XVIII International Conference on Hadron Spectroscopy and Structure

Three pentaquark states or more?

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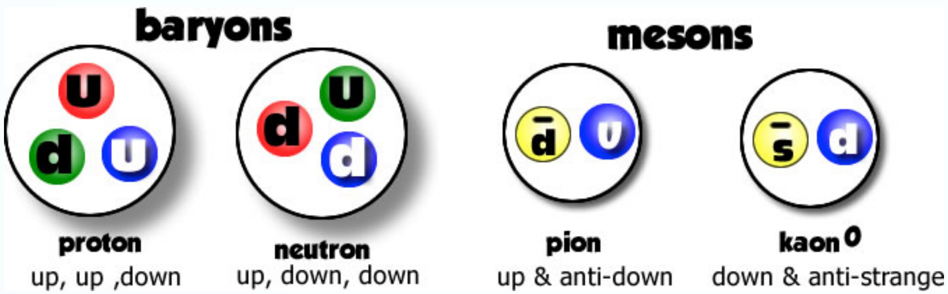
2019. Guilin

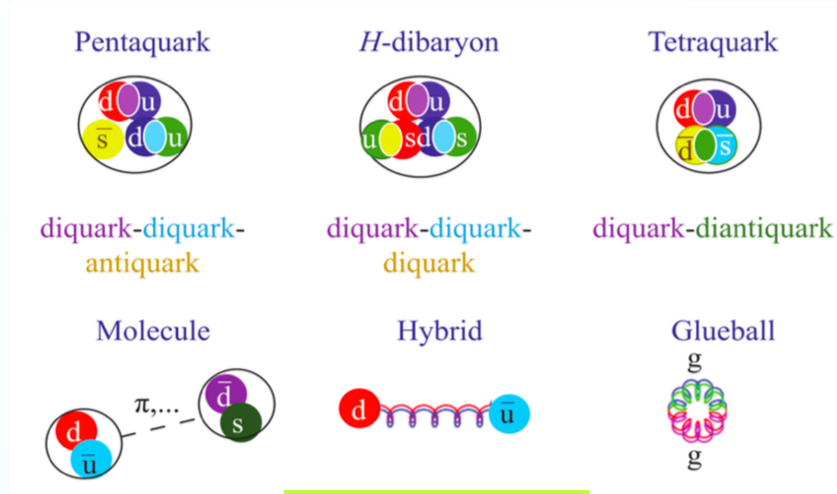
Outline

1. Introduction
2. Formalism
3. Results
4. Summary

§1. Introduction

Quark model





Exotic States

H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, **Phys. Rept. 639** (2016) 1.

A. Esposito, A. Pilloni and A. D. Polosa, **Phys. Rept. 668** (2016) 1.

F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, **Rev. Mod. Phys. 90** (2018) 0115004.

S. L. Olsen, T. Skwarnicki and D. Zieminska, **Rev. Mod. Phys. 90** (2018) 0115003.

Pentaquark

$\Theta^+(1540)$ ✗

Pridictions

PRL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

Jia-Jun Wu,[1,2] R. Molina,[2,3] E. Oset,[2,3] and B. S. Zou[1,3]

J. J. Wu, R. Molina, E. Oset and B. S. Zou, **Phys. Rev. Lett. 105** (2010) 232001.

J. J. Wu, R. Molina, E. Oset and B. S. Zou, **Phys. Rev. C 84** (2011) 015202.

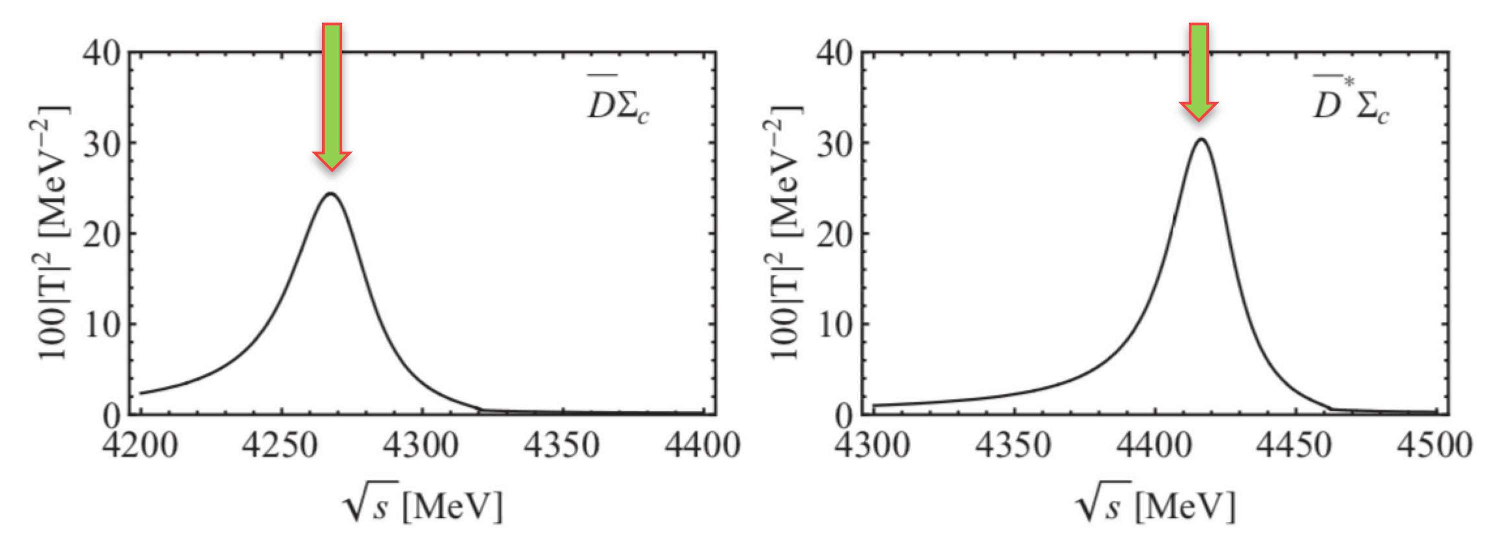
W. L. Wang, F. Huang, Z. Y. Zhang and B. S. Zou, **Phys. Rev. C 84** (2011) 015203.

Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, **Chin. Phys. C 36** (2012) 6.

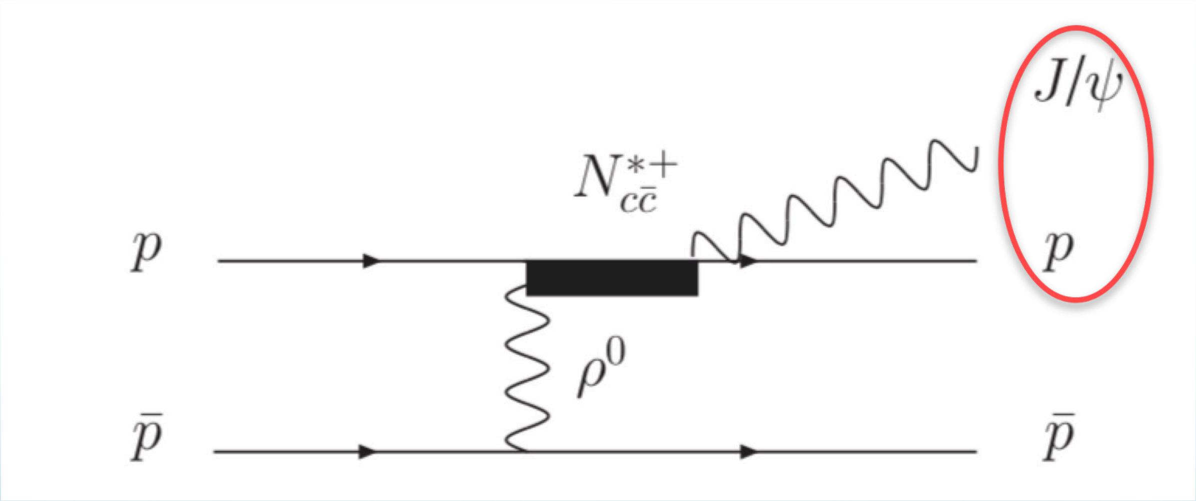
J. J. Wu, T.-S. H. Lee and B. S. Zou, **Phys. Rev. C 85** (2012) 044002.

C. Garcia-Recio, J. Nieves, O. Romanets, L. L. Salcedo and L. Tolos, **Phys. Rev. D 87** (2013) 074034.

*CWX, J. Nieves and E. Oset, **Phys. Rev. D 88** (2013) 056012.*

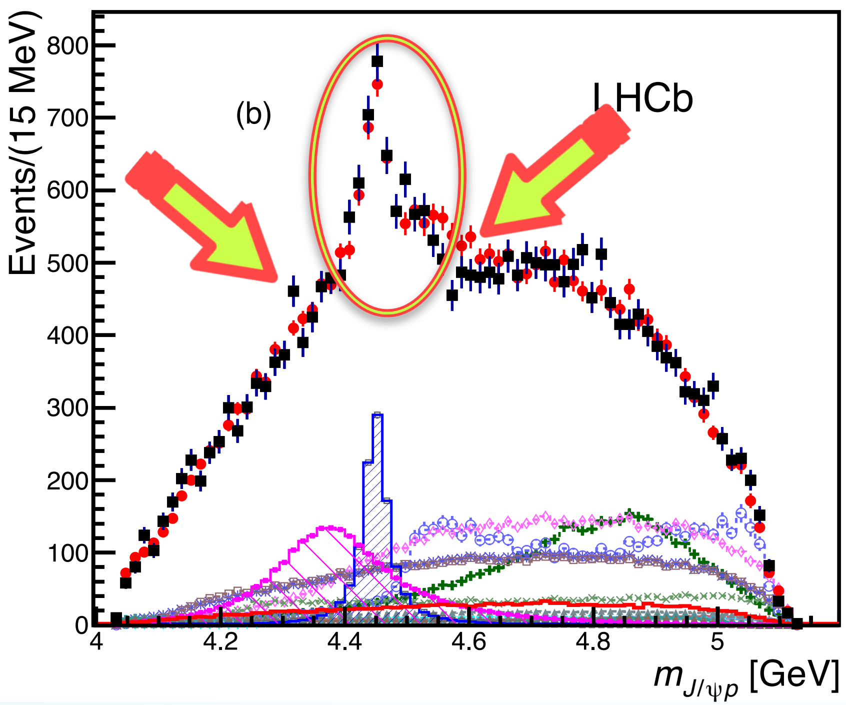


J. J. Wu, R. Molina, E. Oset, and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010)



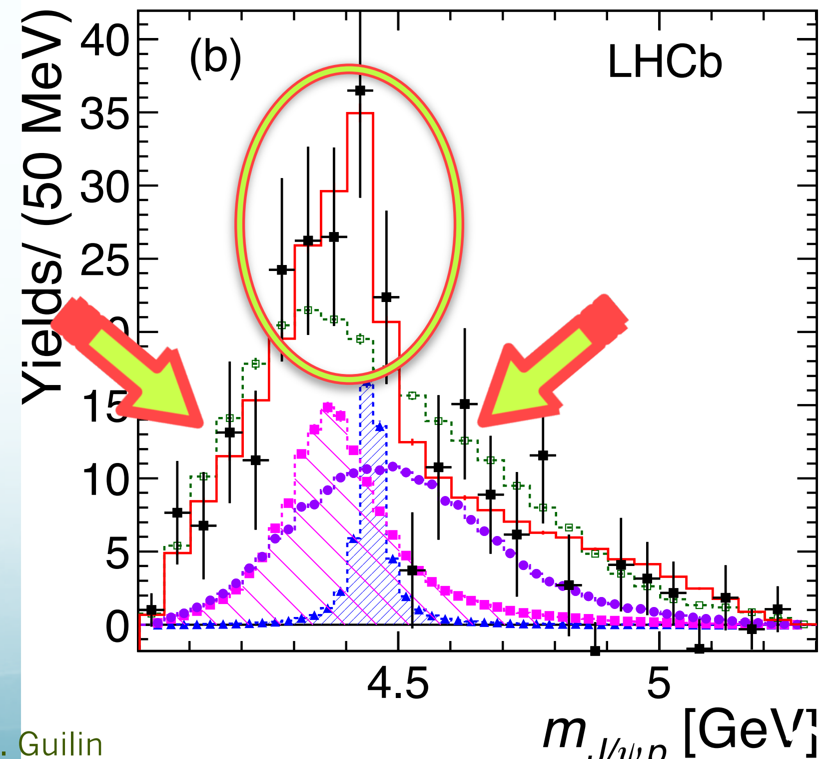
J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C 84 (2011) 015202

First Experimental Findings



R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 115, 072001 (2015)

R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 117, 082003 (2016)



$$P_c(4380)^+, \Gamma = 205$$

$$P_c(4450)^+, \Gamma = 39$$

J^P ?

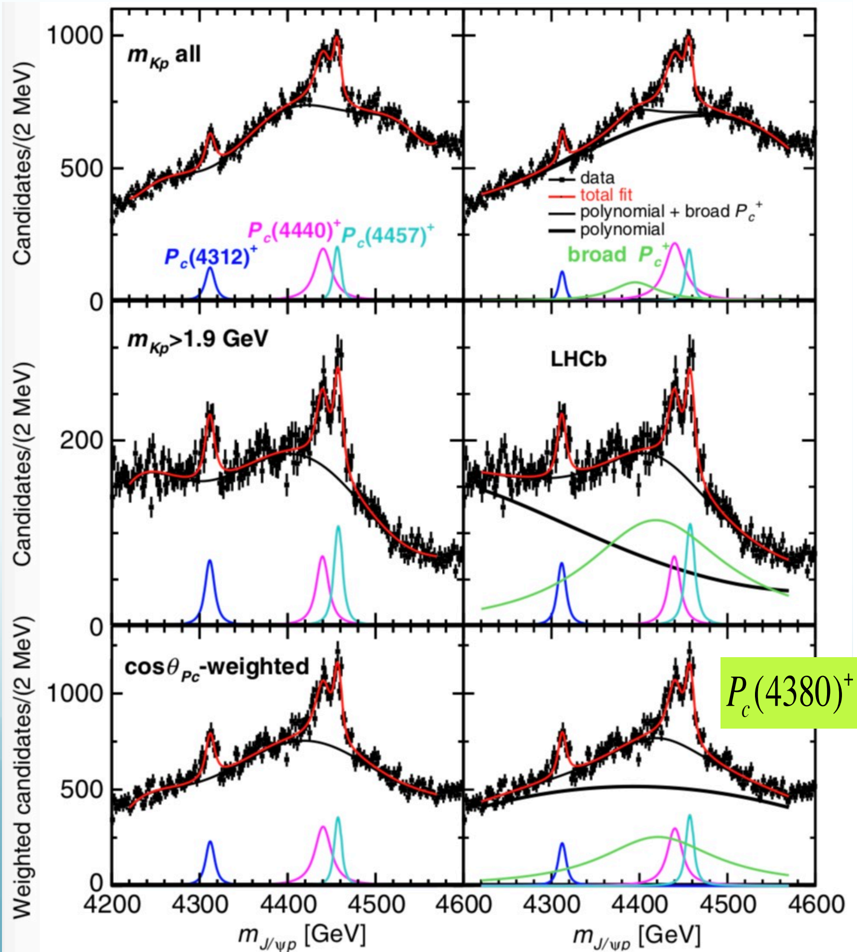
New Experimental Results

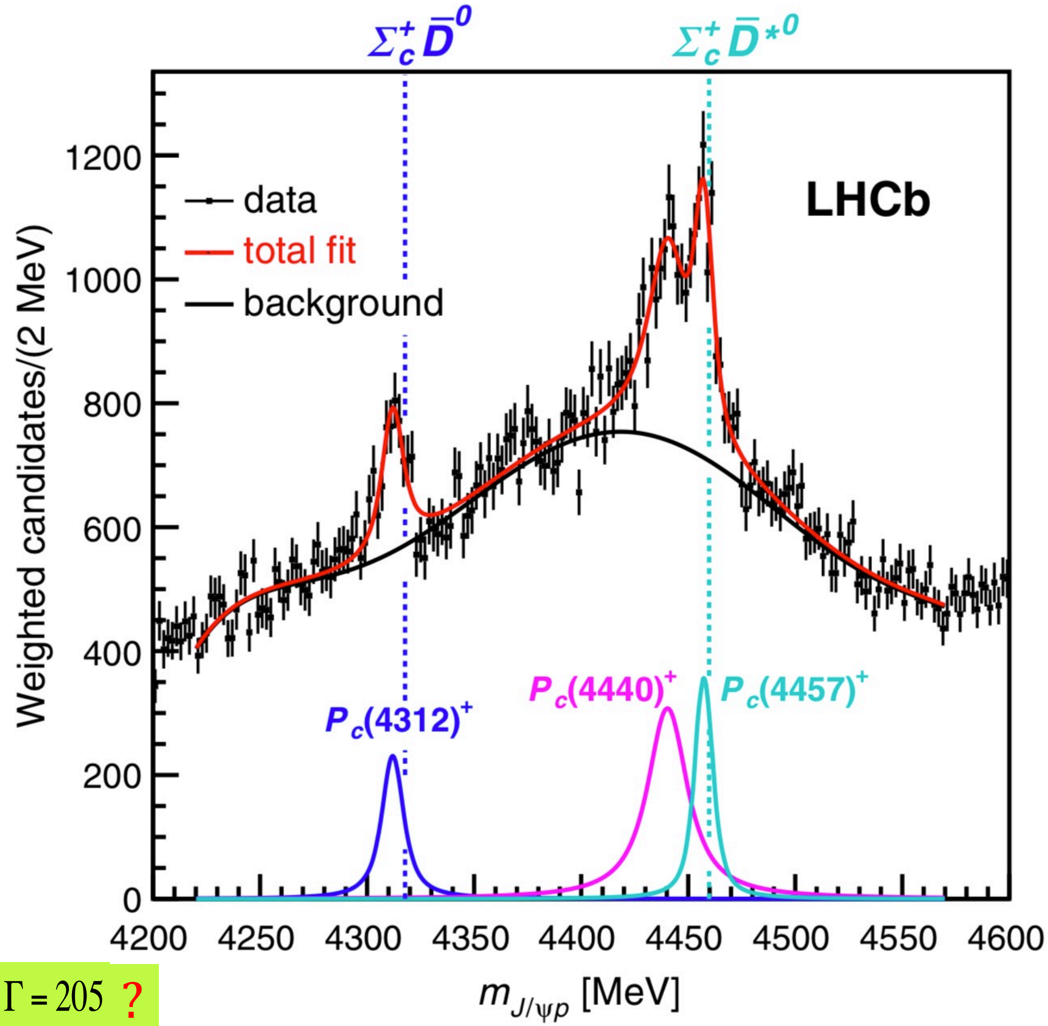
PHYSICAL REVIEW LETTERS **122,** 222001 (2019)

Featured in Physics

Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

R. Aaij *et al.*[*]
(LHCb Collaboration)





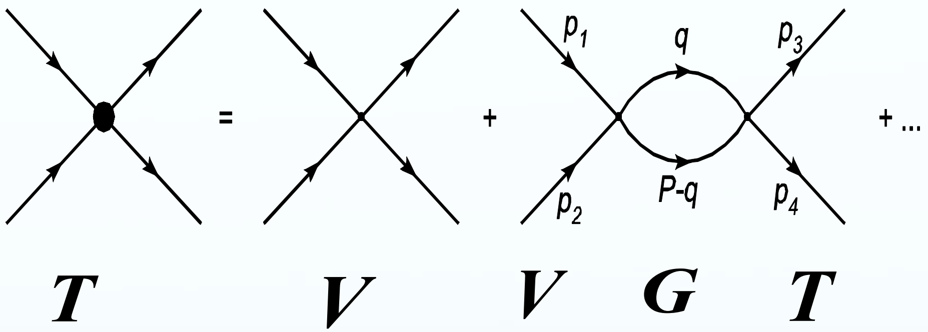
$P_c(4380)^+, \Gamma = 205$?

$$M_{P_{c1}} = 4311.9 \pm 0.7^{+6.8}_{-0.6}, \quad \Gamma_{P_{c1}} = 9.8 \pm 2.7^{+3.7}_{-4.5},$$
$$M_{P_{c2}} = 4440.3 \pm 1.3^{+4.1}_{-4.7}, \quad \Gamma_{P_{c2}} = 20.6 \pm 4.9^{+8.7}_{-10.1},$$
$$M_{P_{c3}} = 4457.3 \pm 0.6^{+4.1}_{-1.7}, \quad \Gamma_{P_{c3}} = 6.4 \pm 2.0^{+5.7}_{-1.9}.$$

§2. Formalism

- Chiral Unitary Approach (ChUA)：coupled channel approach, solving Bethe-Salpeter (BS) equations, which take on-shell approximation to loops.

$$T = V + V\,G\,T, \; T = [1 - V\,G]^{-1}\,V$$



where V matrix (potentials) can be evaluated from chiral Lagrangians.

J. A. Oller and E. Oset, Nucl. Phys. A 620 (1997) 438
E. Oset and A. Ramos, Nucl. Phys. A 635 (1998) 99
J. A. Oller and U. G. Meißner, Phys. Lett. B 500 (2001) 263

G is a diagonal matrix with the loop functions of each channels:

$$G_{ll}(s) = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(P-q)^2 - m_{l1}^2 + i\varepsilon} \frac{1}{q^2 - m_{l2}^2 + i\varepsilon}$$

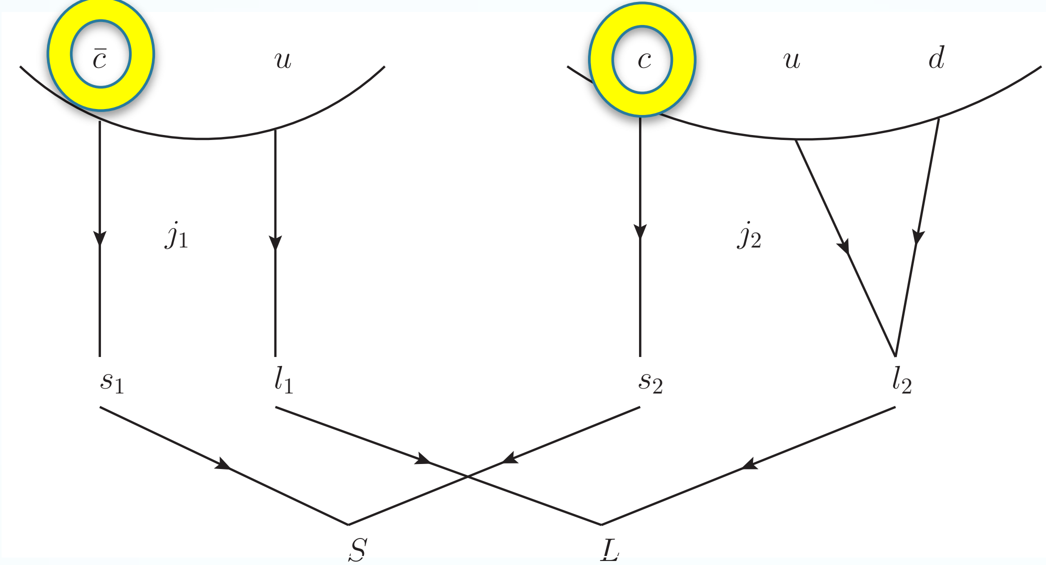
The coupled channel scattering amplitudes **T matrix satisfy the unitary** :

$$\mathrm{Im}\, T_{ij} = T_{in}\, \sigma_{nn}\, T_{nj}^*$$

$$\sigma_{nn} \equiv \mathrm{Im}\, G_{nn} = -\frac{q_{cm}}{8\pi\sqrt{s}} \theta(s - (m_1 + m_2)^2))$$

To search the poles of the resonances, we should extrapolate the scattering amplitudes to the second Riemann sheets:

$$G_{ll}^{II}(s) = G_{ll}^{I}(s) + i \frac{q_{cm}}{4\pi\sqrt{s}}$$



Considering the heavy quark spin-flavor symmetry

$\bar{D} \rightarrow \bar{D}^*$ $\quad \Sigma_c \rightarrow \Sigma_c^*$

$\bar{c}$-quark $\rightarrow$ $\bar{b}$-quark

$\bar{D} \rightarrow B$

$$_{(\ell'_M,\ell'_B)}\langle S'_{c\bar{c}}, \mathcal{L}'; J', \alpha' | H^{QCD} | S_{c\bar{c}}, \mathcal{L}; J, \alpha \rangle_{(\ell_M,\ell_B)}$$
$$= \delta_{\alpha\alpha'}\delta_{JJ'}\delta_{S'_{c\bar{c}}S_{c\bar{c}}}\delta_{\mathcal{L}\mathcal{L}'}\langle \ell'_M \ell'_B \mathcal{L}; \alpha || H^{QCD} || \ell_M \ell_B \mathcal{L}; \alpha \rangle$$

$$|l_1 s_1 j_1; l_2 s_2 j_2; JM\rangle = \sum_{S,L}[(2S+1)(2L+1)(2j_1+1)(2j_2+1)]^{1/2} \begin{Bmatrix} l_1 & l_2 & L \\ s_1 & s_2 & S \\ j_1 & j_2 & J \end{Bmatrix} |l_1 l_2 L; s_1 s_2 S; JM\rangle$$

$$|\bar{D}\Sigma_c\rangle = \frac{1}{2}\left| S_{c\bar{c}} = 0, \mathcal{L} = \frac{1}{2}; J = \frac{1}{2}\right\rangle_{(\ell_M=1/2,\ell_B=1)} - \frac{1}{2\sqrt{3}}\left| S_{c\bar{c}} = 1, \mathcal{L} = \frac{1}{2}; J = \frac{1}{2}\right\rangle_{(\ell_M=1/2,\ell_B=1)}$$
$$+ \sqrt{\frac{2}{3}}\left| S_{c\bar{c}} = 1, \mathcal{L} = \frac{3}{2}; J = \frac{1}{2}\right\rangle_{(\ell_M=1/2,\ell_B=1)},$$

Defined LECs:

$$\mu_1^\alpha = \left\langle \ell'_M = 0, \ell'_B = \frac{1}{2}, \mathcal{L} = 1/2; \alpha \| H^{\rm QCD} \| \ell_M = 0, \ell_B = \frac{1}{2}, \mathcal{L} = 1/2; \alpha \right\rangle,$$

$$\mu_2^\alpha = \langle \ell'_M = 1/2, \ell'_B = 0, \mathcal{L} = 1/2; \alpha \| H^{\rm QCD} \| \ell_M = 1/2, \ell_B = 0, \mathcal{L} = 1/2; \alpha \rangle,$$

$$\mu_3^\alpha = \langle \ell'_M = 1/2, \ell'_B = 1, \mathcal{L} = 1/2; \alpha \| H^{\rm QCD} \| \ell_M = 1/2, \ell_B = 1, \mathcal{L} = 1/2; \alpha \rangle,$$

$$\mu_{12}^\alpha = \left\langle \ell'_M = 0, \ell'_B = \frac{1}{2}, \mathcal{L} = 1/2; \alpha \| H^{\rm QCD} \| \ell_M = 1/2, \ell_B = 0, \mathcal{L} = 1/2; \alpha \right\rangle,$$

$$\mu_{13}^\alpha = \left\langle \ell'_M = 0, \ell'_B = \frac{1}{2}, \mathcal{L} = 1/2; \alpha \| H^{\rm QCD} \| \ell_M = 1/2, \ell_B = 1, \mathcal{L} = 1/2; \alpha \right\rangle,$$

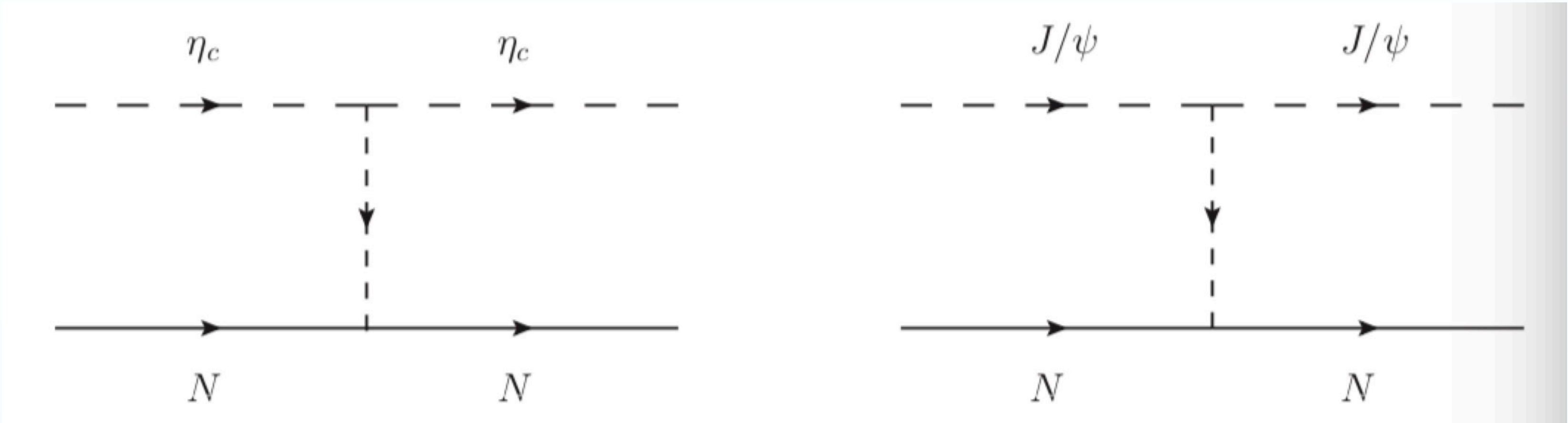
$$\mu_{23}^\alpha = \langle \ell'_M = 1/2, \ell'_B = 0, \mathcal{L} = 1/2; \alpha \| H^{\rm QCD} \| \ell_M = 1/2, \ell_B = 1, \mathcal{L} = 1/2; \alpha \rangle.$$

$J = 1/2, I = 1/2$

$$
\begin{array}{ccccccc}
\eta_c N & J_\Psi N & \bar{D}\Lambda_c & \bar{D}\Sigma_c & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c & \bar{D}^*\Sigma_c^*
\end{array}
$$

$$
\begin{pmatrix}
\mu_1 & 0 & \frac{\mu_{12}}{2} & \frac{\mu_{13}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{13} \\
0 & \mu_1 & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & -\frac{\mu_{12}}{2} & \frac{5\mu_{13}}{6} & \frac{\sqrt{2}\mu_{13}}{3} \\
\frac{\mu_{12}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & \mu_2 & 0 & 0 & \frac{\mu_{23}}{\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{23} \\
\frac{\mu_{13}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & 0 & \frac{1}{3}(2\lambda_2 + \mu_3) & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2-\mu_3)}{3\sqrt{3}} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3 - \lambda_2) \\
\frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{12}}{2} & 0 & \frac{\mu_{23}}{\sqrt{3}} & \mu_2 & -\frac{2\mu_{23}}{3} & \frac{\sqrt{2}\mu_{23}}{3} \\
-\frac{\mu_{13}}{2\sqrt{3}} & \frac{5\mu_{13}}{6} & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2-\mu_3)}{3\sqrt{3}} & -\frac{2\mu_{23}}{3} & \frac{1}{9}(2\lambda_2 + 7\mu_3) & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) \\
\sqrt{\frac{2}{3}}\mu_{13} & \frac{\sqrt{2}\mu_{13}}{3} & \sqrt{\frac{2}{3}}\mu_{23} & \frac{1}{3}\sqrt{\frac{2}{3}}(\mu_3 - \lambda_2) & \frac{\sqrt{2}\mu_{23}}{3} & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) & \frac{1}{9}(\lambda_2 + 8\mu_3)
\end{pmatrix}_{I=1/2}
$$

$$\mathcal{L}_{VVV} = ig \langle [V_\nu, \partial_\mu V_\nu] V^\mu \rangle,$$
$$\mathcal{L}_{PPV} = -ig \langle [P, \partial_\mu P] V^\mu \rangle,$$
$$\mathcal{L}_{BBV} = g \left(\langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle \right)$$

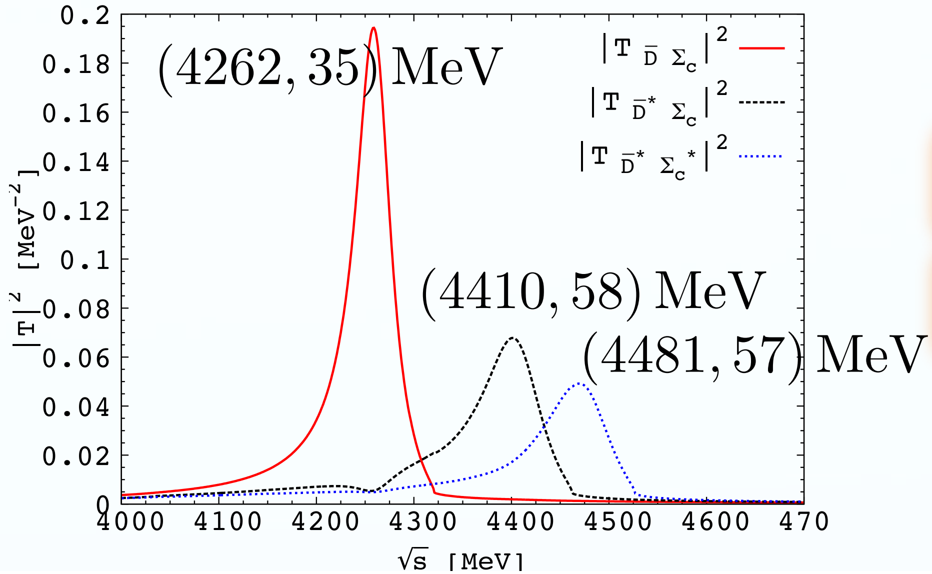


$J = 1/2, I = 1/2$

$$\mu_2 = \frac{1}{4f^2}(k^0 + k'^0), \qquad \mu_3 = -\frac{1}{4f^2}(k^0 + k'^0),$$
$$\mu_{12} = -\sqrt{6}\frac{m_\rho^2}{p_{D^*}^2 - m_{D^*}^2}\frac{1}{4f^2}(k^0 + k'^0), \qquad \mu_1 = 0,$$
$$\mu_{23} = 0, \qquad \lambda_2 = \mu_3, \qquad \mu_{13} = -\mu_{12}.$$

§3. Results

$J = 1/2, I = 1/2$

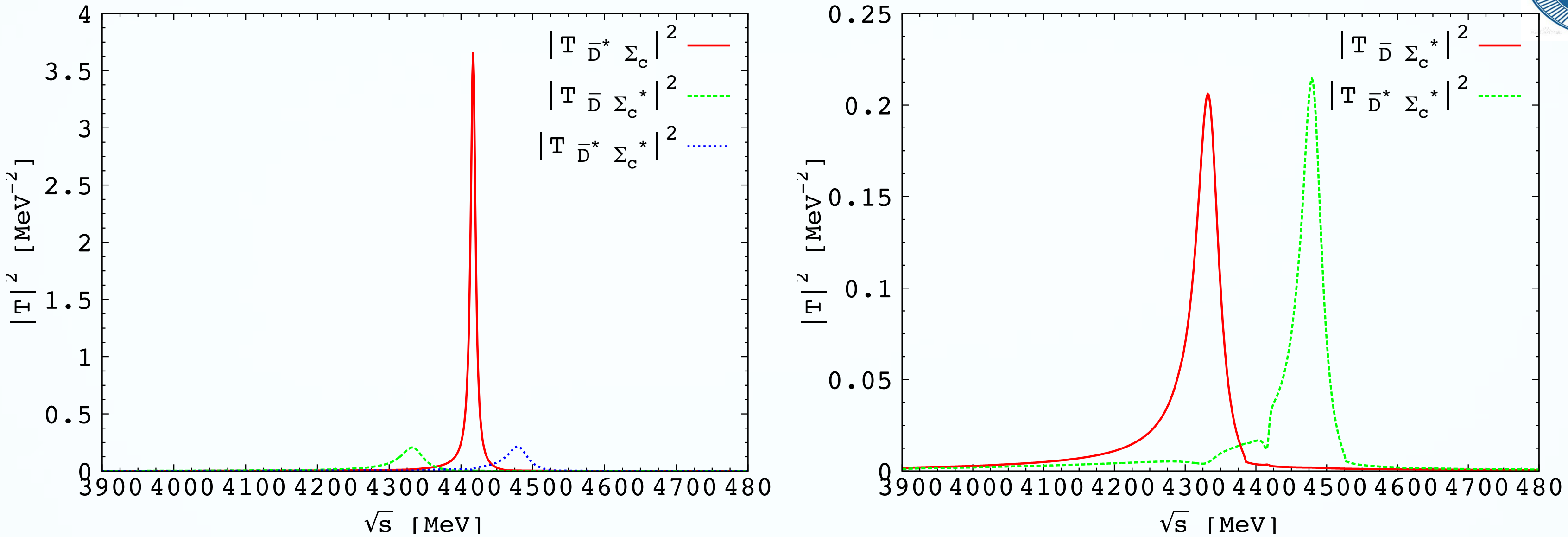


$\mu = 1000$ MeV

$a(\mu) = -2.3$

4261.87 + i17.84							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	1.04 + i0.05	0.76 − i0.08	0.02 − i0.02	**3.12 − i0.25**	0.14 − i0.48	0.33 − i0.68	0.16 − i0.28
$\|g_i\|$	**1.05**	**0.76**	0.02	**3.13**	0.50	0.75	0.32
4410.13 + i29.44							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	0.34 + i0.16	1.43 − 0.12	0.15 − i0.10	0.20 − i0.05	0.17 − i0.11	**3.05 − i0.54**	0.07 − i0.51
$\|g_i\|$	**0.38**	**1.44**	0.18	0.20	0.20	**3.10**	0.51
4481.35 + i28.91							
	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	1.15 − i0.04	0.72 + i0.03	0.18 − i0.08	0.10 − i0.03	0.09 − i0.08	0.09 − i0.06	**2.88 − i0.57**
$\|g_i\|$	**1.15**	**0.72**	0.19	0.10	0.12	0.11	**2.93**

$J = 3/2, I = 1/2$



$4334.45 + i19.41$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.31 - i0.18$	$0.16 - i0.23$	$0.20 - i0.48$	$2.97 - i0.36$	$0.24 - i0.76$
$\|g_i\|$	1.32	0.28	0.52	2.99	0.80
$4417.04 + i4.11$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.53 - i0.07$	$0.08 - i0.07$	$2.81 - i0.07$	$0.12 - i0.10$	$0.11 - i0.51$
$\|g_i\|$	0.53	0.11	2.81	0.16	0.52
$4481.04 + i17.38$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.05 + i0.10$	$0.18 - i0.09$	$0.12 - i0.10$	$0.22 - i0.05$	$2.84 - i0.34$
$\|g_i\|$	1.05	0.20	0.16	0.22	2.86

CWX, J. Nieves and E. Oset, Phys. Rev. D 88, 056012 (2013)

The former exercises have shown that the changes produced by using different couplings obtained in other approaches to QCD, with a certain amount of SU(4) or HQSS breaking, induce changes of the order of 20–30 MeV in bindings estimated in our approach to be of the order of 50 MeV. These uncertainties are in line with other systematic uncertainties that we must also admit from our partial ignorance in the regularization scale of the loops. Yet, with all these uncertainties, the binding of the states remains a solid conclusion, as does the order of magnitude of the binding energies; the maximum one can hope without further experimental information to constrain the input in our theory.

$P_c(4312)^+$ $a(\mu = 1\,\mathrm{GeV}) = -2.09$

$4306.38 + i7.62$	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	$0.67 + i0.01$	$0.46 - i0.03$	$0.01 - i0.01$	$2.07 - i0.28$	$0.03 + i0.25$	$0.06 - i0.31$	$0.04 - i0.15$
$\lvert g_i \rvert$	0.67	0.46	0.01	2.09	0.25	0.31	0.16

$P_c(4440)^+$

$4452.96 + i11.72$	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	$0.24 + i0.03$	$0.88 - 0.11$	$0.09 - i0.06$	$0.12 - i0.02$	$0.11 - i0.09$	$1.97 - i0.52$	$0.02 + i0.19$
$\lvert g_i \rvert$	0.25	0.89	0.11	0.13	0.14	2.03	0.19

$4520.45 + i11.12$	$\eta_c N$	$J/\psi N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
g_i	$0.72 - i0.10$	$0.45 - i0.04$	$0.11 - i0.06$	$0.06 - i0.02$	$0.06 - i0.05$	$0.07 - i0.02$	$1.84 - i0.56$
$\lvert g_i \rvert$	0.73	0.45	0.13	0.06	0.08	0.08	1.92

$4261.87 + i17.84$
g_i
$\lvert g_i \rvert$
$4410.13 + i29.44$
g_i
$\lvert g_i \rvert$
$4481.35 + i28.91$
g_i
$\lvert g_i \rvert$

$a(\mu) = -2.3$

$4374.33 + i6.87$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
$P_c(4457)^+$	$0.73 - i0.06$	$0.11 - i0.13$	$0.02 - i0.19$	$1.91 - i0.31$	$0.03 - i0.30$
$\lvert g_i \rvert$	0.73	0.18	0.19	1.94	0.30
$4452.48 + i1.49$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.30 - i0.01$	$0.05 - i0.04$	$1.82 - i0.08$	$0.08 - i0.02$	$0.01 - i0.19$
$\lvert g_i \rvert$	0.30	0.07	1.82	0.08	0.19
$4519.01 + i6.86$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.66 - i0.01$	$0.11 - i0.07$	$0.10 - i0.3$	$0.13 - i0.02$	$1.79 - i0.36$
$\lvert g_i \rvert$	0.66	0.13	0.10	0.13	1.82

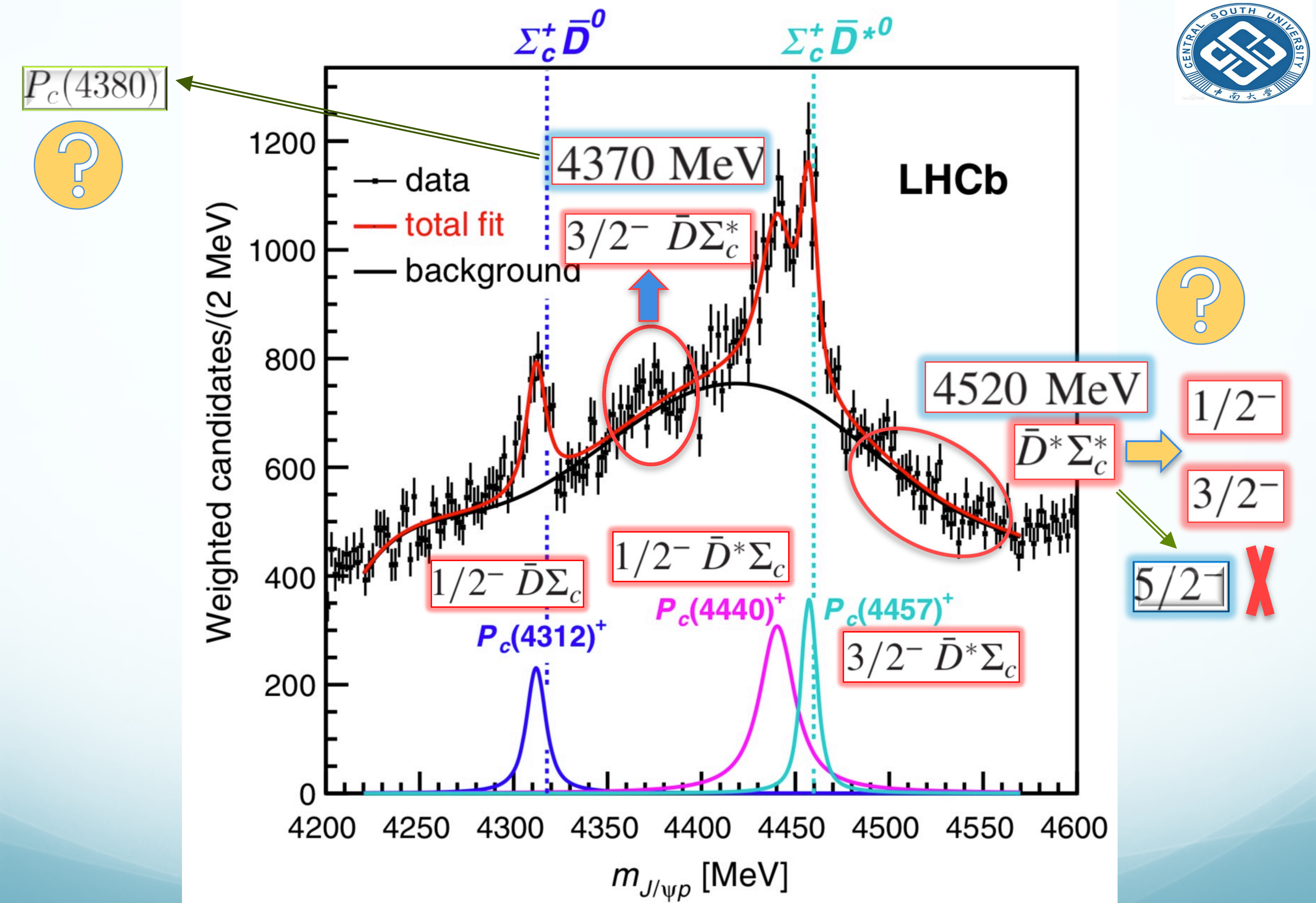
$4334.45 + i19.41$
g_i
$\lvert g_i \rvert$
$4417.04 + i4.11$
g_i
$\lvert g_i \rvert$
$4481.04 + i17.38$
g_i
$\lvert g_i \rvert$

states [MeV]	Widths [MeV]	Main channel	J^P	Experimental state
4306.4	15.2	$\bar{D}\Sigma_c$	$1/2^-$	$P_c(4312)$
4452.9	23.4	$\bar{D}^*\Sigma_c$	$1/2^-$	$P_c(4440)$
4452.5	3.0	$\bar{D}^*\Sigma_c$	$3/2^-$	$P_c(4457)$

M. Z. Liu, Y. W. Pan, F. Z. Peng, M. S. Sanchez, L. S. Geng, A. Hosaka, and M. P. Valderrama, Phys. Rev. Lett. 122 (2019) 242001

Next talk

$$M_{P_{c1}} = 4311.9 \pm 0.7^{+6.8}_{-0.6}, \quad \Gamma_{P_{c1}} = 9.8 \pm 2.7^{+3.7}_{-4.5},$$
$$M_{P_{c2}} = 4440.3 \pm 1.3^{+4.1}_{-4.7}, \quad \Gamma_{P_{c2}} = 20.6 \pm 4.9^{+8.7}_{-10.1},$$
$$M_{P_{c3}} = 4457.3 \pm 0.6^{+4.1}_{-1.7}, \quad \Gamma_{P_{c3}} = 6.4 \pm 2.0^{+5.7}_{-1.9}.$$



CWX, J. Nieves and E. Oset, Phys. Rev. D100 (2019) 014021

§4. Summary

- Our results of bound states ——molecular states

a $\bar{D}\Sigma_c$ state

Having $J = 1/2$. $P_c(4312)^+$

a $\bar{D}\Sigma_c^*$ state

With $J = 3/2$.

a $\bar{D}^*\Sigma_c$ state

Degenerate in $J = 1/2,\ 3/2$. $P_c(4440)^+$ $P_c(4457)^+$

a $\bar{D}^*\Sigma_c^*$ state

Degenerate in $J = 1/2,\ 3/2,\ 5/2$.

$P_c(4380)^+, \Gamma = 205$?

Hope that our predictions can be found in the future experiments!

谢谢大家！

Thanks for your attention!