Molecular P_ψ pentaquarks from light-meson exchange saturation

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Outline

1. Motivation
2. Model on EFT and light meson saturation
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4. Extension to the charmed baryon spectrum
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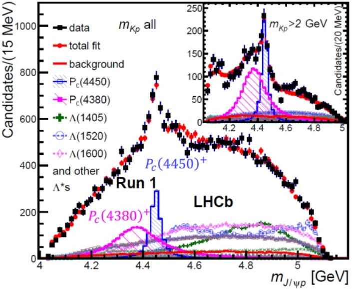
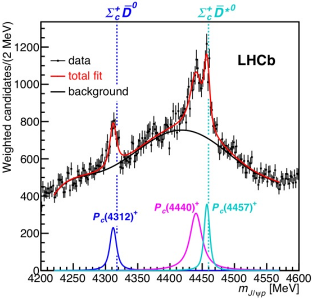
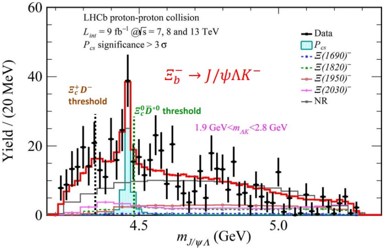
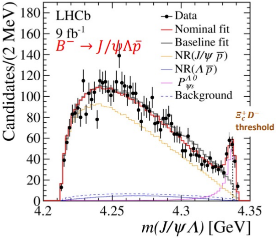
Motivation: observations on $P_{c(s)}$









LHCb,PRL 115 (2015) 072001;PRL 122 (2019) 222001;Science Bulletin 66(2021)1278 ;PRL 131 (2023) 031901

Motivation: observations on $P_{c(s)}$

$P_{c(s)}$ masses and widths [MeV]

- $P_c(4312)$: $M = 4311.9 \pm 0.7^{+6.8}_{-0.6}$, $\Gamma = 9.8 \pm 2.7^{+3.7}_{-4.5}$
- $P_c(4440)$: $M = 4440.3 \pm 1.3^{+4.1}_{-4.7}$, $\Gamma = 20.6 \pm 4.9^{+8.7}_{-10.1}$
- $P_c(4457)$: $M = 4457.3 \pm 0.6^{+4.1}_{-1.7}$, $\Gamma = 6.4 \pm 2.0^{+5.7}_{-1.9}$
- $P_{cs}(4459)$: $M = 4458.8 \pm 2.9^{+4.7}_{-1.1}$, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$
- $P_{cs}(4338)$: $M = 4338.2 \pm 0.7$, $\Gamma = 7.0 \pm 1.2$.

Double-peak $P_{cs}(4459)$

- P_{cs1}: $M = 4454.9 \pm 2.7$, $\Gamma = 7.5 \pm 9.7$
- P_{cs2}: $M = 4467.8 \pm 3.7$, $\Gamma = 5.3 \pm 5.3$.

Thresholds

- $\Sigma_c \bar{D}$: 4320.7; $\Sigma_c \bar{D}^*$: 4462.0;
- $\Xi'_c \bar{D}$: 4446.0;$\Xi_c \bar{D}^*$: 4478.0;$\Xi^*_c \bar{D}$: 4513.2; $\Xi_c \bar{D}$: 4336.3

Motivation: explanations on $P_{c(s)}$

Non-molecular state

- Threshold cusps: F.K. Guo et al, PRD92(2015);M.Bayar et al,Phys.Rev.D 94 (2016);S.X. Nakamura et al,PRD 103 (2021) 111503;PRD104 (2021) 9; T.J. Burns et al, PLB838(2023)$\cdots$
- Hadrocharmonium: M.I. Eides et al,MPL A 35(2020)18; J. Ferretti et al, Sci.Bull. 67 (2022) 1209$\cdots$
- Compact P_c: Fl. Stancu,PRD 101(2020)9; H. Garcilazo et al, PRD 105 (2022) 11$\cdots$

Molecular state

- QCD sum rule: H.X. Chen et al,PRL115(2015)17$\cdots$
- Cont. EFT: M.Z Liu et al, PRL122(2019);M.L. Du et al,PRL124(2020)7, PRD104(2021)11$\cdots$
- Pionful EFT: L. Meng et al, PRD100(2019)1; B. Wang et al, PRD101(2020)3 $\cdots$
- OBE: R. Chen et al, PRL115(2015)13;F.L. Wang et al,PLB 835 (2022) 137583$\cdots$
- Vector-meson Exch.: J.J. Wu et al, PRL105(2010),PRC 84 (2011);C.W. Xiao et al, PRD88(2013),PRD100(2019);L. Roca et al, PRD92 (2015) 9;X.K. Dong et al, Progr.Phys. 41(2021) 65$\cdots$

Model on EFT and light meson saturation

EFT inspired OBE

- The S-wave antimeson-baryon interaction in contact-range

$$\left\langle \vec{p}' \,|V_C|\, \vec{p} \right\rangle = C_0 + C_1 \hat{\vec{S}}_{L1} \cdot \hat{\vec{S}}_{L2},$$

with C_0 and C_1 their respective couplings, and with $\hat{\vec{S}}_{Li} = \vec{S}_{Li} / \left| S_{Li} \right|$ the normalized light-quark spin operator of hadron $i = 1, 2$

Saturation: $\zeta = +1$ for P_c

- The C_0 and C_1 are saturated by scalar and vector meson exchange.

$$V_S = -\frac{g_{S1} g_{S2}}{m_S^2 + \vec{q}^2} |_{C_0}$$

$$V_V = (\zeta + T_{12}) \left[\frac{g_{V1} g_{V2}}{m_V^2 + \vec{q}^2} |_{C_0} + \frac{f_{V1} f_{V2}}{6M^2} \frac{m_V^2}{m_V^2 + \vec{q}^2} \hat{\vec{S}}_{L1} \cdot \hat{\vec{S}}_{L2} \right] + \ldots,$$

Model on EFT and light meson saturation

Couplings

- $g_S = 3.4$ and 6.8 for the charmed mesons and baryons, respectively.
- $g_V = 2.9$ and 5.8 for the charmed mesons and $\Sigma_c^{(*)}$ baryons and $g_V = 2.9$ for the $\Xi_c^{('/*)}$ baryons.
- the magnetic-like couplings we define $f_V = \kappa_V g_V$ with $\kappa_V = \frac{3}{2}(\mu_u/\mu_N)$ for both charmed mesons and baryons (Σ_c, Σ_c^*, Ξ_c', Ξ_c^*), with μ_N the nuclear magneton and $\mu_u \simeq 1.9\,\mu_N$.

Mass inputs

- $m_S = 475\mathrm{MeV}$ (i.e. the average of its $400 - 550)\mathrm{MeV}$.
- $m_V = (m_\rho + m_\omega)/2 = 775\mathrm{MeV}$.
- The extension to the other molecular configurations can be done by modifying the vector meson masses to the K^* and ϕ vector mesons.
- $M = m_N = 938.9\,\mathrm{MeV}$ the nucleon mass.

Model on EFT and light meson saturation

Saturation

- σ-exchange: $C_0^S(\Lambda \sim m_S) \propto -\frac{g_{S1}g_{S2}}{m_S^2}$, $C_1^S(\Lambda \sim m_S) \propto 0$
- vector-meson Exch.:
  $C_0^V(\Lambda \sim m_V) \propto \frac{g_{V1}g_{V2}}{m_V^2}(\zeta + T_{12})$, $C_1^V(\Lambda \sim m_V) \propto \frac{f_{V1}f_{V2}}{6M^2}(\zeta + T_{12})$,

RG evolution

- Owing to $m_S \neq m_V$, the regularization scale for the saturation of the C_0 coupling by mesons is not identical. Considering RGE of V_C,

$$\frac{d}{d\Lambda}\langle \Psi | V_C(\Lambda) | \Psi \rangle = 0,$$

- If $\Psi(r) \sim r^{\alpha/2}$ at distances $r \sim 1/\Lambda$, $\frac{d}{d\Lambda}\left[\frac{C(\Lambda)}{\Lambda^\alpha}\right] = 0$, with $\alpha = 1$.
- $C(\Lambda = m_V) = C_V(m_V) + \left(\frac{m_V}{m_S}\right)^\alpha C_S(m_S)$

Model on EFT and light meson saturation

Inputs

- $V_C = C^{\rm sat}_{\rm mol} f\left(\frac{p'}{\Lambda}\right) f\left(\frac{p}{\Lambda}\right)$ with $f(x) = e^{-x^2}$.
- LS Eq.: $1 + 2\mu_{\rm mol} C^{\rm sat}_{\rm mol} \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{f^2\left(\frac{q}{\Lambda}\right)}{M_{\rm th} + \frac{q^2}{2\mu_{\rm mol}} - M_{\rm mol}} = 0,$

  with a ref. $P_\psi^N(4312)$, $C^{\rm sat}_{\rm ref} = -0.80^{+0.14}_{-0.01}\,{\rm fm}^2$ for $\Lambda = 1\,{\rm GeV}$.

Predictions

- Single channel: $1 + 2\mu_{\rm ref} C^{\rm sat}_{\rm ref} R_{\rm mol} \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{f^2\left(\frac{q}{\Lambda}\right)}{M_{\rm th} + \frac{q^2}{2\mu_{\rm mol}} - M_{\rm mol}} = 0,$

  with the ratio between the relative strength of the coupling:

$$R_{\rm mol} = \frac{\mu_{\rm mol} C^{\rm sat}_{\rm mol}}{\mu_{\rm ref} C^{\rm sat}_{\rm ref}}$$

- $R_{\rm mol} > 0.72^{+0.13}_{-0.01}|_B, \quad \left(R_{\rm mol} \leq 0.72^{+0.13}_{-0.01}\right)|_V$

Model on EFT and light meson saturation

Errors

- The uncertainty of the mass of the $P_\psi^N(4312)$, $C_{\rm ref}^{\rm sat} = -0.80^{+0.14}_{-0.01}\,{\rm fm}^2$
- The uncertainty of the mass of the scalar meson, $m_S = (475 \pm 75)\,{\rm MeV}$, i.e., equivalent to the $m_S = (400 - 550)\,{\rm MeV}$.
- Choosing the largest of these two sources:

$$\Delta M_{\rm mol} = \text{minmax}\{M_{\rm mol}\left(C_{\rm ref}^{\rm sat} \pm \Delta C_{\rm ref}^{\rm sat}\right) - M_{\rm mol},\ M_{\rm mol}\left(m_S \pm \Delta m_S\right) - M_{\rm mol}\}\,,$$

"minmax" refers to the maximum (for the positive error) and minimum (for the negative error) number within the list.

- Widths of charmed hadrons are not included. i.e. $\Gamma(\Sigma_c^*) \approx 15\,{\rm MeV}$.

Predictions on $P_{c(s)}$ spectrum

System	$I(J^P)$	R_{mol}	M_{mol}	Candidate	$M_{\mathrm{candidate}}$
$\Lambda_c\bar{D}$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.69	$(4153.6^{+0.1(B)}_{-3.9})^V$		
$\Lambda_c\bar{D}^*$	$\frac{1}{2}$ $(\frac{1}{2}^-, \frac{3}{2}^-)$	0.72	$(4295.0^{+0.0(B)}_{-2.7})^V$		
$\Lambda_c\bar{D}_s$	0 $(\frac{1}{2}^-)$	0.86	$4252.5^{+2.3}_{-2.0}$		
$\Lambda_c\bar{D}_s^*$	0 $(\frac{1}{2}^-, \frac{3}{2}^-)$	0.89	$4395.2^{+3.2}_{-2.3}$		
$\Xi_c\bar{D}$	0 $(\frac{1}{2}^-)$	1.00	$4327.4^{+6.9}_{-0.9}$	$P^{\Lambda}_{\psi s}(4338)$	4338.2 ± 0.7
$\Xi_c\bar{D}^*$	0 $(\frac{1}{2}^-, \frac{3}{2}^-)$	1.04	$4466.7^{+7.8}_{-1.0}$	$P^{\Lambda}_{\psi s}(4459)$	$4458.9^{+5.5}_{-3.1}$
$\Xi_c\bar{D}$	1 $(\frac{1}{2}^-)$	0.72	$(4336.3^{+0.0(B)}_{-2.9})^V$		
$\Xi_c\bar{D}^*$	1 $(\frac{1}{2}^-, \frac{3}{2}^-)$	0.74	$4477.6^{+0.0(V)}_{-2.2}$		
$\Xi_c\bar{D}_s$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.82	$4436.3^{+1.2}_{-2.5}$		
$\Xi_c\bar{D}_s^*$	$\frac{1}{2}$ $(\frac{1}{2}^-, \frac{3}{2}^-)$	0.85	$4579.2^{+2.0}_{-3.0}$		

System	$I(J^P)$	R_{mol}	M_{mol}	Candidate	$M_{\mathrm{candidate}}$
$\Sigma_c\bar{D}$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	1.00	Input	$P^N_\psi(4312)$	$4311.9^{+6.8}_{-0.9}$
$\Sigma_c^*\bar{D}$	$\frac{1}{2}$ $(\frac{3}{2}^-)$	1.04	$4376.0^{+7.1}_{-0.9}$	$P^N_\psi(4380)$	-
$\Sigma_c\bar{D}^*$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.85	$4459.7^{+2.3}_{-2.5}$	$P^N_\psi(4457)$	$4457.3^{+4.1}_{-1.8}$
$\Sigma_c\bar{D}^*$	$\frac{1}{2}$ $(\frac{3}{2}^-)$	1.13	$4445.2^{+10.4}_{-2.9}$	$P^N_\psi(4440)$	$4440.3^{+4.3}_{-1.8}$
$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}$ $(\frac{1}{2}^-)$	0.82	$4525.4^{+1.3(V)}_{-2.7}$	-	-
$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}$ $(\frac{3}{2}^-)$	0.96	$4520.3^{+5.3}_{-1.7}$	-	-
$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}$ $(\frac{5}{2}^-)$	1.19	$4505.8^{+12.0}_{-4.7}$	-	-

Predictions on $P_{c(s)}$ spectrum

Coupled channel scattering

- When there are two nearby meson-baryon thresholds with the same quantum numbers, we will use the previous equation in matrix form

$$\phi_A + 2\mu_A \sum_B \phi_B C^{\mathrm{sat}}_{\mathrm{ref}} R^{AB}_{\mathrm{mol}} \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{f^2\left(\frac{q}{\Lambda}\right)}{M_{\mathrm{th(B)}} - \frac{q^2}{2\mu} - M_{\mathrm{mol}}} = 0.$$

Channels	System	$I(J^P)$	S	M_{mol}	$\Delta M^{\mathrm{CC}}_{\mathrm{mol}}$	Candidate	$M_{\mathrm{candidate}}$
(1) $\Lambda_c\bar{D}^*$-$\Sigma_c\bar{D}$	$\Lambda_c\bar{D}^*$	$0(\frac{1}{2}^-)$	0	$4291.0^{+3.9}_{-1.9}$	$-4.0^{(*)}$	-	-
	$\Sigma_c\bar{D}$	$0(\frac{1}{2}^-)$	0	$4315.8^{+4.8}_{-2.3} - (6.6^{+8.2}_{-4.2})\,i$	$+3.9$	$P^N_\psi(4312)$	$4311.9^{+6.8}_{-0.9} - (4.9^{+2.3}_{-2.6})\,i$
(2) $\Lambda_c\bar{D}_s$-$\Xi_c\bar{D}$	$\Lambda_c\bar{D}_s$	$0(\frac{1}{2}^-)$	-1	$4251.8^{+3.0}_{-1.6}$	-0.6	-	-
	$\Xi_c\bar{D}$	$0(\frac{1}{2}^-)$	-1	$4328.1^{+6.4}_{-0.8} - (1.1^{+1.3}_{-0.7})\,i$	$+0.7$	$P^\Lambda_{\psi s}(4338)$	$4338.2 \pm 0.7 - (3.5 \pm 0.6)\,i$
(3) $\Lambda_c\bar{D}_s^*$-$\Xi'_c\bar{D}$-$\Xi_c\bar{D}^*$	$\Lambda_c\bar{D}_s^*$	$0(\frac{1}{2}^-)$	-1	$4393.5^{+4.7}_{-1.3}$	-1.7	-	-
	$\Xi'_c\bar{D}$	$0(\frac{1}{2}^-)$	-1	$4433.6^{+8.8}_{-2.6} - (0.5 \pm 0.2)\,i$	-4.3	-	-
	$\Xi_c\bar{D}^*$	$0(\frac{1}{2}^-)$	-1	$4468.8^{+6.4}_{-1.2} - (3.0^{+3.4}_{-1.9})\,i$	$+1.1$	$P^\Lambda_{\psi s}(4459)$	$4458.9^{+5.5}_{-3.1} - (8.7^{+5.2}_{-4.3})\,i$
(4) $\Lambda_c\bar{D}_s^*$-$\Xi_c\bar{D}^*$-$\Xi^*_c\bar{D}$	$\Lambda_c\bar{D}_s^*$	$0(\frac{3}{2}^-)$	-1	$4394.0^{+4.3}_{-1.6}$	-1.2	-	-
	$\Xi_c\bar{D}^*$	$0(\frac{3}{2}^-)$	-1	$4464.6^{+9.1}_{-2.3} - (0.6^{+0.4}_{-0.3})\,i$	-2.1	$P^\Lambda_{\psi s}(4459)$	$4458.9^{+5.5}_{-3.1} - (8.7^{+5.2}_{-4.3})\,i$
	$\Xi'_c\bar{D}$	$0(\frac{3}{2}^-)$	-1	$4503.8^{+6.7}_{-0.9} - (2.0^{+2.3}_{-1.2})\,i$	$+1.3$	-	-

More predictions on $P_{c(s)}$ spectrum

System	$I(J^P)$	R_{mol}	M_{mol}	Candidate	$M_{\mathrm{candidate}}$
$\Sigma_c\bar{D}$	$\frac{1}{2}\,(\frac{1}{2}^-)$	1.00	Input	$P_\psi^N(4312)$	$4311.9^{+6.8}_{-0.9}$
$\Sigma_c^*\bar{D}$	$\frac{1}{2}\,(\frac{3}{2}^-)$	1.04	$4376.0^{+7.1}_{-0.9}$	-	-
$\Sigma_c\bar{D}^*$	$\frac{1}{2}\,(\frac{1}{2}^-)$	0.85	$4459.7^{+2.3}_{-2.5}$	$P_\psi^N(4457)$	$4457.3^{+4.1}_{-1.8}$
$\Sigma_c\bar{D}^*$	$\frac{1}{2}\,(\frac{3}{2}^-)$	1.13	$4445.2^{+10.4}_{-2.9}$	$P_\psi^N(4440)$	$4440.3^{+4.3}_{-1.8}$
$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}\,(\frac{1}{2}^-)$	0.82	$4525.4^{+1.3(V)}_{-2.7}$	-	-
$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}\,(\frac{3}{2}^-)$	0.96	$4520.3^{+5.3}_{-1.7}$	-	-
$\Sigma_c^*\bar{D}^*$	$\frac{1}{2}\,(\frac{5}{2}^-)$	1.19	$4505.8^{+12.0}_{-4.7}$	-	-
$\Xi_c'\bar{D}$	$0\,(\frac{1}{2}^-)$	1.02	$4435.9^{+7.3}_{-0.9}$	-	-
$\Xi_c^*\bar{D}$	$0\,(\frac{3}{2}^-)$	1.03	$4502.5^{+7.5}_{-1.0}$	-	-
$\Xi_c'\bar{D}^*$	$0\,(\frac{1}{2}^-)$	0.88	$4584.2^{+2.8}_{-2.7}$	-	-
$\Xi_c'\bar{D}^*$	$0\,(\frac{3}{2}^-)$	1.16	$4568.8^{+10.3}_{-3.0}$	-	-
$\Xi_c^*\bar{D}^*$	$0\,(\frac{1}{2}^-)$	0.84	$4652.5^{+1.7(V)}_{-3.0}$	-	-
$\Xi_c^*\bar{D}^*$	$0\,(\frac{3}{2}^-)$	0.98	$4646.9^{+5.8}_{-1.8}$	-	-
$\Xi_c^*\bar{D}^*$	$0\,(\frac{5}{2}^-)$	1.22	$4631.8^{+12.5}_{-4.9}$	-	-
$\Sigma_c\bar{D}_s$-$\Xi_c'\bar{D}$	$1\,(\frac{1}{2}^-)$	0.96	$4417.3^{+4.2}_{-1.6}$	-	-
$\Sigma_c^*\bar{D}_s$-$\Xi_c^*\bar{D}$	$1\,(\frac{3}{2}^-)$	0.98	$4481.6^{+4.4}_{-1.7}$	-	-
$\Sigma_c\bar{D}_s^*$-$\Xi_c'\bar{D}^*$	$1\,(\frac{1}{2}^-)$	0.84	$4581.9^{+4.4}_{-2.4} - (0.6^{+0.0}_{-0.5})\,i$	-	-
$\Sigma_c\bar{D}_s^*$-$\Xi_c'\bar{D}^*$	$1\,(\frac{3}{2}^-)$	1.08	$4556.4^{+7.4}_{-1.0}$	-	-
$\Sigma_c^*\bar{D}_s^*$-$\Xi_c^*\bar{D}^*$	$1\,(\frac{1}{2}^-)$	0.81	$4647.4^{+5.3}_{-0.0} - (1.8^{+1.7}_{-0.9})\,i$	-	-
$\Sigma_c^*\bar{D}_s^*$-$\Xi_c^*\bar{D}^*$	$1\,(\frac{3}{2}^-)$	0.94	$4625.5^{+4.3}_{-2.6}$	-	-
$\Sigma_c^*\bar{D}_s^*$-$\Xi_c^*\bar{D}^*$	$1\,(\frac{5}{2}^-)$	1.13	$4618.6^{+8.7}_{-1.1}$	-	-
$\Xi_c'\bar{D}_s$-$\Omega_c\bar{D}$	$\frac{1}{2}\,(\frac{1}{2}^-)$	1.01	$4542.9^{+3.9}_{-1.8}$	-	-
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{3}{2}^-)$	1.02	$4610.0^{+3.9}_{-2.0}$	-	-
$\Xi_c'\bar{D}_s^*$-$\Omega_c\bar{D}^*$	$\frac{1}{2}\,(\frac{1}{2}^-)$	0.87	$4699.6^{+3.8}_{-2.9} - (0.5^{+0.2}_{-0.3})\,i$	-	-
$\Xi_c'\bar{D}_s^*$-$\Omega_c\bar{D}^*$	$\frac{1}{2}\,(\frac{3}{2}^-)$	1.13	$4681.0^{+8.3}_{-1.1}$	-	-
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{1}{2}^-)$	0.84	$4770.8^{+3.4}_{-3.4} - (1.0^{+0.1}_{-0.6})\,i$	-	-
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{3}{2}^-)$	0.97	$4752.0^{+4.9}_{-2.7}$	-	-
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{5}{2}^-)$	1.19	$4746.3^{+9.6}_{-2.3}$	-	-

TABLE II. Molecular octet pentaquark states predicted in this work.

System	$I(J^P)$	R_{mol}	M_{mol}
$\Sigma_c\bar{D}$	$\frac{3}{2}\,(\frac{1}{2}^-)$	0.57	$(4316.8^{+3.9(B)}_{-22.0})^V$
$\Sigma_c^*\bar{D}$	$\frac{3}{2}\,(\frac{3}{2}^-)$	0.58	$(4381.8^{+3.6(B)}_{-21.3})^V$
$\Sigma_c\bar{D}^*$	$\frac{3}{2}\,(\frac{1}{2}^-)$	0.96	$4455.6^{+5.4}_{-1.5}$
$\Sigma_c\bar{D}^*$	$\frac{3}{2}\,(\frac{3}{2}^-)$	0.41	-
$\Sigma_c^*\bar{D}^*$	$\frac{3}{2}\,(\frac{1}{2}^-)$	1.07	$4514.6^{+8.3}_{-1.0}$
$\Sigma_c^*\bar{D}^*$	$\frac{3}{2}\,(\frac{3}{2}^-)$	0.79	$4526.1^{+0.5(V)}_{-2.6}$
$\Sigma_c^*\bar{D}^*$	$\frac{3}{2}\,(\frac{5}{2}^-)$	0.32	-
$\Sigma_c\bar{D}_s$-$\Xi_c'\bar{D}$	$1\,(\frac{1}{2}^-)$	0.65	$(4445.8^{+0.0}_{-2.2(R)} - (0.1^{+4.0}_{-0.1(R)})\,i)^V$
$\Sigma_c^*\bar{D}_s$-$\Xi_c^*\bar{D}$	$1\,(\frac{3}{2}^-)$	0.65	$(4513.0^{+0.0}_{-2.2(R)} - (0.0^{+4.0}_{-0.0(R)})\,i)^V$
$\Sigma_c\bar{D}_s^*$-$\Xi_c'\bar{D}^*$	$1\,(\frac{1}{2}^-)$	1.02	$4560.2^{+4.8}_{-2.0}$
$\Sigma_c\bar{D}_s^*$-$\Xi_c'\bar{D}^*$	$1\,(\frac{3}{2}^-)$	0.50	$(4647.5^{+5.5}_{-2.4(R)} - (4.6^{+17.0}_{-4.6(R)})\,i)^V$
$\Sigma_c^*\bar{D}_s^*$-$\Xi_c^*\bar{D}^*$	$1\,(\frac{1}{2}^-)$	1.12	$4622.5^{+6.6}_{-1.1}$
$\Sigma_c^*\bar{D}_s^*$-$\Xi_c^*\bar{D}^*$	$1\,(\frac{3}{2}^-)$	0.85	$4651.9^{+2.3}_{-3.0} - (0.0 \pm 0.0)\,i$
$\Sigma_c^*\bar{D}_s^*$-$\Xi_c^*\bar{D}^*$	$1\,(\frac{5}{2}^-)$	0.42	$(4656.2^{+11.2}_{-3.0(R)} - (9.8^{+23.5}_{-9.8(R)})\,i)^V$
$\Xi_c'\bar{D}_s$-$\Omega_c\bar{D}$	$\frac{1}{2}\,(\frac{1}{2}^-)$	0.72	$4560.2^{+2.9}_{-2.8} - (1.5^{+0.6}_{-1.2})\,i$
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{3}{2}^-)$	0.73	$4630.6^{+2.9}_{2.8} - (1.5^{+0.6}_{-1.2})\,i$
$\Xi_c'\bar{D}_s^*$-$\Omega_c\bar{D}^*$	$\frac{1}{2}\,(\frac{1}{2}^-)$	1.07	$4680.3^{+7.6}_{-1.0}$
$\Xi_c'\bar{D}_s^*$-$\Omega_c\bar{D}^*$	$\frac{1}{2}\,(\frac{3}{2}^-)$	0.59	$4704.9^{+10.3}_{-5.7} - (4.7^{+3.4}_{-2.2})\,i$
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{1}{2}^-)$	1.17	$4742.8^{+9.9}_{-1.4}$
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{3}{2}^-)$	0.92	$4769.3^{+4.5}_{-2.7} - (0.1 \pm 0.0)\,i$
$\Xi_c^*\bar{D}_s$-$\Omega_c^*\bar{D}$	$\frac{1}{2}\,(\frac{5}{2}^-)$	0.52	$4778.2^{+15.4}_{-7.9} - (6.5^{+5.8}_{-3.1})\,i$
$\Omega_c\bar{D}_s$	$0\,(\frac{1}{2}^-)$	0.78	$4663.1^{+0.5(V)}_{-2.8}$
$\Omega_c^*\bar{D}_s$	$0\,(\frac{3}{2}^-)$	0.79	$4733.6^{+0.7(V)}_{-3.0}$
$\Omega_c\bar{D}_s^*$	$0\,(\frac{1}{2}^-)$	1.12	$4792.9^{+9.2}_{-1.1}$
$\Omega_c\bar{D}_s^*$	$0\,(\frac{3}{2}^-)$	0.67	$(4807.0^{+0.4(B)}_{-10.7})^V$
$\Omega_c^*\bar{D}_s^*$	$0\,(\frac{1}{2}^-)$	1.20	$4857.9^{+11.5}_{-2.3}$
$\Omega_c^*\bar{D}_s^*$	$0\,(\frac{3}{2}^-)$	0.98	$4871.4^{+5.4}_{-2.8}$
$\Omega_c^*\bar{D}_s^*$	$0\,(\frac{5}{2}^-)$	0.60	$(4875.9^{+2.2(B)}_{-23.6})^V$

TABLE III. Molecular decuplet pentaquark states predicted i

Predictions on charmed baryons

Couplings

- $a_0\left(\Lambda N, {}^1S_0\right) = -3.1\,\mathrm{fm},\ a_0\left(\Lambda N, {}^3S_1\right) = -2.9\,\mathrm{fm},\ a_0(\Lambda\Lambda) = -1.3\,\mathrm{fm}$ obtained with $g_{\sigma\Lambda\Lambda} = 3/4 g_{\sigma NN}$.
- $g_S = 10.2, g_V = 2.9, \mu_u = 1.9$ and $\mu_s = -0.6$.

Hadron	g_σ	g_ρ	g_ω	g_ϕ	κ_ρ	κ_ω	κ_ϕ
$D,\ D^*$	$\frac{1}{3}g_S$	g_V	g_V	0	$\frac{3}{2}\mu_u$	$\frac{3}{2}\mu_u$	0
$D_s,\ D_s^*$	$\frac{1}{3}g_S$	0	0	$\sqrt{2}g_V$	0	0	$-3\mu_s$
N	g_S	g_V	$3g_V$	0	$\frac{5}{2}\mu_u$	$\frac{1}{2}\mu_u$	0
Λ	$0.75\,g_S$	0	$2g_V$	$\sqrt{2}g_V$	0	0	$-3\,\mu_s$
Σ	g_S	$2g_V$	$2g_V$	$\sqrt{2}g_V$	μ_u	μ_u	$-\mu_s$
Ξ	g_S	g_V	g_V	$2\sqrt{2}g_V$	$-\frac{1}{2}\mu_u$	$-\frac{1}{2}\mu_u$	$2\mu_s$

Predictions on charmed baryons with $\Lambda = 0.75\,\mathrm{GeV}$

System	S	I	J^P	$R_{\rm mol}(\Lambda_c^*)$	$B_{\rm mol}$	$M_{\rm mol}$	$R_{\rm mol}(\Sigma_c^*)$	$B_{\rm mol}$	$M_{\rm mol}$	Candidate	$M_{\rm cand}$
ND_s	+1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.60	$(2.2)^V$	$(2905.0^{+2.2(B)}_{-6.9})^V$	0.91	2.8	2904.5 ± 1.4	-	-
ND_s^*	+1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.62	$(1.7)^V$	$(3049.4^{+1.7(B)}_{-6.3})^V$	0.95	3.4	$3047.7^{+1.6}_{-1.5}$	-	-
ND_s^*	+1	$\frac{1}{2}$	$\frac{3}{2}^-$	0.62	$(1.7)^V$	$(3049.4^{+1.7(B)}_{-6.4})^V$	0.95	3.4	$3047.7^{+1.6}_{-1.5}$	-	-
ND	0	0	$\frac{1}{2}^-$	0.79	0.6	$2805.6^{+0.5}_{-1.2}$	1.20	17.7	$2788.5^{+4.9}_{-6.8}$	$\Lambda_c(2765)$	2766.6 ± 2.4 [31]
ND^*	0	0	$\frac{1}{2}^-$	0.44	$(16)^V$	$(2932^{+14}_{-34})^V$	0.66	1.2	$2946.3^{+1.0}_{-10.5}$	$\Lambda_c(2940)$	$2939.6^{+1.3}_{-1.5}$ [31]
ND^*	0	0	$\frac{3}{2}^-$	1 (Input)	7.9	2939.6	1.51	42	2906^{+15}_{-22}	$\Lambda_c(2940)$	$2939.6^{+1.3}_{-1.5}$ [31]
ND	0	1	$\frac{1}{2}^-$	0.66	$(0.6)^V$	$(2805.6^{+0.6(B)}_{-3.1})^V$	1 (Input)	6.2	2800.0	$\Sigma_c(2800)$	~ 2800 [31]
ND^*	0	1	$\frac{1}{2}^-$	0.72	$(0.0)^V$	$(2947.5^{+0.0(B)}_{-1.1})^V$	1.09	10.4	$2937.1^{+1.3}_{-1.7}$		
ND^*	0	1	$\frac{3}{2}^-$	0.66	$(0.7)^V$	$(2946.8^{+0.7(B)}_{-3.7})^V$	0.99	5.7	$2941.8^{+0.6}_{-0.5}$		
ΛD_s	0	0	$\frac{1}{2}^-$	0.54	$(5.0)^V$	$(3079.0^{+3.7}_{-1.9})^V$	0.82	0.4	3083.6 ± 0.2		
ΛD_s^*	0	0	$\frac{1}{2}^-$	0.51	$(7.0)^V$	$(3220.9^{+5.2}_{-2.1})^V$	0.77	0.0	$3227.9^{+0.0(V)}_{-0.3}$		
ΛD_s^*	0	0	$\frac{3}{2}^-$	0.59	$(3.0)^V$	$(3224.9^{+2.5}_{-2.4})^V$	0.87	1.4	$3226.5^{+0.0(V)}_{-0.3}$		
ΣD_s	0	1	$\frac{1}{2}^-$	0.74	0.0	$3164.5^{+0.0(V)}_{-1.9}$	1.12	10.6	$3150.9^{+1.6}_{-1.3}$	-	-
ΣD_s^*	0	1	$\frac{1}{2}^-$	0.74	0.0	$3305.3^{+0.0(V)}_{-2.1}$	1.13	10.7	$3294.7^{+2.1}_{-1.8}$	-	-
ΣD_s^*	0	1	$\frac{3}{2}^-$	0.77	0.2	$3305.2^{+0.2(V)}_{-2.4}$	1.16	12.5	$3292.9^{+1.4}_{-1.2}$	-	-
ΛD	−1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.57	$(3.4)^V$	$(2979.6^{+2.5}_{-4.3})^V$	0.87	1.3	$2981.7^{+0.2}_{-0.3}$	-	-
ΛD^*	−1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.59	$(2.6)^V$	$(3121.6^{+2.1}_{-3.9})^V$	0.89	1.8	$3122.5^{+0.3}_{-0.4}$	$\Xi_c(3123)$	3122.9 ± 1.3 [31]
ΛD^*	−1	$\frac{1}{2}$	$\frac{3}{2}^-$	0.59	$(2.6)^V$	$(3121.6^{+2.1}_{-3.9})^V$	0.89	1.8	$3122.5^{+0.3}_{-0.4}$	$\Xi_c(3123)$	3122.9 ± 1.3 [31]
ΣD	−1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.92	3.8	$3056.6^{+1.9}_{-2.5}$	1.40	28.1	$3023.3^{+6.1}_{-8.2}$	$\Xi_c(3055)$	3055.9 ± 0.4 [31]
ΣD^*	−1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.66	$(0.6)^V$	$(3201.1^{+0.6(B)}_{-5.8})^V$	0.99	5.0	$3196.8^{+3.0}_{-3.2}$	-	-
ΣD^*	−1	$\frac{1}{2}$	$\frac{3}{2}^-$	1.10	11.5	$3190.3^{+1.1}_{-1.2}$	1.66	47	3155^{+14}_{-18}	-	-
ΣD	−1	$\frac{3}{2}$	$\frac{1}{2}^-$	0.69	$(0.1)^V$	$(3060.3^{+0.1(B)}_{-3.4})^V$	1.05	7.3	$3053.1^{+2.3}_{-2.1}$	-	-
ΣD^*	−1	$\frac{3}{2}$	$\frac{1}{2}^-$	0.71	$(0.0)^V$	$(3201.7^{+0.0(B)}_{-2.7})^V$	1.08	8.4	$3193.3^{+2.5}_{-2.2}$	-	-
ΣD^*	−1	$\frac{3}{2}$	$\frac{1}{2}^-$	0.71	$(0.0)^V$	$(3201.7^{+0.0(B)}_{-2.7})^V$	1.08	8.4	$3193.3^{+2.5}_{-2.2}$	-	-
ΞD_s	−1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.82	1.0	$3286.7^{+0.9}_{-3.2}$	1.25	16.6	$3270.0^{+0.4}_{-0.3}$	-	-
ΞD_s^*	−1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.91	3.1	$3427.4^{+2.3}_{-3.8}$	1.38	24.2	$3406.3^{+2.0}_{-2.5}$	-	-
ΞD_s^*	−1	$\frac{1}{2}$	$\frac{3}{2}^-$	0.81	0.8	$3429.8^{+0.6}_{-3.4}$	1.23	15.3	$3415.2^{+1.6}_{-1.4}$	-	-
ΞD	−2	0	$\frac{1}{2}^-$	0.90	2.8	$3182.7^{+2.1}_{-3.2}$	1.36	23.9	$3161.6^{+3.0}_{-3.9}$	$\Omega_c(3185)$	$3185.1^{+7.6}_{-1.9}$ [26]
ΞD^*	−2	0	$\frac{1}{2}^-$	1.03	7.6	$3319.3^{+2.5}_{-3.0}$	1.56	36.7	$3290.2^{+7.5}_{-10.0}$	-	-
ΞD^*	−2	0	$\frac{3}{2}^-$	0.87	2.0	$3324.8^{+1.9}_{-3.6}$	1.32	20.9	$3306.0^{+1.1}_{-1.4}$	$\Omega_c(3327)$	$3327.1^{+1.2}_{-1.8}$ [26]
ΞD	−2	1	$\frac{1}{2}^-$	0.73	0.0	$3185.5^{+0.0(V)}_{-2.1}$	1.11	9.8	$3175.8^{+2.6}_{-2.3}$	-	-
ΞD^*	−2	1	$\frac{1}{2}^-$	0.76	0.1	$3326.8^{+0.1(V)}_{-2.6}$	1.15	11.1	$3315.8^{+2.8}_{-2.5}$	-	-
ΞD^*	−2	1	$\frac{1}{2}^-$	0.76	0.1	$3326.8^{+0.1(V)}_{-2.6}$	1.15	11.1	$3315.8^{+2.8}_{-2.5}$	-	-

Summary

- The contact range interaction is derived from the combination of the RG evolution and exchange of light-mesons (σ, ρ, ω) .
- Assuming $P_{\psi}^{N}(4312)$ is a $\bar{D}\Sigma_c$ bound state, we approximately reproduce the masses of the $P_{\psi}^{N}(4440)$ and $P_{\psi}^{N}(4457)$ as $J = \frac{3}{2}$ and $\frac{1}{2}$ $\bar{D}^*\Sigma_c$ bound states, as well as the narrow $P_{\psi}^{N}(4380)$.
- $\bar{D}\Xi_c$ and $\bar{D}^*\Xi_c$ states with masses of $4327\mathrm{MeV}$ and $4467\mathrm{MeV}$, respectively, corresponding to the $P_{\psi s}^{\Lambda}(4338)$ and the $P_{\psi s}^{\Lambda}(4459)$.

- The ΣD and ΛD^* bound states corresponding to the $\Xi_c(3055/3123)$.
- ΞD and ΞD^* bound states with masses matching those of the recently observed $\Omega_c(3185)$ and $\Omega_c(3327)$.

Summary

- The contact range interaction is derived from the combination of the RG evolution and exchange of light-mesons (σ, ρ, ω) .
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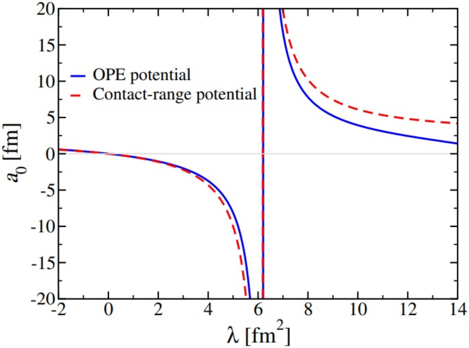
Thanks !

Backup: One-pion-exchange

OPE in $D^*\bar{D}$ scattering, F.Z. Peng et al, PRD 102 (2020)

- $V(\vec{q}) = -\frac{g^2}{6f^2}\tau\vec{\sigma}_1\cdot\vec{\sigma}_2\left[\frac{q^2}{m_\pi^2} - \frac{q^4}{m_\pi^4} + \ldots\right]$
- $C_0^{\mathrm{OPE}}(\mu\sim m_\pi)\sim 0, \quad C_1^{\mathrm{OPE}}(\mu\sim m_\pi)\sim 0$
- $C_0(\mu) + C_1(\mu)\vec{\sigma}_1\cdot\vec{\sigma}_2 = -\lambda$



Backup: Error from the input

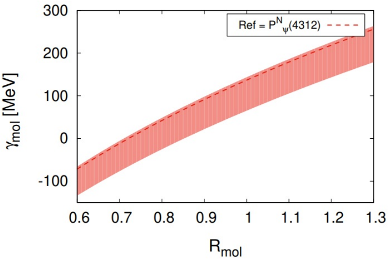


FIG. 1. Dependence of the wave number of a molecule ($\gamma_{\rm mol}$, in MeV) on the molecular ratio $R_{\rm mol}$ (defined in Eq. (20)) when the reference state is the $P_\psi^N(4312)$. This dependence is calculated by solving Eq. (19) with $\Lambda = 1.0\,\text{GeV}$, $C^{\rm sat}_{\rm ref} = -0.80^{+0.14}_{-0.01}\,\text{fm}^2$ (given

Analytic loop integral

- $\int \frac{d^3\vec{q}}{(2\pi)^3} \frac{f^2\left(\frac{q}{\Lambda}\right)}{M_{\rm th}+\frac{q^2}{2\mu_{\rm mol}}-M_{\rm mol}} = \frac{\mu_{\rm mol}}{4\pi^2}\left[\sqrt{2\pi}\Lambda - 2e^{2\gamma^2/\Lambda^2}\pi\gamma\,\mathrm{erfc}\left(\frac{\sqrt{2}\gamma}{\Lambda}\right)\right]$,
  with $\gamma = \sqrt{2\mu\left(M_{\rm th} - M_{\rm mol}\right)}$. Solutions for which $\gamma > 0$ and $\gamma < 0$ correspond to bound and virtual states, respectively.

$SU(3)$ decomposition

$\bar{H}_c T_c$

$$\left|\bar{D}_s\Lambda_c\right\rangle = \frac{1}{\sqrt{3}}|\tilde{1}\rangle + \sqrt{\frac{2}{3}}|\tilde{8}\rangle, \quad \left|\bar{D}\Xi_c(0)\right\rangle = \sqrt{\frac{2}{3}}|\tilde{1}\rangle - \frac{1}{\sqrt{3}}|\tilde{8}\rangle,$$

$\bar{H}_c S_c$

$$\left|\bar{D}_s\Sigma_c\right\rangle = +\sqrt{\frac{2}{3}}|8\rangle + \frac{1}{\sqrt{3}}|10\rangle, \quad \left|\bar{D}\Xi_c'(1)\right\rangle = -\frac{1}{\sqrt{3}}|8\rangle + \sqrt{\frac{2}{3}}|10\rangle$$

$$\left|\bar{D}_s\Xi_c'\right\rangle = +\frac{1}{\sqrt{3}}|8\rangle + \sqrt{\frac{2}{3}}|10\rangle, \quad \left|\bar{D}\Omega_c\right\rangle = -\sqrt{\frac{2}{3}}|8\rangle + \frac{1}{\sqrt{3}}|10\rangle$$

The octet pieces of the $\bar{H}_c T_c$ and $\bar{H}_c S_c$ pentaquarks generate mixing. This requires the spin-spin / M_1 component of vector meson exchange, and it is expected to be weaker. Yet, the mass difference between the thresholds involved is not particularly large (e.g. the $\bar{D}^*\Xi_c$ channel with the $\bar{D}\Xi_c'$ or $\bar{D}\Xi_c^*$ channels), making this effect more important than naively expected.

Backup: coupled channel scattering

- The $J=\frac{1}{2}\ \bar{D}^*\Lambda_c-\bar{D}\Sigma_c$ potential

$$V\left(\bar{D}^*\Lambda_c-\bar{D}\Sigma_c\right)=\begin{pmatrix}\tilde{V}^O & -W^O\\ -W^O & V^O\end{pmatrix},$$

- The $J=\frac{1}{2}D_s\Lambda_c-D\Xi_c$ potential

$$V\left(\bar{D}_s\Lambda_c-\bar{D}_c\right)=\begin{pmatrix}\frac{1}{3}\tilde{V}^S+\frac{2}{3}\tilde{V}^O & \frac{\sqrt{2}}{3}\left(\tilde{V}^S-\tilde{V}^O\right)\\ \frac{\sqrt{2}}{3}\left(\tilde{V}^S-\tilde{V}^O\right) & \frac{2}{3}\tilde{V}^S+\frac{1}{3}\tilde{V}^O\end{pmatrix},$$

- The $J=\frac{1}{2}\bar{D}_s^*\Lambda_c-\bar{D}\Xi_c'-\bar{D}^*\Xi_c$ potential

$$V=\begin{pmatrix}\frac{1}{3}\tilde{V}^S+\frac{2}{3}\tilde{V}^O & -\sqrt{\frac{2}{3}}W^O & \frac{\sqrt{2}}{3}\left(\tilde{V}^S-\tilde{V}^O\right)\\ -\sqrt{\frac{2}{3}}W^O & V^O & \frac{1}{\sqrt{3}}W^O\\ \frac{\sqrt{2}}{3}\left(\tilde{V}^S-\tilde{V}^O\right) & \frac{1}{\sqrt{3}}W^O & \frac{2}{3}\tilde{V}^S+\frac{1}{3}\tilde{V}^O\end{pmatrix},$$