heavy flavor molecules

Kan Chen

Peking University

Collaborators: Rui Chen (Hunan Normal U.), Lu Meng (Ruhr U.),Bo Wang (Hebei U.), and Shi-Lin Zhu (Peking U.)

Eur.Phys.J.C 82 (2022) 7, 581

Outline

- Motivation
- Theoretical framework
- Numerical results
- Summary

Motivation

Discovery of the P_c states

State	Mass (MeV)	Width (MeV)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

Experiment

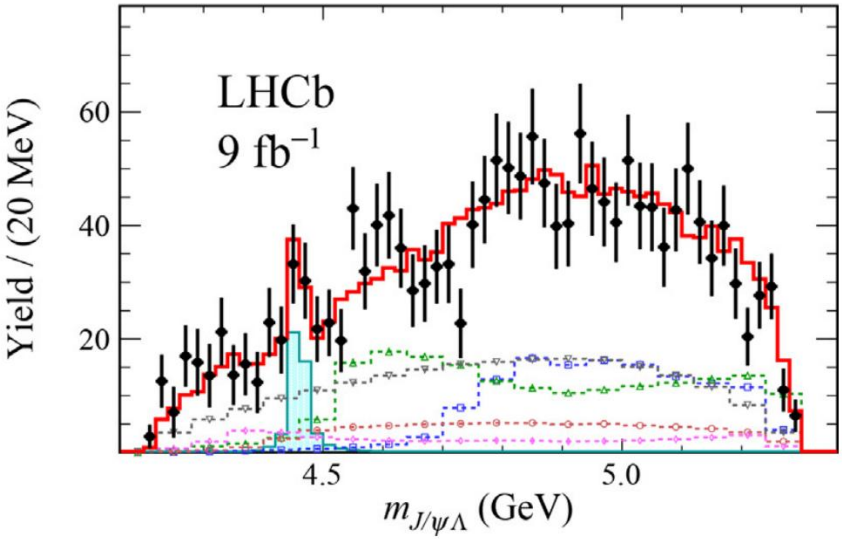
Phys. Rev. Lett. 122, 222001 (2019)
Phys. Rev. Lett. 115, 072001 (2015)
Phys. Rev. Lett. 117, 082002 (2016)

Theoretical interpretation

R. Chen, et al., Phys. Rev. D 100, 011502 (2019)
M. Z. Liu, et.al., Phys. Rev. Lett. 122, 242001 (2019)
J. He, Eur. Phys. J. C 79, 393 (2019)
C. W. Xiao, J. Nieves and E. Oset, Phys. Rev. D 100, no.1, 014021 (2019)
L. Meng, B. Wang, G. J. Wang and S. L. Zhu, Phys. Rev. D 100, 014031 (2019)
M. Pavon Valderrama, Phys. Rev. D 100, 094028 (2019)
H. X. Chen, W. Chen and S. L. Zhu, Phys. Rev. D 100, 051501 (2019)
T. J. Burns and E. S. Swanson, Phys. Rev. D 100, 114033 (2019)
M. L. Du, et. Al., Phys. Rev. Lett. 124, 072001 (2020)
B. Wang, L. Meng and S. L. Zhu, JHEP 11, 108 (2019)
Y. Yamaguchi, et. Al., Phys. Rev. D 101, no.9, 091502 (2020)

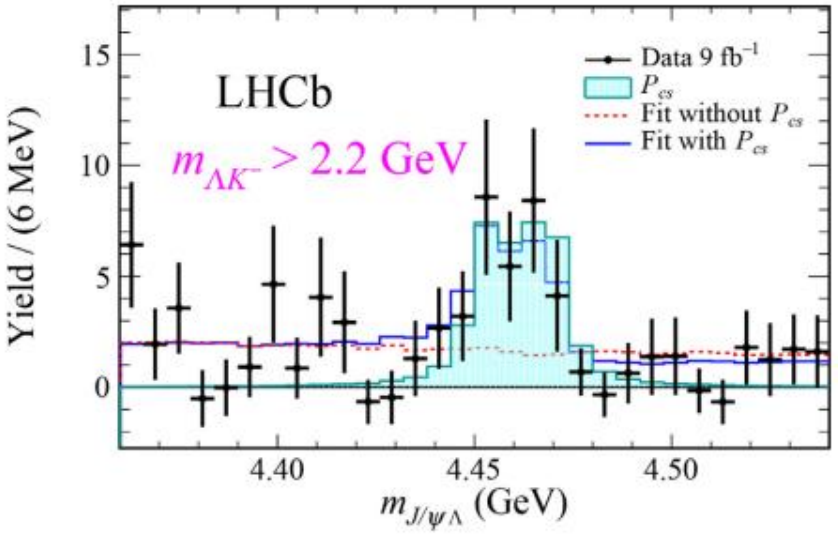
Motivation

Discovery of the P_{cs} states



Sci. Bull. 66, 1278-1287 (2021)

M: 4458.8±2.9 MeV, Γ: 17.3±6.5 MeV

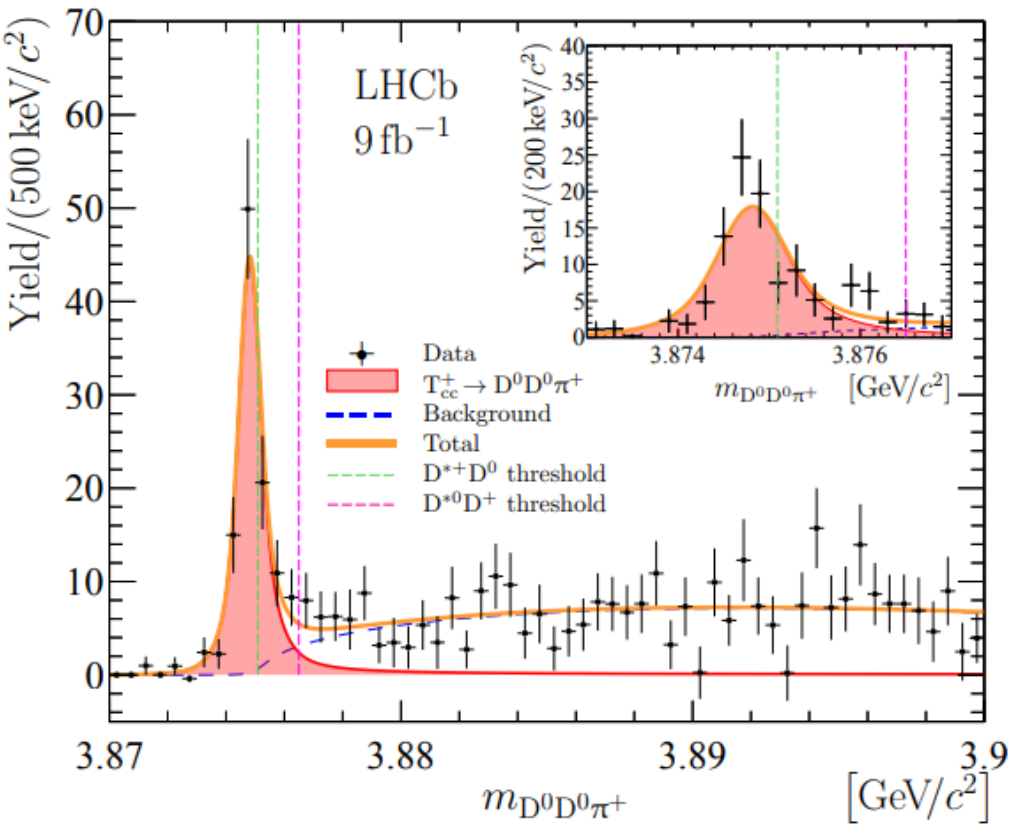


A two peak hypothesis is also tested:
M=4454.9±2.7 MeV, Γ=7.5±9.7 MeV
M=4467.8±3.7 MeV, Γ=5.2±5.3 MeV

Wu J-J, Molina R, Oset E, et al. Phys Rev Lett 2010;105:232001.
Chen R, He J, Liu X. Chin Phys C 2017;41:103105.
Santopinto E, Giachino A, Phys Rev D 2017;96:014014.
Shen C-W, Wu J-J, Zou B-S. Phys Rev D 2019;100:056006.

Xiao C-W, Nieves J, Oset E. Phys Lett B 2019;799:135051.
Wang B, Meng L, Zhu S-L. Phys Rev D 2020;101:034018
Chen H-X, Geng L-S, Liang W-H, et al.. Phys Rev C 2016;93:065203.

Discovery of the T_{cc} state



Nature Phys. 18 (2022) 7, 751-754

Nature Commun. 13 (2022) 1, 3351

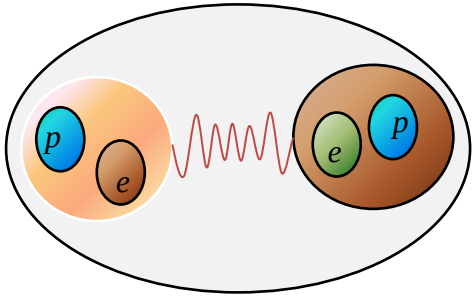
Mass: 3874.8 MeV

N. Li, Z. F. Sun, X. Liu and S. L. Zhu, Chin. Phys. Lett. 38, 092001 (2021)
L. Meng, G. J. Wang, B. Wang and S. L. Zhu, Phys. Rev. D 104, 051502 (2021)
X. K. Dong, F. K. Guo and B. S. Zou, Commun. Theor. Phys. 73, 125201 (2021)
M. J. Yan and M. P. Valderrama, Phys.Rev.D 105 (2022) 1, 014007.
L. Y. Dai, X. Sun, X. W. Kang, A. P. Szczepaniak and J. S. Yu, Phys.Rev.D 105 (2022) 5, L051507.
V. Baru, X. K. Dong, M. L. Du, et. al, Phys.Lett.B 833 (2022) 137290.
M. L. Du, V. Baru, X. K. Dong, et. al, Phys.Rev.D 105 (2022) 1, 014024
L. R. Dai, R. Molina and E. Oset, Phys.Rev.D 105 (2022) 1, 016029…

Motivation

QED

Hydrogen molecule

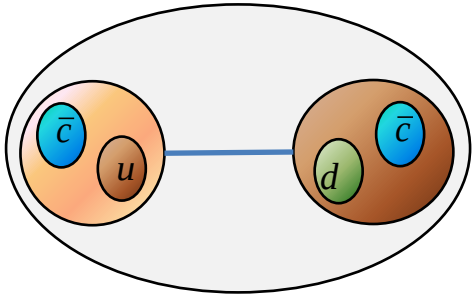


Coulomb potential

QCD

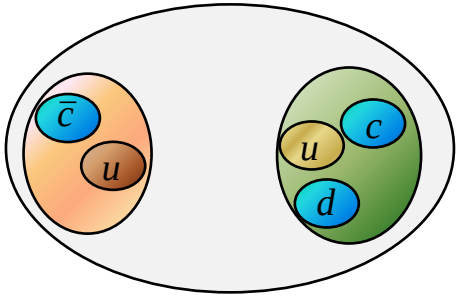
Tcc

Hadronic Molecule

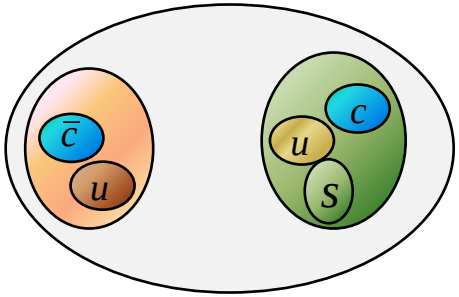


Boson exchange potential

Pc



Pcs

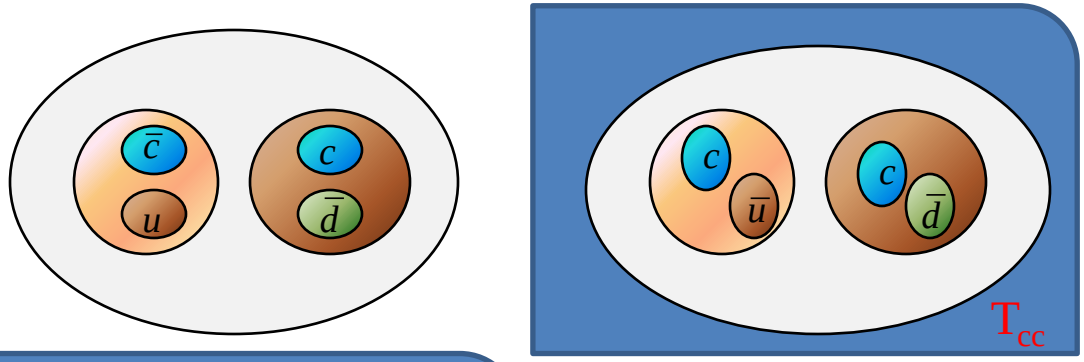


Motivation

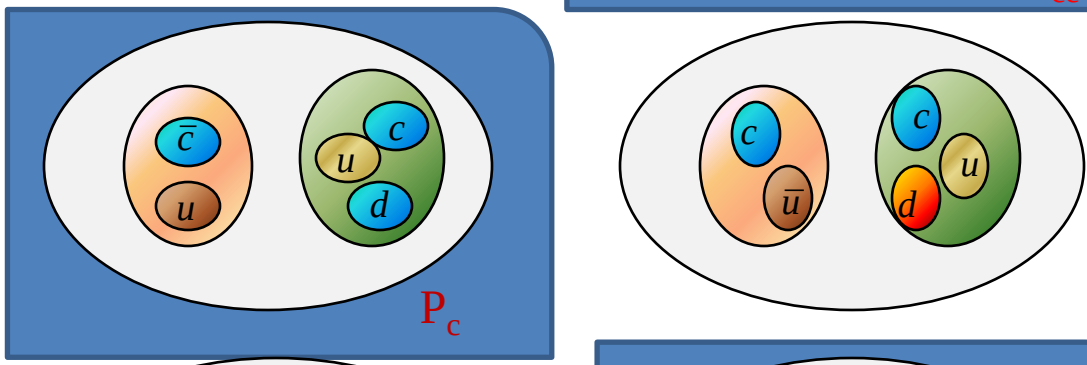
Hidden charm

Open charm

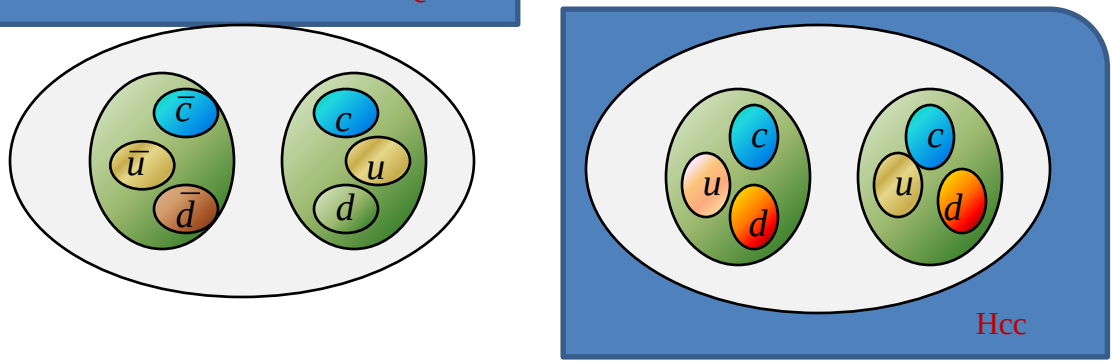
Meson-meson molecular states:



Meson-baryon molecular states:



Baryon-baryon molecular states:



Considered systems

Meson-meson	$[\bar{D}\bar{D}]_0^1$	$[\bar{D}\bar{D}^*]_1^{0,1}$	$[\bar{D}^*\bar{D}^*]_{0,2}^1$
	$[\bar{D}^*\bar{D}^*]_1^0$		
Baryon-meson	$[\Lambda_c\bar{D}]_{\frac{1}{2}}^{\frac{1}{2}}$	$[\Lambda_c\bar{D}^*]_{\frac{1}{2},\frac{3}{2}}^{\frac{1}{2}}$	$[\Sigma_c\bar{D}]_{\frac{1}{2}}^{\frac{1}{2},\frac{3}{2}}$
	$[\Sigma_c D^*]_{\frac{1}{2},\frac{3}{2}}^{\frac{1}{2},\frac{3}{2}}$	$[\Sigma_c^*\bar{D}]_{\frac{3}{2}}^{\frac{1}{2},\frac{3}{2}}$	$[\Sigma_c^*\bar{D}^*]_{\frac{1}{2},\frac{3}{2},\frac{5}{2}}^{\frac{1}{2},\frac{3}{2}}$
	$[\Xi_c\bar{D}]_{\frac{1}{2}}^{0,1}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2},\frac{3}{2}}^{0,1}$	$[\Xi_c'\bar{D}]_{\frac{1}{2}}^{0,1}$
	$[\Xi_c'\bar{D}^*]_{\frac{1}{2},\frac{3}{2}}^{0,1}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}^{0,1}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2},\frac{3}{2},\frac{5}{2}}^{0,1}$
Baryon-baryon	$[\Lambda_c\Lambda_c]_0^0$	$[\Lambda_c\Sigma_c]_{0,1}^1$	$[\Sigma_c\Sigma_c]_0^{0,2}$
	$[\Sigma_c\Sigma_c]_1^1$	$[\Lambda_c\Sigma_c^*]_{1,2}^1$	$[\Sigma_c\Sigma_c^*]_{1,2}^{0,1,2}$
	$[\Sigma_c^*\Sigma_c^*]_{1,3}^1$	$[\Sigma_c^*\Sigma_c^*]_{0,2}^{0,2}$	$[\Xi_c\Xi_c]_0^1$
	$[\Xi_c\Xi_c]_1^0$	$[\Xi_c\Xi_c']_{0,1}^{0,1}$	$[\Xi_c\Xi_c^*]_{1,2}^{0,1}$
	$[\Xi_c'\Xi_c']_0^1$	$[\Xi_c'\Xi_c']_1^0$	$[\Xi_c'\Xi_c^*]_{1,2}^{0,1}$
	$[\Xi_c^*\Xi_c^*]_{1,3}^0$	$[\Xi_c^*\Xi_c^*]_{0,2}^1$	

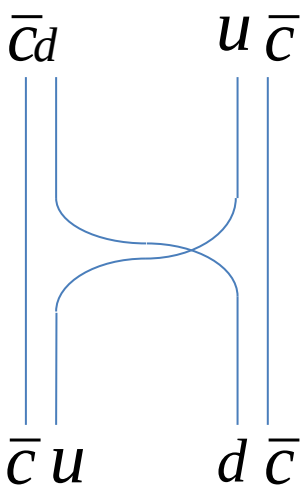
For identical particles (fermion or boson):

$L+S_{tot}+I_{tot}+2i=$Even number

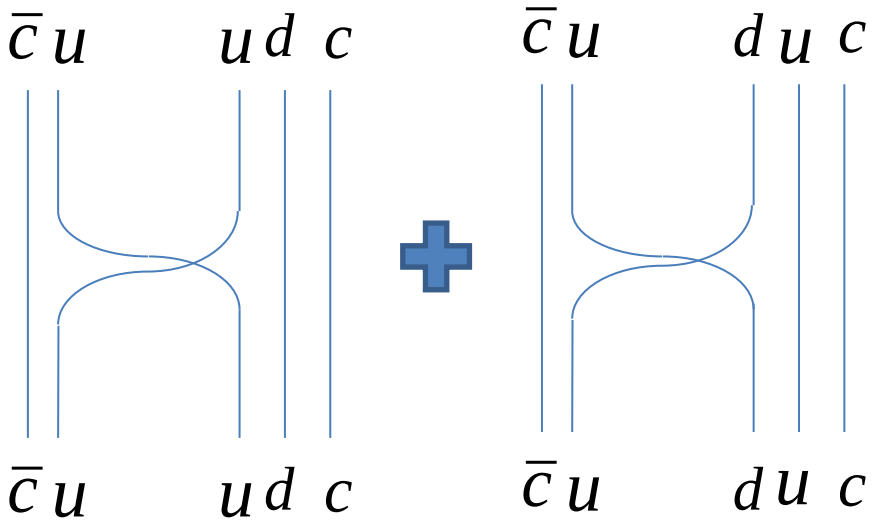
Have vanish contributions from strang light mesons!

Theoretical framework

T_{cc}



P_c



S-wave interaction:

$$\mathcal{L} = g_s \bar{q} \mathcal{S} q + g_a \bar{q} \gamma_\mu \gamma^5 \mathcal{A}^\mu q, \qquad q = (u, d, s)$$

$$\mathcal{S} = \mathcal{S}_3 \lambda^i + \mathcal{S}_1 \lambda^8,$$
$$\mathcal{A}^\mu = \mathcal{A}_3^\mu \lambda^i + \mathcal{A}_1^\mu \lambda^8,$$

$$V_{qq} = \tilde{g}_s \left(\lambda_1^8 \lambda_2^8 + \lambda_1^i \lambda_2^i\right) + \tilde{g}_a \left(\lambda_1^8 \lambda_2^8 + \lambda_1^i \lambda_2^i\right) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2.$$

$$V_{[H_1 H_2]_J^I} = \left\langle [H_1 H_2]_J^I \left| V_{qq} \right| [H_1 H_2]_J^I \right\rangle$$

Solvable Lippmann-Schwinger equation (LSE)

$$V(p,p') = V_{[H_1 H_2]^I_J}\,\Theta(\Lambda - p)\,\Theta(\Lambda - p')$$

$$T(p',p) = V(p',p) + \int \frac{d^3q}{(2\pi)^3}\,\frac{V(p',q)T(q,p)}{E - q^2/2m_\mu + i\varepsilon}$$

$$T(p',p) = \beta(E)\Theta(\Lambda - p')\Theta(\Lambda - p)$$

$$\beta(E) = \frac{V_{[H_1 H_2]^I_J}}{1 - V_{[H_1 H_2]^I_J} G}$$

$$G = \frac{m_\mu}{\pi^2}\left[-\Lambda + k\tan^{-1}\left(\frac{\Lambda}{k}\right)\right] \qquad k = \sqrt{-2m_\mu E}$$

Theoretical framework

$$V_{qq} = \tilde{g}_s \left(\lambda_1^8 \lambda_2^8 + \lambda_1^i \lambda_2^i\right) + \tilde{g}_a \left(\lambda_1^8 \lambda_2^8 + \lambda_1^i \lambda_2^i\right) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

Potentials:	Assignments:
$V_{P_c}(4312) = -\frac{10}{3}\tilde{g}_s$	$[\Sigma_c \bar{D}]^{1/2}_{1/2}$
$V_{P_c}(4440) = -\frac{10}{3}\tilde{g}_s + \frac{40}{9}\tilde{g}_a$	$[\Sigma_c \bar{D}^*]^{1/2}_{1/2}$
$V_{P_c}(4457) = -\frac{10}{3}\tilde{g}_s - \frac{20}{9}\tilde{g}_a$	$[\Sigma_c \bar{D}^*]^{1/2}_{3/2}$

Three solved parameters:

$\tilde{g}_s = 11.739$ GeV^{-2}

$\tilde{g}_a = -2.860$ GeV^{-2}

$\Lambda = 0.409$ GeV

Reproduce the experimental masses

	Mass (Expt.)	BE (Expt.)	Mass (Our)	BE (Our)
$T_{cc}(3875)^+$	3874.8	-1.0	3874.5	-1.8
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	-8.9 (input)	4311.9	-8.9
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	-6.2	4376.2	-9.1
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	-21.8 (input)	4440.2	-21.8
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	-4.8 (input)	4457.3	-4.8
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	-19.7	4468.1	-10.0

Give a good description to the masses of the observed states.

Neglect the corrections from the heavy degrees of freedom: fairly good approximation.

Interchange the assignments of Pc(4440) and Pc(4457) can not reproduce the masses of Tcc and Pcs.

Other predictions

System	$[\bar{D}^*\bar{D}^*]_1^0$	$[\Sigma_c^*\bar{D}^*]_{\frac{1}{2}}^{\frac{1}{2}}$	$[\Sigma_c^*\bar{D}^*]_{\frac{3}{2}}^{\frac{1}{2}}$	$[\Sigma_c^*\bar{D}^*]_{\frac{5}{2}}^{\frac{1}{2}}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}^0$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}^0$	$[\Xi_c'\bar{D}]_{\frac{1}{2}}^0$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}^0$
Mass	$4009.7^{+5.9}_{-2.6}$	$4501.3^{+15.7}_{-5.9}$	$4510.1^{+10.6}_{-4.2}$	$4523.8^{+2.7}_{-1.4}$	$4327.7^{+6.8}_{-2.8}$	$4468.1^{+7.3}_{-3.0}$	$4436.7^{+7.0}_{-2.9}$	$4564.9^{+14.1}_{-5.3}$
BE	$-7.4^{+5.9}_{-2.6}$	$-25.4^{+15.7}_{-5.9}$	$-15.9^{+10.6}_{-4.2}$	$-2.9^{+2.7}_{-1.4}$	$-8.9^{+6.8}_{-2.8}$	$-10.0^{+7.3}_{-3.0}$	$-9.4^{+7.0}_{-2.9}$	$-22.5^{+14.1}_{-5.3}$
System	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}^0$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}^0$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}^0$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}^0$	$[\Xi_c^*\bar{D}^*]_{\frac{5}{2}}^0$	$[\Sigma_c\Sigma_c]_0^0$	$[\Sigma_c\Sigma_c]_1^1$	$[\Sigma_c\Sigma_c^*]_1^0$
Mass	$4582.1^{+4.4}_{-1.9}$	$4503.6^{+7.1}_{-3.0}$	$4628.5^{+16.0}_{-6.0}$	$4638.0^{+11.0}_{-4.2}$	$4651.3^{+2.9}_{-1.4}$	$4825.4^{+43.1}_{-15.2}$	$4903.9^{+2.9}_{-1.5}$	$4894.3^{+41.0}_{-14.5}$
BE	$-5.2^{+4.4}_{-1.9}$	$-9.6^{+7.1}_{-3.0}$	$-26.0^{+16.0}_{-6.0}$	$-16.5^{+11.0}_{-4.2}$	$-3.2^{+2.9}_{-1.4}$	$-81.7^{+43.1}_{-15.2}$	$-3.2^{+2.9}_{-1.5}$	$-77.4^{+41.0}_{-14.5}$
System	$[\Sigma_c\Sigma_c^*]_2^0$	$[\Sigma_c\Sigma_c^*]_1^1$	$[\Sigma_c\Sigma_c^*]_2^1$	$[\Sigma_c^*\Sigma_c^*]_1^1$	$[\Sigma_c^*\Sigma_c^*]_3^1$	$[\Sigma_c^*\Sigma_c^*]_0^0$	$[\Sigma_c^*\Sigma_c^*]_2^0$	$[\Xi_c\Xi_c]_1^0$
Mass	$4931.9^{+22.6}_{-8.2}$	$4958.4^{+9.0}_{-3.5}$	$4969.3^{+2.2}_{-1.2}$	$5021.9^{+9.6}_{-3.8}$	$5035.1^{+*}_{-0.8}$	$4946.5^{+46.9}_{-16.5}$	$4996.1^{+22.8}_{-8.3}$	$4933.1^{+4.6}_{-2.1}$
BE	$-39.8^{+22.6}_{-8.2}$	$-13.3^{+9.0}_{-3.5}$	$-2.4^{+2.2}_{-1.2}$	$-14.4^{+9.6}_{-3.8}$	$-1.2^{+*}_{-0.8}$	$-89.8^{+46.9}_{-16.5}$	$-40.1^{+22.8}_{-8.3}$	$-5.8^{+4.6}_{-2.1}$
System	$[\Xi_c\Xi_c']_{0,1}^0$	$[\Xi_c\Xi_c^*]_{1,2}^0$	$[\Xi_c'\Xi_c']_1^0$	$[\Xi_c'\Xi_c^*]_1^0$	$[\Xi_c'\Xi_c^*]_2^0$	$[\Xi_c^*\Xi_c^*]_1^0$	$[\Xi_c^*\Xi_c^*]_3^0$	
Mass	$5042.1^{+4.9}_{-2.1}$	$5109.0^{+5.0}_{-2.1}$	$5153.6^{+3.4}_{-1.6}$	$5210.3^{+9.6}_{-3.7}$	$5221.7^{+2.8}_{-1.3}$	$5276.4^{+10.1}_{-3.9}$	$5290.3^{+0.0}_{-1.0}$	
BE	$-6.2^{+4.9}_{-2.1}$	$-6.4^{+5.0}_{-2.1}$	$-4.0^{+3.4}_{-1.6}$	$-14.4^{+9.6}_{-3.7}$	$-3.0^{+2.8}_{-1.3}$	$-15.6^{+10.1}_{-3.9}$	$-1.7^{+0.0}_{-1.0}$	

$$V_{qq} = \tilde{g}_s \left(\lambda_1^8\lambda_2^8 + \lambda_1^i\lambda_2^i\right) + \tilde{g}_a \left(\lambda_1^8\lambda_2^8 + \lambda_1^i\lambda_2^i\right) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

Isospin criterion: $\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 = 2\left[I(I+1) - I_1(I_1+1) - I_2(I_2+1)\right]$

Other predictions

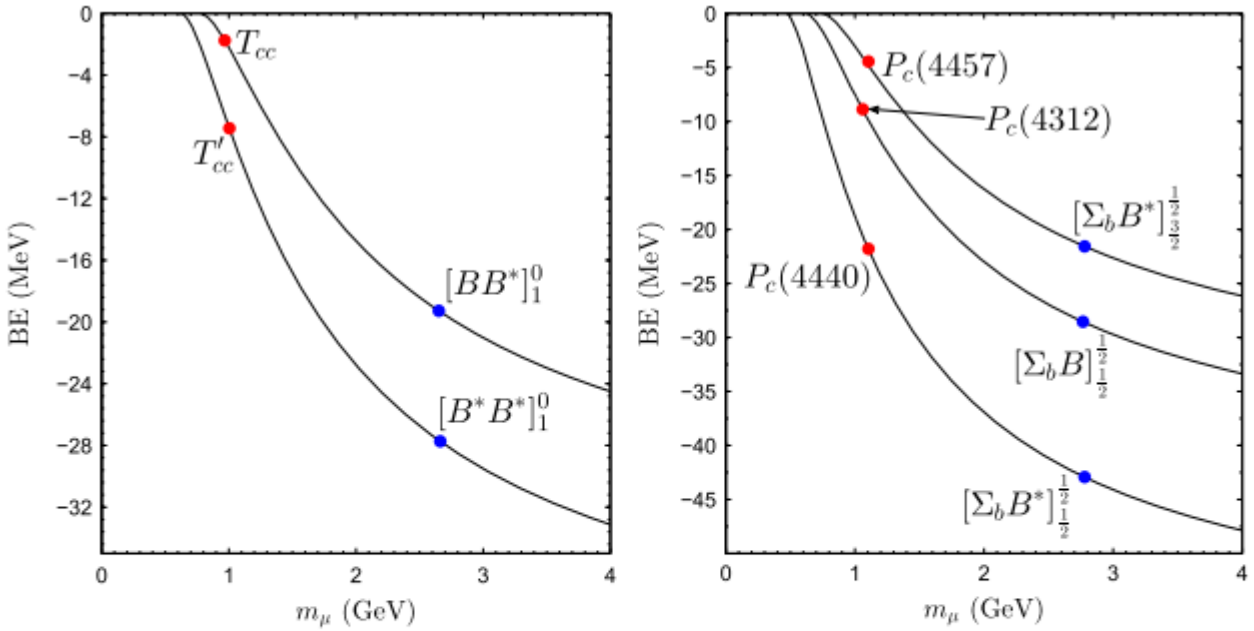


Fig. 1 The variation of binding energies for the T_{cc}^{+}, $T_{cc}^{\prime+}$, $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ states as their reduced masses increase. At $m_Q = m_b$, we have their bottom partners T_{bb}^{-}, $T_{bb}^{\prime-}$, $[\Sigma_b B]_{1/2}^{1/2}$, $[\Sigma_b B^*]_{1/2}^{1/2}$, and $[\Sigma_b B^*]_{3/2}^{1/2}$, respectively

Summary

- 1.Propose a toy model to understand the interactions of the Pc, Pcs, and Tcc states.
- 2.Reproduce the experimental masses of the observed molecular candidates.
- 3.Predict some molecules in M-M, M-B, and B-B systems.
- 4.Our model suggests an isospin criterion to the heavy flavor molecular states.


Thanks for your attention!