

手征夸克模型下重味五夸克系统的研究

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Eur.Phys.J.C 81 (2021) 3, 224

第二届强子与重味物理理论与实验
联合研讨会@兰州大学
2021年3月26日

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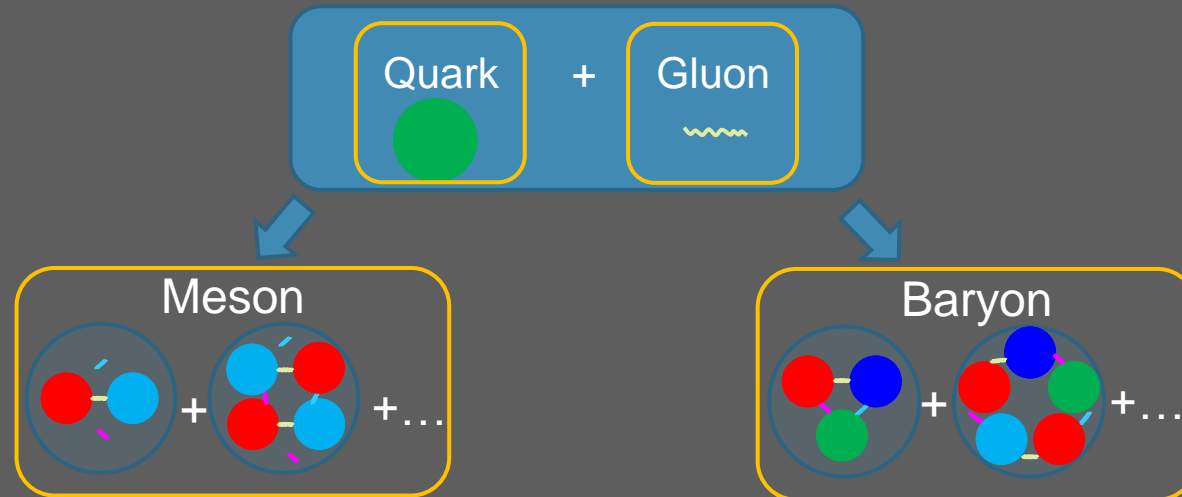
Outline

➤ Introduction

- ⊙ Chiral quark model
- ⊙ $qq\bar{s}\bar{Q}Q$ and $qqq\bar{q}Q$ system
- ⊙ Summary

Introduction

Hadron are made by quarks and gluons



The dynamics of quarks and gluons are described by Quantum chromodynamics (QCD)

- QCD have two important features:
 - ◆ Color confinement
 - ◆ Asymptotic freedom
- In low energy region the perturbative calculation for QCD is impossible, alternatively:
 - ◆ Lattice QCD (non-perturbative calculation)
 - ◆ Effective models (chiral perturbation theory, quark model, etc...)

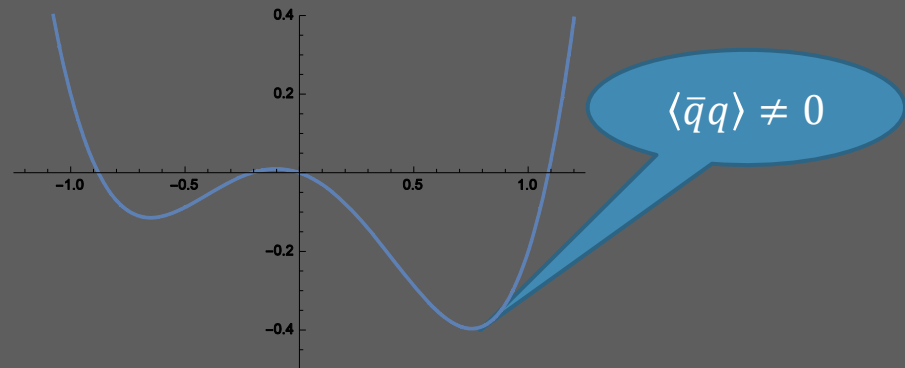
The chiral symmetry

The chiral symmetry:



Spontaneously breaking of chiral symmetry:

$$\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$$



The effective theory based on chiral symmetry:

- Nonlinear sigma model
- Chiral perturbation theory

The $P_{c(s)}$ states

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays #1

$P_c(4380)^+$, $P_c(4450)^+$

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]

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 1,173 citations

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Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure #1

of the $P_c(4450)^+$

$P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Apr 8, 2019)

Published in: *Phys.Rev.Lett.* 122 (2019) 22, 222001 • e-Print: 1904.03947 [hep-ex]

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 280 citations

The $P_{c(s)}$ states

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Published in: *Phys.Rev.Lett.* 122 (2019) 22, 222001 • e-Print: 1904.03947 [hep-ex]

pdf links DOI cite datasets

280 citations

Evidence of a $J/\psi \Lambda$ structure and observation of excited Ξ^- states in the #1

$\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decay

$P_{cs}(4459)^0$

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Dec 18, 2020)

e-Print: 2012.10380 [hep-ex]

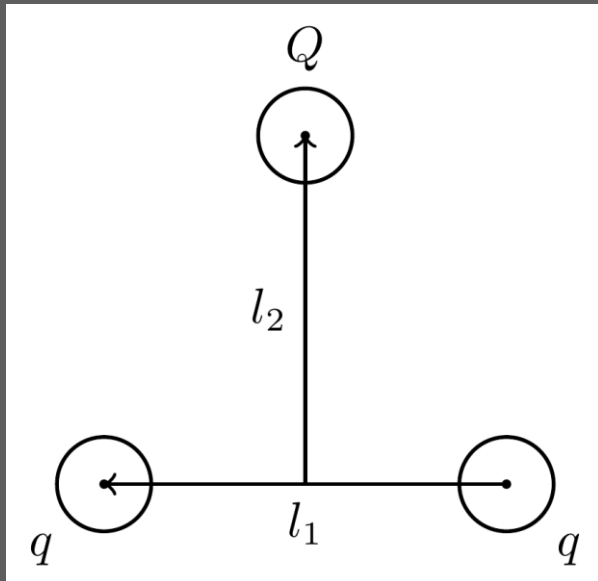
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17 citations

The states beyond 3 quark picture

$\Lambda_c(2595)$

$\Lambda_b(5912)$



State	IJ^P	(l_1, l_2)	I	II	Exp.	$ \Delta M $
Λ_c	$0\frac{1}{2}^-$	(1, 0)	2667	2665		73MeV
		(0, 1)	2465	2456		136MeV
		<i>coupling</i>	2465	2456	2592	136MeV
Σ_c	$1\frac{1}{2}^-$	(1, 0)	2671	2669		
		(0, 1)	2629	2628		
		<i>coupling</i>	2628	2628		
Σ_c^*	$1\frac{1}{2}^-$	(0, 1)	2633	2632		
Λ_b	$0\frac{1}{2}^-$	(1, 0)	6006	6012		100MeV
		(0, 1)	5783	5785		127MeV
		<i>coupling</i>	5783	5785	5912	127MeV
Σ_b	$1\frac{1}{2}^-$	(1, 0)	6008	6015		
		(0, 1)	5954	5963		
		<i>coupling</i>	5954	5963		
Σ_b^*	$1\frac{1}{2}^-$	(0, 1)	5956	5965		

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- *Chiral quark model*

- ◎ $qq\bar{s}\bar{Q}Q$ and $qqq\bar{q}Q$ system

- ◎ Summary

Chiral quark model

Naïve quark model:

- Quark mass term
- Kinetic term
- Color confinement potential (CON)
- One gluon exchange (OGE)

- Gell-Mann, M., 1964, Phys. Lett. 8, 214.
- Zweig, G., 1964, CERN Reports No. 8182/TH. 401 and No. 8419/TH. 412).
- N. Isgur, G. Karl, Phys.Lett.B 72 (1977) 109.

The Nambu–Goldstone boson exchange:

- Chiral symmetry is spontaneously broken
- Pseudoscalars (π , K , η) are the Nambu–Goldstone (NG) bosons of chiral symmetry breaking
- Scalar meson σ as the chiral partner of NG bosons

- Makato Oka, Koichi Yazaki, Nuclear Physics A402 (1983) 477-490
- L.Ya Glazman, Z. Papp, W. Plessas, Physics Letters B 381 (1996) 311-316
- J . Vijande, F . Fernandez, A . Valcarce, J. Phys. G 31, 481(2005)

The Hamiltonian

$$H = \sum_{i=1}^n \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - T_{cm} + \sum_{j>i=1}^n (V_{ij}^{CON} + V_{ij}^{OGE} + V_{ij}^{\pi} + V_{ij}^K + V_{ij}^{\eta} + V_{ij}^{\sigma})$$

J . Vijande, F . Fernandez, A . Valcarce, J. Phys. G 31, 481(2005)

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

$$V_{ij}^{OGE} = \frac{1}{4} \alpha_s (\boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c) \left[\frac{1}{r_{ij}} - \frac{1}{6m_i m_j} \frac{e^{-\frac{r_{ij}}{r_0(\mu_{ij})}}}{r_{ij} r_0^2(\mu_{ij})} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \right],$$

$$V_{ij}^{\sigma} = -\frac{g_{ch}^2}{4\pi} \frac{\Lambda_{\sigma}^2}{\Lambda_{\sigma}^2 - m_{\sigma}^2} m_{\sigma} \left[Y(m_{\sigma} r_{ij}) - \frac{\Lambda_{\sigma}}{m_{\sigma}} Y(\Lambda_{\sigma} r_{ij}) \right],$$

$$V_{ij}^{\pi} = \frac{g_{ch}^2}{4\pi} \frac{m_{\pi}^2}{12m_i m_j} \frac{\Lambda_{\pi}^2}{\Lambda_{\pi}^2 - m_{\pi}^2} m_{\pi} \left[Y(m_{\pi} r_{ij}) - \frac{\Lambda_{\pi}^3}{m_{\pi}^3} Y(\Lambda_{\pi} r_{ij}) \right] \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \sum_{a=1}^3 \lambda_i^a \lambda_j^a,$$

$$V_{ij}^K = \frac{g_{ch}^2}{4\pi} \frac{m_K^2}{12m_i m_j} \frac{\Lambda_K^2}{\Lambda_K^2 - m_K^2} m_K \left[Y(m_K r_{ij}) - \frac{\Lambda_K^3}{m_K^3} Y(\Lambda_K r_{ij}) \right] \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \sum_{a=4}^7 \lambda_i^a \lambda_j^a,$$

$$V_{ij}^{\eta} = \frac{g_{ch}^2}{4\pi} \frac{m_{\eta}^2}{12m_i m_j} \frac{\Lambda_{\eta}^2}{\Lambda_{\eta}^2 - m_{\eta}^2} m_{\eta} \left[Y(m_{\eta} r_{ij}) - \frac{\Lambda_{\eta}^3}{m_{\eta}^3} Y(\Lambda_{\eta} r_{ij}) \right] \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j (\lambda_i^8 \lambda_j^8 \cos \theta_p - \lambda_i^0 \lambda_j^0 \sin \theta_p).$$

The Gaussian expansion method

$$\psi_{lm}(\mathbf{r}) = \sum_{n=1}^{n_{max}} c_n \psi_{nlm}^G(\mathbf{r}),$$

$$\psi_{nlm}^G(\mathbf{r}) = N_{nl} r^l e^{-\nu_n r^2} Y_{lm}(\hat{\mathbf{r}}),$$

$$N_{nl} = \left(\frac{2^{l+2} (2\nu_n)^{l+\frac{3}{2}}}{\sqrt{\pi} (2l+1)!!} \right)^{\frac{1}{2}},$$

$$\nu_n = \frac{1}{r_n^2}, r_n = r_{min} a^{n-1}, a = \left(\frac{r_{max}}{r_{min}} \right)^{\frac{1}{n_{max}-1}}.$$

E. Hiyama, Y. Kino, and M. Kamimura, Prog. Part. Nucl. Phys. 51 223 (2003).

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Wave functions

- Orbital (SO(3)): (ψ_L)
- Spin (SU(2)): (χ_S^σ)
- Flavor (SU(2)): (χ_I^f)
- Color (SU(3)): (χ^c)

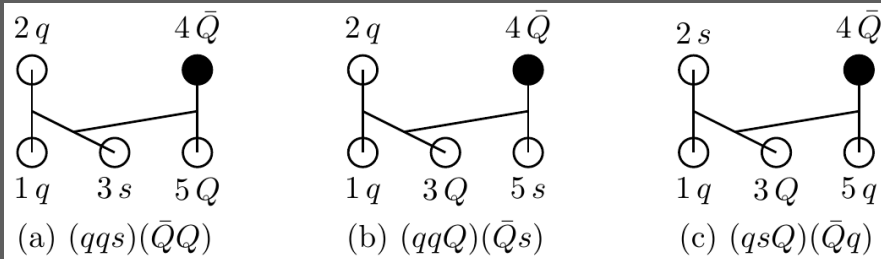
$$\Psi_{JM_J IM_I}^{ijk} = \mathcal{A} \left[[\psi_L \chi_S^{\sigma i}]_{JM_J} \chi_I^{fj} \chi_k^c \right]$$

Wave functions

- Orbital (SO(3)): (ψ_L)
- Spin (SU(2)): (χ_S^σ)
- Flavor (SU(2)): (χ_I^f)
- Color (SU(3)): (χ^c)

$$\Psi_{JM_J I M_I}^{ijk} = \mathcal{A} \left[[\psi_L \chi_S^{\sigma i}]_{J M_J} \chi_I^{f j} \chi_k^c \right]$$

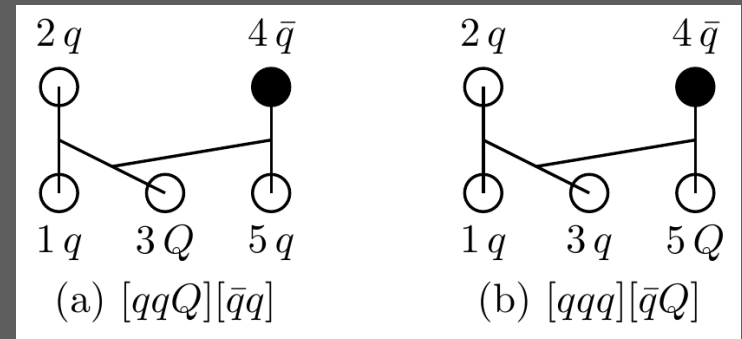
$qq s \bar{Q} Q$:



(a, b): $\mathcal{A} = 1 - (12)$

(c): $\mathcal{A} = 1 - (15)$

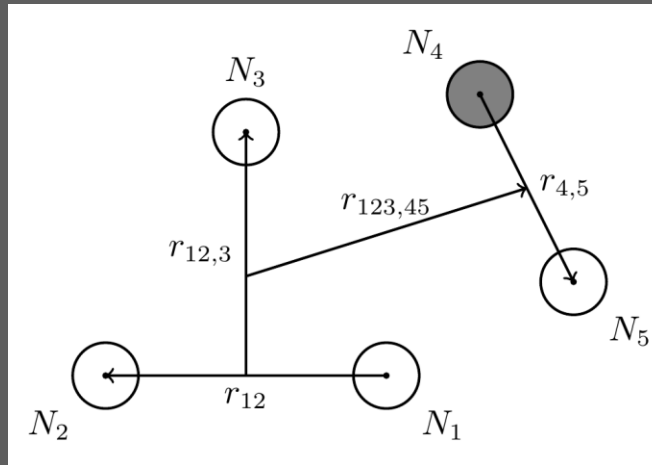
$qqq \bar{q} Q$:



(a): $\mathcal{A} = 1 - (15) - (25)$

(b): $\mathcal{A} = 1 - (13) - (23)$

Orbital wave functions



$$\psi_{LM_L} = [[[\psi_{l_1}(\mathbf{r}_{12}) \psi_{l_2}(\mathbf{r}_{12,3})] l \psi_{l_3}(\mathbf{r}_{45})] l' \psi_{l_4}(\mathbf{r}_{123,45})]_{LM_L}$$

$$\mathbf{r}_{12} = \mathbf{r}_2 - \mathbf{r}_1,$$

$$\mathbf{r}_{12,3} = \mathbf{r}_3 - \frac{m_1 \mathbf{r}_1 + m_2 \mathbf{r}_2}{m_1 + m_2},$$

$$\mathbf{r}_{45} = \mathbf{r}_5 - \mathbf{r}_4,$$

$$\mathbf{r}_{123,45} = \frac{m_4 \mathbf{r}_4 + m_5 \mathbf{r}_5}{m_4 + m_5} - \frac{m_1 \mathbf{r}_1 + m_2 \mathbf{r}_2 + m_3 \mathbf{r}_3}{m_1 + m_2 + m_3}.$$

Spin wave functions

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

$$\chi_{\frac{3}{2}, -\frac{3}{2}}^{\sigma}(3) = \beta\beta\beta,$$

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

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

$$\chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 1}(3) = \sqrt{\frac{1}{6}}(2\alpha\alpha\beta - \alpha\beta\alpha - \beta\alpha\alpha),$$

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

$$\chi_{\frac{1}{2}, -\frac{1}{2}}^{\sigma 1}(3) = \sqrt{\frac{1}{6}}(\alpha\beta\beta + \beta\alpha\beta - 2\beta\beta\alpha),$$

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

$$\chi_{1,1}^{\sigma}(2) = \alpha\alpha,$$

$$\chi_{1,-1}^{\sigma}(2) = \beta\beta,$$

$$\chi_{1,0}^{\sigma}(2) = \sqrt{\frac{1}{2}}(\alpha\beta + \beta\alpha),$$

$$\chi_{0,0}^{\sigma}(2) = \sqrt{\frac{1}{2}}(\alpha\beta - \beta\alpha).$$

$$\begin{aligned} \chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 1}(5) &= \sqrt{\frac{1}{6}}\chi_{\frac{3}{2}, -\frac{1}{2}}^{\sigma}(3)\chi_{1,1}^{\sigma}(2) - \sqrt{\frac{1}{3}}\chi_{\frac{3}{2}, \frac{1}{2}}^{\sigma}(3)\chi_{1,0}^{\sigma}(2) \\ &\quad + \sqrt{\frac{1}{2}}\chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma}(3)\chi_{1,-1}^{\sigma}(2), \end{aligned}$$

$$\chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 2}(5) = \sqrt{\frac{1}{3}}\chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 1}(3)\chi_{1,0}^{\sigma}(2) - \sqrt{\frac{2}{3}}\chi_{\frac{1}{2}, -\frac{1}{2}}^{\sigma 1}(3)\chi_{1,1}^{\sigma}(2),$$

$$\chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 3}(5) = \sqrt{\frac{1}{3}}\chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 2}(3)\chi_{1,0}^{\sigma}(2) - \sqrt{\frac{2}{3}}\chi_{\frac{1}{2}, -\frac{1}{2}}^{\sigma 2}(3)\chi_{1,1}^{\sigma}(2),$$

$$\chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 4}(5) = \chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 1}(3)\chi_{0,0}^{\sigma}(2),$$

$$\chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 5}(5) = \chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 2}(3)\chi_{0,0}^{\sigma}(2),$$

$$\chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma 1}(5) = \sqrt{\frac{3}{5}}\chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma}(3)\chi_{1,0}^{\sigma}(2) - \sqrt{\frac{2}{5}}\chi_{\frac{3}{2}, \frac{1}{2}}^{\sigma}(3)\chi_{1,1}^{\sigma}(2),$$

$$\chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma 2}(5) = \chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma}(3)\chi_{0,0}^{\sigma}(2),$$

$$\chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma 3}(5) = \chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 1}(3)\chi_{1,1}^{\sigma}(2),$$

$$\chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma 4}(5) = \chi_{\frac{1}{2}, \frac{1}{2}}^{\sigma 2}(3)\chi_{1,1}^{\sigma}(2),$$

$$\chi_{\frac{5}{2}, \frac{5}{2}}^{\sigma 1}(5) = \chi_{\frac{3}{2}, \frac{3}{2}}^{\sigma}(3)\chi_{1,1}^{\sigma}(2).$$

Flavor wave functions ($qq\bar{s}\bar{Q}Q$)

$$\chi_{\frac{1}{2},\frac{1}{2}}^f(3) = usb, \quad \chi_{\frac{1}{2},-\frac{1}{2}}^f(3) = dsb,$$

$$\chi_{1,1}^{f1}(3) = uus, \quad \chi_{1,1}^{f2}(3) = uub,$$

$$\chi_{1,0}^{f1}(3) = \sqrt{\frac{1}{2}}(ud + du)s,$$

$$\chi_{1,0}^{f2}(3) = \sqrt{\frac{1}{2}}(ud + du)b,$$

$$\chi_{1,-1}^{f1}(3) = dds, \quad \chi_{1,-1}^{f2}(3) = ddb,$$

$$\chi_{0,0}^{f1}(3) = \sqrt{\frac{1}{2}}(ud - du)s,$$

$$\chi_{0,0}^{f2}(3) = \sqrt{\frac{1}{2}}(ud - du)b,$$

$$\chi_{0,0}^{f1}(2) = \bar{b}b, \quad \chi_{0,0}^{f2}(2) = \bar{b}s,$$

$$\chi_{\frac{1}{2},\frac{1}{2}}^f(2) = \bar{b}u, \quad \chi_{\frac{1}{2},-\frac{1}{2}}^f(2) = \bar{b}d.$$

$$\chi_{0,0}^{f1}(5) = \chi_{0,0}^{f1}(3)\chi_{0,0}^{f1}(2),$$

$$\chi_{0,0}^{f2}(5) = \chi_{0,0}^{f2}(3)\chi_{0,0}^{f2}(2),$$

$$\begin{aligned} \chi_{0,0}^{f3}(5) = & \sqrt{\frac{1}{2}}\chi_{\frac{1}{2},\frac{1}{2}}^f(3)\chi_{\frac{1}{2},-\frac{1}{2}}^f(2) \\ & - \sqrt{\frac{1}{2}}\chi_{\frac{1}{2},-\frac{1}{2}}^f(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2), \end{aligned}$$

$$\chi_{1,1}^{f1}(5) = \chi_{\frac{1}{2},\frac{1}{2}}^f(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2),$$

$$\chi_{1,1}^{f2}(5) = \chi_{1,1}^{f1}(3)\chi_{0,0}^{f1}(2),$$

$$\chi_{1,1}^{f3}(5) = \chi_{1,1}^{f2}(3)\chi_{0,0}^{f2}(2).$$

Flavor wave functions ($qqq\bar{q}Q$)

$$\chi_{0,0}^f(3) = \sqrt{\frac{1}{2}}(ud - du)c,$$

$$\chi_{\frac{1}{2},\frac{1}{2}}^{f1}(3) = \sqrt{\frac{1}{6}}(2uud - udu - duu),$$

$$\chi_{\frac{1}{2},\frac{1}{2}}^{f2}(3) = \sqrt{\frac{1}{2}}(udu - duu),$$

$$\chi_{\frac{1}{2},-\frac{1}{2}}^{f1}(3) = \sqrt{\frac{1}{6}}(udd + dud - 2ddu),$$

$$\chi_{\frac{1}{2},-\frac{1}{2}}^{f2}(3) = \sqrt{\frac{1}{2}}(udd - dud),$$

$$\chi_{1,1}^f(3) = uuc,$$

$$\chi_{1,-1}^f(3) = ddc,$$

$$\chi_{1,0}^f(3) = \sqrt{\frac{1}{2}}(ud + du)c,$$

$$\chi_{\frac{3}{2},\frac{3}{2}}^f(3) = uuu,$$

$$\chi_{\frac{3}{2},\frac{1}{2}}^f(3) = \sqrt{\frac{1}{3}}(uud + udu + duu),$$

$$\chi_{0,0}^f(2) = \sqrt{\frac{1}{2}}(\bar{d}d + \bar{u}u),$$

$$\chi_{\frac{1}{2},\frac{1}{2}}^f(2) = \bar{d}c,$$

$$\chi_{\frac{1}{2},-\frac{1}{2}}^f(2) = -\bar{u}c,$$

$$\chi_{1,1}^f(2) = \bar{d}u,$$

$$\chi_{1,-1}^f(2) = -\bar{u}d,$$

$$\chi_{1,0}^f(2) = \sqrt{\frac{1}{2}}(\bar{d}d - \bar{u}u).$$

$$\chi_{0,0}^{f1}(5) = \chi_{0,0}^f(3)\chi_{0,0}^f(2),$$

$$\chi_{0,0}^{f2}(5) = \sqrt{\frac{1}{2}}\chi_{\frac{1}{2},\frac{1}{2}}^{f1}(3)\chi_{\frac{1}{2},-\frac{1}{2}}^f(2) - \sqrt{\frac{1}{2}}\chi_{\frac{1}{2},-\frac{1}{2}}^{f1}(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2),$$

$$\chi_{0,0}^{f3}(5) = \sqrt{\frac{1}{2}}\chi_{\frac{1}{2},\frac{1}{2}}^{f2}(3)\chi_{\frac{1}{2},-\frac{1}{2}}^f(2) - \sqrt{\frac{1}{2}}\chi_{\frac{1}{2},-\frac{1}{2}}^{f2}(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2),$$

$$\chi_{0,0}^{f4}(5) = \sqrt{\frac{1}{3}}\chi_{1,1}^f(3)\chi_{1,-1}^f(2) - \sqrt{\frac{1}{3}}\chi_{1,0}^f(3)\chi_{1,0}^f(2)$$

$$+ \sqrt{\frac{1}{3}}\chi_{1,-1}^f(3)\chi_{1,1}^f(2),$$

$$\chi_{1,1}^{f1}(5) = \chi_{0,0}^f(3)\chi_{1,1}^f(2),$$

$$\chi_{1,1}^{f2}(5) = \chi_{1,1}^f(3)\chi_{0,0}^f(2),$$

$$\chi_{1,1}^{f3}(5) = \sqrt{\frac{1}{2}}\chi_{1,1}^f(3)\chi_{1,0}^f(2) - \sqrt{\frac{1}{2}}\chi_{1,0}^f(3)\chi_{1,1}^f(2),$$

$$\chi_{1,1}^{f4}(5) = \chi_{\frac{1}{2},\frac{1}{2}}^{f1}(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2),$$

$$\chi_{1,1}^{f5}(5) = \chi_{\frac{1}{2},\frac{1}{2}}^{f2}(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2),$$

$$\chi_{1,1}^{f6}(5) = \sqrt{\frac{3}{4}}\chi_{\frac{3}{2},\frac{3}{2}}^f(3)\chi_{\frac{1}{2},-\frac{1}{2}}^f(2) - \sqrt{\frac{1}{4}}\chi_{\frac{3}{2},\frac{1}{2}}^f(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2),$$

$$\chi_{2,2}^{f1}(5) = \chi_{1,1}^f(3)\chi_{1,1}^f(2),$$

$$\chi_{2,2}^{f2}(5) = \chi_{\frac{3}{2},\frac{3}{2}}^f(3)\chi_{\frac{1}{2},\frac{1}{2}}^f(2).$$

Color wave functions: $S \oplus H (1 \oplus 8)$

$$\chi_1^c = \sqrt{\frac{1}{6}}(rgb - grb + brg - rbg + gbr - bgr) \sqrt{\frac{1}{3}}(\bar{r}r + \bar{g}g + \bar{b}b),$$

$$\begin{aligned} \chi_2^c = & \sqrt{\frac{1}{8}} \left[\sqrt{\frac{1}{6}}(2rrg - rgr - grr)\bar{r}b + \sqrt{\frac{1}{6}}(rgg + grg - 2ggr)\bar{g}b - \sqrt{\frac{1}{6}}(2rrb - rbr - brr)\bar{r}g \right. \\ & - \sqrt{\frac{1}{6}}(rbb + brb - 2bbr)\bar{b}g + \sqrt{\frac{1}{6}}(2ggb - gbg - bgg)\bar{g}r + \sqrt{\frac{1}{6}}(gbb + bgb - 2bbg)\bar{b}r \\ & + \sqrt{\frac{1}{24}}(rbg - gbr + brg - bgr)(2\bar{b}b - \bar{r}r - \bar{g}g) \\ & \left. + \sqrt{\frac{1}{24}}(2rgb - rbg + 2grb - gbr - brg - bgr)(\bar{r}r - \bar{g}g) \right], \end{aligned}$$

$$\begin{aligned} \chi_3^c = & \sqrt{\frac{1}{8}} \left[\sqrt{\frac{1}{2}}(rgr - grr)\bar{r}b + \sqrt{\frac{1}{2}}(rgg - grg)\bar{g}b - \sqrt{\frac{1}{2}}(rbr - brr)\bar{r}g - \sqrt{\frac{1}{2}}(rbb - brb)\bar{b}g \right. \\ & + \sqrt{\frac{1}{2}}(gbg - bgg)\bar{g}r + \sqrt{\frac{1}{2}}(gbb - bgb)\bar{b}r + \sqrt{\frac{1}{8}}(rbg + gbr - brg - bgr)(\bar{r}r - \bar{g}g) \\ & \left. + \sqrt{\frac{1}{72}}(2rgb + rbg - 2grb - gbr - brg + bgr)(2\bar{b}b - \bar{g}g - \bar{r}r) \right]. \end{aligned}$$

Physical channels for $qq s \bar{b} b$

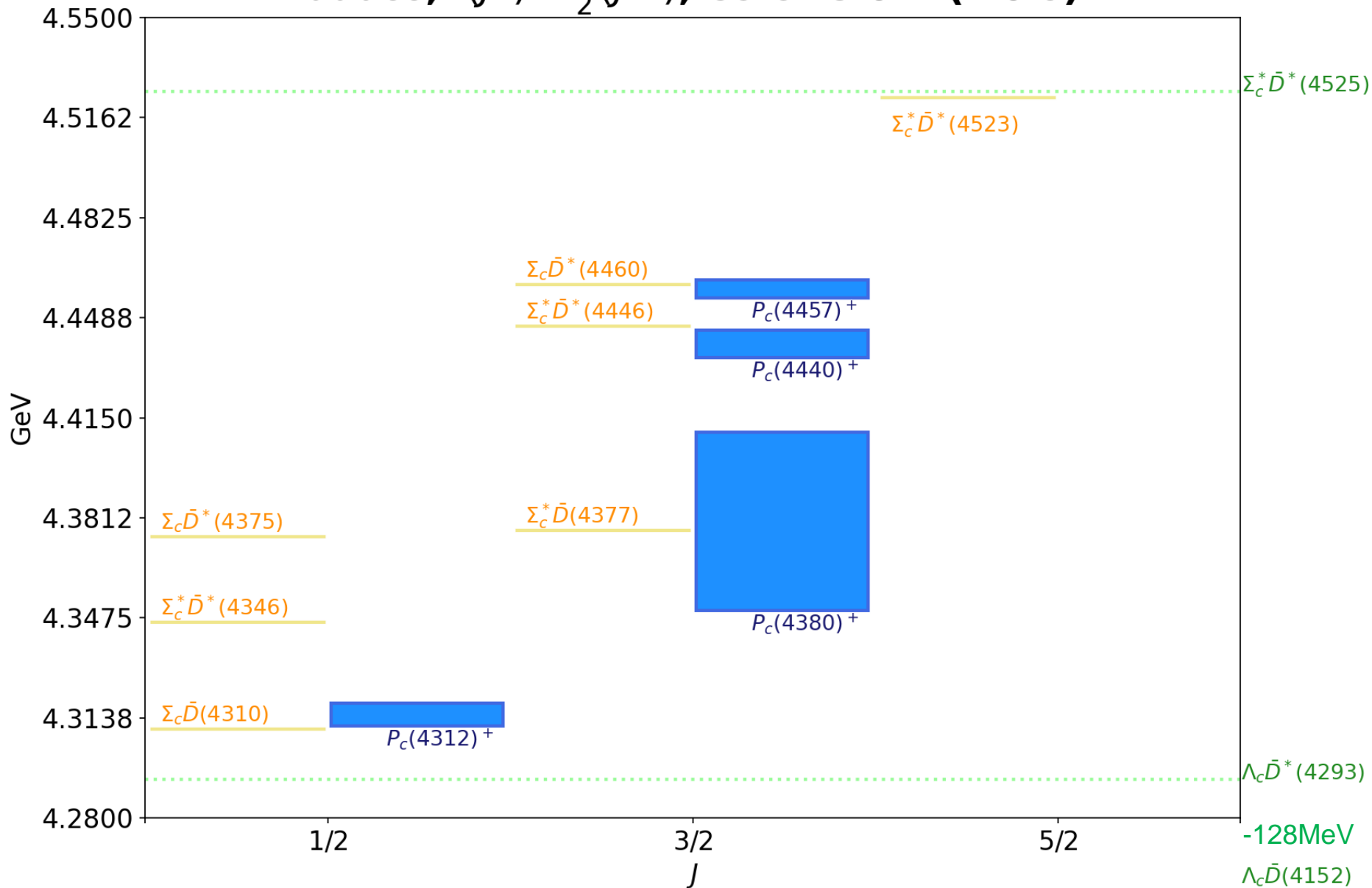
IJ^P	$[i; j; k]$	Channel	IJ^P	$[i; j; k]$	Channel	IJ^P	$[i; j; k]$	Channel
$0\frac{1}{2}^-$	[5; 1; 1, 2, 3]	$\Lambda\eta_b$	$1\frac{1}{2}^-$	[4; 2; 1, 2, 3]	$\Sigma\eta_b$	$1\frac{3}{2}^-$	[3; 2; 1, 2, 3]	$\Sigma\Upsilon$
	[3; 1; 1, 2, 3]	$\Lambda\Upsilon$		[2; 2; 1, 2, 3]	$\Sigma\Upsilon$		[2; 2; 1, 2, 3]	$\Sigma^*\eta_b$
	[5; 2; 1, 2, 3]	$\Lambda_b B_s$		[1; 2; 1, 2, 3]	$\Sigma^*\Upsilon$		[1; 2; 1, 2, 3]	$\Sigma^*\Upsilon$
	[3; 2; 1, 2, 3]	$\Lambda_b B_s^*$		[5; 1; 1, 2, 3]	$\Xi_b B$		[4; 1; 1, 2, 3]	$\Xi_b B^*$
	[5; 3; 1, 2, 3]	$\Xi_b B$		[4; 3; 1, 2, 3]	$\Sigma_b B_s$		[2; 3; 1, 2, 3]	$\Sigma_b^* B_s$
	[3; 3; 1, 2, 3]	$\Xi_b B^*$		[3; 1; 1, 2, 3]	$\Xi_b B^*$		[3; 3; 1, 2, 3]	$\Sigma_b B_s^*$
	[4; 3; 1, 2, 3]	$\Xi'_b B$		[2; 3; 1, 2, 3]	$\Sigma_b B_s^*$		[1; 3; 1, 2, 3]	$\Sigma_b^* B_s^*$
	[2; 3; 1, 2, 3]	$\Xi'_b B^*$		[1; 3; 1, 2, 3]	$\Sigma_b^* B_s^*$		[2; 1; 1, 2, 3]	$\Xi_b^* B$
$0\frac{3}{2}^-$	[1; 3; 1, 2, 3]	$\Xi_b^* B^*$	[4; 1; 1, 2, 3]	$\Xi'_b B$	[3; 1; 1, 2, 3]	$\Xi'_b B^*$		
	[4; 1; 1, 2, 3]	$\Lambda\Upsilon$	[2; 1; 1, 2, 3]	$\Xi'_b B^*$	[1; 1; 1, 2, 3]	$\Xi_b^* B^*$		
	[4; 2; 1, 2, 3]	$\Lambda_b B_s^*$	[1; 1; 1, 2, 3]	$\Xi_b^* B^*$	$1\frac{5}{2}^-$	[1; 2; 1, 2, 3]	$\Sigma^*\Upsilon$	
	[4; 3; 1, 2, 3]	$\Xi_b B^*$				[1; 3; 1, 2, 3]	$\Sigma_b^* B_s^*$	
	[2; 3; 1, 2, 3]	$\Xi_b^* B$				[1; 1; 1, 2, 3]	$\Xi_b^* B^*$	
	[3; 3; 1, 2, 3]	$\Xi'_b B^*$						
[1; 3; 1, 2, 3]	$\Xi_b^* B^*$							
$0\frac{5}{2}^-$	[1; 3; 1, 2, 3]	$\Xi_b^* B^*$						

Model parameters ($qq\bar{s}\bar{Q}Q$)

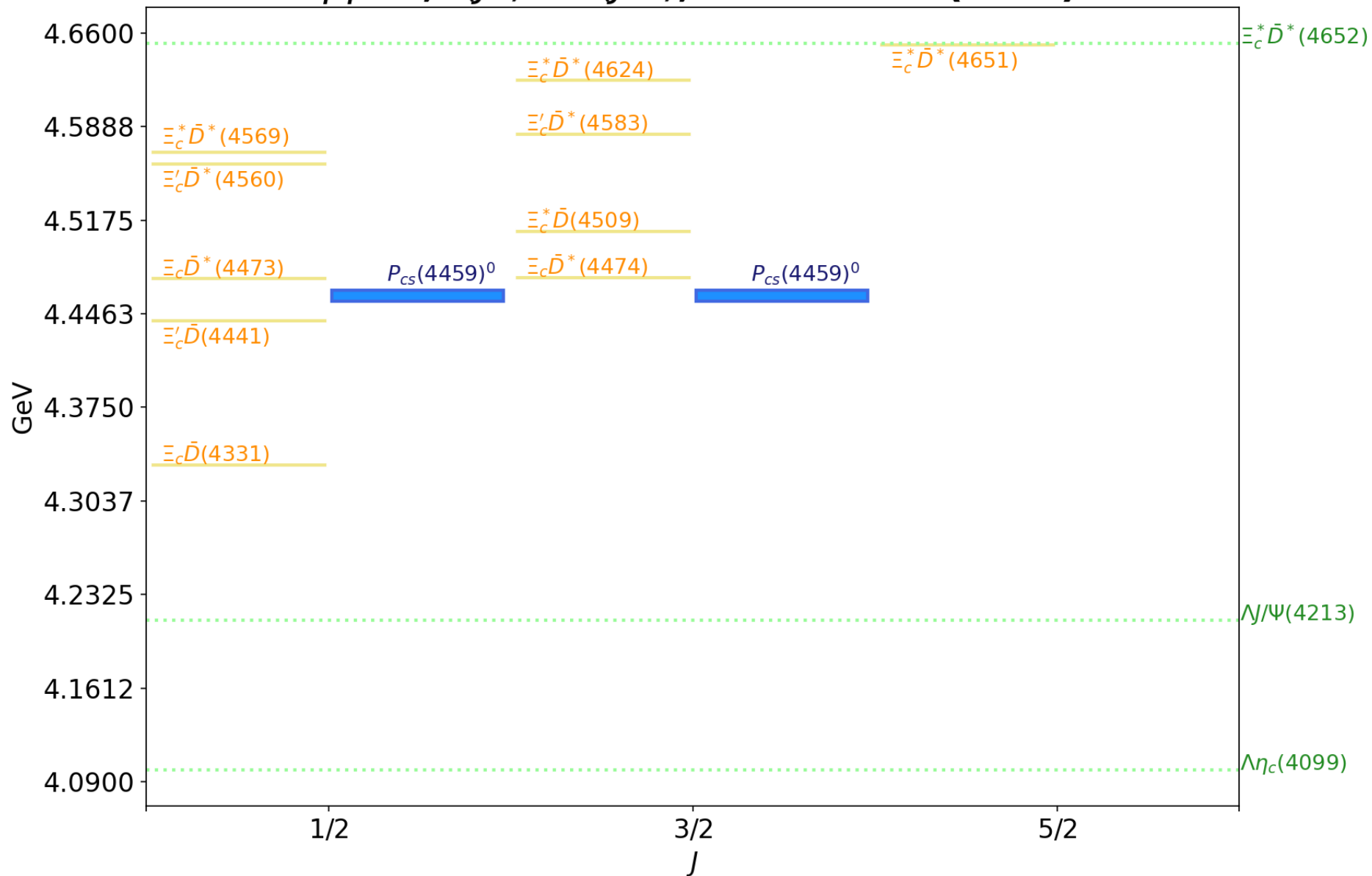
	$m_u = m_d(\text{MeV})$	313
Quark masses	$m_s(\text{MeV})$	555
	$m_c(\text{MeV})$	1752
	$m_b(\text{MeV})$	5100
	$a_c(\text{MeV})$	430
Confinement	$\mu_c(\text{fm}^{-1})$	0.7
	$\Delta(\text{MeV})$	181.1
	α_0	2.118
OGE	$\Lambda_0(\text{fm}^{-1})$	0.113
	$\mu_0(\text{MeV})$	36.976
	$\hat{r}_0(\text{MeV}\cdot\text{fm})$	28.17
	$m_\pi(\text{fm}^{-1})$	0.7
Goldstone bosons	$m_K(\text{fm}^{-1})$	2.51
	$m_\eta(\text{fm}^{-1})$	2.77
	$m_\sigma(\text{fm}^{-1})$	3.42
	$\Lambda_\pi = \Lambda_\sigma(\text{fm}^{-1})$	4.2
	$\Lambda_K = \Lambda_\eta(\text{fm}^{-1})$	5.2
	$g_{ch}^2/(4\pi)$	0.54
	$\theta_p(^{\circ})$	-15

Meson	Theo.	Exp.	Baryon	Theo.	Exp.
D	1898	1865	Λ	1013	1116
D_s	1992	1968	Σ	1341	1189
D^*	2017	2007	Σ^*	1469	1383
D_s^*	2116	2112	Λ_c	2086	2286
η_c	3000	2983	Σ_c	2493	2454
J/ψ	3097	3097	Σ_c^*	2537	2518
B	5278	5279	Ξ_c	2574	2468
B^*	5319	5325	Ξ'_c	2665	2577
B_s	5356	5367	Ξ_c^*	2704	2645
B_s^*	5400	5415	Λ_b	5385	5620
B_c	6283	6275	Σ_b	5818	5811
B_c^*	6331	—	Σ_b^*	5835	5832
η_b	9468	9400	Ξ_b	5867	5792
Υ	9505	9460	Ξ'_b	5978	5935
			Ξ_b^*	5993	5950

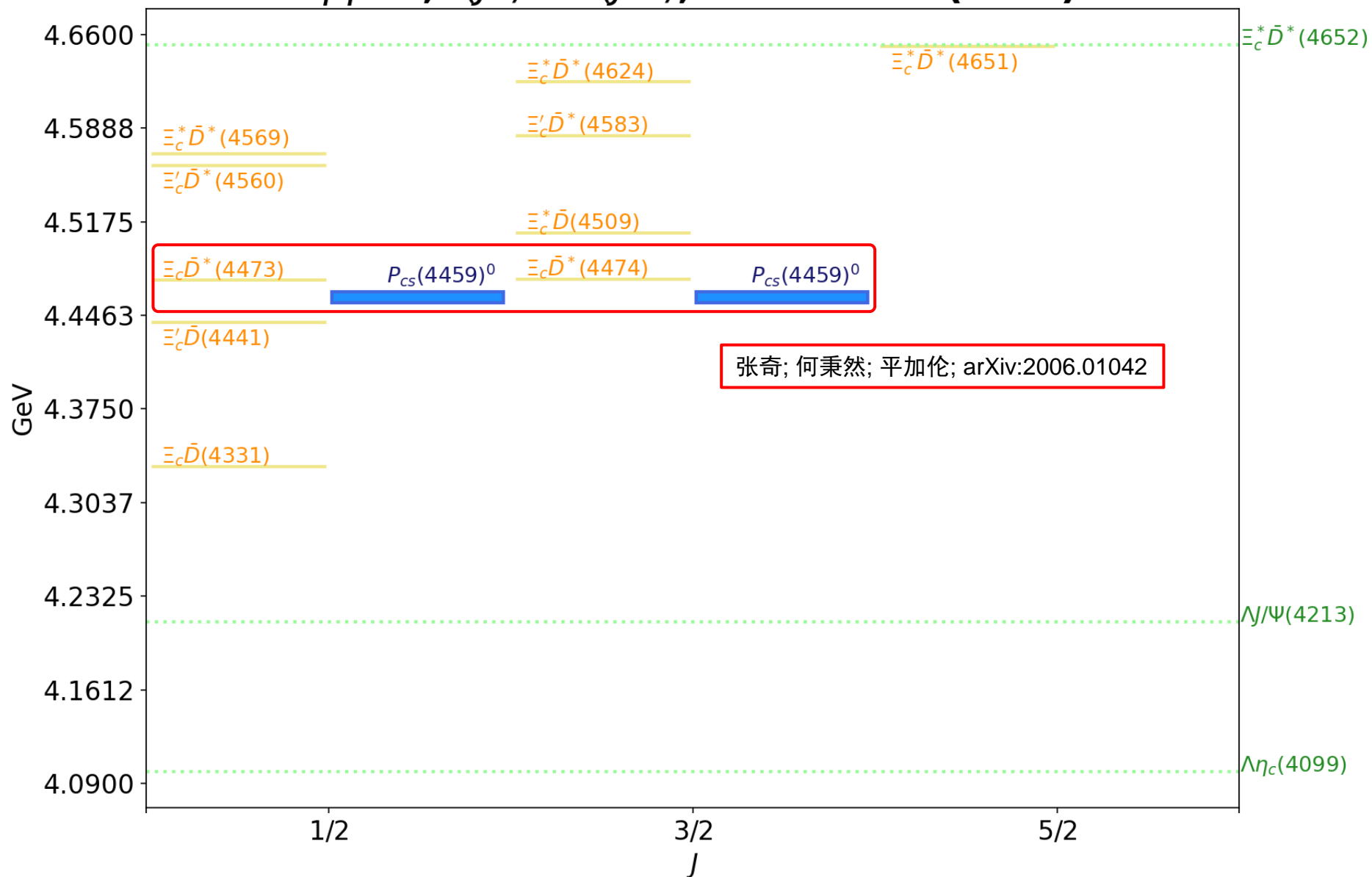
$uud\bar{c}, I(J^P) = \frac{1}{2}(J^-), \text{ color } S \oplus H (1 \oplus 8)$



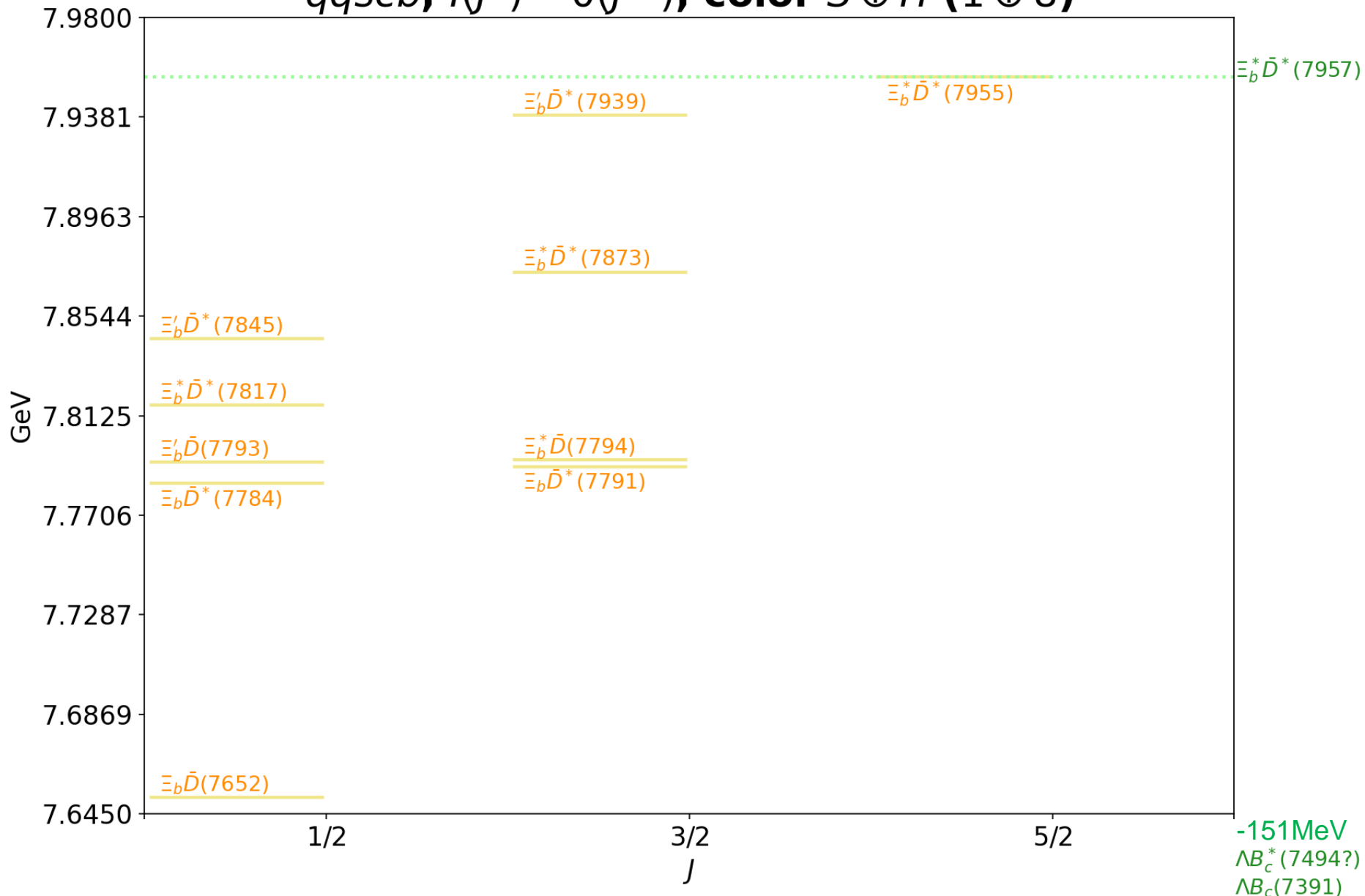
$qq\bar{s}\bar{c}, I(J^P) = 0(J^-), \text{ color } S \oplus H (1 \oplus 8)$



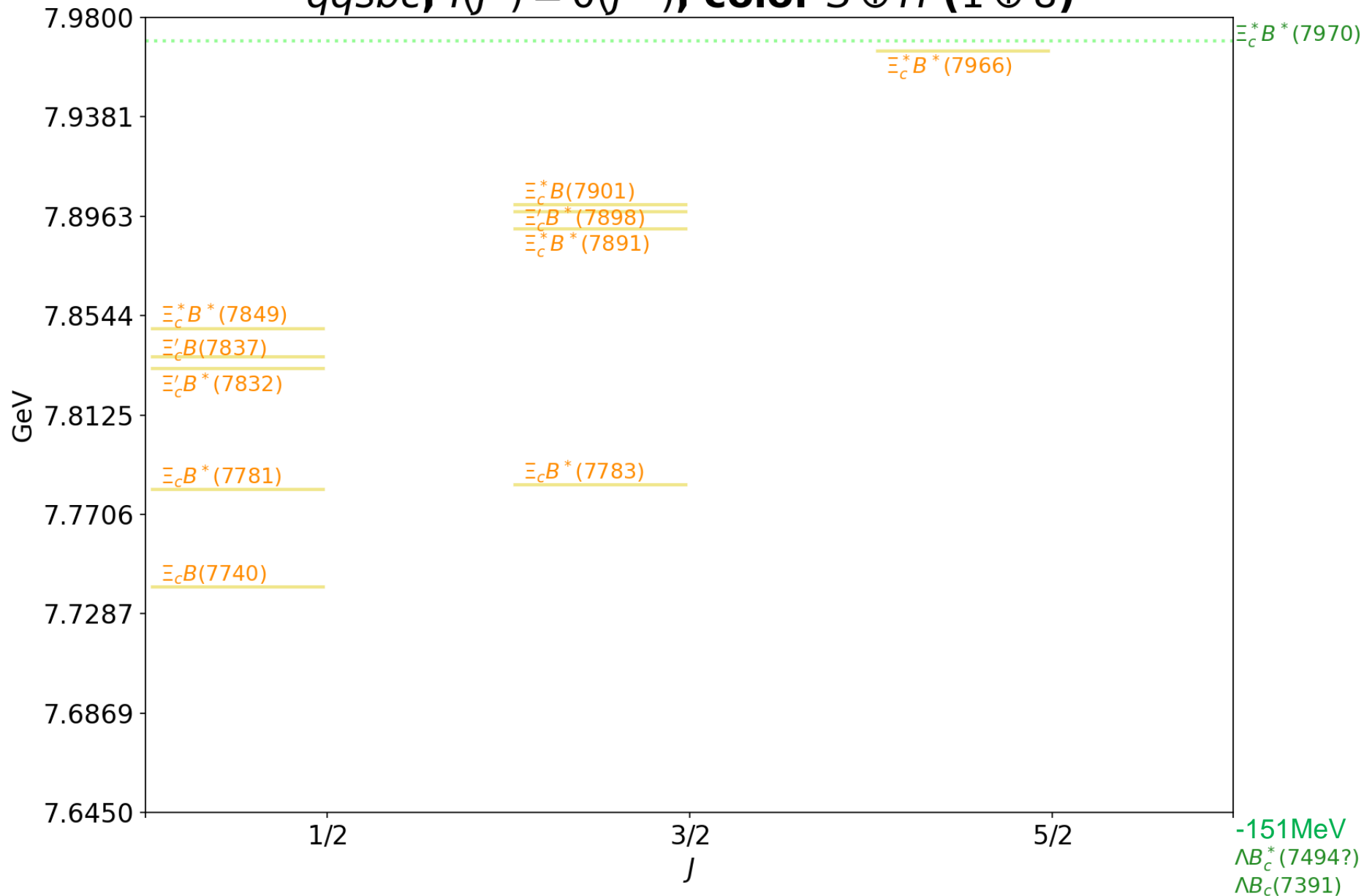
$qq\bar{s}\bar{c}, I(J^P) = 0(J^-), \text{ color } S \oplus H (1 \oplus 8)$



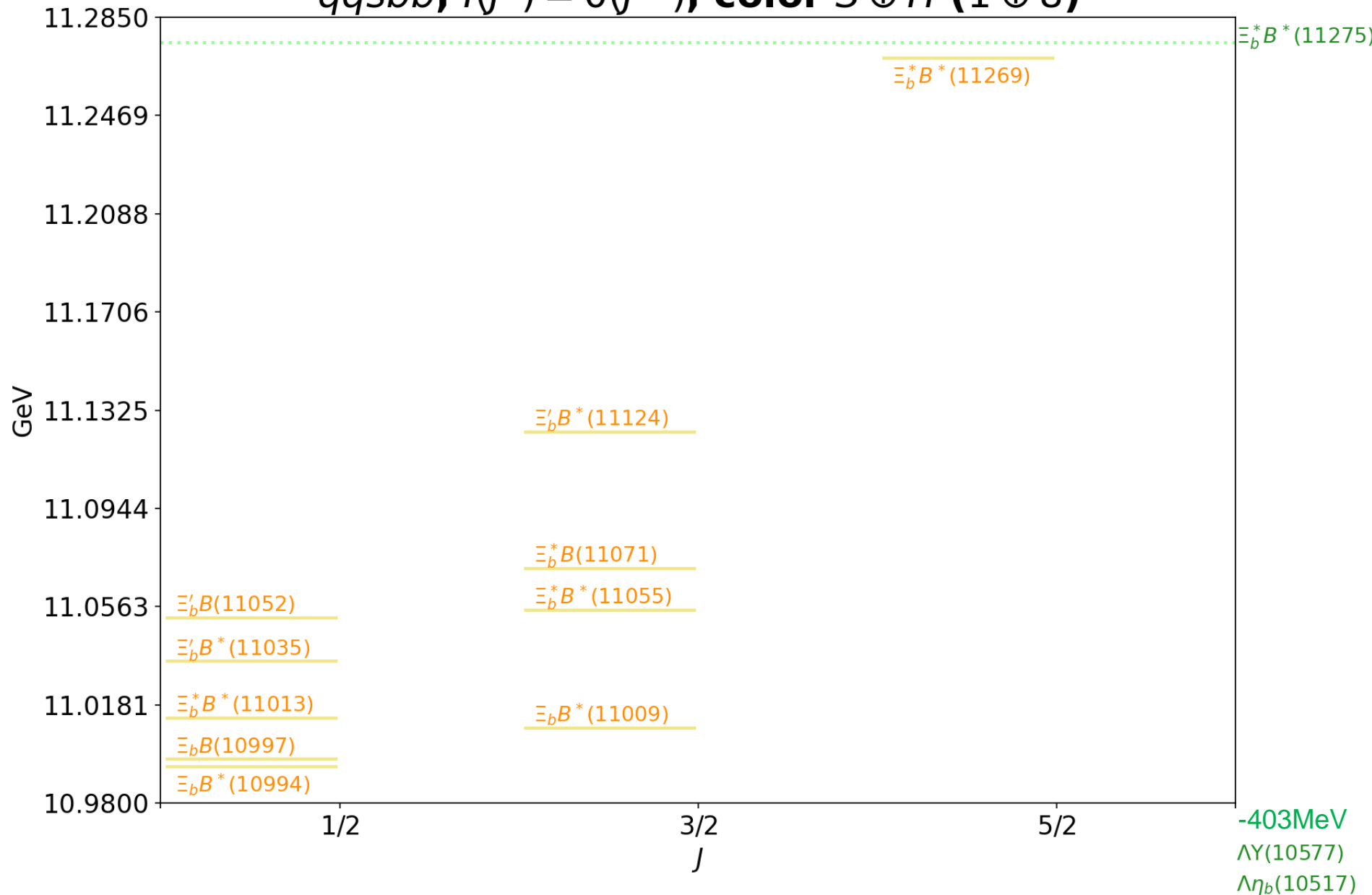
$qq\bar{s}\bar{c}b, I(J^P) = 0(J^-), \text{ color } S \oplus H (1 \oplus 8)$



$qq\bar{s}bc, I(J^P) = 0(J^-), \text{ color } S \oplus H (1 \oplus 8)$



$qq\bar{s}\bar{b}b, I(J^P) = 0(J^-), \text{ color } S \oplus H (1 \oplus 8)$



Root-mean-square distances ($qq s \bar{Q} Q$)

distance between
two clusters

System	$(qsQ)(\bar{Q}q)$	r_{sQ}	r_{qq}	$r_{s\bar{Q}}$	$r_{Q\bar{Q}}$
$qq s \bar{c} c$	$\Xi_c^{(*,')} \bar{D}^{(*)}(qsc, \bar{c}q)$	0.61	2.80	2.76	2.72
$qq s \bar{c} b$	$\Xi_b^{(*,')} \bar{D}^{(*)}(qsb, \bar{c}q)$	0.54	1.14	1.03	0.90
$qq s \bar{b} c$	$\Xi_c^{(*,')} B^{(*)}(qsc, \bar{b}q)$	0.62	1.08	0.90	0.78
$qq s \bar{b} b$	$\Xi_b^{(*,')} B^{(*)}(qsb, \bar{b}q)$	0.59	1.10	0.61	0.33

Root-mean-square distances ($qq\bar{s}\bar{Q}Q$)

distance between
two clusters

System	$(qsQ)(\bar{Q}q)$	r_{sQ}	r_{qq}	$r_{s\bar{Q}}$	$r_{Q\bar{Q}}$
$qq\bar{s}\bar{c}c$	$\Xi_c^{(*,')} \bar{D}^{(*)}(qsc, \bar{c}q)$	0.61	2.80	2.76	2.72
$qq\bar{s}\bar{c}b$	$\Xi_b^{(*,')} \bar{D}^{(*)}(qsb, \bar{c}q)$	0.54	1.14	1.03	0.90
$qq\bar{s}\bar{b}c$	$\Xi_c^{(*,')} B^{(*)}(qsc, \bar{b}q)$	0.62	1.08	0.90	0.78
$qq\bar{s}\bar{b}b$	$\Xi_b^{(*,')} B^{(*)}(qsb, \bar{b}q)$	0.59	1.10	0.61	0.33

molecular states

compact states

compact $\bar{b}b$ -pair surrounded by three other quarks

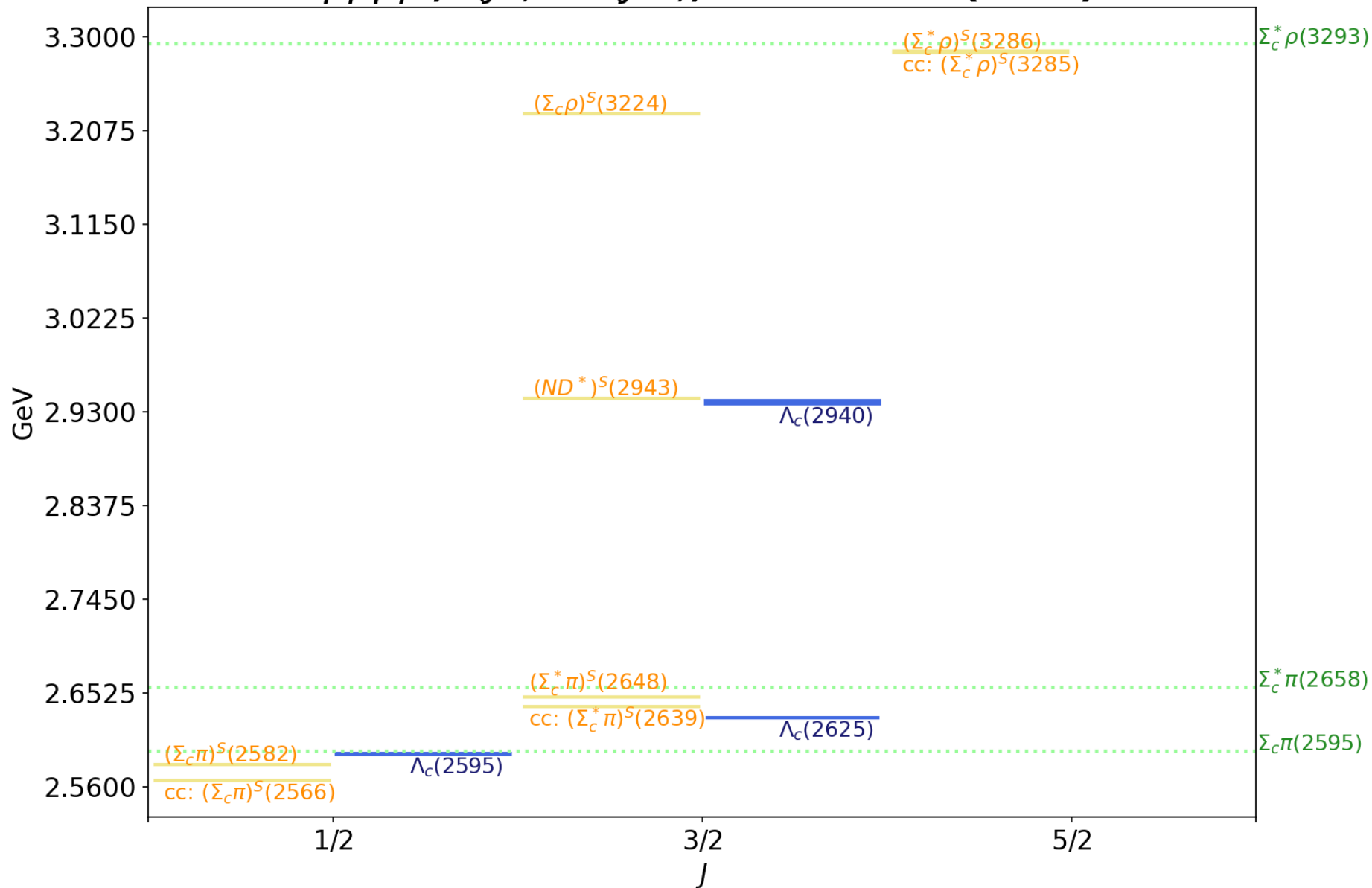
Physical channels for $qqq\bar{q}Q$

$0\frac{1}{2}^-$	[4; 4; 1]	$(\Sigma_c\pi)^S$	IJ^P	[i; j; k]	Channel	$1\frac{3}{2}^-$	[2; 3; 1]	$(\Sigma_c^*\pi)^S$	$2\frac{1}{2}^-$	[4; 1; 1]	$(\Sigma_c\pi)^S$	
	[4; 5; 4; 2; 3]	$(\Sigma_c\pi)^H$		$1\frac{1}{2}^-$	[5; 1; 1]		$(\Lambda_c\pi)^S$	[2; 3; 3]		$(\Sigma_c^*\pi)^H$	[4; 5; 1; 2; 3]	$(\Sigma_c\pi)^H$
	[5; 1; 1]	$(\Lambda_c\eta)^S$		[4; 5; 1; 2; 3]	$(\Lambda_c\pi)^H$		[4; 1; 1]	$(\Lambda_c\rho)^S$		[2; 1; 1]	$(\Sigma_c\rho)^S$	
	[4; 5; 1; 2; 3]	$(\Lambda_c\eta)^H$		[4; 3; 1]	$(\Sigma_c\pi)^S$		[3; 4; 1; 2; 3]	$(\Lambda_c\rho)^H$		[2; 3; 1; 2; 3]	$(\Sigma_c\rho)^H$	
	[3; 1; 1]	$(\Lambda_c\omega)^S$		[4; 5; 3; 2; 3]	$(\Sigma_c\pi)^H$		[2; 2; 1]	$(\Sigma_c^*\eta)^S$		[1; 1; 1]	$(\Sigma_c^*\rho)^S$	
	[2; 3; 1; 2; 3]	$(\Lambda_c\omega)^H$		[4; 2; 1]	$(\Sigma_c\eta)^S$		[2; 2; 3]	$(\Sigma_c^*\eta)^H$		[1; 1; 3]	$(\Sigma_c^*\rho)^H$	
	[2; 4; 1]	$(\Sigma_c\rho)^S$		[4; 5; 2; 2; 3]	$(\Sigma_c\eta)^H$		[3; 3; 1]	$(\Sigma_c\rho)^S$		[1; 2; 1]	$(\Delta D^*)^S$	
	[2; 3; 4; 2; 3]	$(\Sigma_c\rho)^H$		[3; 1; 1]	$(\Lambda_c\rho)^S$		[3; 4; 3; 2; 3]	$(\Sigma_c\rho)^H$		[1; 2; 3]	$(\Delta D^*)^H$	
	[1; 4; 1]	$(\Sigma_c^*\rho)^S$		[2; 3; 1; 2; 3]	$(\Sigma_c\rho)^S$		[3; 2; 1]	$(\Sigma_c\omega)^S$		[2; 1; 1]	$(\Sigma_c^*\pi)^S$	
	[1; 4; 3]	$(\Sigma_c^*\rho)^H$		[2; 3; 3; 2; 3]	$(\Sigma_c\rho)^H$		[3; 4; 2; 2; 3]	$(\Sigma_c\omega)^H$		[2; 1; 3]	$(\Sigma_c^*\pi)^H$	
	[4; 5; 2; 3; 1]	$(ND)^S$		[2; 3; 2; 3]	$(\Sigma_c\rho)^H$		[1; 3; 1]	$(\Sigma_c^*\rho)^S$		[3; 1; 1]	$(\Sigma_c\rho)^S$	
	[4; 5; 2; 3; 2; 3]	$(ND)^H$		[2; 2; 1]	$(\Sigma_c\omega)^S$		[1; 3; 3]	$(\Sigma_c^*\rho)^H$		[3; 4; 1; 2; 3]	$(\Sigma_c\rho)^H$	
	[2; 3; 2; 3; 1]	$(ND^*)^S$		[2; 3; 2; 2; 3]	$(\Sigma_c\omega)^H$		[1; 2; 1]	$(\Sigma_c^*\omega)^S$		[1; 1; 1]	$(\Sigma_c^*\rho)^S$	
	[2; 3; 2; 3; 2; 3]	$(ND^*)^H$		[1; 3; 1]	$(\Sigma_c^*\rho)^S$		[1; 2; 3]	$(\Sigma_c^*\omega)^H$		[1; 1; 3]	$(\Sigma_c^*\rho)^H$	
$0\frac{3}{2}^-$	[2; 4; 1]	$(\Sigma_c^*\pi)^S$	[1; 3; 3]	$(\Sigma_c^*\rho)^H$	[3; 4; 4; 5; 1]	$(ND^*)^S$	[2; 2; 1]	$(\Delta D)^S$				
	[2; 4; 3]	$(\Sigma_c^*\pi)^H$	[1; 2; 1]	$(\Sigma_c^*\omega)^S$	[3; 4; 4; 5; 2; 3]	$(ND^*)^H$	[2; 2; 3]	$(\Delta D)^H$				
	[4; 1; 1]	$(\Lambda_c\omega)^S$	[1; 2; 3]	$(\Sigma_c^*\omega)^H$	[2; 6; 1]	$(\Delta D)^S$	[1; 2; 1]	$(\Delta D^*)^S$				
	[3; 4; 1; 2; 3]	$(\Lambda_c\omega)^H$	[4; 5; 4; 5; 1]	$(ND)^S$	[2; 6; 3]	$(\Delta D)^H$	[1; 2; 3]	$(\Delta D^*)^H$				
	[3; 4; 1]	$(\Sigma_c\rho)^S$	[4; 5; 4; 5; 2; 3]	$(ND)^H$	[1; 6; 1]	$(\Delta D^*)^S$	[1; 1; 1]	$(\Sigma_c^*\rho)^S$				
	[3; 4; 4; 2; 3]	$(\Sigma_c\rho)^H$	[2; 3; 4; 5; 1]	$(ND^*)^S$	[1; 6; 3]	$(\Delta D^*)^H$	[1; 1; 3]	$(\Sigma_c^*\rho)^H$				
	[1; 4; 1]	$(\Sigma_c^*\rho)^S$	[2; 3; 4; 5; 2; 3]	$(ND^*)^H$	[1; 3; 1]	$(\Sigma_c^*\rho)^S$	[1; 2; 1]	$(\Delta D^*)^S$				
	[1; 4; 3]	$(\Sigma_c^*\rho)^H$	[1; 6; 1]	$(\Delta D^*)^S$	[1; 3; 3]	$(\Sigma_c^*\rho)^H$	[1; 2; 3]	$(\Delta D^*)^H$				
	[3; 4; 2; 3; 1]	$(ND^*)^S$	[1; 6; 3]	$(\Delta D^*)^H$	[1; 2; 1]	$(\Sigma_c^*\omega)^S$						
	[3; 4; 2; 3; 2; 3]	$(ND^*)^H$			[1; 2; 3]	$(\Sigma_c^*\omega)^H$						
$0\frac{5}{2}^-$	[1; 4; 1]	$(\Sigma_c^*\rho)^S$			[1; 6; 1]	$(\Delta D^*)^S$						
	[1; 4; 3]	$(\Sigma_c^*\rho)^H$			[1; 6; 3]	$(\Delta D^*)^H$						

Model parameters ($qqq\bar{q}Q$)

Quark masses	$m_q = m_{\bar{q}}(MeV)$	450	430	Meson	I	II	Exp.
	$m_c(MeV)$	1750	1734	π	156	149	140
	$m_b(MeV)$	5100	5092	ρ	795	799	775
Confinement	$a_c(MeV)$	80	74	η	660	672	548
	$\mu_c(fm^{-1})$	0.7	0.7	ω	773	777	783
	$\Delta(MeV)$	46	36	D	1867	1866	1869
				D^*	2031	2034	2007
OGE	α_s^{qq}	0.67	0.68	B	5303	5315	5279
	α_s^{qc}	0.61	0.63	B^*	5350	5362	5325
	α_s^{qb}	0.59	0.61	Baryon	I	II	Exp.
	$\hat{r}_0(MeV \cdot fm)$	28.17	28.17	N	915	908	939
Goldstone bosons	$m_\pi(fm^{-1})$	0.7	0.7	Δ	1229	1235	1232
	$m_K(fm^{-1})$	2.51	2.51	Λ_c	2270	2263	2286
	$m_\eta(fm^{-1})$	2.77	2.77	Σ_c	2469	2473	2455
	$m_\sigma(fm^{-1})$	3.42	3.42	Σ_c^*	2495	2499	2518
	$\Lambda_\pi = \Lambda_\sigma(fm^{-1})$	4.2	4.2	Λ_b	5586	5589	5620
	$\Lambda_K = \Lambda_\eta(fm^{-1})$	5.2	5.2	Σ_b	5808	5821	5811
	$g_{ch}^2/(4\pi)$	0.54	0.54	Σ_b^*	5818	5832	5832
	$\theta_p(^{\circ})$	-15	-15				

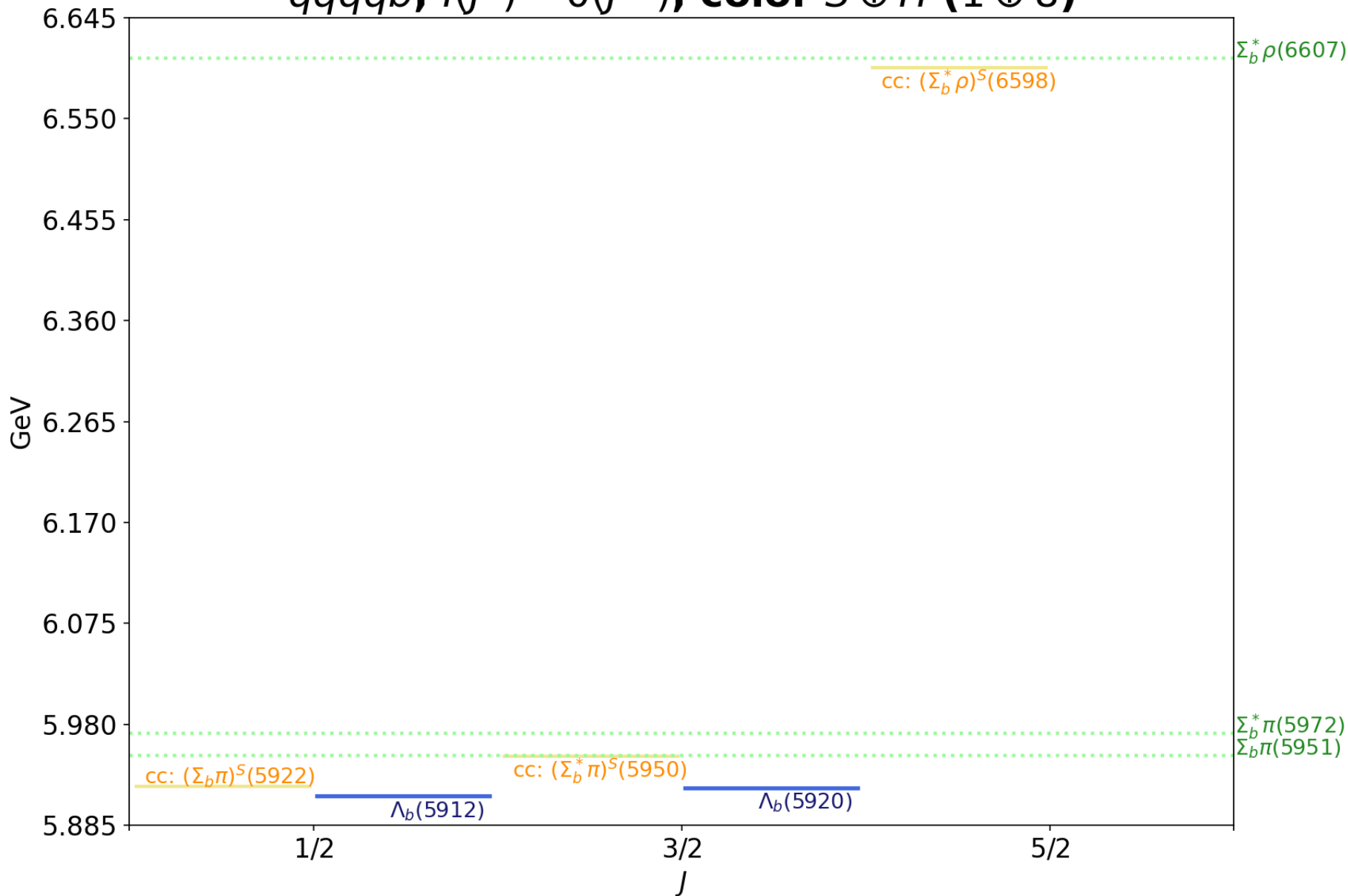
$qqq\bar{c}, I(J^P) = 0(J^-), \text{ color } S \oplus H (1 \oplus 8)$



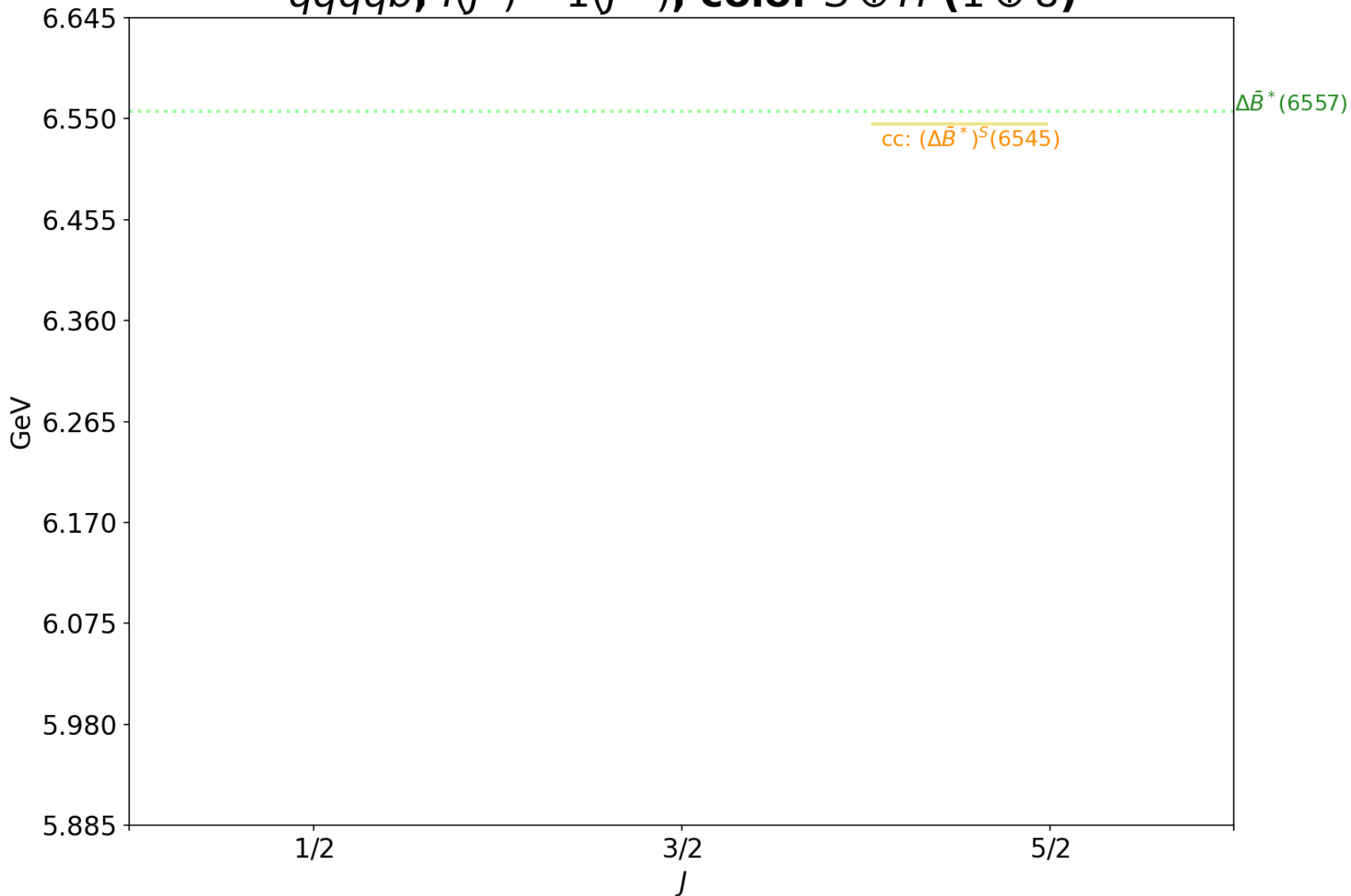
$qqq\bar{c}, I(J^P) = 1(J^-), \text{ color } S \oplus H (1 \oplus 8)$



$qqq\bar{b}, I(J^P) = 0(J^-), \text{ color } S \oplus H (1 \oplus 8)$



$qqq\bar{b}, I(J^P) = 1(J^-), \text{color } S \oplus H (1 \oplus 8)$



Root-mean-square distances ($qqq\bar{q}Q$)

$I(J^P)$	Main channel	r_{qq}	$r_{q\bar{q}}$	r_{qc}	$r_{c\bar{q}}$
$0(\frac{1}{2}^-)$	$\Sigma_c \pi(qqc, \bar{q}q)$	1.1	1.0	0.9	1.0
$0(\frac{3}{2}^-)$	$\Sigma_c^* \pi(qqc, \bar{q}q)$	1.4	1.3	1.1	1.3
$0(\frac{5}{2}^-)$	$\Sigma_c^* \rho(qqc, \bar{q}q)$	2.0	2.0	1.5	2.2
$1(\frac{1}{2}^-)$	$ND(qqq, \bar{q}c)$	4.3	4.3	3.1	5.2
$1(\frac{5}{2}^-)$	$\Delta D^*(qqq, \bar{q}c)$	1.2	1.9	1.7	1.0

$I(J^P)$	Main channel	r_{qq}	$r_{q\bar{q}}$	r_{qb}	$r_{b\bar{q}}$
$0(\frac{1}{2}^-)$	$\Sigma_b \pi(qqb, \bar{q}q)$	1.2	1.1	0.9	1.1
$0(\frac{3}{2}^-)$	$\Sigma_b^* \pi(qqb, \bar{q}q)$	1.3	1.2	1.0	1.2
$0(\frac{5}{2}^-)$	$\Sigma_b^* \rho(qqb, \bar{q}q)$	1.8	1.8	1.3	1.9
$1(\frac{5}{2}^-)$	$\Delta \bar{B}^*(qqq, \bar{q}b)$	1.2	1.6	1.4	0.9

distance
between two
clusters

Root-mean-square distances ($qqq\bar{q}Q$)

$I(J^P)$	Main channel	r_{qq}	$r_{q\bar{q}}$	r_{qc}	$r_{c\bar{q}}$
$0(\frac{1}{2}^-)$	$\Sigma_c \pi(qqc, \bar{q}q)$	1.1	1.0	0.9	1.0
$0(\frac{3}{2}^-)$	$\Sigma_c^* \pi(qqc, \bar{q}q)$	1.4	1.3	1.1	1.3
$0(\frac{5}{2}^-)$	$\Sigma_c^* \rho(qqc, \bar{q}q)$	2.0	2.0	1.5	2.2
$1(\frac{1}{2}^-)$	$ND(qqq, \bar{q}c)$	4.3	4.3	3.1	5.2
$1(\frac{5}{2}^-)$	$\Delta D^*(qqq, \bar{q}c)$	1.2	1.9	1.7	1.0

$I(J^P)$	Main channel	r_{qq}	$r_{q\bar{q}}$	r_{qb}	$r_{b\bar{q}}$
$0(\frac{1}{2}^-)$	$\Sigma_b \pi(qqb, \bar{q}q)$	1.2	1.1	0.9	1.1
$0(\frac{3}{2}^-)$	$\Sigma_b^* \pi(qqb, \bar{q}q)$	1.3	1.2	1.0	1.2
$0(\frac{5}{2}^-)$	$\Sigma_b^* \rho(qqb, \bar{q}q)$	1.8	1.8	1.3	1.9
$1(\frac{5}{2}^-)$	$\Delta \bar{B}^*(qqq, \bar{q}b)$	1.2	1.6	1.4	0.9

molecular
states

compact
states

Outline

- Introduction
- Chiral quark model
- $qq_s\bar{Q}Q$ and $qqq\bar{q}Q$ system
- Summary

Summary:

- A series of possible pentaquarks with heavy flavors are predicted by five-body dynamical calculations.
- Taking hidden color structure into consideration always provides more binding energy than color singlet structure.
- The more heavier quark presents, the easier to form the bound states.

Thank you for your attention!