Status of Z_{cs} states at BESIII

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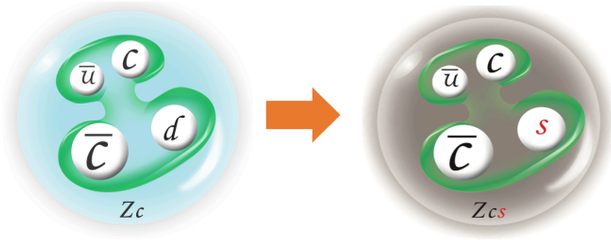
Outline

- Motivation
- BESIII experiment
- Recent results of Z_{cs} states from BESIII
  - Search for Z'_{cs} state in $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$
  - Search for Z_{cs} state in $e^+e^- \to K^+K^-J/\psi$
- Summary

Motivation

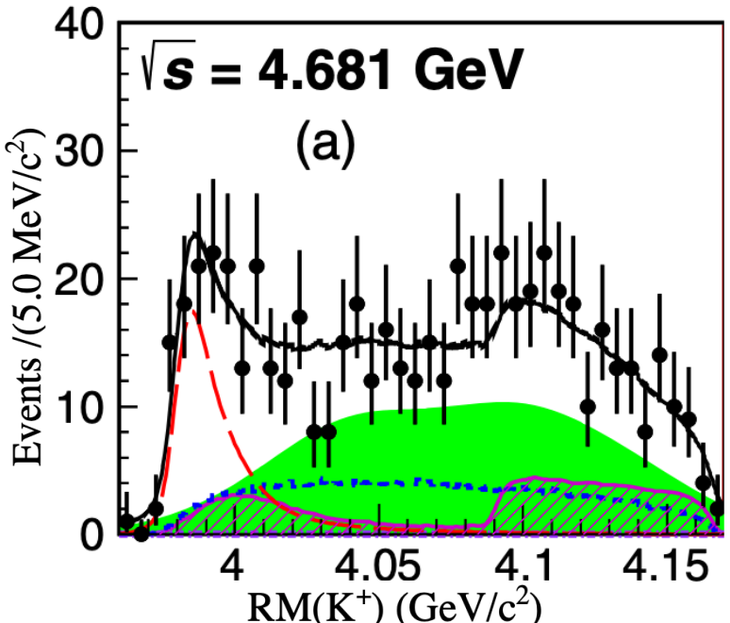
- The first observation of $Z_{cs}(3985)^-$ was reported in $e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$ by BESIII:
  - Manifestly exotic charged hidden-charm tetraquark candidate with strangeness,
  - With a non-zero charge → minimal quark content: $(c\bar{c}s\bar{u})$,
  - Considered to be strange partner of $Z_c(3900)^-$.



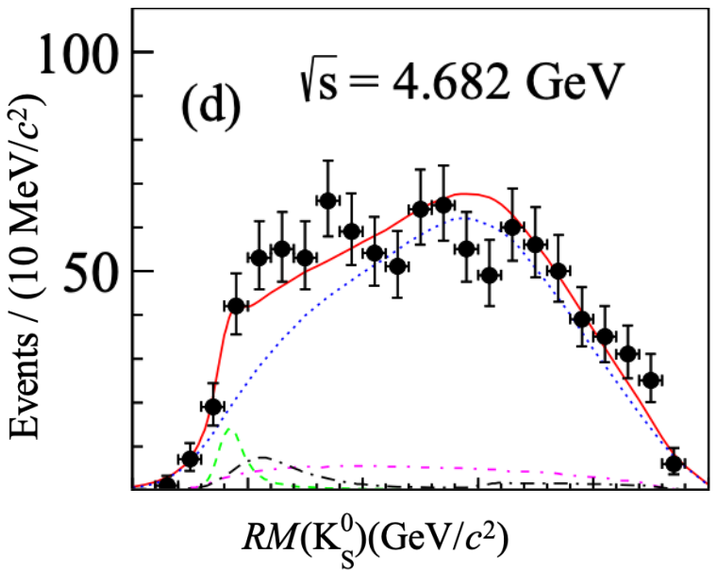
- BESIII reported evidence of the neutral $Z_{cs}(3985)^0$ in $e^+e^- \to K_S^0(D_s^+D^{*-} + D_s^{*+}D^-)$.
- LHCb reported two tetraquark candidates $Z_{cs}(4000)^-/Z_{cs}(4220)^-$ in $B^+ \to K^+J/\psi\phi$:
  - Broader width comparing to $Z_{cs}(3985)^-$.
  - Are they the same state in different decay processes?

	$m_0(Z_{cs})$ (MeV/c^2)	$\Gamma_0(Z_{cs})$ (MeV)
$e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$
$B^+ \to J/\psi\phi K^+$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
$e^+e^- \to K_S^0(D_s^-D^{*+} + D_s^{*-}D^+)$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$

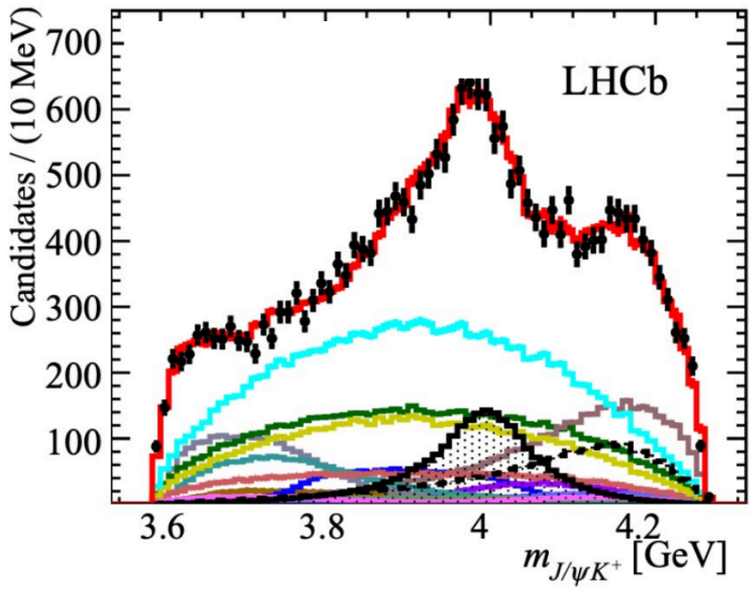
[BESIII Phys. Rev. Lett. 126 (2021) 102001]



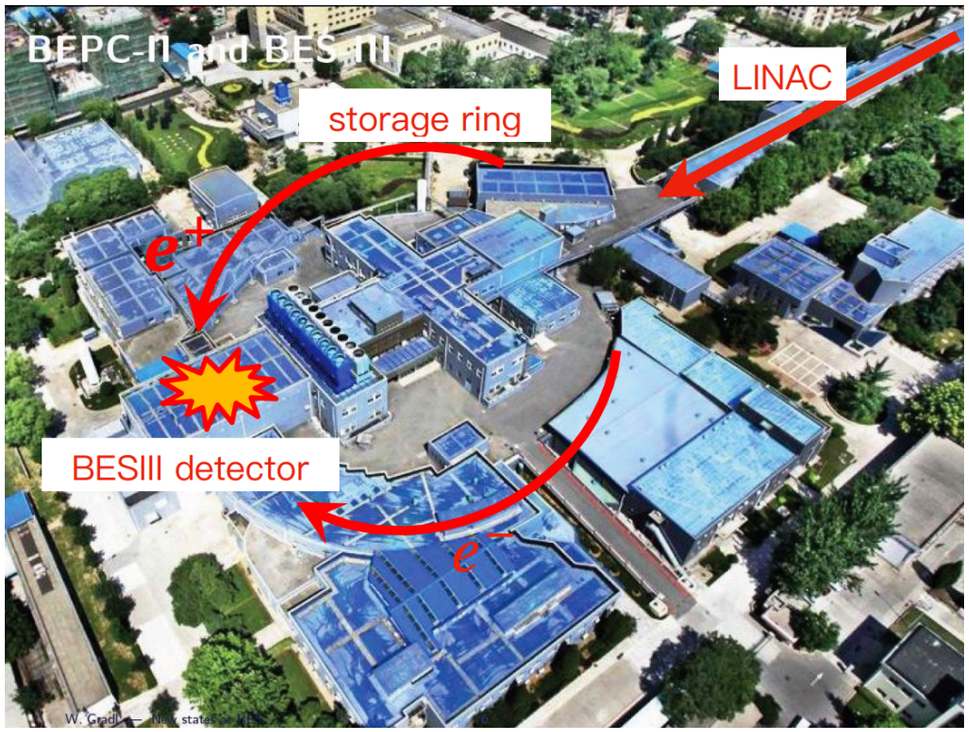
[BESIII, Phys. Rev. Lett. 129 (2022) 112003]



[LHCb, Phys. Rev. Lett. 127 (2021) 8, 082001]

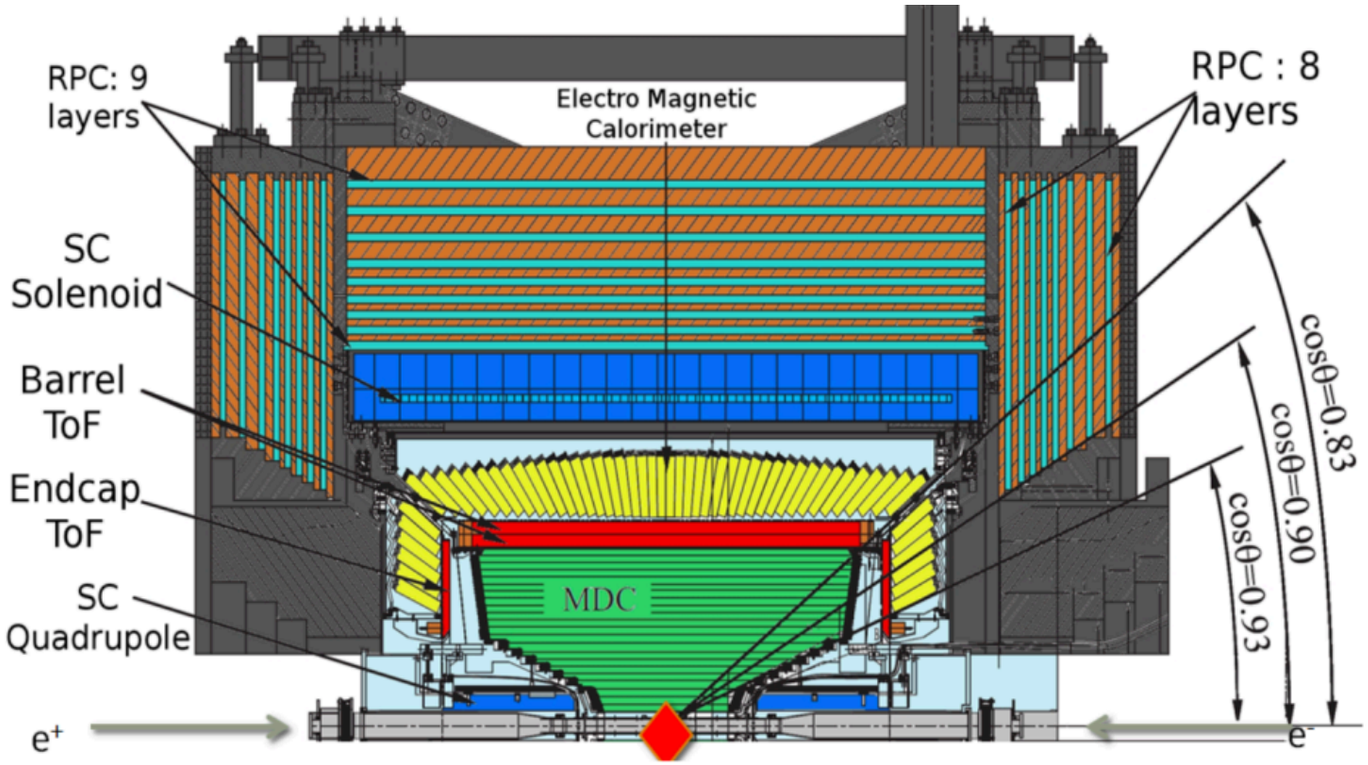


BESIII experiment

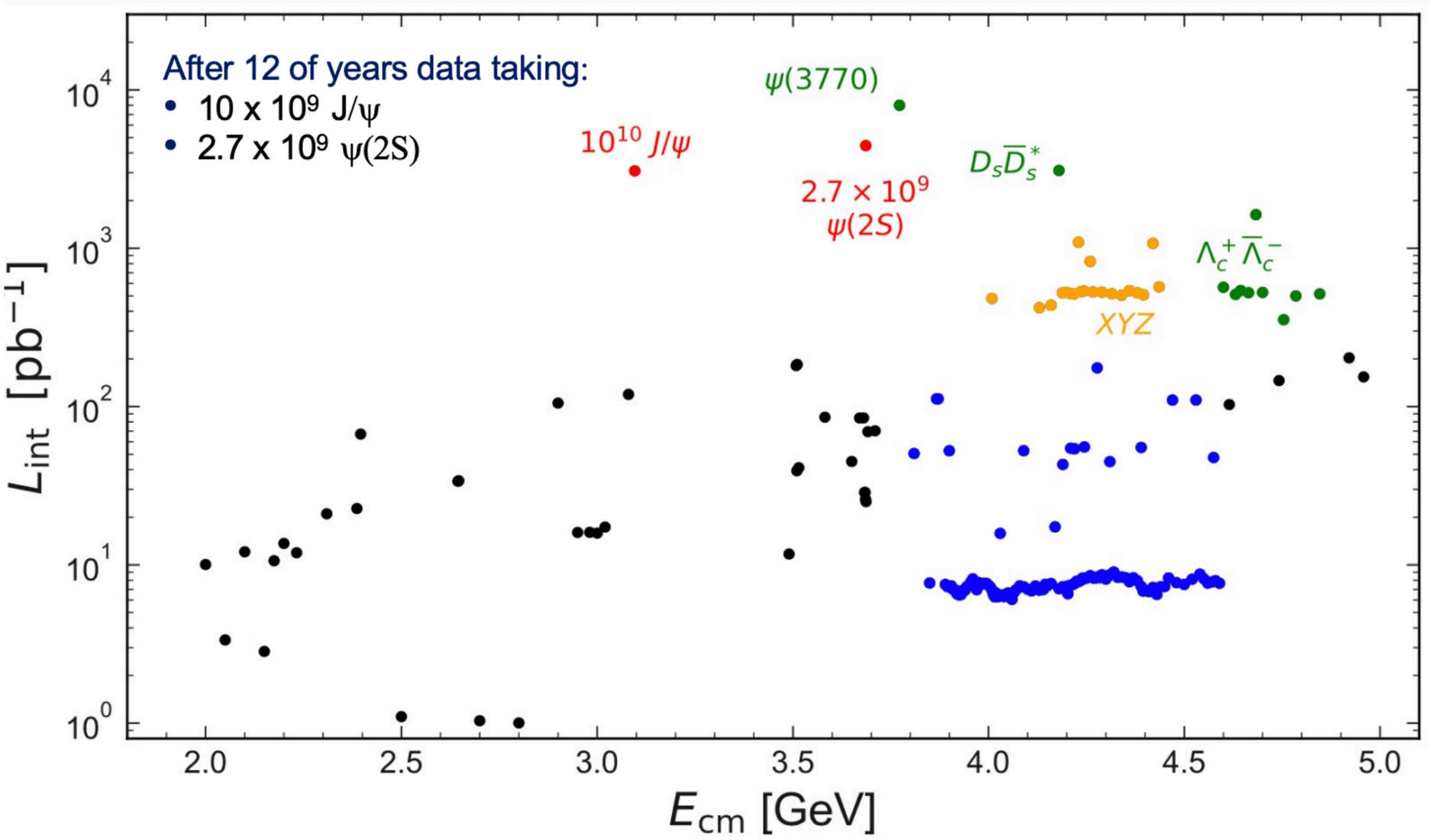


- BEPCII:
  - symmetric electron-positron collider,
  - Energy range $\sqrt{s} = 2.0 \sim 4.9$ GeV,
  - Peak luminosity: $1.1 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ @ $\sqrt{s} = 3.77$ GeV.

- BESIII:
  - Multi-purpose detector covering 4π solid angle,
  - Good particle identification,
  - Excellent energy and momentum resolution.



BESIII datasets



- BESIII has collected rich datasets in the XYZ region $\sqrt{s} > 3.8$ GeV with integrated luminosity of around 22 fb^{-1}.

Search for Z'_{cs} state in $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$

Chin. Phys. C 47 (2023) 033001

Search for Z'_{cs} state in $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$

- Heavier partner of $Z_{cs}(3985)^-$, denoted as Z'_{cs}, are expected to decay to $D_s^{*-}D^{*0}$ state with a large rate.

- Many theoretical models has predicted the masses ranging from 4120 to 4200 MeV/c^2:

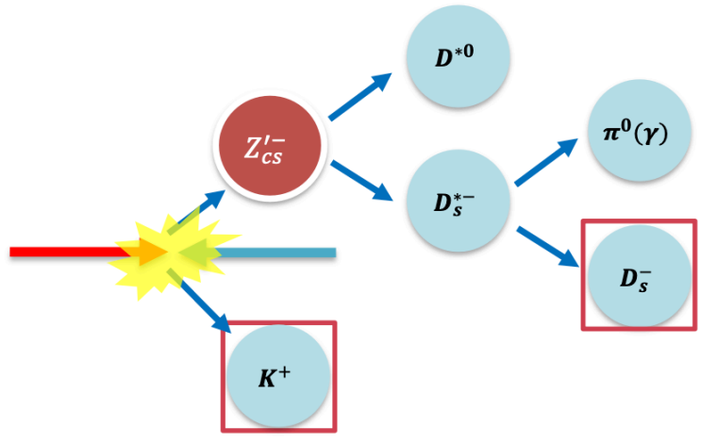
  - $D_s^{*-}D^{*0}$ molecule state, or heavy SU(3)$_f$ partner of $Z_{cs}(3985)^-$?

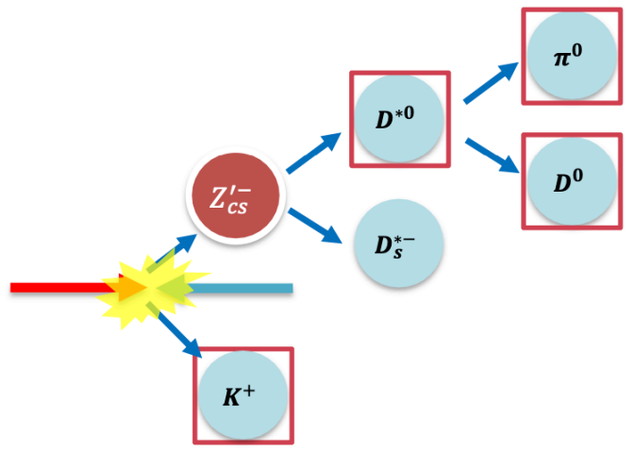
$m(Z_{cs}^-)$ MeV/c^2	Γ MeV	
4130.7 ± 2.5 (4129.4 ± 3.3)	29.1 ± 6.4 (27.3 ± 9.2)	Phys.Rev.D 102 (2020) 11, 111502
4138 ± 6	28 ± 12	Phys.Rev.D 103 (2021) 7, 074029
4130 ± 170		Chin.Phys.C 45 (2021) 9, 093102
$4124.2^{+5.6}_{-3.7}$	$9.8^{+5.2}_{-4.8}$	Phys.Rev.D 103 (2021) 2, L021501
[4140, 4213]		Sci.Bull. 66 (2021), 1288-1295
4190 ± 90		Int.J.Mod.Phys.A 36 (2021) 15, 2150107
4126 ± 3	13 ± 6	Sci.Bull. 66 (2021), 2065-2071

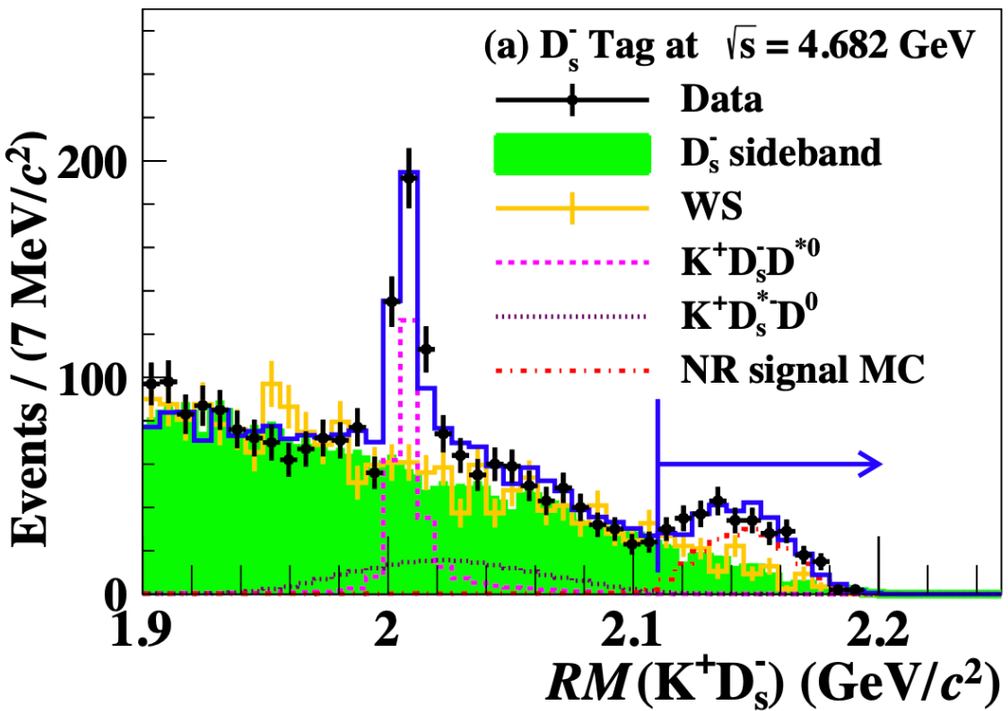
- It is crucial to search for Z'_{cs} state and measure its properties to constraint the theoretical models.

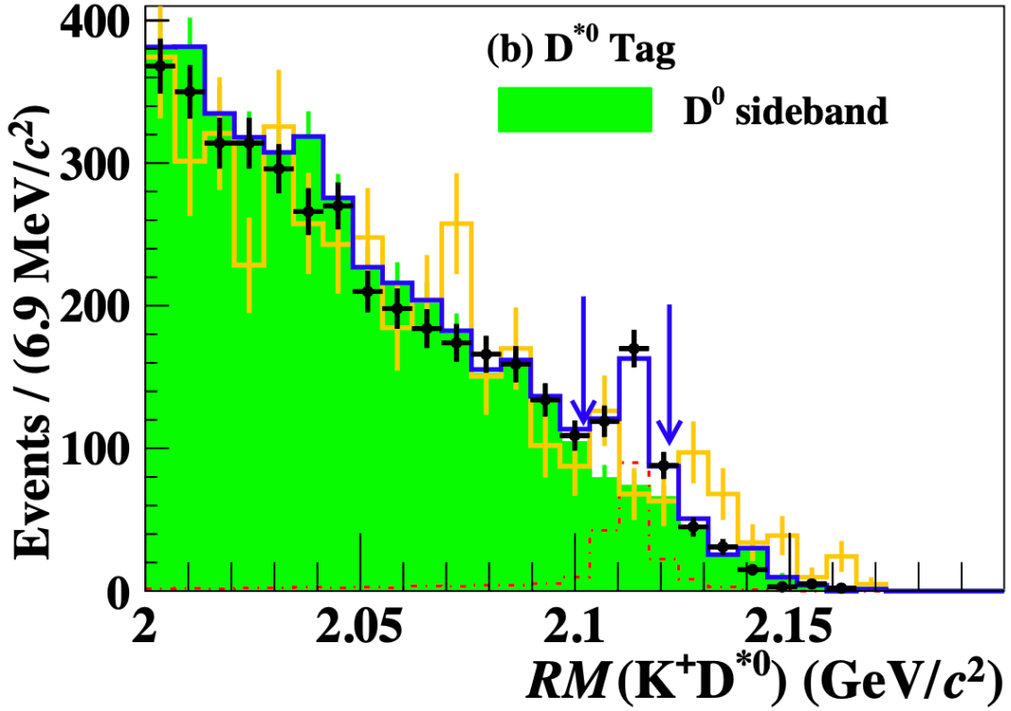
Search for Z'_{cs} state in $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$

- The excited partner of $Z_{cs}(3985)^-$ are searched in process of $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$ at three c.m. energies $\sqrt{s} =$ 4.661 GeV, 4.682 GeV and 4.699 GeV.
- A partial reconstruction method is applied to improve the signal efficiency:
  - D_s^- tag: bachelor K^+ and $D_s^-(\to K_S^0K^-, K^+K^-\pi^-)$,
  - D^{*0}tag: bachelor K^+ and $D^{*0}(\to D^0\pi^0)$.
- Clear $K^+D_s^{*-}D^{*0}$ structure is observed in the spectrum of the $K^+D_s^-$ (K^+D^{*0}) recoil mass, indicated by the blue arrow.









Search for Z'_{cs} state in $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$

- The combinatorial background:
  - Shape extracted from mixed samples
    - Wrong-sign (WS) events of $K^-D_s^-$ or K^-D^{*0} combinations,
    - D_s^- and D^{*0} mass sideband events.
  - Yields determined by a fit to $RM(K^+D_s^-)$ and $RM(K^-D^{*0})$ spectra.
- Excited charmed mesons $D^{**}_{(s)}$:
  - Same final states as signal: $e^+e^- \to D_s^{*-}D_s^{**+}(\to D^{*0}K^+)$ or $D^{*0}D^{**0}(\to D_s^{*-}K^+)$.
  - Contribution from $e^+e^- \to D_s^{*-}D_{s1}^+(2536)(\to D^{*0}K^+)$ estimated by the measured cross section.
  - Other potential $D^{**}_{(s)}$ described by non-resonant signal

Background source	Tag	4.661 GeV	4.682 GeV	4.699 GeV
Comb. bkg	D_s^--tag	27 ± 5	120 ± 11	54 ± 7
	D^{*0}-tag	33 ± 6	216 ± 15	103 ± 10
$D_s^{*-}D_{s1}(2536)^+$	D_s^--tag	18 ± 7	117 ± 27	52 ± 13
	D^{*0}-tag	15 ± 6	91 ± 21	33 ± 9

Search for Z'_{cs} state in $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$

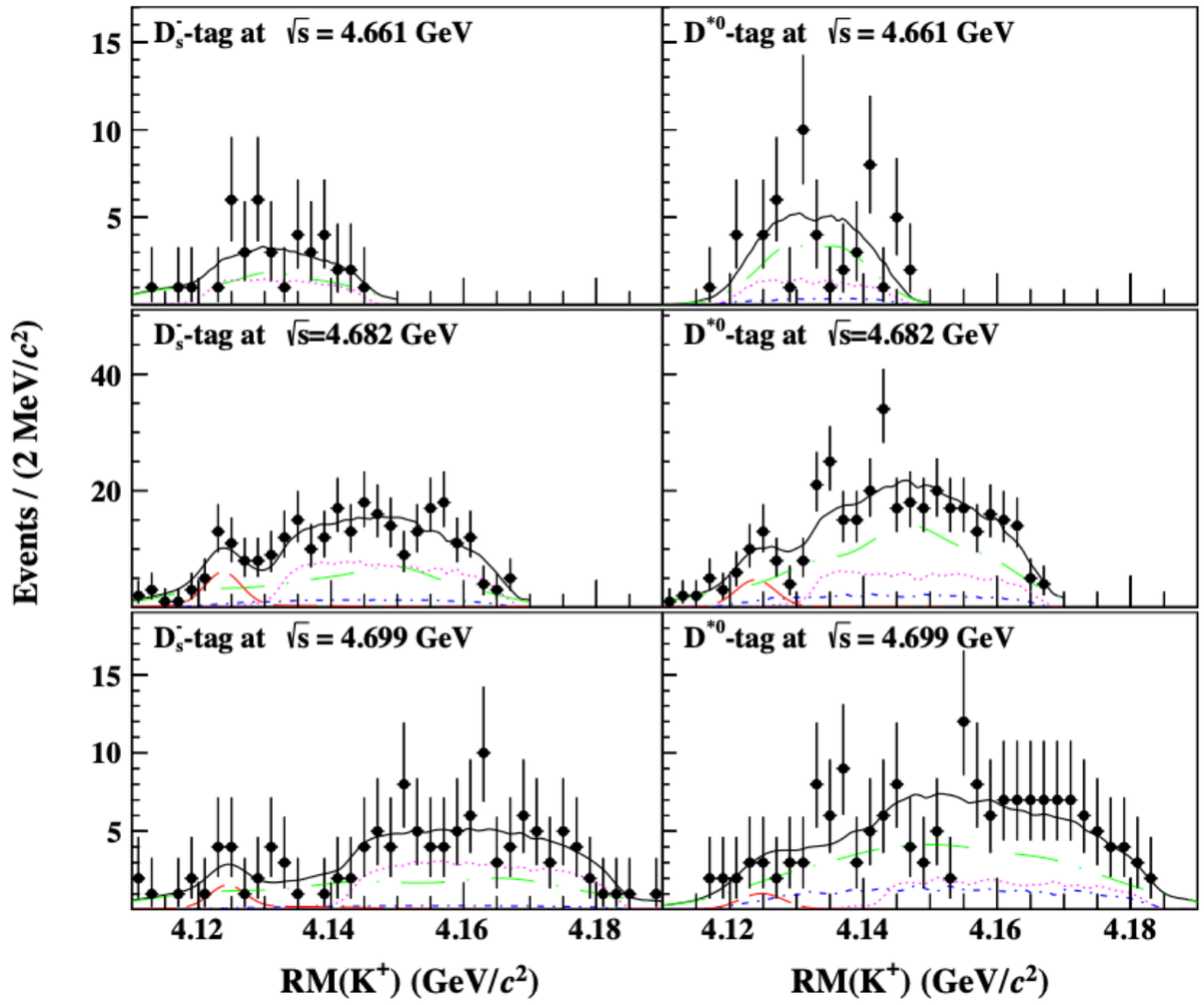
- The enhancement is studied around 4.125 GeV in the recoil mass spectrum of K^+.
- The Z'_{cs} component is modeled with an Breit-Wigner function convolved with resolution function:
  - S-wave Breit-Wigner function:

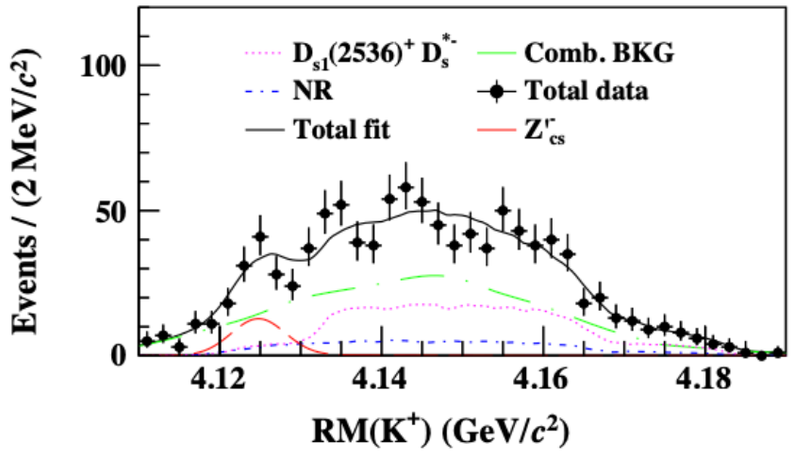
$$\mathcal{F}(M) \propto \left| \frac{\sqrt{q \cdot p}}{M^2 - m_0^2 + i m_0 \Gamma(M)} \right|^2,$$

- The mass of Z'_{cs} is determined to be:
  - $m_0 = 4123.5 \pm 0.7 \pm 4.7\,\mathrm{MeV}/c^2$,
  - statistical significance of 3.9σ (2.1σ w/ systematic uncertainties).
- The width Γ_0 is not reported due to limited statistics.

Systematic uncertainties

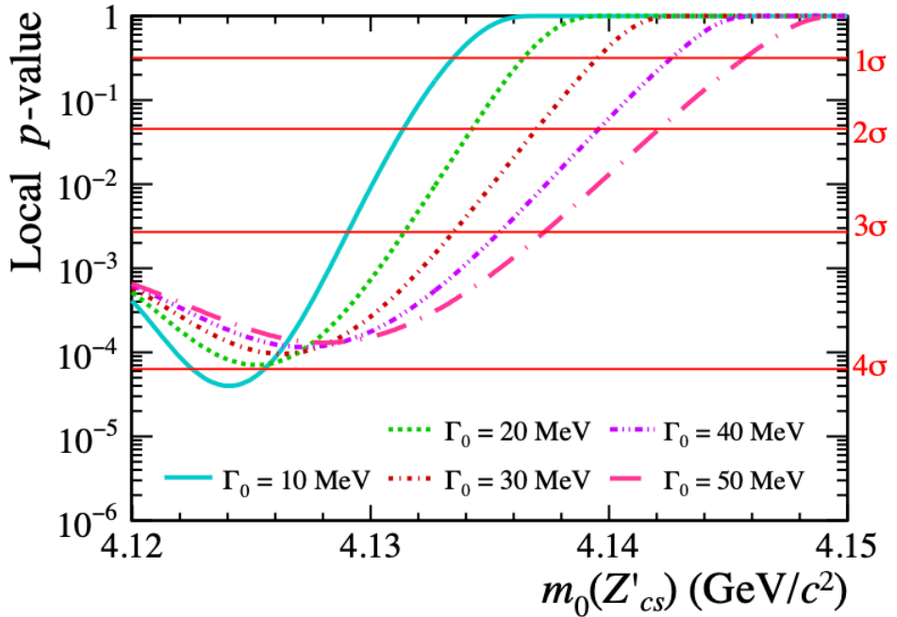
Source	Mass (MeV/c^2)
Comb. background	0.1
$D_s^{*-}D_{s1}(2536)^+$	0.1
$\sigma^{\mathrm{Born}}(e^+e^- \to K^+Z_{cs}'^-)$ line shape	0.5
Signal model	0.1
Mass scaling	0.5
Resolution	0.8
Efficiency curve	< 0.1
Γ_0 assumptions	4.6
Total	4.7



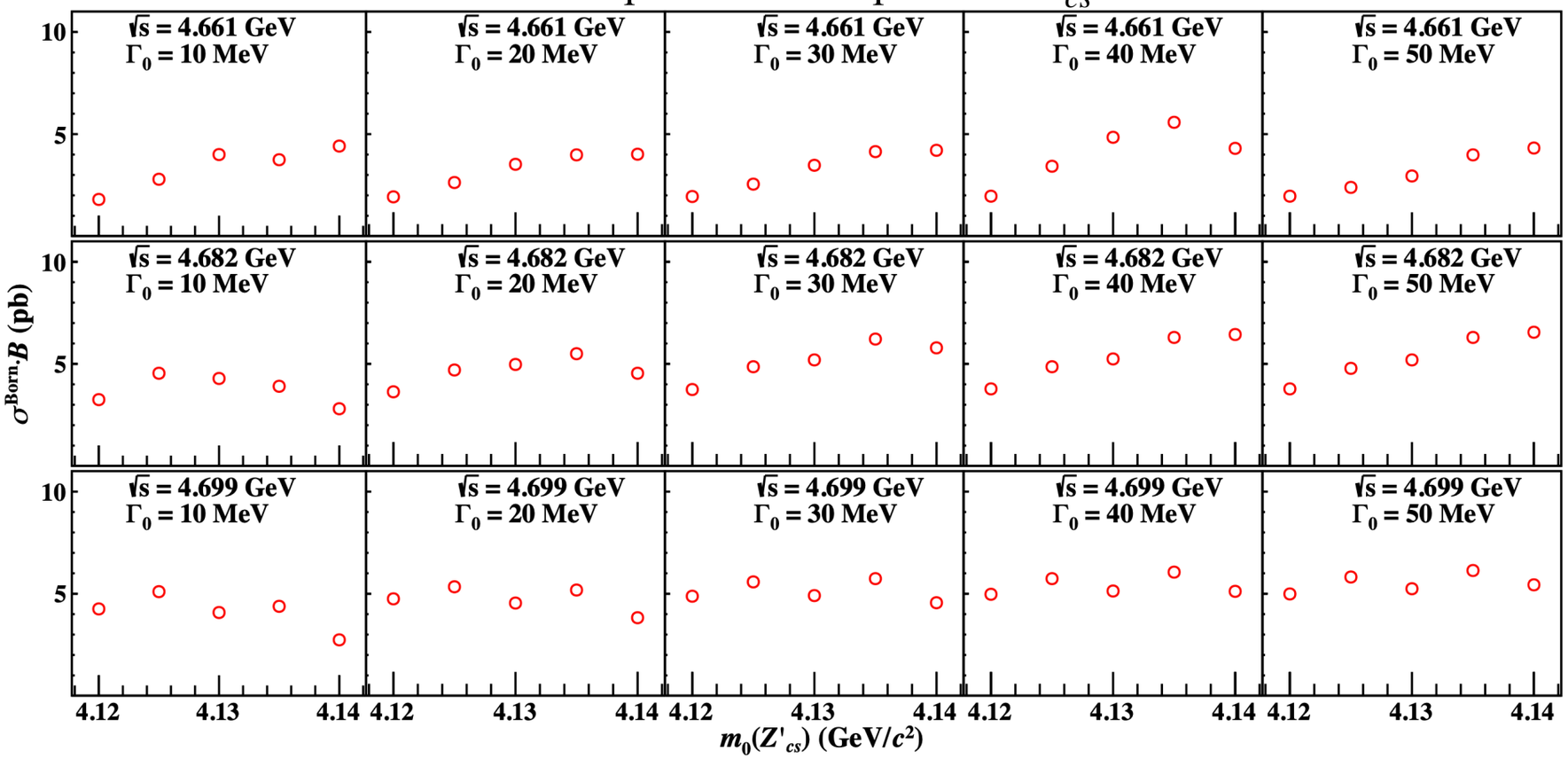


Search for Z'_{cs} state in $e^+e^- \to K^+D_s^{*-}D^{*0} + c.c.$

- Local p-value scans are preformed under different width assumptions:
  - Minimum p-value found at $m_0 = 4124.1\,\mathrm{MeV}/c^2$ and $\Gamma_0 = 10\,\mathrm{MeV}$ with 4.1σ



- Upper limits of $\sigma^{\mathrm{Born}}B$ are at 90% CL are provided: $\mathcal{O}(1)$ pb, under different hypotheses at each energy points.
- More data are needed to establish a clearer picture of the potential Z'_{cs} states.

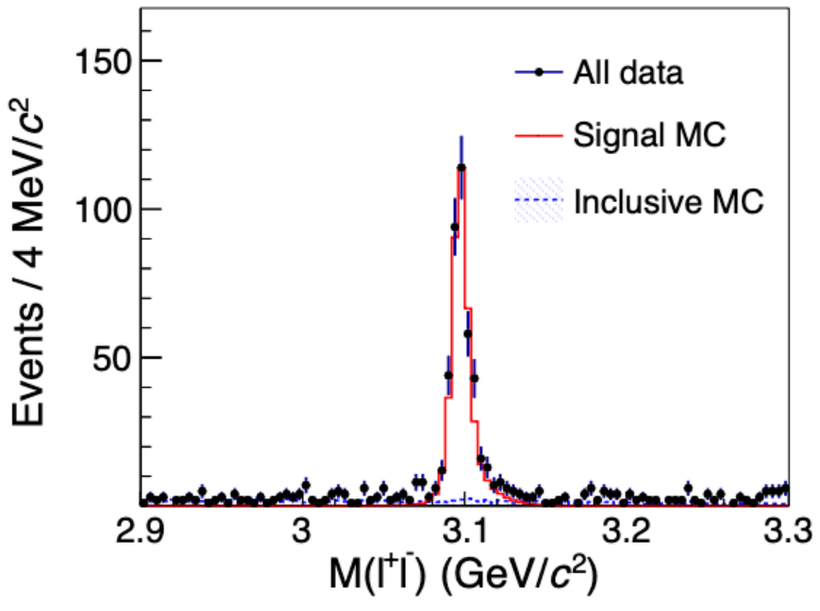


Search for Z_{cs} state in $e^+e^- \to K^+K^-J/\psi$

Phys. Rev. Lett. 131 (2023) 211902

Search for Z_{cs} state in $e^+e^- \to K^+K^-J/\psi$

- Search for Z_{cs} state in $e^+e^- \to K^+K^-J/\psi$, $J/\psi \to \ell^+\ell^-$, where $\ell = e$ or μ, at c.m. energies from 4.63 GeV to 4.92 GeV.
- Both full and partial reconstruction methods are applied to achieve low background level and improve statistics:
  - 4-track event: $e^+e^- \to K^+K^-\ell^+\ell^-$.
  - 3-track event: $e^+e^- \to K^\pm_{\rm miss}K^\mp\ell^+\ell^-$ with only one Kaon identified.
- Background study:
  - $J/\psi \to e^+e^-$ mode: Bhabha events, suppressed by the event kinematic requirements.
  - $J/\psi \to \mu^+\mu^-$ mode: μ/π misidentification events, suppressed by penetration depth of muon cuts.
  - Remaining events modeled by the J/ψ sideband regions.



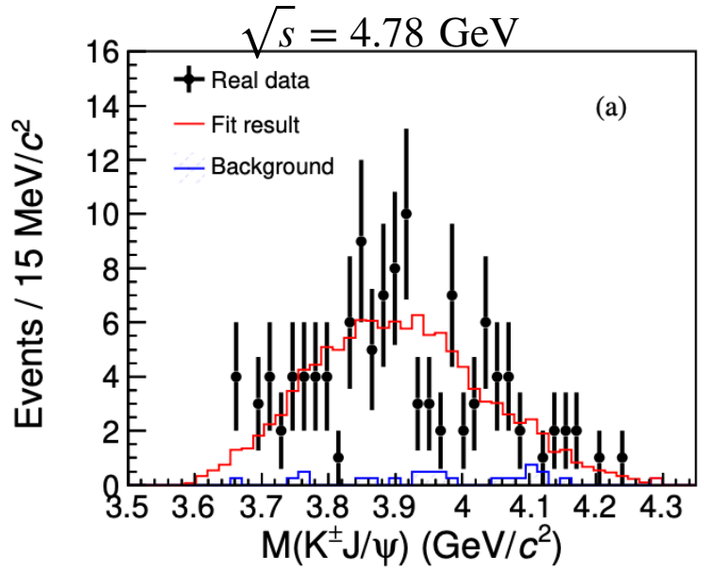
Search for Z_{cs} state in $e^+e^- \to K^+K^-J/\psi$

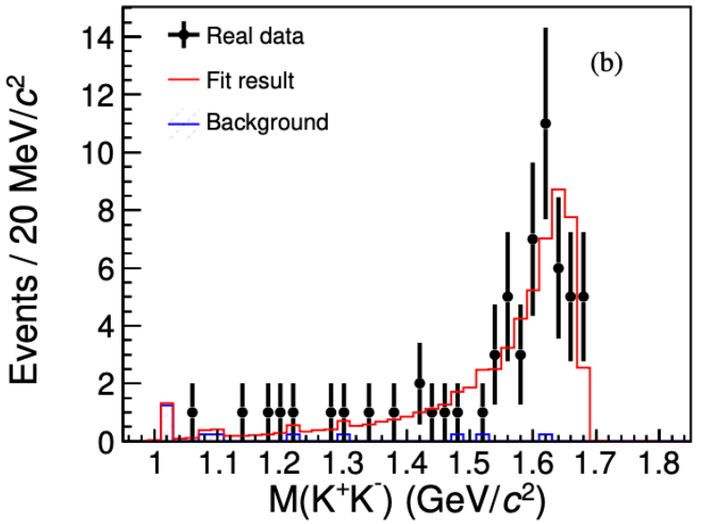
- Partial wave analysis (PWA) is performed to study the intermediate state.
  - No significant Z_{cs} signal detected.
  - $\sqrt{s} < 4.70$ GeV, based on $f_0(980) + f_0(1500)$ assumption.
  - $\sqrt{s} > 4.70$ GeV, based on single $f_0(x)$ with free mass and width.

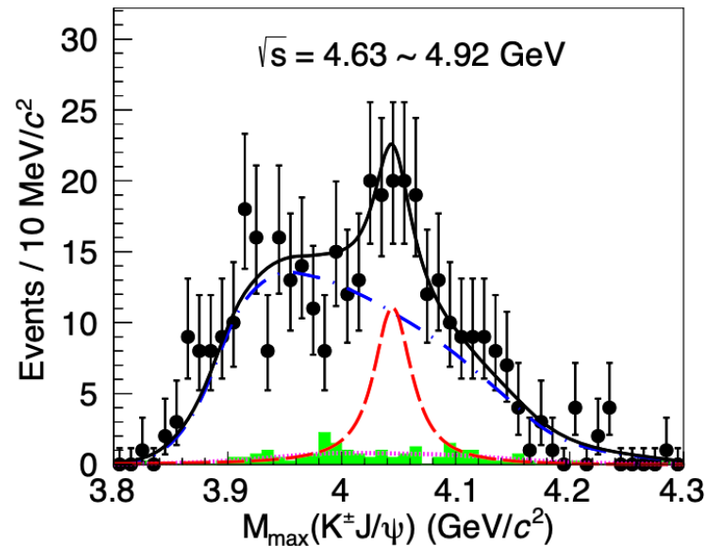
- A simultaneous fit is performed on the $M_{max}(K^{\pm}J/\psi)$ spectra
  - Z_{cs} component modeled with an Breit-Wigner function convolved with resolution function:

$$\mathcal{F}(M) \propto \left| \frac{\sqrt{q \cdot p}}{M^2 - m_0^2 + i m_0 \Gamma(M)} \right|^2,$$

- A small excess of Z_{cs} is observed with statistical significance of 2.3σ:
  - $m_0 = 4.044 \pm 0.006$ GeV/c^2, $\Gamma_0 = 0.036 \pm 0.016$ GeV.

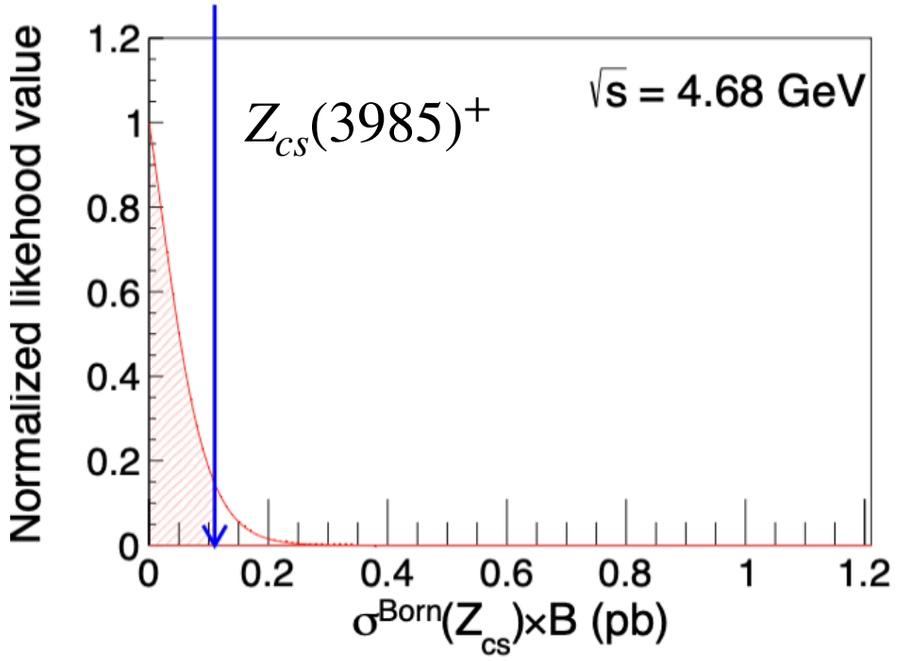


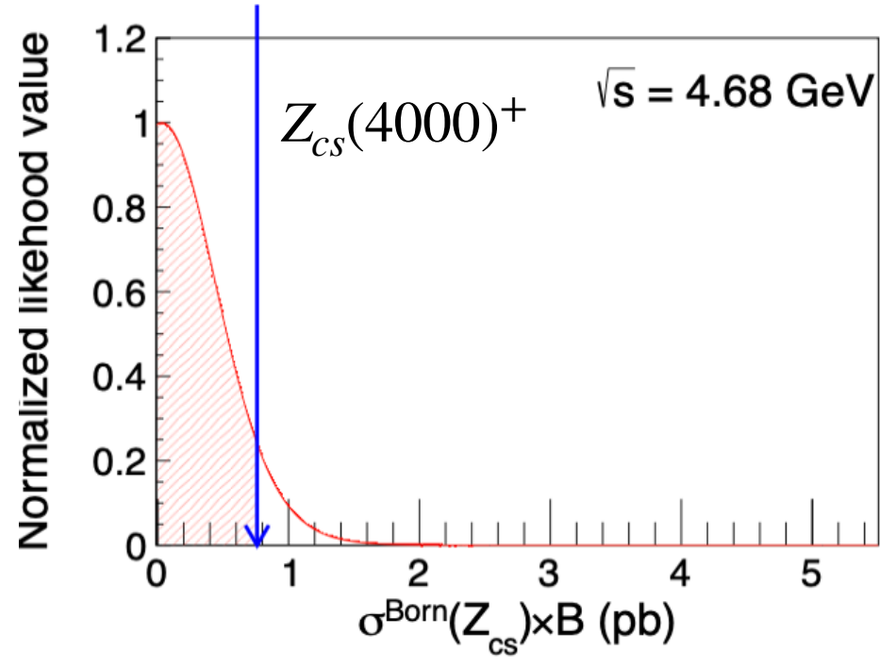




Search for Z_{cs} state in $e^+e^- \to K^+K^-J/\psi$

- Upper limits at 90% CL on the production of $Z_{cs}(3985)^+$ and $Z_{cs}(4000)^+$ are provided:
  - $\sigma^{\text{Born}}(e^+e^- \to K^-Z_{cs}(3985)^+) \times B(Z_{cs}(3985)^+ \to K^+J/\psi)$: $\mathcal{O}(1)$ pb,
  - $\sigma^{\text{Born}}(e^+e^- \to K^-Z_{cs}(4000)^+) \times B(Z_{cs}(4000)^+ \to K^+J/\psi)$: $\mathcal{O}(3)$ pb.



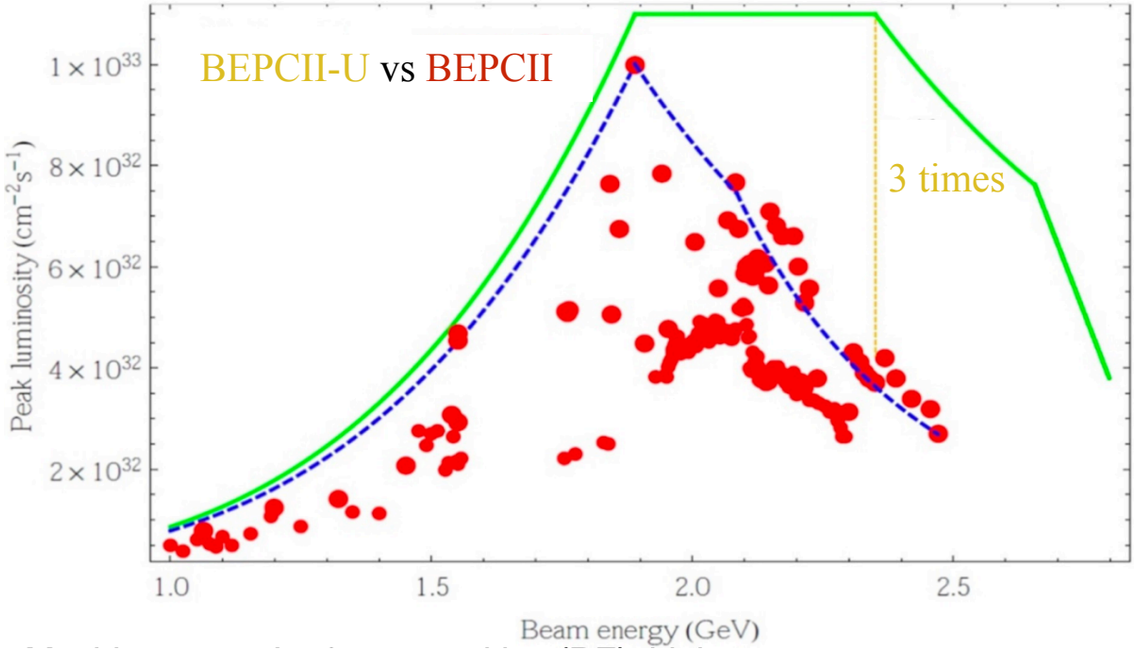


- The upper limit on $R_B = \dfrac{B(Z_{cs}(3985)^+ \to K^+J/\psi)}{B(Z_{cs}(3985)^+ \to (\bar{D}^0D_s^{*+} + \bar{D}^{*0}D_s^+))}$ is determined to be less than 0.03 at 90% CL:
  - Disfavors the QCD sum rule calculation under the molecular state assumption[1].
  - Supports the $Z_{cs}(3985)^+$ and $Z_{cs}(4000)^+$ as two different states[2].
- More statistics are necessary to conduct further PWA.

1. Phys. Rev. D 88 (2013) 9 096014
2. Sci.Bull. 66 (2021) 2065-2071

Summary

- BESIII has achieved meaningful progresses on the Z_{cs} states:
  - The Z'_{cs} state is searched in $Z'^{-}_{cs} \to D_s^{*-}D^{*0}$ process:
    - $m_0 = 4123.5 \pm 0.7 \pm 4.7\,\mathrm{MeV}/c^2$ (2.1σ).
  - The Z_{cs} states are investigated in the KJ/ψ system, but no significant structure observed:
    - $m_0 = 4.044 \pm 0.006\ \mathrm{GeV}/c^2$, $\Gamma_0 = 0.036 \pm 0.016\ \mathrm{GeV}$ (2.3σ).
- Further data taking in the region $\sqrt{s} = 4.6 \sim 4.9\ \mathrm{GeV}$ will improve the studies on the Z_{cs} states.



Thanks for your attention!

Backup