On the nature of exotic Z_{cs} states

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Based on
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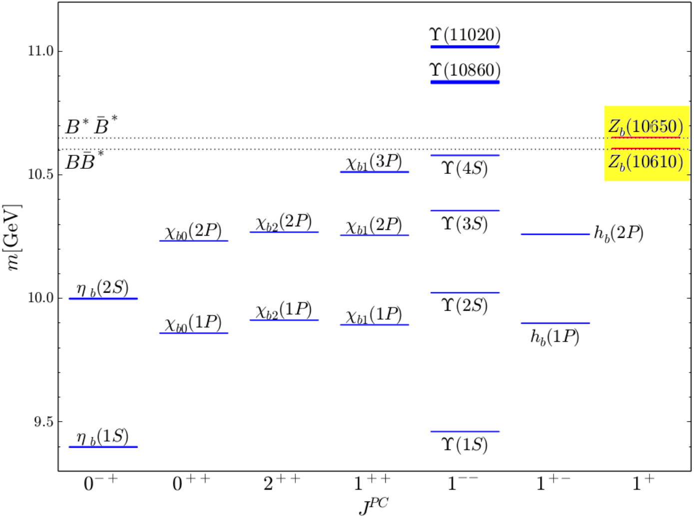
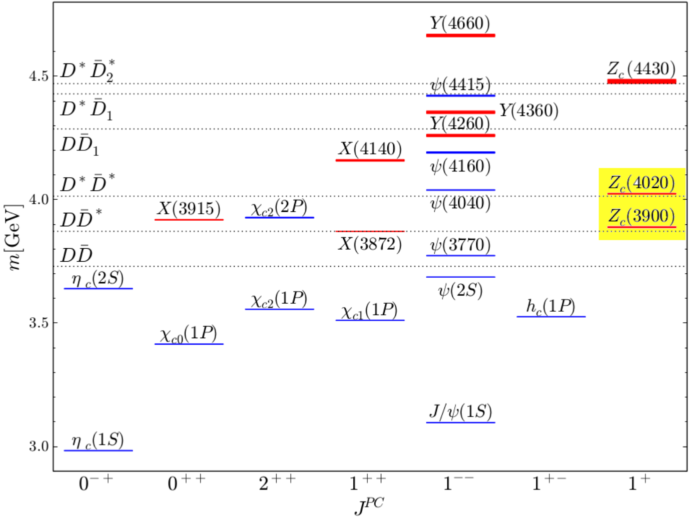
Spectrum of bottomonium



Spectrum of charmonium



Expectations

- Twin bottomonium-like Z_b states $(I=1,\ J^{PC}=1^{+-})$ are $B^{(*)}\bar{B}^*$ molecules

$$Z_b \sim B\bar{B}^* \sim 0^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} + 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}$$

$$Z'_b \sim B^*\bar{B}^* \sim 1^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} - 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}$$

- For $m_Q \gg \Lambda_{\mathrm{QCD}}$ spin of heavy quark decouples (Heavy Quark Spin Symmetry)
  $\Longrightarrow$ Just two LO contact potentials: $\mathcal{C}_d$ & $\mathcal{C}_f$
  $\Longrightarrow$ Prediction for spin partners W_{bJ}'s with $J^{PC}=J^{++}$ $(J=0,1,2)$
- Anticipate similar pattern in the spectrum of charmonium
  $\Longrightarrow$ $Z_c(3900) \sim D\bar{D}^*$
  $\Longrightarrow$ $Z_c(4020) \sim D^*\bar{D}^*$
- Flavour $SU(3)$ for light quarks
  $\Longrightarrow$ Accurate for couplings & potentials
  $\Longrightarrow$ Explicit breaking via $m_s \gg m_{u,d}$
  $\Longrightarrow$ Simple relation between potentials: $\mathcal{C}_{d,f}(I=1/2)=\mathcal{C}_{d,f}(I=1)$

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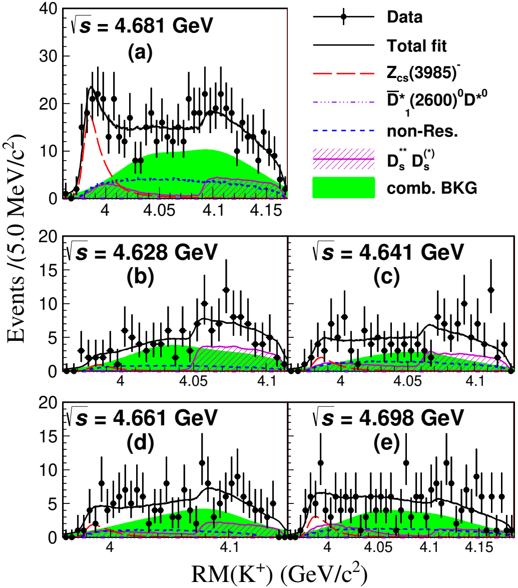
Expect Z_{bs} ($\sqrt{s} \gtrsim 11.2$ GeV) and Z_{cs} ($\sqrt{s} \gtrsim 4.5$ GeV) molecular states to exist

BES III data (Phys.Rev.Lett. 126 (2021) 10, 102001)



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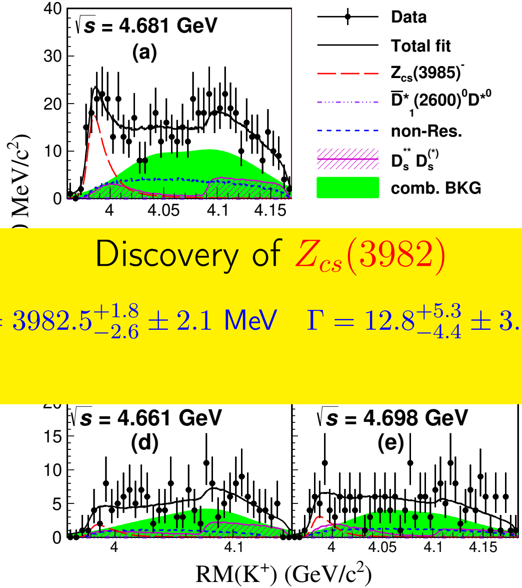


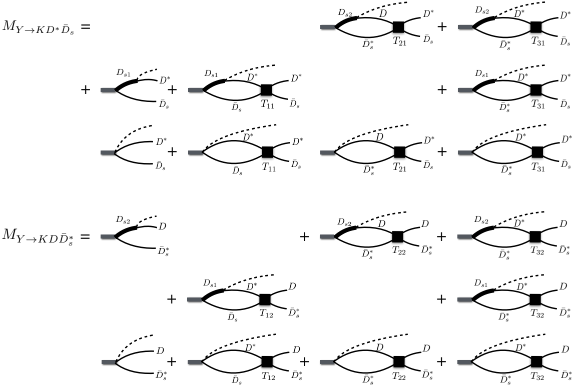
Discovery of $Z_{cs}(3982)$

$M = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV $\quad \Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV

Coupled-channel analysis

Assumption: $e^+e^- \to \gamma^* \to Y(4660) \to K(D^*\bar{D}_s + D\bar{D}_s^*)$

Coupled-channel scheme: $\{1,2,3\} = \{\bar{D}_s D^*, D\bar{D}_s^*, D^*\bar{D}_s^*\}$

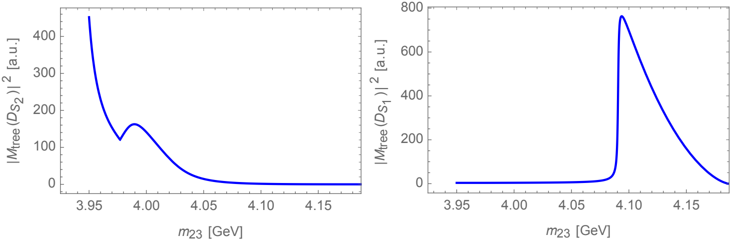


$$T_{\alpha\beta}(\sqrt{s},p,p') = V_{\alpha\beta}(p,p') - \sum_\gamma \int \frac{d^3q}{(2\pi)^3} V_{\alpha\gamma}(p,q) G_\gamma(\sqrt{s},q) T_{\gamma\beta}(\sqrt{s},q,p')$$

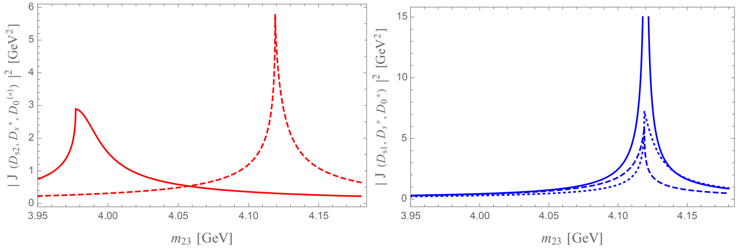
Note: Z_{cs} is a dynamical state (pole of T-matrix)

Relevance of various contributions

Tree-level diagrams with D_{sJ} $(J = 1, 2)$ exchanges



Triangle diagrams



Theoretical framework

- Effective Field Theory (EFT) approach $\Longrightarrow$ LO short-range potential
- Heavy Quark Spin Symmetry (HQSS) $\Longrightarrow$ Multiplets of particles
- Flavour $SU(3)$ $\Longrightarrow$ symmetric potential + explicit breaking via masses
- Number-of-events distribution

$$\frac{dN}{dm_{23}} = \frac{d\sigma}{dm_{23}} \bar{\epsilon}\, \mathcal{L}_{\text{int}}\, f_{\text{corr}}$$

$\bar{\epsilon}$ – efficiency, $\mathcal{L}_{\text{int}}$ – integrated luminosity, f_{corr} – radiative & vacuum polarisation correction

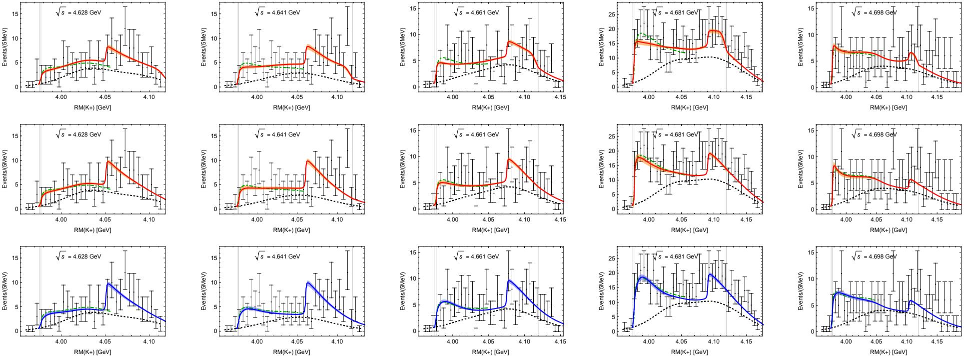
- Maximum likelihood fit

$$-2\log\mathcal{L} = 2\sum_i \left(\mu_i - n_i + n_i \log\frac{n_i}{\mu_i}\right)$$

n_i – number of events, μ_i – theoretical signal function

- Combined fit of 5 distributions with 5 fitting parameters

Fit results



Upper, middle, lower row for fit 1, fit 1′, fit 2, respectively

Fit	$\mathcal{C}_d$, fm^2	$\mathcal{C}_f$, fm^2	$g_{D_{s1}}/g_{D_{s2}}$	$g/g_{D_{s2}}$	$\mathcal{N}$, $10^{-2}\,\frac{\text{pb}}{\text{GeV}}$	$-2\log\mathcal{L}$
fit 1	-0.51 ± 0.02	0.18 ± 0.02	0.26 ± 0.02	-2.5 ± 0.3	0.46 ± 0.05	138
fit 1′	-0.24 ± 0.05	-0.1 ± 0.05	0.37 ± 0.03	-2.8 ± 0.6	0.35 ± 0.04	144
fit 2	0.50	-1.04 ± 0.01	-0.44 ± 0.03	-6.5 ± 2.5	0.28 ± 0.03	146

Two scenarios for Z_{cs} and Z'_{cs}

$$T = V - V \cdot G \cdot T \quad \Longrightarrow \quad T = V \cdot (1 + G \cdot V)^{-1}$$

$$G = \begin{pmatrix} J_0 & 0 & 0 \\ 0 & J_0 & 0 \\ 0 & 0 & J'_0 \end{pmatrix} \qquad V = \begin{pmatrix} \mathcal{C}_d + \frac{1}{2}\mathcal{C}_f & \frac{1}{2}\mathcal{C}_f & -\frac{1}{\sqrt{2}}\mathcal{C}_f \\ \frac{1}{2}\mathcal{C}_f & \mathcal{C}_d + \frac{1}{2}\mathcal{C}_f & \frac{1}{\sqrt{2}}\mathcal{C}_f \\ -\frac{1}{\sqrt{2}}\mathcal{C}_f & \frac{1}{\sqrt{2}}\mathcal{C}_f & \mathcal{C}_d \end{pmatrix}$$

- $|\mathcal{C}_f| \ll |\mathcal{C}_d|$

$$\text{det}(1 + G \cdot V) \approx (\underbrace{\mathcal{C}_d J_0 + 1}_{\sim 0})^2 (\underbrace{\mathcal{C}_d J'_0 + 1}_{\sim 0})$$

- $\Delta\mathcal{C} = \mathcal{C}_d + \mathcal{C}_f$ with $|\Delta\mathcal{C}| \ll |\mathcal{C}_d - \mathcal{C}_f|$

$$\text{det}(1 + G \cdot V) \approx (\underbrace{\Delta\mathcal{C} J_0 + 1}_{\sim 0}) \left(\underbrace{\mathcal{C}_d (J_0 + J'_0) + 1}_{\neq 0}\right)$$

Pole positions

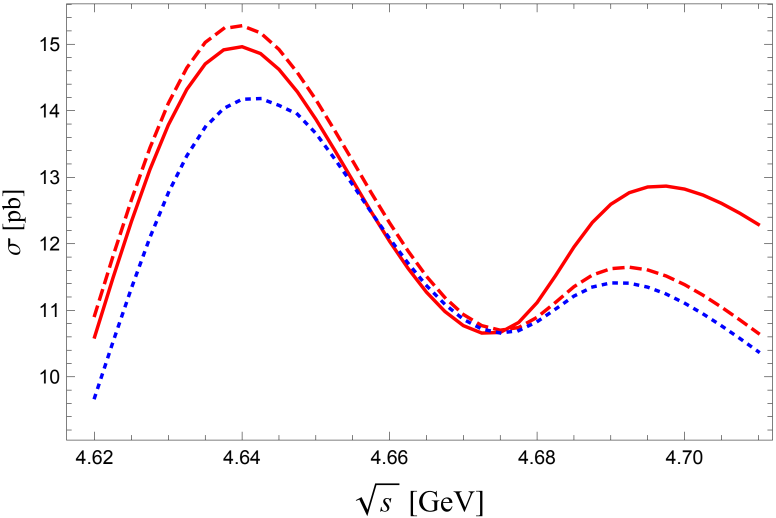
- Scenario 1

$J^{P(C)}$	State	Threshold, MeV		RS	Poles fit 1	RS	Poles fit 1′
1^+	$Z_{cs}(3982)$	$\bar{D}_s D^*/\bar{D}_s^* D$	$3975.2/3977.0$	$(+++)$	3942 ± 11	$(--+)$	3937^{+5}_{-29}
1^+	$Z_{cs}(3982)$	$\bar{D}_s D^*/\bar{D}_s^* D$	$3975.2/3977.0$	$(--+)$	3971 ± 2	$(--+)$	3972 ± 2
1^+	Z'_{cs}	$\bar{D}_s^* D^*$	4119.1	$(--+)$	$4115 \pm 2 - (10 \pm 2)i$	$(++-)$	$4087^{+10}_{-10} + 0^{+45}_{-0} i$
1^{+-}	$Z_c(3900)$	$(D\bar{D}^*, -)$	3871.7	$(++)$	3841 ± 11	$(-+)$	3832^{+25}_{-36}
1^{+-}	$Z_c(4020)$	$\bar{D}^* D^*$	4013.7	$(-+)$	$4009 \pm 18 - (9 \pm 2)i$	$(+-)$	$3975^{+15}_{-10} + 0^{+43}_{-0} i$

- Scenario 2

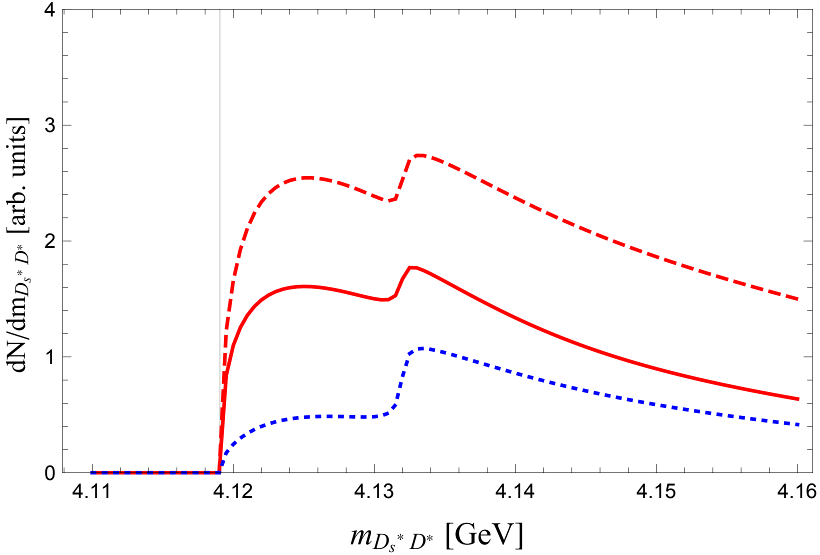
$J^{P(C)}$	State	Threshold, MeV		RS	Poles fit 2
1^+	$Z_{cs}(3982)$	$\bar{D}_s D^*/\bar{D}_s^* D$	$3975.2/3977.0$	$(+++)$	3954 ± 2
1^+	$Z_{cs}(3982)$	$\bar{D}_s D^*/\bar{D}_s^* D$	$3975.2/3977.0$	$(--+)$	$3959 \pm 7 - (47 \pm 16)i$
1^+	Z'_{cs}	$\bar{D}_s^* D^*$	4119.1		No state/not spin partner
1^{+-}	$Z_c(3900)$	$(D\bar{D}^*, -)$	3871.7	$(-+)$	$3864 \pm 7 - (58 \pm 13)i$
1^{+-}	$Z_c(4020)$	$\bar{D}^* D^*$	4013.7		Not spin partner

Total cross section of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



Peaks at 4.64 and 4.69 GeV due to resonance production via D_{s1} and D_{s2}

Predictions for the $e^+e^- \to K^+ D_s^{*-} D^{*0}$ at $\sqrt{s} = 4.681$



Conclusions

- Recent BES III data are consistent with molecular scenario for $Z_{cs}(3982)$
- Present data are not accurate enough to understand the nature of Z_{cs} (most relevant pole, bound vs virtual)
- Various mechanisms play important role for understanding data
  - Production through D_{sJ} $(J = 1, 2)$ intermediate mesons
  - Triangle singularities
  - Delicate interplay between short-range interactions
  - $SU(3)$ nonet exchanges (?) — to be studied
- Data are consistent with two utterly different scenarios
  - Scenario 1: $Z_c(3900)$, $Z_c(4020)$, $Z_{cs}(3982)$, Z'_{cs} — spin partners
  - Scenario 2: $Z_c(3900)$, $Z_{cs}(3982)$ — spin partners, but not $Z(4020)$, and no Z'_{cs} exists
- Precise data are strongly needed in $D_s^- D^{*0} + D_s^{*-} D^0$ and $\bar{D}_s^* D^*$ channels for more robust consclusions on nature of Z_{cs}
- Remains to be seen whether $Z_{cs}(3982)$ is related to structures observed by LHCb