Can the newly Pcs(4459) be a strange hidden-charm $\Xi_c\bar{D}^*$ molecular pentaquarks?

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Outline

- Background: Pc states as meson-baryon molecular scenario and Pcs(4459)

- The theoretical explanation for the Pcs(4459) :

1. Mass spectrum: OBE model and coupled channel analysis
2. Strong decay properties

- Other predictions: hidden-charm molecular pentaquarks with strangeness |S|=1, 2, and 3

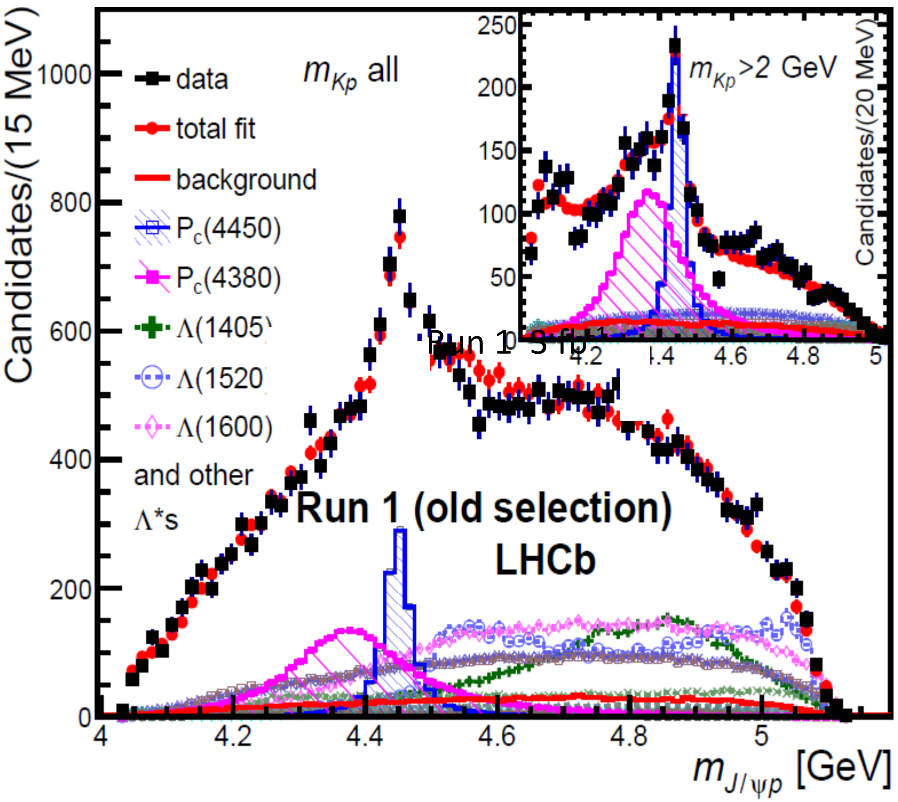
- Summary

1.

Background: Pc states as meson-baryon molecules and Pcs(4459)

Pc states in $\Lambda_b^0 \to J/\psi p K^-$

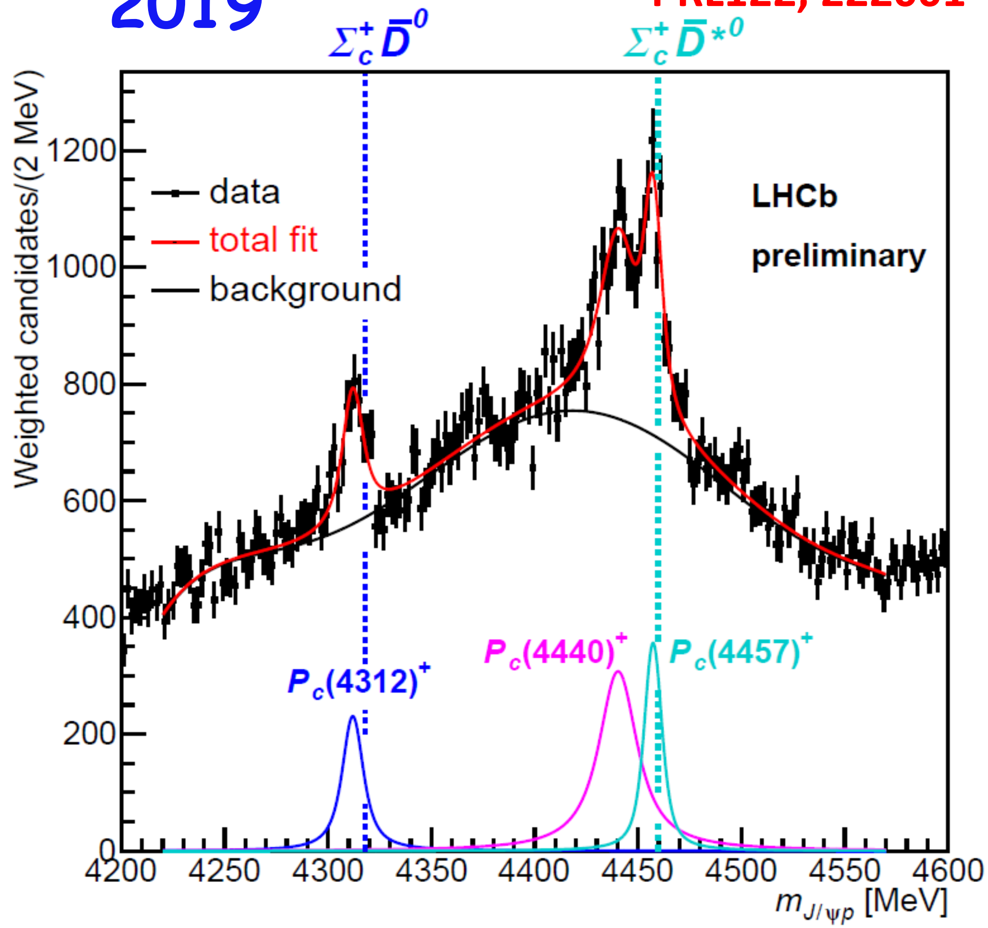
2015 PRL115, 072001



$P_c(4450)^+$ $M = 4450 \pm 2 \pm 3$ MeV
$\Gamma = 39 \pm 5 \pm 19$ MeV

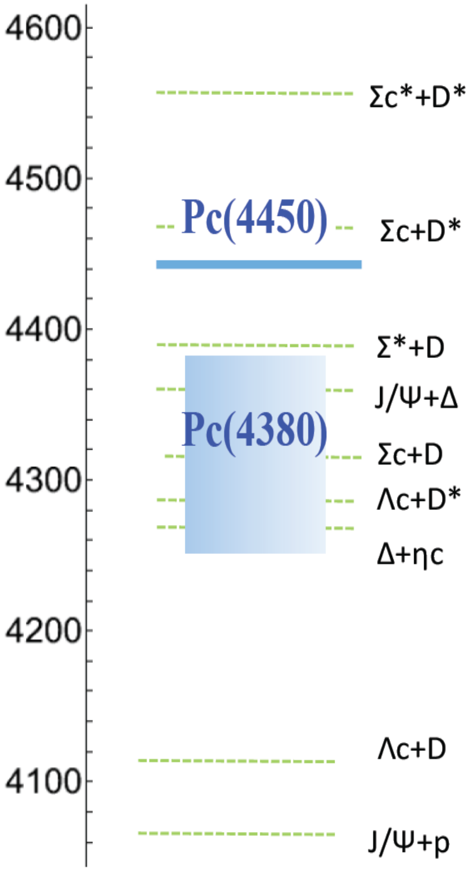
$P_c(4380)^+$ $M = 4380 \pm 8 \pm 29$ MeV
$\Gamma = 205 \pm 18 \pm 86$ MeV

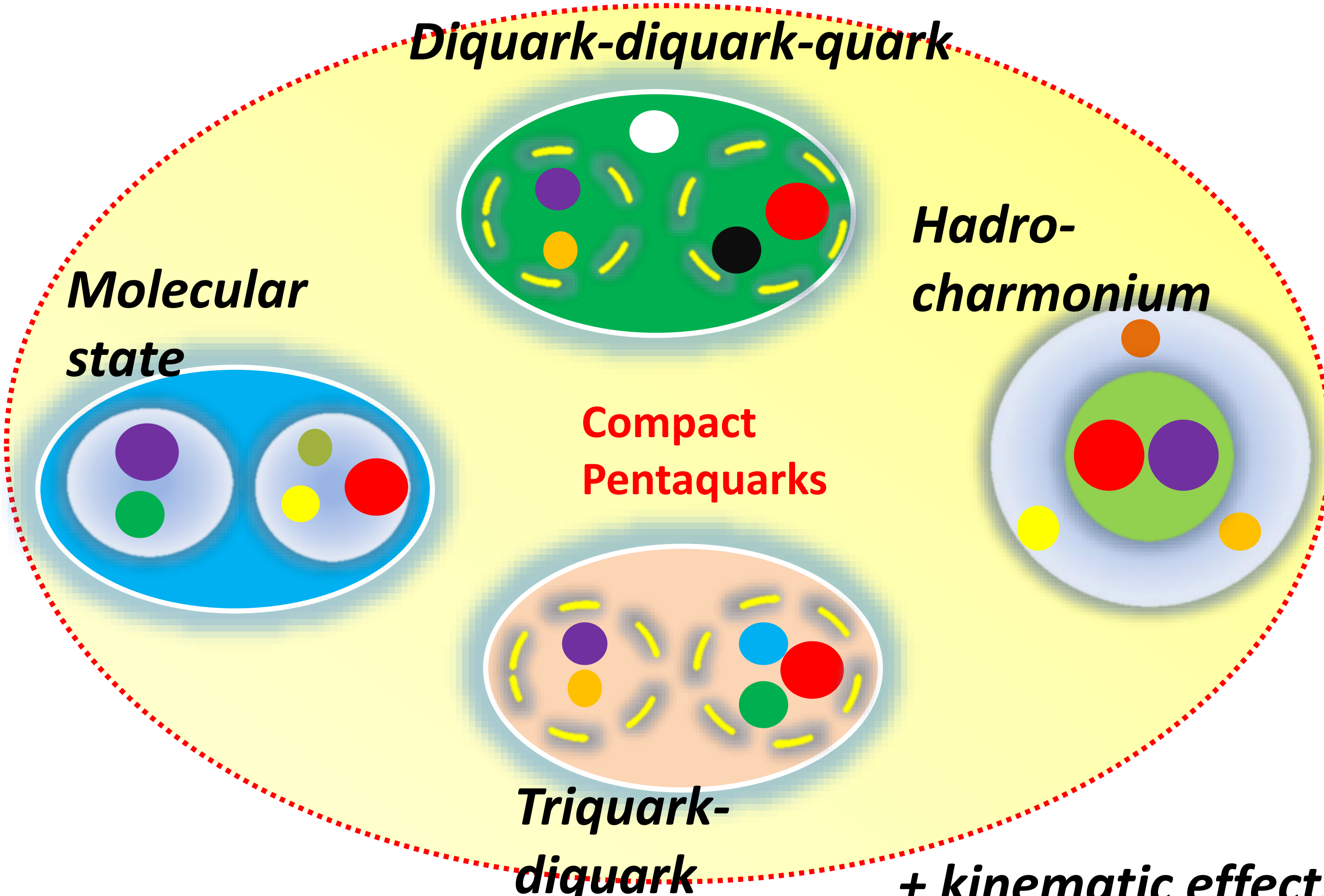
2019 PRL122, 222001



State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)

The nature of Pc(4380) and Pc(4450)





+ kinematic effects

Exotic state *vs* no-resonant

- **Molecular states**: loosely bound states composed of a pair of hadrons, probably bound by the long-range color-singlet pion exchange

M. Karliner and J. L. Rosner, *New exotic meson and baryon resonances from doubly-heavy hadronic molecules*, arXiv:1506.06386; L. Roca, J. Nieves, and E. Oset, *The LHCb pentaquark as a $\overline{D}^*\Sigma_c - \overline{D}^*\Sigma_c^*$ molecular state*, arXiv:1507.04249; R. Chen, X. Liu, X.-Q. Li, and S.-L. Zhu, *Identifying exotic hidden-charm pentaquarks*, arXiv:1507.03704; J. He, *The $\overline{D}\Sigma_c^*$ and $\overline{D}^*\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks*, arXiv:1507.05200; U.-G. Meißner and J. A. Oller, *Testing the $\chi_{c1}\,p$ composite nature of the $P_c(4450)$*, arXiv:1507.07478.

- **Compact Pentaquarks**: bound states of five quarks, bound by colored-force between quarks, decay through rearrangement, some are charged or carry strangeness, there are many states within the same multiplet

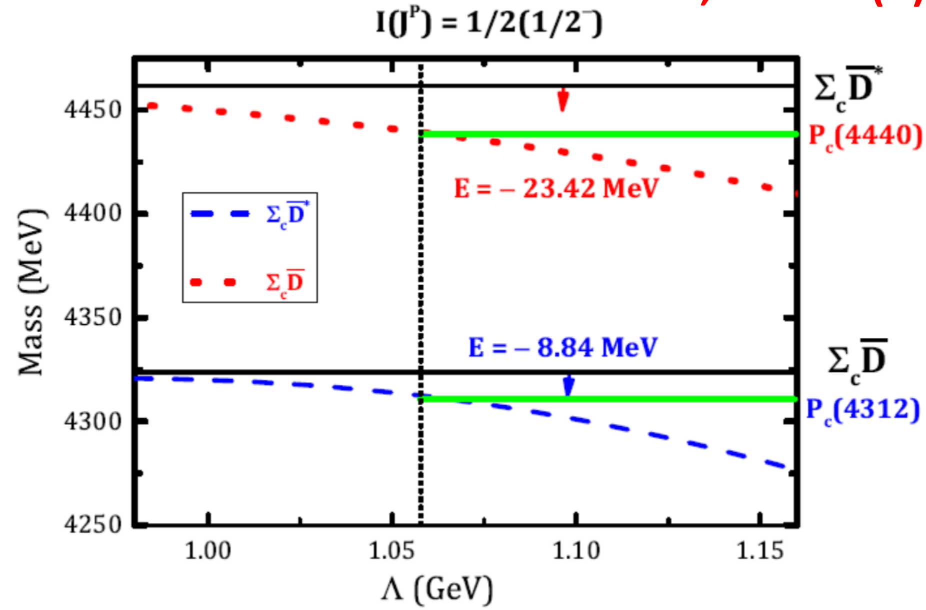
L. Maiani, A. D. Polosa, and V. Riquer, *The new pentaquarks in the diquark model*, Phys. Lett. **B749** (2015) 289, arXiv:1507.04980; R. F. Lebed, *The pentaquark candidates in the dynamical diquark picture*, Phys. Lett. **B749** (2015) 454, arXiv:1507.05867; V. V. Anisovich *et al.*, *Pentaquarks and resonances in the pJ/ψ spectrum*, arXiv:1507.07652; G.-N. Li, M. He, and X.-G. He, *Some predictions of diquark model for hidden charm pentaquark discovered at the LHCb*, arXiv:1507.08252; R. Ghosh, A. Bhattacharya, and B. Chakrabarti, *The masses of $P_c^*(4380)$ and $P_c^*(4450)$ in the quasi particle diquark model*, arXiv:1508.00356; Z.-G. Wang, *Analysis of the $P_c(4380)$ and $P_c(4450)$ as pentaquark states in the diquark model with QCD sum rules*, arXiv:1508.01468; Z.-G. Wang and T. Huang, *Analysis of the $\frac{1}{2}^{\pm}$ pentaquark states in the diquark model with QCD sum rules*, arXiv:1508.04189.

- **No-resonant**: Kinematical artifact? Cusp effect? Final state interaction? Triangle singularity due to the special kinematics?

F.-K. Guo, U.-G. Meißner, W. Wang, and Z. Yang, *How to reveal the exotic nature of the $P_c(4450)$*, arXiv:1507.04950; M. Mikhasenko, *A triangle singularity and the LHCb pentaquarks*, arXiv:1507.06552.

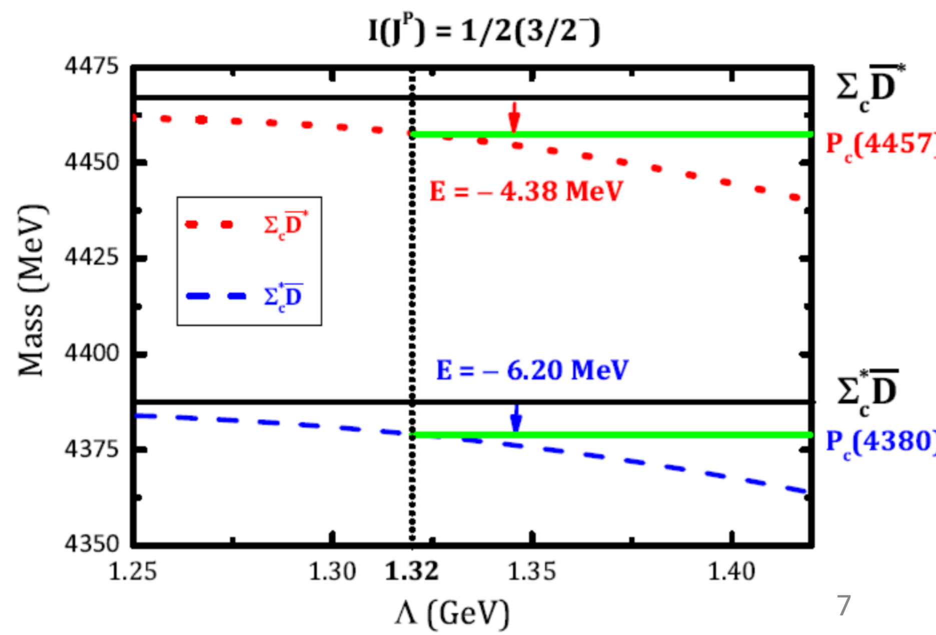
Pc states in meson-baryon molecular scenario

PRD110, 011502(R)



$I(J^P) = 1/2(1/2^-)$ reproduce Pc(4312) and Pc(4440)

- Pc(4312):
  $\boldsymbol{\Sigma_c\overline{D}}: \Sigma_c\overline{D^*}: \Sigma_c^*\overline{D^*}$ =**0.66**:0.18:0.16,
  root-mean-square radius: R=1.03 fm
- Pc(4440): $\boldsymbol{P[\Sigma_c\overline{D^*}] > 92\%}$,
  R=0.83 fm



$I(J^P) = 1/2(3/2^-)$ reproduce Pc(4457)

Pc(4457): $\boldsymbol{\Sigma_c\overline{D^*}}: \Sigma_c^*\overline{D^*} = 3:1$,
root-mean-square radius: R=1.61 fm,
coupled-channel effect: **important**

- Pc(4380)
  M=4379 MeV, **P[$\Sigma_c^*\overline{D}$]>87%,** R=1.40 fm,
  Not observed in 2017 but in 2015

Loosely bound meson-baryon molecular explanations for these three Pc states

1. M. Z. Liu, et al, Phys. Rev. Lett. 122, 242001 (2019).
2. J. He, Eur. Phys. J. C 79, 393 (2019).
3. C. W. Xiao, J. Nieves, and E. Oset, Phys. Rev. D 100, 014021 (2019).
4. L. Meng, B. Wang, G. J. Wang, and S. L. Zhu, Phys. Rev. D 100, 014031 (2019).
5. Y. Yamaguchi, et al, Phys. Rev. D 101, 091502 (2020).
6. M. P. Valderrama, Phys. Rev. D 100, 094028 (2019).
7. H. Huang, J. He, and J. Ping, arXiv:1904.00221.
8. J. J. Wu, T.-S. H. Lee, and B. S. Zou, Phys. Rev. C 100, 035206 (2019).
9. S. Sakai, H. J. Jing, and F. K. Guo, Phys. Rev. D 100, 074007 (2019).
10. Z. H. Guo and J. A. Oller, Phys. Lett. B 793, 144 (2019).
11. C. J. Xiao, et al, Phys. Rev. D 100, 014022 (2019).
12. H. X. Chen, W. Chen, and S. L. Zhu, Phys. Rev. D 100, 051501 (2019).
13. M. B. Voloshin, Phys. Rev. D 100, 034020 (2019).
14. F. K. Guo, H. J. Jing, U. G. Meißner, and S. Sakai, Phys. Rev. D 99, 091501 (2019).
15. Y. H. Lin and B. S. Zou, Phys. Rev. D 100, 056005 (2019).
16. T. Gutsche and V. E. Lyubovitskij, Phys. Rev. D 100, 094031 (2019).
17. T. J. Burns and E. S. Swanson, Phys. Rev. D 100, 114033 (2019).
18. Z. G. Wang and X. Wang, arXiv:1907.04582.
19. M. L. Du, et al, Phys. Rev. Lett. 124, 072001 (2020).
20. B. Wang, L. Meng, and S. L. Zhu, J. High Energy Phys. 11 (2019) 108

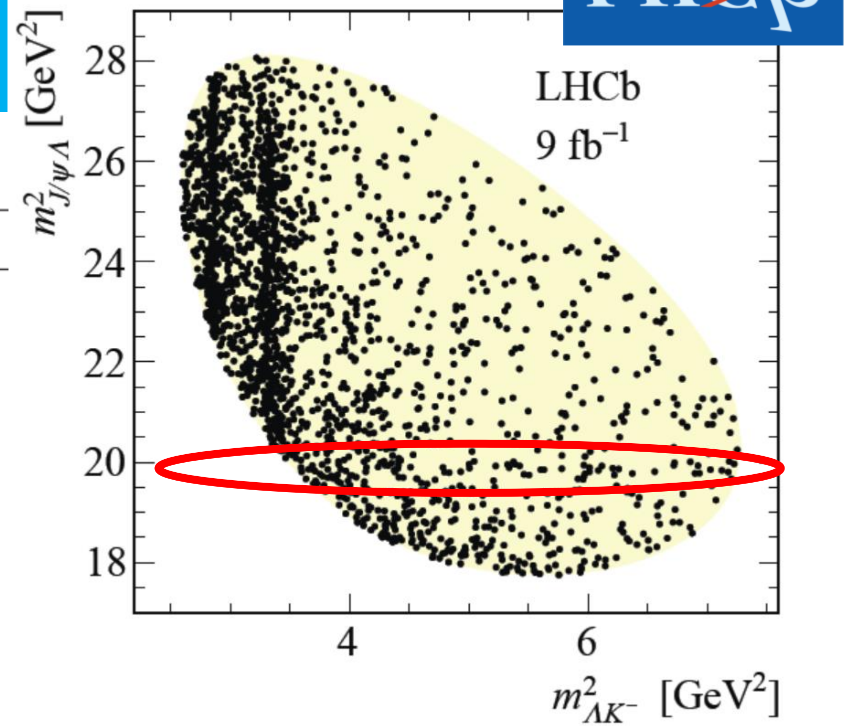
$P_{cs}(4459)$: $\Xi_b^- \to J/\Psi \Lambda K^-$

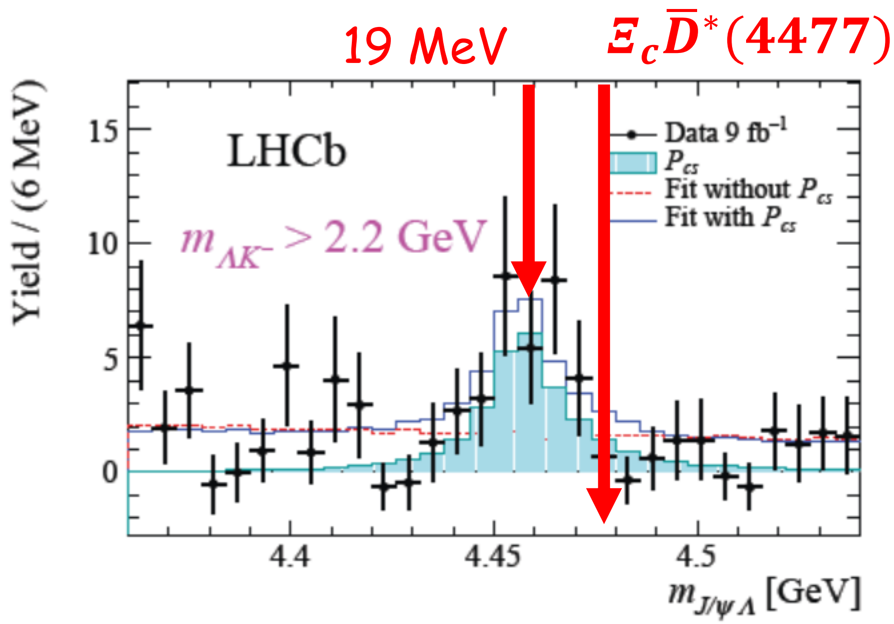
arXiv:2012.10380

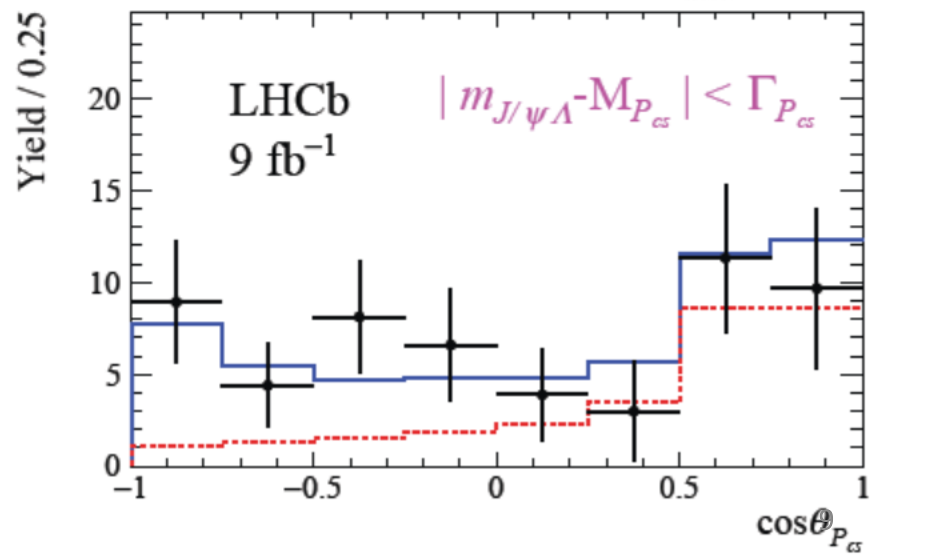
State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$

Including various syst. uncertainty, the smallest significance is 3.1 σ

J^P: Statistics not enough for determination







2.

Question: Can the newly Pcs(4459) be a strange hidden-charm $\Xi_c \bar{D}^*$ molecular pentaquarks?

One-boson-exchange (OBE) model

Yukawa, Proc. Phys. Math. Soc. Japan 17, 48 (1935)

- 1935, Yukawa: pion-exchange and nucleon-nucleon interaction
- Nijimegen potential and Bonn potential: scalar meson **σ exchange~two π** exchange; vector meson-ρ/ω exchange~**multi-π** exchange

1
- OBE model
- Scattering amplitude

$$\langle f|S|i\rangle = \delta_{fi} + i\langle f|T|i\rangle = \delta_{fi} + i(2\pi)^4\delta^4(p_f - p_i)\mathcal{M}_{fi}$$

$$\langle f|S|i\rangle = \delta_{fi} - i(2\pi)\delta(E_f - E_i)V_{fi}(p)$$

2
- Breit approximation
- Effective potential in momentum space

$$V_{fi}(p) = -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2p_f^0 \prod_i 2p_i^0}} \approx -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2m_f^0 \prod_i 2m_i^0}}$$

3
- Fourier transformation
- Effective potential in coordinate space

$$V(r) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}_{fi}(\boldsymbol{q}) \mathcal{F}^2(q^2, m_E^2)$$

One free parameter

Form factor $\mathcal{F}(q^2, m^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$ Λ, m and q are the cutoff, mass and four-momentum of the exchanged meson, respectively.

$\Lambda \sim 1.0$ GeV

N. A. Tornqvist, Z. Phys. C 61, 525 (1994)
N. A. Tornqvist, Nuovo Cim. A 107, 2471 (1994)

Effective Lagrangians

Charmed-strange baryon sector (heavy quark symmetry)

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}} = l_B\langle\bar{\mathcal{B}}_{\bar{3}}\sigma\mathcal{B}_{\bar{3}}\rangle + i\beta_B\langle\bar{\mathcal{B}}_{\bar{3}}v^\mu(\mathcal{V}_\mu - \rho_\mu)\mathcal{B}_{\bar{3}}\rangle,$$

$$\mathcal{L}_{\mathcal{B}_6} = l_S\langle\bar{\mathcal{S}}_\mu\sigma\mathcal{S}^\mu\rangle - \frac{3}{2}g_1\varepsilon^{\mu\nu\lambda\kappa}v_\kappa\langle\bar{\mathcal{S}}_\mu A_\nu\mathcal{S}_\lambda\rangle + i\beta_S\langle\bar{\mathcal{S}}_\mu v_\alpha\left(\mathcal{V}^\alpha_{ab} - \rho^\alpha_{ab}\right)\mathcal{S}^\mu\rangle + \lambda_S\langle\bar{\mathcal{S}}_\mu F^{\mu\nu}(\rho)\mathcal{S}_\nu\rangle,$$

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_6} = ig_4\langle\bar{\mathcal{S}}^\mu A_\mu\mathcal{B}_{\bar{3}}\rangle + i\lambda_I\varepsilon^{\mu\nu\lambda\kappa}v_\mu\langle\bar{\mathcal{S}}_\nu F_{\lambda\kappa}\mathcal{B}_{\bar{3}}\rangle + h.c..$$

$$\mathcal{L}_H = g_S\langle\bar{H}^{(\bar{Q})}_a\sigma H^{(\bar{Q})}_b\rangle + ig\langle\bar{H}^{(\bar{Q})}_a\gamma_\mu A^\mu_{ab}\gamma_5 H^{(\bar{Q})}_b\rangle - i\beta\langle\bar{H}^{(\bar{Q})}_a v_\mu\left(\mathcal{V}^\mu_{ab} - \rho^\mu_{ab}\right)H^{(\bar{Q})}_b\rangle + i\lambda\langle\bar{H}^{(\bar{Q})}_a\sigma_{\mu\nu}F^{\mu\nu}(\rho)H^{(\bar{Q})}_b\rangle$$

$$H^{(\bar{Q})} = [\tilde{\mathcal{P}}^{*\mu}\gamma_\mu - \tilde{\mathcal{P}}\gamma_5]\frac{1-\not{v}}{2} \qquad \mathcal{S}_\mu = -\sqrt{\tfrac{1}{3}}(\gamma_\mu + v_\mu)\gamma^5\mathcal{B}_6 + \mathcal{B}^*_{6\mu}$$

Charm baryon

Light quarks in $\bar{3}_F$

$$\mathcal{B}_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix},$$

Light quarks in 6_F

$$\mathcal{B}_6^{(*)} = \begin{pmatrix} \Sigma_c^{(*)++} & \frac{\Sigma_c^{(*)+}}{\sqrt{2}} & \frac{\Xi_c^{(\prime,*)+}}{\sqrt{2}} \\ \frac{\Sigma_c^{(*)+}}{\sqrt{2}} & \Sigma_c^{(*)0} & \frac{\Xi_c^{(\prime,*)0}}{\sqrt{2}} \\ \frac{\Xi_c^{(\prime,*)+}}{\sqrt{2}} & \frac{\Xi_c^{(\prime,*)0}}{\sqrt{2}} & \Omega_c^{(*)0} \end{pmatrix}$$

Axial current and vector current

$$A_\mu = \frac{1}{2}(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger) = \frac{i}{f_\pi}\partial_\mu P + \ldots \qquad \mathcal{V}_\mu = \frac{1}{2}(\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger) = \frac{i}{2f_\pi^2}\left[P, \partial_\mu P\right] + \ldots$$

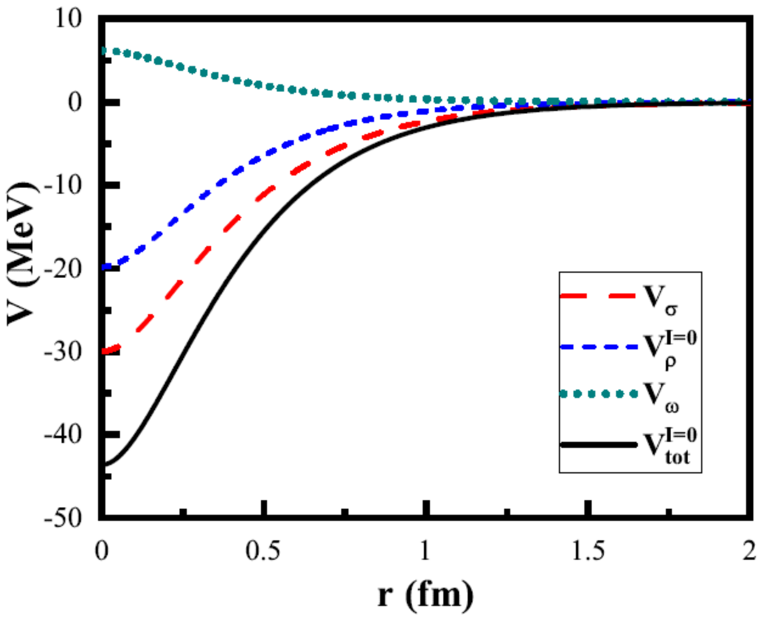
PRD46, 1148 PRD45,2188 PLB280,287 PLB292,119 PRD85, 014015

Pcs(4459) : a $\Xi_c\bar{D}^*$ molecule?

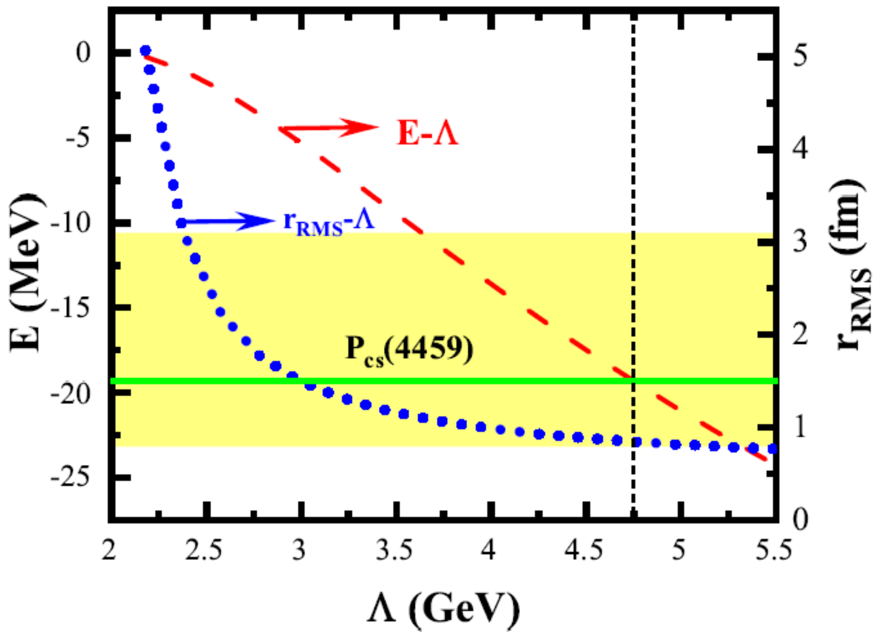
arXiv: 2011.07214

A single channel analysis

$$I(J^P) = 0(1/2^-, 3/2^-)$$



Cutoff dependence of binding energy E and the root-mean-square radius



- ☐ There exist σ, ρ, and ω exchanges
- ☐ σ/ρ −exchange: attractive
- ☐ ω −exchange: repulsive
- ☐ OBE: weak attractive

- ☐ Cutoff is far away from the typical value 1.00 GeV
- ☐ Pcs(4459) cannot be a pure $\Xi_c\bar{D}^*$ molecule

Loosely bound molecular states in the coupled channel systems

$MS = A_1B_1 + A_2B_2 + \cdots + A_nB_n$

- Mass $M_{MS} = M_{A_1} + M_{B_1} - E$, binding energy E
- Asymptotic form of wave function for an S-wave bound state at large distance:

$$\psi(r) \sim e^{-\sqrt{2\mu_k \tilde{E}} r}/r,$$

$$\mu_k = M_{A_k} M_{B_k}/(M_{A_k} + M_{B_k})$$

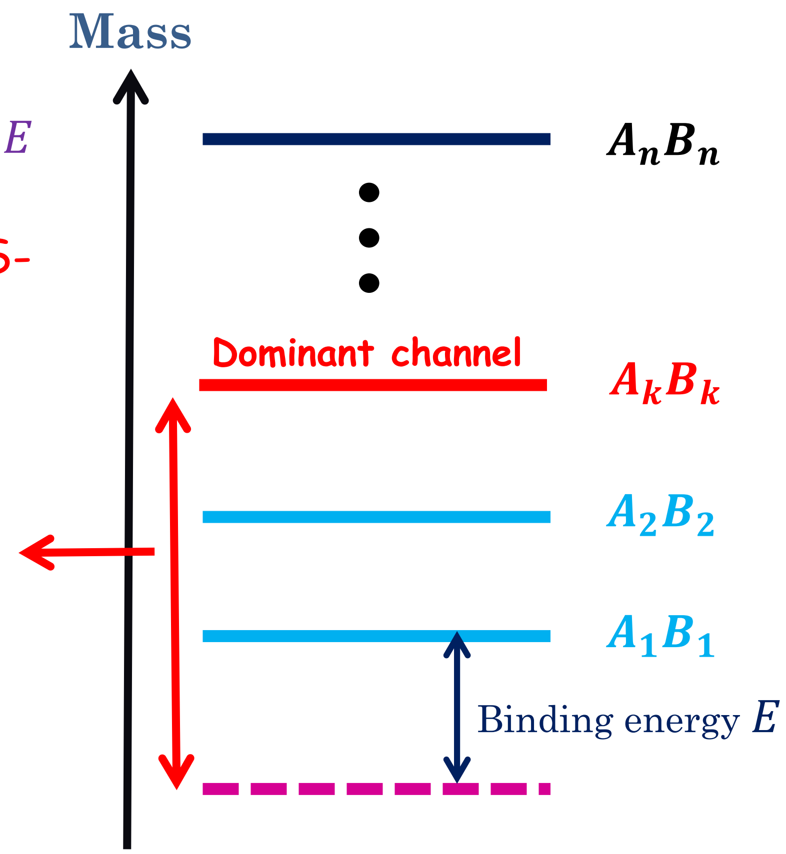
$$\tilde{E} = (M_{A_k} + M_{B_k}) - (M_{A_1} + M_{B_1}) + E$$

- Size of the system : $R_{MS} \sim 1/\sqrt{2\mu_k \tilde{E}}$

  $R_{MS} > R_{A_k} + R_{B_k}$

- $\tilde{E} \sim 200$ MeV, $R_{MS} < 0.5$ fm

Don't satisfy the loosely bound state scenario



A coupled $\Xi_c\bar{D}^*/\Xi_c^*\bar{D}/\Xi_c'\bar{D}^*/\Xi_c^*\bar{D}^*$ channel analysis

	GeV	MeV	fm	Probabilities			
$I(J^P)$	Λ	E	r_{RMS}	$\Xi_c\bar{D}^*$	$\Xi_c^*\bar{D}$	$\Xi_c'\bar{D}^*$	$\Xi_c^*\bar{D}^*$
$0(1/2^-)$	1.17	−1.63	1.39	30.66	...	**64.13**	5.21
	1.18	−7.52	0.62	15.82	...	**77.10**	7.08
	1.19	−14.29	0.50	11.12	...	**80.82**	8.06
	1.20	−21.62	0.45	8.60	...	**82.62**	8.78
$0(3/2^-)$	0.99	−1.46	2.18	**69.44**	19.46	2.81	8.28
	1.01	−5.73	1.09	**53.70**	28.41	5.52	13.37
	1.03	−11.77	0.79	**44.88**	**32.50**	5.69	16.93
	1.05	−19.28	0.65	**38.95**	**34.58**	6.61	18.86

- Pcs(4459): the coupled $\Xi_c\bar{D}^*/\Xi_c^*\bar{D}/\Xi_c'\bar{D}^*/\Xi_c^*\bar{D}^*$ state with I(JP) = 0(3/2−), $\Xi_c\bar{D}^*$and $\Xi_c^*\bar{D}$ channels are dominant
- The coupled channel effect is helpful to form this bound state

Strong decay properties for the Pcs(4459) in a meson-baryon molecular scenario

Accepted by EPJC

Decay width

$$d\Gamma = \frac{1}{2J+1}\frac{|p|}{32\pi^2 m_{P_{cs}}^2}|\mathcal{M}(P_{cs}\to f_1+f_2)|^2 d\Omega$$

Interactions Pcs(4459) = $\Xi_c\bar{D}^*/\Xi_c^*\bar{D}/\Xi_c'\bar{D}^*/\Xi_c^*\bar{D}^*$ state with I(JP) = 0(3/2-)

$$\langle f_1+f_2|P_{cs}\rangle = \langle f_1+f_2|\left(|\Xi_c\bar{D}^*\rangle\langle\Xi_c\bar{D}^*|+|\Xi_c^*\bar{D}\rangle\langle\Xi_c^*\bar{D}| + |\Xi_c'\bar{D}^*\rangle\langle\Xi_c'\bar{D}^*|+|\Xi_c^*\bar{D}^*\rangle\langle\Xi_c^*\bar{D}^*|\right)P_{cs}\rangle$$

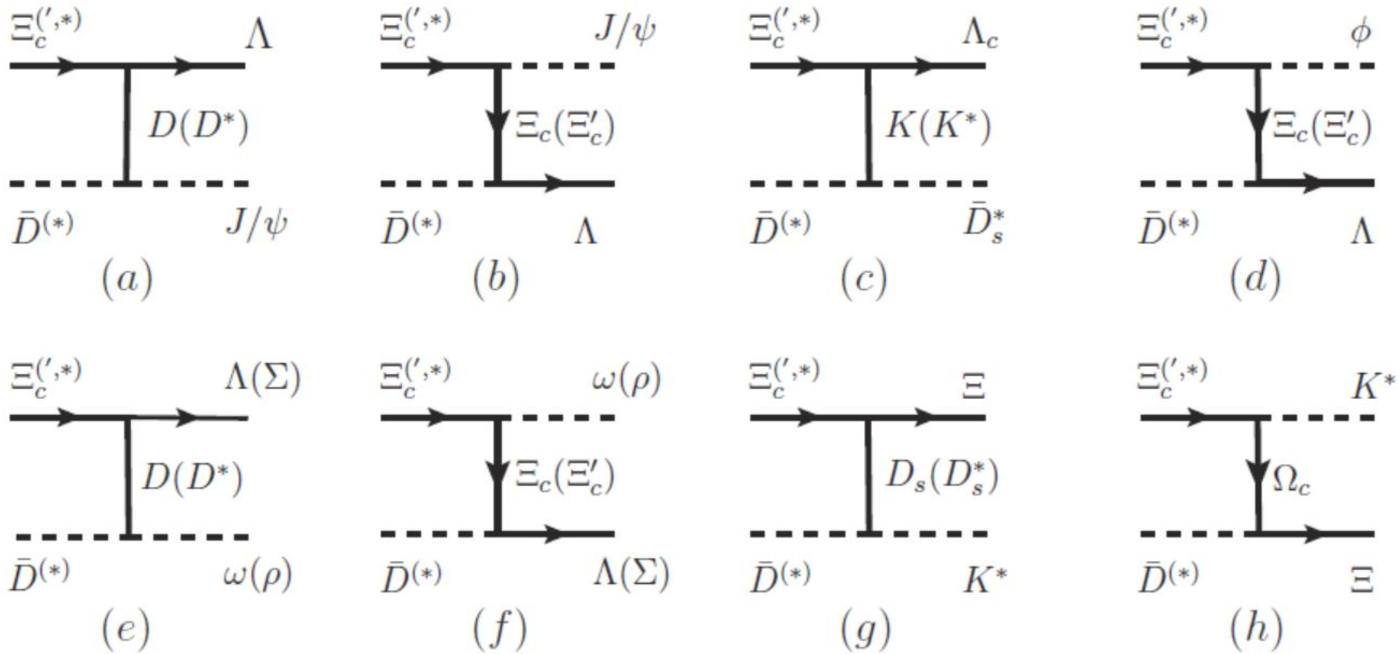
$$= \int\frac{d^3k}{(2\pi)^3}d^3re^{-i\boldsymbol{k}\cdot\boldsymbol{r}}\psi_{\Xi_c\bar{D}^*}(\boldsymbol{r})\langle f_1+f_2|\Xi_c\bar{D}^*\rangle + \int\frac{d^3k}{(2\pi)^3}d^3re^{-i\boldsymbol{k}\cdot\boldsymbol{r}}\psi_{\Xi_c^*\bar{D}}(\boldsymbol{r})\langle f_1+f_2|\Xi_c^*\bar{D}\rangle$$

$$+ \int\frac{d^3k}{(2\pi)^3}d^3re^{-i\boldsymbol{k}\cdot\boldsymbol{r}}\psi_{\Xi_c'\bar{D}^*}(\boldsymbol{r})\langle f_1+f_2|\Xi_c'\bar{D}^*\rangle + \int\frac{d^3k}{(2\pi)^3}d^3re^{-i\boldsymbol{k}\cdot\boldsymbol{r}}\psi_{\Xi_c^*\bar{D}^*}(\boldsymbol{r})\langle f_1+f_2|\Xi_c^*\bar{D}^*\rangle$$

Wave functions for all the coupled $\Xi_c\bar{D}^*/\Xi_c^*\bar{D}/\Xi_c'\bar{D}^*/\Xi_c^*\bar{D}^*$ molecular

$$\langle f_1+f_2|P_{cs}\rangle = -\frac{\mathcal{M}(P_{cs}\to f_1+f_2)}{(2\pi)^{3/2}\sqrt{2E_{P_{cs}}}\sqrt{2E_{f_1}}\sqrt{2E_{f_2}}},\quad \langle f_1+f_2|\Xi_c^{\prime,*}\bar{D}^{(*)}\rangle = -\frac{\mathcal{M}\left(\Xi_c^{\prime,*}(\boldsymbol{k})+\bar{D}^{(*)}(-\boldsymbol{k})\to f_1(\boldsymbol{p})+f_2(-\boldsymbol{p})\right)}{(2\pi)^{3/2}\sqrt{2E_{\Xi_c^{\prime,*}}}\sqrt{2E_{\bar{D}^{(*)}}}\sqrt{2E_{f_1}}\sqrt{2E_{f_2}}}$$

Decay processes



Effective Lagrangians

P, V, B, and D: the pseudoscalar and vector mesons, octet, and decuplet baryons in SU(4)

$$\mathcal{L}_{PPV} = \frac{iG}{2\sqrt{2}}\left\langle \partial^\mu P\left(PV_\mu - V_\mu P\right)\right\rangle,$$

$$\mathcal{L}_{VVP} = \frac{G'}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\left\langle \partial_\mu V_\nu \partial_\alpha V_\beta P\right\rangle,$$

$$\mathcal{L}_{VVV} = \frac{iG}{2\sqrt{2}}\left\langle \partial^\mu V^\nu\left(V_\mu V_\nu - V_\nu V_\mu\right)\right\rangle$$

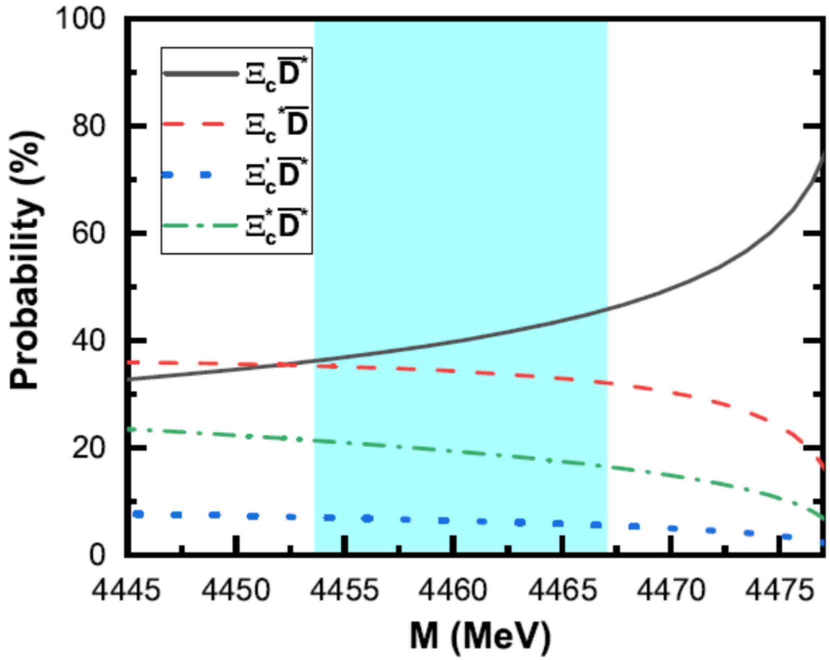
$$\mathcal{L}_{BDV} = -i\frac{g_{BDV}}{m_V}\left(\bar{D}^\mu \gamma^5 \gamma^\nu B + \bar{B}\gamma^5\gamma^\nu D^\mu\right)\left(\partial_\mu V_\nu - \partial_\nu V_\mu\right)$$

$$\mathcal{L}_{BBP} = g_P\left\langle \bar{B} i\gamma_5 P B\right\rangle,$$

$$\mathcal{L}_{BBV} = g_V\langle \bar{B}\gamma^\mu V_\mu B\rangle + \frac{f_V}{2m}\left\langle \bar{B}\sigma^{\mu\nu}\partial_\mu V_\nu B\right\rangle,$$

$$\mathcal{L}_{BDP} = \frac{g_{BDP}}{m_P}\left(\bar{D}^\mu B + \bar{B}D^\mu\right)\partial_\mu P,$$

PRC62, 034903 EPJA36, 73 PRC65, 015203 NPA513,557-583



Probabilities for different channels

- Coupled channel effect: important
- Dominant channels: $\Xi_c\bar{D}^*$and $\Xi_c^*\bar{D}$

Decay amplitude

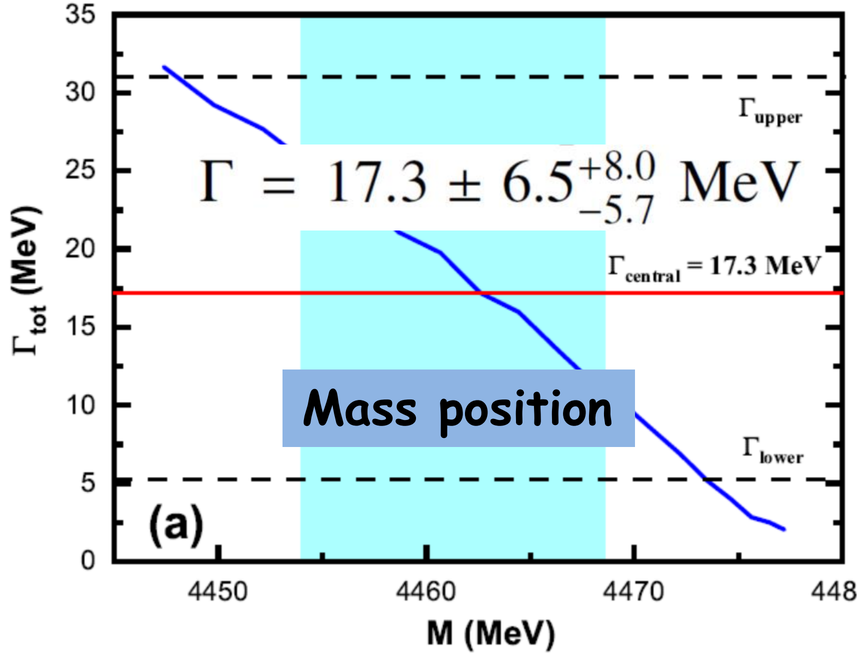
$$\langle f_1 + f_2|\Xi_c^{\prime,*}\bar{D}^{(*)}\rangle = -\frac{\mathcal{M}\left(\Xi_c^{\prime,*}(\boldsymbol{k}) + \bar{D}^{(*)}(-\boldsymbol{k}) \to f_1(\boldsymbol{p}) + f_2(-\boldsymbol{p})\right)}{(2\pi)^{3/2}\sqrt{2E_{\Xi_c^{\prime,*}}}\sqrt{2E_{\bar{D}^{(*)}}}\sqrt{2E_{f_1}}\sqrt{2E_{f_2}}}$$

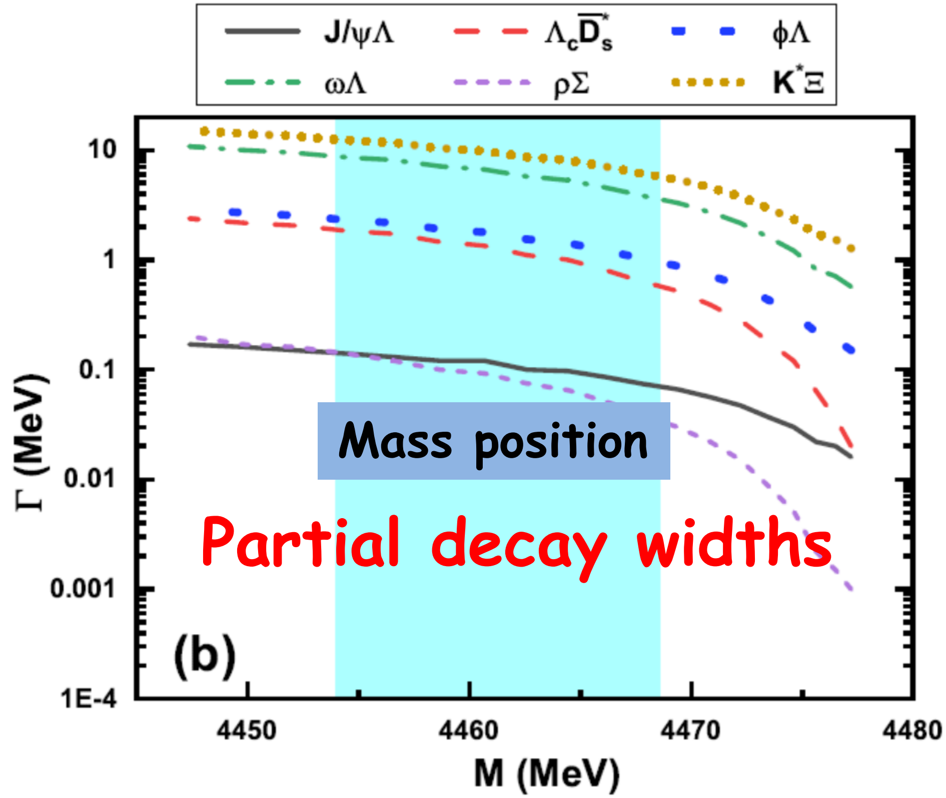
$$\mathcal{M} \sim \frac{c_0 + c_1\boldsymbol{k}^2 + c_2\boldsymbol{p}^2 + c_3\boldsymbol{k}\cdot\boldsymbol{p} + c_i(\boldsymbol{k}^4, \boldsymbol{p}^4, \ldots)}{\boldsymbol{k}^2 + \boldsymbol{p}^2 + 2\boldsymbol{k}\cdot\boldsymbol{p} + M^2}$$

Convergence of the decay widths only depends on the wave functions

A upper limit integral $\int_0^{k_{\rm Max}} d^3k\psi(\boldsymbol{k})^2 = 1$

Total decay widths





Total two-body strong decay width: **10 ~ 25 MeV**
With the decreasing of the mass of the Pcs(4459), the total decay width turns larger.

$$\mathcal{R} = \Gamma_{\Lambda_c \bar{D}^*} / \Gamma_{J/\psi\Lambda} \sim 10$$

Support the *Pcs*(4459) as the coupled $\Xi_c\bar{D}^*/\Xi_c^*\bar{D}/\Xi_c'\bar{D}^*/\Xi_c^*\bar{D}^*$ state with I(JP) = 0(3/2−)

3.

Predictions: hidden-charm molecular pentaquarks with strangeness |S|=1, 2, and 3

Predictions of hidden-charm molecular pentaquarks with |S|=1

New

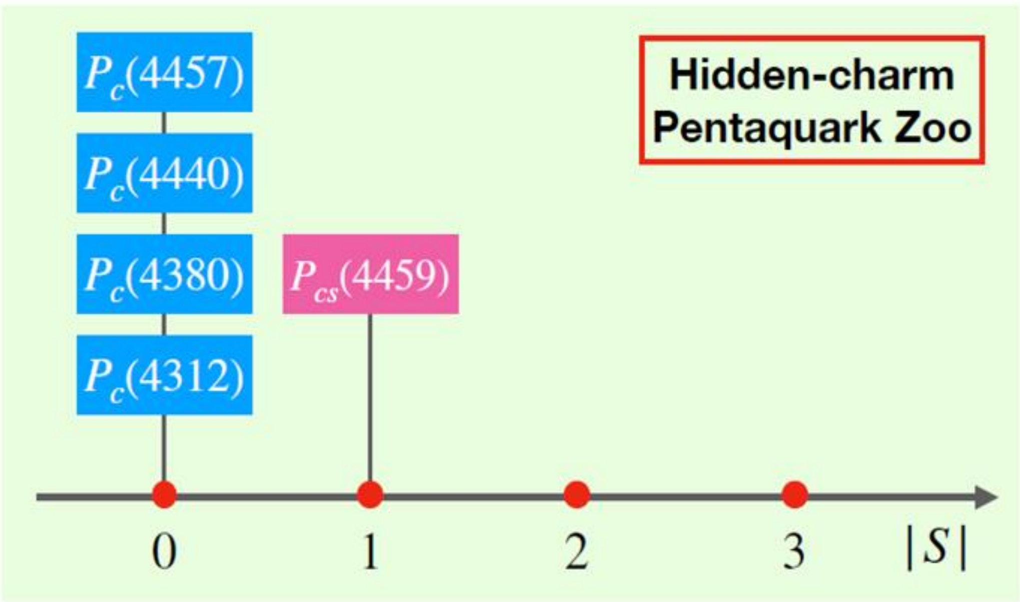


FIG. 1: The hidden-charm pentaquark zoo with different values of strangeness.

Heavy quark symmetry

$$\Lambda_c \to \Xi_c, \Sigma_c^{(*)} \to \Xi_c^{(',*)}$$

Pc(4312): $\Sigma_c \bar{D}$[1/2(1/2−)]
Pc(4380): $\Sigma_c^* \bar{D}$[1/2(3/2-)]
Pc(4440): $\Sigma_c \bar{D}^*$[1/2(1/2−)]
Pc(4457): $\Sigma_c \bar{D}^*$[1/2(3/2−)]

Interactions: strong attractive interactions for $\Sigma_c^{(*)}\bar{D}^{(*)}$ systems with I=1/2 weak attractive or repulsive interactions for the I=3/2 systems

Pcs(4459) : a $\Xi_c \bar{D}^*$ molecule

Question: $\Xi_c^{(',*)}\bar{D}^{(*)}$ Exist or Not?

OBE effective potentials in quark level

$$V_{q_1q_2} = \mathcal{V}_{\sigma,\eta,\omega}(\boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2) + \underline{\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \mathcal{V}_{\pi,\rho}(\boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2)}$$

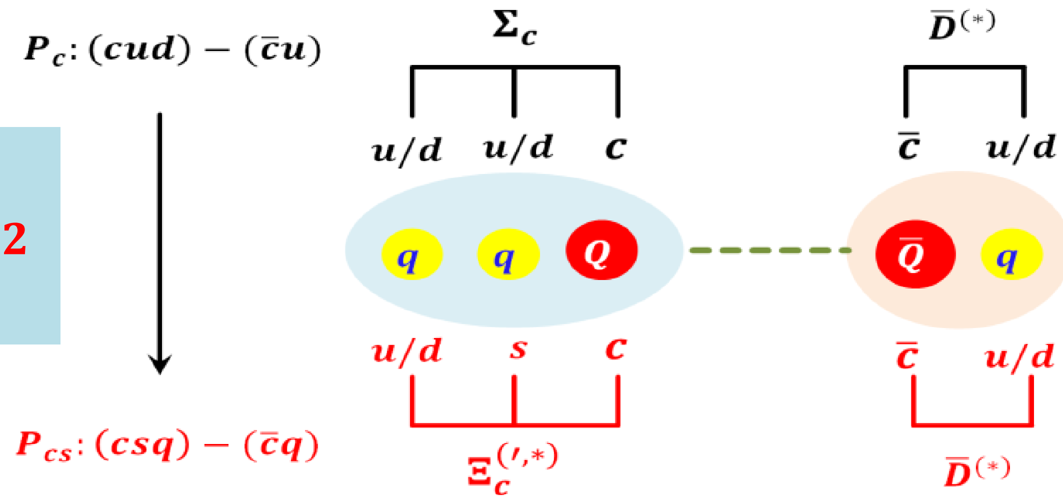
$\boldsymbol{\sigma}$ spin operator

$\boldsymbol{\tau}$ isospin operator

Isospin-related part

Hadron Level

$$V = \sum_{q_i} V_{q1q2}$$



$V(\boldsymbol{\sigma 1}, \boldsymbol{\sigma 2})$: heavy quark spin symmetry

$\Sigma_c^{(*)}\bar{D}^{(*)} \approx \Xi_c^{(\prime,*)}\bar{D}^{(*)}$: exactly the same with the same spin-parity

Flavor wave functions (OBE effective potentials in the isospin-related part)

$$|I_{q_1}; I_{q_2} I_{q_3}(I_{q_2q_3}); I\rangle = \sum_{I_{12}} (-1)^{I_1+I_2+I_3+I} \sqrt{(2I_{12}+1)(2I_{23}+1)} \begin{Bmatrix} I_1 & I_2 & I_{12} \\ I_3 & I & I_{23} \end{Bmatrix} |I_1 I_2(I_{12}); I_3; I\rangle$$

OBE effective potentials

$$\mathcal{U}^0 = \left\langle I'_{q_1q_2(q_3)} = 0 | \boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2} | I_{q_1q_2(q_3)} = 0 \right\rangle$$
$$\mathcal{U}^1 = \left\langle I'_{q_1q_2(q_3)} = 1 | \boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2} | I_{q_1q_2(q_3)} = 1 \right\rangle$$

PRD110, 011502(R)

	σ	η	ω	π	ρ
$\Sigma_c^{(*)}\bar{D}^{(*)}[I=1/2]$	$\mathcal{U}_\sigma$	$\mathcal{U}_\eta$	$2\mathcal{U}_\omega$	$\frac{3}{2}\mathcal{U}_\pi^0 + \frac{1}{2}\mathcal{U}_\pi^1$	$\frac{3}{2}\mathcal{U}_\rho^0 + \frac{1}{2}\mathcal{U}_\rho^1$
$\Sigma_c^{(*)}\bar{D}^{(*)}[I=3/2]$	$\mathcal{U}_\sigma$	$\mathcal{U}_\eta$	$2\mathcal{U}_\omega$	$2\mathcal{U}_\pi^1$	$2\mathcal{U}_\rho^1$
$\Xi_c^{(\prime,*)}\bar{D}^{(*)}[I=0]$	$\mathcal{U}_\sigma$	$-\frac{1}{2}\mathcal{U}_\eta$	$\mathcal{U}_\omega$	$\mathcal{U}_\pi^0$	$\mathcal{U}_\rho^0$
$\Xi_c^{(\prime,*)}\bar{D}^{(*)}[I=1]$	$\mathcal{U}_\sigma$	$-\frac{1}{2}\mathcal{U}_\eta$	$\mathcal{U}_\omega$	$\mathcal{U}_\pi^1$	$\mathcal{U}_\rho^1$

Flavor wave functions

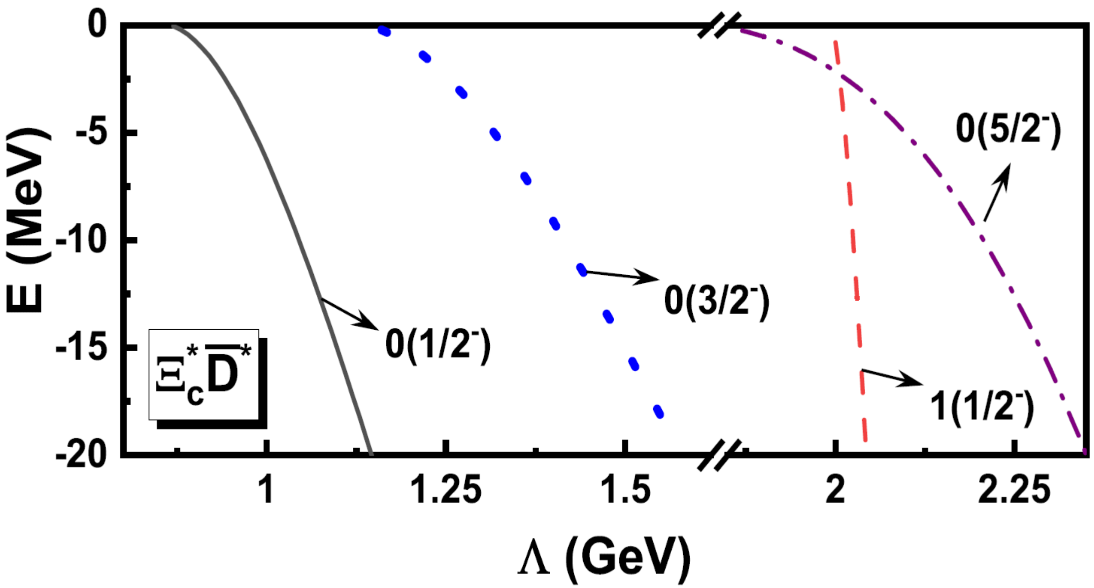
$$|\bar{D}^{(*)}\Sigma_c^{(*)}(I=\frac{1}{2})\rangle = \left|\frac{1}{2};\frac{1}{2},\frac{1}{2}(1);\frac{1}{2}\right\rangle = \frac{\sqrt{3}}{2}\left|\frac{1}{2},\frac{1}{2}(0);\frac{1}{2};\frac{1}{2}\right\rangle + \frac{1}{2}\left|\frac{1}{2},\frac{1}{2}(1);\frac{1}{2};\frac{1}{2}\right\rangle$$

$$|\bar{D}^{(*)}\Sigma_c^{(*)}(I=\frac{3}{2})\rangle = \left|\frac{1}{2};\frac{1}{2},\frac{1}{2}(1);\frac{3}{2}\right\rangle = \left|\frac{1}{2},\frac{1}{2}(1);\frac{1}{2};\frac{3}{2}\right\rangle$$

$$|\bar{D}^{(*)}\Xi_c^{(\prime,*)}(I)\rangle = \left|\frac{1}{2};\frac{1}{2},0(\frac{1}{2});I\right\rangle = \left|\frac{1}{2},\frac{1}{2}(0);0;I\right\rangle$$

Candidates of the hidden-charm molecular pentaquarks with |S|=1

|S|=0	Pc(4312)	Pc(4380)	Pc(4440)	Pc(4457)
	$\Sigma_c\bar{D}$[1/2(1/2−)]	$\Sigma_c^*\bar{D}$[1/2(3/2-)]	$\Sigma_c\bar{D}^*$[1/2(1/2−)]	$\Sigma_c\bar{D}^*$[1/2(3/2−)]
|S|=1	$\Xi_c'\bar{D}$ 0(1/2-)	$\Xi_c^*\bar{D}$ 0(3/2-)	$\Xi_c'\bar{D}^*$0(1/2-)	$\Xi_c'\bar{D}^*$0(3/2-)
	$\Xi_c'\bar{D}$ 1(1/2-)	$\Xi_c^*\bar{D}$ 1(3/2-)	……	$\Xi_c'\bar{D}^*$1(3/2-)



Single $\Xi_c^*\bar{D}^*$ analysis

- Isoscalar systems with (1/2-,3/2-,5/2-) can be good molecular candidates
- $\Lambda\left(\frac{1-}{2}\right) < \Lambda\left(\frac{3-}{2}\right) < \Lambda\left(\frac{5-}{2}\right)$
- $|V^{J=1/2}| < |V^{J=3/2}| < |V^{J=5/2}|$
- No isovector molecular candidates

Hidden-charm molecular pentaquarks with |S|=2 and 3

arXiv: 2011.14296

Prediction of hidden-charm pentaquarks with double strangeness

- Discussed channels: $\Xi_c^{(\prime,*)}\bar{D}_s^{(*)}$ **systems**
- Effects: the S -D wave mixing effect and the coupled channel effect
- Candidates: $\Xi_c'\bar{D}_s^*$ state with 3/2- and $\Xi_c^*\bar{D}_s^*$ state with 5/2-

New

Hidden-charm pentaquarks with triple strangeness due to the $\Omega_c^{(*)}\bar{D}_s^{(*)}$ interactions

- Discussed channels: $\Omega_c^{(*)}\bar{D}_s^{(*)}$ **systems**
- Effects: the S -D wave mixing effect and the coupled channel effect
- Candidates: $\Omega_c\bar{D}_s^*$ state with 3/2- and $\Omega_c^*\bar{D}_s^*$ state with 5/2-

Summary

- Provide an explanation for the newly Pcs(4459) **mass spectrum** and **strong decay behavior**
- Predicting more possible hidden-charm molecular pentaquarks with strangeness |S|=1, 2, and 3

Thanks for your attention !