Search for $Z_c(3900)$ via $\Upsilon(1S, 2S) \to \pi^+ D^0 D^{*-}$ decay at Belle

Quarkonium Group meeting

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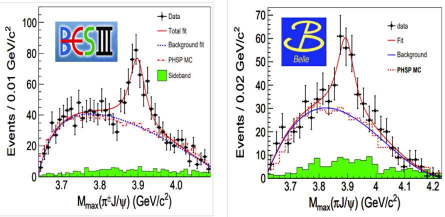
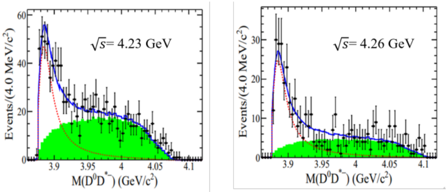
Motivation

- In 2013, BESIII[PRL 110, 252001] and Belle[PRL 110, 252002] observed a charged charmonium-like state $Z_c(3900)$ via $e^+e^- \to \pi^+\pi^- J/\psi$



  - $M = 3899.0 \pm 3.6 \pm 4.9\ \mathrm{MeV}/c^2$, $\Gamma = 46 \pm 16 \pm 20\ \mathrm{MeV}/c^2$

- In 2014-2015, BESIII observed and confirmed a charged charmonium-like state $Z_c(3885)$ via $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$[PRL 112, 022001, PRD 92, 092006]

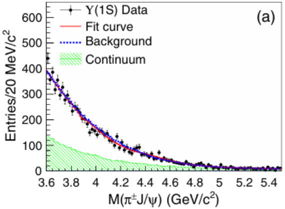


  - $M = 3883.9 \pm 1.5 \pm 4.2\ \mathrm{MeV}/c^2$, $\Gamma = 24.8 \pm 3.8 \pm 11.0\ \mathrm{MeV}/c^2$

- tetraquark ? DD^* molecule ? threshold effect ?

Motivation

- Studies of $Z_c(3900)$ in bottomonium decays only via $\Upsilon(1S) \to Z_c(3900)[\to \pi J/\psi]\,anything$ and set 90% confidence level $< 1.3 \times 10^{-5}$ and searched $\Upsilon(1S,2S) \to Z_c^+ Z_c^-$ assuming $\mathcal{B}(Z_c \to \pi J/\psi) = 1$ [PRD 93 112013]



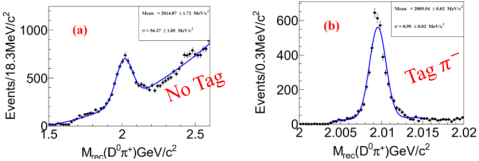
- Assume that the signals of $Z_c(3885) \to D\bar{D}^*$ and $Z_c(3900) \to \pi J/\psi$ have the same origin(named $T_{c\bar{c}1}(3900)$ in PDG). The ratio of partial decay widths [PRL 112, 022001]

$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

- Therefore, it is necessary to search for $Z_c(3900)$ in $\Upsilon(1S,2S)$ decays via $Z_c(3900) \to D\bar{D}^*$ channel to help understand the production mechanism of $Z_c(3900)$.

Analysis Strategy

- We do this analysis in basf2 with B2BII, basf2 version: **release 09-00-15**
- We reconstruct the π^+, D^0 and also reconstruct π^-_{slow} which decays from the $D^{*-}(\to \pi^- \bar{D}^0)$ to improve the resoluton of the recoil mass of $\pi^+ D^0$ system. (the same method as work before [B2N-2023-053])



- Recoil method

$$M(\bar{D}^0) = M_{\text{rec}}(\pi^+ D^0 \pi^-_{\text{slow}}) = \sqrt{(E_{\text{cms}} - E_{\pi^+} - E_{D^0} - E_{\pi^-_{\text{slow}}})^2 - (\vec{p}_{\pi^+} + \vec{p}_{D^0} + \vec{p}_{\pi^-_{\text{slow}}})^2}$$

$$M(D^{*-}) = M_{\text{rec}}(\pi^+ D^0) = \sqrt{(E_{\text{cms}} - E_{\pi^+} - E_{D^0})^2 - (\vec{p}_{\pi^+} + \vec{p}_{D^0})^2}$$

Data and MC samples

Data samples

- 5.8 fb^{-1} data sample collected at $\Upsilon(1S)$ peak $\sqrt{s} = 9.46$ GeV.
- 24.9 fb^{-1} data sample collected at $\Upsilon(2S)$ peak $\sqrt{s} = 10.02$ GeV.
- 89.5 fb^{-1} data sample collected at off-resonance $\sqrt{s} = 10.52$ GeV.

MC simulation

- 4×10^5 signalMC(using results of PRL 112, 022001)
- 4×10^5 no-$Z_c(3900)$ MC
  - prompt D^0 decays to $K^+\pi^-$ and $K^+\pi^+\pi^+\pi^-$(each mode generated half of the sample)
    - $\mathcal{B}(D^0 \to K^+\pi^-) = 3.95 \pm 0.03\%$ $\quad \mathcal{B}(D^0 \to K^+\pi^+\pi^+\pi^-) = 8.23 \pm 0.14\%$
  - inclusive $\bar{D}^0$ from $D^{*-} \to \bar{D}^0\pi^-$
- 1×10^9 generic $\Upsilon(1S, 2S)$ MC samples
- generic continuum MC samples with 4 times luminosity of data samples

Basic Selection

- good tracks
  - $|dr| < 0.5$ cm and $|dz| < 2.0$ cm
  - for kaons: $\frac{\mathcal{L}(K^{\pm})}{\mathcal{L}(K^{\pm})+\mathcal{L}(\pi^{\pm})} > 0.6$ and for pions: $\frac{\mathcal{L}(K^{\pm})}{\mathcal{L}(K^{\pm})+\mathcal{L}(\pi^{\pm})} < 0.4$
- For prompt D^0 candidates
  - Mass Constraint with kFit
- Require $M_{\text{rec}}(\pi^+ D^0) - M_{\text{rec}}(\pi^+ D^0 \pi^-_{\text{slow}}) < 0.20\ \text{GeV}/c^2$ and $1.0\ \text{GeV}/c^2 < M_{\text{rec}}(\pi^+ D^0) < 3.0\ \text{GeV}/c^2$ to reduce the combinatorial background of D^{*-} candidates.

prompt D^0 mass fit in $D^0 \to K^-\pi^+$ mode

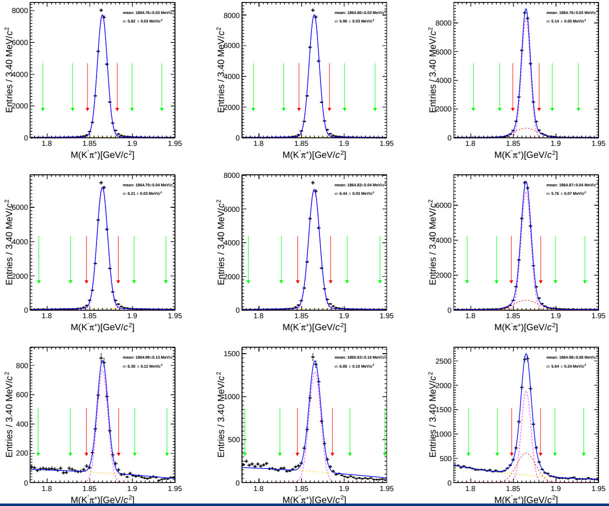
Signal Region: $|M(K^-\pi^+) - m(D^0)| < 3\sigma_{DT}$ and Sideband Region: $|M(K^-\pi^+) - m(D^0) \pm 9\sigma_{DT}| < 3\sigma_{DT}$

$\Upsilon(1S)$ $\Upsilon(2S)$ Continuum

Signal MC

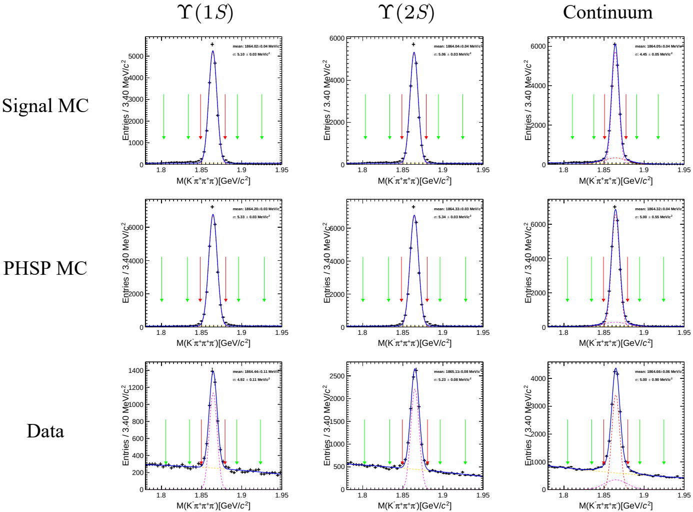
PHSP MC

Data



prompt D^0 mass fit in $D^0 \to K^-\pi^+\pi^+\pi^-$ mode

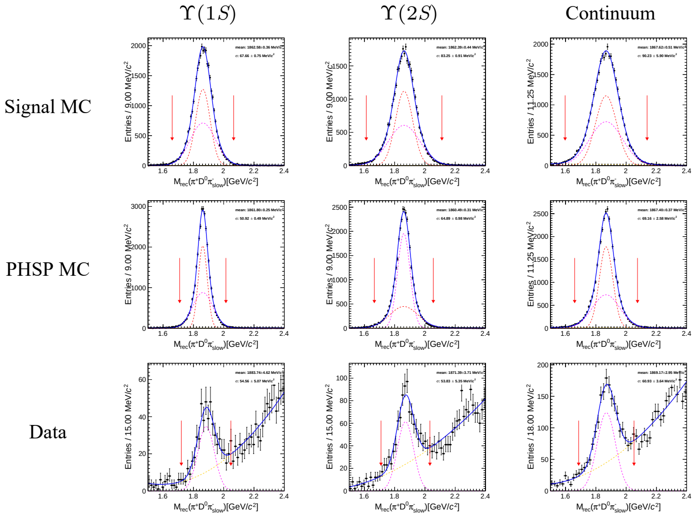
Signal Region: $|M(K^-\pi^+\pi^+\pi^-) - m(D^0)| < 3\sigma_{DT}$ and Sideband Region: $|M(K^-\pi^+\pi^+\pi^-) - m(D^0) \pm 9\sigma_{DT}| < 3\sigma_{DT}$



Recoil mass of $\pi^+ D^0 \pi^-_{\rm slow}$ in $D^0 \to K^- \pi^+$ mode

Mass window: $|M(\bar{D}^0) - m(\bar{D}^0)| < 3\sigma_{DT}$

$$M(\bar{D}^0) = M_{\rm rec}(\pi^+ D^0 \pi^-_{\rm slow}) = \sqrt{(E_{\rm cms} - E_{\pi^+} - E_{D^0} - E_{\pi^-_{\rm slow}})^2 - (\vec{p}_{\pi^+} + \vec{p}_{D^0} + \vec{p}_{\pi^-_{\rm slow}})^2}$$



Recoil mass of $\pi^+ D^0 \pi^-_{\rm slow}$ in $D^0 \to K^-\pi^+\pi^+\pi^-$ mode

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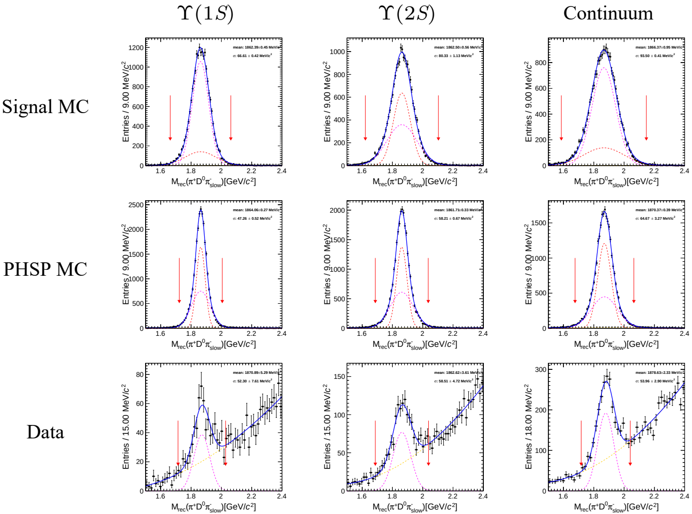
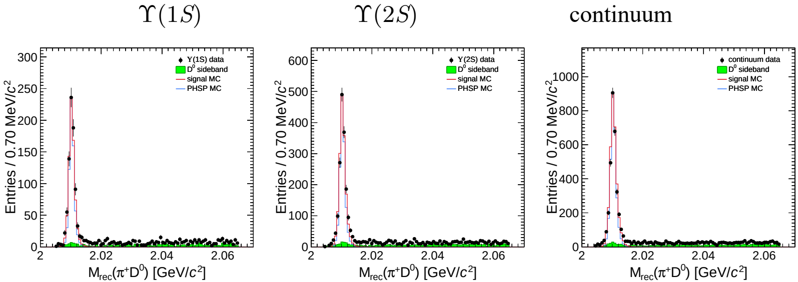


Recoil mass of $\pi^+ D^0$

$$M(D^{*-}) = M_{\text{rec}}(\pi^+ D^0) = M_{\text{rec}}(\pi^+ D^0) - M_{\text{rec}}(\pi^+ D^0 \pi^-_{\text{slow}}) + m(\bar{D}^0)$$

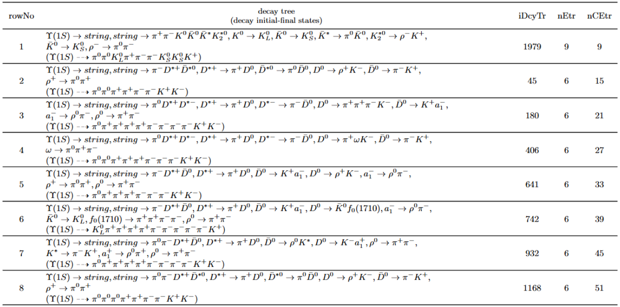


$\Upsilon(1S)$ $\Upsilon(2S)$ continuum

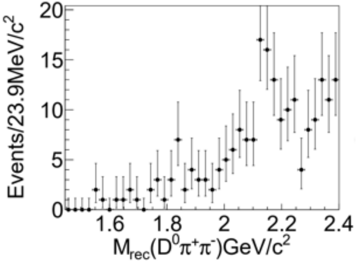
- $\Upsilon(1S)$: $\varepsilon(D \to K^- \pi^+) = 16.0\%$ and $\varepsilon(D \to K^- \pi^+ \pi^+ \pi^-) = 9.4\%$ according to the signal MC samples. ~ 1000 $D^0 D^*$ events according to the data samples.
- $\Upsilon(2S)$: $\varepsilon(D \to K^- \pi^+) = 16.4\%$ and $\varepsilon(D \to K^- \pi^+ \pi^+ \pi^-) = 9.3\%$ according to the signal MC samples. ~ 2000 $D^0 D^*$ events according to the data samples.
- Continuum: $\varepsilon(D \to K^- \pi^+) = 16.6\%$ and $\varepsilon(D \to K^- \pi^+ \pi^+ \pi^-) = 9.9\%$ according to the signal MC samples. ~ 4000 $D^0 D^*$ events according to the data samples.

topo anlysis

showing example of $\Upsilon(1S)$ generic MC



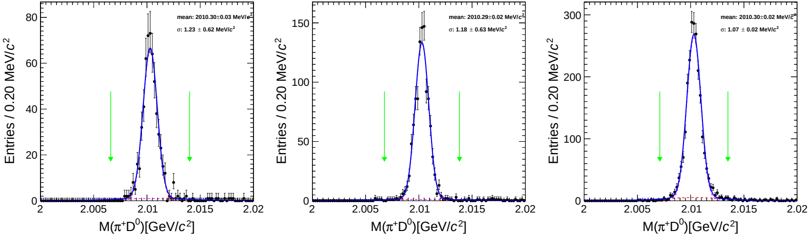
rowNo	decay tree (decay initial-final states)	iDcyTr	nEtr	nCEtr
1	$\Upsilon(1S) \to string, string \to \pi^+\pi^-K^0\bar{K}^0\bar{K}^*K_2^{*0}, K^0 \to K_L^0, \bar{K}^0 \to K_S^0, \bar{K}^* \to \pi^0\bar{K}^0, K_2^{*0} \to \rho^-K^+,$ $\bar{K}^0 \to K_S^0, \rho^- \to \pi^0\pi^-$ $(\Upsilon(1S) \dashrightarrow \pi^0\pi^0K_L^0\pi^+\pi^-\pi^-K_S^0K_S^0K^+)$	1979	9	9
2	$\Upsilon(1S) \to string, string \to \pi^-D^{*+}\bar{D}^{*0}, D^{*+} \to \pi^+D^0, \bar{D}^{*0} \to \pi^0\bar{D}^0, D^0 \to \rho^+K^-, \bar{D}^0 \to \pi^-K^+,$ $\rho^+ \to \pi^0\pi^+$ $(\Upsilon(1S) \dashrightarrow \pi^0\pi^0\pi^+\pi^+\pi^-\pi^-K^+K^-)$	45	6	15
3	$\Upsilon(1S) \to string, string \to \pi^0D^{*+}D^{*-}, D^{*+} \to \pi^+D^0, D^{*-} \to \pi^-\bar{D}^0, D^0 \to \pi^+\pi^+\pi^-K^-, \bar{D}^0 \to K^+a_1^-,$ $a_1^- \to \rho^0\pi^-, \rho^0 \to \pi^+\pi^-$ $(\Upsilon(1S) \dashrightarrow \pi^0\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-K^+K^-)$	180	6	21
4	$\Upsilon(1S) \to string, string \to \pi^0D^{*+}D^{*-}, D^{*+} \to \pi^+D^0, D^{*-} \to \pi^-\bar{D}^0, D^0 \to \pi^+\omega K^-, \bar{D}^0 \to \pi^-K^+,$ $\omega \to \pi^0\pi^+\pi^-$ $(\Upsilon(1S) \dashrightarrow \pi^0\pi^0\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-K^+K^-)$	406	6	27
5	$\Upsilon(1S) \to string, string \to \pi^-D^{*+}\bar{D}^0, D^{*+} \to \pi^+D^0, \bar{D}^0 \to K^+a_1^-, D^0 \to \rho^+K^-, a_1^- \to \rho^0\pi^-,$ $\rho^+ \to \pi^0\pi^+, \rho^0 \to \pi^+\pi^-$ $(\Upsilon(1S) \dashrightarrow \pi^0\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-K^+K^-)$	641	6	33
6	$\Upsilon(1S) \to string, string \to \pi^-D^{*+}\bar{D}^0, D^{*+} \to \pi^+D^0, \bar{D}^0 \to K^+a_1^-, D^0 \to \bar{K}^0f_0(1710), a_1^- \to \rho^0\pi^-,$ $\bar{K}^0 \to K_L^0, f_0(1710) \to \pi^+\pi^+\pi^-\pi^-, \rho^0 \to \pi^+\pi^-$ $(\Upsilon(1S) \dashrightarrow K_L^0\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-K^+)$	742	6	39
7	$\Upsilon(1S) \to string, string \to \pi^0\pi^-D^{*+}\bar{D}^0, D^{*+} \to \pi^+D^0, \bar{D}^0 \to \rho^0K^*, D^0 \to K^-a_1^+, \rho^0 \to \pi^+\pi^-,$ $K^* \to \pi^-K^+, a_1^+ \to \rho^0\pi^+, \rho^0 \to \pi^+\pi^-$ $(\Upsilon(1S) \dashrightarrow \pi^0\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-K^+K^-)$	932	6	45
8	$\Upsilon(1S) \to string, string \to \pi^0\pi^-D^{*+}\bar{D}^{*0}, D^{*+} \to \pi^+D^0, \bar{D}^{*0} \to \pi^0\bar{D}^0, D^0 \to \rho^+K^-, \bar{D}^0 \to \pi^-K^+,$ $\rho^+ \to \pi^0\pi^+$ $(\Upsilon(1S) \dashrightarrow \pi^0\pi^0\pi^0\pi^+\pi^+\pi^-\pi^-K^+K^-)$	1168	6	51



- Topological analysis shows that the upturn in the high-mass region of the $M(\pi^- D^0 \pi_{\text{slow}})$ distributions is mainly caused by the recoil production of excited states, D^* or higher excited charmed mesons and some multi-particle final states.
- So we apply a mass window: $|M_{\text{rec}}(\pi^+ D^0 \pi^-_{\text{slow}}) - m(\bar{D}^0)| < 3\sigma_{DT}$ as mentioned before.

$\Upsilon(1,2S) \to D^{*+}D^{*-}$ veto

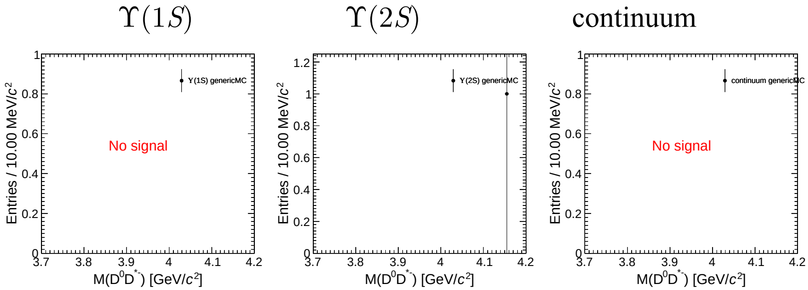
veto $\Upsilon(1,2S) \to D^{*+}D^{*-}$ background



$\Upsilon(1S)$ $\Upsilon(2S)$ continuum

- veto mass window： $|M(\pi^+ D^0) - m(D^{*+})| < 3\sigma_{DT}$

genericMC in signal region



- No signal is found in the generic MC sample lying in the signal region.
- We may extract the background shape by using sideband data.

Summary

- There are lots of $D^0 D^*$ events in the signal region.
- The process $\Upsilon(1S, 2S)/e^+e^- \to \pi^+ D^0 D^{*-}$ has been observed. We can measure the corresponding branching ratio and cross section.

$$\mathcal{B}(\Upsilon(1S, 2S)/e^+e^- \to \pi^+ D^0 D^{*-} + c.c.) = \frac{N^{\text{sig}}_{\Upsilon(1S,2S)} - N^{\text{sig}}_{\text{cont}} \times f_{\text{scale}}}{N_{\Upsilon(1S,2S)} \times \mathcal{B}(D^{*-} \to \pi^- \bar{D}^0) \times \sum_i(\epsilon_i \times \mathcal{B}_i)}$$

$$\sigma(e^+e^- \to \pi^+ D^0 D^{*-})\mathcal{B}(D^{*-} \to \pi^- \bar{D}^0) = \frac{N^{\text{sig}}_{\Upsilon(1S,2S)} \times |1 - \Pi|^2}{\mathcal{L}_{\text{con}} \times \sum_i \epsilon_i \mathcal{B}_i \times (1 + \delta_{\text{ISR}})}$$

- No signal is found in the Generic MC sample.
- We didn't open the box.

Thank you!