y. R. Liu, J. Wu, S. L. Zhu, EPJA 53, 5 (2017)

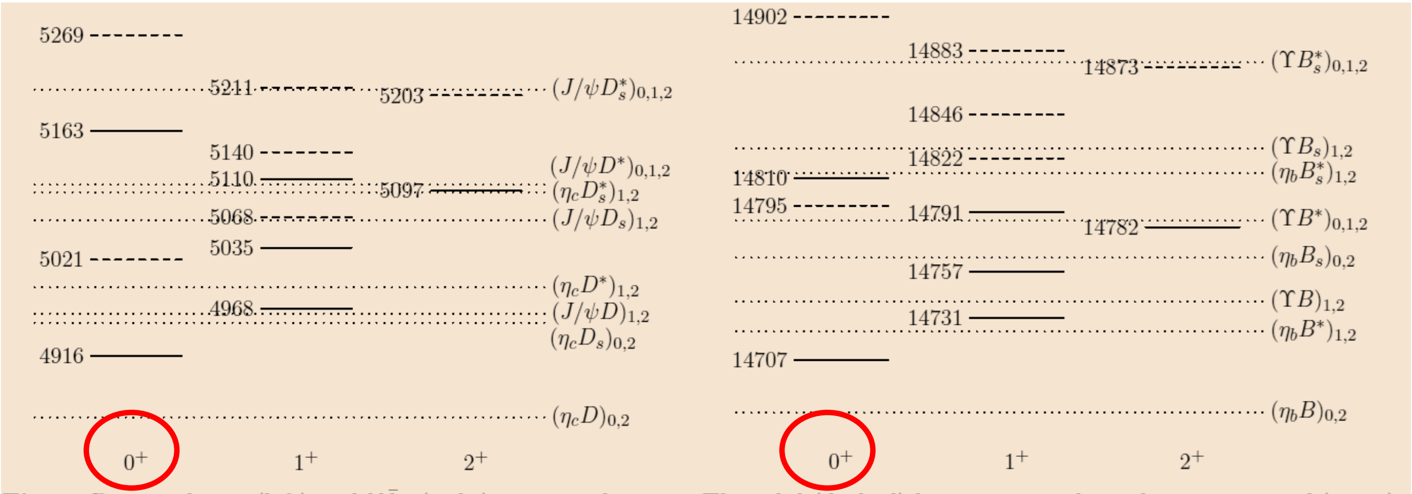


Fig. 1. Proposed $cc\bar{c}\bar{q}$ (left) and $bb\bar{b}\bar{q}$ (right) tetraquark states. The solid (dashed) line corresponds to the case $q = u, d$ ($q = s$). The dotted line indicates various meson-meson thresholds. When a number in the subscript of a meson-meson state is equal to the spin of an initial state, the decay for the initial state into that meson-meson channel through S- or D-wave is allowed. The masses are given in units of MeV.

Triply-heavy mesons

Table 9. Comparison for the masses of different meson systems with only one light antiquark. The symbol (*) means that the system is not constrained by the Pauli principle and the number of mesons is doubled compared to the states constrained by the Pauli principle. The symbol ($) indicates explicitly exotic tetraquark states.

System	Mass (GeV)	System	Mass (GeV)
		$bb\bar{b}\bar{q}$	~ 14.7
$(^*)cb\bar{b}\bar{q}$	~ 11.5	$(\$)bb\bar{c}\bar{q}$	~ 11.6
$(\$)cc\bar{b}\bar{q}$	~ 8.2	$(^*)bc\bar{c}\bar{q}$	~ 8.2
$cc\bar{c}\bar{q}$	~ 5.0	$b\bar{q}$	~ 5.3
$c\bar{q}$	~ 2.0		

- A QCD sum rule study:

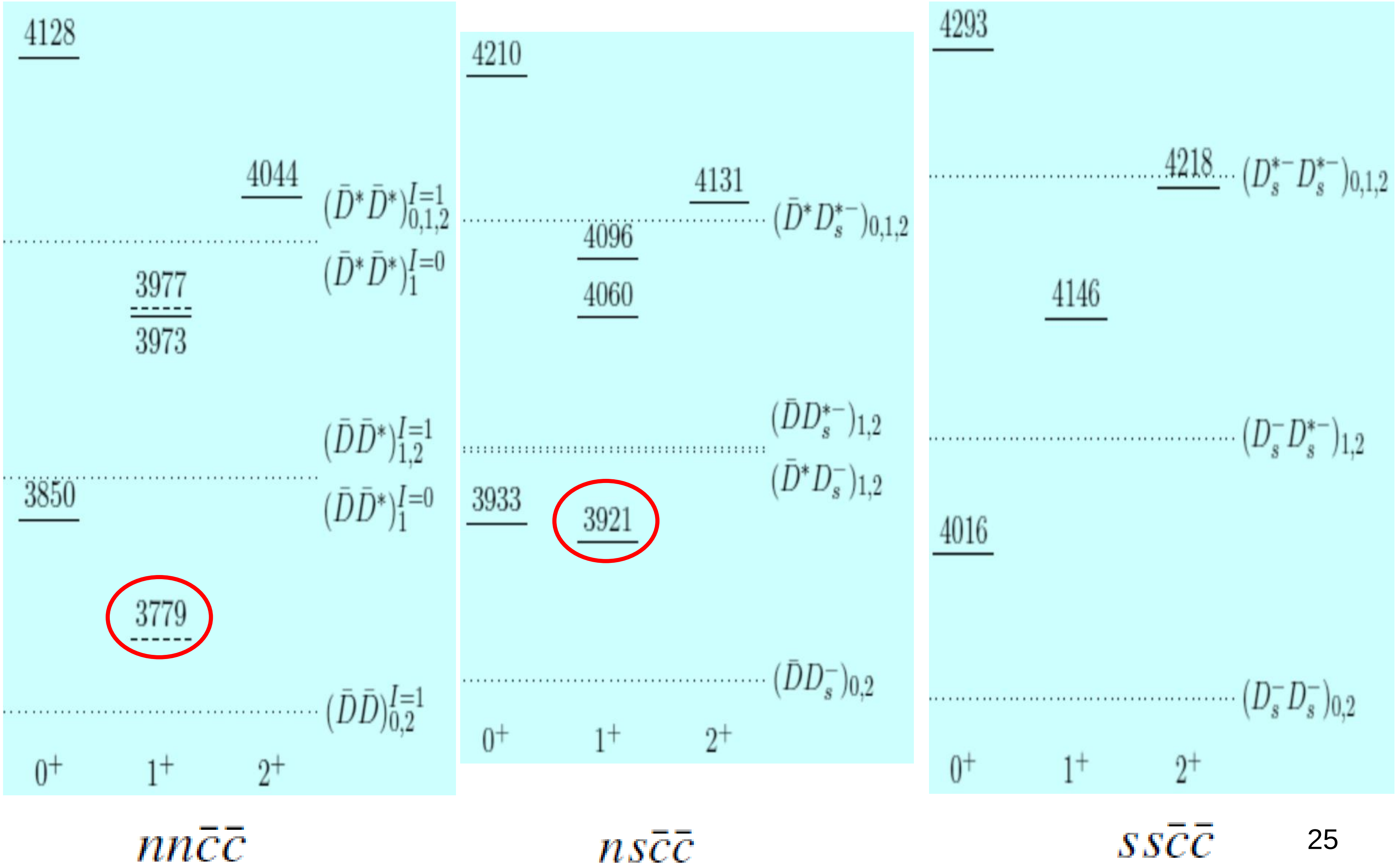
J.F.Jiang, W.Chen, S.L.Zhu,1708.00142 [hep-ph]

Tcc related

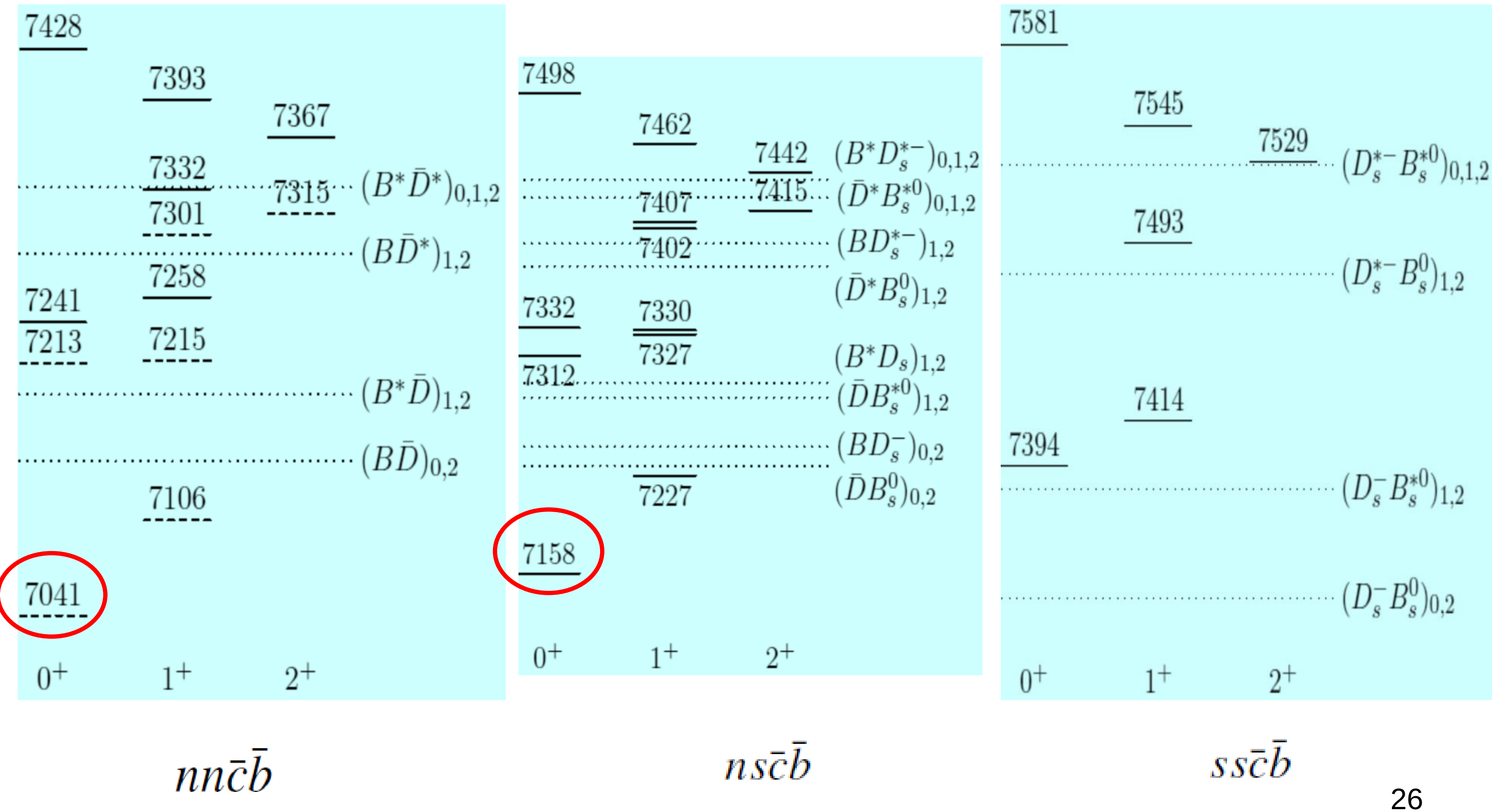
- Many works in the literature …

- T. Hyodo, Y.R. Liu, M. Oka, K. Sudoh, S. Yasui, PLB 721, 56 (2013);
- T. Hyodo, Y.R. Liu, M. Oka, S. Yasui, 1708.05169 [hep-ph].
- S.Q. Luo, K. Chen, X. Liu, Y.R. Liu, S.L. Zhu, 1707.01180 [hep-ph]

Tcc related


4128
4044
$(\bar{D}^*\bar{D}^*)^{I=1}_{0,1,2}$
$(\bar{D}^*\bar{D}^*)^{I=0}_{1}$
3977
3973
$(\bar{D}\bar{D}^*)^{I=1}_{1,2}$
3850
$(\bar{D}\bar{D}^*)^{I=0}_{1}$
3779
$(\bar{D}\bar{D})^{I=1}_{0,2}$
0^+ 1^+ 2^+
$nn\bar{c}\bar{c}$
4210
4131
$(\bar{D}^*D_s^{*-})_{0,1,2}$
4096
4060
$(\bar{D}D_s^{*-})_{1,2}$
$(\bar{D}^*D_s^-)_{1,2}$
3933
3921
$(\bar{D}D_s^-)_{0,2}$
0^+ 1^+ 2^+
$ns\bar{c}\bar{c}$
4293
4218
$(D_s^{*-}D_s^{*-})_{0,1,2}$
4146
$(D_s^-D_s^{*-})_{1,2}$
4016
$(D_s^-D_s^-)_{0,2}$
0^+ 1^+ 2^+
$ss\bar{c}\bar{c}$

Tcc related


7428
7393
7367
7332
7315
$(B^*\bar{D}^*)_{0,1,2}$
7301
$(B\bar{D}^*)_{1,2}$
7258
7241
7213
7215
$(B^*\bar{D})_{1,2}$
$(B\bar{D})_{0,2}$
7106
7041
0^+ 1^+ 2^+
$nn\bar{c}\bar{b}$
7498
7462
7442
$(B^*D_s^{*-})_{0,1,2}$
7415
$(\bar{D}^*B_s^{*0})_{0,1,2}$
7407
7402
$(BD_s^{*-})_{1,2}$
$(\bar{D}^*B_s^0)_{1,2}$
7332
7330
7327
7312
$(B^*D_s)_{1,2}$
$(\bar{D}B_s^{*0})_{1,2}$
$(BD_s^-)_{0,2}$
7227
$(\bar{D}B_s^0)_{0,2}$
7158
0^+ 1^+ 2^+
$ns\bar{c}\bar{b}$
7581
7545
7529
$(D_s^{*-}B_s^{*0})_{0,1,2}$
7493
$(D_s^{*-}B_s^0)_{1,2}$
7414
7394
$(D_s^-B_s^{*0})_{1,2}$
$(D_s^-B_s^0)_{0,2}$
0^+ 1^+ 2^+
$ss\bar{c}\bar{b}$

Tcc related

- Color-mixing effects are relatively important for 0^+ states.
- Some mass relations:

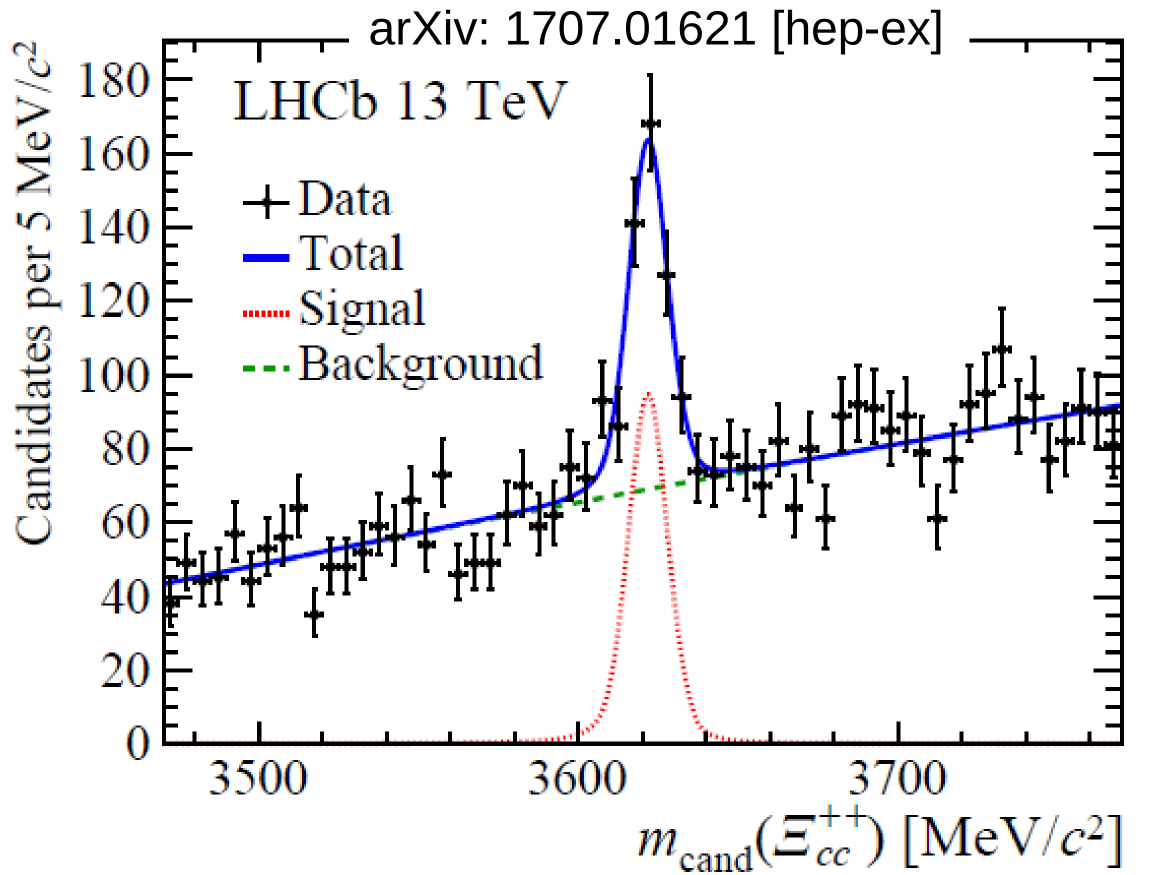
$$m_{nn\bar{Q}\bar{Q}} + m_{ss\bar{Q}\bar{Q}} = 2m_{ns\bar{Q}\bar{Q}}$$

are found with our scheme of estimation in the CMI model.

Tcc related

Both Tcc and Ξcc have cc correlation.

Heavy Quark-Diquark Symmetry:



- T.D. Cohen, P.M. Hohler, PRD 74, 094003 (2006);
- T.Mehen, 1708.05020 [hep-ph].

Summary

- Lower heavy quark pentaquarks are expected
- Triply-heavy mesons (excited D, Ds,B,Bs) may be compact tetraquarks rather than molecules
- Tcc: next intriguing finding after Ξcc?

Thank you very much
for your attention!