Charmonium(like) states at Belle

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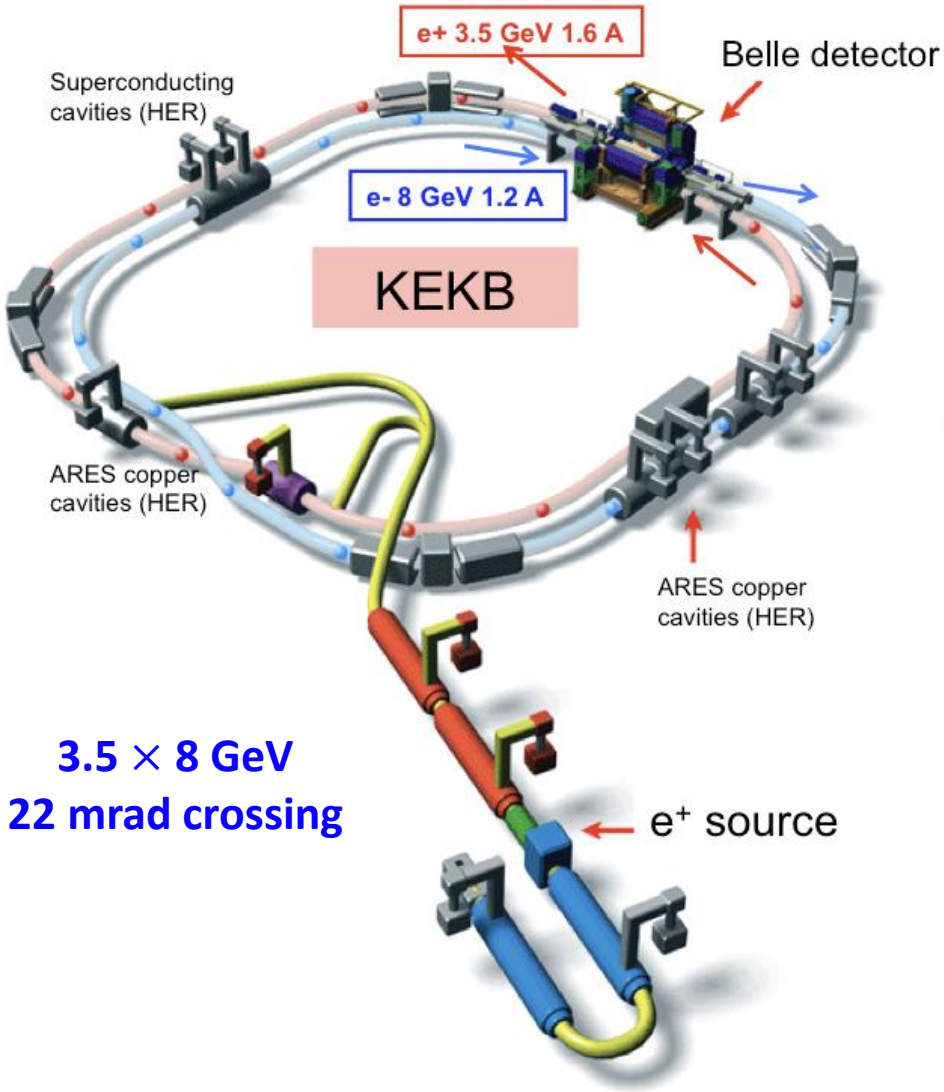
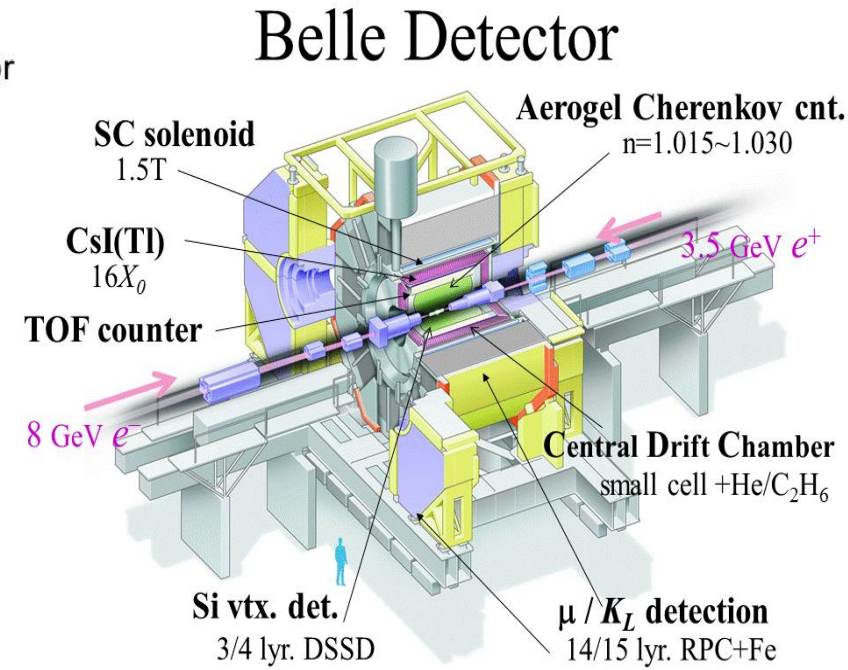
On behalf of Belle Collaboration

The 14th International Workshop on Heavy Quarkonium
Mar 15~19, 2021

Belle experiment and data samples



3.5 × 8 GeV
22 mrad crossing



Data taking: 1999 – 2010

On/off/Scan ϒ(nS) peaks

Total luminosity: 980 fb^{-1}

772M $B\bar{B}$ events @ϒ(4S)

Outline

- *Search for* $\boldsymbol{\eta_{c2}(1D)}$ *in B decays*
- *Y(4626):* $\boldsymbol{e^+e^- \to D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^-}$ **+** *c.c.*
- *Search for a doubly-charged* $\boldsymbol{DDK}$ *bound state*
- *Study of* $\boldsymbol{e^+e^- \to K^+K^- J/\psi}$ *via initial state radiation*
- *Summary*

Search for $\eta_{c2}(1D)$ in B decays

[JHEP 05, 034 (2020)]

Motivation:

- Evidence for the $\psi_2(1D)$ was first found by Belle in $B^+ \to \psi_2(1D)(\to \chi_{c1}(\to J/\psi\gamma)\gamma)K^+$ [1].
- The masses of the $\psi_2(1D)$ and $\eta_{c2}(1D)$ are very close [2-5].
- The $\eta_{c2}(1D)$ is expected to decay predominantly via E1 transition to $h_c\gamma$ [6-9].
- The $B(B^+ \to \eta_{c2}(1D)K^+) \times B(\eta_{c2}(1D) \to \gamma h_c)$ is expected to be 1.0×10^{-5} [9].

Reconstruction:

- $B^+ \to \eta_{c2}(1D)K^+$, $B^0 \to \eta_{c2}(1D)K_S^0$, $B^0 \to \eta_{c2}(1D)\pi^-K^+$, and $B^+ \to \eta_{c2}(1D)\pi^+K_S^0$
- $\eta_{c2}(1D) \to h_c\gamma$ and $h_c \to \eta_c\gamma$
- η_c is reconstructed in the ten decay channels: $K^+K_S^0\pi^-$, $K^+K^-\pi^0$, $K_S^0K_S^0\pi^0$, $K^+K^-\eta$, $K^+K^-K^+K^-$, $\eta'(\to \eta\pi^+\pi^-)\pi^+\pi^-$, $p\bar{p}$, $p\bar{p}\pi^0$, $p\bar{p}\pi^+\pi^-$, and $\Lambda\bar{\Lambda}$.

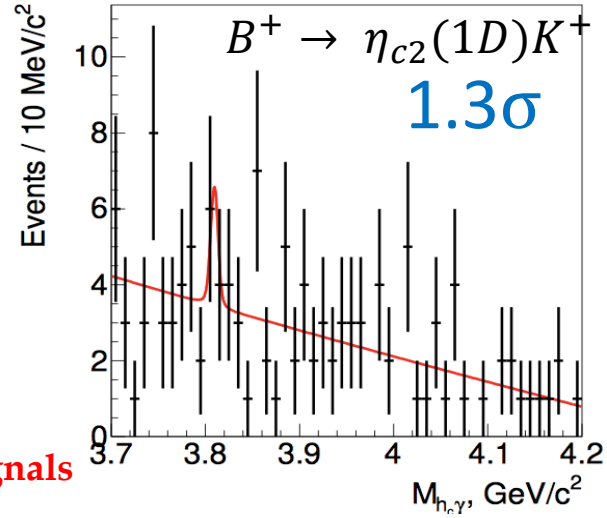
Data sample: 772×10^6 $B\bar{B}$ pairs

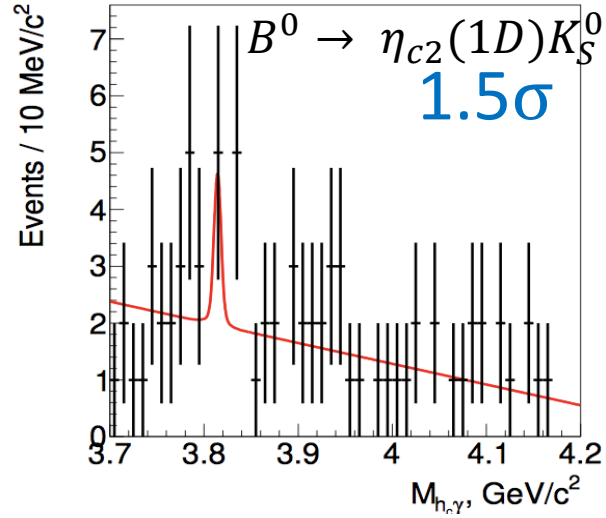
Analysis strategy:

- The multivariate analysis using the multilayer perceptron neural network.
- A global optimization is performed.

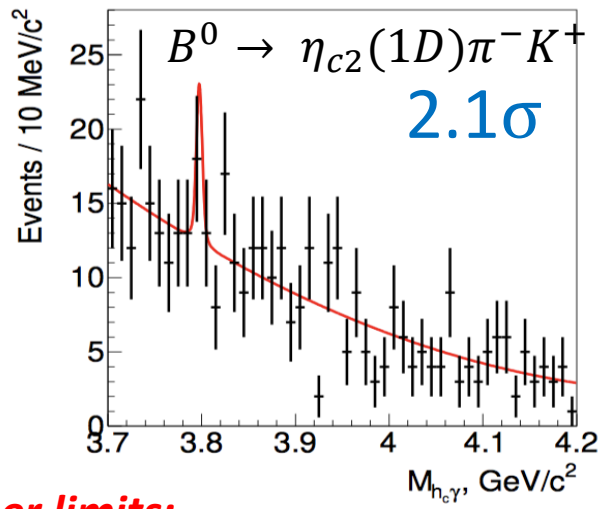
$$F_{\rm opt} = \frac{\sum_i N_{\rm sig}^{(i)}}{\frac{a}{2} + \sqrt{\sum_i N_{\rm bg}^{(i)}}},$$

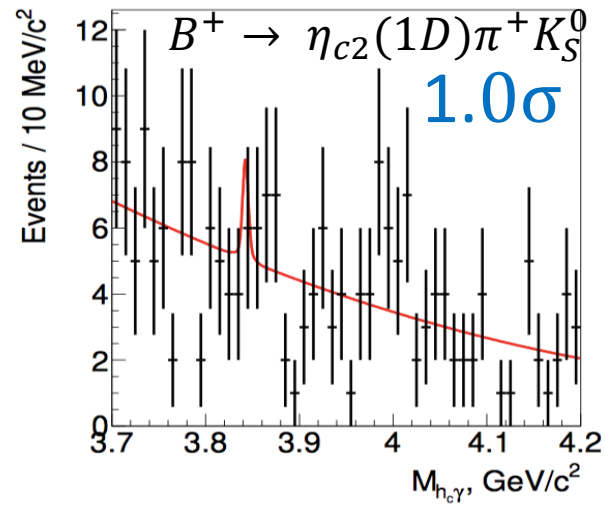
[1] PRL 111, 032001 (2013). [2] PRD 32, 189 (1985). [3] PRD 44, 2079 (1991). [4] PRD 52, 5229 (1995). [5] PRD 67, 014027 (2003). [6] PRL 89, 162002 (2002). [7] PRD 72, 054026 (2005). [8] PRD 80, 014001 (2009). [9] PRD 94, 034005 (2016).





No $\eta_{c2}(1D)$ signals are observed.





$\eta_{c2}(1D)$ mass region: (3.795 – 3.845) GeV/c^2

Signal shape: Breit-Wigner ⊗ double asymmetric Gaussians
Background: 1st or 2nd Polynomial

The $\eta_{c2}(1D)$ width is fixed at 500 keV. [PRD 80 (2019) 014001]

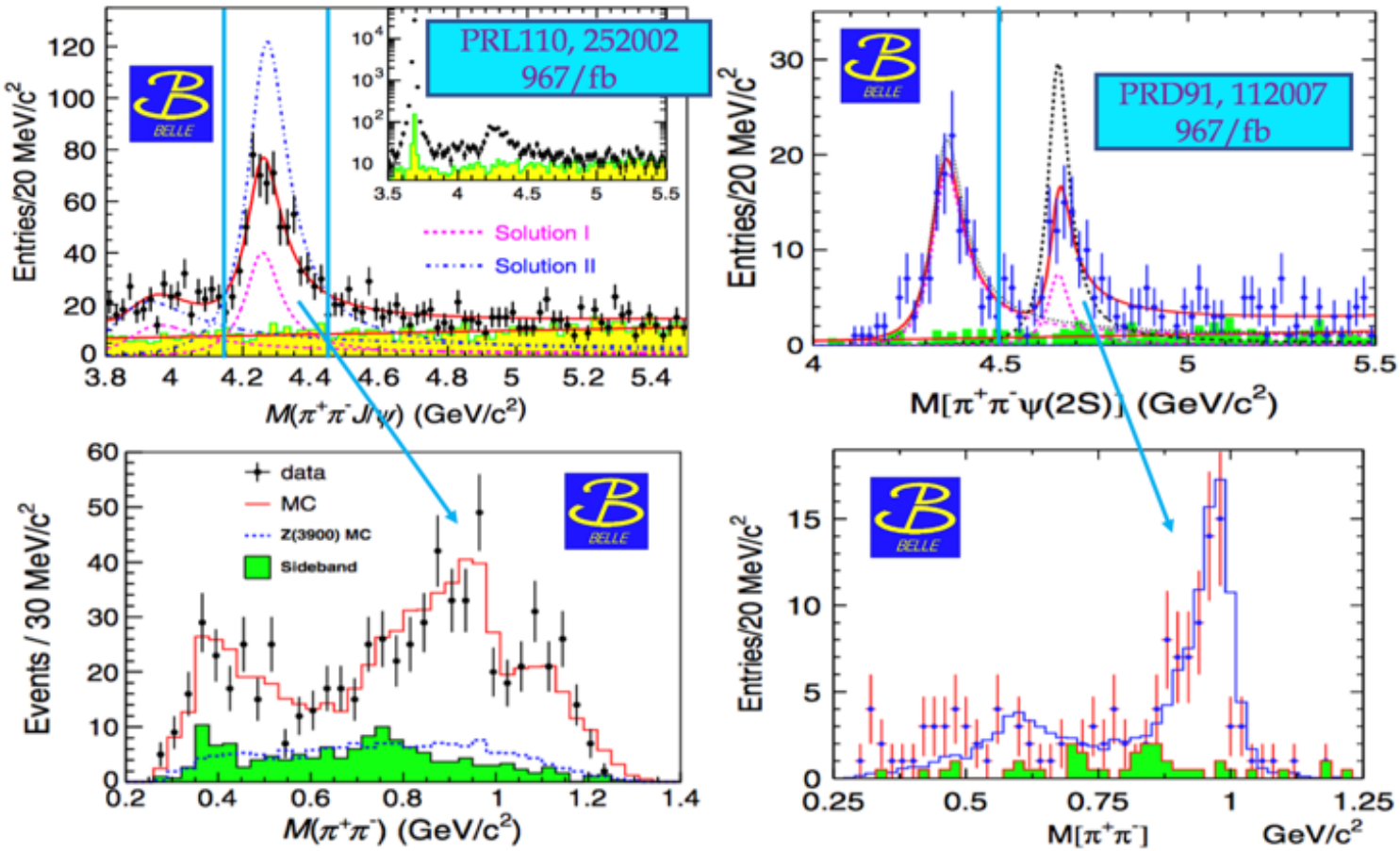
90% C.L. upper limits:

$\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+)\mathcal{B}(\eta_{c2}(1D) \to h_c\gamma)$	3.7×10^{-5}	$\mathcal{B}(B^0 \to \eta_{c2}(1D)K_S^0)\mathcal{B}(\eta_{c2}(1D) \to h_c\gamma)$	3.5×10^{-5}
$\mathcal{B}(B^0 \to \eta_{c2}(1D)\pi^-K^+)\mathcal{B}(\eta_{c2}(1D) \to h_c\gamma)$	1.0×10^{-4}	$\mathcal{B}(B^+ \to \eta_{c2}(1D)\pi^+K_S^0)\mathcal{B}(\eta_{c2}(1D) \to h_c\gamma)$	1.1×10^{-4}

[theoretical prediction: $B(B^+ \to \eta_{c2}(1D)K^+) \times B(\eta_{c2}(1D) \to \gamma h_c) = 1.0 \times 10^{-5}$]

Y(4626): $e^+e^- \to D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^-$ + c.c.

Motivation:



- $\Upsilon(4260) \to f_0(980)(\to \pi^+\pi^-)J/\psi$, $\Upsilon(4660) \to f_0(980)(\to \pi^+\pi^-)\psi(2S)$
  $f_0(980)$ has a $s\bar{s}$ component, and J/ψ has a $c\bar{c}$ component.
- It is natural to search for such Y states with quark component of $(c\bar{s})(\bar{c}s)$, e.g., $D_s\bar{D}_{s1}(2536)$ and $D_s\bar{D}_{s2}^*(2573)$.

Analysis method

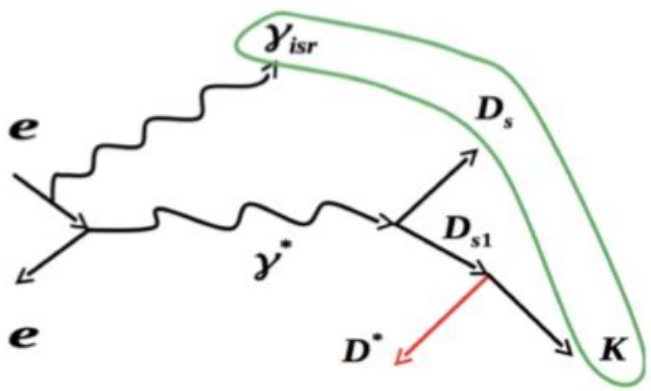
$$e^+e^- \to \gamma_{ISR} D_s^+ D_{s1}(2536)^- (\to \bar{D}^{*0} K^- / D^{*-} K_S^0)$$

We require full reconstruction of the γ_{ISR}, D_s^+ , and K^-/K_S^0.

- $D_s^+ \to \phi\pi^+, \bar{K}^{*0}K^+, K_S^0K^+, K^+K^-\pi^+\pi^0, K_S^0\pi^0K^+, K^{*+}K_S^0, \eta\pi^+$, and $\eta'\pi^+$
- For the signals, the spectrum of the mass recoiling against the $D_s^+K^-\gamma_{ISR}$ system should be accumulated at the $\bar{D}^{*0}/D^{*-}$ nominal mass.

$$M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0) = \sqrt{(E^*_{c.m.} - E^*_{\gamma_{ISR}D_s^+K^-/K_S^0})^2 - \left(p^*_{\gamma_{ISR}D_s^+K^-/K_S^0}\right)^2}$$

- To improve the $M_{rec}(\gamma_{ISR})$ resolution, $M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0)$ is constrained to be the nominal mass of the $\bar{D}^{*0}/D^{*-}$.



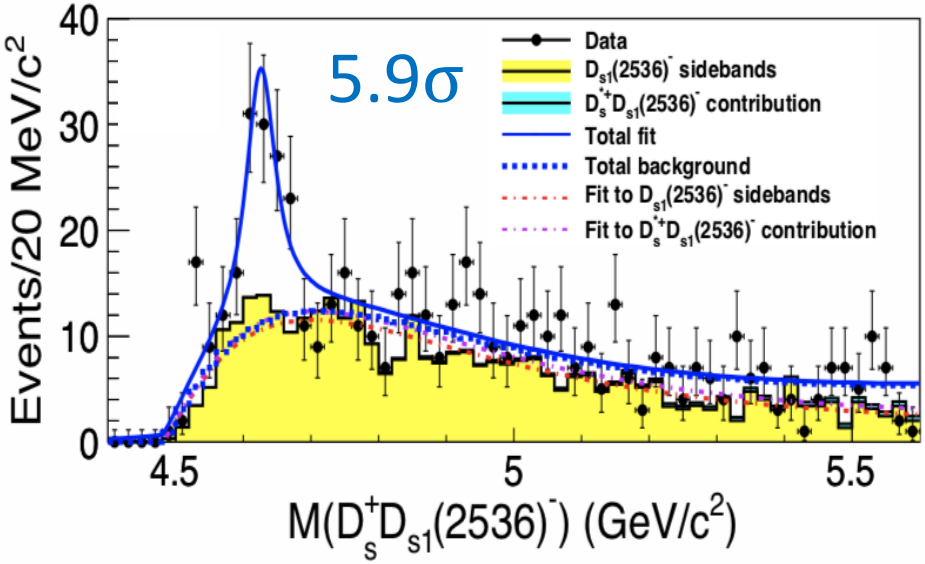
Data samples:

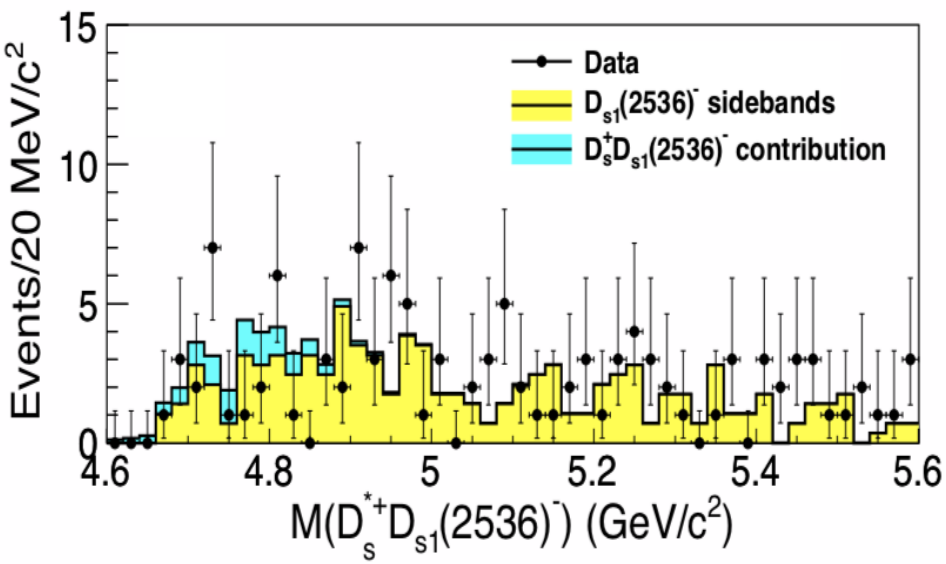
$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})
10.52	89.5±1.3
10.58	711±10
10.867	121.4±1.7
Total	921.9±12.9

- For the study of $e^+e^- \to \gamma_{ISR}D_s^+D_{s2}^*(2573)^-(\to \bar{D}^0K^-)$, the same analysis method is used.

$M(D_s^+ D_{s1}(2536)^-)$

[PRD 100, 111103(R) (2019)]





An unbinned simultaneous likelihood fit:

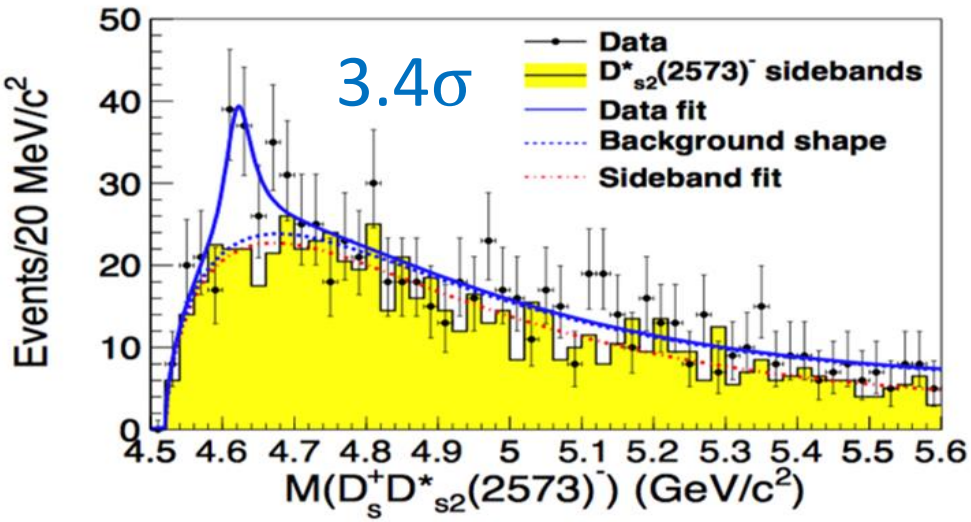
- Signal: a *BW* convolved with a Gaussian function, then multiplied by an efficiency function
- A non-resonant contribution: a two-body phase space form
- $D_{s1}(2536)^-$ mass sidebands: a threshold function
- $e^+e^- \to D_s^{*+}D_{s1}(2536)^-$ background contribution: a threshold function

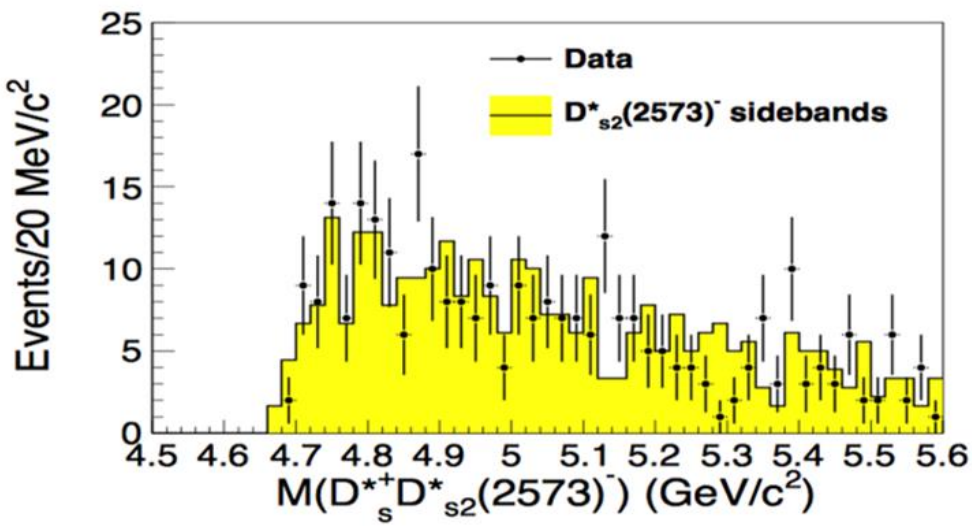
$M=(4625.9^{+6.2}_{-6.0}(\text{stat.}) \pm 0.4(\text{syst.})\ \text{MeV}/c^2$
$\Gamma = (49.8^{+13.9}_{-11.5}(\text{stat.}) \pm 4.0(\text{syst.})\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0}K^-) = (14.3^{+2.8}_{-2.6}(\text{stat.}) \pm 1.5(\text{syst.})\ \text{eV}$

- **One possible background is from $e^+e^- \to D_s^{*+}(\to D_s^+\gamma)D_{s1}(2536)^-$.**

$M(D_s^+ D_{s2}^*(2573)^-)$

[PRD 101, 091101(R) (2020)]





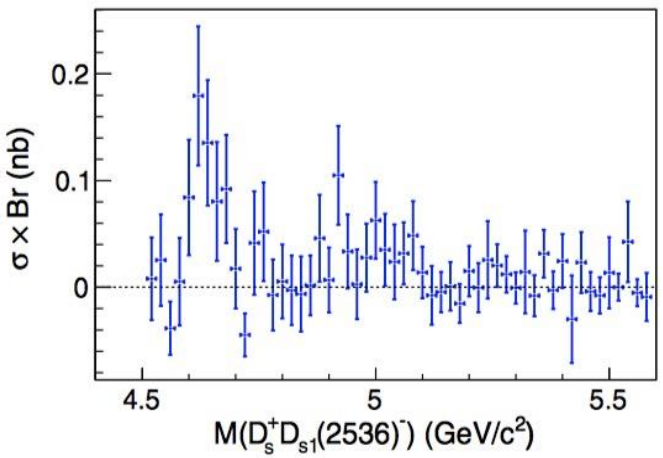
An unbinned simultaneous likelihood fit:

- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- A non-resonant contribution: a two-body phase space form
- $D_{s2}^*(2573)^-$ mass sidebands: a threshold function

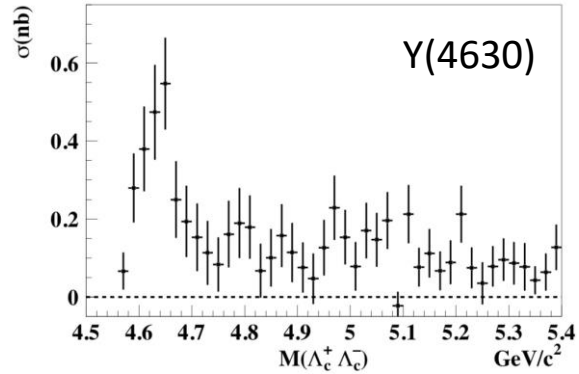
$M=(4619.8^{+8.9}_{-8.0}(\text{stat.}) \pm 2.3(\text{syst.})\ \text{MeV}/c^2$
$\Gamma = (47.0^{+31.3}_{-14.8}(\text{stat.}) \pm 4.6(\text{syst.})\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s2}^*(2573)^-) \times \mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0 K^-) = (14.7^{+5.9}_{-4.5}(\text{stat.}) \pm 3.6(\text{syst.})\ \text{eV}$

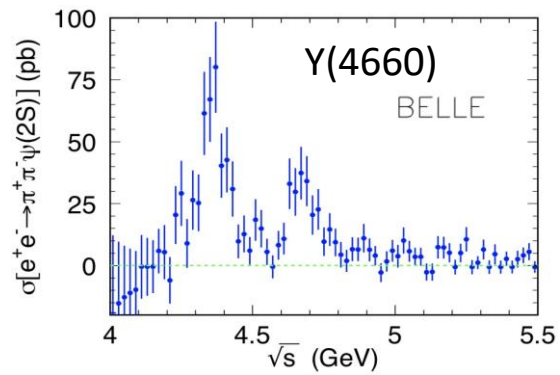
- **One possible background is from $e^+e^- \to D_s^{*+}(\to D_s^+\gamma)D_{s2}^*(2573)^-$.**

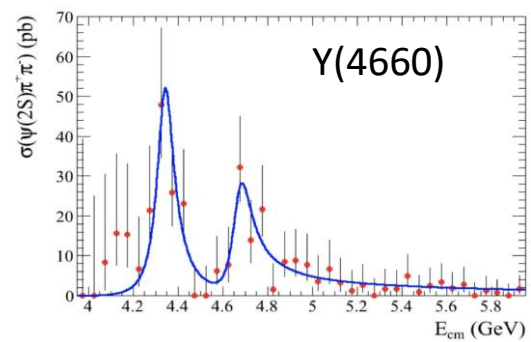
Y(4626)=Y(4630)=Y(4660)?

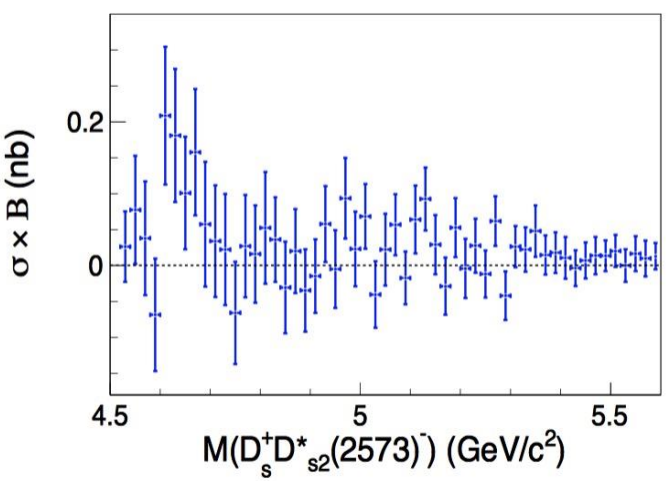


$\sigma(e^+e^- \to D_s^+ D_{s1}(2536)^-) \times B(D_{s1}(2536) \to \bar{D}^{*0}K^-)$







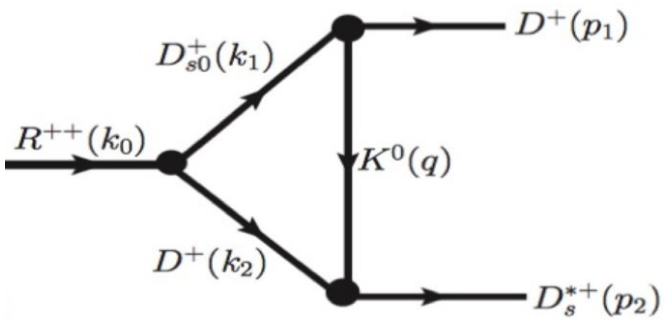


$\sigma(e^+e^- \to D_s^+ D_{s2}^*(2573)^-) \times B(D_{s2}^*(2573) \to \bar{D}^0 K^-)$

Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8\ +5}_{-7\ -8}$	$92^{+40\ +10}_{-24\ -21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
BaBar, $\pi^+\pi^-\psi(2S)$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$
Belle, $D_s^+ D_{s1}(2536)^-$	$4626^{+7}_{-7} \pm 1$	$49.8^{+14}_{-12} \pm 4$
Belle, $D_s^+ D_{s2}^*(2573)^-$	$4620^{+9}_{-8} \pm 3$	$47.0^{+32}_{-15} \pm 5$

Search for a doubly-charged $\boldsymbol{DDK}$ bound state

- A doubly-charged and doubly-charmed molecule $\boldsymbol{R}^{++}$ decays to $D^+D_s^{*+}$ with modest rates according to Refs. [PRD 99, 076017 (2019), PRD 101, 014022 (2020)].
- The mass of R^{++} is predicted to be in the range of 4.13 to 4.17 GeV$/c^2$; the width is (2.30−2.49) MeV.
- A state decaying to $D^+D_s^{*+}$ is also a good candidate for a doubly-charged tetraquark according to Ref. [PRL 119, 202001 (2017)].

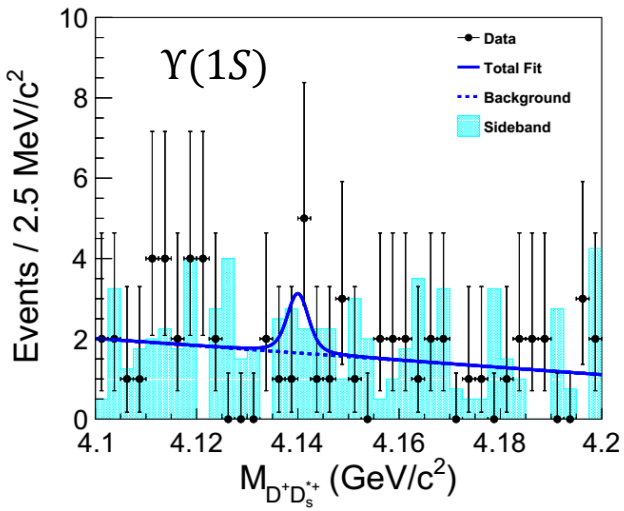


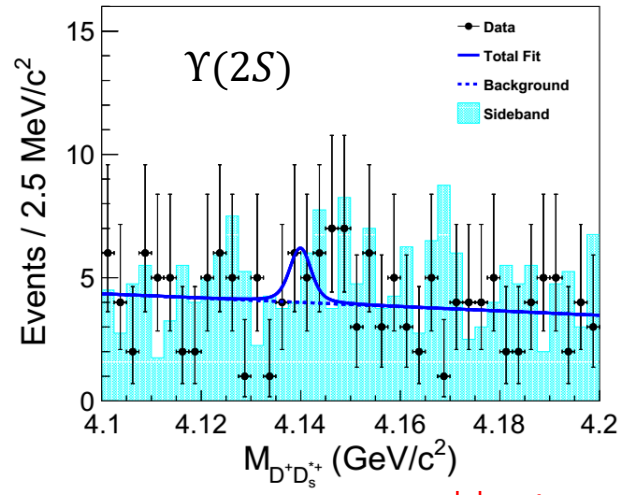
- $\boldsymbol{D^+ \to K^-\pi^+\pi^-/K_S^0(\to \pi^+\pi^-)\pi^+}$
- $\boldsymbol{D_s^{*+} \to D_s^+\gamma}$
- $\boldsymbol{D_s^+ \to \phi\pi^+/\bar{K}^{*0}K^-}$

Data samples:

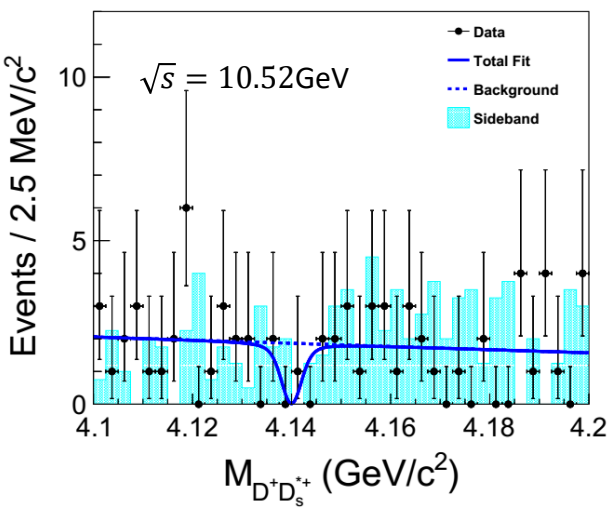
$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})	Events
9.46 [Υ(1S)]	5.74±0.09	(102±3) million
10.023 [Υ(2S)]	24.91±0.35	(158±4) million
10.52	89.5±1.3	-
10.58 [Υ(4S)]	711±10	-
10.867 [Υ(5S)]	121.4±1.7	-

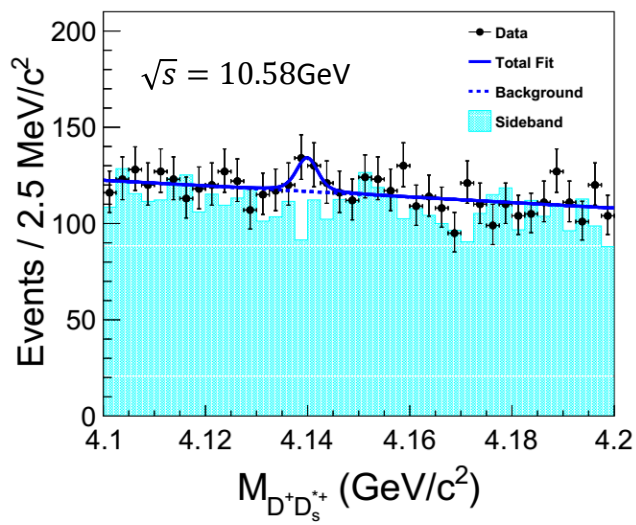
$M(D^+D_s^{*+})$

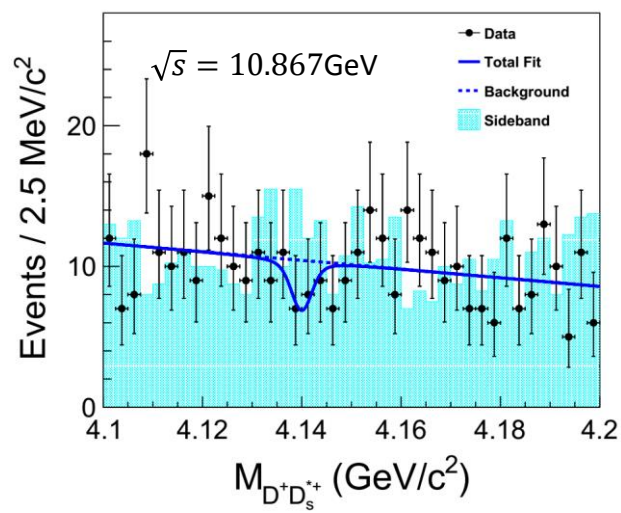




No R^{++} signals are observed.

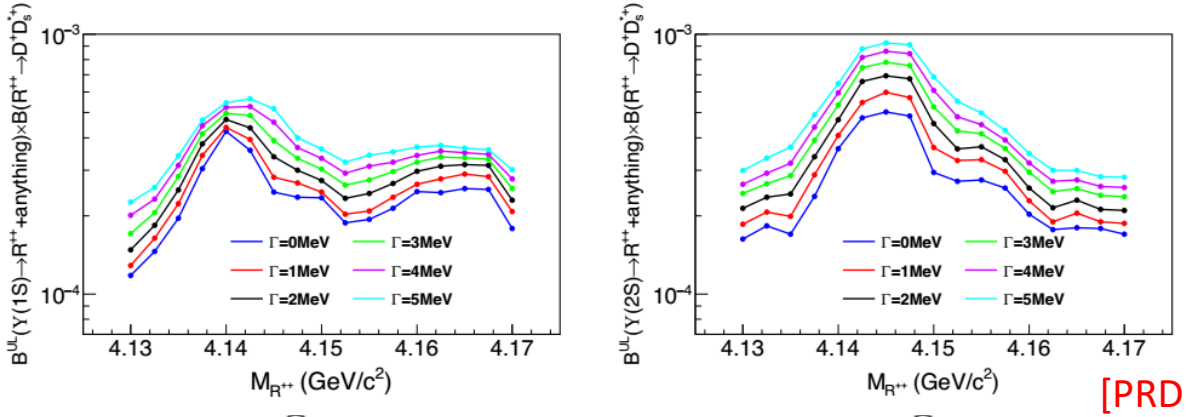




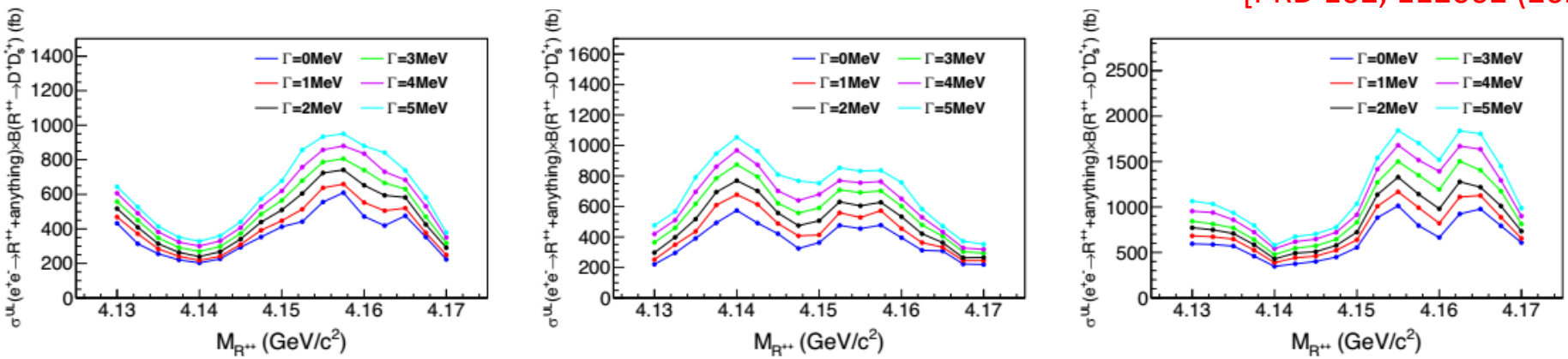


- The fitted results with the R^{++} mass fixed at 4.14 GeV/c^2 and width fixed at 2 MeV.

90% C.L. upper limits



[PRD 102, 112002 (2020)]

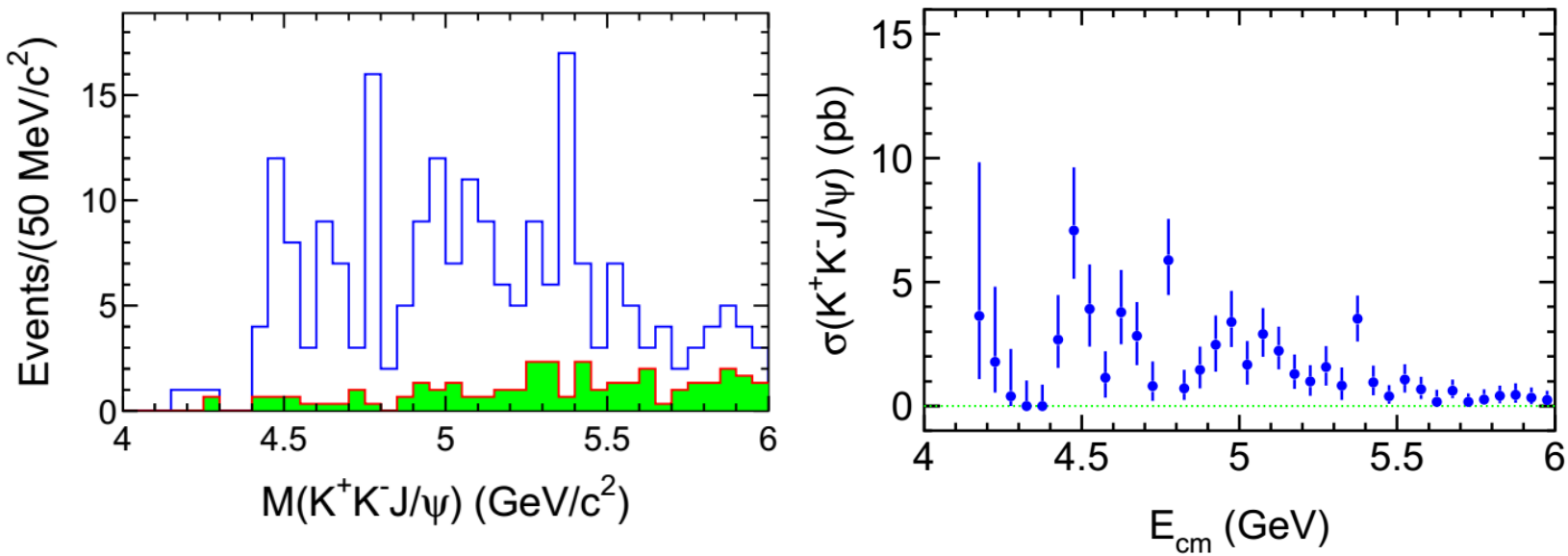


90% C. L. Upper limits [M(R^{++}) varying from 4.13 to 4.17 GeV/c^2, Γ(R^{++}) varying from 0 to 5 MeV]
$\mathcal{B}(\Upsilon(1S) \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+}) < (1.18 - 5.65)\times 10^{-4}$
$\mathcal{B}(\Upsilon(2S) \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+}) < (1.63 - 9.27)\times 10^{-4}$
$\sigma(e^+e^- \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+}) < (202.8 - 950.6)$ fb at $\sqrt{s} = 10.52$ GeV
$\sigma(e^+e^- \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+}) < (218.9 - 1054.0)$ fb at $\sqrt{s} = 10.58$ GeV
$\sigma(e^+e^- \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+}) < (346.6 - 1841.7)$ fb at $\sqrt{s} = 10.867$ GeV

Study of $e^+e^- \to K^+K^-J/\psi$

- Very recently, $Z_{cs}(3985)^-(\to (D_s^- D^{*0} + D_s^{*-} D^0))$ and $Z_{cs}(4000)^-(\to K^-J/\psi)$ were observed by BESIII and LHCb, respectively. [PRL.126.102001 (2021), arXiv: 2103.01803]
- The process $e^+e^- \to K^+K^-\,J/\psi$ via initial state radiation was studied by Belle.

[PRD 77, 011105(R) (2008); PRD 89, 072015 (2014)]



- The K^+K^-J/ψ invariant mass distribution shows a broad enhancement around 4.4 – 5.5 GeV/c^2; the green shaded histogram represents the normalized J/ψ sideband.

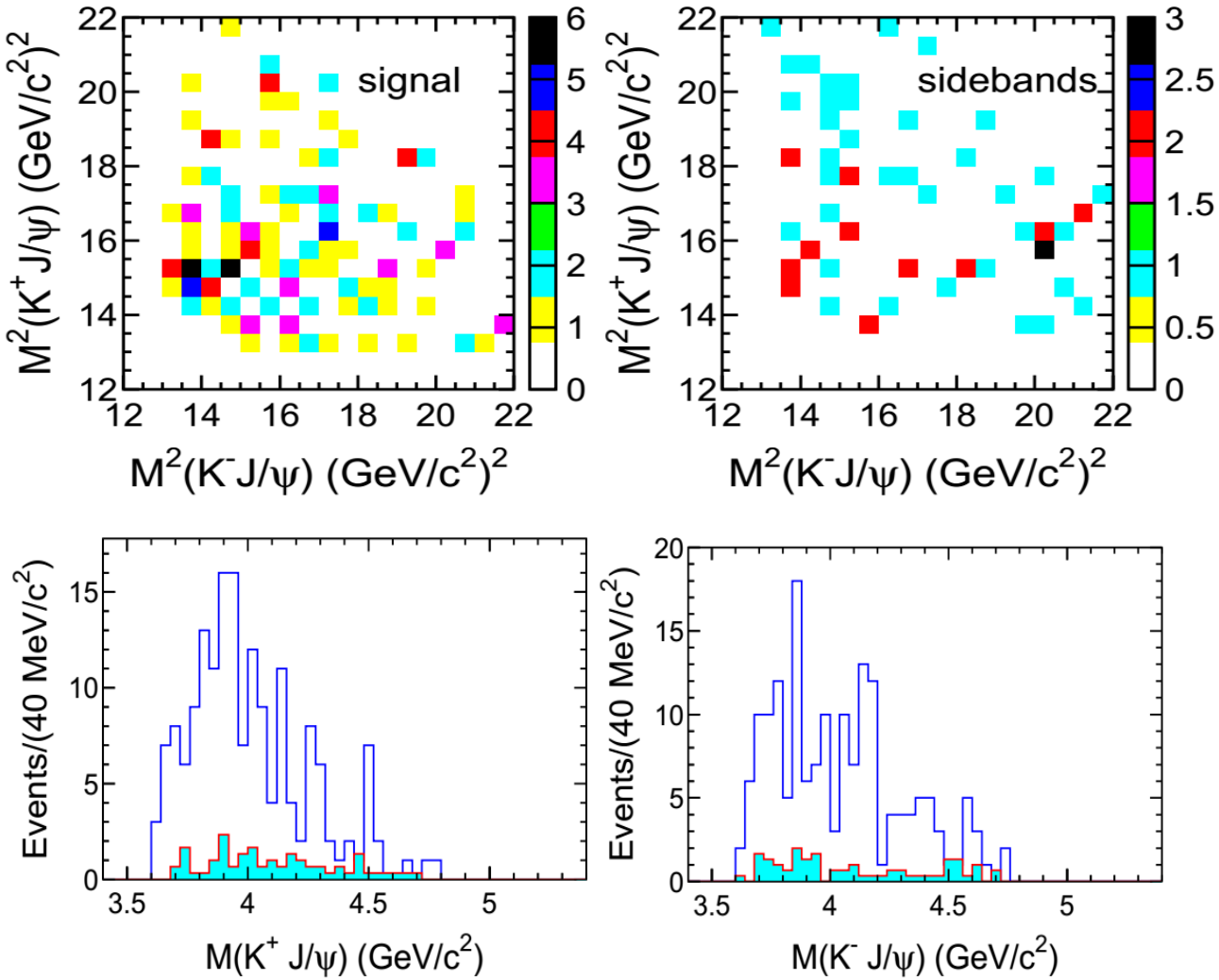
- The $e^+e^- \to K^+K^-\,J/\psi$ cross section at each energy point is calculated using

$$\sigma_i = \frac{n_i^{\rm obs} - f \times n_i^{\rm bkg}}{\mathcal{L}_i \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$

Study of $e^+e^- \to K^+K^-J/\psi$

- A search for resonant structures and associated intermediate states is performed.

In J/ψ signal region



In J/ψ sidebands (not normalized)

- Neither $Z_{cs}(3985)^{\pm}$ nor $Z_{cs}(4000)^{\pm}$ was seen in the $K^{\pm}J/\psi$ system.

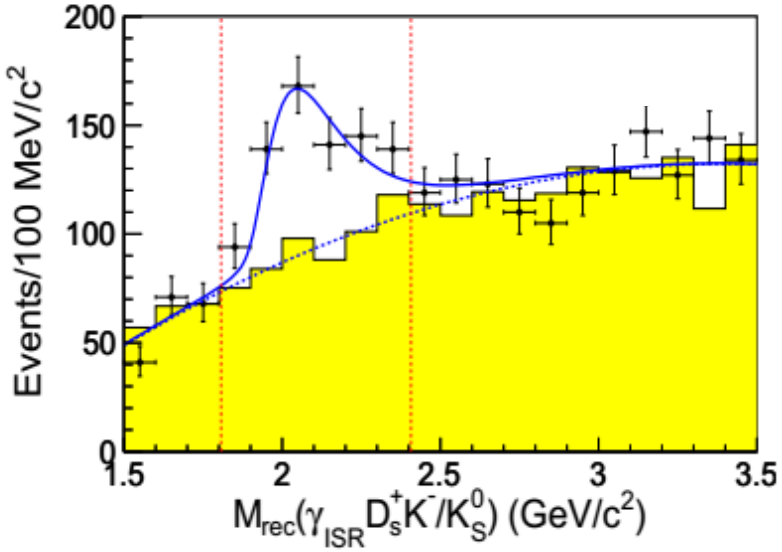
Summary

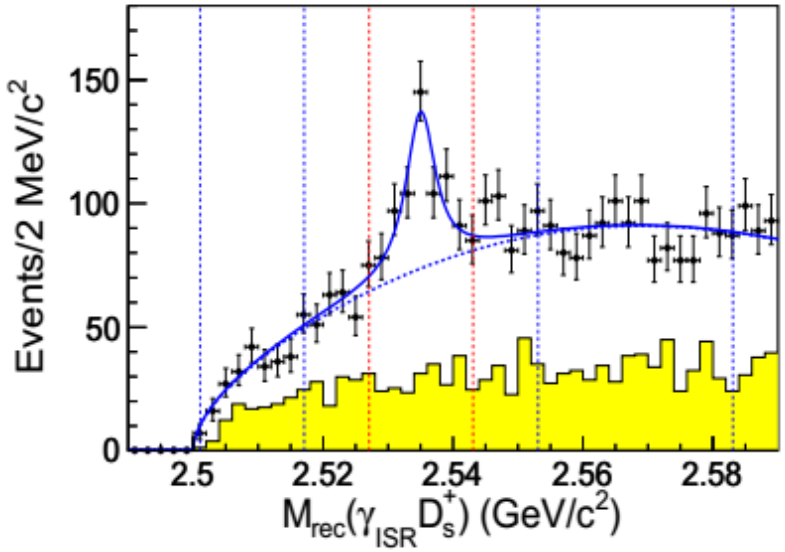
- We first search for the $\eta_{c2}(1D)$ in the $B \to K\eta_{c2}(1D)$ and $B \to K\pi\eta_{c2}(1D)$ decays. No significant signal is found.
- We report the first vector charmonium-like state decaying to the charmed-antistrange and anticharmed-strange meson pairs $D_s^+ D_{s1}(2536)^-$ and $D_s^+ D_{s2}^*(2573)^-$. The masses and widths are close to those of the Y(4660).
- We report the results of a first search for a doubly charged DDK bound state, called the R^{++}. No significant signal is observed in all studied modes. The 90% C.L. upper limits on the production ratio under different assumptions of R^{++} masses and widths are obtained.
- We ever studied the process $e^+e^- \to K^+K^-J/\psi$ via initial state radiation. No obvious structures are observed in the $K^\pm J/\psi$ system.
- Belle II will reach 50 ab^{-1}, which will provide greater sensitivity and precise measurements in charmonium(like) states.

Thanks for your attentions!

Backup

Backup



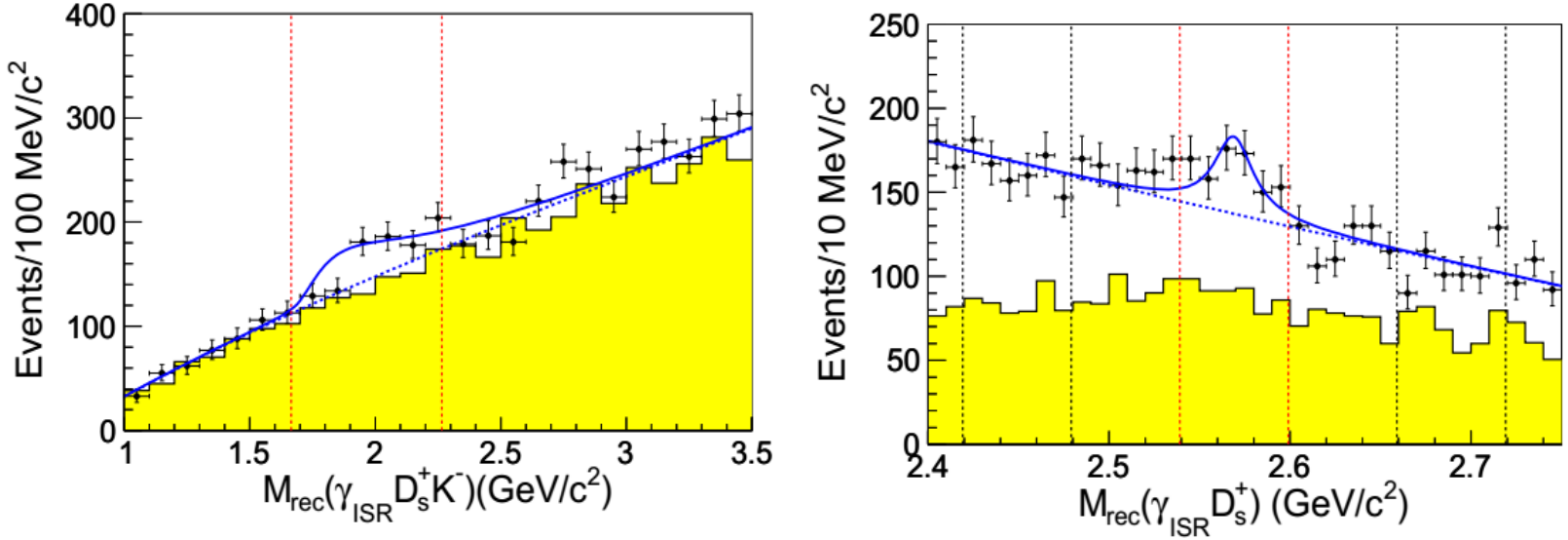


- $M_{rec}(\gamma_{ISR} D_s^+ K^-/K_S^0)$ and $M_{rec}(\gamma_{ISR} D_s^+)$ distribution is making before applying the $\bar{D}^{*0}/D^{*-}$ mass constraint.

- The yellow histograms show the normalized $D_{s1}(2536)^-$ mass sidebands (left plot) and the normalized D_s^+ mass sidebands (right plot).

- Due to the poor mass resolution, the $\bar{D}^{*0}/D^{*-}$ signal is very wide.

Backup

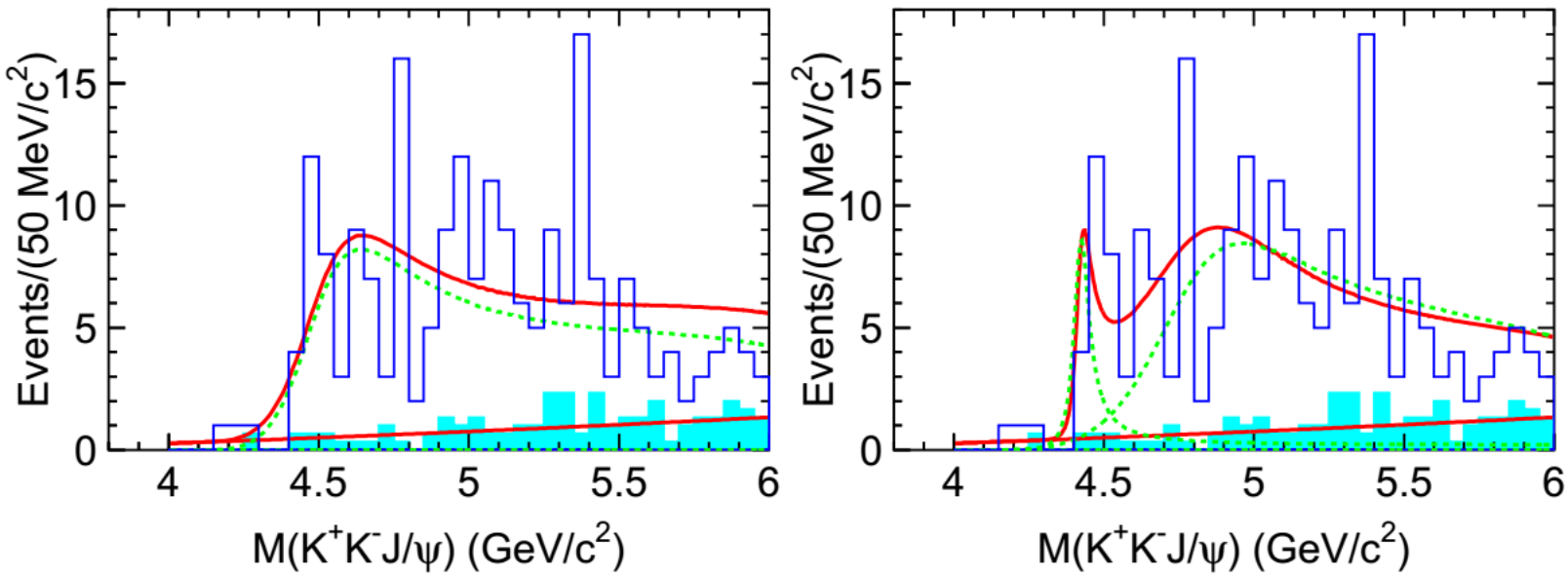


- $M_{rec}(\gamma_{ISR} D_s^+ K^-)$ and $M_{rec}(\gamma_{ISR} D_s^+)$ distribution is making before applying the $\overline{D}^0$ mass constraint.

- The yellow histograms show the normalized $D_{s2}^*(2573)^-$ mass sidebands (left plot) and the normalized D_s^+ mass sidebands (right plot).

- The $\overline{D}^0$ signal is wide and asymmetric due to the asymmetric resolution function of the ISR photon energy and higher order ISR corrections

Backup



$$\sigma(s) = \frac{M^2}{s}\frac{12\pi\Gamma_{e^+e^-}\mathcal{B}(R\to f)\Gamma_{\rm tot}}{(s-M^2)^2+M^2\Gamma_{\rm tot}^2}\frac{\rho(\sqrt{s})}{\rho(M)},$$

Model 1: a single BW function plus a background term,
Fitted mass and width: $M = (4482 \pm 45)\ \mathrm{MeV/c^2}, \Gamma_{\rm tot} = (432 \pm 56)\ \mathrm{MeV}$;

Model 2: a coherent sum of a BW function and a ψ(4415) component with mass and width fixed at their world average values plus a background term,
Fitted mass and width: $M = (4747 \pm 117)\ \mathrm{MeV/c^2}, \Gamma_{\rm tot} = (671 \pm 86)\ \mathrm{MeV}$