

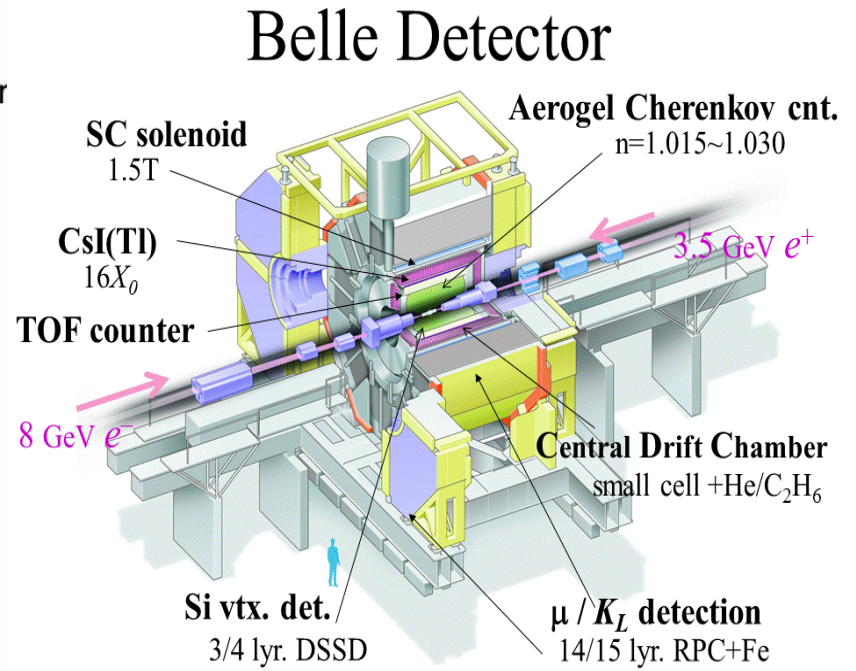
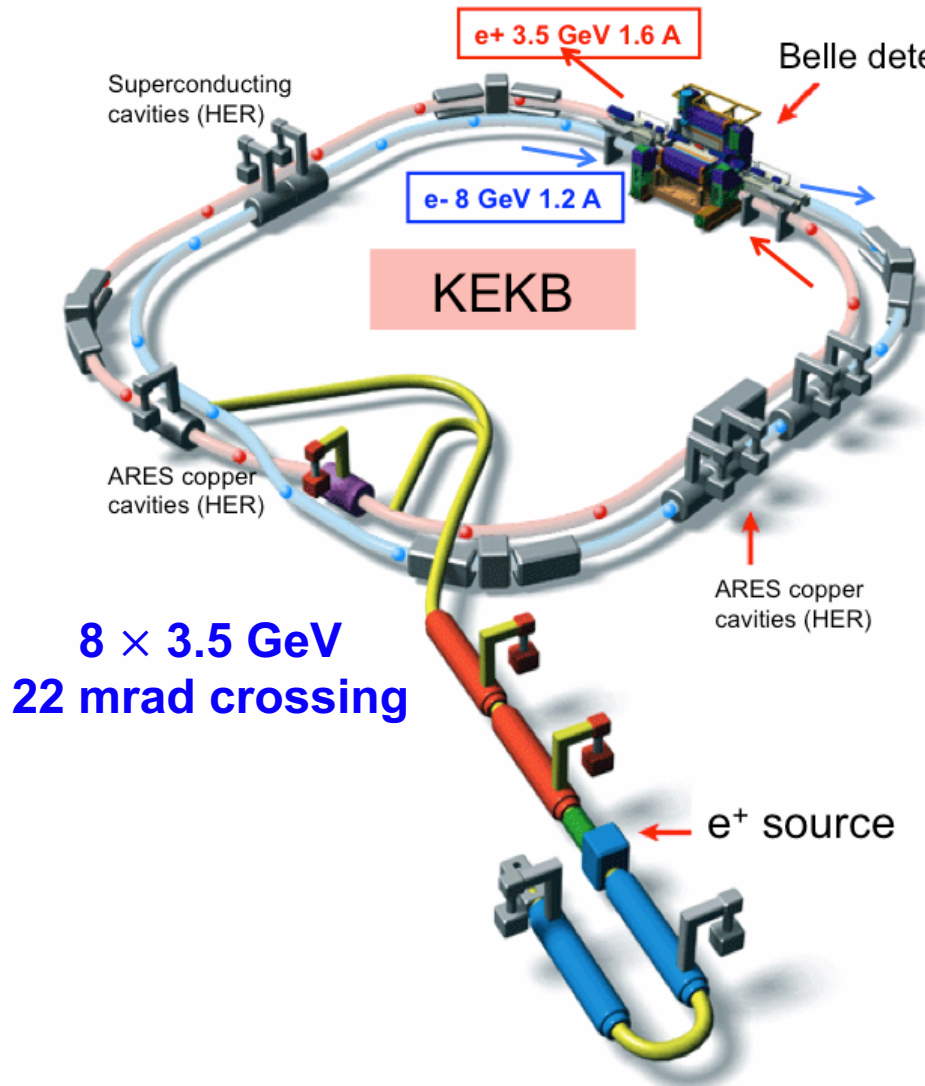


Study of conventional and non-conventional hadrons at Belle

**Sen Jia (Fudan University)
for Belle Collaboration**

**40th International Conference on High Energy Physics
July 31, 2020**

Belle experiment and data samples



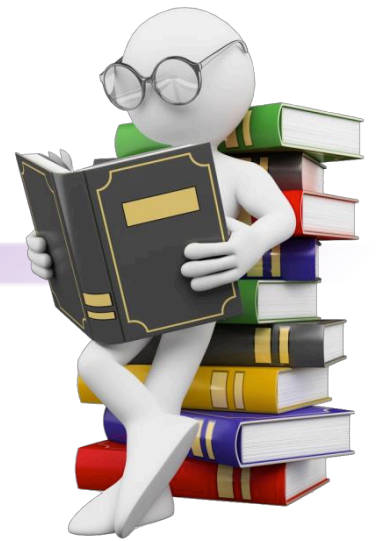
Data taking: 1999 – 2010

On/off/Scan $\Upsilon(nS)$ peaks

Total luminosity: 980 fb^{-1}

772M $B\bar{B}$ events @ $\Upsilon(4S)$

Selected topics



Conventional hadrons at Belle:

- *Observation of $\Upsilon(1S) \rightarrow \Upsilon\chi_{c1}$*
- *Search for $\eta_{c2}(1D)$ in B decays*
- *Search for $\Upsilon(4S, 5S) \rightarrow \omega\eta_b(1S, 2S)$*

Non-Conventional hadrons at Belle:

- *$\Upsilon(4626): e^+e^- \rightarrow D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^- + c.c.$*
- *$X(3872) \rightarrow \pi^+ \pi^- J/\psi$ in two-photon reactions*
- *Search for $R^{++} \rightarrow D^+ D_s^{*+}$*

$\Upsilon(1S) \rightarrow \Upsilon\chi_{c1}$

PRL 124, 122001 (2020)

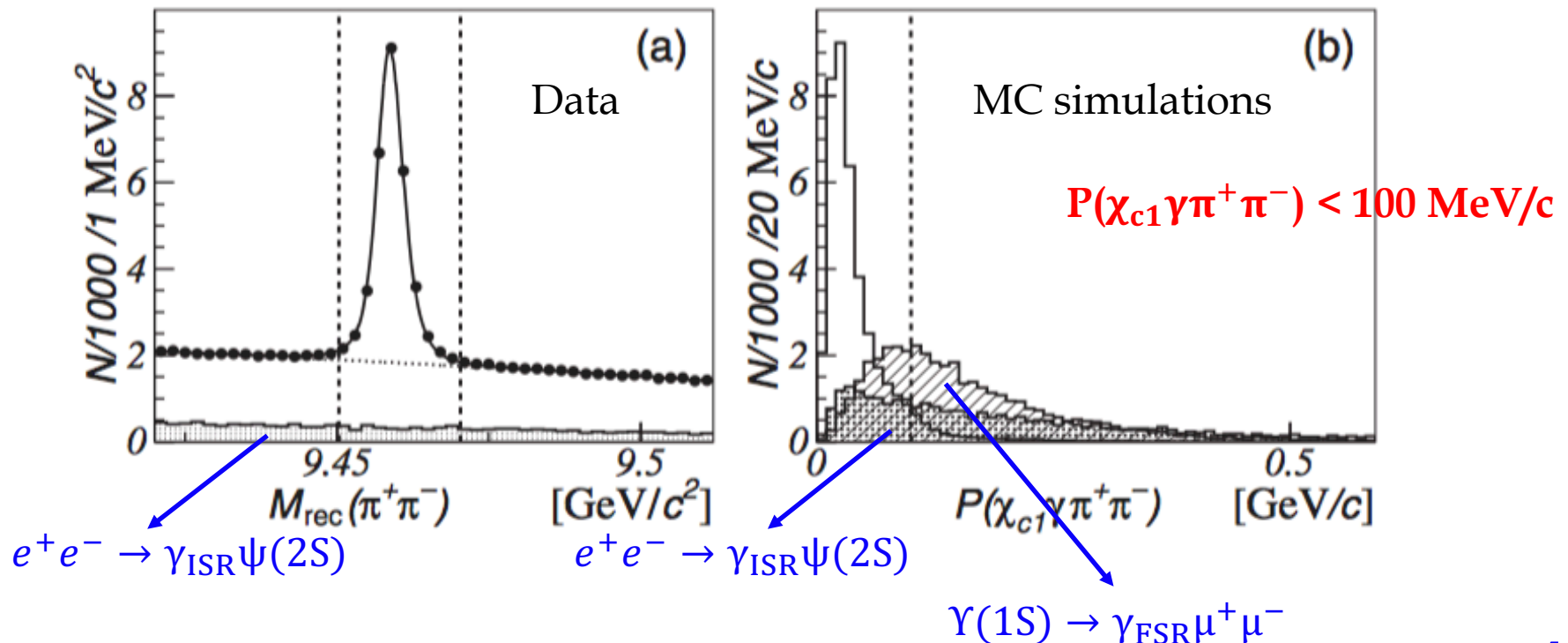
A novel method:

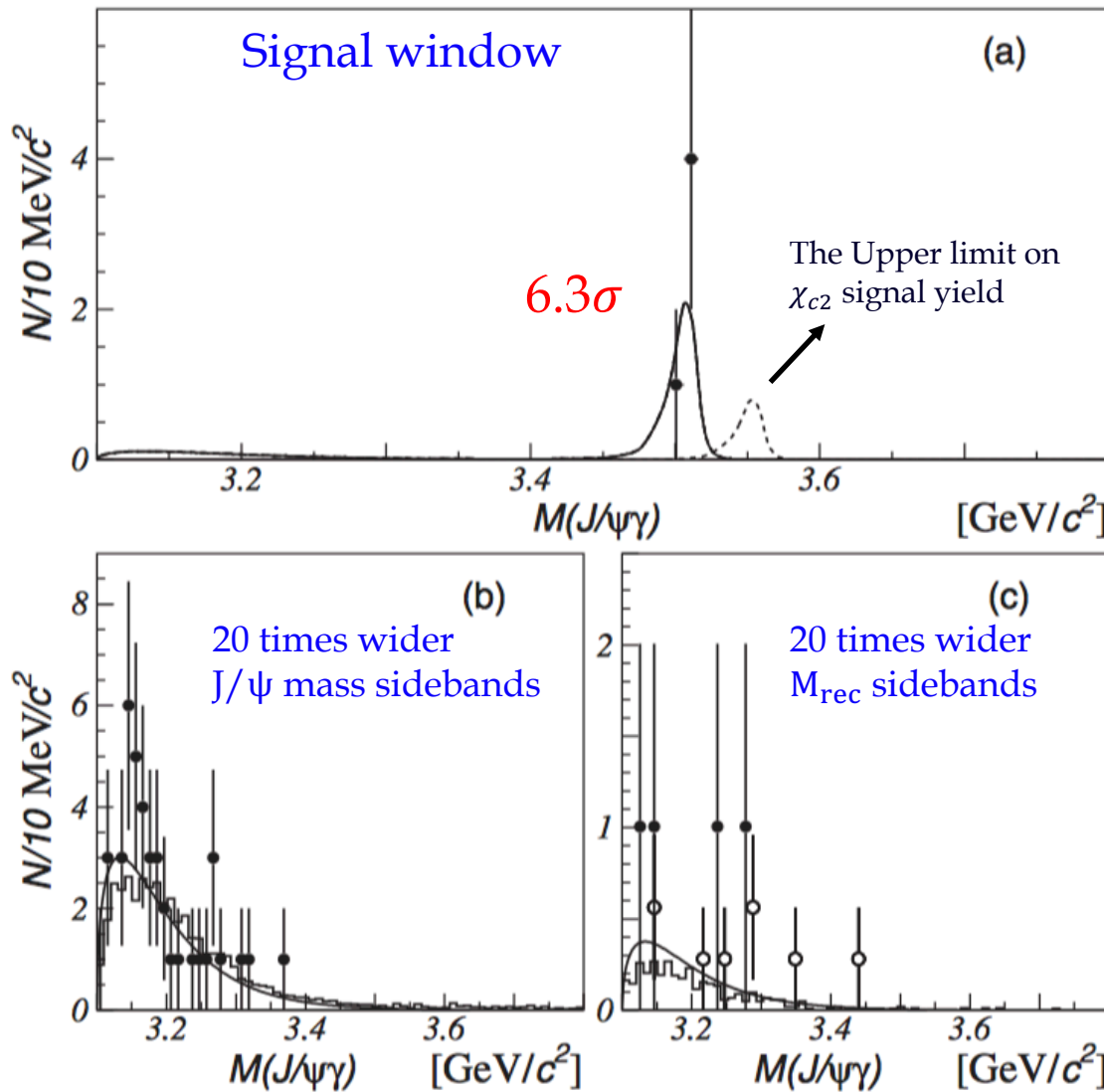
Tag $\Upsilon(1S)$ via the $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ transition.

- ✓ Suppress ISR and FSR backgrounds
- ✓ Increase trigger efficiency

The largest $\Upsilon(2S)$ data sample in e^+e^- colliders:
 $24.9 \text{ fb}^{-1} [(157.3 \pm 3.6) \times 10^6 \text{ events}]$

$$M_{\text{rec}}(\pi^+\pi^-) = \sqrt{[M_{\Upsilon(2S)} - E(\pi^+\pi^-)]^2 - P^2(\pi^+\pi^-)}$$





- Close circles with error bars for $\Upsilon(1S)$ data
- Open circles from continuum data
- The histogram in (b) for $\Upsilon(1S) \rightarrow \gamma_{\text{FSR}} \mu^+ \mu^-$
- The histogram in (c) for $e^+ e^- \rightarrow \gamma_{\text{ISR}} \Psi(2S)$
- The solid curves show the simultaneous fitted results

The branching fraction is calculated to be $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma \chi_{c1}) = (4.7_{-1.8}^{+2.4}(\text{stat})_{-0.5}^{+0.4}(\text{syst})) \times 10^{-5}$. This value is slightly higher than the previous upper limit of $<2.3 \times 10^{-5}$ [PRD 82, 051504 (2010)], and much higher than the theoretical expectations of $(0.45-0.9) \times 10^{-5}$ [arXiv:hep-ph/0701009], indicating the enhancement of χ_{c1} formation from the initial vector state with emission of photon.

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 $B^+ \rightarrow \psi_2(1D)(\rightarrow \chi_{c1}(\rightarrow J/\psi\gamma)\gamma)K^+$ [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].

Reconstruction:

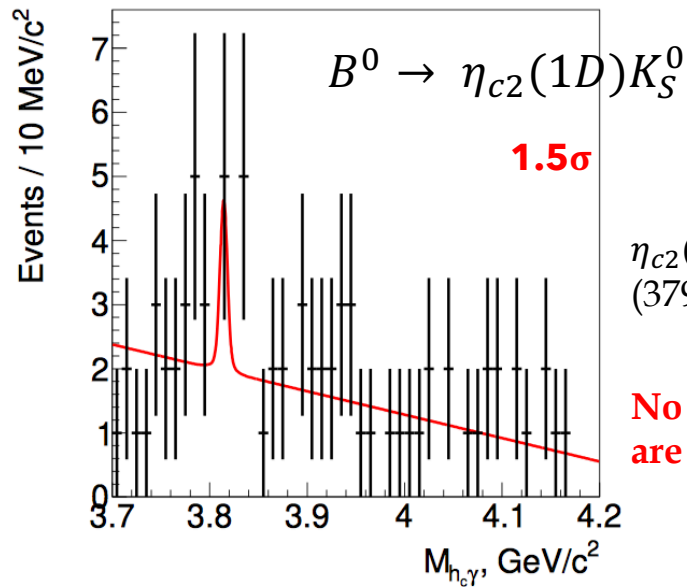
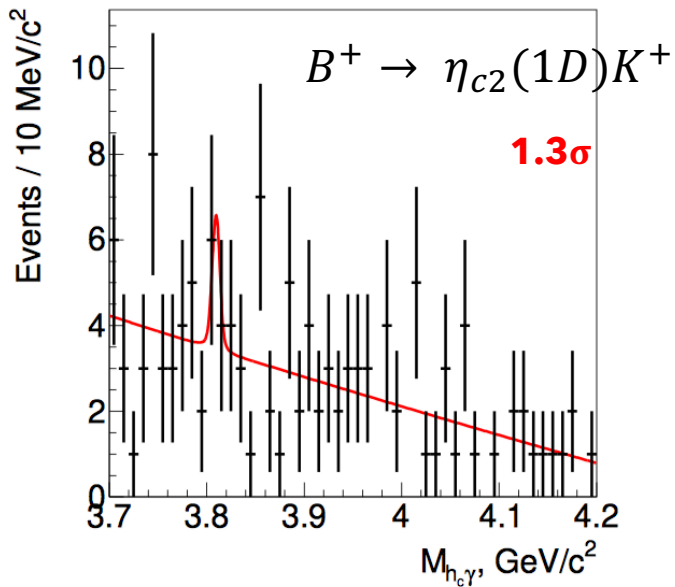
- $B^+ \rightarrow \eta_{c2}(1D)K^+$, $B^0 \rightarrow \eta_{c2}(1D)K_S^0$, $B^0 \rightarrow \eta_{c2}(1D)\pi^-K^+$, and $B^+ \rightarrow \eta_{c2}(1D)\pi^+K_S^0$
- $\eta_{c2}(1D) \rightarrow h_c\gamma$ and $h_c \rightarrow \eta_c\gamma$
- η_c is reconstructed by $K^+K_S^0\pi^-$, $K^+K^-\pi^0$, $K_S^0K_S^0\pi^0$, $K^+K^-\eta$, $K^+K^-K^+K^-$, $\eta'(\rightarrow \eta\pi^+\pi^-)\pi^+\pi^-$, $p\bar{p}$, $p\bar{p}\pi^0$, $p\bar{p}\pi^+\pi^-$, and $\Lambda\bar{\Lambda}$.

Analysis strategy:

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

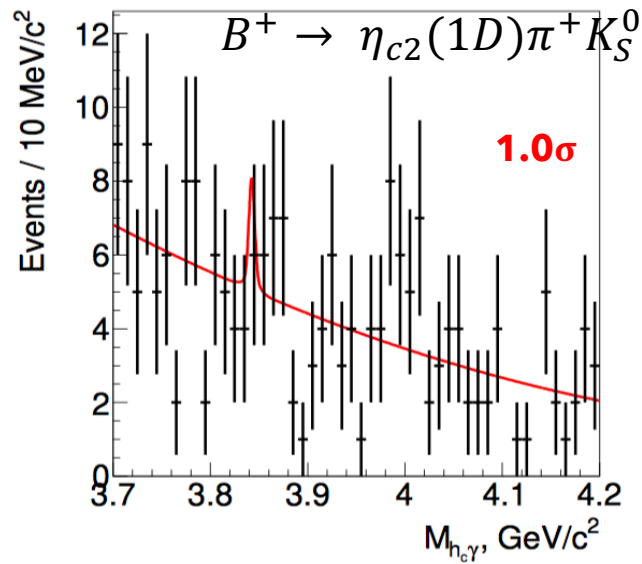
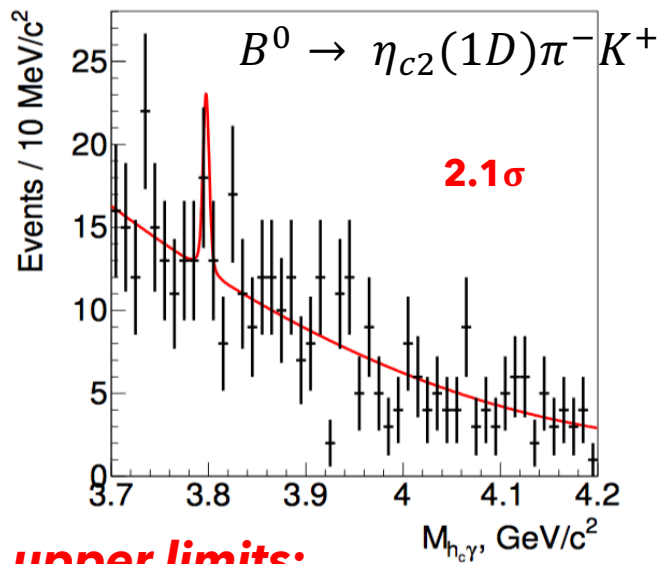
$$F_{\text{opt}} = \frac{\sum_i N_{\text{sig}}^{(i)}}{\frac{a}{2} + \sqrt{\sum_i N_{\text{bg}}^{(i)}}}$$

[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).



$\eta_{c2}(1D)$ mass region:
(3795 - 3845) MeV/c^2

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



90% C.L. upper limits:

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

$\Upsilon(4S, 5S) \rightarrow \omega \eta_b(1S, 2S)$

Preliminary results at Belle

Belle measured:

$$BF[\Upsilon(4S) \rightarrow h_b(1P)\eta] = (2.18 \pm 0.11 \pm 0.18) \cdot 10^{-3}$$

(U. Tamponi *et al.* Phys. Rev. Lett. **115**, 142001 (2015)).

Molecular model $\Rightarrow BF[\Upsilon(4S) \rightarrow \eta_b(1S)\omega]$ could be similar.
(M.B. Voloshin, Phys.Rev. D 85, 034024 (2012))

We search for:

$$\Upsilon(4S) \rightarrow \eta_b(1S)\omega$$

$$\Upsilon(5S) \rightarrow \eta_b(1S)\omega$$

$$\Upsilon(5S) \rightarrow \eta_b(2S)\omega$$

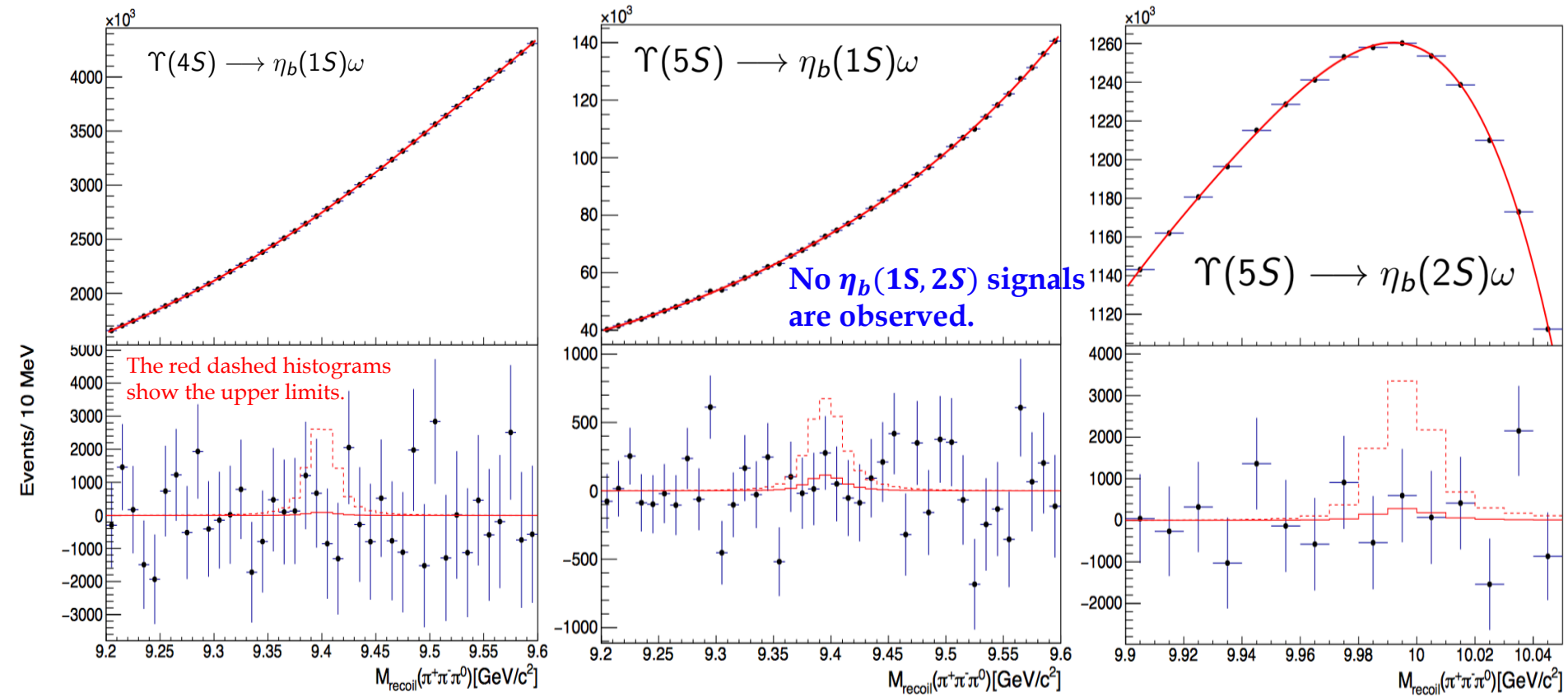
Data sample:

711 fb⁻¹ at $\Upsilon(4S)$ resonance

121 fb⁻¹ at $\Upsilon(5S)$ resonance

We reconstruct only $\omega \rightarrow \pi^+\pi^-\pi^0$ and use the recoil mass of ω to identify the signal.

$$M_{recoil}(\omega) = \sqrt{(\sqrt{s} - E_{\omega}^*)^2 - (P_{\omega}^*)^2}$$

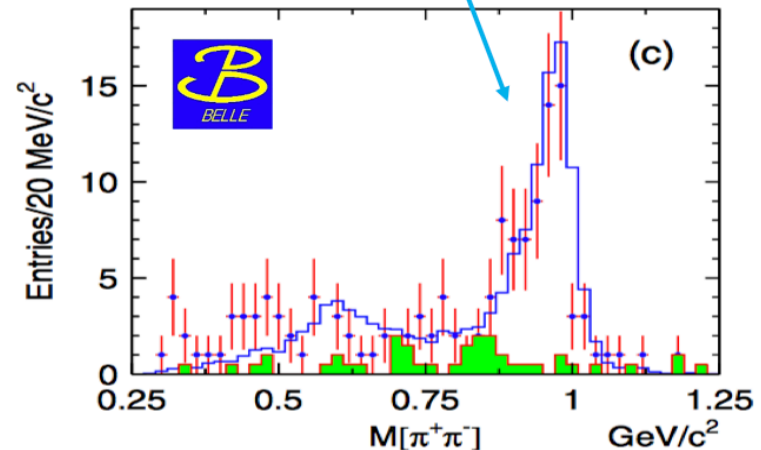
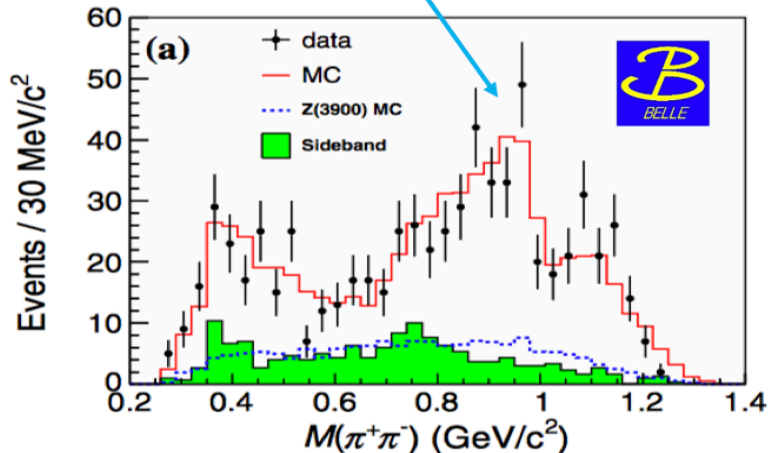
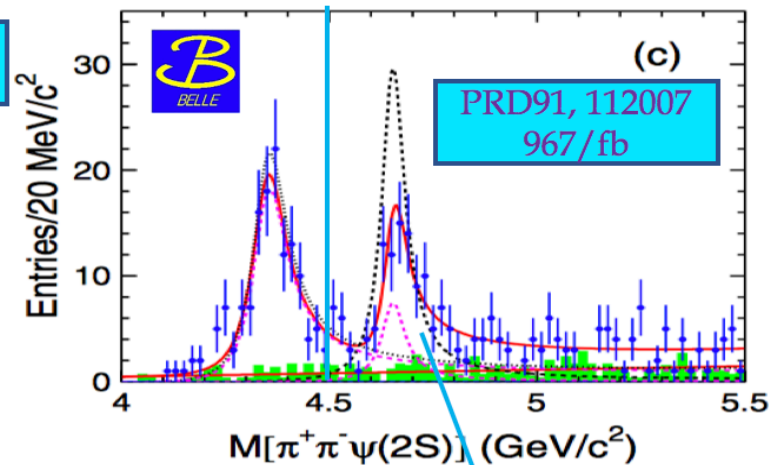
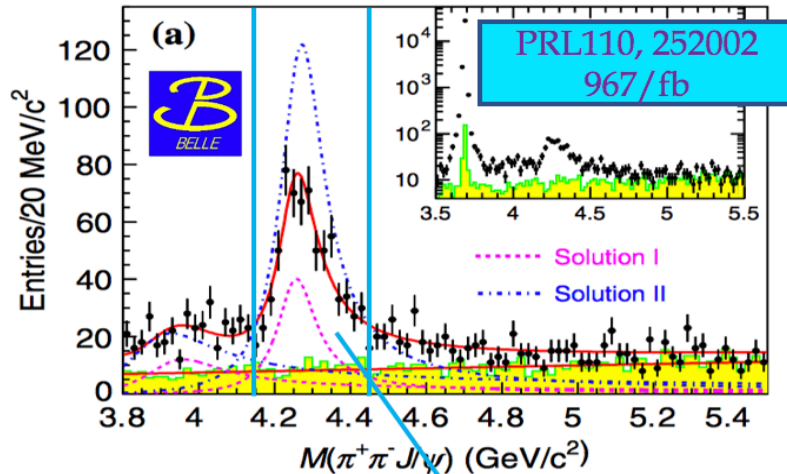


Channel	Signal yield	90% Upper limit on branch fraction
$\Upsilon(4S) \rightarrow \omega\eta_b(1S)$	$(0.4 \pm 6.0^{+1.0}_{-2.3}) \times 10^3$	3.1×10^{-4}
$\Upsilon(5S) \rightarrow \omega\eta_b(1S)$	$(0.5 \pm 1.0^{+1.0}_{-1.2}) \times 10^3$	1.5×10^{-3}
$\Upsilon(5S) \rightarrow \omega\eta_b(2S)$	$(0.8 \pm 3.7^{+3.8}_{-6.3}) \times 10^3$	4.6×10^{-3}

The suppression of the $\Upsilon(4S) \rightarrow \omega\eta_b(1S)$ transition relative to the $\Upsilon(4S) \rightarrow \eta_b(1P)$ could be due to different overlaps between the initial state and the bottomonium in the final state or the details of the η and ω meson production.

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

Motivation: $Y(4260)$ and $Y(4660)$ have a $c\bar{c}s\bar{s}$ component



- $Y(4260) \rightarrow f_0(980)(\rightarrow \pi^+ \pi^-)J/\psi$, $Y(4660) \rightarrow f_0(980)(\rightarrow \pi^+ \pi^-)\psi(2S)$
 $f_0(980)$ 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 a quark component of $(c\bar{s})(\bar{c}s)$, e.g., $D_s \bar{D}_{s1}(2536)$ and $D_s \bar{D}_{s2}^*(2536)$.**

Analysis method

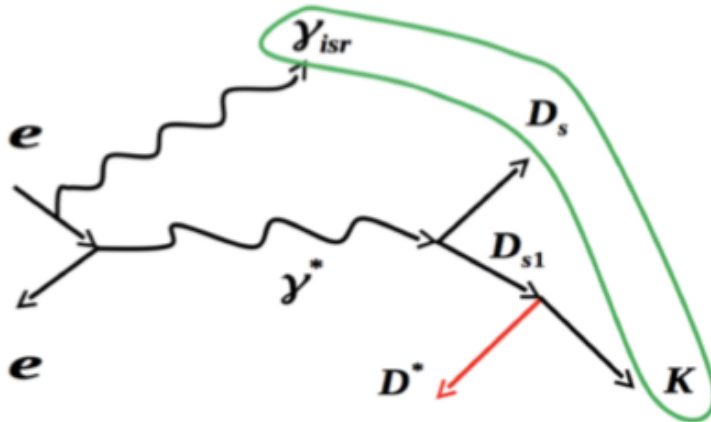
$$e^+e^- \rightarrow \gamma_{\text{ISR}} D_S^+ D_{S1}(2536)^- (\rightarrow \bar{D}^{*0} K^- / D^{*-} K_S^0)$$

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

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

$$M_{\text{rec}}(\gamma_{\text{ISR}} D_S^+ K^- / K_S^0) = \sqrt{(E_{\text{c.m.}}^* - E_{\gamma_{\text{ISR}} D_S^+ K^- / K_S^0}^*)^2 - (p_{\gamma_{\text{ISR}} D_S^+ K^- / K_S^0}^*)^2}$$

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

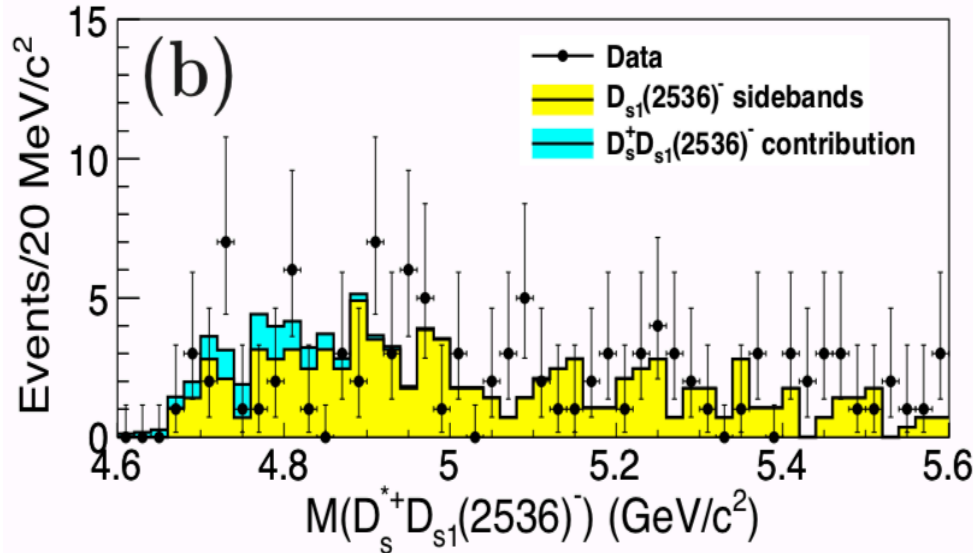
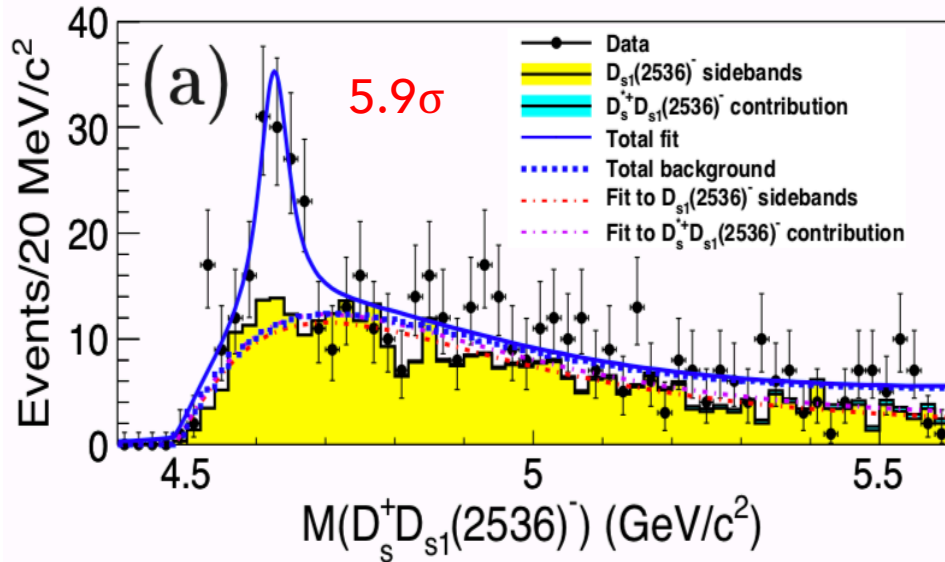


Data samples:

\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

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

PRD 100, 111103(R) (2019)



An unbinned simultaneous likelihood fit:

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

$$M = (4625.9_{-6.0}^{+6.2}(\text{stat.}) \pm 0.4(\text{syst.}) \text{ MeV}/c^2$$

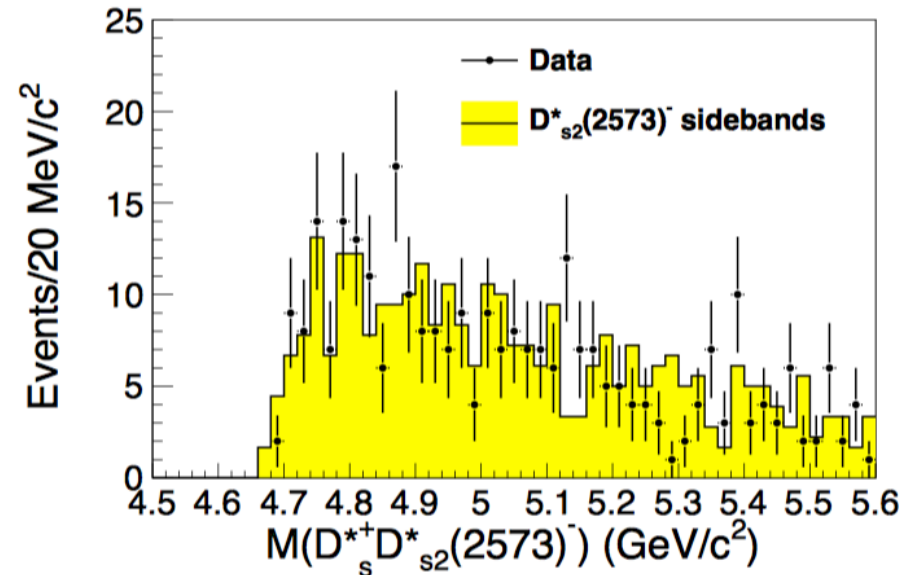
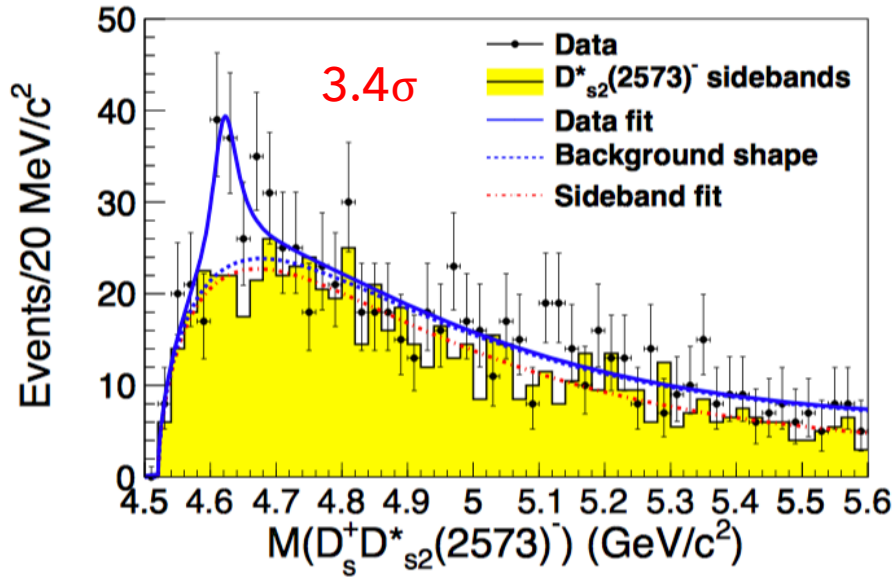
$$\Gamma = (49.8_{-11.5}^{+13.9}(\text{stat.}) \pm 4.0(\text{syst.}) \text{ MeV}$$

$$\Gamma_{ee} \times \mathcal{B}(Y \rightarrow D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \rightarrow \bar{D}^{*0} K^-) = (14.3_{-2.6}^{+2.8}(\text{stat.}) \pm 1.5(\text{syst.}) \text{ eV}$$

One possible background is from $e^+e^- \rightarrow D_s^{*+}(\rightarrow D_s^+ \gamma) D_{s1}(2536)^-$.
 No obvious structure is observed in the $e^+e^- \rightarrow D_s^{*+}(\rightarrow D_s^+ \gamma) D_{s1}(2536)^-$.

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

PRD 101, 091101(R) (2020)



An unbinned simultaneous likelihood fit:

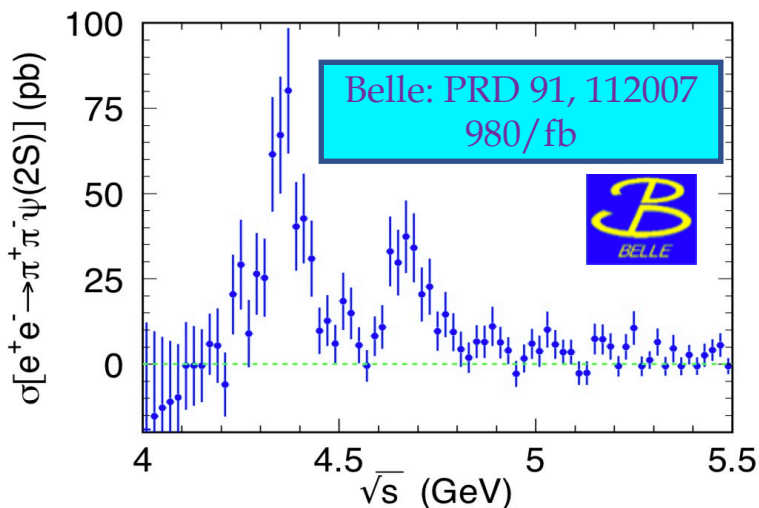
- **Signal:** a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s2}^*(2573)^-$ mass sidebands: a threshold function
- A non-resonant contribution: a two-body phase space form

$$M = (4619.8^{+8.9}_{-8.0}(\text{stat.}) \pm 2.3(\text{syst.}) \text{ MeV/c}^2$$

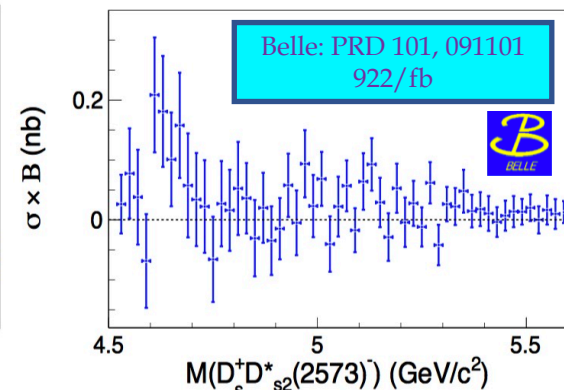
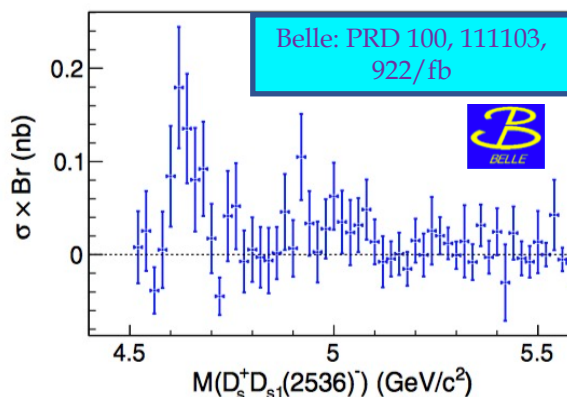
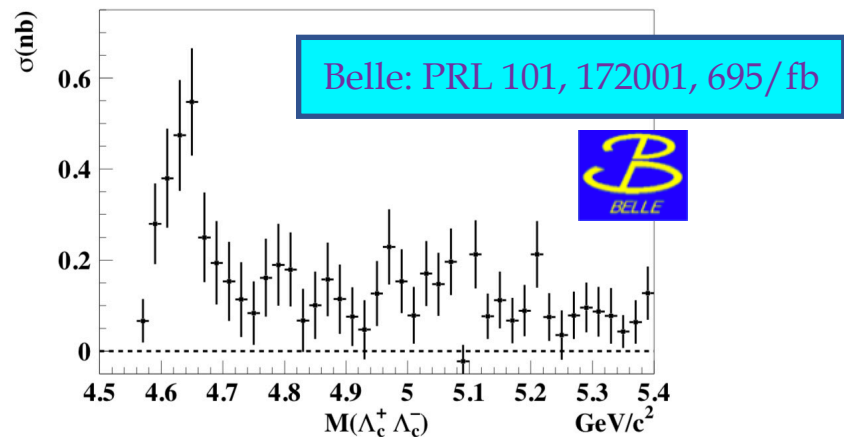
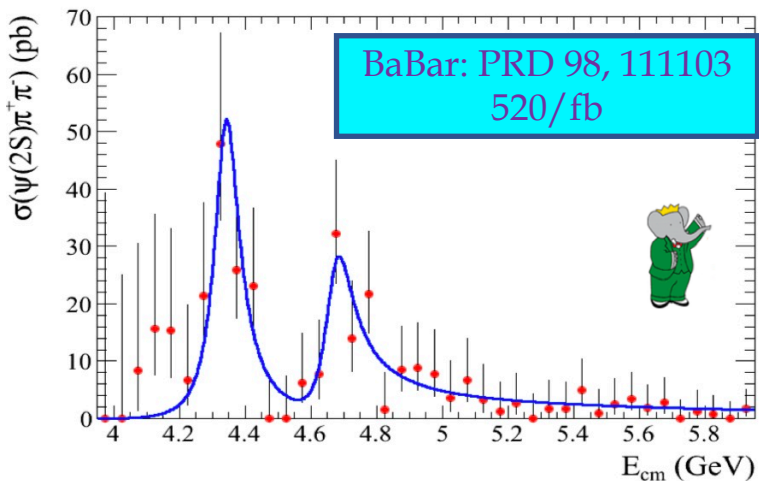
$$\Gamma = (47.0^{+31.3}_{-14.8}(\text{stat.}) \pm 4.6(\text{syst.}) \text{ MeV}$$

$$\Gamma_{ee} \times B(Y \rightarrow D_s^+ D_{s2}^*(2573)^-) \times B(D_{s2}^*(2573)^- \rightarrow \bar{D}^0 K^-) = (14.7^{+5.9}_{-4.5}(\text{stat.}) \pm 3.6(\text{syst.}) \text{ eV}$$

$Y(4630) = Y(4660)?$



$e^+e^- \rightarrow \pi\pi\psi'$



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, $D_s^+ D_{s2}^*(2573)^-$	$4620^{+9}_{-8} \pm 3$	$47.0^{+32}_{-15} \pm 5$

Evidence for $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ produced in single-tag two-photon interactions

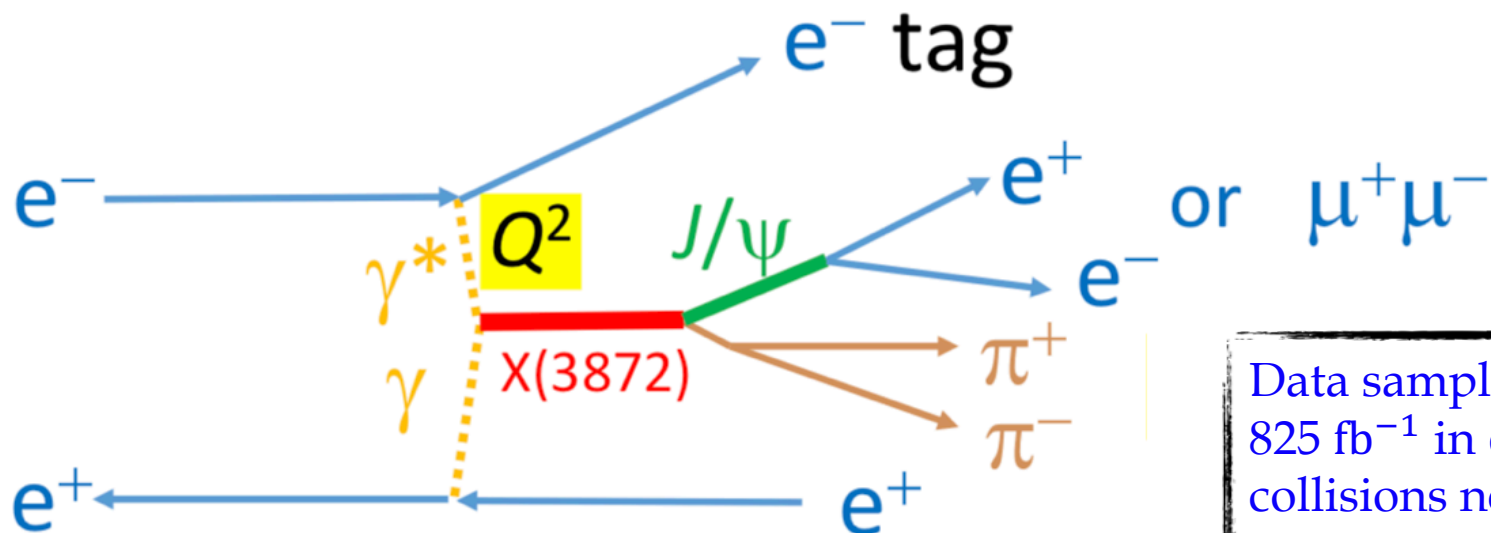
arXiv: 2007.05696 (2020), submitted to PRL

- $X(3872)$ with $J^{PC} = 1^{++}$ could be produced if one or both photons are highly virtual [Nucl. Phys. B 523, 423 (1998)].
- The measurement of $X(3872)$ in two-photon reactions help to understand its internal structure.

$X(3872): J^{PC} = 1^{++}$

$\gamma\gamma \rightarrow X(3872) \rightarrow$ Not allowed

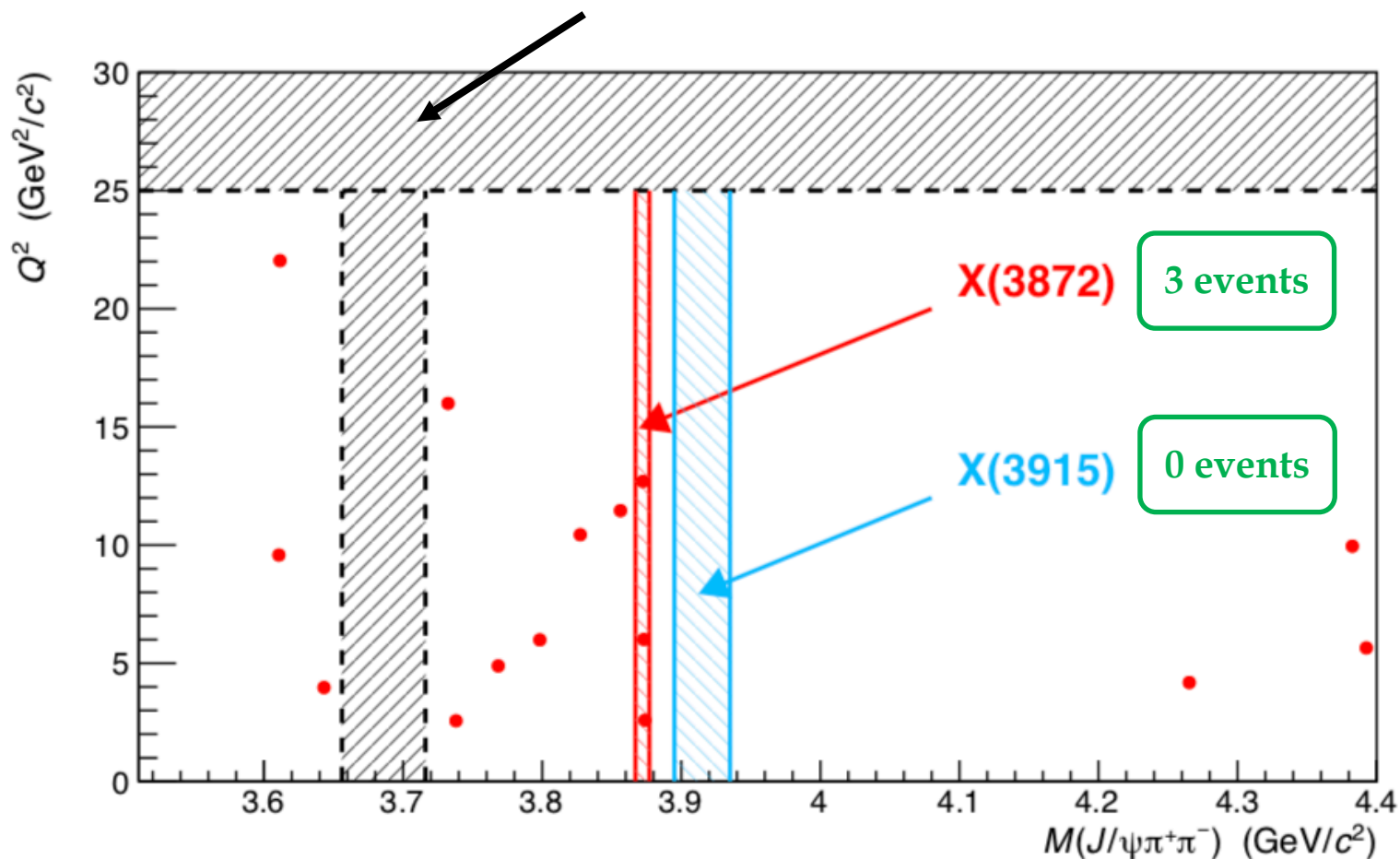
But, $\gamma^*\gamma \rightarrow X(3872) \rightarrow$ Allowed



Data sample:
825 fb^{-1} in e^+e^-
collisions near 10.6 GeV

$-Q^2$ is the invariant mass-squared of the virtual photon.

The veto regions

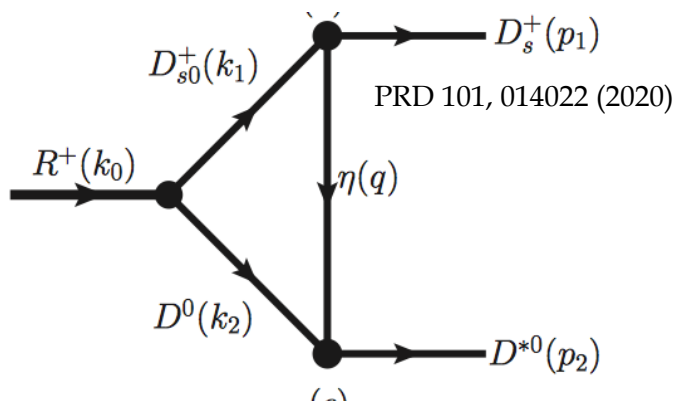


- $M(X(3872)) = (3.8723 \pm 0.0012) \text{ GeV}/c^2$
- With 0.11 ± 0.10 background events, **the number of signal events is $N_{\text{sig}} = 2.9_{-2.0}^{+2.2}(\text{stat.}) \pm 0.1(\text{syst.})$ with a significance of 3.2σ** (Feldman-Cousins method applied [Phys. Rev. D 57, 3873 (1998)]).
- $\tilde{\Gamma}_{\gamma\gamma} \mathcal{B}(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = 5.5_{-3.8}^{+4.1}(\text{stat.}) \pm 0.7(\text{syst.}) \text{ eV}$ using the Q^2 dependence expected from a $c\bar{c}$ meson model.

Search for $R^{++} \rightarrow D^+ D_s^{*+}$

Preliminary results at Belle

- A doubly-charged and doubly-charmed molecule 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)].

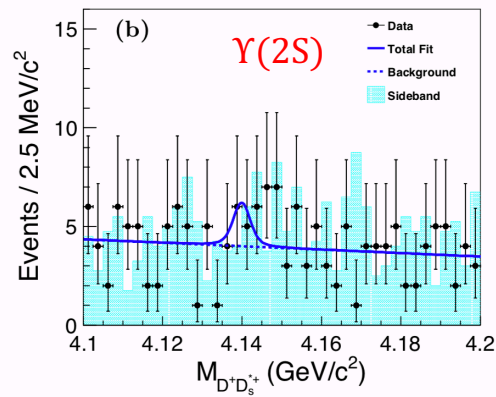
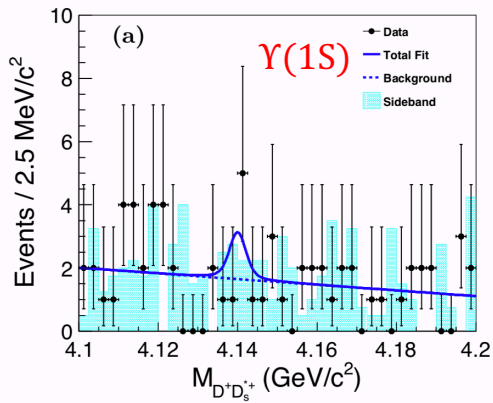


- $D^+ \rightarrow K^- \pi^+ \pi^- / K_s^0 (\rightarrow \pi^+ \pi^-) \pi^+$
- $D_s^{*-} \rightarrow D_s^- \gamma$
- $D_s^- \rightarrow \phi \pi^- / \bar{K}^{*0} K^+$

Data samples:

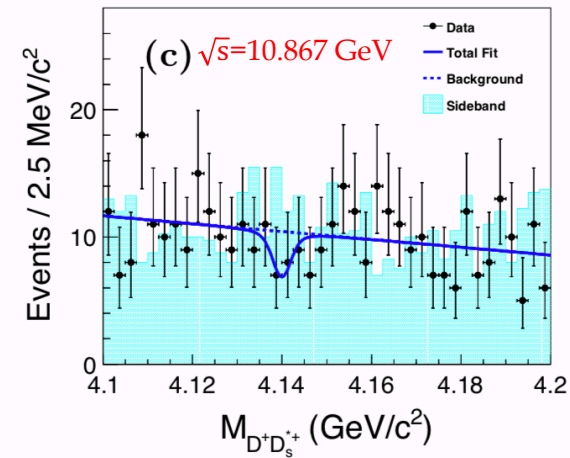
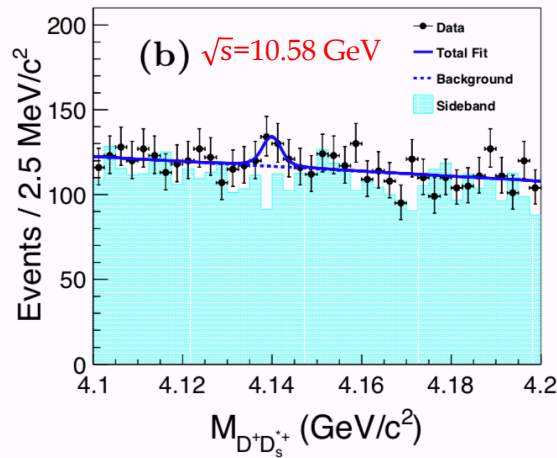
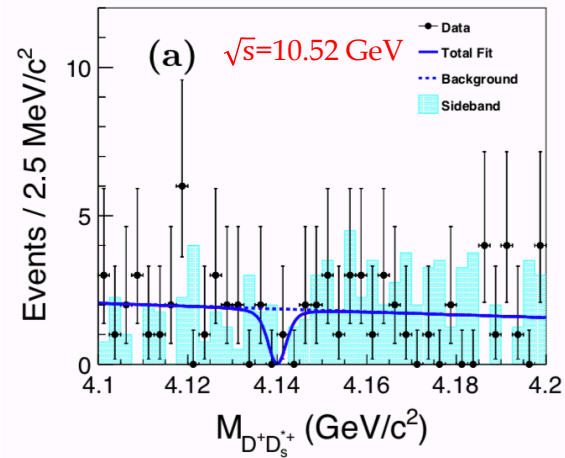
\sqrt{s} (GeV)	Luminosity (fb^{-1})	Events
9.46 [Y(1S)]	5.74 ± 0.09	(102 \pm 3) million
10.023 [Y(2S)]	24.91 ± 0.35	(158 \pm 4) million
10.52	89.5 ± 1.3	-
10.58 [Y(4S)]	711 ± 10	-
10.867 [Y(5S)]	121.4 ± 1.7	-

The Punzi parameter $S/(3/2 + \sqrt{B})$ [arXiv:physics/0308063] is applied to optimize the mass windows of intermediate states. **-17-**



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

No R^{++} signals are observed.



90% C. L. Upper limits [$M(R^{++})$ varying from 4.13 to $4.17 \text{ GeV}/c^2$, $\Gamma(R^{++})$ varying from 0 to 5 MeV]

$$\mathcal{B}(Y(1S) \rightarrow R^{++} + \text{anything})\mathcal{B}(R^{++} \rightarrow D^+D_s^{*+}) = (11.8 - 54.5) \times 10^{-5}$$

$$\mathcal{B}(Y(2S) \rightarrow R^{++} + \text{anything})\mathcal{B}(R^{++} \rightarrow D^+D_s^{*+}) = (16.3 - 68.6) \times 10^{-5}$$

$$\sigma(e^+e^- \rightarrow R^{++} + \text{anything})\mathcal{B}(R^{++} \rightarrow D^+D_s^{*+}) = (202.8 - 880.4) \text{ fb at } \sqrt{s} = 10.52 \text{ GeV}$$

$$\sigma(e^+e^- \rightarrow R^{++} + \text{anything})\mathcal{B}(R^{++} \rightarrow D^+D_s^{*+}) = (218.9 - 1054.0) \text{ fb at } \sqrt{s} = 10.58 \text{ GeV}$$

$$\sigma(e^+e^- \rightarrow R^{++} + \text{anything})\mathcal{B}(R^{++} \rightarrow D^+D_s^{*+}) = (346.6 - 1517.6) \text{ fb at } \sqrt{s} = 10.867 \text{ GeV}$$

Summary

- Although Belle has stopped data taking for ~10 years ago, we are still producing exciting results.
- We report the first observation of the radiative decay of bottomonium to charmonium with $\mathcal{B}(Y(1S) \rightarrow \gamma\chi_{c1}) = (4.7_{-1.8}^{+2.4}(\text{stat})_{-0.5}^{+0.4}(\text{syst})) \times 10^{-5}$.
- 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 first evidence for $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ produced in single-tag two-photon interactions with $\tilde{\Gamma}_{\gamma\gamma} \mathcal{B}(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = 5.5_{-3.8}^{+4.1}(\text{stat.}) \pm 0.7(\text{syst.}) \text{ eV}$.
- Belle II will reach 50 ab^{-1} , which will provide greater sensitivity and precise measurements in hadron physics.

Thanks for your attentions!

Backup