ISR studies at Belle II

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Initial state radiation (ISR)

ISR method was proposed in 1968 by Y. N. BAIER and V. S. FADIN.

Volume 27B, number 4 PHYSICS LETTERS 8 July 1968

ISR technique is a very effective tool to study exotic Y states ($J^{PC} = 1^{--}$).

RADIATIVE CORRECTIONS TO THE RESONANT PARTICLE PRODUCTION

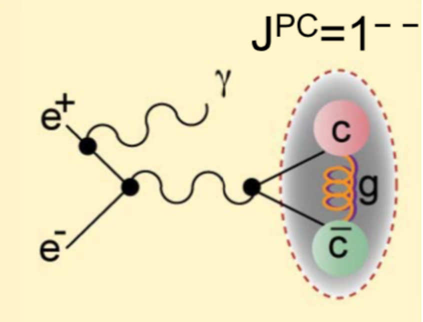
V. N. BAIER and V. S. FADIN
Institute of Nuclear Physics, Novosibirsk, USSR

Received 1 May 1968

Radiative corrections to the resonant cross-sections of particle production in colliding beam experiments have been calculated.

Mechanism of the initial state radiation:

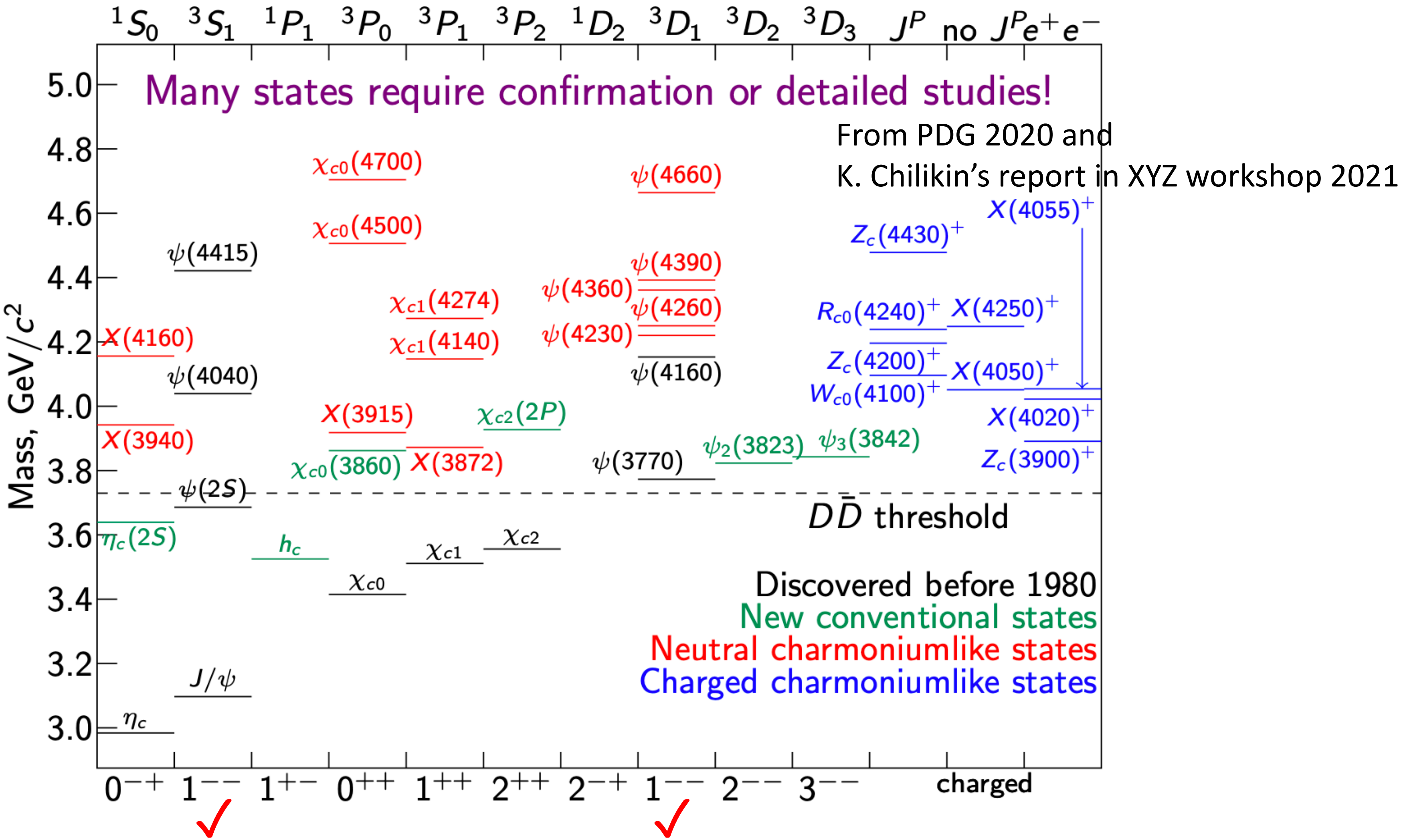
- Allows to study energies below $E_{c.m.}$
- Wide energy range available for the cross section measurements



Initial state radiation

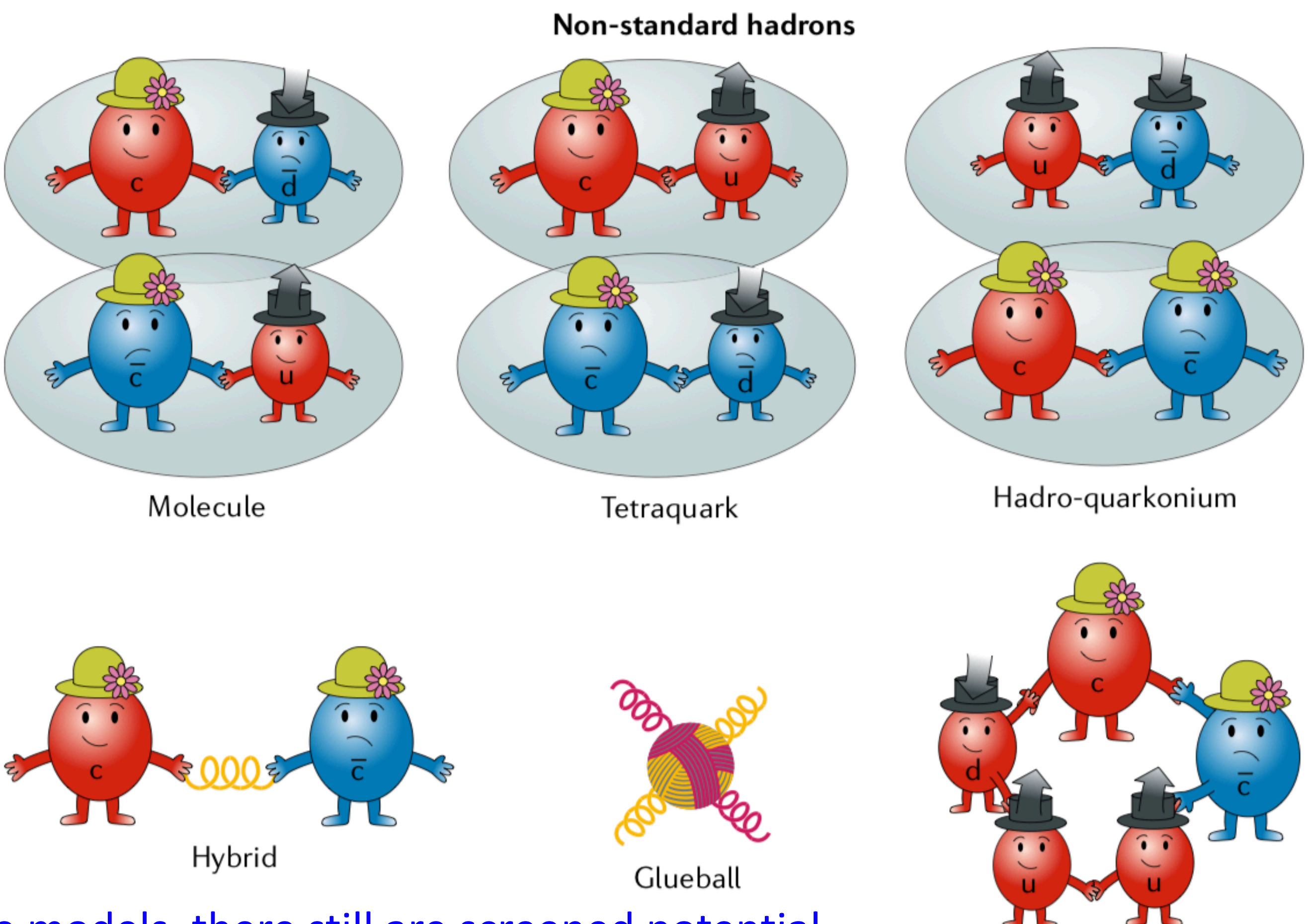
- Suppression from additional photon emission compensated by high luminosity at B-factory

Charmonium(-like) states



- Below $D\bar{D}$ thresholds – charmonium is 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.
- ISR technique helps to explore 1^{--} Y states and sub-particle Z_c states.

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

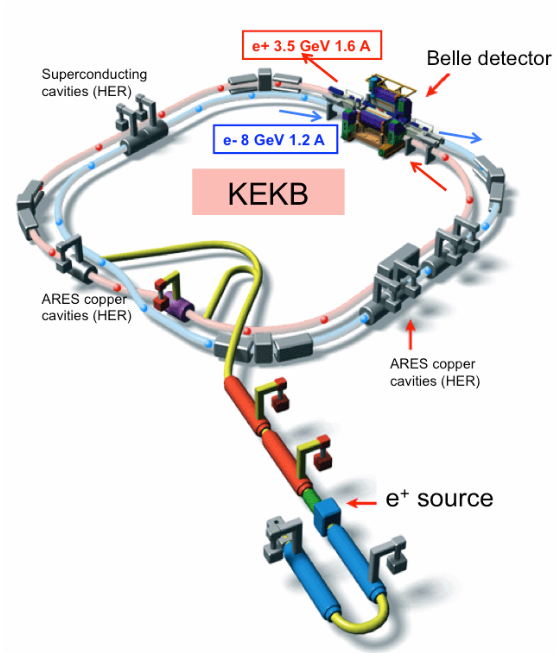
Outline

- SuperKEKB and Belle II detectors
- Overview of ISR results at B-factories
- ISR prospects at Belle II
- ongoing ISR studies at Belle II
- Summary

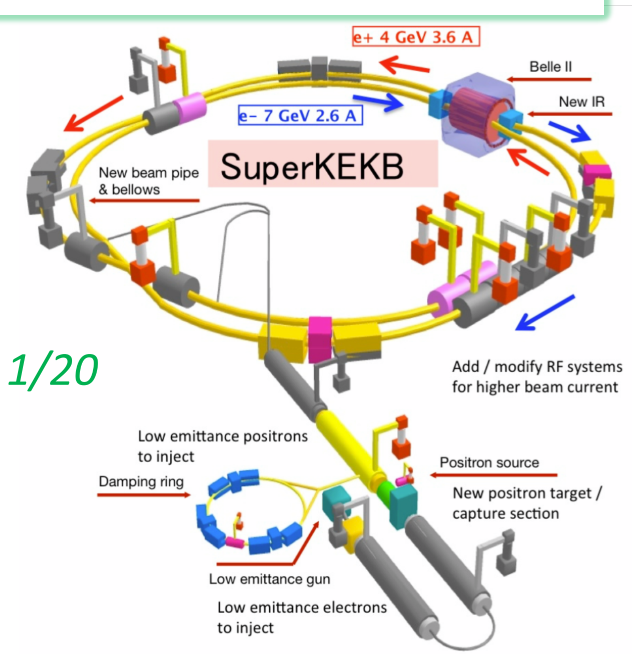
SuperKEKB

- 1st Vs. 2nd generation B-factory

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



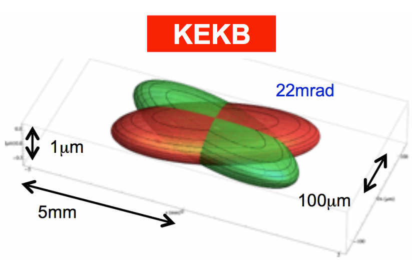
- *Double beam currents*
- *Squeeze beams @IP by 1/20*
- *Reduced CM boost*

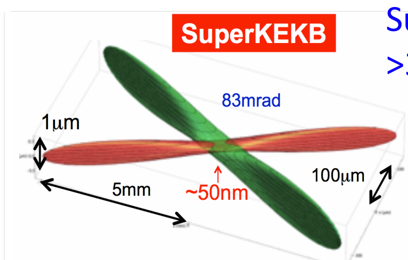


- Nano-beam design (by P. Raimondi for SuperB)

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

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

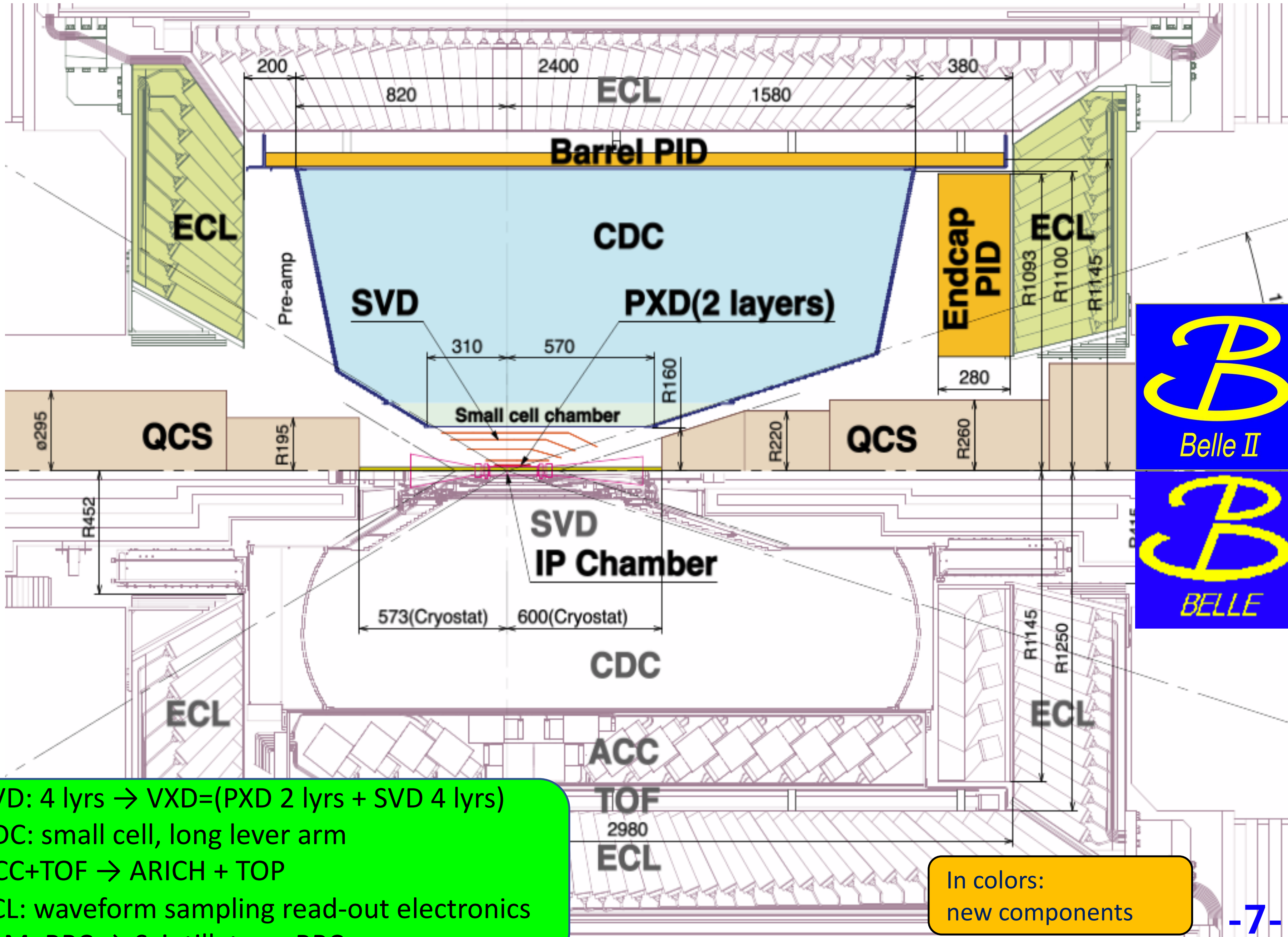




Super-KEKB goal:
>30x instantaneous KEKB luminosity

	$E_\pm$ (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
	$\beta\gamma \sim 2/3$		$\times 2$	$\times 20$

Detector: Belle Vs. Belle II

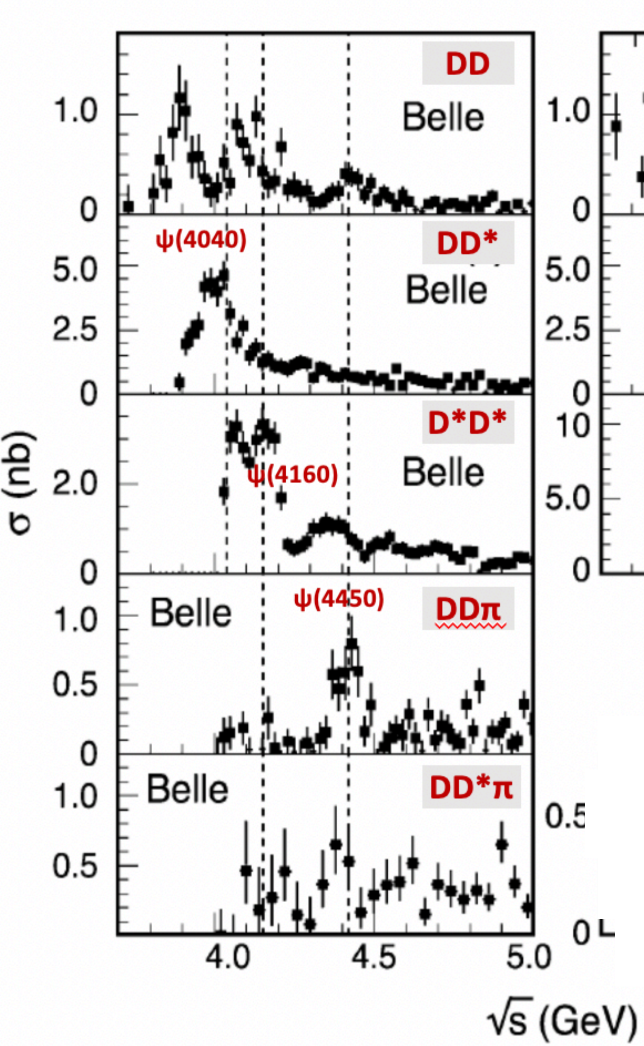


SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → ARICH + TOP
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC

In colors:
new components

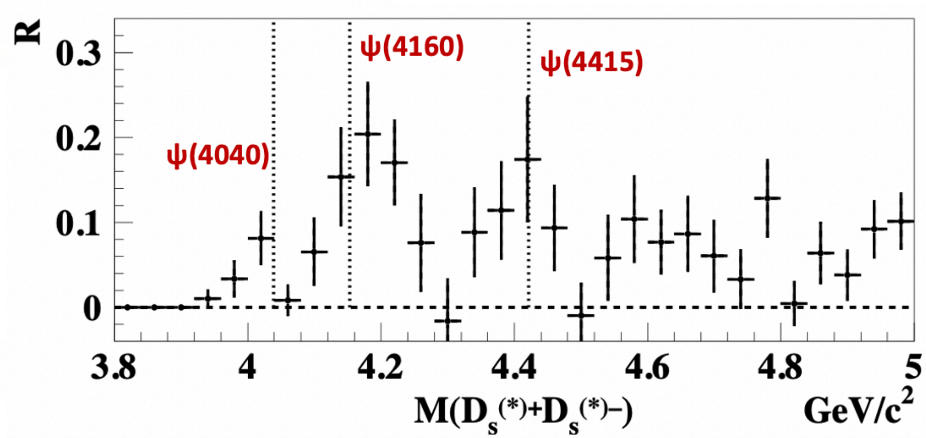
Overview of ISR results at B-factories

Belle, BaBar: $e^+e^- \rightarrow$ open charm

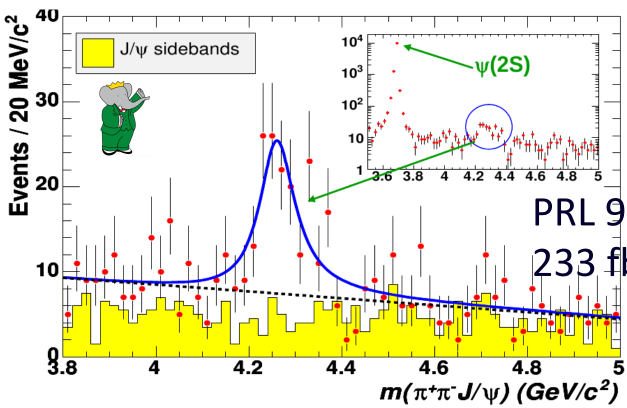


Charminoum states with $J^{PC} = 1^{--}$

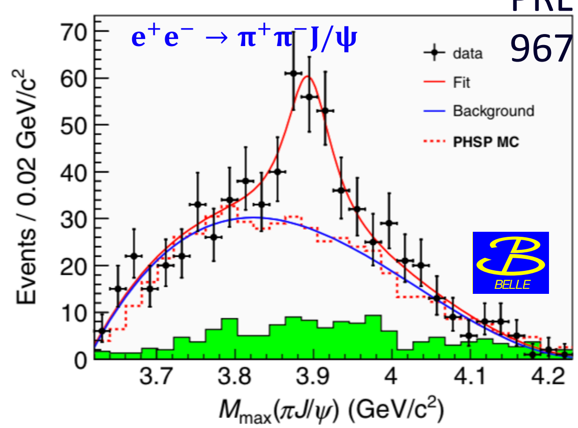
- ψ(4040) is evident in $\bar{D}D^*$, $D^*\bar{D}^*$, $D_s^+D_s^-$
- ψ(4160) is evident in $D^*\bar{D}^*$, $D_s^+D_s^-$
- ψ(4415) is evident in $D\bar{D}\pi$, $D_s^+D_s^-$



Remarkable charmonium-like mesons via ISR：



PRL 95, 142001
233 fb^{-1}



PRL 110, 252002
967 fb^{-1}

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

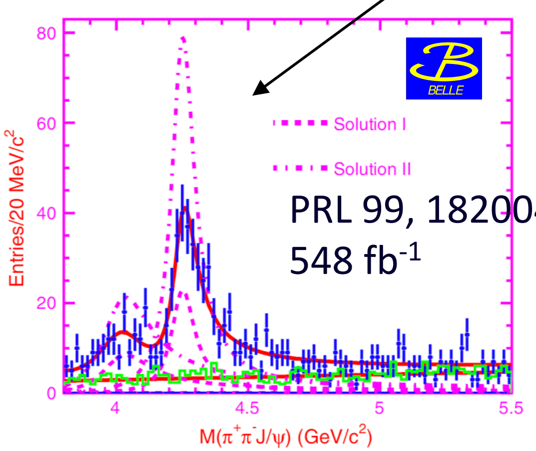
$Z_c^+(3900) \to \pi^+ J/\psi$

2005 → 2007 → 2013 → 2015 Year

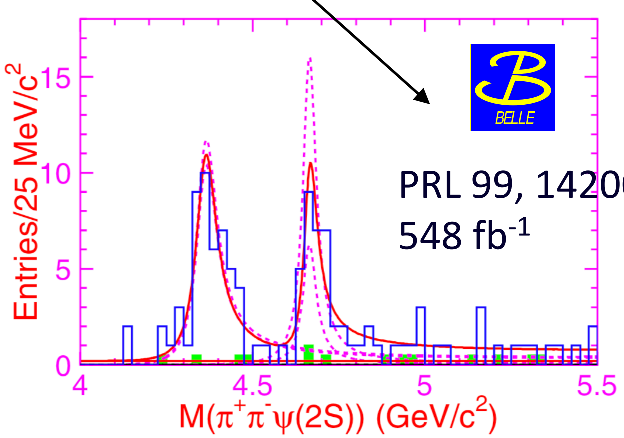
$Y(4008/4260) \to \pi^+\pi^- J/\psi$

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

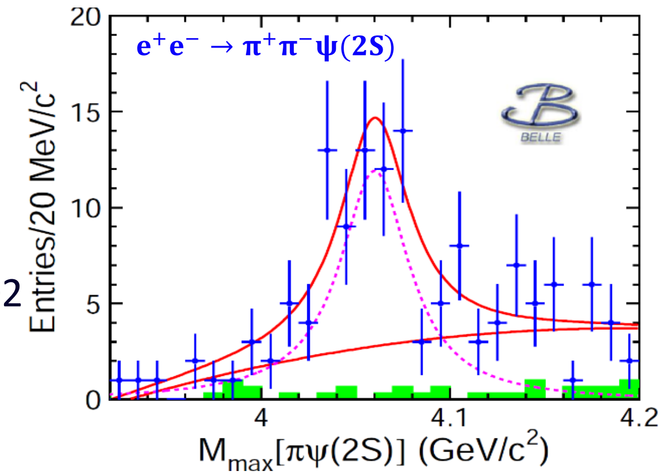
$Z_c^+(4050) \to \pi^+ \psi(2S)$



PRL 99, 182004
548 fb^{-1}

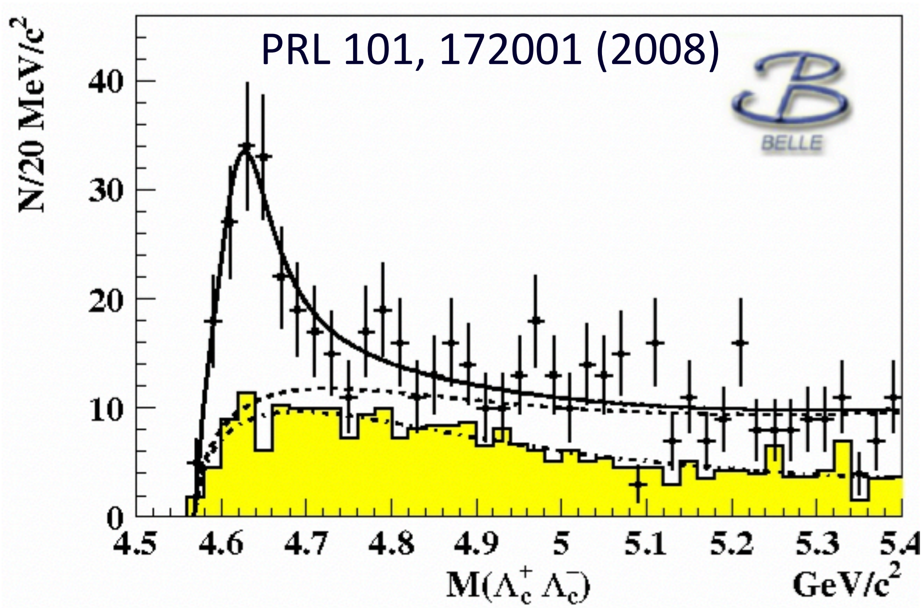


PRL 99, 142002
548 fb^{-1}

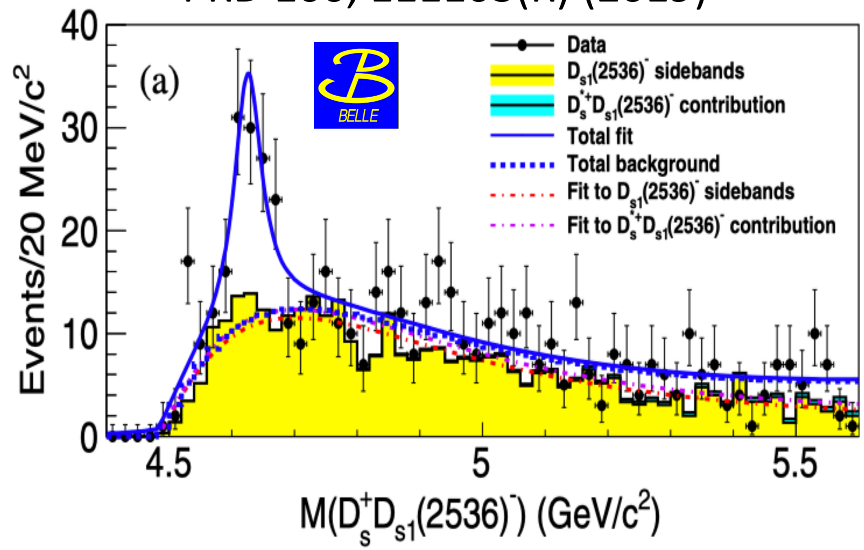


PRD 91, 112007
980 fb^{-1}

Y(4660) also known as ψ(4660) via ISR：

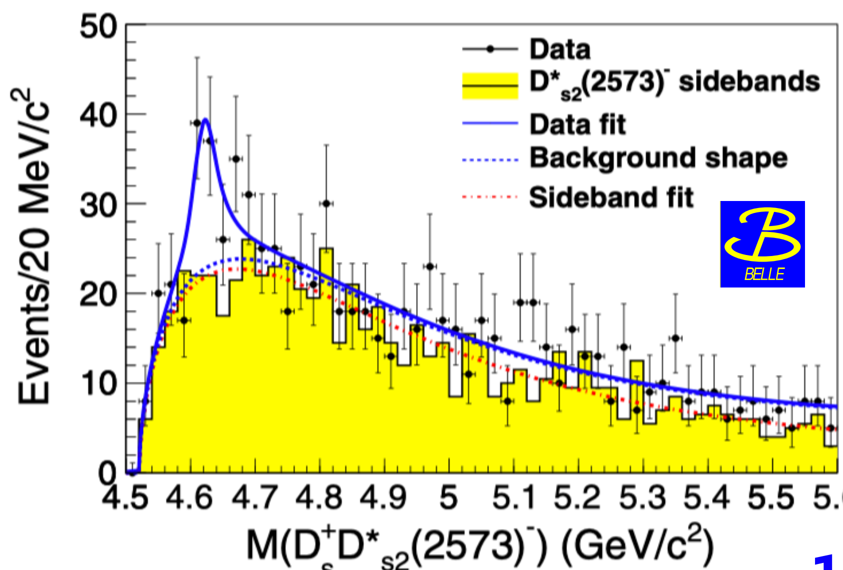


PRD 100, 111103(R) (2019)



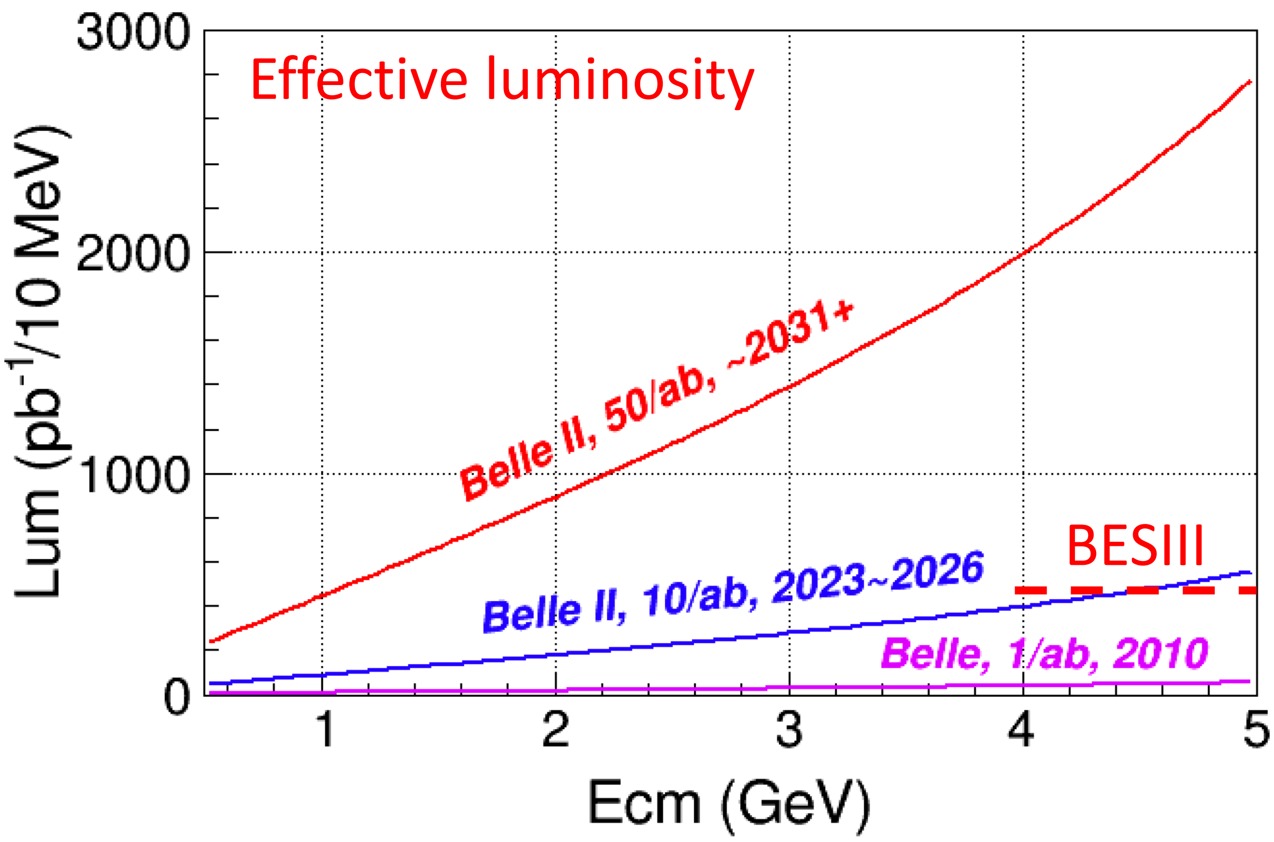
Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
Belle, $D_s^+D_{s1}(2536)^-$	$4626^{+7}_{-7} \pm 1$	$50^{+14}_{-12} \pm 4$
Belle, $D_s^+D_{s2}^*(2573)^-$	$4620^{+9}_{-8} \pm 3$	$47.0^{+32}_{-15} \pm 5$

PRD 101, 091101(R) (2020)



- These states maybe the same.
- Need improved precision.

ISR prospects at Belle II



- Comparable with BESIII in direct e^+e^- annihilations (higher effective luminosity but smaller efficiencies at Belle II)
- Continuous mass range to investigate fine structures
- Higher mass region (> 5.0 GeV) is unique for Belle II

ISR prospects at Belle II

From PTEP 2019 (2019) 12, 123C01, Belle II physics book

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)	$Y(4220)$

10 ab^{-1} ↖ ↗ 50 ab^{-1}

- Measure more precisely the line shapes of more final states in e^+e^- annihilations, including open-charm and charmonium final states.
- Search for the Y states in more processes, such as Y → charmed baryon pairs ($\Lambda_c^+\Sigma_c^-$, $\Sigma_c^+\Sigma_c^-$), charmed strange meson pairs ($D_sD_{s2}(2573)$, $D_s^*D_{s0}(2317)$), … Phys. Rept. 873 (2020)
- Search for Z_{cs} states decaying into $K^\pm J/\psi$, $D_s^- D^{*0}$+c.c., $D_s^{*-}\overline{D}^0$+c.c., …
- Determine the quantum numbers, measure the Argand plot of the resonant amplitude, and search for more decay modes.

ISR studies at Belle II

- $e^+e^- \to J/\psi(\to \mu^+\mu^-)$ via ISR
- $e^+e^- \to \psi(2S) \to \pi^+\pi^- J/\psi$
- $e^+e^- \to \psi(2S) \to \pi^0\pi^0 J/\psi$
- $e^+e^- \to \psi(2S) \to \eta J/\psi$

For ISR production of bottomonium, please see Bryan FULSOM's report on "Bottomonium results and prospects at Belle II" on Thursday, 29 July.

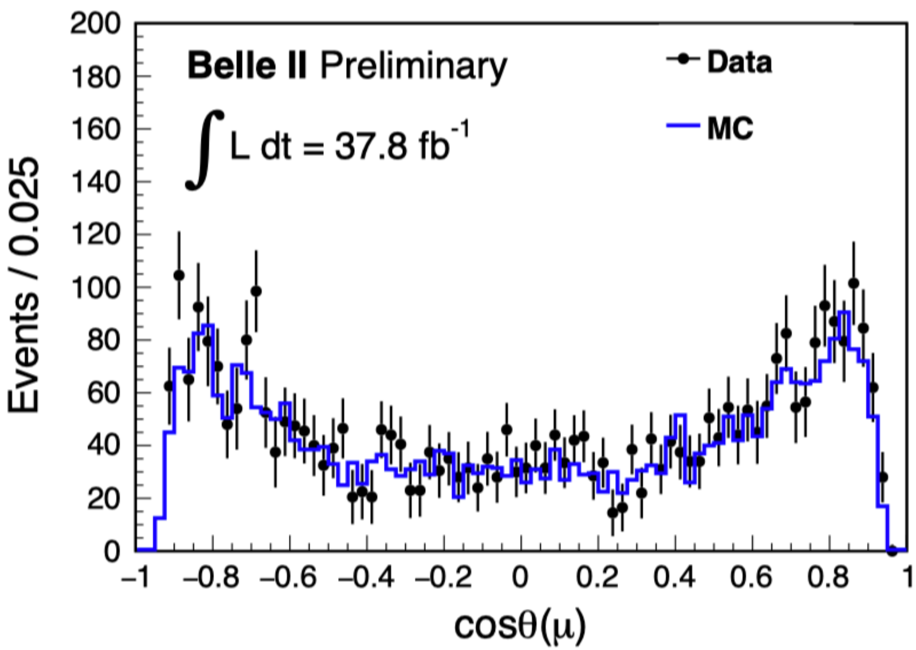
$e^+e^- \to J/\psi(\to \mu^+\mu^-)$ via ISR

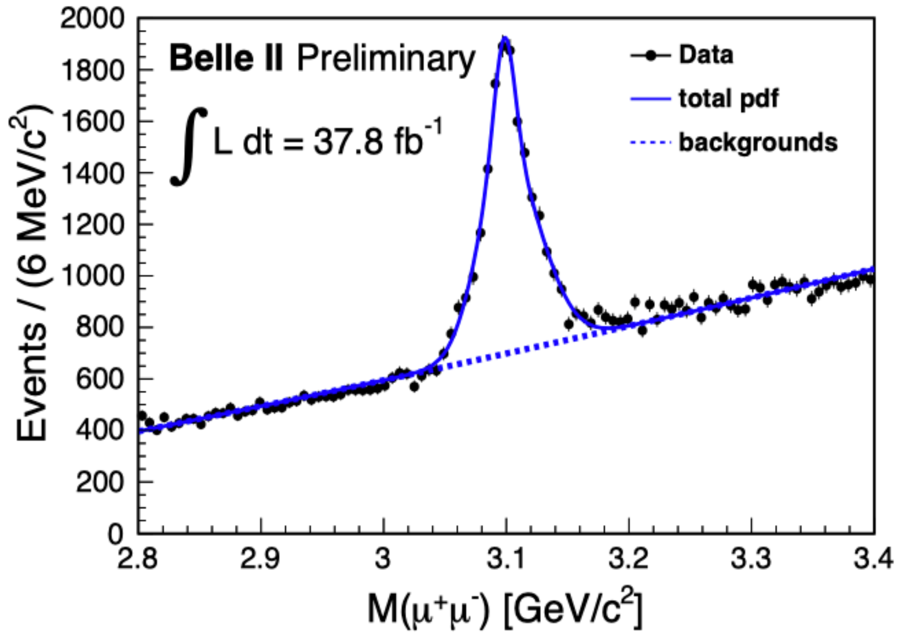
Selection criteria:

- Point of closest approach to the interaction point in $r-\phi$ (along z direction) < 1.0 (3.0) cm
- For muons, $\frac{\mathcal{L}_\mu}{\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\pi+\mathcal{L}_K+\mathcal{L}_p+\mathcal{L}_d} > 0.5$
- Recoil mass square cut: $-2 < \mathrm{M}^2_{\mathrm{recoil}} < 2\ (\mathrm{GeV}/c^2)^2$

PHOKHARA generator has been embeded into Belle2 software framework to simulate ISR events.

The polar angles for muon tracks from signal MC simulations and data after trigger efficiency corrections. Both are consistent.





Results	Data	MC
Mass	(3.097±0.001) MeV/c^2	(3.098±0.001) MeV/c^2
Resolution	(22.0 ± 0.8) MeV	(19.1 ± 0.5) MeV
(Expected) J/ψ signal yield	9566 ± 214	10530 ± 892

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

Selection criteria:

- For muons, electrons, and pions,

$$\frac{\mathcal{L}_\mu}{\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\pi+\mathcal{L}_K+\mathcal{L}_p+\mathcal{L}_d} > 0.5, \frac{\mathcal{L}_e}{\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\pi+\mathcal{L}_K+\mathcal{L}_p+\mathcal{L}_d} > 0.5, \text{and}$$

$$\frac{\mathcal{L}_\pi}{\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\pi+\mathcal{L}_K+\mathcal{L}_p+\mathcal{L}_d} > 0.1$$

- $|M(J/\psi) - m_{J/\psi}| < 75$ MeV/c^2
- ISR photon not required

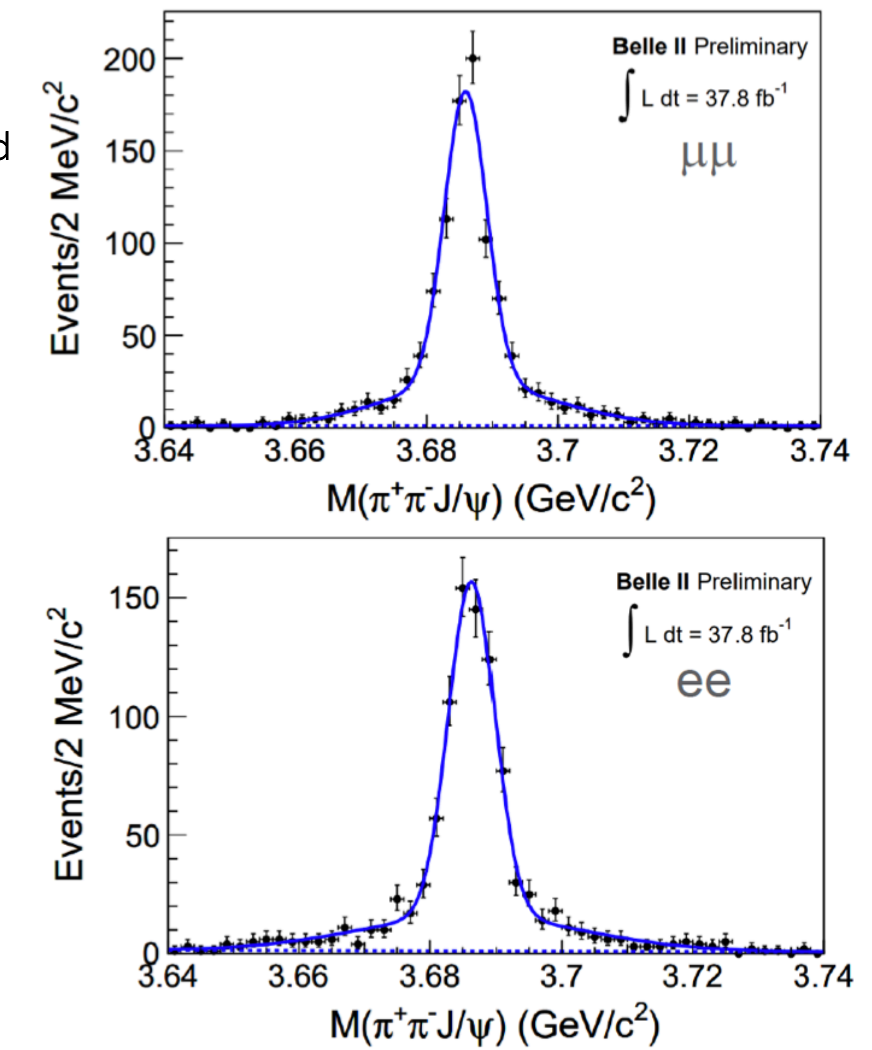
(high efficiency)

- $|M^2_{\mathrm{recoil}}(\pi^+\pi^- J/\psi)| < 2$ (GeV/c^2)^2

Clear observation of ISR $\psi(2S)$ signals with low backgrounds.

Next step:

"Y(4260)" rediscovery [expect ~60 events per 100 fb^{-1}]

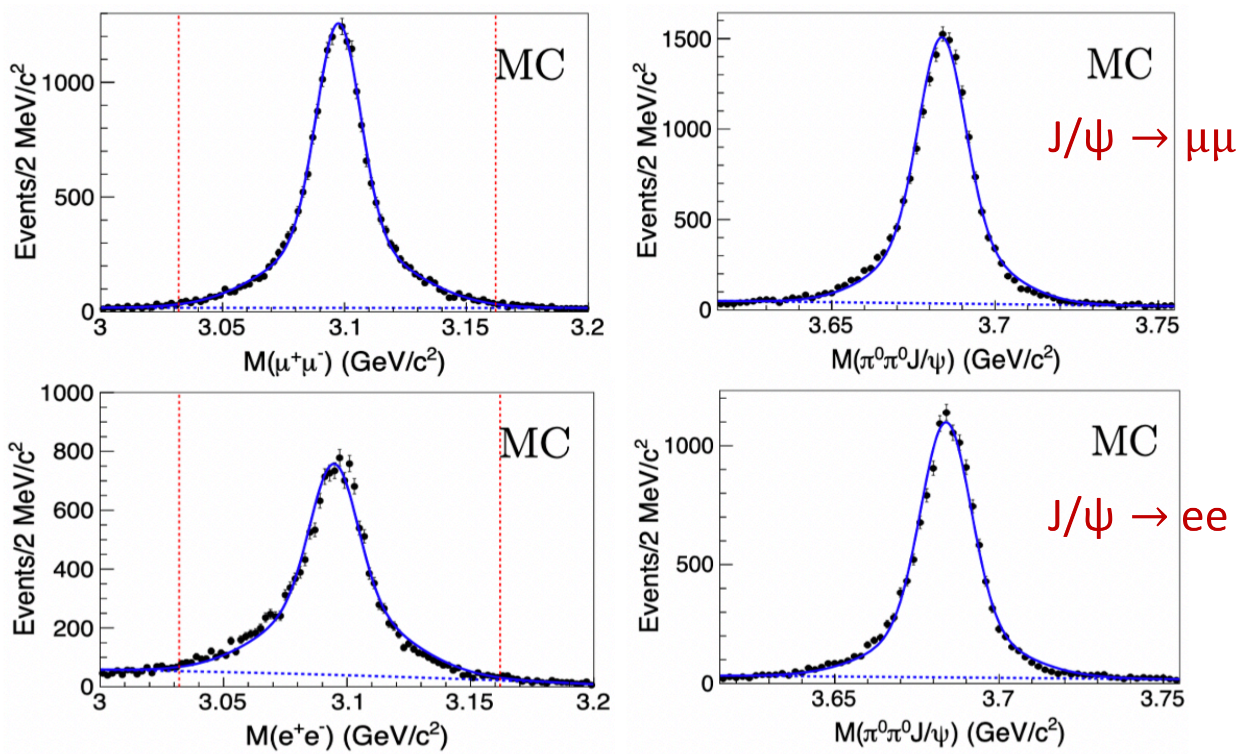


$e^+e^- \to \psi(2S) \to \pi^0\pi^0 J/\psi$

Selection criteria:

- For photons from π^0: $E_\gamma > 50$ MeV in endcaps and $E_\gamma > 30$ MeV in the barrel
- To suppress Bhabha background in $J/\psi \to ee$, the absolute difference between $180°$ and the two polar angles in the center-of-mass frame ($|\theta_{cm}(e^+) + \theta_{cm}(e^-) - 180°|$) is required to be greater than $5°$.
- $|M^2_{recoil}(\pi^0\pi^0 J/\psi)| < 1.5$ (GeV/c²)² to identify ISR events.

Distributions from Phokhara MC simulations:

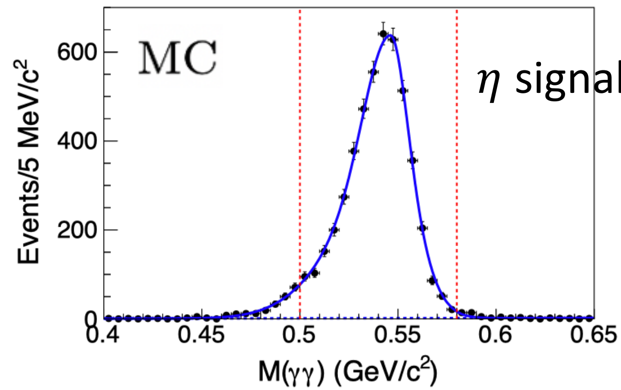


Next step:
"Y(4260)" and neutral Z_c rediscoveries

$e^+e^- \to \psi(2S) \to \eta J/\psi$

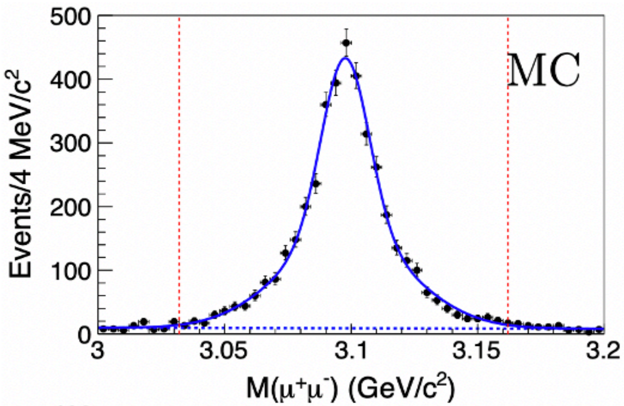
Selection criteria:

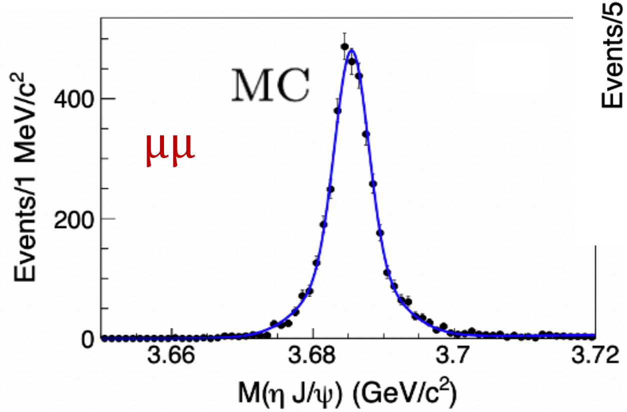
- For photons from η: E_γ > 200 MeV.
- To suppress Bhabha background in $J/\psi \to ee$, the absolute difference between 180° and the two polar angles in the center-of-mass frame ($|\theta_{cm}(e^+) + \theta_{cm}(e^-) - 180^\circ|$) is required to be greater than 5°.
- $|M^2_{recoil}(\eta J/\psi)| < 1.5\ (GeV/c^2)^2$ to identify ISR events

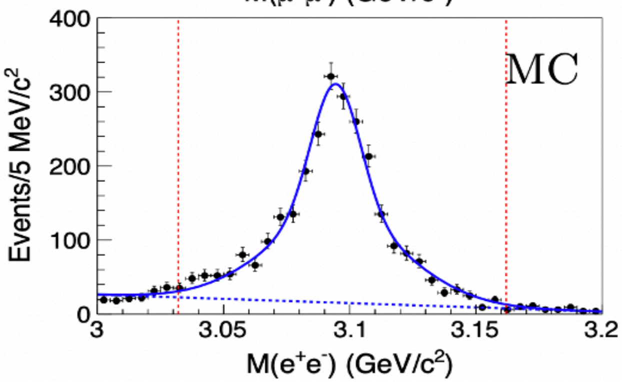


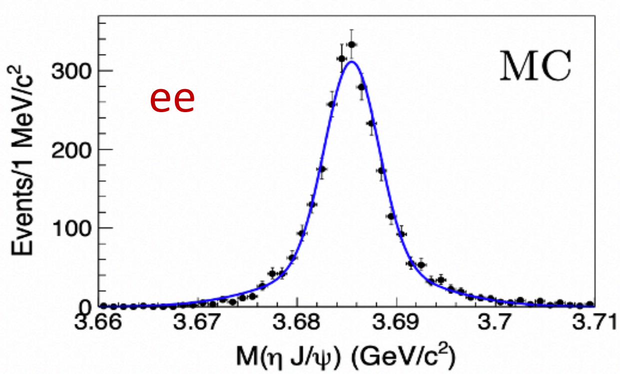
Only the $\eta \to \gamma\gamma$ decay mode is considered.

Distributions from Phokhara MC simulations:







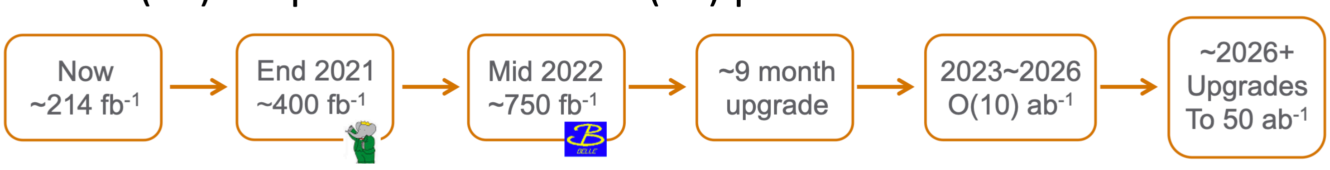


Next step:
explore the extra excited ψ and possible Y states

Summary

- ISR physics is an interesting way to look for resonant states. This is unique to the e^+e^- experiments.
- Preliminary results display the ISR system foundation we are building upon.
- The expected Belle II data sample of 50 ab^{-1} will provide a lot of new opportunities for charmonium-like analyses via ISR process.

$\Upsilon(4S)$ on-peak data + non-$\Upsilon(4S)$ plans



All data samples at any energy points can be used for ISR analysis.

Backup slides