Belle(II) XYZ results in charm sector

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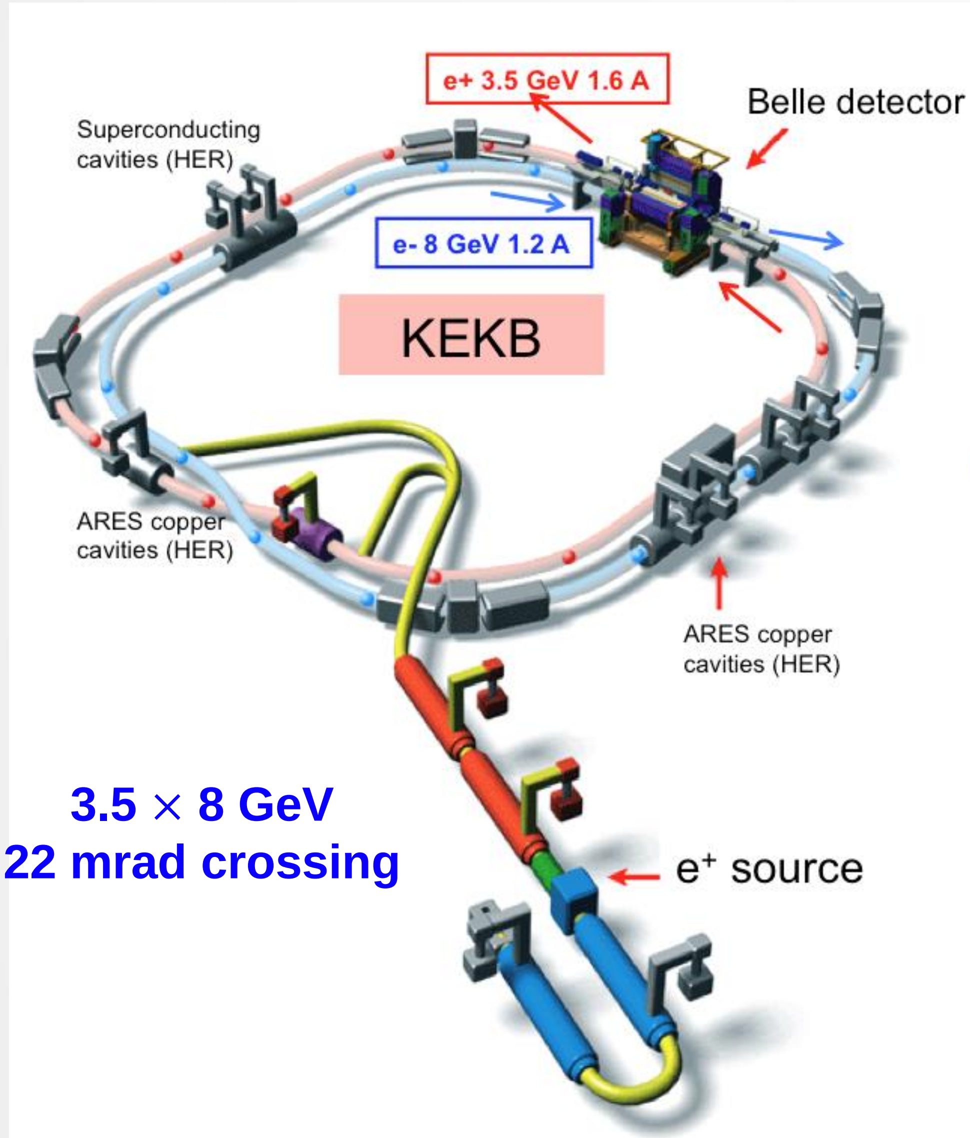
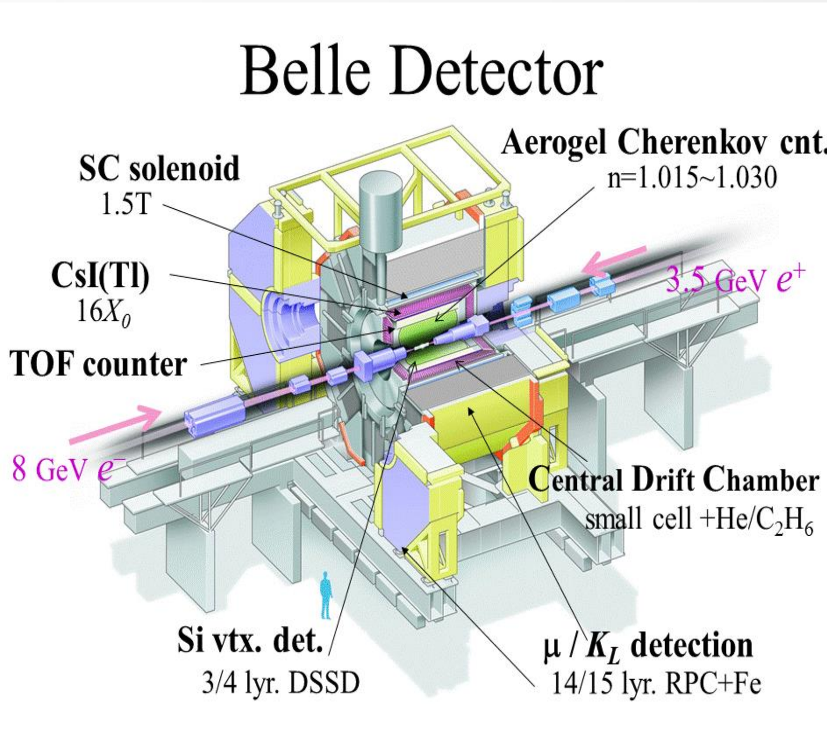
Outline

- Recent results on XYZ results at Belle
- Belle II status
- Potential XYZ results in charm sector at Belle II
- Summary

Success=X+Y+Z=XYZ states

Belle experiment and data samples





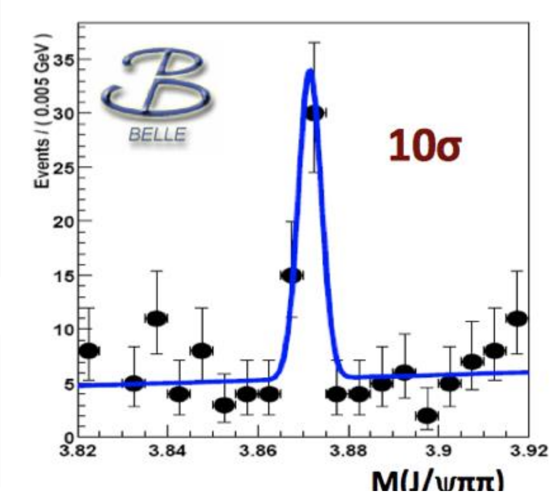
Data taking: 1999 – 2010

On/off/Scan Υ(nS) peaks

Total luminosity: 980 fb^{-1}

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

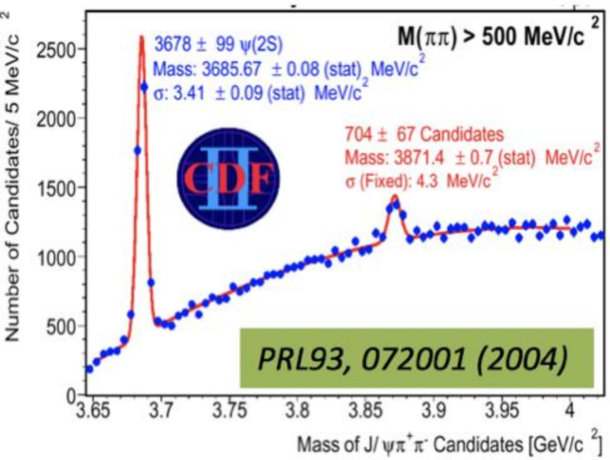
X(3872)→J/ψπ⁺π⁻

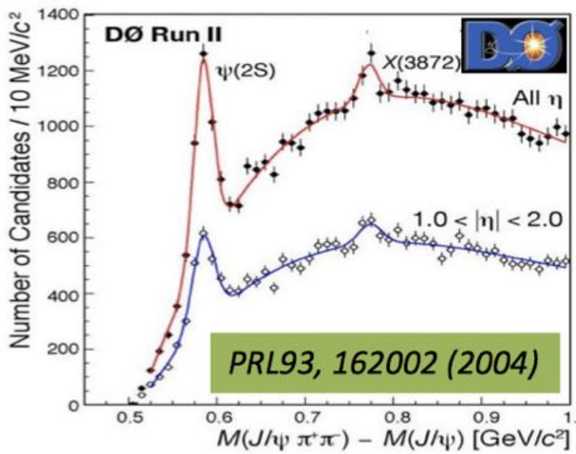


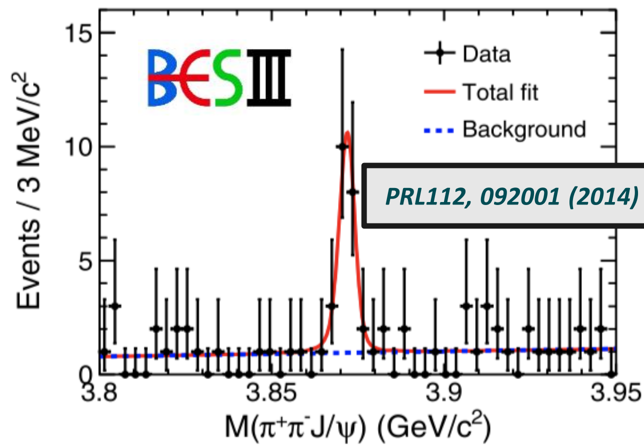
The most-cited article at Belle: 1900+

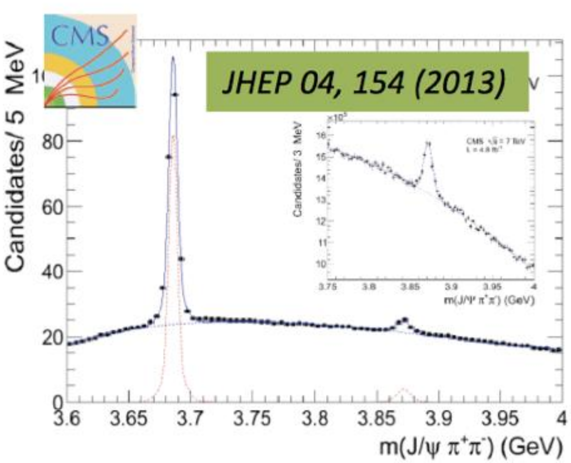
First observed by Belle in $B \to K\, J/\psi\pi^+\pi^-$ ***PRL91, 262001 (2003)***

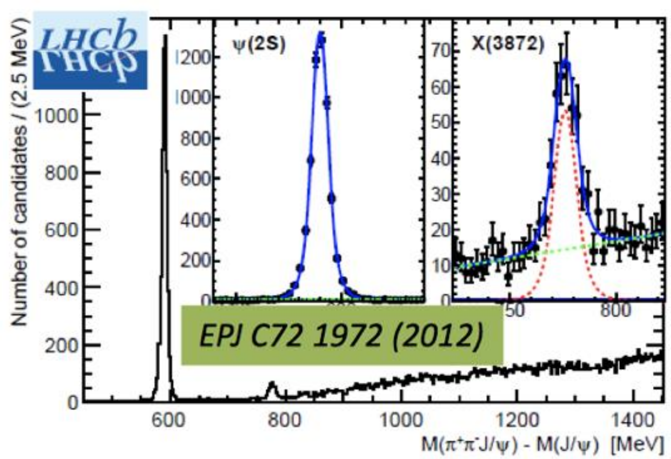
- M_X close to $D^0\bar{D}^{*0}$ threshold M = (3871.68±0.17) MeV
- Surprisingly narrow: $\Gamma_{tot} < 1.2$ MeV at 90% C.L.











X(3872)→J/ψγ: C-even

Angular analysis:

Belle 2006: $J^{PC} = 1^{++}$ or ≥2

CDF 2008: $J^{PC} = 1^{++}$ or 2^{-+}

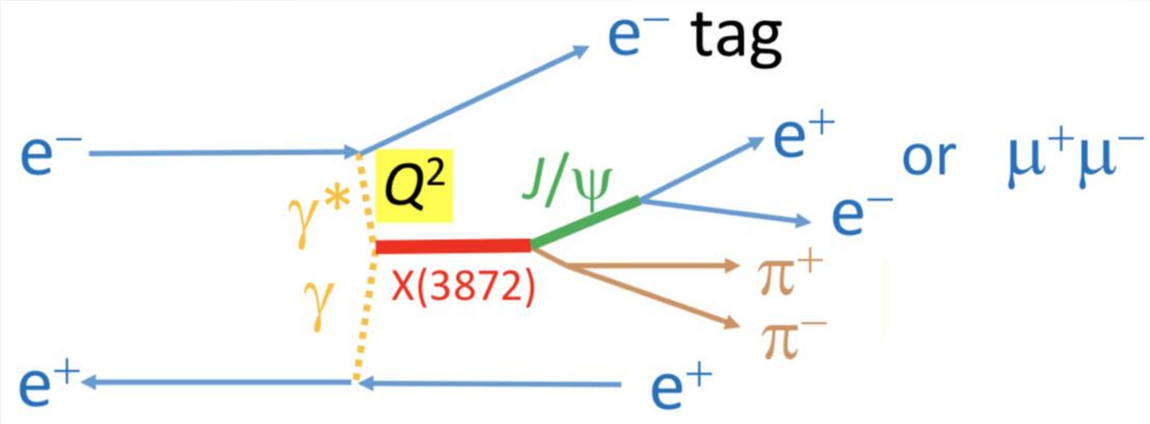
Belle 2011: $J^{PC} = 1^{++}$ or 2^{-+}

LHCb 2013: $J^{PC} = 1^{++}$

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

Phys. Rev. Lett. **126**, 122001 (2021)

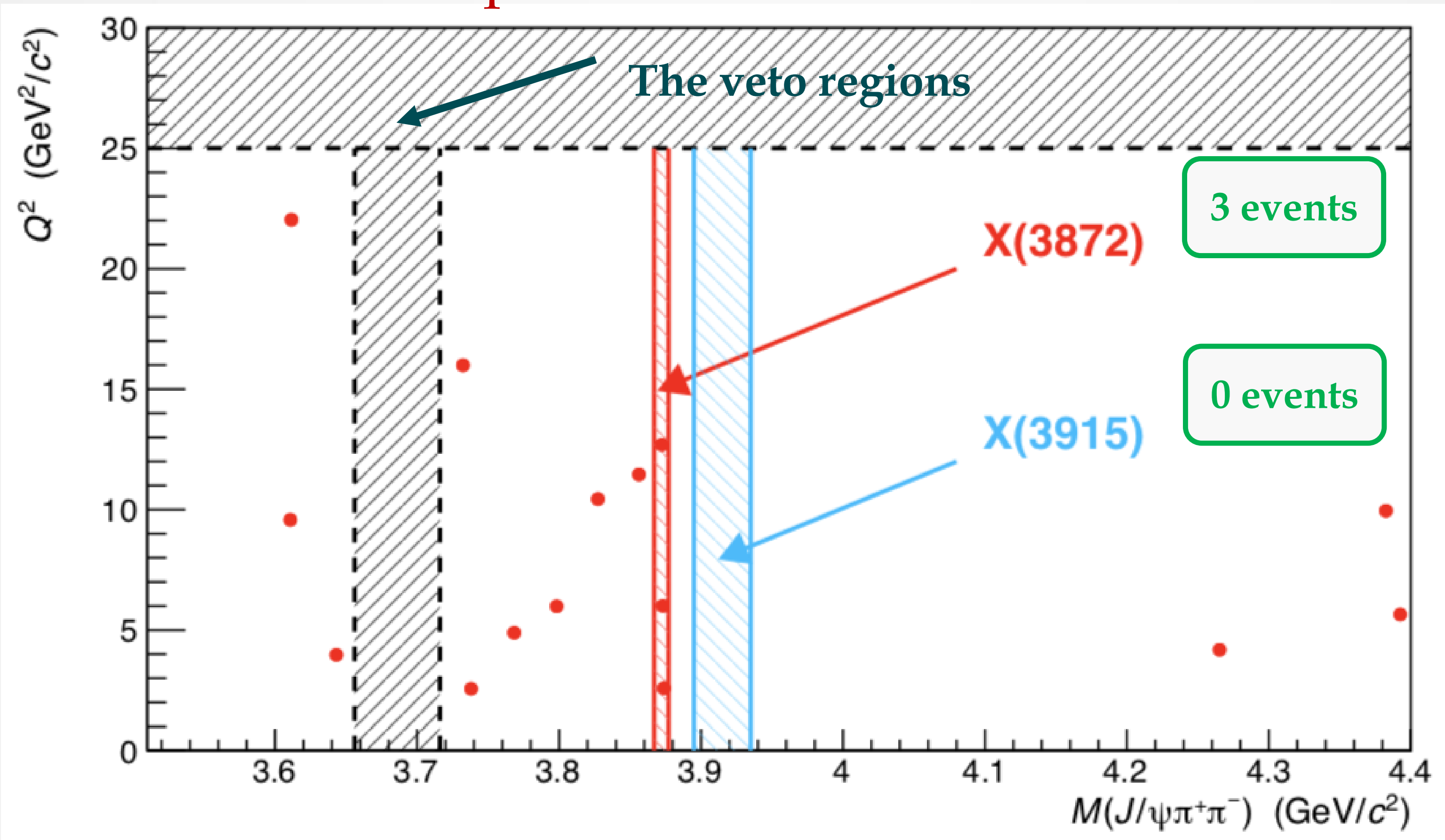
- X(3872) with $J^{PC} = 1^{++}$ is not permitted in γγ → X(3872), here γ is real.
- X(3872) with $J^{PC} = 1^{++}$ could be produced if one or both photons are highly virtual [Nucl. Phys. B 523, 423 (1998)], i.e. γγ* → X(3872), here γ* is virtual.
- The measurement of X(3872) in two-photon reactions help to understand its internal structure.
- Data sample: 825 fb^{-1} in e^+e^- collisions near 10.6 GeV



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

If the X(3872) has a molecular component in its structure, it must have a steeper Q^2 dependence than the regular c cbar state. Hence, the single-tag two-photon interactions provide information on the structure of this state. [from discussion with Marek Karliner]

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

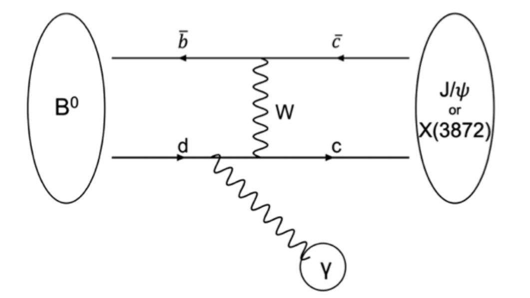


- M(X(3872)) = (3.8723±0.0012) GeV/ c^2
- With 0.11±0.10 background events, **the number of signal events is N_{sig} = $2.9^{+2.2}_{-2.0}$(stat.) ± 0.1(syst.) with a significance of 3.2σ** (Feldman-Cousins method applied [Phys. Rev. D 57, 3873 (1998)]).
- **$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872)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

Search for $B^0 \to X(3872)\gamma$

[PRD 100, 012002 (2019)]

- In the SM, the decay $B^0 \to c\bar{c}\gamma$ proceeds dominantly through an exchange of a W boson and the radiation of a photon from the *d* quark of the B meson.
- Currently, the upper limit for $B^0 \to J/\psi\gamma$ is 1.5×10^{-6} at 90% confidence level.
- Considering X(3872) may be not a pure $c\bar{c}$ state, the branching fraction of $B^0 \to X(3872)\gamma$ is larger?



To suppress generic BB spherical events and the jet-like $q\bar{q}$ continuum events, we do

(1) multivariate analysis based on the neural network package named NEUROBAYES [Nucl. Instrum. Methods Phys. Res., Sect. A 559, 190 (2006)] to distinguish the signal and background with 33 input variables;

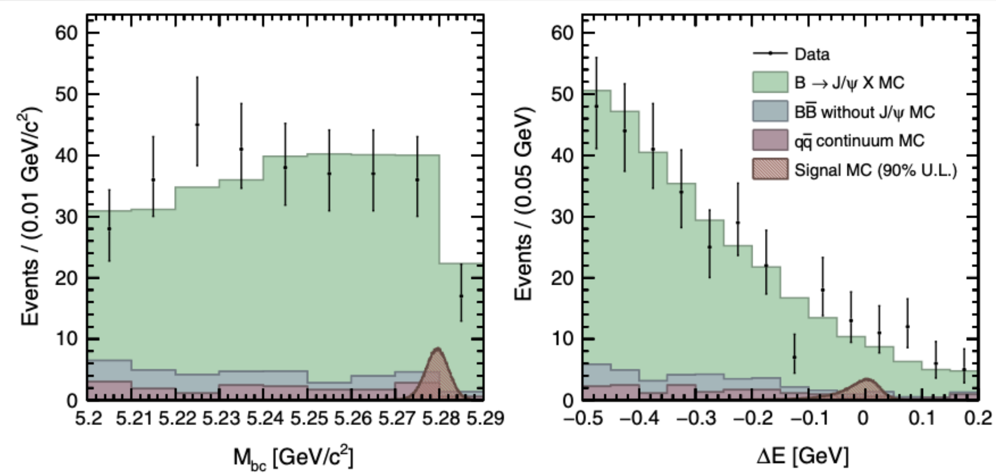
(2) optimize a figure of merit (FOM).

$$\mathrm{FOM} = \frac{\mathrm{efficiency}}{0.5n + \sqrt{N_{\mathrm{bkg}}}}$$

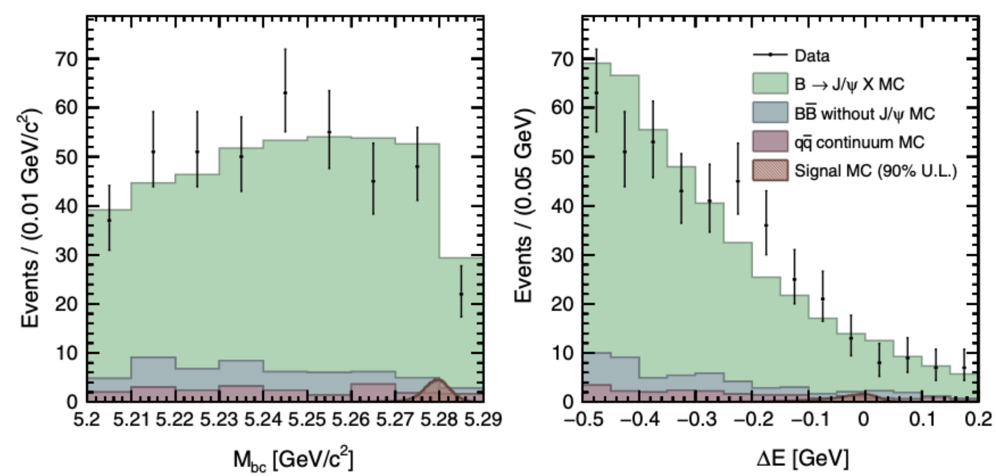
Total luminosity:
711 fb^{-1}; 772×10^6 $B\bar{B}$ pairs

X(3872) decays to $J/\psi\pi^+\pi^-$ entirely via $J/\psi\rho$.

[PRD 100, 012002 (2019)]



(a) Dimuon channel.



(b) Dielectron channel.

$$\Delta E = E^*_{recon} - E^*_{beam}$$

$$M_{bc} = \sqrt{E^2_{beam} - (\sum_i p_i)^2}$$

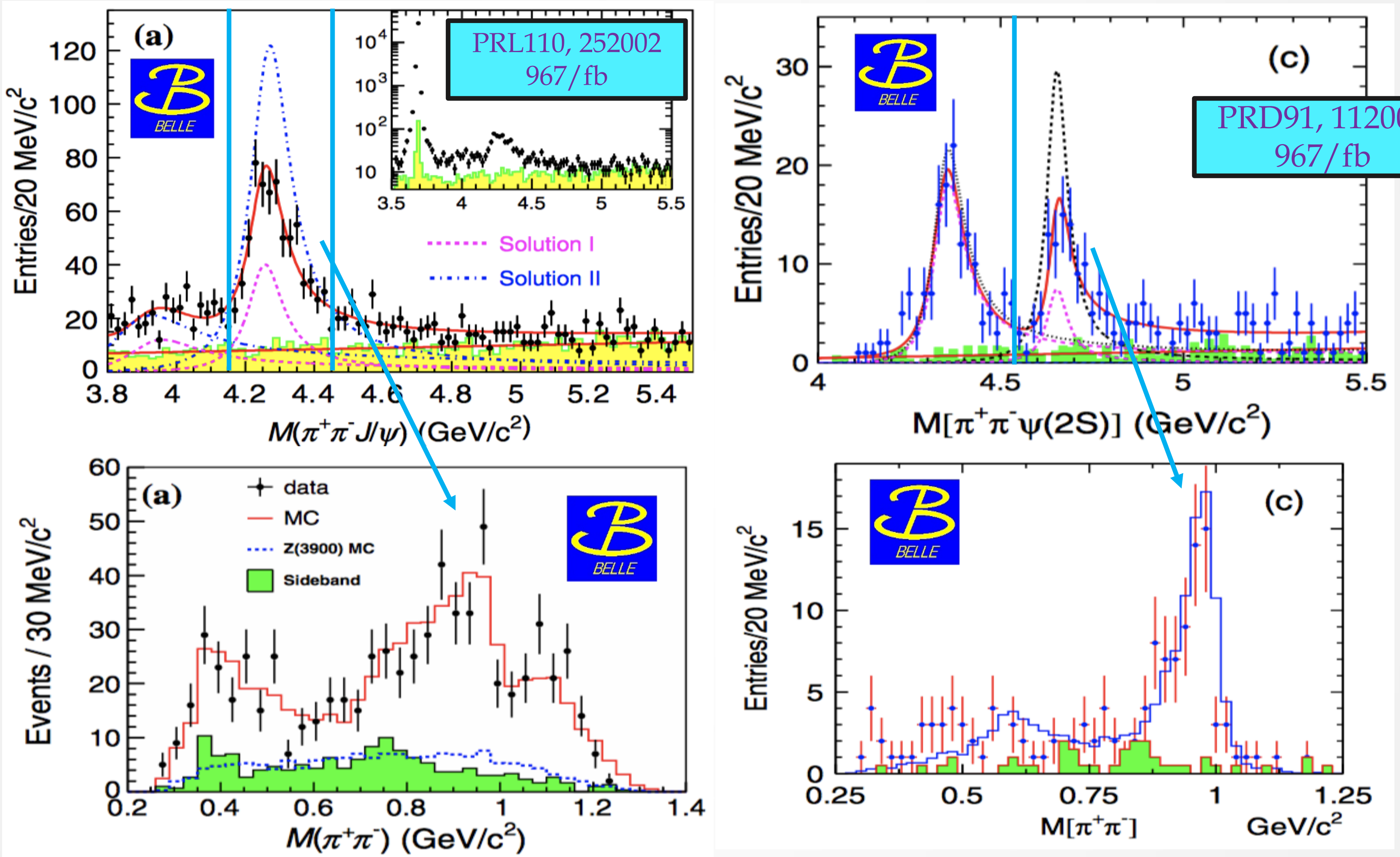
We count the numbers of signal and background events in regions of $M_{bc} > 5.27$ GeV/c^2 and $-0.15 < \Delta E < 0.1$ GeV.

The upper limit on $\mathcal{B}(B^0 \to X(3872)\gamma) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ is obtained with the Feldman-Cousins counting method.

Channel	Dimuon	Dielectron	Total
N_{sig}	9	9	18
N_{bkg}	9.3	12.1	21.4
90% U.L.	9.2×10^{-7}	6.8×10^{-7}	5.1×10^{-7}

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

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



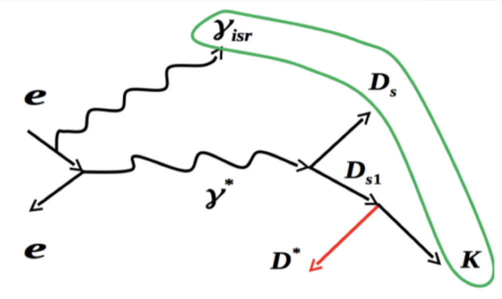
- $Y(4260) \to f_0(980)(\to \pi^+\pi^-)J/\psi$, $Y(4660) \to f_0(980)(\to \pi^+\pi^-)\psi(2S)$
  $f_0(980)$ has a $s\bar{s}$ component, and ψ has a $c\bar{c}$ component.
- **It is natural to search for such Y states with a quark component of $(c\bar{s})(\bar{c}s)$, e.g., $D_sD_{s1}(2536)$ and $D_sD_{s2}^*(2573)$.**

Analysis method

Taking $e^+e^- \to D_s^+ D_{s1}(2536)^-$ as an example

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

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.

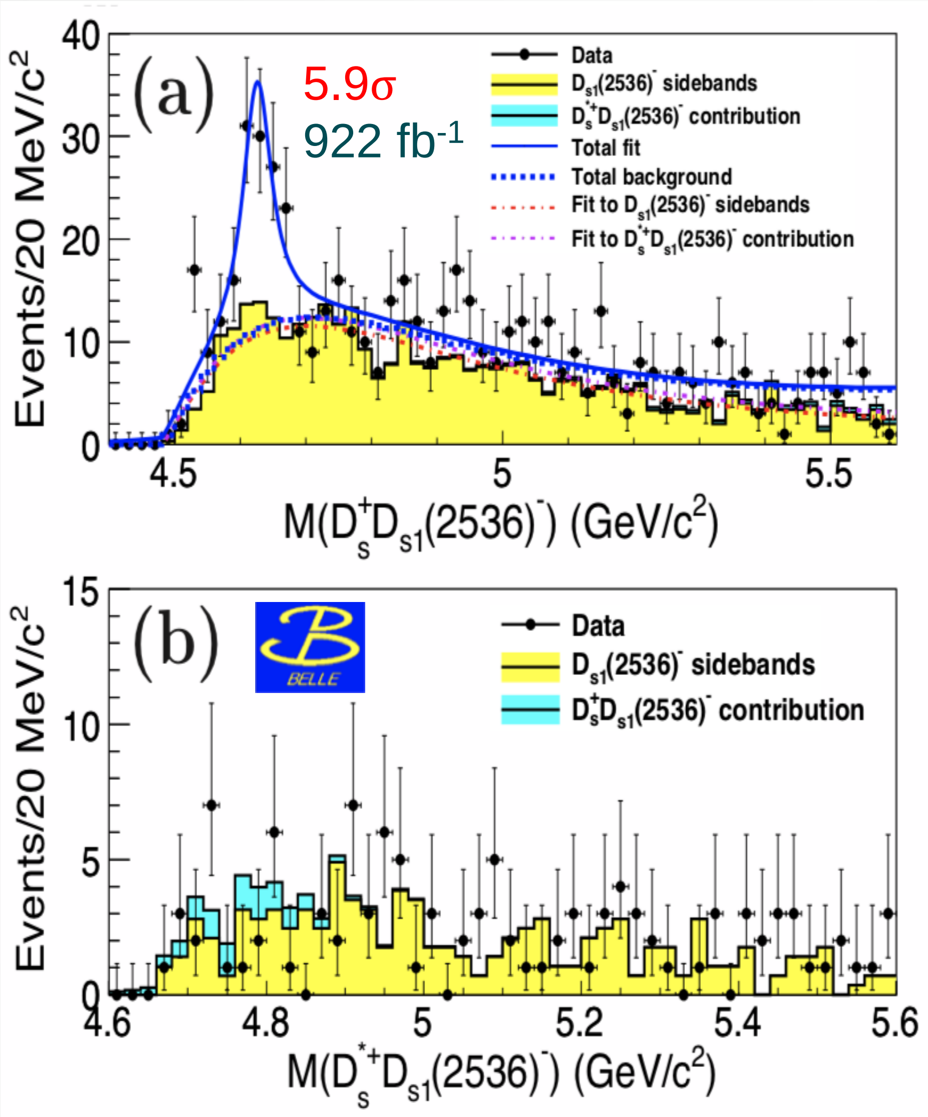
$$M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0) = \sqrt{(E^*_{c.m.} - E^*_{\gamma_{ISR}D_s^+K^-/K_S^0})^2 - \left(p^*_{\gamma_{ISR}D_s^+K^-/K_S^0}\right)^2}$$

- To improve the $M(D_s^+D_{s1}(2536)^-)$ resolution, $M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0)$ is constrained to be the nominal mass of the $\bar{D}^{*0}/D^{*-}$.

Y(4626): $e^+e^- \to D_s^+ D_{s1}(2536)^-$

Belle, PRD100, 111103(R) (2019)

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



An unbinned simultaneous likelihood fit:

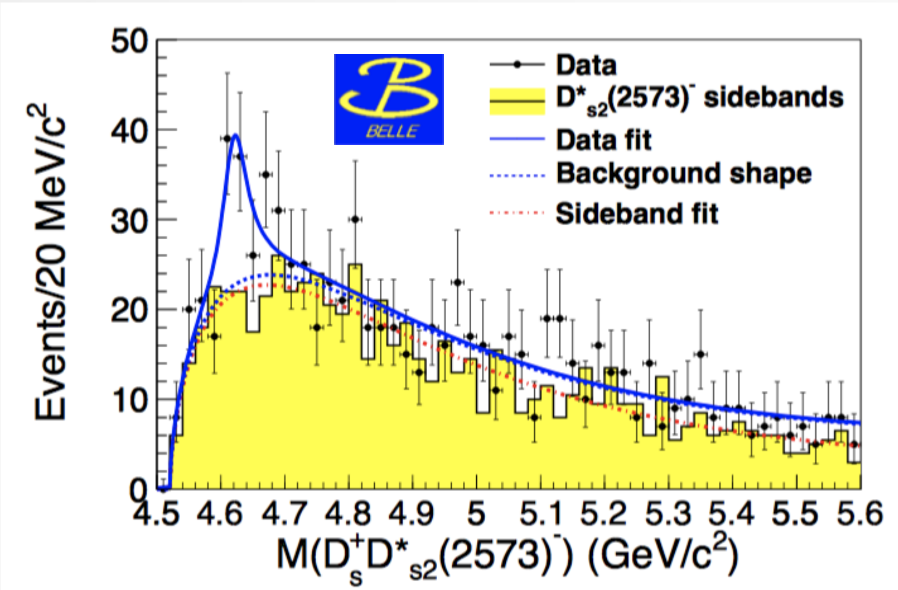
- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s1}(2536)^-$ mass sidebands: a threshold function
- $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$ background contribution: a threshold function
- A non-resonant contribution: a two-body phase space form

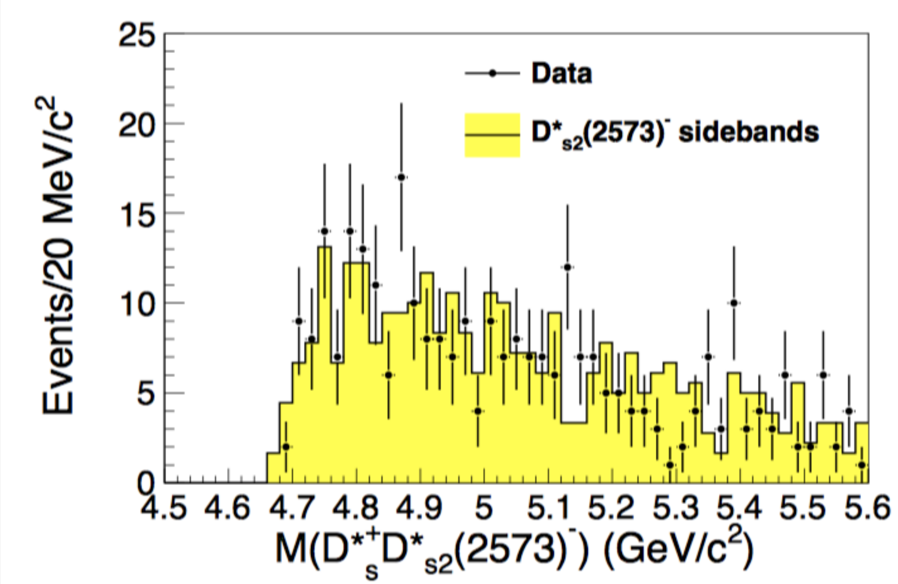
$M=(4625.9^{+6.2}_{-6.0}(\text{stat.}) \pm 0.4(\text{syst.}))\ \text{MeV}/c^2$
$\Gamma = (49.8^{+13.9}_{-11.5}(\text{stat.}) \pm 4.0(\text{syst.}))\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0} K^-) = (14.3^{+2.8}_{-2.6}(\text{stat.})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

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

Y(4626): $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$

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





Belle, PRD101, 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

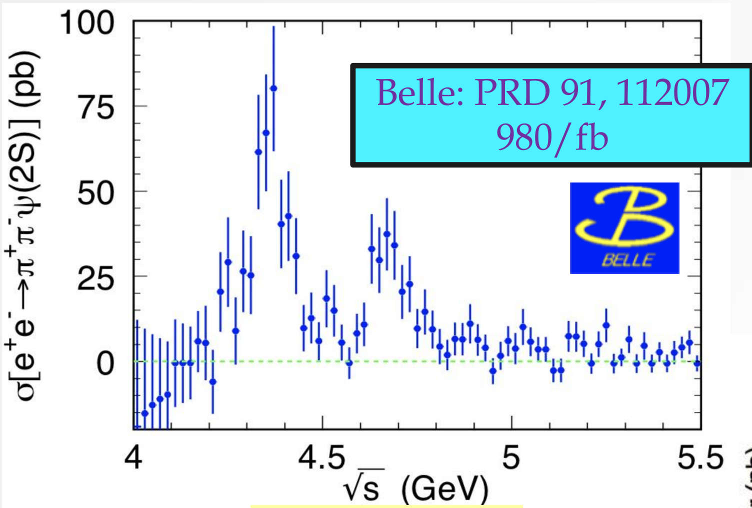
$M=(4619.8^{+8.9}_{-8.0}(\text{stat.}) \pm 2.3(\text{syst.}))$ MeV/c^2
$\Gamma = (47.0^{+31.3}_{-14.8}(\text{stat.}) \pm 4.6(\text{syst.}))$ MeV
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s2}^*(2573)^-) \times \mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0 K^-) = (14.7^{+5.9}_{-4.5}(\text{stat.}) \pm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

Reminder: considering BESIII has had data in this energy region, we need BESIII to cross check. The current error at Belle is large.

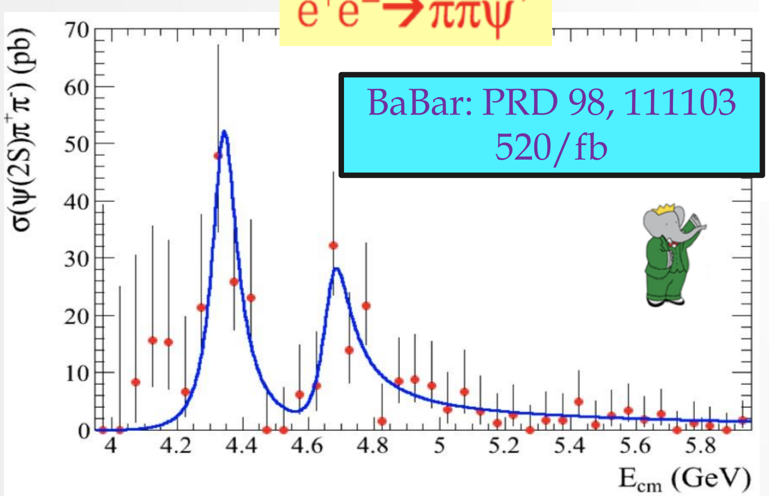
Interpretations of Y(4626)

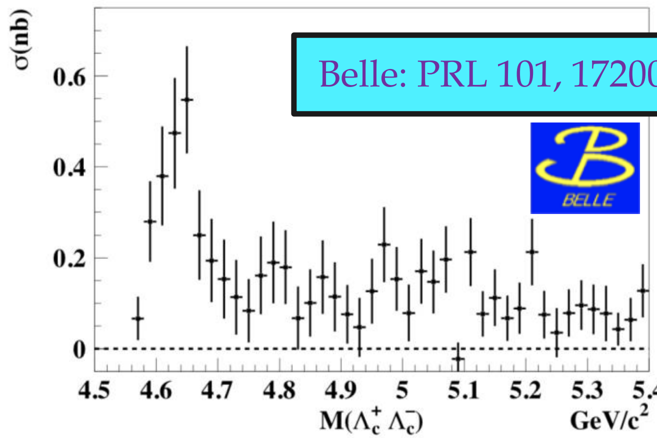
- A tetraquark state in a chiral constituent quark model with a scaling method [Y.Tan and J. L. Ping, PRD101, 054010 (2020)].
- A P-wave tetraquark state $[cs][\bar{c}\bar{s}]$ with 1^{--} in the multiquark color flux-tube model [C. R. Deng, H. Cheng and J.L. Ping, PRD 101, 054039 (2020)].
- A hidden-strange molecular state from $\Lambda_c^+\Lambda_c^-$ interaction [J. T. Zhu, Y. Liu, D. Y. Chen, L. Y. Jiang, and J. He, arXiv:1911.03706 (2020)].
- A molecular state from interaction $D_s^*\bar{D}_{s1}(2536)$ - $D_s\bar{D}_{s1}(2536)$ [J. He, J. T. Zhu, and D. Y. Chen, EPJC 80, 246 (2020)].
- A tetraquark and etc instead of $D_s^*\bar{D}_{s1}(2536)$ molecular within the Bethe-Salpeter framework [H.W.Ke, X.H.Liu, and X.Q.Li, arXiv:2004.03167 (2020)].
- A higher charmonium [J.Z.Wang, R.Q.Qian, X. Liu, and T. Matsuki, PRD 101, 034001 (2020)].
- A hidden-charm exotic mesons in the diquark model [Z. G. He, B. A. Kniehl, and X.P.Wang, PRD 101, 074032 (2020); J.F.Giron, R.F.Lebed arxiv:2005.07100].

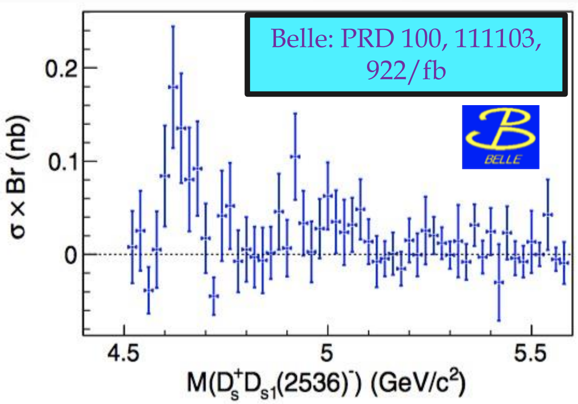
Y(4630) = Y(4660)?

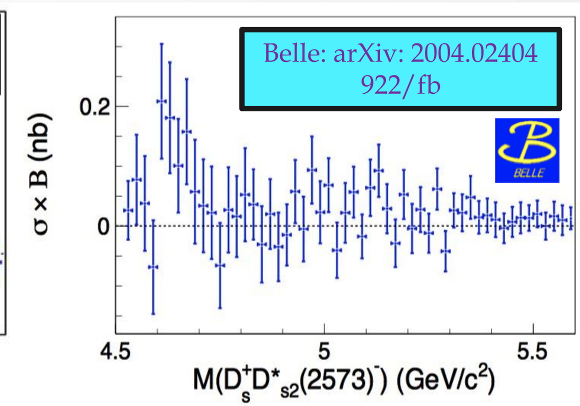


$e^+e^-\to\pi\pi\psi'$









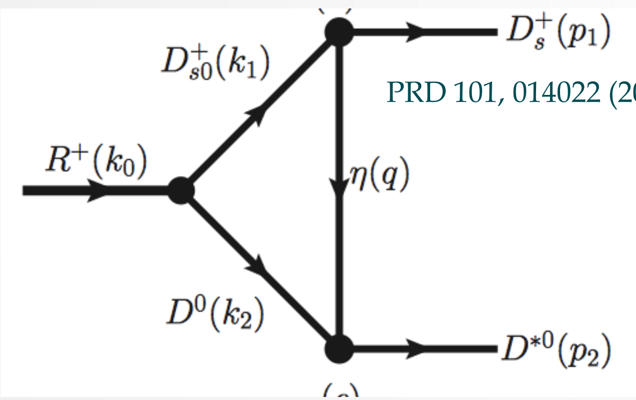
Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi^+\pi^-\psi(2S)$	$4669\pm21\pm3$	$104\pm48\pm10$
Belle, $D_s^+D_{s1}(2536)^-$	$4626^{+7}_{-7}\pm1$	$49.8^{+14}_{-12}\pm4$
Belle, $D_s^+D^*_{s2}(2573)^-$	$4620^{+9}_{-8}\pm3$	$47.0^{+32}_{-15}\pm5$

- These states may be the same
- Need improved precision

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

Phys. Rev. D 102, 112001 (2020)

- 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)].

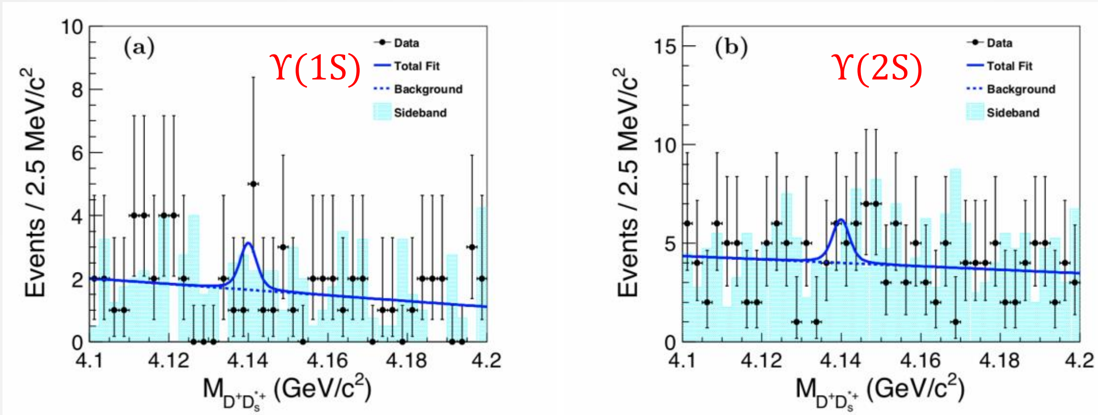


- $D^+ \to K^-\pi^+\pi^- / K_S^0(\to \pi^+\pi^-)\pi^+$
- $D_s^{*-} \to D_s^- \gamma$
- $D_s^- \to \phi\pi^- / \bar{K}^{*0} K^+$

Data samples:

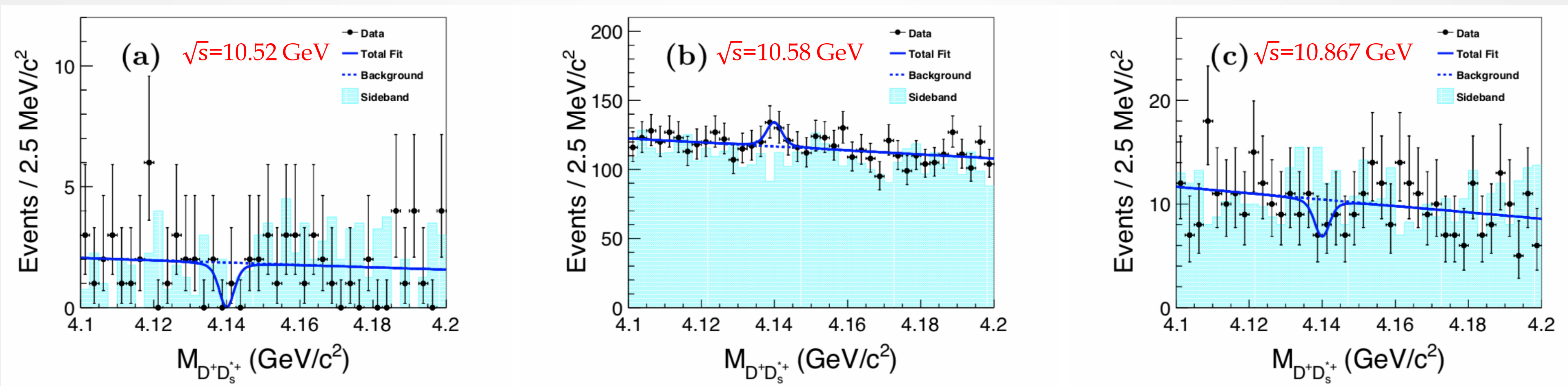
√s (GeV)	Luminosity (fb^{-1})	Events
9.46 [Υ(1S)]	5.74±0.09	(102±3) million
10.023 [Υ(2S)]	24.91±0.35	(158±4) million
10.52	89.5±1.3	-
10.58 [Υ(4S)]	711±10	-
10.867 [Υ(5S)]	121.4±1.7	-

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



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

No R^{++} signals are observed.



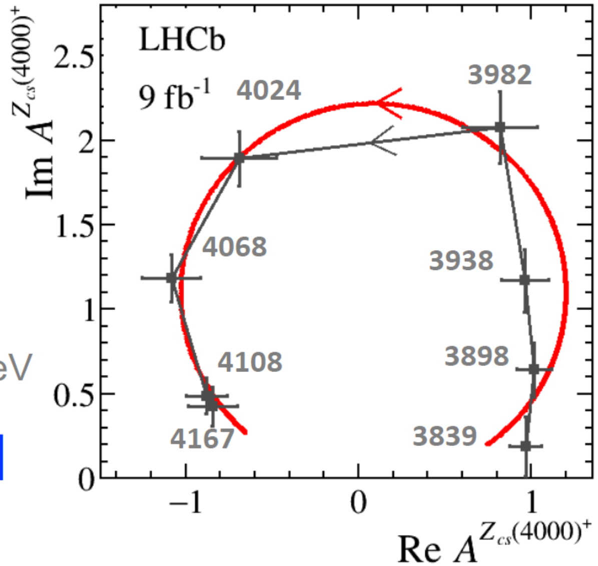
90% C. L. Upper limits [M(R^{++}) varying from 4.13 to 4.17 GeV/c^2, Γ(R^{++}) varying from 0 to 5 MeV]
$\mathcal{B}(\Upsilon(1S) \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$=(11.8 - 54.5)× 10^{-5}
$\mathcal{B}(\Upsilon(2S) \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$=(16.3 - 68.6)× 10^{-5}
$\sigma(e^+e^- \to R^{++} + \text{anything})\mathcal{B}(R^{++} \to D^+D_s^{*+})$ = (202.8 – 880.4) 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 – 1517.6) fb at $\sqrt{s}$ = 10.867 GeV

$Z_{cs}(4000)^+$ at LHCb

[arXiv:2103.01803]

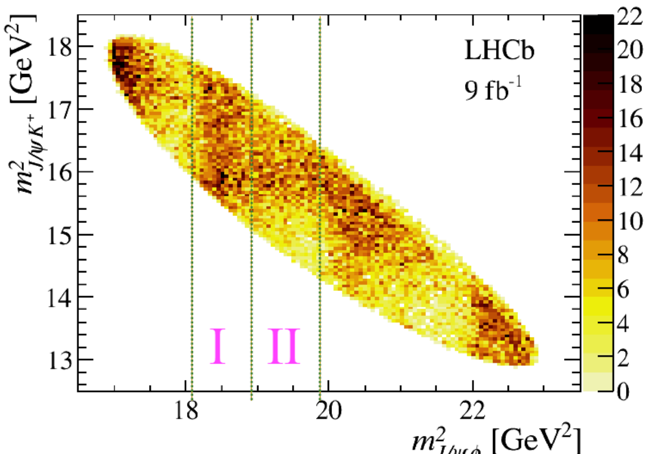
$B^+ \to K^+ \Phi J/\psi$: Run2 (4*Run1)+Run1 data

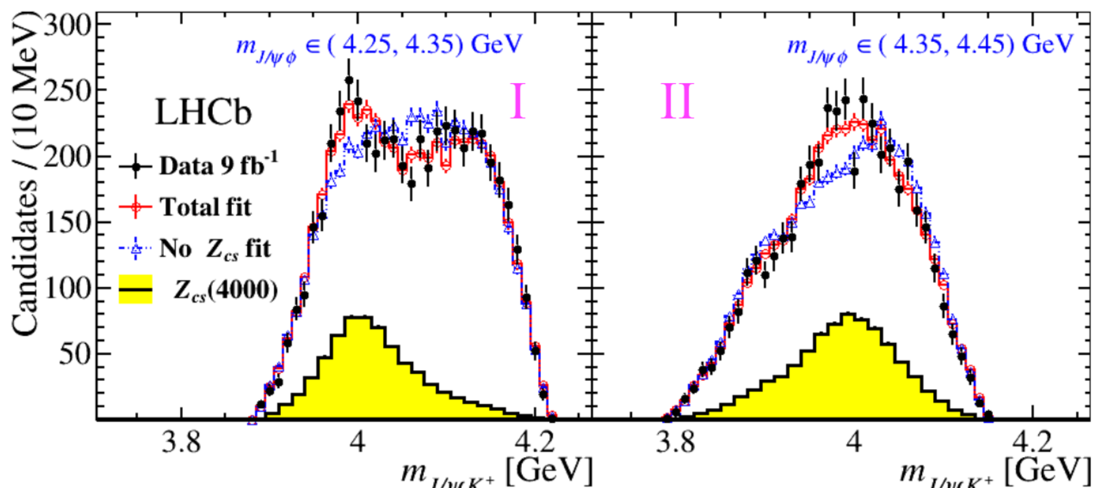
- Argand diagram gives further evidence of resonant character
  - Magnitude and phase evolved in the counter-clockwise direction



numbers are $m_{J/\psi K^+}$ in MeV

- $Z_{cs}(4000)^+$ can be clearly viewed in the two slices of $m_{J/\psi\phi}$





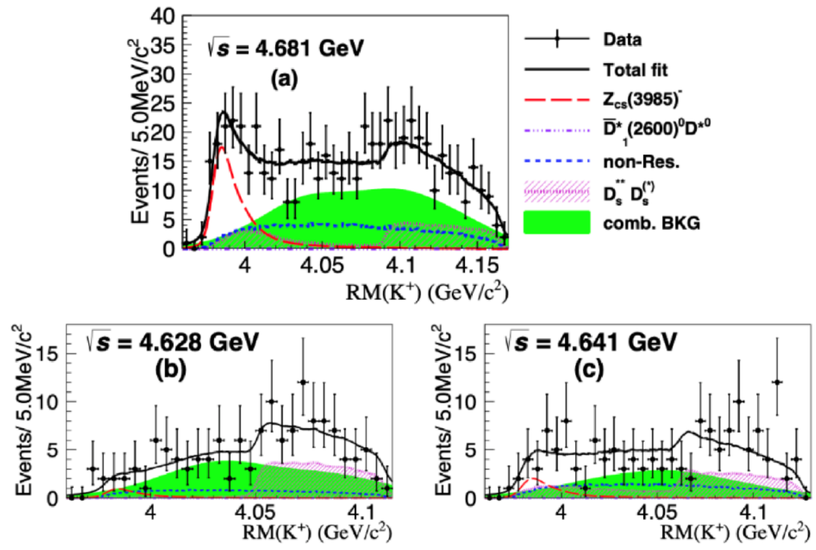
From Liming Zhang

Comparison with BESIII

- BESIII experiment recently reported 5.3σ observation of a very narrow Z_{cs}^{-} in $D_s^- D^* + D D_s^{*-}$ mass distributions
- Their masses are close, but $Z_{cs}(4000)^+$ is $\sim 10\times$ broader
- Tests are applied:
  - Fix $Z_{cs}(4000)^+$ to BESIII's result; $2\ln L$ is worse by 160
  - Adding on top of the default model almost doesn't improve the fit likelihood
- No evidence that $Z_{cs}(4000)^+$ is the same as $Z_{cs}(3985)^-$ seen by BESIII

From Liming Zhang

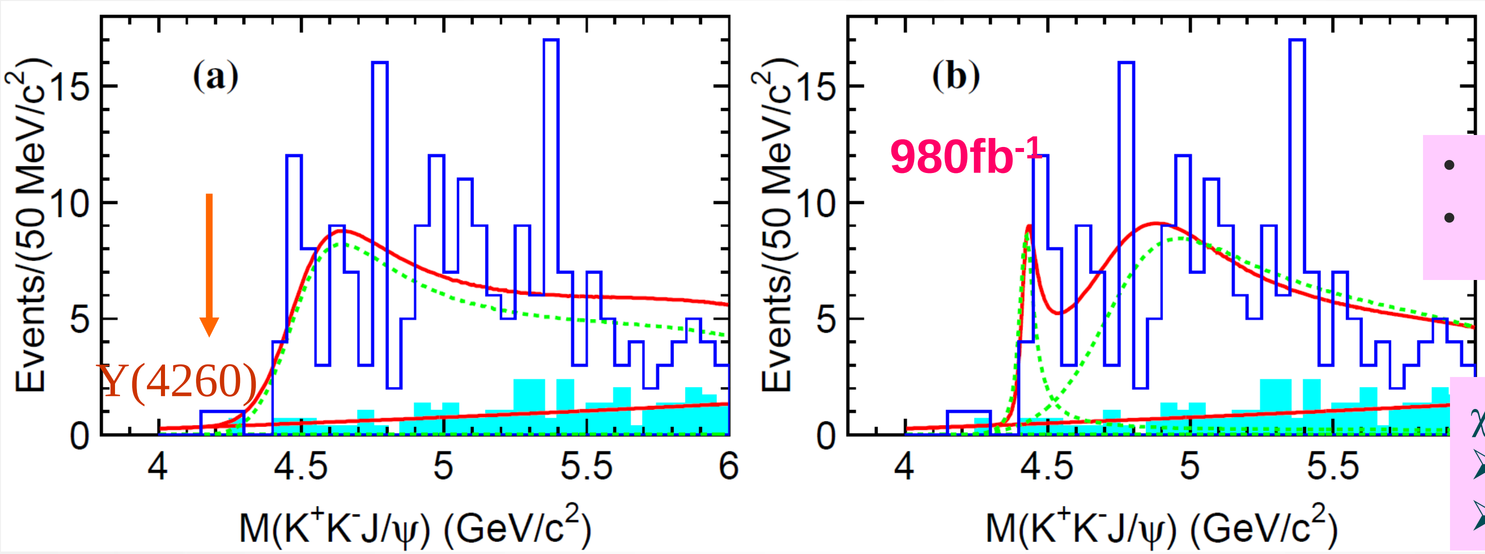
PRL126, 102001 (2021)



$$m_{\text{pole}}(Z_{cs}(3985)^-) = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV}/c^2,$$
$$\Gamma_{\text{pole}}(Z_{cs}(3985)^-) = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \text{MeV}.$$

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

PRD 89,072015(2014)



- +one resonance.
- Fit with $\psi(4415)$

$\chi^2/ndf=30/11$

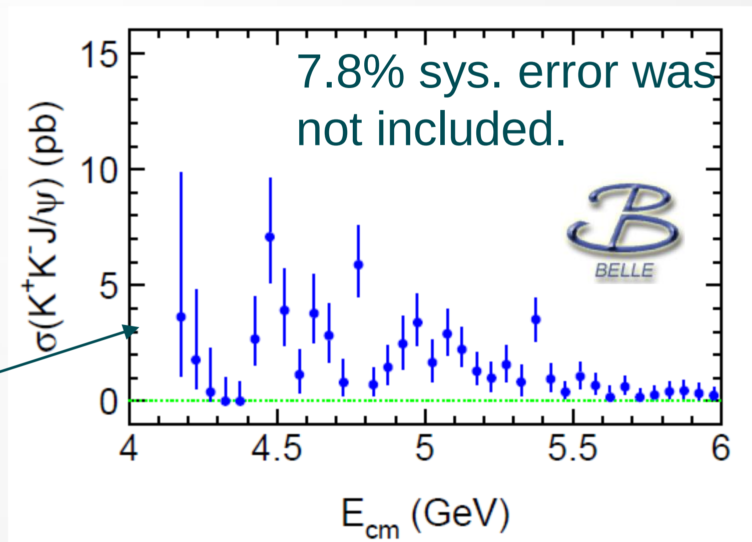
- ➢$M=4747\pm117$MeV
- ➢$\Gamma=671\pm86$ MeV

Shaded hist.: J/ψ mass sidebands

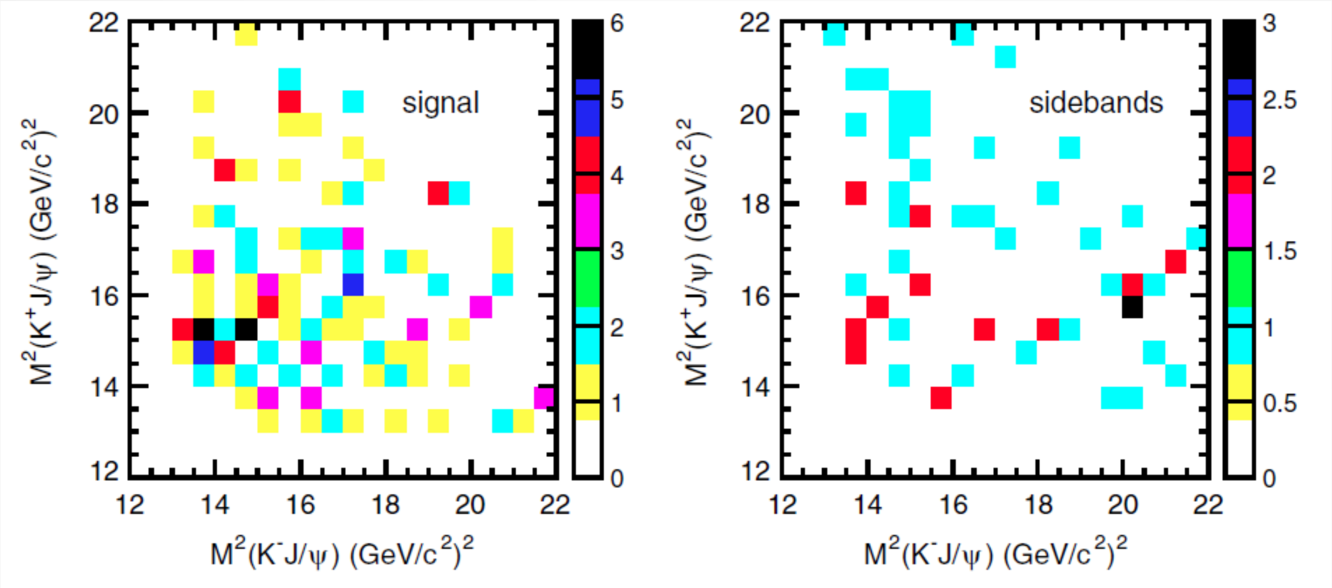
4-6 GeV: 213 events

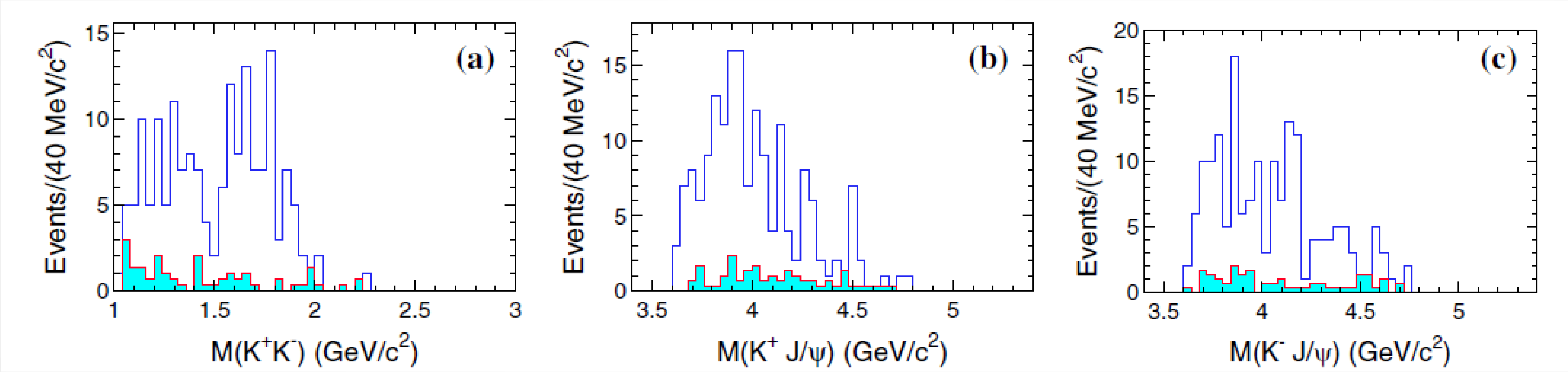
35 bkg, 178±16 signal

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



Search for $Z_{cs} \rightarrow KJ/\psi$ states in $e^+e^- \rightarrow K^+K^-J/\psi$

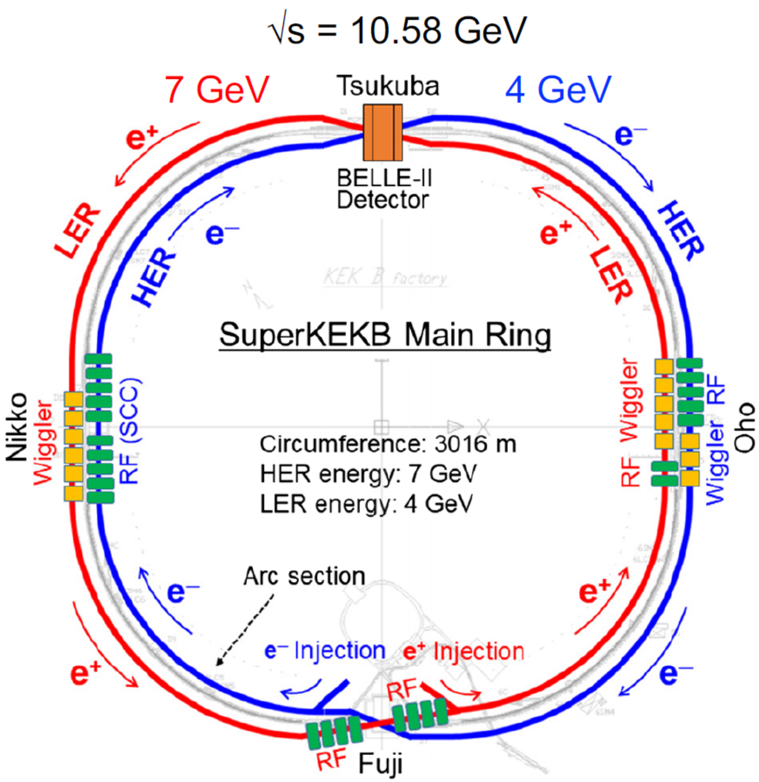




No evident structure in $K^{+-}J/\psi$ mass distribution under current statistics

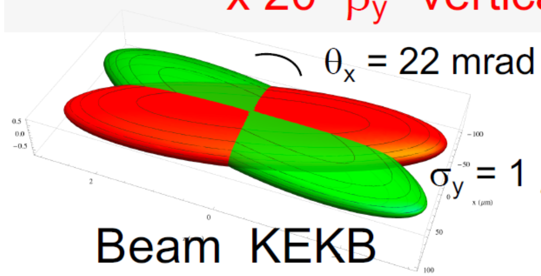
SuperKEKB Collider

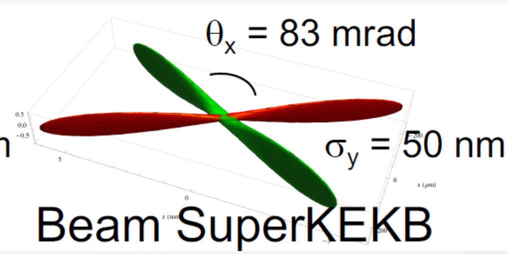
SuperKEKB is a new e^+e^- collider located at KEK (Tsukuba, Japan),
it operates in the **intensity frontier** region with a target instantaneous luminosity of
6×10^{35} $cm^{-2} s^{-1}$ which is 30 times larger than that of the previous KEKB collider.



	Instantaneous luminosity ($cm^{-2} s^{-1}$)	Integrated recorded luminosity (ab^{-1})
Babar PEP-II	1×10^{34} $cm^{-2} s^{-1}$	0.55 0.43 Y(4S)
Belle KEKB	2.11×10^{34} $cm^{-2} s^{-1}$	1 0.71 (Y4S)
Belle II SuperKEKB	6×10^{35} $cm^{-2} s^{-1}$	50

$\mathcal{L}$ x 30 : x1.5 current increase
x 20 β_y^* vertical beta function decrease





Current integrated luminosity

We kept SuperKEKB and Belle II running in 2020/2021 during the COVID-19 crisis, with extra effort from the local crew and the help of remote shifters

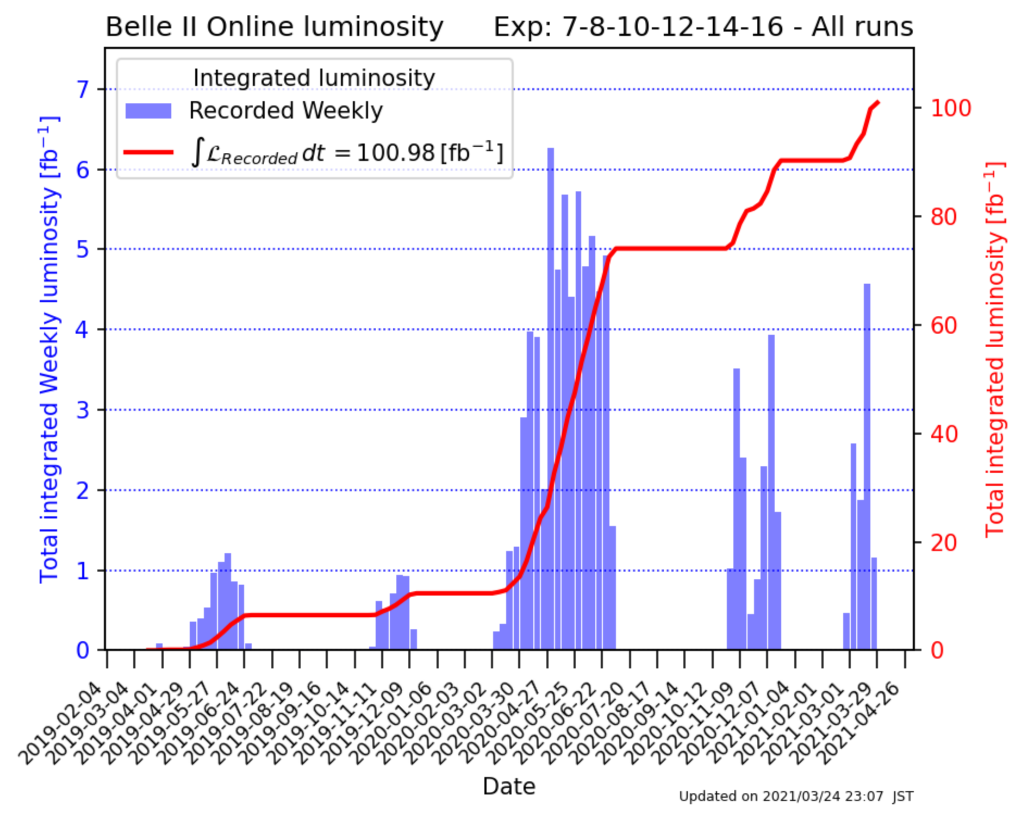
Luminosity world record

$2.11 \times 10^{34}\ cm^{-2}s^{-1}$
(KEK June 2009)

$2.14 \times 10^{34}\ cm^{-2}s^{-1}$
(LHC May 2018)

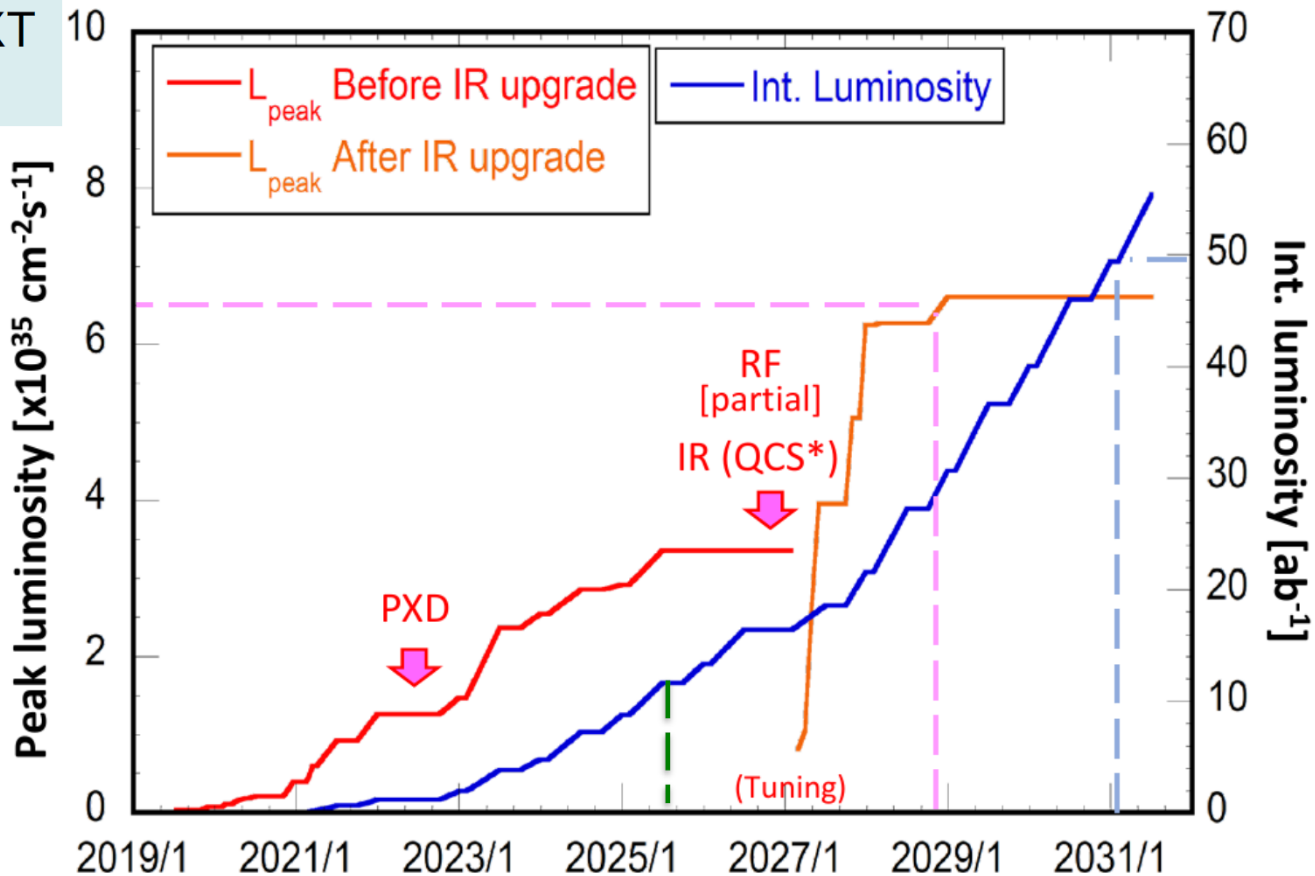
$2.4 \times 10^{34}\ cm^{-2}s^{-1}$
(SuperKEKB June 2020)

$$\int \mathcal{L}_{Recorded}\, dt = 100.98\ [fb^{-1}]$$



Luminosity Plan

Submitted to MEXT roadmap 2020



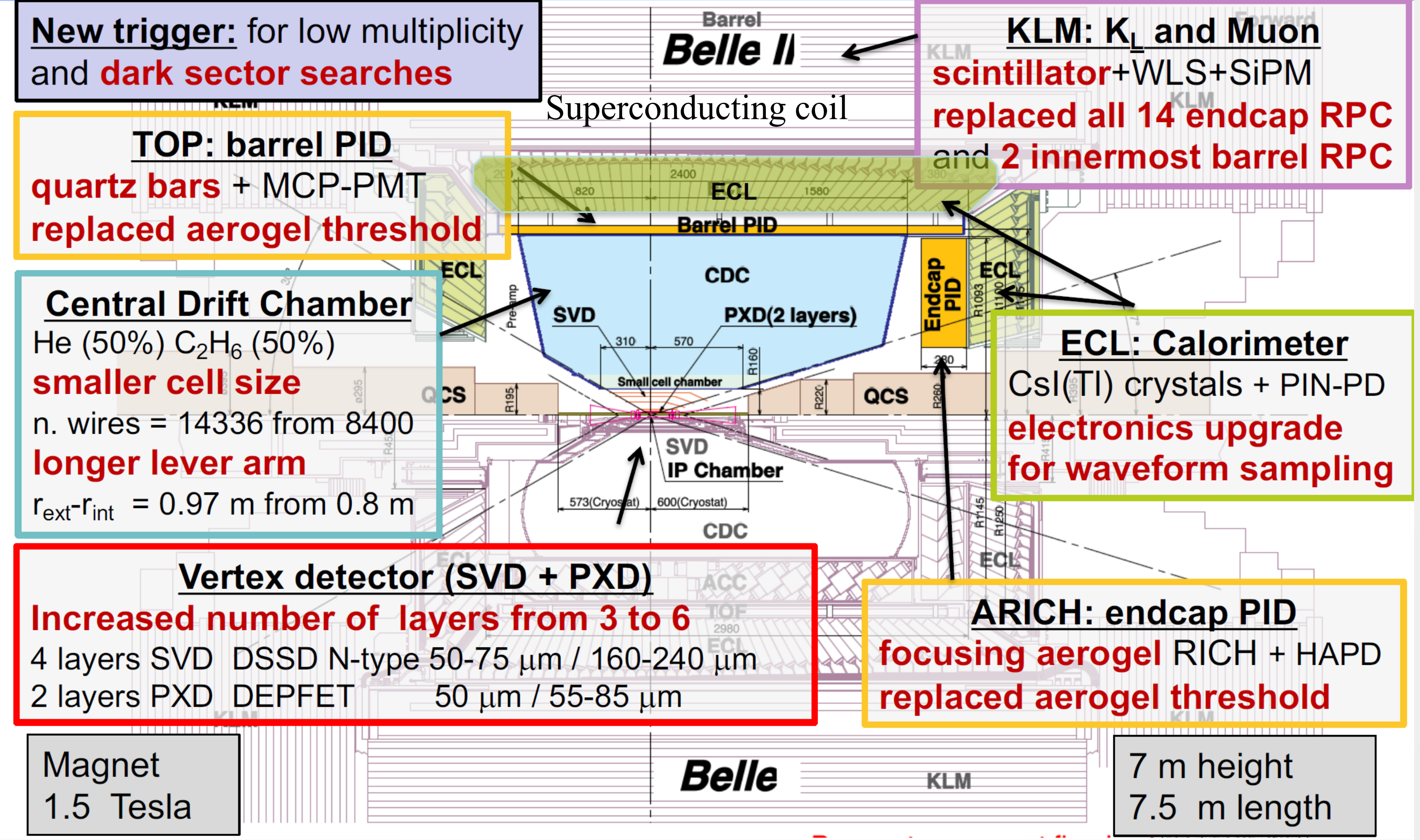
$\int \mathcal{L} = 0.5 \div 1\ ab^{-1}$ in 2022

$\int \mathcal{L} = 10\ ab^{-1}$ in 2026

$\mathcal{L}_{peak} = 6\ 10^{35}\ cm^{-2}\ s^{-1}$ in 2029

$\int \mathcal{L} = 50\ ab^{-1}$ in 2031

Belle II detector



New trigger: for low multiplicity and **dark sector searches**

KLM: K_L and Muon
scintillator+WLS+SiPM
replaced all 14 endcap RPC and 2 innermost barrel RPC

TOP: barrel PID
quartz bars + MCP-PMT
replaced aerogel threshold

Central Drift Chamber
He (50%) C_2H_6 (50%)
smaller cell size
n. wires = 14336 from 8400
longer lever arm
r_{ext}-r_{int} = 0.97 m from 0.8 m

ECL: Calorimeter
CsI(Tl) crystals + PIN-PD
electronics upgrade for waveform sampling

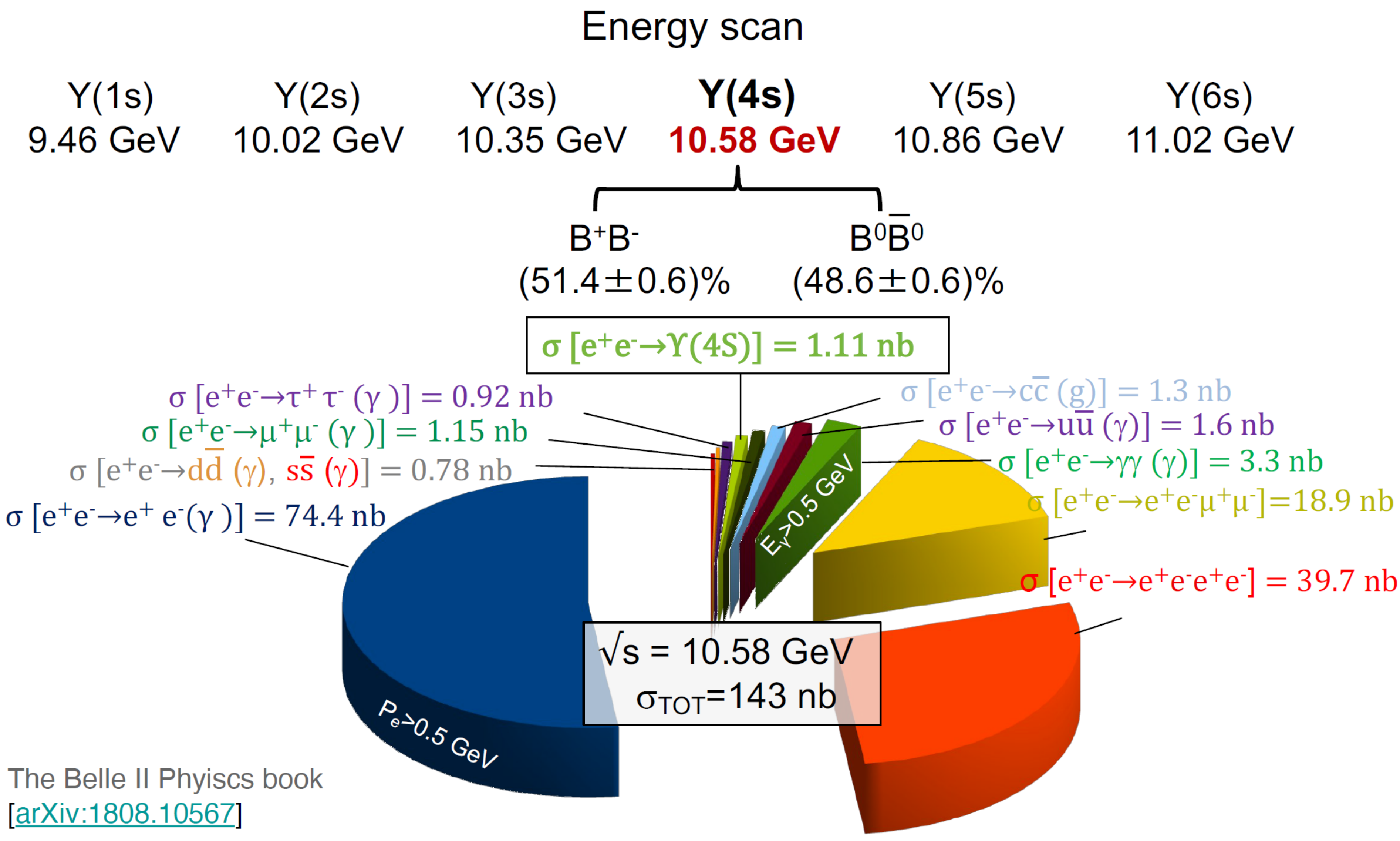
Vertex detector (SVD + PXD)
Increased number of layers from 3 to 6
4 layers SVD DSSD N-type 50-75 μm / 160-240 μm
2 layers PXD DEPFET 50 μm / 55-85 μm

ARICH: endcap PID
focusing aerogel RICH + HAPD
replaced aerogel threshold

Magnet
1.5 Tesla

7 m height
7.5 m length

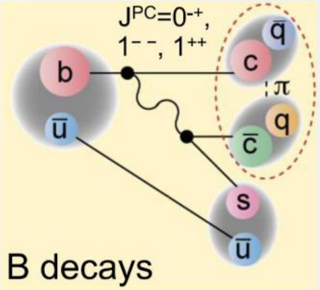
Belle II energy points



Potential XYZ results in charm sector at Belle II

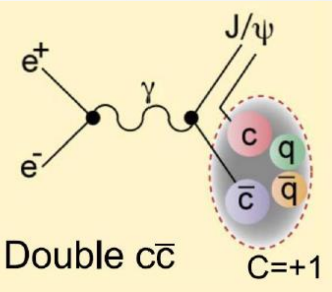
B decays: Competition from LHCb, advantages for modes with neutrals

- Confirm Zc states and search for neutral partners
- Absolute branching fractions B → X(3872,3915) K
- Confirmation of X(3872) width measurement with $D^0\overline{D}^0\pi^0$ mode
- Absolute branching fractions are unique for Belle II



ISR processes:

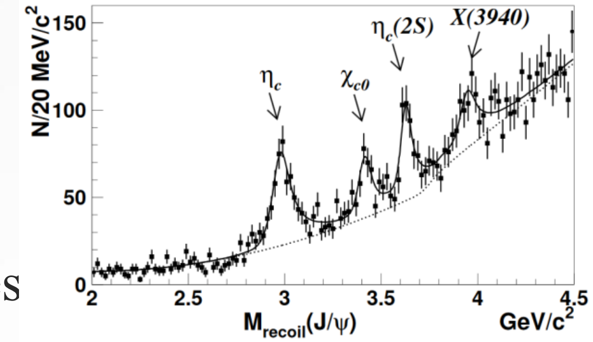
- Continuous mass range to investigate fine structures
- Higher mass region
- Confirm Zc states and search for neutral partners
- Higher mass region (>4.7 GeV) is unique for Belle II

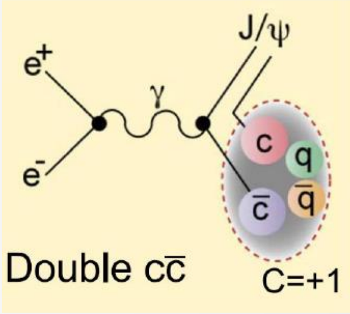


Potential XYZ results in charm sector at Belle II

Double charmonium processes:

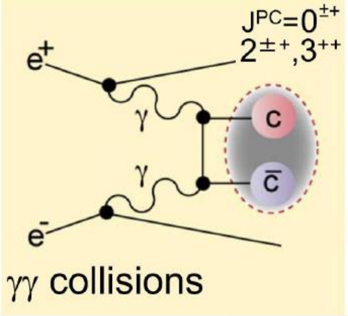
- $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
- Rediscovery of X(3940, 4160)
- Expand to other $c\bar{c}$, search for new states

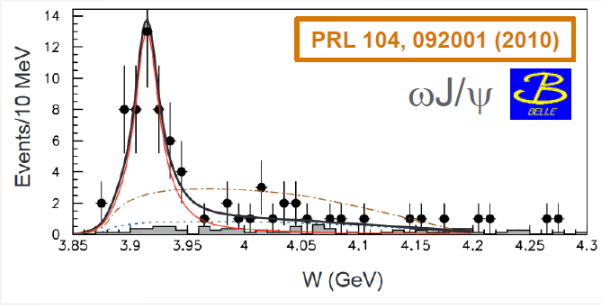


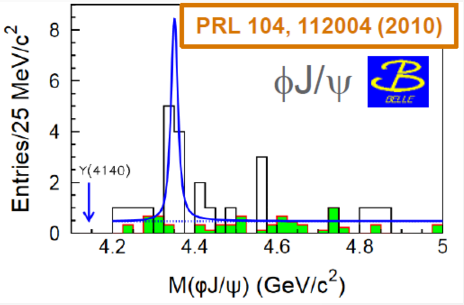


Two-photon processes:

- Determine J^P values for some confirmed states, like X(3915)
- Higher mass region
- Confirm some states with evidence, like X(4350)
- Check more modes, like $D^{(*)}\bar{D}^{(*)}(n)\pi$

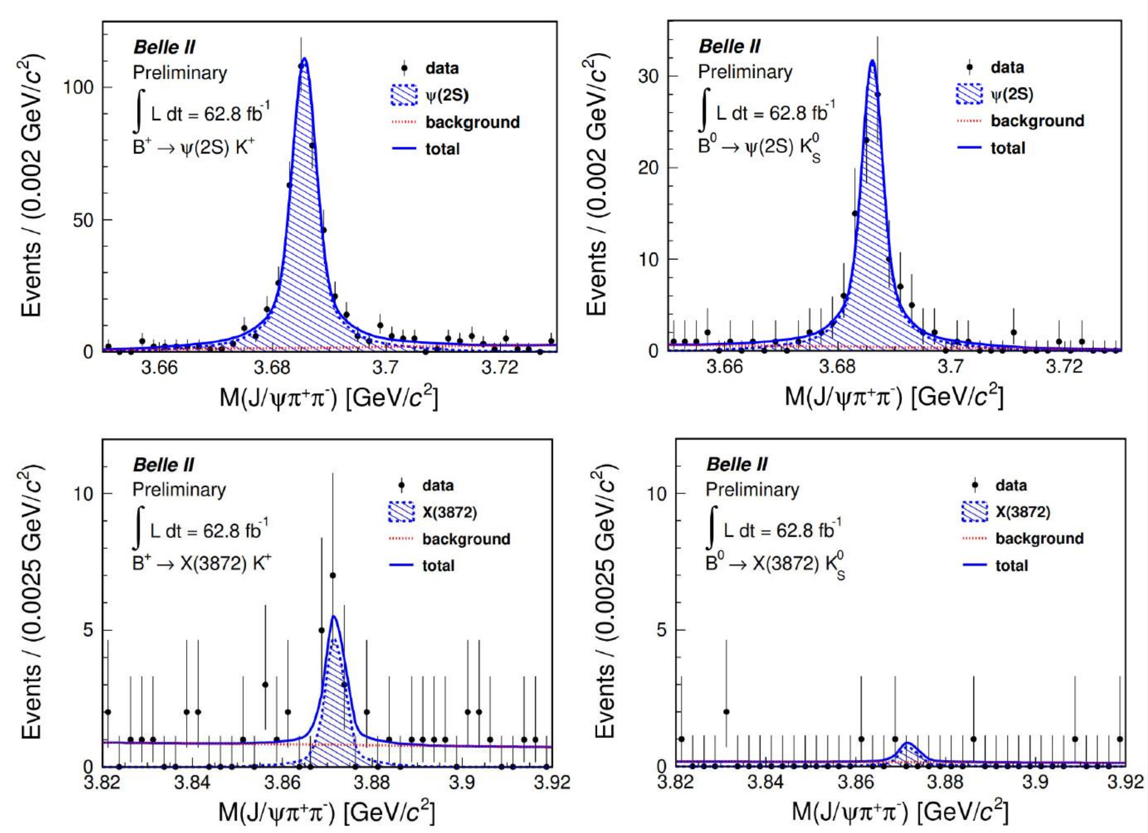






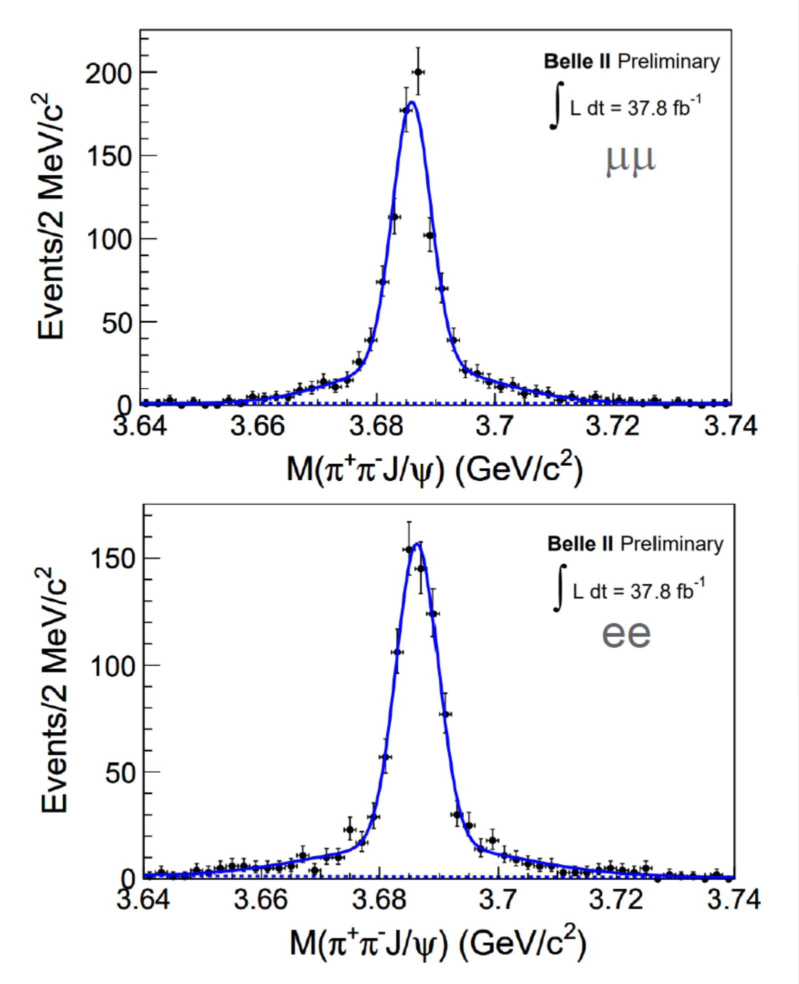
Rediscover the X(3872)

- Reconstruct final states:
  - $B^{\pm} \rightarrow \pi^{+}\pi^{-}J/\psi(\ell^{+}\ell^{-})\ K^{\pm}$
  - $B^{0} \rightarrow \pi^{+}\pi^{-}J/\psi(\ell^{+}\ell^{-})\ K_{S}$
- "Standard" selection criteria
  - Particle identification
  - Continuum: nTracks, R_2
  - Kinematics: $M_{\pi+\pi-}$, M_{BC}, $|\Delta E|$
- Observe $B \rightarrow \psi(2S)\ K$
- First X(3872) at Belle II
  - 14.4±4.6 events (4.6σ)



ISR preliminary studies at Belle II

- $e^+e^-\gamma_{ISR} \to \pi^+\pi^- J/\psi(\ell^+\ell^-)$ final states
  - Nominal PID requirements
  - $|M(J/\psi)-M(PDG)| < 75$ MeV
  - ISR photon not required (high efficiency)
  - $|MM^2(\pi^+\pi^- J/\psi)| < 2$ GeV^2
- Clear observation of ISR $\psi(2S)$ signals
- Next step: "Y(4260)" rediscovery
  - Expect ~60 total events per 100 fb^{-1}



Summary

- We are still producing interesting XYZ results using Belle data
- The expected Belle II data sample of 50 ab^{-1} will provide a lot of new opportunities for physics analyses
- Some of them, for example, double charmonium production, charmonium in two-photon processes, are unique for Belle II.
- Several quarkonium states and exclusive B decays to charmonium and other particles were “rediscovered" using the currently available data.

Thanks a lot!

Thanks for your attention

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