Study of charmoniumlike states with initial state radiation at Belle II

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Introduction

- Potential model works very well for charmonium states below $D\bar{D}$ threshold.
- A lot of charmonum(-like) states above $D\bar{D}$ threshold were observed in the past decade.
- XYZ particles – Charmonium-like states with many exotic properties! What is their nature?

Example potential from Barnes, Godfrey, Swanson:

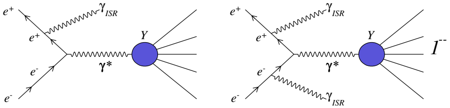
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c\cdot\vec{S}_{\bar{c}}$$

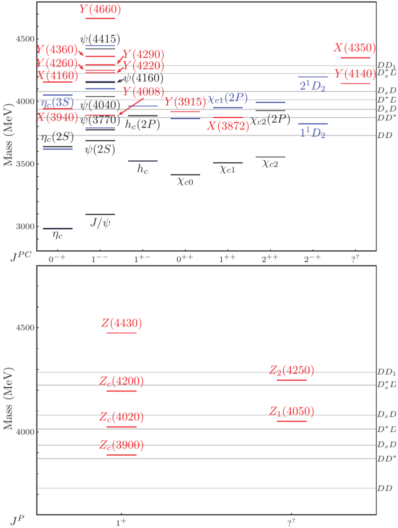
(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)





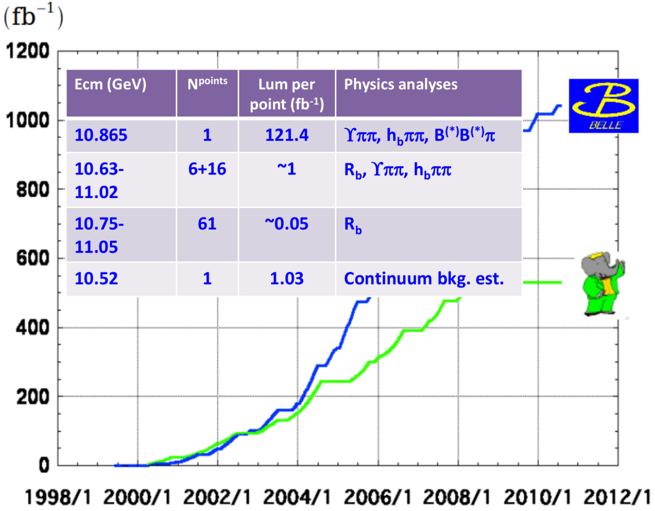
From A. Esposito *et al.*, Int.J.Mod.Phys. A30, 1530002 (2014).

The charmonium(-like) states observed via ISR: $Y(4008)$, $Y(4260)$, $Y(4360)$, $Y(4660)$, $X(4630)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, ...

ISR@Belle

KEK, Tsukuba (near Tokyo), Japan

Belle data sample



Ecm (GeV)	N^{points}	Lum per point (fb^{-1})	Physics analyses
10.865	1	121.4	$\Upsilon\pi\pi$, $h_b\pi\pi$, $B^{(*)}B^{(*)}\pi$
10.63-11.02	6+16	~1	R_b, $\Upsilon\pi\pi$, $h_b\pi\pi$
10.75-11.05	61	~0.05	R_b
10.52	1	1.03	Continuum bkg. est.

> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

All the data samples can be used for ISR studies.

Published ISR results at Belle

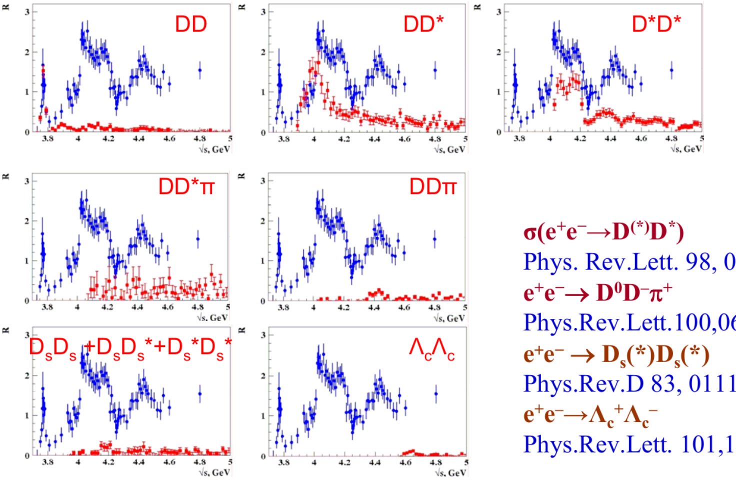
Process	Reference	Int. Lum.	c.m. ene.	Physics Covered
$D^{(*)\pm}D^{(*)\mp}$	PRL 98.092001(2007)	547.8 fb^{-1}	3.9-5.0 GeV	Cross sections
$DD_2^*(2460)$	PRL 100, 062001 (2008)	673 fb^{-1}	4.0-5.0 GeV	ψ(4415)
$\Lambda_c^+\Lambda_c^-$	PRL101,172001 (2008)	695 fb^{-1}	4.8-5.4 GeV	Y(4630)
$D^0D^{*-}\pi^+$	PRD 80, 091101(R) (2009)	695 fb^{-1}	41.-5.2 GeV	Y(4260)
DD	PRD 77, 011103 (2008)	673 fb^{-1}	3.8-5.0 GeV	Cross sections
$\pi^+\pi^-J/\psi$	PRL 99, 182004 (2007)	548 fb^{-1}	3.8-5.5 GeV	Y(4008), Y(4260)
$\pi^+\pi^-\psi(2S)$	PRL 99, 142002 (2007)	673 fb^{-1}	4.0-5.5 GeV	Y(4360), Y(4660)
K^+K^-J/ψ	PRD 77, 011105(R) (2008)	673 fb^{-1}	4.2-6.0 GeV	Y(4260)
$\varphi\pi^+\pi^-$	PRD 80, 031101 (2009)	673 fb^{-1}	1.3-3.0 GeV	Y(2175), ϕ(1680)
$\eta J/\psi$	PRD 87, 051101(R) (2013)	980 fb^{-1}	3.8-5.3 GeV	ψ(4040),ψ(4160)
$\pi^+\pi^-J/\psi$	PRL 110, 252002 (2013)	980 fb^{-1}	3.8-5.5 GeV	Y(4008), Y(4260),Zc(3900)
KKJ/ψ	PRD 89,072015 (2014)	980 fb^{-1}	4.4-5.2 GeV	Y(4260)
$\pi^+\pi^-\psi(2S)$	PRD 91, 112007 (2015)	980 fb^{-1}	4.0-5.5 GeV	Y(4260), Y(4360), Y(4660)
$\gamma\,\chi_{cJ}$	PRD 92, 012011 (2015)	980 fb^{-1}	3.8-5.6 GeV	ψ(4040,4160, 4415); Y(4260, 4360, 4660)

Black font means the significance is low

ISR is a successful story at Belle, while it's similiar to BaBar.

Example I: Cross section measurements via ISR at Belle

Contribution of exclusive cross sections to the total cross section

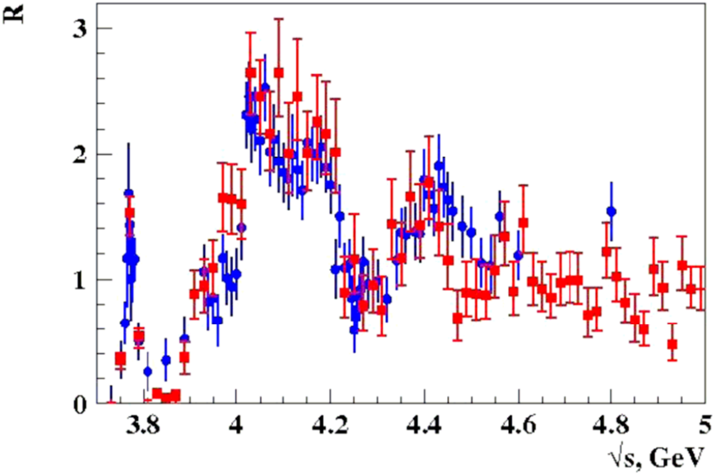


$\sigma(e^+e^- \to D^{(*)}D^{*})$
Phys. Rev.Lett. 98, 092001 (2007)
$e^+e^- \to D^0D^-\pi^+$
Phys.Rev.Lett.100,062001(2008)
$e^+e^- \to D_s(*)D_s(*)$
Phys.Rev.D 83, 011101 (2011)
$e^+e^- \to \Lambda_c^+\Lambda_c^-$
Phys.Rev.Lett. 101,172001(2008)

BES: $R_{tot} - R_{uds}$
Belle: R_{excl}

Example I: Cross section measurements via ISR at Belle

Contribution of exclusive cross sections to the total cross section



BES: $\mathbf{R}_{tot} - \mathbf{R}_{uds}$

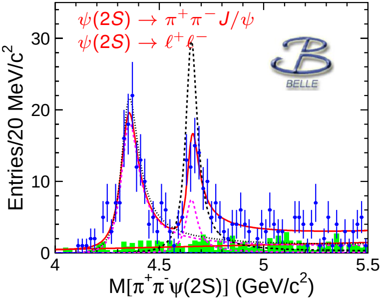
Belle: $\sum \mathbf{R}_{excl}$

Example II: updated $e^+e^- \to \pi^+\pi^-\psi(2S)$ at Belle

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$:

$Amp = BW_1 + e^{i\phi} \cdot BW_2$.

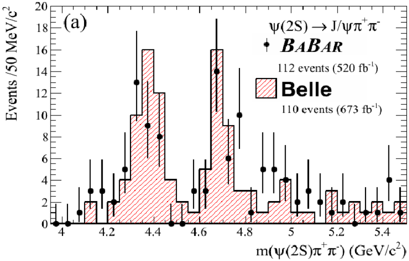
PRL91,112007(2015)



Parameters	Solution I	Solution II
$M_{Y(4360)}$ (MeV$/c^2$)	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$ (MeV)	$103 \pm 9 \pm 5$	
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV)	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$ (MeV$/c^2$)	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$ (MeV)	$68 \pm 11 \pm 5$	
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV)	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ ($^\circ$)	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

$\chi^2/ndf = 18.7/21$.

- $N^{\rm sig}$ doubled in the updated study.
- Consistent with previous measurement. PRL99,142002(2007)
  - $M_{Y(4360)} = 4361 \pm 9 \pm 9$ MeV$/c^2$,
  - $M_{Y(4660)} = 4664 \pm 11 \pm 5$ MeV$/c^2$.
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially in $\pi^+\pi^- J/\psi$ mode.

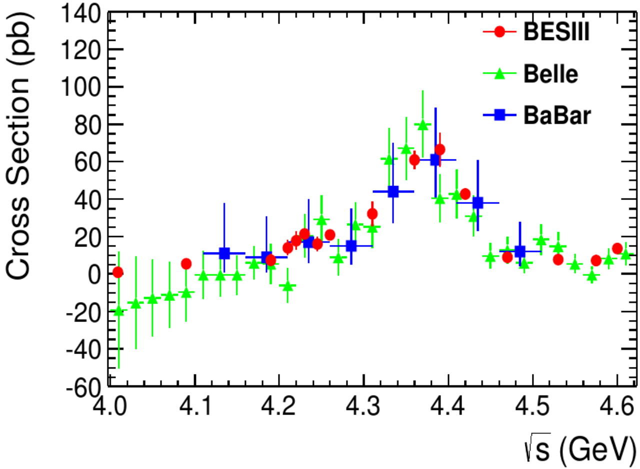


Belle: PRL99,142002(2007)

BaBar: PRD89,111103(R)(2014)

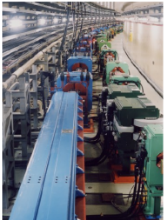
ISR at Belle vs. BESIII

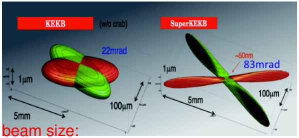
- BESIII: 16 energy points, $L_{tot} = 5.1\ \mathrm{fb}^{-1}$
- $\psi(2S)$ reconstructed modes:
  - Mode I: $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to e^+e^-/\mu^+\mu^-$
  - Mode II: $\psi(2S) \to neutrals + J/\psi$, $neutrals = (\pi^0\pi^0, \pi^0, \eta\ \&\ \gamma\gamma)$, $J/\psi \to e^+e^-/\mu^+\mu^-$



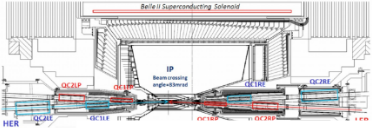
BESIII: arXiv/1703.08787

Advantage of new accelerator: SuperKEKB





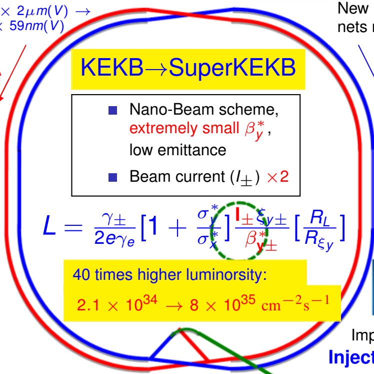
beam size:
$100\mu m(H) \times 2\mu m(V) \rightarrow$
$10\mu m(H) \times 59nm(V)$



New superconducting final focusing magnets near the Interaction Point (IP)

e^+ 3.6A

e^- 2.6A



KEKB→SuperKEKB

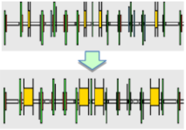
- Nano-Beam scheme, extremely small β_y^*, low emittance
- Beam current ($I_\pm$) $\times 2$

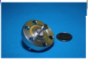
$$L = \frac{\gamma_\pm}{2e\gamma_e}\left[1 + \frac{\sigma_y^*}{\sigma_x^*}\right]\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left[\frac{R_L}{R_{\xi y}}\right]$$

40 times higher luminorsity:

$2.1 \times 10^{34} \rightarrow 8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

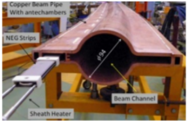
Redesign the lattice to reduce the emittance (replace short dipoles with longer ones, increase wiggler cycles) (being tuned)





Reinforce RF systems for higher beam currents

Replace beam pipes with TiN-coated beam pipes with antechambers (works well)

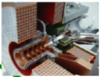


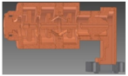
Improve monitors and control system

Injector Linac upgrade:

Upgrade positron capture section

Low emittance RF electron gun

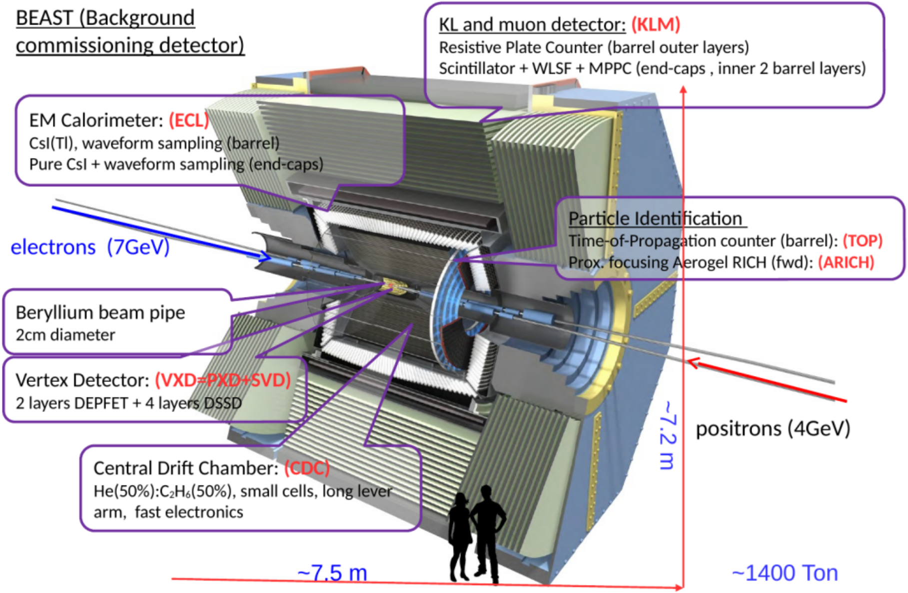




DR tunnel

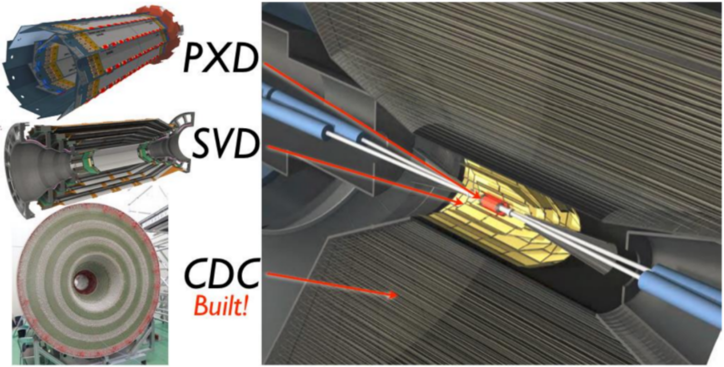
New e^+ Damping Ring constructed

Belle II detector



For more details, see Dr. Jake BENNETT's talk on 3rd, Sept.

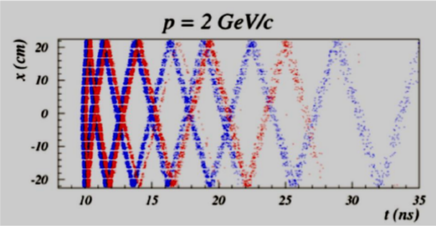
The tracking system

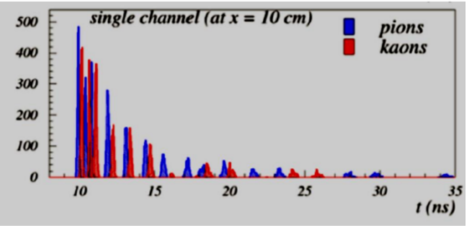


Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	impact parameter resolution $\sigma_{z_0} \sim 20\ \mu$m (PXD and SVD)
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo r = 16 - 112 cm - 83 $\le z \le$ 159 cm	14 k	$\sigma_{r\phi} = 100\ \mu$m, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\% p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\% p_t)^2 + (0.3\%/\beta)^2}$ (with SVD)

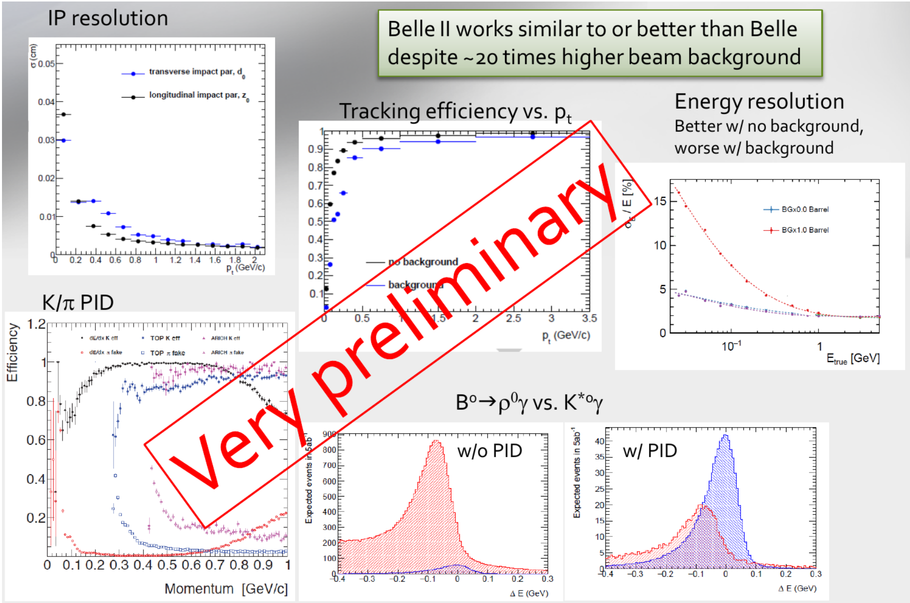
Barrel PID: image Time Of Propagation (iTOP)

Quartz Property	Requirement
Flatness	<6.3µm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection





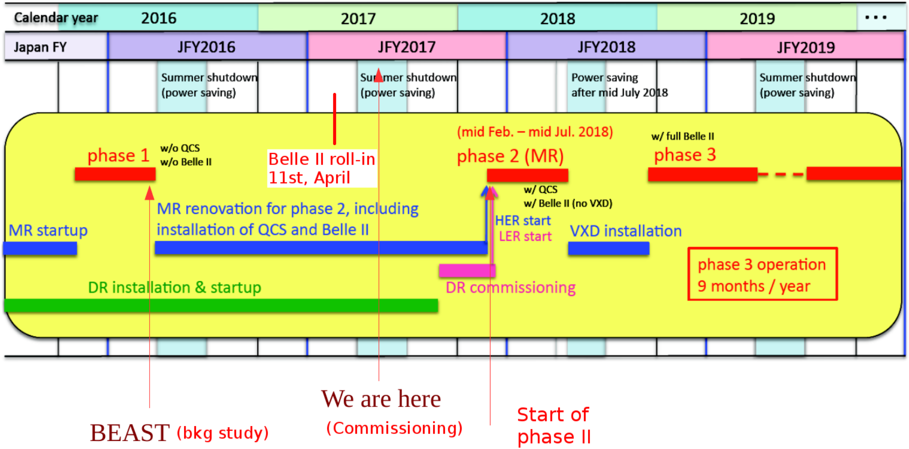
Expected performance of Belle II



From Prof. Ushiroda's talk at LP2017.

The schedule of Belle II

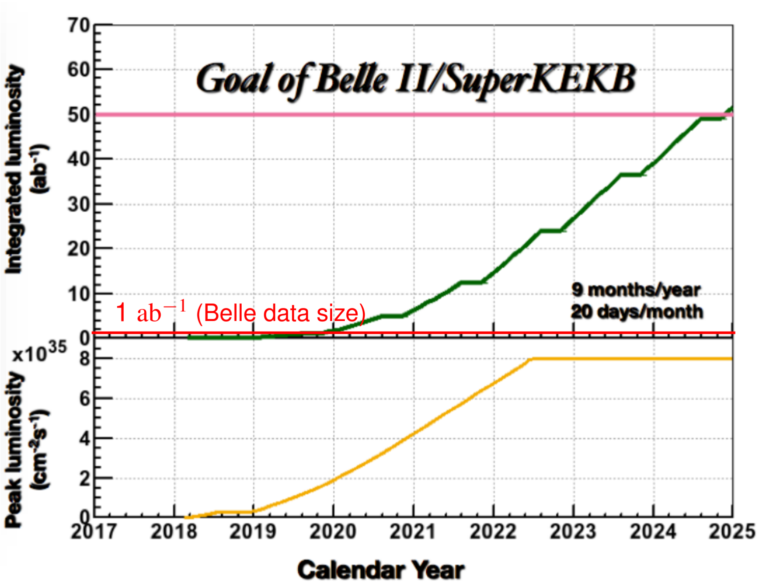
In 2018, launch SuperKEKB for the first collision in Feb., and start physics operation later!!!



Commissioning:

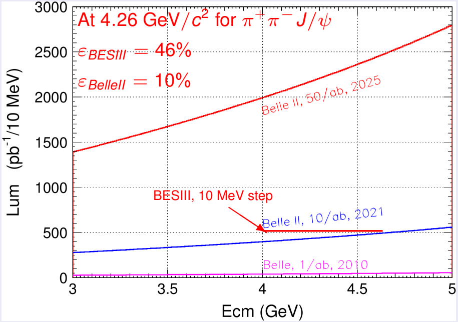
- SuperKEKB: Clean beam pipe, monitor, tuning optics, collimators, ...
- Belle II: Safe operation, bkg study, beam abort system, calibration, ...

Profile of SuperKEKB luminosity and Belle II data sample



ISR at Belle II vs. direct scan at BESIII

Effactive lum at Belle II



ISR

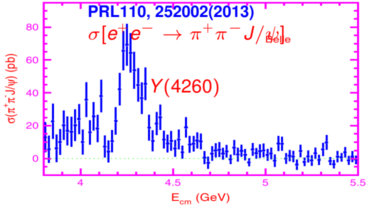
- ISR: many $\sqrt{s}$ simultaneously
- reduced point-to-point systematics
- mass resolution limited by detector performance
- boost of hadronic system vs. $\gamma_{\rm ISR}$ may actually help efficiency

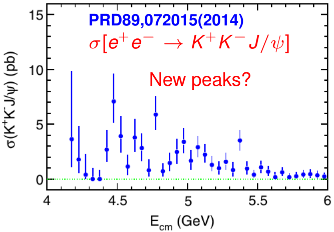
Direct scan

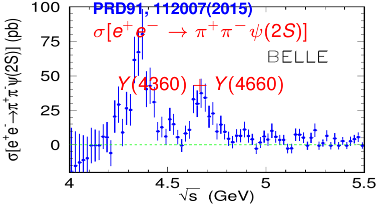
- (very) high luminosity at a few selected $\sqrt{s}$
- better resolution in $\sqrt{s}$ — relevant for direct production of 1^{--} states
- much higher efficiency

- ISR produces events at all CM energies BESIII can reach
- With $> 5(10)\ \mathrm{ab}^{-1}$ data sample, Belle II can do ISR studies on $e^+e^- \to$ charmonium + light hadrons and charm meson pair + light hadrons.
  - charmonium+light hadrons: $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $K^+K^- J/\psi$, $K^+K^-\psi(2S)$, $\gamma X(3872)$, $\pi^+\pi^- X(3872)$, $\pi^+\pi^- h_c$, $\pi^+\pi^- h_c(2P)$, $\omega\chi_{cJ}$, $\phi\chi_{cJ}$, $\eta J/\psi$, $\eta' J/\psi$, $\eta\psi(2S)$, ηh_c, ...
  - charm meson pair + light hadrons: $D\bar{D}$, DD^*, $DD^*\pi$, ...

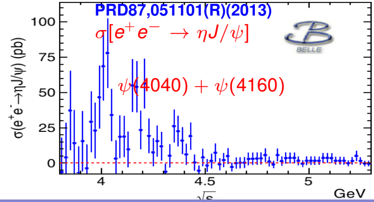
Solve the single-channel puzzle





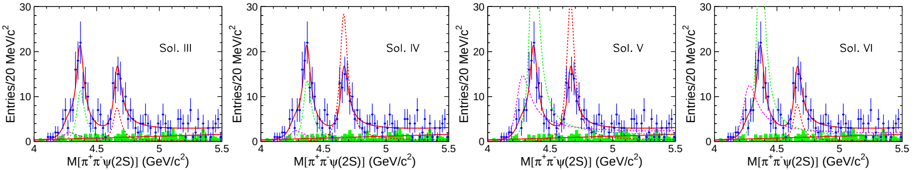


- Different final states have different peaks.
- Each Y or ψ state decays to only one channel.
- Need Belle II data!



Sensitivity study: $Y(4260) \to \pi^+\pi^-\psi(2S)$

$Amp = BW_1 + e^{i\phi_1} \cdot BW_2 + e^{i\phi_2} \cdot BW_3$.



	Sol. III	Sol. IV	Sol. V	Sol. VI
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4260)}$ (eV)	$1.5 \pm 0.6 \pm 0.4$	$1.7 \pm 0.7 \pm 0.5$	$10.4 \pm 1.3 \pm 0.8$	$8.9 \pm 1.2 \pm 0.8$
$M_{Y(4360)}$ (MeV$/c^2$)	$4365 \pm 7 \pm 4$			
$\Gamma_{Y(4360)}$ (MeV)	$74 \pm 14 \pm 4$			
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV)	$4.1 \pm 1.0 \pm 0.6$	$4.9 \pm 1.3 \pm 0.6$	$21.1 \pm 3.5 \pm 1.4$	$17.7 \pm 2.6 \pm 1.5$
$M_{Y(4660)}$ (MeV$/c^2$)	$4660 \pm 9 \pm 12$			
$\Gamma_{Y(4660)}$ (MeV)	$74 \pm 12 \pm 4$			
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV)	$2.2 \pm 0.4 \pm 0.2$	$8.4 \pm 0.9 \pm 0.9$	$9.3 \pm 1.2 \pm 1.0$	$2.4 \pm 0.5 \pm 0.3$
ϕ_1 ($^\circ$)	$304 \pm 24 \pm 21$	$294 \pm 25 \pm 23$	$130 \pm 4 \pm 2$	$141 \pm 5 \pm 4$
ϕ_2 ($^\circ$)	$26 \pm 19 \pm 10$	$238 \pm 14 \pm 21$	$329 \pm 8 \pm 5$	$117 \pm 23 \pm 25$

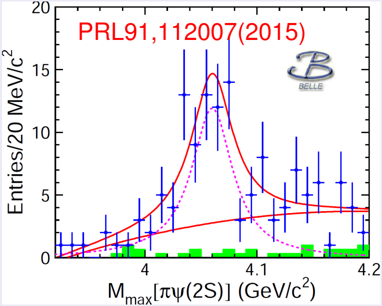
- Significance of $Y(4260)$ is 2.4σ—low, but affects the parameters of $Y(4360)$ and $Y(4660)$!
- FOUR solutions with equally good fit quality, which is $\chi^2/ndf = 14.8/19$.
- Fit w/o $Y(4260)$:
  - $M_{Y(4360)} = 4347 \pm 6 \pm 3$ MeV$/c^2$, $\Gamma_{Y(4360)} = 103 \pm 9 \pm 5$ MeV;
  - $M_{Y(4660)} = 4652 \pm 10 \pm 11$ MeV$/c^2$, $\Gamma_{Y(4660)} = 68 \pm 11 \pm 5$ MeV.

PRD91, 112007(2015)

Sensitivity study: $Y(4360)/Y(4660) \to \pi^+\pi^-\psi(2S)$

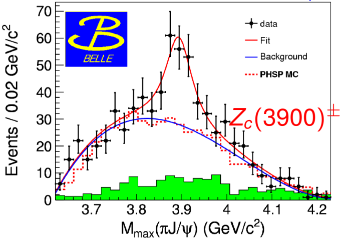
Search for and study the intermediate states of the decays

$Z_c(4050)^\pm \to \pi^\pm\psi(2S)$ in Y(4360) decays

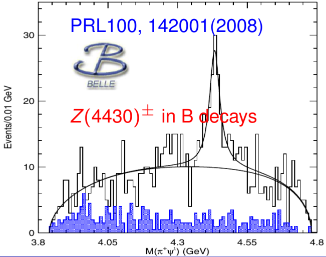


- $Y(4360)$ signal region
- $M = (4054 \pm 3 \pm 1)$ MeV$/c^2$
- $\Gamma = (45 \pm 11 \pm 6)$ MeV
- About 45 signal events.
- Significance: $> 3.5\sigma$

Belle with ISR: PRL110, 252002(2013)

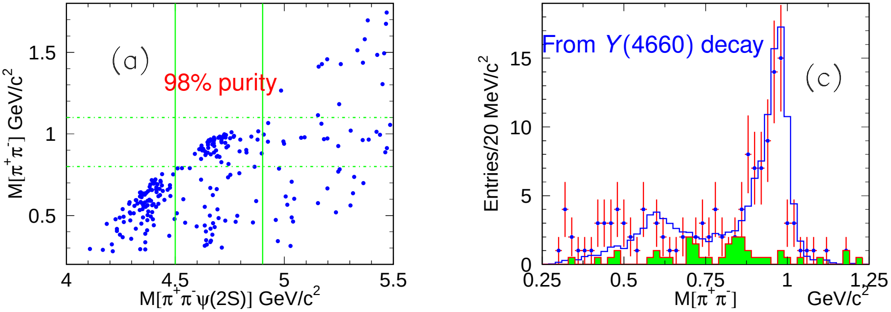


- $M = 3894.5 \pm 6.6 \pm 4.5$ MeV$/c^2$
- $\Gamma = 6 \pm 24 \pm 26$ MeV



Sensitivity study: $Y(4360)/Y(4660) \to \pi^+\pi^-\psi(2S)$

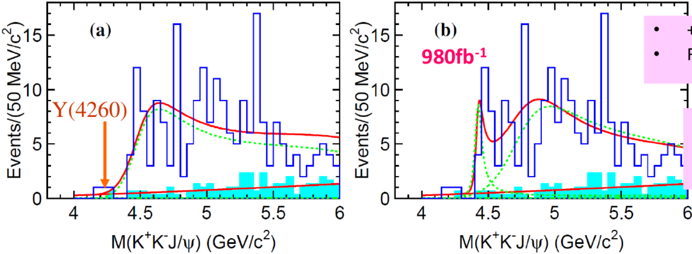
Structure of $Y(4660)$



- $f_0(980)$ dominates in Y(4660) decay, which is quit different to other Y states.
- 10 ab^{-1} data sample can yield 10 times number of signals.
- Searching for intermediate state like $Z_c(4050)^{\pm}$ in Y(4360) decay is possible.

PRD91, 112007(2015)

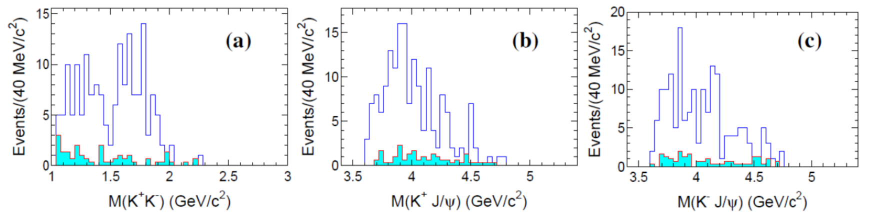
Scan on $e^+e^- \to K^+K^-J/\psi$



- +one resonance.
- Fit with ψ(4415)

χ^2/ndf=30/11
➢M=4747±117MeV
➢Γ=671±86 MeV

Dalitz analysis performed



- Not clear on a structure produced in $e^+e^- \to K^+K^-J/\psi$.
- No evident structure in $K^\pm J/\psi$ mass distribution under current statistics.

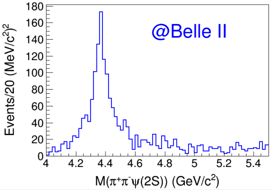
PRD89, 072015(2014)

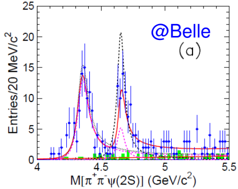
ISR simulation at Belle II

Preliminary study

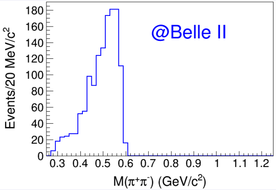
PHOKHARA generator is used to do the ISR simulation at Belle II.

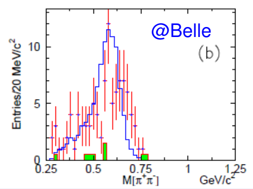
$Y(4360)$ mass



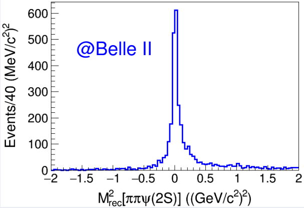


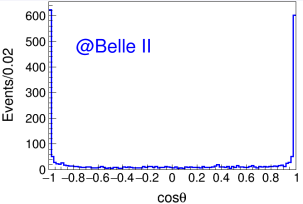
$M_{\pi^+\pi^-}$ in $Y(4360)$ decay





ISR characteristics





More studies are ongoing.

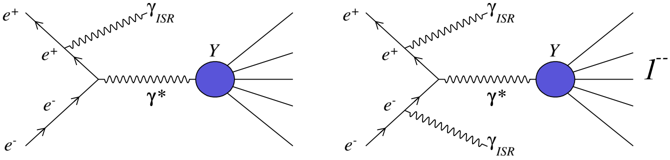
Summary

- ISR is a successful story at Belle, a lot of results were obtained.
- Belle II is going to take data in 2018, and we are going to get a huge data sample, which can be used for ISR studies again.
- The schedule of Belle II is ongoing well.
- With about 10 ab^{-1} data, Belle II plans to study $e^+e^- \to$ a charmonium+light hadrons and charm meson pair+light hadrons.
- There are still problems in some studies, such as $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, K^+K^-J/ψ, $\eta J/\psi$, etc.
- The nature of exotic states should be clear via studying with Belle II data.

Thank you!

Backup

Initial State Radiation



Advantages:

- Cover a wide region below the E_{cm} of collider smoothly. Good for broad structures.
- Avoid the point-to-point systematic error.
- Low beam-wall and beam-gas backgrounds.
- The J^{PC} of final state is still 1^{--}.

Disadvantages:

- Low effective luminosity, especially when $\sqrt{s}$ is far away from E_{cm} of the collider.
- Low efficiency because $\gamma_{\rm ISR}$ and its recoil CMS fly along the e^+e^- beams.
- $\gamma_{\rm ISR}$ has very high energy and not very good resolution.

Machine Parameters

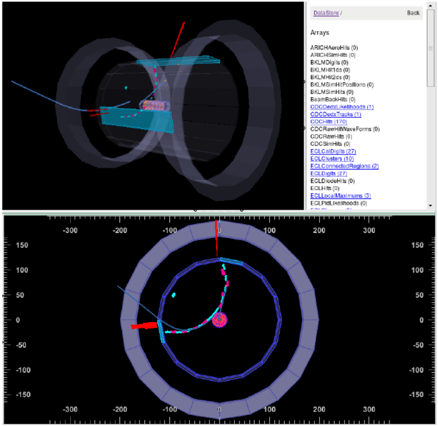
Machine Parameters

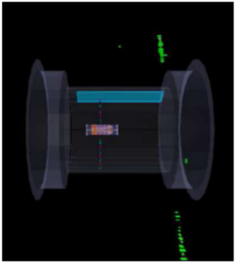
SuperKEKB can exceed the peak luminosity of KEKB when we achieve $\xi_y > 0.05$

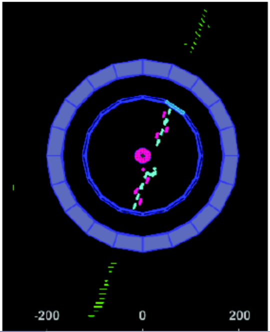
	Phase 2.2 (8x8)		Phase 2.3 (4x8)		Phase 2.4 (4x4)	
	LER	HER	LER	HER	LER	HER
$I_L \times I_H$, n_b	**1000 mA x 800 mA, 1576 bunches (3-bucket spacing)**					
β_x^* [mm]	256	200	128	100	128	100
β_y^* [mm]	2.16	2.40	2.16	2.40	1.08	1.20
$\varepsilon_y/\varepsilon_x$ [%]	**5.0**		**1.4**		**0.7***	
ξ_x	0.0104	0.0041	0.0053	0.0021	0.0053	0.0021
ξ_y	0.0257	0.0265	0.0484	0.0500	0.0496	0.0505
I_{bunch} [mA]	0.64	0.51	0.64	0.51	0.64	0.51
L [$cm^{-2}s^{-1}$]	**1×10^{34} (tentative target)**		2×10^{34}		4×10^{34}	
L_{sp} [$cm^{-2}s^{-1}/mA^2$]	1.97×10^{31}		3.94×10^{31}		7.88×10^{31}	

* conserve β_y^*/ε_y

Cosmic ray run (June, 2017)



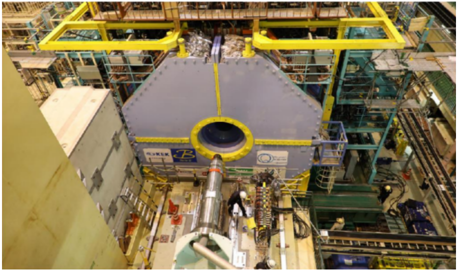




- Systems included: CDC, TOP, ECL, KLM
- Magnetic field: 1.5T

Phase II

Belle II roll in, 11/4/2017



What can be done with Phase 2 data?

- Background studies
- Detector and trigger performance studies
- Simulation validation
- Exercising of calibration and alignment procedures
- Reconstruction algorithm tuning
- Physics measurements

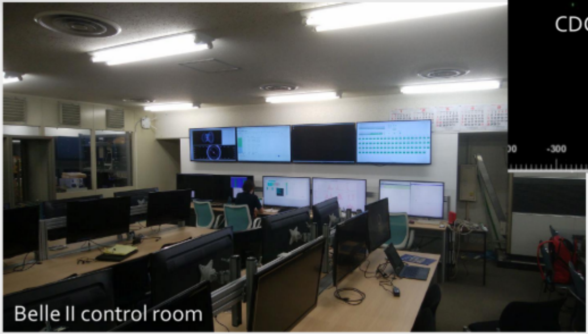
Commissioning of accelerator and sub-detectors

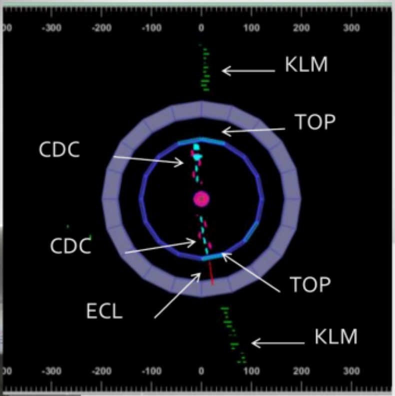
- Start beginning of 2018, duration about 5 months.
- Beam collisions with focusing magnets (QCS).
- Target luminosity is $10^{34}\ cm^{-2}s^{-1}$, which is KEKB level.
- 20-40 fb^{-1} data for physics analyses.
- W/o vertex detector dependent measurements.

The first collision is expected in Feb. 2018, about 8 years after KEKB being shut down.

Readout integration

- Readout integration of installed sub-detectors and central DAQ is in progress.
- Control room built; shift started
- Combined data taking established, though low rate





More about Belle II

Readout (TRG, DAQ)

- Max. 30kHz L1 trigger ∼100% efficient for hadronic events.
- 1MB(PXD) + 100kB(others) per event → over 30GB/sec before reduction, 2-3GB/s to record (&further compression offline)

Offline computing:

- A globally-distributed computing and data-storage system via GRID.