Search for neutral Z_{cs} state at BESIII

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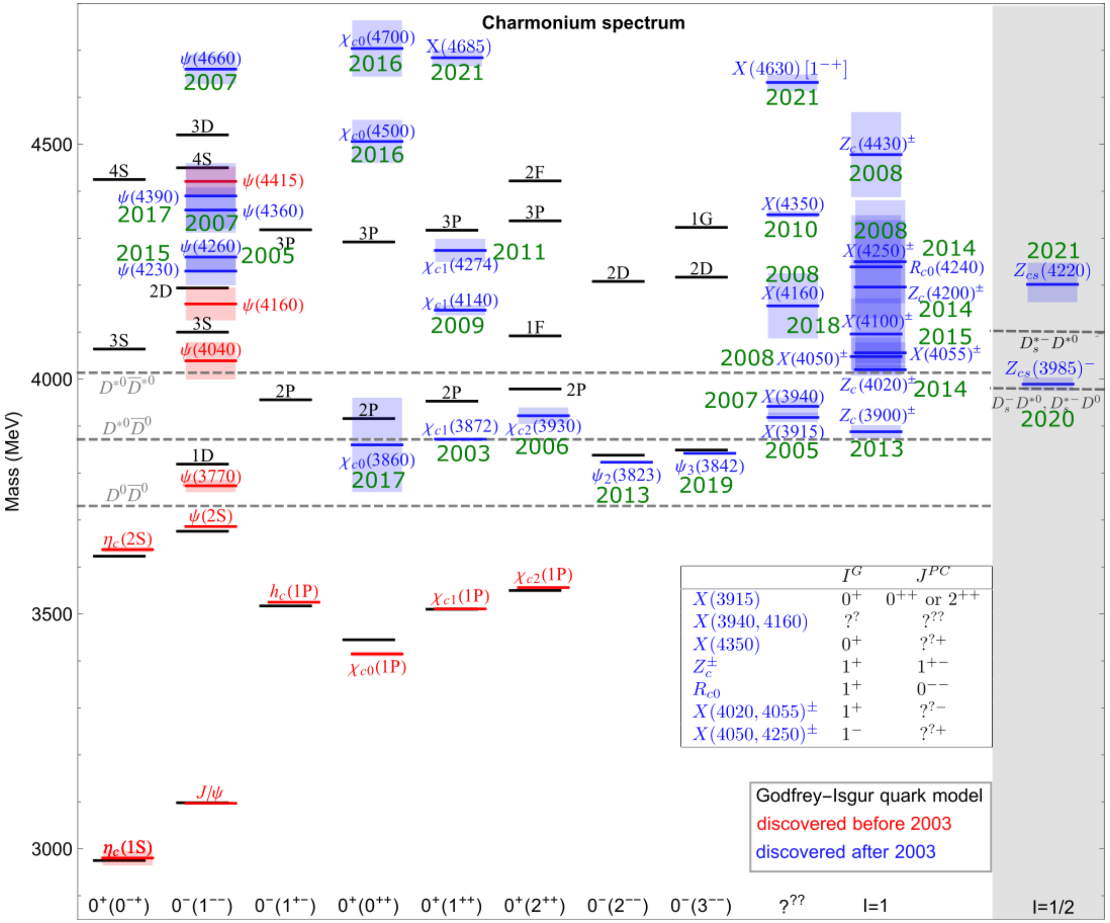
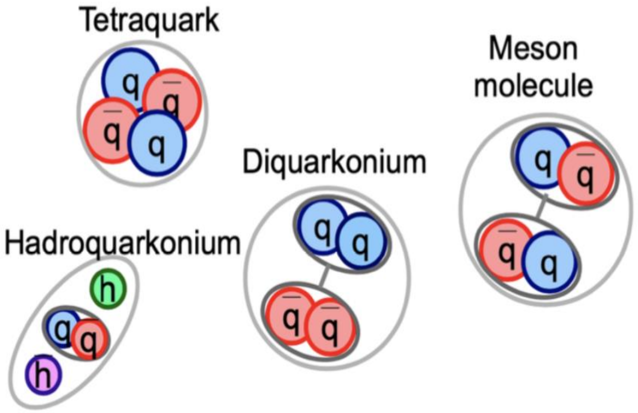


Charmonium(-like) structures[1]

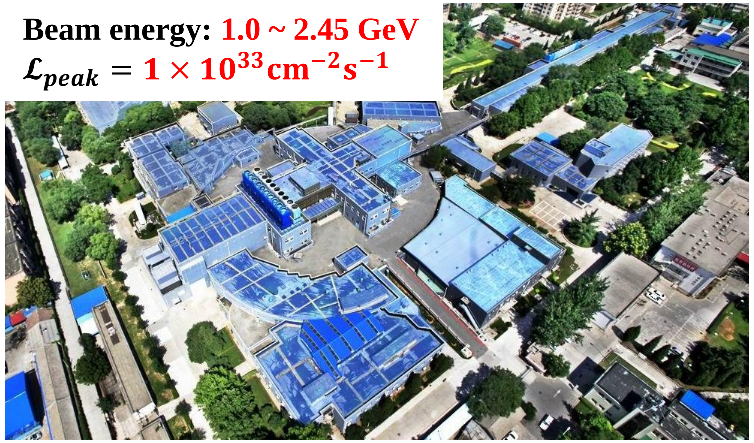


- **The existence of exotic state** has been discussed since **1964[2]**.
- In 2003, Belle Collaboration reported the first observation of $\chi_{c1}(3872)$.
- Many exotic states are observed in the past two decades.
- A series of **theoretical models** are established to describe these states.

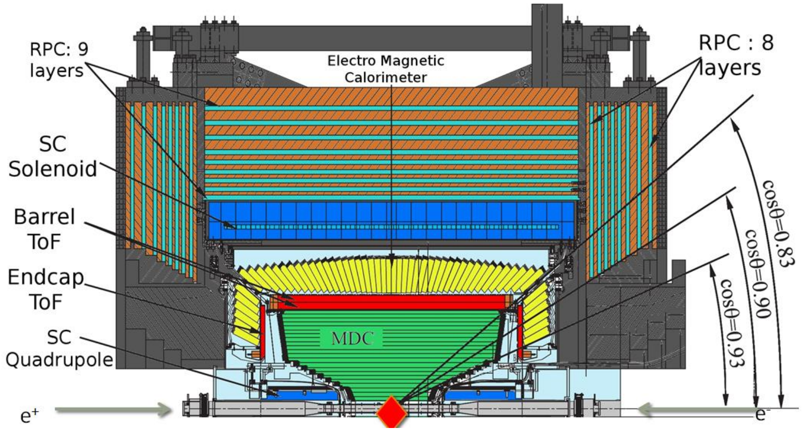
[1] From Fengkun's talk on the *XYZ* Workshop in China
[2] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. 8 (1964) 214.

Beam energy: 1.0 ~ 2.45 GeV

$\mathcal{L}_{peak} = 1 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

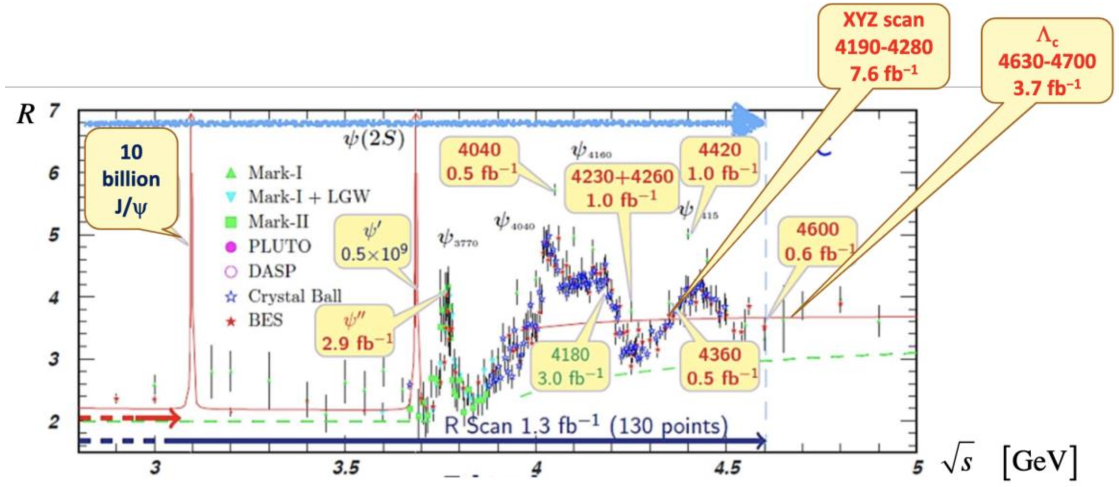


BEPCII



BESIII

Sub-system	Performance
MDC	$\sigma_{xy} = 130$ μm $\Delta P/P = 0.5\%$ @ 1GeV $\sigma_{dE/dx} = 6\%$
TOF	$\sigma_T = 68$ ps (barrel) 60 ps (endcaps)
EMC	$\Delta E/\sqrt{E} = 2.5\%$ @ 1GeV $\sigma_z = 0.5$cm @ 1GeV
Magnet	1.0 Tesla
MUC	$0.9 \times 4\pi$



- **Datasets in BESIII (~14 years):**
  - The worldwide largest e^+e^- datasets in τ-charm region
  - 46 datasets with $\sqrt{s} > 3.8$ GeV, $\sum L_i = 21.9\ \mathrm{fb}^{-1}$
  - 29 energy points with $L_i > 0.4\ \mathrm{fb}^{-1}$
- **Large datasets for exotic analyses!**

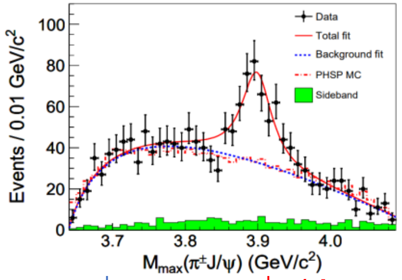
Introduction

- The $\sim$**4 fb^{-1}** data with $\sqrt{s}$ from **4.23 to 4.42 GeV** collected **in 2013 and 2014 years**.

✓ **Observation** of the **charmonium-like Z_c and Z_c^*** states in both **open charm** and **hidden charm** final states!

$Z_c(3900)^+$

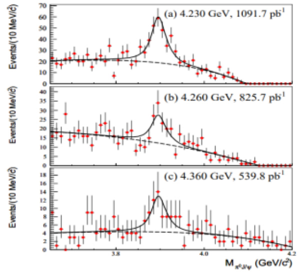
PRL 110, 252001 (2013)



$e^+e^- \to \pi^-\pi^+J/\psi$

$Z_c(3900)^0$

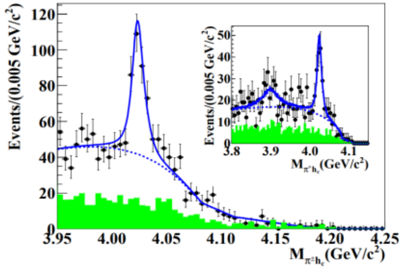
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0J/\psi$

$Z_c(4020)^+$

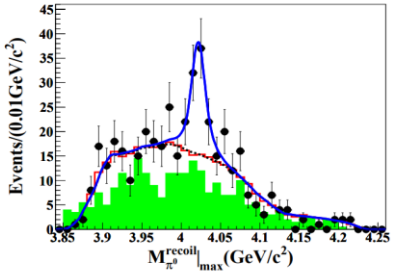
PRL 111, 242001 (2013)



$e^+e^- \to \pi^-\pi^+h_c$

$Z_c(4020)^0$

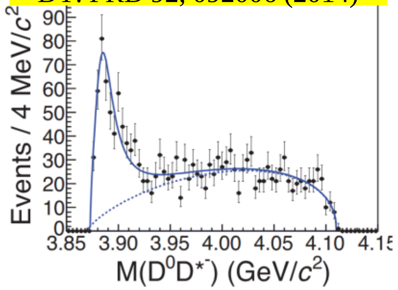
PRL 113, 212002 (2014)



$e^+e^- \to \pi^0\pi^0h_c$

$Z_c(3885)^+$

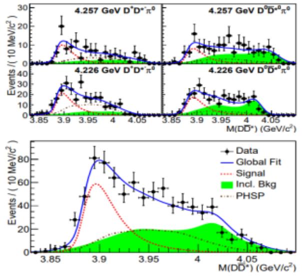
ST: PRL 112, 022001 (2014)
DT: PRD 92, 092006 (2014)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

$Z_c(3885)^0$

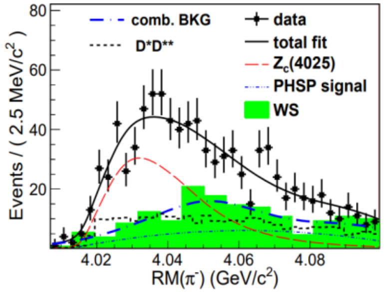
PRL 115, 222002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D})^0$

$Z_c(4025)^+$

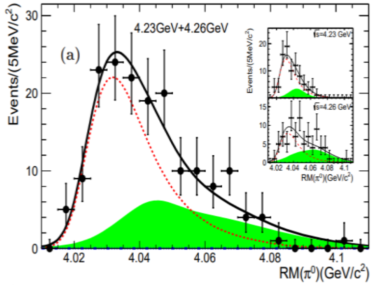
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

$Z_c(4025)^0$

PRL 115, 182002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

- The $\sim$**3.7 fb^{-1}** data with $\sqrt{s}$ from **4.626 to 4.70 GeV** collected **in 2020**[1].

✓ Potential **SU(3) counter-part Z_{cs} state**

[1] arXiv.2205.04809

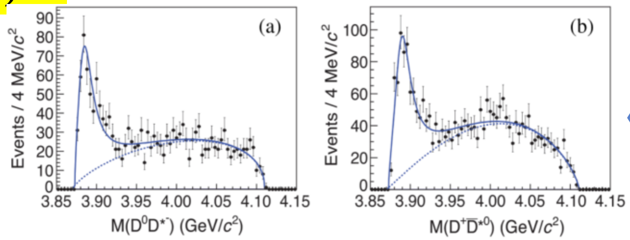
- **Observation of $Z_{cs}(3985)^+$** PRL 126, 102001 (2021)

➢ **Compare with $Z_c(3885)^+$.**

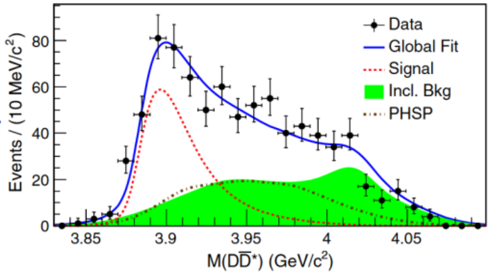
	$Z_{cs}(3985)^+$	$Z_c(3885)^+$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$3883.9 \pm 1.5 \pm 4.2$
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	$24.8 \pm 3.3 \pm 11.0$
$D^0 D^{*-}_{(s)}$ (MeV/c^2)	3977.04	3875.10
$D^{*0} D^{-}_{(s)}$ (MeV/c^2)	3975.20	3876.51

✓ **~10 MeV/c^2** above $D^{*0}D^+_{(s)}/D^0D^{*+}_{(s)}$ mass. -- **SU(3) counter-part.**

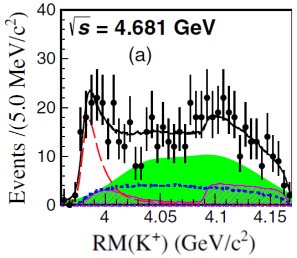
✓ Search for **neutral Z_{cs} in same dataset.**



$Z_c(3885)^+ \to (D^+\bar{D}^{*0} + D^{*+}\bar{D}^0)$



$Z_c(3885)^0 \to (D^-D^{*+} + D^0D^{*0})$



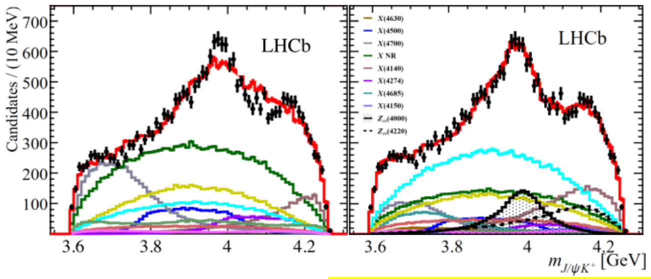
$Z_{cs}(3985)^+ \to (D_s^+\bar{D}^{*0} + D_s^{*+}\bar{D}^0)$

?

$Z_{cs}^0 \to (D_s^-D^{*+} + D_s^{*-}D^+)$

➢ **Compare to $Z_{cs}(4000)^+$ observed by LHCb.**

	$Z_{cs}(3985)^+$	$Z_{cs}(4000)^+$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$4003 \pm 6^{+4}_{-14}$
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	$131 \pm 15 \pm 26$



$Z_{cs}(4000)^+ \to K^+J/\psi$ PRL 127, 082001 (2021)

✓ Mass is **consistent**, but width is **one order larger** than BESIII result.

✓ They are same things? → **Search for neutral Z_{cs} state in open-charm final states.**

Evidence for a Neutral Near-Threshold Structure in the K_s^0 Recoil-Mass Spectra in $e^+e^- \to K_s^0 D_s^+ D^{*-}$ and $e^+e^- \to K_s^0 D_s^{*+} D^-$

New!

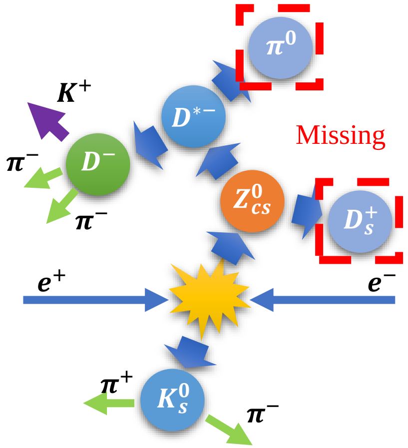
PRL 129, 112003 (2022)

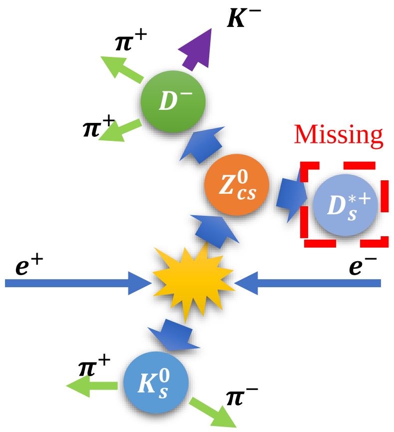
- **Decay chain:** $e^+e^- \to \bar{K}^0 Z_{cs}^0 \to K_s^0(D_s^+D^{*-} + D_s^{*+}D^-)$
  - ✓ **Partial reconstruction**
  - **Two types of tag method**

Tag D^- method

Tag: K_S^0, D^-

Missing: D_s^{*+}
or D_s^+ and π^0



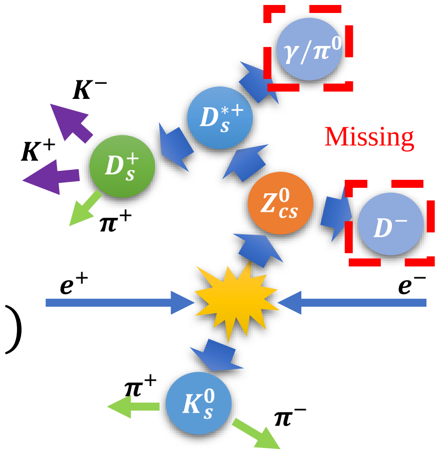


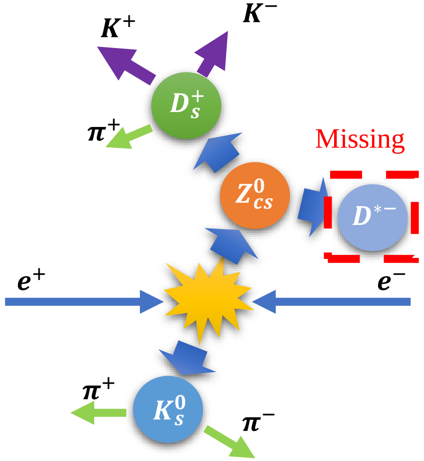
Decay channel: $e^+e^- \to K_S^0 D^{*-} D_S^+$ $\quad$ $e^+e^- \to K_S^0 D^- D_S^{*+}$

Tag D_s^+ method

Tag: K_S^0, D_S^+

Missing: D^{*-}
or D^- and $\gamma(\pi^0)$





- **Compare to $Z_{cs}(3985)^+$ analysis**
  - $e^+e^- \to K^-Z_{cs}^+ \to K^-(D_s^+\bar{D}^{*0} + D_s^{*+}\bar{D}^0)$
    - Two D_s^+ tag mode: $K^-K^+\pi^+$, $K_S^0K^+$
    - Tag D_s^+ and bachelor K^-, fit $RM(K^+)$.
  - $e^+e^- \to \bar{K}^0Z_{cs}^0 \to K_S^0(D_s^+D^{*-} + D_s^{*+}D^-)$
    - $\bar{K}^0$ reconstruction: $\bar{K}^0 \to K_S^0 \to \pi^+\pi^-$
      - ~20% relative efficiency compare to single K^-.
      - More backgrounds.
    - Tag D_s^+/D^- and bachelor K_S^0, fit $RM(K_S^0)$.
    - Need more D_s^+ and D^- tag modes.

✓ **Selected tag modes by Figure of Merit (FoM)**

- ✓ Optimize FoM based on three-body signals.
- ✓ Apply cuts to suppress combinatorial backgrounds.

D_s^+ and D^- tag modes:

D_s^+ tag
$K_S^0K^+$
$K^-K^+\pi^+$
$K^-K^+\pi^+\pi^0$
$K_S^0K^+\pi^+\pi^-$
$\pi^+\eta'_{\pi^+\pi^-\eta}$

D^- tag
$K^+\pi^-\pi^-$
$K_S^0\pi^-$
$K_S^0\pi^+\pi^-\pi^-$

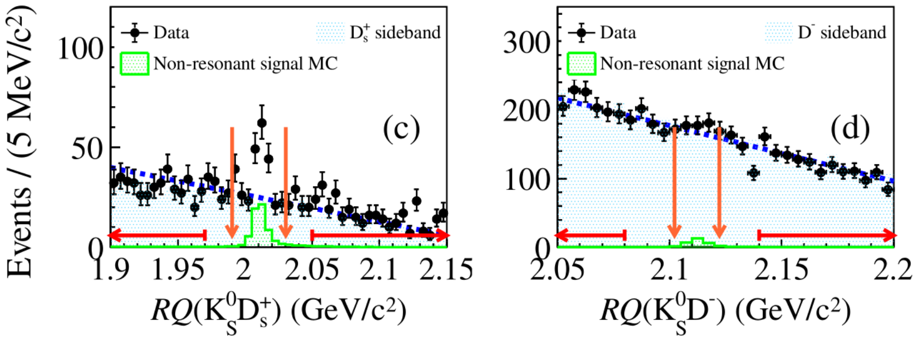
Additional cuts

Final state	Requirement
$D_s^+ \to K^+K^-\pi^+$	$M(K^+K^-) < 1.05$ GeV/c^2 $\lvert M(K^+\pi^-) - m[K^*(892)]\rvert < 70$ MeV/c^2
$D_s^+ \to K^+K^-\pi^+\pi^0$	$M(K^+K^-) < 1.05$ GeV/c^2 $\lvert M(\pi^-\pi^0) - m(\rho)\rvert < 150$ MeV/c^2
$D_s^+ \to K_S^0K^+\pi^+\pi^-$	$\lvert M(K^+\pi^-) - m[K^*(892)]\rvert < 70$ MeV/c^2
$D^- \to K_S^0\pi^+\pi^-\pi^-$	$\lvert M(K_S^0\pi^+) - m[K^*(892)]\rvert < 70$ MeV/c^2

- **Three body signals:**
  - From $K_S^0 Z_{cs}^0$ or $D_{(s)}^{**} D_{(s)}^{(*)}$ processes.
  - $K_S^0 D_s^+ D^{*-}$: $RQ(K_S^0 D_s^+) = RM(K_S^0 D_s^+) + M(D_s^+) - m(D_s^+)$
  - $K_S^0 D_s^{*+} D^-$: $RQ(K_S^0 D^-) = RM(K_S^0 D^-) + M(D^-) - m(D^-)$
- **Extracted number of combinatorial backgrounds**
  - Define signal and sideband region of $RQ(K_S^0 D_s^+)$ and $RQ(K_S^0 D^-)$ spectra.
  - Fit the sideband region with one-order polynomial function.
  - Integral the function to extracted yields of combinatorial backgrounds.
- **Retain the candidates inside three-body signal region.**
- **Fit the $RM(K_S^0)$ spectra to search for the neutral Z_{cs} state.**

Region	Signal (MeV/c^2)	Sideband (MeV/c^2)
$RQ(K_S^0 D_s^+)$	$\lvert RQ(K_S^0 D_s^+) - m(D^{*-})\rvert < 20$	[1.90,1.97] && [2.05,2.15]
$RQ(K_S^0 D^-)$	$\lvert RQ(K_S^0 D^-) - m(D_s^{*+})\rvert < 10$	[2.05,2.08] && [2.14,2.20]

Signal and sideband region



$RQ(K_S^0 D_s^+)$ & $RQ(K_S^0 D^-)$ @ $\sqrt{s} = 4.68$ GeV

$\sqrt{s}$ (MeV)	D_s^+-tag	D^--tag
4628	40.6 ± 3.4	132.1 ± 6.1
4641	49.8 ± 3.7	169.1 ± 6.8
4661	57.5 ± 4.0	184.3 ± 6.9
4682	199.0 ± 7.3	668.8 ± 12.9
4699	68.6 ± 4.2	217.5 ± 7.4

Number of combinatorial backgrounds

Fit strategy on $RM(K_S^0)$ spectra

- **Signal PDF**

$$\left(BW_{D^-D_s^{*+}} \times \boldsymbol{Eff}_{D^-D_s^{*+}} + BW_{D^{*-}D_s^+} \times \boldsymbol{Eff}_{D^{*-}D_s^+}\right) \otimes \boldsymbol{Gauss}\,(\boldsymbol{\mu}, \boldsymbol{\sigma})$$

$$BW_i(M) = p_i \cdot q \left| \frac{1}{M^2 - m_0^2 + im_0[f \cdot \Gamma_1(M) + (1-f) \cdot \Gamma_2(M)]} \right|^2$$

$$\Gamma_1(M) = \Gamma_0 \cdot \frac{p_1}{p_1^*} \cdot \frac{m_0}{M}, \qquad \Gamma_2(M) = \Gamma_0 \cdot \frac{p_2}{p_2^*} \cdot \frac{m_0}{M},$$

M: $RM(K_S^0)$
m_0: mass of the resonance.
Γ_0: width of the resonance.
q: momentum of K_S^0 in e^+e^- system.
p_i: momentum of $D^{(*)-}$ in $D^{(*)-}D_s^{(*)+}$ system.
p_i^*: momentum of $D^{(*)-}$ in $D^{(*)-}D_s^{(*)+}$ system when $M = m_0$.
f: ratio of the two signal channels.

  - **Import a Gaussian constraint:**

    Restrict the width of Z_{cs}^0 within the uncertainty of $Z_{cs}(3985)^+$.

- **The shape of $D^-(D_s^+)$ combinatorial backgrounds**

  The yields of $D^-(D_s^+)$ backgrounds are fixed by **a fit on $RQ(K_S^0D^-)$ ($RQ(K_S^0D_s^+)$) spectra**.

- **The shape of PHSP MC samples**

  To model the contributions form non-resonant three body $K_S^0D_s^+D^{*-}$ and $K_S^0D_s^{*+}D^-$ process.

- **The shape of $D_{(s)}^{**}D_{(s)}^{(*)}$ MC samples**

  The yields of D_s^{**} candidates are fixed by the control samples study in charged Z_{cs} analysis.

◆ **Apply a simultaneous fit between two tag methods at all energy points.**

- ✓ The **mass and width** are measured to be (with $J^P = 1^+$ Breit-Wigner):

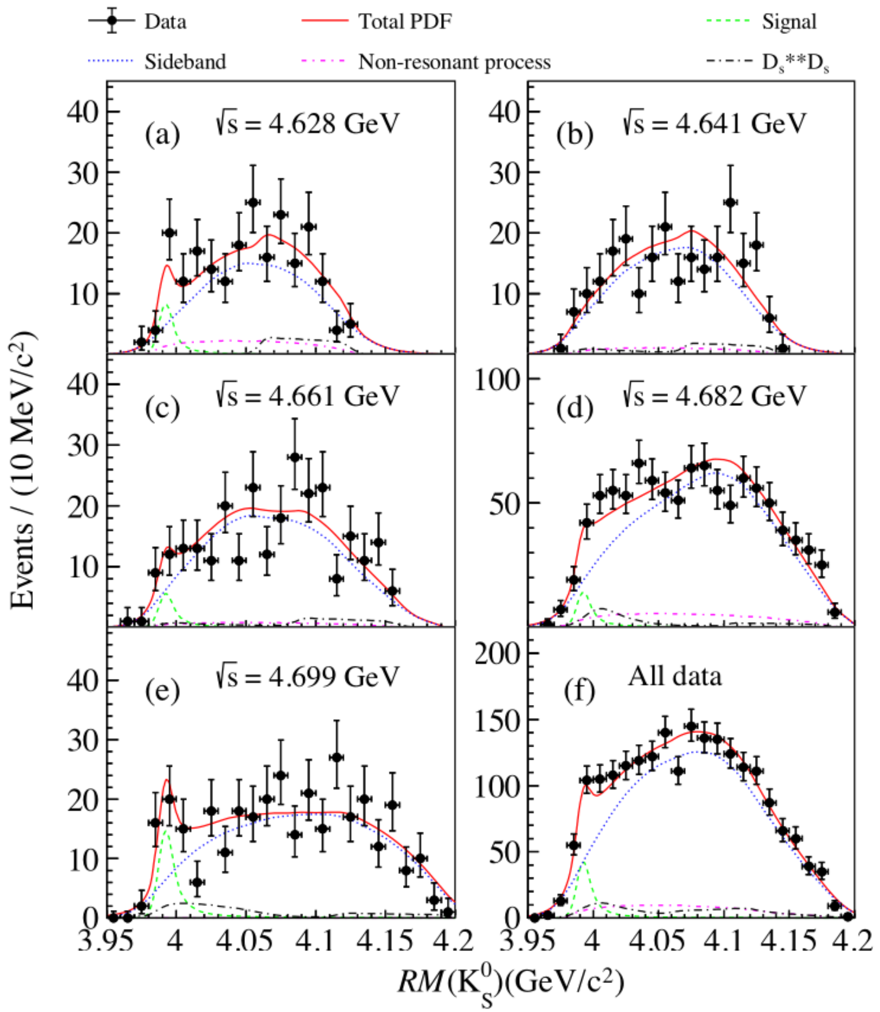
$$m\left(Z_{cs}(3985)^0\right) = (3992.2 \pm 1.7 \pm 1.6)\ \text{MeV}/c^2$$

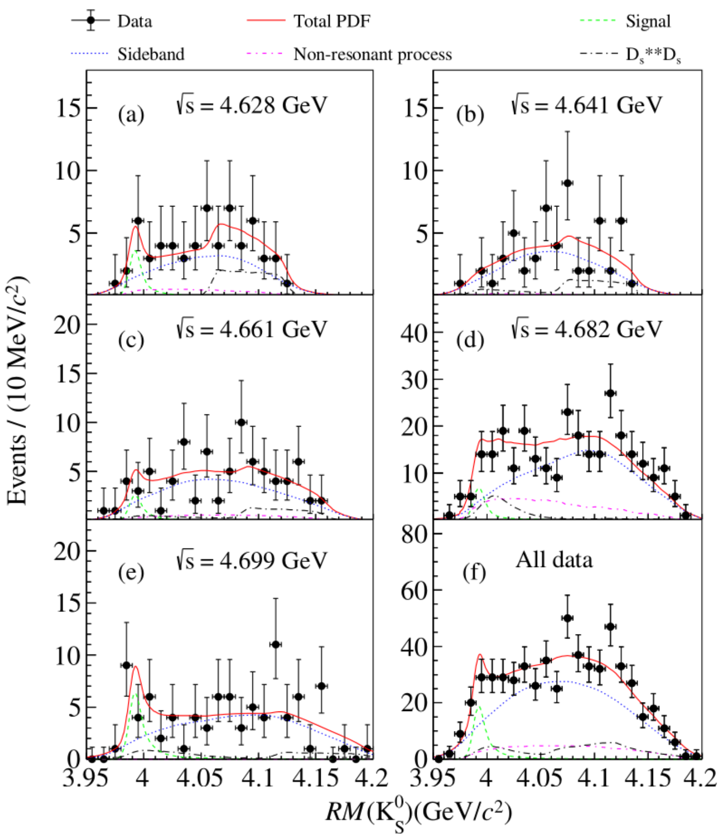
$$\Gamma\left(Z_{cs}(3985)^0\right) = \left(7.7^{+4.1}_{-3.8} \pm 4.3\right)\ \text{MeV}$$

- ✓ The statistical significance is $\mathbf{5.0\sigma}$.
- ✓ Becomes $\mathbf{4.6\sigma}$ after considering systematic uncertainties.
- ✓ The width is $\mathbf{4.1^{+4.7}_{-3.9}}$ **MeV** if remove the width constraint.

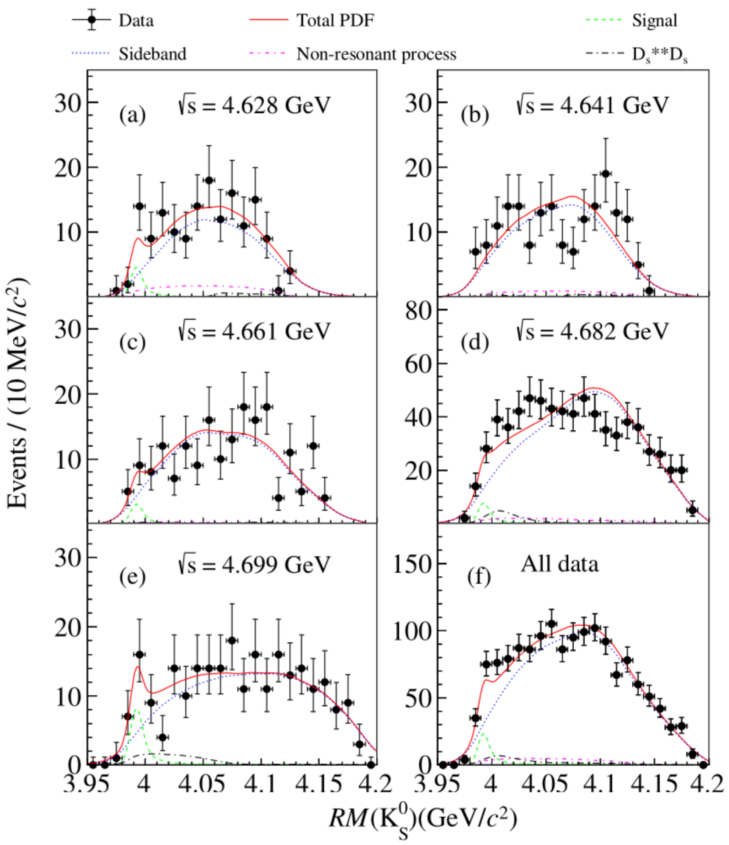
● **Evidence of a neutral Z_{cs} states: $Z_{cs}(3985)^0$**

- ✓ Measured mass near $D_s^+ D^{*-} + D_s^{*+} D^-$ mass threshold.
- ✓ Mass and width consistent with charged Z_{cs} state.





D_s^+-tag method



D^--tag method

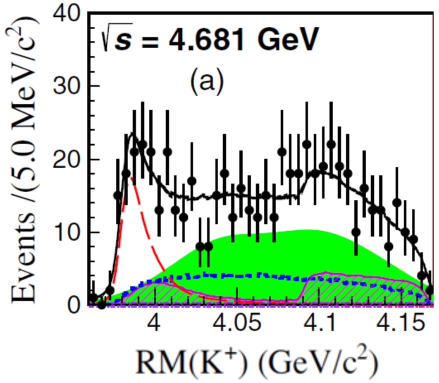
- ✓ D^--tag method suffered **high level** of combinatorial backgrounds.
- ✓ Both the two tag methods contribute to the signal yields.

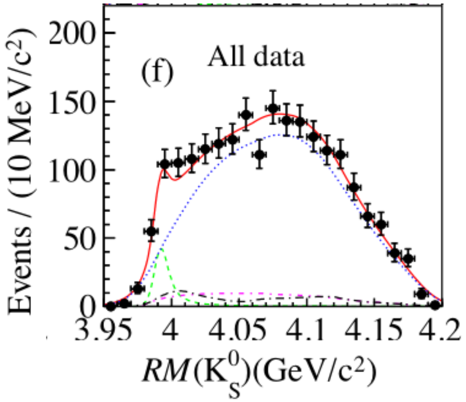
$\sqrt{s}$(MeV)	D_s^+-tag	D^--tag
4628	$6.5^{+4.1}_{-3.4}$	$7.8^{+4.9}_{-4.1}$
4641	$0.0^{+2.7}_{-2.3}$	$0.0^{+3.1}_{-2.7}$
4661	$4.6^{+3.2}_{-2.7}$	$5.3^{+3.7}_{-3.1}$
4682	$12.0^{+6.4}_{-5.3}$	$13.6^{+7.2}_{-6.1}$
4699	$12.2^{+3.9}_{-3.5}$	$14.0^{+4.5}_{-4.0}$

Z_{cs} yields from two tag methods

Compare with $Z_{cs}(3985)^+$

Charged Z_{cs}





Neutral Z_{cs}

	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

	$\sigma^{\text{Born}} \times \mathcal{B}$(pb)			
$\sqrt{s}$ (MeV)	$\bar{K}^0 Z_{cs}(3985)^0$	$K^- Z_{cs}(3985)^+$	χ^2	$\chi^2_{\text{total}}/\text{ndf}$
4628	$4.4^{+2.6}_{-2.2} \pm 2.0$	$0.8^{+1.2}_{-0.8} \pm 0.6$	1.2	
4641	$0.0^{+1.6}_{-0.0} \pm 0.2$	$1.6^{+1.2}_{-1.1} \pm 1.3$	0.5	
4661	$2.8^{+1.8}_{-1.6} \pm 0.6$	$1.6^{+1.3}_{-1.1} \pm 0.8$	0.3	5.1/5
4682	$2.2^{+1.2}_{-1.0} \pm 0.8$	$4.4^{+0.9}_{-0.8} \pm 1.4$	1.0	
4699	$7.0^{+2.2}_{-2.0} \pm 1.8$	$2.4^{+1.1}_{-1.0} \pm 1.2$	2.1	

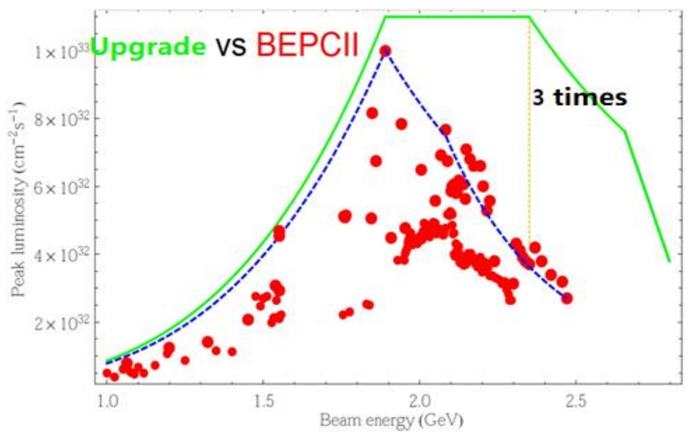
- **Mass and width**
  - ✓ The mass and width of $Z_{cs}(3985)^0$ are consistent with the recently observed $Z_{cs}(3985)^+$ at BESIII.
  - ✓ Also consistent with the theoretical predictions
- **Born cross section × branching fraction**
  - ✓ The $\sigma^{Born}(KZ_{cs}) \times \mathcal{B}(Z_{cs} \to D_s^* D + D_s D^*)$ are consistent with each other.
  - ✓ Agree with the prediction based on isospin symmetry.

The $Z_{cs}(3985)^0$ should be the isospin partner of $Z_{cs}(3985)^+$

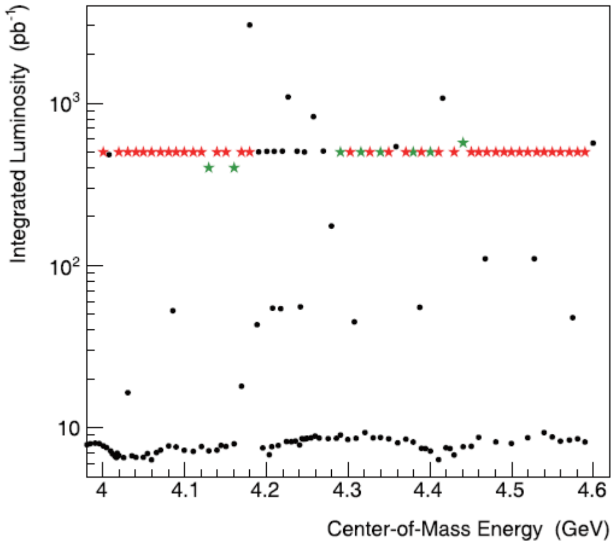
Future Z_{cs} analyses at BESIII

CPC Vol. 44 No.126, 102001 (2021)

- **On going analyses:**
  - $e^+e^- \to K^+K^-J/\psi$
  - $e^+e^- \to K_S^0K_S^0J/\psi$
  - $e^+e^- \to K^-D_s^{*+}\bar{D}^{*0}$
- **Data taking:**
  - BEPCII – Upgrade @ 2024
  - **Three times** peaking luminosity @ $\sqrt{s} = 4.6$ GeV
  - Possibilities for **future *XYZ* data taking** at BESIII.



BEPCII-Upgrade



The plan for *XYZ* data taking

✓ **Detailed Z_{cs} analyses with large statistic and more energy point will come soon!**

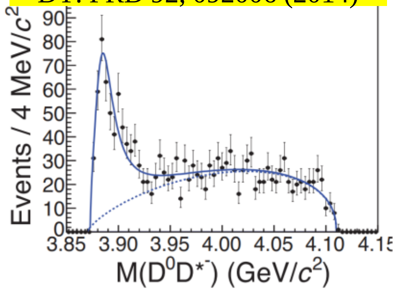
Table 3.4. Data taking requirements for *XYZ* physics and charmonium physics.

plan	data sets
XYZ plan (1)	500 pb^{-1} at a large number of points between 4.0 and 4.6 GeV
XYZ plan (2)	5 fb^{-1} at 4.23, 4.42 GeV for large Z_c samples
XYZ plan (3)	5 fb^{-1} above 4.6 GeV
charmonium plan	3×10^9 $\psi(3686)$ decays

Summary

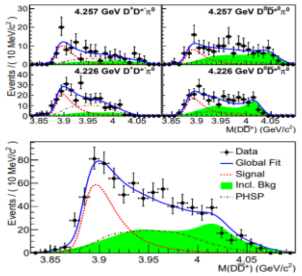
$Z_c(3885)^+$

ST: PRL 112, 022001 (2014)
DT: PRD 92, 092006 (2014)



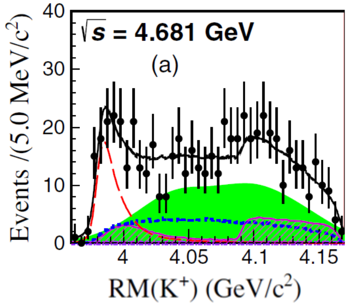
$Z_c(3885)^0$

PRL 115, 222002 (2015)



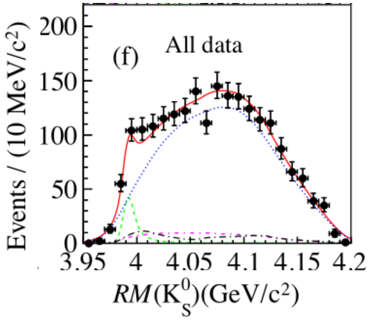
$Z_{cs}(3985)^+$

PRL 126, 102001 (2021)



$Z_{cs}(3985)^0$

PRL 129, 112003 (2022)



What's Next?

- BESIII Collaboration has abundant research results on *XYZ* physics.
- In 2020, about **3.7 fb^{-1}** data samples with $\sqrt{s}$ from $\mathbf{4.626}$ **GeV to** $\mathbf{4.70}$ **GeV** have been collected.
- Based on the new datasets:
  - ✓ The observation of $Z_{cs}(3985)^+$.
  - ✓ **The evidence of $Z_{cs}(3985)^0$.**
    - Significance evaluated to be $\mathbf{4.6\sigma}$.
    - Mass and width and cross sections **consistent** with charged Z_{cs} state.
- ➢ More detailed analyses on Z_{cs} states are **ongoing.**
- ➢ The BESIII Collaboration planed to **collected more high energy datasets**, to further understand the nature of **Z_{cs} states**.

Thank you!

Back Up