第5届LHCb前沿物理研讨会

Study of multi-quark states with strangeness

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  Bing-Song Zou (邹冰松), Jia-Jun Wu (吴佳俊), Wei-Fei Wang (王文飞)

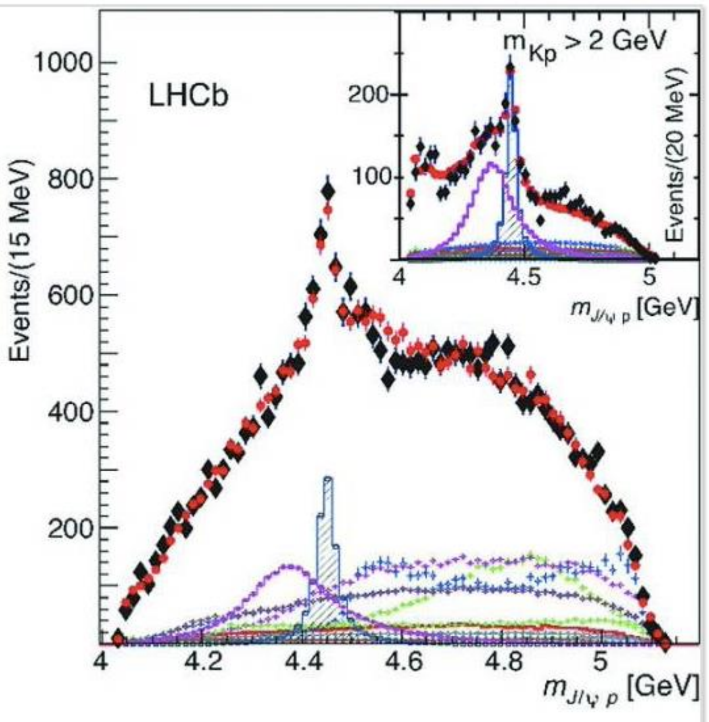
2025.4. 武汉

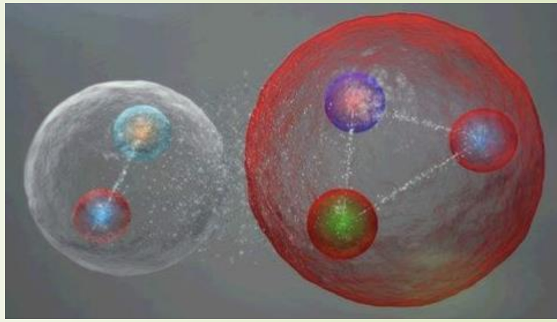
祝贺LHCb中国组！

2015年，两个Pc态的发现

十年再磨一剑

2025年，重子CPV的发现





$$\Lambda_b^0 \to pK^-\pi^+\pi^-$$

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

5.2σ

Outline

1. Introduction
2. Formalism
3. Pentaquark states P_{cs}
4. Tetraquark states
5. Summary

§1. Introduction

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

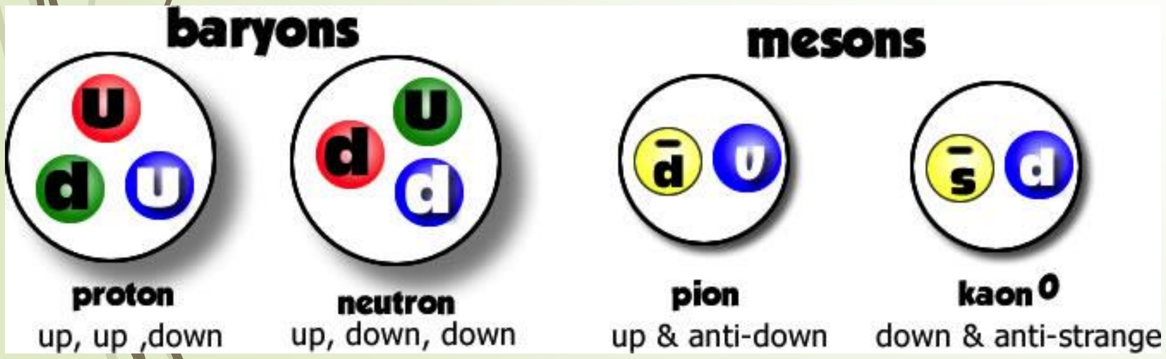
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

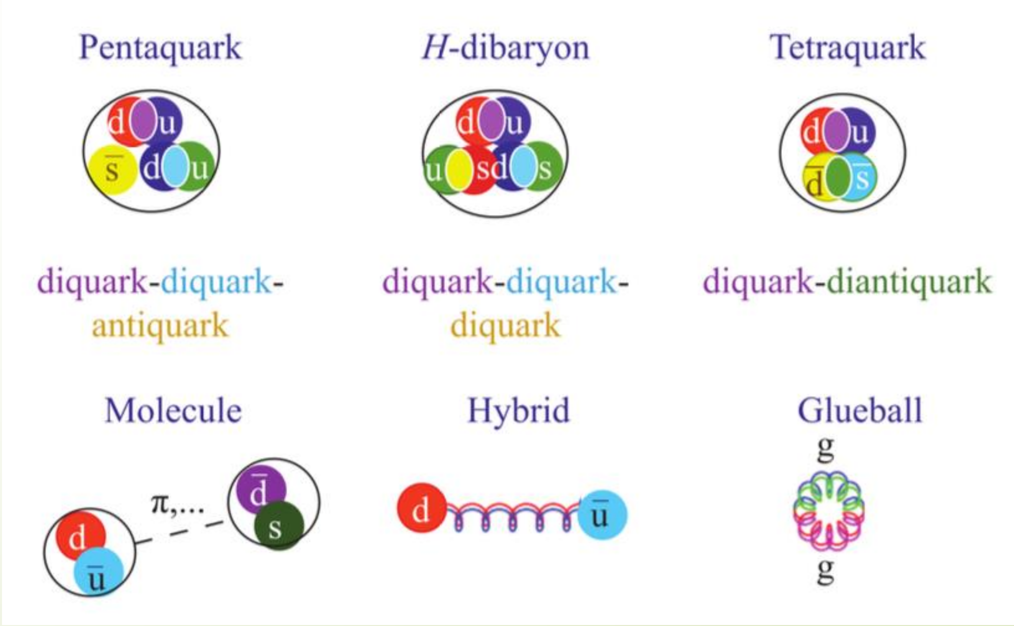
G. Zweig *)
CERN - Geneva

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Quark model

Exotic States



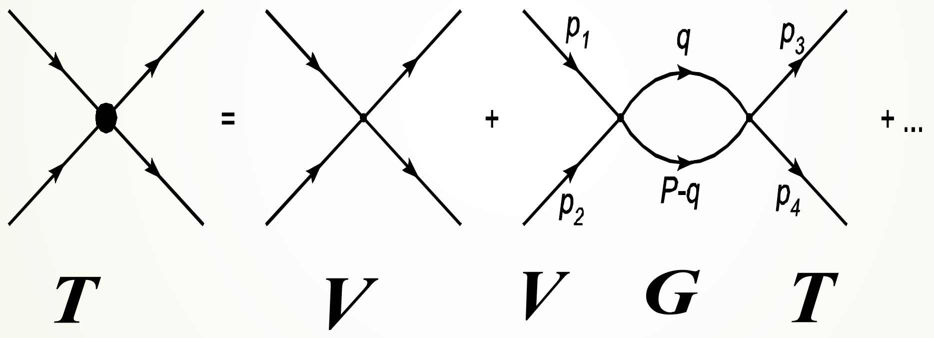


H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Phys. Rept. 639, 1 (2016)
A. Esposito, A. Pilloni and A. D. Polosa, Phys. Rept. 668, 1 (2016)
A. Hosaka, T. Iijima, K. Miyabayashi, Y. Sakai and S. Yasui, PTEP 2016, 062C01 (2016)
H. X. Chen, W. Chen, X. Liu, Y. R. Liu and S. L. Zhu, Rept. Prog. Phys. 80, 076201 (2017)
R. F. Lebed, R. E. Mitchell and E. S. Swanson, Prog. Part. Nucl. Phys. 93, 143 (2017)
A. Ali, J. S. Lange and S. Stone, Prog. Part. Nucl. Phys. 97, 123 (2017)
F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018)
R. A. Bricen˜o, J. J. Dudek and R. D. Young, Rev. Mod. Phys. 90, 025001 (2018)
S. L. Olsen, T. Skwarnicki and D. Zieminska, Rev. Mod. Phys. 90, 015003 (2018)
M. Karliner, J. L. Rosner and T. Skwarnicki, Ann. Rev. Nucl. Part. Sci. 68, 17 (2018)
C. Z. Yuan, Int. J. Mod. Phys. A 33,1830018 (2018)
Y. R. Liu, H. X. Chen, W. Chen, X. Liu and S. L. Zhu, Prog. Part. Nucl. Phys. 107, 237 (2019)
N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo and C. Z. Yuan, Phys. Rept. 873, 1 (2020)

§2. Formalism

- **Coupled Channel Unitary Approach**： solving Bethe-Salpeter equations, which take on-shell approximation for the loops.

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



D. L. Yao, L. Y. Dai, H. Q. Zheng and Z. Y. Zhou, Rept. Prog. Phys. 84, 076201 (2021)

where V matrix (potentials) can be evaluated from the interaction 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:

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

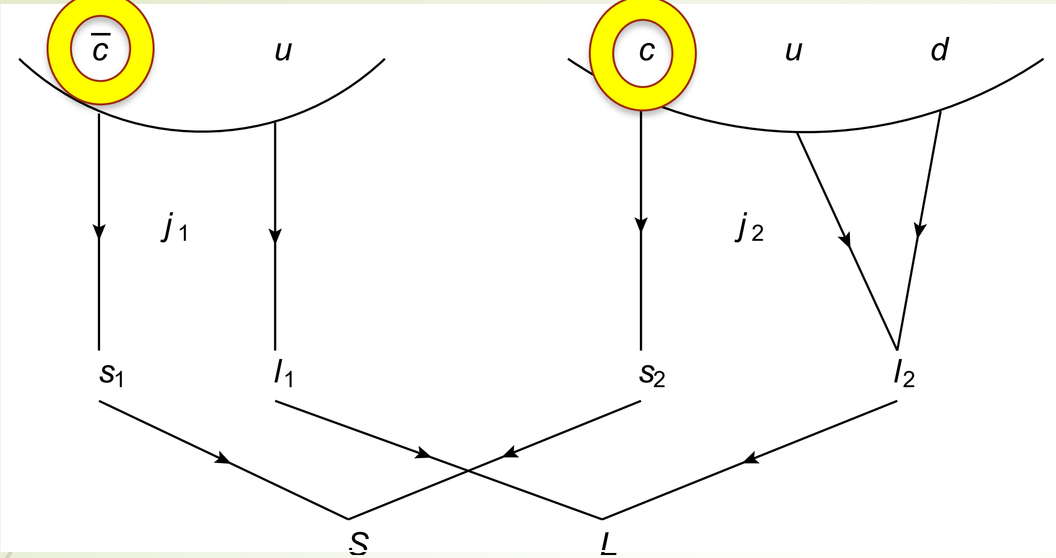
The coupled channel scattering amplitudes **T matrix satisfy the unitary** :

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

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

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 symmetry

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

$\Sigma_c \rightarrow \Sigma_c^*$

$\Xi_c \rightarrow \Xi_c^*$

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

$$|\ell_M s_M j_M S;\, \ell_B s_B j_B;\, J\rangle = \sum_{\mathcal{L}, S_{c\bar{c}}} [(2S_{c\bar{c}}+1)(2\mathcal{L}+1)(2j_M+1)(2j_B+1)]^{\frac{1}{2}} \times \begin{Bmatrix} \ell_M & \ell_B & \mathcal{L} \\ s_M & s_B & S_{c\bar{c}} \\ j_M & j_B & J \end{Bmatrix} |\mathcal{L} S_{c\bar{c}};\, J\rangle_{(\ell_M \ell_B S)}$$

§3. Pentaquark states

Pcs states

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.

H. X. Chen, L. S. Geng, W. H. Liang, E. Oset, E. Wang and J. J. Xie, **Phys. Rev. C 93** (2016) 065203.

R. Chen, J. He and X. Liu, **Chin. Phys. C 41** (2017) 103105.

E. Santopinto and A. Giachino, **Phys. Rev. D 96** (2017) 014014.

C. W. Shen, J. J. Wu and B. S. Zou, **Phys. Rev. D 100** (2019) 056006.

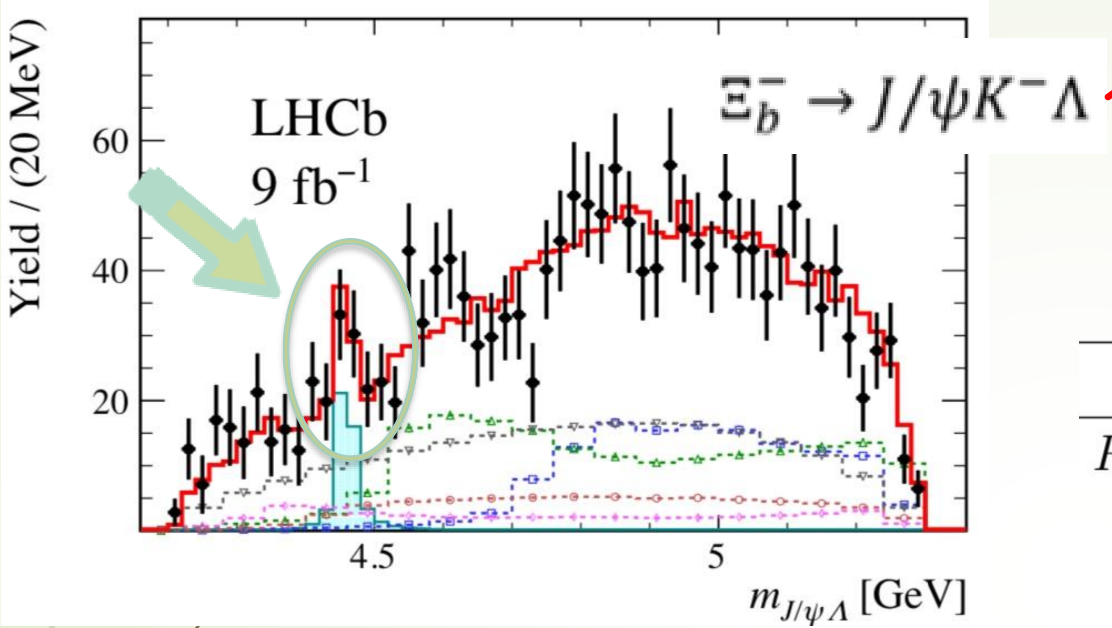
*CWX, J. Nieves and E. Oset, **Phys. Lett. B 799** (2019) 135051.*

B. Wang, L. Meng and S. L. Zhu, **Phys. Rev. D 101** (2020) 034018.

Bing-Song Zou, Sci. Bull 66, 1258 (2021)

Findings for the Pcs state

H.-X. Chen, L.-S. Geng, W.-H. Liang, E. Oset, E. Wang, J.-J. Xie, Phys. Rev. C 93 (2016) 065203

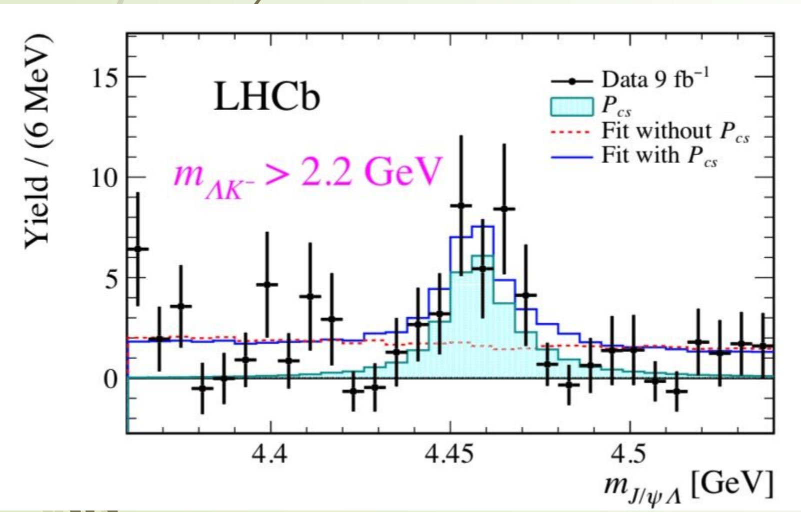


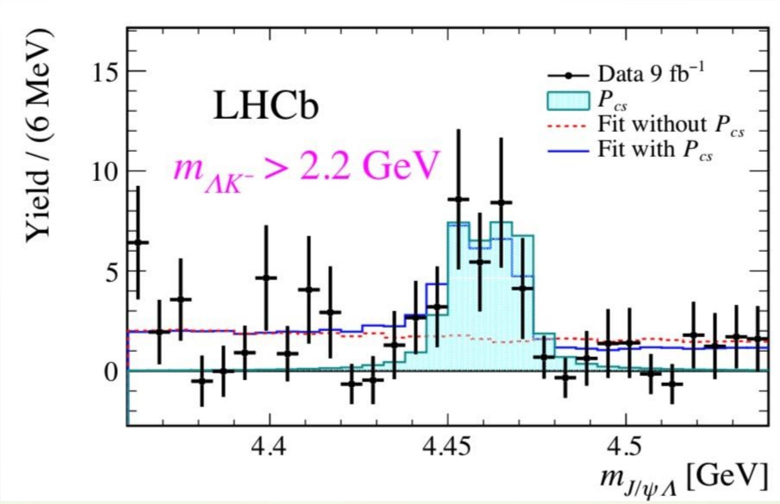
R. Aaij et al. (LHCb Collaboration), **Sci. Bull. 66** (2021) 1278-1287

State	M_0 [MeV]	Γ_0 [MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$

J^P ?

mass difference of about 6 MeV

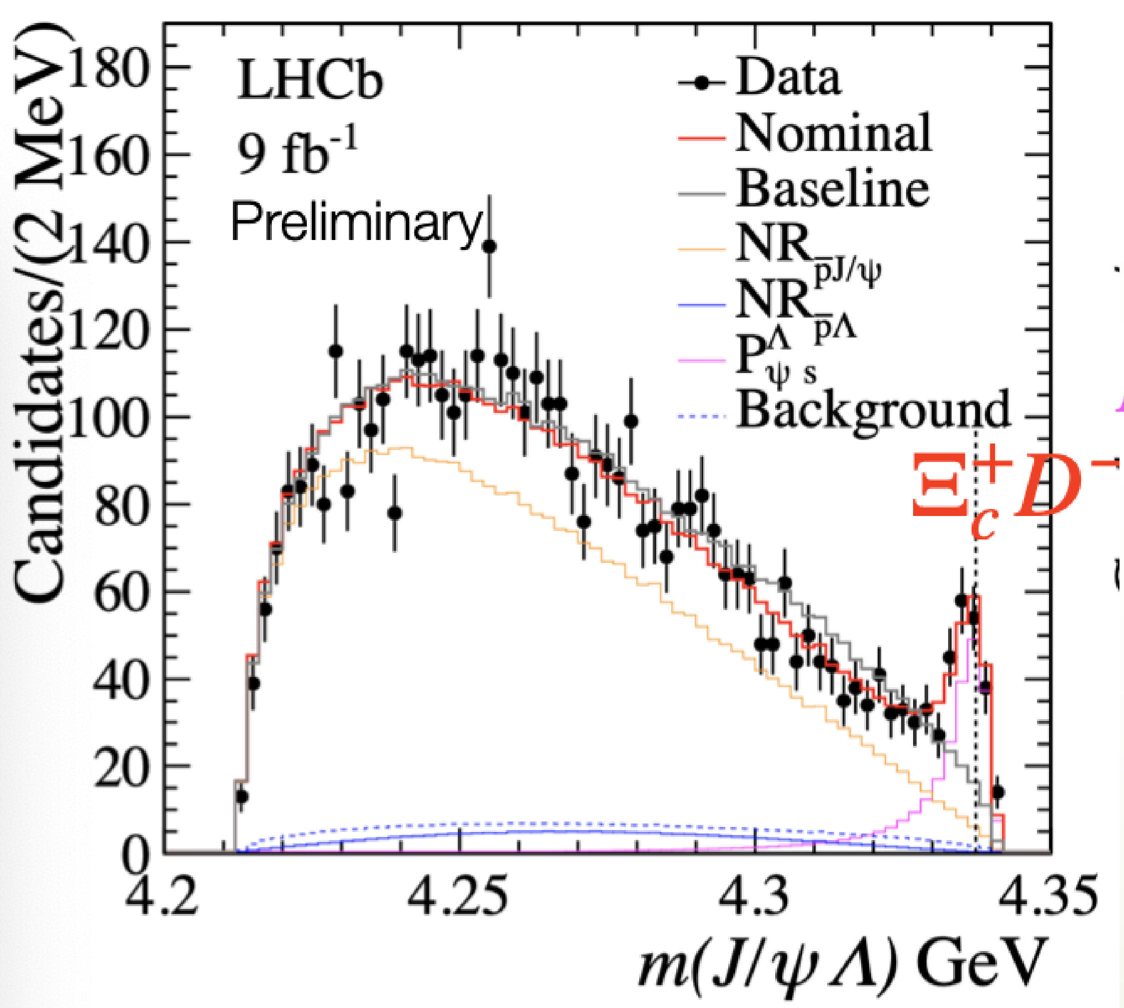




B. Wang, L. Meng and S. L. Zhu, **Phys. Rev. D 101** (2020) 034018.

The data cannot confirm or refute the two-peak hypothesis.

$B^- \to (J/\psi\Lambda)\bar{p}$



$m(P_{\psi s}^{\Lambda})$=4338.3±0.7±0.4 MeV

$\Gamma(P_{\psi s}^{\Lambda})$=7.0±1.2±1.3 MeV

$P_{\psi s}^{\Lambda}(4338)^0$

Significance: >10σ

LHCb, Phys. Rev. Lett. 131, 031901 (2023)

Recalling our prediction for Pcs

i) $J = 1/2,\ I = 0$

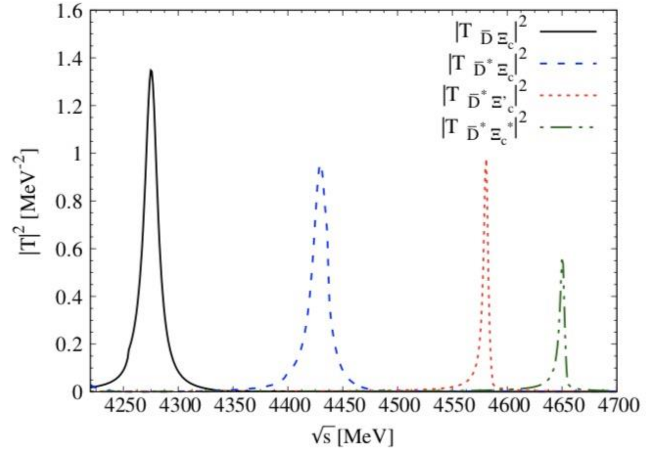
$\eta_c\Lambda,\ J/\psi\Lambda,\ \bar{D}\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}\Xi'_c,\ \bar{D}^*\Xi_c,\ \bar{D}^*_s\Lambda_c,\ \bar{D}^*\Xi'_c,\ \bar{D}^*\Xi^*_c.$

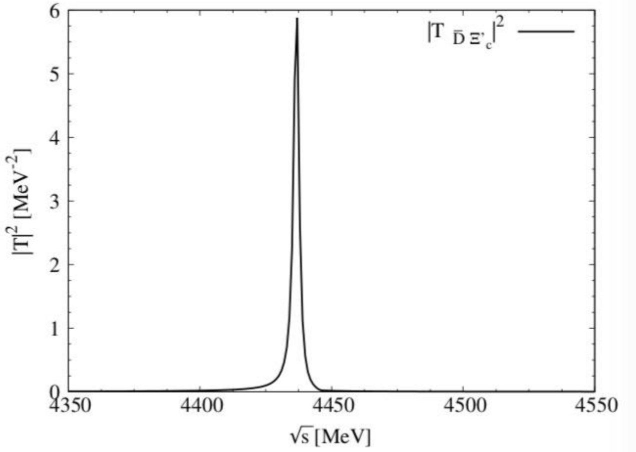
ii) $J = 3/2,\ I = 0$

$J/\psi\Lambda,\ \bar{D}^*\Xi_c,\ \bar{D}_s\Lambda_c,\ \bar{D}^*\Xi'_c,\ \bar{D}\Xi^*_c,\ \bar{D}^*\Xi^*_c.$

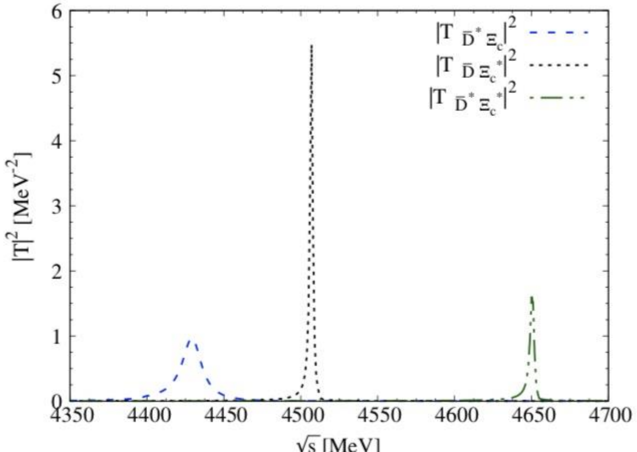
HQSS

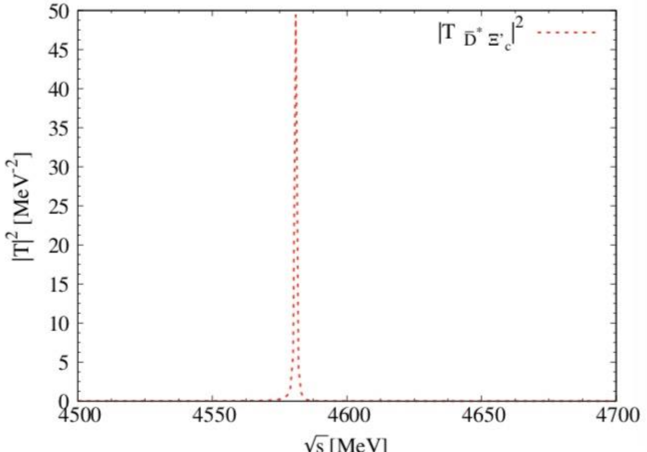
$a(\mu = 1\,\text{GeV}) = -2.09$





CWX, J. Nieves and E. Oset, Phys. Rev. D 100 (2019) 014021





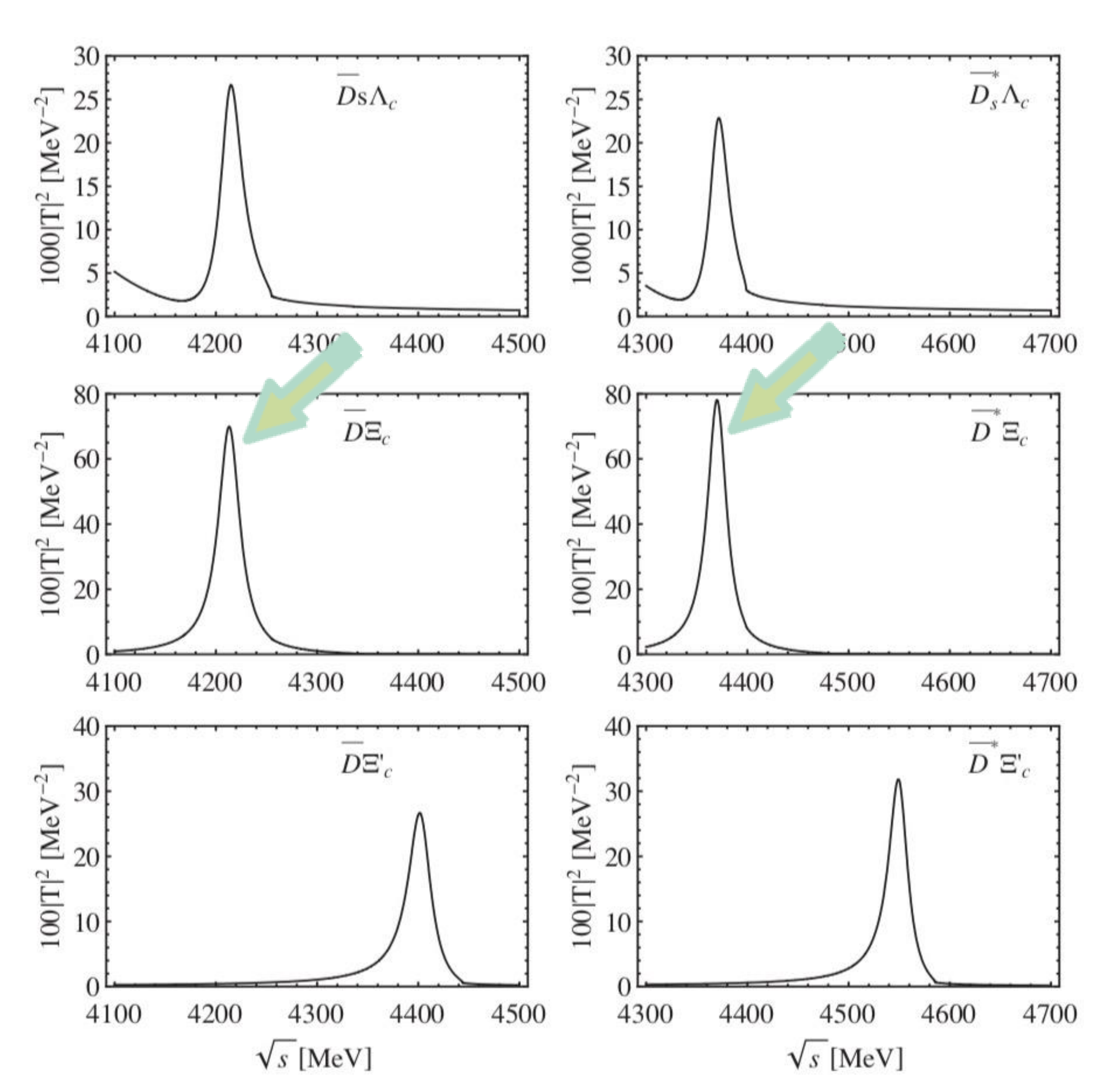
CWX, J. Nieves and E. Oset, Phys. Lett. B 799 (2019) 135051.

- $J = 1/2,\ I = 0$

$a_\mu(\mu = 1\ \text{GeV}) = -1.94$

Chan.	$\eta_c\Lambda$	$J/\psi\Lambda$	$\bar{D}\Xi_c$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c'$	$\bar{D}^*\Xi_c$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c'$	$\bar{D}^*\Xi_c^*$
Thres.	4099.58	4212.58	4336.61	4254.80	4445.34	4477.92	4398.66	4586.66	4654.48
$4310.53 + i8.23$	$P_{\psi s}^{\Lambda}(4338)^0$								
$\lvert g_i\rvert$	0.15	0.27	**2.33**	0.69	0.00	0.04	0.09	0.01	0.02
Γ_i	0.57	1.18	–	13.86	–	–	–	–	–
Br.	3.47%	7.16%	–	84.21%	–	–	–	–	–
$4445.12 + i0.19$									
$\lvert g_i\rvert$	0.10	0.06	0.00	0.00	**0.72**	0.08	0.04	0.01	0.01
Γ_i	0.29	0.08	0.00	0.00	–	–	0.04	–	–
Br.	74.74%	21.22%	0.01%	0.01%	–	–	10.62%	–	–
$4459.07 + i6.89$	$P_{cs}(4459)$								
$\lvert g_i\rvert$	0.22	0.13	0.00	0.00	0.07	**2.16**	0.61	0.03	0.02
Γ_i	1.59	0.46	0.00	0.00	0.01	–	11.14	–	–
Br.	11.57%	3.31%	0.00%	0.00%	0.70%	–	80.86%	–	–
4586.66?									
$\lvert g_i\rvert$	–	–	–	–	–	–	–	–	–
4654.48?									
$\lvert g_i\rvert$	–	–	–	–	–	–	–	–	–

- $J = 3/2,\ I = 0$

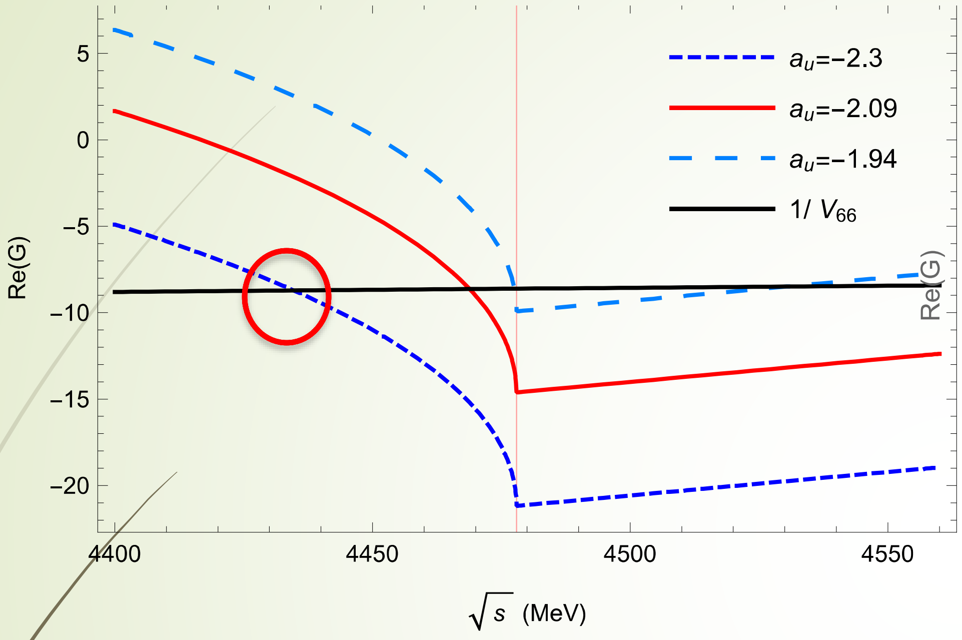


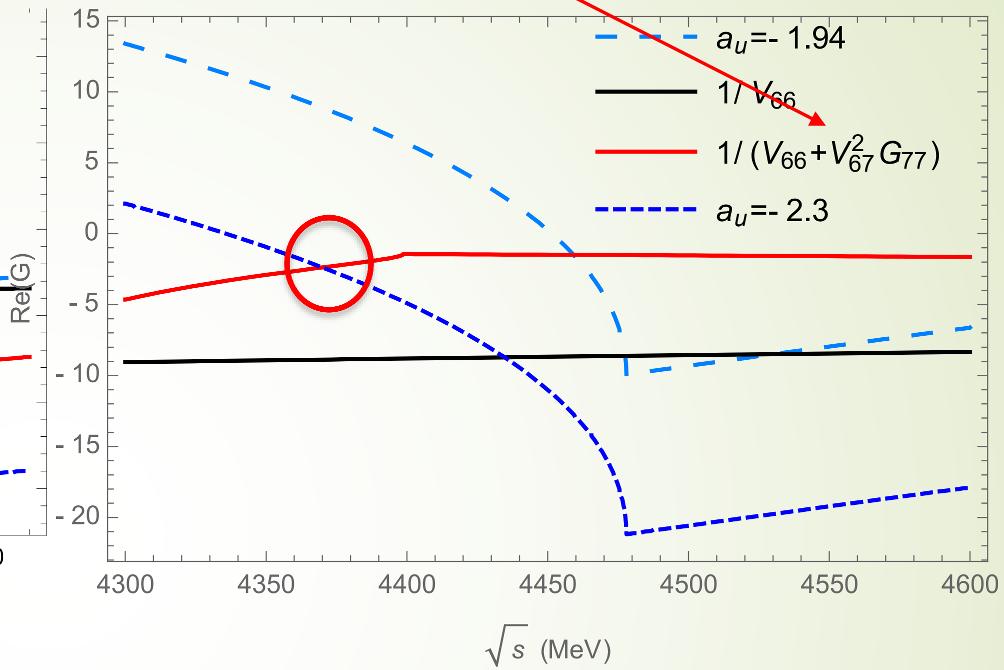
$\mu = 1000$ MeV

$a(\mu) = -2.3$

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C 84 (2011) 015202 for the $\bar{D}^*\Xi_c$ channel

$\bar{D}_s^*\Lambda_c$





	$J/\psi\Lambda$	$\bar{D}_s^*\Lambda_c$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
$J/\psi\Lambda$	0	$-\frac{1}{\sqrt{3}}\lambda$	$\frac{1}{\sqrt{6}}\lambda$	$-\frac{1}{\sqrt{2}}\lambda$
$\bar{D}_s^*\Lambda_c$		0	$-\sqrt{2}$	0
$\bar{D}^*\Xi_c$			-1	0
$\bar{D}^*\Xi_c'$				-1

$\bar{D}\Xi_c$ $\bar{D}_s\Lambda_c$

CWX, J. J. Wu and B. S. Zou, Phys. Rev. D 103 (2021) 054016.

Noting the results for Pc

$$
\begin{array}{ccccccc}
\eta_c N & J/\psi N & \bar{D}\Lambda_c & \bar{D}\Sigma_c & \bar{D}^*\Lambda_c & \bar{D}^*\Sigma_c & \bar{D}^*\Sigma_c^*
\end{array}
$$

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

$$
\mu_1 = 0, \quad \mu_{23} = 0, \quad \lambda_2 = \mu_3, \quad \mu_{13} = -\mu_{12},
$$

$$
\mu_2 = \frac{1}{4f^2}(k^0 + k'^0), \quad \mu_3 = -\frac{1}{4f^2}(k^0 + k'^0),
$$

CWX, J. Nieves and E. Oset, Phys. Rev. D 100 (2019) 014021

Recalling the results in Pc states

$a(\mu = 1\,\mathrm{GeV}) = -2.09$

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

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

$P_c : \bar{D}\Sigma_c, \bar{D}\Lambda_c$ and $\bar{D}^*\Sigma_c, \bar{D}^*\Lambda_c$

CWX, J. Nieves and E. Oset, Phys. Rev. D 100 (2019) 014021

Updated investigation

$PB(1/2^+)$ sector with $J^P = \frac{1}{2}^-$

Poles		$\eta_c \Lambda$	$\bar{D}_s \Lambda_c$	$\bar{D} \Xi_c$	$\bar{D} \Xi'_c$
$4198.94 + i0.11$	g_i	$0.12 - i0.00$	$3.01 - i0.01$	**$4.85 + i0.01$**	$0.01 - i0.03$
	$g_i G_i^{II}$	$-0.35 + i1.01$	$-19.24 + i0.05$	**$-20.35 - i0.07$**	$-0.03 + i0.09$
$4422.79 + i7.75$	g_i	$0.71 - i0.08$	$0.05 + i0.00$	$-0.06 + i0.04$	**$2.79 - i0.35$**
	$g_i G_i^{II}$	$1.14 + i10.71$	$0.76 + i1.82$	$-0.43 - i1.53$	**$-26.54 + i0.64$**

$P_{cs}(4459)$

$VB(1/2^+)$ sector with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$

Poles		$J/\psi \Lambda$	$\bar{D}_s^* \Lambda_c$	$\bar{D}^* \Xi_c$	$\bar{D}^* \Xi'_c$
$4337.98 + i0.12$	g_i	$0.11 - i0.00$	$3.17 - i0.01$	**$5.07 + i0.01$**	$0.00 - i0.04$
	$g_i G_i^{II}$	$-0.13 + i1.07$	$-18.57 + i0.06$	**$-19.94 - i0.07$**	$-0.01 + i0.10$
$4565.73 + i15.58$	g_i	$0.70 - i0.16$	$0.09 - i0.03$	$-0.10 + i0.09$	**$2.84 - i0.72$**
	$g_i G_i^{II}$	$6.24 + i21.04$	$2.07 + i3.40$	$-1.37 - i2.81$	**$-26.31 + i1.15$**

$P^{\Lambda}_{\psi s}(4338)^0$

$P_c : \bar{D}\Sigma_c, \bar{D}\Lambda_c$ and $\bar{D}^*\Sigma_c, \bar{D}^*\Lambda_c$

~~$P_{cs} : \bar{D}\Xi_c, \bar{D}_s\Lambda_c$ and $\bar{D}^*\Sigma_c, \bar{D}_s^*\Lambda_c$~~

A. Feijoo, W. F. Wang, **CWX**, J. J. Wu, E. Oset, J. Nieves, B. S. Zou, Phys. Lett. B 839 (2023) 137760

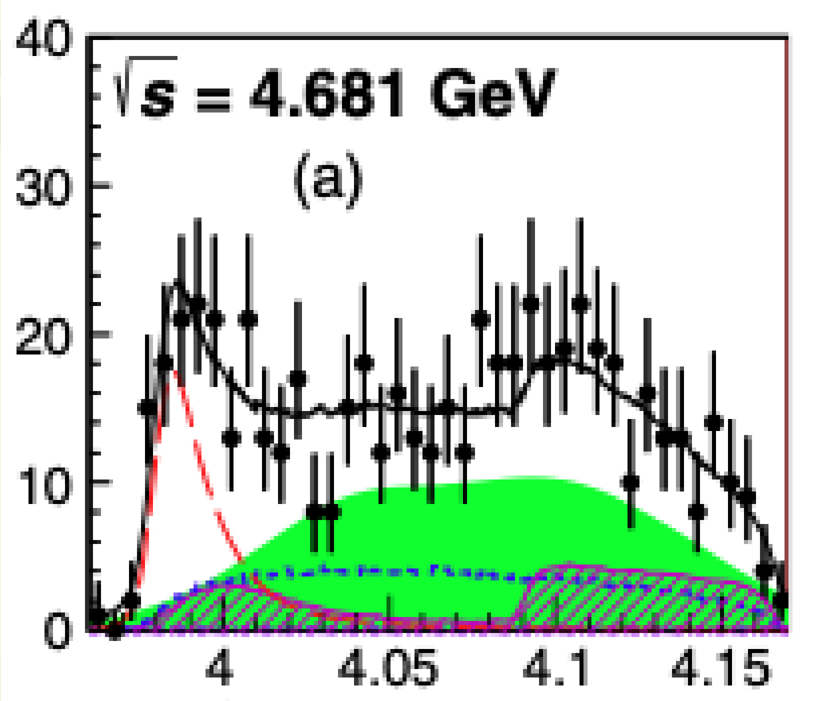
§4. Tetraquark states

BESIII Collaboration

PHYSICAL REVIEW LETTERS **126,** 102001 (2021)

Editors' Suggestion | Featured in Physics

Observation of a Near-Threshold Structure in the K^+ Recoil-Mass Spectra in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



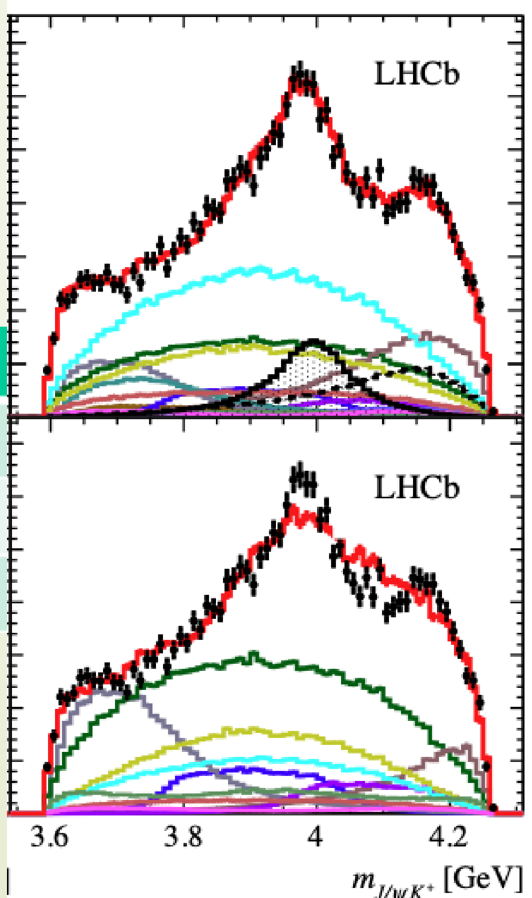
PHYSICAL REVIEW LETTERS **127,** 082001 (2021)

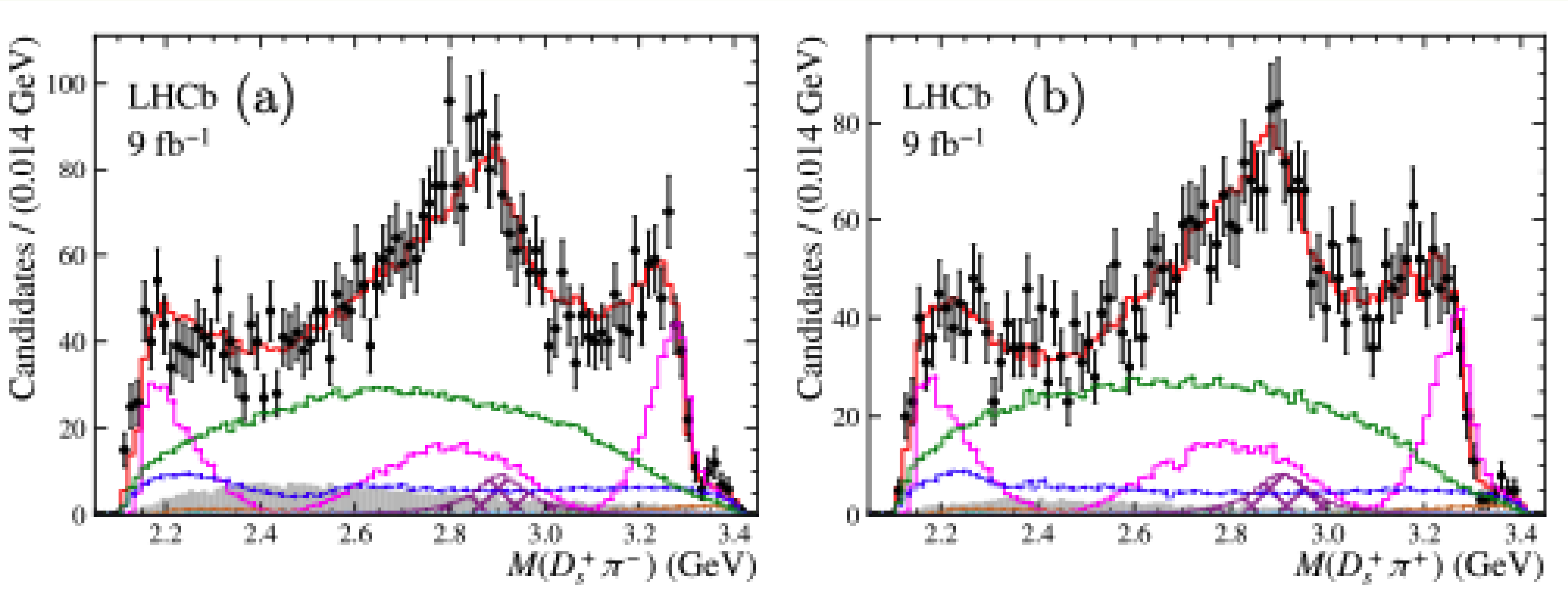
Editors' Suggestion

Observation of New Resonances Decaying to $J/\psi K^+$ and $J/\psi\phi$

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

State	Signif.	JP	Mass (MeV)	Width (MeV)
$Z_{cs}(3985)$	5.3σ	??	$3982.5^{+1.8}_{-2.6} \pm 2.1$	$12.8^{+5.3}_{-4.4} \pm 3.0$
$Z_{cs}(4000)$	15σ	1+	$4003 \pm 6^{+4}_{-14}$	131±15±26
$Z_{cs}(4220)$	5.9σ	1+	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$





$$
\begin{aligned}
T^a_{c\bar{s}0}(2900)^0 : M &= 2.892 \pm 0.014 \pm 0.015\,\mathrm{GeV}, \\
\Gamma &= 0.119 \pm 0.026 \pm 0.013\,\mathrm{GeV}, \\
T^a_{c\bar{s}0}(2900)^{++} : M &= 2.921 \pm 0.017 \pm 0.020\,\mathrm{GeV}, \\
\Gamma &= 0.137 \pm 0.032 \pm 0.017\,\mathrm{GeV},
\end{aligned}
$$

R. Aaij et al. [LHCb], Phys. Rev. Lett. 131 (2023) 4, 041902

第 41 卷　第 2 期
2021 年 04 月

物　理　学　进　展
PROGRESS IN PHYSICS

A survey of heavy-antiheavy hadronic molecules

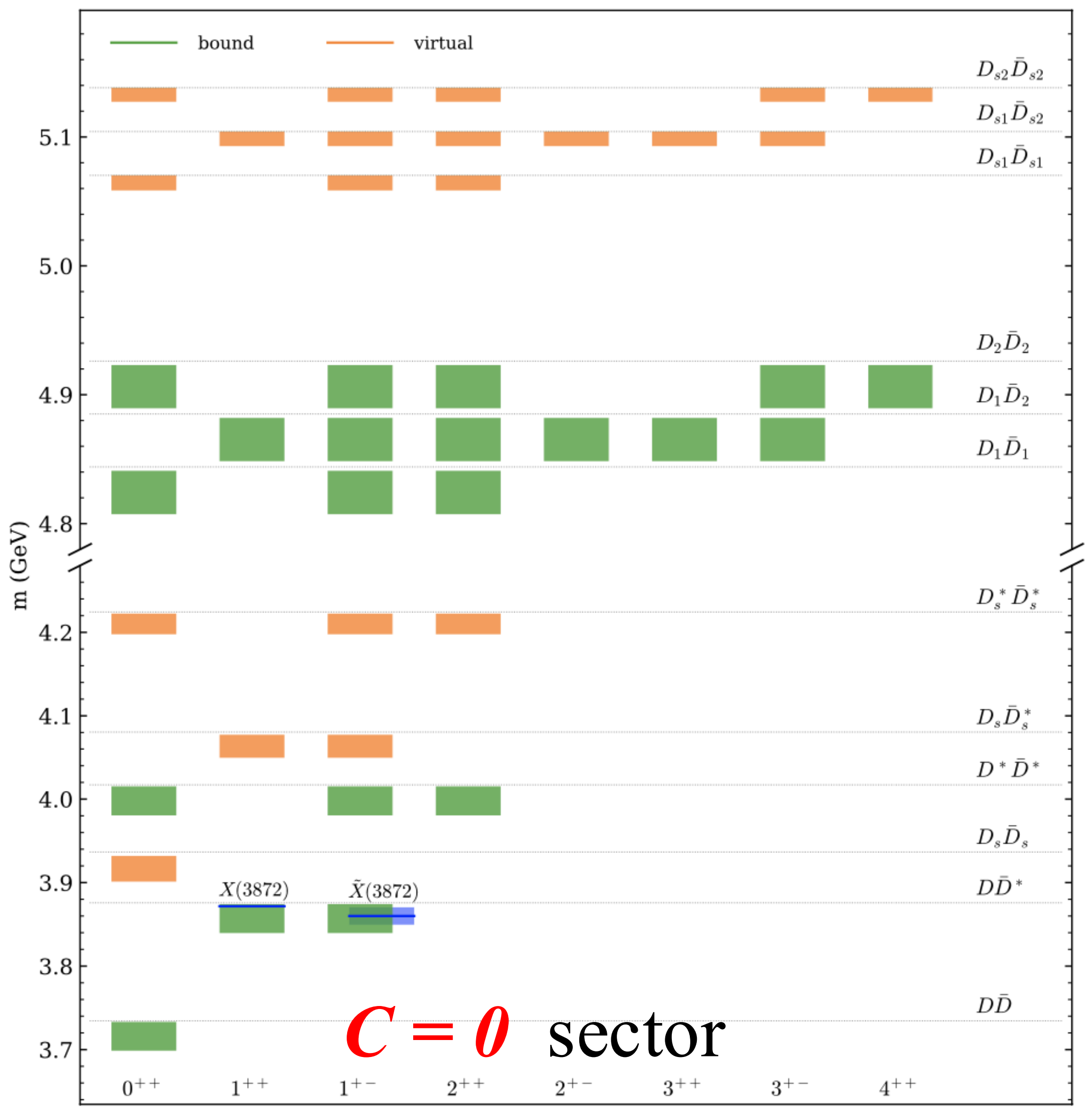
Dong Xiang-Kun [1,2*], Guo Feng-Kun [1,2†], Zou Bing-Song [1,2,3‡]

Progr. Phys. **41** (2021) 65

A survey of heavy-antiheavy hadronic molecules

Xiang-Kun Dong[1,2,*] Feng-Kun Guo[1,2,†] and Bing-Song Zou[1,2,3‡]

System	$E_{\rm th}$	J^{PC}	Pole (0.5)	Pole (1.0)
$D\bar{D}$	3734	0^{++}	(1, 1.31)	(1, 35.8)
$D\bar{D}^*$	3876	$1^{+\pm}$	(1, 1.56)	(1, 36.2)
$D_s\bar{D}_s$	3937	0^{++}	(2, 35.5)	(2, 4.72)
$D^*\bar{D}^*$	4017	$(0,2)^{++}, 1^{+-}$	(1, 1.82)	(1, 36.6)
$D_s\bar{D}_s^*$	4081	$1^{+\pm}$	(2, 31.0)	(2, 3.15)
$D_s^*\bar{D}_s^*$	4224	$(0,2)^{++}, 1^{+-}$	(2, 26.7)	(2, 1.92)
$D\bar{D}_2$	4330	$2^{-\pm}$	(1, 2.2)	(1, 36.7)
$D_s\bar{D}_{s2}$	4537	$2^{-\pm}$	(2, 21.3)	(2, 0.713)
$D_1\bar{D}_1$	4844	$(0,2)^{++}, 1^{+-}$	(1, 3.01)	(1, 36.7)
$D_1\bar{D}_2$	4885	$(1,2,3)^{+\pm}$	(1, 3.06)	(1, 36.6)
$D_2\bar{D}_2$	4926	$(0,2,4)^{++}, (1,3)^{+-}$	(1, 3.1)	(1, 36.6)
$D_{s1}\bar{D}_{s1}$	5070	$(0,2)^{++}, 1^{+-}$	(2, 11.7)	(1, 0.074)
$D_{s1}\bar{D}_{s2}$	5104	$(1,2,3)^{+\pm}$	(2, 11.3)	(1, 0.104)
$D_{s2}\bar{D}_{s2}$	5138	$(0,2,4)^{++}, (1,3)^{+-}$	(2, 10.9)	(1, 0.139)



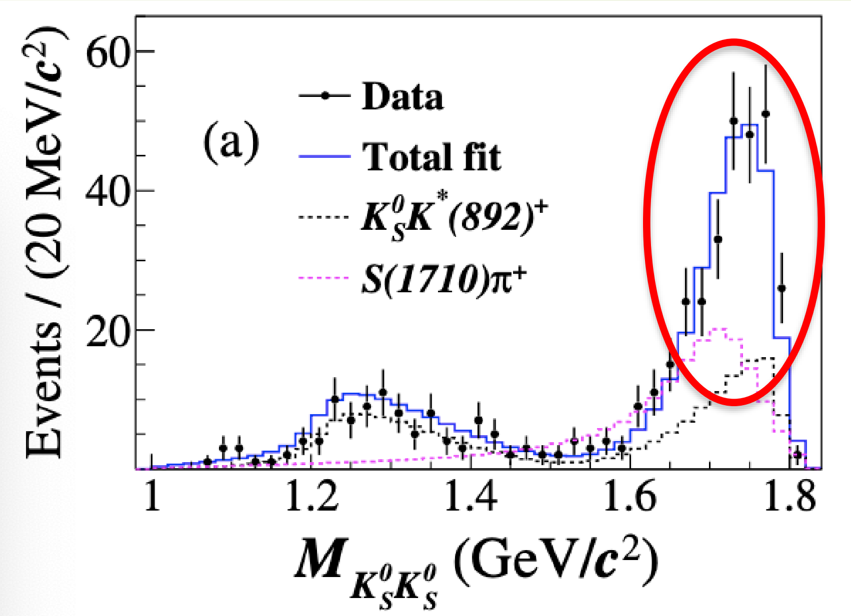
Findings from BESIII

PHYSICAL REVIEW D **105**, L051103 (2022)

Letter

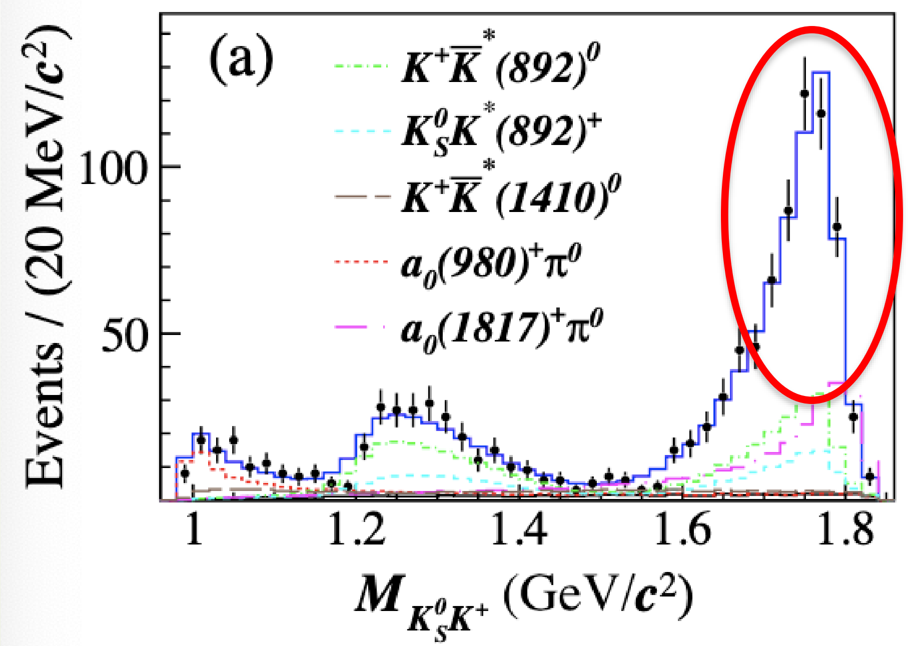
Study of the decay $D_s^+ \to K_S^0 K_S^0 \pi^+$ and observation of an isovector partner to $f_0(1710)$

existence of an isospin one partner of the $f_0(1710)$.



PHYSICAL REVIEW LETTERS **129**, 182001 (2022)

Observation of an a_0-like State with Mass of 1.817 GeV in the Study of $D_s^+ \to K_S^0 K^+ \pi^0$ Decays



Molecular nature

PHYSICAL REVIEW LETTERS **126**, 152001 (2021)

Explaining the Many Threshold Structures in the Heavy-Quark Hadron Spectrum

Xiang-Kun Dong[1,2] Feng-Kun Guo[1,2,*] and Bing-Song Zou[1,2,3]

F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018)
H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Phys. Rept. 639, 1 (2016)
N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo and C. Z. Yuan, Phys. Rept. 873, 1 (2020)

ELSEVIER Nuclear Physics A 620 (1997) 438–456

Chiral symmetry amplitudes in the *S*-wave isoscalar and isovector channels and the σ, $f_0(980)$, $a_0(980)$ scalar mesons

J.A. Oller, E. Oset

$f_0(1710)$ and $a_0(1710)$ states

L. S. Geng and E. Oset, Phys. Rev. D 79, 074009 (2009): Coupled channel approach

$K\bar{K}$ **molecular state** → $K^*\bar{K}^*$ **molecular state**

$S = 0$ sector $S \neq 0$ sector ?

We try to investigate……

	Systems	Coefficients $I=0$	Coes. $I=1,\ (\frac{1}{2})$	Exp.
$S=2,\ C=0$	KK	$\frac{1}{2}(-3P_t^\rho + P_t^\omega + 2V_t^\phi)g^2$ $-\frac{1}{2}(-3V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$ $+\frac{1}{2}(V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	
	KK^*	$\frac{1}{2}(-3V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$	
	K^*K^*	$\frac{1}{2}(-3V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$ $-\frac{1}{2}(-3V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_t^\phi)g^2$ $+\frac{1}{2}(V_u^\rho + V_u^\omega + 2V_u^\phi)g^2$	
$S=-1,\ C=1$	$\bar{K}D$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega - 2V_u^{D_s^*})g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_u^{D_s^*})g^2$	$X(2900)$
	$\bar{K}D^*$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega)g^2$	
	$\bar{K}^*D$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega)g^2$	
	$\bar{K}^*D^*$	$\frac{1}{2}(-3V_t^\rho + V_t^\omega - 2V_u^{D_s^*})g^2$	$\frac{1}{2}(V_t^\rho + V_t^\omega + 2V_u^{D_s^*})g^2$	$X_0(2866)$
$S=1,\ C=1$	KD	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	$D_{s0}^*(2317)$
	KD^*	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	$D_{s1}(2460),\ D_{s1}(2536)$
	K^*D	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	
	K^*D^*	$\frac{1}{2}(-3V_t^\rho - V_t^\omega)g^2$	$\frac{1}{2}(V_t^\rho - V_t^\omega)g^2$	$D_{s2}^*(2573)$

$S = 2,\ C = 1$

KD_s	$(V_t^{\phi} + V_u^{D^*})g^2$	
KD_s^*	$V_t^{\phi} g^2$	
K^*D_s	$V_t g^2$	
$K^*D_s^*$	$(V_t^{\phi} + V_u^{D^*})g^2$	
$\bar{D}D_s$	$-V_t^{J/\psi} g^2$	
$\bar{D}D_s^*$	$-V_t^{J/\psi} g^2$	$Z_{cs}(3985)$
$\bar{D}^*D_s$	$-V_t^{J/\psi} g^2$	
$\bar{D}^*D_s^*$	$-V_t^{J/\psi} g^2$	$Z_{cs}(4000)$

$S = 1,\ C = 0$

$S = 1,\ C = 2$

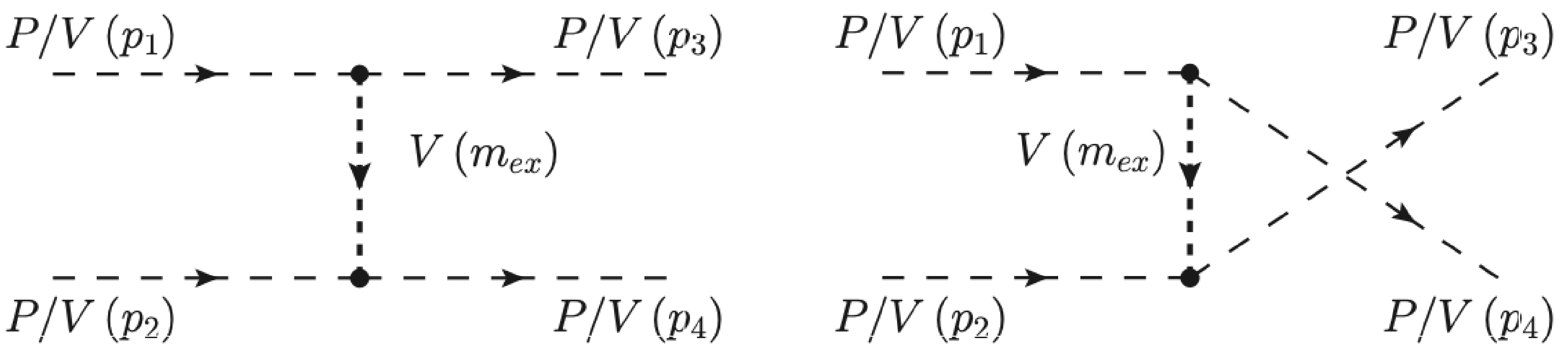
DD_s	$(V_t^{J/\psi} + V_u^{K^*})g^2$
DD_s^*	$V_t^{J/\psi} g^2$
D^*D_s	$V_t^{J/\psi} g^2$
$D^*D_s^*$	$(V_t^{J/\psi} + V_u^{K^*})g^2$
D_sD_s	$(V_t^{J/\psi} + V_t^{\phi})g^2 + (V_u^{J/\psi} + V_u^{\phi})g^2$
$D_sD_s^*$	$(V_t^{J/\psi} + V_t^{\phi})g^2$
$D_s^*D_s^*$	$(V_t^{J/\psi} + V_t^{\phi})g^2 + (V_u^{J/\psi} + V_u^{\phi})g^2$

$S = 2,\ C = 2$

$$V_{t(u)}^{ex} = \frac{-V_{t(u)}}{t(u) - m_{ex}^2},$$

$$V_t = (k_1 + k_3) \cdot (k_2 + k_4)$$

$$V_u = (k_1 + k_4) \cdot (k_2 + k_3)$$



(a) t-channel (b) u-channel

$$\frac{1}{2}\int_{-1}^{+1} \mathrm{d}\cos\theta \frac{-V_t}{t - m_{ex}^2}$$
$$= -\frac{s}{\sqrt{\lambda(s, m_1^2, m_2^2)\,\lambda(s, m_3^2, m_4^2)}}\left(m_1^2 + m_2^2 + m_3^2 + m_4^2 - 2s - m_{ex}^2\right)$$
$$\times \log \frac{m_1^2 + m_3^2 - \frac{(s+m_1^2-m_2^2)(s+m_3^2-m_4^2)}{2s} - \frac{\sqrt{\lambda(s,m_1^2,m_2^2)\lambda(s,m_3^2,m_4^2)}}{2s} - m_{ex}^2}{m_1^2 + m_3^2 - \frac{(s+m_1^2-m_2^2)(s+m_3^2-m_4^2)}{2s} + \frac{\sqrt{\lambda(s,m_1^2,m_2^2)\lambda(s,m_3^2,m_4^2)}}{2s} - m_{ex}^2} - 1,$$

Systems	Ours-new ($q_{max}=883$)	Oset's ($q_{max}=1100$)	Ours-new2 ($q_{max}=760$)	Oset's-2 ($q_{max}=843$)	Exp.
$\bar{K}D$ (2362.89)	2354.10	2346.74	2362.40	2362.82	
$\bar{K}D^*$ (2504.20)	–	2502.68	–	–	
$\bar{K}^*D$ (2760.86)	$2694.17+i42.94$	2689.01	2747.40	2741.24	
$\bar{K}^*D^*$, $J=0$ (2902.17)	2866.14	2866.38	2897.82	2897.02	$X_0(2866)$
$\bar{K}^*D^*$, $J=1$ (2902.17)	2894.66	2859.98	2902.06	2895.50	
$\bar{K}^*D^*$, $J=2$ (2902.17)	$2813.41-i135.96$	2745.76	$2807.55\pm i66.51$	2837.49	
KD (2362.89)	2258.22	2262.15	2317.36	2317.14	$D^*_{s0}(2317)$
KD^* (2504.20)	2391.78	2400.22	24555.06	2456.29	$D_{s1}(2460)$
K^*D (2760.86)	$2698.42-i237.63$	2504.39	$2684.60\pm i170.50$	2620.27	
K^*D^*, $J=0$ (2902.17)	$2874.93+i192.31$	2713.15	$2849.62+i135.30$	2804.40	
K^*D^*, $J=1$ (2902.17)	$2866.91+i164.04$	2748.72	$2857.40\pm i112.55$	2826.76	
K^*D^*, $J=2$ (2902.17)	$2824.87+i259.85$	2600.70	$2817.27+i189.09$	2732.68	$D^*_{s2}(2573)$

CWX, J. J. Wu, arXiv: 2406.08313

§5. Summary

- Are there also existing two Pcs states $P_{cs}(4459)$?
- From the view of molecular state, what components are for $P_{cs}(4459)$ $P^{\Lambda}_{\psi s}(4338)^0$
- We dynamically generate the resonances:

$$X_0(2866),\ D^*_{s0}(2317)\ \text{and}\ D_{s1}(2460)$$

- We find some attractive interactions, which would be more molecular (tetraquark) states with strangeness as our predictions?

Hope future experiments and theories bring more clarifications on these issues…….

第八届强子谱和强子结构研讨会

Jul 11 – 15, 2025

Asia/Shanghai timezone

会议计划于2025年7月11日至15日在桂林市桂林宾馆召开，其中11日报到注册。会议统一安排食宿，费用自理。会议收取注册费，教师及博士后1500元/人，学生1000元/人。

会议网址：https://indico.ihep.ac.cn/event/24044/ ，注册截止时间为6月20日。

Thanks for your attention!

感谢大家的聆听！