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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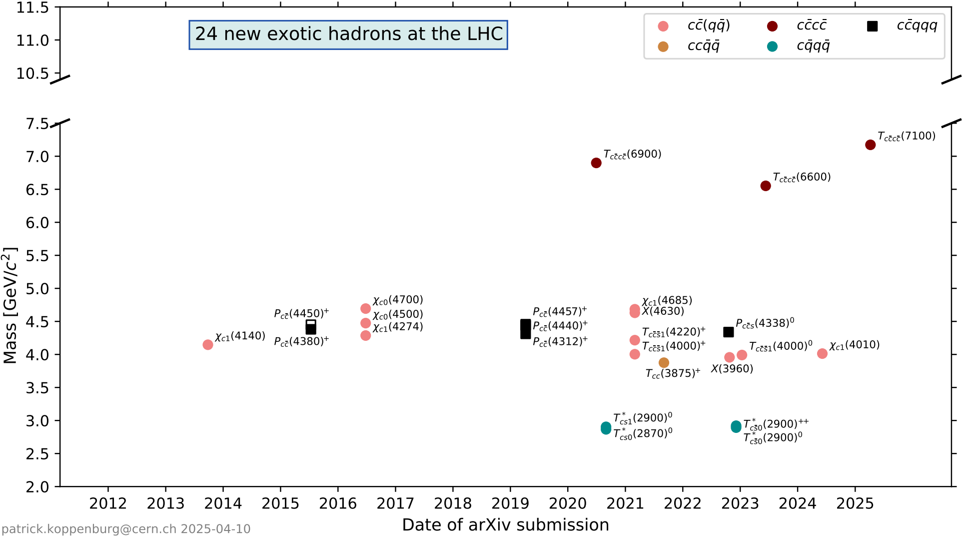
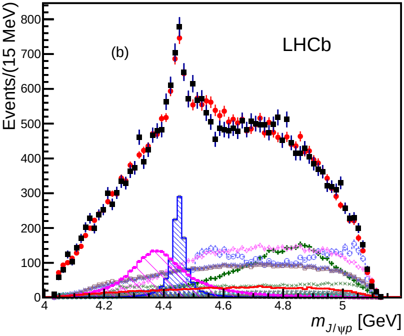
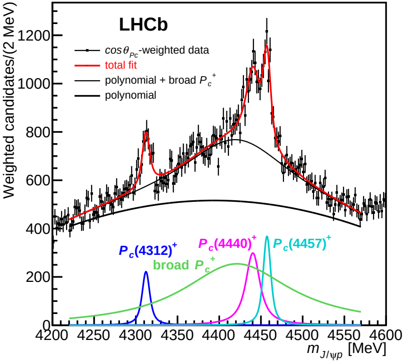
Exotic hadrons at LHC



- 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

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

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

- Methodology: combining the effective field theory and Bethe-Salpeter framework.

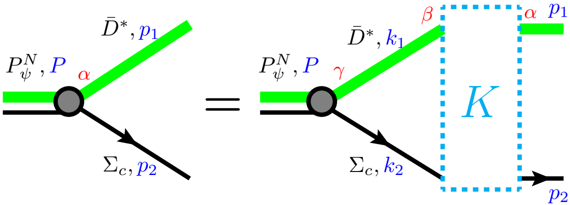
- Based on arXiv: 2503.08440.

- Collaborator: Chao-Hsi Chang(ITP&UCAS), Xin Tong(NPU), Xiao-Ze Tan(DESY&FDU), Tianhong Wang(HIT), Guo-Li Wang(Hebei Univ.).

Outline

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

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

- 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, $\varphi_\alpha = -i\frac{1}{2\pi}\int dq_P \psi_\alpha(q)$.

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

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

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

- $J^P = \frac{1}{2}^-$ formed by a 1^- meson and $\frac{1}{2}^+$ baryon

$$\varphi_\alpha(x) = A_\alpha(x) u(P, r)$$
$$A_\alpha = (g_1 + g_2 \not{x})(\gamma_\alpha - \hat{P}_\alpha) + (g_3 + g_4 \not{x})\, x_\alpha$$

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

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

$$\varphi_\alpha(x) = A_{\alpha\beta}\gamma_5 u^\beta(P, r)$$
$$A_{\alpha\beta}(x) = (h_1 + h_2 \not{x})\, g_{\alpha\beta} + (h_3 + h_4 \not{x})(\gamma_\alpha + \hat{P}_\alpha) x_\beta + \mathrm{i}\epsilon_{\alpha\beta\hat{P}x}(h_5 + h_6 \not{x})\gamma_5 + (h_7 + h_8 \not{x})\, x_\alpha x_\beta,$$

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

- Normalization is expressed as

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

Interaction kernel

- $P_\psi^N(4440, 4457)^+$ (minimal quark content $[c\bar{c}uud]$) is taken as the $\bar{D}^*\Sigma_c$ molecular state with isospin $|I, I_3\rangle = |\frac{1}{2}, +\frac{1}{2}\rangle$

$$|\tfrac{1}{2}, \tfrac{1}{2}\rangle = \frac{\sqrt{2}}{\sqrt{3}}\,|\Sigma_c^{++} D^{*-}\rangle - \frac{1}{\sqrt{3}}\,|\Sigma_c^{+}\bar{D}^{*0}\rangle$$

- Interaction kernels are calculated from the constituent particles $\bar{D}^*\Sigma_c$ scattering based on the one-boson $(\sigma, \pi, \eta, \rho, \omega)$ exchange.

- For $P_\psi^N(4440, 4457)^+$, the light (pseudo)scalar and vector mesons contribute.

- Throughout this work, the isospin symmetry is used

$$\langle\tfrac{1}{2}, \tfrac{1}{2}|H_{\text{eff}}|\tfrac{1}{2}, \tfrac{1}{2}\rangle = \tfrac{3}{2}\,\langle\Sigma_c^{++} D^{*-}|\,H_{\text{eff}}\,|\Sigma_c^{++} D^{*-}\rangle - \tfrac{1}{2}\,\langle\Sigma_c^{+}\bar{D}^{*0}|H_{\text{eff}}|\Sigma_c^{+}\bar{D}^{*0}\rangle$$

$$H_{\text{eff}} = \sum L_{\text{MM}i} L_{\text{BB}i}, \quad i = \sigma, \pi, \eta, \rho, \omega$$

Effective Lagrangian

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

$$L_{\mathrm{M}} = g_{\mathrm{s}} \langle \bar{H}_{\bar{Q}} \sigma H_{\bar{Q}} \rangle + g \langle \bar{H}_{\bar{Q}} \not{u} \gamma_5 H_{\bar{Q}} \rangle - \beta \langle \bar{H}_{\bar{Q}} v_\alpha \rho^\alpha H_{\bar{Q}} \rangle - \lambda \langle \bar{H}_{\bar{Q}} \sigma^{\alpha\beta} F_{\alpha\beta} H_{\bar{Q}} \rangle ,$$

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

$$H_{\bar{Q}} = (\bar{D}^{*\mu}\gamma_\mu + \mathrm{i}\bar{D}\gamma_5)\, \frac{1-\not{v}}{2},$$

- $u_\alpha = -\frac{1}{f}\partial_\alpha \Sigma + \cdots$, $F_{\alpha\beta} = (\partial_\alpha \rho_\beta - \partial_\beta \rho_\alpha)$ with $\rho = (g_V/\sqrt{2})V$.
- Σ and V denote the 3×3 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

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

- 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

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

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, $\hat{s} = \frac{s}{|\boldsymbol{s}|}$,

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

- 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.

Main Decay Channels

- Eight decay channels are considered: $J/\psi p$, $\bar{D}^{*0}\Lambda_c^+$, $\eta_c p$, $\bar{D}^0\Lambda_c^+$, $D^-\Sigma_c^{++}$, $\bar{D}^0\Sigma_c^+$, $D^-\Sigma_c^{*++}$, $\bar{D}^0\Sigma_c^{*+}$.
- $P_\psi^N(4440, 4457)^+$ 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

$$L_R = \mathrm{i} g_R \mathrm{Tr}\,(\bar{R} H_Q \gamma_\alpha \partial^\alpha H_{\bar{Q}} - \bar{R} \partial^\alpha H_Q \gamma_\alpha H_{\bar{Q}}) + \mathrm{H.c.}$$

- S-wave charmonium doublet

$$H_Q = \frac{1+\not{v}}{2}(D^{*\alpha}\gamma_\alpha + \mathrm{i} D\gamma_5), \quad R = \frac{1+\not{v}}{2}(\psi^\mu \gamma_\mu + \mathrm{i}\eta_c \gamma_5)\frac{1-\not{v}}{2}.$$

- Expand to obtain the Lagrangians

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

- Only one parameter g_R.

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

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

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

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

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

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

Interaction for B and Light Mesons

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

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

- Lagrangian for B and light vector mesons

$$\begin{aligned} L_{BBV} = & - g_{\bar{B}BV} \langle \bar{B}\gamma_\alpha V^\alpha B \rangle \\ & - g_{\bar{B}B^*V} \langle \mathrm{i}\bar{B}\gamma_\alpha\gamma_5 (\partial^\alpha V^\beta - \partial^\beta V^\alpha) B^*_\beta \rangle \\ & + g_{\bar{B}^*BV} \langle \mathrm{i}\bar{B}^*_\beta \gamma_\alpha\gamma_5 (\partial^\alpha V^\beta - \partial^\beta V^\alpha) B \rangle \\ & + g_{\bar{B}^*B^*V} \langle \mathrm{i}\bar{B}^*_\alpha (\partial^\alpha V^\beta - \partial^\beta V^\alpha) B^*_\beta \rangle \end{aligned}$$

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

- The single-heavy baryon in flavor anti-triplet

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

- Lagrangian for Λ and light mesons

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

- Expanding to obtain Lagrangian

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

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

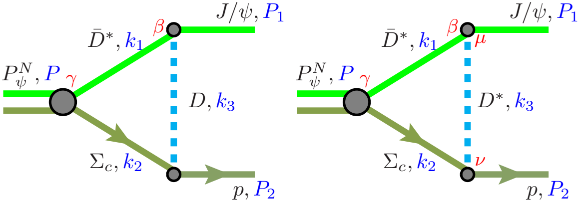
$$
\begin{aligned}
& L_{\bar{N}\Sigma_c D^{(*)}} \\
=& g_{N\Sigma_c D} \mathrm{i}\bar{N}\gamma_5\Sigma_c(-\mathrm{i}\sigma_2)\cdot D^{\dagger} + g_{N\Sigma_c D^*}\bar{N}\gamma^{\alpha}\Sigma_c(-\mathrm{i}\sigma_2)\cdot D^{*\dagger}_{\alpha} \\
=& -g_{N\Sigma_c D}\mathrm{i}\left(\bar{p}\gamma_5\Sigma_c^{++}D^{+\dagger} - \frac{1}{\sqrt{2}}\bar{p}\gamma_5\Sigma_c^{+}D^{0\dagger} + \frac{1}{\sqrt{2}}\bar{n}\gamma_5\Sigma_c^{+}D^{+\dagger} - \bar{n}\gamma_5\Sigma_c^{0}D^{0\dagger}\right) \\
& - g_{N\Sigma_c D^*}\left(\bar{p}\gamma^{\alpha}\Sigma_c^{++}D^{*+\dagger}_{\alpha} - \frac{1}{\sqrt{2}}\bar{p}\gamma^{\alpha}\Sigma_c^{+}D^{*0\dagger}_{\alpha} + \frac{1}{\sqrt{2}}\bar{n}\gamma^{\alpha}\Sigma_c^{+}D^{*+\dagger}_{\alpha} - \bar{n}\gamma^{\alpha}\Sigma_c^{0}D^{*0\dagger}_{\alpha}\right).
\end{aligned}
$$

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

Outline

Amplitude for $P_\psi^N \to J/\psi p$

- 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.



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

$$\mathcal{A}_{11}[P^N_{\psi 1/2}] = -\mathrm{i}^3 g_{ND\Sigma_c} g_{D\bar{D}^*\psi} \bar{u}_2 \gamma_5 \int \frac{\mathrm{d}^4 k}{(2\pi)^4} [S(k_2)\Gamma^\gamma(k,r) D_{\gamma\beta}(k_1)] D(k_3) \frac{\epsilon^{\mu\nu\alpha\beta}}{M_1} P_{1\mu} e^*_{1\nu} k_{3\alpha}$$
$$= G_{11} e_1^{*\alpha} \bar{u}_2 T_{11\alpha} u(P,r)$$

where integral over k behaves

$$T_{11}^\nu u(P,r) = \mathrm{i}\frac{\epsilon^{\alpha\beta P_1 \nu}}{M_1}\gamma_5 \int \frac{\mathrm{d}^4 k}{(2\pi)^4}[S(k_2)\Gamma^\gamma(k,r)D_{\gamma\beta}(k_1)]D(k_3)k_{1\alpha}$$

- 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

$$a_{1\alpha} = c_1x_{1\alpha} + c_3x_{3\alpha} + c_5x_{5\alpha},$$
$$a_{2\alpha} = c_2x_{2\alpha} + c_4x_{4\alpha} + c_6x_{6\alpha},$$

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

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

- $k_1 = \alpha_1 P + k$, and c_is $(i = 1,\cdots 6)$

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

Amplitude expressed by wave function

- Contour integral over k_P to obtain six poles

$$T^{\nu}_{11} u(P,r) = \mathrm{i}\frac{\epsilon^{\alpha\beta P_1 \nu}}{M_1}\gamma_5 \int \frac{\mathrm{d}k^3_\perp}{(2\pi)^3}\frac{1}{2w_3}\left(a_{1\alpha}\Lambda^+ + a_{2\alpha}\Lambda^-\right)\gamma_0 \varphi_\beta(k_\perp)$$
$$= (s_{111}\gamma^\nu + s_{112}\hat{P}^\nu)u(P,r)$$

- Amplitude for $P^N_{\psi 1/2}$ by D exchange expressed with form factors

$$\mathcal{A}_{11;P^N_{\psi 1/2}} = G_{11} e_1^{*\alpha} \bar{u}_2 \left(s_{111}\gamma_\alpha + s_{112}\hat{P}_\alpha\right) u(P,r).$$

- $P^N_{\psi 3/2} \to J/\psi p$ by D 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

- $P^N_{\psi 1/2}$ to $J/\psi p$ by D^* exchange

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

$$O_{\alpha\beta\mu\rho} \equiv -\left(g_{\alpha\mu}g_{\beta\rho} - \frac{1}{2}\iota_2 g_{\beta\mu}g_{\alpha\rho} + \iota_3 g_{\alpha\beta}g_{\mu\rho}\right),$$

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

$$\mathcal{A}_{12}[P^N_{\psi 1/2}] = G_{12}(e_1^\alpha)^*\bar{u}_2 T_{12\alpha}u(P,r),$$

$$T_{12\alpha}u(P,r) = O_{\alpha\beta\mu\rho}\gamma_\nu \int \frac{\mathrm{d}^3 k_\perp}{(2\pi)^3}\frac{1}{2w_3}\left(a_3^{\mu\nu\rho}\Lambda^+ + a_4^{\mu\nu\rho}\Lambda^-\right)\gamma_0\varphi^\beta$$

- After integral over $k_\perp$ obtain

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

Total amplitude for $J/\psi p$ decay

- Combing the contributions from D and D^* to obtain the total amplitude for $P^N_{\psi 1/2} \to J/\psi p$ 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

$$s_{11} = G_{11}s_{111} + G_{12}s_{121},$$
$$s_{12} = G_{11}s_{112} + G_{12}s_{122}.$$

- 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, $\bar{D}^{*0}\Lambda_c^+$ is similar with ψp case,

$$\mathcal{A}[P^N_{\psi 1/2} \to \bar{D}^{*0}\Lambda_c^+] = e_1^{*\alpha}\bar{u}_2\left(s_{21}\gamma_\alpha + s_{22}\hat{P}_\alpha\right)u(P,r),$$

$$\mathcal{A}[P^N_{\psi 3/2} \to \bar{D}^{*0}\Lambda_c^+] = e_1^{*\alpha}\bar{u}_2\left(t_{21}\mathrm{i}\epsilon_{\alpha\beta\hat{P}\hat{P}_1} + (t_{22}g_{\alpha\beta} + t_{23}\gamma_\alpha\hat{P}_{1\beta} + t_{24}\hat{P}_\alpha\hat{P}_{1\beta})\gamma_5\right)u(P,r).$$

- 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

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

- Form factors can be obtained by making replacements

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

Amplitude for $\eta_c p$ decay

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

$$\mathrm{i}\mathcal{A}_{31}[P^N_{\psi 1/2}] = \mathrm{i}\bar{u}_2(-\mathrm{i}g_{ND\Sigma_c})\gamma_5 \int \frac{\mathrm{d}^4 k}{(2\pi)^4}[S(k_2)\Gamma^\gamma(k,r)D_{\beta\gamma}(k_1)]D(k_3)(-\mathrm{i}g_{D\bar{D}^*\eta_c})(\mathrm{i}P_1^\beta)$$
$$\mathrm{i}\mathcal{A}_{32}[P^N_{\psi 1/2}] = -\mathrm{i}G_{32}\bar{u}_2\gamma^\nu \int \frac{\mathrm{d}^4 k}{(2\pi)^4}[S(k_2)\Gamma^\gamma(k,r)D_{\beta\gamma}(k_1)]D_{\mu\nu}(k_3)\frac{\epsilon^{k_3\beta\mu P_1}}{M_1},$$

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

$$\mathrm{i}\mathcal{A}[P^N_{\psi 1/2} \to \eta_c p] = s_3\bar{u}_2\gamma_5 u(P,r),$$
$$\mathrm{i}\mathcal{A}[P^N_{\psi 3/2} \to \eta_c p] = t_3\bar{u}_2\left(\hat{P}_{1\alpha}\right)u^\alpha(P,r).$$

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, $\bar{D}^{*0}\Lambda_c^+$ can be realized by π and ρ exchange corresponding to the D and D^* exchange in $\eta_c p$ channel.

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

- 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.
- $\bar{D}^0\Sigma_c^+$ 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, $D^-\Sigma_c^{*++}$ and $\bar{D}^0\Sigma_c^{*+}$ can be realized by π, ρ and ω exchange.

$$\mathrm{i}\mathcal{A}_7[P^N_{\psi 1/2} \to D^-\Sigma_c^{*++}] = \bar{u}^\alpha(P_2,r_2)\left(G_{71}T_{71\alpha} + G_{72}T_{72\alpha} + G_{74}T_{74\alpha}\right)u(P,r)$$

- Strong decay strength for π, ρ and ω exchange

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

- 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

$$\mathrm{i}\mathcal{A}[P^N_{\psi 1/2} \to D^- \Sigma_c^{*++}] = \bar{u}_2^{\alpha}(s_7 \hat{P}_{\alpha}) u(P, r),$$

$$\mathrm{i}\mathcal{A}[P^N_{\psi 3/2} \to D^- \Sigma_c^{*++}] = \bar{u}_{2\alpha}\left(\mathrm{i}t_{71}\frac{\epsilon^{\alpha\beta P P_1}}{M M_1} + t_{72} g^{\alpha\beta}\gamma_5 + t_{73}\hat{P}^{\alpha}\hat{P}_1^{\beta}\gamma_5\right) u_{\beta}(P, r),$$

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

$$\Gamma[P_\psi^N \to M_{P(V)} B^{(*)}] = \frac{|\boldsymbol{P}_1|}{8\pi M^2} C_i^2 \frac{1}{2J+1} \sum |\mathcal{A}|^2,$$

- $\sum |\mathcal{A}|^2$ denotes summing over all the polarization states.
- J, spin of the initial P_ψ^N state;

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

- C_i^2 denotes the isospin factor

$$C_1^2 = C_2^2 = C_3^2 = C_4^2 = \tfrac{3}{2}, \\ C_5^2 = C_7^2 = \tfrac{8}{3}, \\ C_6^2 = C_8^2 = \tfrac{4}{3}.$$

Outline

Coupling constants

- Chiral constants used

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

- Other coupling constants

$$g_{D\bar{D}\psi} = 14.89, \; g_{D\bar{D}^*\psi} = 15.43, \; g_{D^*\bar{D}^*\psi} = 8.01, \; g_{D\bar{D}^*\eta_c} = 7.58, \; g_{D^*\bar{D}^*\eta_c} = 15.72.$$
$$g_{ND\Sigma_c} = 2.69, \quad g_{ND^*\Sigma_c} = 3.0.$$

- Finally obtain the strong interaction strength constants

$$G_{11} = 41.5, \quad G_{12} = 24.0, \quad G_{21} = 371.9, \quad G_{22} = 485.2,$$
$$G_{31} = 20.4, \quad G_{32} = 47.2, \quad G_{41} = 359.0, \quad G_{42} = 455.0,$$
$$G_{51} = 302.7, \quad G_{52} = 380.9, \quad G_{71} = 134.5, \quad G_{72} = 169.2,$$
$$G_{54} = G_{52}, \quad G_{61} = G_{51}, \quad G_{62} = G_{52}, \quad G_{64} = G_{54},$$
$$G_{74} = G_{72}, \quad G_{81} = G_{71}, \quad G_{82} = G_{72}, \quad G_{84} = G_{74}.$$

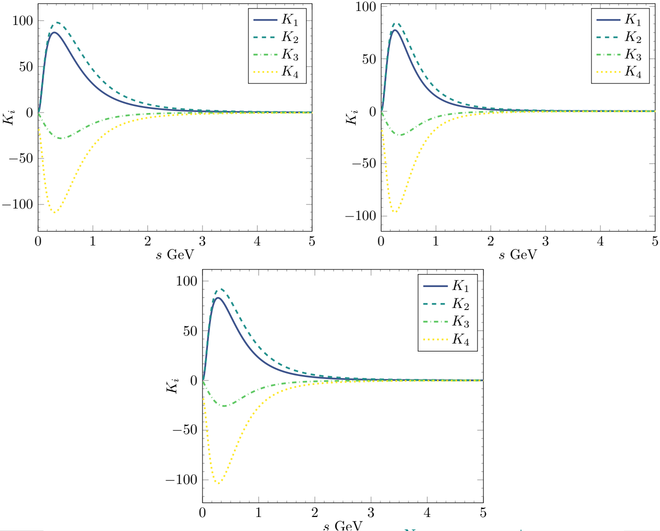
Masses for possible $\bar{D}^*\Sigma_c$ bound states

- Mass spectra under the $\bar{D}^*\Sigma_c$ 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 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	Mass	Mass	m_Λ	Mass	Mass	m_Λ	Mass	Mass	m_Λ
$\frac{1}{2}^-$	4.440	4.443	1.07	4.457	4.458	0.860	4.453	4.454	0.915
$\frac{3}{2}^-$	4.457	4.4625	0.754	4.440	4.450	0.974	4.445	4.454	0.915

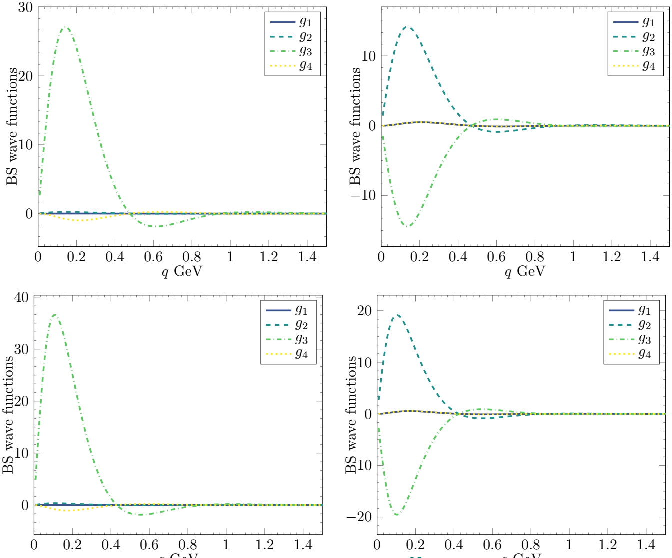
Interaction kernel

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



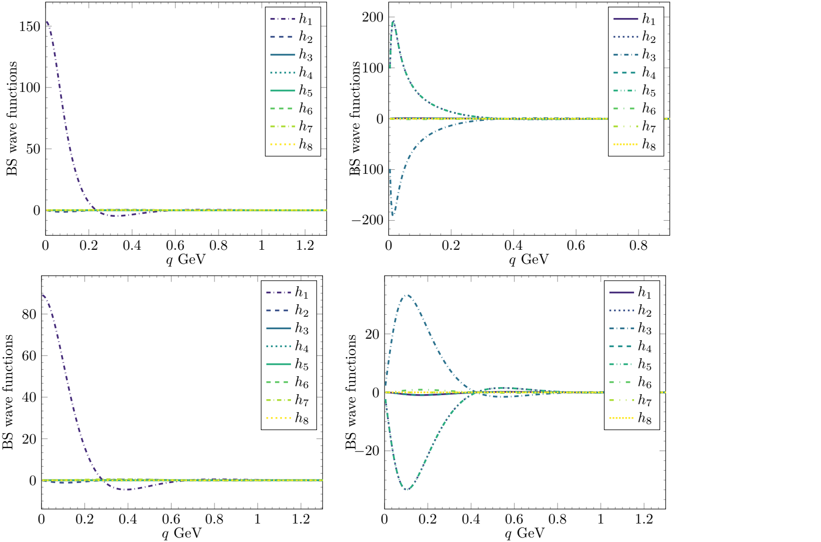
BS radial wave functions for $P^N_{\psi 1/2}$

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



BS radial wave functions for $P^N_{\psi 3/2}$

- BS wave functions for $P^N_{\psi 3/2}$ with mass 4.457, 4.4625, 4.445 and 4.454 GeV, respectively, with $m_\Lambda = 0.754$(up) and 0.917 GeV(down).



Form factors

Numerical values of strong decay form factors for P_ψ^N with $m = 1, \cdots, 8$ 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_{m1}^1	1.9×10^{-4}	1.3×10^{-6}	-3.5×10^{-5}	-2.6×10^{-3}	-5.7×10^{-6}	4.1×10^{-3}
s_{m1}^2	-4.5×10^{-4}	-1.9×10^{-5}	2.4×10^{-5}	8.0×10^{-5}	1.1×10^{-6}	-1.3×10^{-4}
s_{m2}^1	-2.7×10^{-4}	-2.9×10^{-6}	–	–	–	–
s_{m2}^2	-2.2×10^{-4}	-1.0×10^{-5}	–	–	–	–

t_{mo}^n	$\bar{D}^{*0}\Lambda_c^+$	$J/\psi p$	$\bar{D}^0\Lambda_c^+$	$\bar{D}\Sigma_c$	$\eta_c p$	$\bar{D}\Sigma_c^*$
t_{m1}^1	3.1×10^{-3}	9.1×10^{-5}	-1.9×10^{-3}	-8.5×10^{-3}	-1.6×10^{-6}	-3.8×10^{-8}
t_{m1}^2	2.4×10^{-7}	1.2×10^{-8}	-1.0×10^{-4}	-3.4×10^{-4}	-3.2×10^{-5}	1.3×10^{-4}
t_{m2}^1	-3.4×10^{-4}	-7.6×10^{-6}	–	–	–	1.9×10^{-5}
t_{m2}^2	1.8×10^{-3}	5.3×10^{-5}	–	–	–	3.9×10^{-4}
t_{m3}^1	-9.8×10^{-5}	-4.2×10^{-6}	–	–	–	-2.1×10^{-2}
t_{m3}^2	-1.3×10^{-3}	-1.3×10^{-4}	–	–	–	1.5×10^{-3}
t_{m4}^1	8.3×10^{-5}	2.3×10^{-7}	–	–	–	–
t_{m4}^2	1.3×10^{-2}	-2.4×10^{-4}	–	–	–	–

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]
$P_\psi^N(4440) \to \bar{D}^{*0}\Lambda_c^+$	4.9	4.5	-	13.9 − 6.2
$P_\psi^N(4440) \to J/\psi p$	2.7×10^{-4}	2.1×10^{-4}	4.1 − 4.1	0.03 − 0.02
$P_\psi^N(4440) \to \bar{D}^0\Lambda_c^+$	1.1	8.1×10^{-2}	5.98 − 4.53	5.6 − 1.7
$P_\psi^N(4440) \to \bar{D}\Sigma_c$	27.1	2.5	10.43 − 5.45	3.4 − 0.5
$P_\psi^N(4440) \to \eta_c p$	1.7×10^{-5}	4.7×10^{-8}	-	0 − 0
$P_\psi^N(4440) \to \bar{D}\Sigma_c^*$	1.8	3.5×10^{-1}	-	0.8 − 5.4
Total	34.8	7.4	20.52 − 13.98	23.7 − 13.9
$P_\psi^N(4457) \to \bar{D}^{*0}\Lambda_c^+$	7.2×10^{-1}	1.5×10^{-1}	-	12.5 − 6.1
$P_\psi^N(4457) \to J/\psi p$	3.6×10^{-5}	7.6×10^{-5}	1.52 − 1.52	0.02 − 0.01
$P_\psi^N(4457) \to \bar{D}^0\Lambda_c^+$	1.4×10^{-3}	2.8×10^{-3}	2.47 − 2.15	3.8 − 1.5
$P_\psi^N(4457) \to \bar{D}\Sigma_c$	8.8×10^{-1}	13.9	5.60 − 4.11	2.6 − 1.0
$P_\psi^N(4457) \to \eta_c p$	3.0×10^{-9}	4.9×10^{-6}	-	0 − 0
$P_\psi^N(4457) \to \bar{D}\Sigma_c^*$	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.

谢谢