第四届LHCb前沿物理研讨会@烟台大学

Productions and decays of the heavy flavor hadronic molecules

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Based on: Phys. Rev. D 108 (2023), 114022
arXiv: 2405.04341
arXiv: 2407.17318

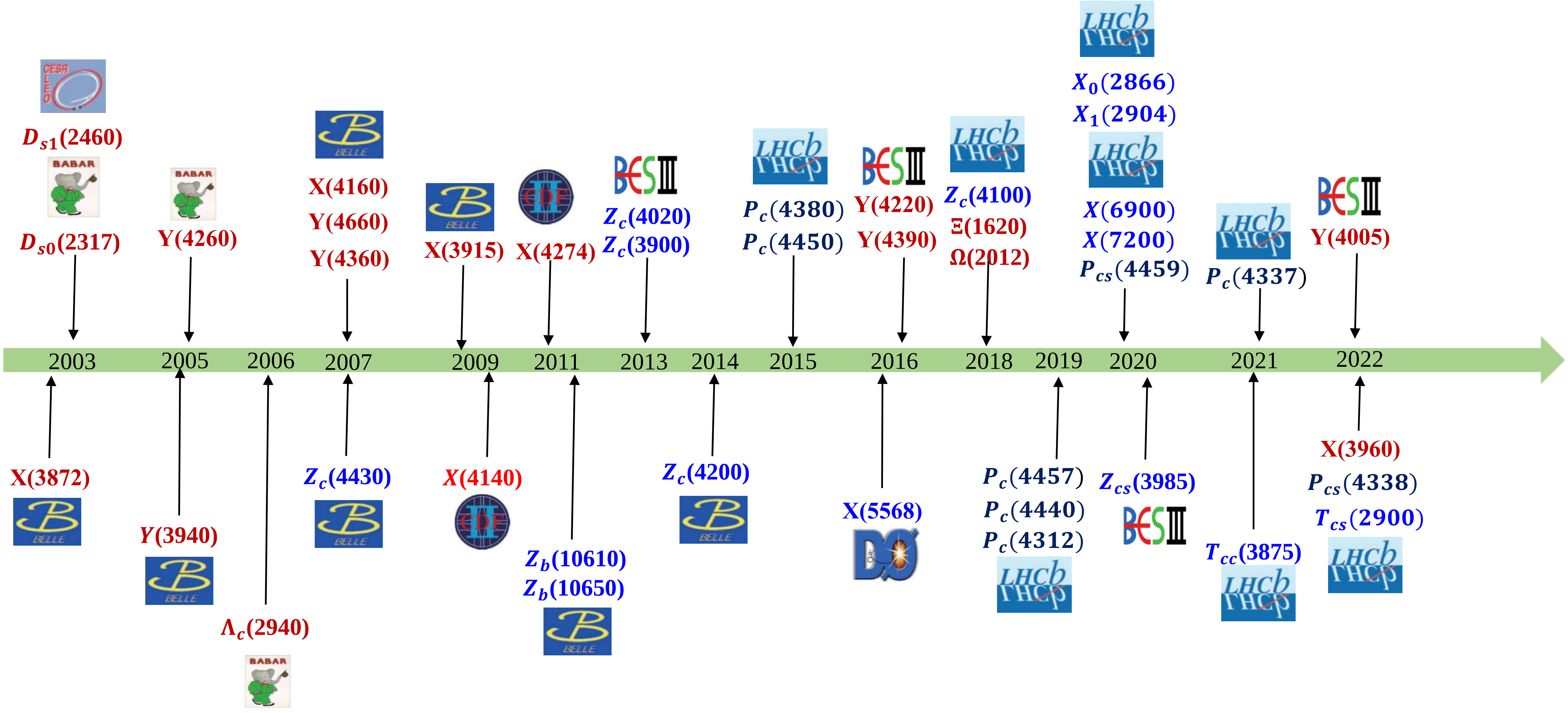
2024-7-28

Outline

- Heavy flavor hadronic molecular candidates (P_c and T_{cc}) and their partners
- Decays of the heavy flavor hadronic molecules
- Productions of the heavy flavor hadronic molecules
- Summary and Outlook

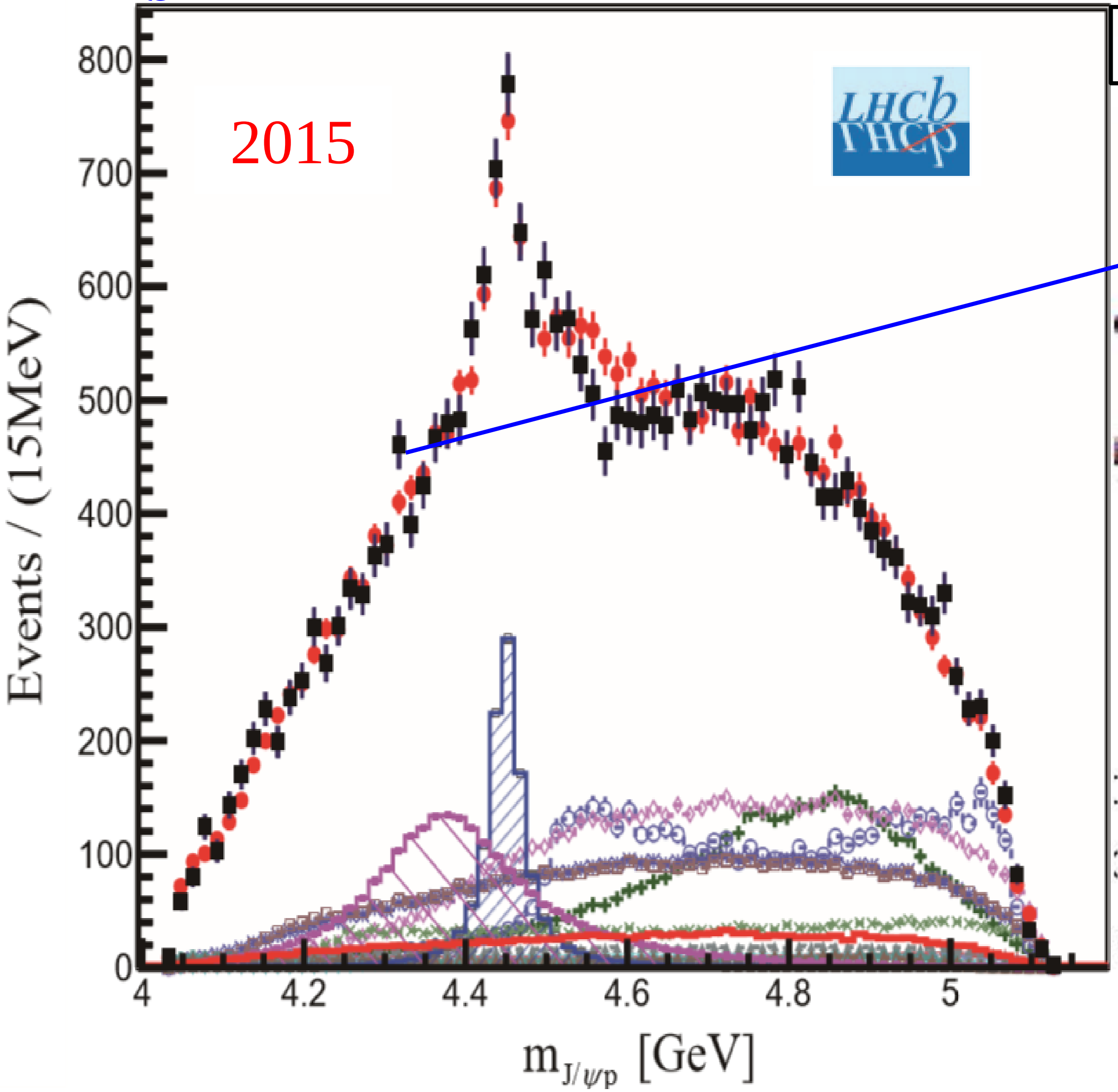
Exotic states

Exotic mesons or baryons   Tetraquark states   Pentaquark states

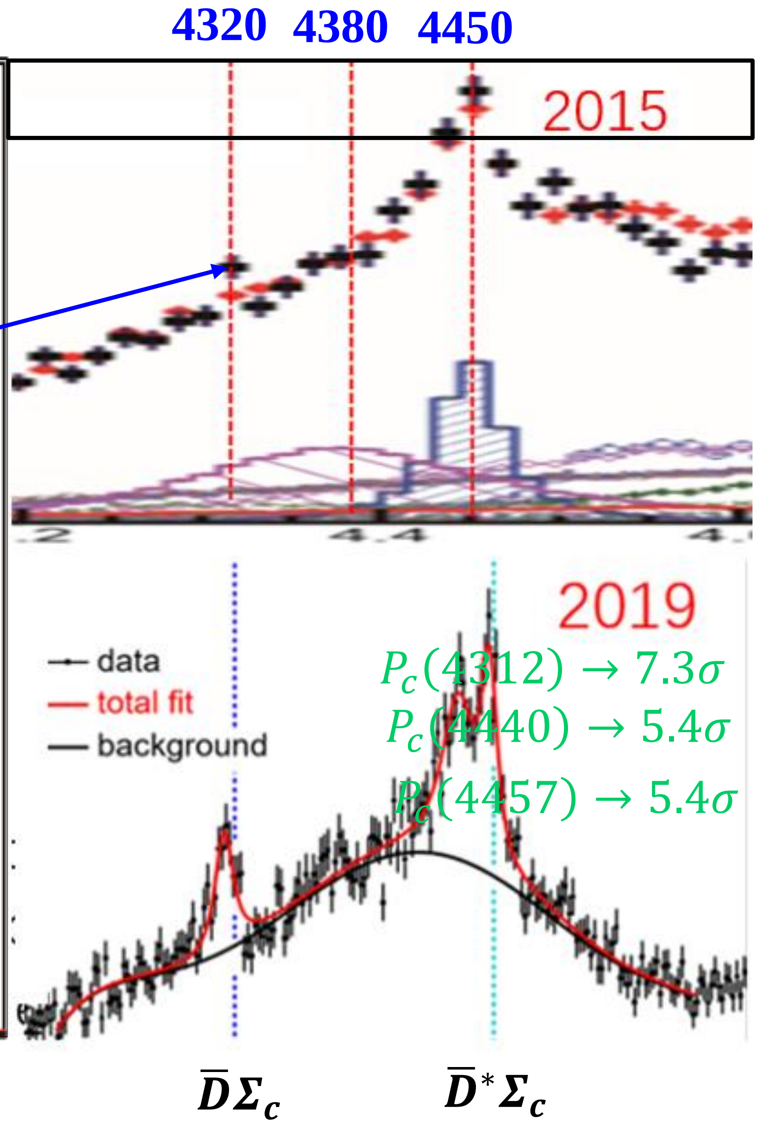


Hidden charm pentaquark states

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



LHCb, Phys.Rev.Lett. 115 (2015) 072001



LHCb, Phys.Rev.Lett. 122 (2019) 222001

2015

$$P_{c1} = 4380 \pm 8 \pm 29 + \frac{i}{2} 205 \pm 18 \pm 86$$

$$P_{c2} = 4449.8 \pm 1.7 \pm 2.5 + \frac{i}{2} 39 \pm 5 \pm 19$$

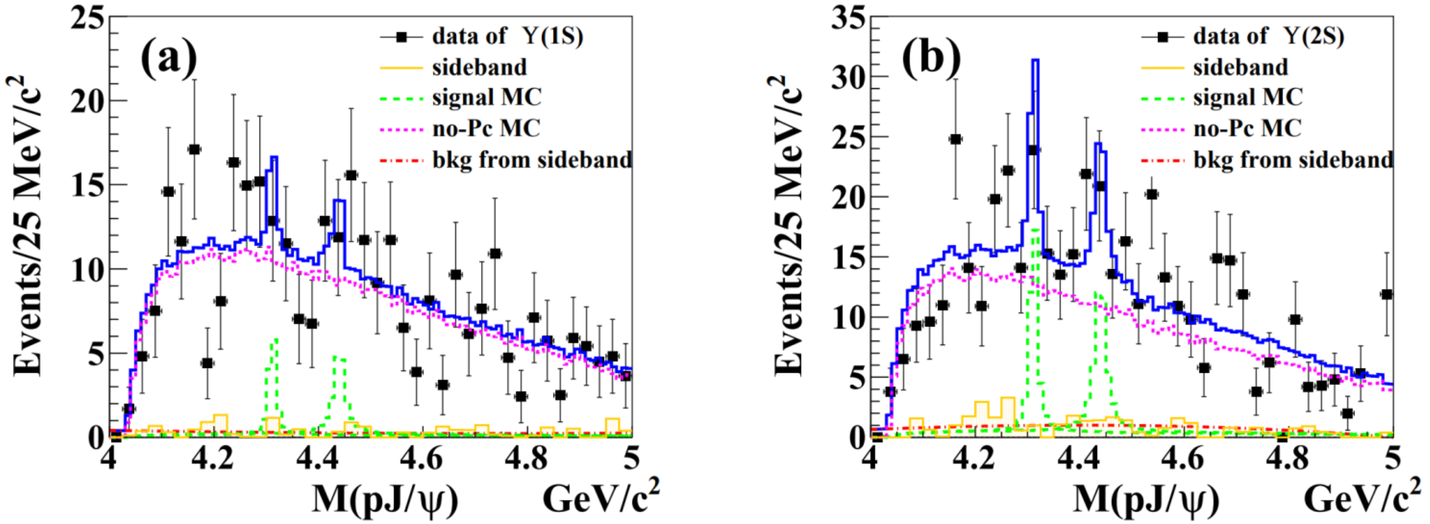
2019

$$P_{c1} = 4311.9 \pm 0.7^{+6.8}_{-0.6} + \frac{i}{2} 9.8 \pm 2.7^{+3.7}_{-4.5}$$

$$P_{c2} = 4440.3 \pm 1.3^{+4.1}_{-4.7} + \frac{i}{2} 20.6 \pm 4.9^{+8.7}_{-10.1}$$

$$P_{c3} = 4457.3 \pm 0.6^{+4.1}_{-1.7} + \frac{i}{2} 6.4 \pm 2.0^{+5.7}_{-1.9}$$

Productions of pentaquark states in recent experiments



No significant signal of three pentaquark states is observed in e^+e^- collisions

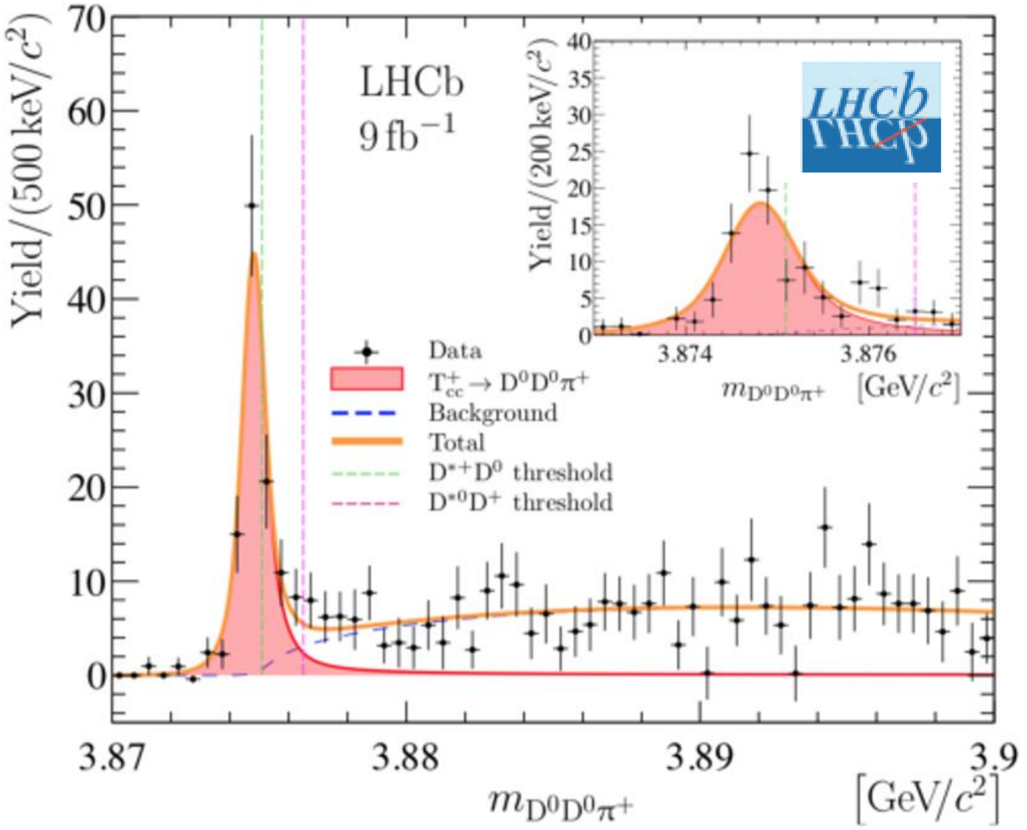
Belle Collaboration, arXiv: 2403.04340

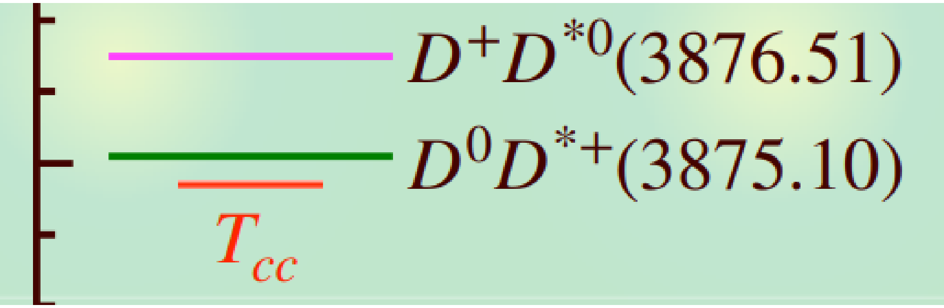
Decay Mode	Pentaquark Hypothesis	p-value	Significance (σ)	Signal Yield	Upper Limit ($\times 10^{-3}$) (90% CL)	(95% CL)
$\Lambda_c^+ \bar{D}^0$	$P_c(4312)^+$	0.32	0.48	19.78 ± 22.27	1.17	1.29
	$P_c(4440)^+$	0.44	0.15	26.91 ± 28.17	1.41	1.53
	$P_c(4457)^+$	0.53	0.00	6.20 ± 13.60	1.27	1.43
$\Lambda_c^+ \pi^+ D^{*-}$	$P_c(4440)^+$	1.00	0.00	0.00 ± 0.96	0.72	0.91
	$P_c(4457)^+$	1.00	0.00	0.00 ± 1.73	0.77	0.97
$\Lambda_c^+ \pi^- D^{*-}$	$P_c(4440)^+$	1.00	0.00	0.00 ± 0.80	0.63	0.80
	$P_c(4457)^+$	1.00	0.00	0.00 ± 0.74	0.59	0.74
$\Lambda_c^+ \pi^+ D^-$	$P_c(4312)^+$	1.00	0.00	0.00 ± 1.56	0.69	0.88
	$P_c(4440)^+$	0.65	0.00	4.43 ± 11.67	3.71	4.24
	$P_c(4457)^+$	0.65	0.00	5.94 ± 12.68	3.13	3.61
$\Lambda_c^+ \pi^- D^-$	$P_c(4312)^+$	1.00	0.00	0.00 ± 1.42	0.67	0.86
	$P_c(4440)^+$	0.53	0.00	12.52 ± 15.89	3.91	4.37
	$P_c(4457)^+$	0.53	0.00	8.60 ± 12.22	3.10	3.51

No significant signal of three pentaquark is observed in the prompt process of pp collisions

LHCb Collaboration, arXiv:2404.07131

Open charm tetraquark states





Precise measurement for exotic state

B.W

$\delta = -273 \pm 61 \pm 5^{+11}_{-14}$ keV

$\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}$ keV

LHCb, Nature Phys. 18 (2022) 7, 751-754

U.B.W

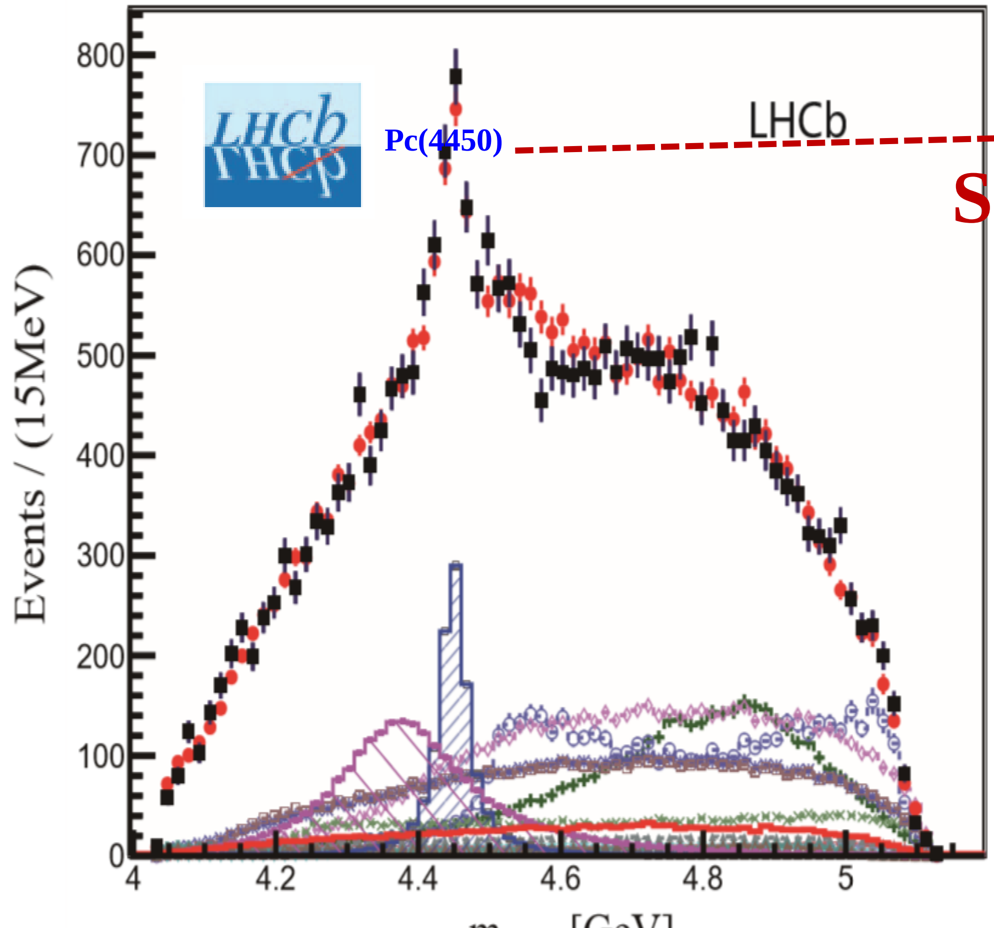
$\delta = -360 \pm 40^{+4}_{-0}$ keV

$\Gamma = 48 \pm 2^{+0}_{-14}$ keV

LHCb, Nature Commun. 13 (2022) 1, 3351

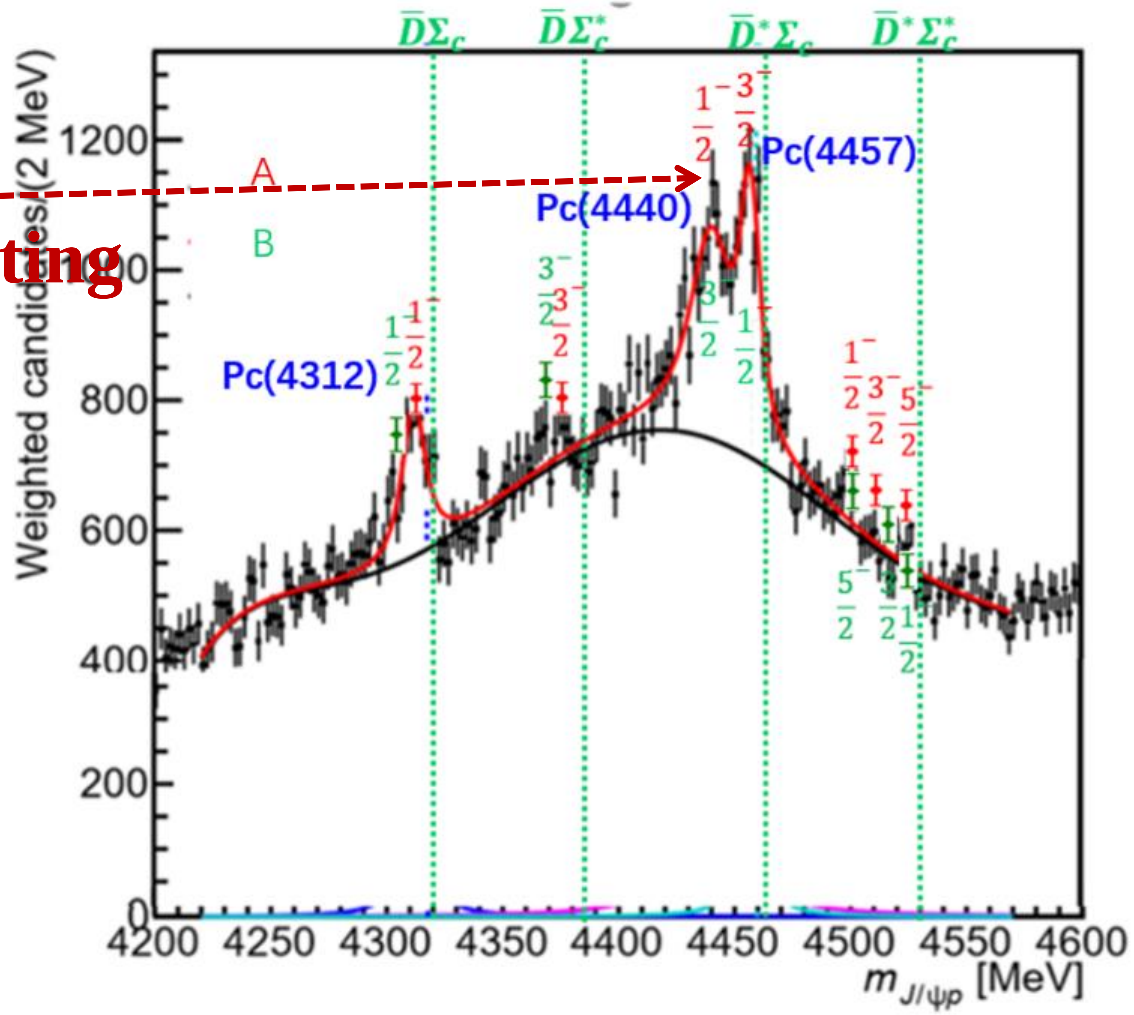
The fine structures of exotic states

➢ Hidden charm pentaquark states



2015

Splitting



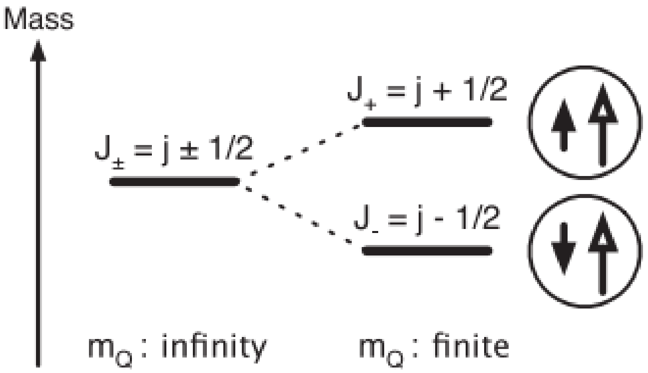
2019

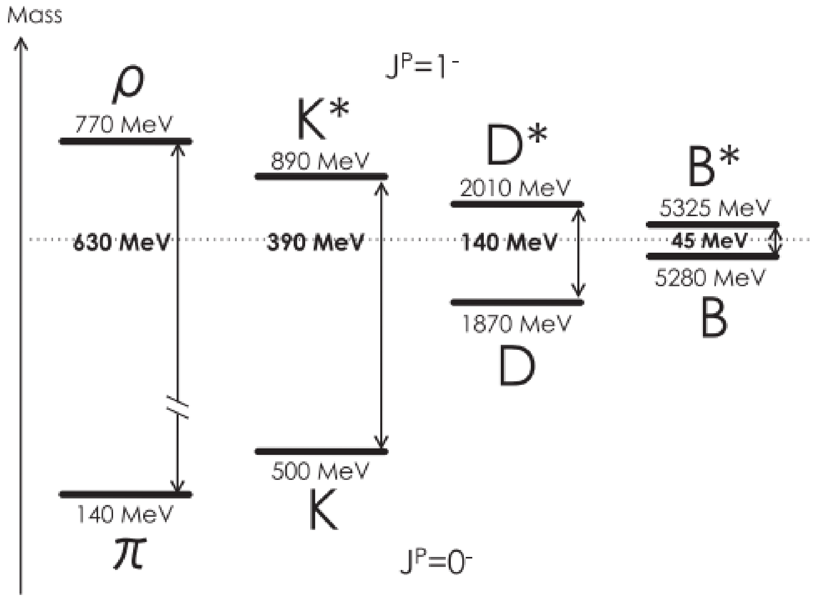
Fine structure!

Heavy quark spin symmetry(HQSS)

QCD interaction can not flip the spin of heavy quark

- **Spin doublet**



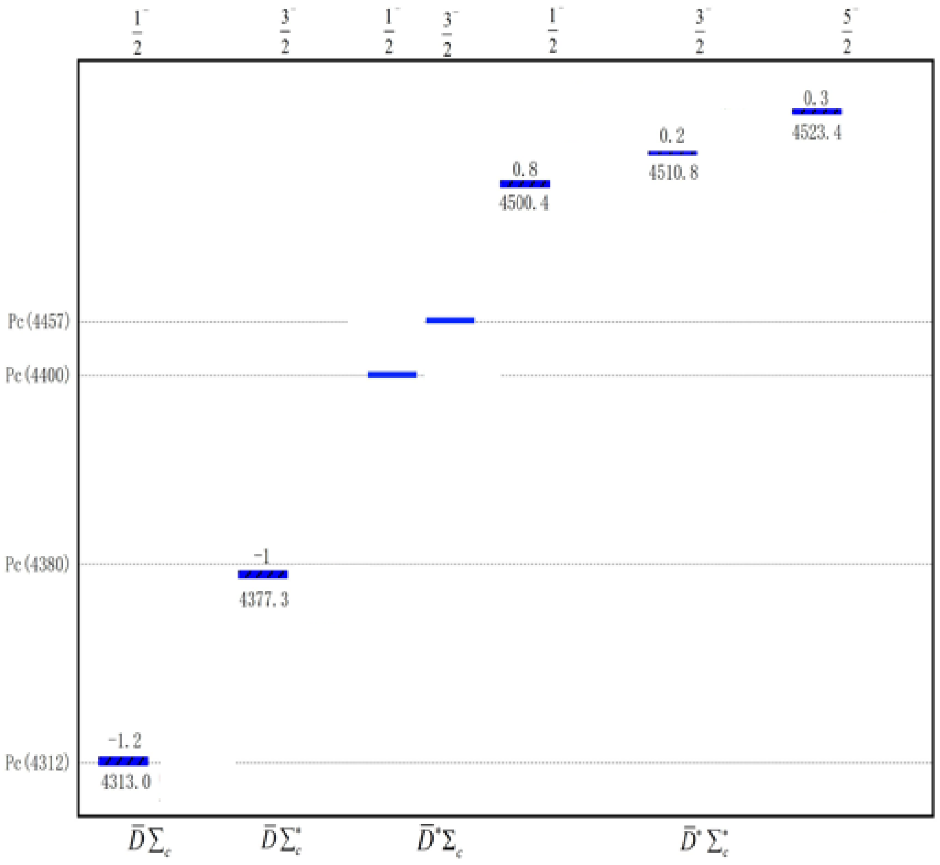


Lagrangian $$L = C_a Tr[H_c^\dagger H_c] S_c^\dagger \cdot S_c + C_b Tr[H_c^\dagger \sigma H_c] S_c^\dagger \cdot (J_i S_c)$$

Superfield $$H_c = \frac{1}{\sqrt{2}}(D + \vec{D}^* \vec{\sigma}) \qquad S_c = \frac{1}{\sqrt{3}}(\Sigma_c \vec{\sigma} + \vec{\Sigma}^*{}_c)$$

The low energy constants reduced from 4 to 2 within HQSS

HQSS multiplet hadronic molecules



Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	13.1 – 14.5	4306.3 – 4307.7
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	13.6 – 14.8	4370.5 – 4371.7
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	3.1 – 3.5	4523.2 – 4523.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	10.1 – 10.2	4516.5 – 4516.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	25.7 – 26.5	4500.2 – 4501.0

- Assigning three states as $\bar{D}^{(*)}\Sigma_c$ bound states
- A compelte multiplet hadronic molecules $\bar{D}^{(*)}\Sigma_c^{(*)}$

Fine structure of hadronic molecules

Liu et al., Phys.Rev.Lett. 122 (2019) 242001

HQSS, SU(3)$_f$ and HQFS partners of T_{cc}

- **Contact-range potentials**

$$V(I=0,\, DD^*) \;=\; C_a + C_b$$
$$V(I=0,\, D^*D^*) \;=\; C_a + C_b$$

- **Spectrum of relevant partners of T_{cc}**

molecule	I	J^{PC}	m (MeV)	Experimental data (MeV)
DD^*	0	1^+	Input	3874.73
D^*D^*	0	1^+	4015.3	-
D_sD^*	$\frac{1}{2}$	1^+	3975.2	-
$D_s^*D^*$	$\frac{1}{2}$	1^+	4118.3	-
BB^*	0	1^+	10551.2	-
B^*B^*	0	1^+	10596.1	-

Liu et al., arXiv:2404.06399

- One HQSS partner is predicted
- Two SU(3)-flavor partners are predicted
- Two HQFS partners are predicted

- **$D\bar{B}$ molecule**

$$V(I=0,\, D\bar{B}) \;=\; C_a \quad \begin{cases} m_{D\bar{B}} = 7144 \text{ MeV} \\ B_{D\bar{B}} = 2.6 \text{ MeV} \end{cases}$$

$$C_a^{sat} \;\propto\; -\frac{g_\sigma^2}{m_\sigma^2} + \frac{g_v^2}{m_v^2}(1+\vec{\tau}_1\cdot\vec{\tau}_2),$$
$$C_b^{sat} \;\propto\; \frac{f_v^2}{4M^2}(1+\vec{\tau}_1\cdot\vec{\tau}_2),$$

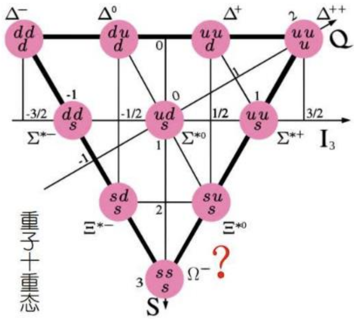
Liu et al., arXiv: 2405.04341

↓ Consistent

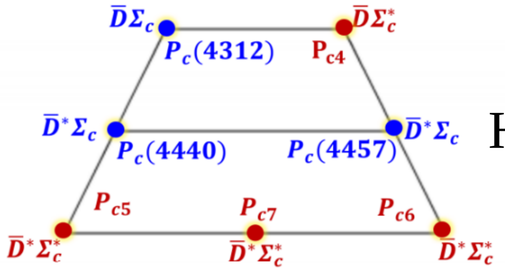
Constantia et al., Phys.Rev.Lett. 132 (2024), 151902

- **A model independent approach to verify the molecular nature of exotic state**

Liu et al., arXiv:2404.06399



SU(3)-flavor symmetry → Ω



HQSS

$T_{cc}(D^*D)$

↓ HQFS

$T_{cb}(D\bar{B})$

Outline

- Heavy flavor hadronic molecular candidates and their partners
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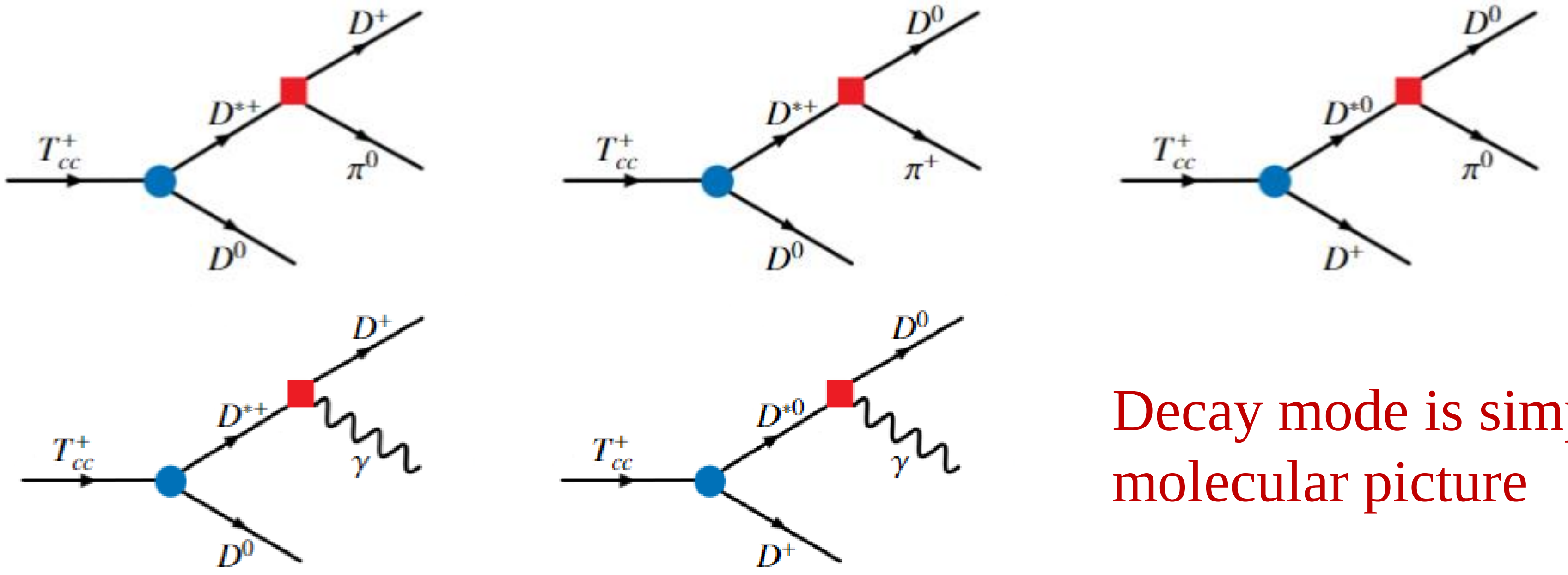
Decay modes of T_{cc}

➢ **Three-body partial decays of T_{cc} in the molecular picture**



Decay mode is simple within the molecular picture

➢ **Effective Lagrangian Approach**

$$\mathcal{L}_{T_{cc}}(x) = ig_{T_{cc}} T^{\mu}_{cc}(x) \int dy \Phi(y^2) D(x + \omega_{D^*} y) D^*_{\mu}(x - \omega_D y)$$

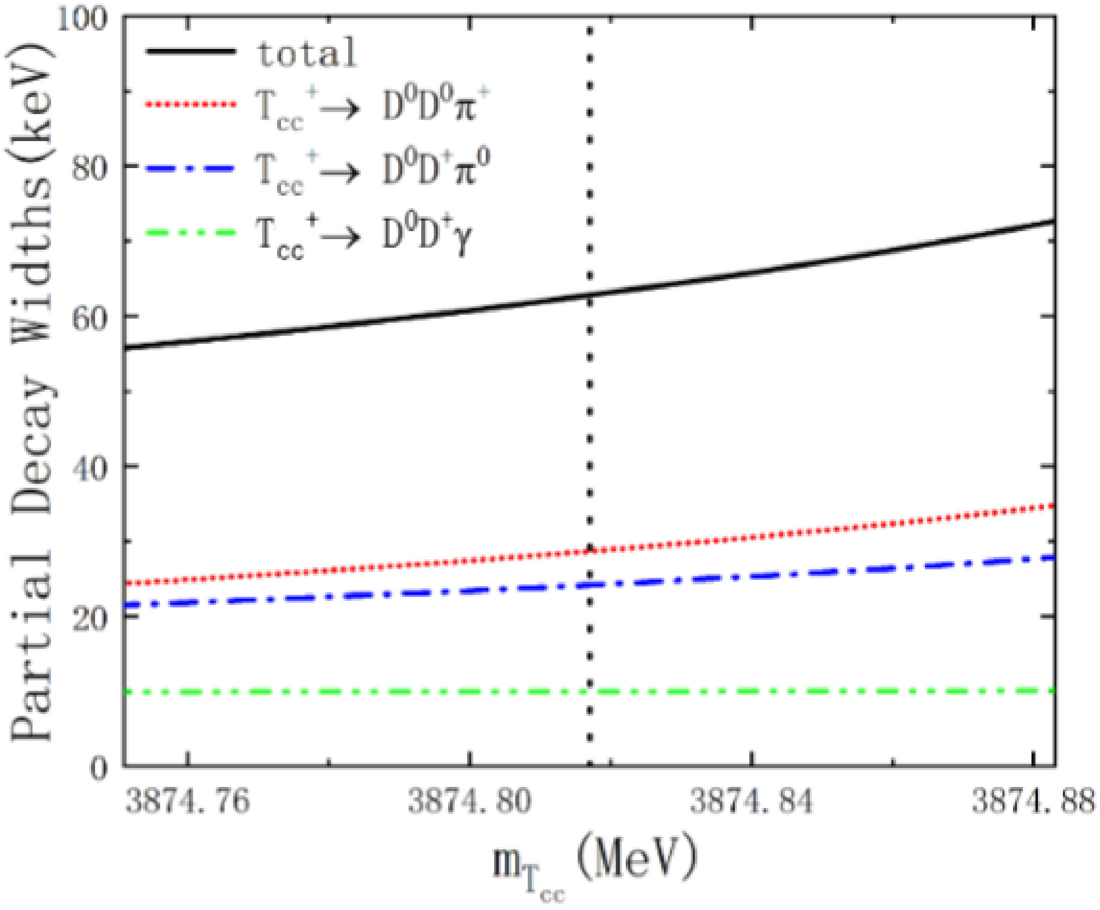
The coupling is determined by compositeness condition rule

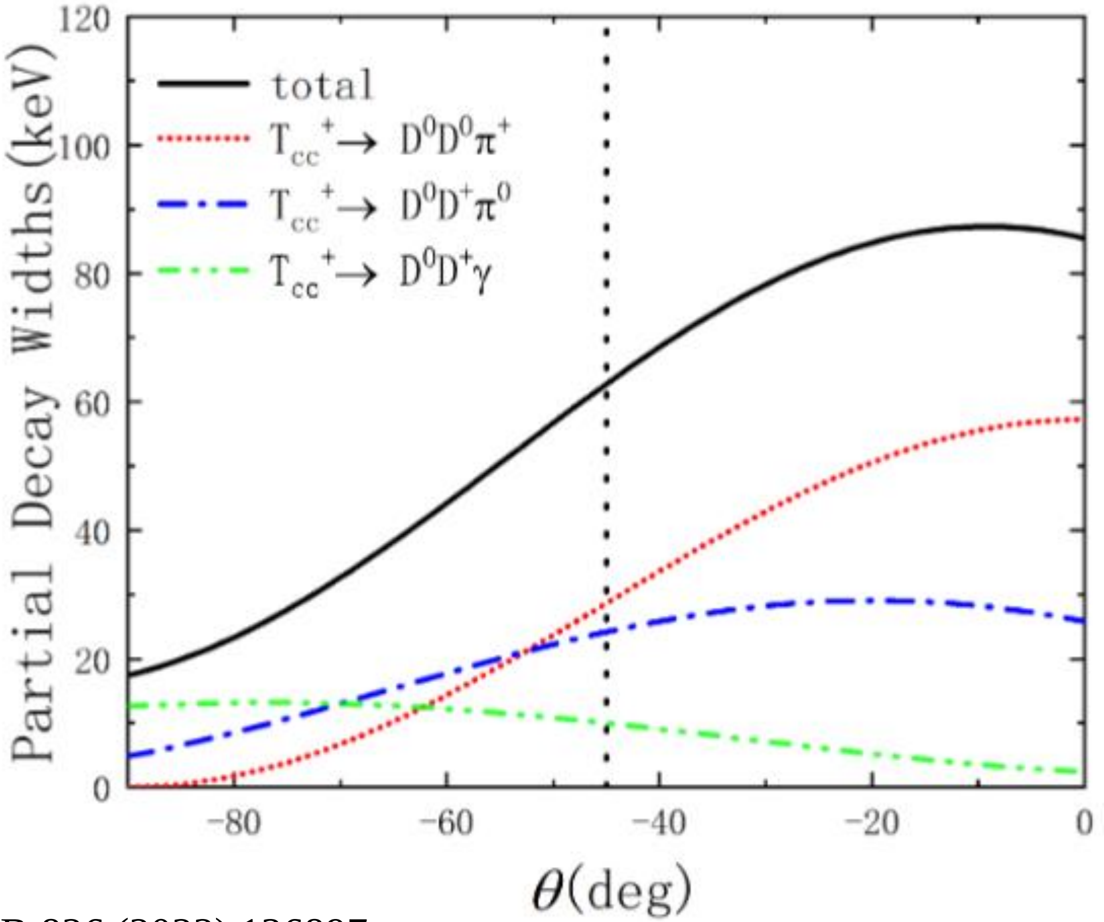
$$\mathcal{L}_{DD^*\pi} = -ig_{DD^*\pi}(D\partial^{\mu}\pi D^{*\dagger}_{\mu} - D^*_{\mu}\partial^{\mu}\pi D^{\dagger}),$$

$$\mathcal{L}_{DD^*\gamma} = eg_{DD^*\gamma}\varepsilon^{\mu\nu\alpha\beta}\partial_{\mu}A_{\nu}\partial_{\alpha}D^*_{\beta}D,$$

These couplings are totally determined by the experimental data

Partial decay widths of T_{cc}



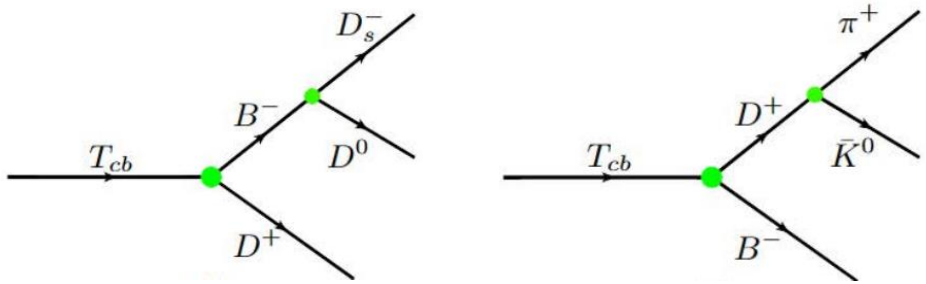


Ling et al., Phys.Lett.B 826 (2022) 136897

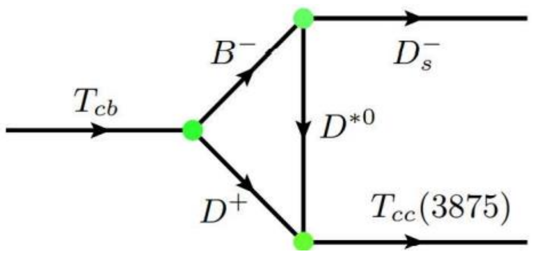
- Well describe the width of T_{cc} in the molecular picture
- The isospin breaking of T_{cc} is small

Decays of T_{cb}

➢ Weak decay modes of T_{cb}



Three-body partial decays



Final state interaction

➢ Partial decay widths of T_{cb}

Molecules coupling to their constituents

$$\mathcal{L}_{T_{cb}D\bar{B}} = g_{T_{cb}D\bar{B}} T_{cb} D\bar{B},$$
$$\mathcal{L}_{T_{cc}DD^*} = g_{T_{cc}DD^*} T^{\mu}_{cc} D D^*_{\mu},$$

Amplitudes of Cabbibo-favored weak decays

$$\mathcal{A}(\bar{B}\to\bar{D}_s D) = \frac{G_F}{\sqrt{2}} V_{cb}V_{cs} a_1 f_{\bar{D}_s}(m_{\bar{B}}^2 - m_D^2)F_0(q_1^2),$$
$$\mathcal{A}(D\to K\pi) = \frac{G_F}{\sqrt{2}} V_{sc}V_{ud} a_1 f_{\pi}(m_D^2 - m_K^2)F_0(q_1^2),$$

$\Gamma_{T_{bc}} = 0.2$ ps Hai-Yang Cheng et al., Phys. Rev. D 99, 073006 (2019)

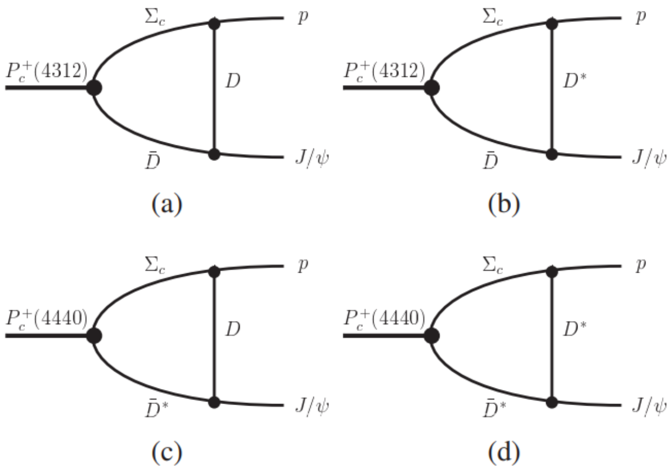
Decay mode	Width (GeV)	Branching fraction
$T_{cb}\to D_s^- D^0 D^+$	5.13×10^{-15}	0.002
$T_{cb}\to \pi^+ \bar{K}^0 B^-$	9.15×10^{-15}	0.004
$T_{cb}\to \pi^+ K^- \bar{B}^0$	3.51×10^{-14}	0.020
$T_{cb}\to T_{cc}^+ D_s^-$	3.07×10^{-16}	0.0001
$T_{cb}\to T_{cc}^+ \pi^-$	0.88×10^{-16}	0.00004

Liu et al., arXiv: 2405.04341

Predicting the promising channel to measure T_{cb}

Two approaches estimating two-body decays of molecule

➢ Triangle diagrams



Xiao et al., Phys.Rev.D 100 (2019) 1, 014022

Effective Lagrangian ➞ $\Gamma_{P_c} = \frac{1}{2J+1}\frac{1}{8\pi}\frac{|\vec{p}|^2}{m_0^2}\overline{|\mathcal{M}|^2}$

EFT ➞ $T = \frac{V}{1-VG}$

➢ Coupled channel scattering equation

$\bar{D}^*\Sigma_c^* - \bar{D}^*\Sigma_c - \bar{D}\Sigma_c^* - \bar{D}^*\Lambda_c - J/\psi N$

$$\begin{pmatrix} C_a - \frac{2}{3}C_b & -\frac{\sqrt{5}}{3}C_b & \sqrt{\frac{5}{3}}C_b & \sqrt{\frac{5}{3}}C_b' & \frac{\sqrt{5}}{3}g_2 \\ -\frac{\sqrt{5}}{3}C_b & C_a + \frac{2}{3}C_b & \frac{1}{\sqrt{3}}C_b & \frac{1}{\sqrt{3}}C_b' & -\frac{1}{3}g_2 \\ \sqrt{\frac{5}{3}}C_b & \frac{1}{\sqrt{3}}C_b & C_a & -C_b' & \frac{1}{\sqrt{3}}g_2 \\ \sqrt{\frac{5}{3}}C_b' & \frac{1}{\sqrt{3}}C_b' & -C_b' & C_a' & g_1 \\ \frac{\sqrt{5}}{3}g_2 & -\frac{1}{3}g_2 & \frac{1}{\sqrt{3}}g_2 & g_1 & 0 \end{pmatrix}$$

Coupled channel contact range potentials

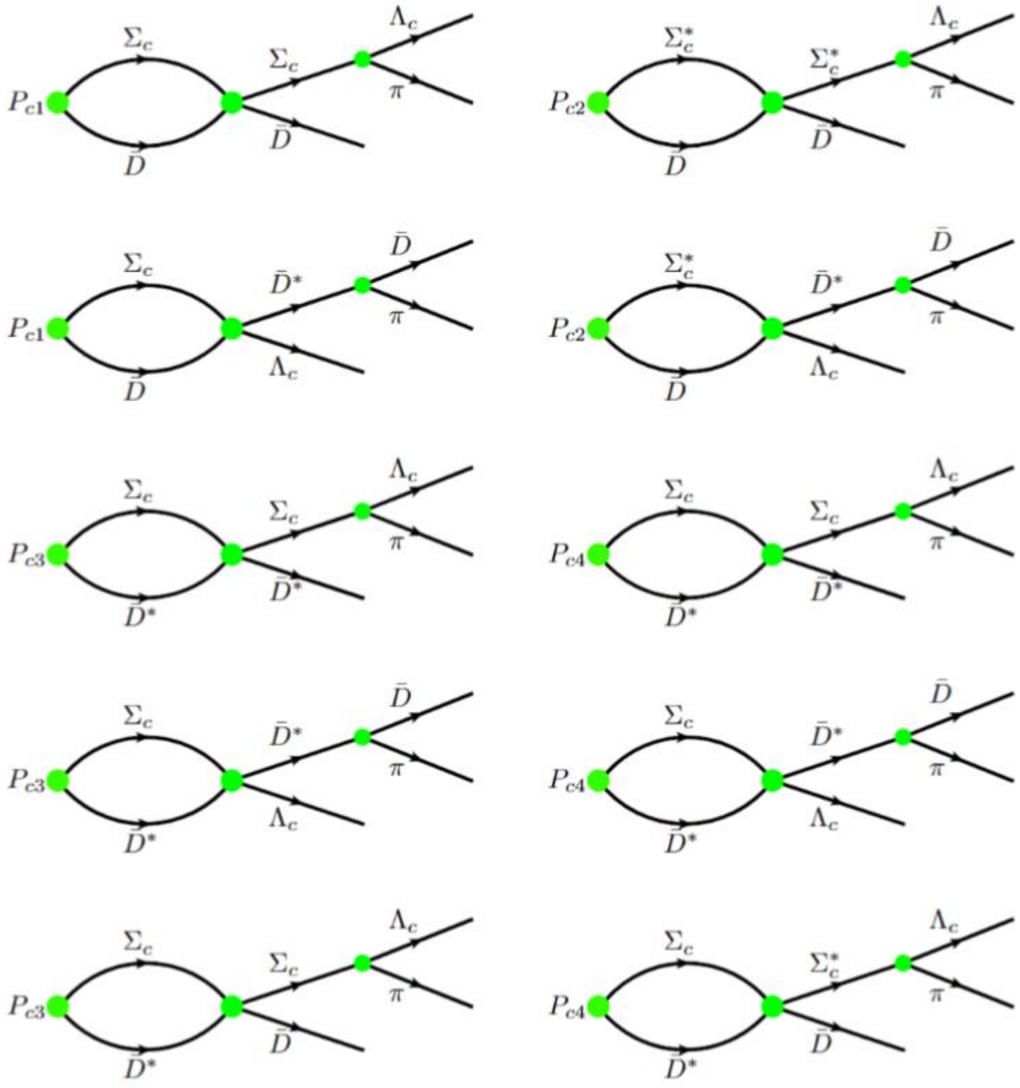
$\bar{D}^*\Sigma_c^* - \bar{D}^*\Sigma_c - \bar{D}\Sigma_c - \bar{D}^*\Lambda_c - \bar{D}\Lambda_c - J/\psi N - \eta_c N$

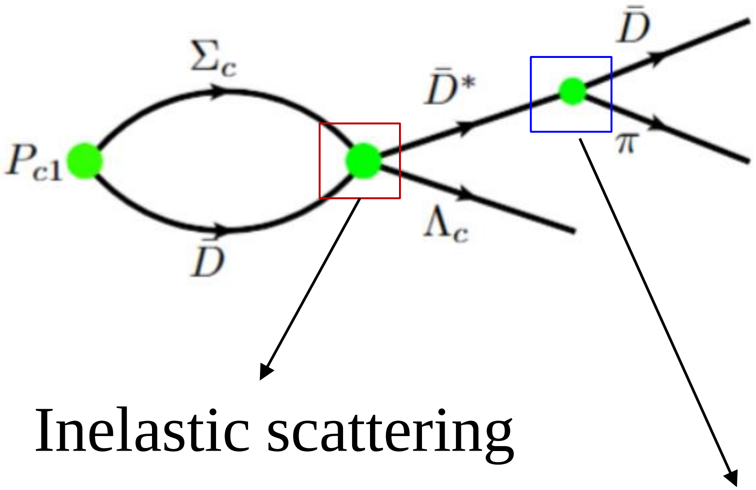
$$\begin{pmatrix} C_a - \frac{5}{3}C_b & -\frac{\sqrt{2}}{3}C_b & -\sqrt{\frac{2}{3}}C_b & \sqrt{\frac{2}{3}}C_b' & \sqrt{2}C_b' & -\frac{\sqrt{2}}{3}g_2 & \sqrt{\frac{2}{3}}g_2 \\ -\frac{\sqrt{2}}{3}C_b & C_a - \frac{4}{3}C_b & \frac{2}{\sqrt{3}}C_b & -\frac{2}{\sqrt{3}}C_b' & C_b' & \frac{5}{6}g_2 & \frac{1}{2\sqrt{3}}g_2 \\ -\sqrt{\frac{2}{3}}C_b & \frac{2}{\sqrt{3}}C_b & C_a & C_b' & 0 & \frac{1}{2\sqrt{3}}g_2 & \frac{1}{2}g_2 \\ \sqrt{\frac{2}{3}}C_b' & -\frac{2}{\sqrt{3}}C_b' & C_b' & C_a' & 0 & \frac{1}{2}g_1 & \frac{\sqrt{3}}{2}g_1 \\ \sqrt{2}C_b' & C_b' & 0 & 0 & C_a' & \frac{\sqrt{3}}{2}g_1 & -\frac{1}{2}g_1 \\ -\frac{\sqrt{2}}{3}g_2 & \frac{5}{6}g_2 & \frac{1}{2\sqrt{3}}g_2 & \frac{1}{2}g_1 & \frac{\sqrt{3}}{2}g_1 & 0 & 0 \\ \sqrt{\frac{2}{3}}g_2 & \frac{1}{2\sqrt{3}}g_2 & \frac{1}{2}g_2 & \frac{\sqrt{3}}{2}g_1 & -\frac{1}{2}g_1 & 0 & 0 \end{pmatrix}$$

- Search for poles existing at unphysical sheet
- Their imaginary part corresponding to the widths of pentaquark molecules

Strong decays of P_c

- **Three-body partial decays of P_c**





Inelastic scattering

On shell or off-shell hadron decays

- **Final decay modes of P_c**

Two-body partial decays

$P_c \to \bar{D}\Lambda_c,\ \eta_c p, J/\psi p$

Three-body partial decays

$P_c \to \bar{D}\Lambda_c\pi, \bar{D}^*\Lambda_c\pi$

Partial decay widths of P_c

A

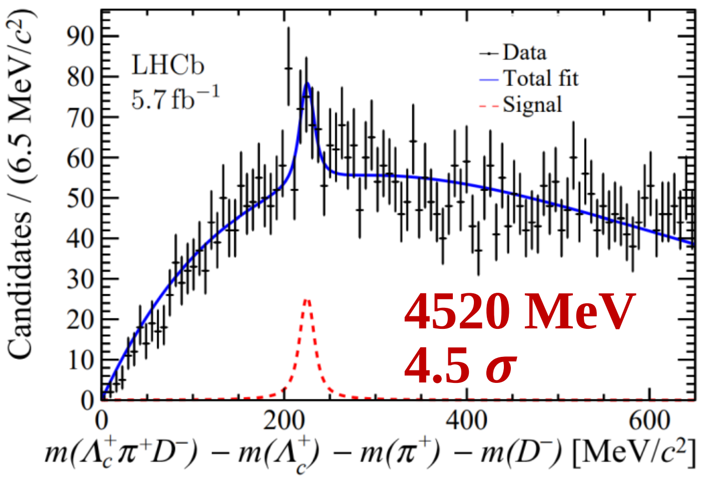
Mode	$D^-\Lambda_c^+\pi^+$	$\bar{D}^0\Lambda_c^+\pi^0$	$D^{*-}\Lambda_c^+\pi^+$	$\bar{D}^{*0}\Lambda_c^+\pi^0$	$\bar{D}\Lambda_c$	$J/\psi N$	$\eta_c N$	Total
$P_{c1}[P_\psi(4312)^N]$	0.036	0.812	-	-	0.004	2.014	3.917	6.783
P_{c2}	2.043	2.235	-	-	-	5.995	-	10.273
$P_{c3}[P_\psi(4440)^N]$	0.814	1.631	0.002	0.035	0.622	13.560	1.841	18.505
$P_{c4}[P_\psi(4457)^N]$	0.171	0.152	0.095	0.388	-	0.347	-	1.153
P_{c5}	0.315	0.722	2.370	1.970	1.154	8.116	7.487	22.134
P_{c6}	1.354	2.407	4.275	3.601	-	9.877	-	21.514
P_{c7}	-	-	2.745	2.499	-	-	-	5.244

B

Mode	$D^-\Lambda_c^+\pi^+$	$\bar{D}^0\Lambda_c^+\pi^0$	$D^{*-}\Lambda_c^+\pi^+$	$\bar{D}^{*0}\Lambda_c^+\pi^0$	$\bar{D}\Lambda_c$	$J/\psi N$	$\eta_c N$	Total
$P_{c1}[P_\psi(4312)^N]$	0.023	1.988	-	-	0.008	2.208	3.784	8.011
P_{c2}	1.401	1.547	-	-	-	14.259	-	17.207
$P_{c3}[P_\psi(4457)^N]$	0.410	2.703	0.686	2.803	0.932	3.128	0.699	11.361
$P_{c4}[P_\psi(4440)^N]$	0.052	0.635	0.001	0.014	-	0.904	-	1.606
P_{c5}	0.371	2.818	7.731	7.037	2.181	4.365	2.949	27.452
P_{c6}	0.760	1.899	5.668	5.090	-	3.432	-	17.849
P_{c7}	-	-	1.084	0.959	-	-	-	2.043

Liu et al., arXiv: 2407.17318

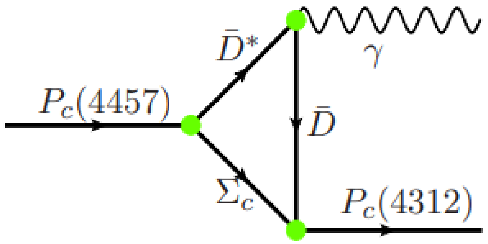
- $Br(P_c(4312) \to \bar{D}\Lambda_c\pi) = 13\sim25\%$
  $Br(P_c(4312) \to \bar{D}^*\Lambda_c\pi) = 0$
- $Br(P_c(4440) \to \bar{D}\Lambda_c\pi) = 13\sim43\%$
  $Br(P_c(4440) \to \bar{D}^*\Lambda_c\pi) = 0.2\sim0.9\%$
- $Br(P_c(4457) \to \bar{D}\Lambda_c\pi) = 27\sim28\%$
  $Br(P_c(4457) \to \bar{D}^*\Lambda_c\pi) = 31\sim42\%$
- $Br(P_{c5} \to \bar{D}\Lambda_c\pi) = 5\sim12\ \%$
  $Br(P_{c5} \to \bar{D}^*\Lambda_c\pi) = 20\sim54\%$
- $Br(P_{c6} \to \bar{D}\Lambda_c\pi) = 15\sim18\%$
  $Br(P_{c6} \to \bar{D}^*\Lambda_c\pi) = 37\sim60\%$
- $Br(P_{c7} \to \bar{D}^*\Lambda_c\pi) = 100\ \%$

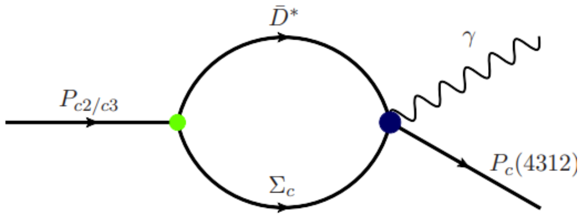


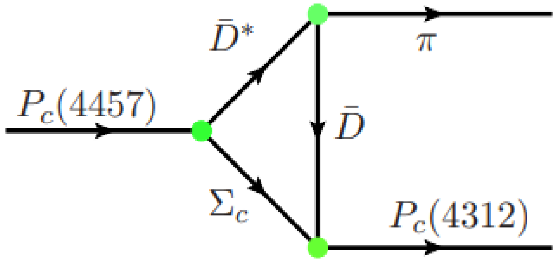
LHCb Collaboration, arXiv: 2404.07131

Radiative decays of P_c

- **Keep gauge invariance of radiative decays**



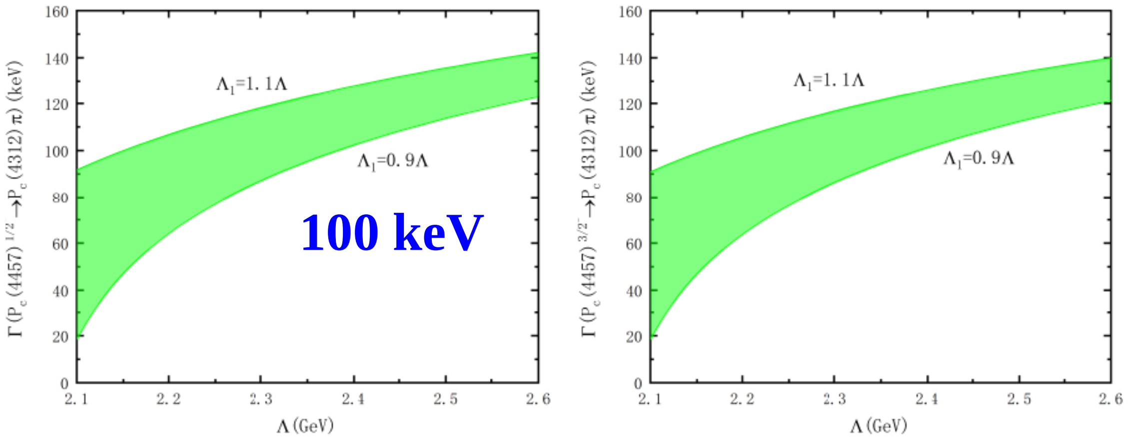


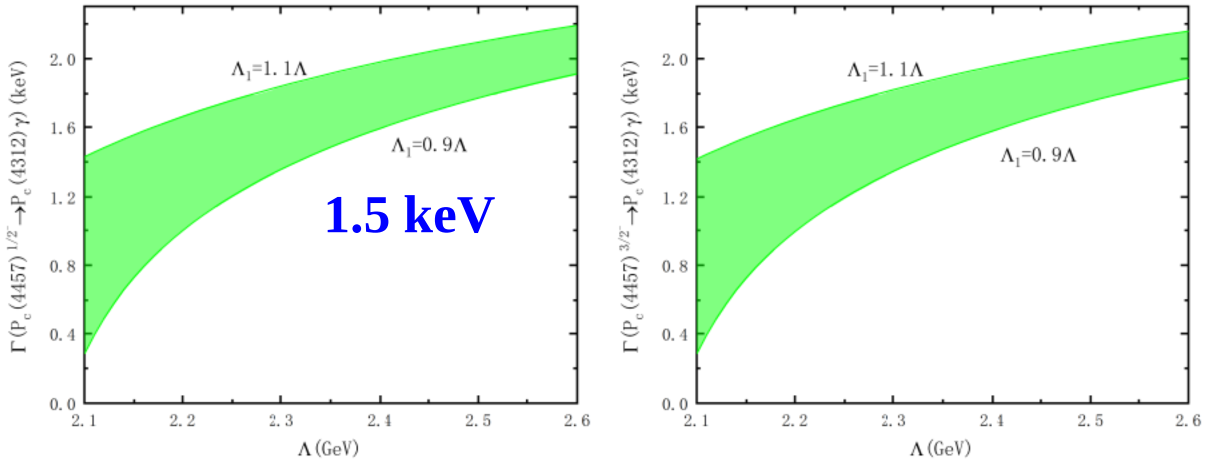


$$\mathcal{M}_{1/2}^{Tri} = \varepsilon_\mu(p_2)\bar{u}(p_1)(g_1^{Tri1/2}\gamma^\mu + g_2^{Tri1/2}\frac{p_1^\mu \not{p}_2}{p_1 \cdot p_2})u(k_0)$$

$$\mathcal{M}_{3/2}^{Tri} = \varepsilon_\mu(p_2)\bar{u}(p_1)(g_1^{Tri3/2}\gamma^\mu p_2^\nu - g_2^{Tri3/2}\not{p}_2 g^{\mu\nu})u_\nu(k_0)$$

Ling et al., Phys.Rev.D 104 (2021) 7, 074022





$P_c(4457)$ $\bar{D}\Lambda_{c1}$ **11 MeV**

Different parity

Wu et al., arXiv:2407.05743

1.7 keV → OBE Li et al., Phys.Rev.D 104 (2021) 5, 054016

Outline

- Heavy flavor hadronic molecular candidates and their partners
- Decays of the heavy flavor hadronic molecules
- Productions of the heavy flavor hadronic molecules
- Summary and Outlook

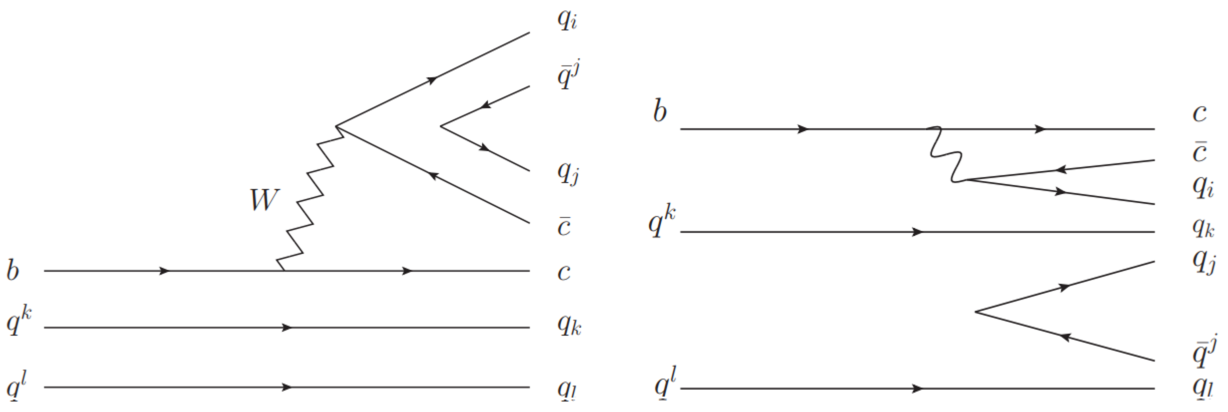
Productions of pentaquark states in large facility

states	EIcC (60 fb^{-1})	CEPC (100 ab^{-1})	LHC (9 fb^{-1})
$P_c(4312)$	$(0.02\sim0.08)$ pb	$(0.002\sim0.01)$ pb	$(3\sim9)$ nb
	$1200\sim4800$	$(0.2\sim1)\times10^6$	$(3\sim8)\times10^7$
$P_c(4440)$	$(0.01\sim0.06)$ pb	$(0.002\sim0.01)$ pb	$(1\sim5)$ nb
	$600\sim3600$	$(0.2\sim1)\times10^6$	$(1\sim5)\times10^7$
$P_c(4457)$	$(3.4\sim16.4)\times10^{-3}$ pb	$(0.001\sim0.006)$ pb	$(0.3\sim1)$ nb
	$204\sim984$	$(1\sim6)\times10^5$	$(3\sim9)\times10^6$
	Shi et al., 2208.02639	Jia et al., 2405.02619	Ling et al., 2104.11133

The future CEPC is a good platform to produce hidden charm pentaquark states

Productions of pentaquark states in b-baryon decays

➢ The topological diagrams for b-baryon decays



Hai-Yang Cheng et al., Phys.Rev.D 92 (2015) 9, 096009

$$H_{\rm eff} = \mathcal{B}_a H^i \Pi^j_i \bar{\mathcal{P}}^a_j (T_1 - T_2) + \mathcal{B}_a H^a \Pi^j_i \bar{\mathcal{P}}^i_j T_2 + \mathcal{B}_a H^i \Pi^j_j \bar{\mathcal{P}}^a_i T_3 - \mathcal{B}_a H^i \Pi^a_l \bar{\mathcal{P}}^l_i T_3$$
$$+ \mathcal{B}^{kl} H^i \Pi^j_i \epsilon_{jka} \bar{\mathcal{P}}^a_l t_1 + \mathcal{B}^{kl} H^i \Pi^j_l \epsilon_{ika} \bar{\mathcal{P}}^a_j t_2 + \mathcal{B}^{kl} H^i \Pi^j_l \epsilon_{akj} \bar{\mathcal{P}}^a_i t_3.$$

$$\frac{Br(\Lambda_b \to P_c(4380)\pi^-)}{Br(\Lambda_b \to P_c(4380)K^-)} = 0.016^{+0.026}_{-0.016} \pm 0.025$$

$$\left|\frac{V_{cd}}{V_{cs}}\right|^2 \approx 0.05$$

Consistent

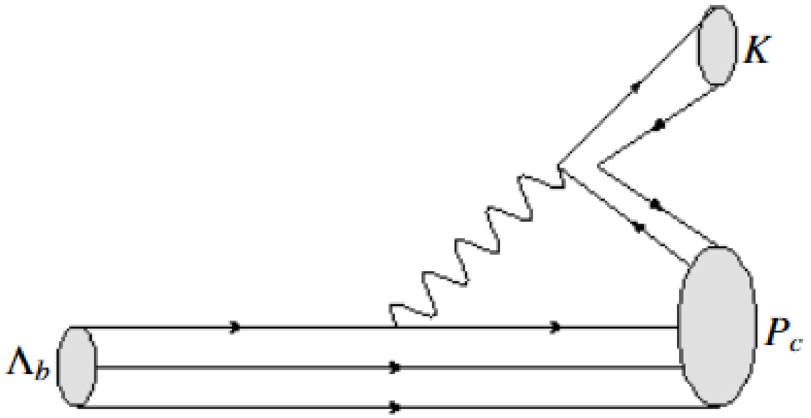
$$\frac{Br(\Lambda_b \to P_c(4450)\pi^-)}{Br(\Lambda_b \to P_c(4450)K^-)} = 0.033^{+0.016+0.011}_{-0.014-0,010} \pm 0.009$$

LHCb Collaboration., Phys.Rev.Lett. 117 (2016) 8, 082002

➢ Predicting pentaquark states with strange quark

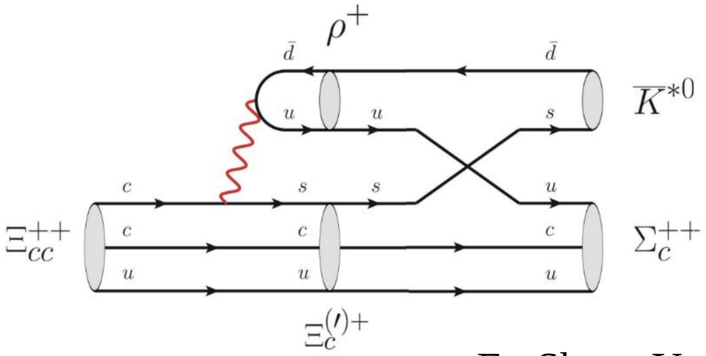
$\Lambda_b^0 \to P_p K^-$	T_1
$\Lambda_b^0 \to P_p \pi^-$	$t_1 - t_2$
$\Xi_b^0 \to P_{\Sigma^+} K^-$	$T_1 - T_2$
$\Omega_b^- \to P_{\Xi^0} K^-$	$-t_1 + t_3$

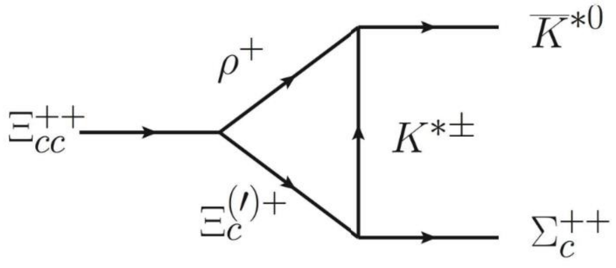
S=-1 and S=-2 hidden charm pentaquark are likely to be observed in these processes

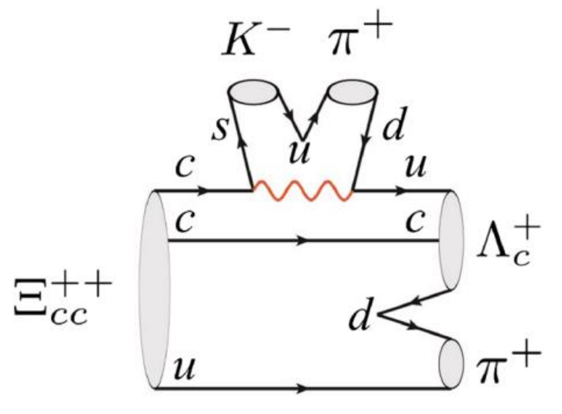


Final states interaction

➢ Predicting the dominant decay channels of Ξ_{cc}^{++}





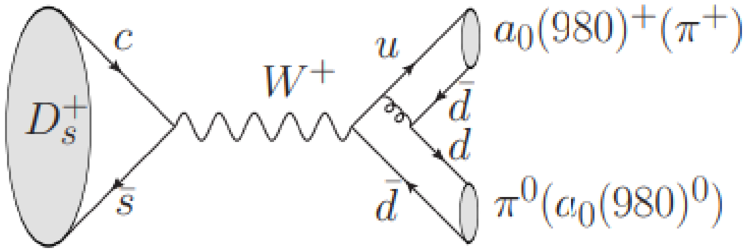


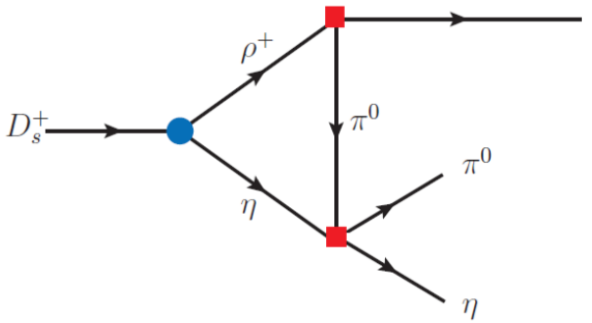
Fu-Sheng Yu et al., Chin.Phys.C 42 (2018) 5, 051001

➢ Explaining the W-boson annihilation process

$$\mathcal{B}[D_s^+ \to a_0(980)^{+(0)}\pi^{0(+)},\ a_0(980)^{+(0)} \to \pi^{+(0)}\eta] = (1.46 \pm 0.15_{\text{sta.}} \pm 0.23_{\text{sys.}})\%$$

BESIII Collaboration, Phys.Rev.Lett. 123 (2019) 11, 112001



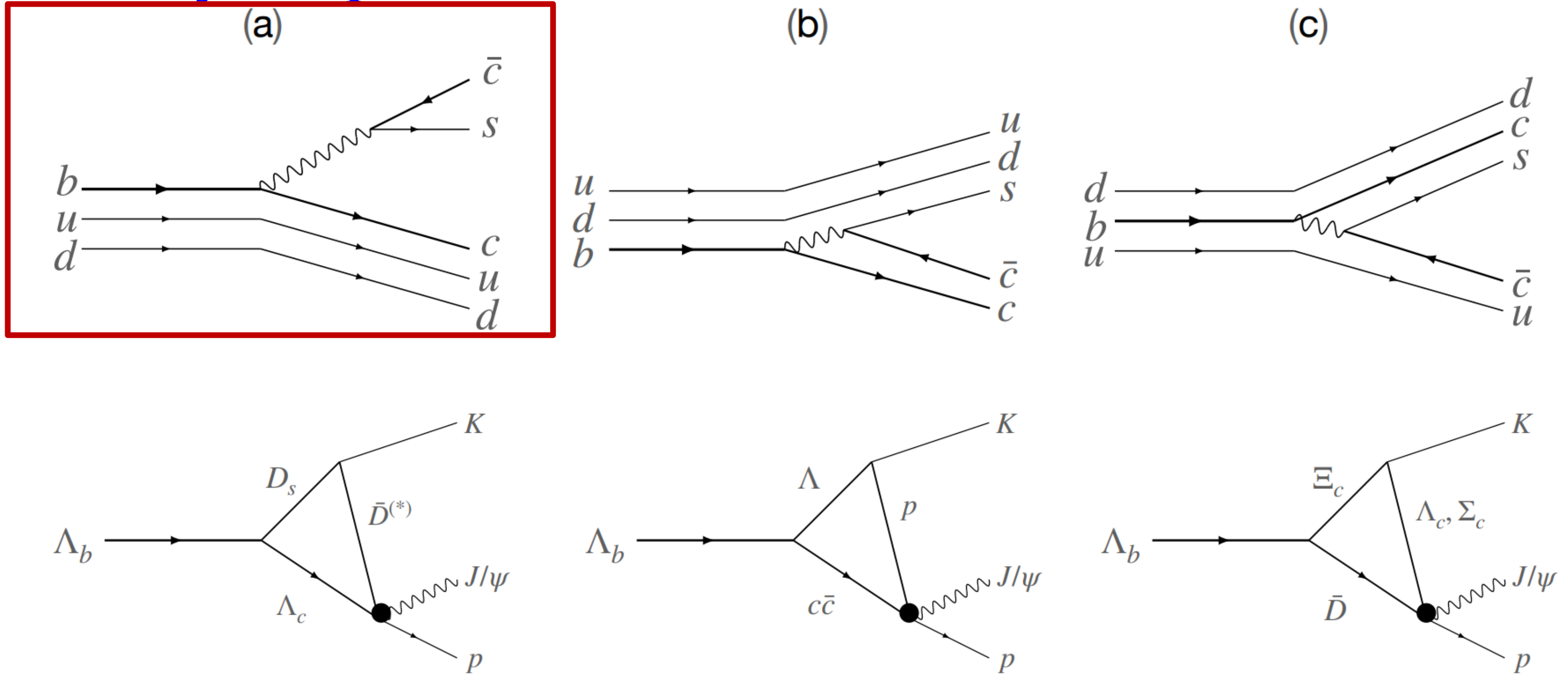


Xi-Zhe Ling et al.,
Phys.Rev.D 103 (2021) 11, 116016

Yu-Kuo Hsiao et al.,
Eur.Phys.J.C 80 (2020) 9, 895

Productions of pentaquark states in b-hadron decays

➢ Weak decays at quark level



T. J. Burns et al., Eur.Phys.J.A 58 (2022) 4, 68

➢ Select the vertices of weak decays

$\Lambda_b \to \Lambda_c D_s^{(*)}$

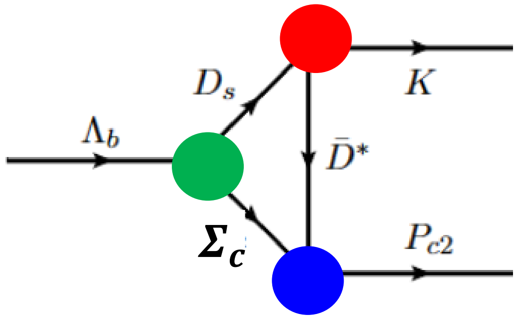
$\Lambda_b \to \Sigma_c D_s^{(*)}$

$$\mathcal{A}\left(\Lambda_b \to \Lambda_c D_s^+\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_1 \left\langle D_s^+ | (s\bar{c}) | 0 \right\rangle \left\langle \Lambda_c | (c\bar{b}) | \Lambda_b \right\rangle$$

$$\mathcal{A}\left(\Lambda_b \to \Lambda_c D_s^{*+}\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_1 \left\langle D_s^{*+} | (s\bar{c}) | 0 \right\rangle \left\langle \Lambda_c | (c\bar{b}) | \Lambda_b \right\rangle$$

Estimation of the branching fraction of decay $\Lambda_b \to D_s\Sigma_c$

- $\Lambda_b \to \Sigma_c D_s$



- $\Lambda_b \to \Sigma_c$

$$\frac{f(\Lambda_b \to \Sigma_c)}{f(\Lambda_b \to \Lambda_c)} = 0.1$$

Wu et al., Phys.Rev.D 100 (2019) 11, 114002

Such form factor is zero in the leading order of HQET

Nathan Isgur et al., Nucl.Phys.B 348 (1991) 276-292

$\mathcal{O}[(m_u - m_d)/m_c\ ]$

- $Br(\Lambda_b \to \Sigma_c D_s)$ Collaborate with F.S.Y

$$\frac{N(\Lambda_b \to \Sigma_c^+ D_s^-)}{N(B^- \to D^{*0} D_s^-)} = \frac{Br(\Lambda_b \to \Sigma_c^+ D_s^-)}{Br(B^- \to D^{*0} D_s^-)} \frac{f_{\Lambda_b}}{f_u} \frac{Br(\Sigma_c^+ \to \Lambda_c^+ \pi^0)}{Br(D^{*0} \to D^0 \pi^0)} \frac{Br(\Lambda_c^+ \to pK^-\pi^+)}{Br(D^0 \to K^-\pi^+)} \epsilon(p)$$

$$\frac{N(\Lambda_b \to \Sigma_c^+ D_s^-)}{N(B^- \to D^{*0} D_s^-)} = \frac{Br(\Lambda_b \to \Sigma_c^+ D_s^-)}{Br(B^- \to D^{*0} D_s^-)} \frac{\epsilon(p)}{r}$$

$$r = \frac{f_{\Lambda_b}}{f_u} \frac{Br(\Sigma_c^+ \to \Lambda_c^+ \pi^0)}{Br(D^{*0} \to D^0 \pi^0)} \frac{Br(\Lambda_c^+ \to pK^-\pi^+)}{Br(D^0 \to K^-\pi^+)} = \frac{0.5}{1} \frac{1}{2/3} \frac{4\%}{6\%} \approx 1 \qquad \epsilon(p) \sim 30\%$$

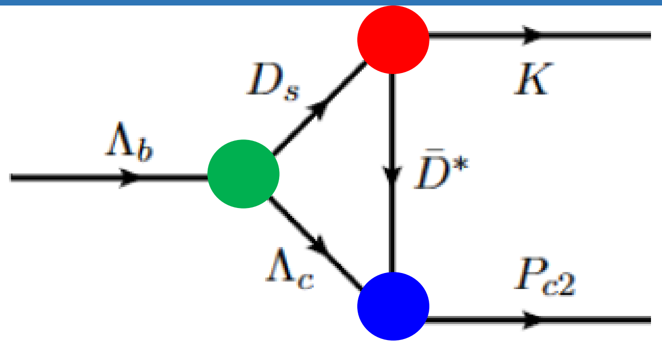
$$Br(B^- \to D^{*0} D_s^-) = (8.2 \mp 1.7) \times 10^{-3}$$

$$N(B^- \to D^{*0} D_s^-) \sim 1.3 \times 10^5$$

$$Br(\Lambda_b \to \Sigma_c^+ D_s^-) = \frac{N(\Lambda_b \to \Sigma_c^+ D_s^-)}{N(B^- \to D^{*0} D_s^-)} Br(B^- \to D^{*0} D_s^-) \frac{r}{\epsilon(p)}$$

$$\begin{cases} N(\Lambda_b \to \Sigma_c^+ D_s^-) < 10 & Br(\Lambda_b \to \Sigma_c^+ D_s^-) < 2 \times 10^{-6} \\ N(\Lambda_b \to \Sigma_c^+ D_s^-) < 100 & Br(\Lambda_b \to \Sigma_c^+ D_s^-) < 2 \times 10^{-5} \end{cases}$$

Productions of pentaquark states in b-hadron decays



$$\mathcal{A}\left(\Lambda_b \to \Lambda_c D_s^+\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_1 \left\langle D_s^+ |(s\bar{c})| 0 \right\rangle \left\langle \Lambda_c |(c\bar{b})| \Lambda_b \right\rangle$$

$$\mathcal{A}\left(\Lambda_b \to \Lambda_c D_s^{*+}\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_1 \left\langle D_s^{*+} |(s\bar{c})| 0 \right\rangle \left\langle \Lambda_c |(c\bar{b})| \Lambda_b \right\rangle$$

- Coupled-channel potentials

$$\bar{D}^*\Sigma_c^* - \bar{D}^*\Sigma_c - \bar{D}\Sigma_c - \bar{D}^*\Lambda_c - \bar{D}\Lambda_c - J/\psi N - \eta_c N$$

$$\begin{pmatrix}
C_a - \frac{5}{3}C_b & -\frac{\sqrt{2}}{3}C_b & -\sqrt{\frac{2}{3}}C_b & \sqrt{\frac{2}{3}}C_b' & \sqrt{2}C_b' & -\frac{\sqrt{2}}{3}g_2 & \sqrt{\frac{2}{3}}g_2 \\
-\frac{\sqrt{2}}{3}C_b & C_a - \frac{4}{3}C_b & \frac{2}{\sqrt{3}}C_b & -\frac{2}{\sqrt{3}}C_b' & C_b' & \frac{5}{6}g_2 & \frac{1}{2\sqrt{3}}g_2 \\
-\sqrt{\frac{2}{3}}C_b & \frac{2}{\sqrt{3}}C_b & C_a & C_b' & 0 & \frac{1}{2\sqrt{3}}g_2 & \frac{1}{2}g_2 \\
\sqrt{\frac{2}{3}}C_b' & -\frac{2}{\sqrt{3}}C_b' & C_b' & C_a' & 0 & \frac{1}{2}g_1 & \frac{\sqrt{3}}{2}g_1 \\
\sqrt{2}C_b' & C_b' & 0 & 0 & C_a' & \frac{\sqrt{3}}{2}g_1 & -\frac{1}{2}g_1 \\
-\frac{\sqrt{2}}{3}g_2 & \frac{5}{6}g_2 & \frac{1}{2\sqrt{3}}g_2 & \frac{1}{2}g_1 & \frac{\sqrt{3}}{2}g_1 & 0 & 0 \\
\sqrt{\frac{2}{3}}g_2 & \frac{1}{2\sqrt{3}}g_2 & \frac{1}{2}g_2 & \frac{\sqrt{3}}{2}g_1 & -\frac{1}{2}g_1 & 0 & 0
\end{pmatrix}$$

- Branching fractions

Scenario	A					
Molecule	$P_{\psi1}^N$	$P_{\psi2}^N$	$P_{\psi3}^N$	$P_{\psi4}^N$	$P_{\psi5}^N$	$P_{\psi6}^N$
Ours	7.11	1.44	8.21	0.09	1.77	4.82
ChUA [103]	1.82	8.62	0.13	0.83	0.04	2.36
Exp	0.96	-	3.55	1.70	-	-
Scenario	B					
Molecule	$P_{\psi1}^N$	$P_{\psi2}^N$	$P_{\psi3}^N$	$P_{\psi4}^N$	$P_{\psi5}^N$	$P_{\psi6}^N$
Ours	18.24	2.22	6.06	1.79	3.83	2.76
ChUA [103]	-	-	-	-	-	-
Exp	0.96	-	1.70	3.55	-	-

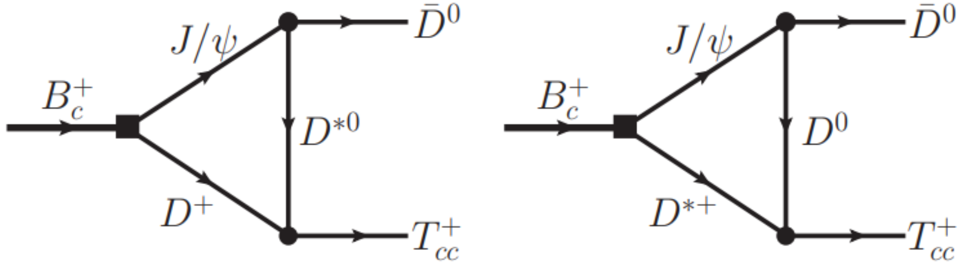
The order of magnitude of production rates can be explained

Pan et al., Phys.Rev.D 108 (2023) 11, 114022

Productions of T_{cc} in large facility

T_{cc}	CEPC (100 ab^{-1})	LHC (9 fb^{-1})	EIcC (60 fb^{-1})
Hadronic Molecule	$(2.3 \sim 9.7) \times 10^{-3}$ pb	$(4 \sim 6)$ nb	$(0.3 \sim 1.2) \times 10^{-3}$ pb
	$(2.3 \sim 9.7) \times 10^{5}$	$(4 \sim 6) \times 10^{7}$ (10^{2})	$18 \sim 72$
	Jia et al., 2405.02619	Hua et al 2310.04258	Shi et al., 2208.02639
Compact Traquark	$(3 \sim 9) \times 10^{-4}$ pb	$(17 \sim 38)$ nb	
	$(3 \sim 10) \times 10^{5}$	10^{8} (10^{2})	
	Qin et al., 2008.08026	Qin et al., 2008.08026	

$B_c \to T_{cc} D$	10^{-7}



Li et al., Eur. Phys. J. C 83 (2023) 3, 258

Decay modes	Cross sections	Events
$\sigma(pp \to B_c X)$	130 nb	10^2
$\sigma(e^+e^- \to Z \to B_c X)$	5 pb	10

The event number via the exclusive process are quite small

Outline

- Heavy flavor hadronic molecular candidates and their partners
- Decays of the heavy flavor hadronic molecules
- Productions of the heavy flavor hadronic molecules
- Summary and Outlook

Summary and outlook

- We propose to verify the molecular nature of T_{cc} and three P_c states discovered by LHCb Collaboration by searching for their relevant partners associated with symmetry.
  - The three-body and two-body decays of HQSS $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules are investigated, indicating that $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules decaying into $\bar{D}^{(*)}\Lambda_c\pi$ are so sizable that could be the good channels to experimentally search for pentaquark states. In particular, a state around 4.52 GeV discovered in the $\bar{D}\Lambda_c\pi$ mass distribution possibly correspond to one of HQSS partner of three P_c states.
  - The productions of HQSS $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules in Λ_b decay are investigated by the final state interaction, further revealing the production mechanism of pentaquark states in b-baryon decays.
  - The decay of T_{cb} as the $D\bar{B}$ bound state only proceeds via the weak interaction, which offers the chance to study the weak decay of hadronic molecules. In the molecular picture, we predicted the dominant decay channels of $D\bar{B}$ molecule.

- Reducing the uncertainty of constructing inelastic potentials and systematically estimating the production rates of these molecules is expected to give more valuable reference for experiments to search for possible heavy hadronic molecules.

Thanks for your attention!

Backup

$$\frac{N(B^-\to D^{*0}D_s^-)}{N(B^-\to D^{*0}\pi^-)} \sim \frac{N(B^-\to D^0D_s^-)}{N(B^-\to D^0\pi^-)}$$

$$N(B^- \to D^{*0}D_s^-) = N(B^- \to D^{*0}\pi^-)\frac{N(B^- \to D^0D_s^-)}{N(B^- \to D^0\pi^-)}$$

$N(B^- \to D^{*0}\pi^-)$ → 1.1×10^6 (2012.09903)

$N(B^- \to D^0D_s^-)$ → 5×10^3 (1302.5854)

$N(B^- \to D^0\pi^-)$ → 4×10^4 (1203.3662)

Backup

Process	Amplitude	Process	Amplitude
$\Lambda_b^0 \to P_p K^-$	T_1	$\Lambda_b^0 \to P_n \bar{K}^0$	T_1
$\Lambda_b^0 \to P_\Lambda \eta$	$\frac{1}{3}[(2T_1+T_2-2T_3)\cos\theta$ $+(2T_1+T_2-2T_3)\sin\theta]$	$\Lambda_b^0 \to P_\Lambda \eta'$	$\frac{1}{3}[-\sqrt{2}(T_1-T_2+2T_3)\cos\theta$ $+\sqrt{2}(T_1-T_2+2T_3)\sin\theta]$
$\Lambda_b^0 \to P_{\Sigma^+}\pi^-$	T_2	$\Lambda_b^0 \to P_{\Sigma^-}\pi^+$	T_2
$\Lambda_b^0 \to P_{\Xi^0} K^0$	T_2-T_3	$\Lambda_b^0 \to P_{\Xi^-} K^+$	T_2-T_3
$\Lambda_b^0 \to P_{\Sigma^0}\pi^0$	T_2	$\Lambda_b^0 \to P_\Lambda \pi^0$	0
$\Lambda_b^0 \to P_{\Sigma^0}\eta$	0	$\Lambda_b^0 \to P_{\Sigma^0}\eta'$	0
$\Xi_b^0 \to P_{\Sigma^+} K^-$	T_1-T_2	$\Xi_b^0 \to P_{\Sigma^0}\bar{K}^0$	$\frac{1}{\sqrt{2}}(-T_1+T_2)$
$\Xi_b^0 \to P_{\Xi^0}\eta$	$-\frac{1}{\sqrt{6}}(2T_1-2T_2+T_3)\cos\theta$ $-\frac{1}{\sqrt{6}}(2T_1-2T_2+T_3)\sin\theta$	$\Xi_b^0 \to P_{\Xi^0}\eta'$	$\frac{1}{\sqrt{3}}(T_1-T_2+2T_3)\cos\theta$ $-\frac{1}{\sqrt{3}}(T_1-T_2+2T_3)\sin\theta$
$\Xi_b^0 \to P_{\Xi^-}\pi^+$	$-T_3$	$\Xi_b^0 \to P_{\Xi^0}\pi^0$	$\frac{1}{\sqrt{2}}T_3$
$\Xi_b^0 \to P_\Lambda \bar{K}^0$	$\frac{1}{\sqrt{6}}(T_1-T_2+2T_3)$		
$\Xi_b^- \to P_{\Sigma^-}\bar{K}^0$	T_1-T_2	$\Xi_b^- \to P_{\Sigma^0} K^-$	$\frac{1}{\sqrt{2}}(T_1-T_2)$
$\Xi_b^- \to P_{\Xi^-}\pi^0$	$-\frac{1}{\sqrt{2}}T_3$	$\Xi_b^- \to P_{\Xi^0}\pi^-$	$-T_3$
$\Xi_b^- \to P_{\Xi^-}\eta$	$-\frac{1}{\sqrt{6}}(2T_1-2T_2+T_3)\cos\theta$ $-\frac{1}{\sqrt{3}}(T_1-T_2+2T_3)\sin\theta$	$\Xi_b^- \to P_{\Xi^-}\eta'$	$\frac{1}{\sqrt{3}}(T_1-T_2+2T_3)\cos\theta$ $-\frac{1}{\sqrt{6}}(2T_1-2T_2+T_3)\sin\theta$
$\Xi_b^- \to P_\Lambda K^-$	$\frac{1}{\sqrt{6}}(T_1-T_2+2T_3)$		
$\Omega_b^- \to P_{\Xi^-}\bar{K}^0$	t_1-t_3	$\Omega_b^- \to P_{\Xi^0} K^-$	$-t_1+t_3$

Backup

Process	Amplitude	Process	Amplitude
$\Lambda_b^0 \to P_p \pi^-$	$T_1' - T_2'$	$\Lambda_b^0 \to P_n \pi^0$	$-\frac{1}{\sqrt{2}}(T_1' - T_2')$
$\Lambda_b^0 \to P_{\Sigma^0} K^0$	$\frac{1}{\sqrt{2}} T_3'$	$\Lambda_b^0 \to P_{\Sigma^-} K^+$	$-T_3'$
$\Lambda_b^0 \to P_n \eta$	$(\frac{\cos\theta}{\sqrt{6}} - \frac{\sin\theta}{\sqrt{3}})(T_1' - T_2' + 2T_3')$	$\Lambda_b^0 \to P_n \eta'$	$(\frac{\cos\theta}{\sqrt{3}} + \frac{\sin\theta}{\sqrt{6}})(T_1' - T_2' + 2T_3')$
$\Lambda_b^0 \to P_\Lambda K^0$	$-\frac{1}{\sqrt{6}}(2T_1' - 2T_2' + T_3')$		
$\Xi_b^0 \to P_{\Sigma^+} \pi^-$	T_1'	$\Xi_b^0 \to P_{\Sigma^0} \pi^0$	$\frac{1}{2}(T_1' + T_2' - T_3')$
$\Xi_b^0 \to P_{\Xi^0} K^0$	$T_1{}'$	$\Xi_b^0 \to P_{\Xi^-} K^+$	T_2'
$\Xi_b^0 \to P_\Lambda \eta$	$\frac{1}{6}\cos\theta(T_1' + 5T_2' - T_3')$ $-\frac{1}{3\sqrt{2}}\sin\theta(T_1' - T_2' + 2T_3')$	$\Xi_b^0 \to P_\Lambda \eta'$	$\frac{1}{3\sqrt{2}}\cos\theta(T_1' - T_2' + 2T_3')$ $+\frac{1}{6}\sin\theta(T_1' + 5T_2' - T_3')$
$\Xi_b^0 \to P_{\Sigma^0} \eta$	$\frac{1}{2\sqrt{3}}\cos\theta(-T_1' + T_2' + T_3')$ $+\frac{1}{\sqrt{6}}\sin\theta(T_1' - T_2' + 2T_3')$	$\Xi_b^0 \to P_{\Sigma^0} \eta'$	$-\frac{1}{\sqrt{6}}\cos\theta(T_1' - T_2' + 2T_3') \frac{1}{2\sqrt{3}}\sin\theta(-T_1' + T_2' + T_3')$
$\Xi_b^0 \to P_p K^-$	T_2'	$\Xi_b^0 \to P_n \bar{K}^0$	$T_2' - T_3'$
$\Xi_b^0 \to P_{\Sigma^-} \pi^+$	$T_2' - T_3'$	$\Xi_b^0 \to P_\Lambda \pi^0$	$\frac{1}{2\sqrt{3}}(-T_1' + T_2' + T_3')$
$\Xi_b^- \to P_{\Xi^-} K^0$	$T_1' - T_2'$	$\Xi_b^- \to P_n K^-$	$-T_3'$
$\Xi_b^- \to P_{\Sigma^-} \eta$	$\frac{1}{\sqrt{6}}\cos\theta(T_1' - T_2' - T_3')$ $-\frac{1}{\sqrt{3}}\sin\theta(T_1' - T_2' + 2T_3')$	$\Xi_b^- \to P_{\Sigma^-} \eta'$	$\frac{1}{\sqrt{3}}\cos\theta(T_1' - T_2' + 2T_3')$ $+\frac{1}{\sqrt{6}}\sin\theta(T_1' - T_2' - T_3')$
$\Xi_b^- \to P_{\Sigma^-} \pi^0$	$-\frac{1}{\sqrt{2}}(T_1' - T_2' + T_3')$	$\Xi_b^- \to P_{\Sigma^0} \pi^-$	$\frac{1}{\sqrt{2}}(T_1' - T_2' + T_3')$
$\Xi_b^- \to P_\Lambda \pi^-$	$\frac{1}{\sqrt{6}}(T_1' - T_2' - T_3')$		
$\Omega_b^- \to P_{\Xi^-} \pi^0$	$-\frac{1}{\sqrt{2}} t_1'$	$\Omega_b^- \to P_{\Xi^0} \pi^-$	$-t_1'$
$\Omega_b^- \to P_{\Xi^-} \eta$	$\frac{1}{\sqrt{6}}\cos\theta(t_1' - 2t_2') - \frac{1}{\sqrt{3}}\sin\theta(t_1' + t_2')$	$\Omega_b^- \to P_{\Xi^-} \eta'$	$\frac{1}{\sqrt{3}}\cos\theta(t_1' + t_2') + \frac{1}{\sqrt{6}}\sin\theta(t_1' - 2t_2')$
$\Omega_b^- \to P_{\Sigma^-} \bar{K}^0$	$t_2' - t_3'$	$\Omega_b^- \to P_{\Sigma^0} K^-$	$\frac{1}{\sqrt{2}}(t_2' - t_3')$
$\Omega_b^- \to P_\Lambda K^-$	$\frac{1}{\sqrt{6}}(t_2' + t_3')$		

Radiative decays of P_c

IV $bb\bar{u}\bar{d}$ DECAY MODES AND LIFETIME

We focus on the decay of the $bb\bar{u}\bar{d}$ tetraquark which is deeply bound, unlike $cc\bar{u}\bar{d}$ and $bc\bar{u}\bar{d}$ which are, respectively, above and close to their relevant thresholds.

A crude estimate of the lifetime can be obtained similarly to Ref. [2]. We assume an initial state with mass 10,389.4 MeV, a final state with $M(\bar{B}) + M(D) = 7,144.5$ MeV, a charged weak current giving rise to $e\bar{\nu}_e$, $\mu\bar{\nu}_\mu$, $\tau\bar{\nu}_\tau$ and three colors of $\bar{u}d$ and $\bar{c}s$, a kinematic suppression factor

$$F(x) = 1 - 8x + 8x^3 - x^4 + 12x^2 \ln(1/x) \ , \quad x \equiv \{[M(\bar{B}) + M(D)]/M(bb\bar{u}\bar{d})\}^2, \qquad (1)$$

a value of $|V_{cb}| = 0.04$ as in Ref. [2], and a factor of 2 to count each decaying b quark. The resulting decay rate is

$$\Gamma(bb\bar{u}\bar{d}) = \frac{18\ G_F^2 M(bb\bar{u}\bar{d})^5}{192\pi^3} F(x)|V_{cb}|^2 = 17.9 \times 10^{-13}\ \text{GeV} \ , \qquad (2)$$

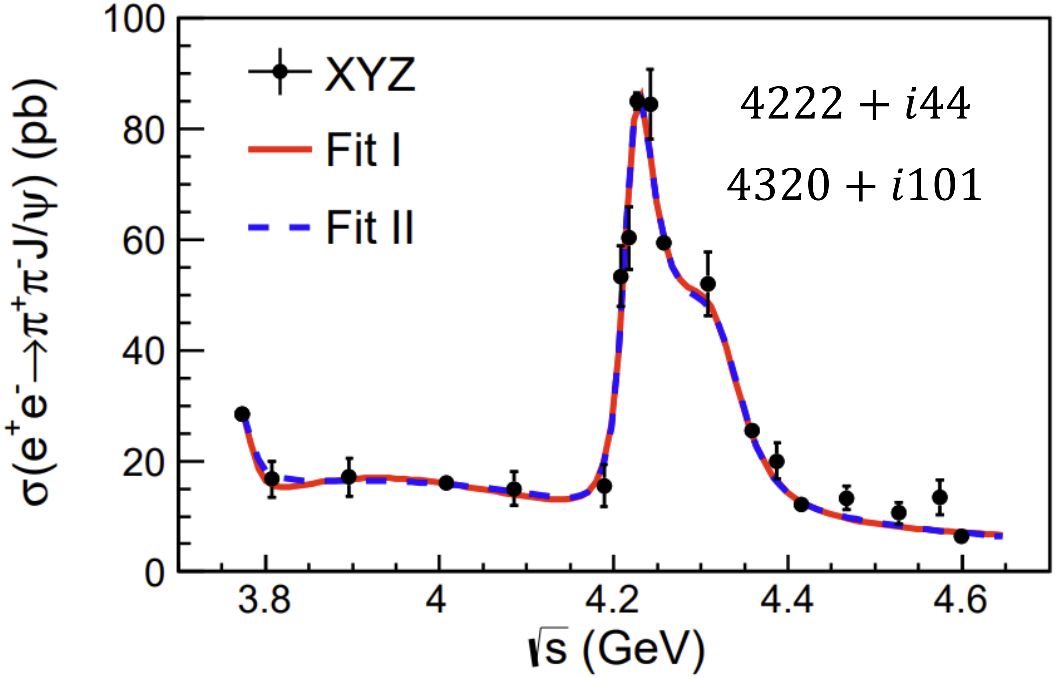
leading to a predicted lifetime $\tau(bb\bar{u}\bar{d}) = 367$ fs.

The $bb\bar{u}\bar{d}$ decay can occur through one of two channels:

PhysRevLett.119.202001

Backup

➢ Vector charmonium-like states



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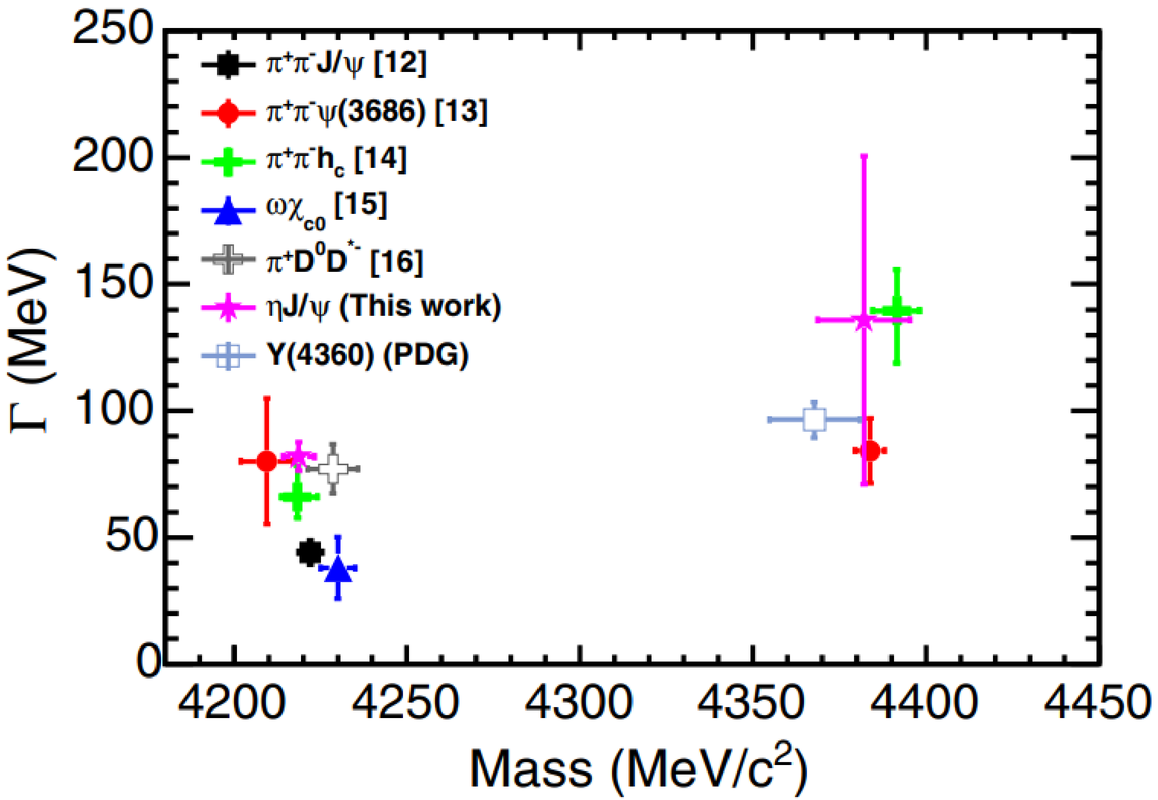

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$$Y(4260) \rightarrow \begin{cases} Y(4230) \\ Y(4360) \end{cases}$$

Fine structure!