

Z_c and Other Charged Charmonium-like States at BESIII

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Outline

- Introduction of Z_c
- Study of Z_c decay modes
- Observation of $Z_{cs}(3985)$
- Summary



Hadrons and Exotic Hadrons



Z_c States

State	$M \; ({\rm MeV}/c^2)$	Γ (MeV)	J^{PC}	Process	Experiment
$Z_c(3900)^{(\pm,0)}$	3888.4 ± 2.5	28.3 ± 2.5	1+-	$e^+e^- \to \pi^{(+,0)}(\pi^{(-,0)}J/\psi)$	BESIII, Belle
				$e^+e^- \to \pi^{(+,0)} (D\bar{D}^*)^{(-,0)}$	BESIII
				$H_b \to X \pi^+ (\pi^- J/\psi)$	D0
				$e^+e^- \to \pi^+(\eta_c \rho^-)$	BESIII
$Z_c(4020)^{(\pm,0)}$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e^- \to \pi^{(+,0)}(\pi^-h_c)$	BESIII, Belle
				$e^+e^- \to \pi^{(+,0)} (D^* \bar{D}^*)^{(-,0)}$	BESIII
$Z(4050)^{\pm}$	4051^{+24}_{-40}	82^{+50}_{-28}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4055)^{\pm}$ 3.5	$\sigma 4054 \pm 3.2$	45 ± 13	??-	$e^+e^- \to \pi^+(\pi^-\psi(2S))$	Belle
$Z(4100)^{\pm}$ 3.4	$\sigma 4096 \pm 28$	152^{+80}_{-70}	???	$B^0 \to K^+(\pi^-\eta_c)$	LHCb
$Z(4200)^{\pm}$	4196^{+35}_{-32}	370^{+100}_{-150}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle, LHCb
$Z(4250)^{\pm}$	4248_{-50}^{+190}	$177^{+\bar{3}\bar{2}\bar{0}}_{-70}$	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4430)^{\pm}$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$B^0 \to K^+(\pi^-\psi(2S))$	Belle, LHCb
first/2008	-			$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle
$R_{c0}(4240)$	4239^{+50}_{-21}	220^{+120}_{-90}	$0^{}$	$B^0 \to K^+ \pi^- \psi(2S)$	LHCb
$Z_{cs}(3985)^{\pm}$	$3982.5^{+2.8}_{-3.4}$	$12.8^{+6.1}_{-5.3}$?	$e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$	BESIII
$Z_{cs}(4000)^{\pm}$	4003^{+7}_{-15}	131 ± 30	1^{+}	$B^+ \to \phi(J/\psi K^+)$	LHCb
$Z_{cs}(4220)^{\pm}$	4216_{-38}^{+49}	233^{+110}_{-90}	1^{+}	$B^+ \to \phi(J/\psi K^+)$	LHCb

Produced in e^+e^- annihilation or b-flavor hadron decays

Typically in h+charmonium final states

Intrinsic nature unclear, exotic states? kinematic effects?

Spin-parity and Argand plot; Production mechanism;

More decay modes; Partner states;...



BESIII & Data Samples



Z_c States from e^+e^- Annihilation

 $Z_c(3900)/Z_c(3885)$

PRL110, 252001 (2013)



Z_c States from e^+e^- Annihilation

 $Z_c(3900)/Z_c(3885)$



Z_c States from e^+e^- Annihilation

 $Z_c(4020)/Z_c(4025)$

PRL111, 242001 (2013)

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PRL113, 212002 (2014)



 $Z_c \operatorname{in} e^+ e^- \to \pi \pi \psi(2S)$ Process



Z_c States in $\rho\eta_c$ Mode

• $e^+e^- \rightarrow \pi^{\pm}\rho^{\mp}\eta_c$



PRD100, 111102 (2019)

Ratio	Measurement	Tetraquark	Molecule	
$\overline{R_{Z_c(3900)}}$	2.3 ± 0.8 [29]	230^{+330}_{-140} [12]	$0.046^{+0.025}_{-0.017}$ [12]	
		$0.27^{+0.40}_{-0.17}$ [12]	1.78 ± 0.41 [17]	
		0.66 [13]	6.84×10^{-3} [18]	
		0.56 ± 0.24 [14]	0.12 [19]	
		0.95 ± 0.40 [15]		
		1.08 ± 0.88 [16]		
		1.28 ± 0.37 [17]		
		1.86 ± 0.41 [17]		
$R_{Z_{c}(4020)}$	<1.2 [4]	$6.6^{+56.8}_{-5.8}$ [12]	$0.010^{+0.006}_{-0.004}$ [12]	
[12]PLB746, 194 (2015) [13]PRD87, 111102 (2013) [14]PRD93, 074002(2016) [15]PRD88, 016004 (2013)		[16]EPJC78, 14 (2018) [17]PRD94, 094017 (2016) [18]Porc.Sci.Hadron2013, 189 [19]EPJC73, 2561 (2013)		



 $Z_c \rightarrow \pi \eta_c$ and $\eta \eta_c$

• $e^+e^- \rightarrow \eta_c \eta \pi^+ \pi^-$

PRD103, 032004 (2021)

- 4.1 fb^{-1} data between 4.23 and 4.60 GeV
- No signal for $\eta_c \eta \pi^+ \pi^-$ [also apply for Z_c search]
- $\sigma^{\rm up} < 6.2, 10.8, 27.6, 22.6, 23.7 \text{ pb at } 90\%$ C.L.



• $e^+e^- \rightarrow \eta_c \pi^+\pi^-\pi^0$, $\eta_c \pi^+\pi^-$, $\eta_c \pi^0 \gamma$ in search of Z_c close to $m(D\bar{D})$



 $Z_c \rightarrow \pi \eta_c$ and $\eta \eta_c$

PRD103, 032006 (2021)

• $e^+e^- \rightarrow Z_c[\rightarrow \eta_c \pi^{\pm,0}]\pi\pi$ in search of Z_c close to $m(D\bar{D})$

[qd] 20 b 15 25 20 م 15 25 20 م 15 역 25 신 20 0 0 ^b 15 15 \cap 0 10 10 10 10 0 00 Ο 00 5 -10 -10 -10 -10 -15 -15 -15 -15 $Z_c^{\pm}\pi^{\mp}\pi^0$, $\Gamma_{Z_c}=18$ MeV $Z_{c}^{\pm}\pi^{\mp}\pi^{0}$, $\Gamma_{Z_{c}}$ =28 MeV **Ζ**[±]_cπ[∓]π⁰, Γ₇ =8 MeV -20 Z[±]_cπ[∓]π⁰, Γ_Z=38 MeV -20 -20 -20 -25 -25 -25 -25 3650 3700 3750 3800 m_Z [MeV/c²] 3650 3700 3750 3800 m_Z [MeV/c²] 3650 3700 3750 3800 m_Z [MeV/c²] [qd] 20 p 15 [qd] 20 b 15 [qd 25 20 [q 25] 20 \cap ່^ບ 15 ^b 15 10 10 10 10 5 Ο 0 2.8*o* 2.7*o* -5 -5 -5 -5 -10 -10 -10 -10 -15 -15 -15 -15 $Z_c^0 \pi^+ \pi^-$, Γ_{Z_c} =28 MeV $Z_{c}^{0}\pi^{+}\pi^{-}, \Gamma_{Z_{c}}=18 \text{ MeV}$ Z⁰_cπ⁺π⁻, Γ_{Z_c}=38 MeV $Z_c^0 \pi^+ \pi^-$, Γ_{Z_c} =8 MeV -20 -20 -20 -20 -25 -25 -25 -25 3750 3800 3650 3700 3750 3800 3650 3700 3750 3800 3650 3700 3750 3800 3650 3700 m_Z [MeV/c²] m_Z [MeV/c²] m_{7} [MeV/c²] m_z [MeV/c²]



 $Z_c \rightarrow \pi^{\pm} \chi_{cI}$

- $Z_c(4050)$ and $Z_c(4250)$ in $\pi^{\pm}\chi_{c1}$ from *B* decays
- $Z_c(3900)$ and $Z_c(4020)$ from e^+e^- annihilation at BESIII



PRD103, 052010(2021)

Xai

- No obvious signal of $e^+e^- \rightarrow \pi^+\pi^-\chi_{cI}$
- Upper limit of cross section also apply for $Z_c \rightarrow \pi^{\pm} \chi_{cJ}$



 $Z_c(4020) \rightarrow \gamma X(3872)$

- Connection between Z_c states and X states in molecule picture
- Branching fraction of $Z_c(4020)^0 \rightarrow \gamma X(3872)$ and $Z_c(4020)^{\pm} \rightarrow \pi^{\pm} X(3872)$ of several per mille level

PRD99, 054028 (2019)







Do not contradict with theoretical prediction!



• $e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$

PRL126, 102001 (2021)

- 3.7 fb⁻¹ data at 4628, 4640, 4660, 4680, and 4700
- Partial reconstruction of the process, tag K and D_s^-
- D_s^- reconstructed with $K^+K^-\pi^-$ [$\phi\pi$ or K^*K] and $K_S^0K^-$



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- Both decay modes can survive the selection
- Combinatorial background described by wrong sign (WS) events
- Absolute contribution in signal region determined from a fit to $RM(K^+D_s^-)$



PRL126, 102001 (2021)

- An enhancement around 3.98 GeV
- Cannot be described by processes contain excited D mesons, $D_s^{(*)-}D_s^{**+}$ and $D^{(*)0}\bar{D}^{**0}$
- Cannot be described by interference between two open-charm processes



PRL126, 102001 (2021)



- Assume J^P=1⁺
- Simultaneous fit to five data samples
- Signal component:

 $\left|\frac{\sqrt{q \cdot p_{j}}}{M^{2} - m_{0}^{2} + im_{0}(f\Gamma_{1}(M) + (1 - f)\Gamma_{2}(M))}\right|^{2}$

- f = 0.5 represents the fraction of the two decay modes
- Pole position:

 $M = (3982.5^{+1.8}_{-2.6} \pm 2.1) \text{ MeV}/c^2$ $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0) \text{ MeV}$

- Significance: 5.3σ
- At least four quarks (ccsū)





Summary and Outlook

- Unique data samples from 4.0 GeV to 4.9 GeV
 - New data samples between 4.1 GeV to 4.4 GeV and above 4.7 GeV
- New decay modes of Z_c states are searched for
 - $\gamma X(3872)$, $\eta_c \pi$, $\eta_c \eta$, and $\chi_{cJ} \pi$, no obvious signal observed
- A new Z_{cs} state observed in $D_s^-D^{*0} + D_s^{*-}D^0$ modes
 - Significant at 4680 data sample (>5 σ)
 - Intrinsic nature unclear, strangeness-partner of $Z_c(3900)$?
- More results about the production & decay of $Z_{\!{\cal C}(s)}$, structure properties are ongoing

