Prospects of Hadron Exotics at Belle II

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(On behalf of Belle II Collaboration)
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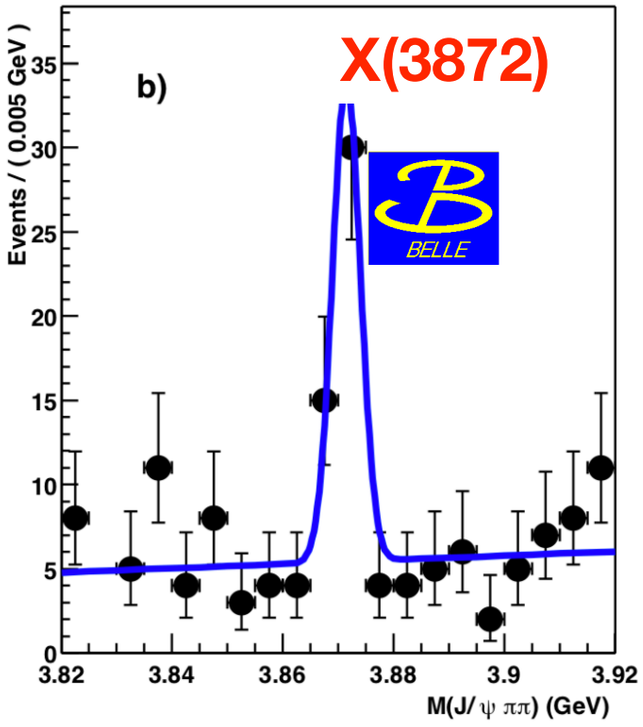
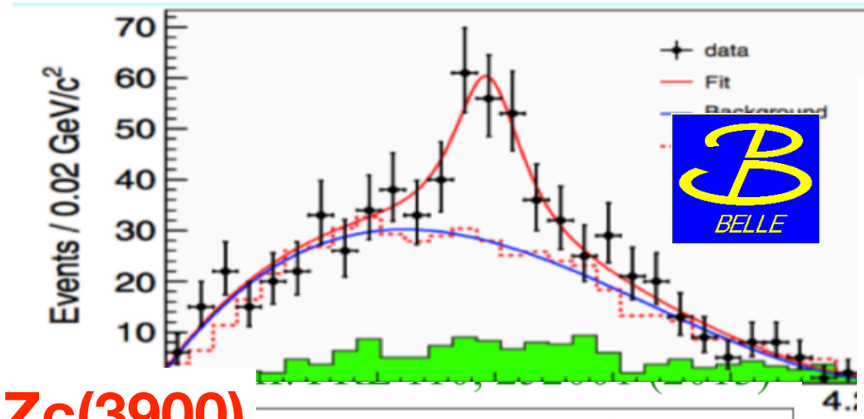
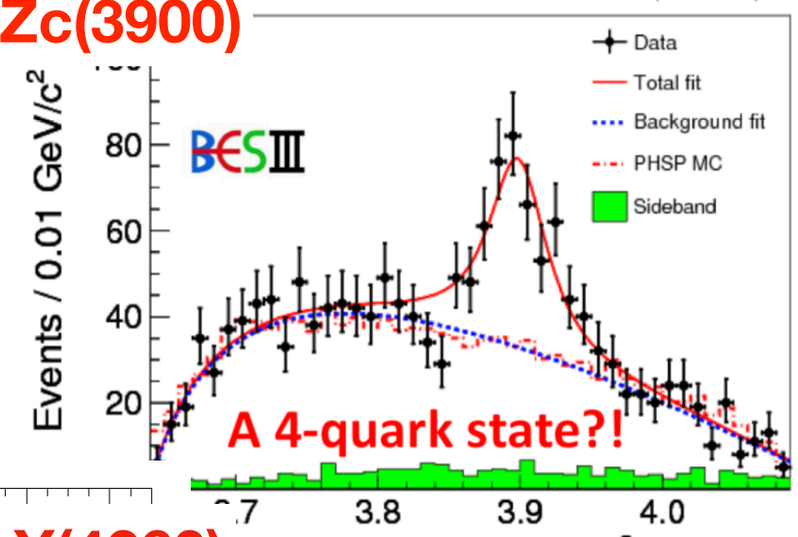
Exotic Hadrons: Theory and Experiment at Lepton and Hadron Colliders
T.D. Lee Institute, Shanghai Jiao Tong University, Jun.25-27, 2019

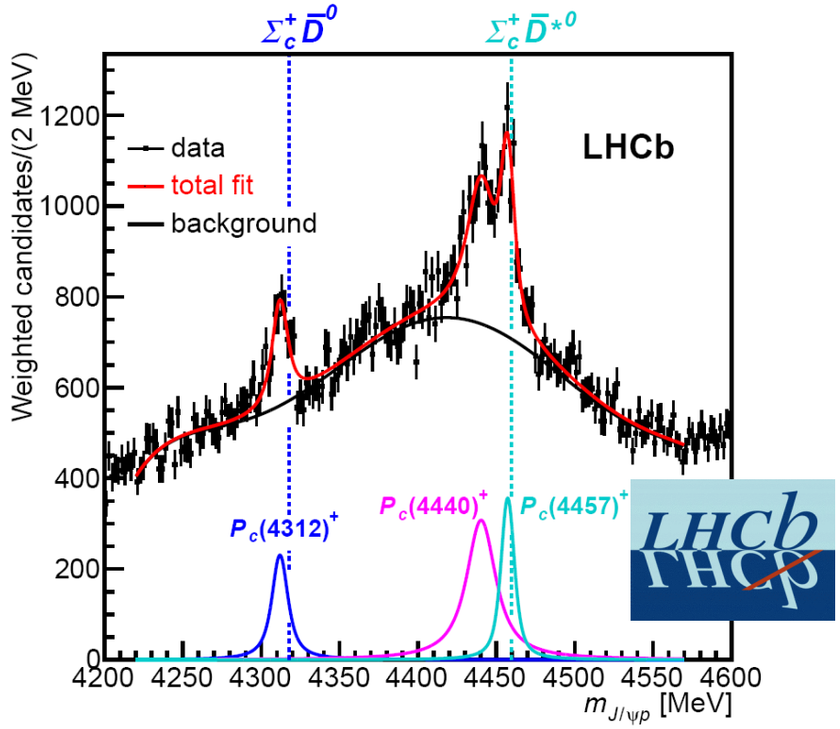
XYZ observed in experiments

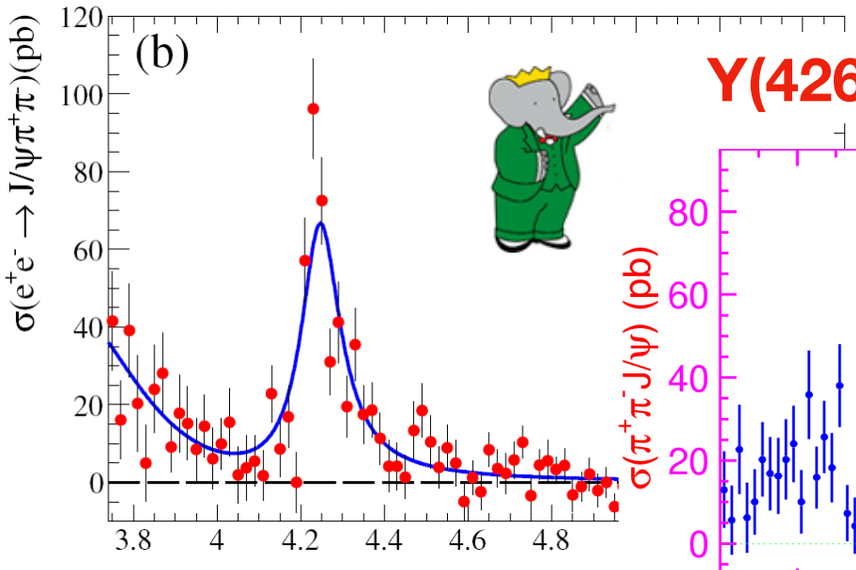




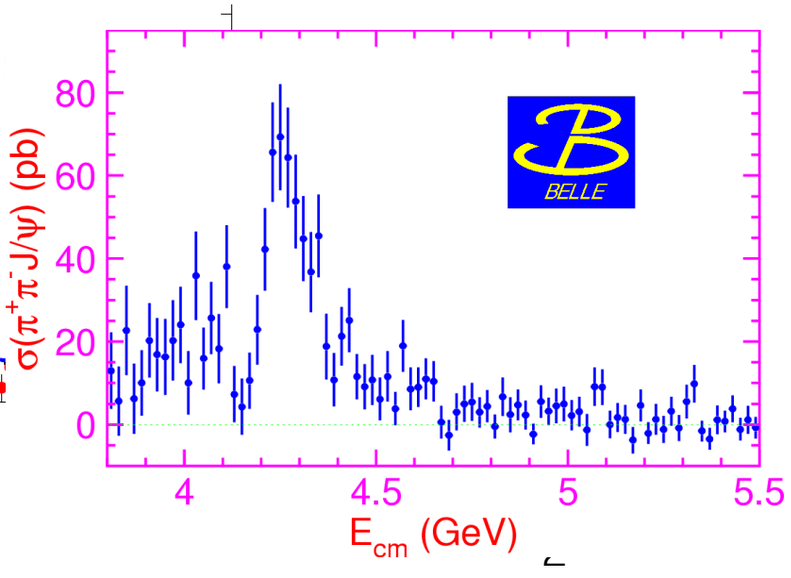
Zc(3900)

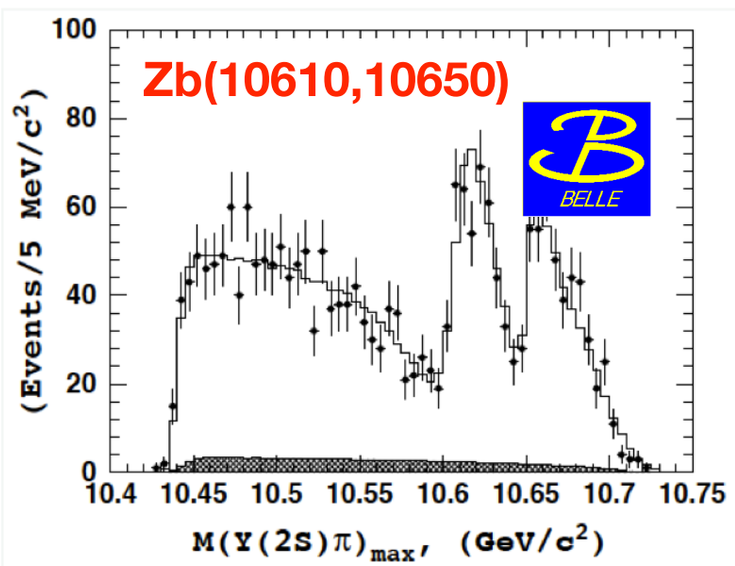






Y(4260)

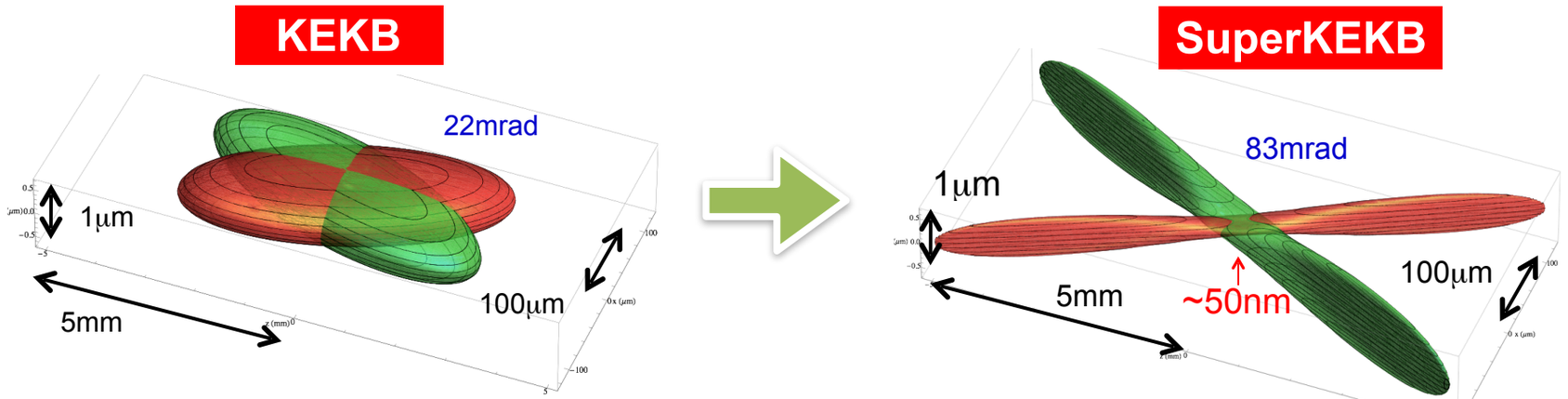




SuperKEKB

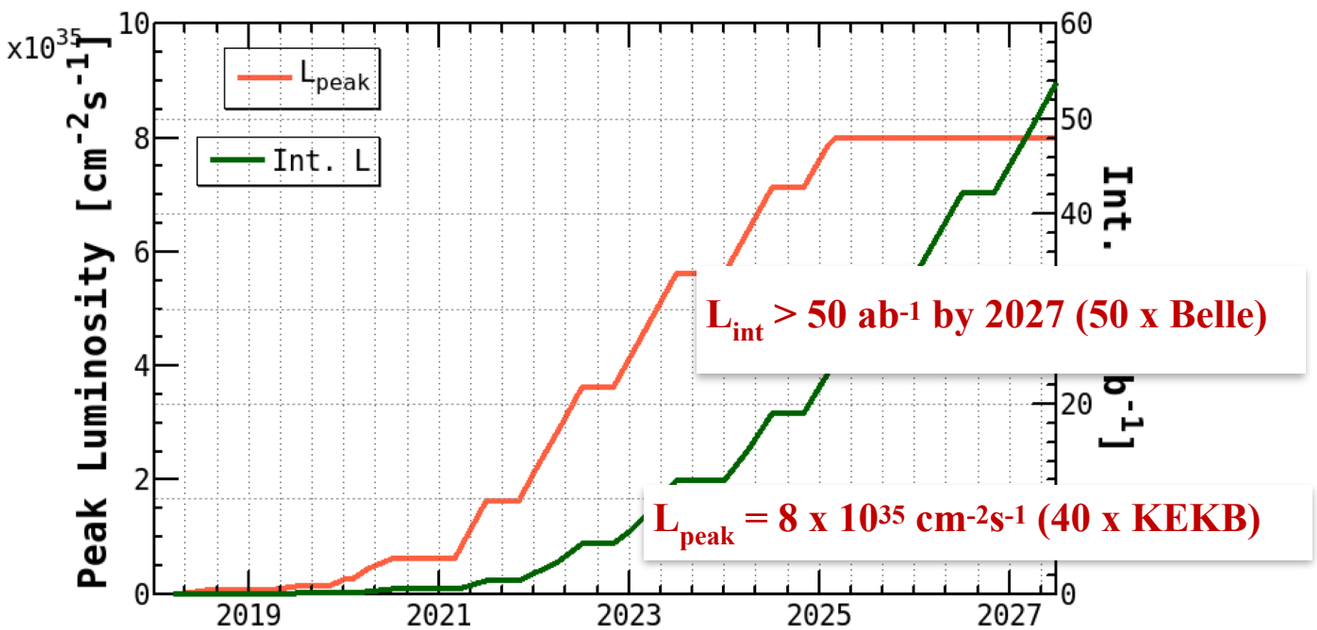
An asymmetric electron-positron collider

e^+~ 4GeV e^-~ 7GeV



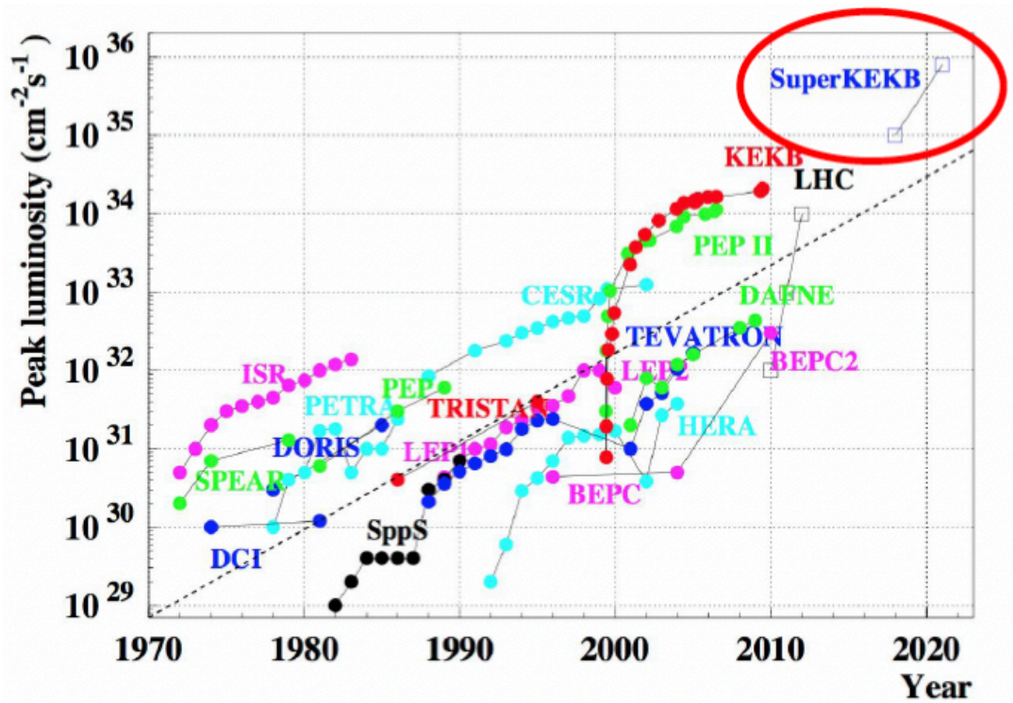
Nano-Beam Scheme

SuperKEKB Luminosity Project

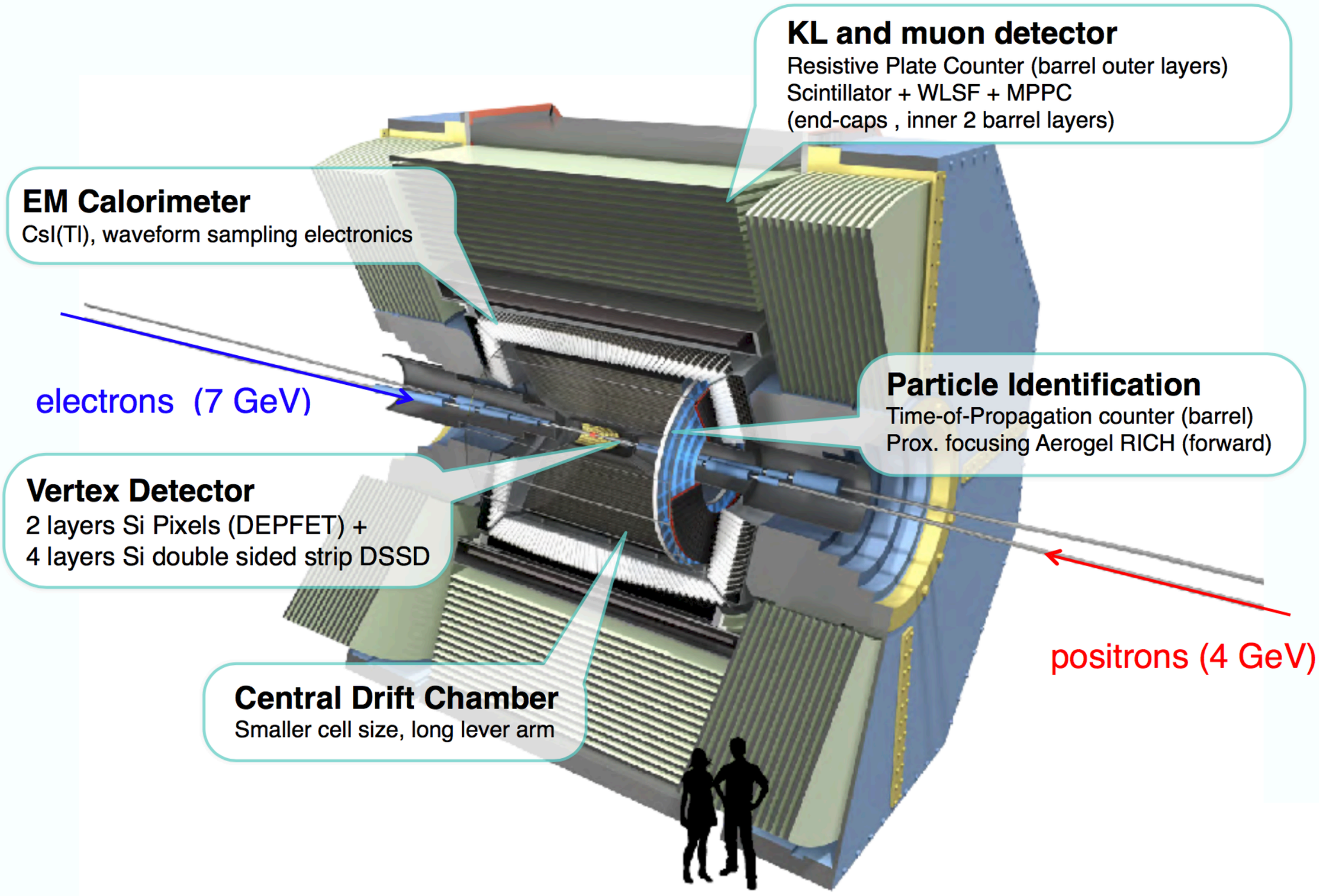


L_{int} > 50 ab^{-1} by 2027 (50 x Belle)

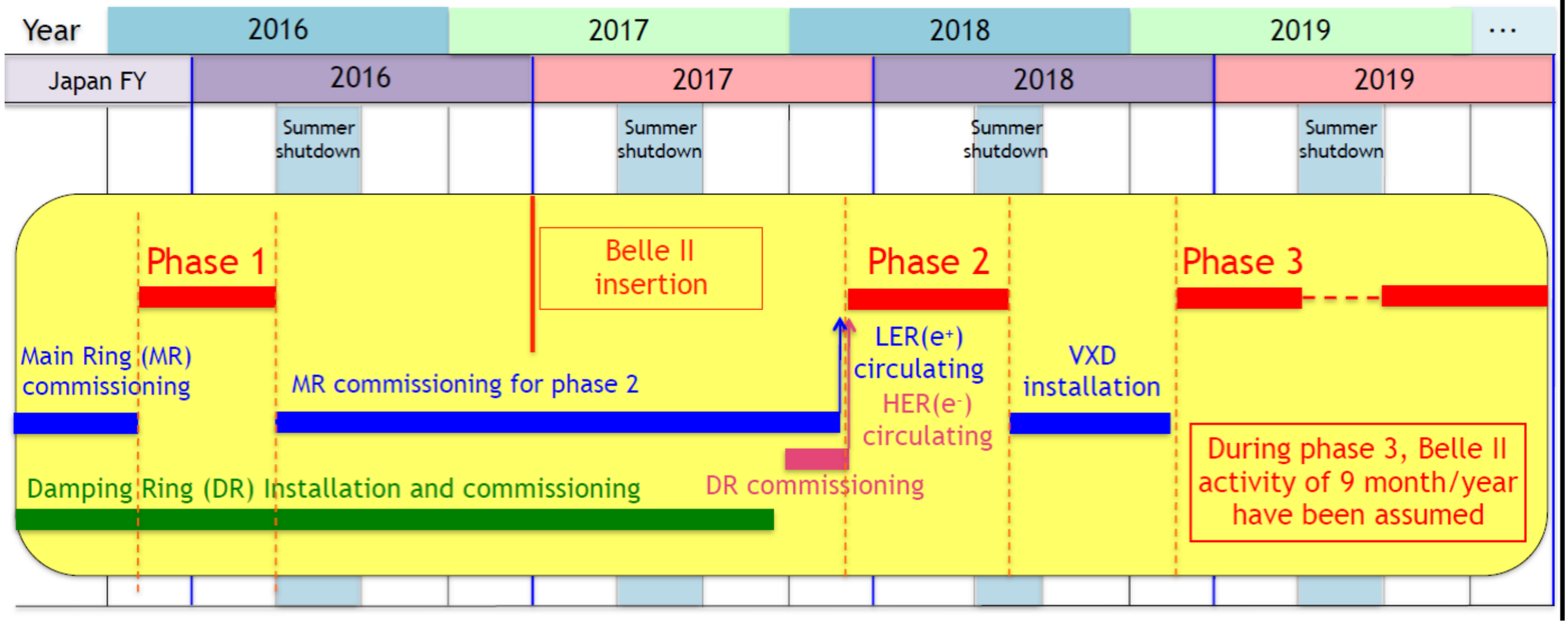
L_{peak} = 8 x 10^{35} cm^{-2}s^{-1} (40 x KEKB)



Belle II Detector

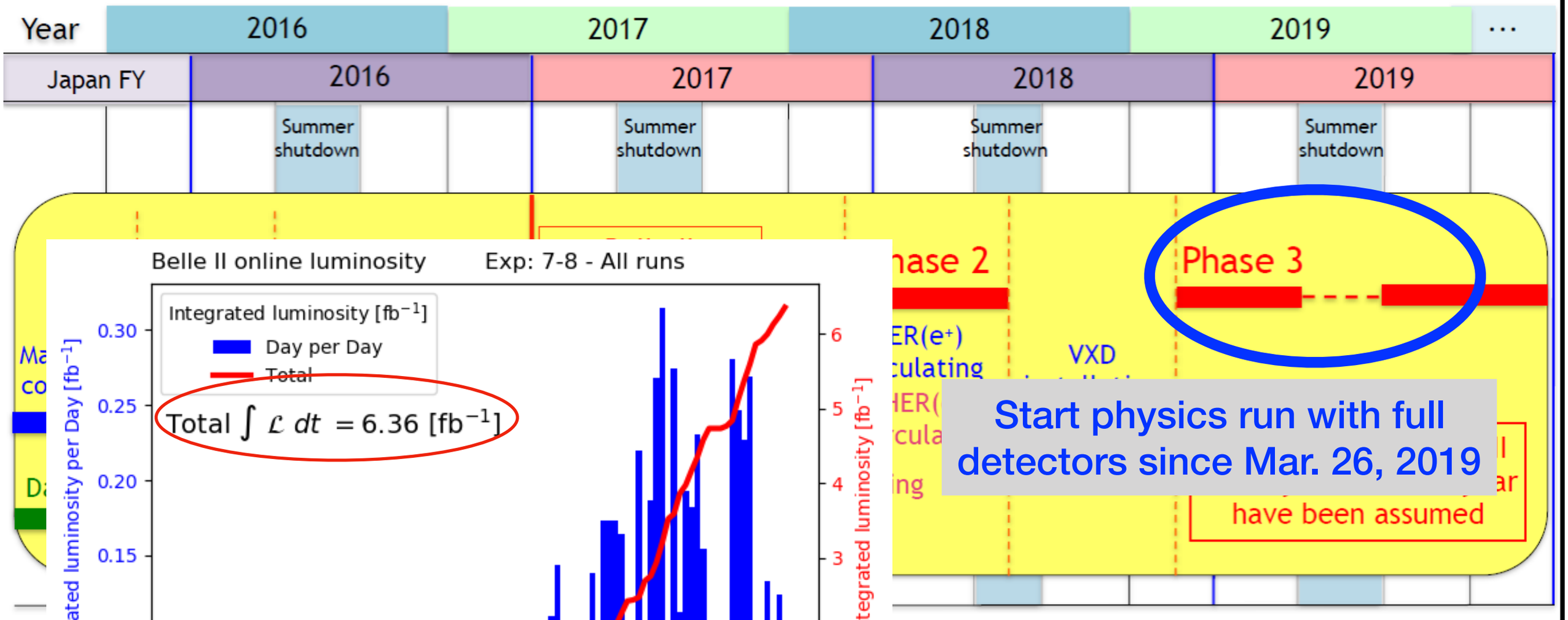


Belle II Schedule

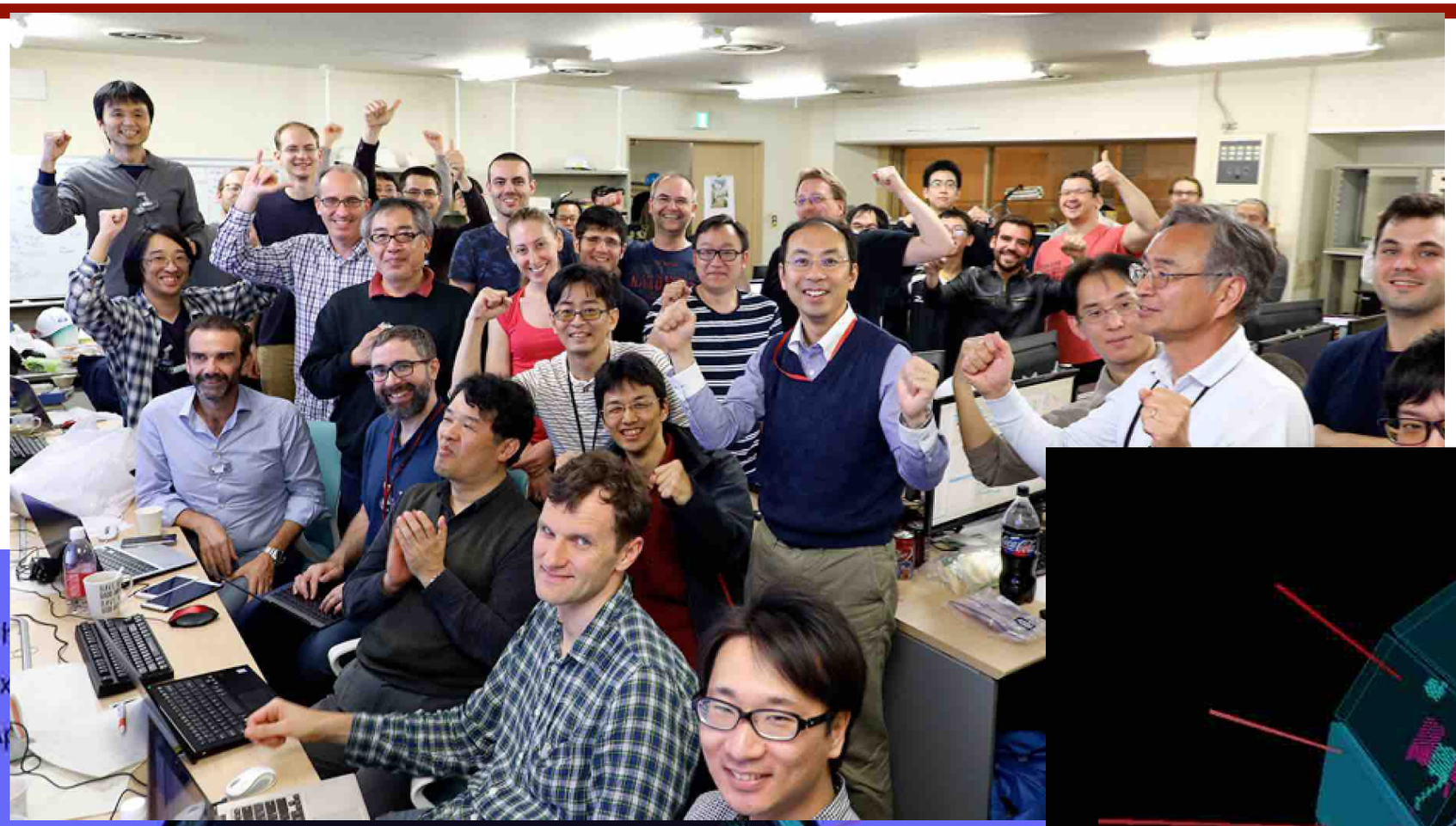


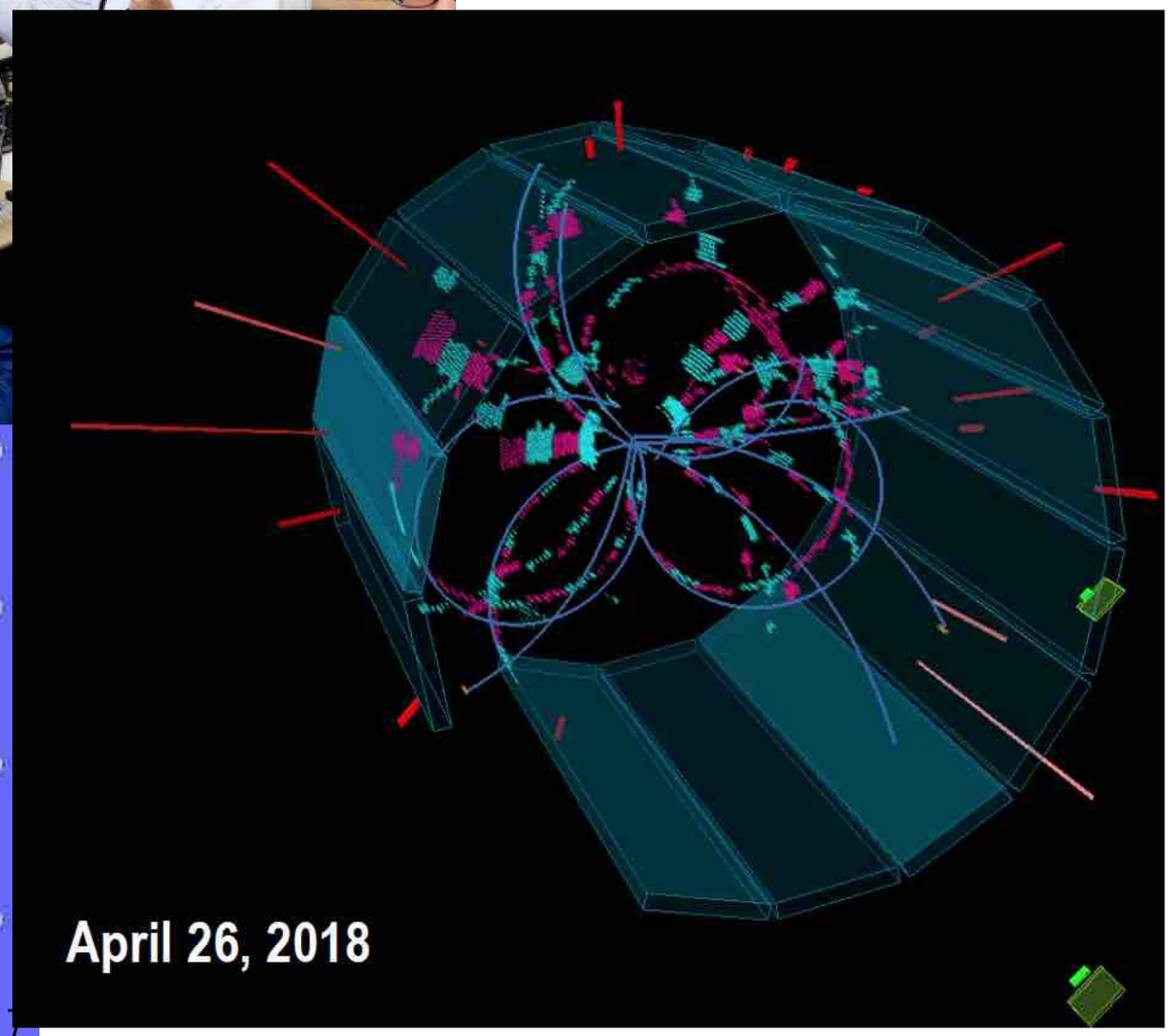
- ✅ **Phase1, Feb.-June, 2016**
  - **Accelerator commissioning, no collision**
- ✅ **Phase2, Feb.-July 17, 2018**
  - **Collision w/o vertex detectors**
  - **Understand background and detector performance**
  - **Instantaneous luminosity reach ~0.5x10^{34} cm^{-2}s^{-1}**
  - **~0.5 fb^{-1} data at the Y(4S) resonance was collected**

Belle II Schedule

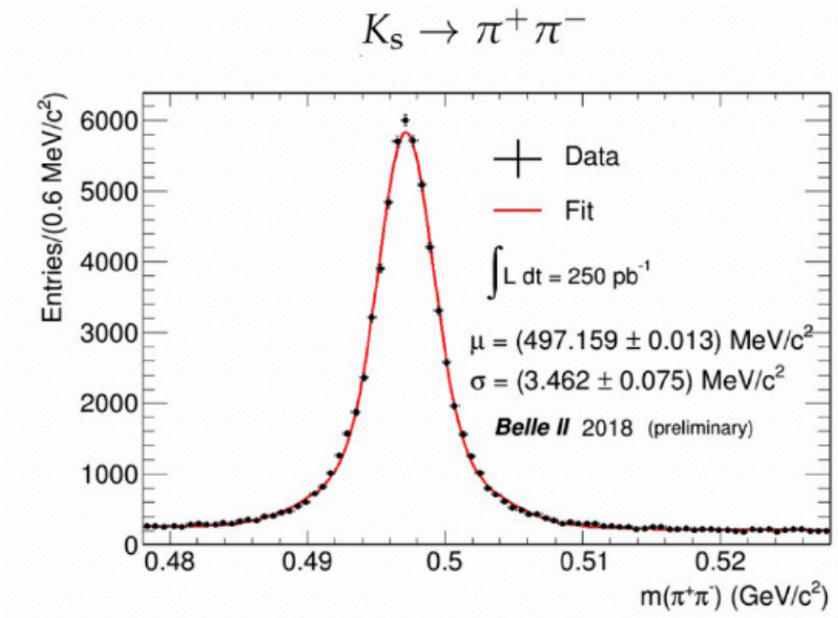


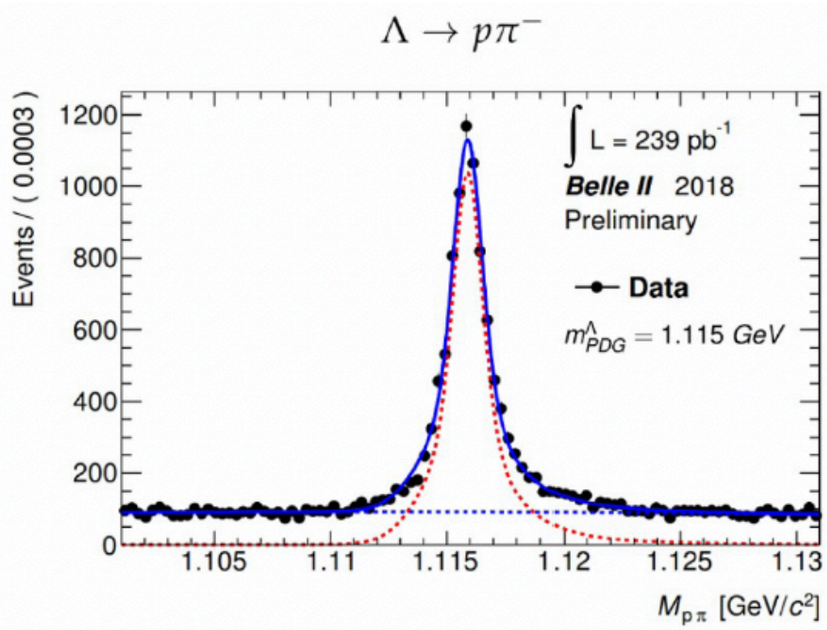
First Collision on Apr. 26, 2018

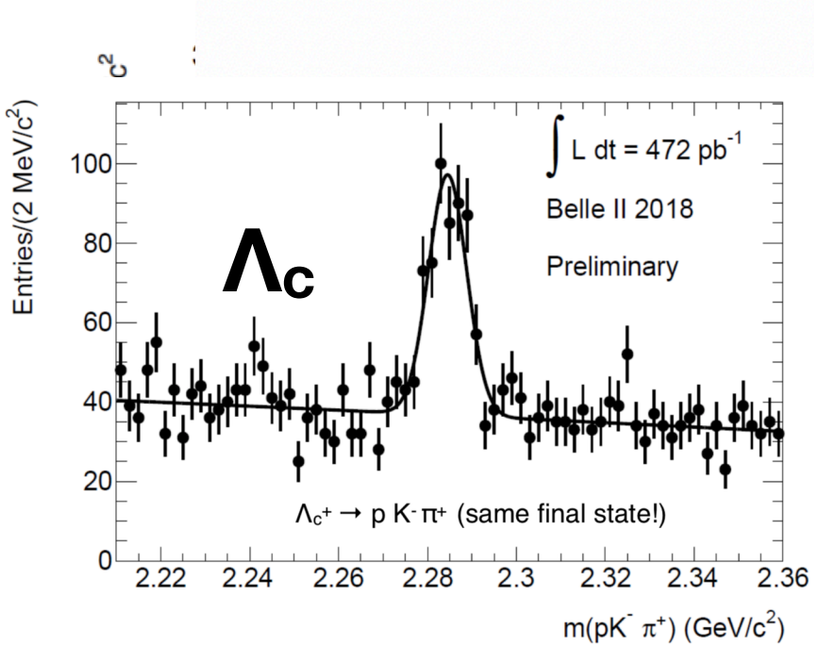


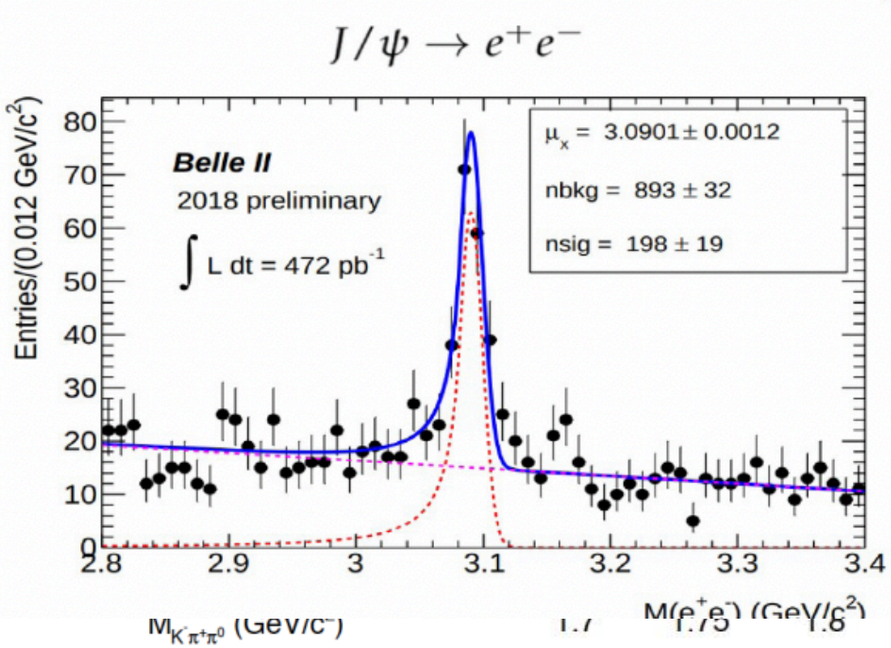


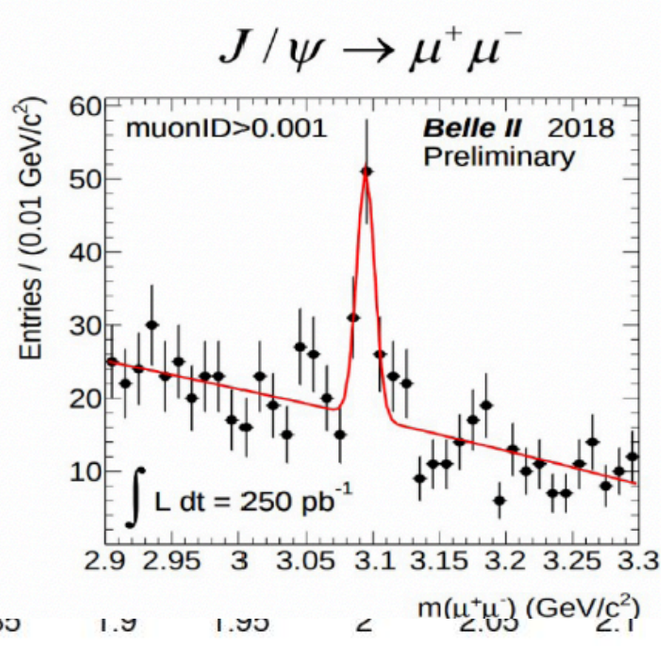
Belle II Performance (Phase2 data)



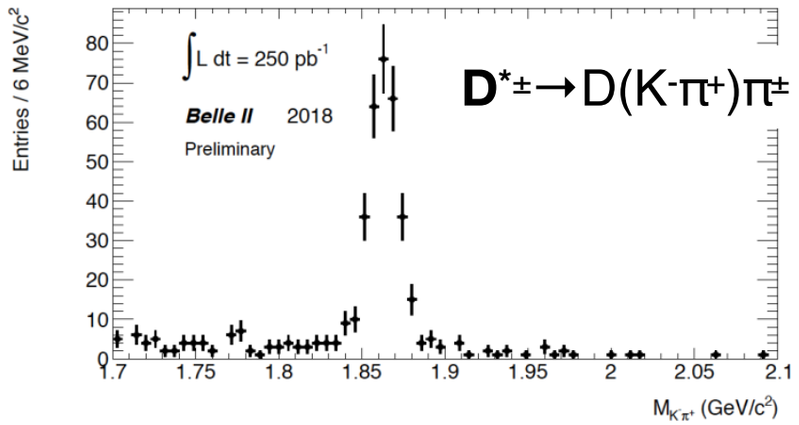


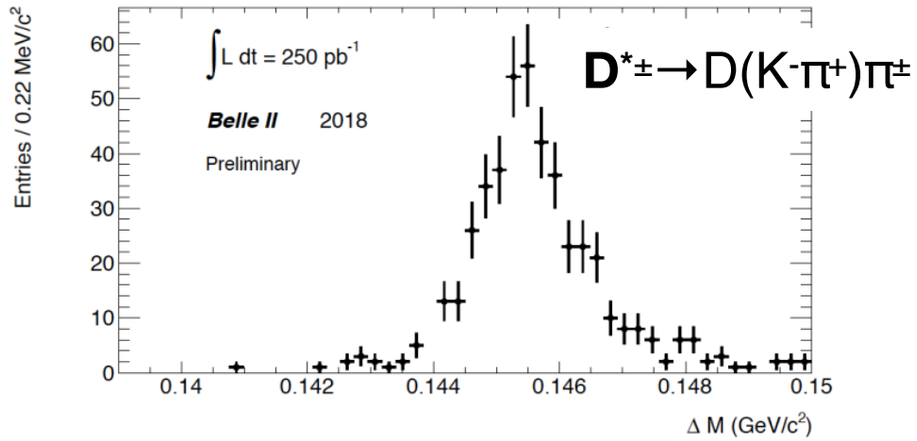


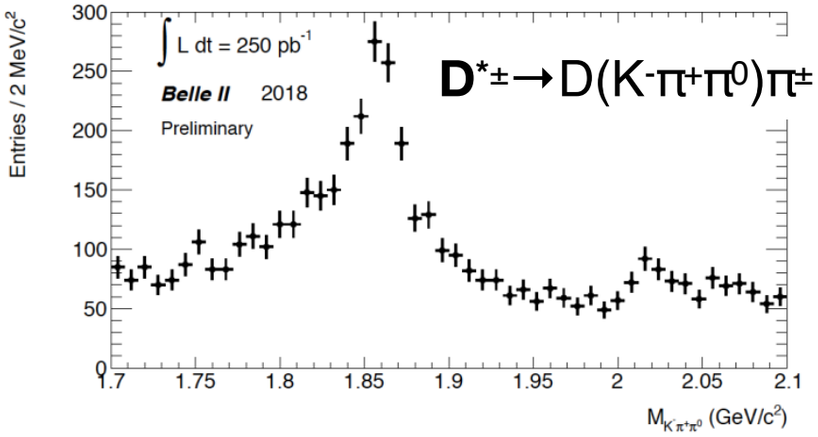


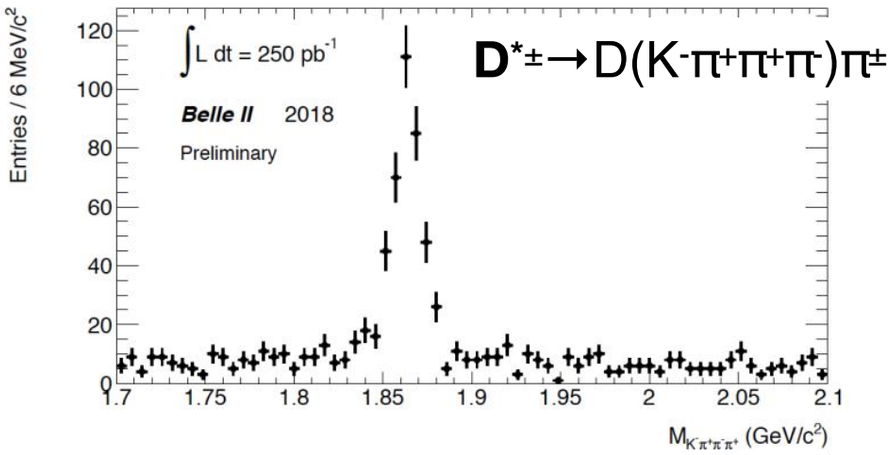


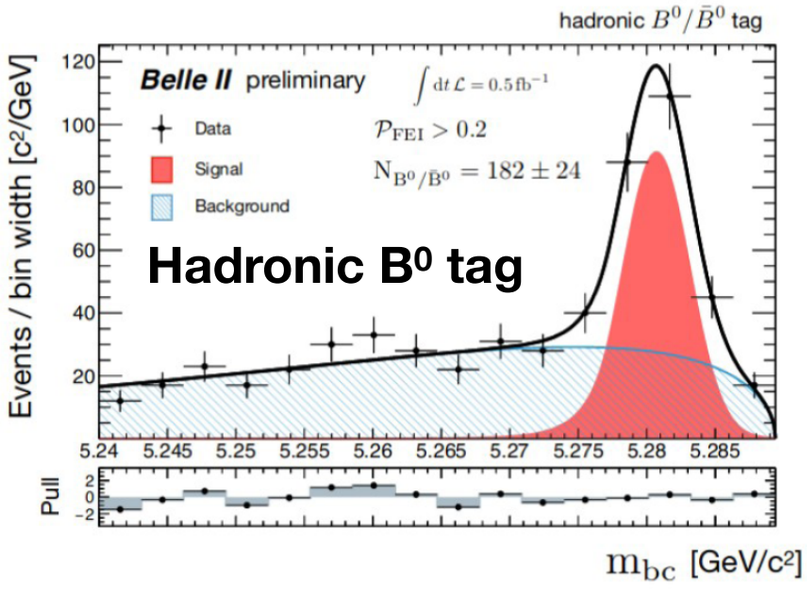
Belle II Performance (Phase2 data)

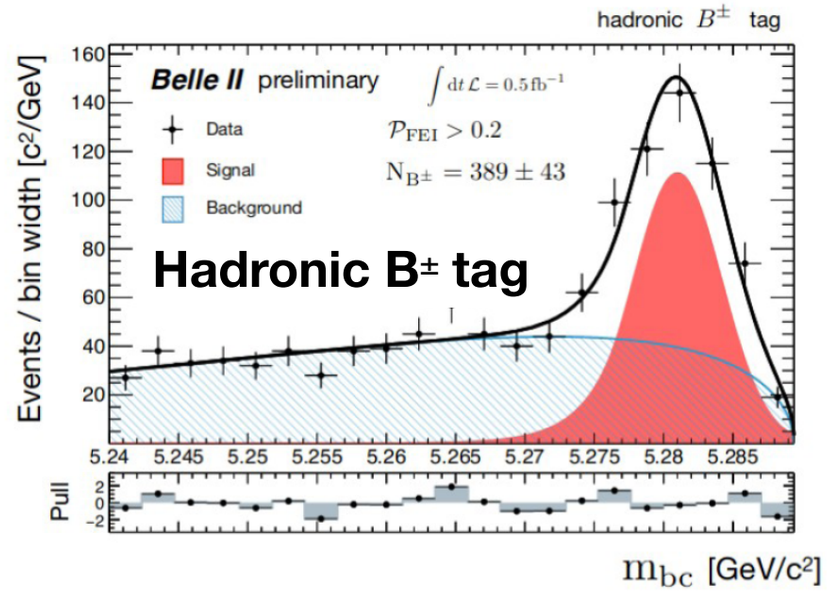






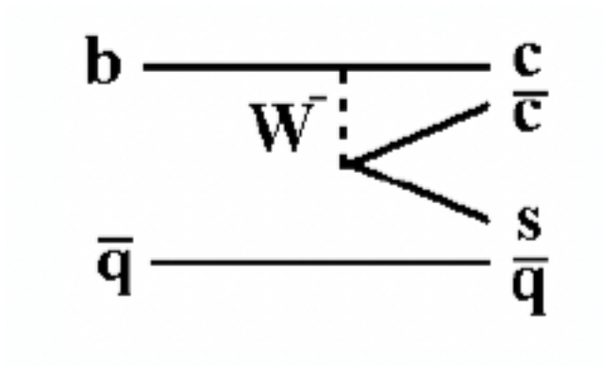


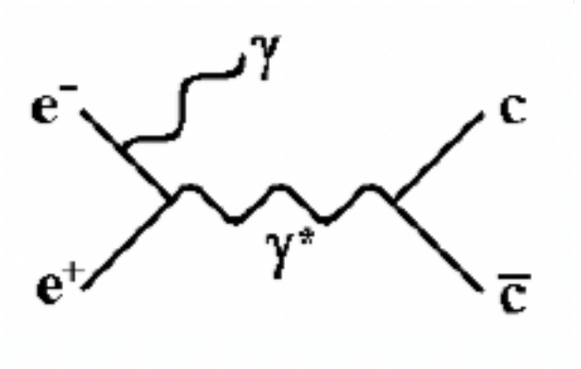


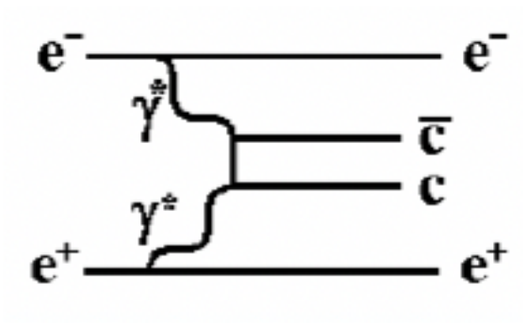


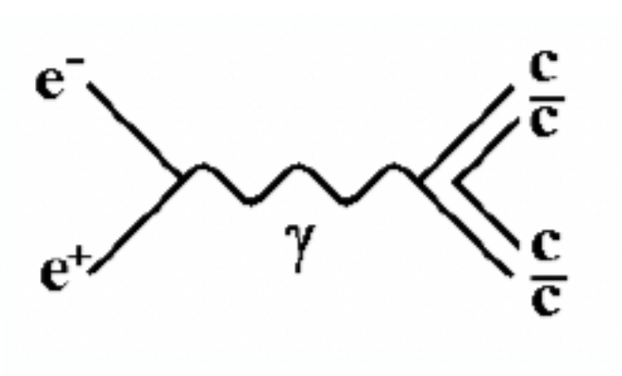
Production of charmonium(-like) states at B-factory

- B decay $B \to KX(c\bar{c})$
  - $X(3872) \to \pi\pi J/\psi$, $X(3915) \to \omega J/\psi$, $Z(4050)^+/Z(4250)^+ \to \pi^+\chi_{c1}$…
  - $\eta_c(2S) \to K_S K\pi$, $\psi_2(1D) \to \gamma\chi_{c1}$
- Initial state radiation (ISR)
  - $J^{PC} = 1^{--}$
  - $Y(4260) \to \pi\pi J/\psi$, $Zc(3900) \to \pi J/\psi$…
- Two-photon
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$…
  - $X(3915) \to \omega J/\psi$, $X(4350) \to \phi J/\psi$…
- Double charmonium
  - $X(3940) \to DD^*$, $X(4160) \to D^*D^*$…









Expected statistics @50 ab^{-1} of XYZ

State	Production and Decay	N
X(3872)	$B \to K X(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$	$\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

Belle II Physics Book: arXiv:1808.10567

Charmonium(-like) by B Decays

$B \to K X_{c\bar{c}}$

Search for the missing narrow charmonium

- Spin-singlet $\eta_{c2}(1D)$ $J^{PC} = 2^{-+}$
- Cannot decay to $D\bar{D}$ due to parity conservation
- Promising search channel: $B \to K(h_c \gamma)$

Study of exotics

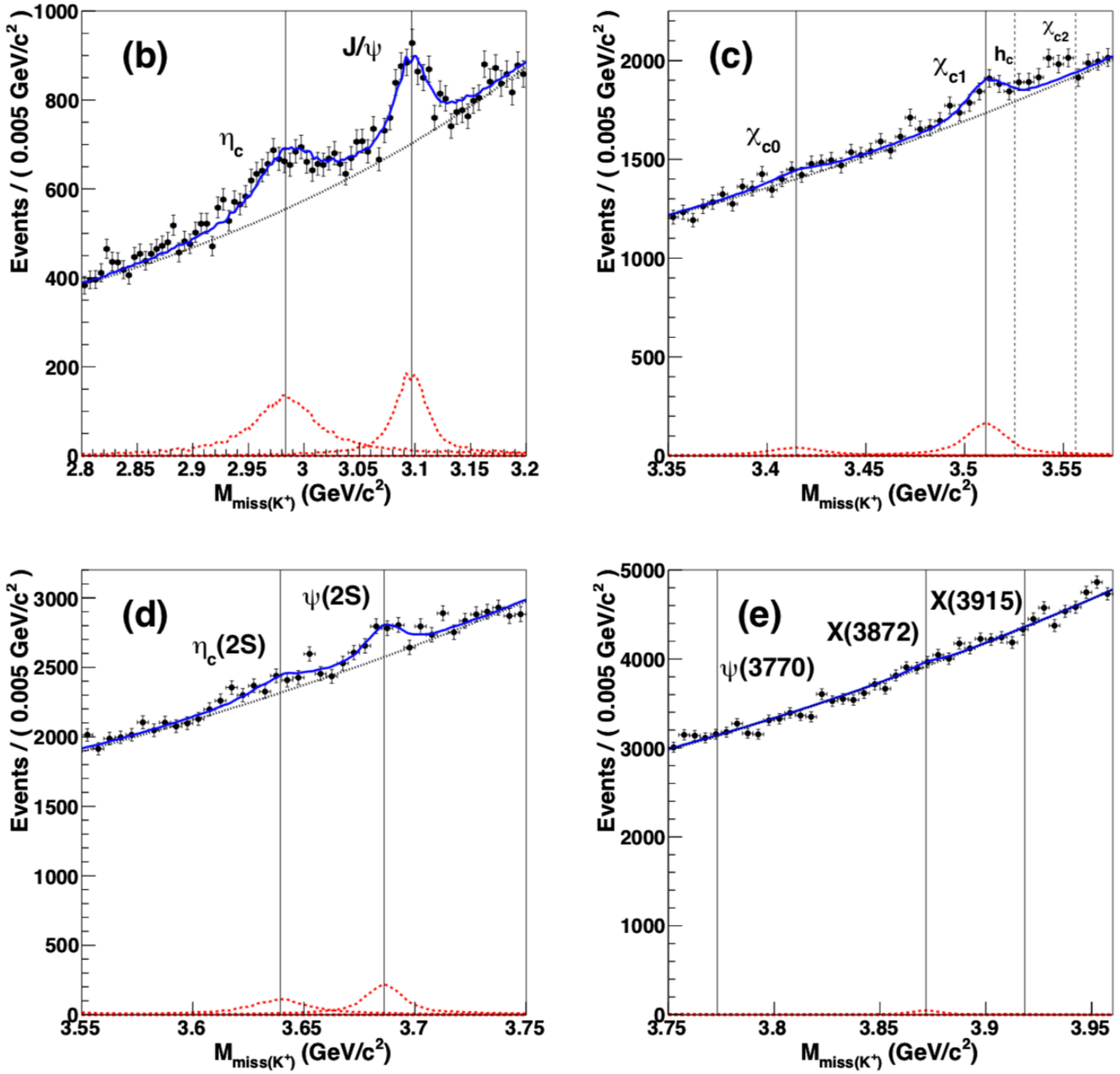
- Determine spin-parities of the observed states with full amplitude analyses e.g. X(3915), Z(4050), Z(4250).
- Confirm or deny the existing unconfirmed states, e.g.
  - Four states were observed by LHCb, X(4140), X(4274), X(4500), X(4700) in $B \to K(\varphi J/\psi)$
- Search for new exotics

Charmonium(-like) by B Decays

$B \to K X_{c\bar{c}}$

Determination of absolute branching of $Xc\bar{c}$ and search for new exotics with inclusive reconstruction

- Full reconstruction of one B
- Recoil of the Kaon in another B
- Extract the $Br(B \to K X_{c\bar{c}})$



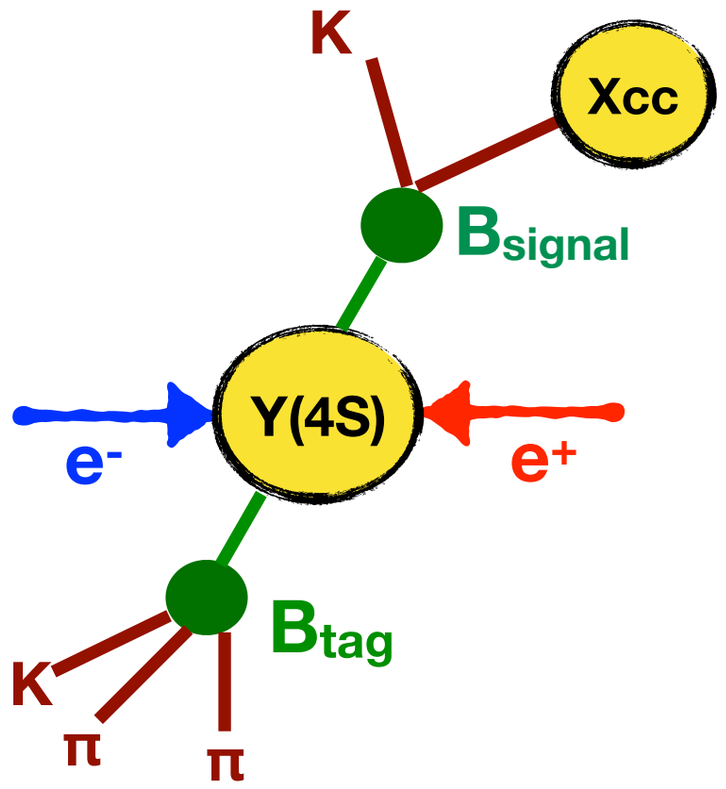
Belle: PRD 97, 012005 (2018)

$$\mathcal{B}(B^+ \to \eta_c K^+) = (12.0 \pm 0.8 \pm 0.7) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \eta_c(2S) K^+) = (4.8 \pm 1.1 \pm 0.3) \times 10^{-4}$$

Uniquely done in e+e- B-factories

Full Event Interpretation (FEI)

- Reconstruct one out of the two B mesons
- Increasing efficiency by tagging more decay channels than Belle
- More automation and analysis-specific optimizations
- Training includes generic-mode for analysis w/o signal-side selection and specific modes for w/ signal-side selection
- Essential for the analysis w/o full reconstruction of B meson e.g. (semi-)leptonic decay, $B \to K X_{c\bar{c}}$ inclusive analysis

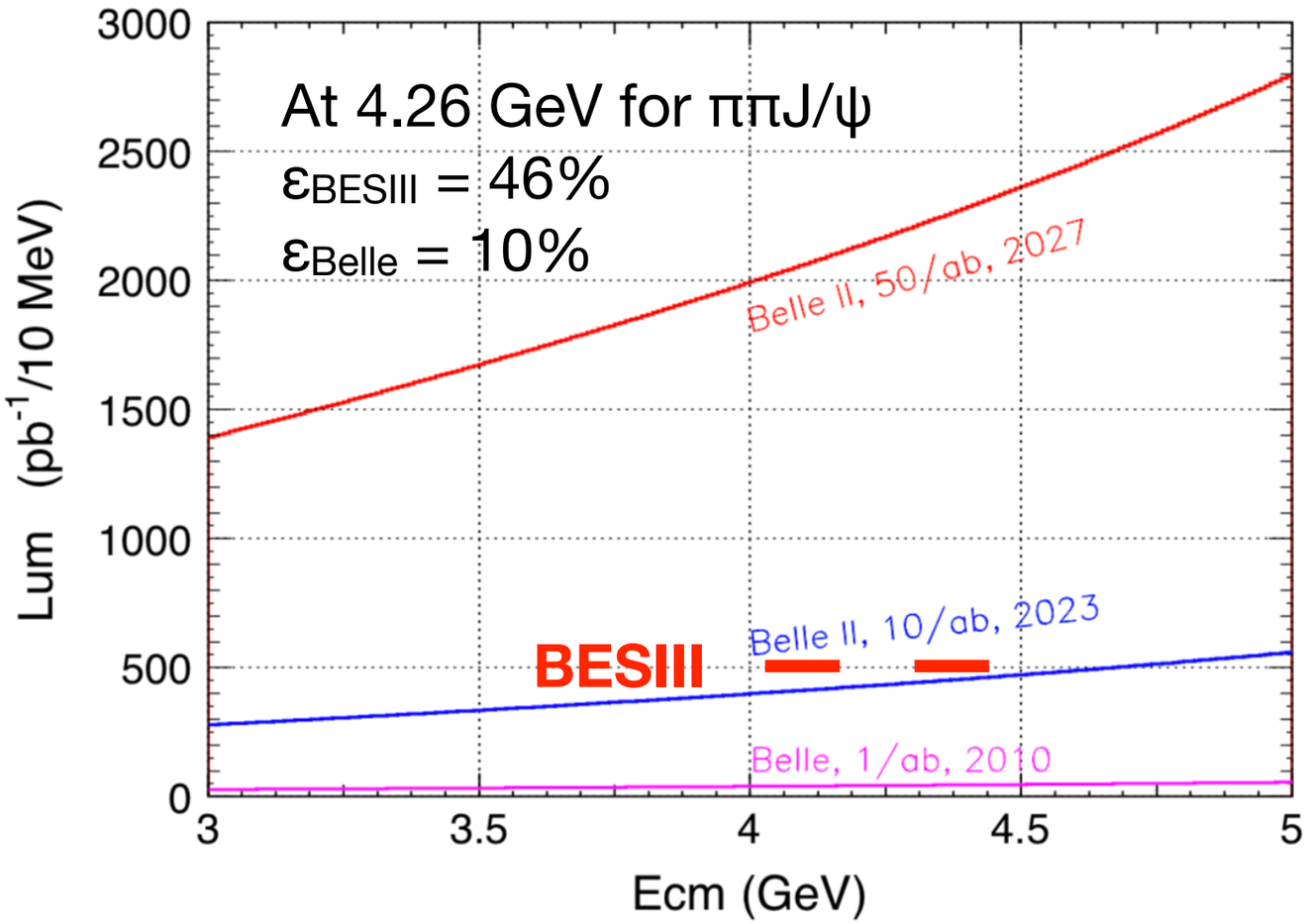


Tag	FR[10] @ Belle	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %

Belle II Physics Book: arXiv:1808.10567

Charmonium(-like) by ISR

- Main force of the discovery of exotics at Belle
  - Discover new exotics
  - Study of the properties of the states
- Study the line shapes in lower regions



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}

Belle II Physics Book: arXiv:1808.10567

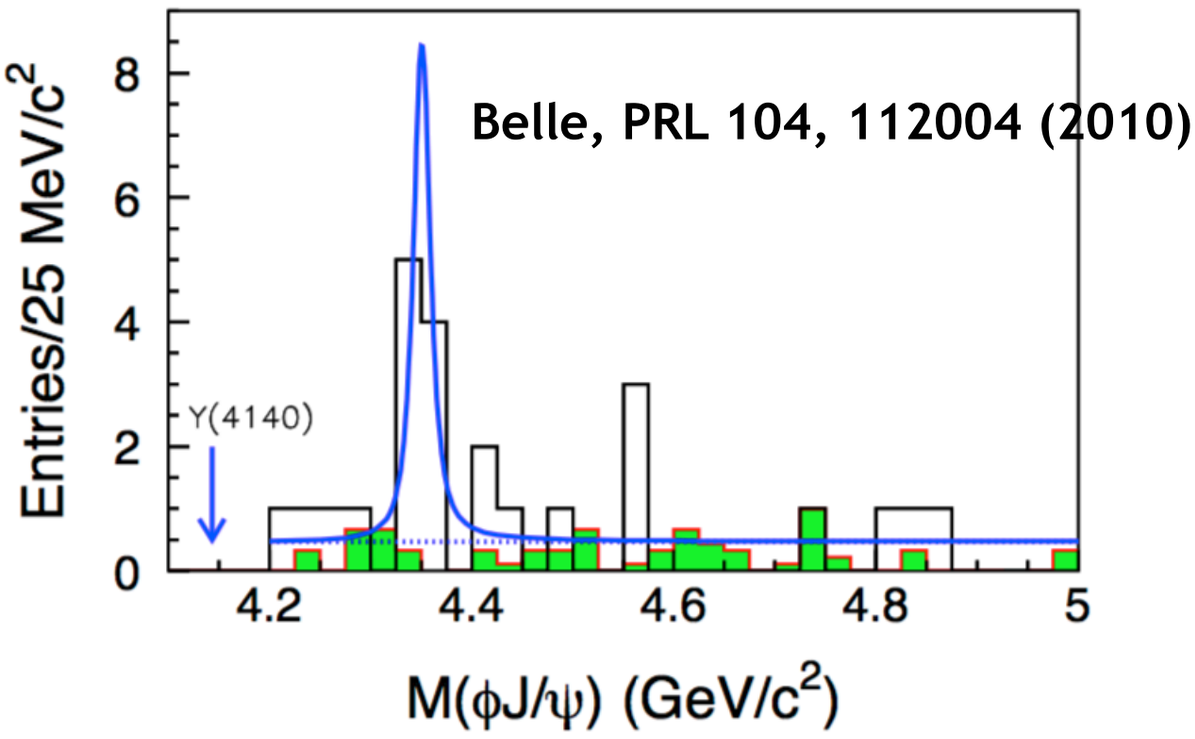
Charmonium-like by two-photon

- $\gamma\gamma \to \omega J/\psi$ by Belle and BaBar
  X(3915) = $\chi_{c0}(2P)$?

- $\gamma\gamma \to D\bar{D}$ by Belle and BaBar
  X(3930) = $\chi_{c2}(2P)$?

- Precise measurements of the properties of X(3915), X(3930) are needed

- X(4350) in $\gamma\gamma \to \phi J/\psi$ (3.2σ) by Belle
- limited statistics
- Belle II will revisit the process (also in B decay) to confirm or deny the state



Double Charmonium

Observed the $x_{c0}(2P)$ candidate X(3860) by Belle

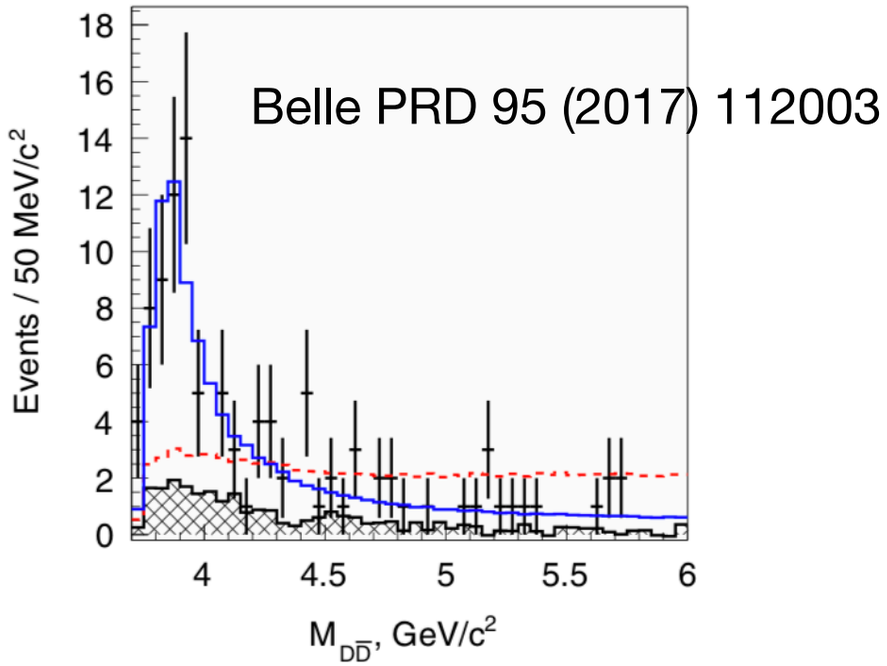
- $e^+e^- \rightarrow J/\psi\, D\bar{D}$
- Reconstruct J/ψ and one D,
- Another D is identified by the recoil mass M(J/ψD)

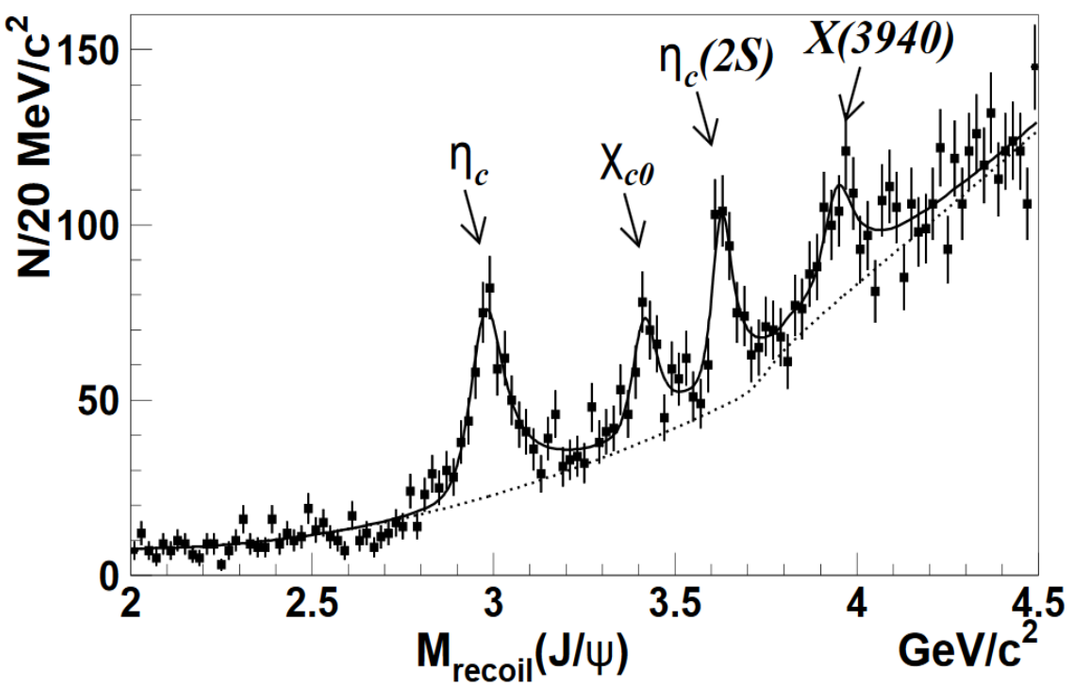
$e^+e^- \rightarrow J/\psi X$

- The recoil of J/ψ or ψ(2S)
- Observed X(3940), X(4160)

Prospects at Belle II

- Full amplitude analysis to measure spin-pariti of the observed new states
- Studies of $e+e- \rightarrow h_c X$, $e+e- \rightarrow \eta_c X$ …



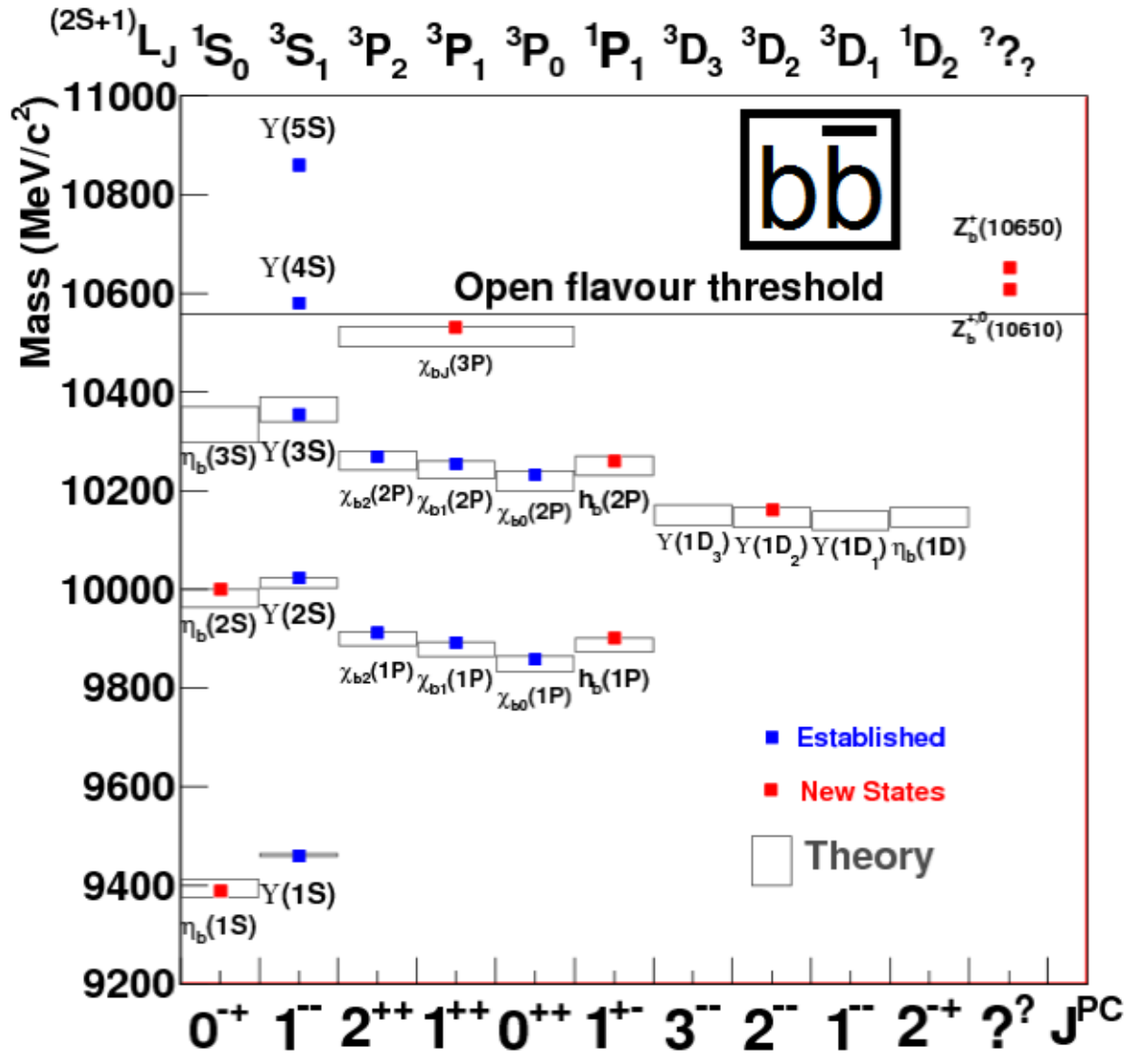


Belle, PRL 98, 082001 (2005)

Bottomonium(-like) States

- Precious measurements of observed resonances e.g. $M(\eta_b)$, $\Gamma(\eta_b)$, $\Gamma(x_{b0})$

- Search for the missing conventional bottomonia below the $B\bar{B}$ threshold e.g.
  - $Y(2D_3)$ triplet
  - $\eta_b(3S)$, $\eta_b(1D)$, $Y(1D_{1,3})$
  - F-wave states



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]

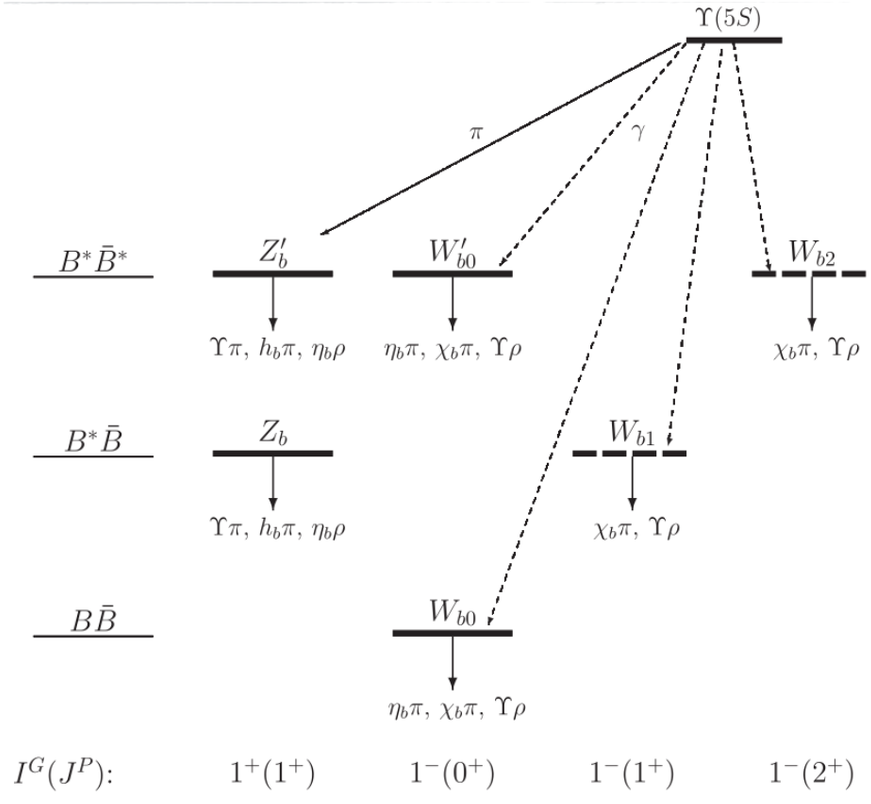
Belle II Physics Book: arXiv:1808.10567

Search for molecular states near $B^{(*)}\bar{B}^{(*)}$ thresholds

- Observed $Z_b(10610)$, $Z_b(10650)$ in $\Upsilon(5S, 6S)$ transitions
- Search for new molecular states near $B^{(*)}B^{(*)}$ thresholds, produced threshold is up to 11.43GeV

Table 132: Expected molecular states with the structure $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ [1370].

$I^G(J^P)$	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]	$\Upsilon(nS)\omega$, $\chi_{bJ}(nP)\pi^+\pi^-$



Belle II Physics Book: arXiv:1808.10567

Energy frontier of Belle II

- Existing Y datasets, Belle II could collect large datasets in these points

Experiment	Scans Off. Res.	$\Upsilon(6S)$ fb^{-1}	$\Upsilon(5S)$ fb^{-1}	10^6	$\Upsilon(4S)$ fb^{-1}	10^6	$\Upsilon(3S)$ fb^{-1}	10^6	$\Upsilon(2S)$ fb^{-1}	10^6	$\Upsilon(1S)$ fb^{-1}	10^6
CLEO	17.1	-	0.1	0.4	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan			433	471	30	122	14	99	–	
Belle	100	~ 5.5	36	121	711	772	3	12	25	158	6	102

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- Interesting physics beyond Y(6S)
  - $\Lambda_b\overline{\Lambda}_b$ threshold ~ 11.24 GeV, up to 11.35GeV could cover $\Lambda_b\overline{\Lambda}_b$ threshold region
  - Search for new molecular states around 11.5-11.6 GeV e.g. partners of X(3872) and Z_b via vector states transition
- Machine limits
  - The range of beam energies covers the Y(1S) and Y(6S) resonance for physics operation.
  - Maximum center of mass energy is 11.24GeV in SuperKEKB due to the maximum beam energy of the injector linac.
  - Linac upgrade is required for running beyond 11.24GeV.

Summary

- As a intensity frontier experiment, Belle II will play an important role in answering existing puzzles in the field of quarkonium with its huge statistical samples.
  - Confirm or deny the observed unconventional states
  - Precise measurements of the properties of the observed exotics
  - Search for missing conventional states and new exotics
- Belle II phase3 operation has started, 6 fb^{-1} are collected, and the luminosity is to $5x10^{33}$ so far, machine tunning is undergoing for the target luminosity.
- We aim to operate 8-9 months per year.