The hidden-charm strong decays of the Z_c states

arXiv:1912.12781[hep-ph]

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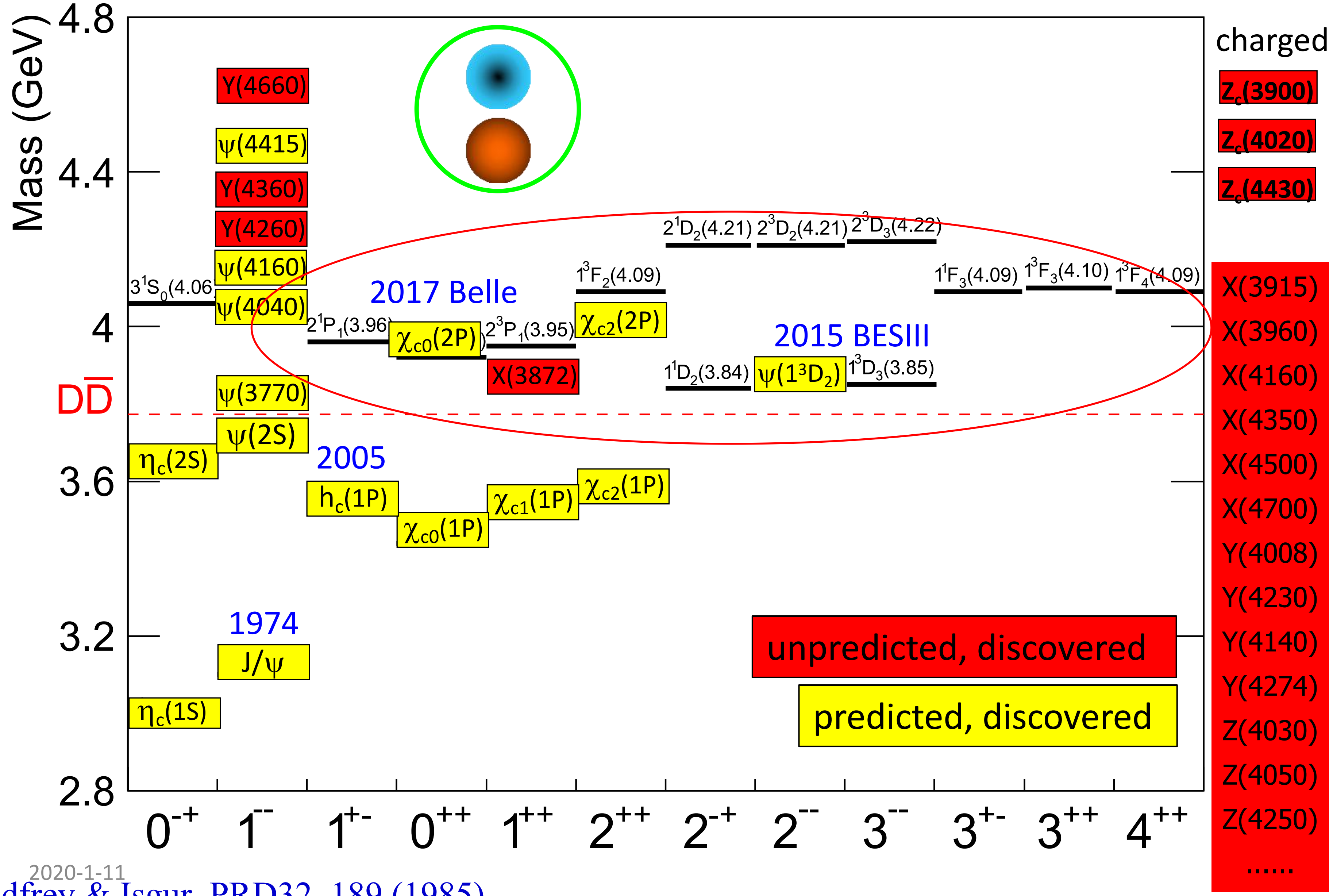
Outline

- Zc states
  - Experimental status
  - Theoretical status
- quark-exchange model
  - Zc(3900)
  - Zc(4020)
  - Zc(4430)

Charmonium(like) spectroscopy



Godfrey & Isgur, PRD32, 189 (1985)

XYZ states production mechanisms

<table>
<tr><th>B meson decays</th><th>ISR in the e⁺e⁻ annihination</th><th>Double charmonium production processes</th><th>Two photon fusion processes</th><th>Hadronic decays of Y(4260)</th></tr>
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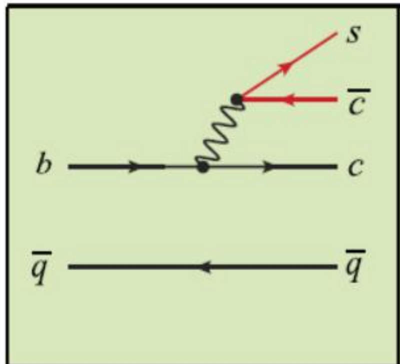
<td>
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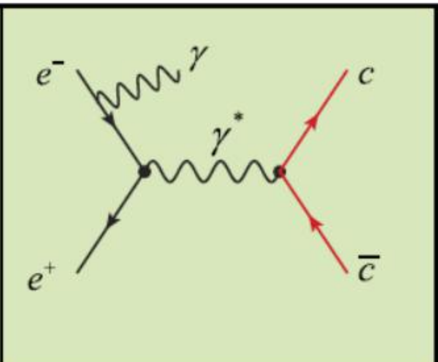
<td>
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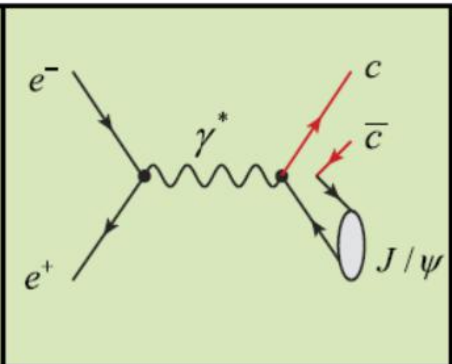
<td>
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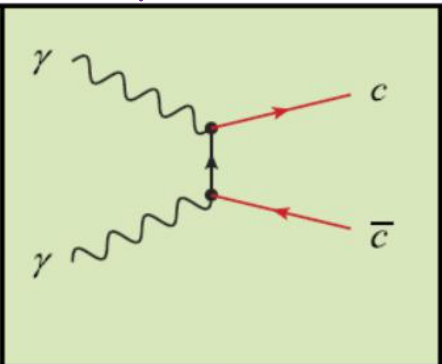
<td>
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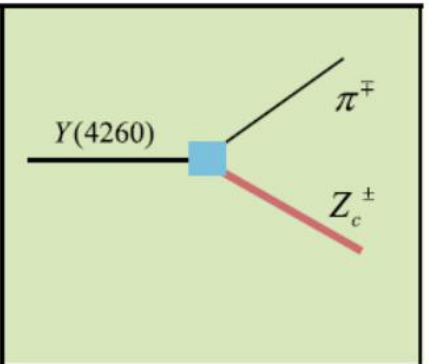
<td>
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<tr>
<td>$X(3872)$
$Y(3940)$
$Z^+(4430)$
$Z^+(4051)$
$Z^+(4248)$
$Y(4140)$
$Y(4274)$
$Z_c^+(4200)$
$Z^+(4240)$
$X(3823)$</td>
<td>$Y(4260)$
$Y(4008)$
$Y(4360)$
$Y(4630)$
$Y(4660)$</td>
<td>$X(3940)$
$X(4160)$</td>
<td>$X(3915)$
$X(4350)$
$Z(3930)$</td>
<td>$Z_c(3900)$
$Z_c(4025)$
$Z_c(4020)$
$Z_c(3885)$</td>
</tr>
</table>

Chen, Physics Reports 639,1-121(2016)

Experimential status: Zc(3900) & Zc(4020)

Experimental information of the charged charmonium-like states Zc(3900), Zc(3885), Zc(4020), Zc(4025)

State	M (MeV)	Γ (MeV)	Process (decay mode)	
$Z_c(3900)$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$e^+e^- \to Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII
	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$	$e^+e^- \to Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	Belle
	$3886 \pm 4 \pm 2$	$37 \pm 4 \pm 8$	$e^+e^- \to \psi(4160) \to \pi^- + (J/\psi\,\pi^+)$	Xiao et al.
$Z_c(3885)$	$3882.2 \pm 1.1 \pm 1.5$	$26.5 \pm 1.7 \pm 2.1$	$e^+e^- \to Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII
$Z_c(4020)$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$e^+e^- \to Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII
$Z_c(4025)$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$e^+e^- \to Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII

The productions and decay modes:

$$e^+e^- \to \begin{cases} Z_c(3900)\pi^\mp \to J/\psi\pi^\pm\pi^\mp, \\ Z_c(4025)\pi^\mp \to (D^*\bar{D}^*)^\pm\pi^\mp, \\ Z_c(4020)\pi^\mp \to h_c\pi^\pm\pi^\mp, \\ Z_c(3885)\pi^+ \to (D\bar{D}^*)^-\pi^+. \end{cases}$$

$$\pi^\mp Z_c(3900)^\pm \to \pi^\mp\rho^\pm\eta_c$$

$$\pi^\mp Z_c(4020)^\pm \to \pi^\mp\rho^\pm\eta_c$$

$$R_{Zc(3900)} = \frac{\eta_c\rho^\pm}{J/\psi\pi^\pm} = 2.2 \pm 0.9$$

$J^P=1^+$

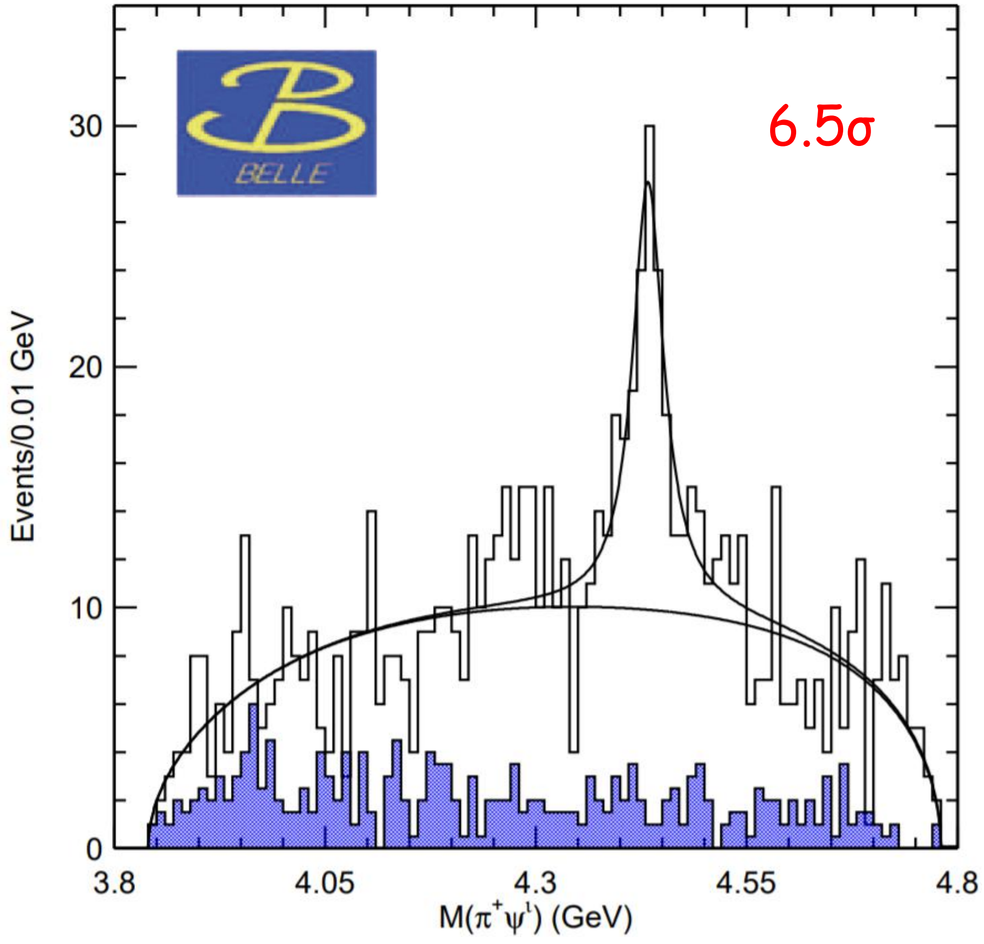
$$R_{Zc(4020)} = \frac{\eta_c\rho^\pm}{h_c\pi^\pm} < 1.6$$

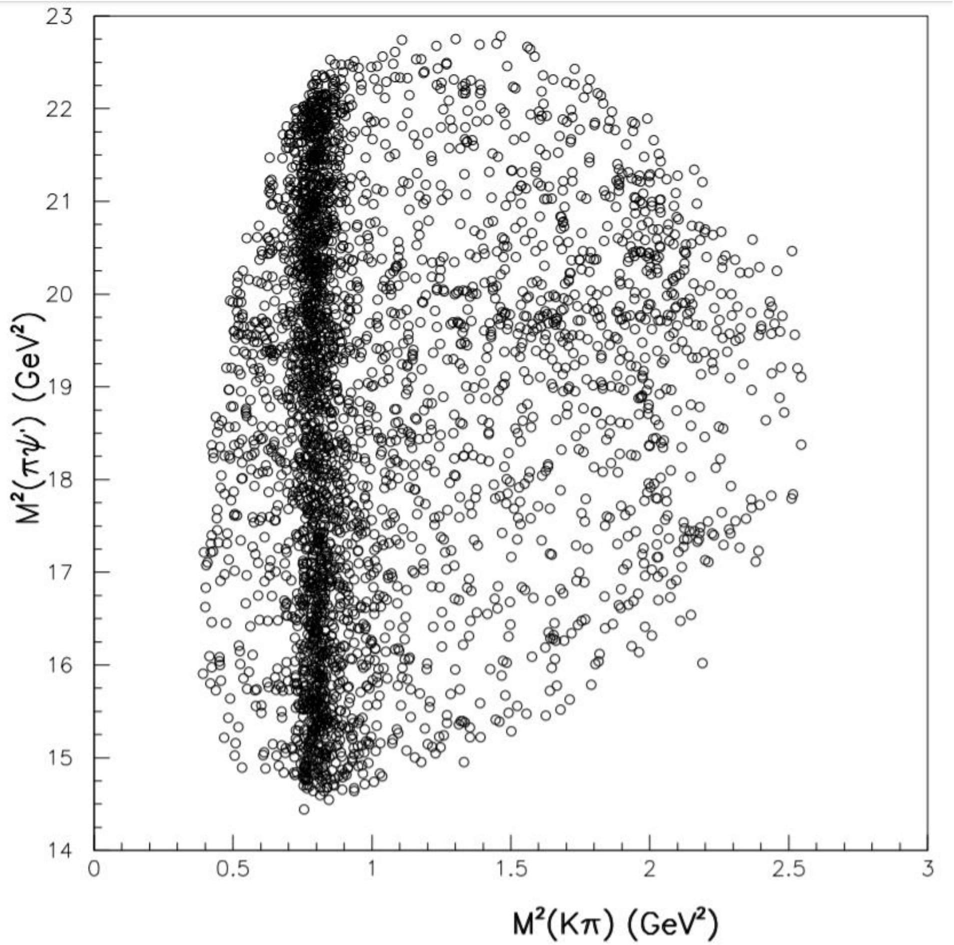
$J^P=1^+?$

Experimential status: Zc(4430)

PRL 100, 142001(2008)

$$B \to K\pi^{\pm}\psi(3686)$$





M=4433±4±2 MeV

Γ=45$^{+18}_{-13}$$^{+30}_{-13}$ MeV

Experimential status: Zc(4430)

Babar: not seen PRD 79, 112001(2009)

Belle: continued

The resonance parameters for the $Z^+(4430)$ and the observed decay channels.

Experiment	Mass [MeV]	Width [MeV]	Decay mode
Belle[2] [104]	4443^{+15+19}_{-12-13}	107^{+86+74}_{-43-56}	$Z^+(4430) \to \pi^+\psi(3686)$
Belle[3] [106]	$4485 \pm 22^{+28}_{-11}$	200^{+41+26}_{-46-35}	$Z^-(4430) \to \pi^-\psi(3686)$ favored 1^+
Belle[4] [107]	–	–	Evidence for $Z^+(4430) \to \pi^+ J/\psi$
LHCb [108]	$4475 \pm 7^{+15}_{-25}$	$172 \pm 13^{+37}_{-34}$	$Z^-(4430) \to \pi^-\psi(3686)$ established 1^+

104 PRD 80, 031101(2009)

107 PRD 90, 112009(2014)

106 PRD 88, 074026(2013)

108 PRL 112, 222002(2014)

$J^P=1^+$

Theoretical interpretations of the Zc states

Zc(3900) & Zc(4020)

- Molecular resonances: $D\bar{D}^* \& D^*\bar{D}^*$ — CPC 36, 194-204(2012)
- S-wave tetraquark state assignment: $c\bar{c}q\bar{q}$ — PRD 83, 034010(2011); PRD 92, 054002(2015); EPJC 74, 2773(2014)
- Kinematical effects: triangle singularities, coupled channel cusp effects and so on — PLB 747, 410-416(2015); PRD 91, 034009(2015); PRD 84, 034032(2011)

Zc(4430)

- Molecular states: S-wave $\bar{D}_1 D^*$ with $0^-, 1^-, 2^-$ — PRD 77, 034003(2018)

  P-wave $\bar{D}_1 D^*$ or $\bar{D}_2 D^*$ with 1^+ — PRD 90, 037502(2014)
- tetraquark states: $2S\ cq\bar{c}\bar{q}$ — EPJC 58, 399-405(2008)
- Cusp effect — J.Phys.G 35, 075005(2008)
- triangle singularities — arXiv:1909.03976

Theoretical ratios for Zc(3900)

TABLE I: The theoretical predictions of $R_{Z_c(3900)}$ in various models.

Experiment	Molecular	Tetraquark
2.2 ± 0.9 [43]	$0.046^{+0.025}_{-0.017}$ [46]	230^{+330}_{-140} [46]
	$1.78^{+0.41}_{-0.37}$ [44]	$0.27^{+0.40}_{-0.17}$ [46]
	0.12 [47]	$1.86^{+0.41}_{-0.35}$ [44]
	0.007 [45]	$1.28^{+0.37}_{-0.30}$ [44]
	0.059 [51]	2.2 [51]
		1.08 ± 0.88 [49]
		0.95 ± 0.40 [48]
		0.66 [36]
		0.57 ± 0.17 [50]

$$R_{Zc(3900)} = \frac{\eta_c \rho^{\pm}}{J/\psi \pi^{\pm}} = 2.2 \pm 0.9$$

36、PRD 87, 111102(2013)

43、arXiv:1906.00831[hep.ex]

44、PRD94, 094017(2016)

45、PoS Hadron 2013, 189(2013)

46、PLB 746, 194(2015)

47、EPJC 73, 2561(2013)

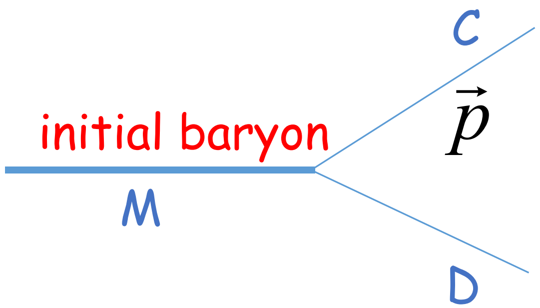
48、PRD 88, 016004(2013)

49、EPJC 78, 14(2018)

50、PRD 93, 074002(2016)

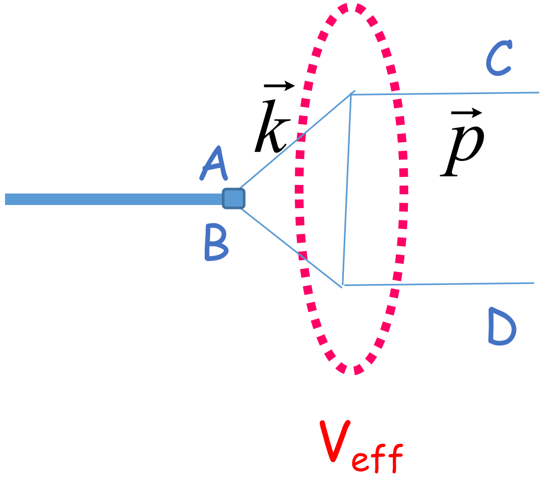
51、arXiv:1910.03269[hep-ph]

Two-body decay ⟶ Molecualr states decay



three-momentum of the final state

$$\frac{d\Gamma}{d\Omega} = (2\pi)^3 \frac{E_C E_D}{4\pi^2} \frac{|\vec{p}|}{M} |h_{fi}|^2$$



$$h_{fi} = \langle f | V_{eff} | i \rangle = \frac{1}{(2\pi)^3} \int d\vec{p} d\vec{k} \delta^3(\vec{p} - \vec{c}) V_{eff} \sum_l R_l(\vec{k}) Y_{lm}(\vec{k})$$

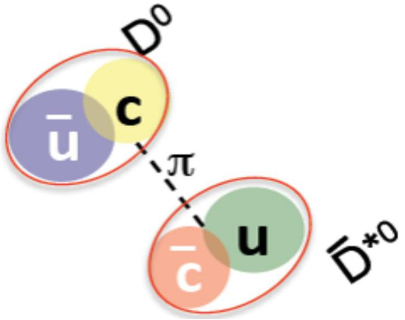
$$\Rightarrow \quad \Gamma = \frac{E_C E_D |\vec{p}|}{M(2\pi)^3} |M_{ll}|^2$$

$$M_{ll} = \int_{-1}^{1} P_l(x) V_{eff}(k, p, x) R(k) k^2 dk dx$$

The wave functions in the molecular scenario

Molecular

- Zc(3900): $D\overline{D}^{*}+c.c$
- Zc(4020): $D^{*}\overline{D}^{*}$
- Zc(4430): $D(2S)\overline{D}^{*}+c.c$



- Mesons spatial wave function: GI, PRD 32, 189(1985)

$$\phi = \sum_1^n a_n\phi_n(\vec{p}) = \sum_1^n a_n N_n (2\vec{p})^l \sqrt{\frac{4\pi}{(2l+1)!!}} Y_{lm}(\vec{p}) \exp^{-\frac{p^2}{2n\beta^2}}$$

$$N_n = \left(\frac{1}{\pi n\beta^2}\right)^{\frac{3}{4}}\left(\frac{1}{2n\beta^2}\right)^{-\frac{l}{2}}$$

- Relative spatial wave function:

$$\phi_r = \frac{2\exp^{-\frac{p_r^2}{2\alpha^2}}}{\pi^{\frac{1}{4}}\alpha^{\frac{3}{2}}} \qquad \sqrt{\frac{3}{2\alpha^2}} = r_{mean}$$

The wave functions in the tetraquark scenario

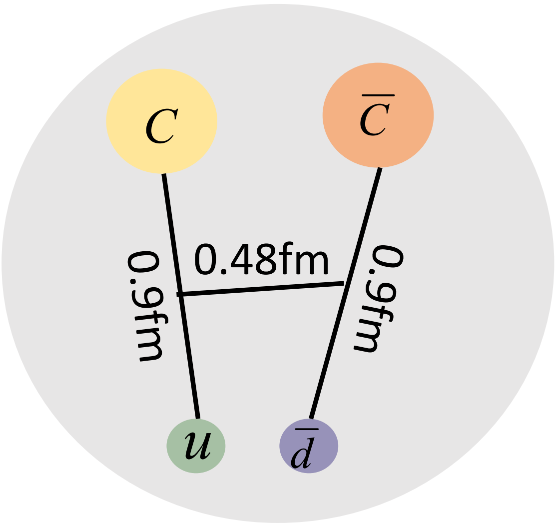
Tetraquark

Zc(3900): $\frac{1}{\sqrt{2}}\left\{\left[[cu]^{s=0}_{\bar{3}_c}[\bar{c}\bar{d}]^{s=1}_{3_c}\right]^{s=1}_{1_c}+\left[[cu]^{s=1}_{\bar{3}_c}[\bar{c}\bar{d}]^{s=0}_{3_c}\right]^{s=1}_{1_c}\right\}$

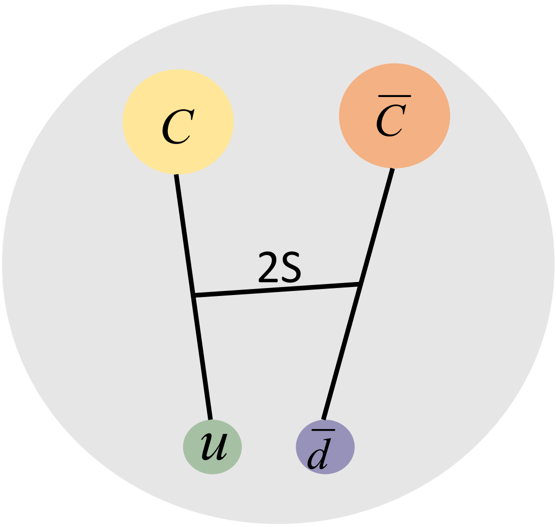
Zc(4020): $\left[[cu]^{s=1}_{\bar{3}_c}[\bar{c}\bar{d}]^{s=1}_{3_c}\right]^{s=1}_{1_c}$

PLB 749, 194(2015) Ping

Zc(4430): $\frac{1}{\sqrt{2}}\left\{\left[[cu]^{s=0}_{\bar{3}_c}[\bar{c}\bar{d}]^{s=1}_{3_c}\right]^{s=1}_{1_c}+\left[[cu]^{s=1}_{\bar{3}_c}[\bar{c}\bar{d}]^{s=0}_{3_c}\right]^{s=1}_{1_c}\right\}$



Zc(3900)/Zc(4020)



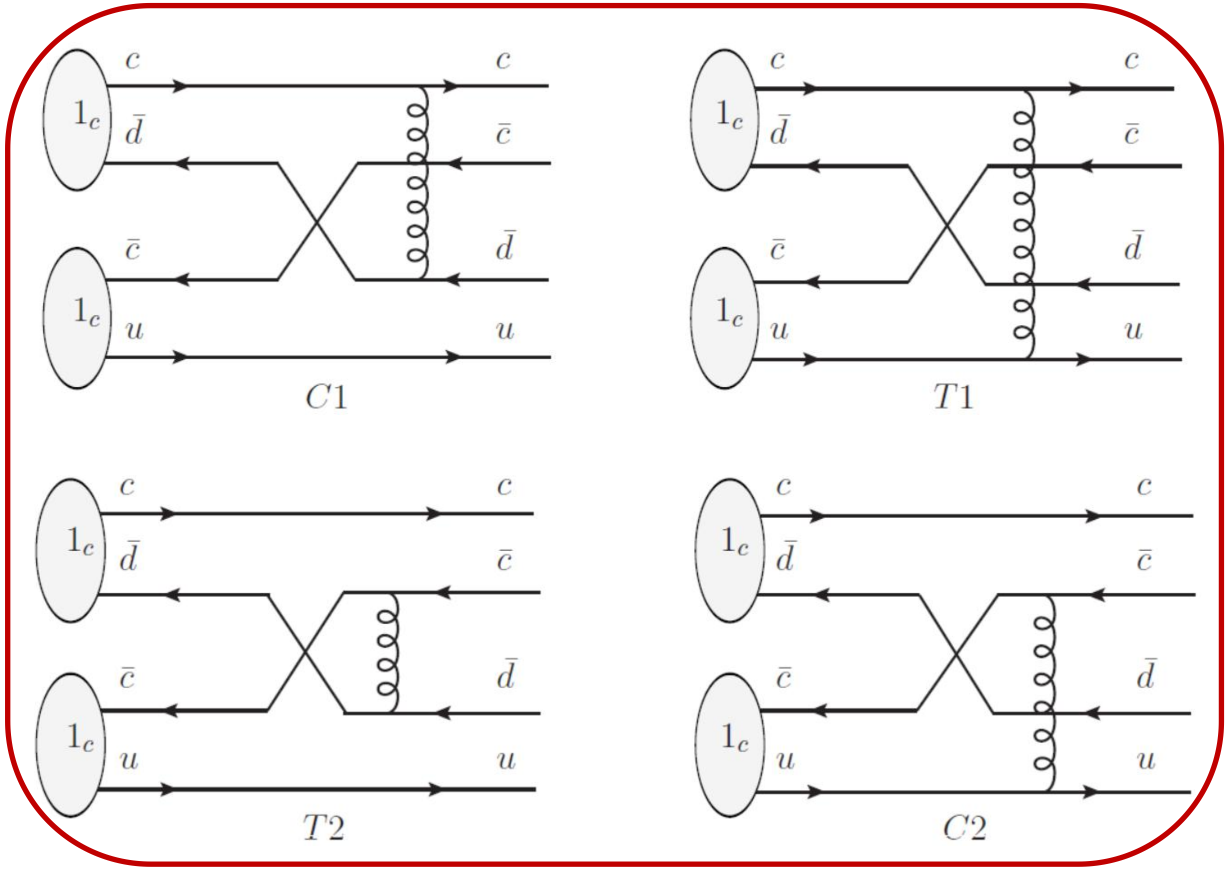
Zc(4430)

$$\frac{\sqrt{6}\exp^{-\frac{k_X^2}{2\alpha_X^2}}}{\pi^{1/4}\alpha_X^{3/2}}\left(1-\frac{2k_X^2}{3\alpha_X^2}\right)$$

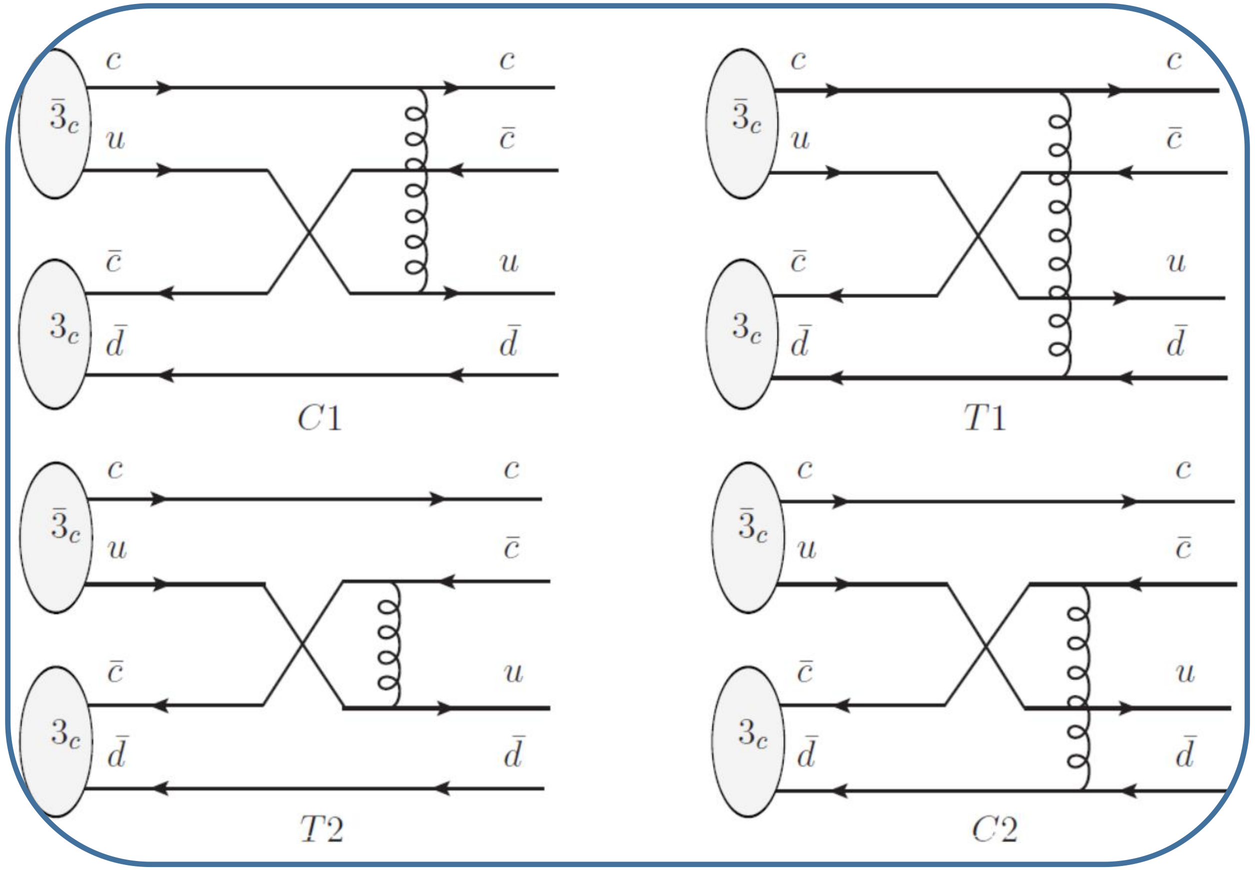
$$\sqrt{\frac{7}{2\alpha_X{}^2}}=r_{mean}$$

Quark-exchange Model

- At the hadron level: $A(c\bar{d}) + B(\bar{c}u) \rightarrow C(c\bar{c}) + D(u\bar{d})$ short-range interactions
- At the quark level:



Molecular



Tetraquark

One-gluon-exchange (OGE) potential at quark level

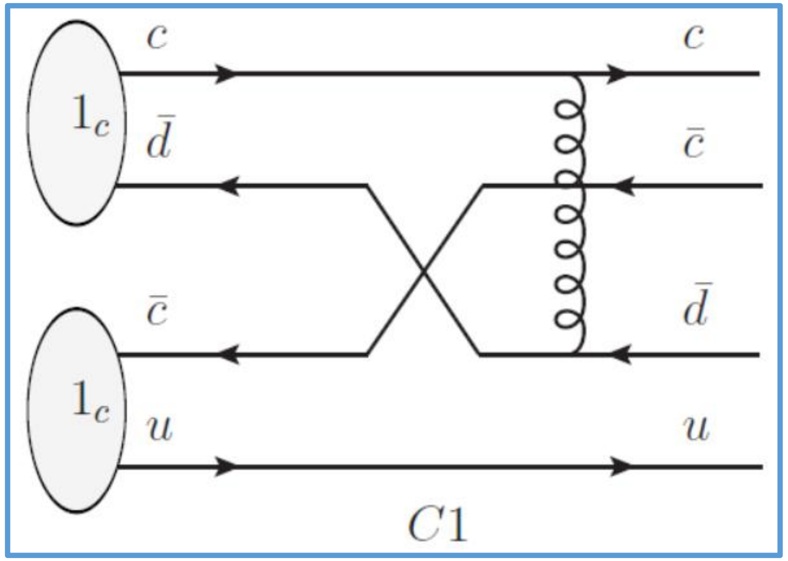
Quark-exchange Model:

PRC 65,014903(2002)

Model:

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\ln(A+Q^2/B^2)}$$

$$H_{ij} = \sum_{i<j} \frac{\lambda_i}{2}\frac{\lambda_j}{2}\left\{\frac{\alpha_s}{r_{ij}} - \frac{3b}{4}r_{ij} - \frac{8\pi\alpha_s}{3m_i m_j}\frac{\sigma^3}{\pi^{3/2}}e^{-\sigma^2 r_{ij}^2} S_i \cdot S_j\right\}$$



Parameter	b	0.18	GeV^2
	σ	0.897	GeV
	A	10	
	B	0.31	GeV
Constituent quark mass	m_q	0.334	GeV
	m_c	1.776	GeV

The effective potential are given as the product of the factors

$$h_{fi} = I_{color} I_{spin-flavor} I_{space}$$

$$I_{\text{color}} = \left\langle \omega(13)_{1_c}\, \omega(24)_{1_c} \left| \frac{\lambda_i \lambda_j}{4} \right| \underline{\omega(12)_{1_c}\, \omega(34)_{1_c}} \right\rangle$$ Molecular

$$I_{\text{color}} = \left\langle \omega(13)_{1_c}\, \omega(24)_{1_c} \left| \frac{\lambda_i \lambda_j}{4} \right| \underline{\omega(12)_{\bar{3}_c}\, \omega(34)_{3_c}} \right\rangle$$ Tetraquark

$$I_{\text{spin-flavor}} = \left\langle \left[\chi_C(13)^{I_C}_{S_C}\, \chi_D(24)^{I_D}_{S_D} \right]^{I'}_{S'} \left| \hat{O}_s \right| \left[\chi_A(12)^{I_A}_{S_A}\, \chi_B(34)^{I_B}_{S_B} \right]^{I}_{S} \right\rangle$$

$$I_{\text{space}} = \left\langle \psi(13)\psi(24) \left| \hat{O}_r \right| \psi(12)\psi(34) \right\rangle$$

$$\lambda_i = \begin{cases} \lambda_i & \text{Quark} \\ -\lambda_i^T & \text{Antiquark} \end{cases}$$

$$\hat{O}_s = \begin{cases} 1 & \text{Coul \& Linear} \\ s_i \cdot s_j & \text{Hyperfine} \end{cases}$$

$$\hat{O}_r = \begin{cases} \frac{1}{r_{ij}} & \text{Coul} \\ r_{ij} & \text{Linear} \\ e^{-\sigma^2 r_{ij}^2} & \text{Hyperfine} \end{cases}$$

The spin-flavor-color factors for the diagrams [C1,T1,T2,C2]

Molecular:

Initial state	Final state	Coul & linear	Hyperfine
$D\bar{D}^*$	$\eta_c\rho$	$\frac{2}{9}[-1,1,1,-1]$	$\frac{1}{18}[3,-1,3,-1]$
	$J/\psi\pi$	$-\frac{2}{9}[-1,1,1,-1]$	$\frac{1}{18}[-3,-3,1,1]$
$D^*\bar{D}^*$	$\eta_c\rho$	$\frac{2\sqrt{2}}{9}[-1,1,1,-1]$	$-\frac{\sqrt{2}}{18}[1,1,1,1]$
	$J/\psi\pi$	$\frac{2\sqrt{2}}{9}[-1,1,1,-1]$	$-\frac{\sqrt{2}}{18}[1,1,1,1]$
$D(2S)\bar{D}^*$	$\eta_c\rho$	$\frac{2}{9}[-1,1,1,-1]$	$\frac{1}{18}[3,-1,3,-1]$
	$J/\psi\pi$	$-\frac{2}{9}[-1,1,1,-1]$	$\frac{1}{18}[-3,-3,1,1]$

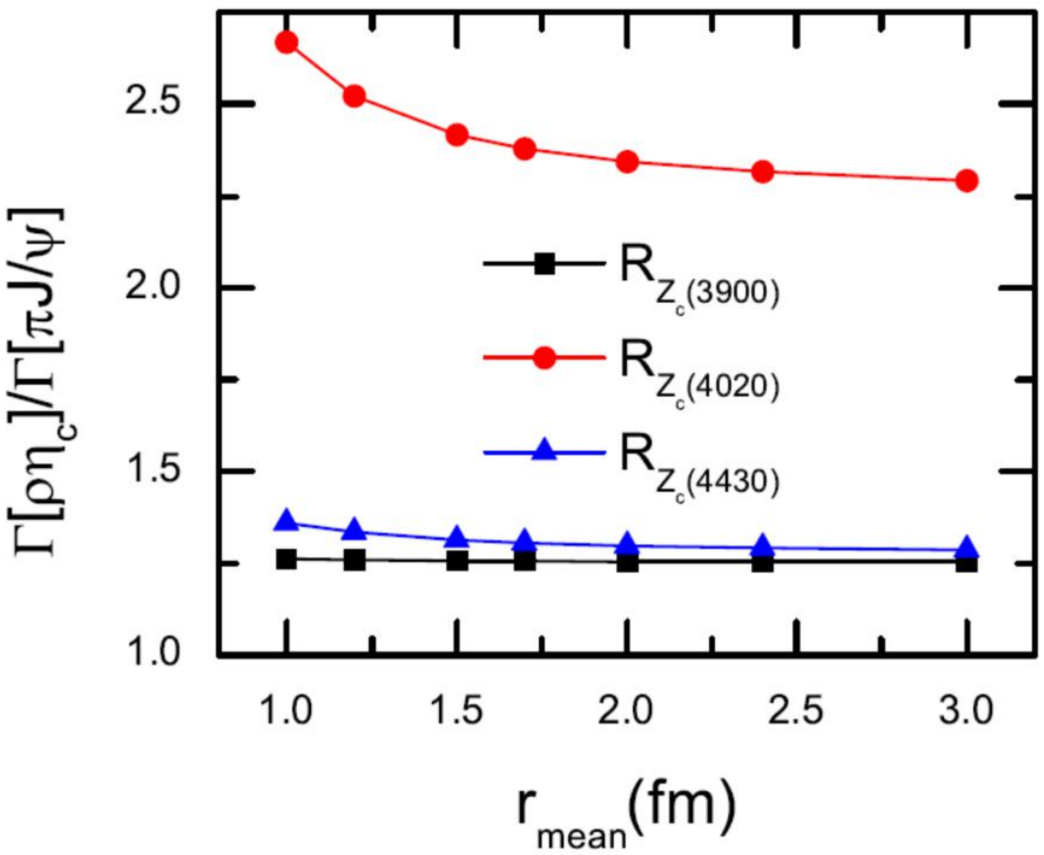
Tetraquark:

$Z_c(3900)\left[[cu]^{S=0}_{\bar{3}_c}[\bar{c}\bar{u}]^{S=1}_{3_c}\right]^{S=1}_{1_c}$	$\eta_c\rho$	$\frac{1}{3\sqrt{3}}[-1,1,1,-1]$	$[\frac{1}{4\sqrt{3}},-\frac{1}{12\sqrt{3}},\frac{1}{4\sqrt{3}},-\frac{1}{12\sqrt{3}}]$
	$J/\psi\pi$	$-\frac{1}{3\sqrt{3}}[-1,1,1,-1]$	$[-\frac{1}{4\sqrt{3}},-\frac{1}{4\sqrt{3}},\frac{1}{12\sqrt{3}},\frac{1}{12\sqrt{3}}]$
$Z_c(4020)\left[[cu]^{S=1}_{\bar{3}_c}[\bar{c}\bar{u}]^{S=1}_{3_c}\right]^{S=1}_{1_c}$	$\eta_c\rho$	$\frac{2}{3\sqrt{6}}[-1,1,1,-1]$	$[-\frac{1}{6\sqrt{6}},-\frac{1}{6\sqrt{6}},-\frac{1}{6\sqrt{6}},-\frac{1}{6\sqrt{6}}]$
	$J/\psi\pi$	$\frac{2}{3\sqrt{6}}[-1,1,1,-1]$	$[-\frac{1}{6\sqrt{6}},-\frac{1}{6\sqrt{6}},-\frac{1}{6\sqrt{6}},-\frac{1}{6\sqrt{6}}]$
$Z_c(4430)\left[[cu]^{S=0}_{\bar{3}_c}[\bar{c}\bar{u}]^{S=1}_{3_c}\right]^{S=1}_{1_c}$	$\eta_c\rho$	$\frac{1}{3\sqrt{3}}[-1,1,1,-1]$	$[\frac{1}{4\sqrt{3}},-\frac{1}{12\sqrt{3}},\frac{1}{4\sqrt{3}},-\frac{1}{12\sqrt{3}}]$
	$J/\psi\pi$	$-\frac{1}{3\sqrt{3}}[-1,1,1,-1]$	$[-\frac{1}{4\sqrt{3}},-\frac{1}{4\sqrt{3}},\frac{1}{12\sqrt{3}},\frac{1}{12\sqrt{3}}]$

The spatial factors for the diagrams [C1,T1,T2,C2]

$$
\begin{aligned}
I^{C1}_{\text{space}} &= \int\int d\vec{q}d\vec{p}_3\psi_A(-\vec{q}-\vec{p}_3+\vec{p}_c-f_1\vec{k})\psi_B(\vec{p}_3+f_2\vec{k}) \\
&\quad \hat{O}_q\psi^*_C(-\vec{p}_3+f_3\vec{p}_c)\psi^*_D(\vec{p}_3-f_4\vec{p}_c+\vec{k}), \\
I^{T1}_{\text{space}} &= \int\int d\vec{q}d\vec{p}_3\psi_A(-\vec{q}-\vec{p}_3+\vec{p}_c-f_1\vec{k})\psi_B(\vec{p}_3+f_2\vec{k}) \\
&\quad \hat{O}_q\psi^*_C(-\vec{p}_3+f_3\vec{p}_c)\psi^*_D(\vec{q}+\vec{p}_3-f_4\vec{p}_c+\vec{k}), \\
I^{T2}_{\text{space}} &= \int\int d\vec{q}d\vec{p}_3\psi_A(-\vec{p}_3+\vec{p}_c-f_1\vec{k})\psi_B(\vec{p}_3+f_2\vec{k}) \\
&\quad \hat{O}_q\psi^*_C(\vec{q}-\vec{p}_3+f_3\vec{p}_c)\psi^*_D(\vec{p}_3-f_4\vec{p}_c+\vec{k}), \\
I^{C2}_{\text{space}} &= \int\int d\vec{q}d\vec{p}_3\psi_A(-\vec{q}-\vec{p}_3+\vec{p}_c-f_1\vec{k})\psi_B(\vec{p}_3+f_2\vec{k}) \\
&\quad \hat{O}_q\psi^*_C(-\vec{q}-\vec{p}_3+f_3\vec{p}_c)\psi^*_D(\vec{q}+\vec{p}_3-f_4\vec{p}_c+\vec{k}).
\end{aligned}
$$

Ratios within the molecular scenario



$R_{Zc(3900)}$~1.3

$R_{Zc(4020)}$~(2.7-2.3)

$R_{Zc(4430)}$~(1.4-1.3)

$M_{Zc(3900)}$=3886.6±2.4 MeV
$\Gamma_{Zc(3900)}$=28.2±2.6 MeV

$D\bar{D}^*$ I(J^{PC})=1(1^{+-})

$$\frac{\eta_c \rho^\pm}{J/\psi\pi^\pm} = 2.2 \pm 0.9$$

$M_{Zc(4020)}$=4024.1±1.9 MeV
$\Gamma_{Zc(4020)}$=13±5 MeV

$D^*\bar{D}^*$ I(J^{PC})=1($?^{?-}$) 1^{+-}?

$M_{Zc(4430)}$=4478^{+15}_{-18} MeV
$\Gamma_{Zc(4430)}$=181±31 MeV

$D(2S)\bar{D}^*$ I(J^{PC})=1(1^{+-})

Ratios are similar within the molecular and tetraquark scenarios

Tetraquark

$R_{Zc(3900)}$~1.6

$R_{Zc(4020)}$~1.6

$R_{Zc(4430)}$~(1.7-1.4)

Molecular

$R_{Zc(3900)}$~1.3

$R_{Zc(4020)}$~(2.7-2.3)

$R_{Zc(4430)}$~(1.4-1.3)

$M_{Zc(3900)}$=3886.6±2.4 MeV
$\Gamma_{Zc(3900)}$=28.2±2.6 MeV

$I(J^{PC})=1(1^{+-})$

$$\frac{\eta_c \rho^\pm}{J/\psi\pi^\pm} = 2.2 \pm 0.9$$

$M_{Zc(4020)}$=4024.1±1.9 MeV
$\Gamma_{Zc(4020)}$=13±5 MeV

$I(J^{PC})=1(?^{?-})$ 1^{+-}?

$M_{Zc(4430)}$=4478^{+15}_{-18} MeV
$\Gamma_{Zc(4430)}$=181±31 MeV

$I(J^{PC})=1(1^{+-})$

Ratios between Zc(3900) and Zc(4020) are greatly different in two scenarios:

√ **Molecular:**

$$\frac{\Gamma[Z_c(3900) \to \eta_c\rho]}{\Gamma[Z_c(4020) \to \eta_c\rho]} = 12.5,$$

$$\frac{\Gamma[Z_c(3900) \to J/\psi\pi]}{\Gamma[Z_c(4020) \to J/\psi\pi]} = 24.2.$$

Tetraquark:

$$\frac{\Gamma[Z_c(3900) \to \eta_c\rho]}{\Gamma[Z_c(4020) \to \eta_c\rho]} = 1.2,$$

$$\frac{\Gamma[Z_c(3900) \to J/\psi\pi]}{\Gamma[Z_c(4020) \to J/\psi\pi]} = 1.2.$$

Experiments

	$\eta_c\rho$	$J/\psi\pi$
Zc(3900)	√	√
Zc(4020)	√	✗

Summary

◆ The ratios are similar in two physical scenarios :

$$R = \frac{\eta_c \rho^{\pm}}{J/\psi \pi^{\pm}}$$

	观测道	Molecular	Tetraquark
Zc(3900) Γ_{Tot}=28.2±2.6MeV	$\eta_c\rho$、$J/\Psi\pi$	R~1.3	R~1.6
Zc(4020) Γ_{Tot}=13±5MeV	$\eta_c\rho$、$h_c\pi$	R~2.7-2.3	R~1.6
Zc(4430) Γ_{Tot}=181±31MeV	$\psi(2S)\pi$、$J/\Psi\pi$	R~1.4-1.3	R~1.7-1.4

Summary

◆ The ratios between Zc(3900) and Zc(4020) are greatly different,

Molecular:

$$\frac{\Gamma[Z_c(3900) \to \eta_c\rho]}{\Gamma[Z_c(4020) \to \eta_c\rho]} = 12.5,$$

$$\frac{\Gamma[Z_c(3900) \to J/\psi\pi]}{\Gamma[Z_c(4020) \to J/\psi\pi]} = 24.2.$$

Tetraquark:

$$\frac{\Gamma[Z_c(3900) \to \eta_c\rho]}{\Gamma[Z_c(4020) \to \eta_c\rho]} = 1.2,$$

$$\frac{\Gamma[Z_c(3900) \to J/\psi\pi]}{\Gamma[Z_c(4020) \to J/\psi\pi]} = 1.2.$$

and strongly indicates that Zc(3900) and Zc(4020) are molecular-like signals which arise from the $D^{(*)}\overline{D}^{(*)}$ hadronic interactions.

Thanks

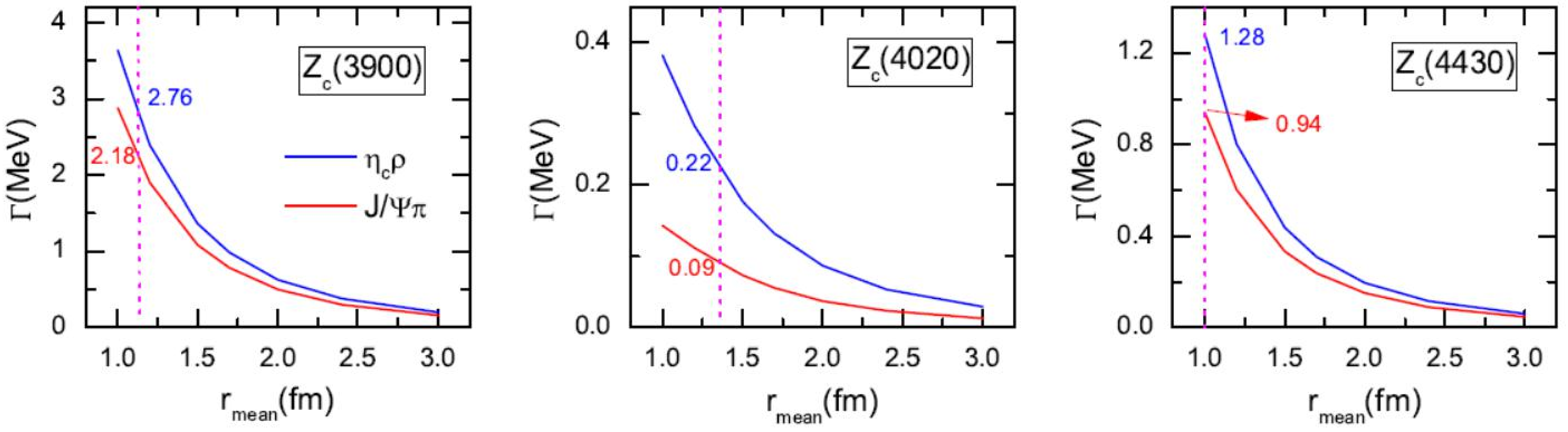
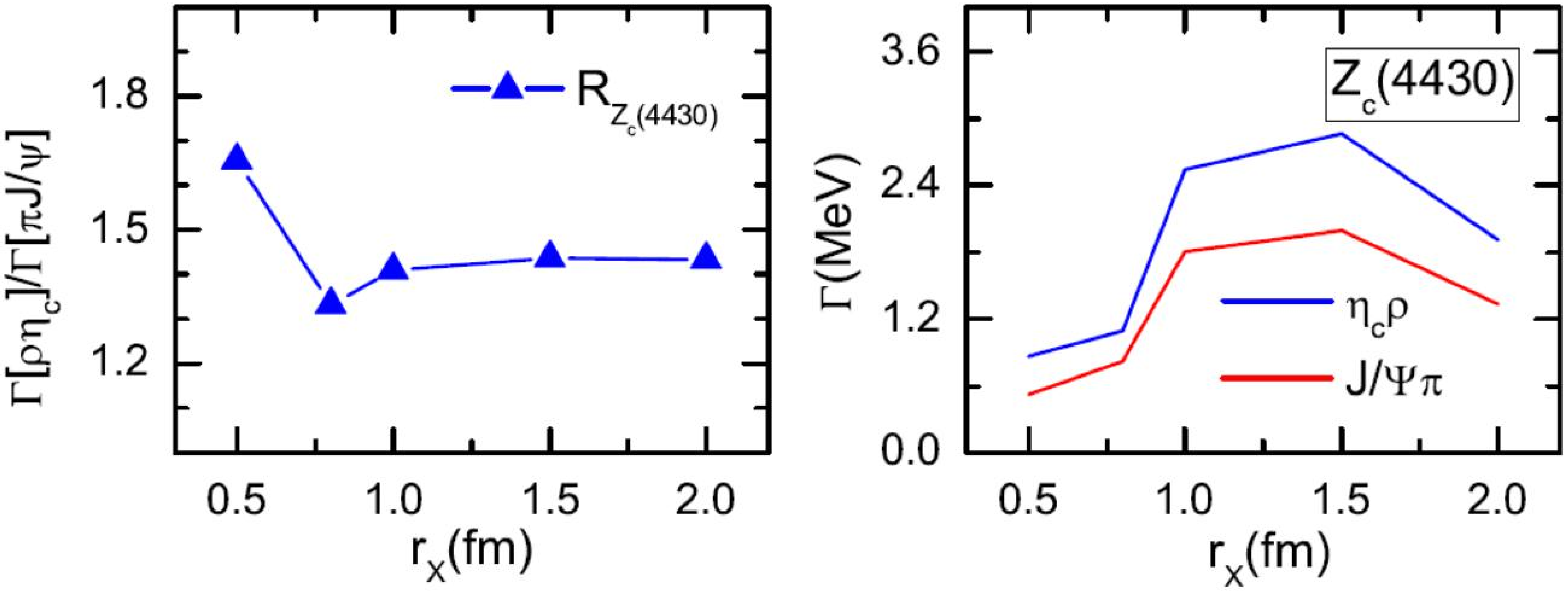


FIG. 4: The partial widths of the $\eta_c\rho$ and $J/\psi\pi$ decay modes for $Z_c(3900)$, $Z_c(4020)$ and $Z_c(4430)$ as the $D\bar{D}^*$, $D^*\bar{D}^*$ and $D(2S)\bar{D}^*$ molecular states, respectively. Their masses are fixed respectively on the physical masses, namely 3886.6 MeV, 4024.1 MeV and 4478 MeV.



$R_{Z_c(4430)}$
1.8
1.5
1.2
$\Gamma[\rho\eta_c]/\Gamma[\pi J/\psi]$
0.5
1.0
1.5
2.0
r_X(fm)
$Z_c(4430)$
3.6
2.4
1.2
0.0
Γ(MeV)
$\eta_c\rho$
$J/\Psi\pi$
0.5
1.0
1.5
2.0
r_X(fm)