Quarkonium in ISR at Belle and Belle II

Xuyang Gao [1]

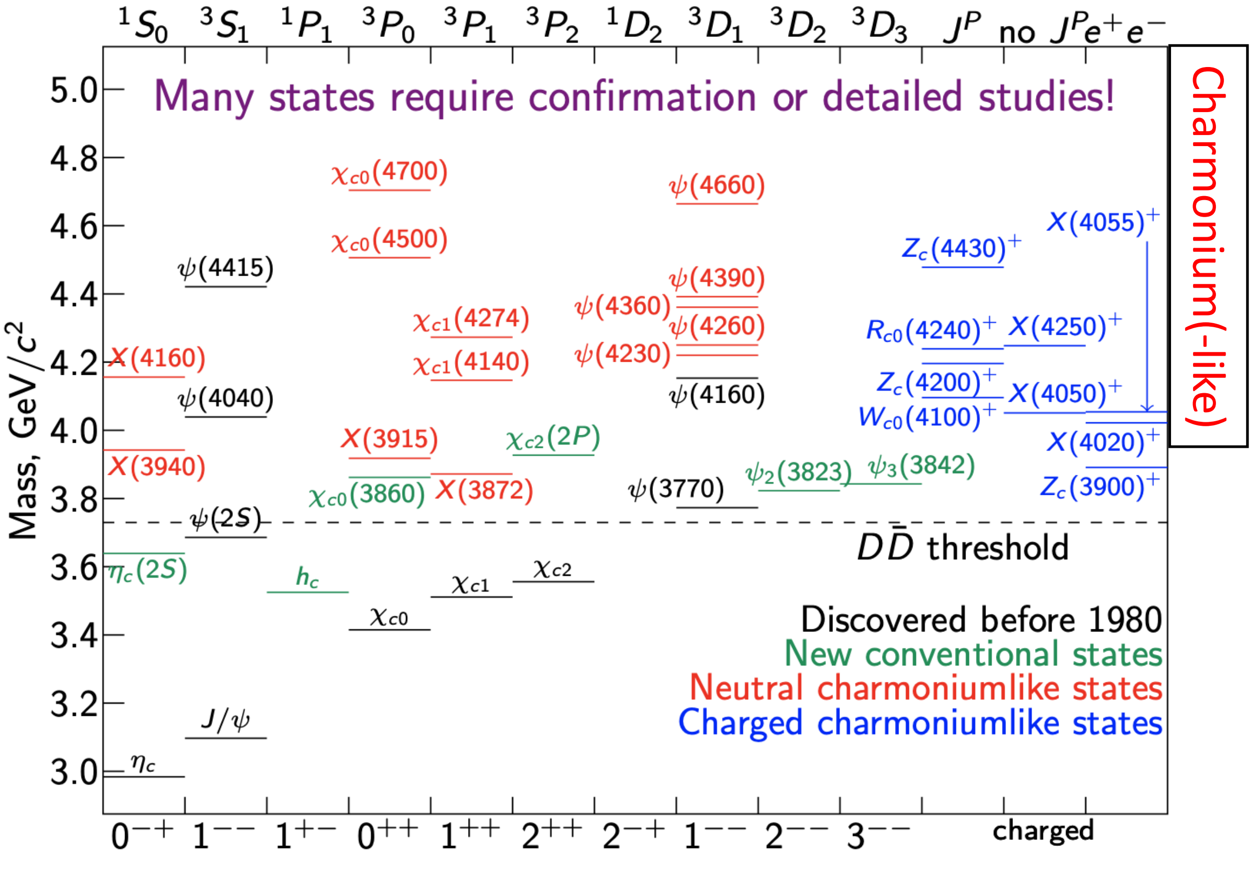
1. Fudan University, Shanghai, China

MITP virtual workshop

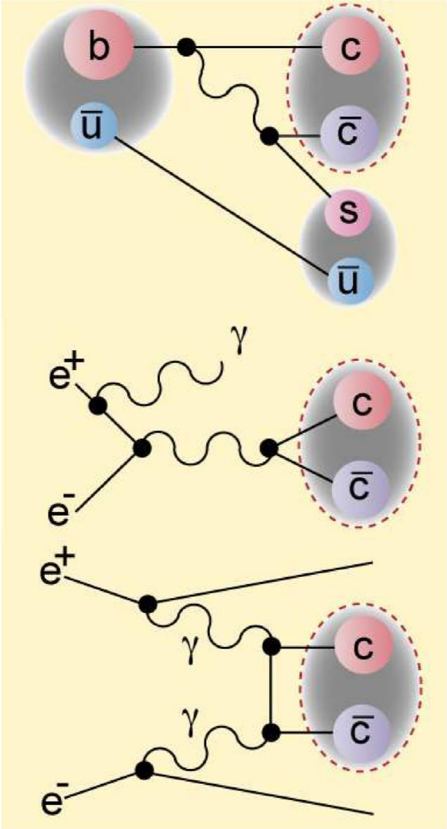
Quarkonium(-like) states in e^+e^-

$Q\bar{Q}$ meson with a pair of heavy quark (i.e., Q = c or b)

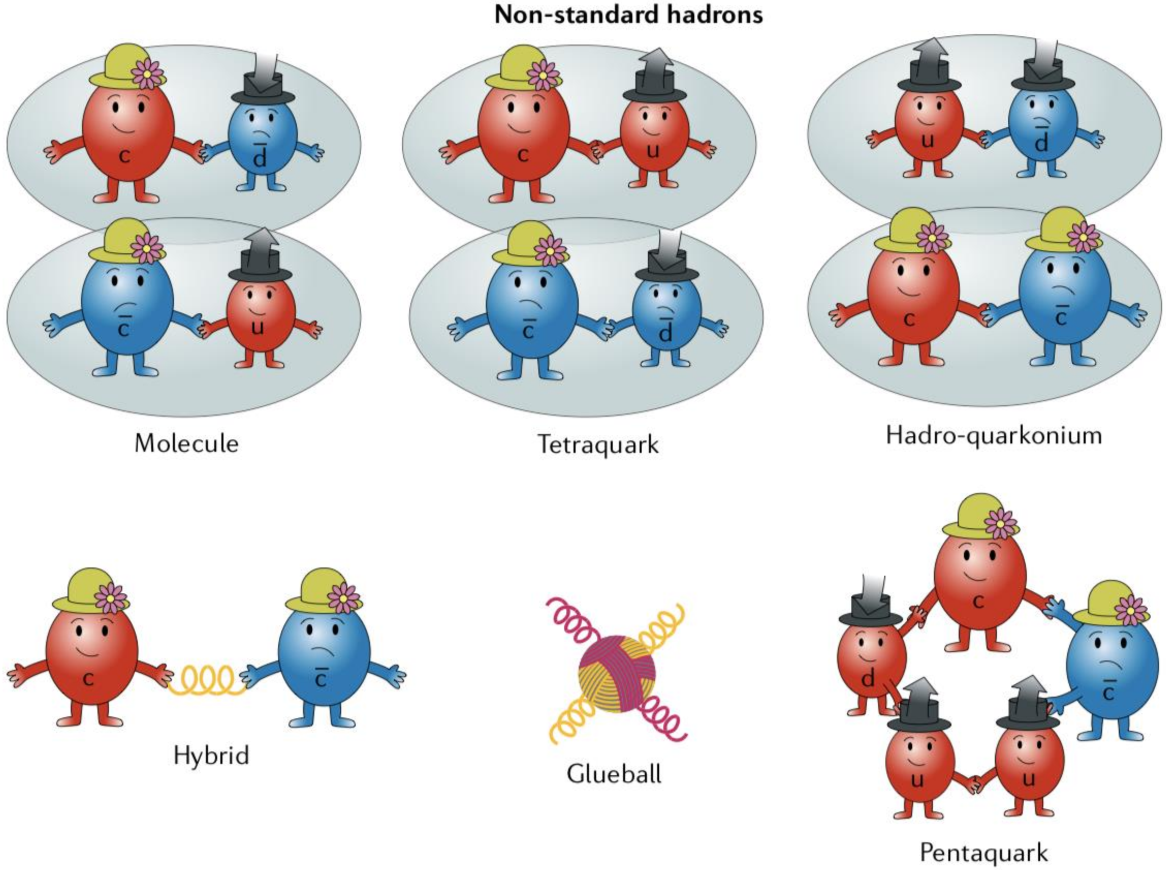
Good playground for quark model and for exotic XYZ states



From K. Chilikin's report in XYZ workshop 2021



Various interpretations of the exotic states



Nature Reviews Physics 1, 480 (2019)

High Priority:

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

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

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

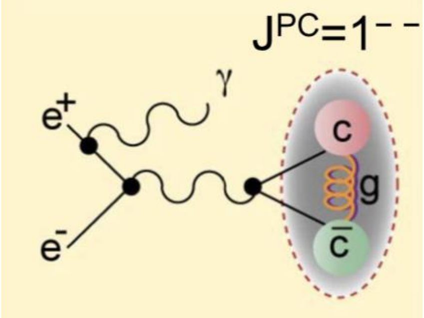
V.N. BAIER and V.S. FADIN
Institute of Nuclear Physics, Novosibirsk, USSR

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 $E_{c.m.}$
- Compensated by high luminosity at B-factory
- Wide energy range available for the cross section measurements

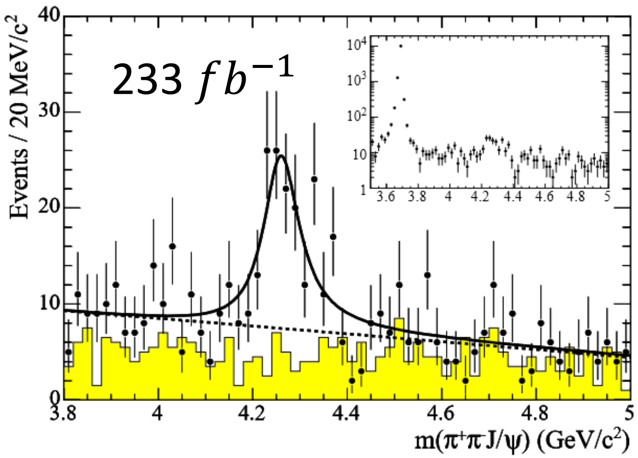


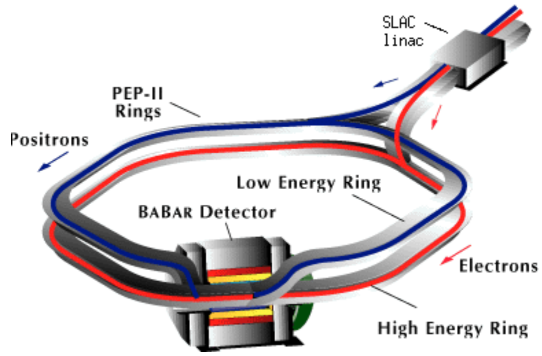
Initial state radiation

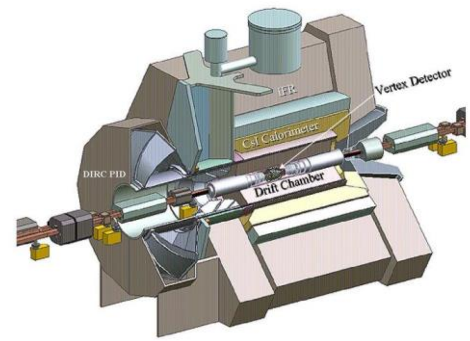
Results in BABAR

$$e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$$

PRL 95, 142001 (2005)

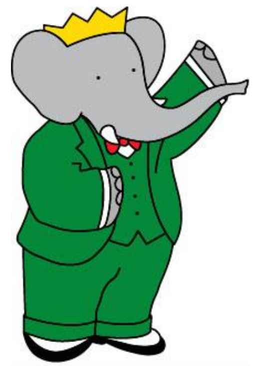






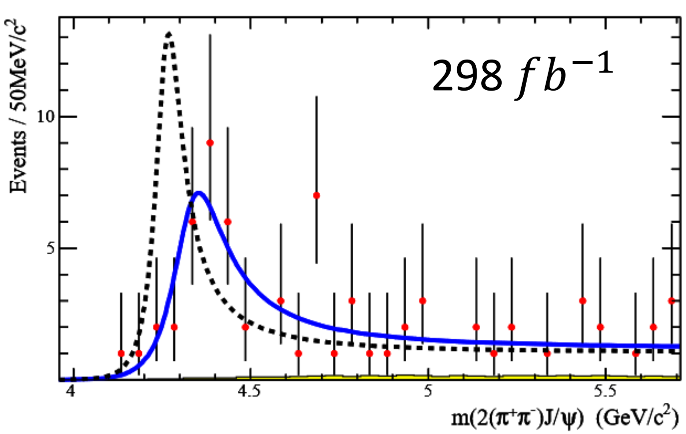
$$e^+e^- \to \gamma_{ISR}D_s^{(*)+}D_s^{(*)-}$$

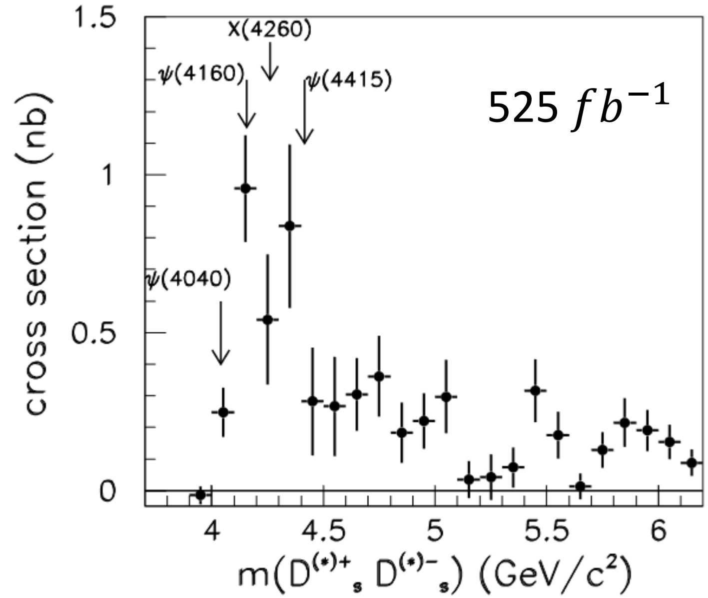
PRD 82, 052004 (2010)



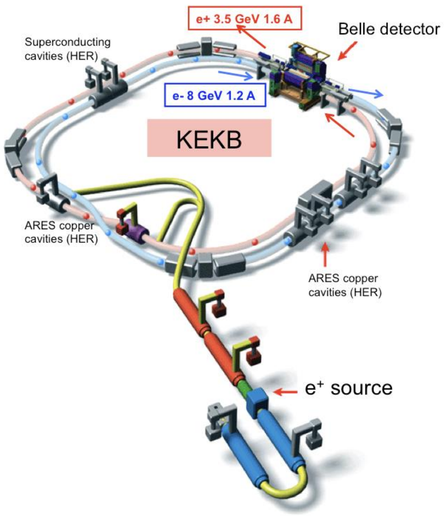
$$e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(2S)$$

PRL 98, 212001 (2007)

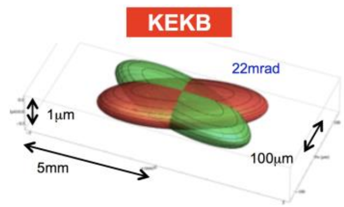


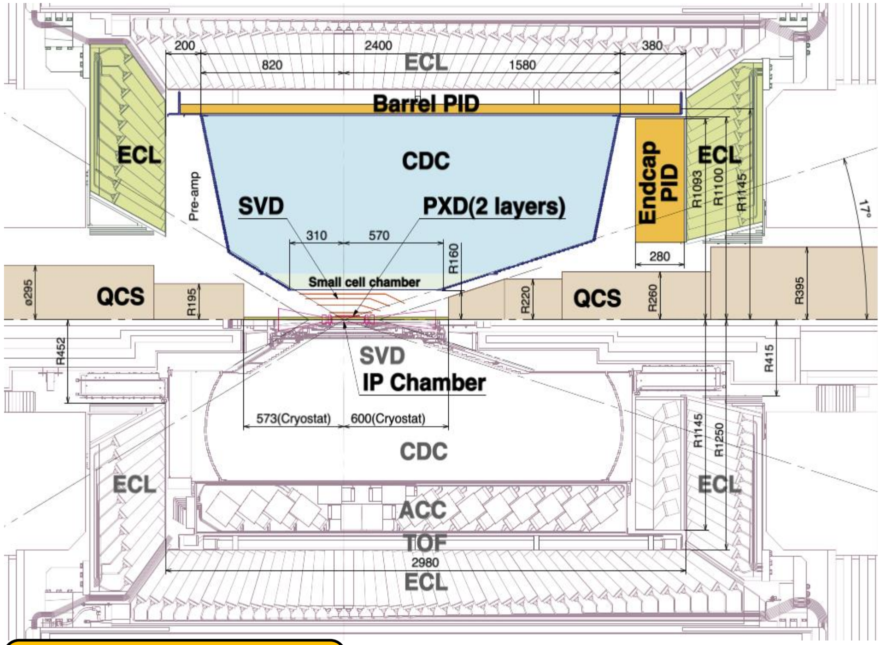


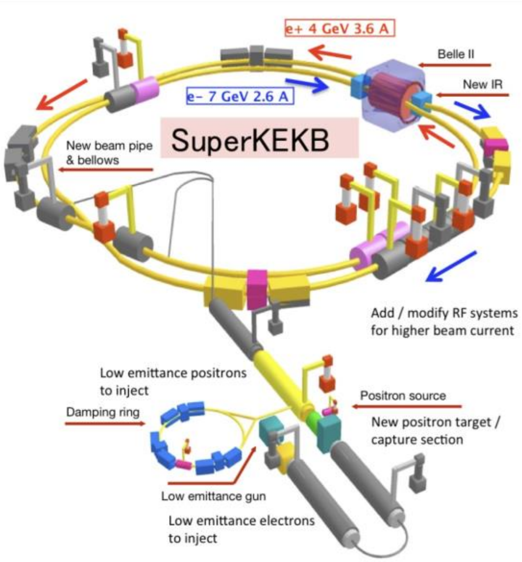
SuperKEKB



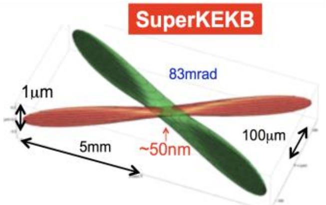
BELLE







Belle II



New components

- 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

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

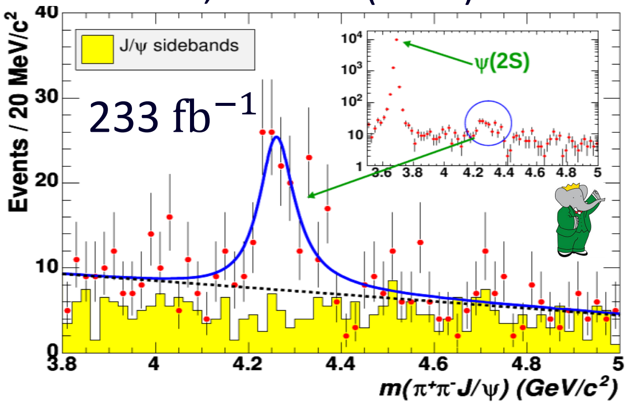
Results in Belle

Process	Reference	Int. Lum.	Physics Covered
$\pi^+\pi^- J/\psi$	PRL 99, 182004 (2007)	548 fb^{-1}	Y(4008), Y(4260)
$\pi^+\pi^-\psi(2S)$	PRL 99, 142002 (2007)	673 fb^{-1}	Y(4360), Y(4660)
$DD_2(2460)$	PRL 100, 062001 (2008)	673 fb^{-1}	ψ(4415)
$\Lambda_c^+\Lambda_c^-$	PRL101,172001 (2008)	695 fb^{-1}	Y(4630)
$D^0D^{*-}\pi^+$	PRD 80, 091101(R) (2009)	695 fb^{-1}	U.L.
$K^+K^- J/\psi$	PRD 77, 011105(R) (2008)	673 fb^{-1}	U.L.
$\pi^+\pi^-\phi$	PRD 80, 031101 (2009)	673 fb^{-1}	Y(2175), ϕ(1680)
$\eta J/\psi$	PRD 87, 051101(R) (2013)	980 fb^{-1}	ψ(4040), ψ(4160)
$\pi^+\pi^- J/\psi$	PRL 110, 252002 (2013)	980 fb^{-1}	Y(4008), Y(4260), $Z_c^+(3900)$
$K^+K^- J/\psi$	PRD 89,072015 (2014)	980 fb^{-1}	U.L.
$\pi^+\pi^-\psi(2S)$	PRD 91, 112007 (2015)	980 fb^{-1}	Y(4360), Y(4660)
γX_{cJ}	PRD 92, 012011 (2015)	980 fb^{-1}	U.L.
$\pi^+\pi^-\psi(2S)$	PRD 91, 112007 (2015)	980 fb^{-1}	$Z_c^+(4050)$
$D_s^+D_{s1}(2536)^-$	PRD 100, 111103(R) (2019)	922 fb^{-1}	Y(4626)
$D_s^+D_{s2}^*(2573)^-$	PRD 101, 091101(R) (2020)	922 fb^{-1}	Y(4626)

evidence

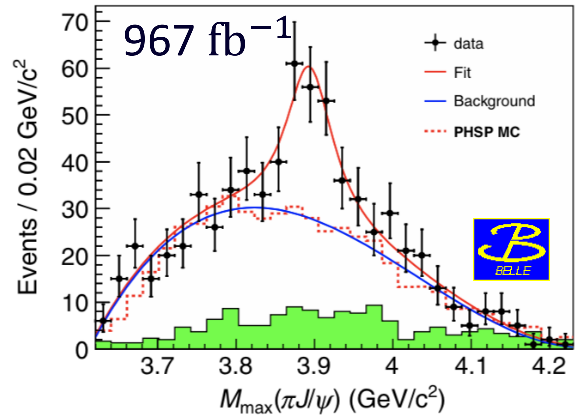
Remarkable charmonium-like mesons via ISR

PRL 95, 142001 (2005)



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

PRL 110, 252002 (2013)



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

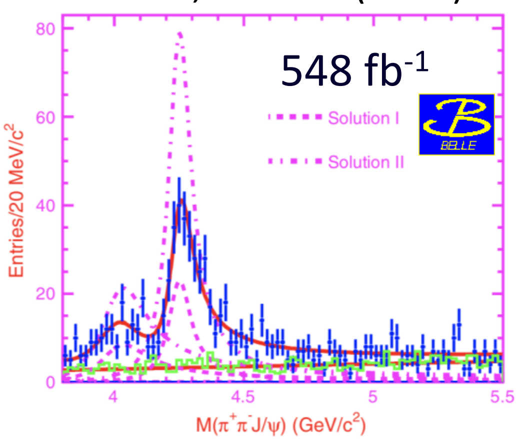
2005 → 2007 → 2013 → 2015

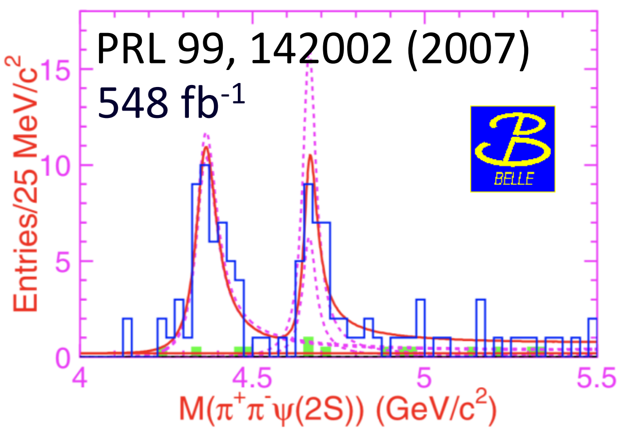
$Y(4008/4260) \to \pi^+\pi^- J/\psi$

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

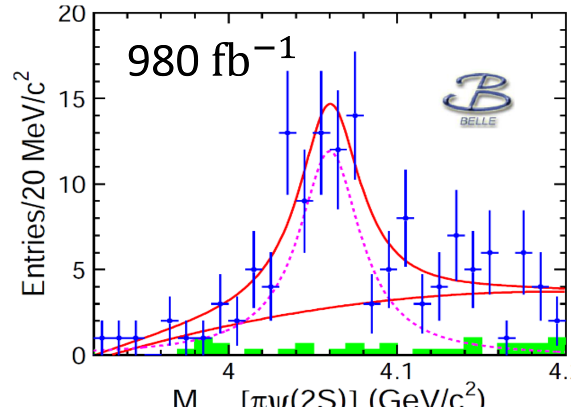
$Z_c^+(4050) \to \pi^+ \psi(2S)$

PRL 99, 182004 (2007)





PRD 91, 112007 (2015)



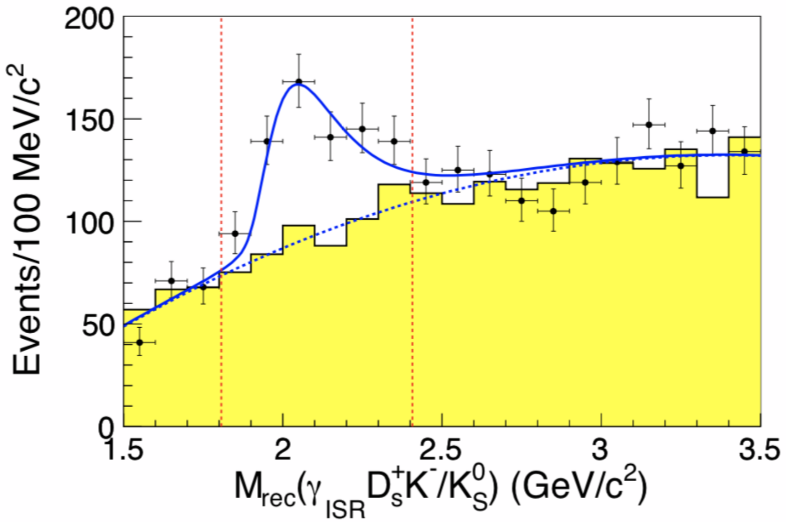
Study Y(4660)

$Y(4626)$ in $e^+e^- \to \gamma_{ISR} D_s^+ D_{s1}(2536)^- (\to \bar{D}^{*0} K^- / D^{*-} K_S^0)$+c.c.

For $\bar{D}^{*0} K^-$ mode, full reconstruction of the γ_{ISR}, D_s^+ , and K^-.

D_s: $K^+K^-\pi^+$, K_sK^+, $K^+K^-\pi^+\pi^0$, $K_sK^+\pi^0$, $\eta\pi^+$, $\eta'\pi^+$,and require $D_s^+ K^- \gamma_{ISR}$ recoil mass ~ $\bar{D}^{*0}$ mass.

For $D^{*-} K_S^0$ mode, full reconstruction of the γ_{ISR}, D_s^+ , and K_S^0, and do similar selection



- $M_{rec}(\gamma_{ISR} D_s^+ K^- / K_S^0)$ distribution is making before applying the $\bar{D}^{*0}/D^{*-}$ mass constraint.
- Due to the poor mass resolution, the $\bar{D}^{*0}/D^{*-}$ signal is very wide.
- The yellow histogram shows the normalized $D_{s1}(2536)^-$ mass sidebands.

Phys. Rev. D 100, 111103(R) (2019)

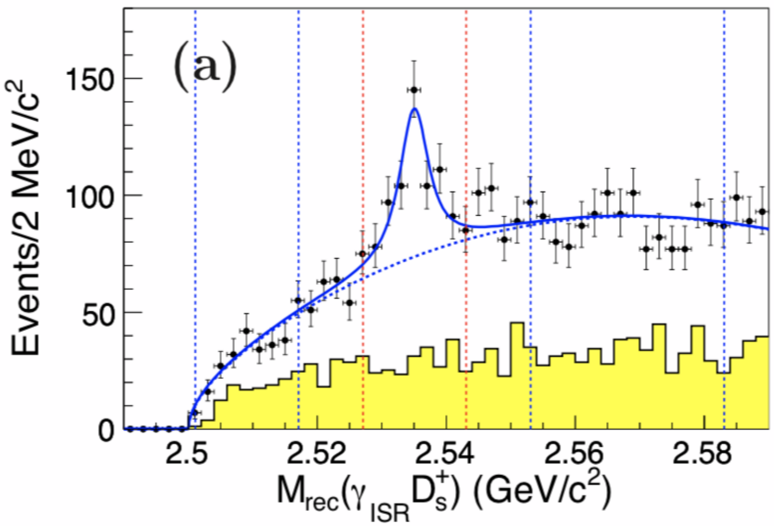
Study Y(4660)

$\mathrm{Y(4626)\ in\ e^+e^- \to \gamma_{ISR} D_s^+ D_{s1}(2536)^-(\to \bar{D}^{*0}K^-/D^{*-}K_S^0)+c.c.}$

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

The resolution of $M_{rec}(\gamma_{ISR})$ is drastically improved (~180 → ~ 5 MeV).

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



- $M_{rec}(\gamma_{ISR} D_s^+)$ distribution is making after applying the $\bar{D}^{*0}/D^{*-}$ mass constraint.
- The yellow histogram shows the normalized D_s^+ mass sidebands.
- The fit yields 275±32 $D_{s1}(2536)^-$ signal events with the statistical significance of 8.0σ.

Phys. Rev. D 100, 111103(R) (2019)

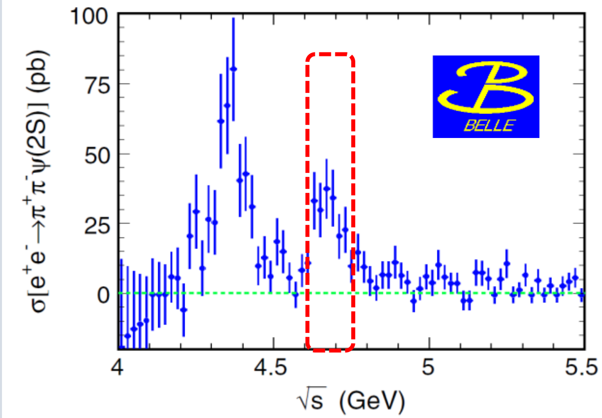
Study Y(4660)

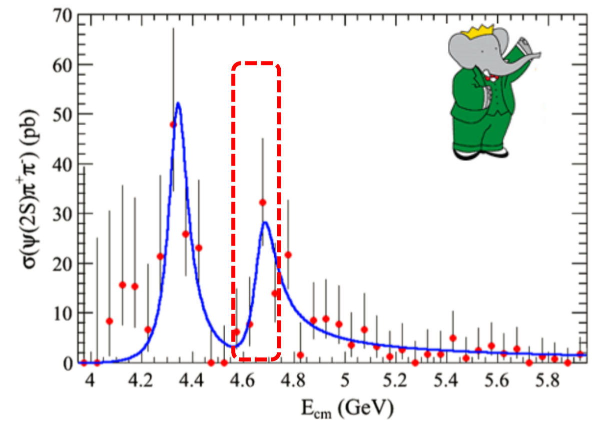
Similar mass and width of Y state at around 4.6 GeV in following channels, are they from same resonance?

Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda^+_c\Lambda^-_c$	$4634^{+8\ +5}_{-7\ -8}$	$92^{+40\ +10}_{-24\ -21}$
Belle, $\pi\pi\psi'$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi\pi\psi'$	$4669\pm21\pm3$	$104\pm48\pm10$
Belle, D_sD_{s1}	$4625.9^{+6.2}_{-6.0}\pm0.4$	$49.8^{+13.9}_{-11.5}\pm4.0$

$$Y(4626) = Y(4660)?$$

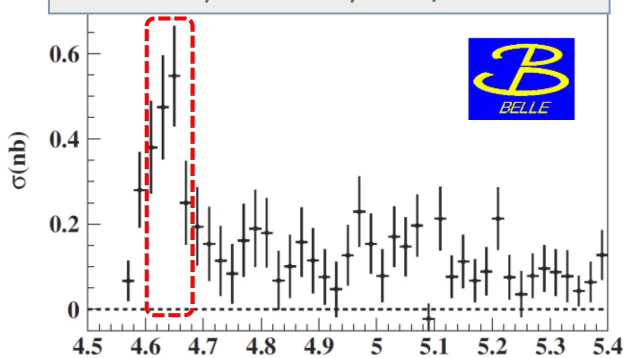
Belle: PRD91, 112007, (980/fb)
BaBar: PRD89, 111103, (520/fb)





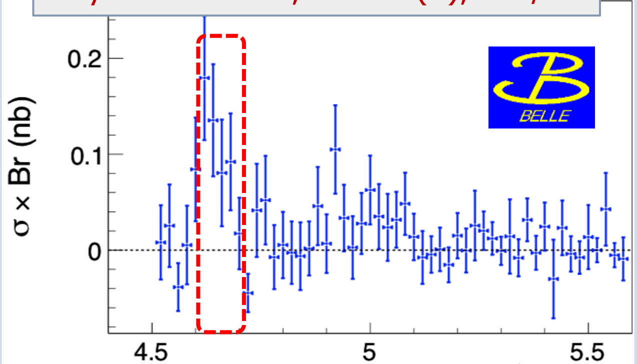
$e^+e^- \to \pi^+\pi^-\psi'$

PRL 101, 172001, 695/fb



$e^+e^- \to \Lambda_c^+\Lambda_c^-$

Phys. Rev. D 100, 111103(R), 922/fb



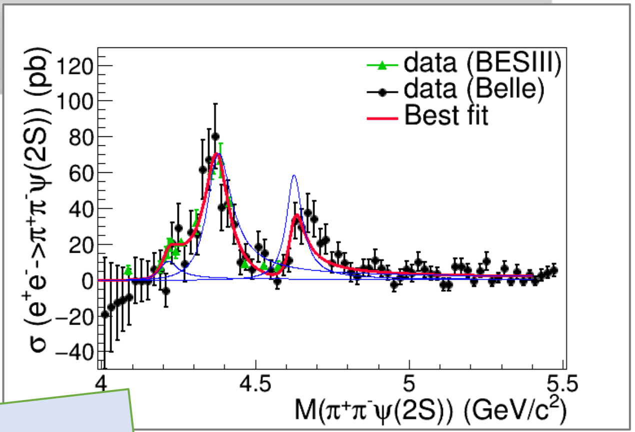
$e^+e^- \to D_s^+D_{s1}^-$

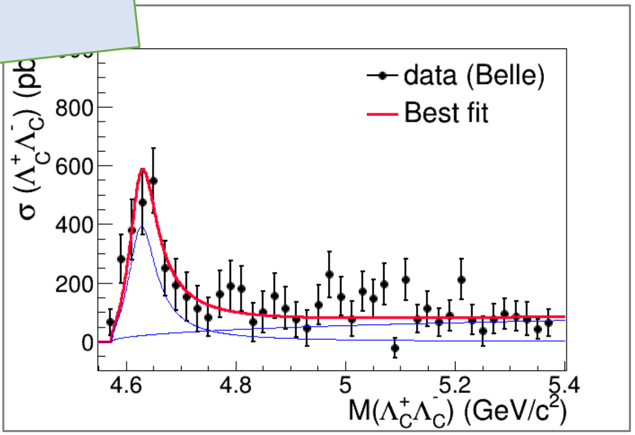
Study Y(4660)

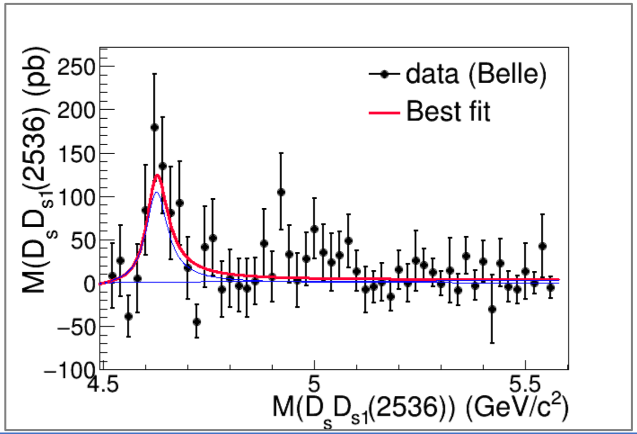
- Consider all possible signals at 4.63 GeV from same resonance, fit on the cross sections simultaneously:

M = 4623.7 ± 4.4 MeV/c^2
Γ = 62.0 $\pm$ 6.8 MeV

Private work







- Why does Y(4660) couple to $\bar{s}s$ and charmed baryon strongly?

Tetraquark state?
- PRD 101, 054010 (2020)
- PRD 101, 054039 (2020)

Molecular state?
- EPJC 80, 3 (2020)

High charmonia?
- PRD 101, 034001 (2020)

New structure near 10.75 GeV

- Energy dependence of the $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1,2,3)$

- ISR process in the $\Upsilon(10860)$ on-resonance data provides support for the new structure.

- New structure has global significance of 6.8σ

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

D-wave bottomonium?

- Phys. Rev. D 101, 014020 (2020)
- EPJC 80, 59 (2020)

$\bar{B}^{(*)}B^{(*)}$ dynamically generated pole?

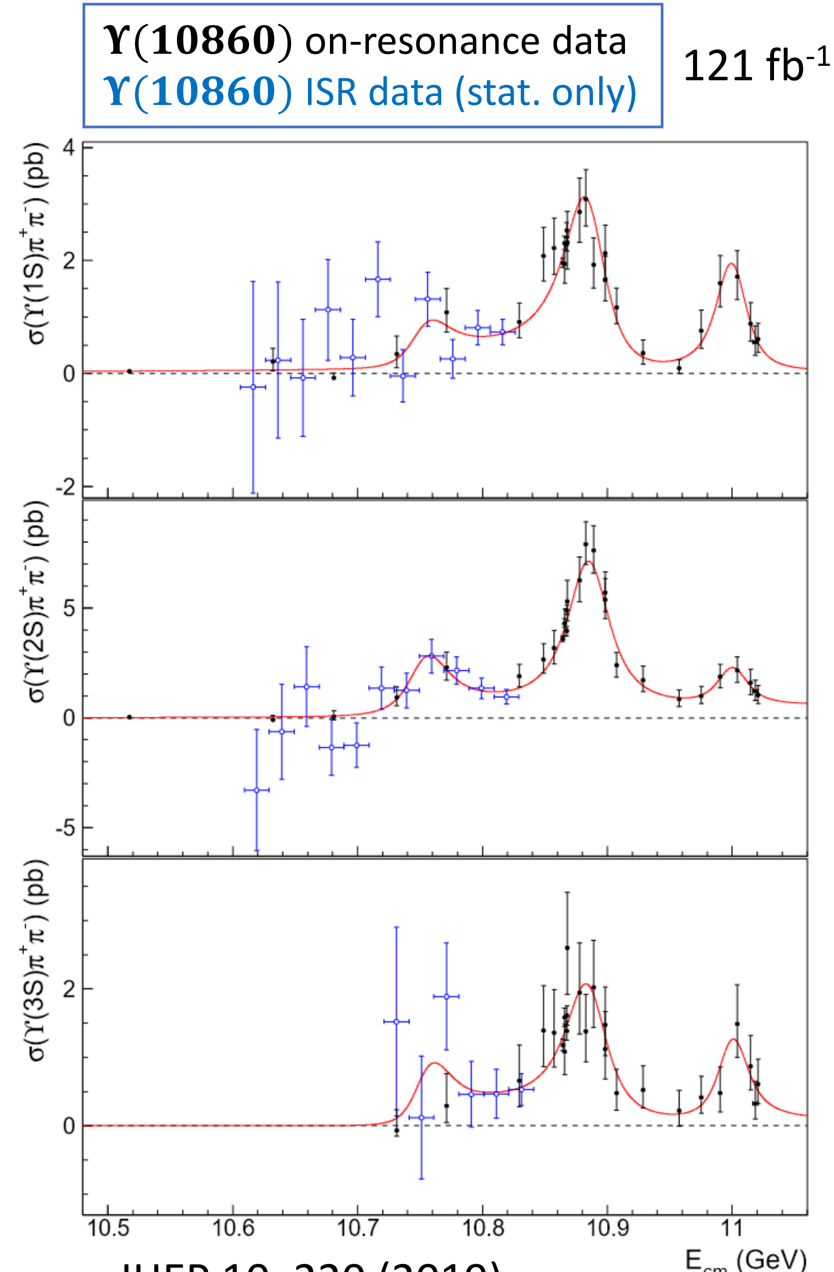
- Phys. Rev. D 101, 034503 (2020)

Hybrid?

- arXiv:1908.05179

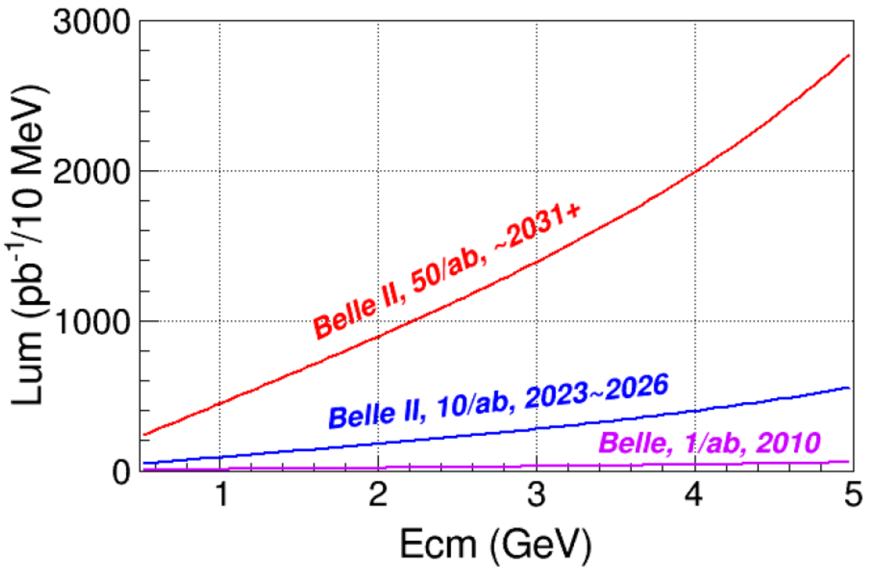
Tetraquark state?

- Physics Letters B 802, 135217 (2020)



JHEP 10, 220 (2019)

ISR study and prospects at BelleII



- **Comparable** with BESIII in direct e^+e^- annihilations
- **Continuous** mass range to investigate fine structures
- **Higher mass region** (> 5.0 GeV) is unique for 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}

ISR prospects at BelleII

- 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 ($D_sD_{s2}(2573)$, $D_s^*D_{s0}(2317)$), …

- Search for Z_{cs} states decaying into $K^{\pm}J/\psi$, $D_s^-D^{*0}$+c.c., $D_s^{*-}\overline{D}^0$+c.c., …

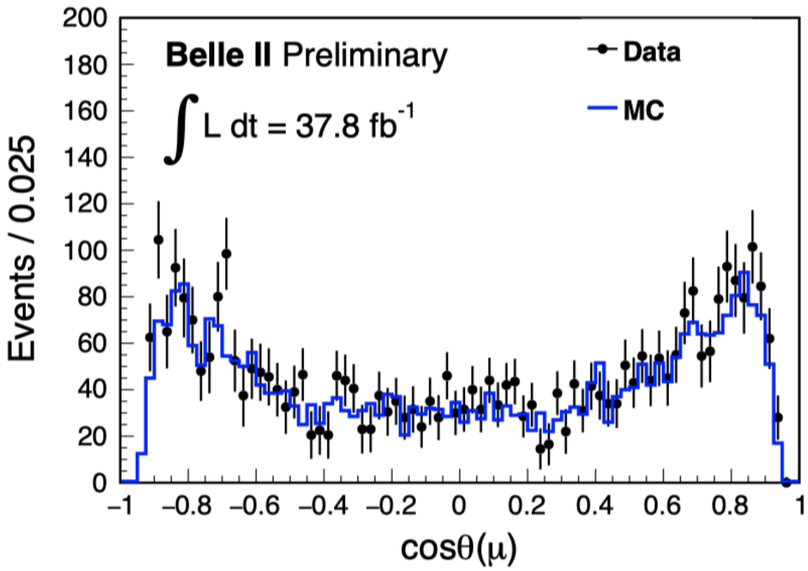
- Determine the quantum numbers, measure the Argand plot of the resonant amplitude, and search for more decay modes.

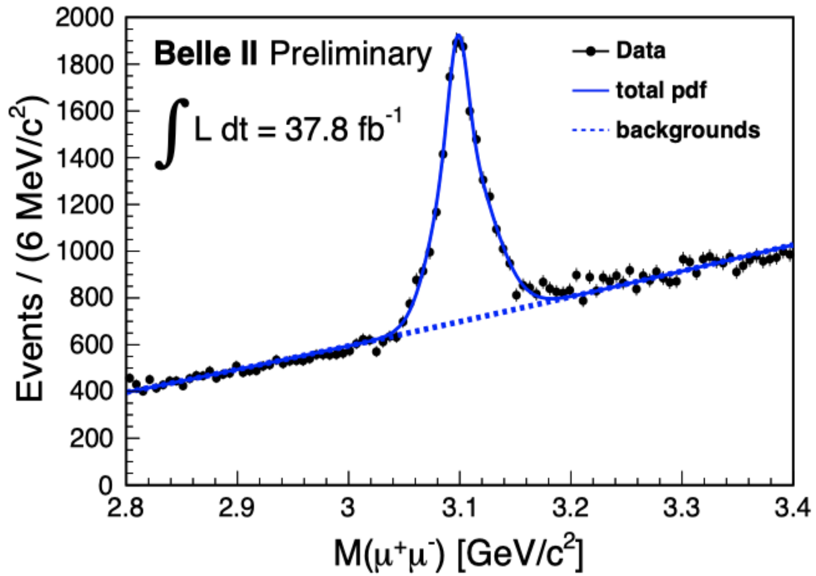
Ongoing ISR analysis on BelleII

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

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.

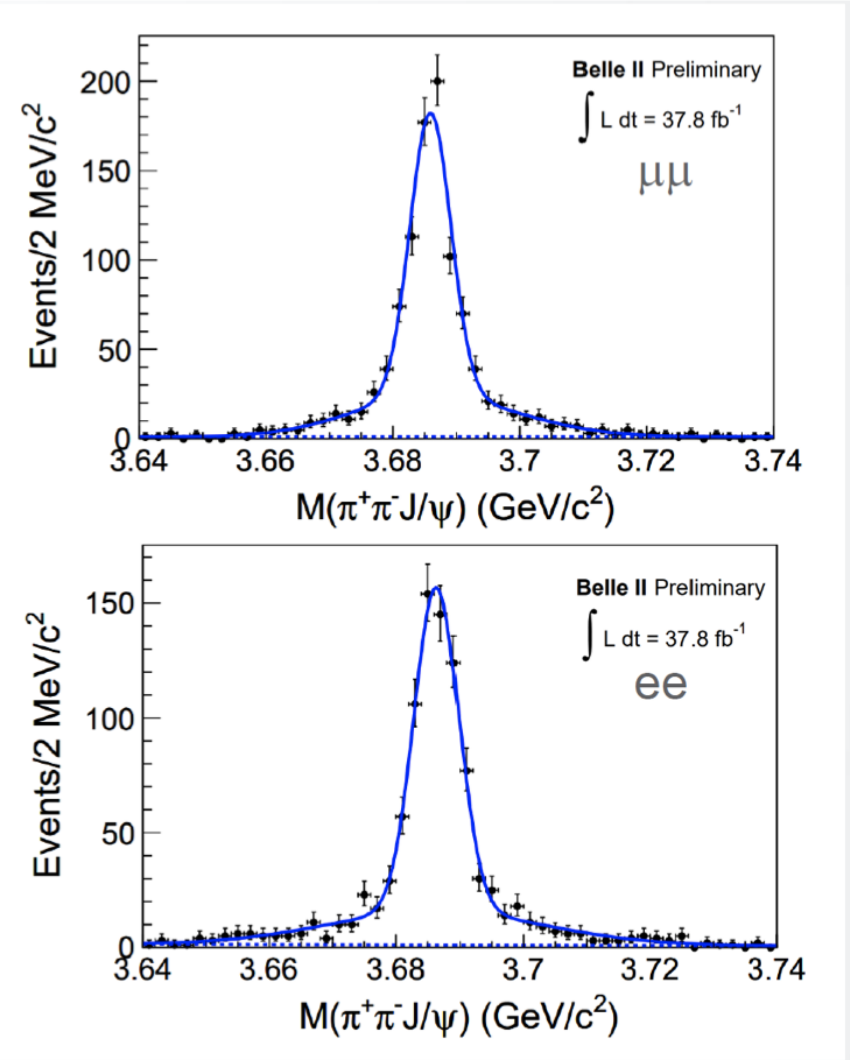




Results	Data	MC
Mass	(3.097 ± 0.001) MeV/c^2	(3.098 ± 0.001) MeV/c^2
Resolution	(22.0 ± 0.8) MeV	(19.1 ± 0.5) MeV
(Expected) J/ψ signal yield	9566 ± 214	10530 ± 892

Ongoing ISR analysis on BelleII

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



Selection criteria:

- $PID(\mu) > 0.5, PID(e) > 0.5, PID(\pi) > 0.1$
- $|M(J/\psi) - m_{J/\psi}| < 75$ MeV/c²
- ISR photon not required (high efficiency)
- $|M^2_{recoil}(\pi^+\pi^- J/\psi)| < 2$ (GeV/c²)²

Clear observation of ISR ψ(2S) signals with low backgrounds.

Next step:

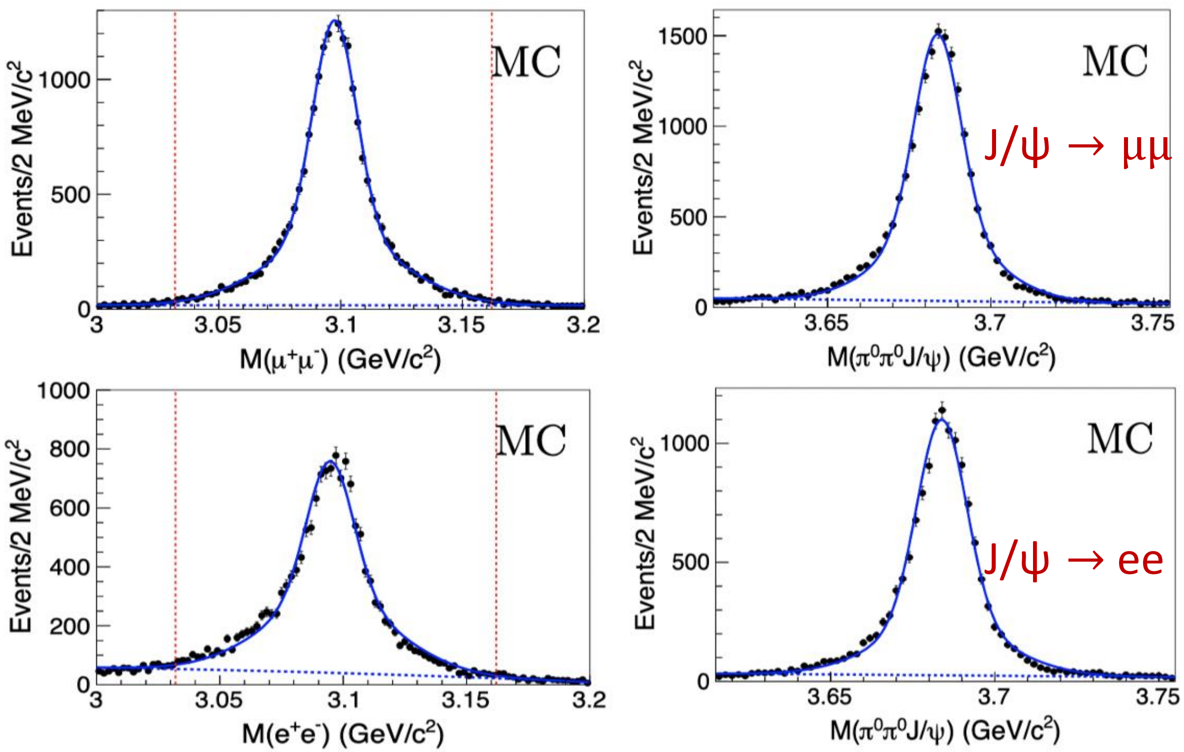
"Y(4260)" rediscovery

[expect ~60 events per 100 fb^{-1}]

Motivation:

- Rediscover $\Psi(2S)$ at current statistical level.
- Validate PHOKHARA generator performance.
- Check strategy with well known cross section $e^+e^- \to \psi(2S)$
- Prepare for later large data sample.

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



Next step:

"Y(4260)" and neutral Z_c rediscoveries

Ongoing ISR analysis on BelleII

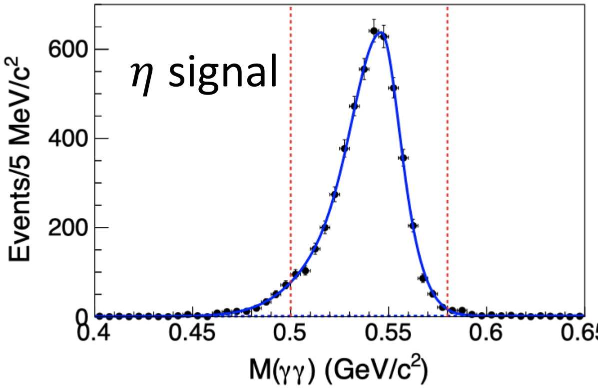
Motivation:

- $\psi(4040)$ and $\psi(4160)$ are evident at Belle
- Prepare for later large data sample.

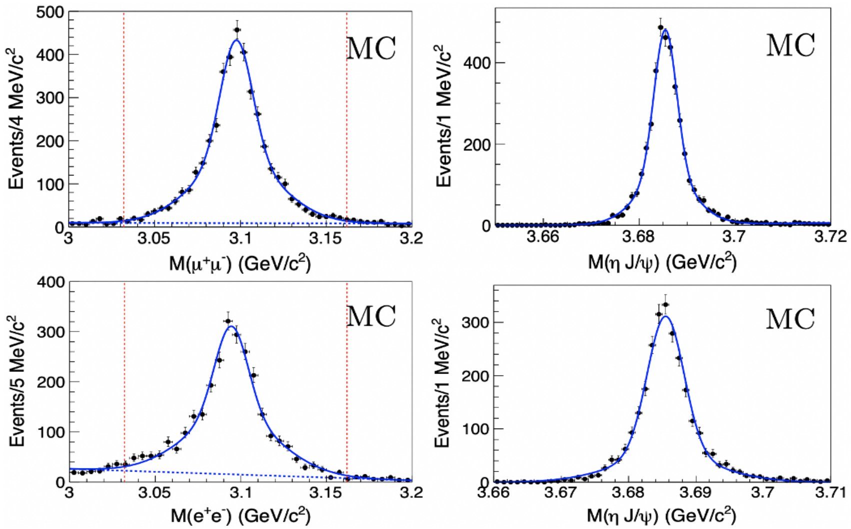
$e^+e^- \rightarrow \psi(2S) \rightarrow \eta J/\psi$

Selection criteria:

- For photons from η: E_γ > 200 MeV.
- To suppress Bhabha background in $J/\psi \rightarrow ee$, $(|\theta_{cm}(e^+) + \theta_{cm}(e^-) - 180°|)$ 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 $\eta \rightarrow \gamma\gamma$ decay mode is considered.



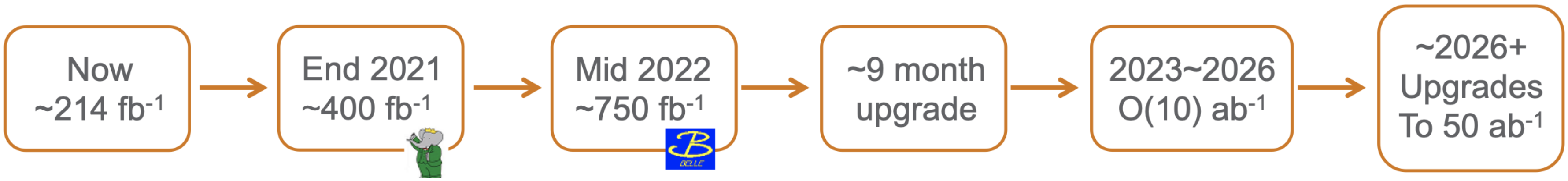
Next step:

Explore the extra excited ψ and possible Y states

- ISR physics is an interesting way to look for resonant states. This is unique to the e^+e^- experiments.

- The expected Belle II data sample of 50 ab^{-1} will provide a lot of new opportunities for charmonium-like analyses via ISR process.

Υ(4S) on-peak data + non-Υ(4S) plans



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

Back up