Exotic states at Belle II

Qingping Ji jiqingping@htu.edu.cn

（On behalf of the Belle II Collaboration）

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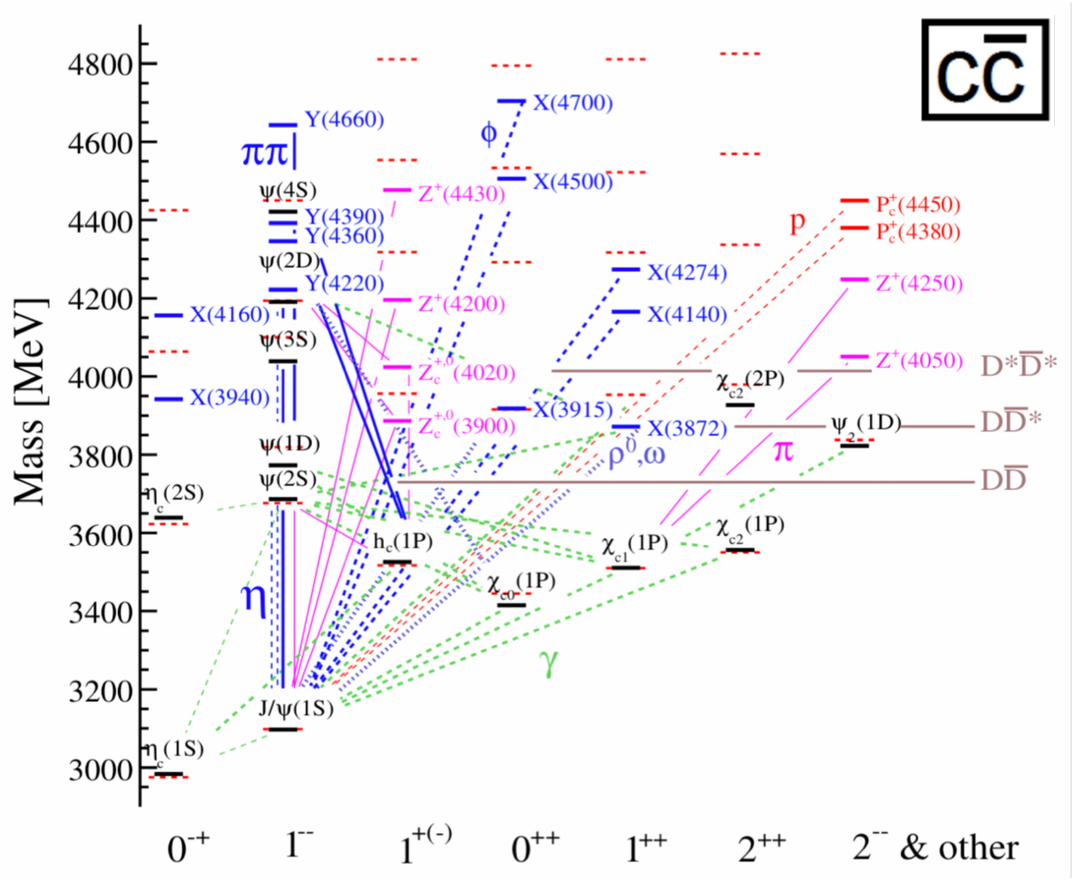
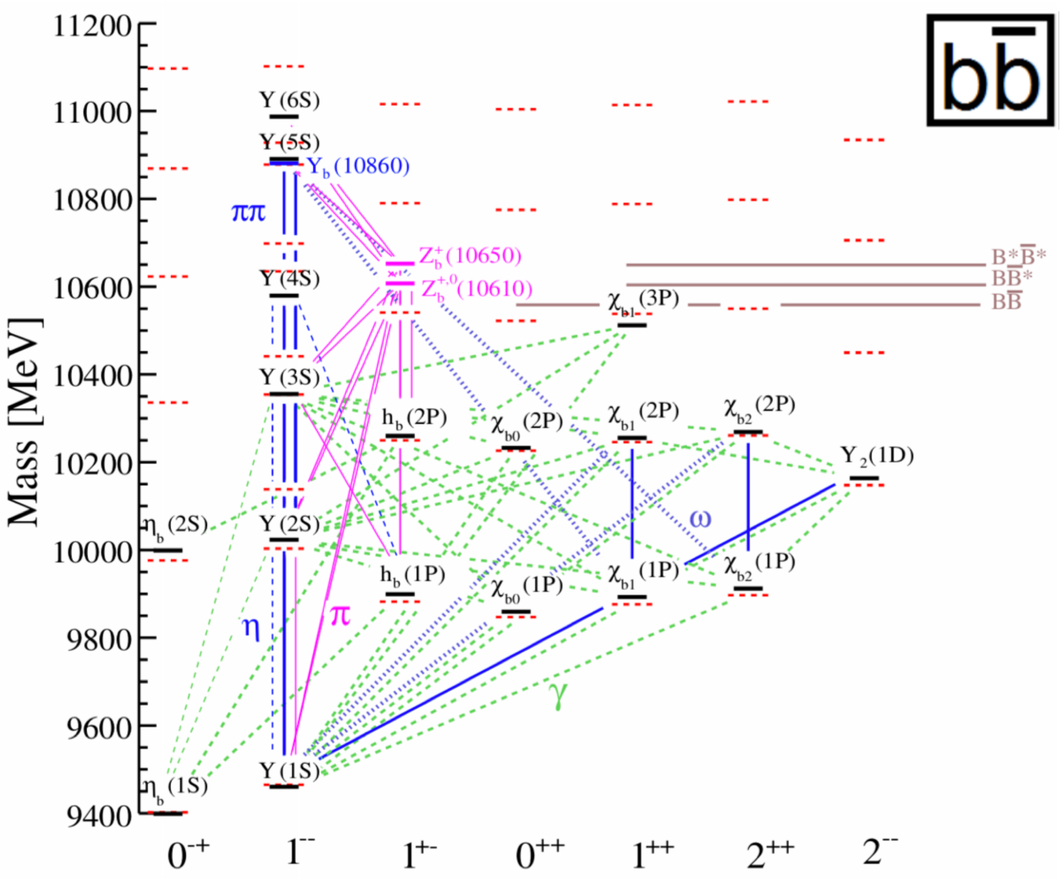
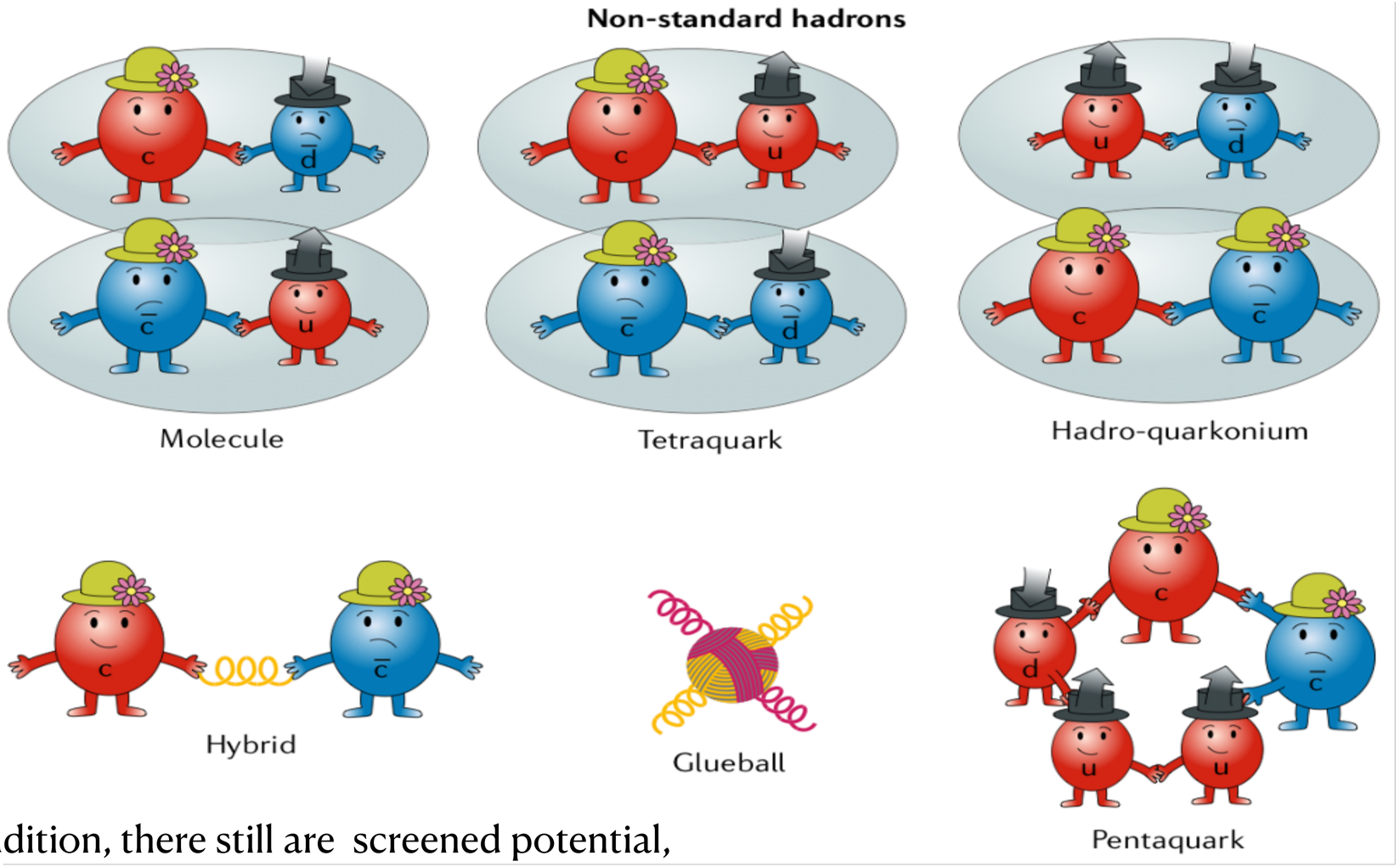
Quarkonium





- 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



In addition, there still are screened potential,
Cusp effect, final state interaction ...

Nature Rev. Phys. 1(2019)8, 480-494

Seek unique picture describing all XYZ states, not state-by-state ?

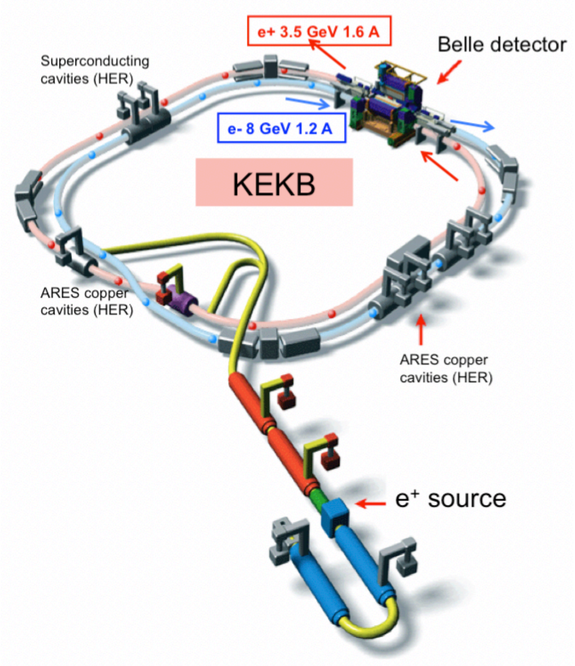
Outline

- SuperKEKB and Belle II detector
- Charmonium-like prospects at Belle II
- Bottomonium-like prospects at Belle II
- Summary

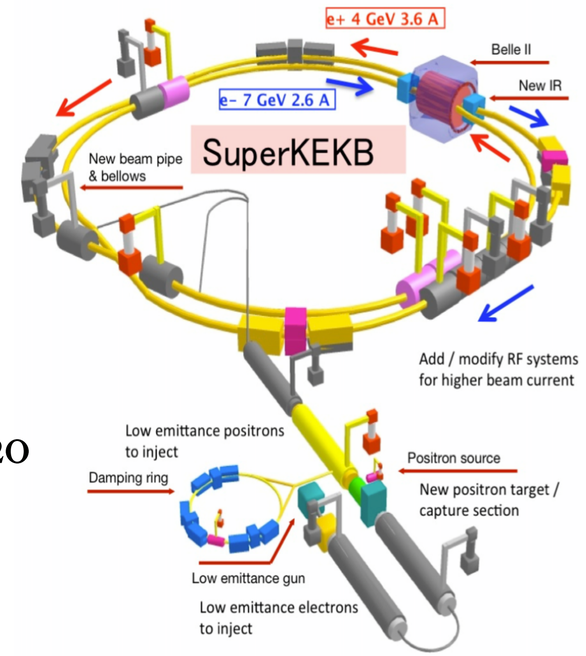
SuperKEKB

- **1st VS. 2nd** generation *B*-factory

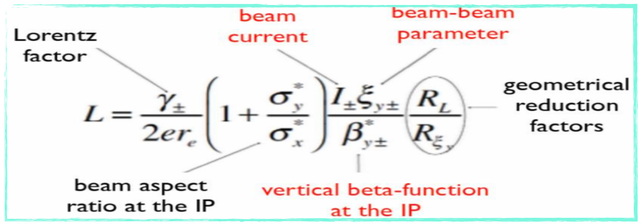
$$\int^{goal} \mathscr{L} dt = 50\ \mathbf{ab}^{-1} = 50 \times \mathscr{L}^{\text{int}}_{\text{Belle}}$$



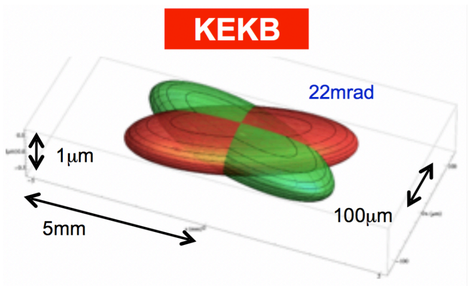
- Double beam currents
- Squeeze beams @ IP by 1/20
- Reduced CM boost

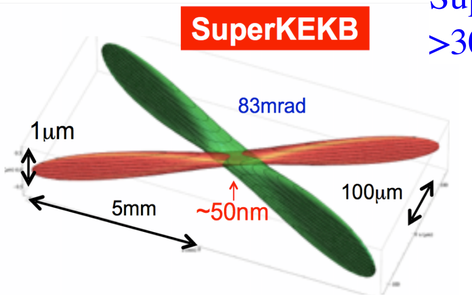


- Nano-beam design (by P. Raimondi For SuperB)



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





Super-KEKB 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
	$\beta\gamma \sim 2/3$		$\times 2$	$\times 20$

Belle vs. Belle II

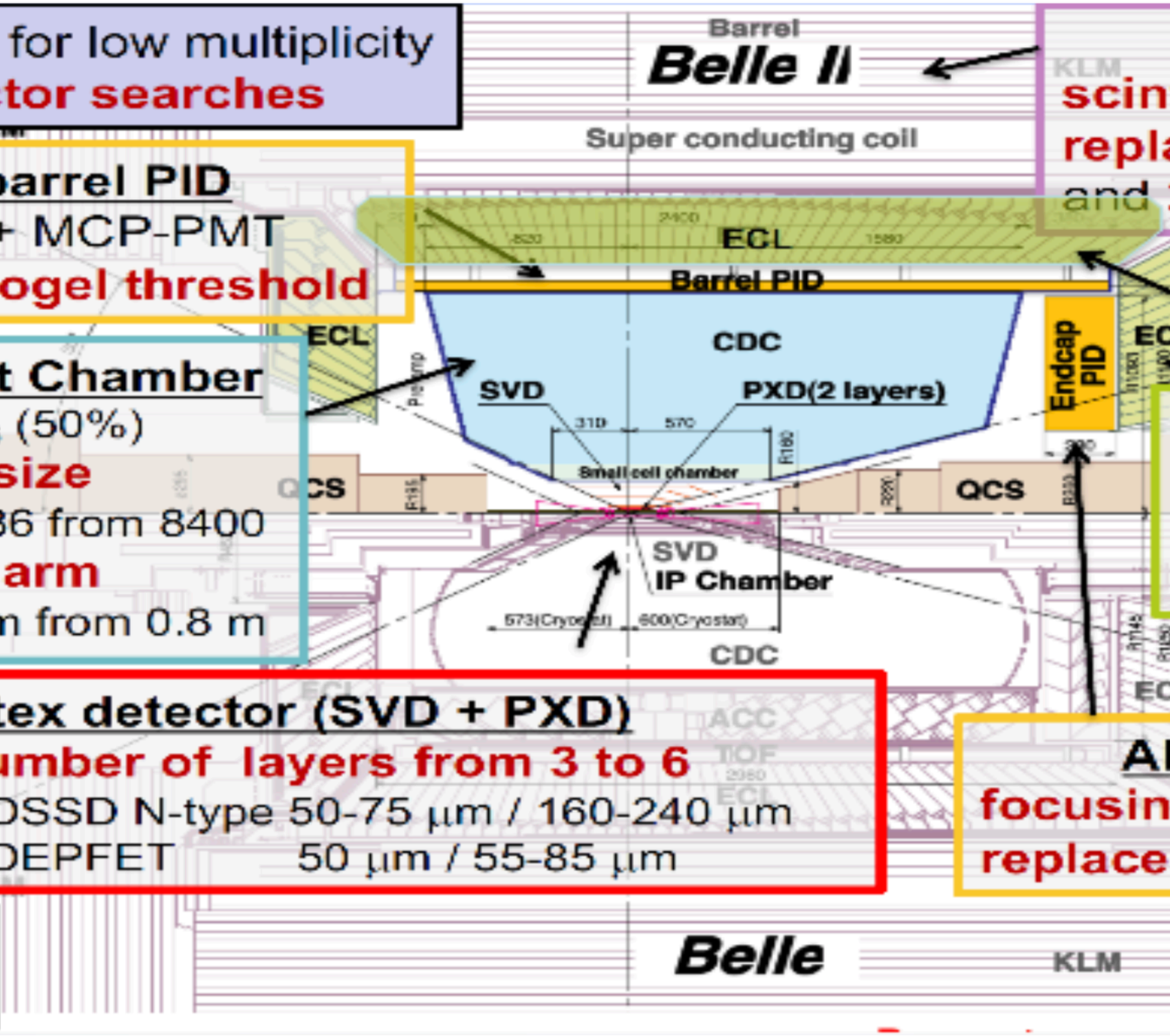
New trigger: for low multiplicity and **dark sector searches**

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

Magnet
1.5 Tesla



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

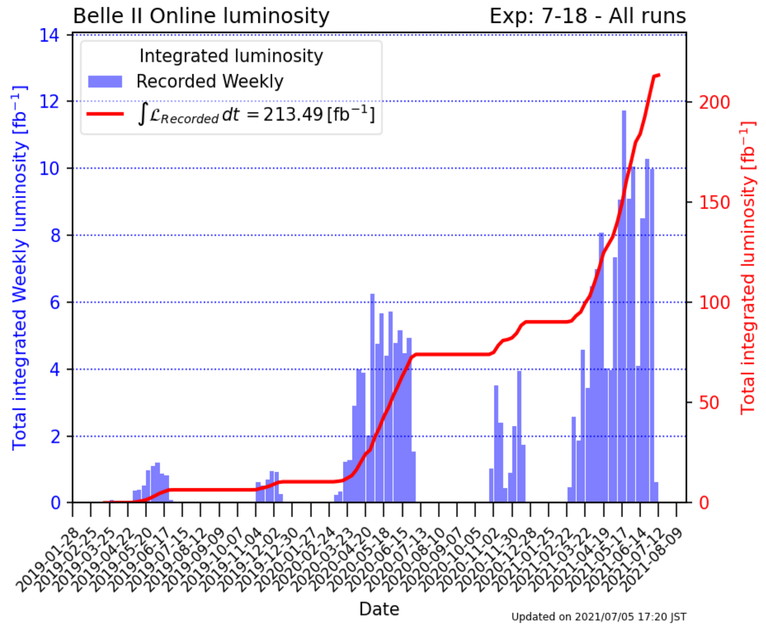
ECL: Calorimeter
CsI(Tl) crystals + PIN-PD
electronics upgrade
for waveform sampling

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

7 m height
7.5 m length

Belle II current status

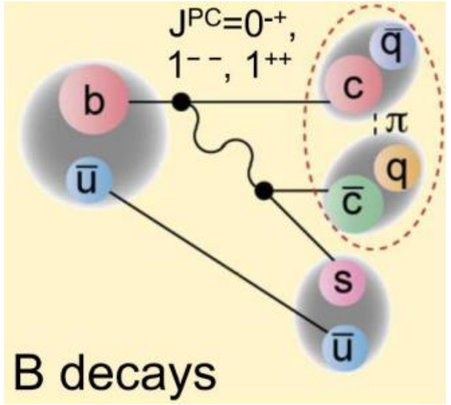
- Running at $\Upsilon(4S)$
  - Recorded $213.49\ \mathrm{fb}^{-1}$!
    - Luminosity record: $3.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, Goal: $65 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
    - Will accumulate around $50\ \mathrm{ab}^{-1}$ around 2031
  - By 2022 Belle II should have as much $\Upsilon(4S)$ as Belle
    - Many analysis already ongoing, just need more data
    - Rediscovery analysis
    - Feasibility studies for future

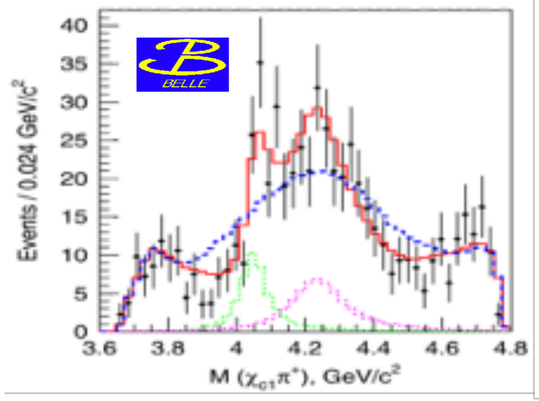


Charmonium-like states

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

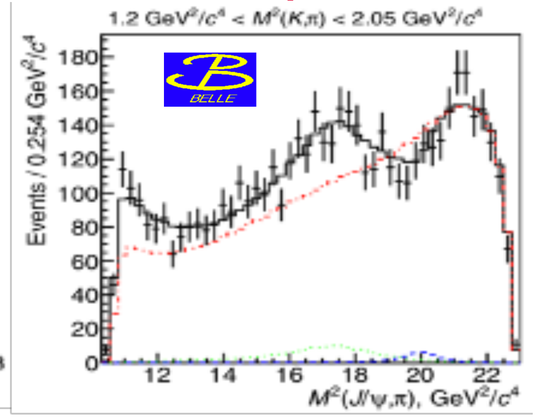
- Confirm Z_c states $Z(4050)^+$, $Z(4200)^+$, $Z(4250)^+$ and search for neutral partners
- Full amplitude analysis to $B \to K\omega J/\psi$ and $B \to K\omega\chi_{c1}$ to determine the spin-parities of X(3915), $Z(4050)^+$ and $Z(4250)^+$.
- Confirmation of $X(3872)$ width measurement with $D^0\bar{D}^0\pi^0$ mode, search for more open-flavor decay modes, e.g., $B \to K(D\bar{D})$, $B \to K(D\bar{D}^*)$, $B \to K(D^*\bar{D}^*)$, $B \to K(D\bar{D}^{**})$ and ....
- Absolute branching fractions are unique for Belle II





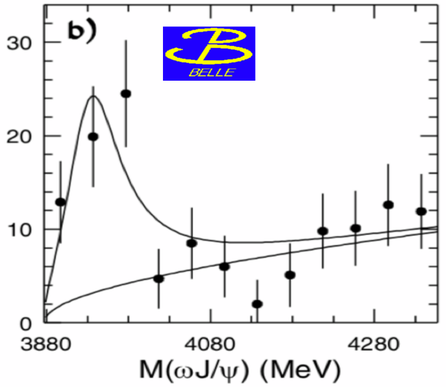
$Z(4050/4250)^+ \to \pi^+\chi_{c1}$

PRD 78, 072004



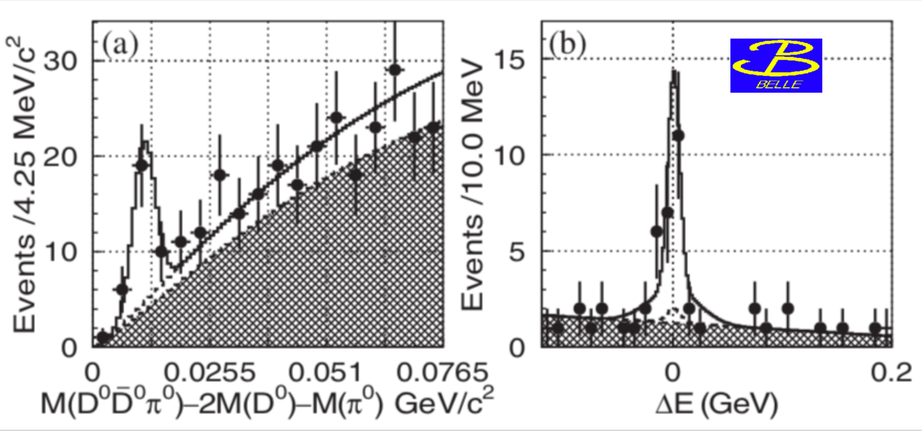
$Z(4200/4430)^+ \to \pi^+ J/\psi$

PRD 90, 112009



$X(3915) \to \omega J/\psi$

PRL 94, 182002



$B \to KX(3872)(\to D^0\bar{D}^0\pi^0)$

PRL 97, 162002

Rediscovery of X(3872)

Reconstruction of final states

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

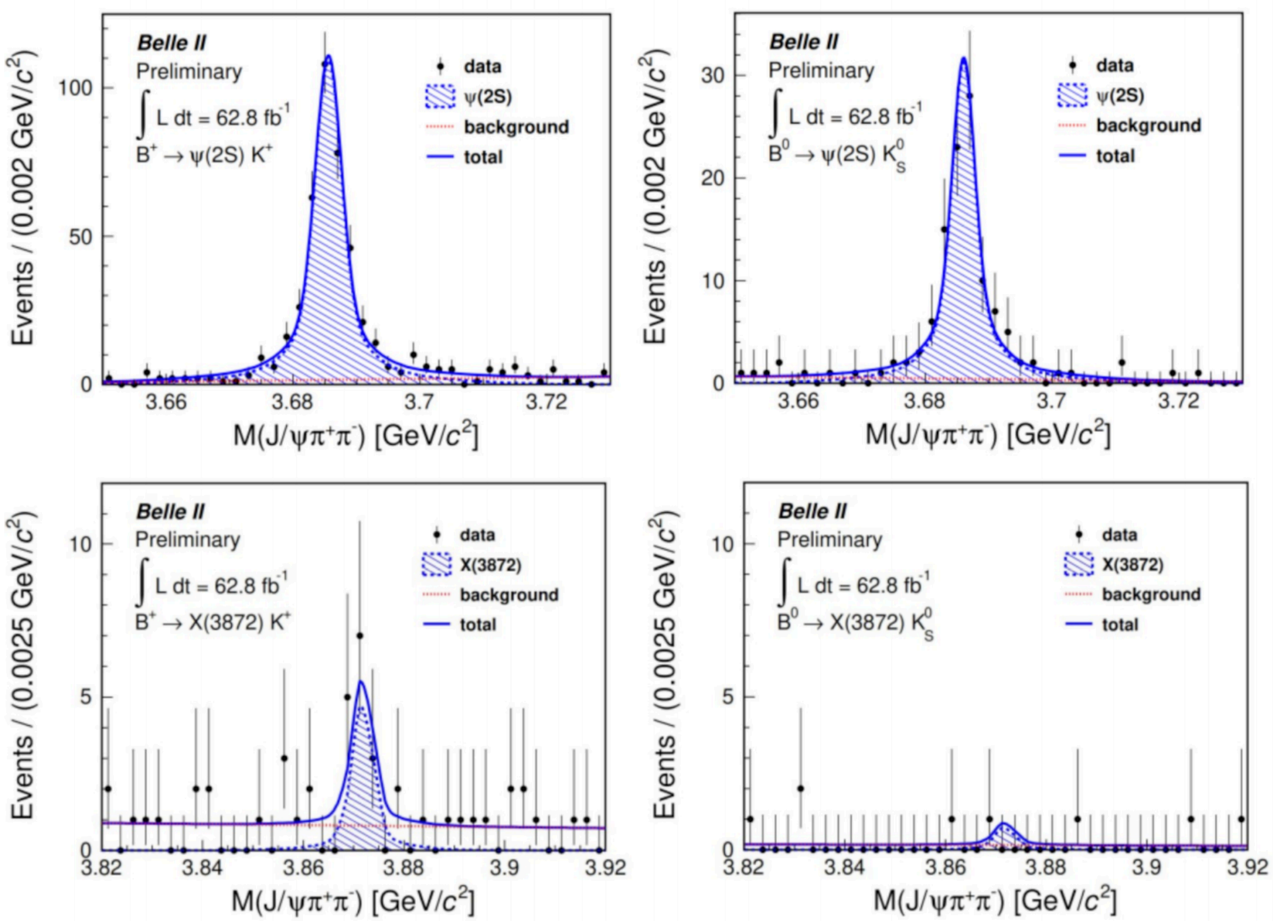
Selection criteria

- Particle identification
- Continuum suppression
- Kinematics criteria: M_{bc}, $|\Delta E|$

Significant $B \to \psi(2S)\ K$,

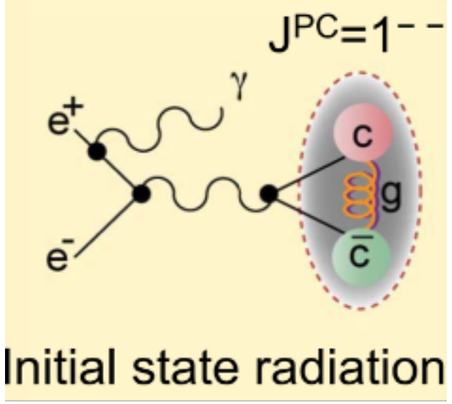
First X(3872) at Belle II

- 14.4 ± 4.6 events (4.6σ)



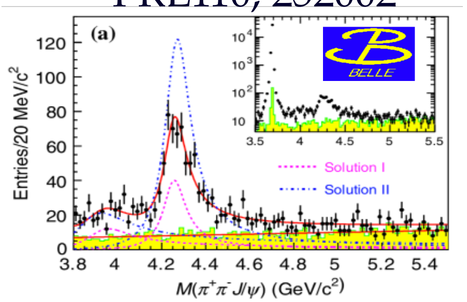
(2) ISR processes:

- Confirm Z_c states and search for neutral partners
- Higher mass region (>4.9 GeV) is unique for Belle II
- Measure more precisely the line-shapes of more final state, including open-charm charm final states.



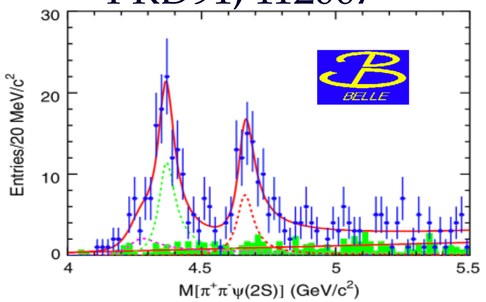
- Search for more Y states in more process, such as Y →charmed baryon pairs, charmed strange meson pairs

PRL110, 252002



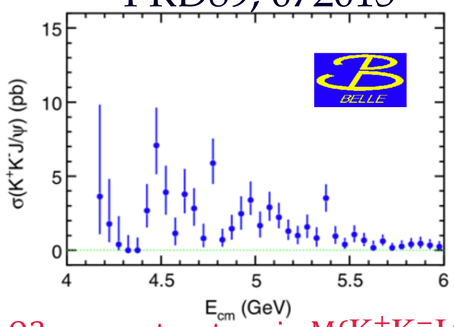
Q1: existence of the Y(4008) ?

PRD91, 112007



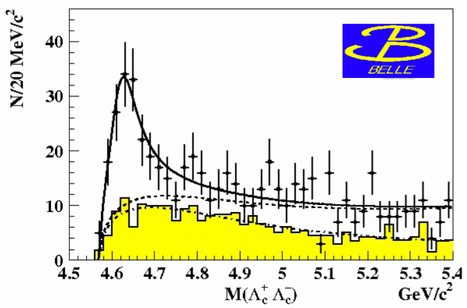
Q2: existence of the Y(4260) ?

PRD89, 072015



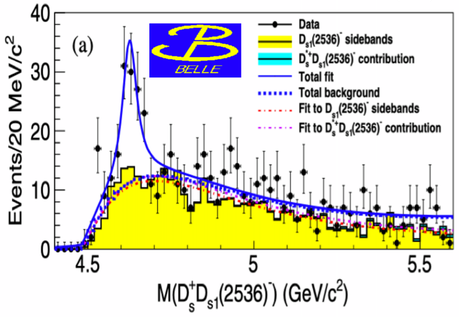
Q3: more structure in $M(K^+K^-J/\psi)$?

PRL 101, 172001

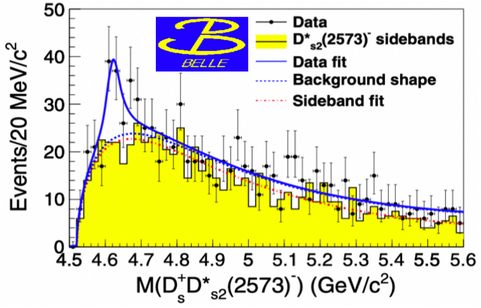


Q4: same?

PRD 100, 111103(R)



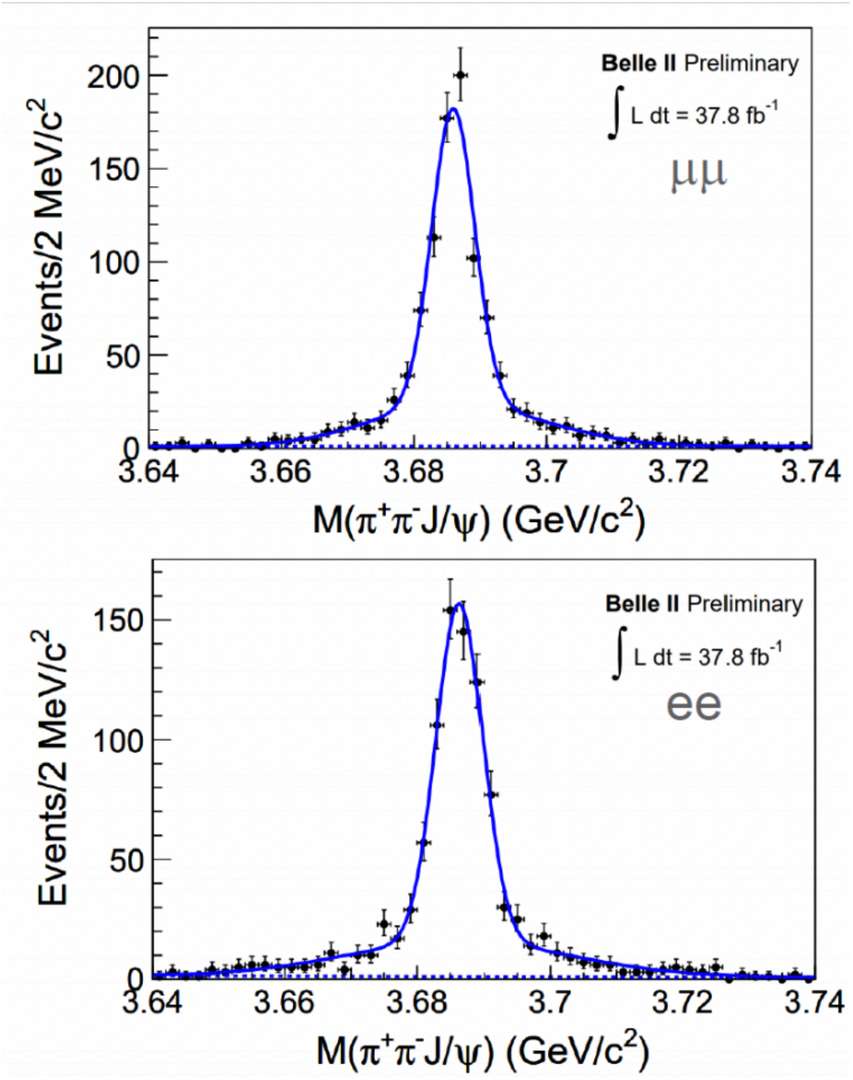
PRD 101, 091101(R)



Mode	Mass/MeV	Width/MeV
$\Lambda_c^+\bar{\Lambda}_c^-$	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
$\pi^+\pi^-\psi(2S)$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
$D_S^+D_{S1}(2536)^-$	$4626^{+7}_{-7} \pm 1$	$50^{+14}_{-12} \pm 4$
$D_S^+D_{S1}^*(2573)^-$	$4620^{+9}_{-8} \pm 3$	$47^{+32}_{-15} \pm 5$

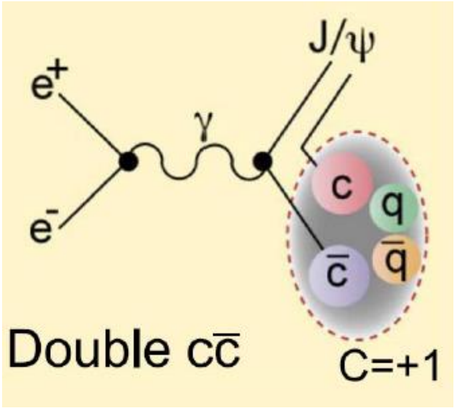
ISR preliminary studies

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

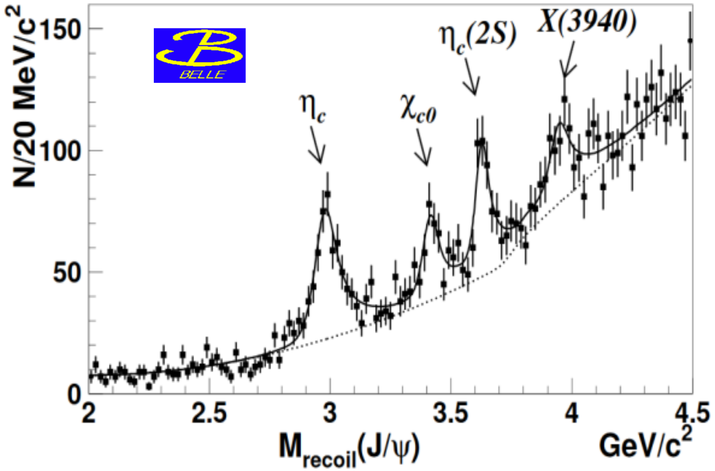


(3) Double charmonium processes:

- $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
- Rediscovery of $X(3940,\ 4160)$
- Expand to other $c\bar{c}$ (h_c, η_c, $\eta_c(2S)$, $\psi(2S)$, χ_{cJ}, etc.), search for new states

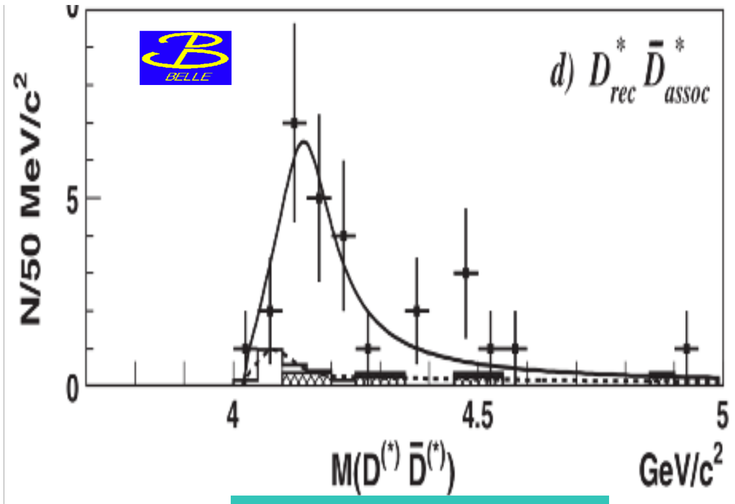


PRL 98, 082001



$X(3940) \to D\bar{D}^*$

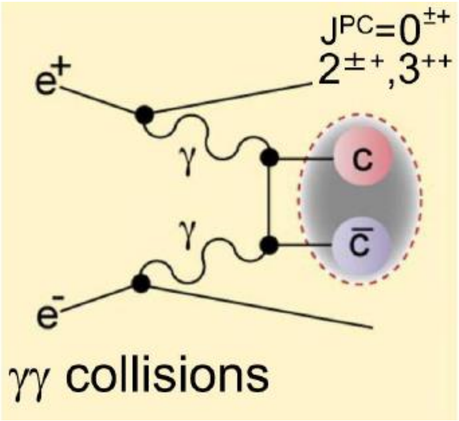
PRL 100, 202001



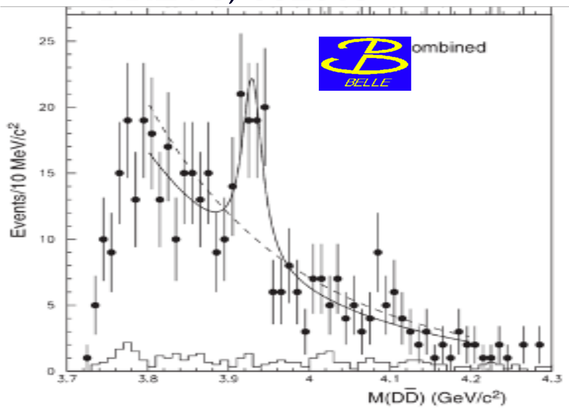
$X(4160) \to D^*\bar{D}^*$

(4) Two-photon processes:

- Give more precise parameters of $X(3930)$ ($\chi_{c2}(2P)$)
- Determine J^P values for some confirmed states, like $X(3915)$ ($\chi_{c0}(2P)$?)
- Confirm some states with evidence, like $X(4350)$?
- Search for X(4500) and X(4700) via two photons processes

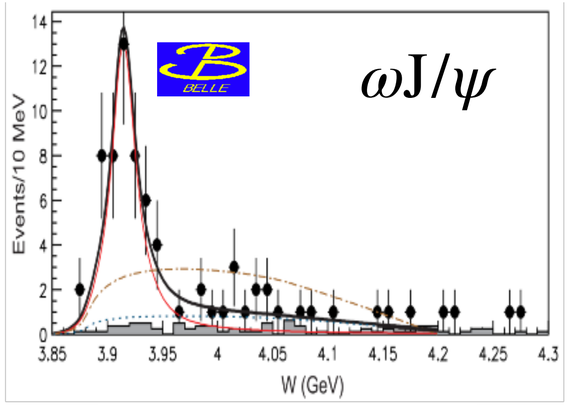


PRL 96, 082003



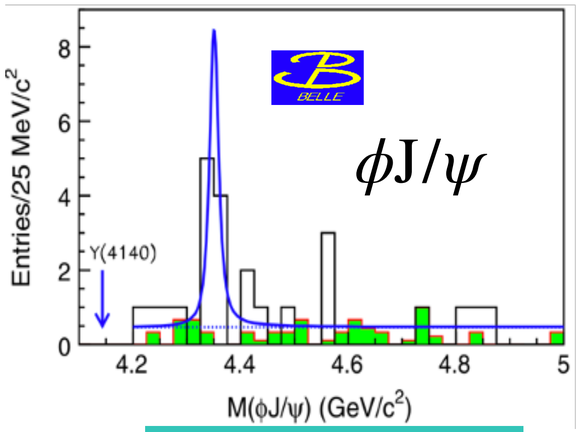
X(3930) → $D\bar{D}$

PRL 104, 092001



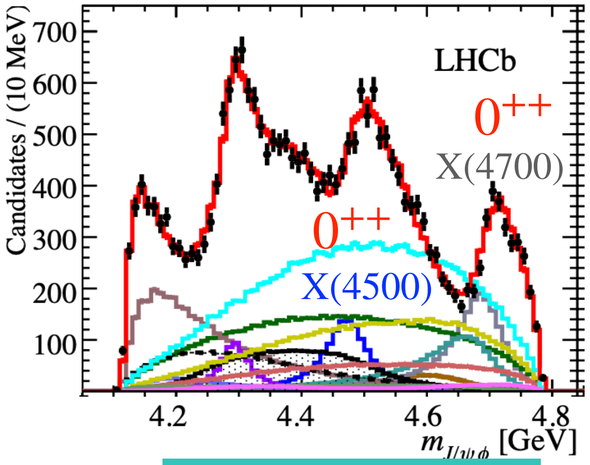
X(3915) → $\omega J/\psi$

PRL 104, 112004



X(4350) → $\phi J/\psi$

arXiv: 2103.01803

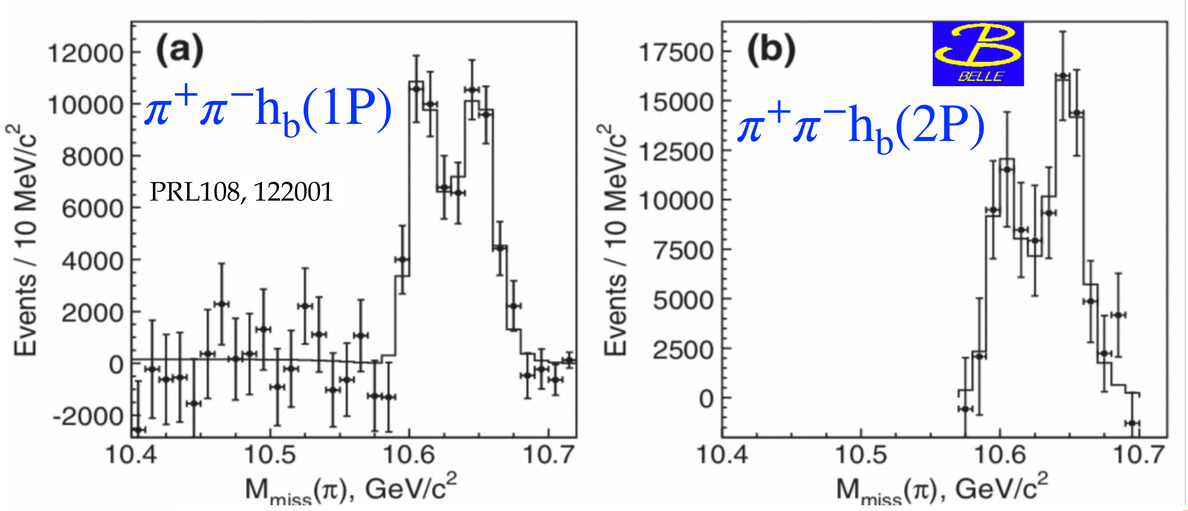


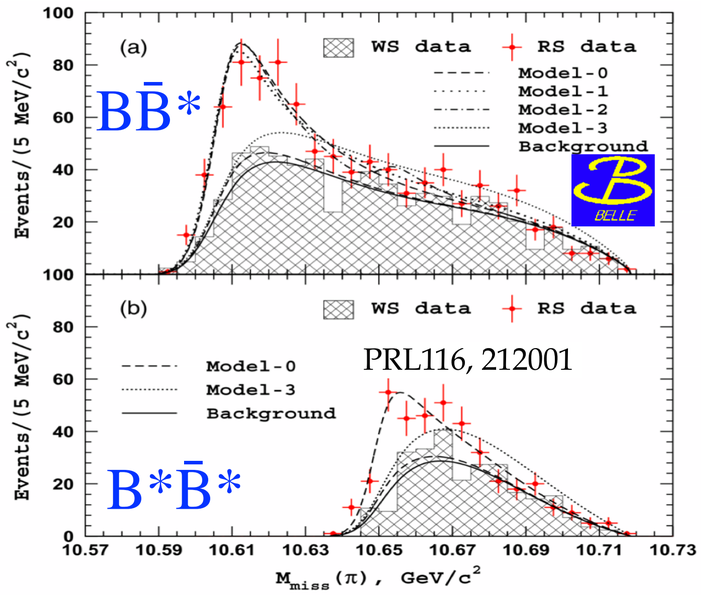
$B^+ \to J/\psi\phi K^+$

Bottomonium-like states

Search for new exotic states at Belle II

- Observed $Z_b(10610)$ and $Z_b(10650)$ in $\Upsilon(5S)\,\pi\pi$ transitions
- The decays $Z_b(10610) \to B\bar{B}^*$ and $Z_b(10650) \to B^*\bar{B}^*$ are dominant.





The expected molecular states with the structures $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$

$I^G(J^P)$	Name	Content	Co-produced particles [Threshold, GeV/c^2]	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z_b'	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], γ [10.56]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(0^+)$	W_{b0}'	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$, $\eta_b(nS)\pi$
$1^-(1^+)$	W_{b1}	$B\bar{B}^*$	ρ [11.38], γ [10.61]	$\Upsilon(nS)\rho$
$1^-(2^+)$	W_{b2}	$B^*\bar{B}^*$	ρ [11.43], γ [10.65]	$\Upsilon(nS)\rho$
$0^-(1^+)$	X_{b1}	$B\bar{B}^*$	η [11.15]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^-(1^+)$	X_{b1}'	$B^*\bar{B}^*$	η [11.20]	$\Upsilon(nS)\eta$, $\eta_b(nS)\omega$
$0^+(0^+)$	X_{b0}	$B\bar{B}$	ω [11.34], γ [10.56]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$, $\eta_b(nS)\eta$
$0^+(0^+)$	X_{b0}'	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$, $\eta_b(nS)\eta$
$0^+(1^+)$	X_b	$B\bar{B}^*$	ω [11.39], γ [10.61]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$
$0^+(2^+)$	X_{b2}	$B^*\bar{B}^*$	ω [11.43], γ [10.65]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$

arXiv: 1610.01102

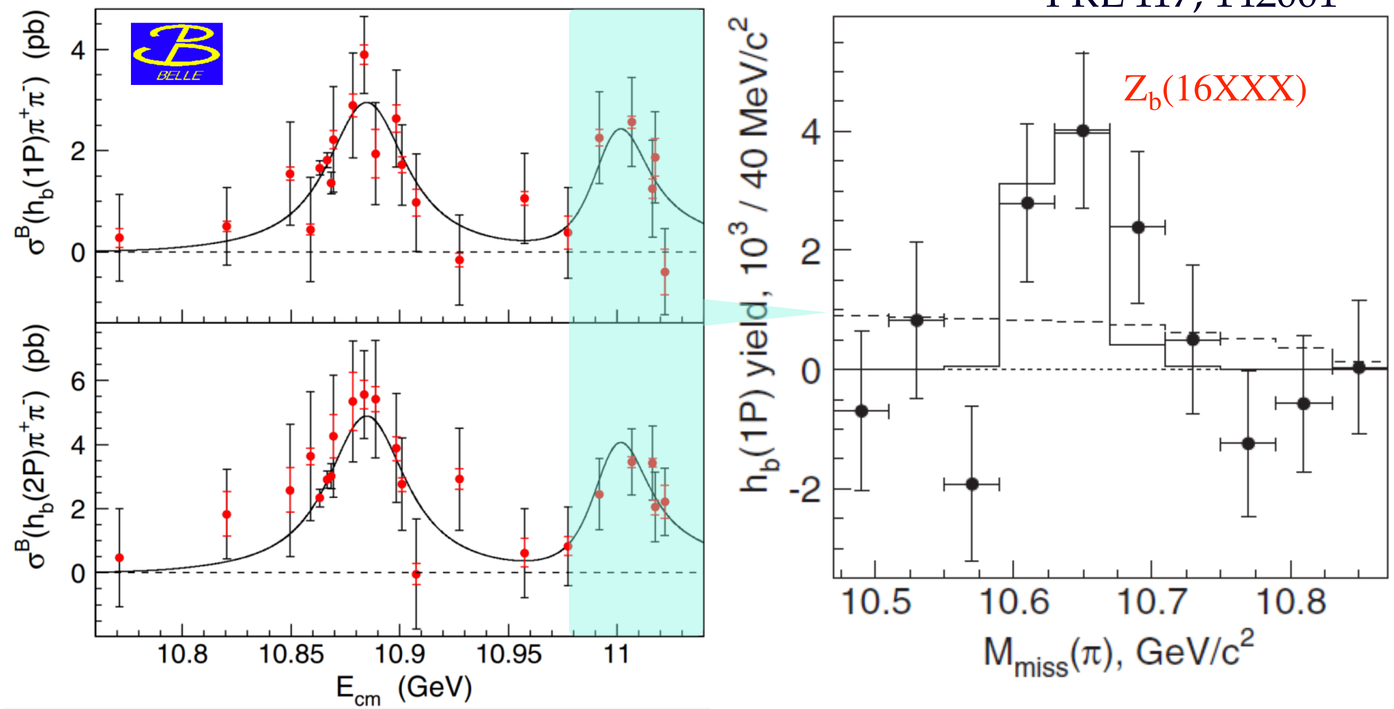
Potential $\Upsilon(6S)$ at Belle II

- Belle limited by statistics
- $< 1\ \mathrm{fb}^{-1}$ per scan point

- $\Upsilon(6S) \to \pi^+\pi^- X$
  - Evidence for Z_b

- Include other decay modes
- Investigate nature of $\Upsilon(6S)$ and Z_b, how many ? Neutral partner ?

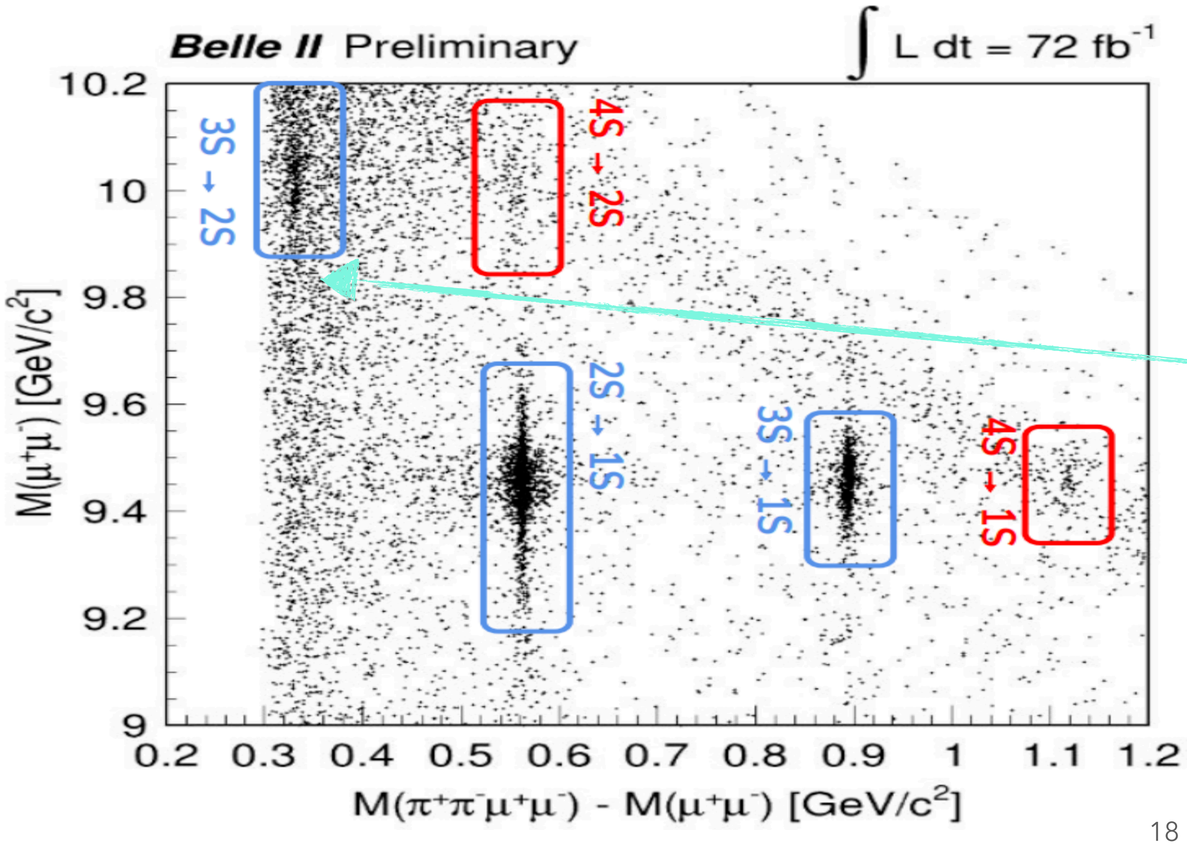
PRL 117, 142001



Dipion transition among bottomonia

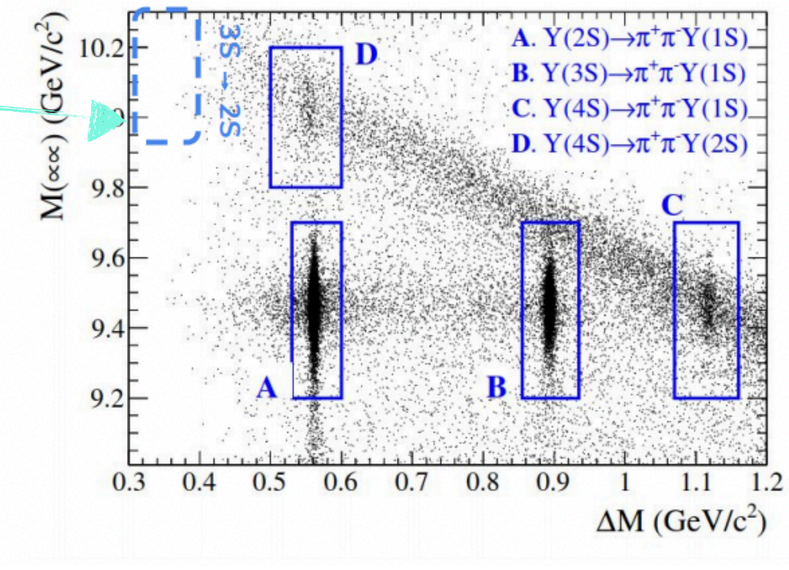
Study $e^+e^- \to \pi^+\pi^-\mu^+\mu^-(+\gamma_{ISR}$ undetected)

- **$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(nS)$**
- **$e^+e^- \to \gamma_{ISR}\Upsilon(mS)$, $\Upsilon(mS) \to \pi^+\pi^-\Upsilon(nS)$**



Compared with Belle, 496 fb^{-1}

improved low momentum tracking



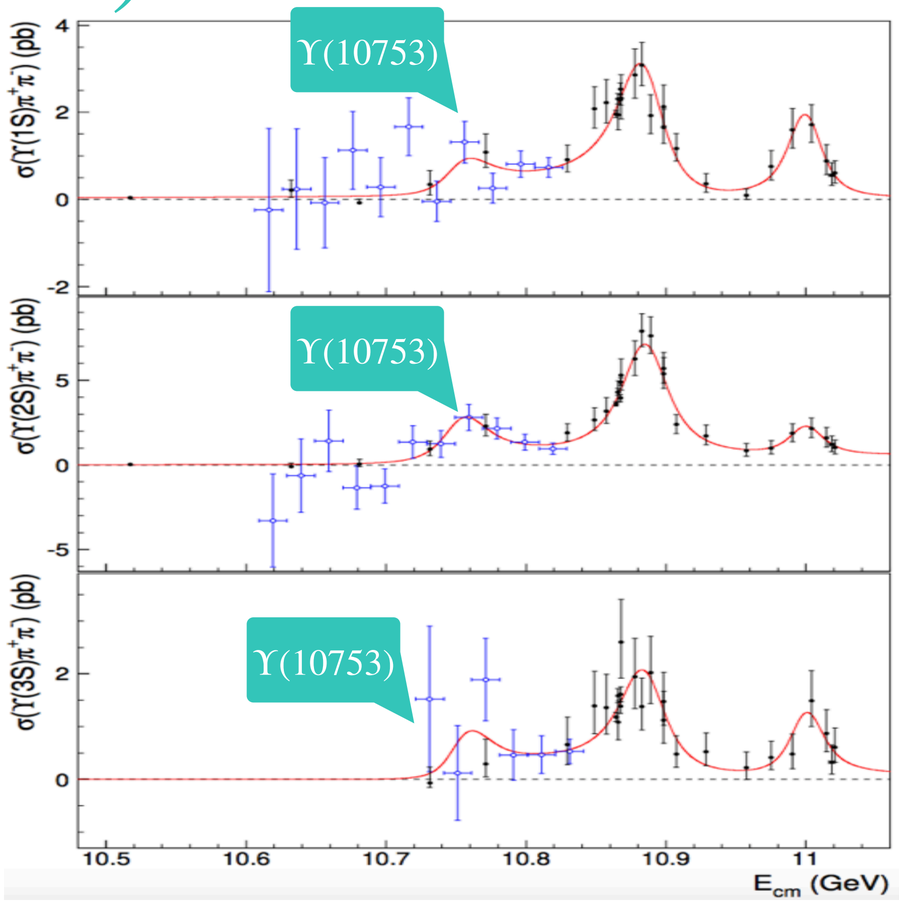
Belle

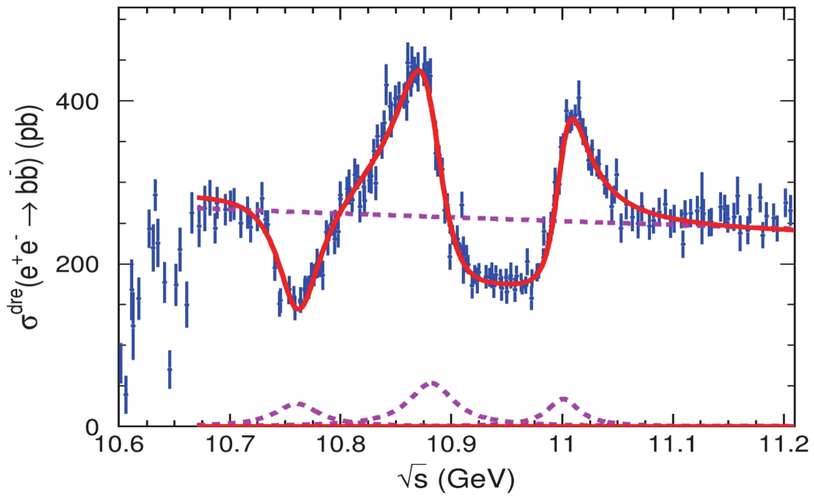
PRD 96 (2017) 5, 052005

About $\Upsilon(10753)$

Recent result: JHEP 10 (2019) 220 (Belle)

- $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$
  - $\Upsilon(nS) \to e^+e^-, \mu^+\mu^-$
  - $n = 1, 2, 3$
- High-stat scan point: 1 fb^{-1} each (black)
- +ISR process at the $\Upsilon(10860)$ [$\Upsilon(5S)$] (blue)
- New $J^{PC} = 1^{--}$ structure
  - Significance of 5.2σ



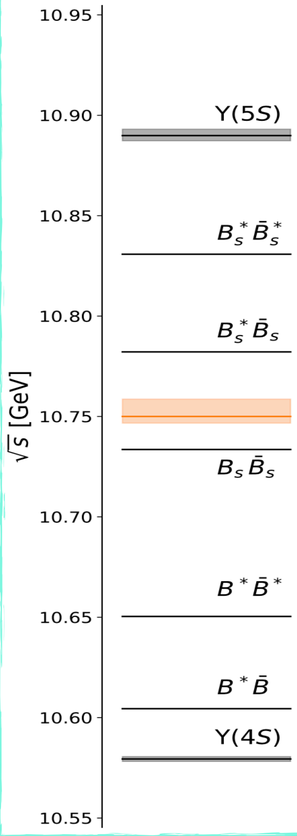


- Chin. Phys. C 44 8,083001 (2020):
  - Refit the Belle + BaBar R_b scan
  - Evidence of $\Upsilon(10753)$ in interference

About $\Upsilon(10753)$

Possible interpretations

- **Unlikely to be a molecule as it's far from any S-threshold**



Conventional
D- os S-D mixed state

Phys.Rev.D 101 (2020) 1, 014020
Phys.Lett.B 803 (2020) 135340
Eur.Phys.J.C 80 (2020) 1, 59

"Exotica"

Arxiv:2008.05605
Chin.Phys.C 43 (2019) 12, 123102
Phys.Lett.B 802 (2020) 135217
Phys.Rev.D 102 (2020) 1, 014036

Working plans

End of 2021

Taken data at:

- 10.751 GeV (9.5 fb^{-1}) (on resonance)
- 3 scan point for $B\bar{B}$ decomposition study
  - 10.657 GeV (1.5 fb^{-1})
  - 10.706 GeV (3.5 fb^{-1})
  - 10.810 GeV (2.0 fb^{-1})

Summary

Physical run started in March 2019: There are much better vertexing, particle ID, etc than those at Belle.

Belle II plays an important role to resolve the existing puzzles in quarkonium field with its huge statistical samples.

- Confirm or reject the observed unconventional states
- Precise measurements of the properties of the observed exotics
- Search for missing conventional states and new exotics

We expect many exciting results in the coming years !