全国第二十届重味物理和CP 破坏研讨会@复旦大学

Production rates of X(3872)/X(4013) and Zc(3900)/Zc(4020) states in B decays

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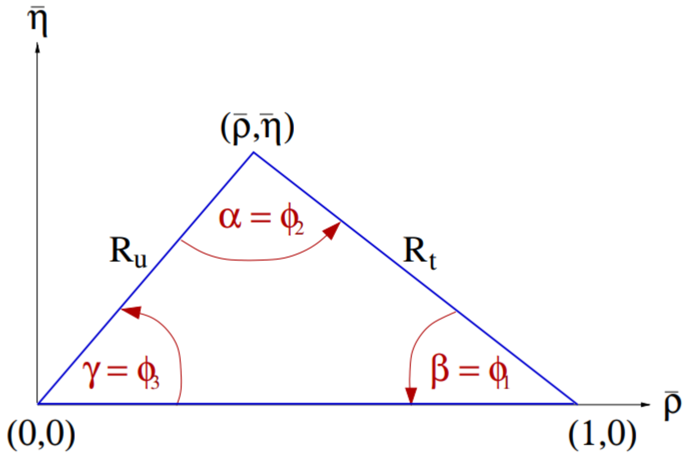
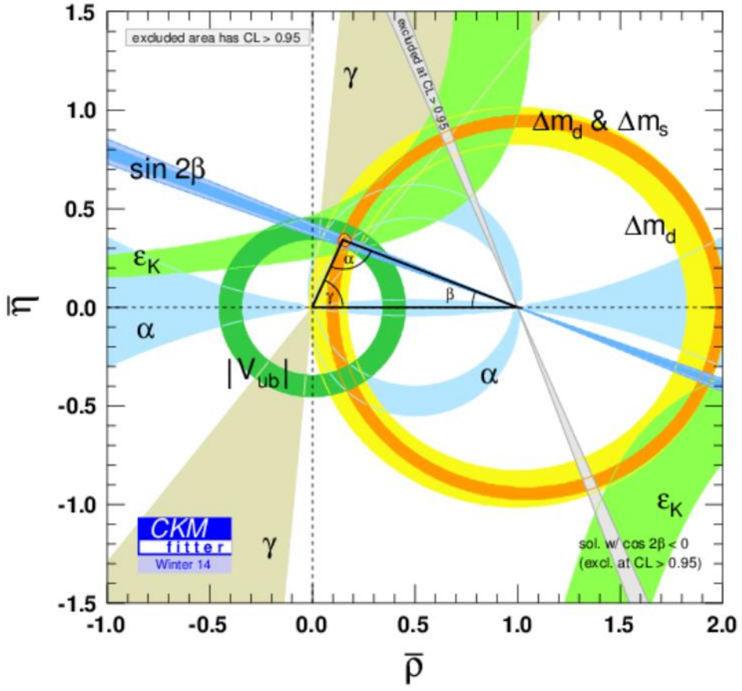
Outline

- Research Background
- X(3872)/X(4013) and Zc(3900)/Zc(4020) as $\bar{D}^{(*)}D^*$ HQSS multiplet hadronic molecules
- Producing XZ states in B decays
- Summary

Flavor Physics

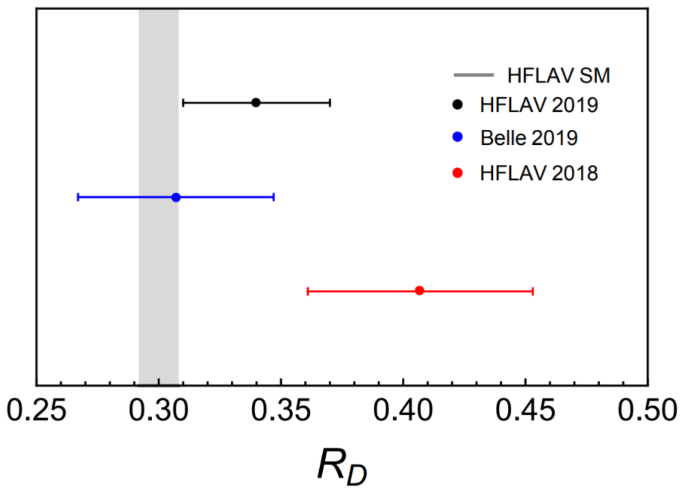
- **Precise test for Standard Model**

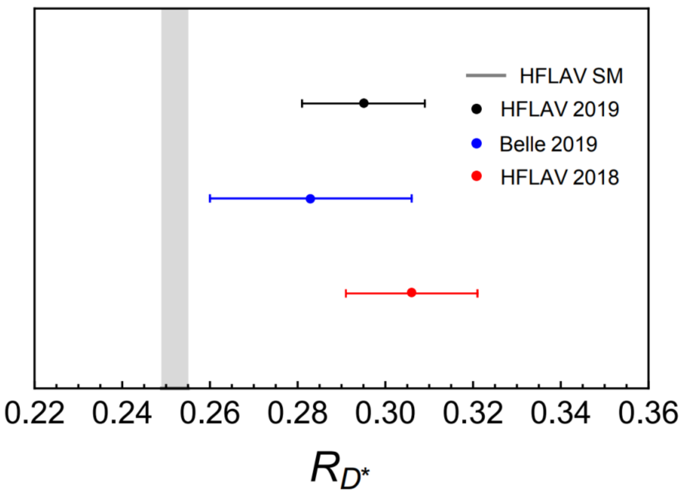




- **Search for New Physics**

$$R^{SM}_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}\ell\bar{\nu})}, \qquad (\ell = \mu, e)$$





Flavor Physics

➢ **Producing a series of exotic states in b-flavored hadron decays**

$\overline{B}^0 \to X(3872)\overline{K}^0$

$\overline{B}^0 \to Z(4430)^+K^-$

$\overline{B}^0 \to Z_1(4050)K^-$

$\overline{B}^0 \to Z_2(4250)K^-$

$\overline{B}^0 \to Y(3940)\overline{K}^0$

$B^- \to Y(4260)K^-$

$B^- \to X(4140)K^-$

$B^- \to X(4274)K^-$

$B^+ \to \chi_{c0}(3915)K^+$

$B^+ \to \chi_{c2}(3930)K^+$

$B^+ \to \chi_{c0}(4500)K^+$

$B^+ \to \chi_{c0}(4700)K^+$

$B^+ \to X(3960)K^+$

→ **XYZ states**

$\overline{B}^0 \to D^+D^*_{sJ}(2317)^-$

$\overline{B}^0 \to D^+D_{sJ}(2460)^-$

$B^+ \to X_0(2900)D^+$

$B^+ \to X_1(2900)D^+$

$B^+ \to T^a_{c\bar{s}0}(2900)^{++}\bar{D}^-$

$B^0 \to T^a_{c\bar{s}0}(2900)^0\bar{D}^0$

↓

Tetraquark states

$\Lambda_b^0 \to P_c(4380)^+K^-$

$\Lambda_b^0 \to P_c(4312)^+K^-$

$\Lambda_b^0 \to P_c(4440)^+K^-$

$\Lambda_b^0 \to P_c(4457)^+K^-$

$\Xi_b^- \to P_{cs}(4459)^0K^-$

$B_s^0 \to P_c(4337)^-p$

$B^- \to P_{cs}(4338)^0\bar{p}$

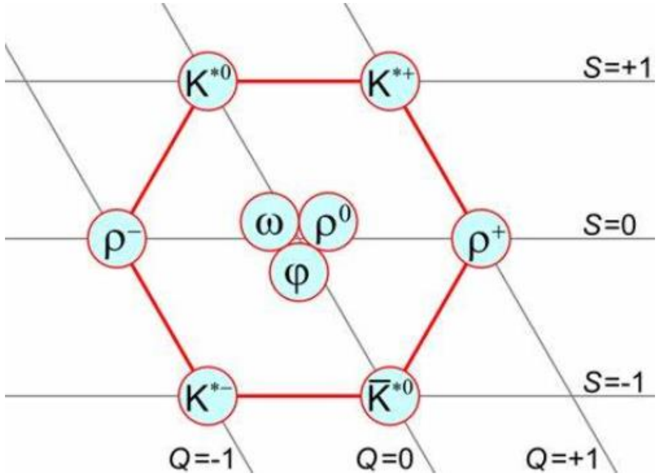
↓

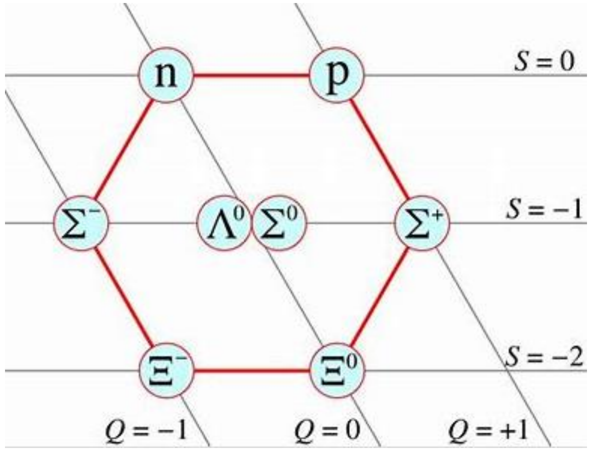
Pentaquark states

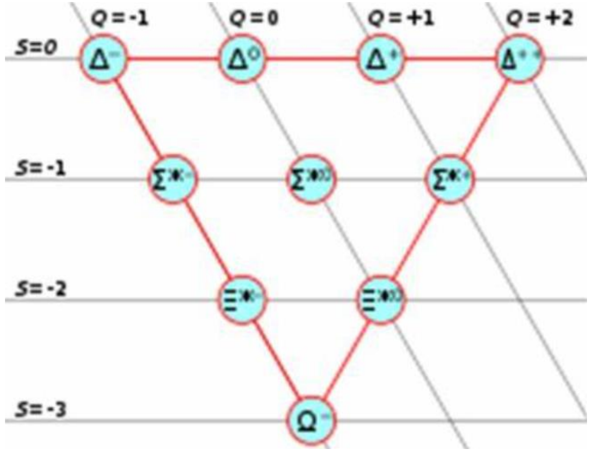
Exotic states

➢ Quark model

Phys.Lett. 8 (1964) 214-215







Meson： $3 \otimes \bar{3} = 1 \oplus 8$

Baryon： $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$

Conventional hadron

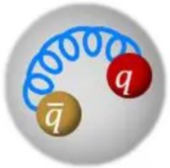
Exotic state

Baryon

Meson

Tetraquark

Pentaquark



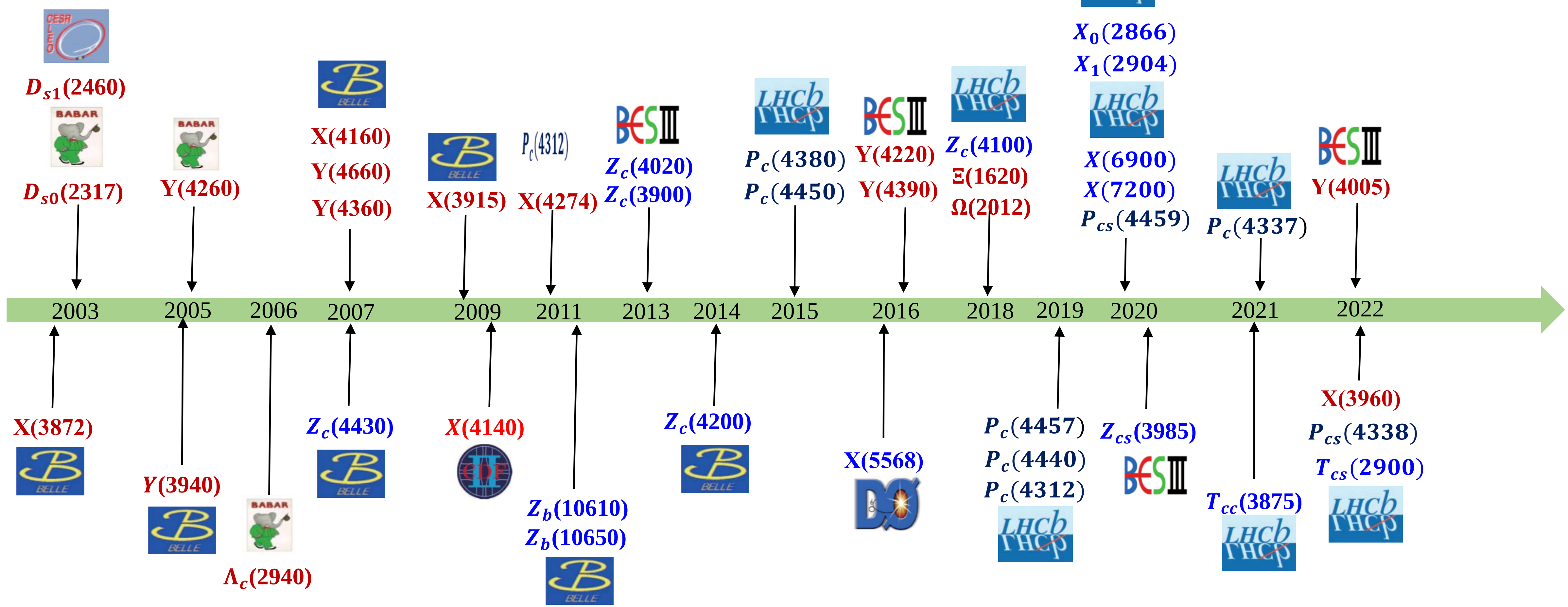
Hybrid

glueball

… …

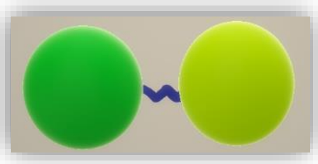
Exotic states in experiments

Exotic meson and baryon **Tetrquark** **Pentaquark**

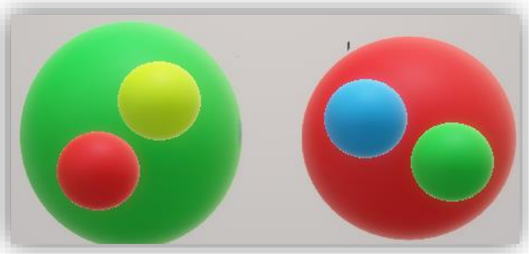


The nature of the exotic state?

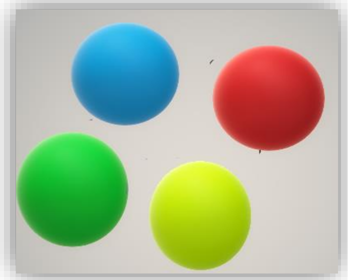
Hadronic molecular candidate



Charmonium



Hadronic molecules



Compact multiquark

Mixing states

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X(3872) is a molecular candidate

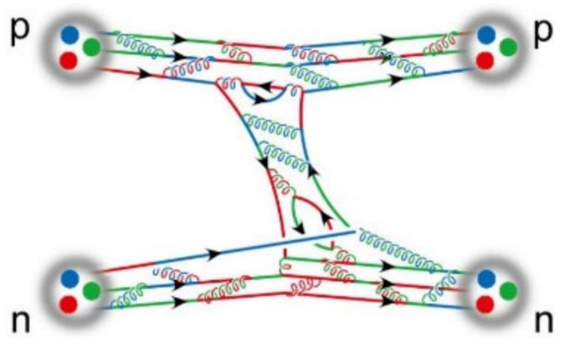
Hadronic molecule
- Mass
- Width
- $R^{I} = \frac{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$

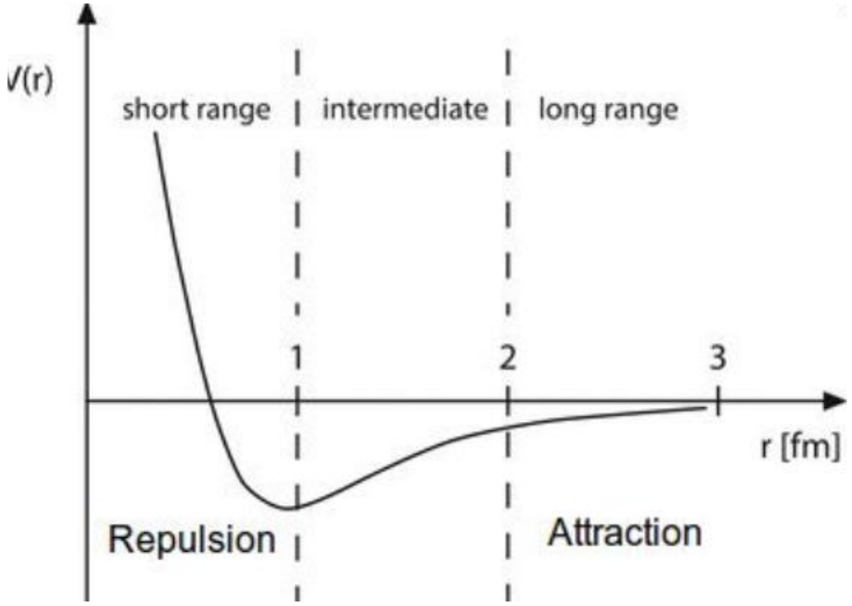
$Z_c(3900)$	$I(J^{PC}) = 1(1^{+-})$	$\bar{D}D^*$
$Z_c(4020)$	$I(J^{PC}) = 1(1^{+-})$	$\bar{D}^*D^*$
$D_{s0}(2317)$	$I(J^P) = 0(0^+)$	DK
$D_{s1}(2460)$	$I(J^P) = 0(1^+)$	D^*K

$P_c(4312)$	$I(J^P) =?\,(?^?)$	$\bar{D}\Sigma_c$
$P_c(4440)$	$I(J^P) =?\,(?^?)$	$\bar{D}^*\Sigma_c$
$P_c(4457)$	$I(J^P) =?\,(?^?)$	$\bar{D}^*\Sigma_c$

Hadron-Hadron interaction

➢ Non-perturbative strong interaction





- One Boson Exchange(OBE) model — Eur.Phys.J.C 61 (2009) 411-428
- Chiral Unitary Approach(ChUA) — Phys.Rev.D 81 (2010) 014029
- Effective Field Theory(EFT) — Phys.Rev.D 88 (2013) 054007
- Lattice QCD — Phys.Rev.Lett. 111 (2013) 192001

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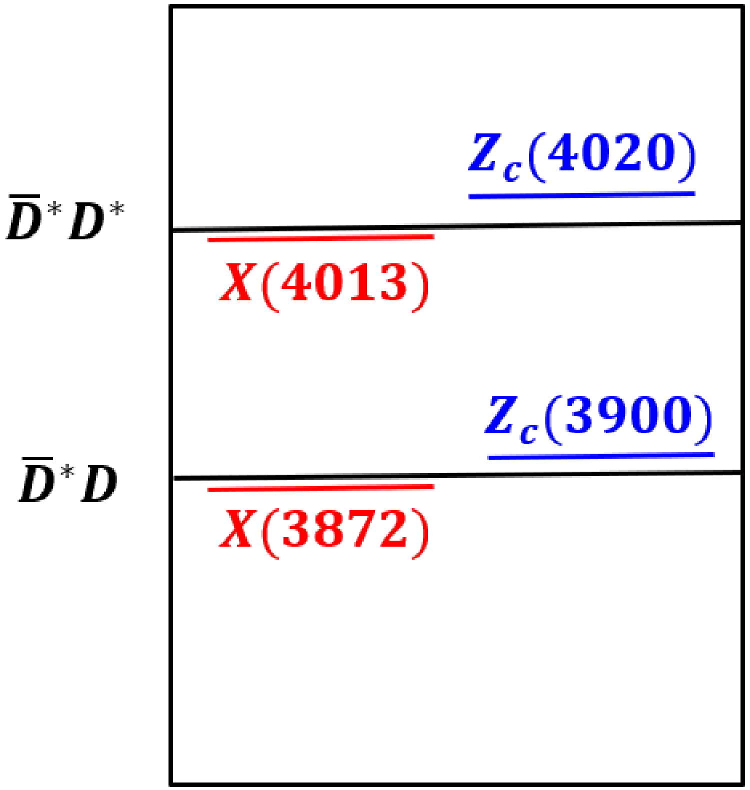
X(3872)/X(4013) and Zc(3900)/Zc(4020) as $\bar{D}^{(*)}D^*$ molecules



➢ **Lippmann-Schwinger Equation**

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

$$\langle \vec{k}|V|\vec{q}\rangle = C(\Lambda)\theta(\Lambda - |\vec{k}|)\theta(\Lambda - |\vec{q}|)$$

$$\boldsymbol{T = \frac{V}{1 - VG}}$$

➢ **Loop function**

$$G(s) = \int \frac{d^3\vec{q}}{(2\pi)^3}\frac{1}{\sqrt{s} - m_1 - m_1 - \frac{\vec{q}^2}{2\mu_{12}} + i\epsilon}$$

- **Dimensional regularization scheme**
- **Momentum Cutoff scheme** ⟶ **Form factor**

X(3872) and X(4013) as the isoscalar molecules

➢ **Contact-range potential**

state	J^{PC}	V
$D\bar{D}$	0^{++}	C_a
$D^*\bar{D}/D\bar{D}^*$	1^{++}	$C_a + C_b$
	1^{+-}	$C_a - C_b$
$D^*\bar{D}^*$	0^{++}	$C_a - 2C_b$
	1^{+-}	$C_a - C_b$
	2^{++}	$C_a + C_b$

输入

1^{++} $C_a + C_b$: **X(3872)**

2^{++} $C_a + C_b$: **X(4013)**

Isoscalar sector

$$|X(3872)\rangle = \frac{1}{2}\left[(|D^{*+}D^-\rangle + |D^{*0}\bar{D}^0\rangle) - (|D^+D^{*-}\rangle + |D^0\bar{D}^{*0}\rangle)\right]$$

$$|X(4013)\rangle = \frac{1}{\sqrt{2}}\left(|D^{*+}D^{*-}\rangle + |D^{*0}\bar{D}^{*0}\rangle\right)$$

Particle Basis

$$C_c = \frac{1}{\sqrt{2}}(D^{*+}D^- - D^+D^{*-}) \quad C_n = \frac{1}{\sqrt{2}}(\bar{D}^{*0}D^0 - \bar{D}^0D^{*0})$$

$$V_{C_n-C_c} = \begin{pmatrix} C'_a + C'_b & C''_a + C''_b \\ C''_a + C''_b & C'_a + C'_b \end{pmatrix}$$

Isospin I=0

3871.69
4013.03

→ With HQSS X(3872) has a partner X(4013)

Zc(3900) and Zc(4020) as the isovector molecules

➢ **Contact-range potential**

state	J^{PC}	V
$D\bar{D}$	0^{++}	C_a
$D^*\bar{D}/D\bar{D}^*$	1^{++}	$C_a + C_b$
	1^{+-}	$C_a - C_b$
$D^*\bar{D}^*$	0^{++}	$C_a - 2C_b$
	1^{+-}	$C_a - C_b$
	2^{++}	$C_a + C_b$

输入

Zc(3900)

Zc(4020)

Isosvector sector

$$|Z_c(3900)\rangle = \frac{1}{2}\left[(|D^{*+}D^-\rangle - |D^{*0}\bar{D}^0\rangle) + (|D^+D^{*-}\rangle - |D^0\bar{D}^{*0}\rangle)\right]$$

$$|Z_c(4020)\rangle = \frac{1}{\sqrt{2}}(|D^{*+}D^{*-}\rangle - |D^{*0}\bar{D}^{*0}\rangle)$$

Isospin Basis

$$C_s + C_d\, q^2$$

Isospin I=1

3887 -28/2 I	
4024 -13/2 I	4024 -13/2 I

With HQSS Zc(3900) has a partner Zc(4020)

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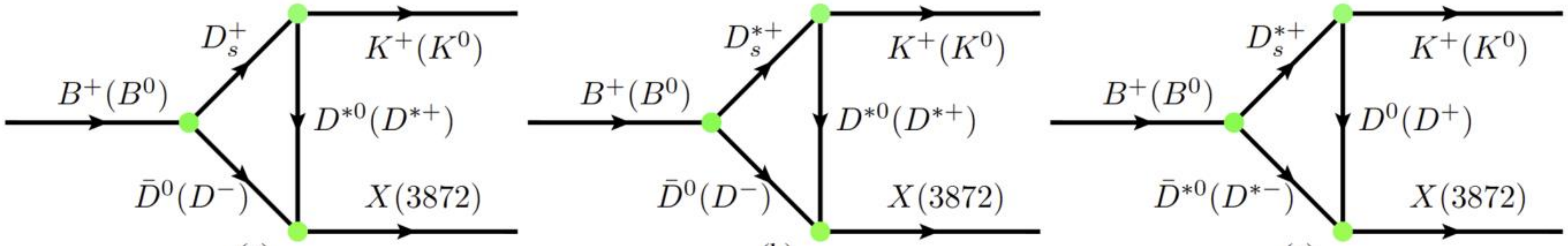
Producing XZ states in B meson decays

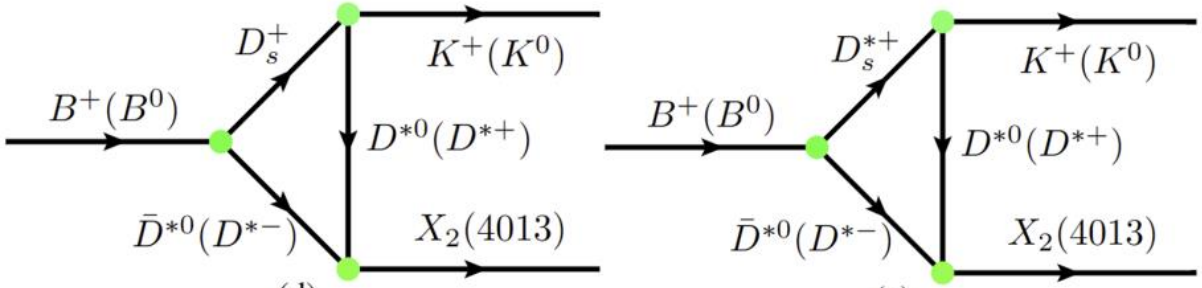
➢ **Triangle diagram mechanism**



(a) (b) (c)

$$|X(3872)\rangle = \frac{1}{2}\left[(|D^{*+}D^-\rangle + |D^{*0}\bar{D}^0\rangle) - (|D^+D^{*-}\rangle + |D^0\bar{D}^{*0}\rangle)\right]$$

$$|Z_c(3900)\rangle = \frac{1}{2}\left[(|D^{*+}D^-\rangle - |D^{*0}\bar{D}^0\rangle) + (|D^+D^{*-}\rangle - |D^0\bar{D}^{*0}\rangle)\right]$$

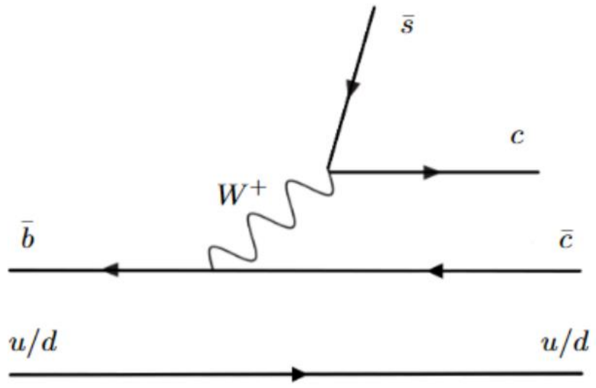


(d) (e)

$$|X(4013)\rangle = \frac{1}{\sqrt{2}}\left(|D^{*+}D^{*-}\rangle + |D^{*0}\bar{D}^{*0}\rangle\right) \qquad |Z_c(4020)\rangle = \frac{1}{\sqrt{2}}\left(|D^{*+}D^{*-}\rangle - |D^{*0}\bar{D}^{*0}\rangle\right)$$

Effective Lagrangian Approach

➢ Weak interaction



	Decay mode	RPP. [62]
a'_{1+}	$B^+ \to \bar{D}^0 D_s^+$	9.0 ± 0.9
a'_{10}	$B^0 \to D^- D_s^+$	7.2 ± 0.8
a^*_{1+}	$B^+ \to \bar{D}^0 D_s^{*+}$	7.6 ± 1.6
a^*_{10}	$B^0 \to D^- D_s^{*+}$	7.4 ± 1.6
a_{1+}	$B^+ \to \bar{D}^{*0} D_s^+$	8.2 ± 1.7
a_{10}	$B^0 \to D^{*-} D_s^+$	8.0 ± 1.1
a'^*_{1+}	$B^+ \to \bar{D}^{*0} D_s^{*+}$	17.1 ± 2.4
a'^*_{10}	$B^0 \to D^{*-} D_s^{*+}$	17.7 ± 1.4

10^{-2}

Naïve Factorisation

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

$$\mathcal{A}\left(B^+ \to D_s^+ \bar{D}^{0}\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a'_1 \left\langle D_s^+ |(s\bar{c})| 0\right\rangle \left\langle \bar{D}^{0} |(c\bar{b})| B^+\right\rangle ,$$

$$\mathcal{A}\left(B^+ \to D_s^{*+} \bar{D}^{0}\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a^*_1 \left\langle D_s^{*+} |(s\bar{c})| 0\right\rangle \left\langle \bar{D}^{0} |(c\bar{b})| B^+\right\rangle ,$$

$$\mathcal{A}\left(B^+ \to D_s^{*+} \bar{D}^{*0}\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a'^*_1 \left\langle D_s^{*+} |(s\bar{c})| 0\right\rangle \left\langle \bar{D}^{*0} |(c\bar{b})| B^+\right\rangle ,$$

Current matrix elements

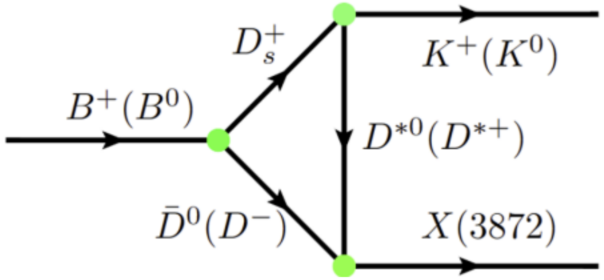
$$\left\langle D_s^- |(s\bar{c})| 0\right\rangle = i\, f_{D_s^-} p^\mu_{D_s^-} , \quad \left\langle D_s^{*-} |(s\bar{c})| 0\right\rangle = m_{D_s^{*-}} f_{D_s^{*-}} \epsilon^*_\mu$$

$$\left\langle \bar{D}^{*0} |(c\bar{b})| B^+\right\rangle = \epsilon^*_\alpha \left\{ -g^{\mu\alpha} (m_{\bar{D}^{*0}} + m_{B^+}) A_1\left(q^2\right) + P^\mu P^\alpha \frac{A_2\left(q^2\right)}{m_{\bar{D}^{*0}} + m_{B^+}} \right.$$

$$\left. + i\varepsilon^{\mu\alpha\beta\gamma} P_\beta q_\gamma \frac{V\left(q^2\right)}{m_{\bar{D}^{*0}} + m_{B^+}} + q^\mu P^\alpha \left[\frac{m_{\bar{D}^{*0}} + m_{B^+}}{q^2} A_1\left(q^2\right) - \frac{m_{B^+} - m_{\bar{D}^{*0}}}{q^2} A_2\left(q^2\right) - \frac{2 m_{\bar{D}^{*0}}}{q^2} A_0\left(q^2\right) \right] \right\} ,$$

$$\left\langle \bar{D}^{0} |(c\bar{b})| B^+\right\rangle = \left[(p_{B^+} + p_{\bar{D}^0})^\mu - \frac{m^2_{B^+} - m^2_{\bar{D}^0}}{q'^2} q'_\mu \right] F_{1D}(q'^2) + \frac{m^2_{B^+} - m^2_{\bar{D}^0}}{q'^2} q'_\mu F_{0D}(q'^2),$$

Effective Lagrangian Approach



➢ Hadron rescattering

$$\mathcal{L}_{D_s^* DK} = -ig_{D_s^* DK}(D\partial^\mu K D_{s\mu}^{*\dagger} - D_{s\mu}^*\partial^\mu K D^\dagger),$$
$$\mathcal{L}_{D_s D^* K} = -ig_{D_s D^* K}(D_s\partial^\mu K D_\mu^{*\dagger} - D_\mu^*\partial^\mu K D_s^\dagger),$$
$$\mathcal{L}_{D_s^* D^* K} = -g_{D_s^* D^* K}\varepsilon_{\mu\nu\alpha\beta}\partial^\mu D_s^{*\nu}\partial^\alpha D^{*\beta\dagger} K,$$

➢ Dynamical generation of molecules

$$\mathcal{L}_{X\bar{D}D^*} = g_{X\bar{D}D^*}X^\mu D_\mu^*\bar{D},$$
$$\mathcal{L}_{X_2\bar{D}^*D^*} = g_{X_2\bar{D}^*D^*}X_{2\mu\nu}D^{*\mu}\bar{D}^{*\nu},$$
$$\mathcal{L}_{Z_c D\bar{D}^*} = g_{Z_c D\bar{D}^*}Z_c^\mu D\bar{D}_\mu^*,$$
$$\mathcal{L}_{Z_c' D^*\bar{D}^*} = ig_{Z_c' D^*\bar{D}^*}\varepsilon_{\mu\nu\alpha\beta}\partial^\mu Z_c'^\nu D^{*\alpha}\bar{D}^{*\beta},$$

Molecules	$D^{*+}D^-$	D^+D^{*-}	$D^{*0}\bar{D}^0$	$D^0\bar{D}^{*0}$
$X(3872)$	$1/2$	$-1/2$	$1/2$	$-1/2$
$Z_c(3900)$	$1/2$	$1/2$	$-1/2$	$-1/2$
Molecules	$D^{*+}D^{*-}$	$D^{*0}\bar{D}^{*0}$		
$X_2(4013)$	$1/\sqrt{2}$	$1/\sqrt{2}$		
$Z_c(4020)$	$1/\sqrt{2}$	$-1/\sqrt{2}$		

Residues of the corresponding poles

$$T = (1 - VG)^{-1}V$$
$$g_i g_j = \lim_{\sqrt{s}\to\sqrt{s_0}}\left(\sqrt{s} - \sqrt{s_0}\right)T_{ij}(\sqrt{s})$$

Molecules	g_n	g_c
$X(3872)$	3.86 GeV	3.39 GeV
$X_2(4013)$	5.36 GeV	4.86 GeV
$Z_c(3900)$	5.02 GeV	5.02 GeV
$Z_c(4020)$	1.25	1.25

Production rates of XZ states in B meson decays

- **No extra parameters**

$$F(q^2) = \frac{F(0)}{1 - a\left(q^2/m_B^2\right) + b\left(q^4/m_B^4\right)}$$

Parameterise →

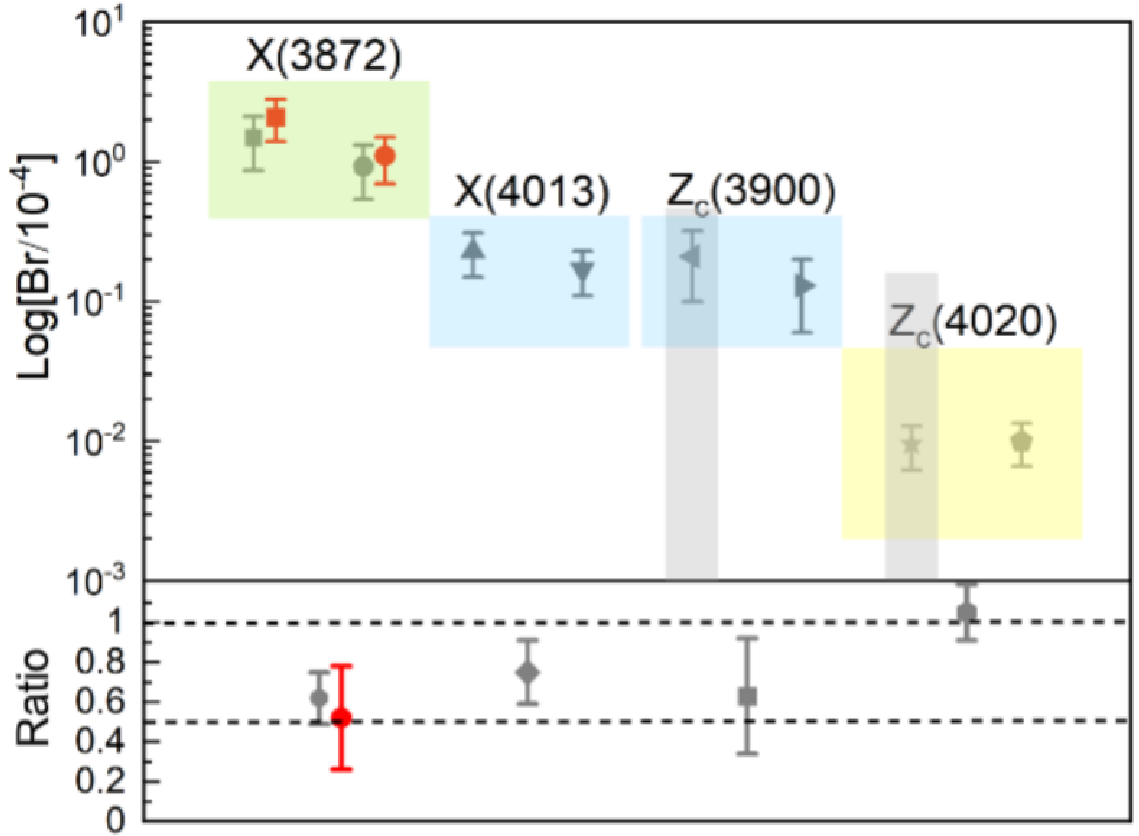
$$F(q^2) = F(0)\frac{\Lambda_1^2}{q^2-\Lambda_1^2}\frac{\Lambda_2^2}{q^2-\Lambda_2^2}$$

R. C. Verma, J. Phys. G 39, 025005 (2012)

Decay modes	Our predictions	Exp. [62]	Ratio	Exp. data [62]
$B^+ \to X(3872)K^+$	1.49 ± 0.62	2.1 ± 0.7	0.62 ± 0.13	0.52 ± 0.26
$B^0 \to X(3872)K^0$	0.93 ± 0.39	1.1 ± 0.4		
$B^+ \to X(4013)K^+$	0.23 ± 0.08	–	0.75 ± 0.16	–
$B^0 \to X(4013)K^0$	0.17 ± 0.06	–		
$B^+ \to Z_c(3900)K^+$	0.21 ± 0.11	$< 4.7 \times 10^{-5}$	0.63 ± 0.29	–
$B^0 \to Z_c(3900)K^0$	0.13 ± 0.07	–		
$B^+ \to Z_c(4020)K^+$	0.0095 ± 0.0033	$< 1.6 \times 10^{-5}$	1.05 ± 0.14	–
$B^0 \to Z_c(4020)K^0$	0.0100 ± 0.0034	–		

- Well describe the production rates of X(3872) in both B+ and B0 mesons as well as their ratio
- Attribute the isospin breaking two decays to the difference of X(3872) couplings to the neutral channel and electric component of $D^*\bar{D}$

Production rates of XZ states in B meson decays

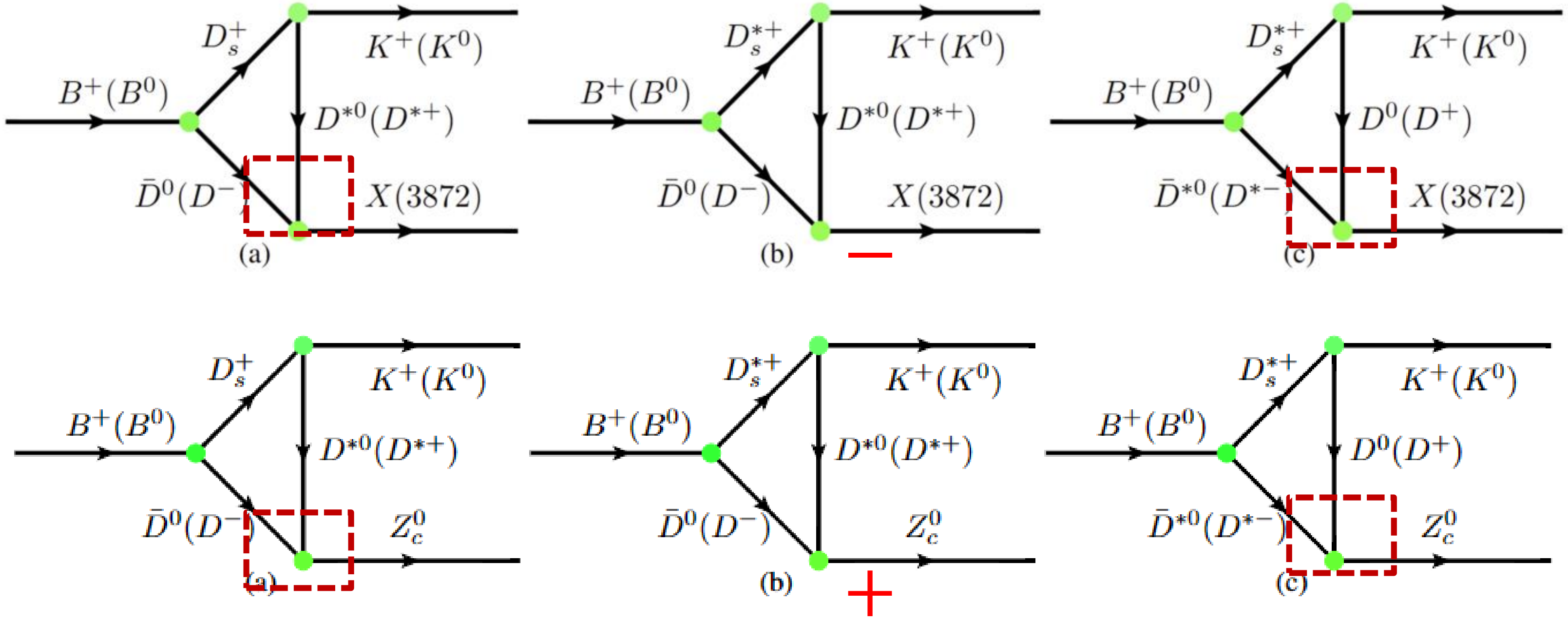


- Production rates of X(3872) in B decays are larger than those of X(4013) by one order of magnitude
- Production rates of Zc(3900) in B decays are larger than those of Zc(4020) by one order of magnitude
- Production rates of Zc(3900) in B decays are smaller than those of X(3872) by one order of magnitude

A hierarchy for the branching fractions of $\bar{D}^{(*)}D^{(*)}$ molecules in B decays

Production rates of XZ states in B meson decays

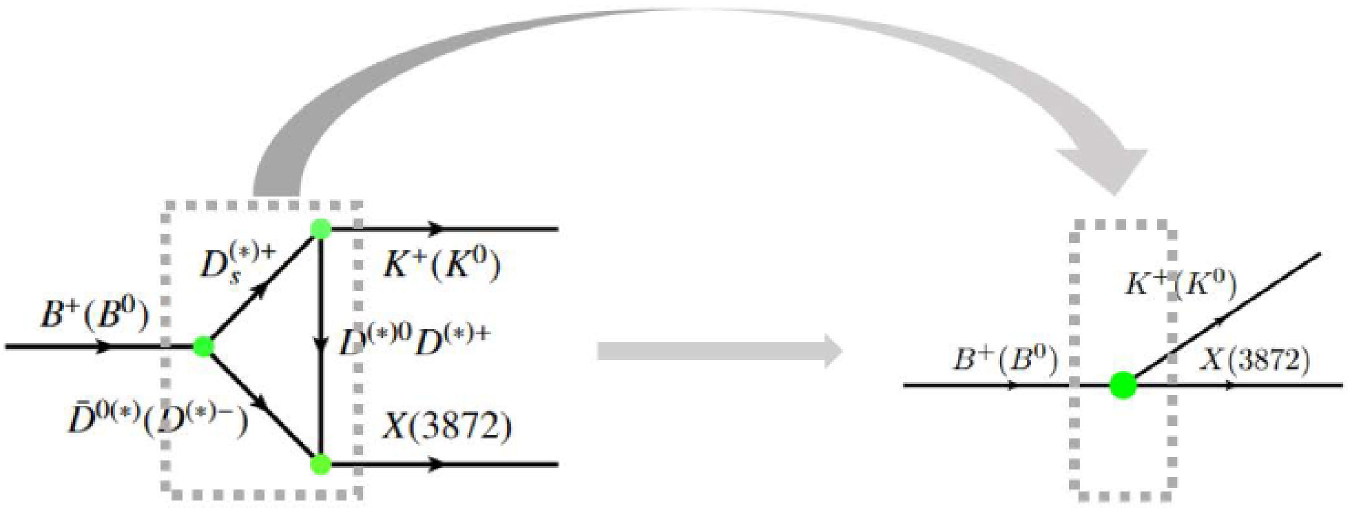
- **Why branching fractions of isoscalar molecules are larger than those of isovector molecules**

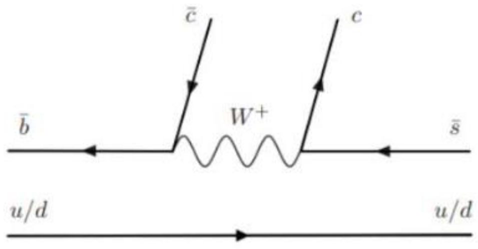


Molecules	$D^{*+}D^-$	D^+D^{*-}	$D^{*0}\bar{D}^0$	$D^0\bar{D}^{*0}$
$X(3872)$	1/2	−1/2	1/2	−1/2
$Z_c(3900)$	1/2	1/2	−1/2	−1/2

Amp a and c for isoscalar molecules add constructively, but those for isovector molecules add destructively

Decay constants of the charmoniumlike state





$$\langle X(3872)|(c\bar{c})|0\rangle = m_{X(3872)} f_{X(3872)} \varepsilon^\mu$$

$$\mathscr{A}_a = \int \frac{d^4 q_3}{(2\pi)^4} \frac{\mathrm{i}\mathscr{A}(B^+ \to D_s^+ \bar{D}^0)\mathscr{A}(D_s^+ \to D^{*0}K^+)\mathscr{A}(D^{*0}\bar{D}^0 \to X(3872))}{\left(q_1^2 - m_{D_s^+}^2\right)\left(q_2^2 - m_{\bar{D}^0}^2\right)\left(q_3^2 - m_{D^{*0}}^2\right)} \Longleftrightarrow \mathscr{A}(B \to X(3872)K) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_2 \langle X(3872)|(c\bar{c})|0\rangle \langle K|(s\bar{b})|B\rangle$$

➢ **Decay constants of XZ states as $\bar{D}^{(*)}D^{(*)}$ molecules**

Molecules	Decay Constants
$X(3872)$	$182.22^{+34.62}_{-42.98}$
$Z_c(3900)$	$68.85^{+16.14}_{-21.33}$
$Z_c(4020)$	$15.69^{+2.52}_{-3.01}$

Decay constant of X(3872) is extracted as 182 MeV

Decay Constant of X(3872) as a pure charmonium is 329 MeV

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Production rates of XZ states in b-flavored mesons decays

➢ Branching fractions of X(3872) in other decay processes

Decay modes	Exp. [44]	a_2	Decay modes	Our predictions	Exp. [44]
$B^+ \to J/\psi K^+$	10.20 ± 0.19	$0.271^{+0.002}_{-0.003}$	$B^+ \to X(3872) K^+$	$1.49^{+0.62}_{-0.62}$	2.1 ± 0.7
$B^+ \to J/\psi K^{*+}$	14.3 ± 0.8	$0.236^{+0.007}_{-0.007}$	$B^+ \to X(3872) K^{*+}$	$3.47^{+0.85}_{-0.85}$	$2.8 \sim 6$
$B_s^0 \to J/\psi \phi$	10.4 ± 0.4	$0.206^{+0.004}_{-0.004}$	$B_s^0 \to X(3872) \phi$	$2.39^{+0.58}_{-0.58}$	1.1 ± 0.4
$B_s^0 \to J/\psi \eta$	4.0 ± 0.7	$0.212^{+0.018}_{-0.019}$	$B_s^0 \to X(3872) \eta$	$0.41^{+0.11}_{-0.11}$	$-$

Consistent with the experimental data

➢ Predicting branching fractions of Zc(3900) and Zc(4020) in b-flavored mesons

Decay modes	Our Predictions	Decay modes	Our predictions
$B^+ \to Z_c(3900) K^{*+}$	$49.64^{+15.15}_{-15.15}$	$B^+ \to Z_c(4020) K^{*+}$	$2.51^{+0.51}_{-0.51}$
$B_s^0 \to Z_c(3900) \phi$	$34.07^{+10.36}_{-10.36}$	$B_s^0 \to Z_c(4020) \phi$	$1.63^{+0.33}_{-0.33}$
$B_s^0 \to Z_c(3900) \eta$	$5.83^{+1.86}_{-1.86}$	$B_s^0 \to Z_c(4020) \eta$	$0.23^{+0.05}_{-0.05}$

A new approach extracting the decay constants

Outline

- Research Background
- X(3872)/X(4013) and Zc(3900)/Zc(4020) as $\bar{D}^{(*)}D^*$ HQSS multiplet hadronic molecules
- Producing XZ states in B decays
- Summary

Summary

- We propose a triangle diagram mechanism to produce $\boldsymbol{X(3872)}$ and $\boldsymbol{Zc(3900)}$ as $\bar{\boldsymbol{D}}^{*}\boldsymbol{D}$ molecules as well as their HQSS partners $\bar{\boldsymbol{D}}^{*}\boldsymbol{D}^{*}$ molecules in B decays.
  - The absolute branching fraction of $\boldsymbol{X(3872)}$ in B decays as well as their ratio
  - A hierarchy of branching fractions for all the $\bar{\boldsymbol{D}}^{*}\boldsymbol{D}$ and $\bar{\boldsymbol{D}}^{*}\boldsymbol{D}^{*}$ molecules in B decays
  - Why production rate of $\boldsymbol{Zc(3900)}$ in B decay is lower than that of $\boldsymbol{X(3872)}$

- Using triangle diagram mechanism, we extract the decay constants of $\bar{\boldsymbol{D}}^{*}\boldsymbol{D}^{(*)}$ molecules, and predict their branching fractions in other decay modes

Thanks for your attention!