Exotic and Conventional Quarkonium Physics Prospects at Belle II

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On behalf of the Belle II Collaboration
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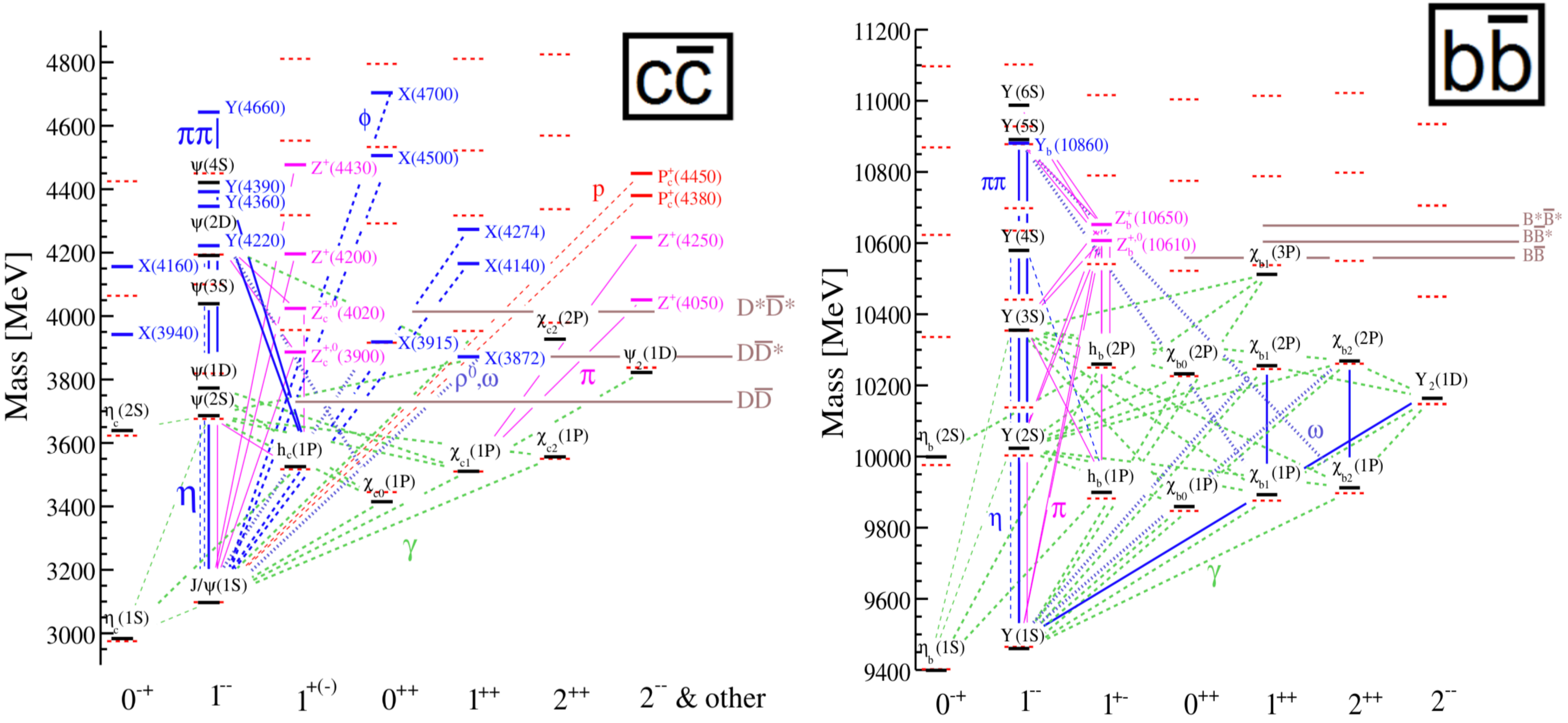
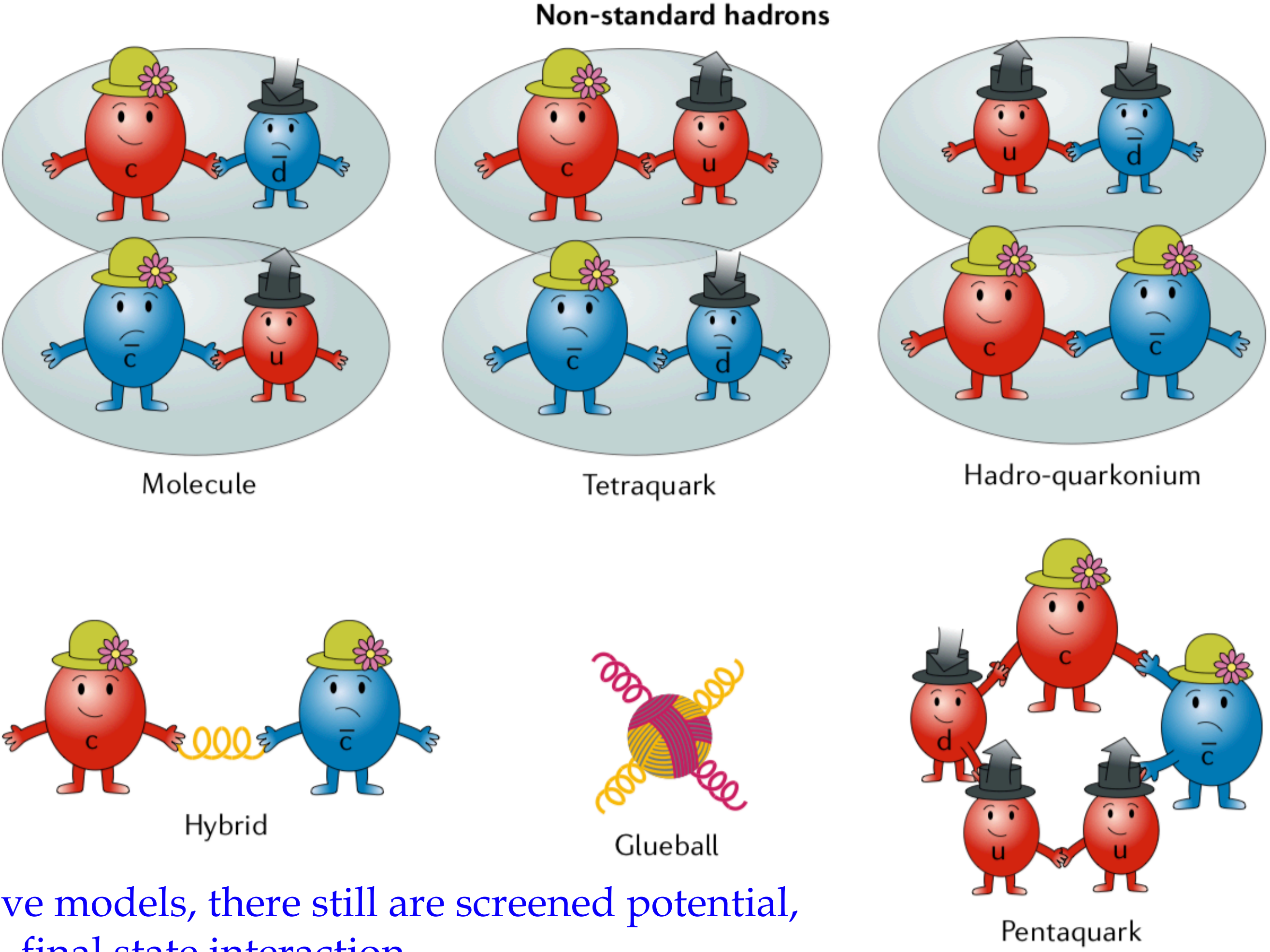
Quarknium



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



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

Nature Reviews Physics 1, 480 (2019)

<u>High Priority:</u>

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

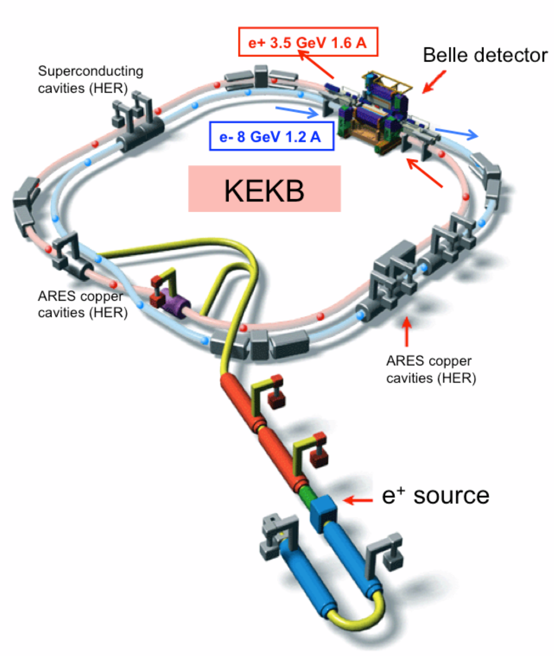
Overview

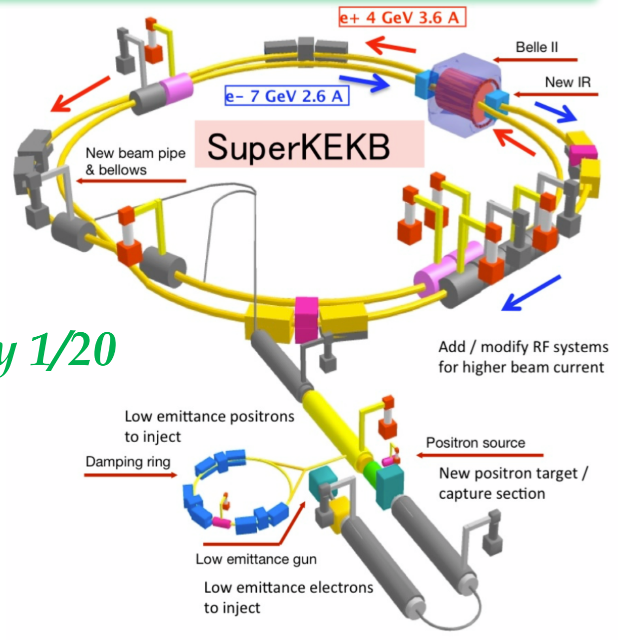
- SuperKEKB and Belle II detectors
- Charmonium(-like) prospects at Belle II
- Bottomonium(-like) prospects at Belle II
- Summary

SuperKEKB

- 1st Vs. 2nd generation B-factory

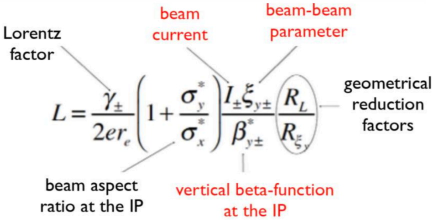
$$\int^{\text{goal}} \mathcal{L}\, dt = 50\ \text{ab}^{-1} = 50 \times \mathcal{L}^{\text{int}}_{\text{Belle}}$$



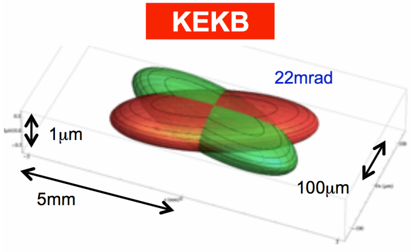


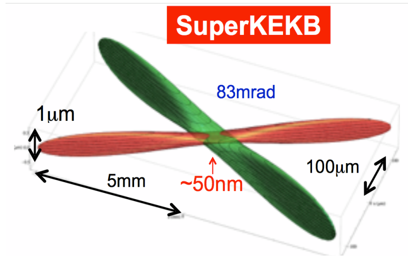
- *Double beam currents*
- *Squeeze beams @IP by 1/20*
- *Reduced CM boost*

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



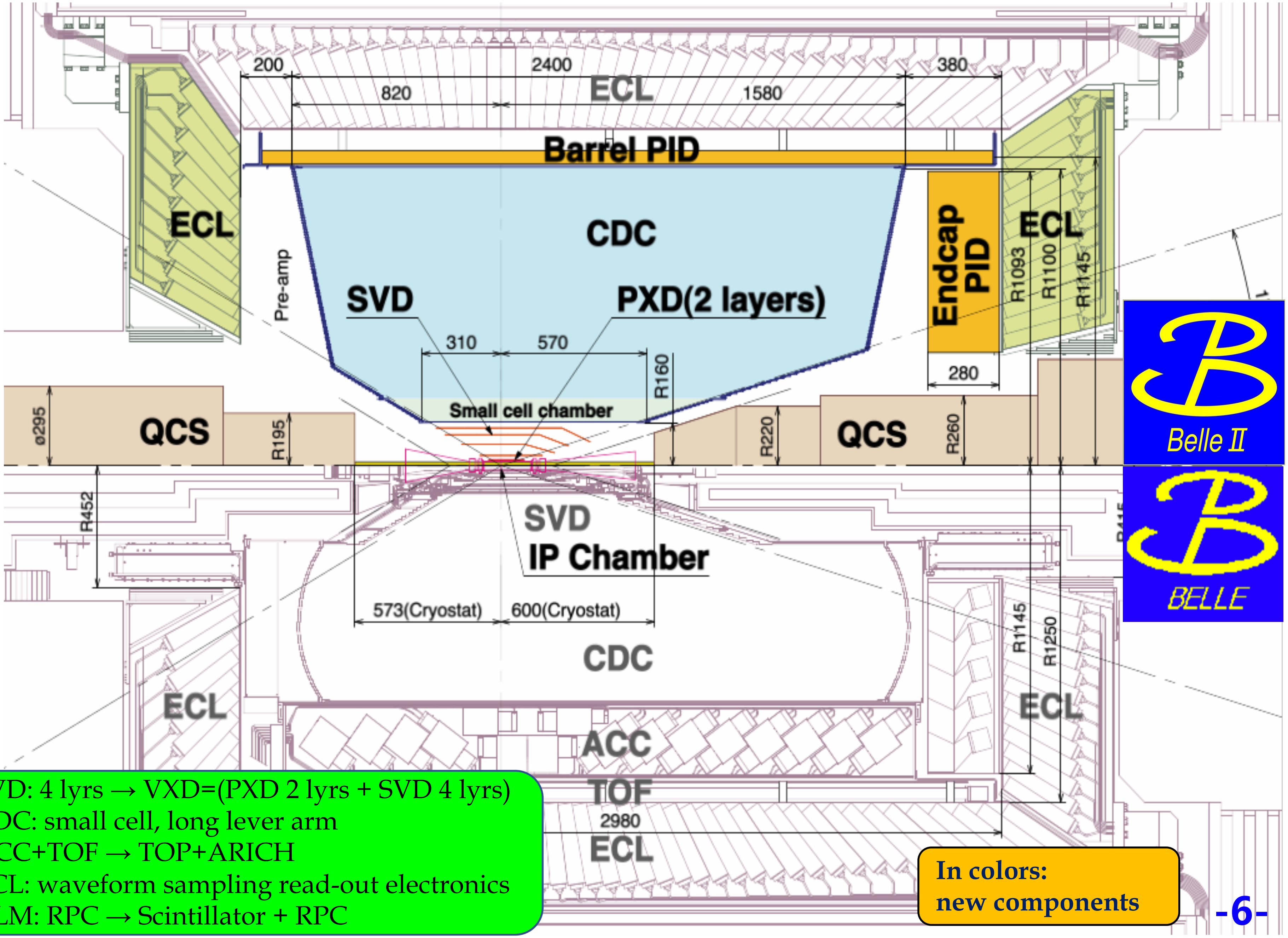
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$





	$E_\pm$ (GeV) LER/HER	Cross Angle (mrad)	$I_\pm$ (A) LER/HER	β_y^* (mm) LER/HER	$\mathcal{L}$ $(cm^{-2}s^{-1})$
KEKB	3.5/8.0	22	1.64/1.19	5.9/5.9	2.1×10^{34}
SuperKEKB	4.0/7.0	83	3.60/2.60	0.27/0.31	80×10^{34}
	$\beta\gamma \sim 2/3$		×2	×20	×40

Detector: Belle Vs. Belle II

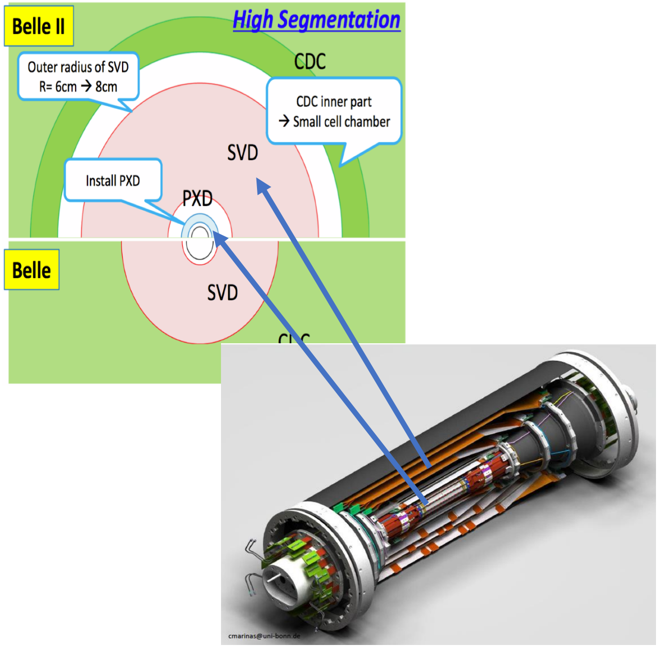


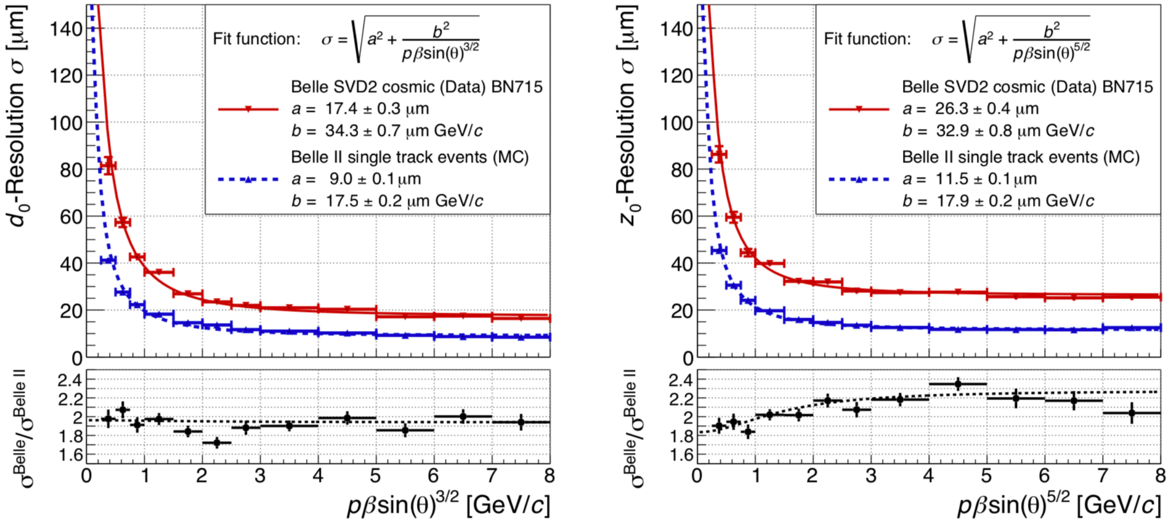
SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC

In colors:
new components

Detector highlights at Belle II

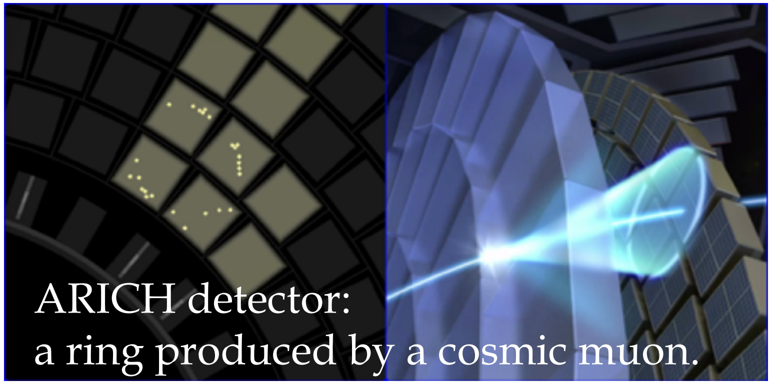
- **New Vertex Detectors: PXD + SVD**



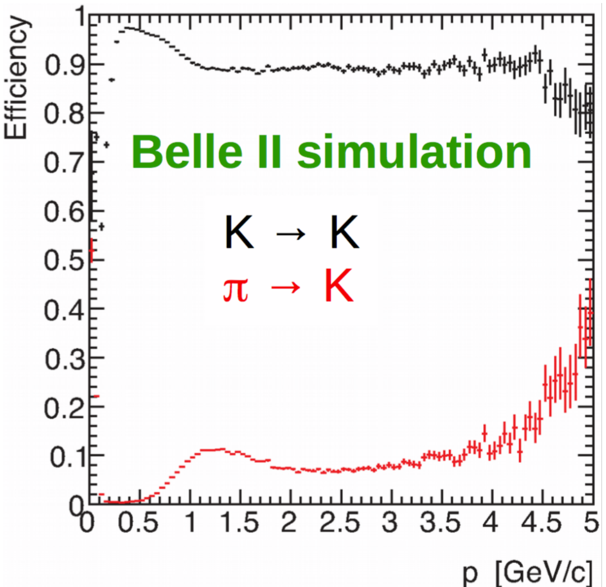


d0: along the beam direction
z0: perpendicular to the beam direction

- **New PID System: Barrel TOP + Endcap ARICH**



ARICH detector:
a ring produced by a cosmic muon.

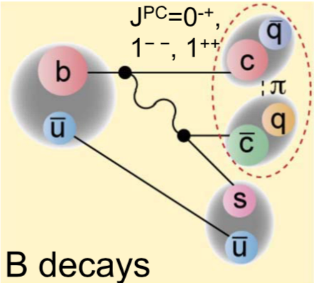


- **higher machine backgrounds (×20)**
- **higher event rate (×10)**

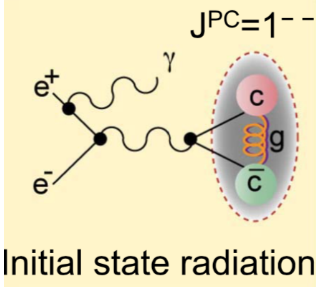
Charmonium(-like) states

Production of charmonium(-like) states at B-factory

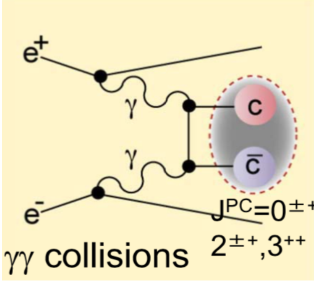
- **B decay** ($B \to KX_{c\bar{c}}$)
  - CKM favored process, large branching fractions $10^{-3} \sim 10^{-4}$
  - $J^{PC} = 0^{-+}, 1^{--}, 1^{++}, \ldots$



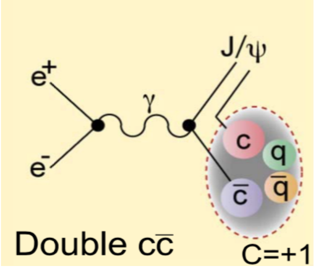
- **Initial-state radiation (ISR)**
  - $J^{PC} = 1^{--}$



- **Two-photon process**
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}, 2^{-+}, \ldots$



- **Double charmonium**
  - e.g. $e^+e^- \to J/\psi X(3940)$ [PRL 98, 082001 (2007)]



Expected statistics @50 ab-1 of XYZ

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

Charmonium(-like) in B decays

Charmonium(-like) states are produced in B meson decays in association with a kaon: **$B \to KX_{c\bar{c}}$**

- Both the B and the kaon are spinless, therefore the state $X_{c\bar{c}}$ is produced polarized.
- The absolute branching fractions of the $X_{c\bar{c}}$ can be measured.

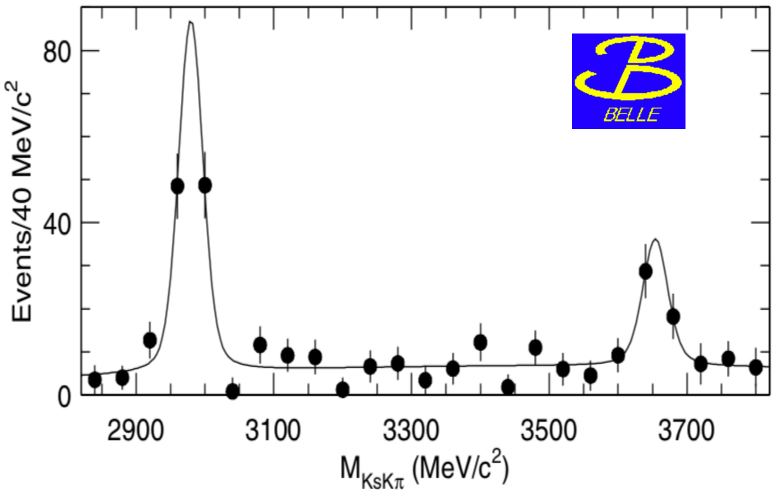
Remarkable charmonium mesons in B decays at Belle:

- $\eta_c(2S) \to K_S^0 K\pi$
- $\psi_2(1D) \to \gamma\chi_{c1}$

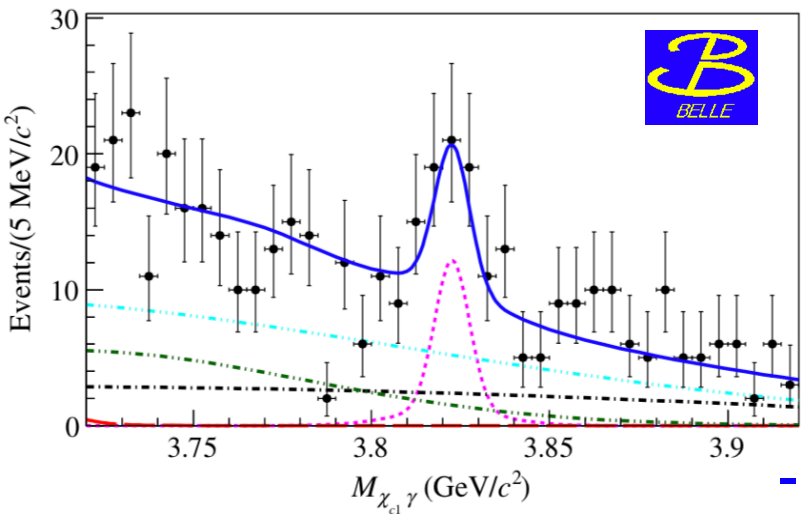
Search for missing narrow charmonium $\boldsymbol{\eta_{c2}(1D)}$ at Belle II

- ➢ $J^{PC} = 2^{-+}$
- ➢ Expect to reside between the $D\bar{D}$ and $D\bar{D}^*$ thresholds
- ➢ A promising search channel: $B \to K(h_c\gamma)$

PRL89, 102001

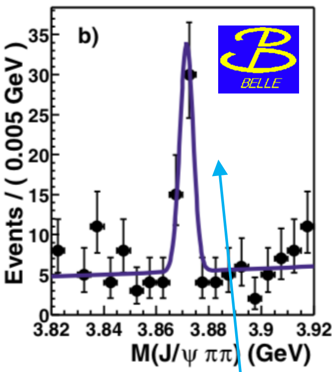


PRL111, 032001

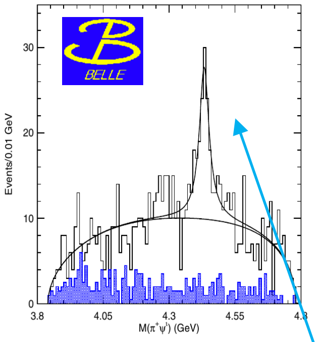


Remarkable charmonium-like mesons in B decays ($B \to KX_{c\bar{c}}$)

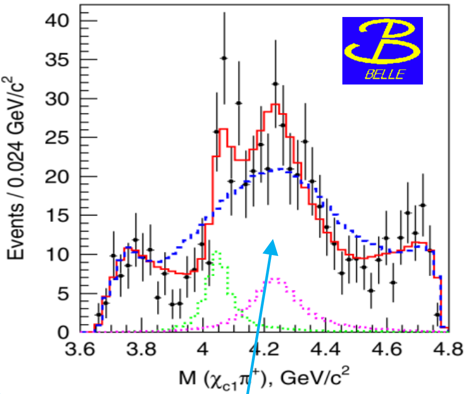
PRL91, 262001



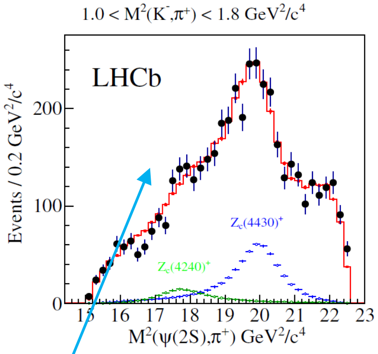
PRL100, 142001



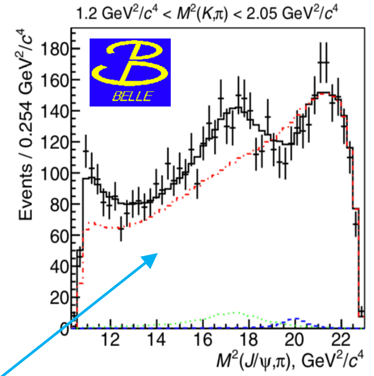
PRD78, 072004

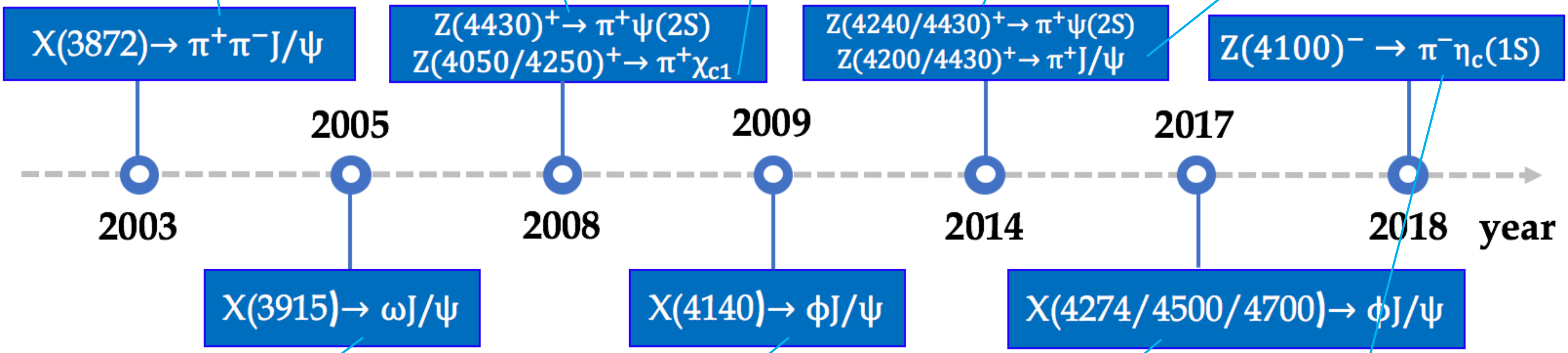


PRL112, 222002



PRD90, 112009





$X(3872) \to \pi^+\pi^- J/\psi$

$Z(4430)^+ \to \pi^+\psi(2S)$
$Z(4050/4250)^+ \to \pi^+\chi_{c1}$

$Z(4240/4430)^+ \to \pi^+\psi(2S)$
$Z(4200/4430)^+ \to \pi^+ J/\psi$

$Z(4100)^- \to \pi^-\eta_c(1S)$

2005 2009 2017

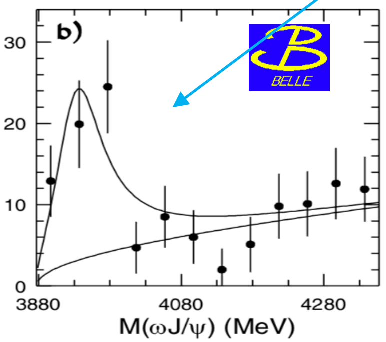
2003 2008 2014 2018 year

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

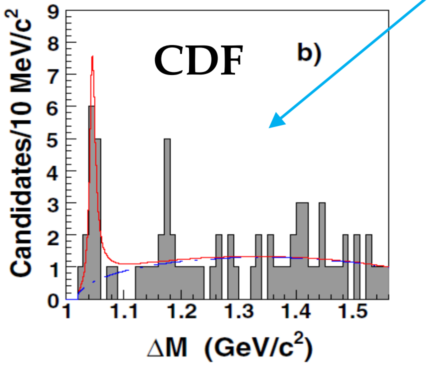
$X(4140) \to \phi J/\psi$

$X(4274/4500/4700) \to \phi J/\psi$

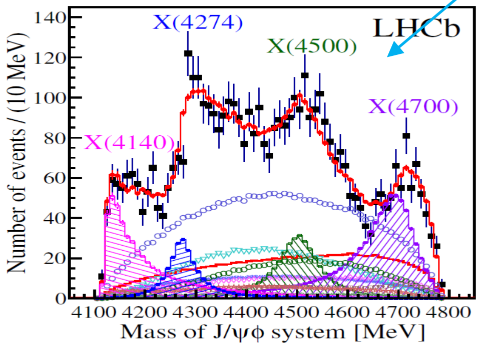
PRL94, 182002



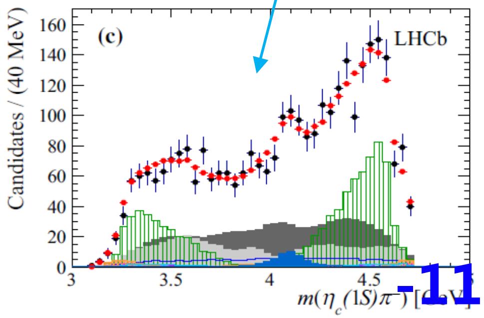
PRL102, 242002



PRL118, 022003

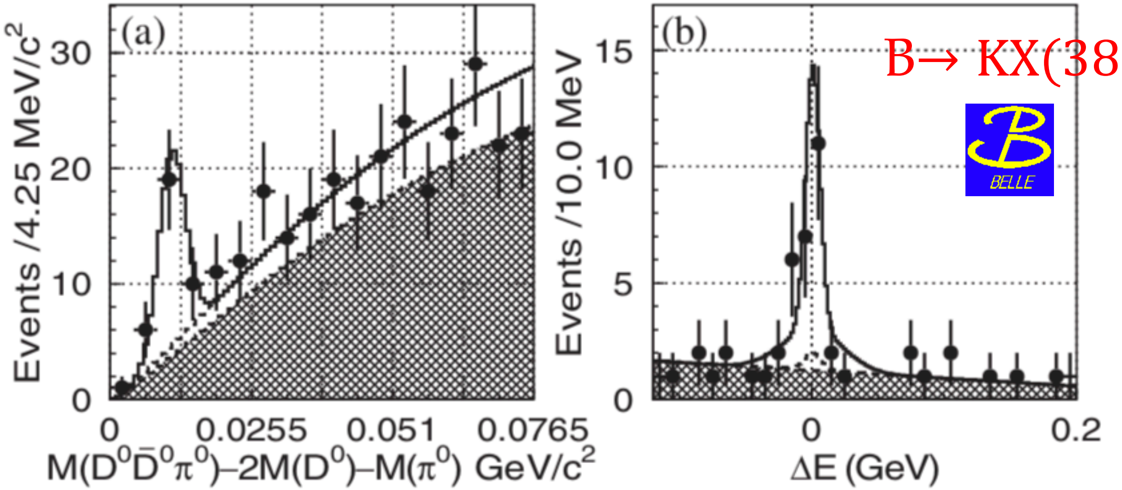


EPJC78, 1019



Further investigations at Belle II with more B mesons

1. 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 $B \to K(D^*\bar{D}^{**})$



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

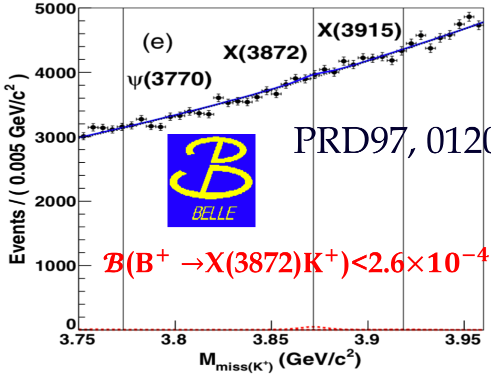
PRL 97, 162002

2. Confirm the $Z(4050)^+$, $Z(4200)^+$, $Z(4250)^+$ and high mass X state.

3. Full amplitude analysis to $B \to K\omega J/\psi$ and $B \to K\pi\chi_{c1}$ decays to determine the spin-parities of the X(3915), $Z(4050)^+$, and $Z(4250)^+$.

4. Absolute branching fraction measurements

5. Systematic investigations of charmonium plus light hadron final states: ***$B \to K(c\bar{c}+h)$***



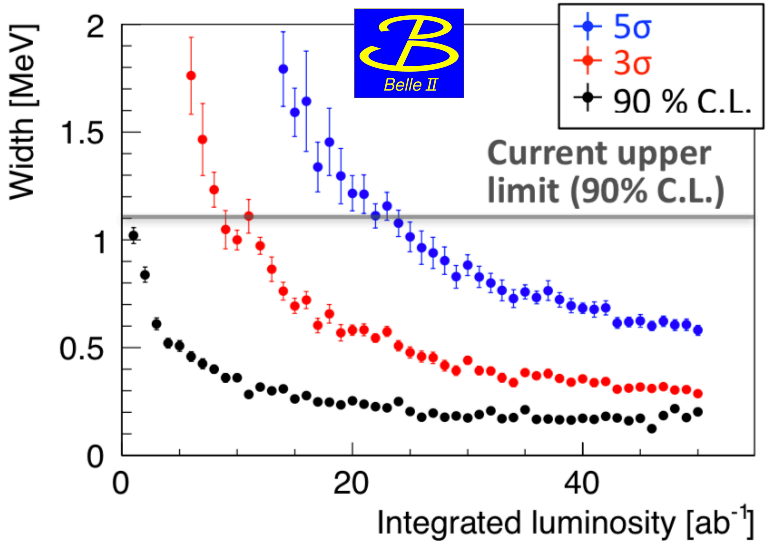
PRD97, 012005

$\mathcal{B}(B^+ \to X(3872)K^+) < 2.6 \times 10^{-4}$ at 90% C.L.

Sensitivity of X(3872) total width and search for X(4014) at Belle II

Sensitivity of X(3872) total width

$B^{\pm} \to K^{\pm} X(3872)(\to D^0 \bar{D}^0 \pi^0)$



With the full data sample of Belle II (50 ab^{-1}), total width with values up to

[90% C.L.] ~ 180 keV

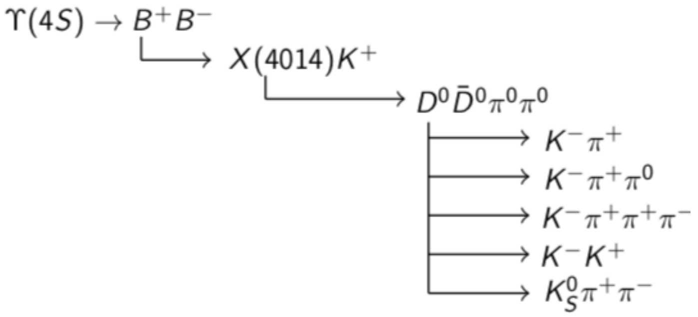
[3σ significance] ~ 280 keV

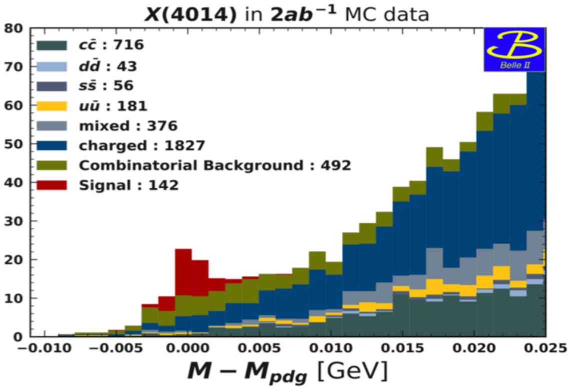
[5σ significant] ~ 570 keV

can be measured.

For details, please see Hikari's report "Sensitivity to the X(3872) total width at the Belle II experiment".

Search for X(4014) at Belle II



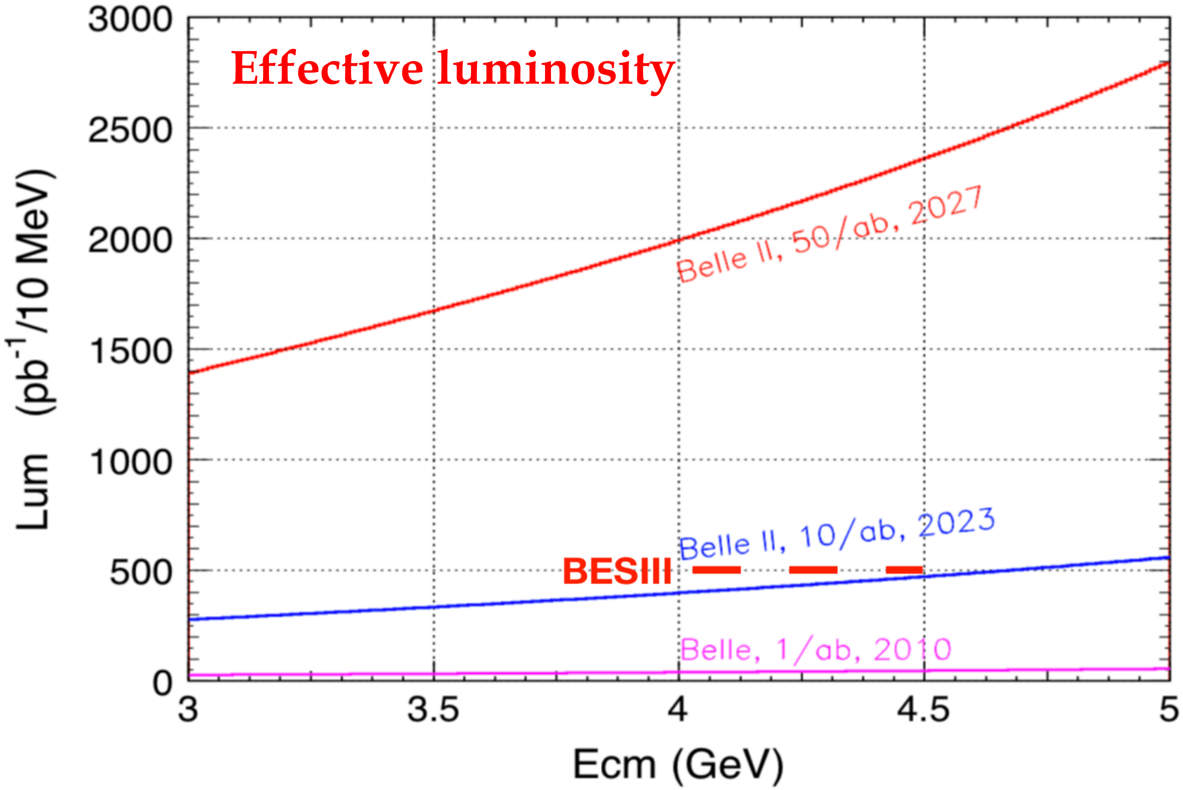


- Belle II will search for the partner of the X(3872) at the $D^{*0}\bar{D}^{*0}$ threshold
- About 5σ significance with 1.3% reconstruction efficiency is expected.

Charmonium-like via ISR

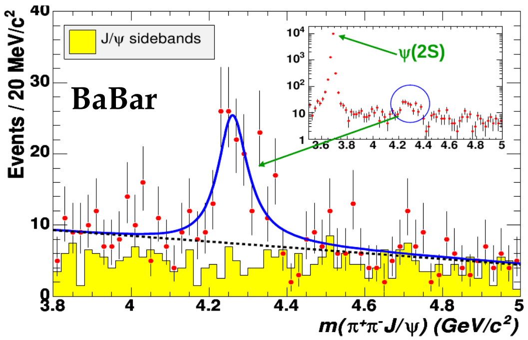
ISR technique is an effective tool to search for new exotics and study their properties:

- The whole hadron spectrum is visible so that the line shape of the resonance and fine structures can be investigated.
- The disadvantage is the effective luminosity and detection efficiency are relatively low.

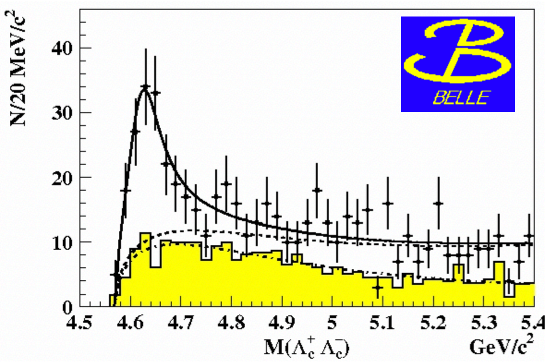


Remarkable charmonium-like mesons via ISR

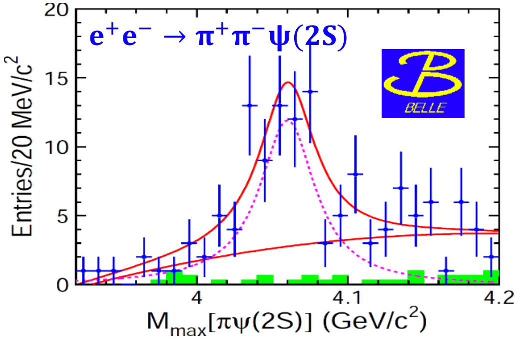
PRL95, 142001



PRL101, 172001



PRD91, 112007



$Y(4260) \to \pi^+\pi^- J/\psi$

$Y(4630) \to \Lambda_c^+ \Lambda_c^-$

$Z_c^\pm(4050) \to \pi^+\psi(2S)$

2005

2007

2008

2013

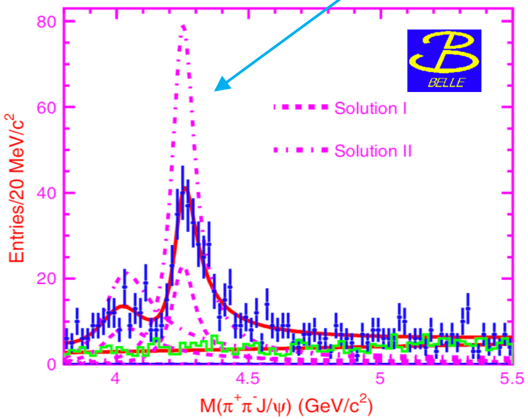
2015

year

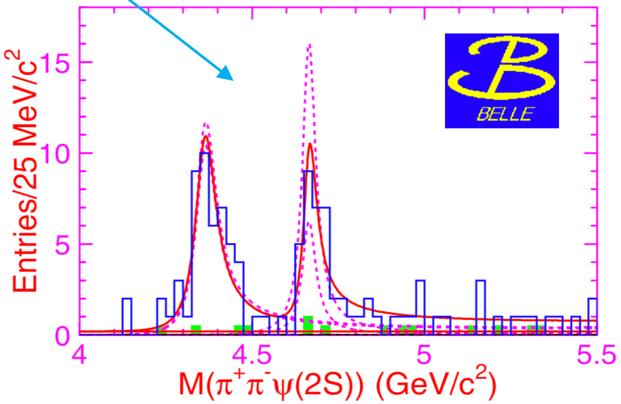
$Y(4008/4260) \to \pi^+\pi^- J/\psi$
$Y(4360/4660) \to \pi^+\pi^-\psi(2S)$

$Z_c^+(3900) \to \pi^+ J/\psi$

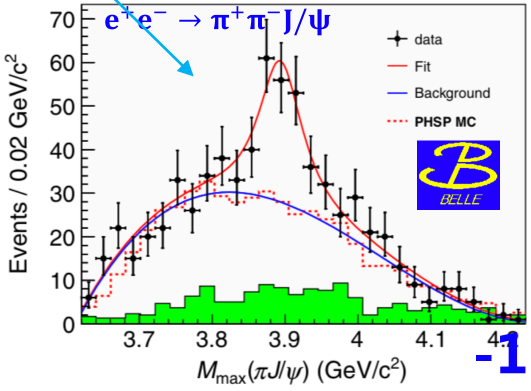
PRL99, 182004



PRL98, 212001



PRL110, 252002

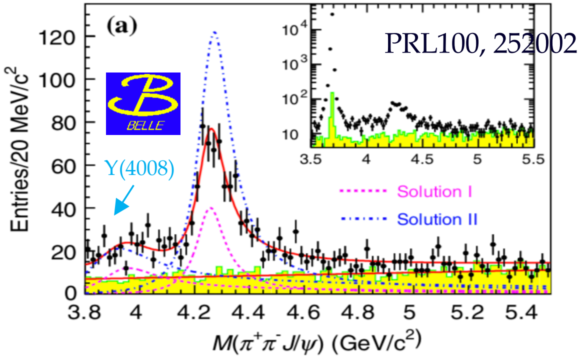


Further investigations at Belle II via ISR

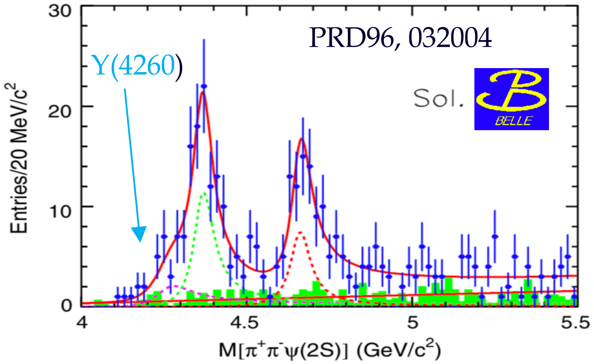
Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$

10ab^{-1} ← → 50ab^{-1}

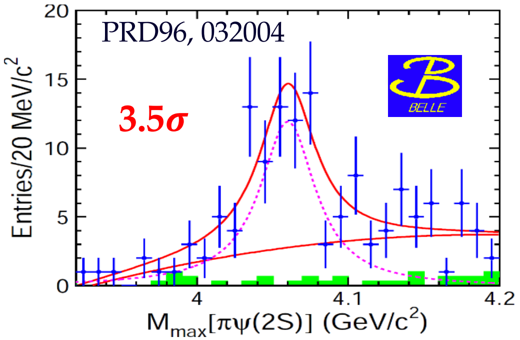
Q1: existence of the Y(4008)?



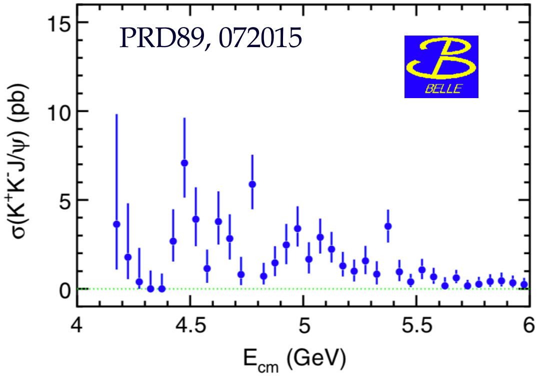
Q2: existence of the Y(4260)?



Q3: existence of the $Z_c(4050)$?



Q4: more structures in M(K^+K^-J/ψ)?

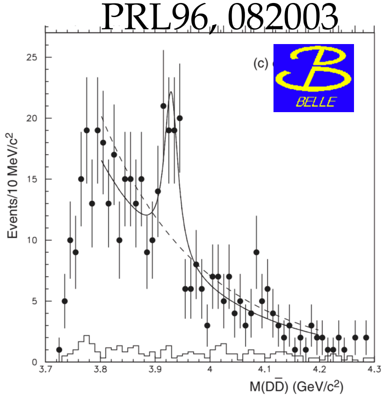


- Perform the analysis of $e^+e^- \to \pi^+\pi^- h_c$, $\omega\chi_{c0}$, and $(D^*\bar{D}^*)^\pm\pi^\mp$ to confirm the results with BESIII.
- Study the processes $e^+e^- \to \pi^+\pi^-\psi_2(1D)$, $K^+K^-\psi(2S)$, $\phi\chi_{cJ}$, $\eta J/\psi$, $\eta' J/\psi$, $\eta\psi(2S)$, $\omega\chi_{cJ}$, etc to search for more charmonium-like states and new decay modes.

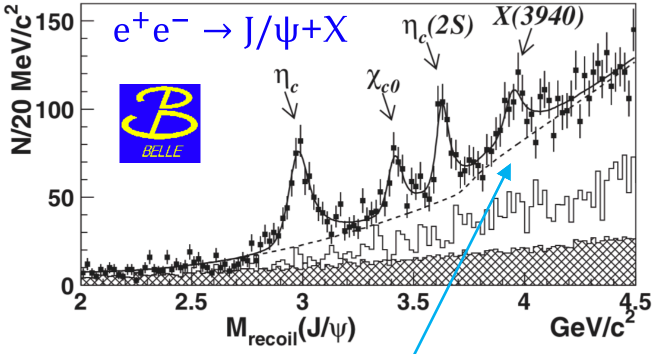
Charmonium(-like) in two photons collisions and double charmonium production

Remarkable charmonium-like mesons

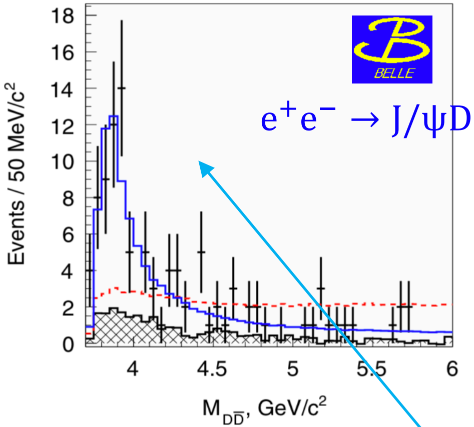
PRL96, 082003

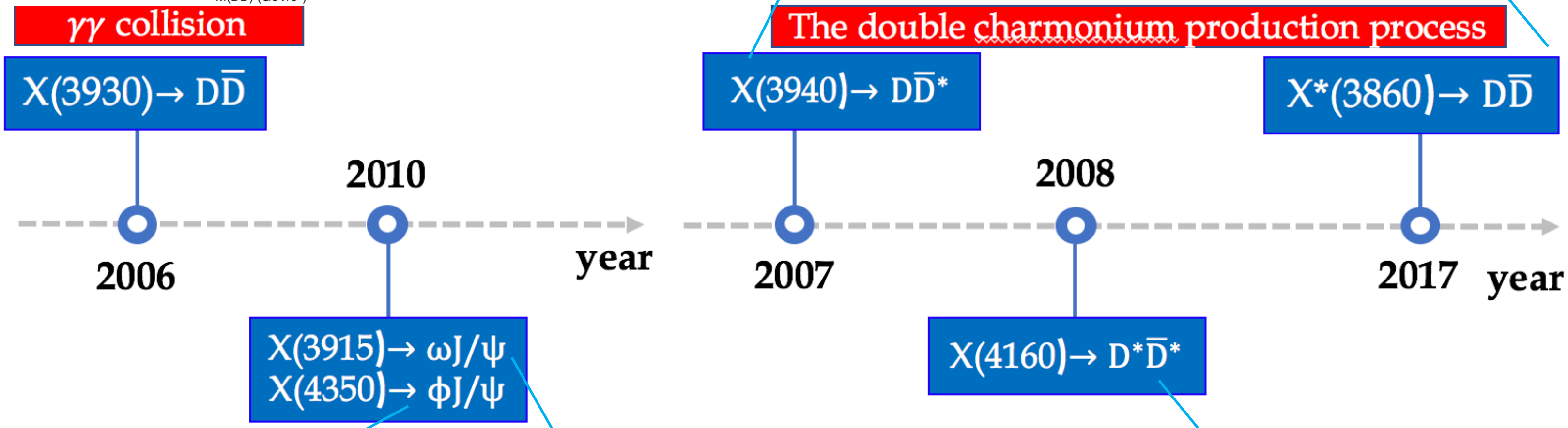


PRL98, 082001



PRD95, 112003





$\gamma\gamma$ collision

The double charmonium production process

X(3930)→ DD̄

X(3940)→ DD̄*

X*(3860)→ DD̄

2010

2008

2006

year

2007

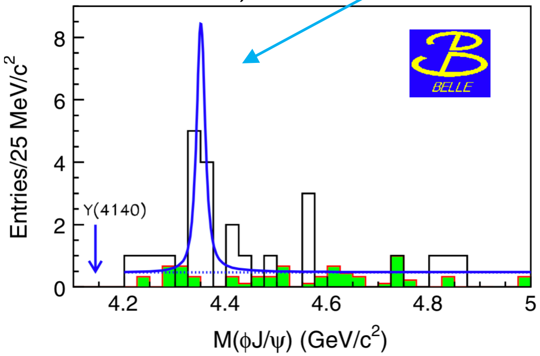
2017

year

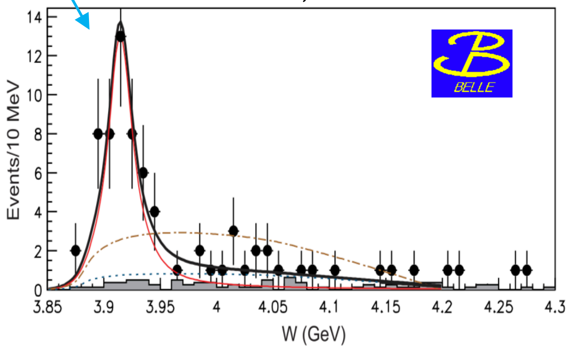
X(3915)→ ωJ/ψ
X(4350)→ ϕJ/ψ

X(4160)→ D*D̄*

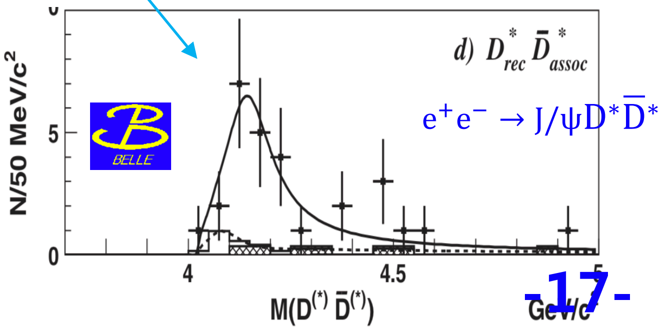
PRL104, 112004



PRL104, 092001



PRL100, 202001

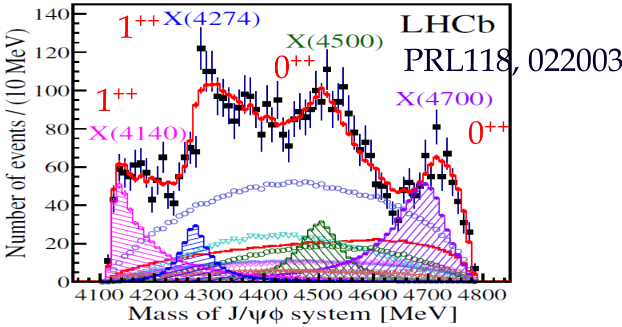


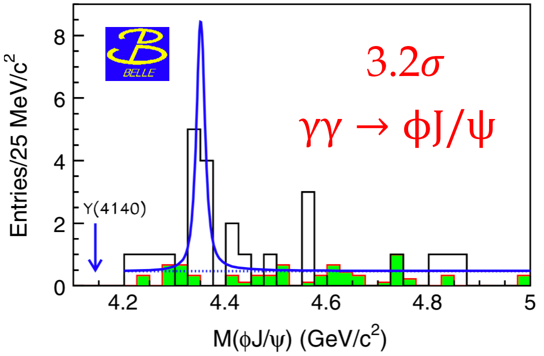
Further investigations in two photons collisions and double charmonium production at Belle II

Two photons collisions

- Give more precise parameters of the X(3930) ($\chi_{c2}(2P)$).
- Determine J^P value of the X(3915) with angular distribution analysis ($\chi_{c0}(2P)$?).
- Existence of the X(4350)? Search for X(4500) and X(4700) via two photons processes.
- With smaller boost at Belle II, the efficiency in two-photon process may be a little higher.

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





Double charmonium production

- Perform a full amplitude analysis at Belle II to measure spin-parities of the observed new states.
- Studies of the $e^+e^- \to h_cX, \eta_cX, \eta_c(2S)X, \psi(2S)X, \chi_{cJ}X$, etc.

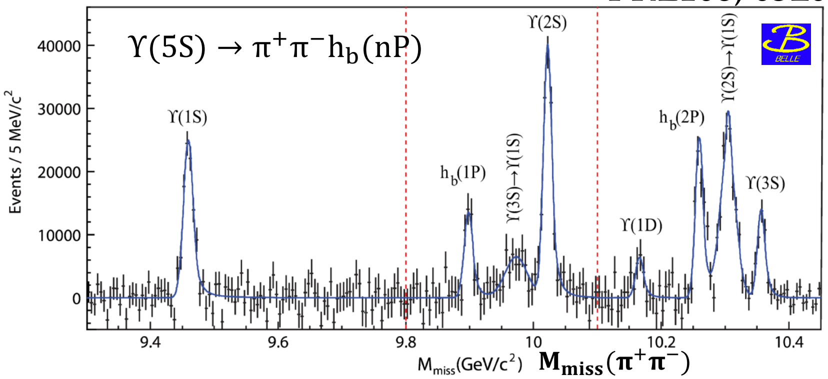
Bottomonium(-like) states

Bottomonium(-like) from e^+e^- B-factories

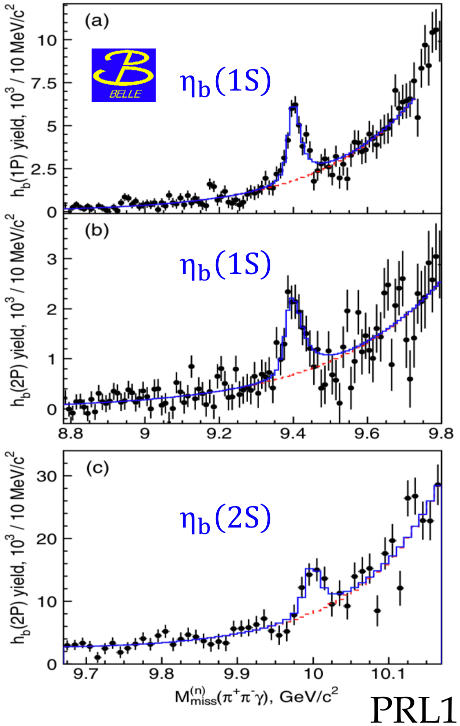
Achievements at Belle

- Discovery of η_b, h_b
- Discovery of charged exotics Z_b states
- Anomalous $\pi^+\pi^-$ and η transitions
- New bottomonium transition decays
- …

PRL108, 032001



$\Upsilon(5S) \to \pi^+\pi^- h_b(nP)(\to \gamma\eta_b(mS))$



PRL109, 232002

Operation energies (in fb-1 (M events))

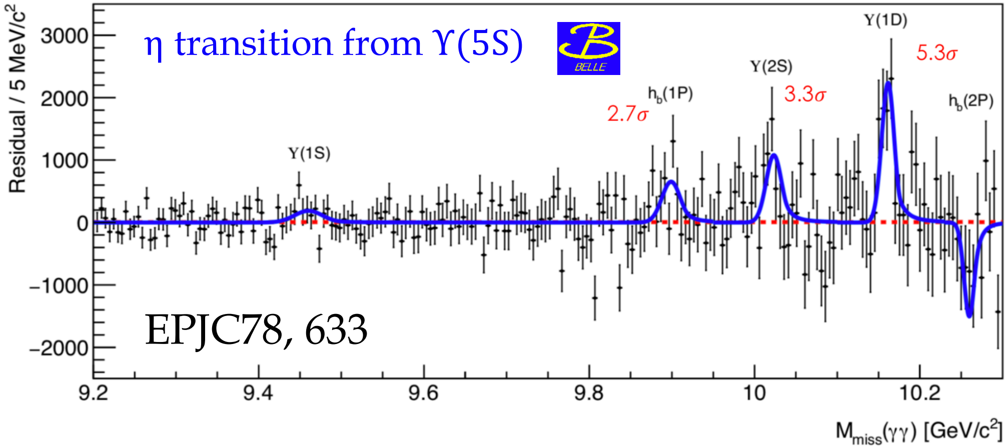
Experiment	**Υ(1S)**	**Υ(2S)**	**Υ(3S)**	**Υ(4S)**	**Υ(5S)**	**Υ(6S)**
CLEO	**1.2 (21)**	**1.2 (10)**	**1.2 (5)**	**16 (17.1)**	**0.1 (0.4)**	**-**
BaBar	**-**	**14 (99)**	**30 (122)**	**433 (471)**	**R_b scan**	**R_b scan**
Belle	**6 (102)**	**25 (158)**	**3 (12)**	**711 (772)**	**121 (36)**	**5.5**
Belle II			**300 (1200)**	**5×10^4 (5.4×10^4)**	**1000 (300)**	**100 + 400 (scan)**

More data samples provide opportunities to explore bottomonium spectrum further.

Search for missing conventional bottomonia below the $B\bar{B}$ threshold at Belle II

Three ways to access bottomonia below $B\bar{B}$ threshold:

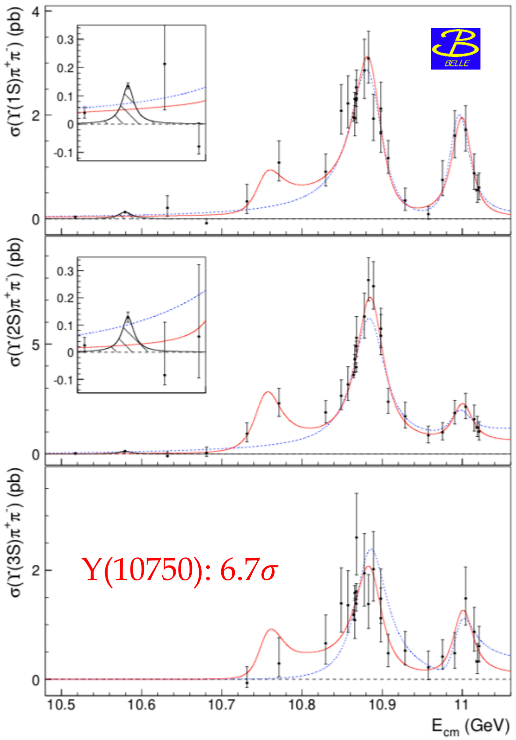
- ➢ Decays of higher mass states (e.g. Υ(4S,5S,6S))
- ➢ Production of 1^{--} states via initial-state radiation
- ➢ Direct production via operation at a lower center-of-mass energy.



η transition from Υ(5S)

EPJC78, 633

arXiv:1905.05521



Υ(10750): 6.7σ

Datasets: scan data from 10.63 GeV to 11.02 GeV + Υ(5S) + continuum

Predicted Missing bottomonium levels below $B\bar{B}$ threshold

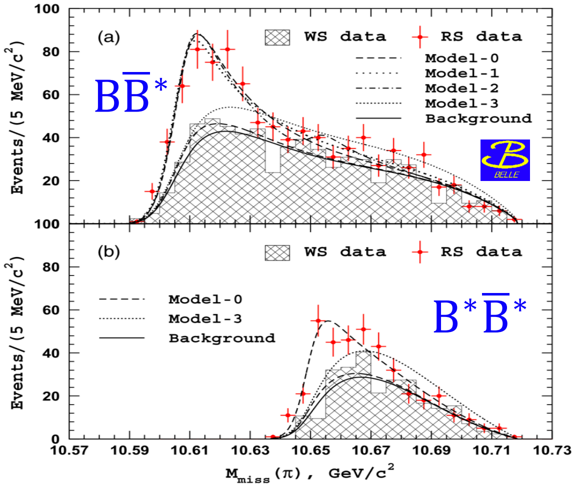
Name	L	S	J^{PC}	Mass, MeV/c^2	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	10336	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	10541	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	10148	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	10450	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	2	1	$(1,2,3)^{--}$	$10441-10455$	$\pi^+\pi^-$ [10.73], η [11.00], η' [11.41]
$h_{b3}(1F)$	3	0	3^{+-}	10355	$\pi^+\pi^-$ [10.63], η [10.90], η' [11.31]
$\chi_{bJ}(1F)$	3	1	$(2,3,4)^{++}$	$10350-10358$	ω [11.14], ϕ [11.38]
$\eta_{b4}(1G)$	4	0	4^{-+}	10530	ω [11.31], ϕ [11.55]
$\Upsilon_J(1G)$	4	1	$(3,4,5)^{--}$	$10529-10532$	$\pi^+\pi^-$ [10.81], η [11.08], η' [11.49]

PRD92, 054034

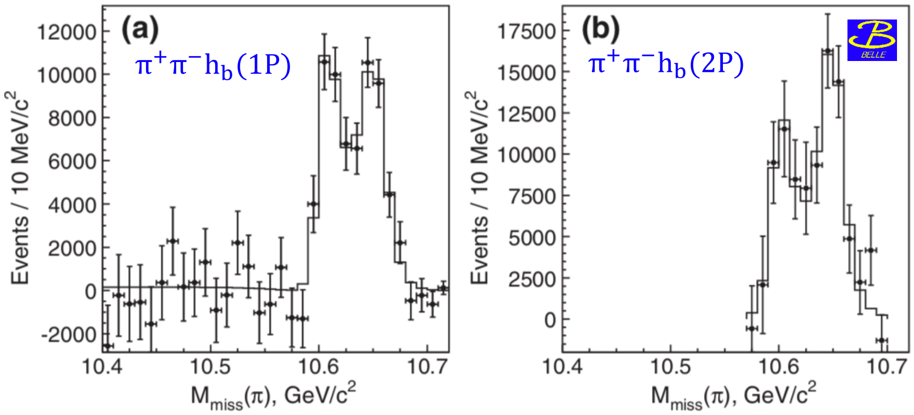
Search for new exotics at Belle II

- Observed $Z_b(10610)$ and $Z_b(10650)$ in $\Upsilon(5S,6S)\ \pi\pi$ transitions.
- The decays $Z_b(10610) \to B\bar{B}^*$ and $Z_b(10650) \to B^*\bar{B}^*$ are dominant.

PRL116, 212001



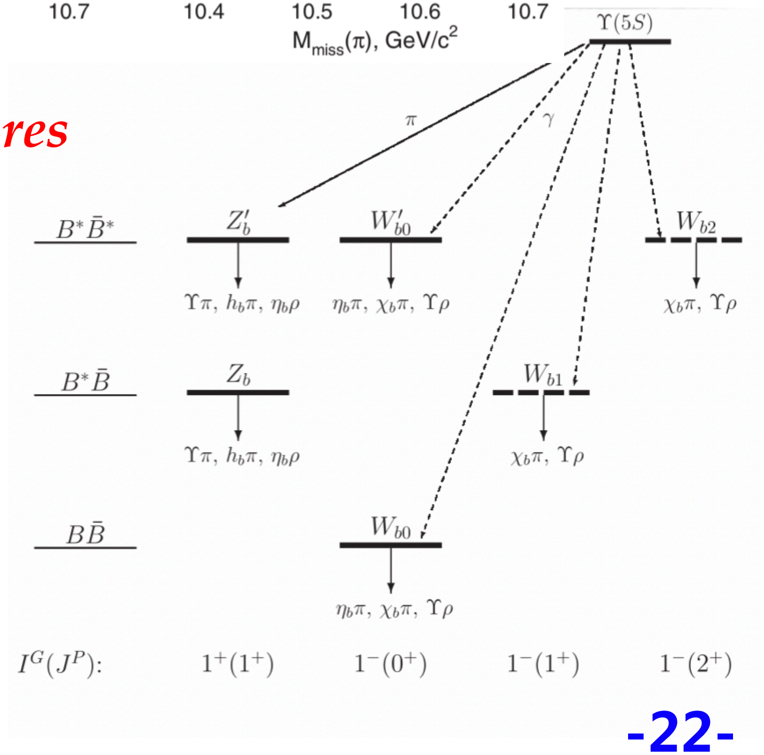
PRL108, 122001



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

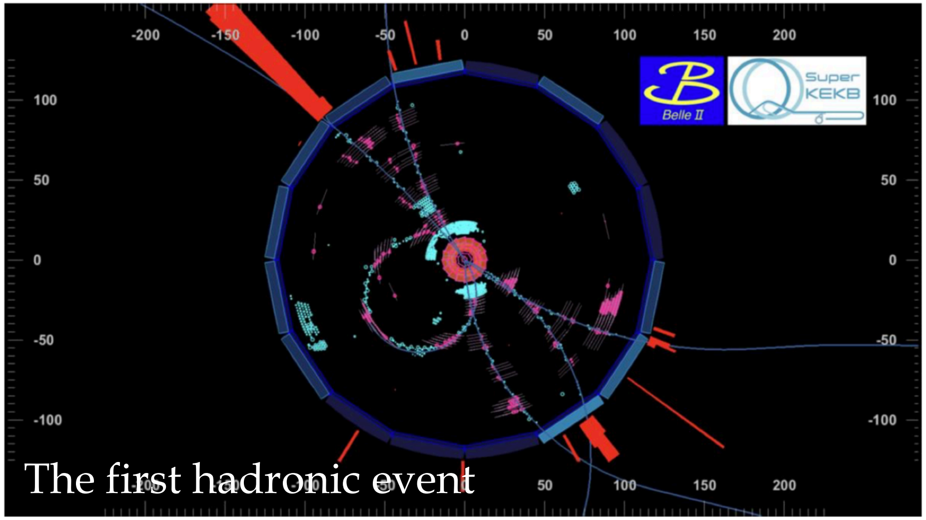
$I^G(J^P)$	Name	Content	Co-produced particles [Threshold, GeV/c^2]	Decay channels
$1^+(1^+)$	Z_b	$B\bar{B}^*$	π [10.75]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^+(1^+)$	Z'_b	$B^*\bar{B}^*$	π [10.79]	$\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$
$1^-(0^+)$	W_{b0}	$B\bar{B}$	ρ [11.34], 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

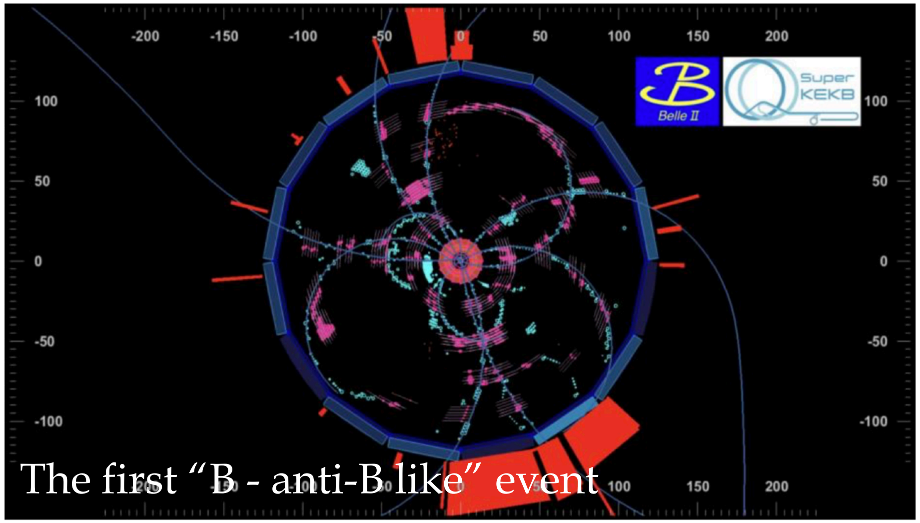


Belle II is back to the game

Kick-off of the Belle II Physics Run (Phase III)



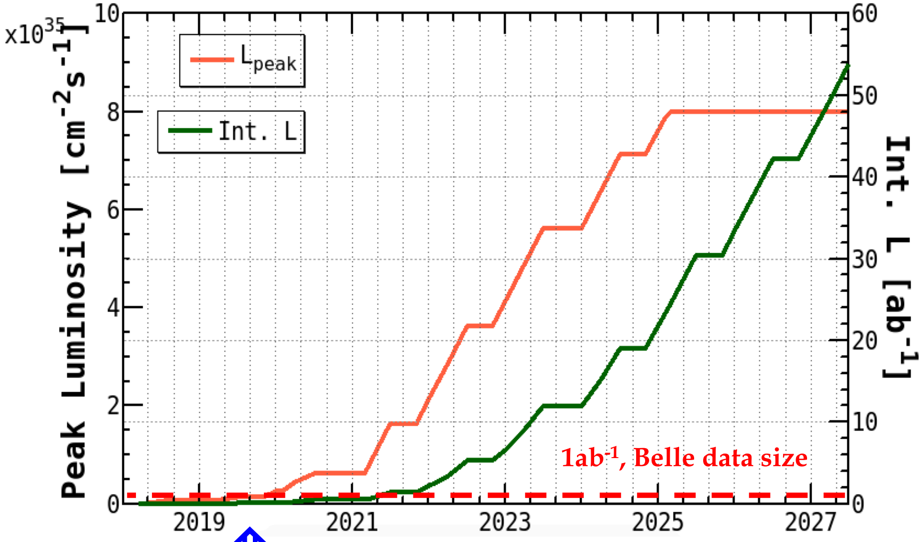
The first hadronic event



The first “B - anti-B like” event

On **March 25 19:44 (JST), 2019**, electron-positron collisions have restarted at the SuperKEKB collider, and the Belle II experiment has now **kicked off its physics data taking**.

PHASE III: Full detectors operation; increased luminosity



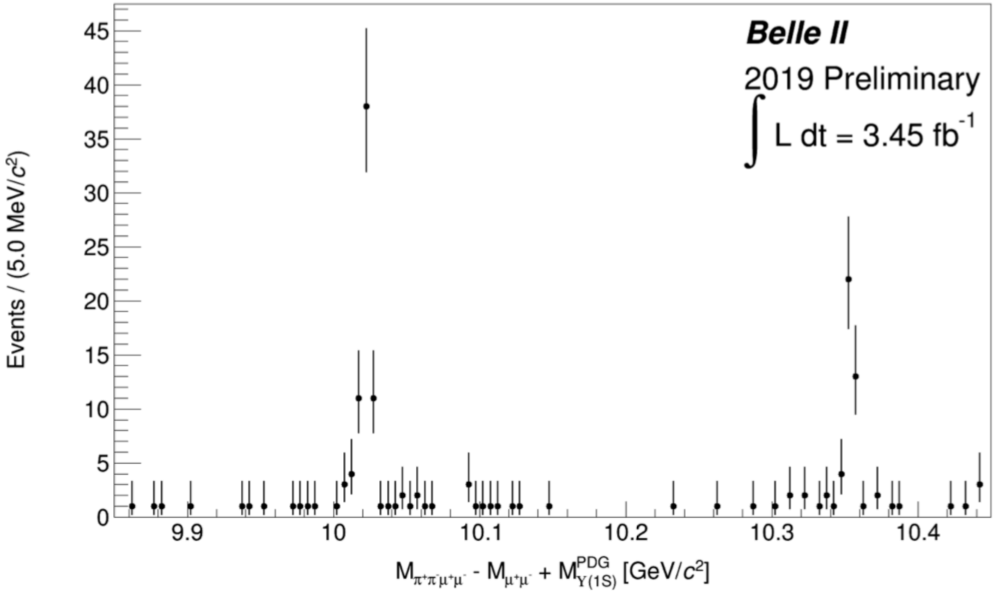
⇑
We are here

Each 1 ab^{-1} dataset at B-factory provides:

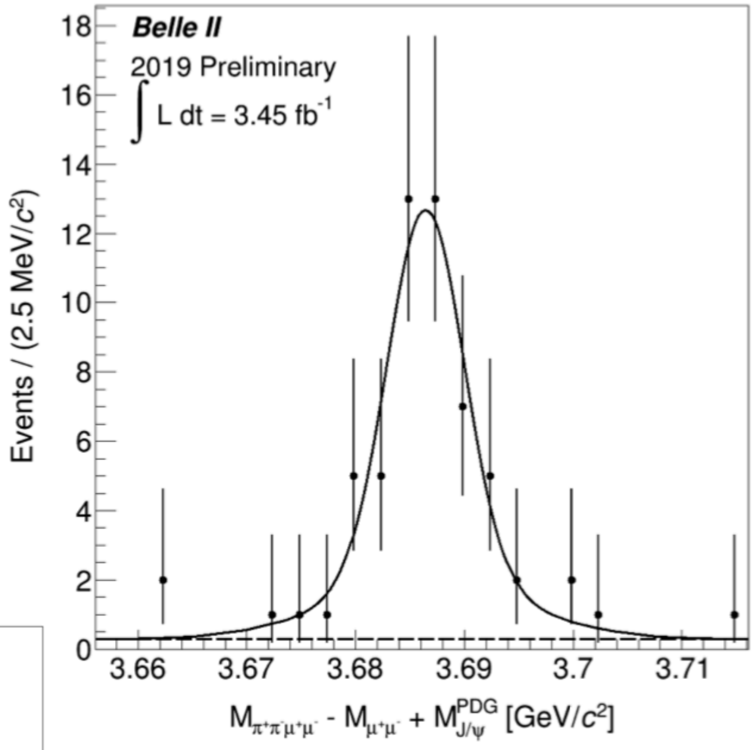
- $\sim 1.1 \times 10^9$ $B\bar{B}$ ⇒ a B-factory;
- $\sim 1.3 \times 10^9$ $c\bar{c}$ ⇒ a charm-factory;
- $\sim 0.9 \times 10^9$ $\tau^+\tau^-$ ⇒ a τ-factory;
- wide region $E^{eff.}_{c.m}$=[0.5-10] GeV via ISR process.

The results on quarkonium physics in early Phase 3

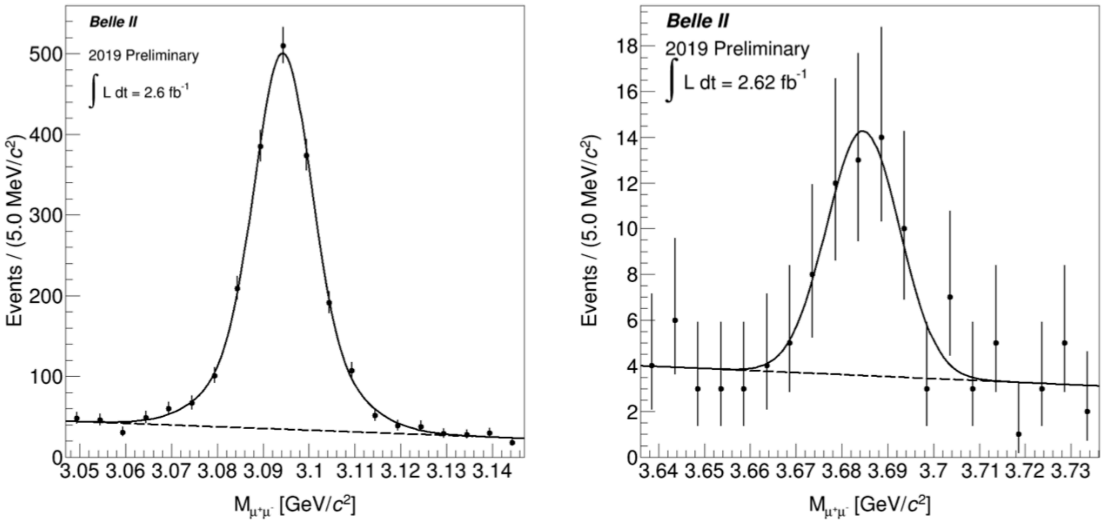
$\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)(\to \mu^+\mu^-)$



$\psi(2S) \to \pi^+\pi^- J/\psi(\to \mu^+\mu^-)$

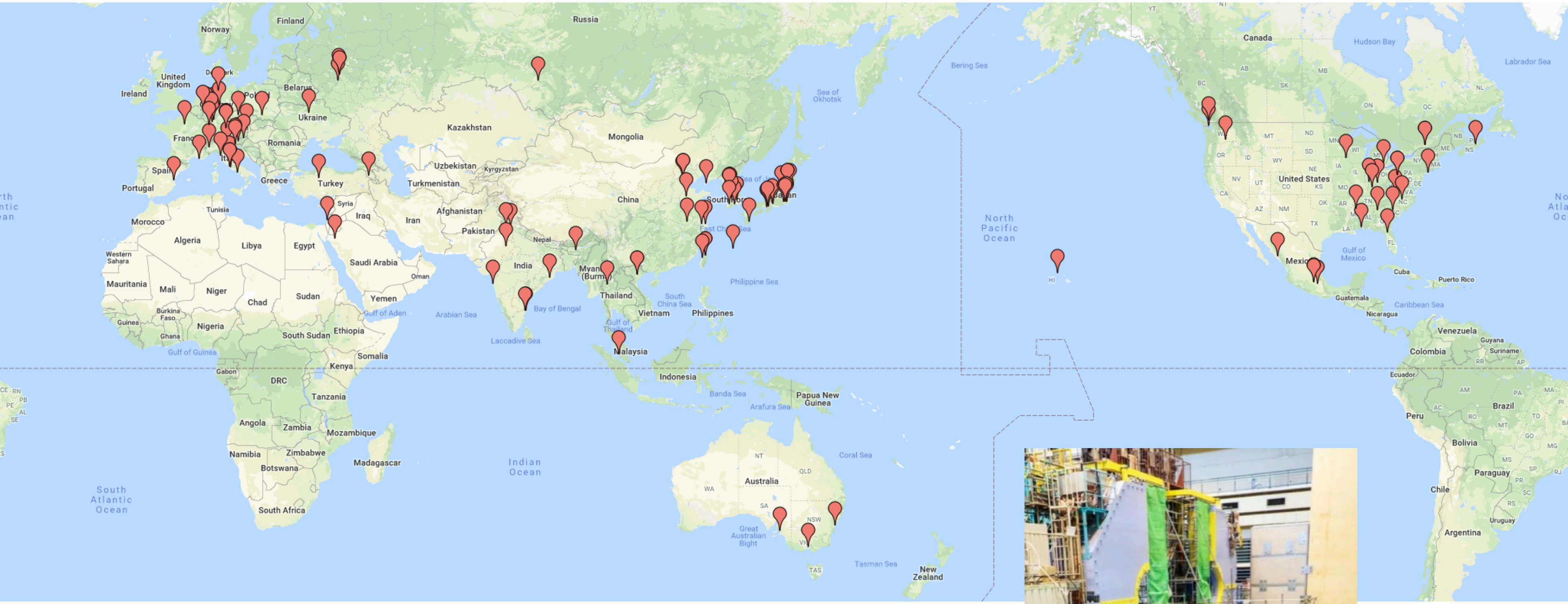


$J/\psi \to \mu^+\mu^-$, $\psi(2S) \to \mu^+\mu^-$



For more results in early Phase 3 from Belle II , please see Longke's report "Belle II status and first results".

The Belle II Collaboration



Belle Collaboration:
536 colleagues, 91 institutions, 20 countries/regions

Belle II Collaboration:
952 colleagues, 116 institutions, 26 countries/regions

Summary

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

As a density frontier experiment, Belle II play an important role to resolve the existing puzzles in quarkonium field with its huge statistical samples.

- **Confirm or deny the observed unconventional states**
- **Precious 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 !

Thanks for your attentions!

Backup slides

Energy frontier at Belle II

- Interesting physics beyond ϒ(6S)

- $\Lambda_b\bar{\Lambda}_b$ threshold ~ 11.24 GeV. The increase to about 11.35GeV could cover $\Lambda_b\bar{\Lambda}_b$ threshold to study potentially interesting baryon-antibaryon dynamics.
- Search for new molecular states around 11.5-11.6 GeV, e.g., partners of X(3872) and Z_b via vector states transitions.

- Machine limits

- The range of beam energies covers the ϒ (1S) and ϒ (6S) resonances for physics operation, but no enough spare cavities to run safely at ϒ (6S).
- Maximum center of mass energy is 11.24 GeV in SuperKEKB due to the maximum beam energy of the injector linac.
- Linac upgrade is required for running beyond 11.24GeV.