第九届手征有效场论研讨会@湖南大学

# Productions and decays of the hidden charm pentaquark molecules

**Reporter:** Ming-Zhu Liu (刘明珠)

**Collaborators:** Li-Sheng Geng (耿立升)
Ya-Wen Pan(潘亚文)

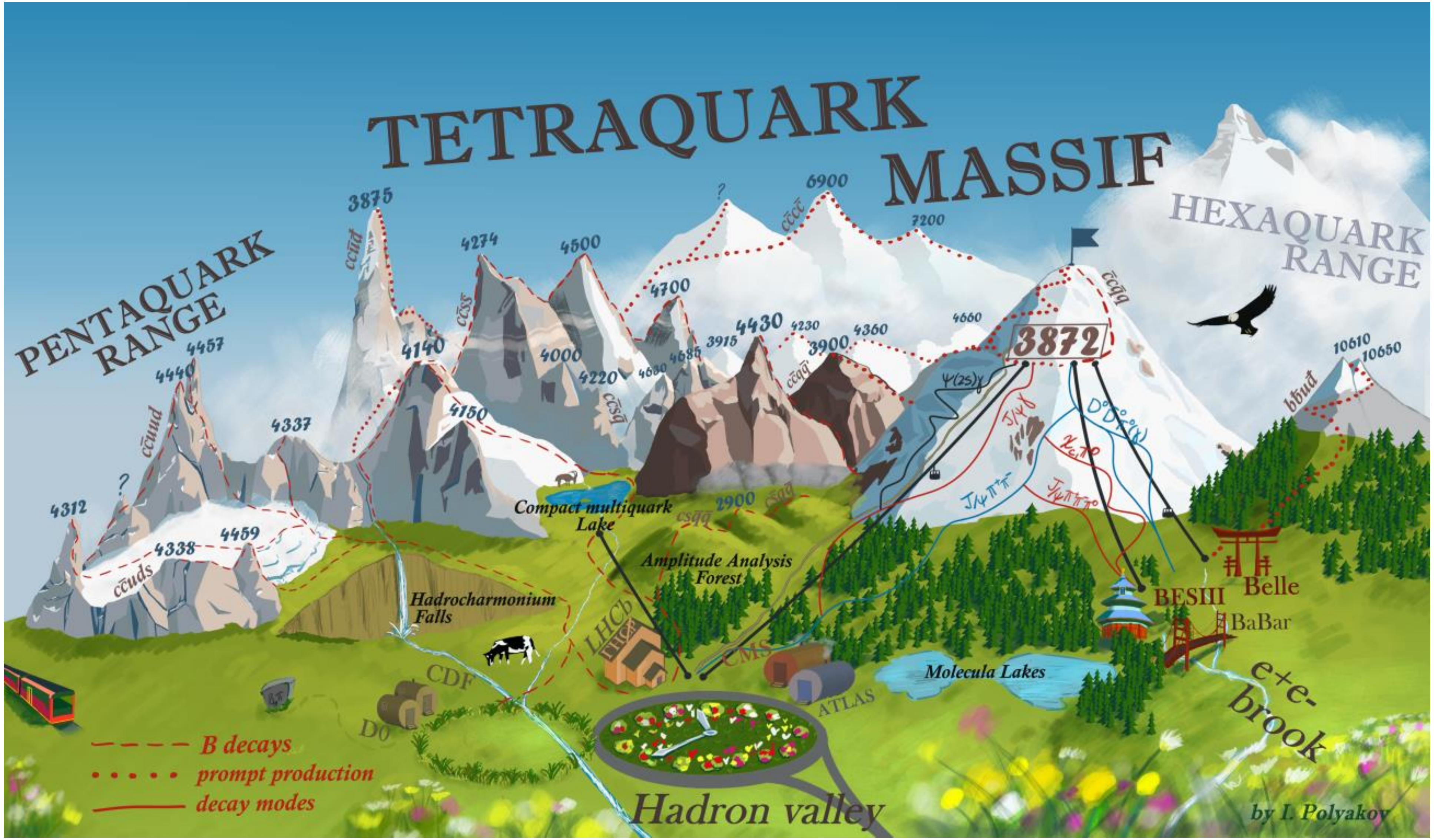
**Based on:** Phys. Rev. D **108** (2023) 114022
arXiv: 2407.17318

2024-10-20

# Outline

- Hidden charm pentaquark molecules and their partners
- Decays of the hidden charm pentaquark molecules
- Productions of the hidden charm pentaquark molecules
- Summary and Outlook

# Exotic states




ArXiv: 2410.06923

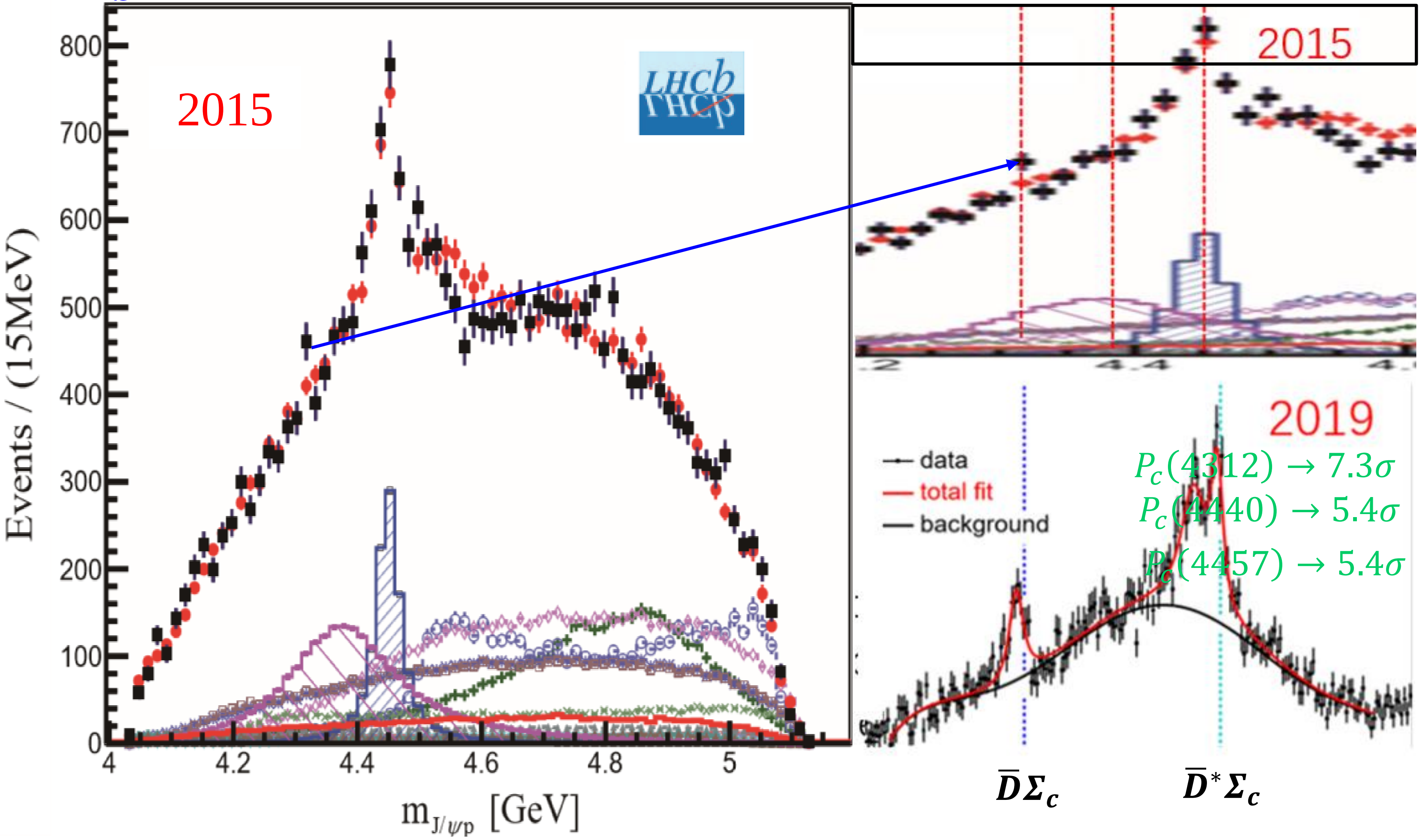
➢ **Rich Information**

- **Mass and Width**
- **Production**
- **Interpretation**
- **Collaboration**

➢ **Pentaquark**

# 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**

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

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

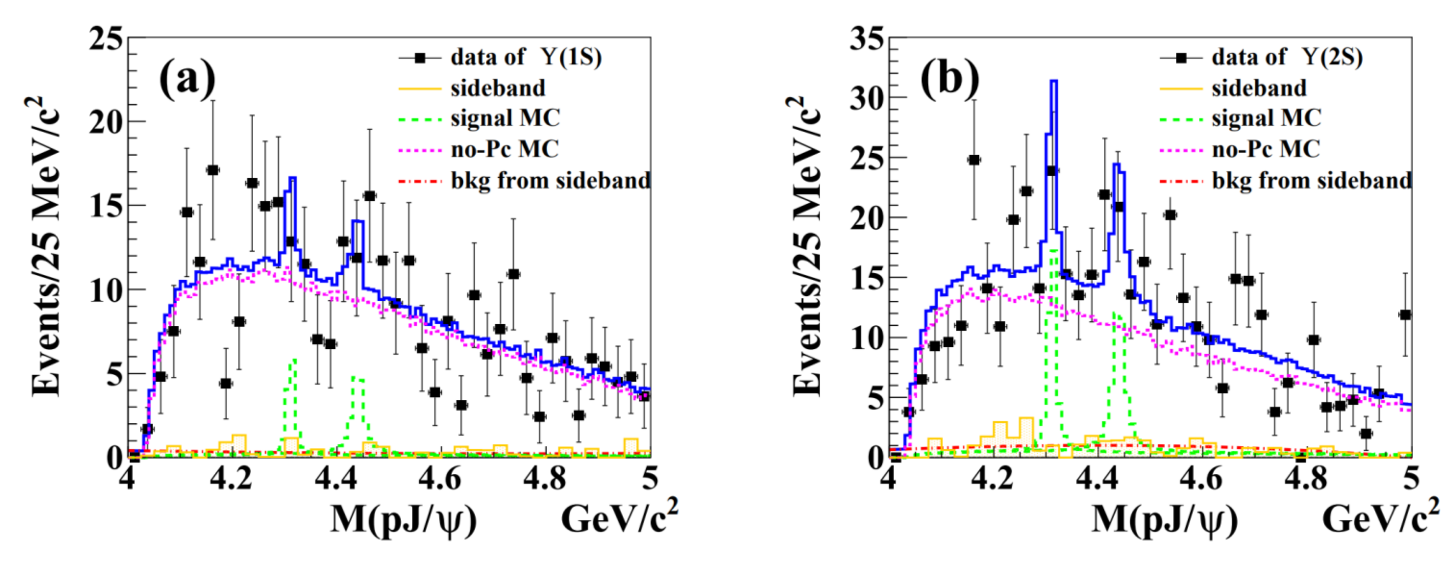
**2019**

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

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

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

# Hidden charm pentaquark states in recent experiments




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

Belle Collaboration, arXiv: 2403.04340

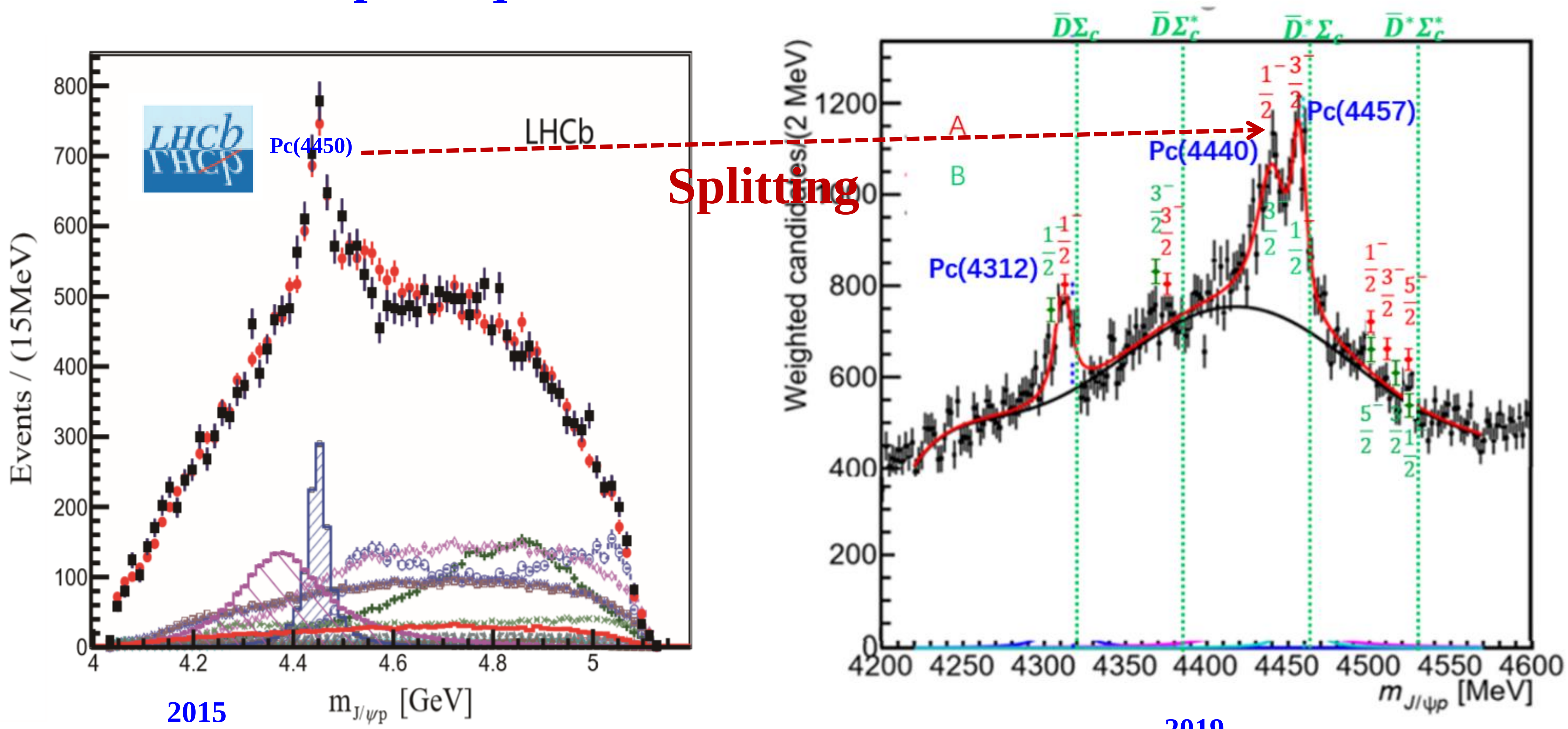
| Decay Mode | Pentaquark Hypothesis | $p$-value | Significance ($\sigma$) | Signal Yield | Upper Limit ($\times10^{-3}$) (90% CL) | (95% CL) |
|---|---|---|---|---|---|---|
| $\Lambda_c^+\overline{D}^0$ | $P_c(4312)^+$ | 0.32 | 0.48 | $19.78 \pm 22.27$ | 1.17 | 1.29 |
| | $P_c(4440)^+$ | 0.44 | 0.15 | $26.91 \pm 28.17$ | 1.41 | 1.53 |
| | $P_c(4457)^+$ | 0.53 | 0.00 | $6.20 \pm 13.60$ | 1.27 | 1.43 |
| $\Lambda_c^+\pi^+D^{*-}$ | $P_c(4440)^+$ | 1.00 | 0.00 | $0.00 \pm 0.96$ | 0.72 | 0.91 |
| | $P_c(4457)^+$ | 1.00 | 0.00 | $0.00 \pm 1.73$ | 0.77 | 0.97 |
| $\Lambda_c^+\pi^-D^{*-}$ | $P_c(4440)^+$ | 1.00 | 0.00 | $0.00 \pm 0.80$ | 0.63 | 0.80 |
| | $P_c(4457)^+$ | 1.00 | 0.00 | $0.00 \pm 0.74$ | 0.59 | 0.74 |
| $\Lambda_c^+\pi^+D^-$ | $P_c(4312)^+$ | 1.00 | 0.00 | $0.00 \pm 1.56$ | 0.69 | 0.88 |
| | $P_c(4440)^+$ | 0.65 | 0.00 | $4.43 \pm 11.67$ | 3.71 | 4.24 |
| | $P_c(4457)^+$ | 0.65 | 0.00 | $5.94 \pm 12.68$ | 3.13 | 3.61 |
| $\Lambda_c^+\pi^-D^-$ | $P_c(4312)^+$ | 1.00 | 0.00 | $0.00 \pm 1.42$ | 0.67 | 0.86 |
| | $P_c(4440)^+$ | 0.53 | 0.00 | $12.52 \pm 15.89$ | 3.91 | 4.37 |
| | $P_c(4457)^+$ | 0.53 | 0.00 | $8.60 \pm 12.22$ | 3.10 | 3.51 |

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

LHCb Collaboration,
Phys.Rev.D 110 (2024) 032001

# Fine structures of exotic states

➤ **Hidden charm pentaquark states**



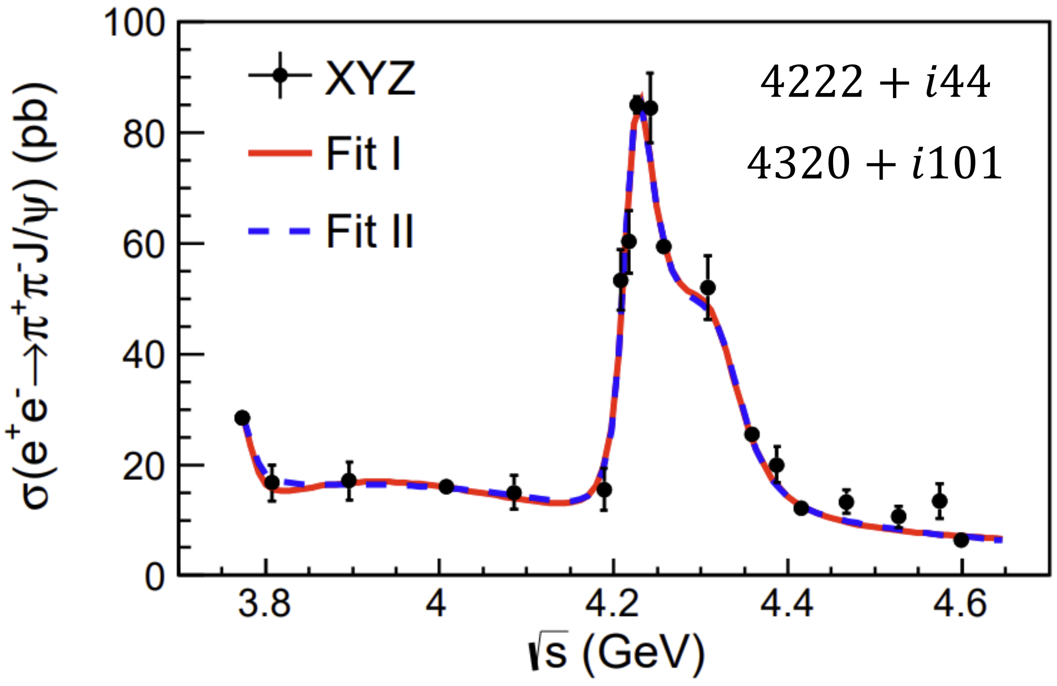

2015

2019

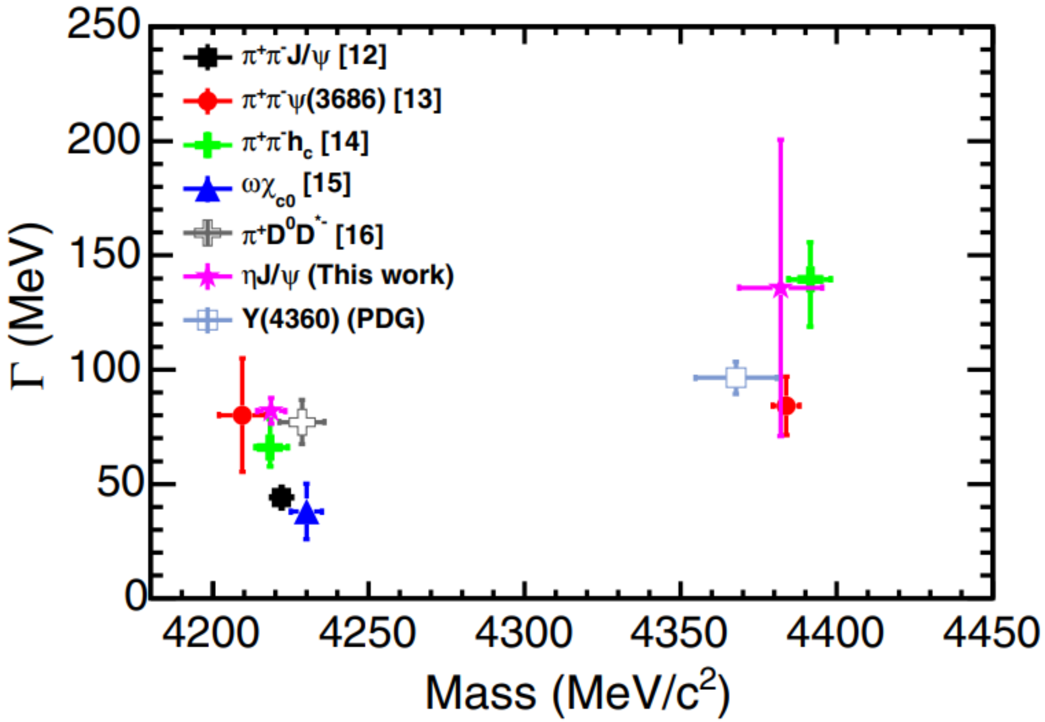
**Fine structure!**

# Fine structures of exotic states

## ➢ Vector charmonium-like states




BESIII Collaboration, Phys.Rev.Lett. 118 (2017) 092001




BESIII Collaboration, Phys.Rev.D 102 (2020) 031101

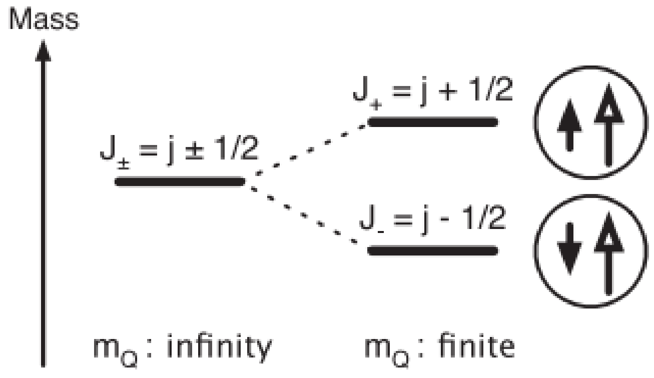
$Y(4260) \rightarrow \begin{cases} Y(4230) \\ Y(4360) \end{cases}$

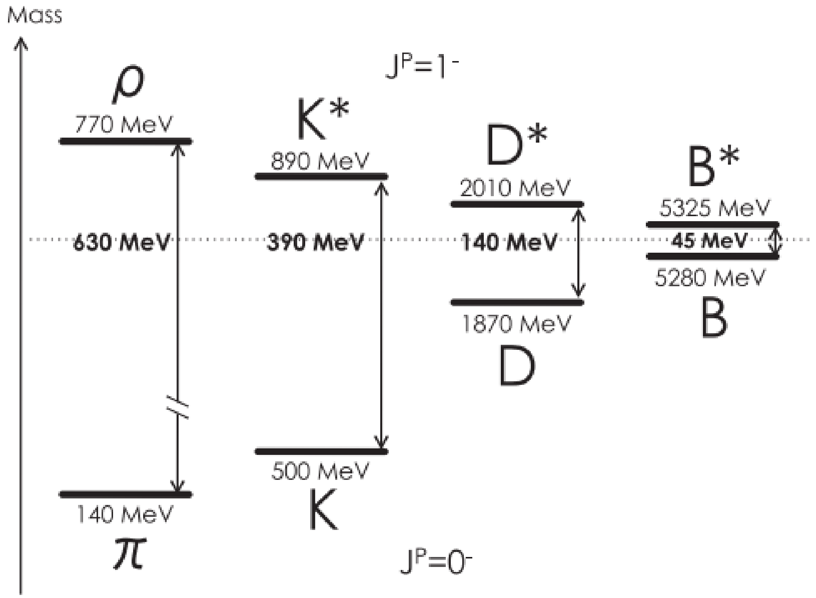
**Fine structure!**

# Heavy quark spin symmetry(HQSS)

QCD interaction can not flip the spin of heavy quark

- **Spin doublet**



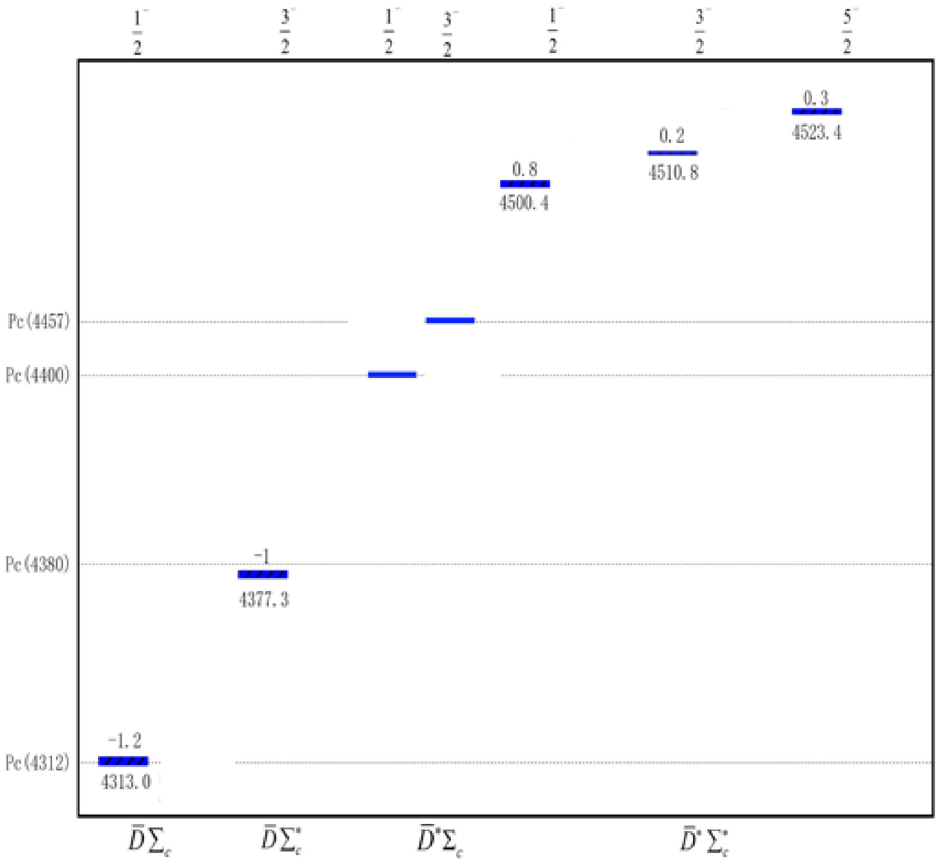




Lagrangian $L = C_a Tr[H_c^\dagger H_c] S_c^\dagger \cdot S_c + C_b Tr[H_c^\dagger \sigma H_c] S_c^\dagger \cdot (J_i S_c)$

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

The number of low energy constants decreases within HQSS

# HQSS multiplet hadronic molecules




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

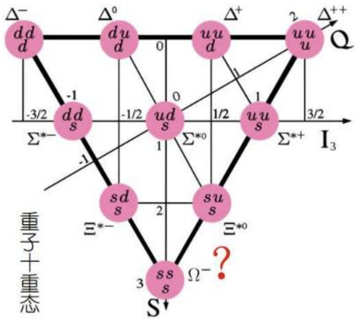
Fine structure of hadronic molecules

| 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 |

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

# What should we do next?

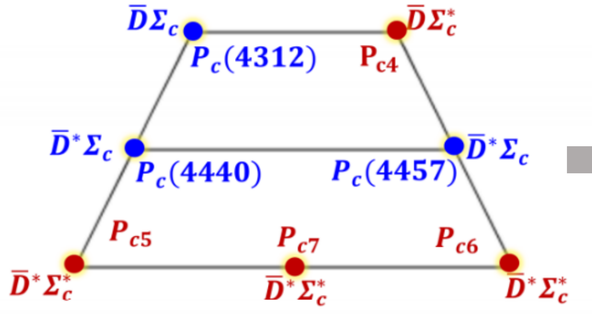
## ➢ How to verify the molecular nature of pentaquark states




SU(3)-flavor

symmetry

Ω




HQSS

Partners

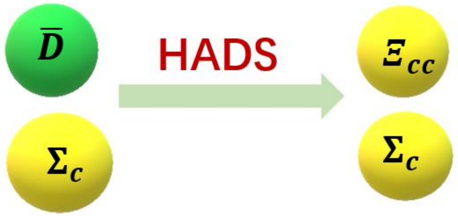
?

**Where(decay modes) and How(production modes) to search for these partners?**

## ➢ Spin order of Pc(4440) and Pc(4457)

- **Scenario A**
  - **Machine Learning** — Zhang et al., Sci.Bull. 68 (2023) 981-989
  - **ChUPT** — Xiao et al., Phys.Rev.D 100 (2019) 014021
  - **OBE** — Chen et al., Phys.Rev.D 100 (2019) 011502
- **Scenario B**
  - **Pionful EFT** — Du et al., Phys.Rev.Lett. 124 (2020) 072001
  - **OBE Remove Delta** — Liu et al., Phys.Rev.D 103 (2021) 054004
- **Mass splitting of $\Xi_{cc}\Sigma_c$ system** **Lattice QCD**

**Effective physical observable** Pan et al., Phys.Rev.D 102 (2020) 011504




$1^+ - 0^+ = -8\ MeV$ $\quad$ $1^+ - 0^+ = 10\ MeV$

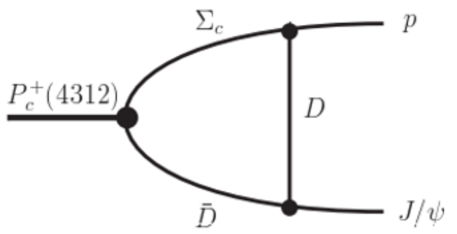
$\Delta_m < 0$ $\quad$ $\Delta_m > 0$

# 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

# Two-body decay of hadronic molecule

## ➢ Charmed Meson Exchange




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

Triangle diagrams → $\Gamma_{P_c} = \frac{1}{2J+1}\frac{1}{8\pi}\frac{|\vec{p}|^2}{m_0^2}\overline{|\mathcal{M}|^2}$

Scatterring equation → $T = \frac{V}{1-VG}$

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

## ➢ EFT within HQSS

**J = 3/2** $\bar{D}^*\Sigma_c^* - \bar{D}^*\Sigma_c - \bar{D}\Sigma_c^* - \bar{D}^*\Lambda_c - J/\psi N$

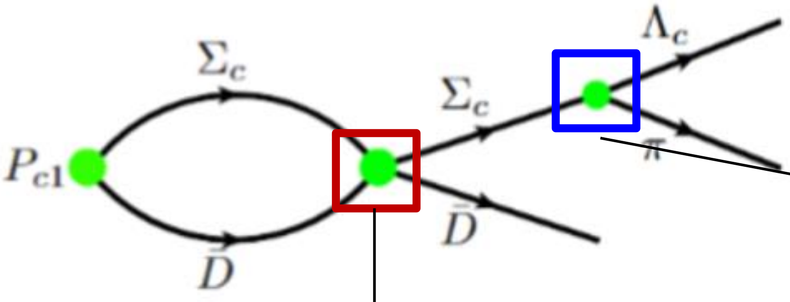
$$\begin{pmatrix} C_a - \frac{2}{3}C_b & -\frac{\sqrt{5}}{3}C_b & \sqrt{\frac{5}{3}}C_b & \sqrt{\frac{5}{3}}C_b' & \frac{\sqrt{5}}{3}g_2 \\ -\frac{\sqrt{5}}{3}C_b & C_a + \frac{2}{3}C_b & \frac{1}{\sqrt{3}}C_b & \frac{1}{\sqrt{3}}C_b' & -\frac{1}{3}g_2 \\ \sqrt{\frac{5}{3}}C_b & \frac{1}{\sqrt{3}}C_b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

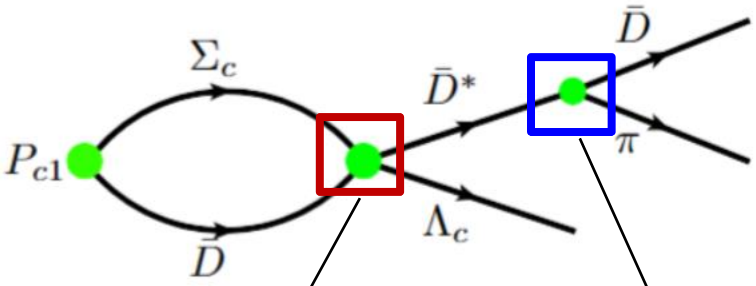
**J = 1/2** $\bar{D}^*\Sigma_c^* - \bar{D}^*\Sigma_c - \bar{D}\Sigma_c - \bar{D}^*\Lambda_c - \bar{D}\Lambda_c - J/\psi N - \eta_c N$

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

# Three-body decay of hadronic molecule

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




**Elastic scattering**

**Inelastic scattering**

**On shell or off-shell hadron decays**

- **Final decay modes of $P_c$**

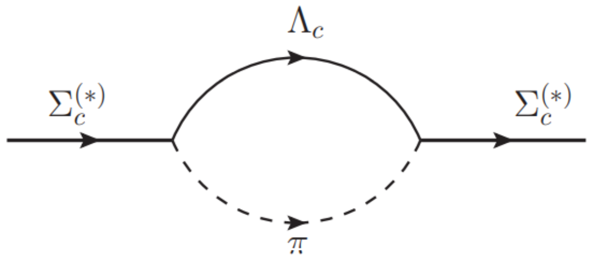
**Two-body partial decays**

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

**Three-body partial decays**

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

- **EFT with three-body cut dynamics**




Du et al., JHEP 08 (2021) 157

# Partial decay widths of hadronic molecules

A

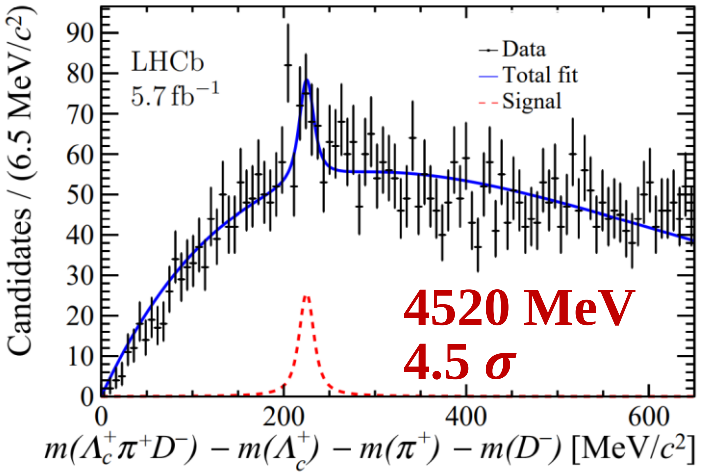
| Mode | $D^-\Lambda_c^+\pi^+$ | $\bar{D}^0\Lambda_c^+\pi^0$ | $D^{*-}\Lambda_c^+\pi^+$ | $\bar{D}^{*0}\Lambda_c^+\pi^0$ | $\bar{D}\Lambda_c$ | $J/\psi N$ | $\eta_c N$ | Total |
|---|---|---|---|---|---|---|---|---|
| $P_{c1}[P_\psi(4312)^N]$ | 0.036 | 0.812 | - | - | 0.004 | 2.014 | 3.917 | 6.783 |
| $P_{c2}$ | 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

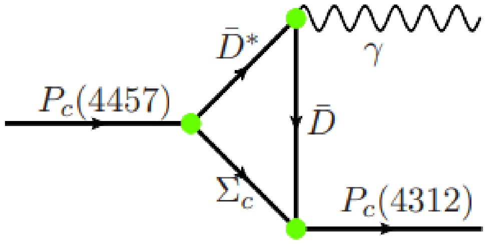
- $Br(P_c(4312) \to \bar{D}\Lambda_c\pi) = 13\sim25\%$
  $Br(P_c(4312) \to \bar{D}^*\Lambda_c\pi) = 0$
- $Br(P_c(4440) \to \bar{D}\Lambda_c\pi) = 13\sim43\%$
  $Br(P_c(4440) \to \bar{D}^*\Lambda_c\pi) = 0.2\sim0.9\%$
- $Br(P_c(4457) \to \bar{D}\Lambda_c\pi) = 27\sim28\%$
  $Br(P_c(4457) \to \bar{D}^*\Lambda_c\pi)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

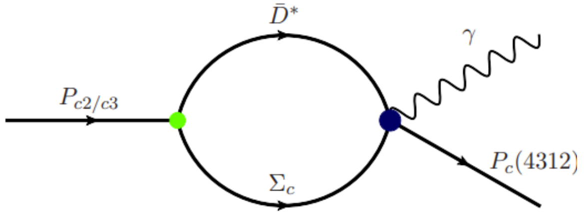



LHCb Collaboration, Phys.Rev.D 110 (2024) 032001

# Radiative and pionic decay of hadronic molecules

## ➢ Keep gauge invariance of radiative decays

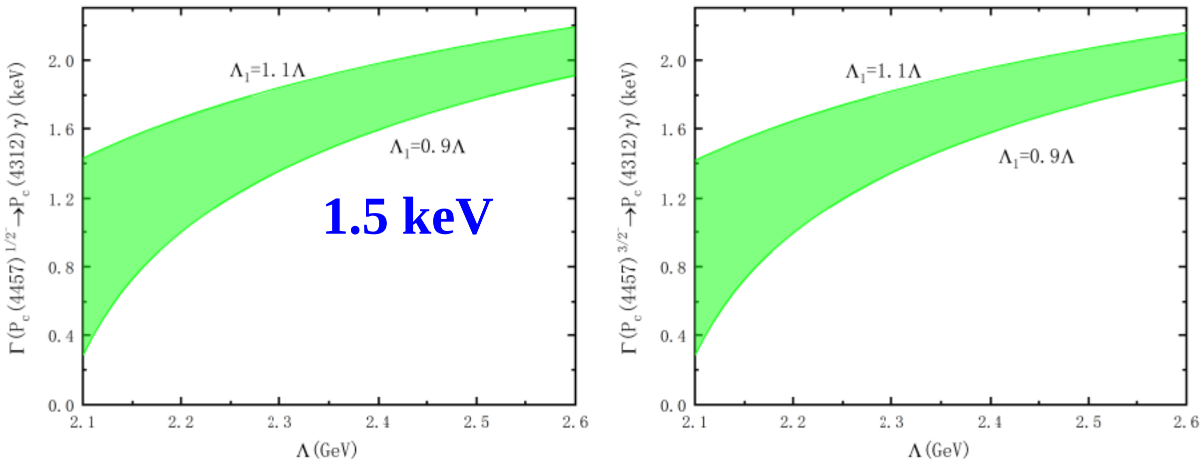



$$\mathcal{M}^{Tri}_{1/2} = \varepsilon_\mu(p_2)\bar{u}(p_1)(g_1^{Tri1/2}\gamma^\mu + g_2^{Tri1/2}\frac{p_1^\mu \not{p}_2}{p_1 \cdot p_2})u(k_0)$$

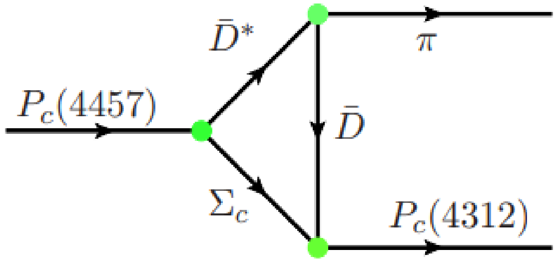
$$\mathcal{M}^{Tri}_{3/2} = \varepsilon_\mu(p_2)\bar{u}(p_1)(g_1^{Tri3/2}\gamma^\mu p_2^\nu - g_2^{Tri3/2}\not{p}_2 g^{\mu\nu})u_\nu(k_0)$$

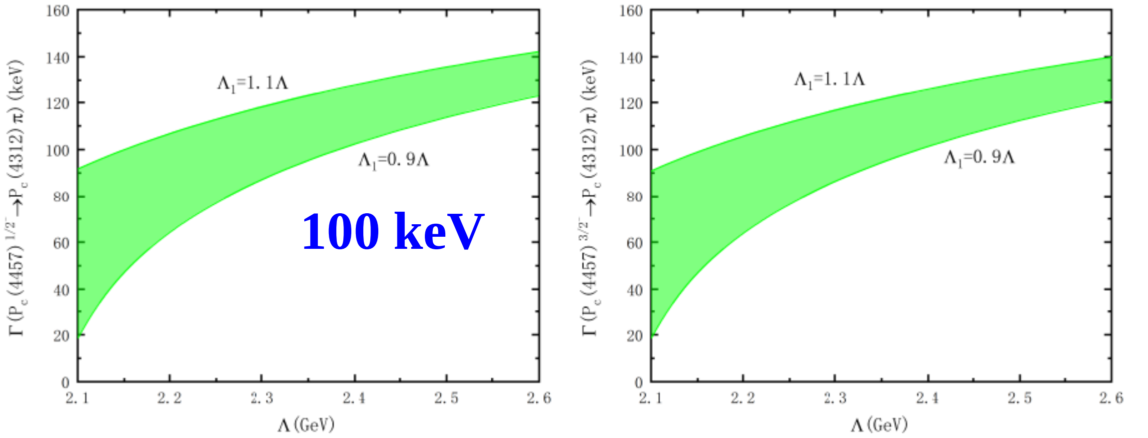
Ling et al., Phys.Rev.D 104 (2021) 074022



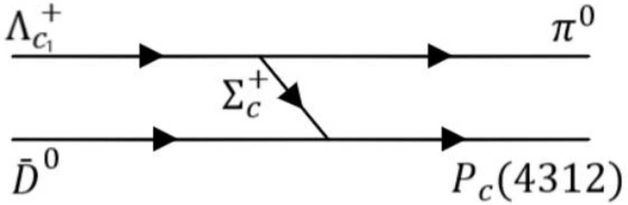

**1.7 keV** → **OBE** Li et al., Phys.Rev.D 104 (2021) 054016

## ➢ Pionic decays of hadronic molecules




**Different parity** **11 MeV**




Wu et al., Chin.Phys.Lett. 41 (2024) 091201

# 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

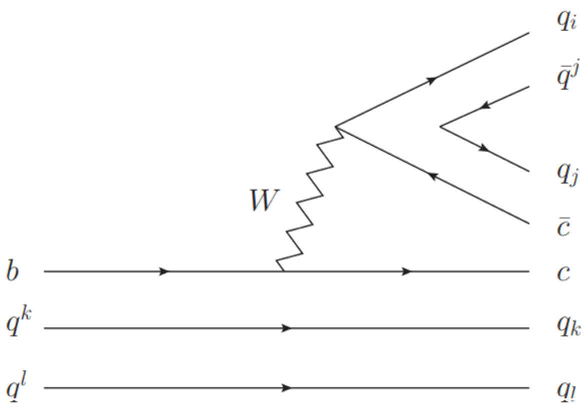
# Productions of pentaquark states in large facility

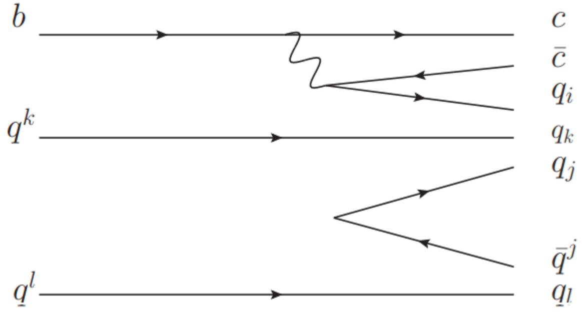
| states | EIcC (60 $fb^{-1}$) | CEPC (100 $ab^{-1}$) | LHC (9 $fb^{-1}$) |
|---|---|---|---|
| $P_c(4312)$ | $(0.02\sim0.08)$ pb | $(0.002\sim0.01)$ pb | $(3\sim9)$ nb |
| | $1200\sim4800$ | $(0.2\sim1)\times10^6$ | $(3\sim8)\times10^7$ |
| $P_c(4440)$ | $(0.01\sim0.06)$ pb | $(0.002\sim0.01)$ pb | $(1\sim5)$ 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




$$\mathcal{B}_a H^i \Pi_i^j \bar{\mathcal{P}}_j^a (T_1 - T_2) + \mathcal{B}_a H^a \Pi_i^j \bar{\mathcal{P}}_j^i T_2$$

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

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

$$\frac{Br(\Lambda_b \to P_c(4380)\pi^-)}{Br(\Lambda_b \to P_c(4380)K^-)} = 0.050 \pm 0.016^{+0.026}_{-0.016} \pm 0.025$$

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

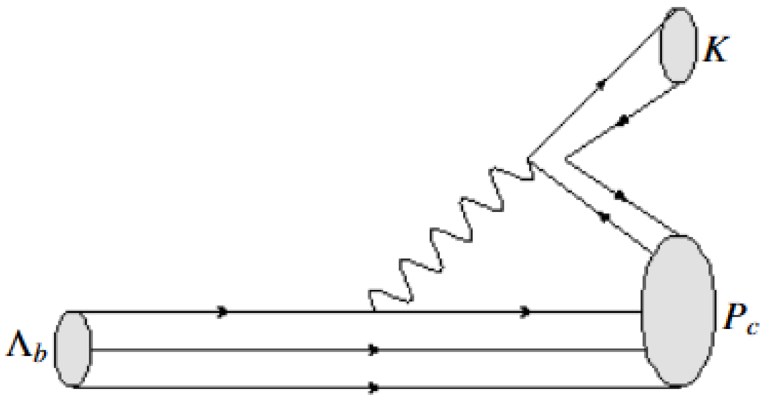
} Consistent

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

## ➢ Predicting pentaquark states with strange quark

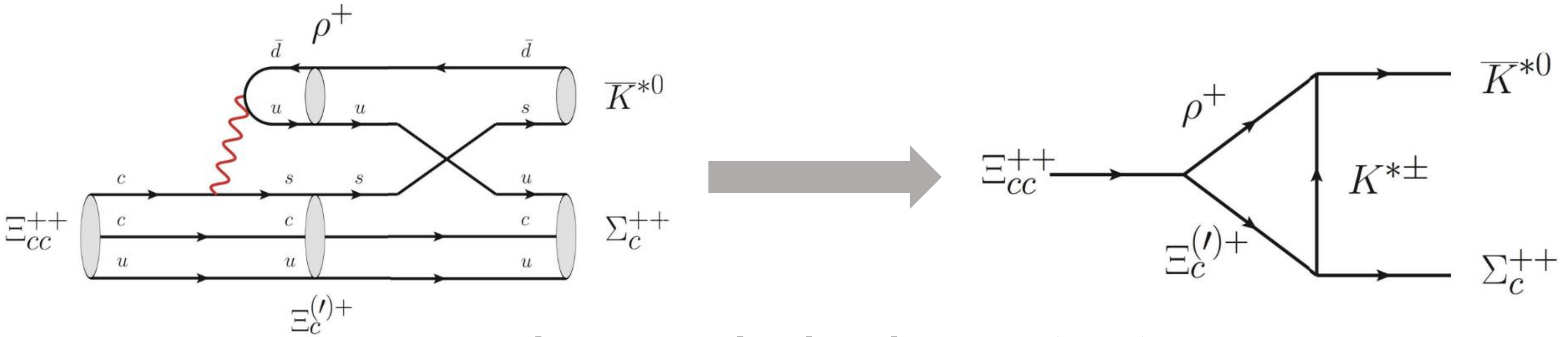
| | |
|---|---|
| $\Lambda_b^0 \to P_p K^-$ | $T_1$ |
| $\Lambda_b^0 \to P_p \pi^-$ | $t_1 - t_2$ |
| $\Xi_b^0 \to P_{\Sigma^+} K^-$ | $T_1 - T_2$ |
| $\Omega_b^- \to P_{\Xi^-} \bar{K}^0$ | $t_1 - t_3$ |

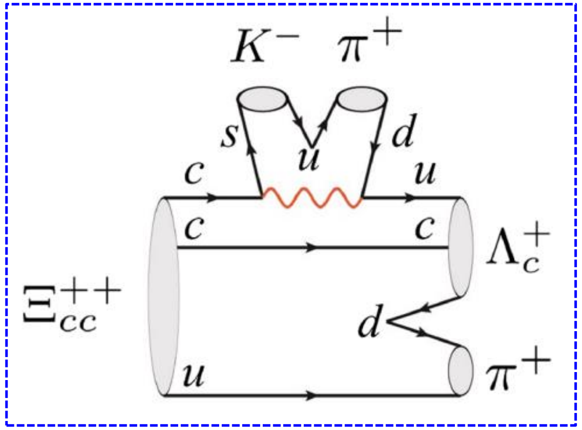
S=-1 and S=-2 hidden charm pentaquark are likely to be observed in these processes



# Final states interaction

## ➢ Predicting the dominant decay channels of $\Xi_{cc}^{++}$



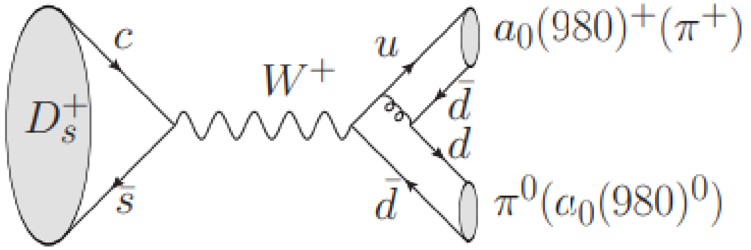



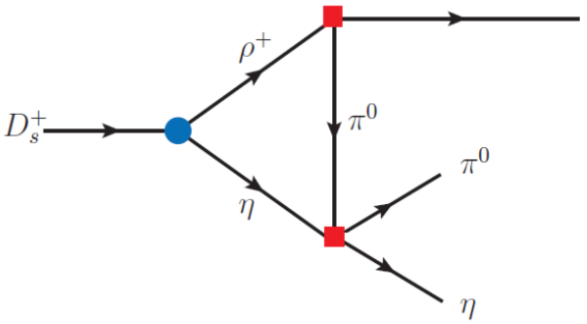

Fu-Sheng Yu et al., Chin.Phys.C 42 (2018) 051001

## ➢ 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) 112001



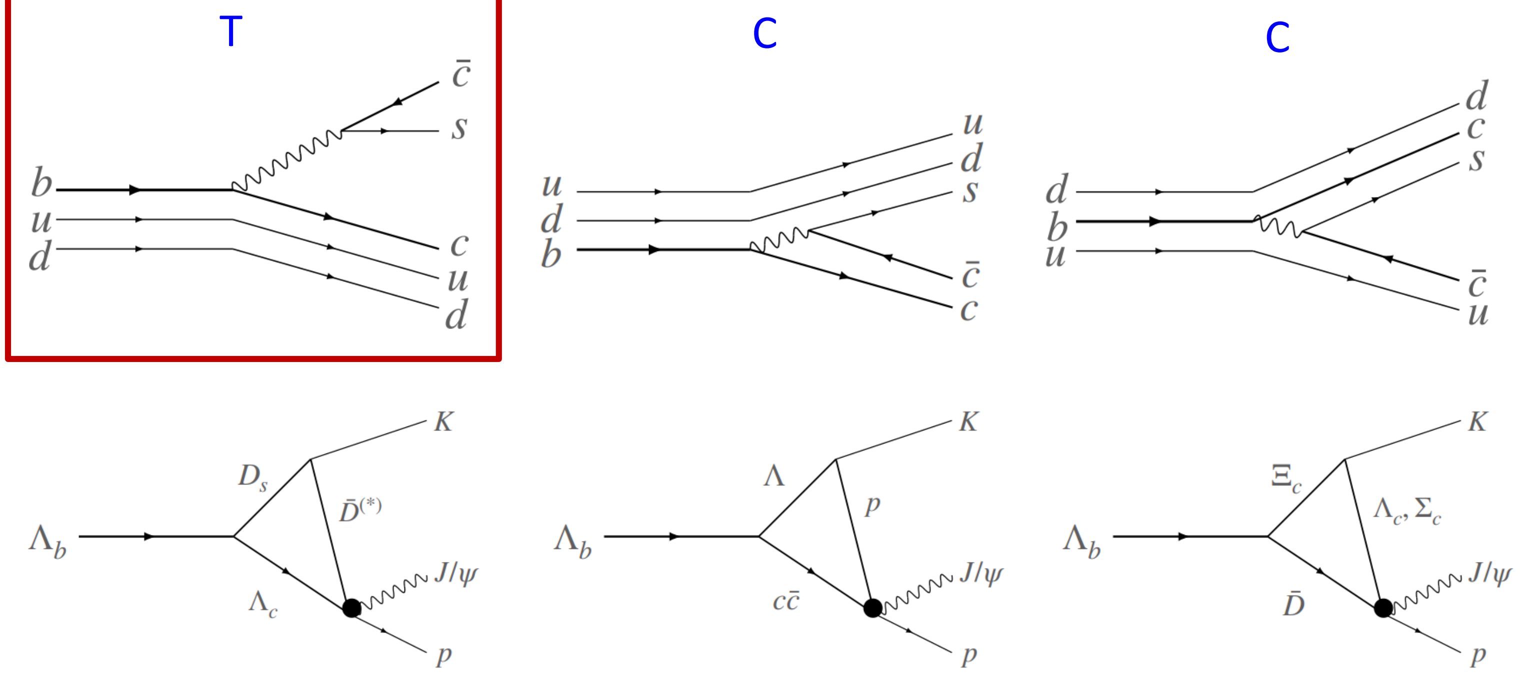

$\pi^+$

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

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

# Productions of pentaquark states in b-hadron decays

## ➢ Weak decays at quark level



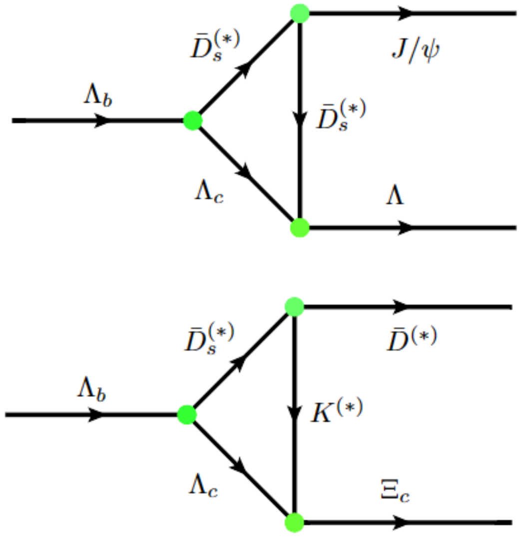

T. J. Burns et al., Eur.Phys.J.A 58 (2022) 68

- **Color Suppressed**

$$\frac{|C|}{|T|} \sim \mathcal{O}\left(\frac{\Lambda^h_{QCD}}{m_Q}\right)$$

| | |
|---|---|
| 1 | Charm |
| 0.2 | Bottom |

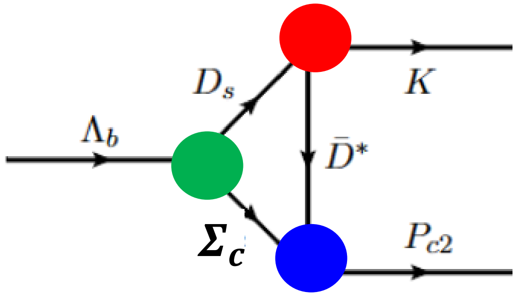
- **Double Counting**




## ➢ Select the vertices of weak decays

$\Lambda_b \to \Lambda_c D_s^{(*)}$ ⟷ $\Lambda_c \to \Lambda\, K^{(*)}$

$\Lambda_b \to \Sigma_c D_s^{(*)}$ ⟷ $\Lambda_c \to \Sigma\, K^{(*)}$



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

- $\Lambda_b \to \Sigma_c$

$$\frac{f(\Lambda_b \to \Sigma_c)}{f(\Lambda_b \to \Lambda_c)} = 0.1$$ 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 $\mathcal{O}[(m_u - m_d)/m_c]$

- $\Lambda_b \to \Sigma_c D_s$
  - **Color Suppressed**
  - **No quark level diagram**

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

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

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

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

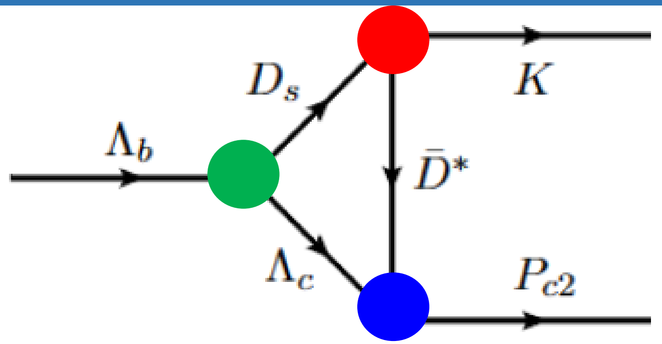
$$Br(B^- \to D^{*0} D_s^-) = (8.2 \mp 1.7) \times 10^{-3}$$

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

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

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

# Productions of pentaquark states in b-hadron decays




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

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

- Branching fractions

| Scenario | A | | | | | |
|---|---|---|---|---|---|---|
| Molecule | $P_{\psi 1}^N$ | $P_{\psi 2}^N$ | $P_{\psi 3}^N$ | $P_{\psi 4}^N$ | $P_{\psi 5}^N$ | $P_{\psi 6}^N$ |
| 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 | $P_{\psi 1}^N$ | $P_{\psi 2}^N$ | $P_{\psi 3}^N$ | $P_{\psi 4}^N$ | $P_{\psi 5}^N$ | $P_{\psi 6}^N$ |
| Ours | 18.24 | 2.22 | 6.06 | 1.79 | 3.83 | 2.76 |
| ChUA [103] | - | - | - | - | - | - |
| Exp | 0.96 | - | 1.70 | 3.55 | - | - |

- Coupled-channel potentials

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

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

The order of magnitude of production rates can be explained

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

# 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

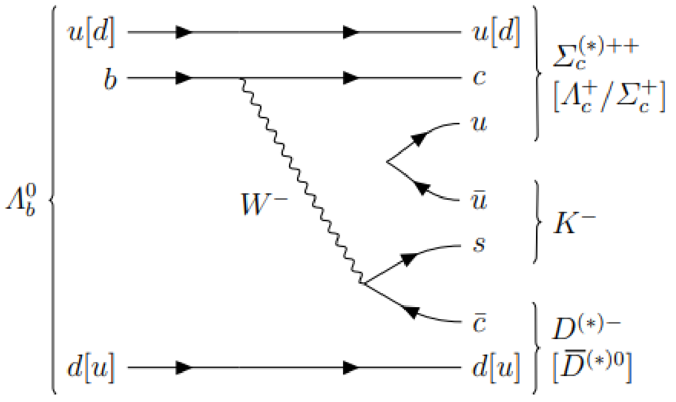
# Summary and outlook

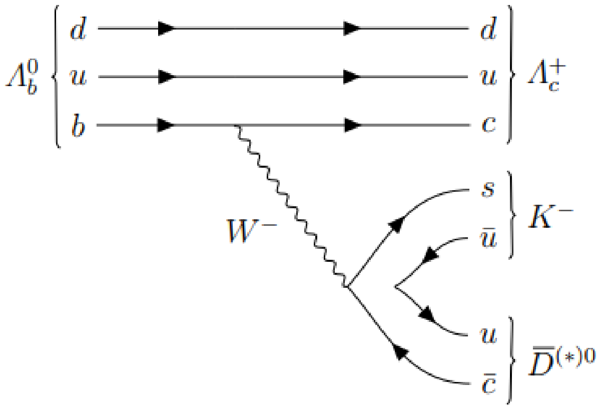
- We propose to verify the molecular nature of three $P_c$ states discovered by LHCb Collaboration by searching for their relevant partners associated with symmetry.

  - 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 $\Lambda_b$ decay are investigated by the final state interaction, further revealing the production mechanism of pentaquark states in b-baryon decays.

- Three-body weak decays may contribute to the productions of pentaquark states




$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-\right)} = 0.282 \pm 0.016 \pm 0.016 \pm 0.005,$$

LHCb Collaboration, Phys.Rev.D 110 (2024) L031104

# Thanks for your attention!

# Backup

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

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

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

2012.09903

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

1302.5854

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

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