

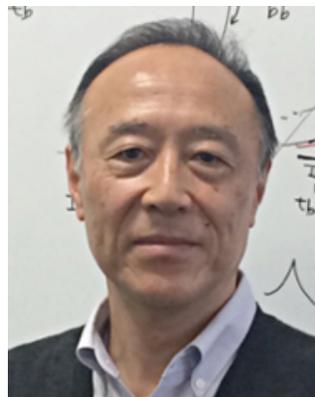
Quark-model search for compact strange-hidden-charm pentaquark states

Makoto Oka (Nishina Center for Accelerator Based Science, RIKEN)

A. Hosaka (Osaka)

E. Hiyama (Tohoku)

G. Wolschin (Heidelberg)



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Introduction

- ✦ Many narrow exotic (non $q\bar{q}$, qqq) resonances have been discovered since 2003.

Facts:

- They appear mainly in systems with heavy quarks, (s), c or b.
- Many appear at the vicinity of two-hadron thresholds and look like hadron-molecule states.

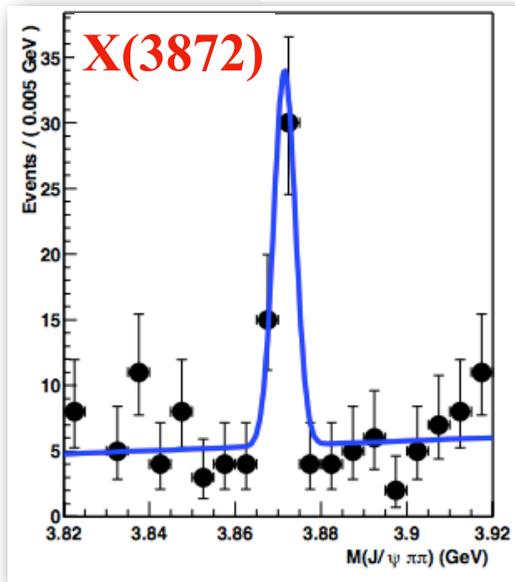
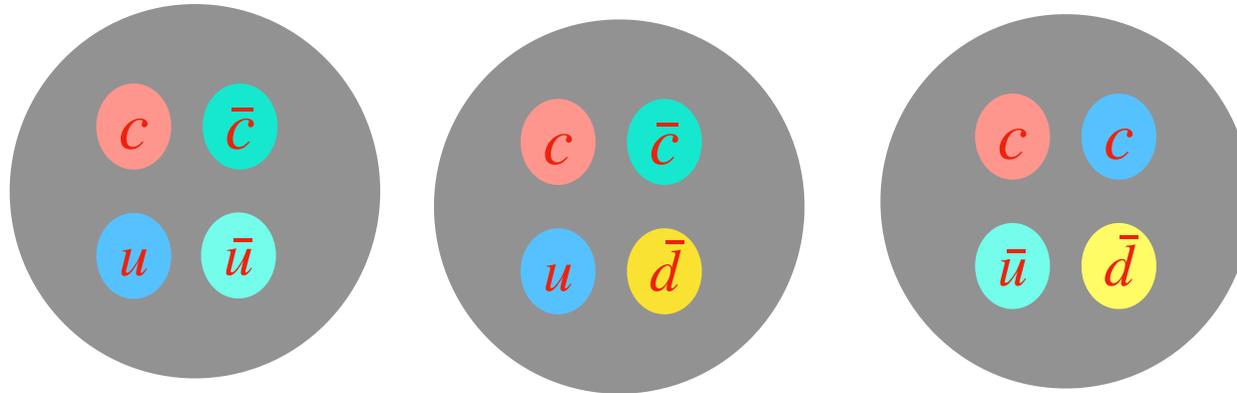
- ✦ Question: Are there any “compact multi-quark” states?

- ✦ Related questions and possible new concepts in hadron spectroscopy:

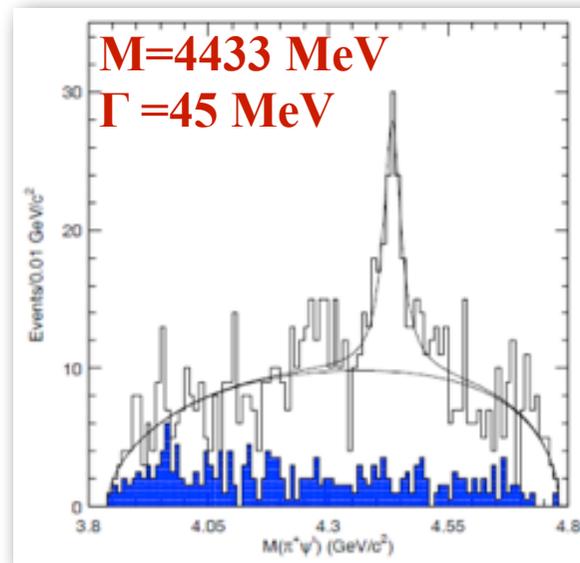
- Bound states with 4 or more quarks may reveal non-trivial confinement dynamics of multi-quark systems.
- There may appear “exotic” color configurations that may play important roles in the multi-quark states.

“Exotic” Multiquark Hadrons

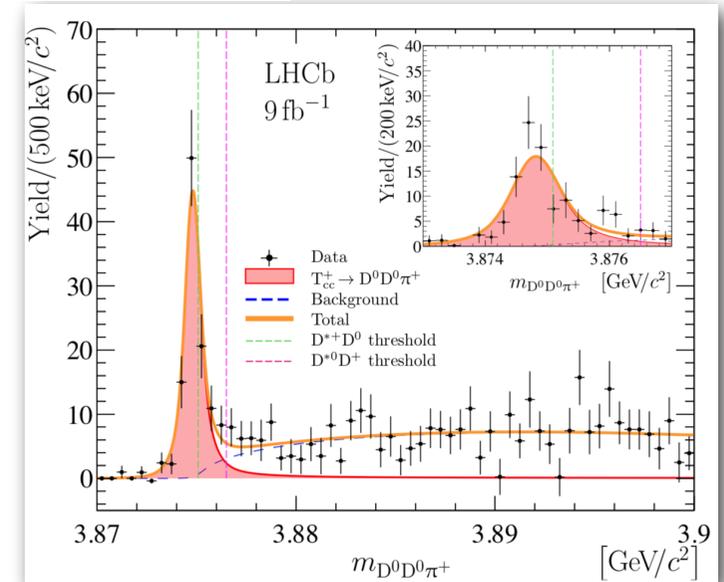
Hidden-charm and Doubly-charmed tetra-quarks, $T_{c\bar{c}}$, T_{cc}



Belle, PRL 91 (2003)
most cited paper for Belle



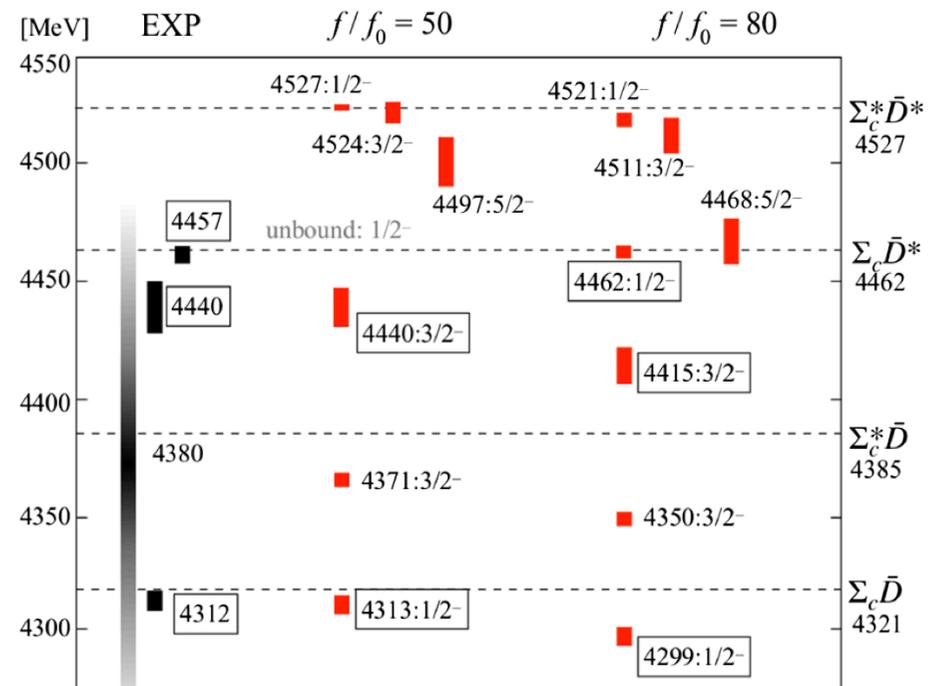
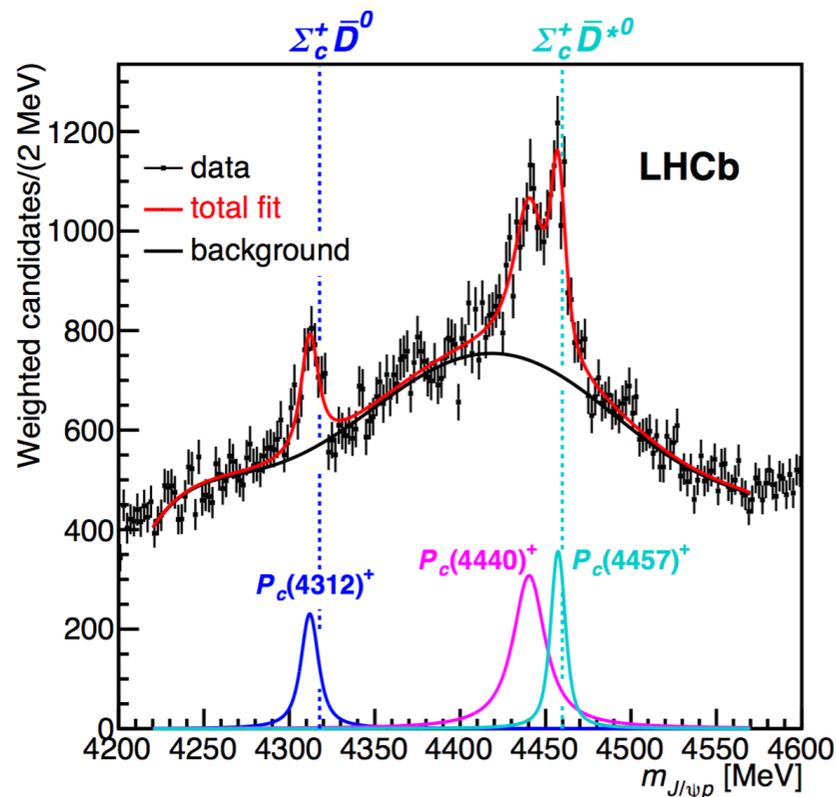
$Z_c^+(4430)$ *Belle*
PRL 100 (2008) 142001



T_{cc} *LHCb*
Nature Phys. 18 (2022) 751

“Exotic” Multiquark Hadrons

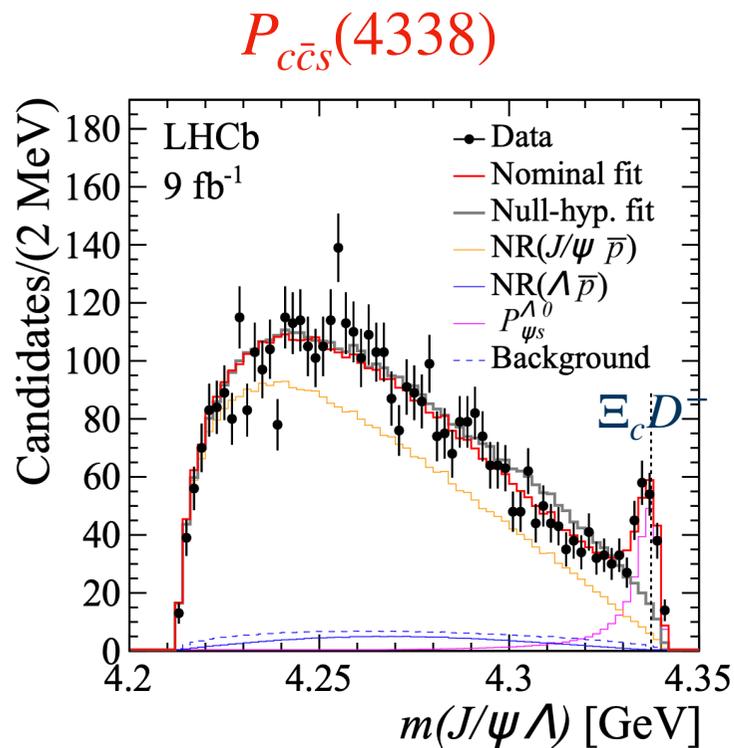
- # Hidden-charm pentaquark baryons, $P_{c\bar{c}}(c\bar{c}uud)$ observed in $p + J/\psi$ final states at LHCb, *PRL* 115 (2015), *PRL* 122 (2019)



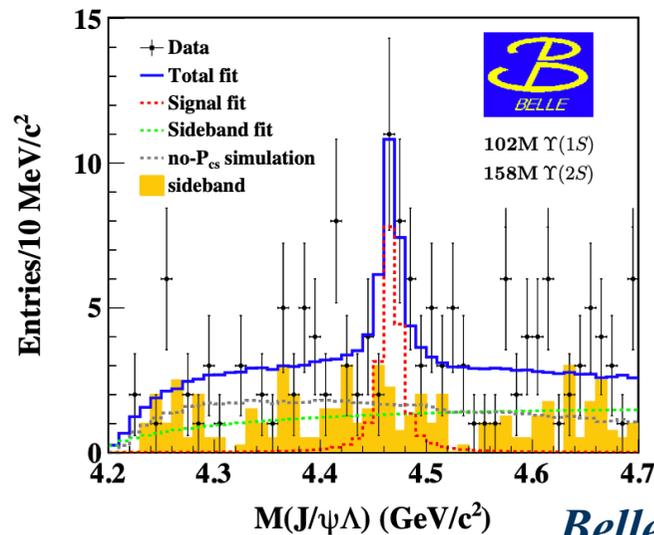
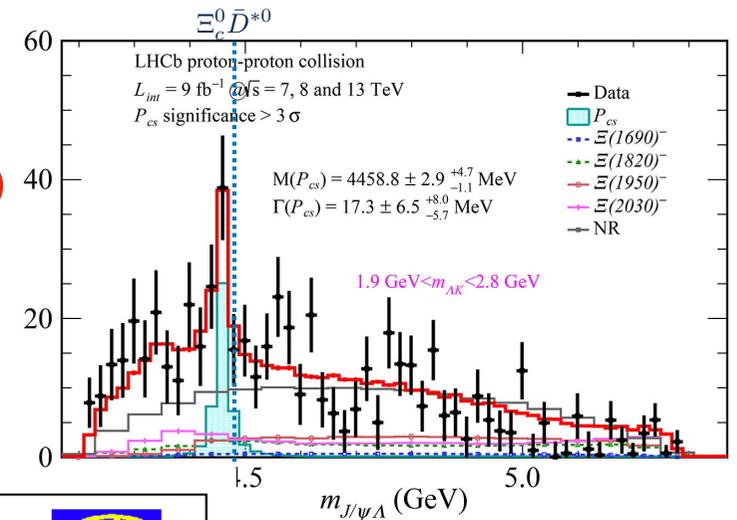
Model calculation by Y. Yamaguchi et al., *Phys. Rev. D* 101 (2020)

“Exotic” Multiquark Hadrons

- # Hidden-charm **strange** pentaquark baryons, $P_{c\bar{c}s}(c\bar{c}uds)$
LHCb: PRL 131, 031901 (2023), Science Bulletin, 66 (2021)



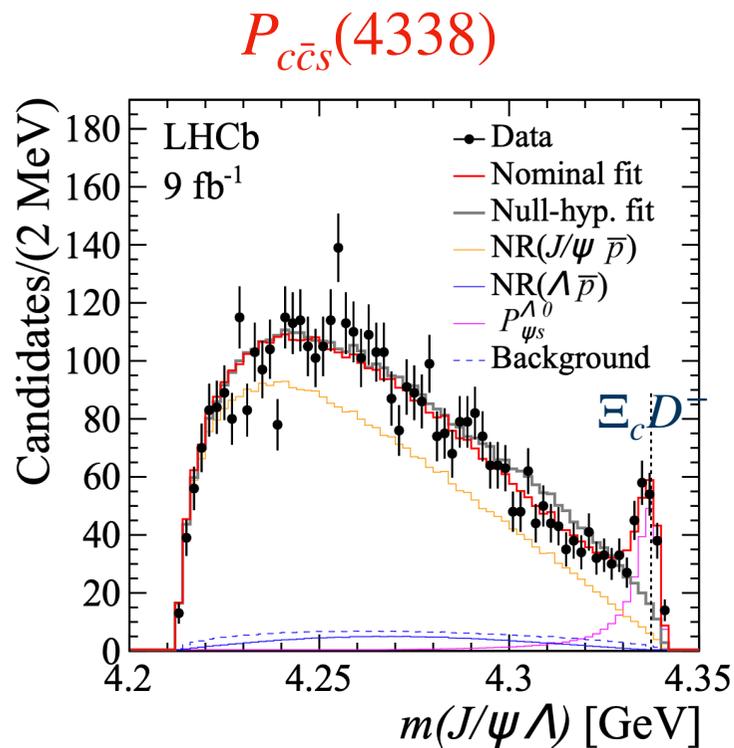
$P_{c\bar{c}s}(4459/4471)$



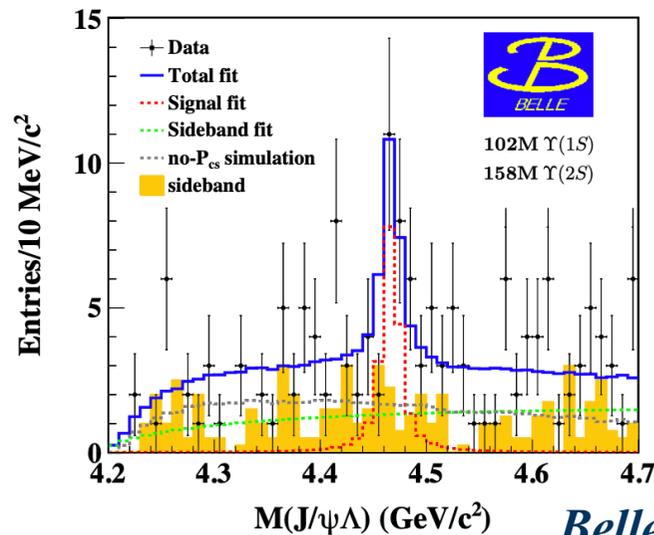
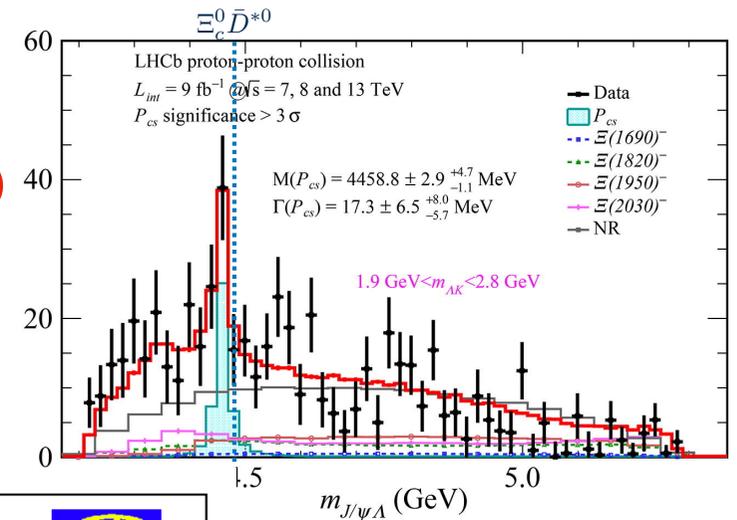
Belle: arXiv:2502.09951 (2025)

“Exotic” Multiquark Hadrons

- # Hidden-charm **strange** pentaquark baryons, $P_{c\bar{c}s}(c\bar{c}uds)$
LHCb: PRL 131, 031901 (2023), Science Bulletin, 66 (2021)



$P_{c\bar{c}s}(4459/4471)$



Belle: arXiv:2502.09951 (2025)

Studies of $P_{c\bar{c}s}$

■ Molecular picture is the most popular approach.

$\Xi_c D$ for $P_{c\bar{c}s}$ (4338), $\Xi_c D^*$ for $P_{c\bar{c}s}$ (4459/4471)

J-J. Wu, et al, PRL 105, 232001 (2010)

H-X. Chen, et al., EPJ C 81, 409(2021)

F-Z. Peng, et al., EPJ C 81, 666 (2021)

R. Chen, PRD 103, 054007 (2021)

C.W. Xiao, et al., PRD 103, 054016 (2021)

J-T. Zhu, et al., PRD 103, 074007 (2021)

M-L. Du, et al., PRD 104, 114034 (2021)

A. Giachino, et al., PRD 108, 074012 (2023)

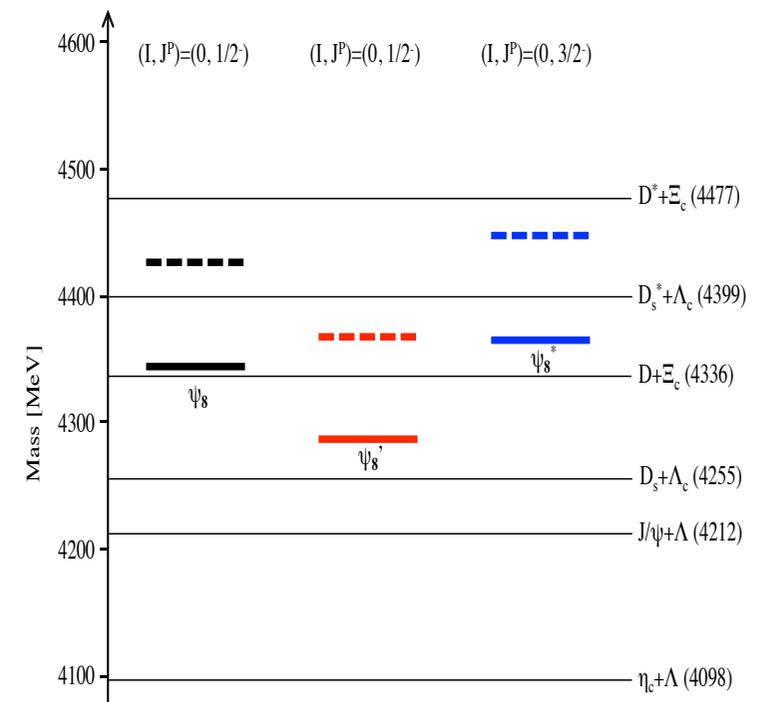
S. Clymton, et al., PRD 112, 014041 (2025)

■ Quark model study

Y. Irie, MO, S. Yasui, PRD 97, 034006 (2018)

S. Takeuchi et al., Proc. HADRON 2019 (2020)

(before the discovery)



Target $P_{c\bar{c}s} (c\bar{c}uds)$

- # Search “*flavor singlet*” $P_{c\bar{c}s} (c\bar{c}uds)$ with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$.
 - Perform *a full 5-body calculation* by the Gaussian Expansion Method (GEM) with the most updated quark model Hamiltonian.
 - New color configuration, *Color-octet* $[(c\bar{c})_8 (qqq)_8]_1$ are explicitly taken into account.
 - Resonances are identified by the *real scaling method* including all the $\eta_c\Lambda, J/\psi\Lambda, D_s\Lambda_c, D_s\Sigma_c^{(*)}, D\Xi_c^{(*)}$ scattering states.
 - We search for resonances up to the $\Xi_c D^*$ mass region.
- # Previous researches in the same method and direction.
 - $P_{c\bar{c}}(c\bar{c}uud)$: E. Hiyama et al., *Phys. Rev. C* 98, 045208 (2018)
 - $P_{c\bar{c}sss}(c\bar{c}ssss)$: Q. Meng, et al., *Phys. Lett. B* 798, 135028 (2019)

Quark model setup

- **Non-relativistic quark model for S-wave (ground-state) hadrons confinement + OGE (Coulomb + color-magnetic interaction)**
- **“AP1” potential by Silvestre-Brac, Few-Body Syst. 20, 1 (1996)**

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

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

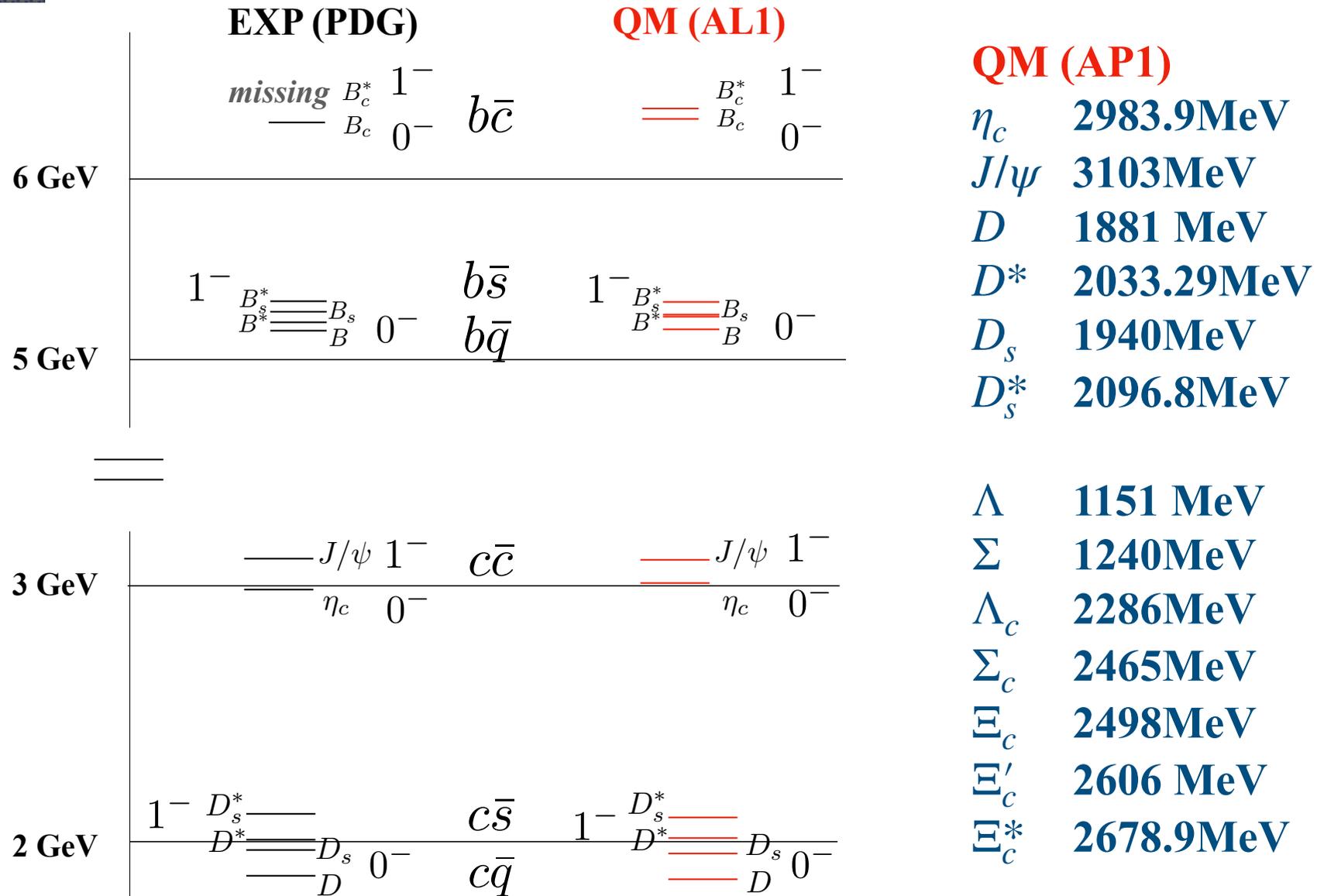
$$f(r, r_0) = \frac{\exp(-r^2/r_0^2)}{\pi^{3/2} r_0^3} \quad r_{0ij} = A \left(\frac{2m_i m_j}{m_i + m_j} \right)^{-B}$$

$$m_{u/d} = 0.277\text{GeV}, m_s = 0.553\text{GeV}, m_c = 1.819\text{GeV}, m_b = 5.206\text{GeV}$$

$$p = 2/3, \lambda = 0.3898 \text{ GeV}^{5/3}, \alpha = 0.4242, \alpha' = 1.8025$$

$$B = 0.3263, A = 1.5296 \text{ GeV}^{B-1}, \Lambda = 1.1313 \text{ GeV}$$

Quark model setup



Q. Meng, S. Ohno

Roles of color octet $(qqq)_8$

- # Estimate based on the simple Ansätze for $P_{Q\bar{Q}}(Q\bar{Q}qqq)$
 - Spin independent (CE) force is roughly a constant.
 - Spin-dependent interaction (CM) is suppressed for heavy quarks.
 - Consider only the orbitally-symmetric S-wave qqq states.
- # CM is estimated by $V_{\text{CM}} \simeq (18.8 \text{ MeV}) \times \Delta_{\text{CM}}$ with the color-spin operator $\Delta_{\text{CM}} = - \sum (\lambda_i^c \lambda_j^c)(\sigma_i \sigma_j)$

Δ_{CM} favors **flavor-anti-symmetric** states with the lowest spin.

$$\langle \Delta_{\text{CM}} \rangle = n(n - 10) + \frac{4}{3}S(S + 1) + 2C_2[SU(3)_c] + 4C_2[SU(3)_f]$$

$$C_2[SU(3)_f](p, q) = \frac{p^2 + pq + q^2}{3} + p + q$$

$$n = 3, S = 1/2, 3/2$$

$$\langle \Delta_{\text{CM}} \rangle = -14 \text{ for flavor-singlet color-octet } (qqq)_8$$

$$\langle \Delta_{\text{CM}} \rangle = -8 \text{ for the flavor-octet color-singlet } (qqq)_1$$

Roles of color octet $(qqq)_8$

- # Check the contribution of the flavor SU(3) singlet state.
*Note that the flavor SU(3) singlet state is not allowed for $(qqq)_1$ but appears only as a **color-octet** $(qqq)_8$ ($L = 0, J = 1/2$) state. In the $P_{c\bar{c}}(c\bar{c}qqq)$, it may contribute for the **color-octet** $[(c\bar{c})_8 (qqq)_8]_1$ components.*
- # We take into account the **color-octet** $[(c\bar{c})_{8(S=0,1)} (qqq)_8]_1$ configurations explicitly in the GEM calculation.
- # If there is a resonance below the $D_s\Lambda_c, D_s\Sigma_c^{(*)}$ or $D\Xi_c^{(*)}$ thresholds, then it would be **narrow** because *the decays to $\eta_c\Lambda$ or $J/\psi\Lambda$ (flavor-octet) states are forbidden* by the flavor SU(3) symmetry.

Real Scaling Method (RSM)

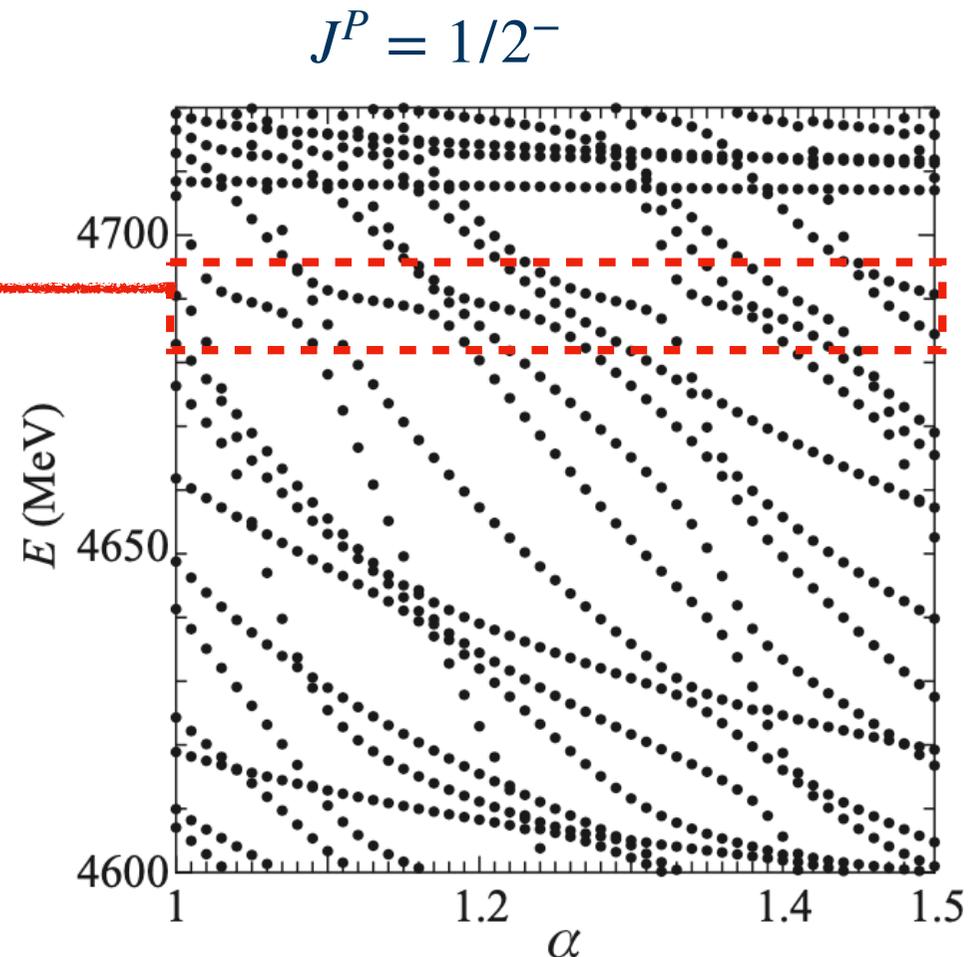
- Change the scale (or the box size)

$$r \rightarrow \alpha r$$

- For $P_{c\bar{c}}(c\bar{c}uud)$, the RSM with $\alpha = 1 \rightarrow 1.5$ has identified the resonances at 4690 MeV for $J^P = 1/2^-$ at 4920 MeV for $J^P = 3/2^-$

But they are much heavier than the observed resonances

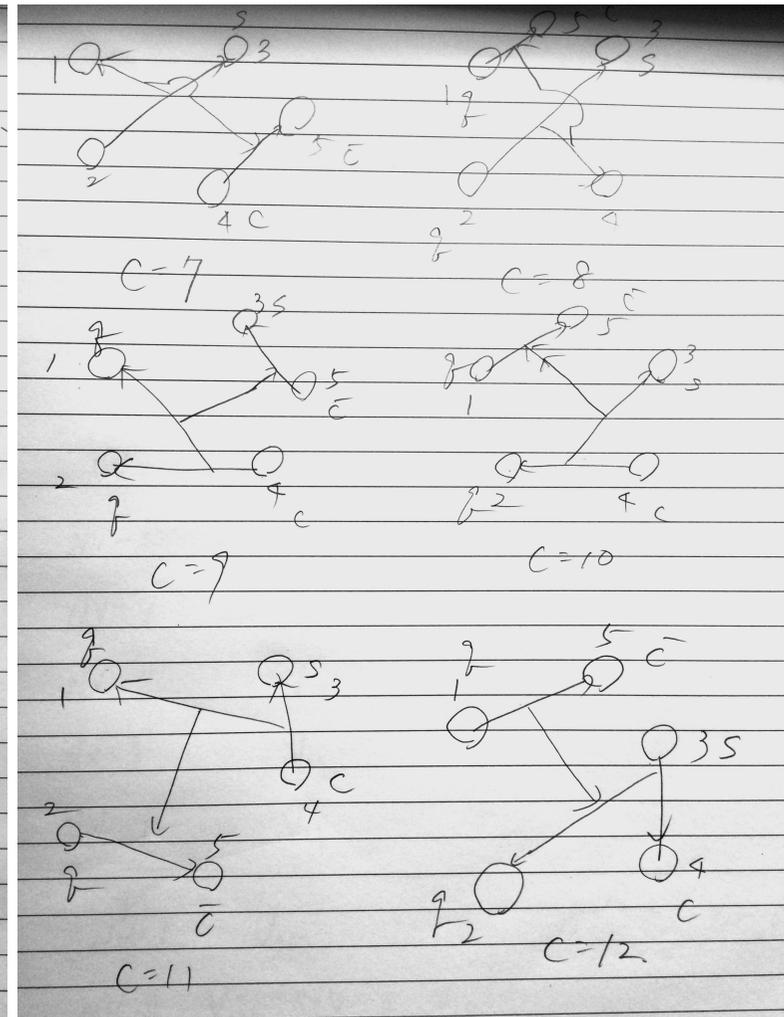
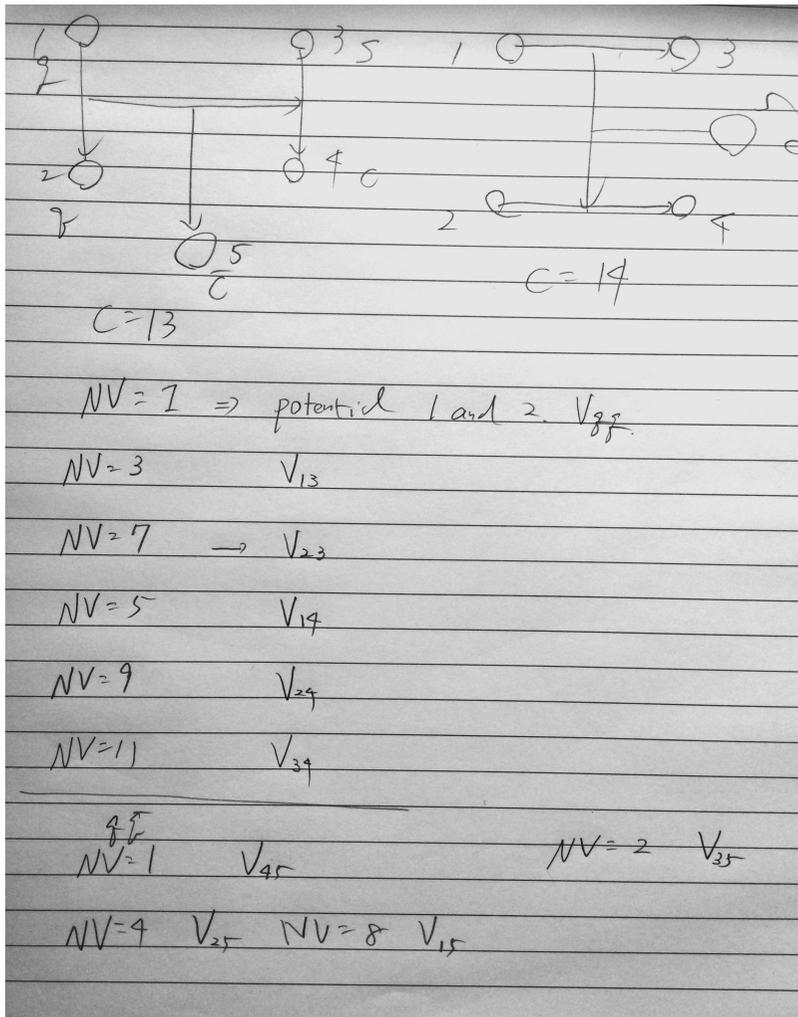
$$P_{c\bar{c}}(4312)(4440)(4457).$$



E. Hiyama, A. Hosaka, MO, J.-M. Richard, PRC 98, 045208 (2018)

Setup of the 5-body calculation

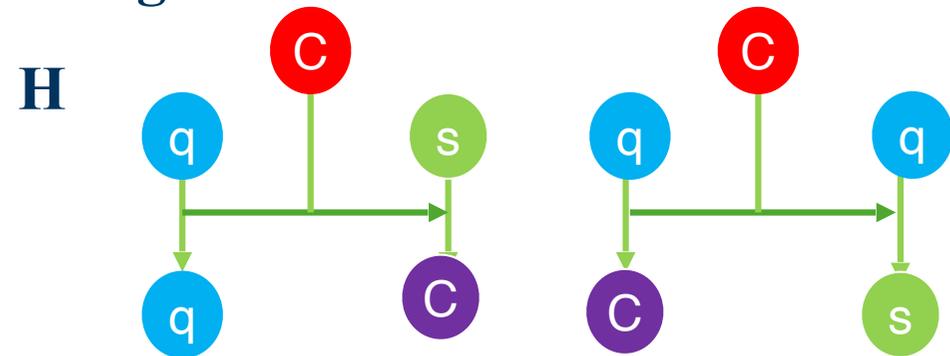
- Gaussian Expansion Method (GEM) for 5-quark states**
Jacobi coordinates: H (confined), K(1) (B₁M₁), and K(8) (B₈M₈)



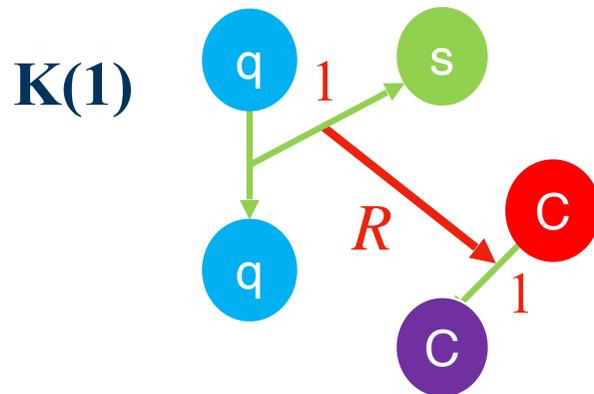
Results

Jacobi coordinates and real scaling

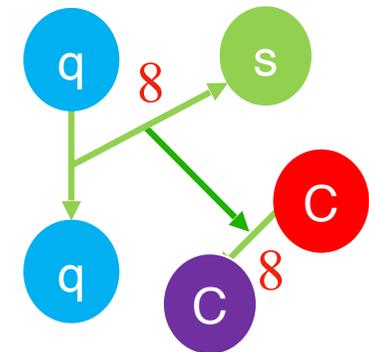
Confined coordinates



Scattering coordinates



K(8)



real scaling $R \rightarrow \alpha R$

Confined states

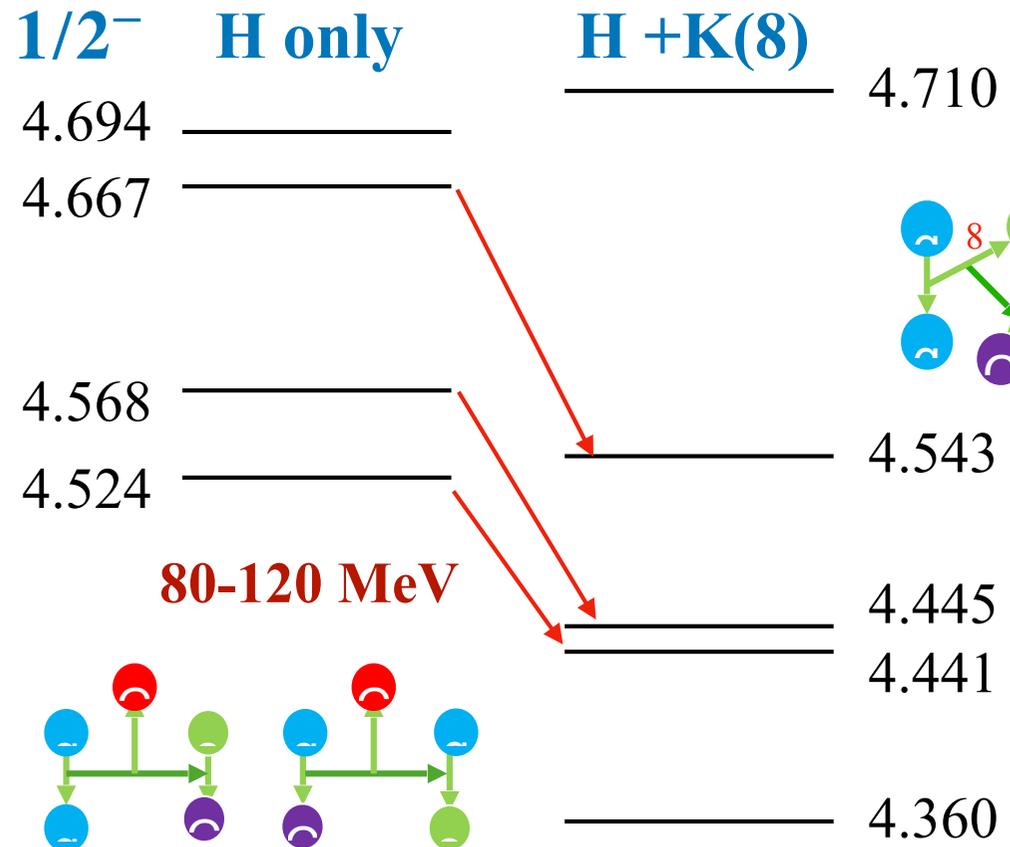
Comparison of H and H+K(8) (both confined)

$$J^P = \frac{3}{2}^-$$

H only
4.62014
4.71470
4.99974
H + K(8)
4.47553
4.57050
4.75728
4.85769
4.88644
4.91958
4.98244

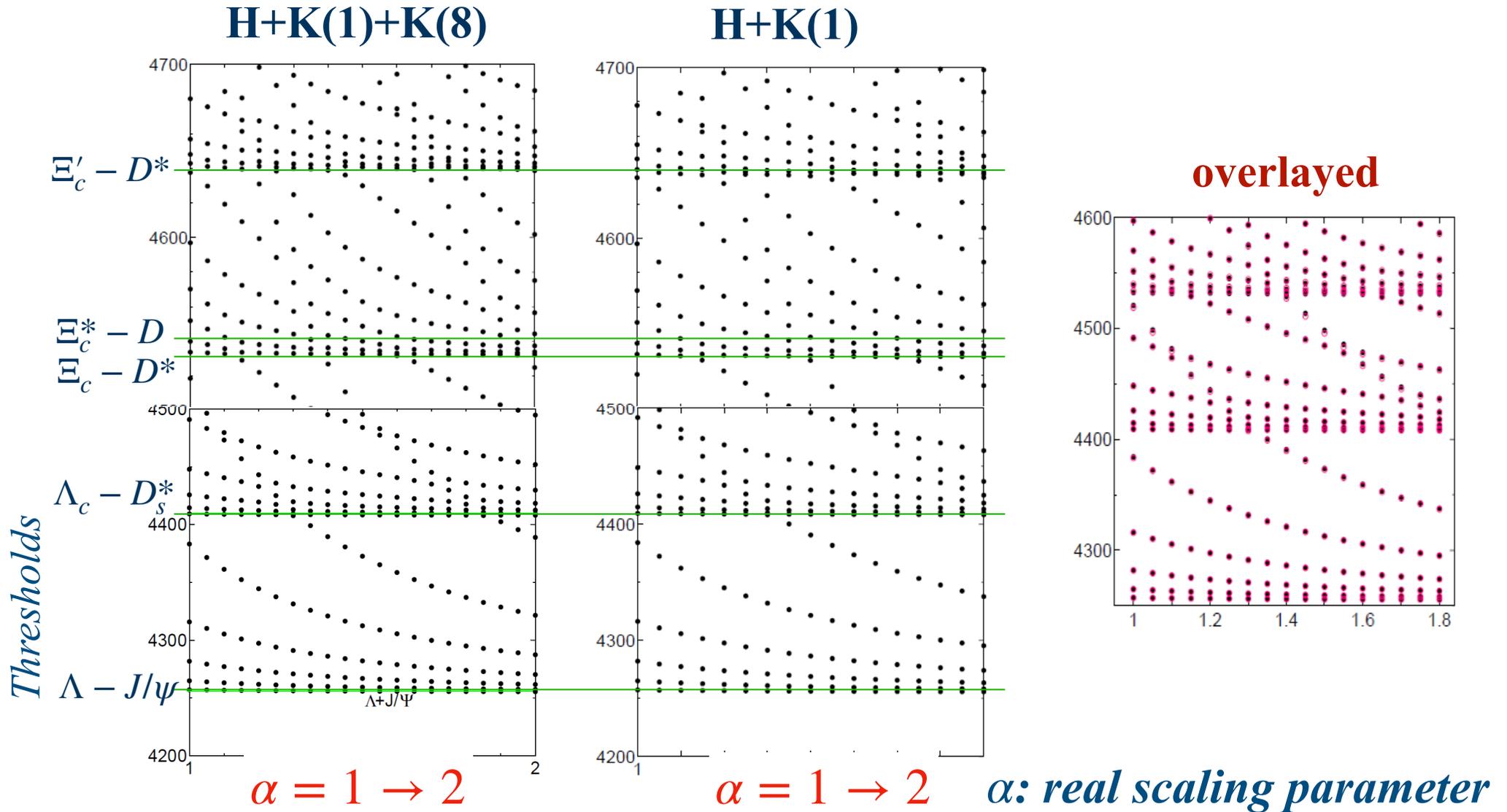
$$J^P = \frac{1}{2}^-$$

H only
4.52367
4.56834
4.66655
4.69378
H + K(8)
4.35956
4.44087
4.45130
4.54302
4.70963



Results for $P_{c\bar{c}s} (J^P = \frac{3^-}{2})$

Comparison of with/without the color octet configurations

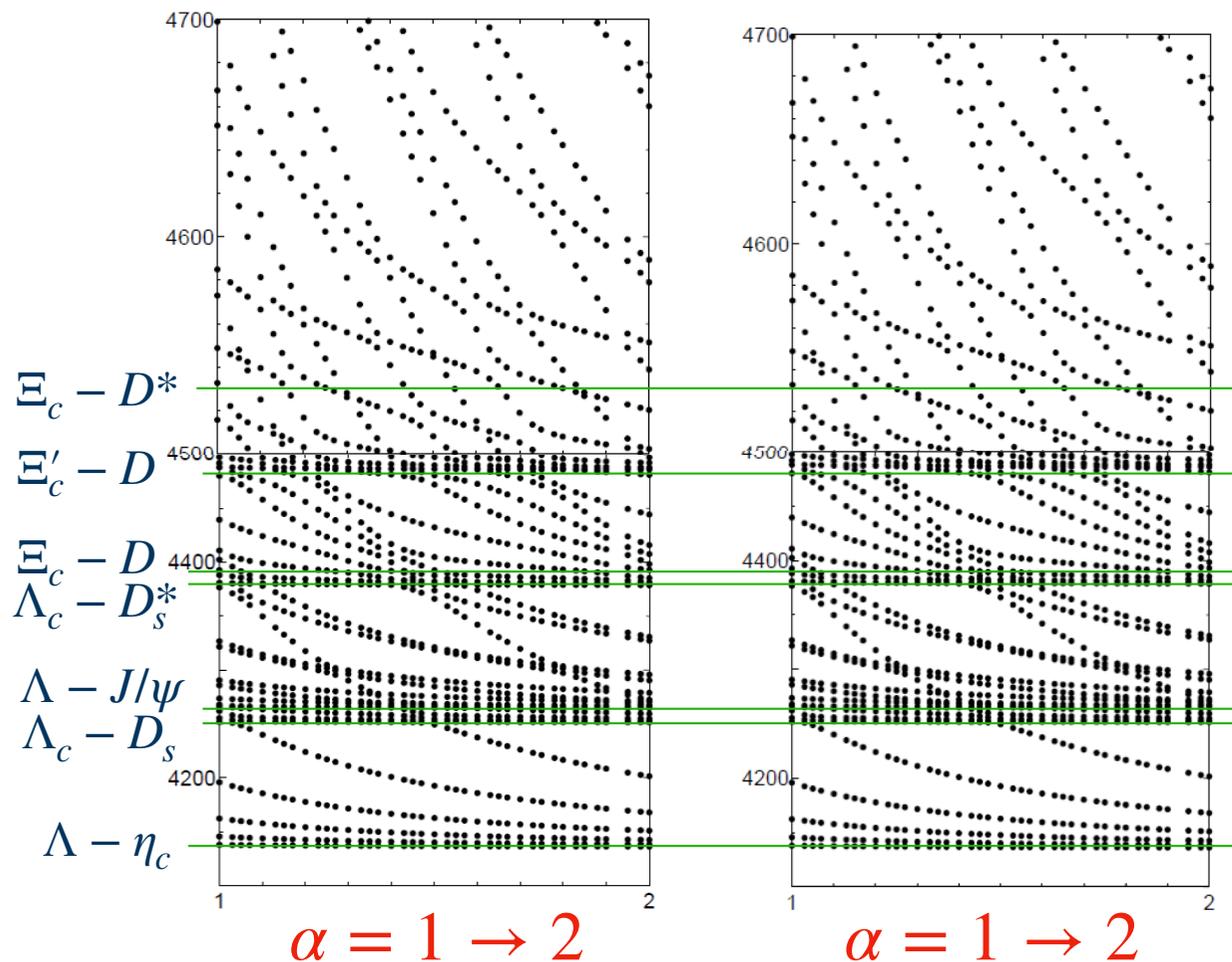


Results for $P_{c\bar{c}s} (J^P = \frac{1}{2}^-)$

Comparison of with/without the color octet configurations

H+K(1)+K(8)

H+K(1)



No resonance state is found with/without K(8)

High resources

$\frac{1}{2}^-$: 47,000 dim, 8 hrs/a

$\frac{3}{2}^-$: 32,000 dim, 3 hrs/a

Conclusion

- ✦ Full 5-body calculations for $P_{c\bar{c}s}(I = 0, J^P = 1/2^-, 3/2^-)$ have been performed. The real scaling method is employed to identify resonant state from meson-baryon scattering states.
- ✦ We confirm that the color-octet (flavor-singlet) $(qqq)_8$ configuration lowers the pentaquark energy.
- ✦ No bound state nor narrow resonance is observed either in $J^P = 1/2^-$ or $3/2^-$.
- ✦ Physical interpretation is not yet complete, while the results support that the observed sharp resonances are most likely hadron molecule states. We need more analyses.
- ✦ Future problems
 - Take into account contributions of long-range B-M interactions, such as meson exchange forces so that molecule states are represented.
 - Check the confinement mechanism for 5-quark systems.