Comparison between the P_c and P_{cs} states

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Based on Phys. Rev. D 106, 116017

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- Framework
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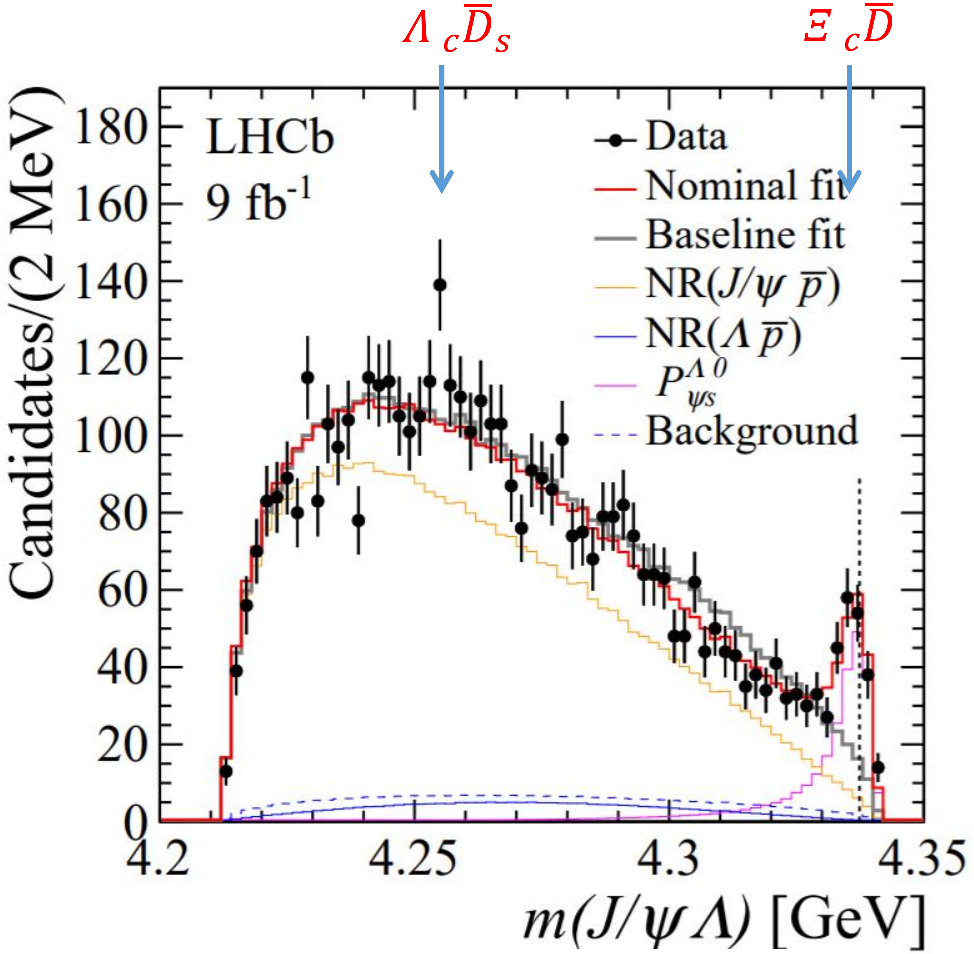
Motivation



$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4 \quad \text{MeV}$$
$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3 \quad \text{MeV}$$

arXiv:2210.10346

Other reported P_c and P_{cs} states

	Mass (MeV)	BE (MeV)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$-8.9^{+6.8}_{-0.9}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$-21.8^{+4.3}_{-4.9}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$-4.8^{+4.1}_{-1.8}$
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$-19.7^{+5.5}_{-3.1}$

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What is the correspondence between the P_c and P_{cs} states if we consider a flavor-spin symmetry?

Hadronic molecules   Rescattering effects   Compact pentaquark states

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Motivation

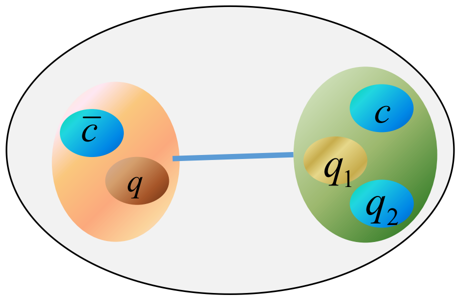
P_c		P_{cs}			
$\Lambda_c\bar{D}$	4153.7	$\Lambda_c\bar{D}_s$	4255.5	$\Xi_c\bar{D}$	4336.7
$\Lambda_c\bar{D}^*$	4295.0	$\Lambda_c\bar{D}_s^*$	4398.7	$\Xi_c\bar{D}^*$	4478.0
$\Sigma_c\bar{D}$	4320.8	$\Sigma_c\bar{D}_s$	4422.5	$\Xi_c'\bar{D}$	4446.0
$\Sigma_c^*\bar{D}$	4385.4	$\Sigma_c^*\bar{D}_s$	4487.1	$\Xi_c^*\bar{D}$	4513.2
$\Sigma_c\bar{D}^*$	4462.1	$\Sigma_c\bar{D}_s^*$	4565.7	$\Xi_c'\bar{D}^*$	4587.4
$\Sigma_c^*\bar{D}^*$	4526.7	$\Sigma_c^*\bar{D}_s^*$	4630.3	$\Xi_c^*\bar{D}^*$	4654.5

Two types of meson-baryon thresholds for the P_{cs} states

Can we understand the $P_{cs}(4255)$ and $P_{cs}(4338)$ simultaneous through a coupled-channel effect?

Framework

Hadronic Molecule



Boson exchange potential

S-wave interaction

Scalar mesons: a_0, b_0, f_0, σ_0 $\tilde{g}_s$

Axial-vector mesons: a_1,b_1, f_1, h_1 $\tilde{g}_a$

$$\frac{g^2}{m_{\text{ex}}^2 + q^2} \approx \frac{g^2}{m_{\text{ex}}^2} \approx \tilde{g}_s/\tilde{g}_a$$

$$\mathcal{V} = C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

$$\mathcal{V} = \tilde{g}_s \boldsymbol{\lambda}_1 \cdot \boldsymbol{\lambda}_2 + \tilde{g}_a \boldsymbol{\lambda}_1 \cdot \boldsymbol{\lambda}_2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

Coupled-channel Lippmann-Schwinger equation (LSE)

$$\mathbb{T}(E) = \mathbb{V} + \mathbb{V}\mathbb{G}(E)\,\mathbb{T}(E)$$

$$\mathbb{V} = \begin{pmatrix} v_{11} & \cdots & v_{1i} & \cdots & v_{1n} \\ \vdots & & \vdots & & \vdots \\ v_{j1} & \cdots & v_{ji} & \cdots & v_{jn} \\ \vdots & & \vdots & & \vdots \\ v_{n1} & \cdots & v_{ni} & \cdots & v_{nn} \end{pmatrix} \qquad \mathbb{T}(E) = \begin{pmatrix} t_{11}(E) & \cdots & t_{1i}(E) & \cdots & t_{1n}(E) \\ \vdots & & \vdots & & \vdots \\ t_{j1}(E) & \cdots & t_{ji}(E) & \cdots & t_{jn}(E) \\ \vdots & & \vdots & & \vdots \\ t_{n1}(E) & \cdots & t_{ni}(E) & \cdots & t_{nn}(E) \end{pmatrix}$$

$$\mathbb{G}(E) = \mathrm{diag}\left\{G_1(E), \cdots, G_i(E), \cdots, G_n(E)\right\}$$

$$G_i = \frac{1}{2\pi^2}\int dq \frac{q^2}{E - \sqrt{m_{i1}^2 + q^2} - \sqrt{m_{i2}^2 + q^2}} u^2(\Lambda)$$

$$u(\Lambda) = (1 + q^2/\Lambda^2)^{-2} \qquad \Lambda = 1.0\ \mathrm{GeV}$$

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Numerical results and discussion

		Our		Exp	
State	J^P	Mass	Γ	Mass	Width
$P_c(4312)$	$\frac{1}{2}^-$	$4308.2^{+2.6}_{-4.5}$	$2.6^{+2.4}_{-1.7}$	$4311.9^{+7.0}_{-0.9}$	10 ± 5
$P_c(4440)$	$\frac{1}{2}^-$	$4440.3^{+4.0}_{-5.0}$ (input)	$9.8^{+4.6}_{-5.8}$	$4440.3^{+4.0}_{-5.0}$	21^{+10}_{-11}
$P_c(4457)$	$\frac{3}{2}^-$	$4457.7^{+4.0}_{-1.8}$ (input)	$2.0^{+1.4}_{-0.8}$	$4457.3^{+4.0}_{-1.8}$	$6.4^{+6.0}_{-2.8}$
$P_c(4380)$	$\frac{3}{2}^-$	$4373.3^{+3.4}_{-6.8}$	$5.2^{+20.2}_{-3.5}$	–	–
$P_c(4500)$	$\frac{1}{2}^-$	$4501.4^{+5.0}_{-6.2}$	$8.8^{+17.2}_{-5.4}$	–	–
$P_c(4510)$	$\frac{3}{2}^-$	$4513.4^{+5.8}_{-3.1}$	$7.6^{+9.4}_{-0.0}$	–	–

$\tilde{g}_s = 8.28 \quad \mathrm{GeV}^{-2}$ $\tilde{g}_a = -1.46 \quad \mathrm{GeV}^{-2}$

Dominant Spin-splitting structure

Numerical results and discussion

P_ψ^N	Mass	BE	$P_{\psi s}^\Lambda$	Mass	BE	V
$[\Sigma_c\bar{D}]^{\frac{1}{2}}$	$4312.7^{+4.1}_{-2.6}$	$-8.1^{+4.1}_{-2.6}$	$[\Xi_c\bar{D}]^{\frac{1}{2}}$	$4328.5^{+4.1}_{-2.7}$	$-8.2^{+4.1}_{-2.7}$	$-\frac{10}{3}\tilde{g}_s$
			$[\Xi_c\bar{D}^*]^{\frac{1}{2},\frac{3}{2}}$	$4468.3^{+4.5}_{-2.9}$	$-9.7^{+4.5}_{-2.9}$	
$[\Sigma_c^*\bar{D}]^{\frac{3}{2}}$	$4376.9^{+4.2}_{-2.7}$	$-8.5^{+4.2}_{-2.7}$	$[\Xi_c'\bar{D}]^{\frac{1}{2}}$	$4437.2^{+4.5}_{-2.8}$	$-8.8^{+4.3}_{-2.8}$	
			$[\Xi_c^*\bar{D}]^{\frac{3}{2}}$	$4503.9^{+4.4}_{-2.8}$	$-9.3^{+4.4}_{-2.8}$	
$[\Sigma_c\bar{D}^*]^{\frac{1}{2}}$	$4438.9^{+4.9}_{-8.9}$	$-23.2^{+4.9}_{-8.9}$	$[\Xi_c'\bar{D}^*]^{\frac{1}{2}}$	$4562.9^{+2.8}_{-9.1}$	$-24.5^{+2.8}_{-9.1}$	$-\frac{10}{3}\tilde{g}_s+\frac{40}{9}\tilde{g}_a$
$[\Sigma_c\bar{D}^*]^{\frac{3}{2}}$	$4457.5^{+3.7}_{-1.8}$	$-4.6^{+3.7}_{-1.8}$	$[\Xi_c'\bar{D}^*]^{\frac{3}{2}}$	$4582.2^{+4.0}_{-2.0}$	$-5.2^{+4.0}_{-2.0}$	$-\frac{10}{3}\tilde{g}_s-\frac{20}{9}\tilde{g}_a$
$[\Sigma_c^*\bar{D}^*]^{\frac{1}{2}}$	$4498.8^{+6.6}_{-6.0}$	$-27.9^{+6.6}_{-6.0}$	$[\Xi_c^*\bar{D}^*]^{\frac{1}{2}}$	$4625.3^{+6.8}_{-12.7}$	$-29.2^{+6.8}_{-12.7}$	$-\frac{10}{3}\tilde{g}_s+\frac{50}{9}\tilde{g}_a$
$[\Sigma_c^*\bar{D}^*]^{\frac{3}{2}}$	$4510.3^{+4.1}_{-4.1}$	$-16.4^{+4.1}_{-4.1}$	$[\Xi_c^*\bar{D}^*]^{\frac{3}{2}}$	$4637.9^{+4.3}_{-4.2}$	$-16.6^{+4.3}_{-4.2}$	$-\frac{10}{3}\tilde{g}_s+\frac{20}{9}\tilde{g}_a$

Very close to the results obtained from the coupled-channel calculation

Numerical results and discussion

TABLE II. The matrix elements of $[\langle \boldsymbol{\lambda}_1 \cdot \boldsymbol{\lambda}_2 \rangle, \langle \boldsymbol{\lambda}_1 \cdot \boldsymbol{\lambda}_2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \rangle]$ for the meson-baryon channels associated with the $J^P = 1/2^-$ and $3/2^-$ P_c systems.

$\mathbb{V}^{P_c}_{1/2}$					
Channel	$\Lambda_c \bar{D}$	$\Lambda_c \bar{D}^*$	$\Sigma_c \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\Lambda_c \bar{D}$	$[\frac{2}{3},0]$	$[0,0]$	$[0,0]$	$[0,2\sqrt{3}]$	$[0,2\sqrt{6}]$
$\Lambda_c \bar{D}^*$		$[\frac{2}{3},0]$	$[0,2\sqrt{3}]$	$[0,-4]$	$[0,2\sqrt{2}]$
$\Sigma_c \bar{D}$			$[-\frac{10}{3},0]$	$[0,-\frac{20}{3\sqrt{3}}]$	$[0,\frac{10\sqrt{\frac{2}{3}}}{3}]$
$\Sigma_c \bar{D}^*$				$[-\frac{10}{3},\frac{40}{9}]$	$[0,\frac{10\sqrt{2}}{9}]$
$\Sigma_c^* \bar{D}^*$					$[-\frac{10}{3},\frac{50}{9}]$

$\mathbb{V}^{P_c}_{3/2}$				
Channel	$\Lambda_c \bar{D}^*$	$\Sigma_c^* \bar{D}$	$\Sigma_c \bar{D}^*$	$\Sigma_c^* \bar{D}^*$
$\Lambda_c \bar{D}^*$	$[\frac{2}{3},0]$	$[0,-2\sqrt{3}]$	$[0,2]$	$[0,2\sqrt{5}]$
$\Sigma_c^* \bar{D}$		$[-\frac{10}{3},0]$	$[0,-\frac{10}{3\sqrt{3}}]$	$[0,-\frac{10\sqrt{\frac{5}{3}}}{3}]$
$\Sigma_c \bar{D}^*$			$[-\frac{10}{3},-\frac{20}{9}]$	$[0,\frac{10\sqrt{5}}{9}]$
$\Sigma_c^* \bar{D}^*$				$[-\frac{10}{3},\frac{20}{9}]$

$$\tilde{g}_s = 8.28 \quad \mathrm{GeV}^{-2}$$

$$\tilde{g}_a = -1.46 \quad \mathrm{GeV}^{-2}$$

Dominant

Spin-splitting structure

Numerical results and discussion

TABLE III. The matrix elements of $[\langle \boldsymbol{\lambda}_1 \cdot \boldsymbol{\lambda}_2 \rangle, \langle \boldsymbol{\lambda}_1 \cdot \boldsymbol{\lambda}_2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \rangle]$ for the meson-baryon channels associated with the $J^P = 1/2^-$ and $3/2^-$ P_{cs} systems.

$\mathbb{V}^{P_{cs}}_{1/2}$							
Channel	$\Lambda_c \bar{D}_s$	$\Lambda_c \bar{D}_s^*$	$\Xi_c \bar{D}$	$\Xi_c \bar{D}^*$	$\Xi_c' \bar{D}$	$\Xi_c' \bar{D}^*$	$\Xi_c^* \bar{D}^*$
$\Lambda_c \bar{D}_s$	$[-\frac{4}{3},0]$	$[0,0]$	$[2\sqrt{2},0]$	$[0,0]$	$[0,0]$	$[0,2\sqrt{2}]$	$[0,4]$
$\Lambda_c \bar{D}_s^*$		$[-\frac{4}{3},0]$	$[0,0]$	$[2\sqrt{2},0]$	$[0,2\sqrt{2}]$	$[0,-4\sqrt{\frac{2}{3}}]$	$[0,\frac{4}{\sqrt{3}}]$
$\Xi_c \bar{D}$			$[-\frac{10}{3},0]$	$[0,0]$	$[0,0]$	$[0,2]$	$[0,2\sqrt{2}]$
$\Xi_c \bar{D}^*$				$[-\frac{10}{3},0]$	$[0,2]$	$[0,-\frac{4}{\sqrt{3}}]$	$[0,2\sqrt{\frac{2}{3}}]$
$\Xi_c' \bar{D}$					$[-\frac{10}{3},0]$	$[0,-\frac{20}{3\sqrt{3}}]$	$[0,\frac{10\sqrt{\frac{2}{3}}}{3}]$
$\Xi_c' \bar{D}^*$						$[-\frac{10}{3},\frac{40}{9}]$	$[0,\frac{10\sqrt{2}}{9}]$
$\Xi_c^* \bar{D}^*$							$[-\frac{10}{3},\frac{50}{9}]$

$\mathbb{V}^{P_{cs}}_{3/2}$					
Channel	$\Lambda_c \bar{D}_s^*$	$\Xi_c \bar{D}^*$	$\Xi_c^* \bar{D}$	$\Xi_c' \bar{D}^*$	$\Xi_c^* \bar{D}^*$
$\Lambda_c \bar{D}_s^*$	$[-\frac{4}{3},0]$	$[2\sqrt{2},0]$	$[0,-2\sqrt{2}]$	$[0,2\sqrt{\frac{2}{3}}]$	$[0,2\sqrt{\frac{10}{3}}]$
$\Xi_c \bar{D}^*$		$[-\frac{10}{3},0]$	$[0,-2]$	$[0,\frac{2}{\sqrt{3}}]$	$[0,2\sqrt{\frac{5}{3}}]$
$\Xi_c^* \bar{D}$			$[-\frac{10}{3},0]$	$[0,-\frac{10}{3\sqrt{3}}]$	$[0,-\frac{10\sqrt{\frac{5}{3}}}{3}]$
$\Xi_c' \bar{D}^*$				$[-\frac{10}{3},-\frac{20}{9}]$	$[0,\frac{10\sqrt{5}}{9}]$
$\Xi_c^* \bar{D}^*$					$[-\frac{10}{3},\frac{20}{9}]$

$\tilde{g}_s = 8.28 \quad \mathrm{GeV}^{-2}$

Dominant

$\tilde{g}_a = -1.46 \quad \mathrm{GeV}^{-2}$

Spin-splitting structure

For $J = \frac{1}{2}, \Lambda_c \bar{D}_s - \Xi_c \bar{D}, \Lambda_c \bar{D}_s^* - \Xi_c \bar{D}^*$

For $J = \frac{3}{2}, \Lambda_c \bar{D}_s^* - \Xi_c \bar{D}^*$ coupling

For $J = \frac{1}{2}, \Lambda_c \bar{D}_s - \Xi_c \bar{D}, \Lambda_c \bar{D}_s^* - \Xi_c \bar{D}^*$

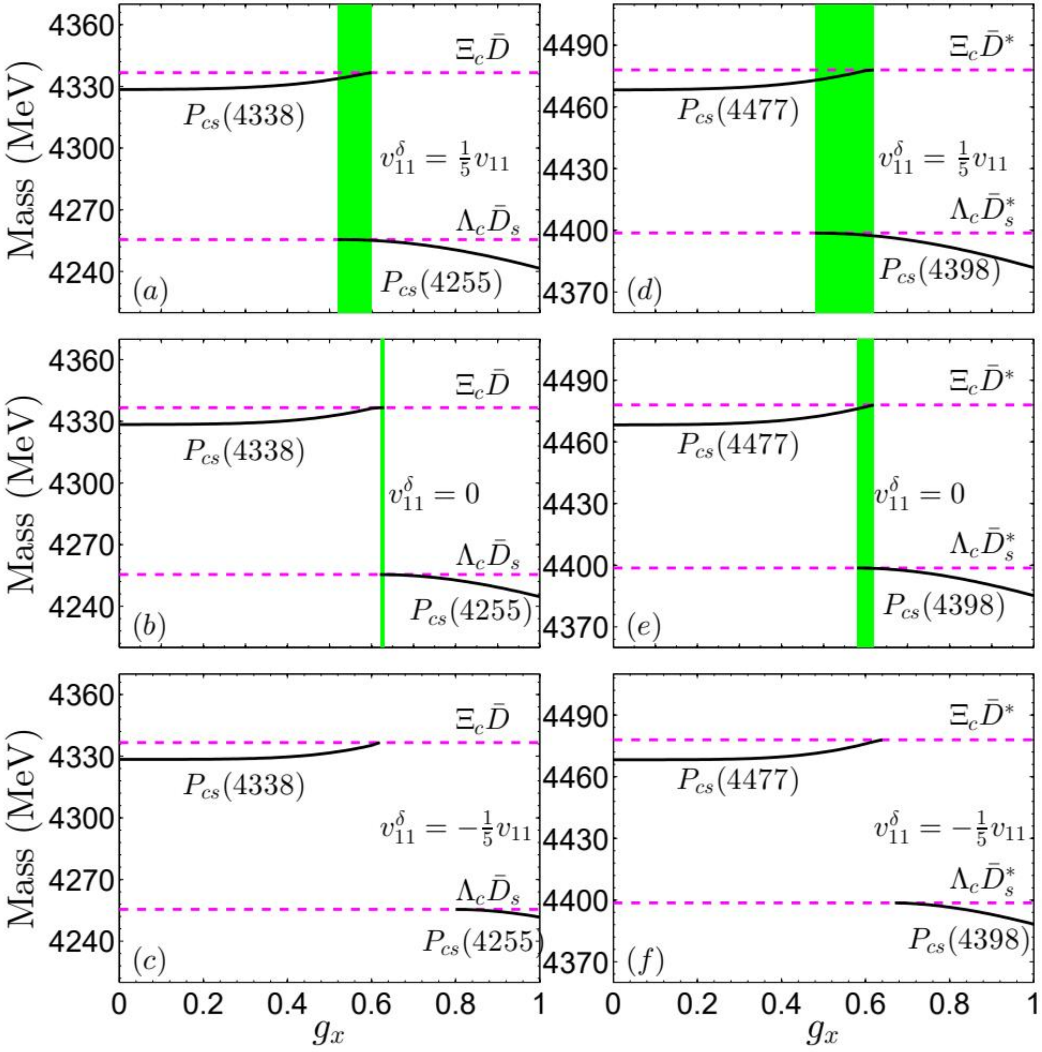
For $J = \frac{3}{2}, \Lambda_c \bar{D}_s^* - \Xi_c \bar{D}^*$ coupling

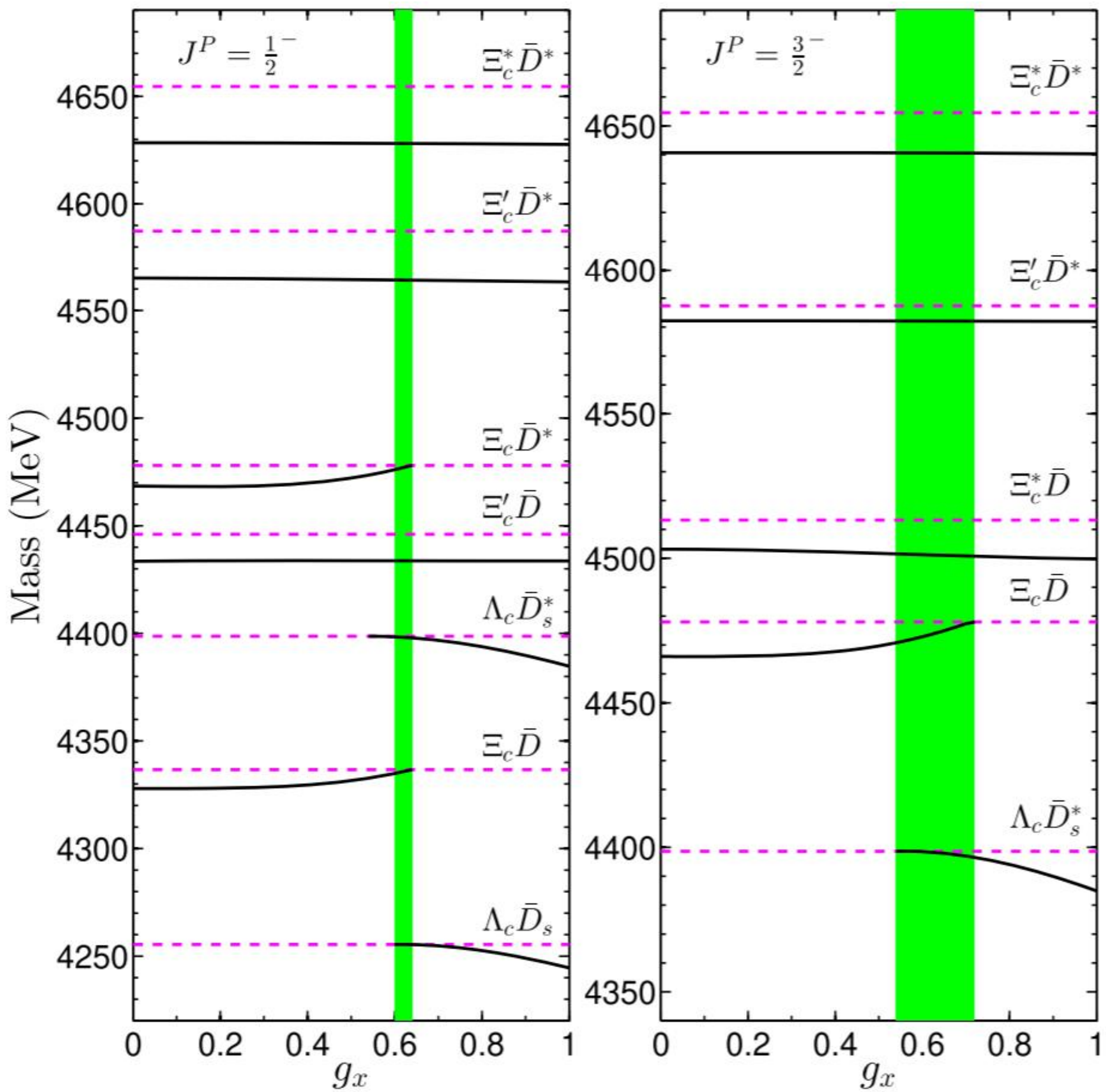
$$\mathbb{V} = \begin{pmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{pmatrix}$$

$$v_{11} = -\frac{4}{3}\tilde{g}_s, \quad v_{22} = -\frac{10}{3}\tilde{g}_s,$$
$$v_{12} = v_{21} = 2\sqrt{2}\tilde{g}_s g_x.$$

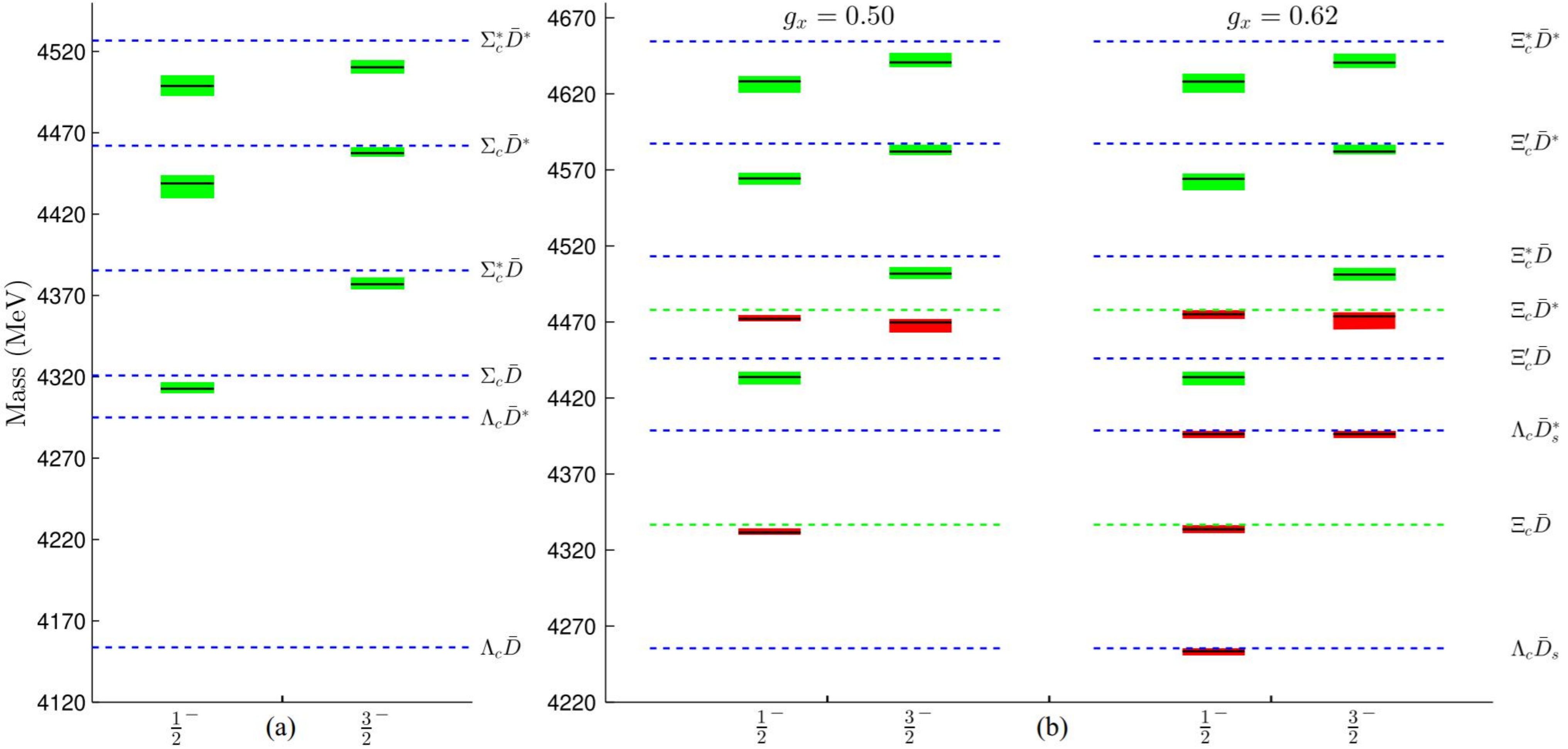
$$v'_{11} = v_{11} + v^{\delta}_{11}$$

$$v^{\delta}_{11} = 0, \pm\frac{1}{5}v_{11}$$





$\Lambda_c \bar{D}_s^{(*)} - \Xi_c \bar{D}^{(*)}$ coupling plays a special role in shifting the masses of P_{cs} states



Correspondence of the P_c and P_{cs} states within the F-S symmetry

$g_x = 0.50$	$g_x = 0.62$
$P_c(4312) \leftrightarrow P_{cs}(4434)$	$P_c(4312) \leftrightarrow P_{cs}(4472)$
$P_c(4440) \leftrightarrow P_{cs}(4564)$	$P_c(4440) \leftrightarrow P_{cs}(4564)$
$P_c(4457) \leftrightarrow P_{cs}(4582)$	$P_c(4457) \leftrightarrow P_{cs}(4582)$

Summary

1. The $\Lambda_c \bar{D}_s{}^{(*)} - \Xi_c \bar{D}^{(*)}$ coupling plays a special role in shifting the masses of P_{cs} states.

2. We present a complete correspondence between the P_c and P_{cs} states.

Thanks for your attention!