Heavy Quarknium at Belle II + DsDs1 from Belle

International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy (PWA 12 / ATHOS 7)

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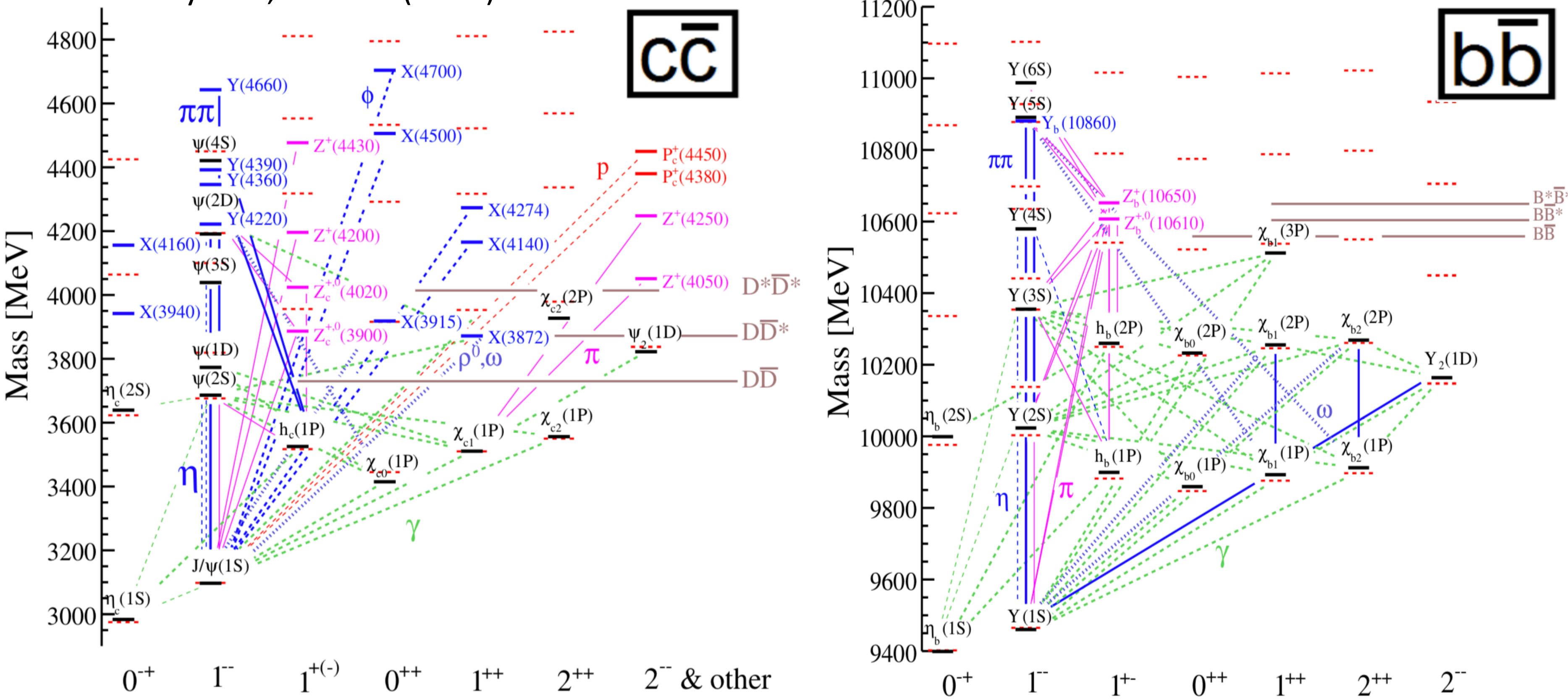
on behalf of the Belle and Belle II Collaborations

Quarknium

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



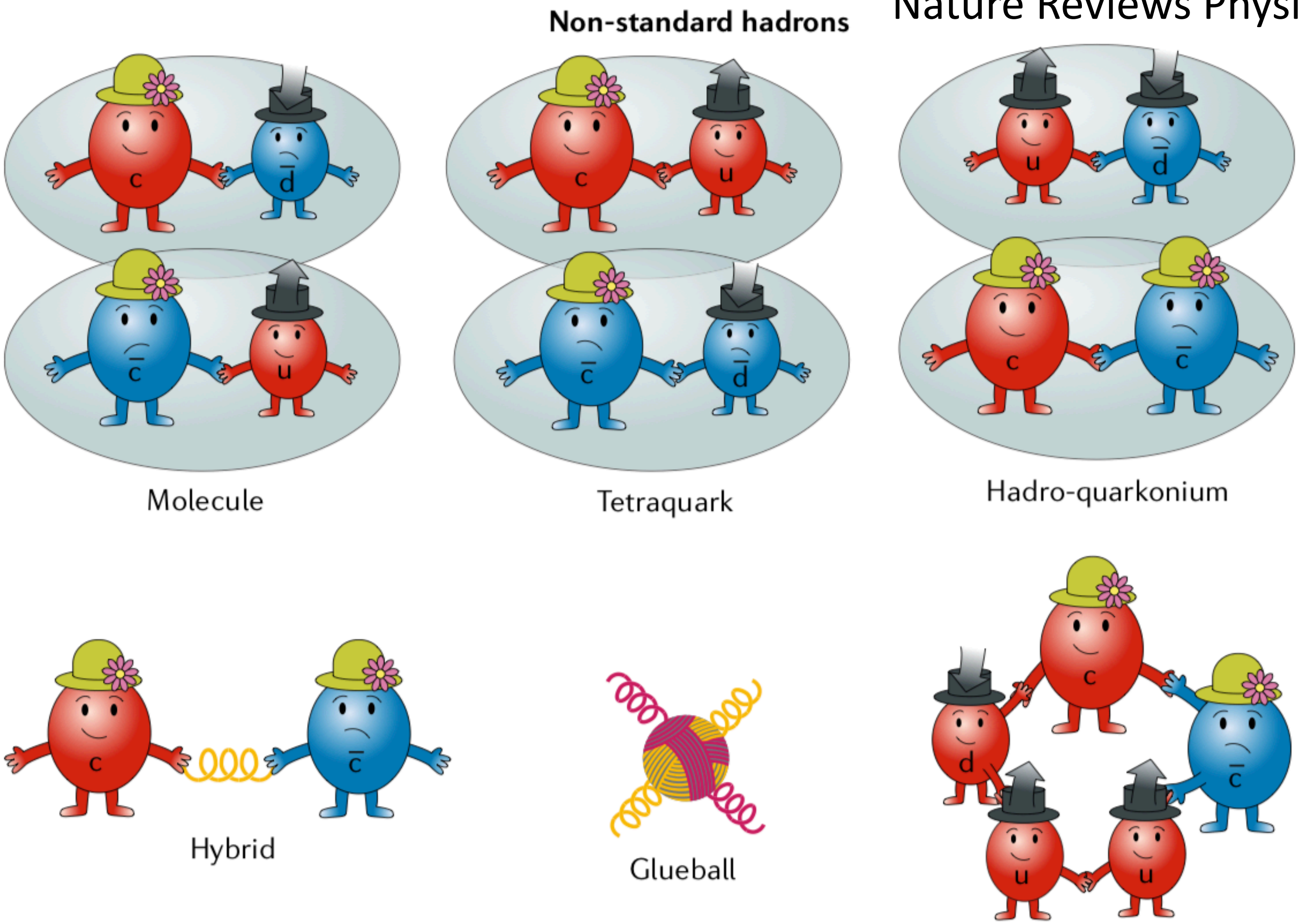
Observed States:

- Conventional Charmonium
- Unconventional neutral states
- Unconventional charged states
- Pentaquark candidates

- 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 …

High Priority: Seek unique picture describing all XYZ states, not state-by-state

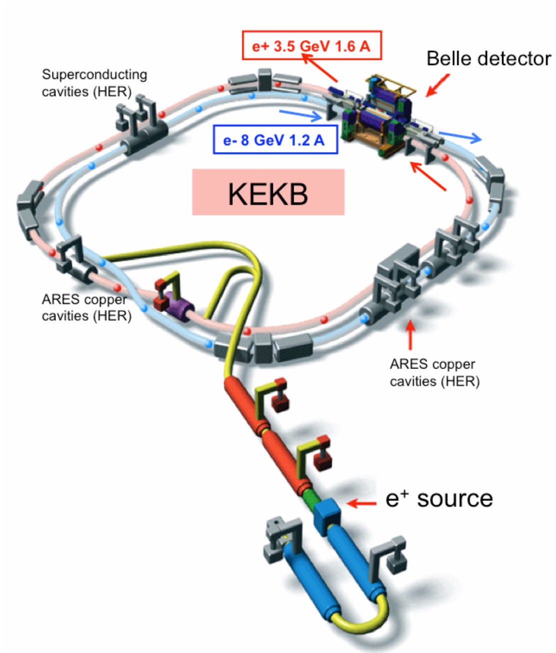
Overview

- SuperKEKB and Belle II detectors
- Analysis of $e^+e^- \rightarrow D_s^+ D_{s1}(2536)^-$ at Belle
- Charmonium(-like) states at Belle II
- Bottomonium(-like) states at Belle II
- Summary

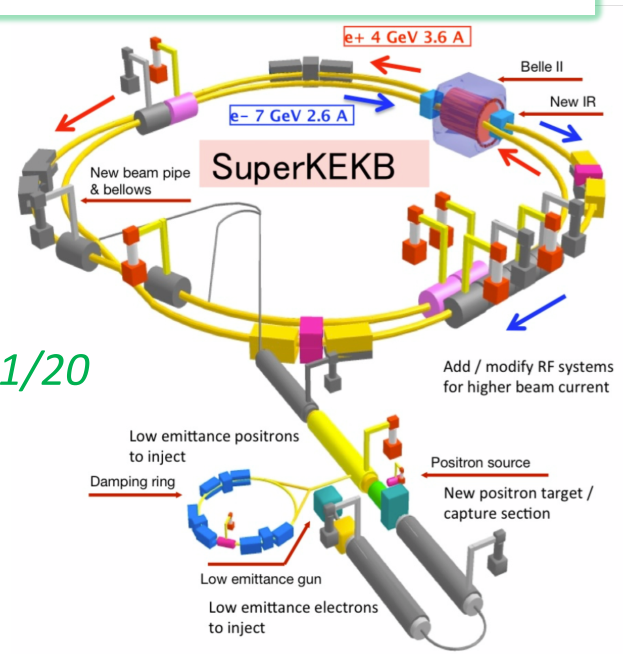
SuperKEKB

- 1st Vs. 2nd generation B-factory

$$\int^{\mathrm{goal}} \mathcal{L}\, dt = 50\ \mathrm{ab}^{-1} = 50 \times \mathcal{L}^{\mathrm{int}}_{\mathrm{Belle}}$$



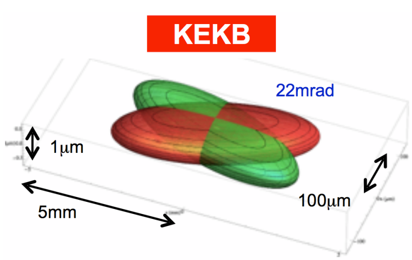
- *Double beam currents*
- *Squeeze beams @IP by 1/20*
- *Reduced CM boost*

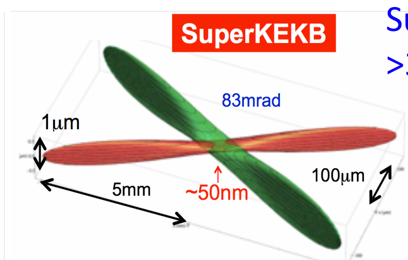


- Nano-beam design (by P. Raimondi for SuperB)

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

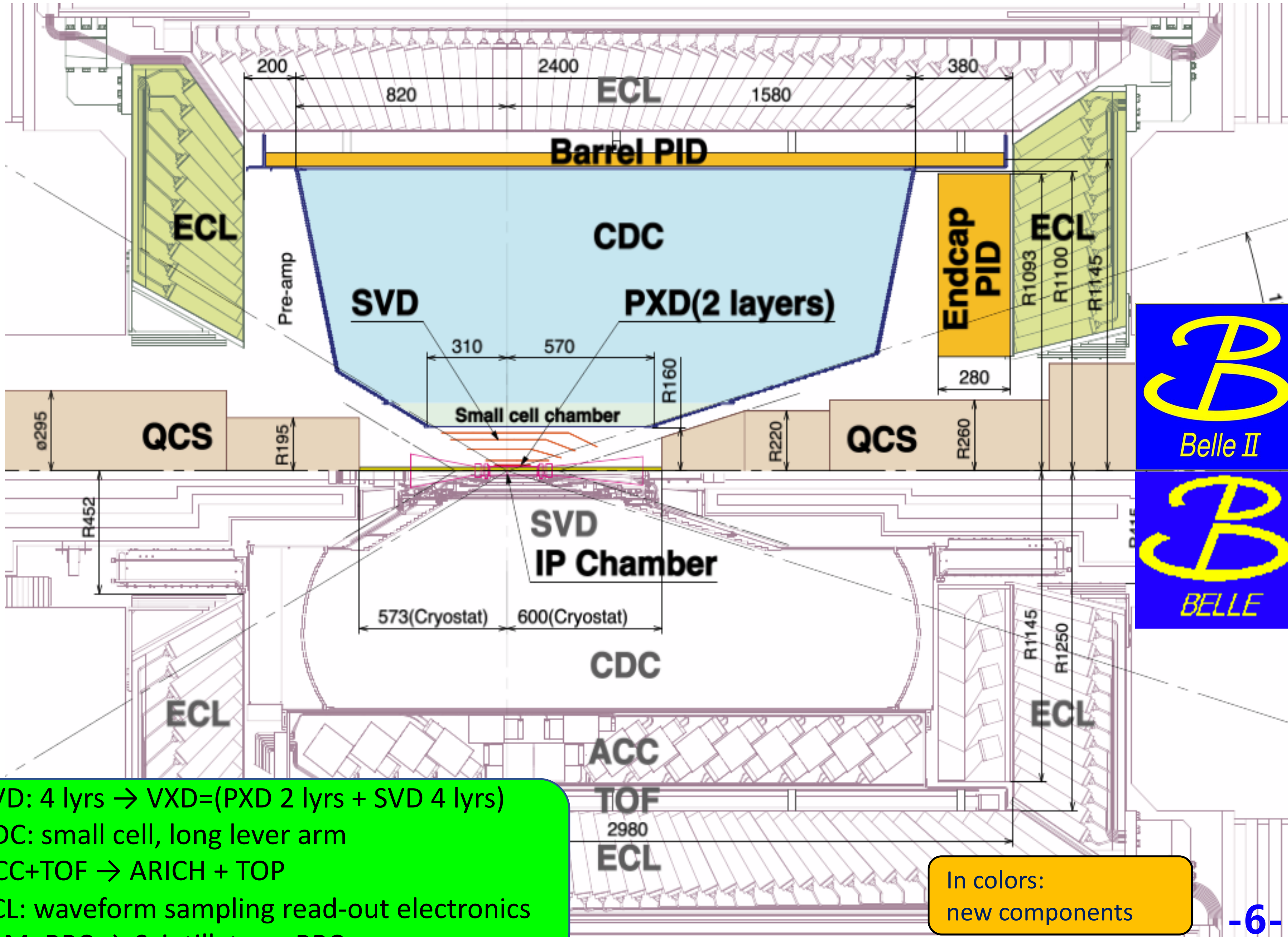




SuperKEKB goal:
>30x instantaneous KEKB luminosity

	$E_\pm$ (GeV) LER/HER	Cross Angle (mrad)	$I_\pm$ (A) LER/HER	β_y^* (mm) LER/HER
KEKB	3.5/8.0	22	1.64/1.19	5.9/5.9
SuperKEKB	4.0/7.0	83	3.60/2.60	0.27/0.31
	$\beta\gamma \sim 2/3$		$\times 2$	$\times 20$

Detector: Belle Vs. Belle II

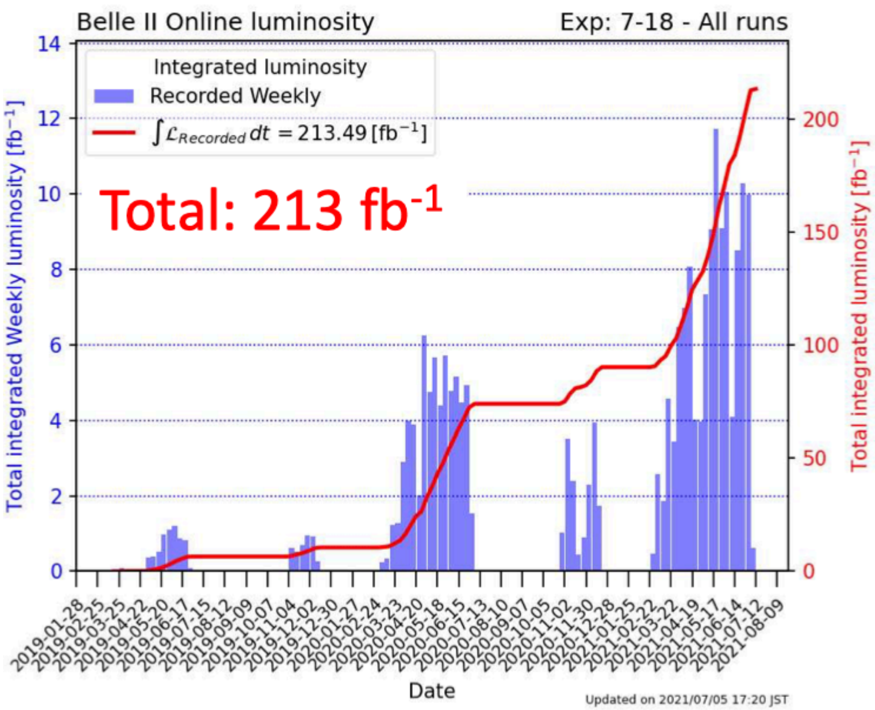


- SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
- CDC: small cell, long lever arm
- ACC+TOF → ARICH + TOP
- ECL: waveform sampling read-out electronics
- KLM: RPC → Scintillator + RPC

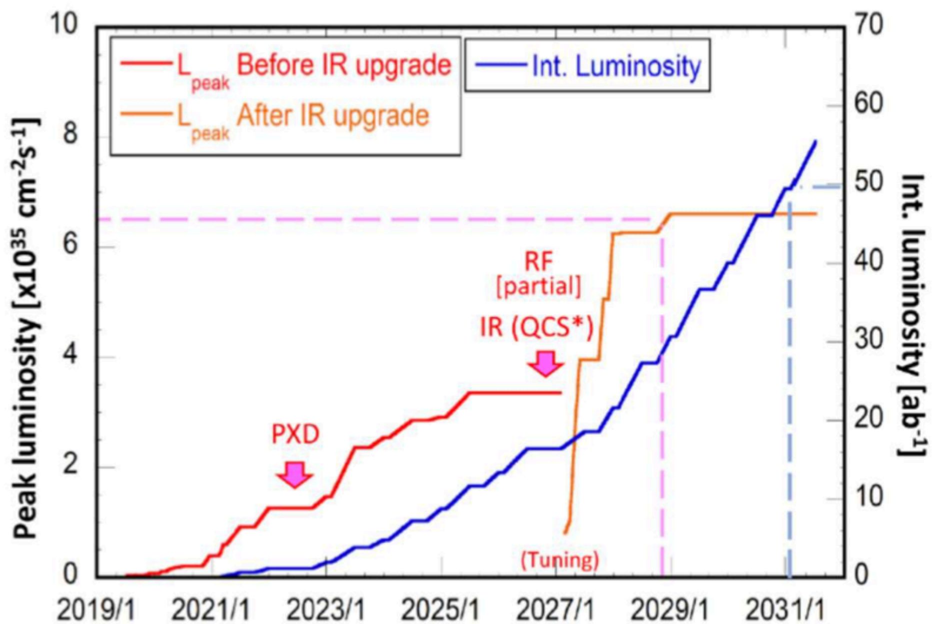
In colors:
new components

Belle II integrated luminosity

Achieved



Prospect

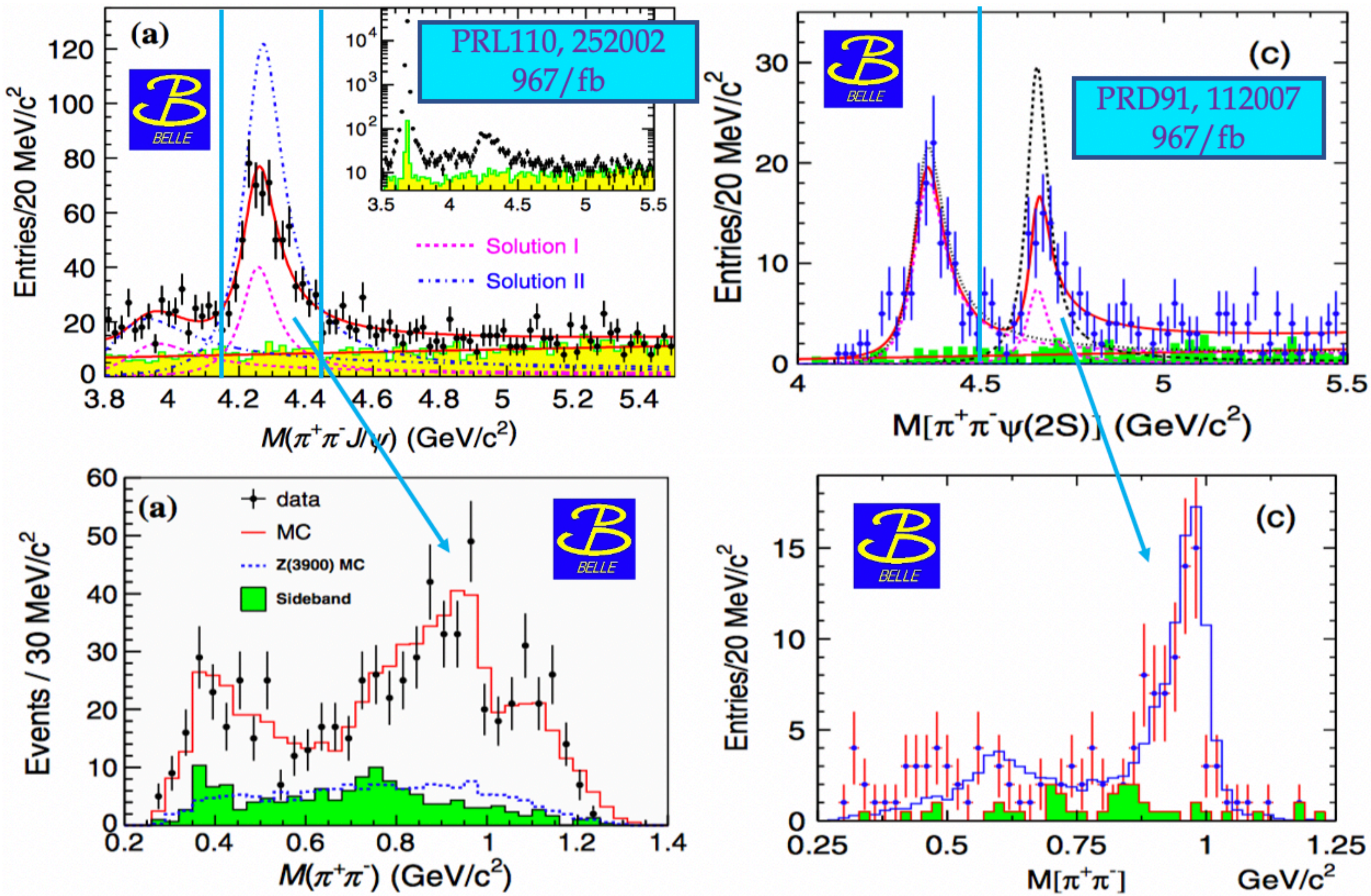


- Instantaneous luminosity already exceeded Belle
- Integrated luminosity will exceed Belle within a few years
- Goal: 50 ab^{-1} around 2031

Analysis of $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{D}_s^+ \mathrm{D}_{s1}(2536)^-$ at Belle

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

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



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

Analysis method

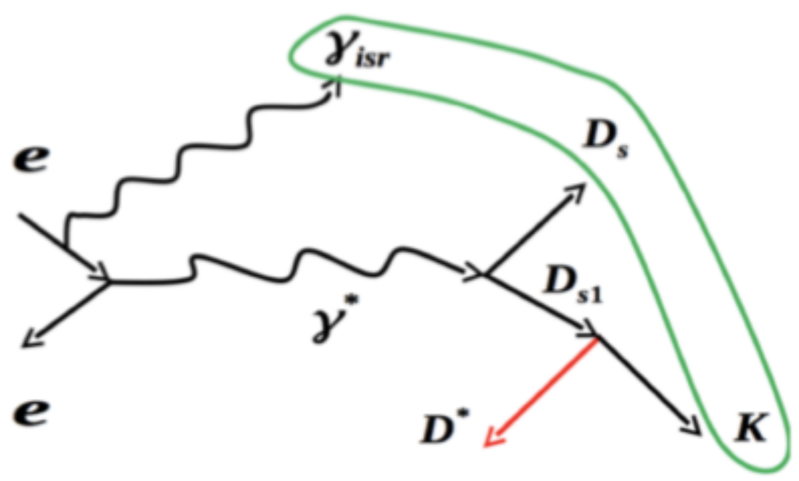
$$e^+e^- \to \gamma_{ISR} D_s^+ D_{s1}(2536)^- (\to \bar{D}^{*0} K^- / D^{*-} K_S^0)$$

We require full reconstruction of the 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.

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

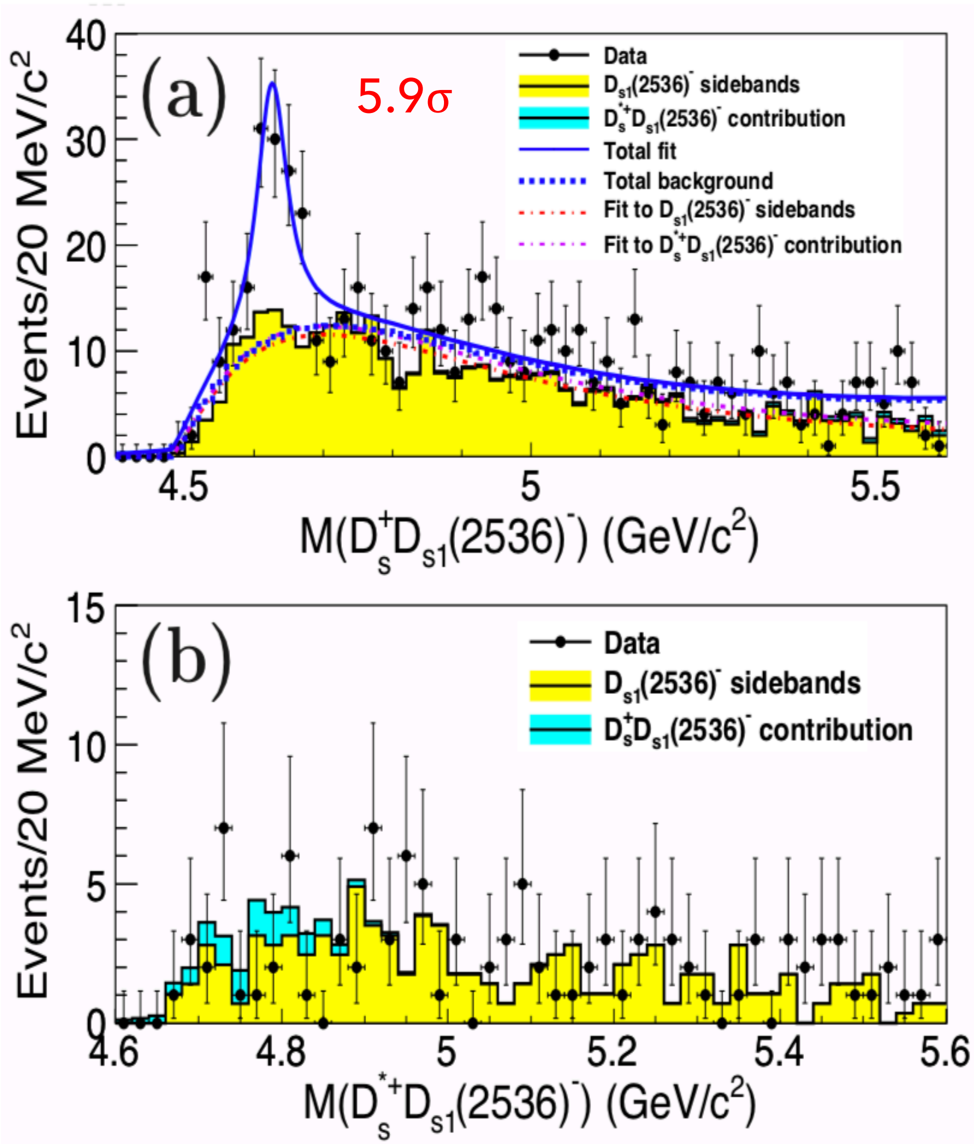
- To improve the $M_{rec}(\gamma_{ISR})$ resolution, $M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0)$ is constrained to be the nominal mass of the $\bar{D}^{*0}/D^{*-}$.



Belle 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
- $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$ background contribution: a threshold function
- A non-resonant contribution: a two-body phase space form

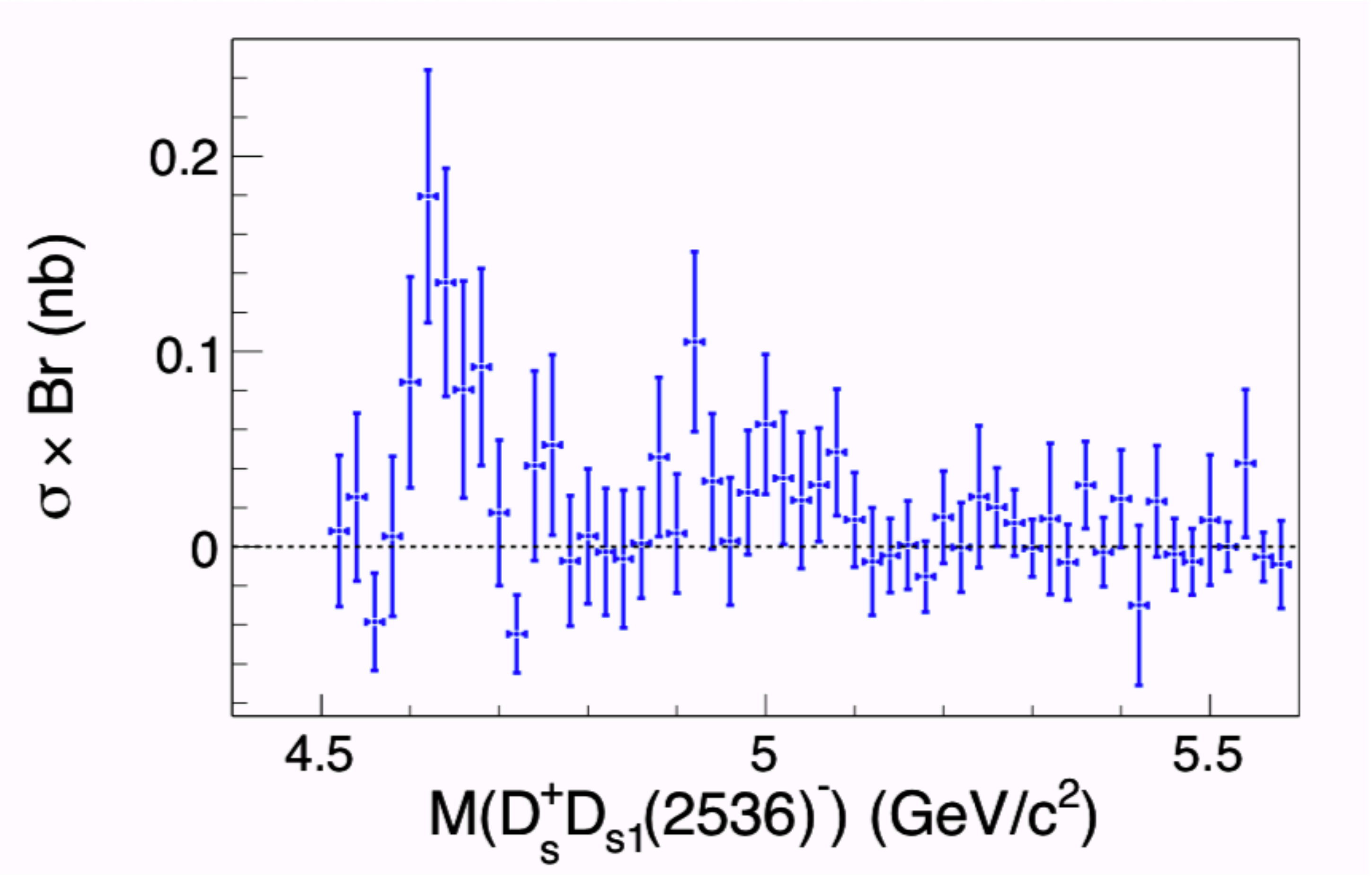
$M=(4625.9^{+6.2}_{-6.0}(\text{stat.}) \pm 0.4(\text{syst.})\ \text{MeV}/c^2$
$\Gamma = (49.8^{+13.9}_{-11.5}(\text{stat.}) \pm 4.0(\text{syst.})\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0} K^-) = (14.3^{+2.8}_{-2.6}(\text{stat.})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

We call this charmonium-like state decaying into $D_s^+ D_{s1}(2536)^-$ as Y(4630).

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

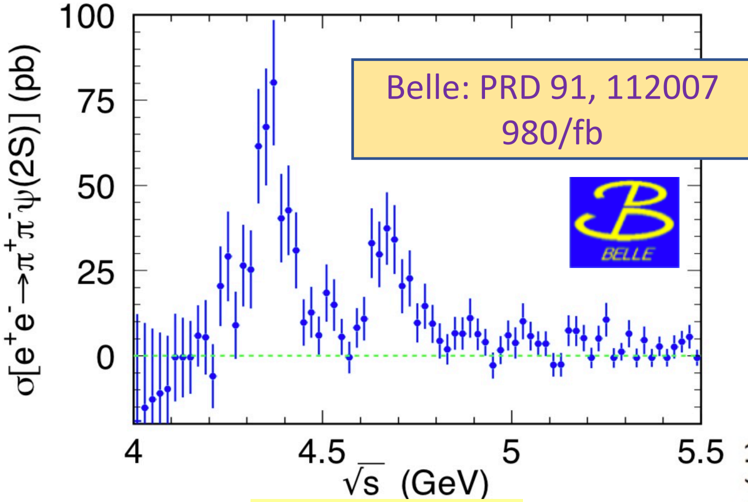
Cross section:

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

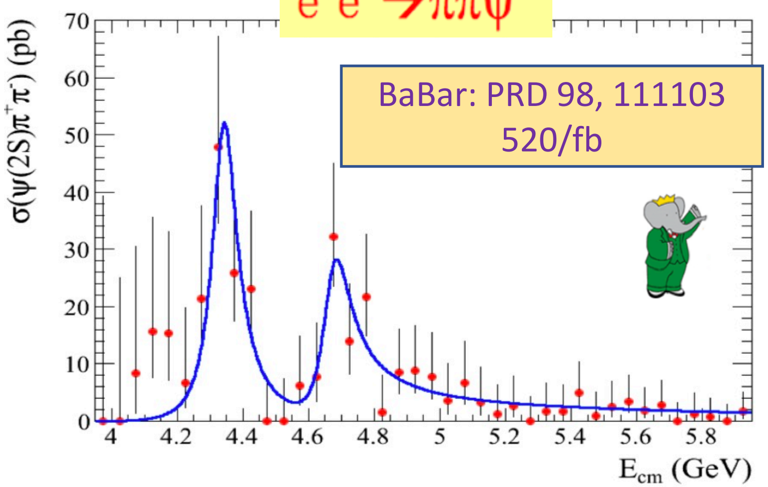


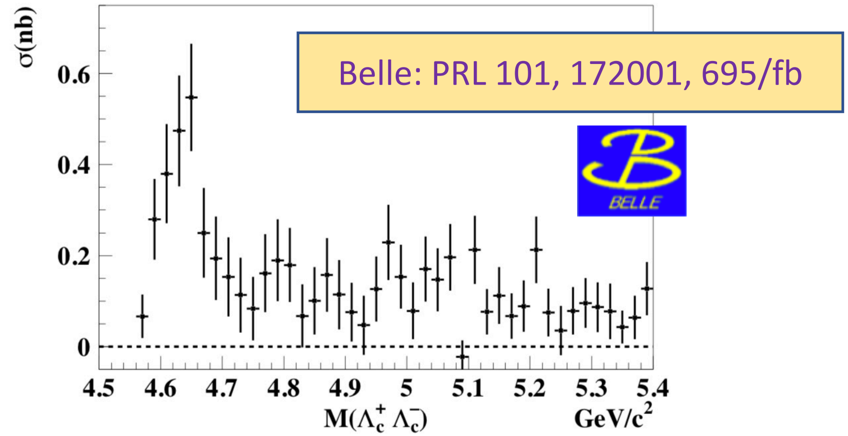
The peak value of the σ × Br at $M(D_s^+ D_{s1}(2536)^-) \sim 4.63\ GeV/c^2$ is about (0.18± 0.06) nb.

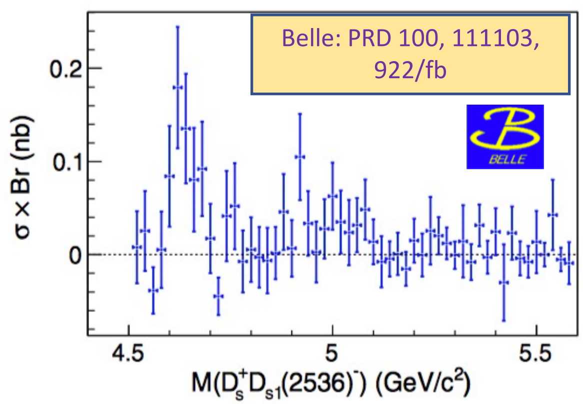
Y(4630) = Y(4660)?

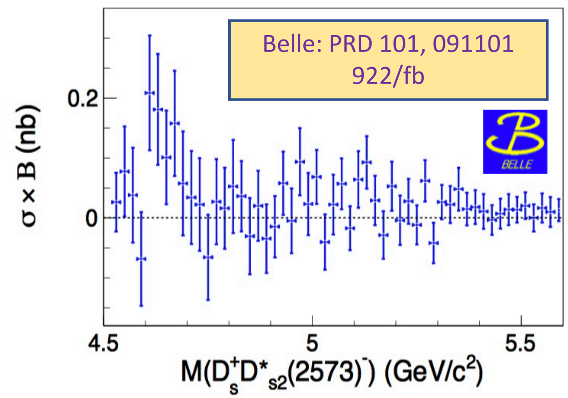


$e^+e^- \rightarrow \pi\pi\psi'$









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

- These states may be the same.
- Need improved precision.

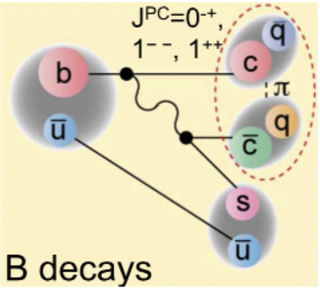
Charmonium(-like) and bottomonium(-like) states at Belle II

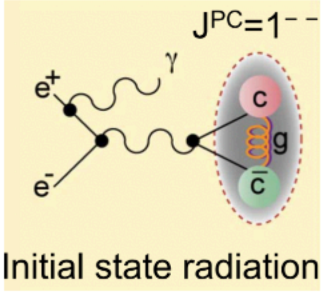
Charmonium(-like) prospects at Belle II

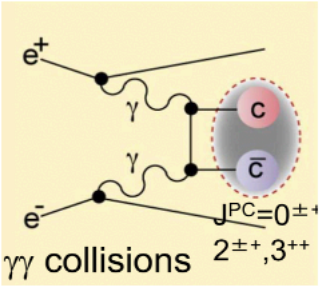
- B decay ($B \to KX_{c\bar{c}}$)
  - CKM favored process, large branching fractions $10^{-3} \sim 10^{-4}$
  - Absolute branching fractions B → X(3872,3915)K
  - X(3872) width measurement with $D^0\bar{D}^0\pi^0$
  - Confirm Z_c states and search for neutral partners
- Initial-state radiation (ISR)
  - Continuous mass range > 4.7 GeV/c^2
  - Y → charmed baryon pairs ($\Lambda_c^+\Sigma_c^-$, $\Sigma_c^+\Sigma_c^-$), charmed strange meson pairs ($D_sD_{s2}(2573)$, $D_s^*D_{s0}(2317)$)
  - Search for Z_{cs} states decaying into $K^\pm J/\psi$, $D_s^-D^{*0}$+c.c.
- Two-photon process
  - J^{PC} of X(3915) → $\omega J/\psi$; confirm X(4350) → $\phi J/\psi$
- Double charmonium
  - $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
  - J^{PC} of X(3940)

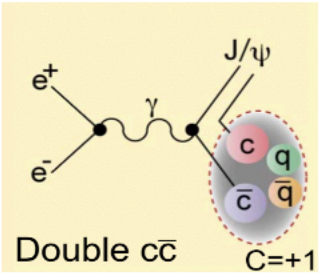
Expected statistics @50 ab^{-1} of XYZ

State	Production and Decay	N
X(3872)	$B \to KX(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$	≃14400
Y(4260)	ISR, $Y(4260) \to J/\psi\pi^+\pi^-$	≃29600
Z(4430)	$B \to K^\mp Z(4430)$, $Z(4430) \to J/\psi\pi^\pm$	≃10200





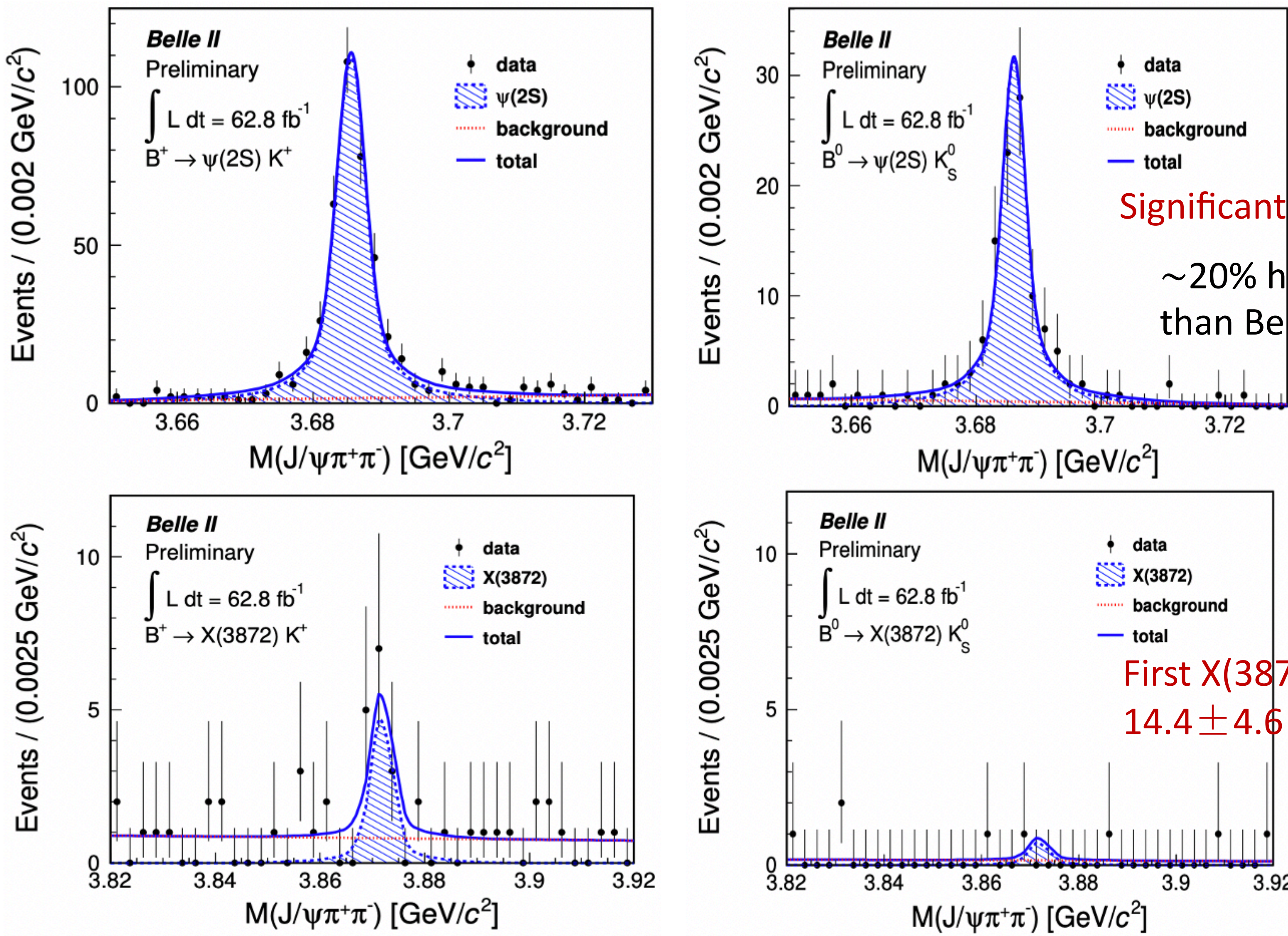




Rediscovery of X(3872)

$B^{\pm} \to \pi^+\pi^- J/\psi K^{\pm}$, $B^0 \to \pi^+\pi^- J/\psi K_S$

BELLE2-NOTE-PL-2021-002



Significant B → ψ(2S)K

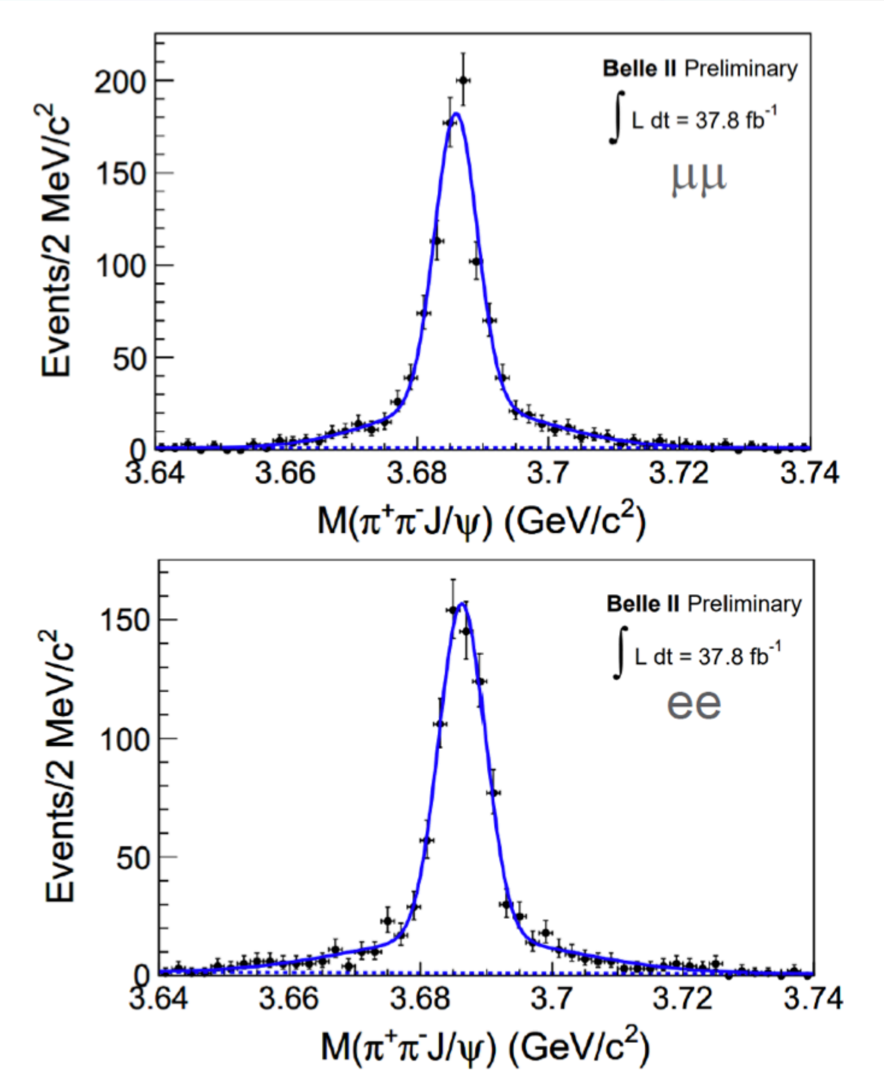
~20% higher efficiency than Belle

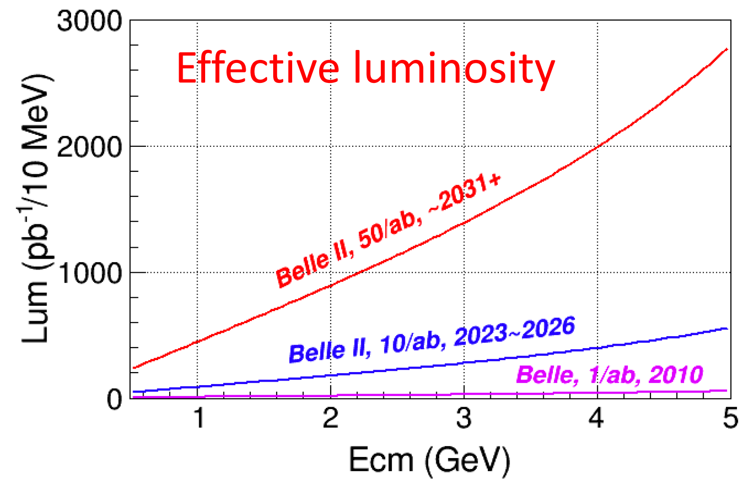
First X(3872) at Belle II

14.4 ± 4.6 events (4.6σ)

ISR preliminary studies

$e^+e^- \to \psi(2S) \to \pi^+\pi^- J/\psi$ via ISR:





- ISR photon is not required (high efficiency), and $|M^2_{\rm recoil}(\pi^+\pi^- J/\psi)| < 2$ $({\rm GeV}/c^2)^2$ is applied to select ISR events.
- Clear observation of ISR $\psi(2S)$ signals with low backgrounds.
- Next step:
  "Y(4260)" rediscovery [expect about 60 events per 100 fb^{-1}]

Bottomonium(-like) prospects at Belle II

Three ways to access bottomonia:

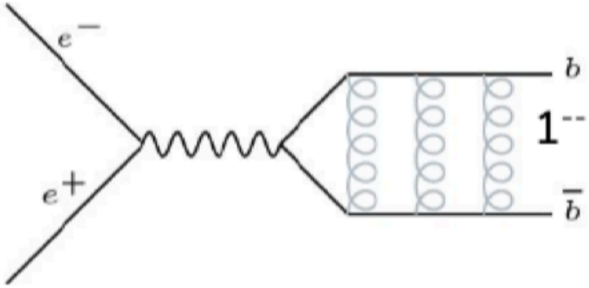
- Direct production from e^+e^-
- Production of 1^{--} states via ISR
- Hadronic/Radiative transitions from Y(nS)

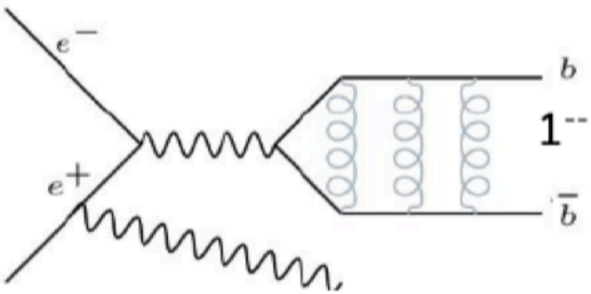
Run at Y(6S) and Y(5S) and high energy scan:

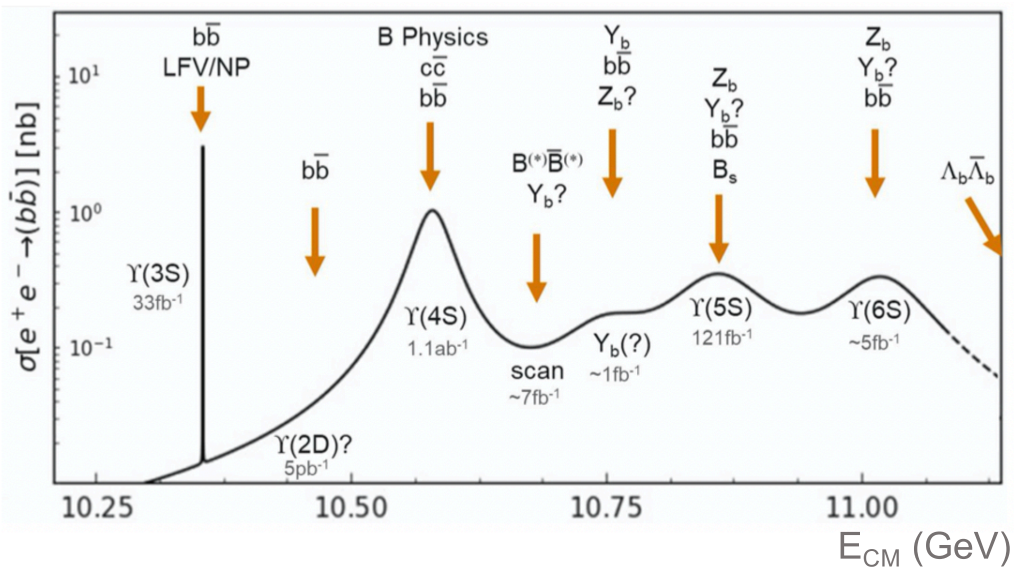
- Search for new missing bottomonia $h_b(3P)$, $\Upsilon(D)$, exotic states Y_b, Z_b, etc

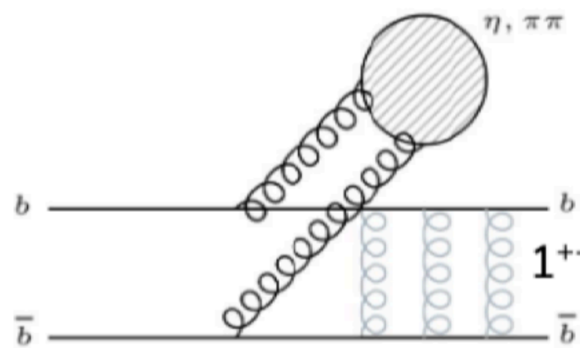
Run at Y(3S) and Y(2S):

- Search for new physics: LFV, LFU
- 'sexaquark' search

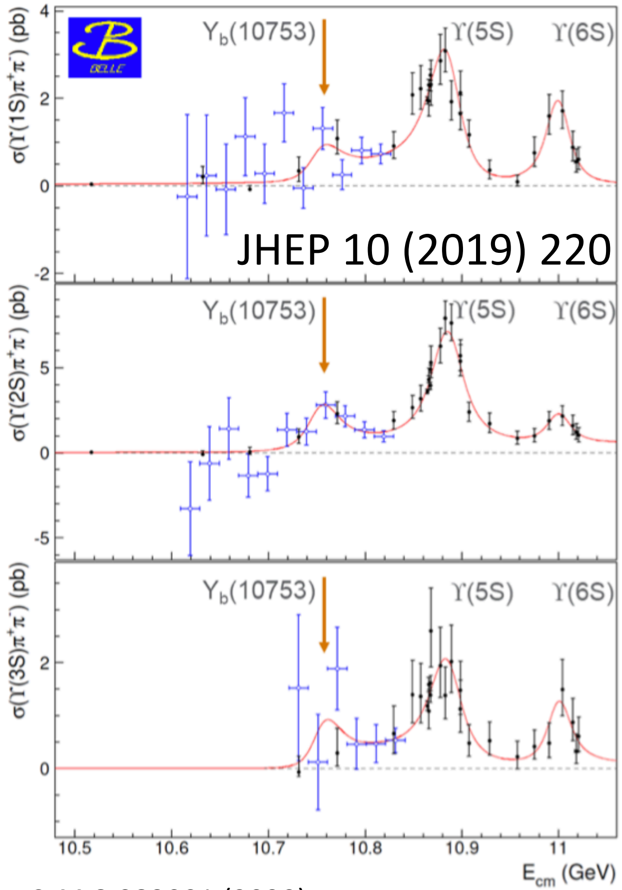








Belle II Potential – 10.75 GeV



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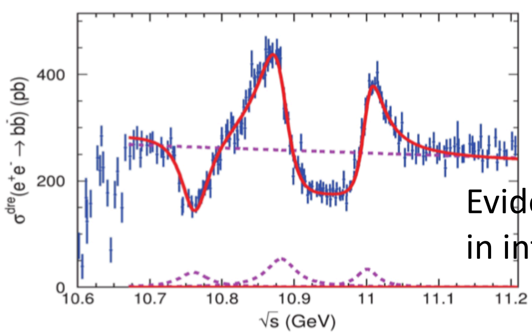
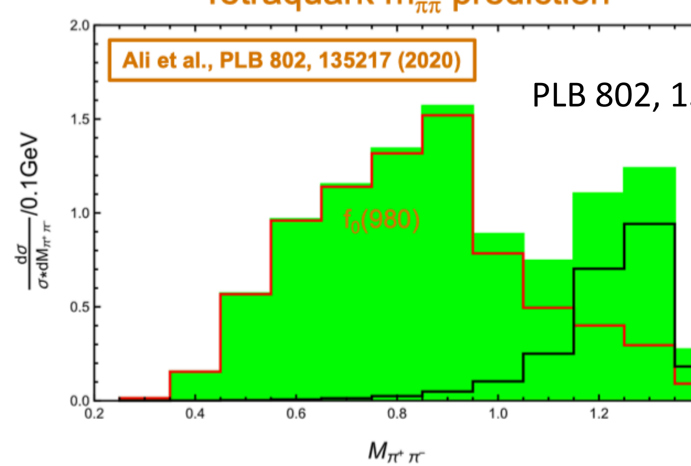
- New structure observed in $\pi^+\pi^-\Upsilon(nS)$ transitions at Belle
- Belle II plans to conduct a limited higher statistics scan in Nov 2021
  - 10.571 GeV (10 fb^{-1}): study $Y_b(10753)$ on-peak
  - 10.657, 10.706, 10.810 (1+2+3 fb^{-1}): additional points for $B\overline{B}$ decomposition
- Physics goal: understand the nature of $Y_b(10753)$ energy region
  - Differing predictions for tetraquarks and bottomonium
  - Invariant mass distributions may hold clues

Chin. Phys. C 44 8,083001 (2020)
Refit the Belle + BaBar R_b scan



Evidence of $Y_b(10753)$ in interference

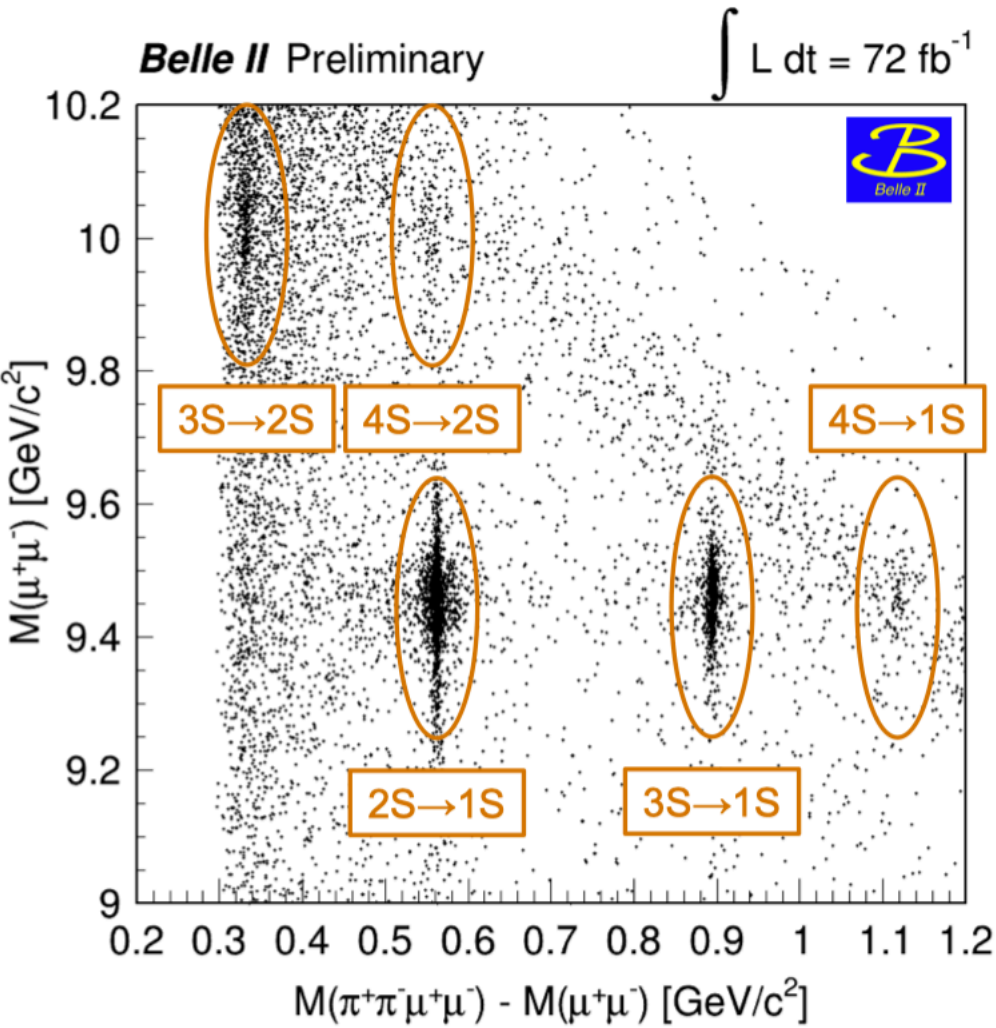
Tetraquark $m_{\pi\pi}$ prediction



PLB 802, 135217 (2020)

Belle II Progress – Dipion transitions

BELLE2-NOTE-PL-2021-001



- Initial State Radiation production: $\gamma_{ISR}\Upsilon(2S) \rightarrow \pi^{+}\pi^{-}\Upsilon(1S)$, $\gamma_{ISR}\Upsilon(3S) \rightarrow \pi^{+}\pi^{-}\Upsilon(1S, 2S)$
- Direct transitions: $\Upsilon(4S) \rightarrow \pi^{+}\pi^{-}\Upsilon(1S, 2S)$
- Better than previous Belle result [PRD96 (2017)052005]; the 3S → 2S transition is seen
- Dalitz analysis of $\Upsilon(4S) \rightarrow \pi^{+}\pi^{-}\Upsilon(nS)$ is ongoing

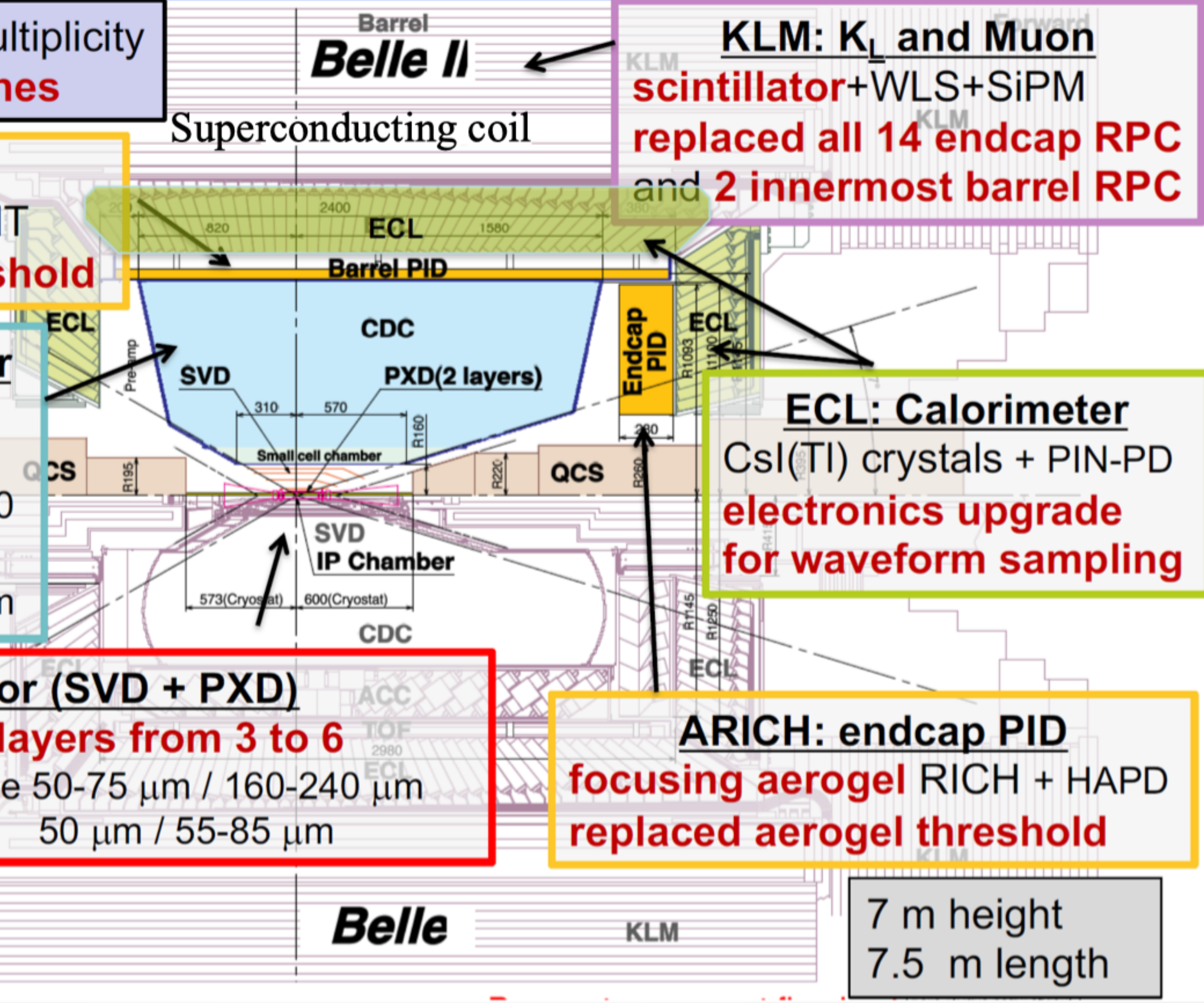
Summary

- We report the first vector charmonium-like state decaying to the charmed-antistrange and anticharmed-strange meson pair $D_s^+ D_{s1}(2536)^-$ using Belle data samples. The masses and widths are close to those of Y(4660).
- Charmonia@Belle II
  - Rediscoveries of $X(3872) \to \pi^+\pi^- J/\psi$ and ISR $e^+e^- \to \psi(2S) \to \pi^+\pi^- J/\psi$
  - Higher efficiency than Belle
  - Other XYZ states will be rediscovered soon
- Bottomonia@Belle II
  - Good performance demonstrated in $\gamma_{ISR}\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$
  - Plan to take data around 10.75 GeV for $Y_b(10753)$ in Nov 2021
  - Explore missing bottomonia and exotic states Y_b, Z_b in the near future

Thanks for your attention!

Backup slides

Belle II detector



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

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

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

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

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

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

Magnet
1.5 Tesla

7 m height
7.5 m length