辽宁师范大学

中国物理学会高能物理分会学术年会

# Study of the pentaquark states


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# Outline

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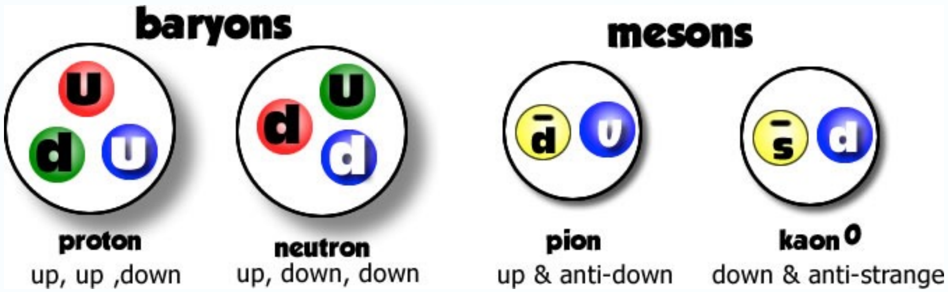
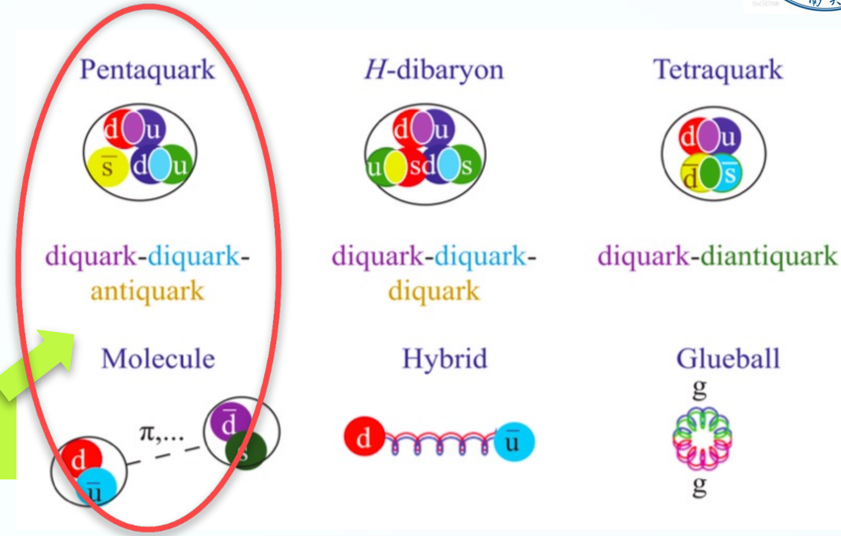
# §1. Introduction




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.

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** (2020) 1.

# Pridictions

## In hidden charm strangeness sector

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

**Prediction of Narrow $N^*$ and $\Lambda^*$ 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.

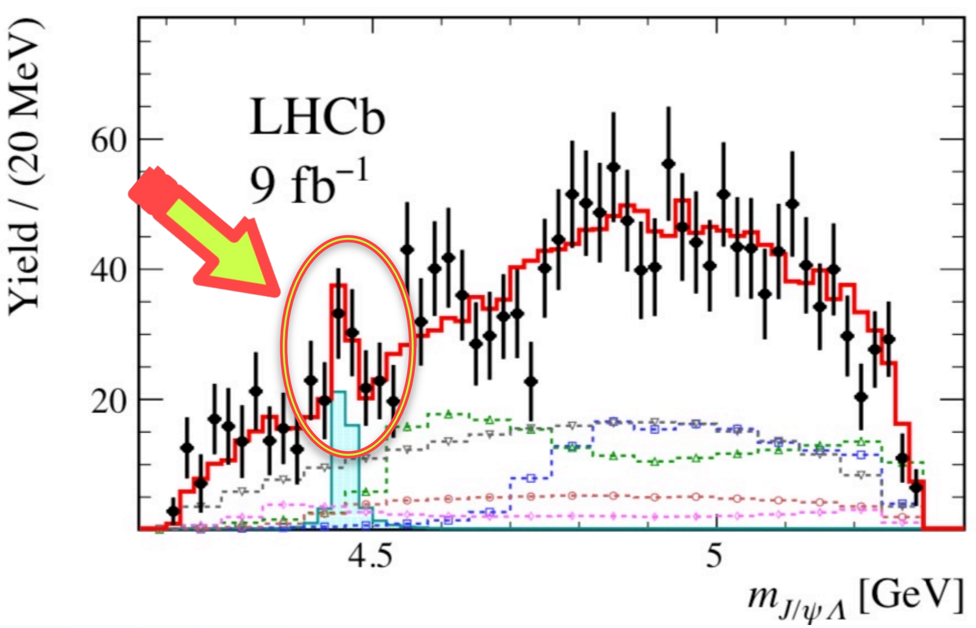
E. Santopinto and A. Giachino, **Phys. Rev. D 96** (2017) 014014.

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.

# Experimental findings for the Pcs state

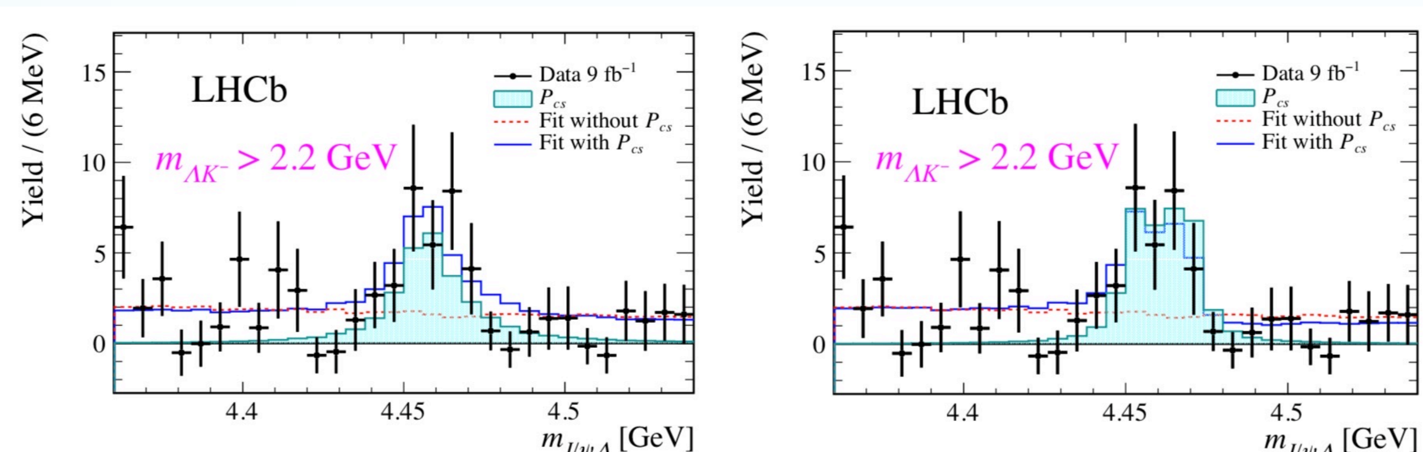



R. Aaij et al. (LHCb Collaboration), **Sci. Bull. 66** (2021) 1278-1287

| State | $M_0$ [MeV] | $\Gamma_0$ [MeV] |
|---|---|---|
| $P_{cs}(4459)^0$ | $4458.8 \pm 2.9\,^{+4.7}_{-1.1}$ | $17.3 \pm 6.5\,^{+8.0}_{-5.7}$ |

$J^P$ ?

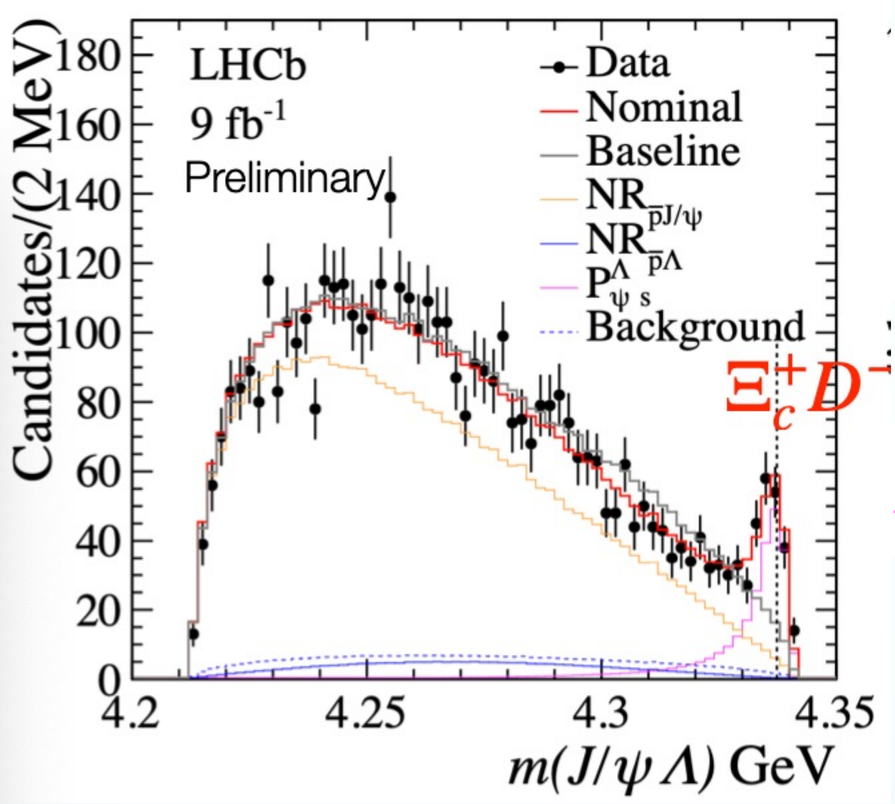
mass difference of about 6 MeV




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

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

# New findings for the Pcs state




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

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

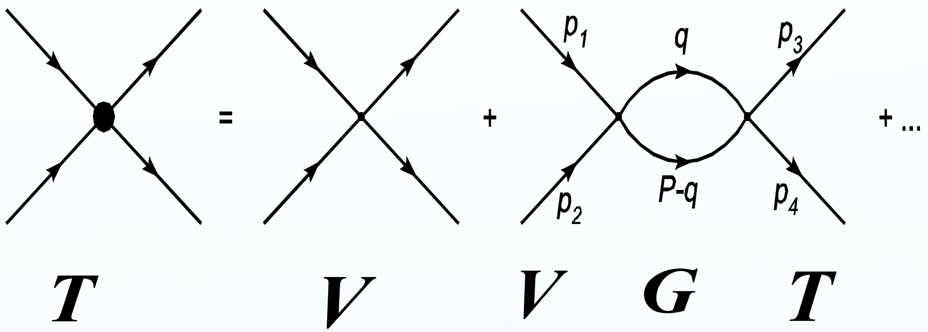
$P_{\psi s}^{\Lambda}(4338)^0$

Significance: >10$\sigma$

# §2. Formalism

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

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




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:

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

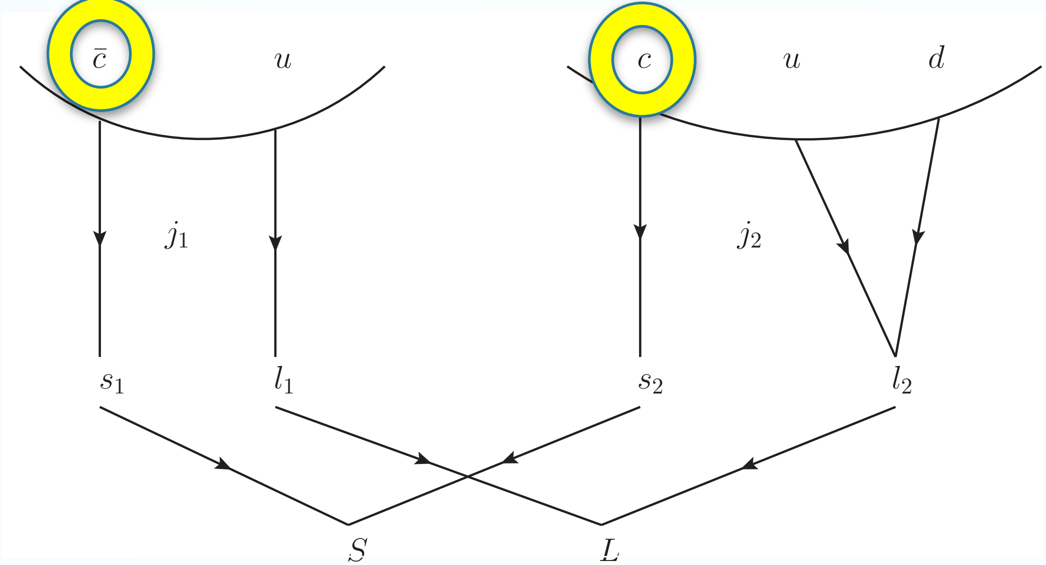
The coupled channel scattering amplitudes **T matrix satisfy the unitary** :

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

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

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

$$G_{ll}^{II}(s) = G_{ll}^{I}(s) + \boxed{\frac{i}{2\pi}\frac{M_l q_{cml}(s)}{\sqrt{s}}}$$




Considering the heavy quark spin symmetry

$\bar{D} \longrightarrow \bar{D}^*$ $\Xi_c \longrightarrow \Xi_c^*$

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

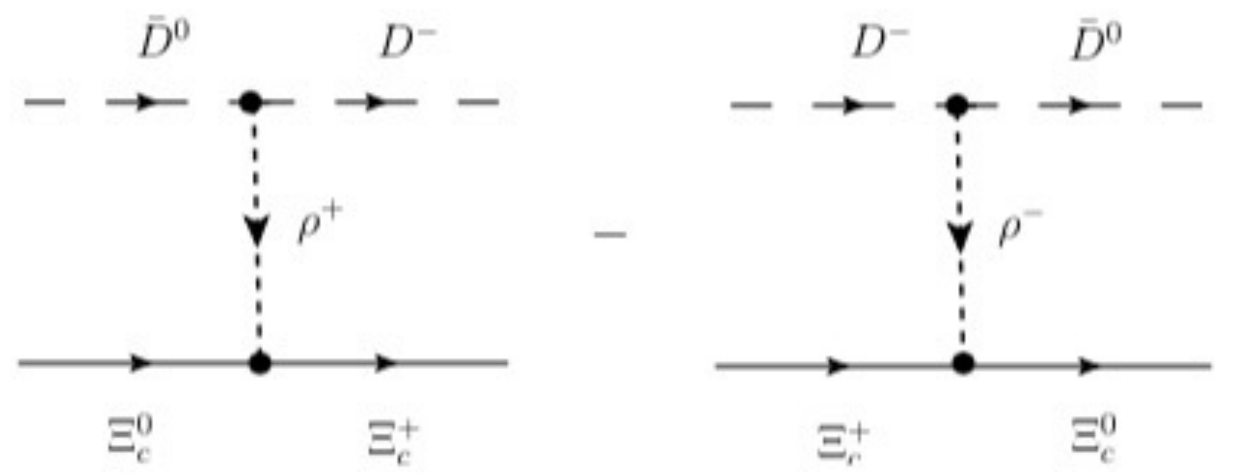
$$|\ell_M s_M j_M S; \ell_B s_B j_B; J\rangle = \sum_{\mathcal{L}, S_{c\bar{c}}} [(2S_{c\bar{c}}+1)(2\mathcal{L}+1)(2j_M+1)(2j_B+1)]^{\frac{1}{2}} \times \begin{Bmatrix} \ell_M & \ell_B & \mathcal{L} \\ s_M & s_B & S_{c\bar{c}} \\ j_M & j_B & J \end{Bmatrix} |\mathcal{L}S_{c\bar{c}}; J\rangle_{(\ell_M\ell_B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

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

$$
\begin{array}{c}
\begin{array}{ccccccccc}
\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^*
\end{array} \\
\begin{pmatrix}
\hat{\mu}_1 & 0 & -\frac{\hat{\mu}_{12}}{2} & -\frac{\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{14}}{2} & \frac{\sqrt{3}\hat{\mu}_{12}}{2} & \frac{\sqrt{3}\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{14}}{2\sqrt{3}} & \sqrt{\frac{2}{3}}\hat{\mu}_{14} \\
0 & \hat{\mu}_1 & \frac{\sqrt{3}\hat{\mu}_{12}}{2} & \frac{\sqrt{3}\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{14}}{2\sqrt{3}} & \frac{\hat{\mu}_{12}}{2} & \frac{\hat{\mu}_{13}}{2} & \frac{5\hat{\mu}_{14}}{6} & -\frac{\sqrt{2}\hat{\mu}_{14}}{3} \\
-\frac{\hat{\mu}_{12}}{2} & \frac{\sqrt{3}\hat{\mu}_{12}}{2} & \hat{\mu}_2 & \hat{\mu}_{23} & 0 & 0 & 0 & \frac{\hat{\mu}_{24}}{\sqrt{3}} & -\sqrt{\frac{2}{3}}\hat{\mu}_{24} \\
-\frac{\hat{\mu}_{13}}{2} & \frac{\sqrt{3}\hat{\mu}_{13}}{2} & \hat{\mu}_{23} & \hat{\mu}_3 & 0 & 0 & 0 & \frac{\hat{\mu}_{34}}{\sqrt{3}} & -\sqrt{\frac{2}{3}}\hat{\mu}_{34} \\
\frac{\hat{\mu}_{14}}{2} & \frac{\hat{\mu}_{14}}{2\sqrt{3}} & 0 & 0 & \frac{1}{3}(2\hat{\lambda}+\hat{\mu}_4) & \frac{\hat{\mu}_{24}}{\sqrt{3}} & \frac{\hat{\mu}_{34}}{\sqrt{3}} & -\frac{2(\hat{\lambda}-\hat{\mu}_4)}{3\sqrt{3}} & \frac{1}{3}\sqrt{\frac{2}{3}}(\hat{\mu}_4-\hat{\lambda}) \\
\frac{\sqrt{3}\hat{\mu}_{12}}{2} & \frac{\hat{\mu}_{12}}{2} & 0 & 0 & \frac{\hat{\mu}_{24}}{\sqrt{3}} & \hat{\mu}_2 & \hat{\mu}_{23} & \frac{2\hat{\mu}_{24}}{3} & \frac{\sqrt{2}\hat{\mu}_{24}}{3} \\
\frac{\sqrt{3}\hat{\mu}_{13}}{2} & \frac{\hat{\mu}_{13}}{2} & 0 & 0 & \frac{\hat{\mu}_{34}}{\sqrt{3}} & \hat{\mu}_{23} & \hat{\mu}_3 & \frac{2\hat{\mu}_{34}}{3} & \frac{\sqrt{2}\hat{\mu}_{34}}{3} \\
\frac{\hat{\mu}_{14}}{2\sqrt{3}} & \frac{5\hat{\mu}_{14}}{6} & \frac{\hat{\mu}_{24}}{\sqrt{3}} & \frac{\hat{\mu}_{34}}{\sqrt{3}} & -\frac{2(\hat{\lambda}-\hat{\mu}_4)}{3\sqrt{3}} & \frac{2\hat{\mu}_{24}}{3} & \frac{2\hat{\mu}_{34}}{3} & \frac{1}{9}(2\hat{\lambda}+7\hat{\mu}_4) & \frac{1}{9}\sqrt{2}(\hat{\lambda}-\hat{\mu}_4) \\
\sqrt{\frac{2}{3}}\hat{\mu}_{14} & -\frac{\sqrt{2}\hat{\mu}_{14}}{3} & -\sqrt{\frac{2}{3}}\hat{\mu}_{24} & -\sqrt{\frac{2}{3}}\hat{\mu}_{34} & \frac{1}{3}\sqrt{\frac{2}{3}}(\hat{\mu}_4-\hat{\lambda}) & \frac{\sqrt{2}\hat{\mu}_{24}}{3} & \frac{\sqrt{2}\hat{\mu}_{34}}{3} & \frac{1}{9}\sqrt{2}(\hat{\lambda}-\hat{\mu}_4) & \frac{1}{9}(\hat{\lambda}+8\hat{\mu}_4)
\end{pmatrix}
\end{array}
$$

LECs

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




$\boxed{J = 1/2,\ I = 0}$

X. K. Dong, F. K. Guo and B. S. Zou, *Progr. Phys.* 41 (2021) 65; *Commun. Theor. Phys.* 73 (2021) 125201.

$$\hat{\mu}_1 = \hat{\mu}_3 = \hat{\mu}_{24} = \hat{\mu}_{34} = 0$$

$$\hat{\mu}_2 = \hat{\mu}_{23}/\sqrt{2} = \hat{\mu}_4 = \hat{\lambda} = \underline{-F}, \qquad F = \frac{1}{4f^2}(p^0 + p')$$

$$\hat{\mu}_{12} = -\hat{\mu}_{13}/\sqrt{2} = \hat{\mu}_{14}/\sqrt{3} = -\sqrt{\frac{2}{3}}\,\frac{m_V^2}{m_{D^*}^2}\,F,$$

# §3. Results

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

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

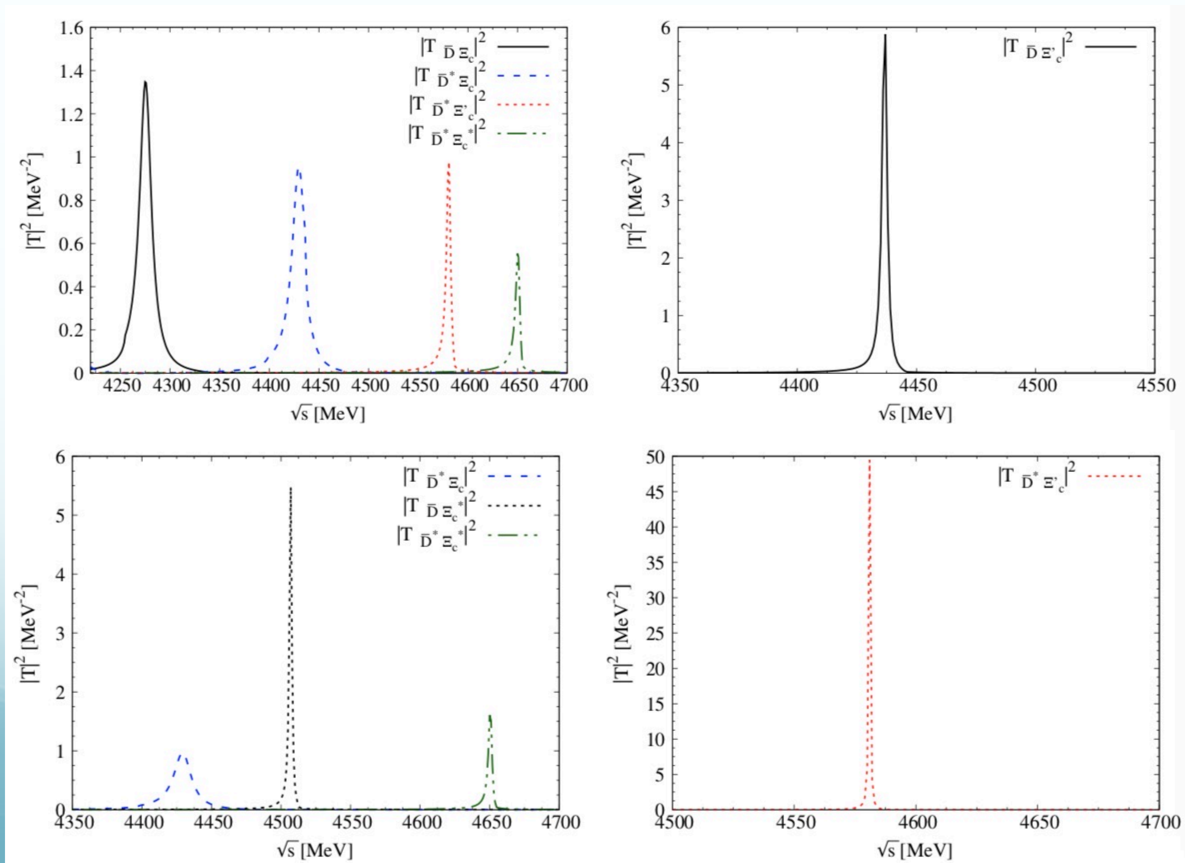
ii) $J = 3/2,\ I = 0$

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

**HQSS**

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

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



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

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

| Thres. | 4099.58 | 4212.58 | 4366.61 | 4254.80 | 4445.34 | 4477.92 | 4398.66 | 4586.66 | 4654.48 |
|---|---|---|---|---|---|---|---|---|---|
| | $\eta_c\Lambda$ | $J/\psi\Lambda$ | $\bar{D}\Xi_c$ | $\bar{D}_s\Lambda_c$ | $\bar{D}\Xi'_c$ | $\bar{D}^*\Xi_c$ | $\bar{D}^*_s\Lambda_c$ | $\bar{D}^*\Xi'_c$ | $\bar{D}^*\Xi^*_c$ |
| $4276.59 + i7.67$ | | | | | | | | | |
| $g_i$ | $0.17 - i0.03$ | $0.29 - i0.07$ | $\mathbf{2.93 + i0.08}$ | $0.76 + i0.31$ | $0.00 + i0.01$ | $0.01 + i0.02$ | $0.01 + i0.04$ | $0.01 - i0.02$ | $0.01 - i0.03$ |
| $\lvert g_i\rvert$ | 0.17 | 0.30 | **2.93** | 0.82 | 0.01 | 0.02 | 0.05 | 0.02 | 0.03 |
| $4429.84 + i7.92$ | | | | | | | | | |
| $g_i$ | $0.29 - i0.11$ | $0.17 - i0.07$ | $0.00 - i0.00$ | $0.00 - i0.00$ | $0.15 - i0.26$ | $\mathbf{2.78 + i0.01}$ | $0.66 + i0.32$ | $0.01 + i0.05$ | $0.01 + i0.03$ |
| $\lvert g_i\rvert$ | 0.31 | 0.18 | 0.00 | 0.00 | 0.30 | **2.78** | 0.73 | 0.05 | 0.04 |
| $4436.70 + i1.17$ | | | | | | | | | |
| $g_i$ | $0.24 + i0.03$ | $0.14 + 0.01$ | $0.00 - i0.00$ | $0.00 - i0.00$ | $\mathbf{1.72 - i0.04}$ | $0.22 - i0.31$ | $0.06 - i0.01$ | $0.01 - i0.04$ | $0.01 - i0.03$ |
| $\lvert g_i\rvert$ | 0.24 | 0.14 | 0.00 | 0.00 | **1.72** | 0.38 | 0.07 | 0.04 | 0.03 |
| $4580.96 + i2.44$ | | | | | | | | | |
| $g_i$ | $0.12 - i0.00$ | $0.37 - i0.04$ | $0.02 - i0.01$ | $0.02 - i0.01$ | $0.03 - i0.00$ | $0.02 - i0.02$ | $0.03 - i0.02$ | $\mathbf{1.57 - i0.17}$ | $0.00 + i0.02$ |
| $\lvert g_i\rvert$ | 0.12 | 0.37 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | **1.58** | 0.02 |
| $4650.86 + i2.59$ | | | | | | | | | |
| $g_i$ | $0.32 - i0.05$ | $0.19 - i0.03$ | $0.02 - i0.01$ | $0.03 - i0.02$ | $0.02 - i0.00$ | $0.01 - i0.01$ | $0.02 - i0.01$ | $0.01 - i0.00$ | $\mathbf{1.41 - i0.23}$ |
| $\lvert g_i\rvert$ | 0.32 | 0.19 | 0.03 | 0.04 | 0.02 | 0.02 | 0.02 | 0.02 | **1.43** |

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

| Thres. | | 4212.58 | 4477.92 | 4398.66 | 4586.66 | 4513.17 | 4654.48 |
|---|---|---|---|---|---|---|---|
| | | $J/\psi\Lambda$ | $\bar{D}^*\Xi_c$ | $\bar{D}_s^*\Lambda_c$ | $\bar{D}^*\Xi_c'$ | $\bar{D}\Xi_c^*$ | $\bar{D}^*\Xi_c^*$ |
| $4429.52 + i7.67$ | | | | | | | |
| | $g_i$ | $0.31 - i0.10$ | $\mathbf{2.77 - i0.02}$ | $0.67 + i0.32$ | $0.00 + i0.0.02$ | $0.00 - i0.06$ | $0.00 + i0.0.04$ |
| | $\lvert g_i \rvert$ | $0.32$ | $\mathbf{2.77}$ | $0.74$ | $0.02$ | $0.06$ | $0.04$ |
| $4506.99 + i1.03$ | | | | | | | |
| | $g_i$ | $0.27 - i0.02$ | $0.02 - i0.03$ | $0.02 - i0.02$ | $0.00 - i0.03$ | $\mathbf{1.56 - i0.07}$ | $0.00 - i0.05$ |
| | $\lvert g_i \rvert$ | $0.27$ | $0.03$ | $0.03$ | $0.03$ | $\mathbf{1.56}$ | $0.05$ |
| $4580.96 + i0.34$ | | | | | | | |
| | $g_i$ | $0.14 - i0.01$ | $0.01 - i0.01$ | $0.01 - i0.01$ | $\mathbf{1.54 - i0.02}$ | $0.02 - i0.00$ | $0.00 - i0.04$ |
| | $\lvert g_i \rvert$ | $0.14$ | $0.01$ | $0.02$ | $\mathbf{1.54}$ | $0.02$ | $0.04$ |
| $4650.58 + i1.48$ | | | | | | | |
| | $g_i$ | $0.29 - i0.02$ | $0.02 - i0.01$ | $0.03 - i0.02$ | $0.03 - i0.01$ | $0.03 - i0.00$ | $\mathbf{1.40 - i0.13}$ |
| | $\lvert g_i \rvert$ | $0.29$ | $0.03$ | $0.03$ | $0.03$ | $0.03$ | $\mathbf{1.41}$ |

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

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

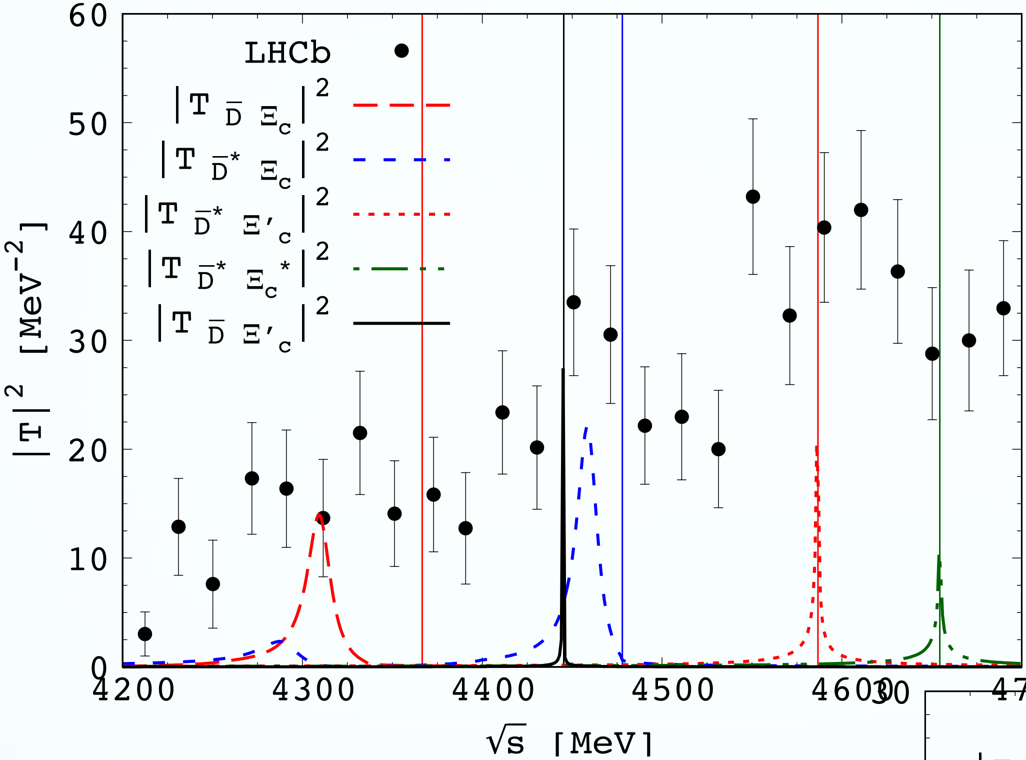
$a_\mu(\mu = 1\ \text{GeV}) = -1.94$

| 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 | 4366.61 | 4254.80 | 4445.34 | 4477.92 | 4398.66 | 4586.66 | 4654.48 |
| $4310.53 + i8.23$ | $P^{\Lambda}_{\psi s}(4338)^0$ | | | | | | | | |
| $\lvert g_i \rvert$ | 0.15 | 0.27 | **2.33** | 0.69 | 0.00 | 0.04 | 0.09 | 0.01 | 0.02 |
| $\Gamma_i$ | 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 |
| $\Gamma_i$ | 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 |
| $\Gamma_i$ | 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? | | | | | | | | | |
| $\lvert g_i \rvert$ | – | – | – | – | – | – | – | – | – |

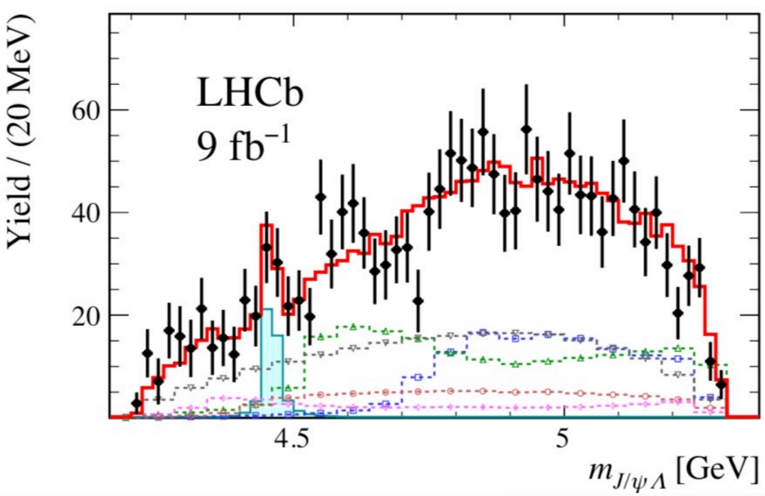
- $J = 3/2,\ I = 0$

| Chan. | $J/\psi\Lambda$ | $\bar{D}^*\Xi_c$ | $\bar{D}_s^*\Lambda_c$ | $\bar{D}^*\Xi_c'$ | $\bar{D}\Xi_c^*$ | $\bar{D}^*\Xi_c^*$ |
|---|---|---|---|---|---|---|
| Thres. | 4212.58 | 4477.92 | 4398.66 | 4586.66 | 4513.17 | 4654.48 |
| $4459.02 + i6.83$ | | $P_{cs}(4459)$ | | | | |
| $\|g_i\|$ | 0.28 | **2.16** | 0.61 | 0.02 | 0.04 | 0.03 |
| $\Gamma_i$ | 2.00 | – | 11.15 | – | – | – |
| Br. | 14.68% | – | 81.64% | – | – | – |
| 4586.66? | | | | | | |
| $\|g_i\|$ | – | – | – | – | – | – |
| 4513.17? | | | | | | |
| $\|g_i\|$ | – | – | – | – | – | – |
| 4654.48? | | | | | | |
| $\|g_i\|$ | – | – | – | – | – | – |

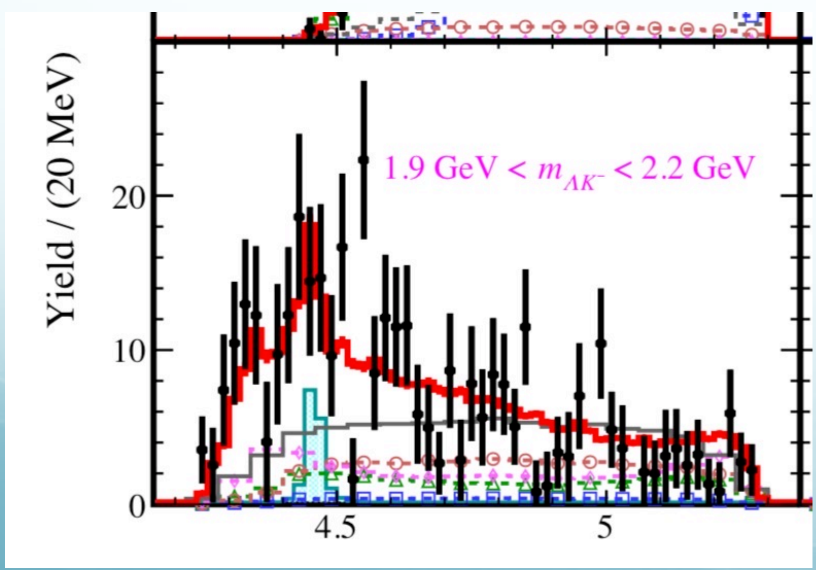
*CWX*, J. J. Wu and B. S. Zou, Phys. Rev. D 103 (2021) 054016.



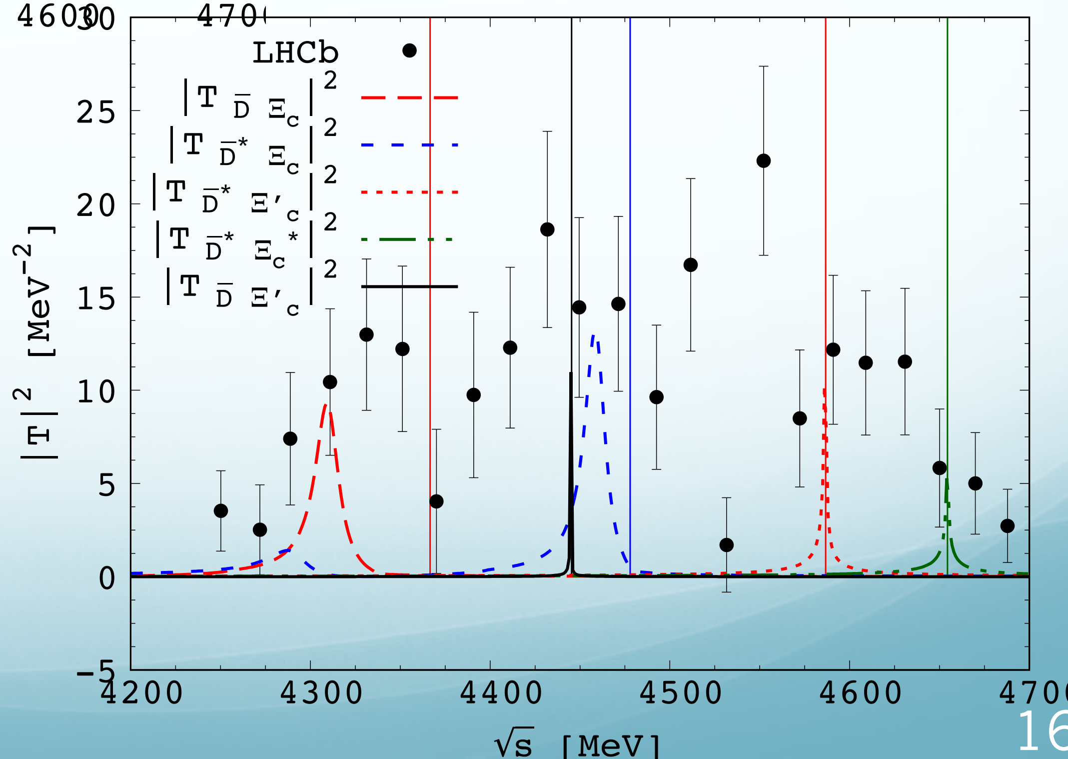
LHCb
$|T_{\bar{D}\Xi_c}|^2$
$|T_{\bar{D}^*\Xi_c}|^2$
$|T_{\bar{D}^*\Xi'_c}|^2$
$|T_{\bar{D}^*\Xi_c^*}|^2$
$|T_{\bar{D}\Xi'_c}|^2$
$|T|^2$ [MeV$^{-2}$]
$\sqrt{s}$ [MeV]

LHCb
9 fb$^{-1}$
Yield / (20 MeV)
$m_{J/\psi\Lambda}$ [GeV]

Yield / (20 MeV)
1.9 GeV < $m_{\Lambda K^-}$ < 2.2 GeV

LHCb
$|T_{\bar{D}\Xi_c}|^2$
$|T_{\bar{D}^*\Xi_c}|^2$
$|T_{\bar{D}^*\Xi'_c}|^2$
$|T_{\bar{D}^*\Xi_c^*}|^2$
$|T_{\bar{D}\Xi'_c}|^2$
$|T|^2$ [MeV$^{-2}$]
$\sqrt{s}$ [MeV]

# §4. Summary

- Our results of bound states ——molecular states

a $\bar{D}\Xi_c$ state
Having $J = 1/2$.
$4310.53$
$P_{\psi s}^{\Lambda}(4338)^0$
$\bar{D}\Xi_c'$
$P_c(4312)^+$

?

a $\bar{D}\Xi_c^*$ state
With $J = 3/2$.
$P_c(4450)$

?

a $\bar{D}^*\Xi_c$ state
Degenerate in $J = 1/2,\ 3/2$.
$P_{cs}(4459)$
$\bar{D}^*\Xi_c'$
$P_c(4440)^+$
$P_c(4457)^+$

a $\bar{D}^*\Xi_c^*$ state
Degenerate in $J = 1/2,\ 3/2,\ 5/2$.

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

***Thanks for your attention!***