# Observation of a charmonium-like state in $e^+e^- \to D_s^+ D_{s1}(2536)^-$ at Belle

[arxiv: 1911.00671]

Sen Jia
Fudan University
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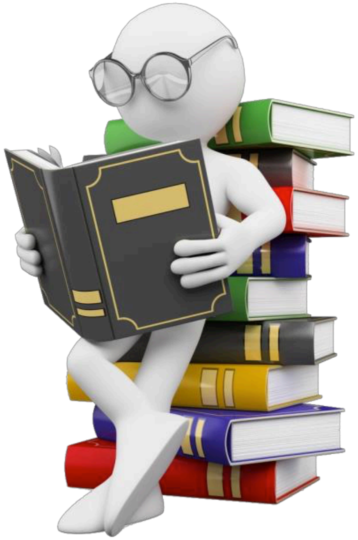
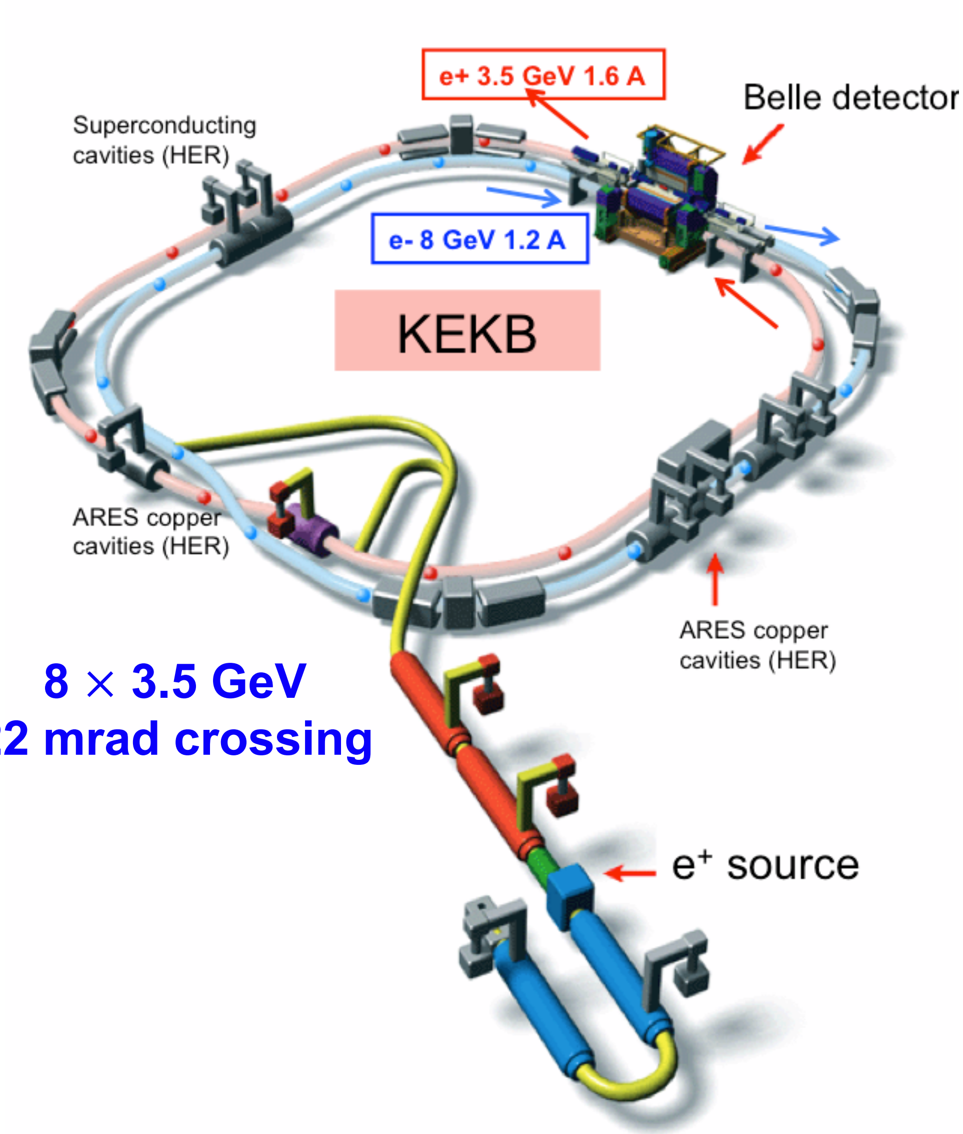
# Outline

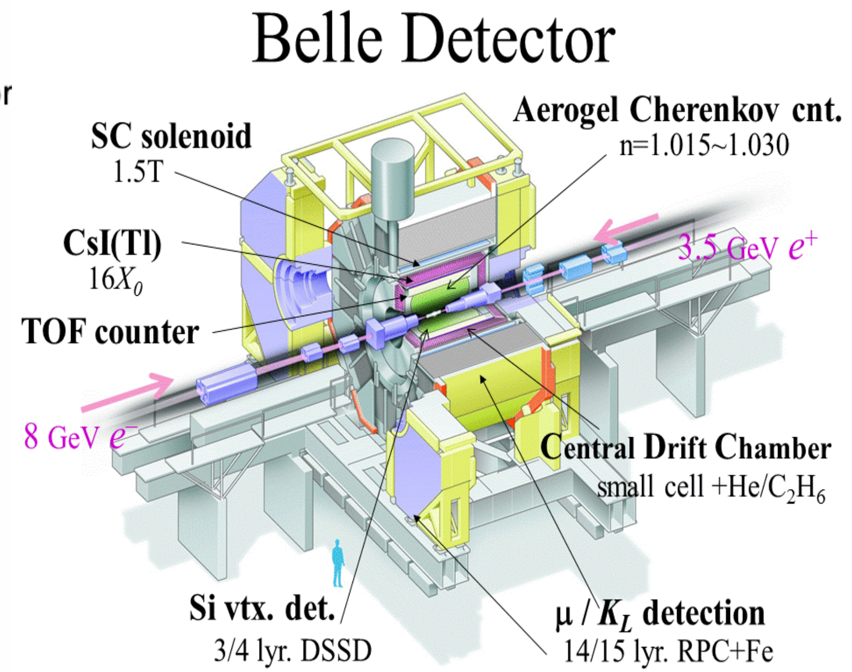
- ***Belle experiment***
- ***Motivation***
- ***Analysis strategy and results***
- ***Discussion and summary***



# Belle experiment and data samples




**8 × 3.5 GeV**
**22 mrad crossing**



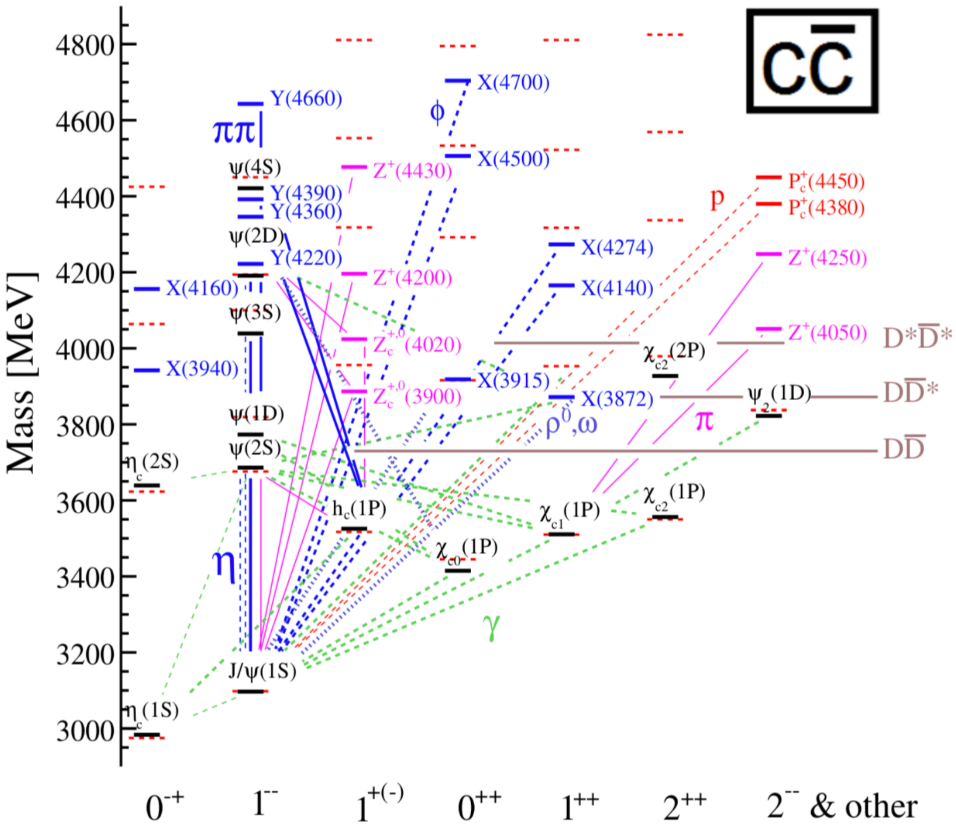

Data taking: 1999 – 2010

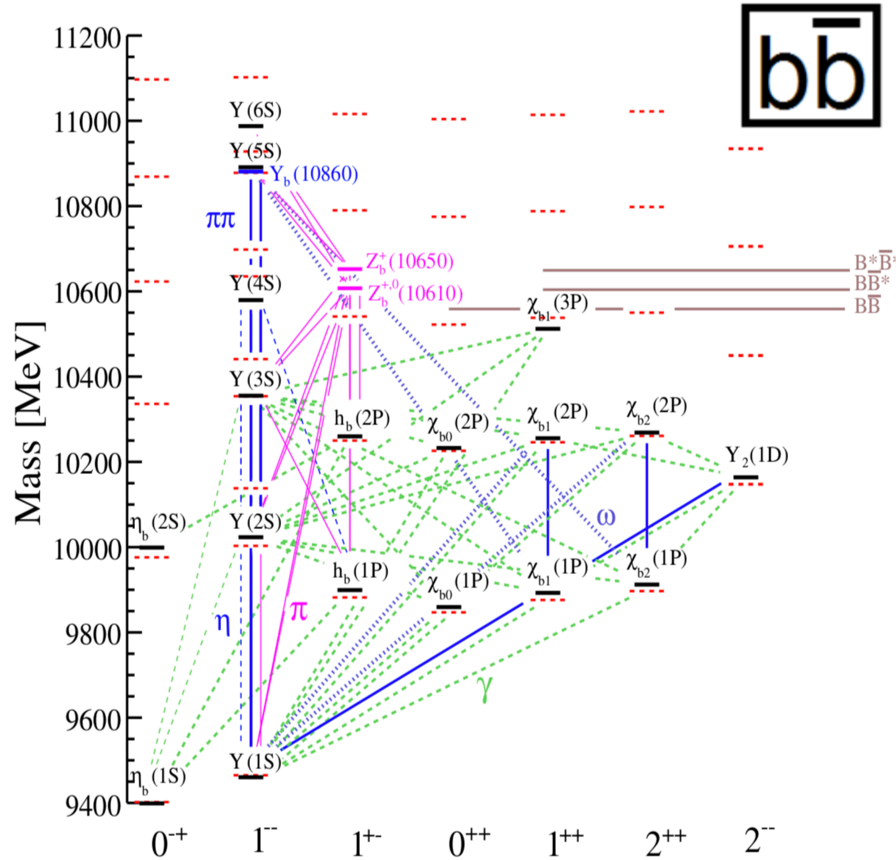
On/off/Scan $\Upsilon(nS)$ peaks

Total luminosity: 980 $fb^{-1}$

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

# Quarknium

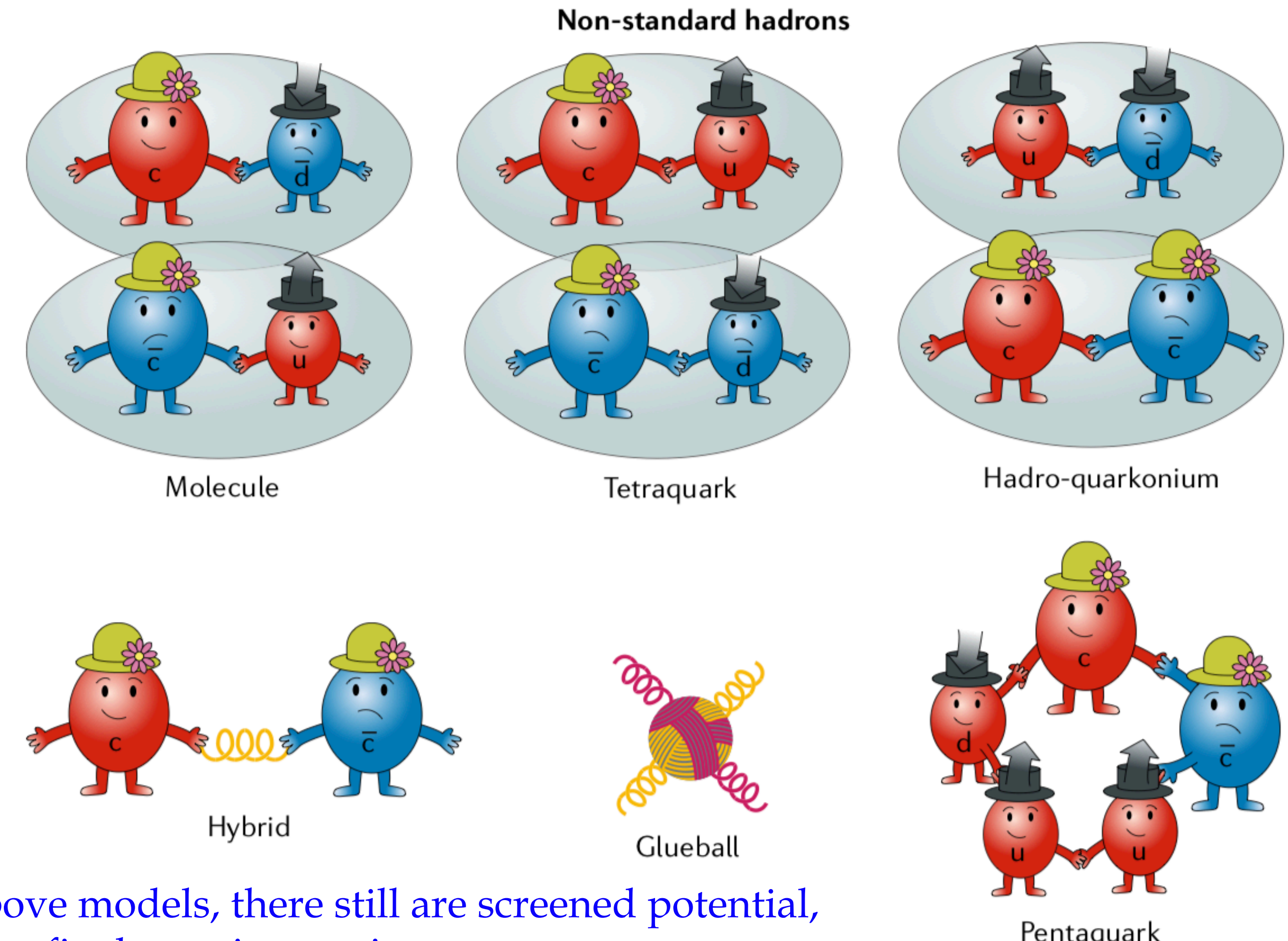



Rev. Mod. Phys. 90, 015003 (2018)

- Quarkonium: $q\bar{q}$, the simplest system of a hadron.
- Below $D\bar{D}/B\bar{B}$ thresholds – both charmonium and bottomonium are successful stories of QCD.
- But there are many exotic states observed in the past decade, and they are hard to fit in the two families.

# Various interpretations of the exotic states




Nature Reviews Physics 1, 480 (2019)

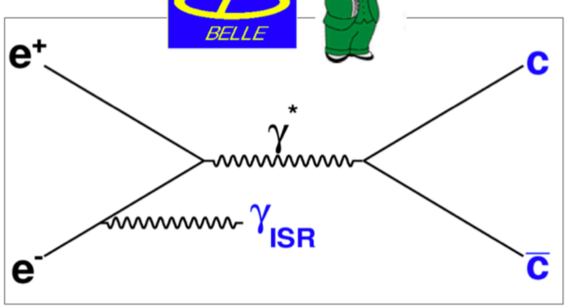
Besides above models, there still are screened potential, cusps effect, final state interaction …

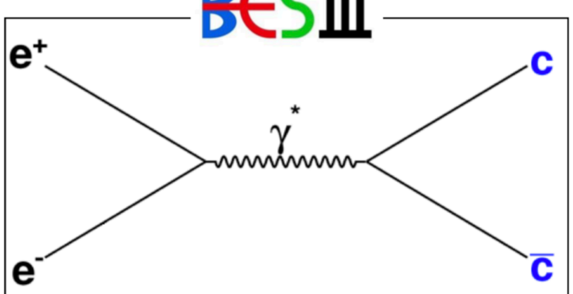
***<u>High Priority:</u>***

- Identify most prominent component in wave function
- Seek unique picture describing all XYZ states, not state-by-state

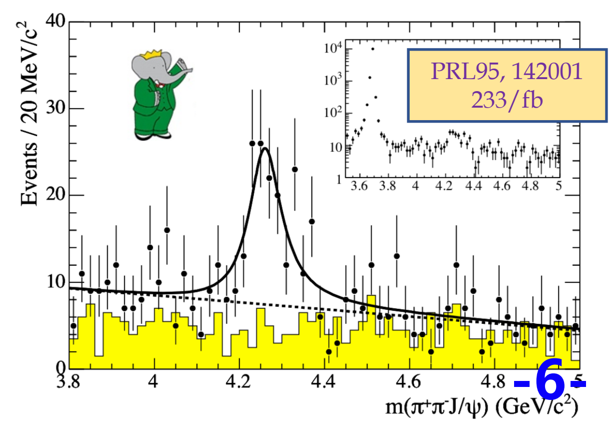
# Y states

- Y(4008), Y(4260), Y(4360), Y(4630), Y(4660): $J^{PC} = 1^{--}$
- Strong coupling to hidden-charm final states in contract to the vector charmonium states in the same energy region [$\psi(4040)$, $\psi(4160)$, $\psi(4415)$], which couple dominantly to open-charm meason pairs.
- Many theoretical interpretations: tetraquark, molecule, hybrids, or hadrocharmonia?
- Observed in Initial state radiation processes (Belle and Babar) and $e^+e^-$ annihilations in the charmonium energy region (BESIII)




The first observed Y state (Y(4260))



# Y states

Y(4008)

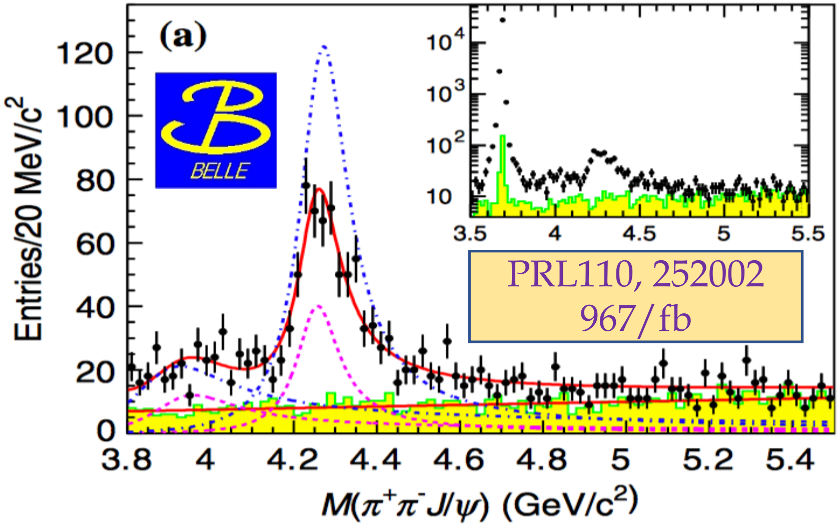
Y(4260)

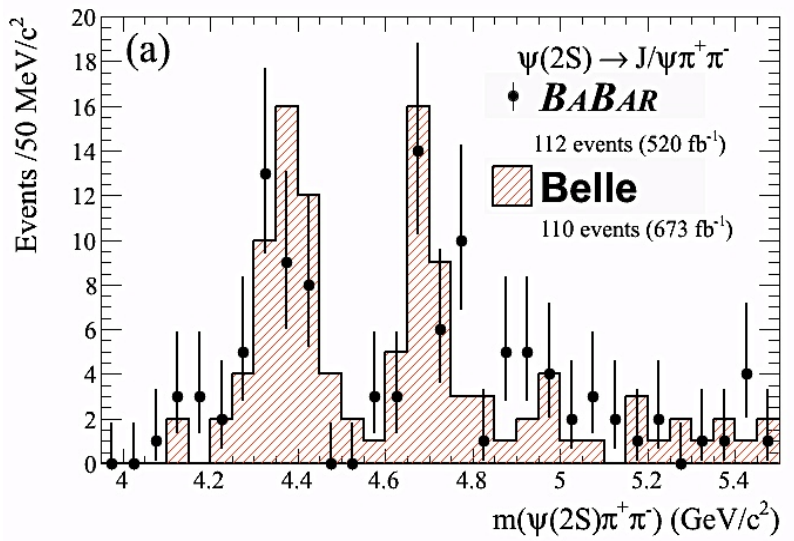
Y(4360)

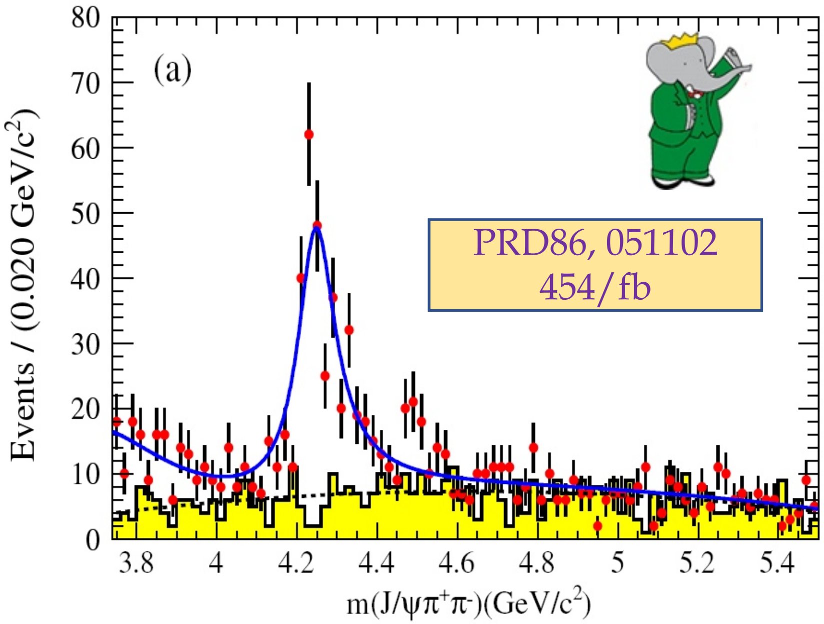
Y(4630)

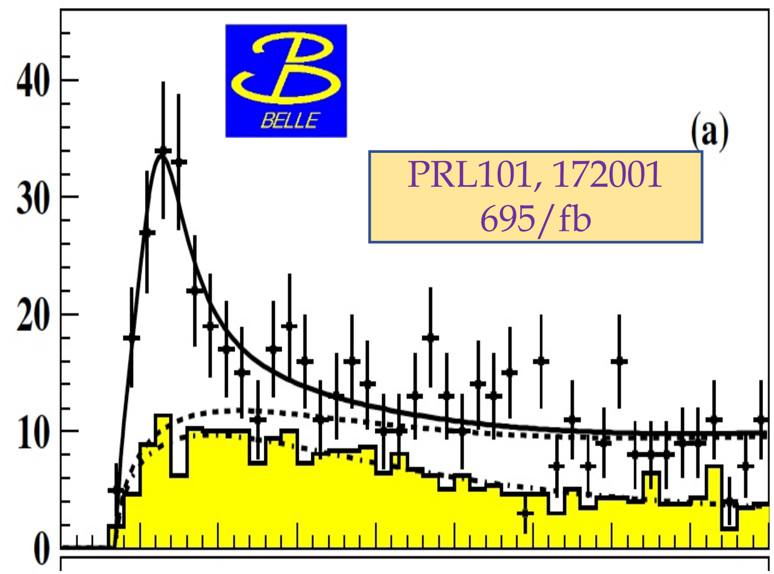
Y(4660)

Belle: PRL99, 142002, 670/fb
BaBar: PRD89, 111103, 670/fb



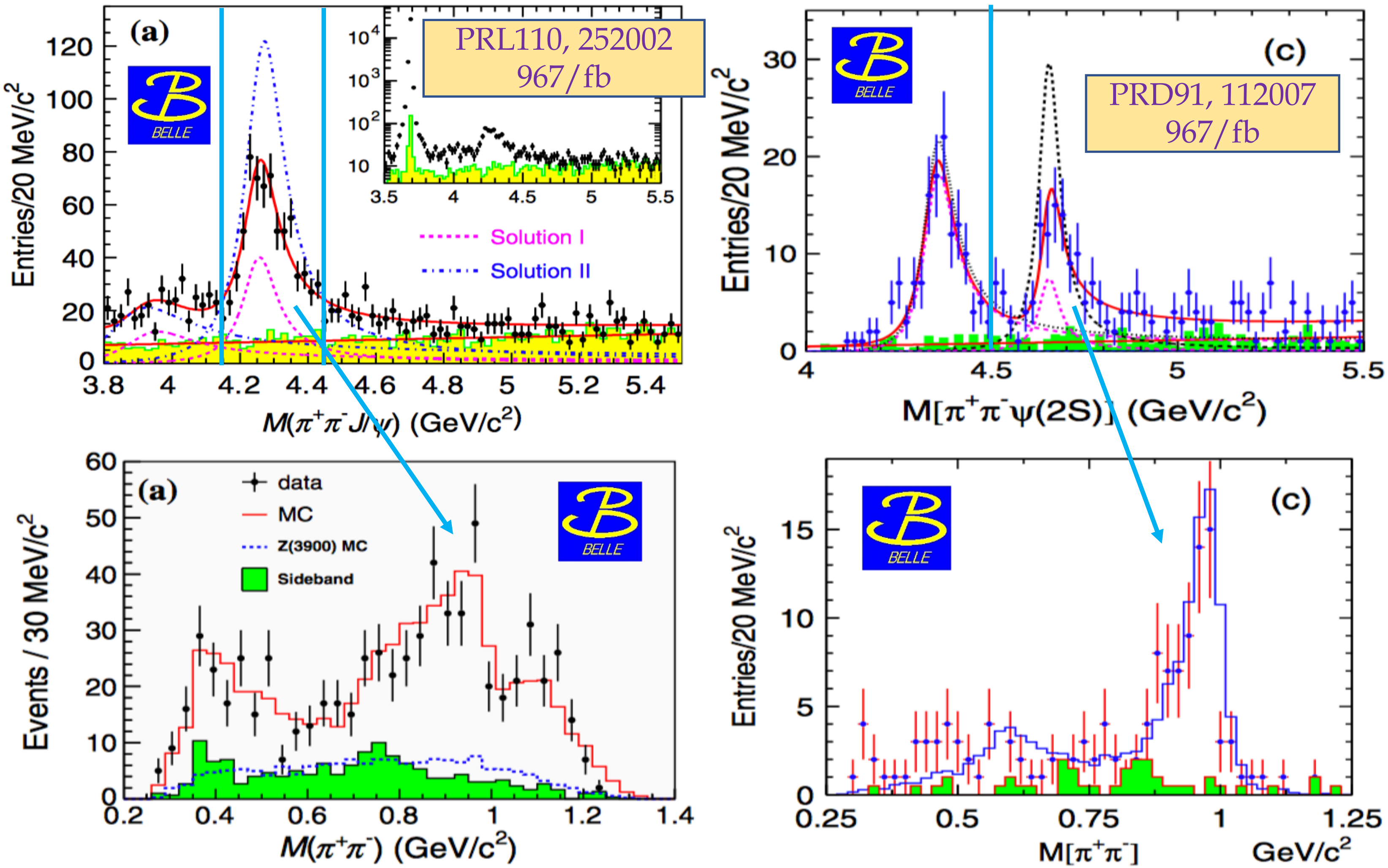




$M(\Lambda_c^+ \Lambda_c^-)$

# M(π⁺π⁻) in Y(4260) and Y(4660) signal region




- Y(4260) → $f_0(980)(\rightarrow \pi^+\pi^-)J/\psi$, Y(4660) → $f_0(980)(\rightarrow \pi^+\pi^-)\psi(2S)$
  $f_0(980)$ 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., $D_sD_{s1}(2536)$.**

# Analysis method

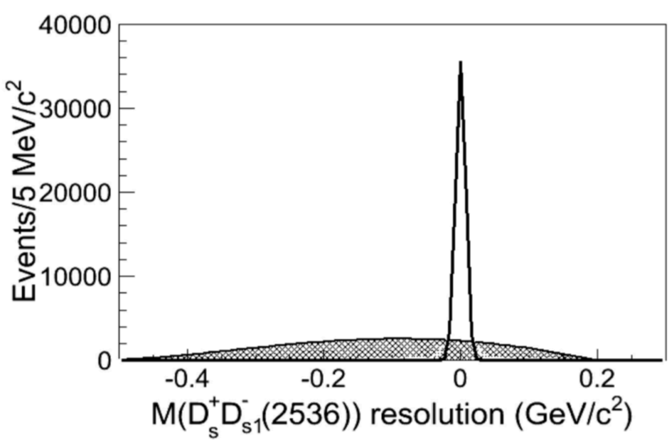
$$e^+e^- \to \gamma_{ISR} D_s^+ D_{s1}(2536)^- (\to \bar{D}^{*0}K^- / D^{*-}K_S^0)$$

We require full reconstruction of the $\gamma_{ISR}$, $D_s^+$ , 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.

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

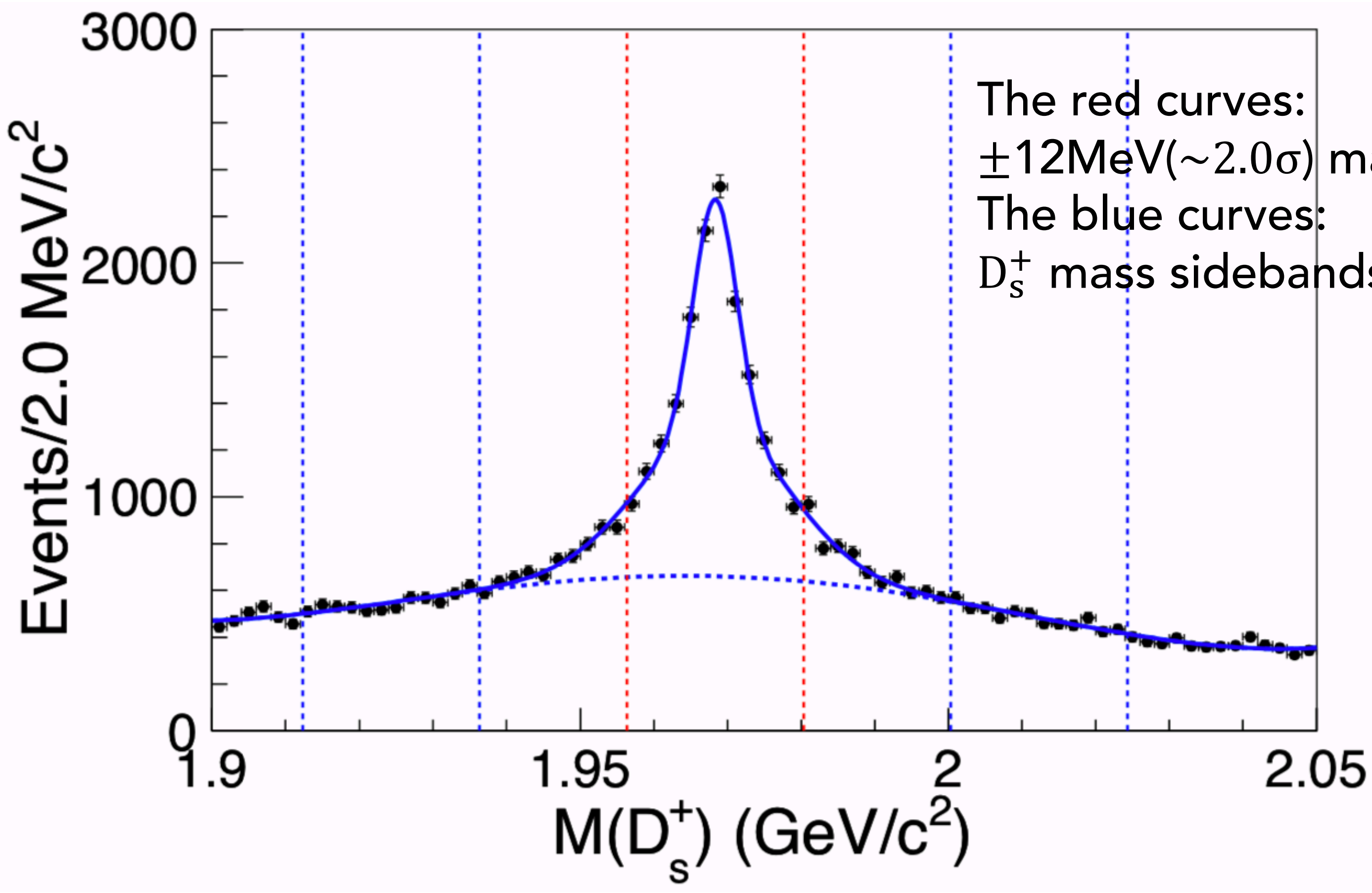
- To improve the $M_{rec}(\gamma_{ISR})$ resolution, $M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0)$ is constrained to be the nominal mass of the $\bar{D}^{*0}/D^{*-}$. As a result, the resolution of $M_{rec}(\gamma_{ISR}) \equiv M(D_s^+D_{s1}(2536)^-)$ is drastically improved ($\sim$180MeV $\to \sim$ 5MeV).




## Data samples:

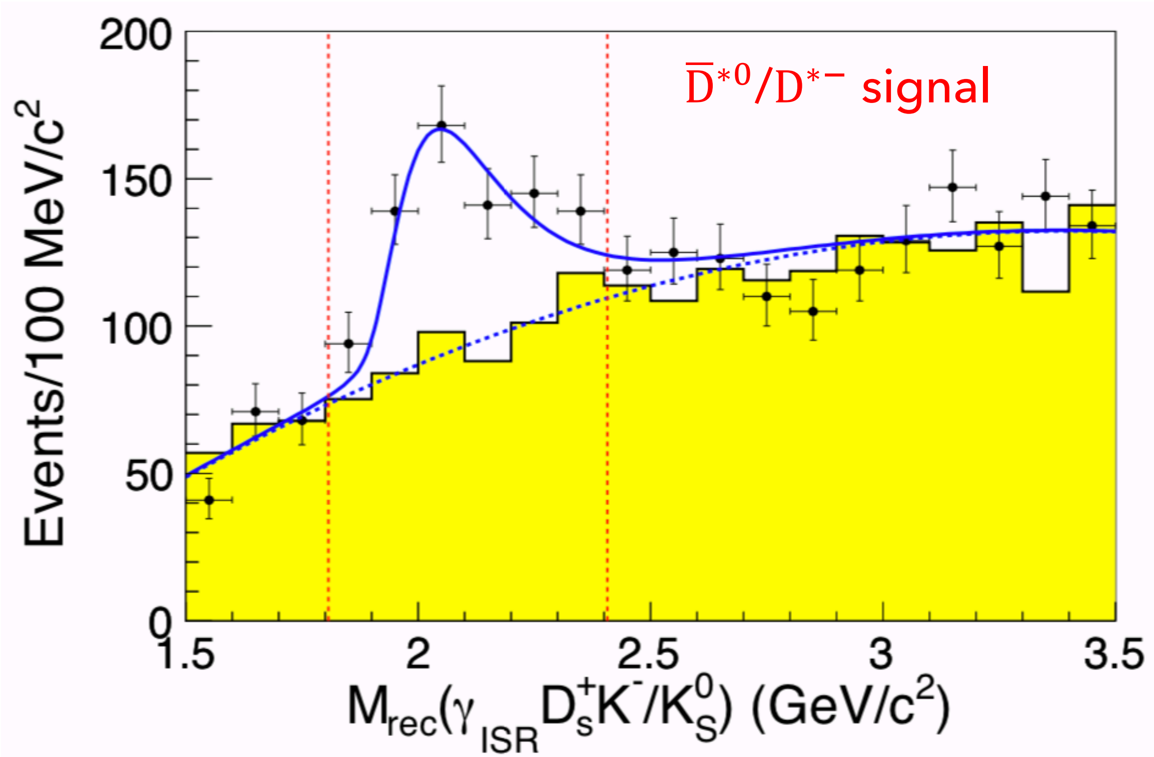
| $\sqrt{s}$ (GeV) | Luminosity (fb$^{-1}$) |
|---|---|
| 10.52 | 89.5±1.3 |
| 10.58 | 711±10 |
| 10.867 | 121.4±1.7 |
| Total | 921.9±12.9 |

# The invariant mass distribution for $D_s^+$ candidates




- Since the intrinsic width of the $D_s^+$ could be neglected, a double Gaussian function is used to fit the $D_s^+$ mass spectrum.
- The purity is $N_{sig}/(N_{sig} + N_{bkg})$=64%.

# The recoil mass spectrum against $\gamma_{ISR} D_s^+ K^- / K_S^0$




$\overline{D}^{*0}/D^{*-}$ signal:
Gaussian ⊗ Novosibirsk

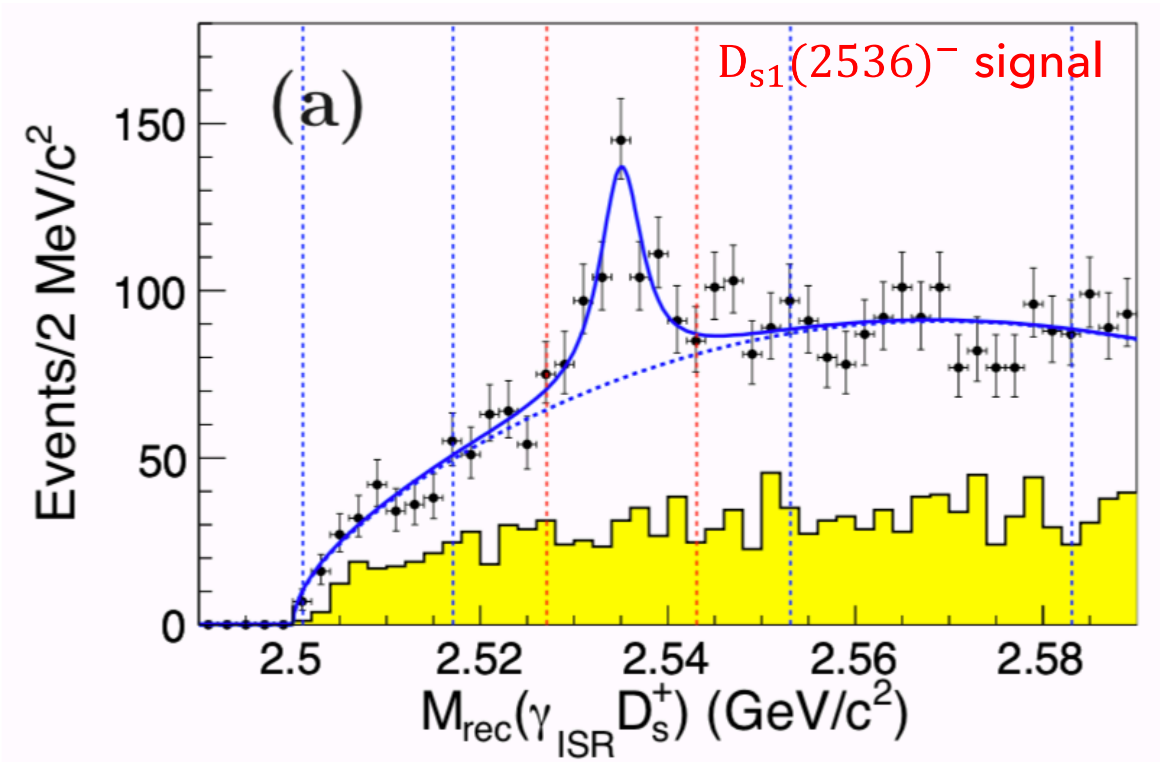
The combinatorial backgrounds:
a second-order polynomial

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

- The yellow histogram shows the normalized $D_{s1}(2536)^-$ mass sidebands (see below).

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

# The recoil mass spectrum against $\gamma_{ISR} D_s^+$



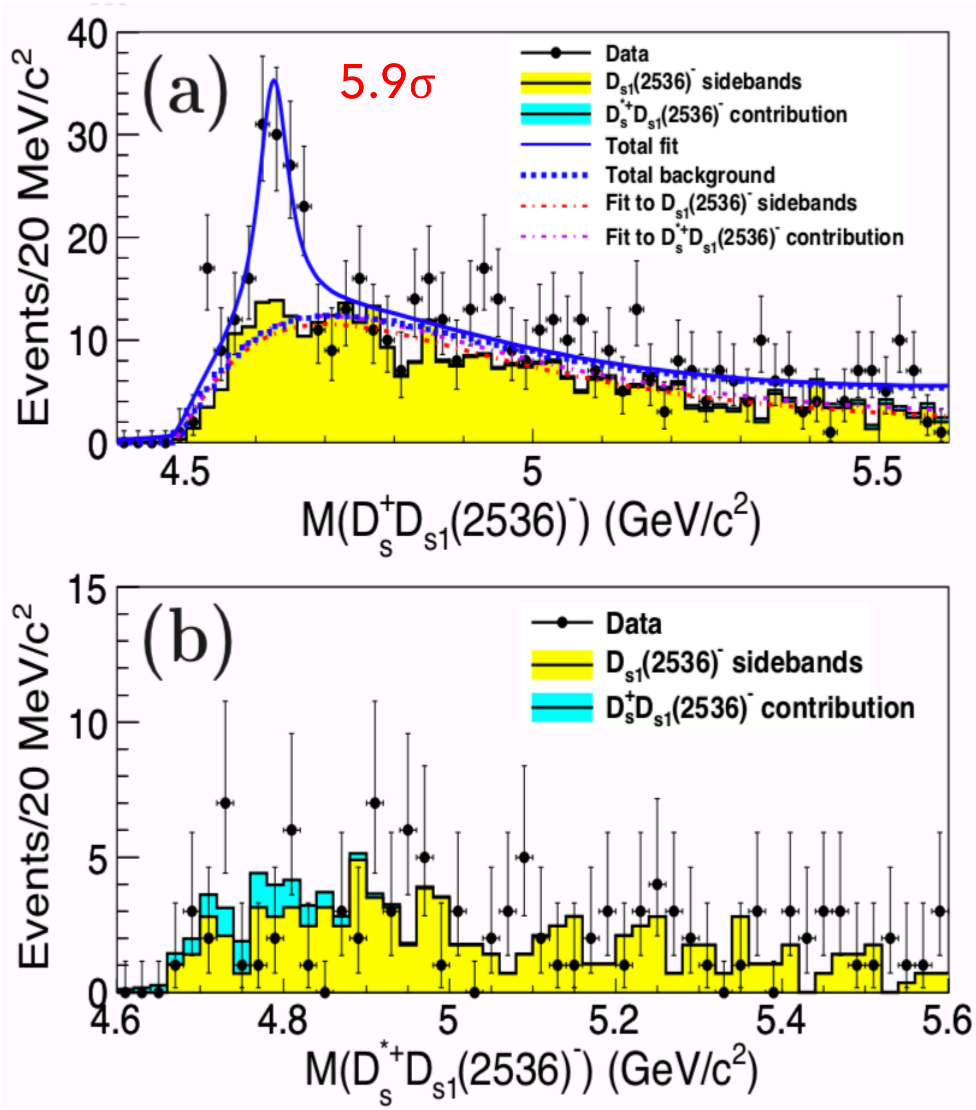

$D_{s1}(2536)^-$ signal: Double Gaussian

The combinatorial backgrounds: threshold function

- $M_{rec}(\gamma_{ISR} D_s^+)$ distribution is making after applying the $\bar{D}^{*0}/D^{*-}$ mass constraint.
- The yellow histogram shows the normalized $D_s^+$ mass sidebands.
- The fit yields 275±32 $D_{s1}(2536)^-$ signal events with the statistical significance of $8.0\sigma$.

# Final mass spectrum $M(D_s^+ D_{s1}(2536)^-)$

After applying the $\bar{D}^{*0}/D^{*-}$ mass constraint




An unbinned simultaneous likelihood fit:

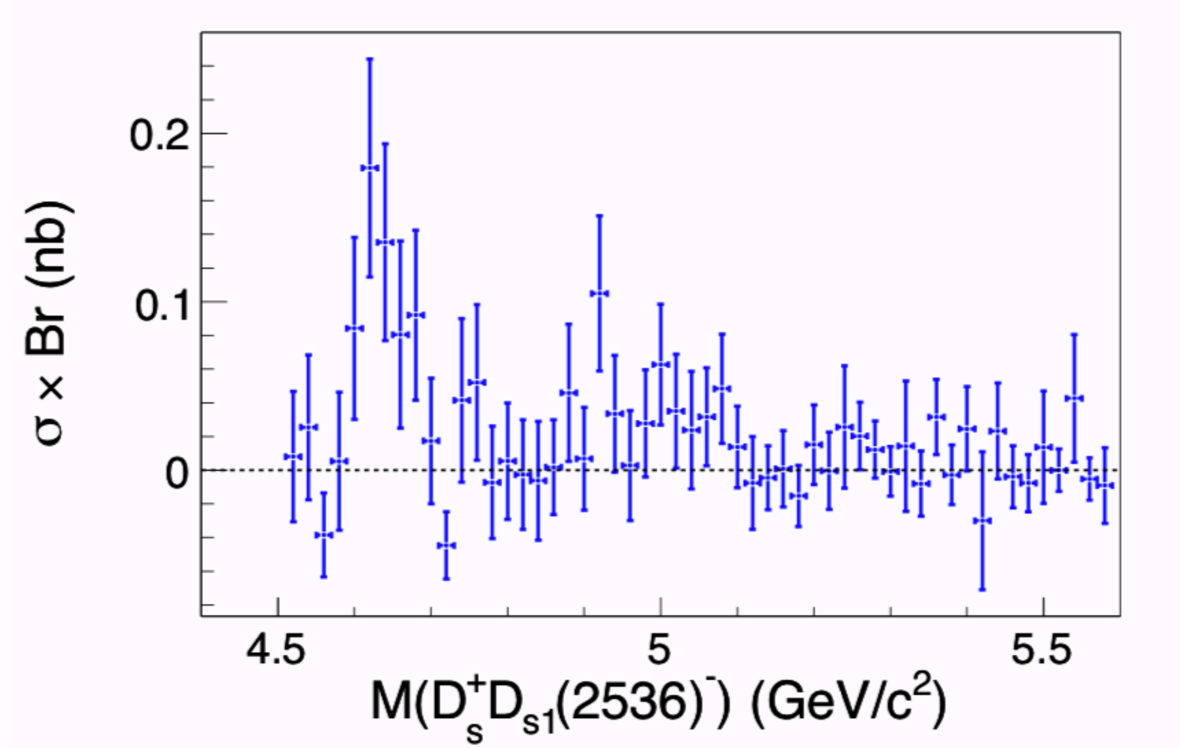
- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s1}(2536)^-$ mass sidebands: a threshold function
- $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$ background contribution: a threshold function
- A non-resonant contribution: a two-body phase space form

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

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

# Cross section

$$\sigma(e^+e^- \to D_s^+ D_{s1}(2536)^-)\mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0}K^-) = \frac{N_{\rm fit}^{D_{s1}(2536)^-}}{d\mathcal{L} \times [\Sigma_i(\varepsilon_i^{\bar{D}^{*0}K^-} \times \mathcal{B}_i) + R_{\bar{D}^{*0}K^-}^{D^{*-}K_S^0} \times \Sigma_i(\varepsilon_i^{D^{*-}K_S^0} \times \mathcal{B}_i)]},$$




**The yield of fitted $\mathbf{D_{s1}(2536)^-}$ signal events after subtracting the $\mathbf{e^+e^- \to D_s^{*+}D_{s1}(2536)^-}$ background contribution.**

The peak value of the σ×Br at M($D_s^+D_{s1}(2536)^-$) ~ 4.63 $\mathrm{GeV}/c^2$ is about (0.18± 0.06) nb.

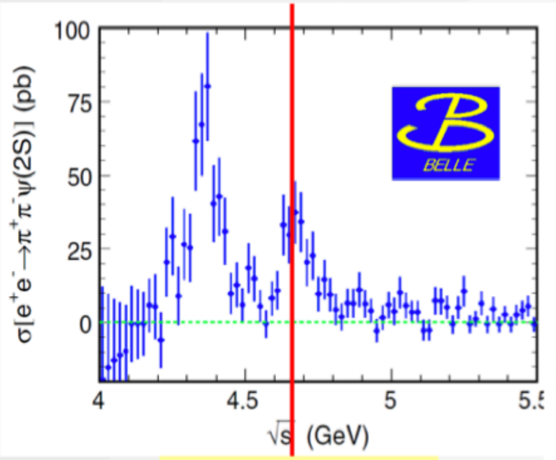
# Y(4630) = Y(4660)?

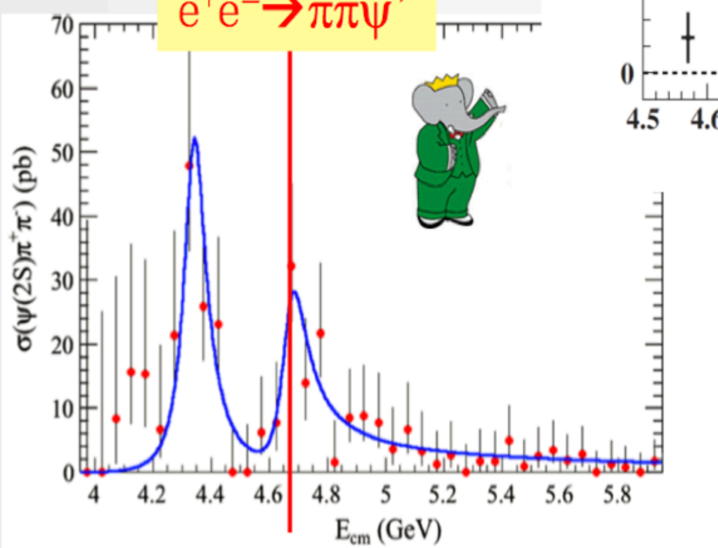
*Slides from C. P. Shen*

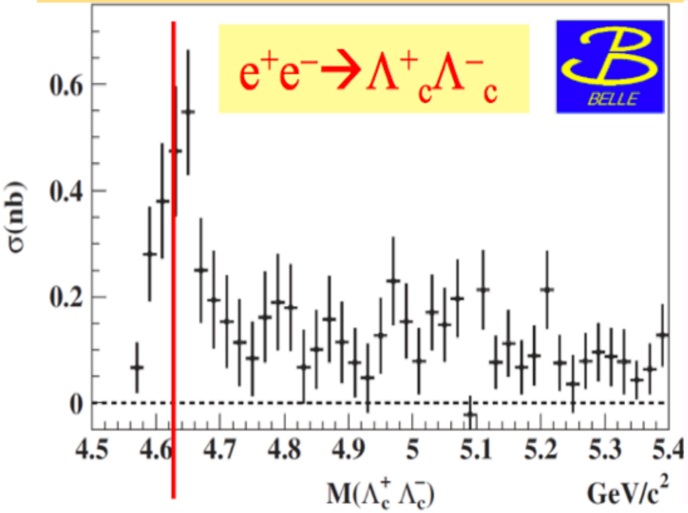
Belle: PRD91, 112007 (2015), 980/fb
BaBar: PRD89, 111103 (2014), 520/fb

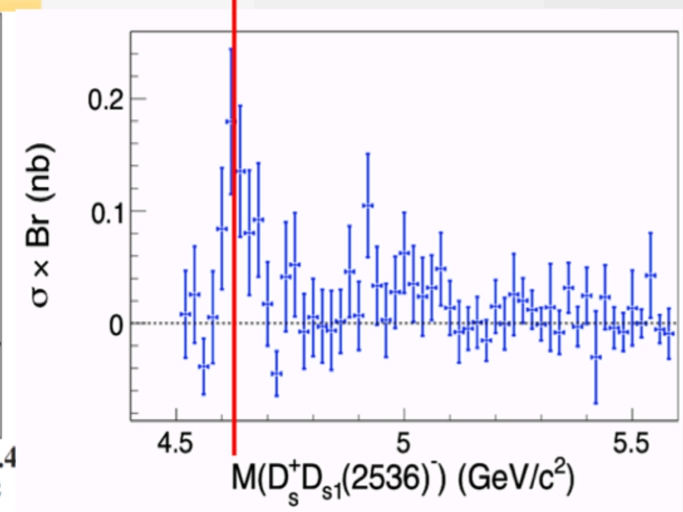
Belle: PRL101, 172001 (2008), 695/fb

Belle preliminary, 922/fb




| Experiment | Mass (MeV) | Width (MeV) |
|---|---|---|
| Belle, $\Lambda_c^+\Lambda_c^-$ | $4634^{+8}_{-7}{}^{+5}_{-8}$ | $92^{+40}_{-24}{}^{+10}_{-21}$ |
| Belle, $\pi^+\pi^-\psi(2S)$ | 4652±10±8 | 68±11±1 |
| BaBar, $\pi^+\pi^-\psi(2S)$ | 4669±21±3 | 104±48±10 |
| Belle, $D_s^+D_{s1}(2536)^-$ | $4626^{+7}_{-7}$ ±0.4 | $49.8^{+2.8}_{-2.6}$ ±1.5 |

# What is Y(4660)?

- Charmonium?
- Molecule [$f_0(980)\psi'$, $\bar{\Lambda}_c\Lambda_c$]?
- Hadron-charmonium?
- Tetraquark state?
- Hybrid?
- ……

Experimental measurements:

$Y(4660) \rightarrow$

- $D_s^*D_{s0}(2317)$
- $D_sD_{s1}(2460)$
- $D_s^*D_{s1}(2460)$
- $D_sD_{s2}(2573)$

May these rates be estimated according to $D_sD_{s1}(2536)$?

at Belle with ISR; and

at BESIII with data to be taken in 2019-2020 running year ($E_{cm}$=4.62, 4.64, 4.66, 4.68, 4.70 GeV, 500 $pb^{-1}$ at each energy)

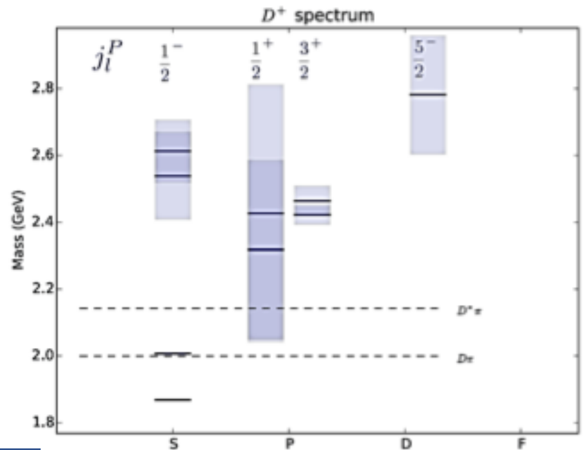
Why does Y(4660) couple to $\bar{s}s$ strongly?

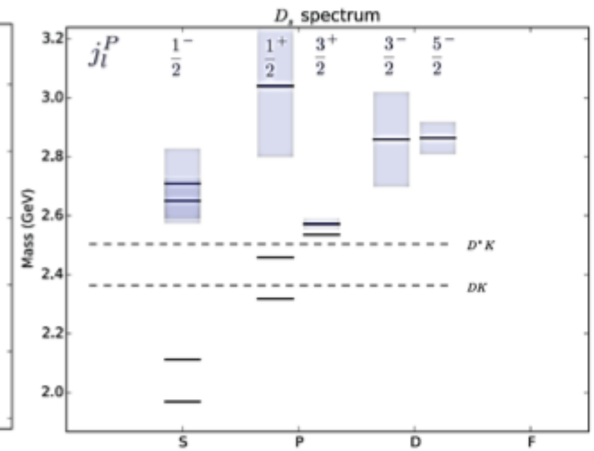
Why does Y(4660) couple to charmed baryon strongly?

# Comparison between $D_1(2420)\bar{D}$ and $D_{s1}(2536)^-D_s^-$

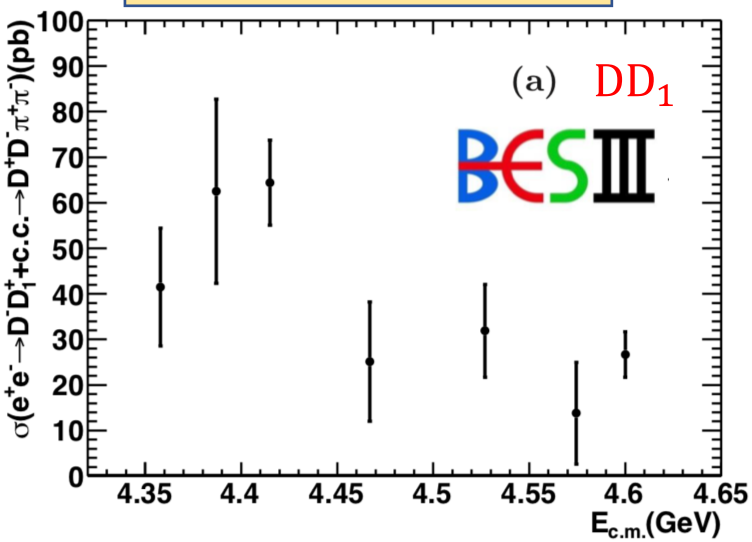
*Slides from C. Z. Yuan*

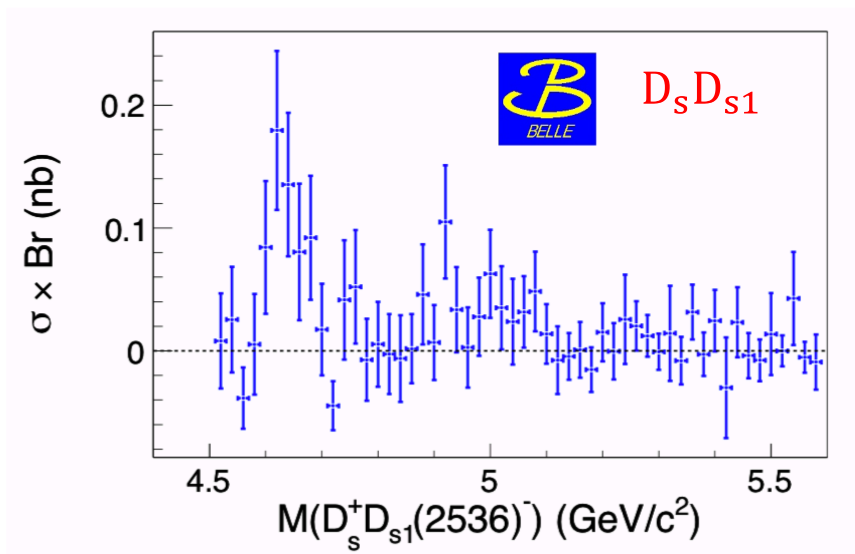
$D_1$ and $D_{s1}$ are $j_l^P = \frac{3}{2}^+$ heavy-light states:
Y(4360)/Y(4390)/$\psi(4415)$ & Y(4630)/Y(4660) are just above $DD_1$ and $D_sD_{s1}$ thresholds, respectively.



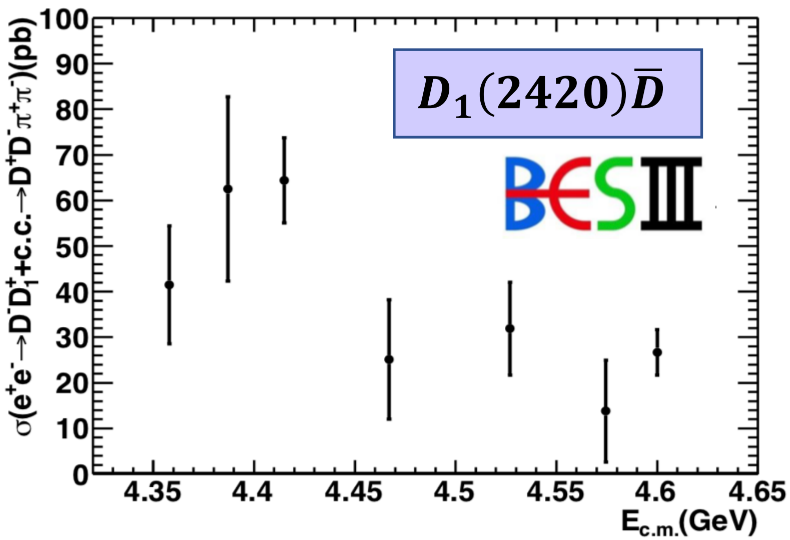

arxiv: 1909.12478

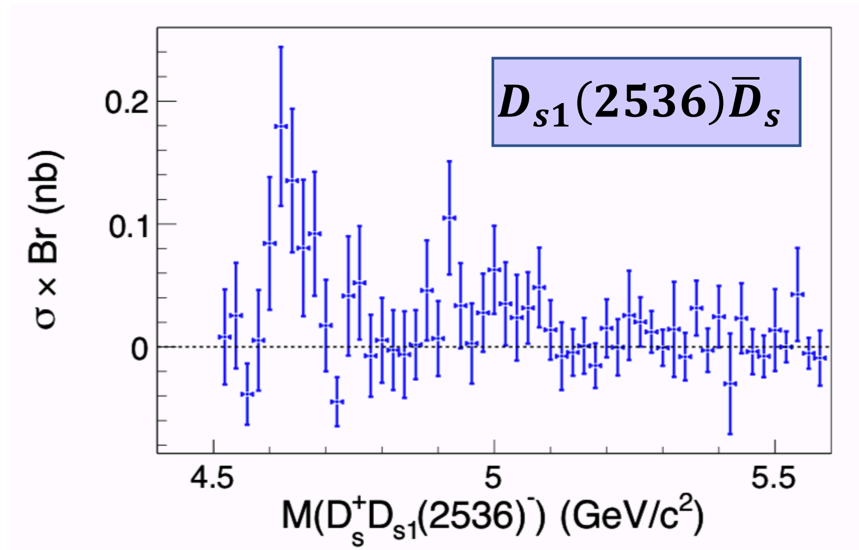


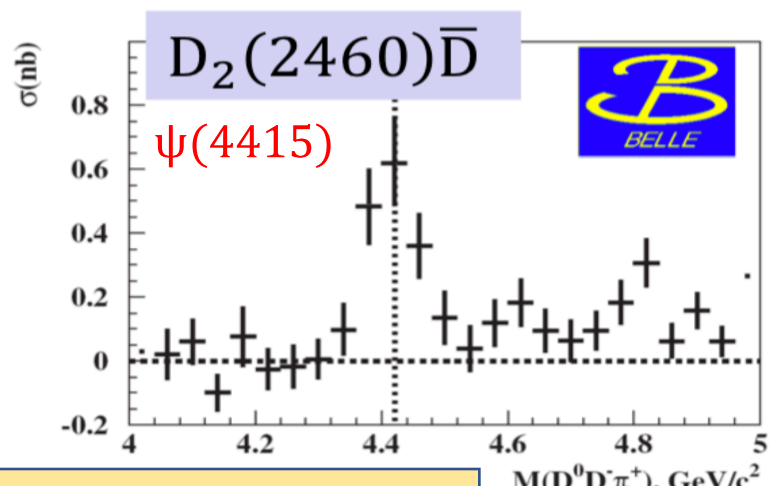




Do Y(4360)/Y(4390)/$\psi(4415)$ & Y(4630)/Y(4660) have similar structures?

# Other $j_l^P = \frac{3}{2}^+$ states: $D_2(2460)\bar{D}$ and $D_{s2}(2573)^- D_s^-$




PRL 100, 062001 (2008)

$D_{s2}(2573)\bar{D}_s$ ?

Do Y(4360)/Y(4390)/ψ(4415) & Y(4630)/Y(4660) have similar structures?

# Summary

- We observe the first vector charmonium-like state decaying to a charmed-antistrange and anticharmed-strange meson pair $D_s^+ D_{s1}(2536)^-$ with a signal significance of 5.9σ.

- Inspired by our discovery, the studies of $D_s^+ D_{s2}^*(2573)^-$, $D_s^{*+} D_{s0}(2317)^-$, and $D_s^{(*)+} D_{s1}(2460)^-$ should be performed.

- Belle II started data taking on 25 March with its full detector. Belle II will reach 50 $ab^{-1}$ by 2027, which will provide greater sensitivity and precise measurements in hadron physics.

***Thanks for your attentions!***