Mass spectra and strong decays of $P_{\psi}^{N}(4440, 4457)^{+}$

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OUTLINE

- 1. Introduction
- 2. P_{ψ}^{N} as the $\bar{D}^{*}\Sigma_{c}$ molecular state
- 3. Decay mode and involved effective Lagrangians
- 4. Strong decays $P_{\psi}^{N}(4440)^{+}$ and $P_{\psi}^{N}(4457)$
- 5. Numerical results and discussions

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Exotic hadrons at LHC



Pentaquark with hidden charms

- In 2015 LHCb detected 2 pentaquark states with quark content $c\bar{c}qqq$, $P_c(4380)$ and $P_c(4450)$, PRL115, 072001 (2015).
- In 2019 LHCb discovered $P_c(4312)^+$ and resolved the previous $P_c(4450)$ as two peaks $P_c(4440)^+$ and $P_c(4457)^+$, PRL122, 222001 (2019).



About this talk

 $\circ~$ Study the mass spectra and strong decays of $P_{\psi}^{N}(4440,4457)$ under the molecule picture.

State	Mass[MeV]	$\Gamma \ [MeV]$
$P_{\psi}^{N}(4440)^{+}$ $P_{\psi}^{N}(4457)^{+}$	$\begin{vmatrix} 4440.3 \pm 1.3^{+4.1}_{-4.7} \\ 4457.3 \pm 0.6^{+4.1}_{-1.7} \end{vmatrix}$	$\begin{array}{c} 20.6 \pm 4.9^{+8.7}_{-10.1} \\ 6.4 \pm 2.0^{+5.7}_{-1.9} \end{array}$

- Methodology: combining the effective field theory and Bethe-Salpeter framework.
- Based on arXiv: 2503.08440.
- Collaborator: Chao-Hsi Chang(ITP&UCAS), Xin Tong(NPU), Xiao-Ze Tan(DESY&FDU), Tianhong Wang(HIT), Guo-Li Wang(Hebei Univ.).

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BSE of bound state for J = 1 and $\frac{1}{2}$ constituents

• P_{ψ}^{N} as the $\bar{D}^{*}\Sigma_{c}$ molecular states: $P_{\psi 1/2}^{N}$ and $P_{\psi 3/2}^{N}$.



Bethe-Salpeter equation for a vector meson and a baryon reads

$$\Gamma^{\alpha}(P,q,r) = \int \frac{\mathrm{d}^4 k}{(2\pi)^4} (-\mathrm{i}) K^{\alpha\beta}(k,q) [S(k_2)\Gamma^{\gamma}(P,k,r)D_{\gamma\beta}(k_1)],$$

- BS wave function $\psi_{\alpha}(q) = S(p_2)\Gamma^{\beta}(P,q)D_{\beta\alpha}(p_1).$
- Effective interaction kernel: $K(k,q) \sim K(k_{\perp} q_{\perp})$.
- Salpeter wave function, $\varphi_{\alpha} = -i\frac{1}{2\pi}\int dq_P\psi_{\alpha}(q)$.

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Instantaneous approximation

• Under the instataneous approximation, the BSE can be rewritten as

$$M\varphi_{\alpha} = (w_1 + w_2)H_2(p_{2\perp})\varphi_{\alpha} + \frac{1}{2w_1}d_{\alpha\beta}(p_1)\gamma_0\Gamma^{\beta}(q_{\perp}).$$

• Vertex $\Gamma(q_{\perp})$ is expressed as the integral of the Salpeter wave function,

$$\Gamma^{\beta}(q_{\perp}) = \int \frac{\mathrm{d}^{3}k_{\perp}}{(2\pi)^{3}} K^{\beta\gamma}(k_{\perp} - q_{\perp})\varphi_{\gamma}(k_{\perp}).$$

• Normalization condition

$$-\mathrm{i} \int \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \frac{\mathrm{d}^4 k}{(2\pi)^4} \bar{\psi}^{\alpha}(P,q,\bar{r}) \frac{\partial}{\partial P^0} I_{\alpha\beta}(P,k,q) \psi^{\beta}(P,k,r) = 2M \delta_{r\bar{r}}.$$

• Integral kernel in the normalization condition

$$I_{\alpha\beta}(P,q,k) = (2\pi)^2 \delta^4(k-q) S^{-1}(p_2) D_{\alpha\beta}^{-1}(p_1) + i K_{\alpha\beta}(P,k,q).$$

BS wave functions for $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$

$$\varphi J^P = \frac{1}{2}^-$$
 formed by a 1⁻ meson and $\frac{1}{2}^+$ baryon
 $\varphi_{\alpha}(x) = A_{\alpha}(x)u(P,r)$
 $A_{\alpha} = (g_1 + g_2 \not) (\gamma_{\alpha} - \hat{P}_{\alpha}) + (g_3 + g_4 \not z) x_{\alpha}$

where introduced a spacelike variant $x_{\alpha} = \frac{q_{\perp \alpha}}{|\vec{q}|}$.

$$J^{P} = \frac{3}{2}^{-}$$

$$\varphi_{\alpha}(x) = A_{\alpha\beta}\gamma_{5}u^{\beta}(P,r)$$

$$A_{\alpha\beta}(x) = (h_{1} + h_{2}\not{x}) g_{\alpha\beta} + (h_{3} + h_{4}\not{x}) (\gamma_{\alpha} + \hat{P}_{\alpha})x_{\beta}$$

$$+ i\epsilon_{\alpha\beta}\hat{P}_{x}(h_{5} + h_{6}\not{x})\gamma_{5} + (h_{7} + h_{8}\not{x}) x_{\alpha}x_{\beta},$$

where $u^{\beta}(P, r)$ is the Rarita-Schwinger spinor.

• Normalization is expressed as

$$\int \frac{\mathrm{d}^3 q_\perp}{(2\pi)^3} 2w_1 \vartheta^{\alpha\beta} \left(\bar{u}_{\bar{r}}^{\nu} \gamma_5 \bar{A}_{\alpha\nu} \gamma_0 A_{\beta\mu} \gamma_5 u_r^{\mu} \right) = 2M \delta_{r\bar{r}}.$$

Interaction kernel

• $P_{\psi}^{N}(4440, 4457)^{+}$ (minimal quark content [*cc̄uud*]) is taken as the $\bar{D}^{*}\Sigma_{c}$ molecular state with isospin $|I, I_{3}\rangle = |\frac{1}{2}, +\frac{1}{2}\rangle$

$$\left|\frac{1}{2}, \frac{1}{2}\right\rangle = \frac{\sqrt{2}}{\sqrt{3}} \left|\Sigma_{c}^{++}D^{*-}\right\rangle - \frac{1}{\sqrt{3}} \left|\Sigma_{c}^{+}\bar{D}^{*0}\right\rangle$$

- Interaction kernels are calculated from the constituent particles $\bar{D}^*\Sigma_c$ scattering based on the one-boson $(\sigma, \pi, \eta, \rho, \omega)$ exchange.
- $\circ~$ For $P_{\psi}^{N}(4440,4457)^{+},$ the light (pseudo)scalar and vector mesons contribute.
- Throughout this work, the isospin symmetry is used

$$\begin{split} \langle \frac{1}{2}, \frac{1}{2} | H_{\text{eff}} | \frac{1}{2}, \frac{1}{2} \rangle &= \frac{3}{2} \left\langle \Sigma_c^{++} D^{*-} | H_{\text{eff}} | \Sigma_c^{++} D^{*-} \right\rangle - \frac{1}{2} \left\langle \Sigma_c^{+} \bar{D}^{*0} | H_{\text{eff}} | \Sigma_c^{+} \bar{D}^{*0} \right\rangle \\ H_{\text{eff}} &= \sum L_{\text{MM}i} L_{\text{BB}i}, \quad i = \sigma, \pi, \eta, \rho, \omega \end{split}$$

Effective Lagrangian

• Involved Lagrangian describing the charmed anti-heavy-light meson and a light scalar and vector meson reads

$$L_{\rm M} = g_{\rm s} \left\langle \bar{H}_{\bar{Q}} \sigma H_{\bar{Q}} \right\rangle + g \left\langle \bar{H}_{\bar{Q}} \psi \gamma_5 H_{\bar{Q}} \right\rangle - \beta \left\langle \bar{H}_{\bar{Q}} v_\alpha \rho^\alpha H_{\bar{Q}} \right\rangle - \lambda \left\langle \bar{H}_{\bar{Q}} \sigma^{\alpha\beta} F_{\alpha\beta} H_{\bar{Q}} \right\rangle,$$

• $H_{\bar{Q}}$ represents the field of the $\bar{D}^{(*)}$ doublet with $\bar{D} = (\bar{D}^0, D^-, D^-_s)^{\mathrm{T}}$

$$H_{\bar{Q}} = \left(\bar{D}^{*\mu}\gamma_{\mu} + \mathrm{i}\bar{D}\gamma_{5}\right)\frac{1-\psi}{2},$$

•
$$u_{\alpha} = -\frac{1}{f} \partial_{\alpha} \Sigma + \cdots, F_{\alpha\beta} = (\partial_{\alpha} \rho_{\beta} - \partial_{\beta} \rho_{\alpha})$$
 with $\rho = (g_V / \sqrt{2}) V.$

• Σ and V denote the 3 \times 3 light pseudoscalar and vector meson fields

$$\Sigma = \begin{bmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{bmatrix}, \quad V = \begin{bmatrix} \frac{(\rho^0 + \omega)}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{(\rho^0 - \omega)}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{bmatrix}.$$

Chiral effective Lagrangian for baryons

• Effective Lagrangian of the heavy-light baryon and light vector mesons

$$L_{\rm B} = \frac{3}{2} g_1 \mathrm{i} \epsilon^{\alpha\beta\mu\nu} \left\langle \bar{S}_{\alpha} u_{\beta} S_{\mu} \right\rangle + \beta_S \left\langle \bar{S}_{\alpha} v_{\beta} \rho^{\beta} S^{\alpha} \right\rangle + \mathrm{i} \lambda_S \left\langle \bar{S}_{\alpha} F^{\alpha\beta} S_{\beta} \right\rangle + l_S \left\langle \bar{S}_{\alpha} \sigma S^{\alpha} \right\rangle$$

• Baryon spin doublet

$$S_{\alpha} = -\frac{1}{\sqrt{3}}(\gamma_{\alpha} + v_{\alpha})\gamma^5 B + B_{\alpha}^*$$

• Systematic baryon sextet B in 3×3 matrix

$$B = \begin{bmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}} \Sigma_c^{+} & \frac{1}{\sqrt{2}} \Xi_c^{\prime+} \\ \frac{1}{\sqrt{2}} \Sigma_c^{+} & \Sigma_c^{0} & \frac{1}{\sqrt{2}} \Xi_c^{\prime0} \\ \frac{1}{\sqrt{2}} \Xi_c^{\prime+} & \frac{1}{\sqrt{2}} \Xi_c^{\prime0} & \Omega_c^{0} \end{bmatrix}.$$

Interaction kernel under one-boson exchange

• Under one-boson exchange, interaction kernel for $\bar{D}^*\Sigma_c$ in isospin- $\frac{1}{2}$

$$K_{\alpha\beta}(s) = K_1 \gamma_\alpha \gamma_\beta + K_2 (\gamma_\alpha \hat{s}_\beta - \gamma_\beta \hat{s}_\alpha) \hat{s} \cdot \gamma + K_3 (\hat{P}_\alpha \hat{s}_\beta - \hat{P}_\beta \hat{s}_\alpha) + K_4 g_{\alpha\beta}$$

• Exchanged momentum $s, \hat{s} = \frac{s}{|s|},$

$$\begin{split} K_i &= F^2(s^2) M_{\bar{D}^*} V_i, \\ V_1 &= \frac{1}{3} \frac{gg_1}{f^2} s^2 (6D_\pi - D_\eta), \\ V_2 &= \frac{1}{3} \frac{gg_1}{f^2} s^2 (6D_\pi - D_\eta) + \frac{1}{3} \lambda \lambda_S g_V^2 s^2 (4D_\rho - 2D_\omega), \\ V_3 &= \beta_S \lambda_s g_V^2 (2D_\rho - D_\omega), \\ V_4 &= -\frac{1}{3} \frac{gg_1}{f^2} s^2 (6D_\pi - D_\eta) + 2g_s l_s D_\sigma + \frac{1}{2} \beta \beta_S g_V^2 (2D_\rho - D_\omega). \end{split}$$

• Propagator $D_{\eta} \equiv (s^2 - m_{\eta}^2)^{-1}$, similar for $\sigma, \pi, \rho, \omega$.

Regulator function

• It is clear that when $(-s^2) \to \infty$, the obtained $V_{1(2,4)}$ does not converge to 0,

$$V_{1,2,4} \sim \frac{s^2}{s^2 - m_3^2} \sim 1$$

- Caused by the Lagrangian containing the derivative item.
- To obtain the stable bound state, it is necessary to introduce a regulator function to suppress the contribution from high momentum.
- Propagator-type regulator function

$$F(s^2) = \frac{m_{\Lambda}^2}{s^2 - m_{\Lambda}^2}$$

where $m_{\Lambda} \sim 0.9 \,\text{GeV}$ is the only introduced cutoff parameter and the value is fixed by P_{ψ}^N mass.

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Main Decay Channels

- Eight decay channels are considered: $J/\psi p, \bar{D}^{*0}\Lambda_c^+, \eta_c p, \bar{D}^0\Lambda_c^+, D^-\Sigma_c^{++}, \bar{D}^0\Sigma_c^{++}, \bar{D}^0\Sigma_c^{++}$.
- $\circ \ P_{\psi}^{N}(4440,4457)^{+}$ decay to (V+B) by exchanging pseudoscalar and vector mesons
 - 1. $J/\psi p$ by D and D^* exchange
 - 2. $\bar{D}^{*0}\Lambda_c^+$ by π and ρ exchange
- $P_{\psi}^{N}(4440, 4457)^{+}$ decay to (P+B)
 - 1. $\eta_c p$ by D and D^* exchange
 - 2. $\bar{D}\Lambda_c$ and $\bar{D}\Sigma_c$ by π , ρ and ω exchange
- $P_{\psi}^{N}(4440, 4457)^{+}$ decay to $(P + B^{*})$, $\bar{D}\Sigma_{c}^{*}$ by π , ρ and ω exchange.

Interaction between Charmonia and $D^{(*)}$

• Under symmetry of heavy quark spin, the effective Lagrangian between charmonia and the heavy-light mesons reads

$$L_R = ig_R \text{Tr} \left(\bar{R} H_Q \gamma_\alpha \partial^\alpha H_{\bar{Q}} - \bar{R} \partial^\alpha H_Q \gamma_\alpha H_{\bar{Q}} \right) + \text{H.c.}$$

• S-wave charmonium doublet

$$H_{Q} = \frac{1+\not}{2} (D^{*\alpha} \gamma_{\alpha} + iD\gamma_{5}), \ R = \frac{1+\not}{2} (\psi^{\mu} \gamma_{\mu} + i\eta_{c}\gamma_{5}) \frac{1-\not}{2}.$$

• Expand to obtain the Lagrangians

$$\begin{split} L_{D(*)\,\bar{D}(*)\,\psi^{\dagger}} &= +\,g_{\bar{D}\,D\psi}\mathrm{i}D\partial_{\alpha}\bar{D}\psi^{\dagger\,\alpha} \\ &+ g_{D\,\bar{D}^{*}\,\psi}\,\frac{1}{M_{\psi}}\epsilon^{\alpha\beta\mu\nu}(\partial_{\alpha}D\bar{D}_{\beta}^{*} - \partial_{\alpha}D_{\beta}^{*}\bar{D})\partial_{\mu}\psi^{\dagger}_{\nu} \\ &- g_{D^{*}\bar{D}^{*}\,\psi}\mathrm{i}(\partial_{\alpha}D_{\beta}^{*}\bar{D}^{*\alpha}\psi^{\dagger\,\beta} + 2D_{\alpha}^{*}\partial_{\beta}\bar{D}^{*\alpha}\psi^{\dagger\,\beta} + D^{*\alpha}\bar{D}_{\beta}^{*}\partial_{\alpha}\psi^{\dagger\,\beta}) \\ L_{D(*)\,\bar{D}(*)\,\eta^{\dagger}_{c}} &= -\,g_{D\,\bar{D}^{*}\,\eta_{c}}\mathrm{i}(D\bar{D}^{*\alpha} - D^{*\alpha}\bar{D})\partial_{\alpha}\eta^{\dagger}_{c} \\ &- g_{D^{*}\bar{D}^{*}\,\eta_{c}}\,\frac{1}{M_{\eta_{c}}}\epsilon^{\alpha\beta\mu\nu}\partial_{\alpha}D_{\beta}^{*}\bar{D}_{\mu}^{*}\partial_{\nu}\eta^{\dagger}_{c}, \end{split}$$

• Only one parameter g_R .

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Interaction for $D^{(*)}$ and Light Mesons

- Expand the chiral Lagrangian to obtain interactions needed.
- $\circ~$ The Lagrangian between $\bar{D}^{(*)}$ and light pseudoscalar mesons

$$\begin{split} L_{\bar{D}^{(*)}\Sigma\bar{D}^{(*)}} &= + g_{\bar{D}\Sigma\bar{D}^*} \mathrm{i}\bar{D}^{\dagger} \partial_{\alpha}\Sigma\bar{D}^{*\alpha} \\ &- g_{\bar{D}^*\Sigma\bar{D}} \mathrm{i}(\bar{D}^{*\alpha})^{\dagger} \partial_{\alpha}\Sigma\bar{D} \\ &+ g_{\bar{D}^*\Sigma\bar{D}^*} \epsilon^{\alpha\beta\mu\nu} \partial_{\alpha}(\bar{D}^*_{\beta})^{\dagger} \partial_{\mu}\Sigma\bar{D}^*_{\nu}, \end{split}$$

 $\,\circ\,$ Lagrangian for $\bar{D}^{(*)}$ and light vector mesons

$$\begin{split} L_{\bar{D}^{(*)}V\bar{D}^{(*)}} &= -g_{\bar{D}V\bar{D}}\mathrm{i}\partial_{\alpha}\bar{D}^{\dagger}V^{\alpha}\bar{D} \\ &+ g_{\bar{D}^{*}V\bar{D}}\epsilon^{\alpha\beta\mu\nu}\partial_{\alpha}\bar{D}^{*\dagger}_{\beta}\partial_{\mu}V_{\nu}\bar{D} \\ &- g_{\bar{D}V\bar{D}^{*}}\epsilon^{\alpha\beta\mu\nu}\partial_{\alpha}\bar{D}^{\dagger}\partial_{\beta}V_{\mu}\bar{D}^{*}_{\nu} \\ &+ g_{\bar{D}^{*}V\bar{D}^{*}}\mathrm{i}(A_{\mathrm{r}}\partial_{\alpha}\bar{D}^{*\dagger}_{\beta}V^{\alpha}\bar{D}^{*\beta} + \bar{D}^{*\dagger}_{\alpha}\partial_{\beta}V^{\alpha}\bar{D}^{*\beta} + \bar{D}^{*\dagger}_{\alpha}V_{\beta}\partial_{\alpha}\bar{D}^{*\beta}) \end{split}$$

with $A_{\rm r} = \frac{1}{2} \beta / \lambda M_{\langle \bar{D}^{*\dagger} \bar{D}^* \rangle}$.

Interaction for B and Light Mesons

- Expand the chiral Lagrangian to obtain interaction for baryon sextet and light mesons.
- $\circ~$ The Lagrangian between B and light pseudoscalar mesons

$$L_{BB\Sigma} = -g_{\bar{B}B\Sigma} \langle i\bar{B}\gamma_5\Sigma B \rangle + g_{BB^*\Sigma} \langle (\bar{B}\partial_{\alpha}\Sigma B^{*\alpha} + \bar{B}^{*\alpha}\partial_{\alpha}\Sigma B) \rangle - g_{\bar{B}^*B^*\Sigma} \epsilon^{\alpha\beta\mu\nu} \langle \partial_{\beta}\bar{B}^*_{\nu}\partial_{\alpha}\Sigma B^*_{\mu} \rangle$$

 \circ Lagrangian for B and light vector mesons

$$\begin{split} L_{BBV} &= -g_{\bar{B}BV} \left\langle \bar{B} \gamma_{\alpha} V^{\alpha} B \right\rangle \\ &- g_{\bar{B}B^{*}V} \left\langle i \bar{B} \gamma_{\alpha} \gamma_{5} (\partial^{\alpha} V^{\beta} - \partial^{\beta} V^{\alpha}) B^{*}_{\beta} \right\rangle \\ &+ g_{\bar{B}^{*}BV} \left\langle i \bar{B}^{*}_{\beta} \gamma_{\alpha} \gamma_{5} (\partial^{\alpha} V^{\beta} - \partial^{\beta} V^{\alpha}) B \right\rangle \\ &+ g_{\bar{B}^{*}B^{*}V} \left\langle i \bar{B}^{*}_{\alpha} (\partial^{\alpha} V^{\beta} - \partial^{\beta} V^{\alpha}) B^{*}_{\beta} \right\rangle \end{split}$$

L for baryon $\bar{3}$ and light mesons

• The single-heavy baryon in flavor anti-triplet

$$\Lambda = egin{bmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \ -\Lambda_c^+ & 0 & \Xi_c^0 \ -\Xi_c^+ & -\Xi_c^0 & 0 \end{bmatrix}$$

 $\circ~$ Lagrangian for Λ and light mesons

$$L_{\Lambda B} = g_4 \left\langle \bar{\Lambda} u_\alpha S^\alpha \right\rangle + \lambda_I \epsilon^{\alpha\beta\mu\nu} v_\alpha \left\langle \bar{\Lambda} F_{\mu\nu} S_\beta \right\rangle + \text{H.c.}.$$

• Expanding to obtain Lagrangian

$$\begin{split} L_{\Lambda B} &= -g_{\Lambda \Sigma B} \left\langle \mathrm{i}\bar{\Lambda}\Sigma\gamma_5 B + \mathrm{i}\bar{B}\Sigma\gamma_5\Lambda \right\rangle \\ &- g_{\Lambda \Sigma B^*} \left\langle \bar{\Lambda}\partial^{\alpha}\Sigma B^*_{\alpha} + \bar{B}^*_{\alpha}\partial^{\alpha}\Sigma\Lambda \right\rangle \\ &+ g_{\Lambda VB} \left\langle \bar{\Lambda}V_{\alpha}\gamma^{\alpha}B + \bar{B}V_{\alpha}\gamma^{\alpha}\Lambda \right\rangle \\ &- g_{\Lambda VB^*}\epsilon^{\alpha\beta\mu\nu} \left\langle \mathrm{i}\partial_{\beta}\bar{\Lambda}\partial_{\alpha}V_{\nu}B^*_{\mu} + \mathrm{i}\partial_{\beta}\bar{B}^*_{\mu}\partial_{\alpha}V_{\nu}\Lambda \right\rangle \end{split}$$

$N\Sigma_c D^{(*)}$ interaction

- Responsible for baryon sector of $J/\psi(\eta_c)p$ decay channels.
- Nucleon $N = \begin{pmatrix} p \\ n \end{pmatrix}$ forms a SU(2) doublet of the isospin.

• Three
$$\Sigma_c = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 \end{pmatrix}$$
 form a triplet representation of the isospin, namely 1-2 sector of sextet B ,

• Under isospin symmetry, Lagrangian for $N\Sigma_c D^{(*)}$

$$\begin{split} & L_{\bar{N}\Sigma_{c}D}(*) \\ = g_{N\Sigma_{c}D}i\bar{N}\gamma_{5}\Sigma_{c}(-i\sigma_{2})\cdot D^{\dagger} + g_{N\Sigma_{c}D*}\bar{N}\gamma^{\alpha}\Sigma_{c}(-i\sigma_{2})\cdot D_{\alpha}^{*\dagger} \\ = & -g_{N\Sigma_{c}D}i\left(\bar{p}\gamma_{5}\Sigma_{c}^{++}D^{+\dagger} - \frac{1}{\sqrt{2}}\bar{p}\gamma_{5}\Sigma_{c}^{+}D^{0\dagger} + \frac{1}{\sqrt{2}}\bar{n}\gamma_{5}\Sigma_{c}^{+}D^{+\dagger} - \bar{n}\gamma_{5}\Sigma_{c}^{0}D^{0\dagger}\right) \\ & - g_{N\Sigma_{c}D*}\left(\bar{p}\gamma^{\alpha}\Sigma_{c}^{++}D_{\alpha}^{*+\dagger} - \frac{1}{\sqrt{2}}\bar{p}\gamma^{\alpha}\Sigma_{c}^{+}D_{\alpha}^{*0\dagger} + \frac{1}{\sqrt{2}}\bar{n}\gamma^{\alpha}\Sigma_{c}^{+}D_{\alpha}^{*+\dagger} - \bar{n}\gamma^{\alpha}\Sigma_{c}^{0}D_{\alpha}^{*0\dagger}\right) \end{split}$$

where σ_2 the second Pauli matrix, and here $D^{(*)} = (D^{(*)0}, D^{(*)+})$.

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Amplitude for $P_{\psi}^N \rightarrow J/\psi p$

• P_{ψ}^N as the $\bar{D}^*\Sigma_c$ molecule can decay to $J/\psi p$ by exchanging either a D or a D^* meson.



 $\circ~$ Invariant amplitude for $P_\psi^N \to J/\psi p$ by exchanging a D

$$\begin{split} \mathsf{A}_{11}[P^N_{\psi 1/2}] &= -\mathrm{i}^3 g_{ND\Sigma_c} g_{D\bar{D}^*\psi} \bar{u}_2 \gamma_5 \int \frac{\mathrm{d}^4 k}{(2\pi)^4} [S(k_2)\Gamma^{\gamma}(k,r) D_{\gamma\beta}(k_1)] D(k_3) \frac{\epsilon^{\mu\nu\alpha\beta}}{M_1} P_{1\mu} \epsilon^*_{1\nu} k_{3\alpha} \\ &= G_{11} \epsilon_1^{*\alpha} \bar{u}_2 T_{11\alpha} u(P,r) \end{split}$$

where integral over k behaves

$$T_{11}^{\nu}u(P,r) = i\frac{\epsilon^{\alpha\beta P_{1}\nu}}{M_{1}}\gamma_{5}\int \frac{d^{4}k}{(2\pi)^{4}}[S(k_{2})\Gamma^{\gamma}(k,r)D_{\gamma\beta}(k_{1})]D(k_{3})k_{1\alpha}$$

• Dimensionless interaction strength $G_{11} = g_{ND\Sigma_c} g_{D\bar{D}^*\psi}$.

Triangle integral

• Contour integral over k_P to obtain six poles

$$\int \frac{\mathrm{d}k_P}{2\pi} [S(k_2)\Gamma_{\gamma}(k,r)D_{\gamma\beta}(k_1)]D(k_3)k_{1\alpha} = \frac{1}{2w_3} \left(a_{1\alpha}\Lambda^+ + a_{2\alpha}\Lambda^-\right)\gamma_0\varphi_{\beta}$$

• $\Lambda^{\pm}\gamma_0 = \frac{1}{2} \pm \frac{1}{2w_2}H(p_{2\perp})$, and coefficients a_1 and a_2

$$a_{1\alpha} = c_1 x_{1\alpha} + c_3 x_{3\alpha} + c_5 x_{5\alpha},$$

$$a_{2\alpha} = c_2 x_{2\alpha} + c_4 x_{4\alpha} + c_6 x_{6\alpha},$$

where $x_i = k_1(k_P = k_{Pi})$ with $(i = 1, \dots 6)$

$$k_{P1} = \zeta_1^+, \ k_{P2} = \zeta_1^-, \ k_{P3} = \zeta_2^+, \ k_{P4} = \zeta_2^-, \ k_{P5} = \zeta_3^+, \ k_{P6} = \zeta_3^-.$$

• $k_1 = \alpha_1 P + k$, and c_i s $(i = 1, \dots 6)$

$$\begin{split} c_{1(2)} &= \mp \frac{1}{E_1 \mp (w_1 + w_3)}, \\ c_{3(4)} &= \mp \frac{1}{E_2 \mp (w_2 + w_3)}, \\ c_{5(6)} &= \pm \frac{M \mp (w_1 + w_2)}{[E_1 \pm (w_1 + w_3)][E_2 \mp (w_2 + w_3)]} \end{split}$$

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Amplitude expressed by wave function

• Contour integral over k_P to obtain six poles

$$\begin{split} T_{11}^{\nu}u(P,r) &= \mathrm{i}\frac{\epsilon^{\alpha\beta P_{1}\nu}}{M_{1}}\gamma_{5}\int\frac{\mathrm{d}k_{\perp}^{3}}{(2\pi)^{3}}\frac{1}{2w_{3}}\left(a_{1\alpha}\Lambda^{+}+a_{2\alpha}\Lambda^{-}\right)\gamma_{0}\varphi_{\beta}(k_{\perp})\\ &= (s_{111}\gamma^{\nu}+s_{112}\hat{P}^{\nu})u(P,r) \end{split}$$

• Amplitude for $P_{\psi 1/2}^N$ by D exchange expressed with form factors

$$\mathcal{A}_{11;P_{\psi^{1/2}}^{N}} = G_{11} e_{1}^{*\alpha} \bar{u}_{2} \left(s_{111} \gamma_{\alpha} + s_{112} \hat{P}_{\alpha} \right) u(P,r).$$

 $\circ \ P^N_{\psi 3/2} \to J/\psi p \text{ by } D \text{ exchange, } T_{11\alpha} u \to T_{11\alpha\beta} u^\beta,$

$$\mathcal{A}_{11;P^{N}_{\psi^{3}/2}} = G_{11}e_{1}^{\alpha*}\bar{u}_{2}T_{11\alpha\beta}u^{\beta}(P,r),$$

with

$$T_{11\alpha\beta} = t_{111} \epsilon_{\alpha\beta\hat{P}\hat{P}_{1}} + (t_{112}g_{\alpha\beta} + t_{113}\gamma_{\alpha}\hat{P}_{1\beta} + t_{114}\hat{P}_{\alpha}\hat{P}_{1\beta})\gamma_{5}$$

Amplitude by D^* exchange

• $P_{\psi 1/2}^N$ to $J/\psi p$ by D^* exchange

$$\begin{aligned} \mathcal{A}_{12;1/2} &= G_{12} \bar{u}_2 \gamma_{\nu} \int \frac{\mathrm{d}^4 k}{(2\pi)^4} [S(k_2) \Gamma_{\gamma}(k,r) D^{\gamma\beta}(k_1)] D^{\mu\nu}(k_3) e_1^{*\alpha} O_{\alpha\beta\mu\rho}(k_1+k_3)^{\rho} \\ O_{\alpha\beta\mu\rho} &\equiv -\left(g_{\alpha\mu}g_{\beta\rho} - \frac{1}{2} \iota_2 g_{\beta\mu}g_{\alpha\rho} + \iota_3 g_{\alpha\beta}g_{\mu\rho}\right), \end{aligned}$$

• $G_{12} = g_{ND^*\Sigma_c} g_{D^*\bar{D}^*\psi}$. Amplitude can be expressed as

$$\begin{aligned} \mathcal{A}_{12}[P^{N}_{\psi 1/2}] &= G_{12}(e_{1}^{\alpha})^{*} \bar{u}_{2} T_{12\alpha} u(P,r), \\ T_{12\alpha} u(P,r) &= O_{\alpha\beta\mu\rho} \gamma_{\nu} \int \frac{\mathrm{d}^{3} k_{\perp}}{(2\pi)^{3}} \frac{1}{2w_{3}} \left(a_{3}^{\mu\nu\rho} \Lambda^{+} + a_{4}^{\mu\nu\rho} \Lambda^{-} \right) \gamma_{0} \varphi^{\beta} \end{aligned}$$

• After integral over k_{\perp} obtain

$$T_{12\alpha} = T_{12\alpha}^1 + T_{12\alpha}^2 = (s_{121}\gamma_\alpha + s_{122}\hat{P}_\alpha).$$

Total amplitude for $J/\psi p$ decay

• Combing the contributions from D and D^* to obtain the total amplitude for $P_{\psi 1/2}^N \rightarrow J/\psi p$ decay by two form factors,

$$\mathcal{A} = \mathcal{A}_{11} + \mathcal{A}_{12} = e_1^{*\alpha} \bar{u}_2 \left(s_{11} \gamma_{\alpha} + s_{12} \hat{P}_{\alpha} \right) u.$$

• Form factors s_{11} and s_{12} are expressed as

$$s_{11} = G_{11}s_{111} + G_{12}s_{121},$$

$$s_{12} = G_{11}s_{112} + G_{12}s_{122}.$$

 $\circ~$ Total amplitude for $P^N_{\psi 3/2} \to J/\psi p$

$$\mathcal{A} = e_1^{*\alpha} \bar{u}_2 \left(\mathrm{i} t_{11} \epsilon_{\alpha\beta\hat{P}\hat{P}_1} + t_{12} g_{\alpha\beta} \gamma_5 + t_{13} \hat{P}_{1\beta} \gamma_\alpha \gamma_5 + t_{14} \hat{P}_\alpha \hat{P}_{1\beta} \gamma_5 \right) u^\beta,$$

where t_{1i} (i = 1, 2, 3, 4) is related to the coupling constants by

$$t_{1i} = G_{11}t_{11i} + G_{12}t_{12i}$$

Amplitude for $\bar{D}^{*0}\Lambda_c^+$

• As a V + B decay mode, $\overline{D}^{*0} \Lambda_c^+$ is similar with ψp case,

$$\begin{aligned} \mathcal{A}[P_{\psi^{1/2}}^{N} \to \bar{D}^{*0} \Lambda_{c}^{+}] &= e_{1}^{*\alpha} \bar{u}_{2} \left(s_{21} \gamma_{\alpha} + s_{22} \hat{P}_{\alpha} \right) u(P,r), \\ \mathcal{A}[P_{\psi^{3/2}}^{N} \to \bar{D}^{*0} \Lambda_{c}^{+}] &= e_{1}^{*\alpha} \bar{u}_{2} \left(t_{21} i \epsilon_{\alpha\beta\hat{P}\hat{P}_{1}} + (t_{22} g_{\alpha\beta} + t_{23} \gamma_{\alpha} \hat{P}_{1\beta} + t_{24} \hat{P}_{\alpha} \hat{P}_{1\beta}) \gamma_{5} \right) u(P,r). \end{aligned}$$

• Form factors s_{2i} (i = 1, 2) and t_{2j} (j = 1, 2, 3, 4) are defined as

$$s_{2i} = G_{21}s_{21i} + G_{22}s_{22i},$$

$$t_{2j} = G_{21}t_{21j} + G_{22}t_{22j},$$

where we define two dimensionless constants

$$\begin{aligned} G_{21} &= g_{\Lambda_c^+ \Sigma_c^{++} \pi} g_{\bar{D}^{*0} \bar{D}^{*-} \pi}, \\ G_{22} &= g_{\Lambda_c^+ \Sigma_c^{++} \rho} g_{\bar{D}^{*0} \bar{D}^{*-} \rho} \end{aligned}$$

• Form factors can be obtained by making replacements

$$\begin{split} s_{21i} &= s_{11i} [M_1 \to M_{\bar{D}^{*0}}, M_2 \to M_{\Lambda_c^+}, m_3 \to M_{\pi}], \\ t_{21j} &= t_{11j} [M_1 \to M_{\bar{D}^{*0}}, M_2 \to M_{\Lambda_c^+}, m_3 \to M_{\pi}], \\ s_{22i} &= s_{12i} [M_1 \to M_{\bar{D}^*}, M_2 \to M_{\Lambda_c^+}, m_3 \to M_{\rho}, \iota_2 \to 1, \iota_3 \to A_r], \\ t_{22j} &= t_{12j} [M_1 \to M_{\bar{D}^*}, M_2 \to M_{\Lambda_c^+}, m_3 \to M_{\rho}, \iota_2 \to 1, \iota_3 \to A_r], \end{split}$$

Amplitude for $\eta_c p$ decay

 $\circ~$ As a P+B decay mode, the amplitude $\eta_c p$ by D and D^* exchange behaves

$$\begin{split} &\mathrm{i}\mathcal{A}_{31}[P^{N}_{\psi 1/2}] = \mathrm{i}\bar{u}_{2}(-\mathrm{i}g_{ND\Sigma_{c}})\gamma_{5}\int \frac{\mathrm{d}^{4}k}{(2\pi)^{4}}[S(k_{2})\Gamma^{\gamma}(k,r)D_{\beta\gamma}(k_{1})]D(k_{3})(-\mathrm{i}g_{D\bar{D}}*_{\eta_{c}})(\mathrm{i}P^{\beta}_{1})\\ &\mathrm{i}\mathcal{A}_{32}[P^{N}_{\psi 1/2}] = -\mathrm{i}G_{32}\bar{u}_{2}\gamma^{\nu}\int \frac{\mathrm{d}^{4}k}{(2\pi)^{4}}[S(k_{2})\Gamma^{\gamma}(k,r)D_{\beta\gamma}(k_{1})]D_{\mu\nu}(k_{3})\frac{\epsilon^{k_{3}\beta\mu}P_{1}}{M_{1}}, \end{split}$$

• Combining the amplitudes for D and D^* exchange,

$$\begin{split} &\mathrm{i}\mathcal{A}[P^{N}_{\psi 1/2} \to \eta_{c}p] = s_{3}\bar{u}_{2}\gamma_{5}u(P,r), \\ &\mathrm{i}\mathcal{A}[P^{N}_{\psi 3/2} \to \eta_{c}p] = t_{3}\bar{u}_{2}\left(\hat{P}_{1\alpha}\right)u^{\alpha}(P,r). \end{split}$$

where the form factors s_3 and t_3 behave

$$s_3 = G_{31}s_{31} + G_{32}s_{32},$$

$$t_3 = G_{31}t_{31} + G_{32}t_{32}.$$

Amplitude for P + B decay mode

• For other P + B decay mode, $\overline{D}^{*0}\Lambda_c^+$ can be realized by π and ρ exchange corresponding to the D and D^* exchange in $\eta_c p$ channel.

$$\mathcal{A}_4[\bar{D}^0\Lambda_c^+] = \mathcal{A}_3[\eta + cp] \left(M_1 \to M_{\bar{D}^*}, M_2 \to M_{\Lambda_c^+}, M_D \to M_{\pi}, M_{D^*} \to M_{\rho} \right)$$

• For $D^-\Sigma_c^{++}$ and $\bar{D}^0\Sigma_c^+$ channel, besides π and ρ , ω also contributes

$$\mathcal{A}_5[D^-\Sigma_c^{++}] = \mathcal{A}_{\pi} + \mathcal{A}_{\rho} - \frac{1}{2}\mathcal{A}_{\omega}$$

- $\frac{1}{2}$ from a relative isospin factor of ω over ρ .
- $\overline{D}^0 \Sigma_c^+$ is similar with $D^- \Sigma_c^{++}$ but isospin factor $C_6 = \frac{1}{\sqrt{2}} C_5$,

$$\mathcal{A}_{6}[\bar{D}^{0}\Sigma_{c}^{+}] = \frac{1}{\sqrt{2}}\mathcal{A}_{5}[D^{-}\Sigma_{c}^{++}].$$

Amplitude for $P + B^*$ decay mode

• For $P + B^*$ decay mode, $D^- \Lambda_c^{*++}$ and $\overline{D}^0 \Lambda_c^{*+}$ can be realized by π , ρ and ω exchange.

$$i\mathcal{A}_{7}[P_{\psi 1/2}^{N} \to D^{-}\Sigma_{c}^{*++}] = \bar{u}^{\alpha}(P_{2}, r_{2}) \left(G_{71}T_{71\alpha} + G_{72}T_{72\alpha} + G_{74}T_{74\alpha}\right) u(P, r)$$

• Strong decay strength for π , ρ and ω exchange

$$\begin{split} &G_{71} = g_{\Sigma_c^*} + +_{\Sigma_c^+} +_{\pi} g_{D^- D^{*-}\pi}, \\ &G_{72} = g_{\Sigma_c^*} + +_{\Sigma_c^+} +_{\rho} g_{D^- D^{*-}\rho}, \\ &G_{74} = g_{\Sigma_c^*} + +_{\Sigma_c^+} +_{\omega} g_{D^- D^{*-}\omega} \end{split}$$

• T_{71}, T_{72}, T_{74} denotes triangle integral for π , ρ and ω ,

$$T_{71\alpha}u = \frac{P_1^{\beta}}{M_2} \int \frac{\mathrm{d}^4k}{(2\pi)^4} [S(k_2)\Gamma^{\gamma}(k,r)D_{\gamma\beta}(k_1)]D(k_3)k_{3\alpha},$$

$$T_{72}^{\sigma}u = \mathrm{i}\frac{\epsilon^{\alpha\beta\mu\hat{P}_1}}{M_2} (g^{\rho\sigma}\gamma_{\mu} - g_{\mu\nu}g^{\sigma\nu}\gamma^{\rho})\gamma_5 \int \frac{\mathrm{d}^4k}{(2\pi)^4} [S(k_2)\Gamma^{\gamma}(k,r)D_{\gamma\beta}(k_1)]D(k_3)k_{3\rho}k_{1\alpha}.$$

with $T_{74} = T_{72}[m_{\rho} \to m_{\omega}].$

Amplitude for $P + B^*$ decay mode

• Total amplitude

$$\begin{split} &i\mathcal{A}[P_{\psi_{1/2}}^{N} \to D^{-}\Sigma_{c}^{*++}] = \bar{u}_{2}^{\alpha}(s_{7}\hat{P}_{\alpha})u(P,r), \\ &i\mathcal{A}[P_{\psi_{3/2}}^{N} \to D^{-}\Sigma_{c}^{*++}] = \bar{u}_{2\alpha}\left(it_{71}\frac{\epsilon^{\alpha\beta PP_{1}}}{MM_{1}} + t_{72}g^{\alpha\beta}\gamma_{5} + t_{73}\hat{P}^{\alpha}\hat{P}_{1}^{\beta}\gamma_{5}\right)u_{\beta}(P,r), \end{split}$$

where s_7 and t_{7i} (i = 1, 2, 3) behaves

$$s_7 = G_{71}s_{61} + G_{72}s_{72} - \frac{1}{2}G_{74}s_{74},$$

$$t_{7i} = G_{71}t_{71i} + G_{72}t_{72i} - \frac{1}{2}G_{74}t_{74i}.$$

with the form factors from ω exchange reading

$$s_{74} = s_{72}[m_3 \to m_{\omega}],$$

$$t_{74i} = t_{72i}[m_3 \to m_{\omega}].$$

Decay widths

• Two-body partial decay width

$$\Gamma[P_{\psi}^{N} \to M_{P(V)}B^{(*)}] = \frac{|P_{1}|}{8\pi M^{2}}C_{i}^{2}\frac{1}{2J+1}\sum |\mathcal{A}|^{2},$$

∑ |A|² denotes summing over all the polarization states.
J, spin of the initial P^N_ψ state;

$$|\mathbf{P}_1| = \frac{1}{2M} \sqrt{[(M^2 - (M_1 + M_2)^2][(M^2 - (M_1 - M_2))]}$$

• C_i^2 denotes the isospin factor

$$\begin{array}{l} C_1^2 = C_2^2 = C_3^2 = C_4^2 = \frac{3}{2},\\ C_5^2 = C_7^2 = \frac{8}{3},\\ C_6^2 = C_8^2 = \frac{4}{3}. \end{array}$$

OUTLINE

- 1. Introduction
- 2. P_{ψ}^{N} as the $\bar{D}^{*}\Sigma_{c}$ molecular state
- 3. Decay mode and involved effective Lagrangians
- 4. Strong decays $P_{\psi}^{N}(4440)^{+}$ and $P_{\psi}^{N}(4457)$
- 5. Numerical results and discussions

Coupling constants

• Chiral constants used

$$\begin{split} g &= 0.59, \quad (\lambda g_V) = 3.25 \ \text{GeV}^{-1}, \quad (\beta g_V) = 5.22, \quad g_s = 0.76, \\ g_1 &= 0.94, \quad (\lambda_S g_V) = 19.20 \ \text{GeV}^{-1}, \quad (\beta_S g_V) = 10.09, \quad l_S = 6.2; \\ g_4 &= 1.0, \quad (\lambda_I g_V) = (\lambda_S g_V)/\sqrt{8}. \end{split}$$

• Other coupling constants

$$\begin{split} g_{D\bar{D}\psi} &= 14.89, \ g_{D\bar{D}^*\psi} = 15.43, \ g_{D^*\bar{D}^*\psi} = 8.01, \ g_{D\bar{D}^*\eta_c} = 7.58, \ g_{D^*\bar{D}^*\eta_c} = 15.72, \\ g_{ND\Sigma_c} &= 2.69, \ g_{ND^*\Sigma_c} = 3.0. \end{split}$$

• Finally obtain the strong interaction strength constants

Masses for possible $\bar{D}^*\Sigma_c$ bound states

- Mass spectra under the $\overline{D}^*\Sigma_c$ molecule picture in $I = \frac{1}{2}$ with cutoff m_{Λ} in units of GeV with different J^P configuration, where the blue values are fixed by fitting to data.
- Two bound states are only robust within a range of $\pm 15\%$ for m_{Λ} .
- The second bound state would disappear when m_{Λ} is less than ~ 0.74 GeV.

$J^P \mid Mass$	Mass	m_{Λ} Mass	Mass	$m_{\Lambda} \parallel Mass$	Mass	m_{Λ}
$\frac{1}{2}^{-}$ 4.440	4.443	$1.07 \mid \mid 4.457$	4.458	$0.860 \mid\mid 4.453$	4.454	0.915
$\frac{3}{2}^{-}$ 4.457	4.4625	0.754 4.440	4.450	$0.974 \left \right 4.445$	4.454	0.915

Interaction kernel

• The interaction kernel K_i $(i = 1, \dots, 4)$ in the isospin- $\frac{1}{2}$ with $m_{\Lambda} = 1.07$ GeV, 0.754 GeV, and 0.917 GeV, respectively.



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BS radial wave functions for $P_{\psi 1/2}^N$

• BS wave functions for $P_{\psi 1/2}^N$ with mass 4.440, 4.443, 4.453, 4.454 GeV, respectively, with $m_{\Lambda} = 1.07(\text{up})$ and 0.917 GeV(down), respectively.



33-37

BS radial wave functions for $P_{\psi 3/2}^N$

• BS wave functions for $P_{\psi_{3/2}}^N$ with mass 4.457, 4.4625, 4.445 and 4.454 GeV, respectively, with $m_{\Lambda} = 0.754(\text{up})$ and 0.917 GeV(down).



QIANG LI

Mass spectra and strong decays of $P_{ab}^N(4440, 4457)^+$

Form factors

Numerical values of strong decay form factors for P_{ψ}^{N} with $m = 1, \dots, 8$ denoting the 8 decay channels we calculated.

s_{mo}^n	$\bar{D}^{*0}\Lambda_c^+$	$J/\psi p$	$\bar{D}^0 \Lambda_c^+$	$\bar{D}\Sigma_c$	$\eta_c p$	$\bar{D}\Sigma_c^*$
$s^{1}_{m1} \\ s^{2}_{m1}$	$\begin{array}{c} 1.9 \times 10^{-4} \\ -4.5 \times 10^{-4} \end{array}$	1.3×10^{-6} -1.9 × 10 ⁻⁵	$\begin{array}{c} -3.5\times 10^{-5} \\ 2.4\times 10^{-5} \end{array}$	$\begin{array}{c} -2.6\times 10^{-3} \\ 8.0\times 10^{-5} \end{array}$	-5.7×10^{-6} 1.1×10^{-6}	$\begin{array}{c} 4.1 \times 10^{-3} \\ -1.3 \times 10^{-4} \end{array}$
s_{m2}^{1}	-2.7×10^{-4}	-2.9×10^{-6}	-	-	-	-
s_{m2}^2	-2.2×10^{-4}	-1.0×10^{-5}	-	_	-	-

	D_{c}
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	10^{-8} 10^{-4} 10^{-5} 10^{-4} 10^{-2} 10^{-3} -

Numerical decay widths and comparison

• Decay widths in units of MeV. Assuming J^P for $P_{\psi}^N(4440)$ and $P_{\psi}^N(4457)$ are $\frac{3}{2}^-$ and $\frac{1}{2}^-$ respectively in scenario I while opposite in II. LHCb: $\Gamma[P_{\psi}^N(4440)] = 20.6 \pm 4.9$ and $\Gamma[P_{\psi}^N(4457)] = 6.4 \pm 2.0$.

Channel	I	II	[71]	[17]
$P_{\psi}^{N}(4440) \rightarrow \bar{D}^{*0} \Lambda_{c}^{+}$	4.9	4.5	-	13.9 - 6.2
$P_{\psi}^{N}(4440) \rightarrow J/\psi p$	$2.7 imes 10^{-4}$	$2.1 imes 10^{-4}$	4.1 - 4.1	0.03 - 0.02
$P_{\psi}^{N}(4440) \rightarrow \bar{D}^{0}\Lambda_{c}^{+}$	1.1	8.1×10^{-2}	5.98 - 4.53	5.6 - 1.7
$P_{\psi}^{N}(4440) \rightarrow \bar{D}\Sigma_{c}$	27.1	2.5	10.43 - 5.45	3.4 - 0.5
$P_{\psi}^N(4440) \rightarrow \eta_c p$	1.7×10^{-5}	4.7×10^{-8}	-	0 - 0
$P_{\psi}^{N}(4440) \rightarrow \bar{D}\Sigma_{c}^{*}$	1.8	$3.5 imes 10^{-1}$	-	0.8 - 5.4
Total	34.8	7.4	20.52 - 13.98	23.7 - 13.9
$P_{\psi}^N(4457) \rightarrow \bar{D}^{*0} \Lambda_c^+$	7.2×10^{-1}	$1.5 imes 10^{-1}$	-	12.5 - 6.1
$P_{\psi}^N(4457) \rightarrow J/\psi p$	$3.6 imes 10^{-5}$	7.6×10^{-5}	1.52 - 1.52	0.02 - 0.01
$P_{\psi}^{N}(4457) \rightarrow \bar{D}^{0}\Lambda_{c}^{+}$	1.4×10^{-3}	2.8×10^{-3}	2.47 - 2.15	3.8 - 1.5
$P_{\psi}^N(4457) \rightarrow \bar{D}\Sigma_c$	8.8×10^{-1}	13.9	5.60 - 4.11	2.6 - 1.0
$P_{\psi}^{N}(4457) \rightarrow \eta_{c}p$	3.0×10^{-9}	4.9×10^{-6}	-	0 - 0
$P_{\psi}^{N}(4457) \rightarrow \bar{D}\Sigma_{c}^{*}$	5.5×10^{-1}	9.5×10^{-3}	-	1.9 - 6.2
Total	2.2	14.1	9.59 - 7.78	20.7 - 14.7

Discussion and summary

- Based on the effective field theory and Bethe-Salpeter framework, we calculate the strong decay widths of $P_{\psi}^{N}(4440, 4457)$ under the $\bar{D}^{*}\Sigma_{c}$ molecule picture.
- The results show existence of two possible bound states of P_{ψ}^{N} in both $J^{P} = \frac{1}{2}^{-}$ and $\frac{3}{2}^{-}$ (cutoff dependent).
- Obtained partial decay widths are directly dependent on the hadron coupling constants in the relevant effective Lagrangian.
- Our results more favor $P_{\psi}^{N}(4440)$ and $P_{\psi}^{N}(4457)$ as the isospin $I = \frac{1}{2}$ $J^{P} = \frac{3}{2}^{-}$ and $\frac{1}{2}^{-} \bar{D}^{*} \Sigma_{c}$ molecule respectively.
- $\bar{D}^{(*)0}\Lambda_c^+$ and $\bar{D}\Sigma_c^{(*)}$ are more promising decay channels to be detect $P_{\psi}^N(4440, 4457)^+$ states in experiments.

