第六届粒子物理天问论坛

Productions of DK and relevant three-body molecules in B decays

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Based on: Phys. Rev. D **109** (2024) 056014
In preparation

2024-11-10

Outline

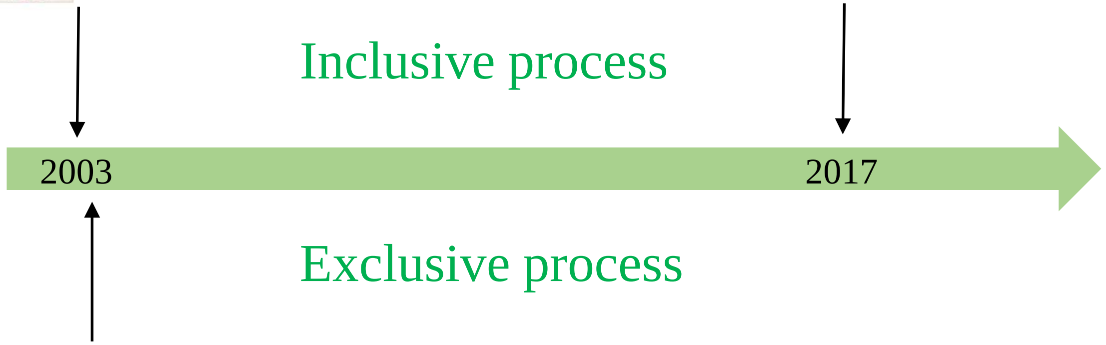
- Spectra of two-body DK molecule and three-body $\bar{D}_s DK$ molecule
- Productions of DK and $\bar{D}_s DK$ molecules in B decays
- Summary and Outlook

Exotic state $D_{s0}^*(2317)$

➢ Experimental measurements of $D_{s0}^*(2317)$

$e^+e^- \to D_s^+\pi^0 X$

$e^+e^- \to D_s^{*+}(D_{s0}^{*-} \to D_s^-\pi^0)$



$B \to D_{s0}^*(\to D_s^+\pi^0)\bar{D}$

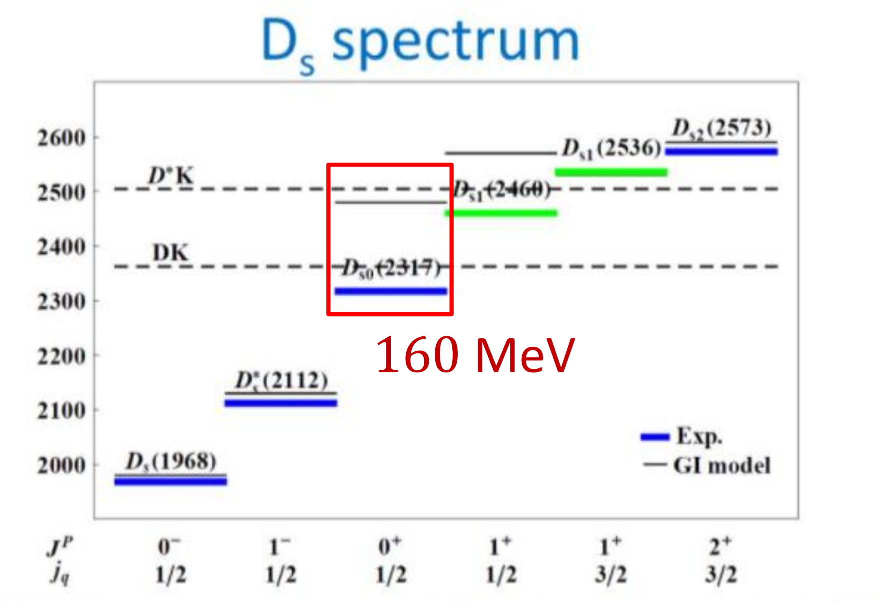
- **Mass and width**

$$D_{s0}^*(2317) = 2317.8 \pm 0.5 + \frac{i}{2} < 3.8$$

- **Decay Channel**

$$D_{s0}^{*-} \to D_s^-\pi^0$$

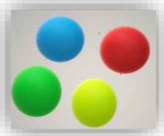
➢ Large mass deviation

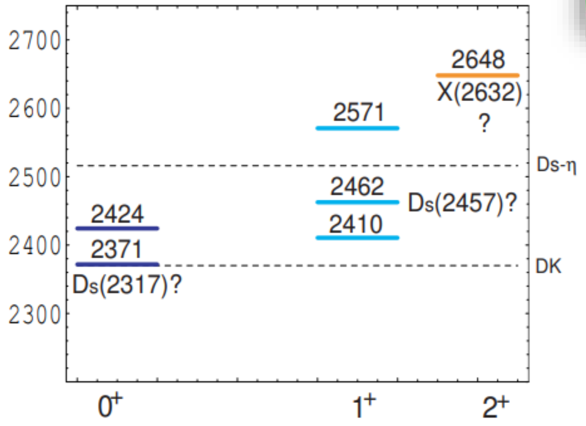


$D_{s0}^*(2317)$ is regarded as an exotic state

Molecular interpretation of $D_{s0}^*(2317)$

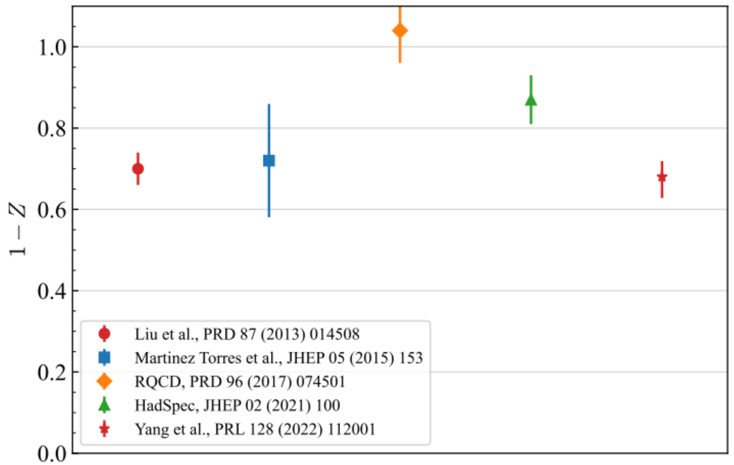
- **Compact tetraquark**





Maiani et al., Phys.Rev.D 71 (2005) 014028

- **Mixture of molecular and other component**



Guo, PoS LATTICE2022 (2023) 232

- **Molecular interpretation**

✓ **Mass and mass splitting**

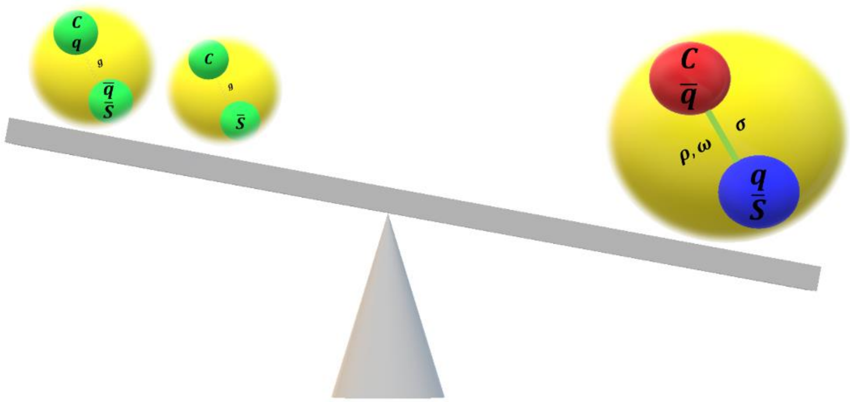
✓ **Narrow width**

$D_{s0}(2317)$	$I(J^P) = 0(0^+)$	DK
$D_{s1}(2460)$	$I(J^P) = 0(1^+)$	D^*K

ChPT Guo et al., Phys.Lett.B 641 (2006) 278-285

Lattice QCD Liu et al., Phys.Rev.D 87 (2013) 014508

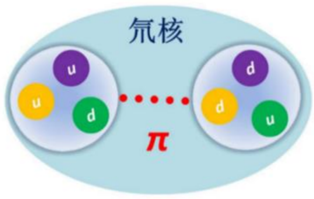
Bare states **Molecule**

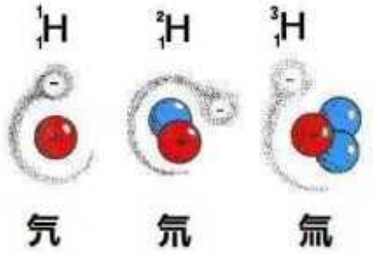


✓ **Molecular component more than 70%**

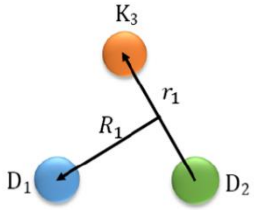
Three-body hadronic molecule

➢ Existence of three-body hadronic molecules





Nuclear Physics

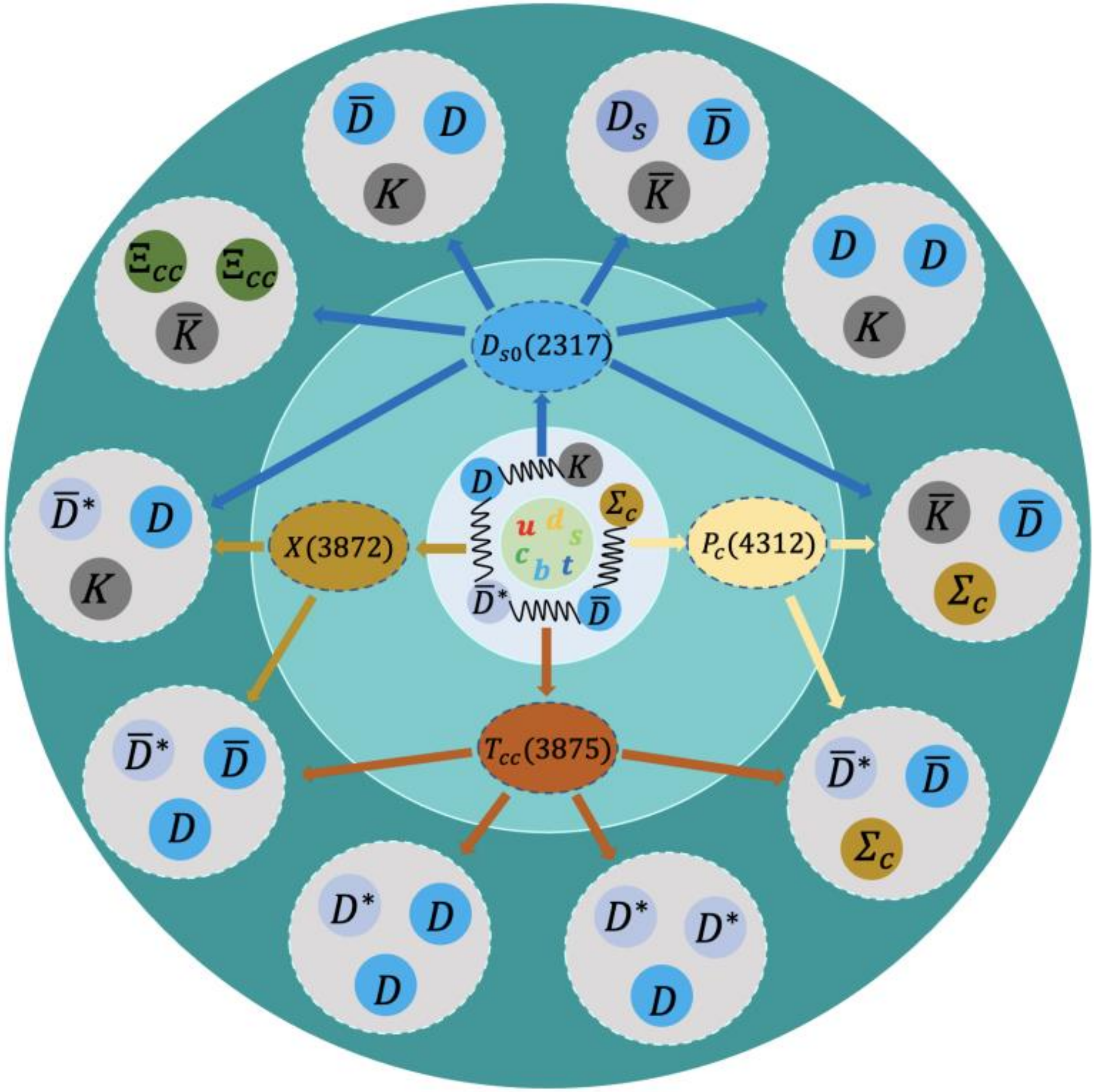


Hadron Physics

➢ Verify hadron-hadron interactions

Experimental search for three-body hadronic molecule potentially verify the hadron-hadron interaction

Liu et al., Arxiv: 2404.06399

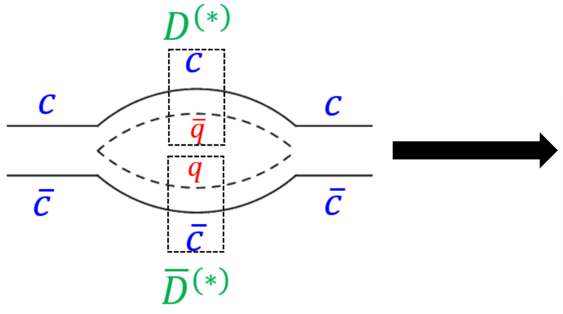


Wu et al., Sci.Bull. 67 (2022) 1735-1738

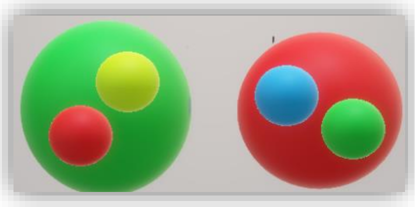
Experimental signal of three-body hadronic molecule

➢ Two-body hadronic molecules

L=1

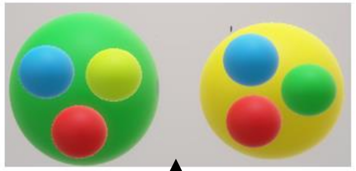


Meson- Meson

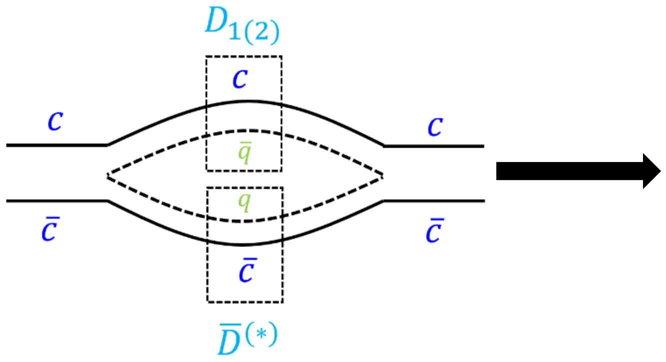


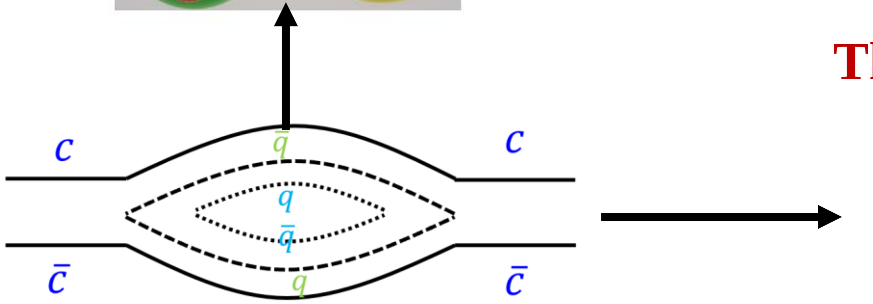
➢ Three-body hadronic molecules and the resonant states

Baryon-AntiBaryon

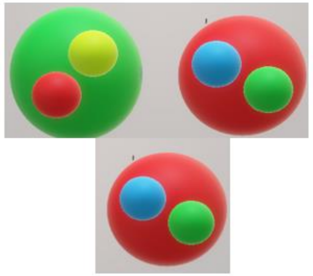


L=0/2



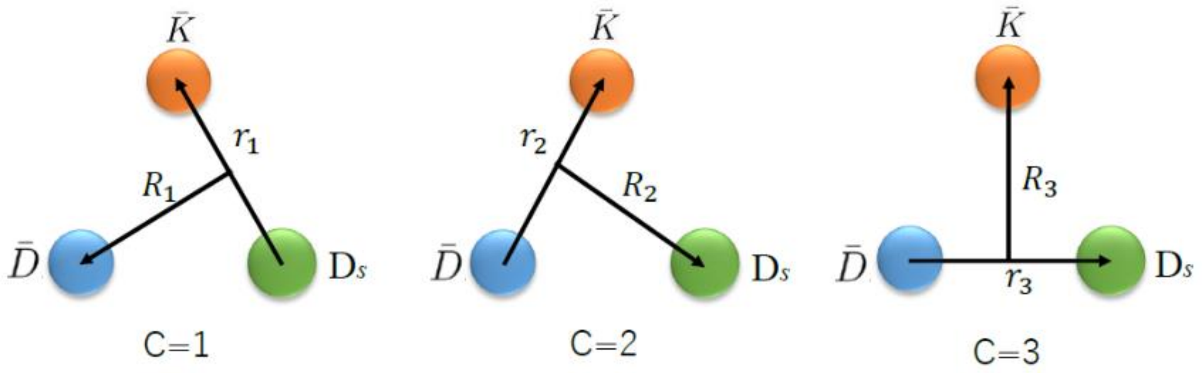


Three-body hadron



Experimental observation of three-body molecule

➢ A good candidate: $\bar{D}_s D K$ molecule



$\bar{D}_s D K \quad \mathrm{I}(J^{PC}) = 0(0^{--})$

58~65 MeV

- ✓ No mixture of conventional hadrons

  Contain exotic quantum number

- ✓ Two-body subsystem can not bind

  Suppressed by the OBE model or OZI rule

- ✓ Low mass with hidden charm/strange quantum number

  Can be observed at both e^+e^- and pp collisions

Productions of DK and $\bar{D}_s DK$ molecules in B decays

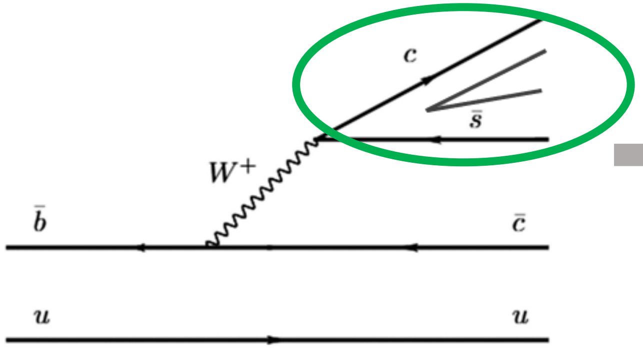
Decay modes	PDG	BarBar
$B^+ \to \bar{D}^0 D_{s0}^{*+}(2317)$	$0.80^{+0.16}_{-0.13}$	$1.0 \pm 0.3 \pm 0.1$
$B^0 \to D^- D_{s0}^{*+}(2317)$	$1.06^{+0.16}_{-0.16}$	$1.8 \pm 0.4 \pm 0.3$
$B^+ \to \bar{D}^{*0} D_{s0}^{*+}(2317)$	$0.90^{+0.70}_{-0.70}$	$0.9 \pm 0.6 \pm 0.2$
$B^0 \to D^{*-} D_{s0}^{*+}(2317)$	$1.50^{+0.60}_{-0.60}$	$1.5 \pm 0.4 \pm 0.2$
$B^+ \to \bar{D}^0 D_{s1}^{+}(2460)$	$3.1^{+1.0}_{-0.9}$	$2.7 \pm 0.7 \pm 0.5$
$B^0 \to D^- D_{s1}^{+}(2460)$	3.5 ± 1.1	$2.8 \pm 0.8 \pm 0.5$
$B^+ \to \bar{D}^{*0} D_{s1}^{+}(2460)$	12.0 ± 3.0	$7.6 \pm 1.7 \pm 1.8$
$B^0 \to D^{*-} D_{s1}^{+}(2460)$	9.3 ± 2.2	$5.5 \pm 1.2 \pm 1.0$

- Explain these branching fractions
- Explore the three-body molecule $\bar{D}_s DK$ in B decays

Outline

- Spectra of two-body DK molecules and three-body $\bar{D}_s DK$ molecules
- Productions of DK and $\bar{D}_s DK$ molecules in B decays
- Summary and Outlook

Productions of $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$ in B decays



$$\mathcal{A}\left(B^- \to D_{s0}^{*-}\bar{D}^{(*)0}\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_1 \left\langle D_{s0}^{*-}|(s\bar{c})|0\right\rangle \left\langle \bar{D}^{(*)0}|(c\bar{b})|B^-\right\rangle$$

➢ **Form factors**

$$\langle \bar{D}^{*0}|(c\bar{b})|B^+\rangle = \epsilon_\alpha^* \left\{ -g^{\mu\alpha}(m_{\bar{D}^{*0}} + m_{B^+})A_1(q^2) + P^\mu P^\alpha \frac{A_2(q^2)}{m_{\bar{D}^{*0}} + m_{B^+}} + i\varepsilon^{\mu\alpha\beta\gamma} P_\beta q_\gamma \frac{V(q^2)}{m_{\bar{D}^{*0}} + m_{B^+}} + q^\mu P^\alpha \left[\frac{m_{\bar{D}^{*0}} + m_{B^+}}{q^2} A_1(q^2) - \frac{m_{B^+} - m_{\bar{D}^{*0}}}{q^2} A_2(q^2) - \frac{2m_{\bar{D}^{*0}}}{q^2} A_0(q^2) \right] \right\}$$

$$\langle \bar{D}^0|(c\bar{b})|B^+\rangle = \left[P^\mu - \frac{m_{B^+}^2 - m_{\bar{D}^0}^2}{q^2} q_\mu \right] F_1(q^2) + \frac{m_{B^+}^2 - m_{\bar{D}^0}^2}{q^2} q_\mu F_0(q^2)$$

➢ **Decay constants**

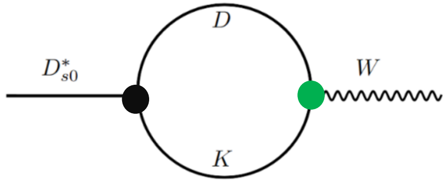
$$\langle D_{s0}^{*+}|(s\bar{c})|0\rangle = f_{D_{s0}^{*+}} p^\mu_{D_{s0}^{*+}}$$

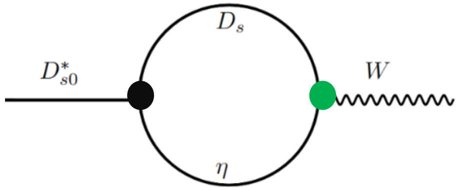
$$\langle D_{s1}^{+}|(s\bar{c})|0\rangle = m_{D_{s1}^+} f_{D_{s1}^+} \epsilon_\mu^*$$

Decay constants characterize the internal structure of exotic state

Calculating decay constants of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

➢ Effective Lagrangian approach





$$\mathcal{L}_{D_{s0}^*DK} = g_{D_{s0}^*DK} D_{s0}^* DK, \quad \mathcal{L}_{D_{s0}^*D_s\eta} = g_{D_{s0}^*D_s\eta} D_{s0}^* D_s\eta$$

$$\mathcal{L}_{VDK} = f_1^{DK}(0) V^\mu (D\partial_\mu K - \partial_\mu DK), \quad \mathcal{L}_{VD_s\eta} = f_1^{D_s\eta}(0) V^\mu (D_s\partial_\mu \eta - \partial_\mu D_s\eta)$$

➢ Loop integral

$$\mathcal{A}_a = g_{D_{s0}^*DK} f_1^{DK}(0) \int \frac{d^4q}{(2\pi)^4} \frac{1}{k_1^2 - m_1^2} \frac{1}{k_2^2 - m_2^2} (k_1^\mu - k_2^\mu) \varepsilon_\mu(V),$$

$$\mathcal{A}_b = g_{D_{s0}^*D_s\eta} f_1^{D_s\eta}(0) \int \frac{d^4q}{(2\pi)^4} \frac{1}{k_1^2 - m_1^2} \frac{1}{k_2^2 - m_2^2} (k_1^\mu - k_2^\mu) \varepsilon_\mu(V),$$

$$\langle D_{s0}^{*+} | (s\bar{c}) | 0 \rangle = f_{D_{s0}^{*+}} p^\mu_{D_{s0}^{*+}}$$

Extracting decay constant

$$f_{D_{s0}^*}^{m_1m_2} = g_{D_{s0}^*m_1m_2} f_1^{m_1m_2}(0) \frac{1}{16\pi^2} \int_0^1 dx (2x-1) ln \frac{\Delta^2}{\mu^2}$$

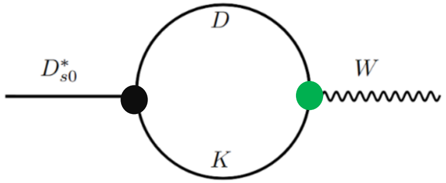
➢ Unknown parameters

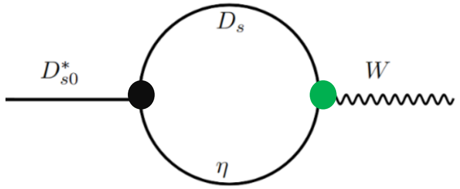
- Renormalization energy scale
  - Dimensional Regularization Scheme
- Coupling constants

$$\int \frac{d^4k_1}{(2\pi)^4} \frac{k_1^\mu - k_2^\mu}{(k_1^2 - m_1^2)[(p-k_1)^2 - m_2^2]} = \frac{p^\mu}{16\pi^2} \int_0^1 dx (2x-1) ln \frac{\Delta^2}{\mu^2}$$

Calculating decay constants of $D^*_{s0}(2317)$ and $D_{s1}(2460)$

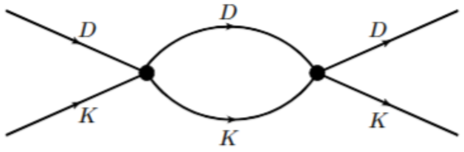
➢ Coupling constants





decay modes	Exp [34]	decay modes	Exp [34]
$D^+ \to \bar{K}^0 e^+ \nu_e$	8.72 ± 0.09	$D_s^+ \to \eta e^+ \nu_e$	2.32 ± 0.08
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	5.40 ± 0.10	$D_s^+ \to \phi e^+ \nu_e$	2.39 ± 0.16
$D^0 \to K^- e^+ \nu_e$	3.549 ± 0.026		
$D^0 \to K^{*-} e^+ \nu_e$	2.15 ± 0.16		

$$g_i g_j = \lim_{\sqrt{s} \to \sqrt{s_0}} \left(\sqrt{s} - \sqrt{s_0}\right) T_{ij}(\sqrt{s})$$



$$\langle \vec{k}' | T | \vec{k} \rangle = \langle \vec{k}' | T | \vec{k} \rangle + \int \frac{d^3 \vec{q}}{(2\pi)^3} \langle \vec{k}' | V | \vec{q} \rangle G(s) \langle \vec{q} | T | \vec{k} \rangle$$

$$V^{J^P=0^+}_{DK-D_s\eta} = \begin{pmatrix} -2C_a & \sqrt{3}C_a \\ \sqrt{3}C_a & 0 \end{pmatrix} \qquad V^{J^P=1^+}_{D^*K-D_s^*\eta} = \varepsilon(k_1)\cdot\varepsilon(k_1') \begin{pmatrix} -2C_a & \sqrt{3}C_a \\ \sqrt{3}C_a & 0 \end{pmatrix}$$

$$f^{m_1 m_2}_{D^*_{s0}} = g_{D^*_{s0} m_1 m_2} f_1^{m_1 m_2}(0) \frac{1}{16\pi^2} \int_0^1 dx (2x-1) ln \frac{\Delta^2}{\mu^2}$$

$$G(\sqrt{s})^{D^*_{s0}} = \frac{1}{16\pi^2} \int_0^1 dx ln \frac{\Delta^2}{\mu^2},$$

$$G(\sqrt{s})^{D_{s1}} = \frac{1}{16\pi^2} \int_0^1 dx \left[ln \frac{\Delta^2}{\mu^2} - \frac{1}{2m_1^2} \Delta^2 (ln \frac{\Delta^2}{\mu^2} - 1) \right]$$

Similar regularization approach

Calculating decay constants of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

- **Strong decay constants of $D_{s0}^*(2317)$ and $D_{s1}(2460)$**

Couplings	$\mu = 1.00$	$\mu = 1.50$	$\mu = 2.00$
$g_{D_{s0}^* DK}$	11.75	11.92	11.95
$g_{D_{s0}^* D_s \eta}$	8.13	7.47	7.32
$g_{D_{s1} D^* K}$	12.06	12.16	12.15
$g_{D_{s1} D_s^* \eta}$	8.78	7.76	7.53

- **Decay constants of $D_{s0}^*(2317)$ and $D_{s1}(2460)$**

Decay Constants	$\mu = 1000$	$\mu = 1500$	$\mu = 2000$
$f_{D_{s0}^*(2317)}$	59.36	58.74	58.59
$f_{D_{s1}(2460)}$	56.10	133.76	187.48

Decay constant of $D_{s0}^*(2317)$ is almost independent on the renormalization energy scale

Production rates of $D_{s0}^*(2317)$ and $D_{s1}(2460)$ in B decays

- **Branching fractions of $B \to \bar{D}^{(*)} D_{s0,s1}$**

10^{-3}

Decay modes	Ours	Experiments [29]
$B^+ \to \bar{D}^0 D_{s0}^{*+}(2317)$	0.48	$0.80^{+0.16}_{-0.13}$
$B^+ \to \bar{D}^{*0} D_{s0}^{*+}(2317)$	0.39	$0.90^{+0.70}_{-0.70}$
$B^+ \to \bar{D}^0 D_{s1}^{+}(2460)$	1.39	$3.1^{+1.0}_{-0.9}$
$B^+ \to \bar{D}^{*0} D_{s1}^{+}(2460)$	4.36	12.0 ± 3.0

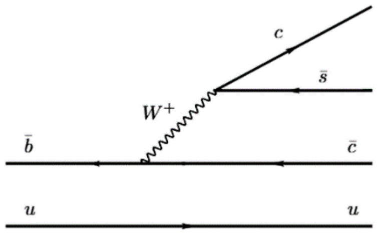
70%

50%

Decay Constants	$f_{D_{s0}^*}$	$f_{D_{s1}}$
QCD sum rule [896]	333 ± 20	345 ± 17
Quark model [421]	110	233
Salpeter method [897]	112	219
covariant light-front quark model [898]	$74.4^{+10.4}_{-10.6}$	159^{+36}_{-32}
Ours	115.71	265.74

Decay constants of $D_{s0}^*(2317)$ and $D_{s1}(2460)$ as the bare states

- **Production rates of $D_{s0}^*(2317)$ and $D_{s1}(2460)$ in b-flavored decays**

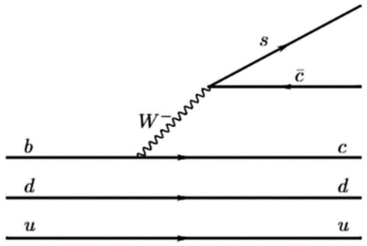


Decay modes	10^{-3} Ours
$B_s^0 \to D_s^- D_{s0}^{*+}(2317)$	0.47
$B_s^0 \to D_s^{*-} D_{s0}^{*+}(2317)$	0.27
$B_s^0 \to D_s^- D_{s1}^{+}(2460)$	1.18
$B_s^0 \to D_s^{*-} D_{s1}^{+}(2460)$	4.11

$\mathcal{B}(\Lambda_b \to \Lambda_c M)/\mathcal{B}(B \to DM)$

$\mathcal{B}(\Xi_b \to \Xi_c M)/\mathcal{B}(B_s \to D_s M)$

R_u^M	Ours	R_s^M	Ours
$R_u^{D_s}$	1.22	$R_s^{D_s}$	1.94
$R_u^{D_s^*}$	2.44	$R_s^{D_s^*}$	2.35
$R_u^{D_{s0}^*}$	1.46	$R_s^{D_{s0}^*}$	1.23
$R_u^{D_{s1}}$	3.12	$R_s^{D_{s1}}$	3.64



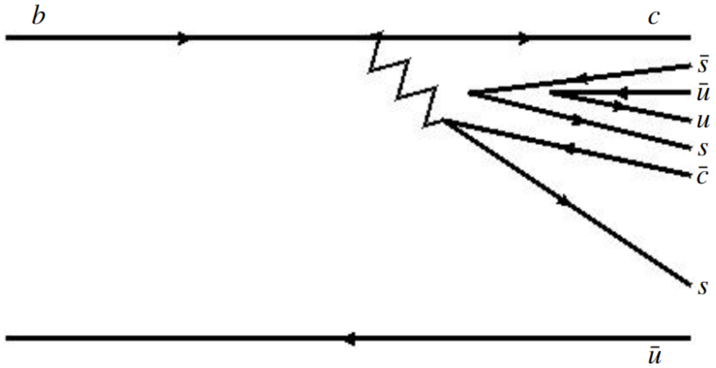
Decay modes	Branching fractions	Decay modes	Branching fractions
$\Lambda_b \to \Lambda_c D_{s0}^*(2317)$	0.70	$\Xi_b \to \Xi_c D_{s0}^*(2317)$	0.58
$\Lambda_b \to \Lambda_c D_{s1}(2460)$	4.34	$\Xi_b \to \Xi_c D_{s1}(2460)$	4.29

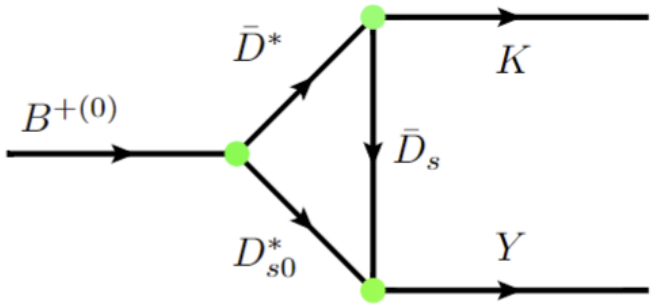
10^{-3}

Production rates of D_{s0}^* and D_{s1} in baryons are larger than those in meson

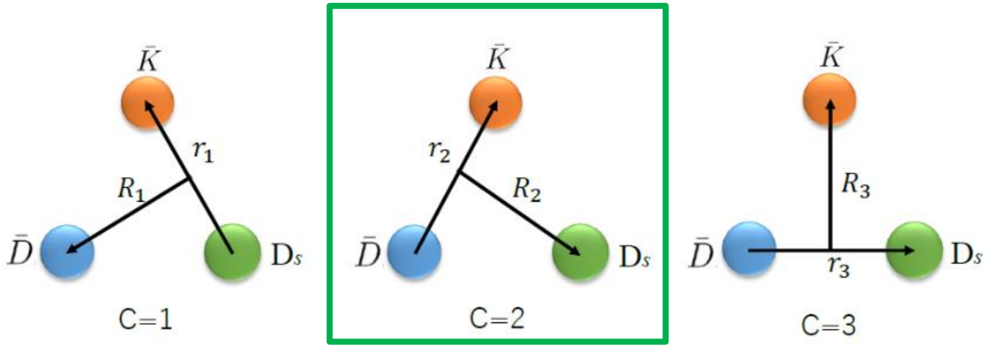
Productions of $\bar{D}_s DK$ molecule in B decays

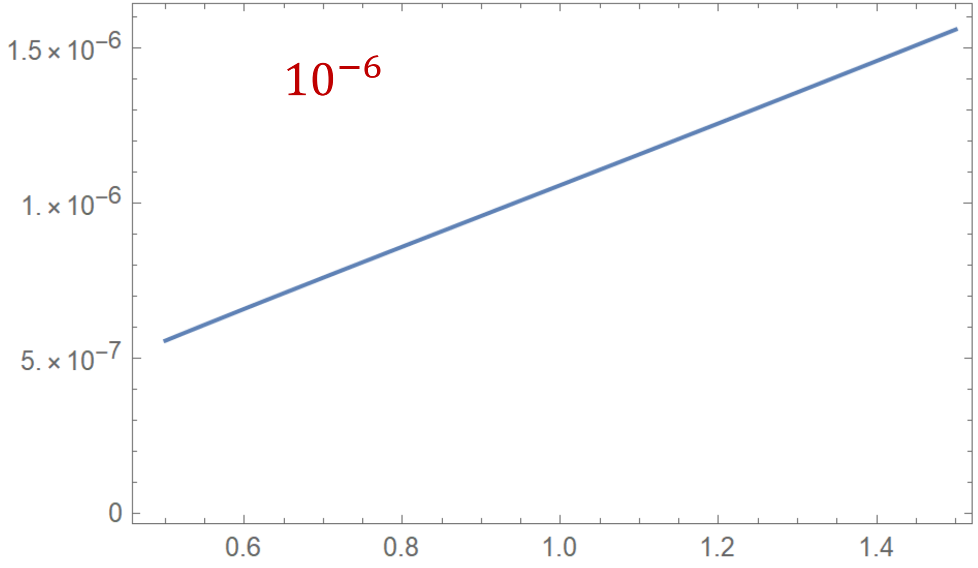
➢ **The topological diagrams for b-baryon decays**





➢ **The $\bar{D}_s DK$ molecule coupling to the $\bar{D}_s D^*_{s0}$ channel**





$$1 - Z = g^2 \frac{\partial G(s)}{\partial s}\Big|_{s=4270} \qquad g = 15.79 \text{ GeV}$$

Outline

- Spectra of two-body DK molecules and three-body $\bar{D}_s DK$ molecules
- Productions of DK and $\bar{D}_s DK$ molecules in B decays
- Summary and Outlook

Summary and outlook

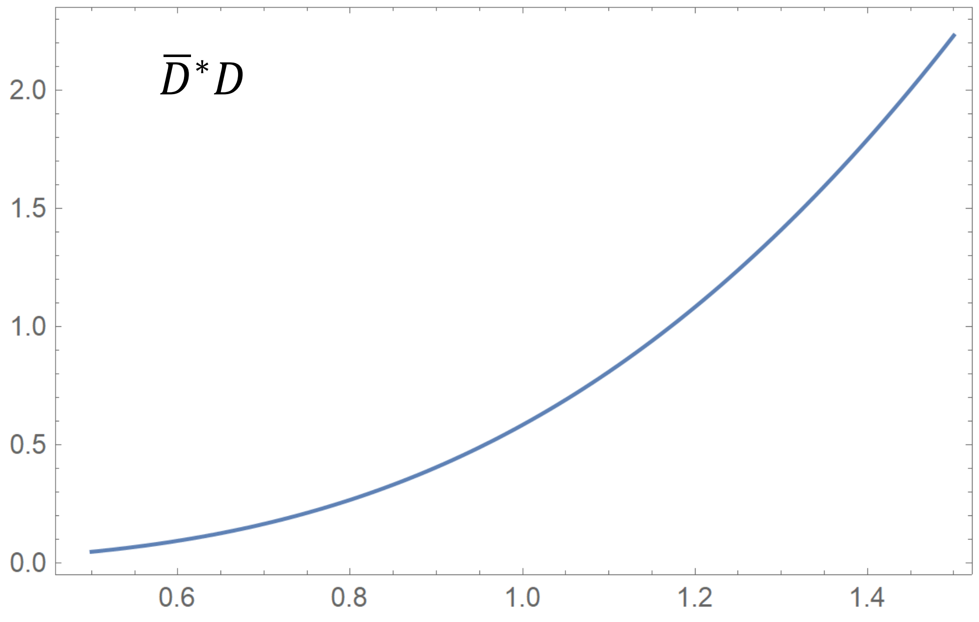
- With predominant DK molecular component of $D_{s0}^*(2317)$, we predict a three-body hadronic molecule $\bar{D}_s DK$, and their productions in B decays.
  - ✓ From the perspective of B decays, the $D_{s0}^*(2317)$ can not be explained as the pure hadronic molecule instead of mixture of molecule and other bare components.
  - ✓ We firstly calculated the production rates of three-body $\bar{D}_s DK$ molecule in B decay (10^{-6})

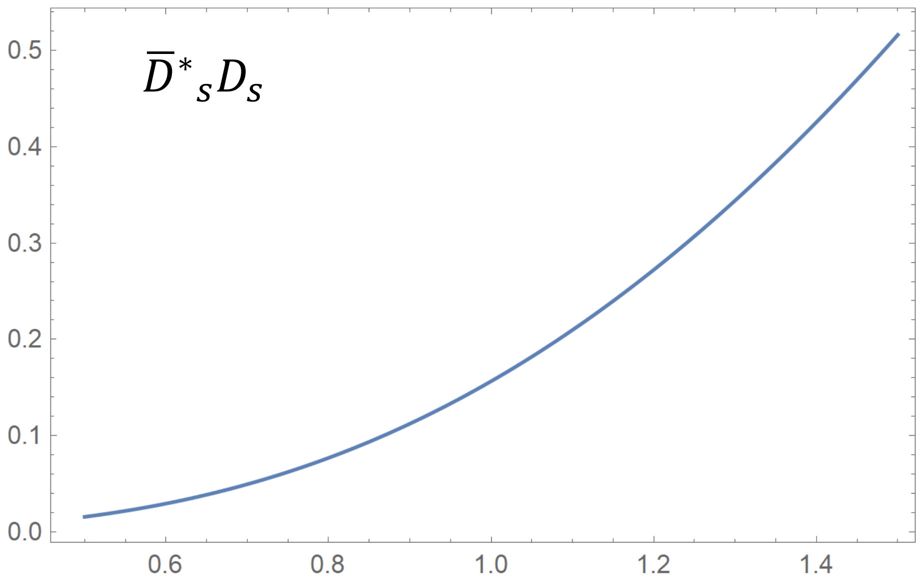
- Available physical measurements to measure the three-body hadronic molecule
  - Decay modes of $\bar{D}_s DK$ molecule and the efficiency of experimental measurements
  - Estimating the events of productions of three-body hadronic molecules with the B cross sections in LHC or e+e- collisions

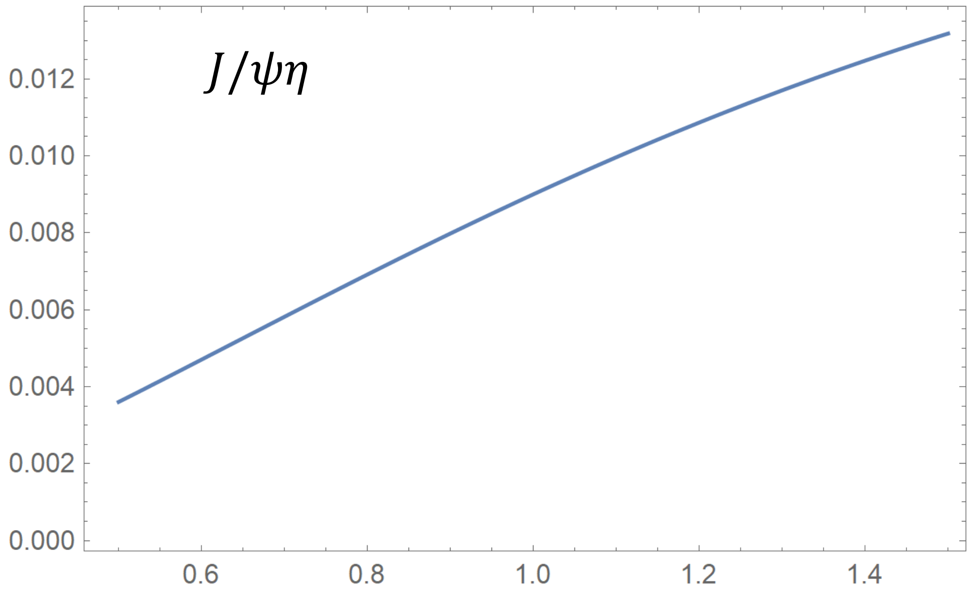
Thanks for your attention!

Backup

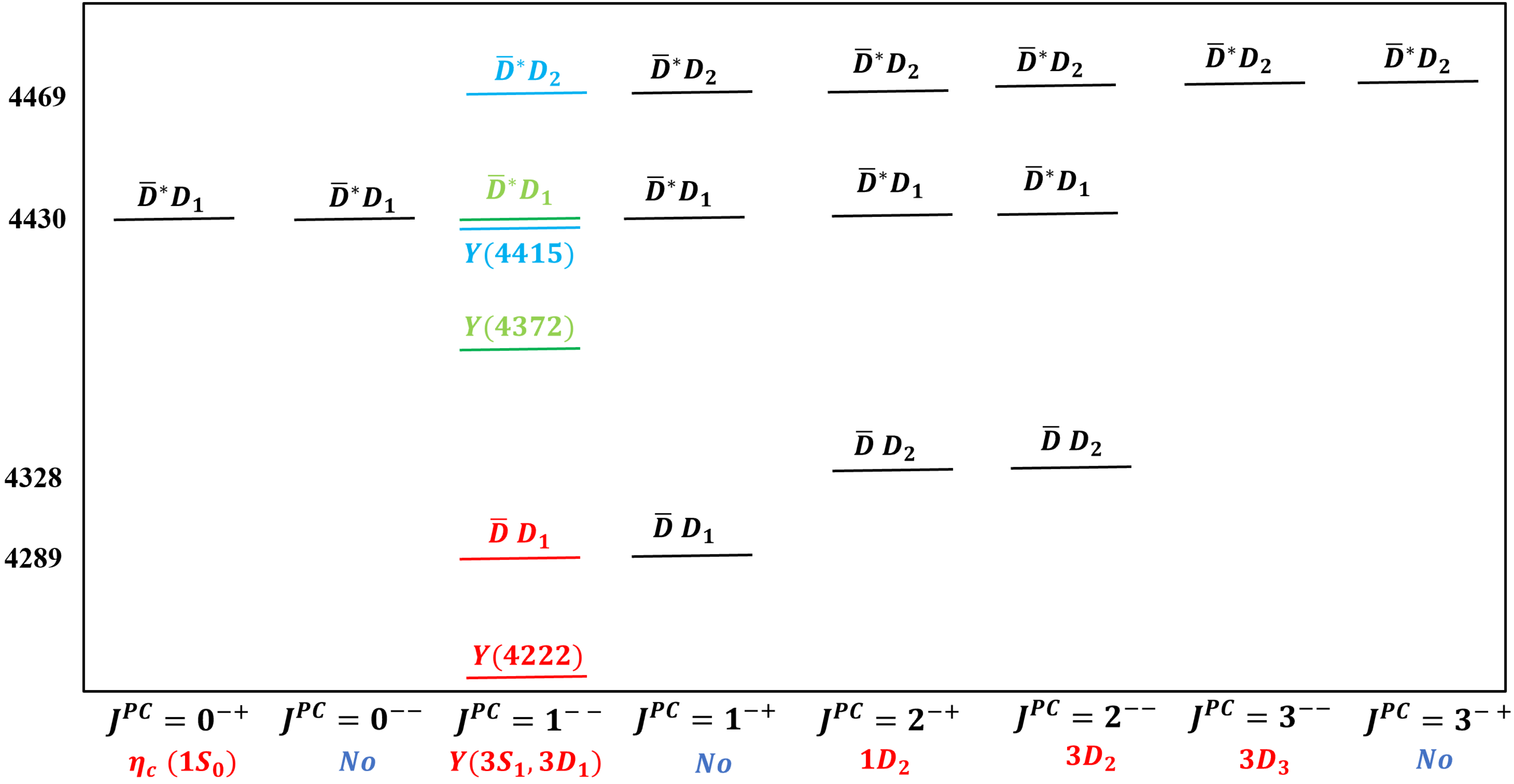
- **Strong decay of $\bar{D}_s D K$ molecule**







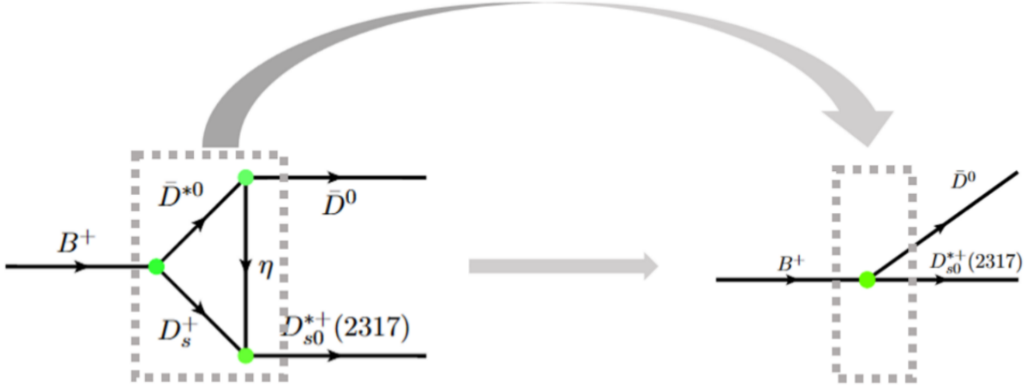
Backup



4469
4430
4328
4289
$\bar{D}^* D_2$
$\bar{D}^* D_2$
$\bar{D}^* D_2$
$\bar{D}^* D_2$
$\bar{D}^* D_2$
$\bar{D}^* D_2$
$\bar{D}^* D_1$
$\bar{D}^* D_1$
$\bar{D}^* D_1$
$\bar{D}^* D_1$
$\bar{D}^* D_1$
$\bar{D}^* D_1$
$Y(4415)$
$Y(4372)$
$\bar{D} D_2$
$\bar{D} D_2$
$\bar{D} D_1$
$\bar{D} D_1$
$Y(4222)$
$J^{PC} = 0^{-+}$
$\eta_c\ (1S_0)$
$J^{PC} = 0^{--}$
No
$J^{PC} = 1^{--}$
$Y(3S_1, 3D_1)$
$J^{PC} = 1^{-+}$
No
$J^{PC} = 2^{-+}$
$1D_2$
$J^{PC} = 2^{--}$
$3D_2$
$J^{PC} = 3^{--}$
$3D_3$
$J^{PC} = 3^{-+}$
No

Productions of pentaquark states in b-baryon decays

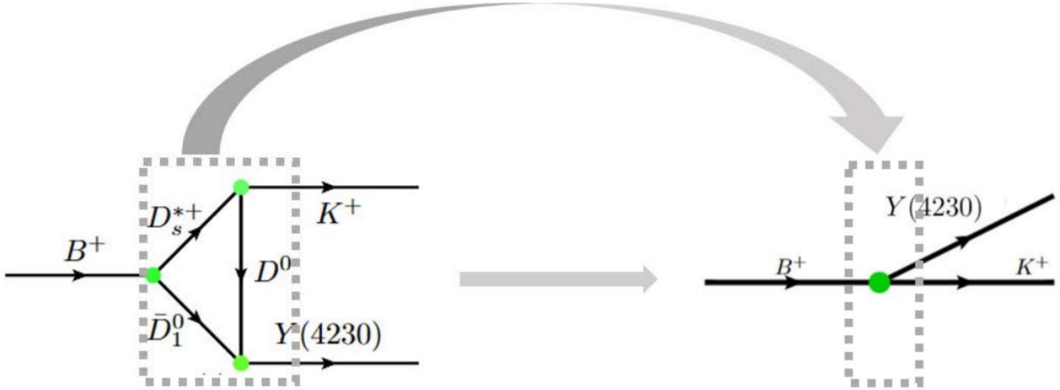
➢ Comparison with the final state interactions



Decay modes	Ours	Triangle [56]	Exp [29]
$B^+ \to \bar{D}^0 D_{s0}^{*+}(2317)$	0.48	0.68	$0.80^{+0.16}_{-0.13}$
$B^+ \to \bar{D}^{*0} D_{s0}^{*+}(2317)$	0.39	1.21	$0.90^{+0.70}_{-0.70}$
$B^+ \to \bar{D}^0 D_{s1}^{+}(2460)$	1.39	1.26	$3.1^{+1.0}_{-0.9}$
$B^+ \to \bar{D}^{*0} D_{s1}^{+}(2460)$	4.36	3.07	12.0 ± 3.0

Liu et al., Phys. Rev. D **109** (2024) 056014

➢ An approach to extracting the decay constants of hadronic molecules



State	Decay constant(B decay)	Decay constant(decay to e^+e^-) [86]
$Y(4230)$	$10.8 \sim 42.1$	$39.4 \sim 93.8$
$Y(4360)$	$34.0 \sim 128.6$	$73.9 \sim 210.2$

Liu et al., ArXiv:2409.06539