Heavy Hadrons - Exotic and Conventional Quarkonium Physics at Belle II

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on behalf of the

Belle II Collaboration

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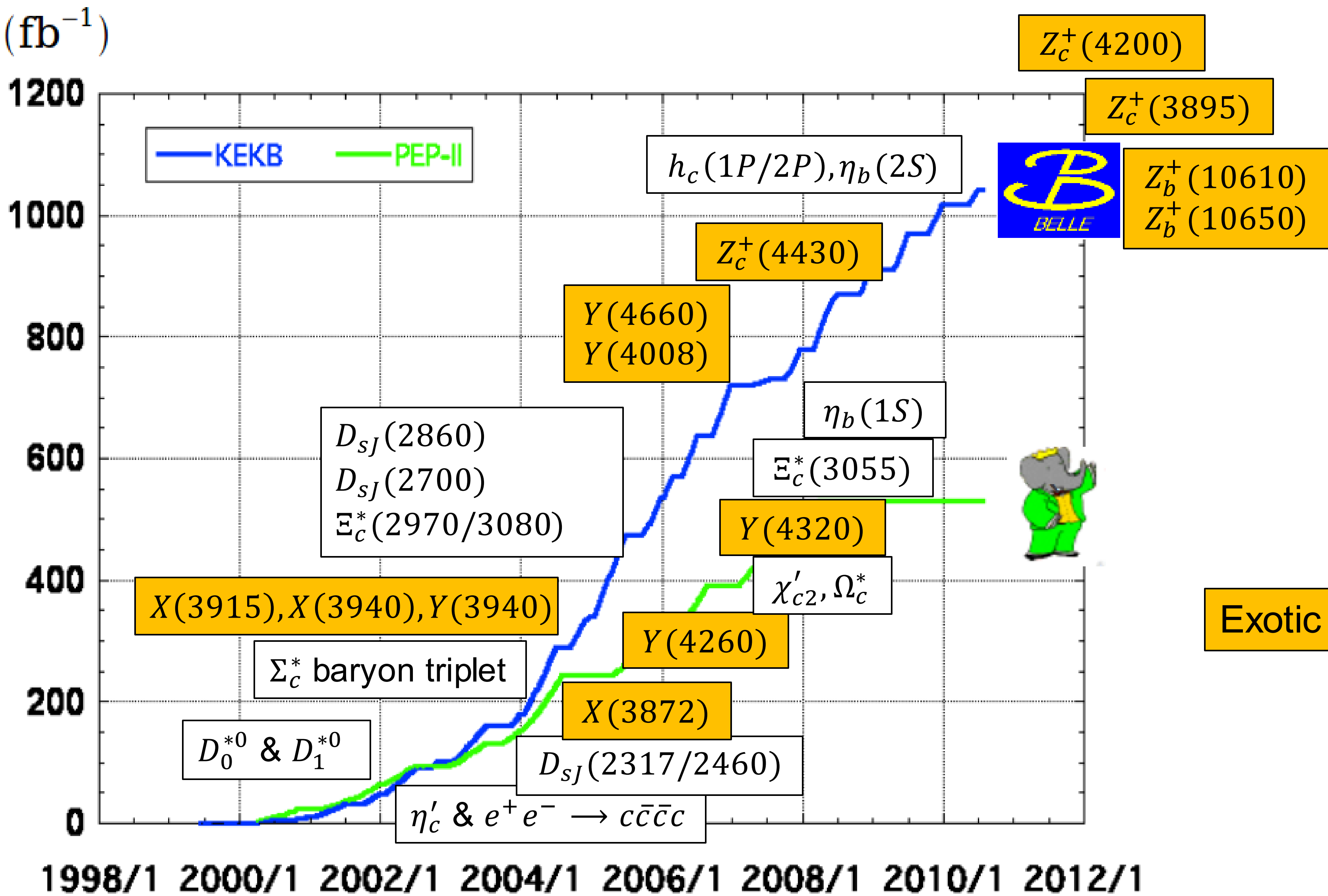
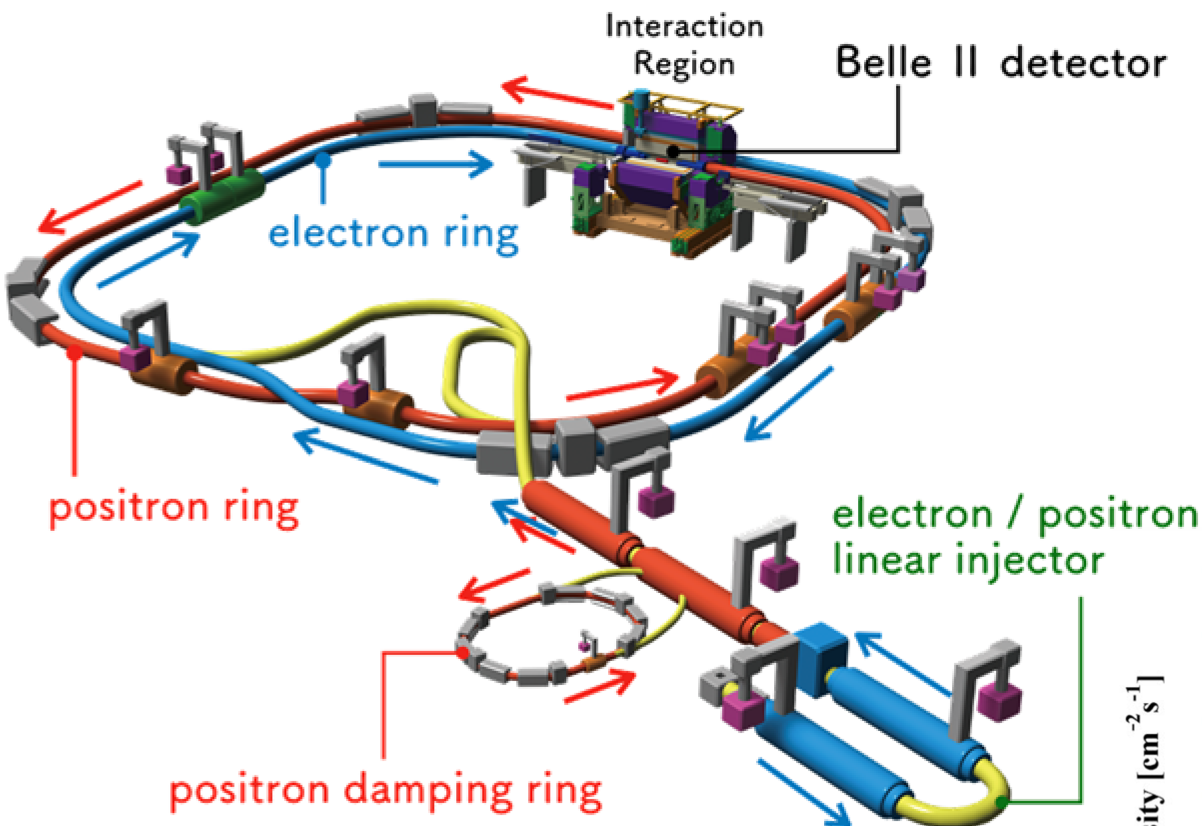
New Hadrons at 1st Generation B-Factories

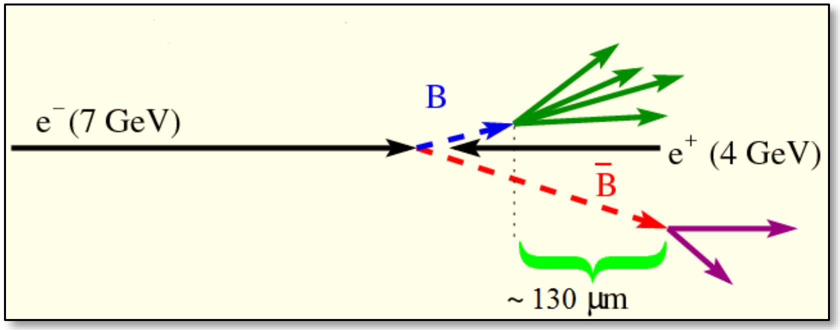


Exotic candidates

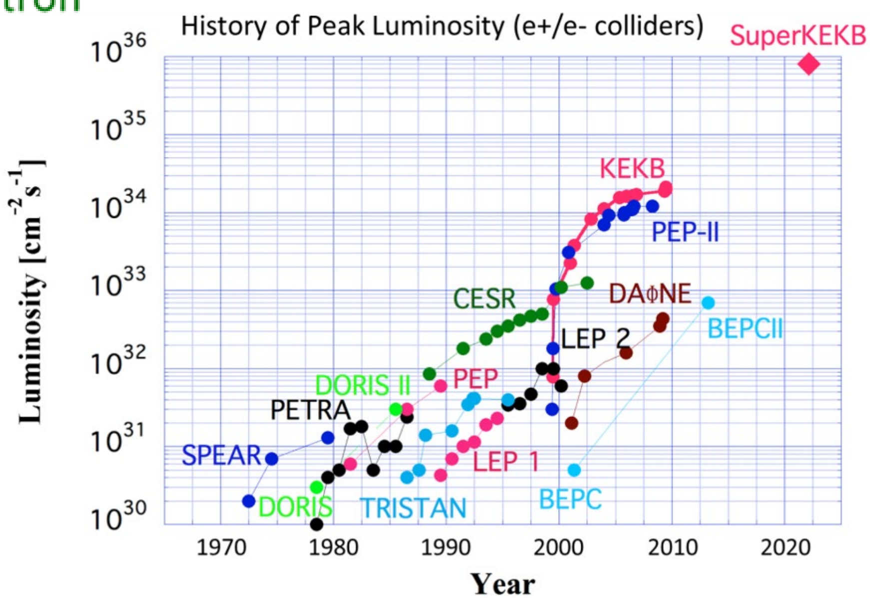
Where the Future starts – KEK (Tsukuba, Ibaraki)

SuperKEKB - Overview

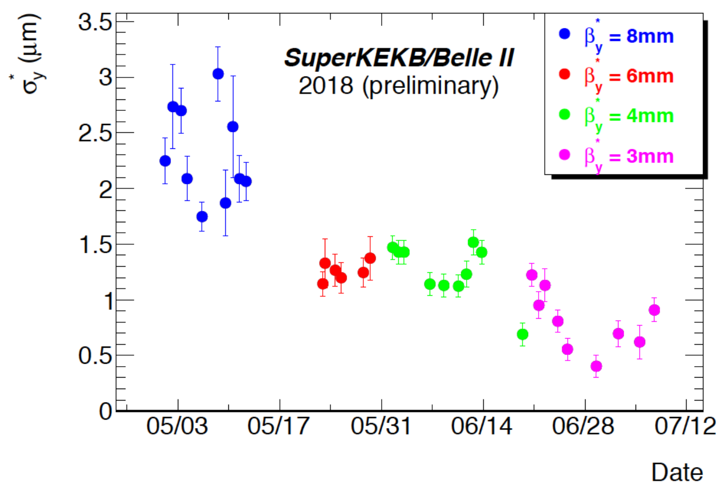




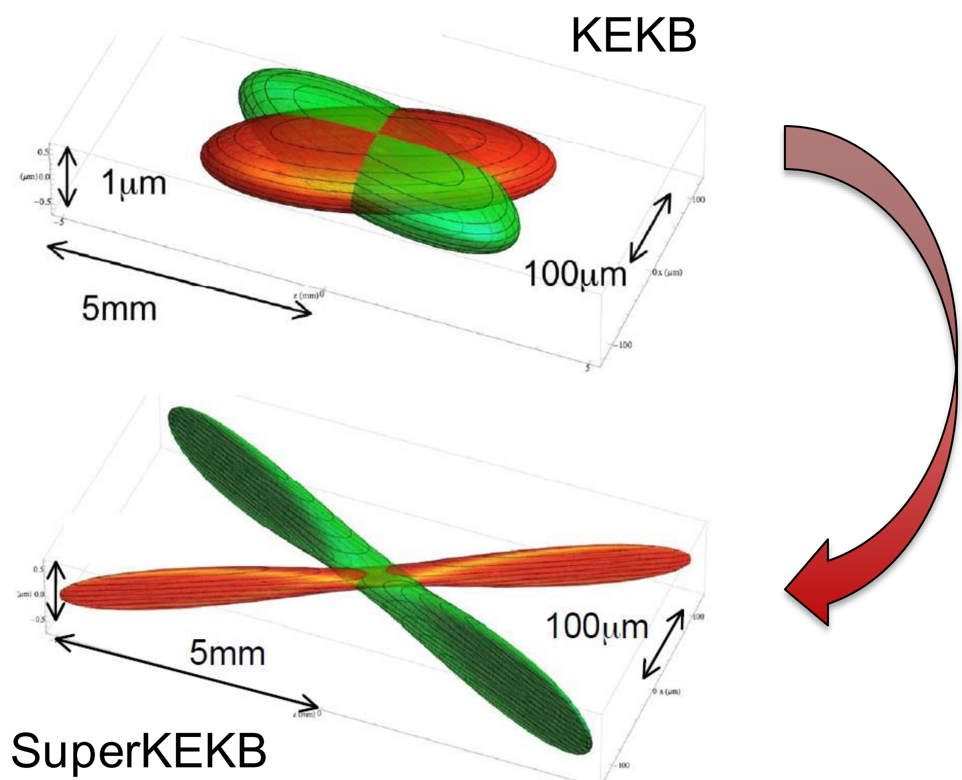
- Asymmetric e^+e^- collider
  - 7 GeV e^- (2.6A)
  - 4 GeV e^+ (3.6A)
- 40 times KEKB luminosity
  - $\mathcal{L} = 8 \times 10^{35} cm^{-2} s^{-1}$



SuperKEKB – Increasing Luminosity

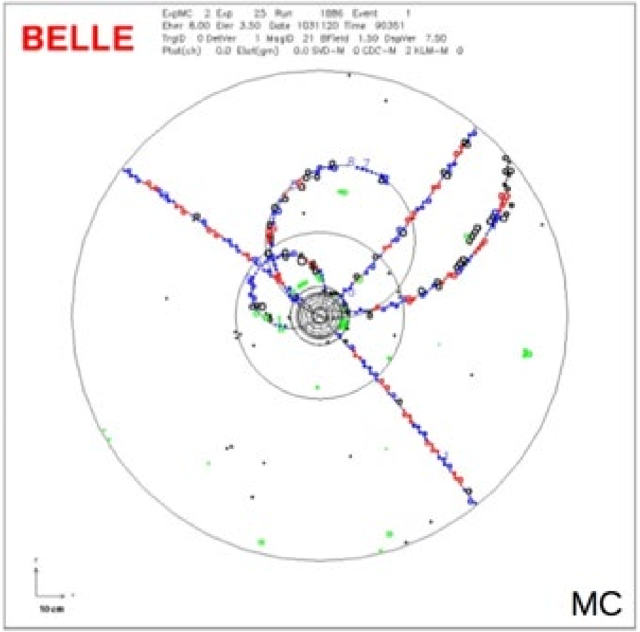


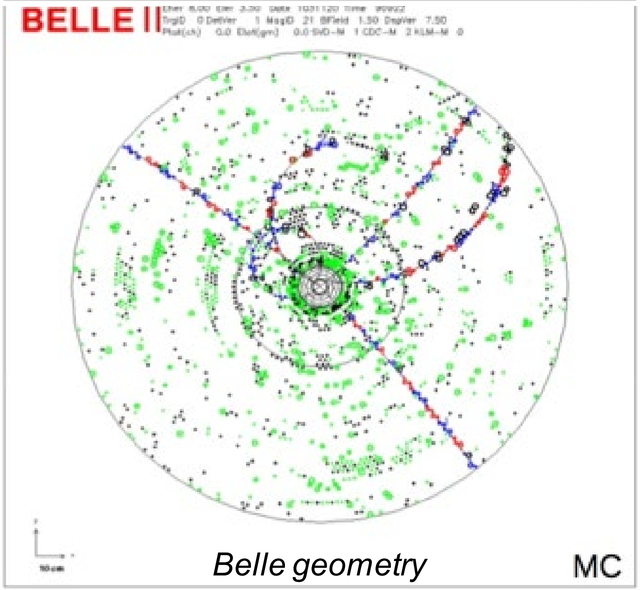
Nano-beam Scheme



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

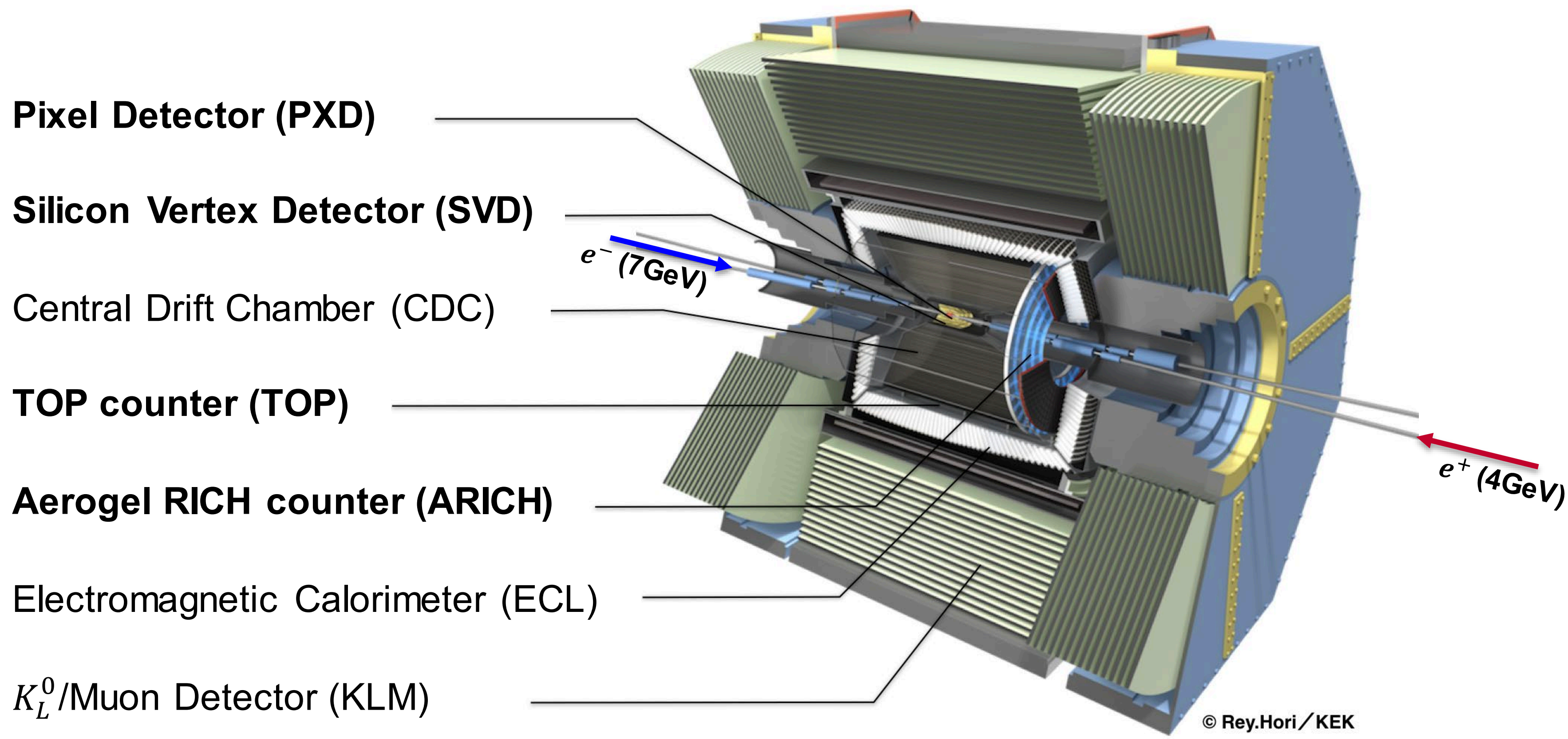
Belle II Detector - Challenges





- Lower boost
  - Better vertex resolution
- Higher background
  - Detector occupancy, fake hits
  - Radiation damage
- Higher event rate
  - Trigger rate
  - DAQ
  - Computing
- Important to have a dedicated phase for
  - Background studies
  - Detector response and alignment

Belle II Detector - Overview



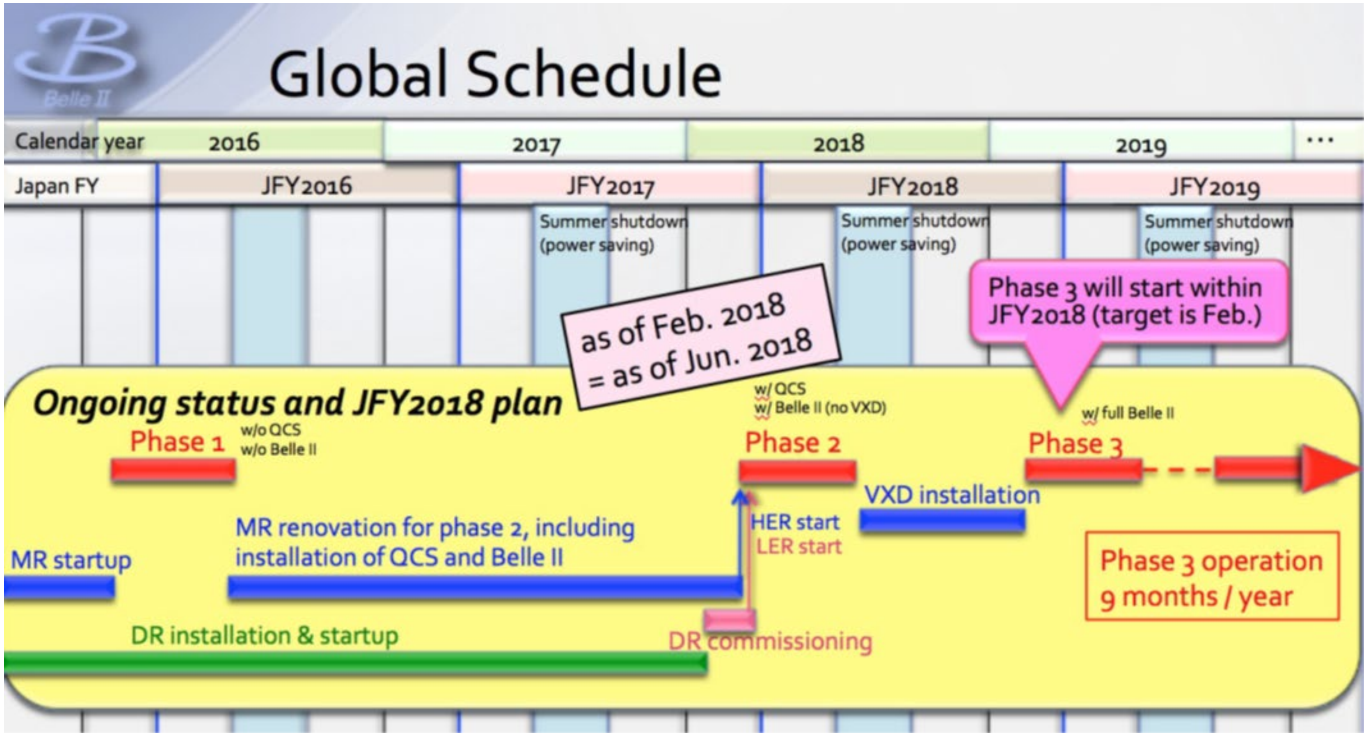
Belle II - Commissioning

Phase 1

- ❑ SuperKEKB accelerator w/o QCS
- ❑ No Belle II Detector

Phase 2

- ❑ SuperKEKB w QCS
- ❑ Belle II w partial Vertex Detector
- ❑ Beam optimization
- ❑ Background studies
- ❑ Detector Calibration



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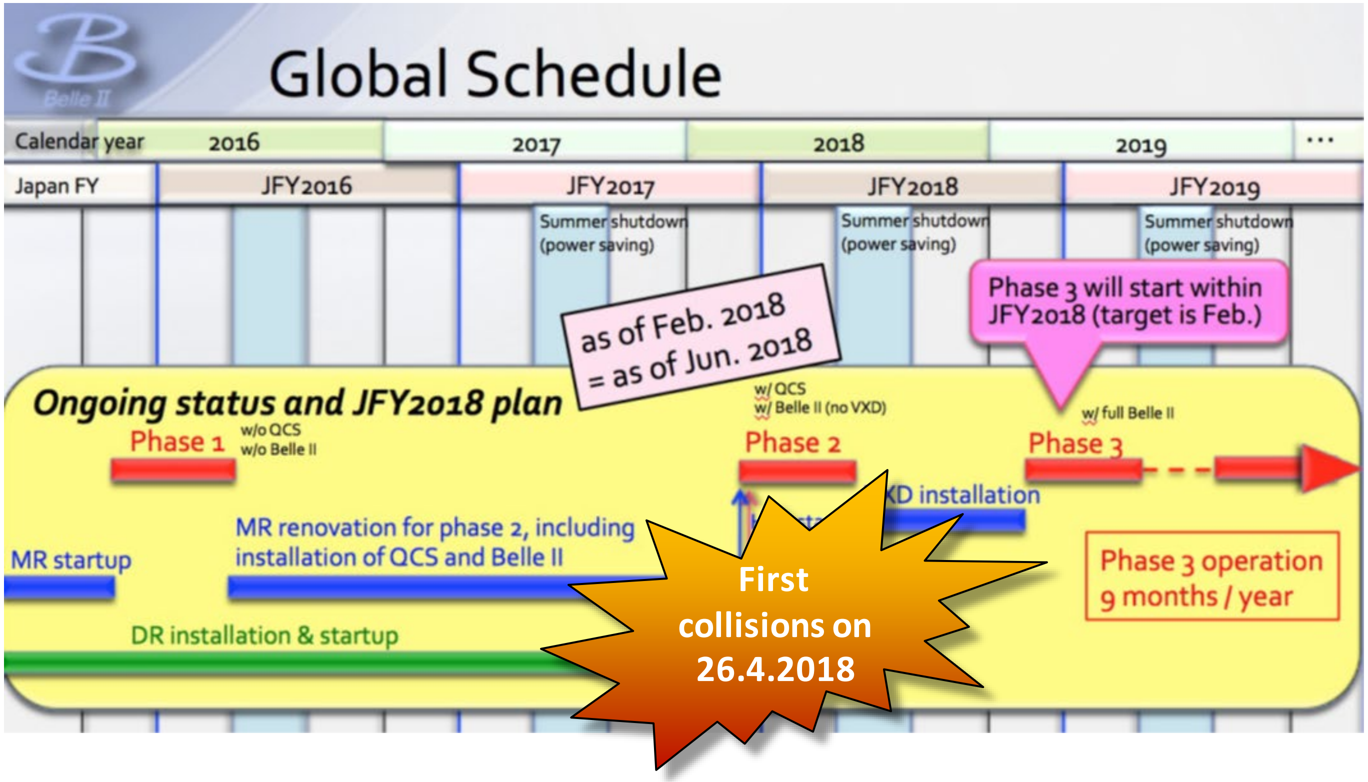

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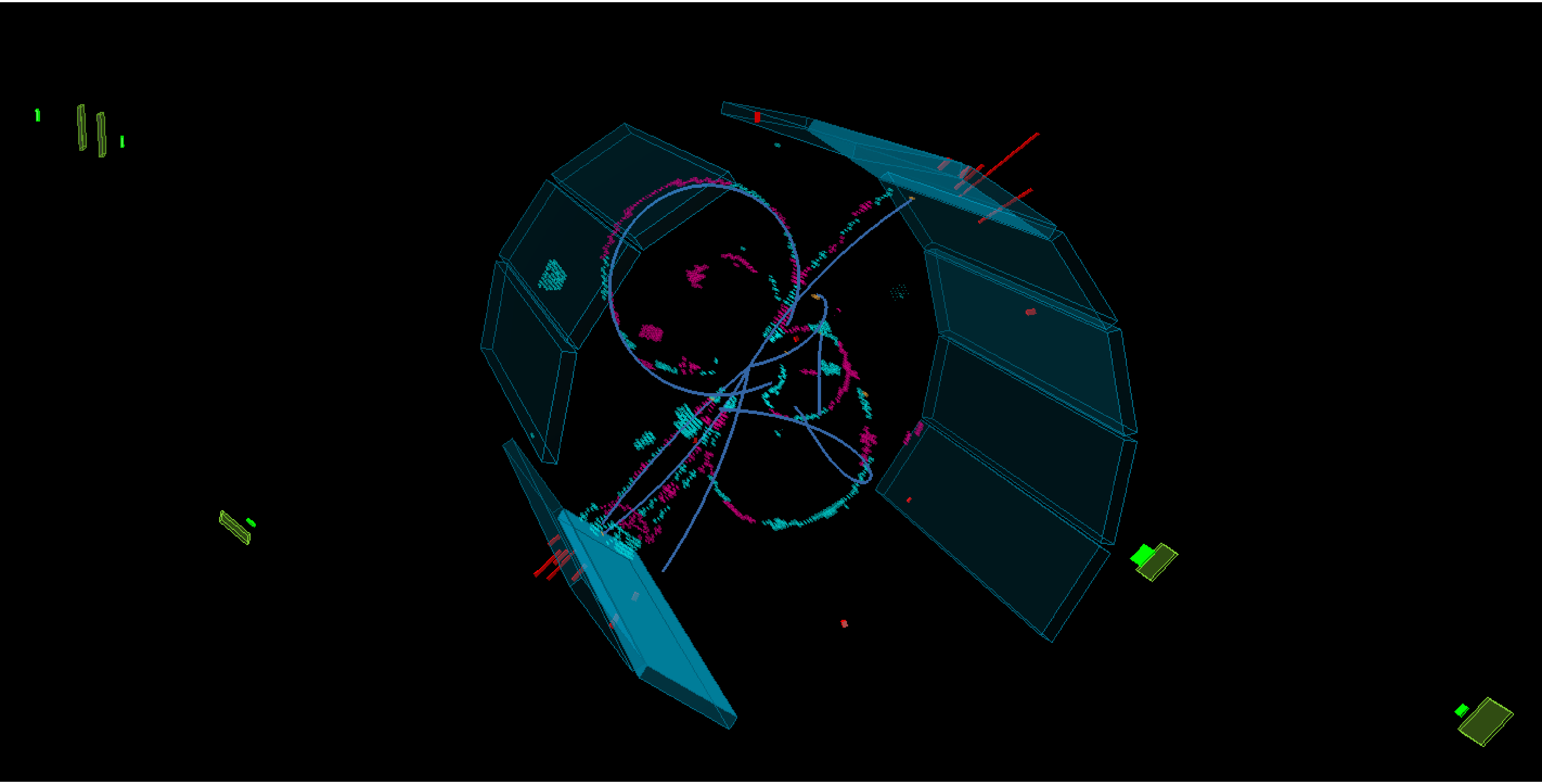
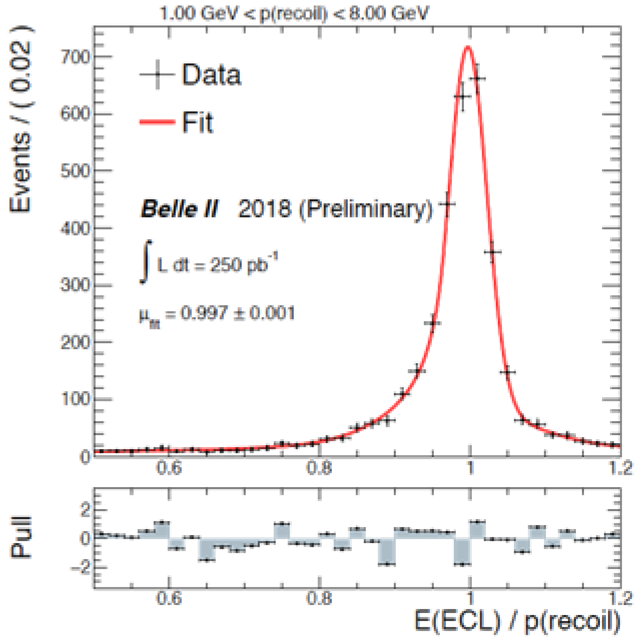
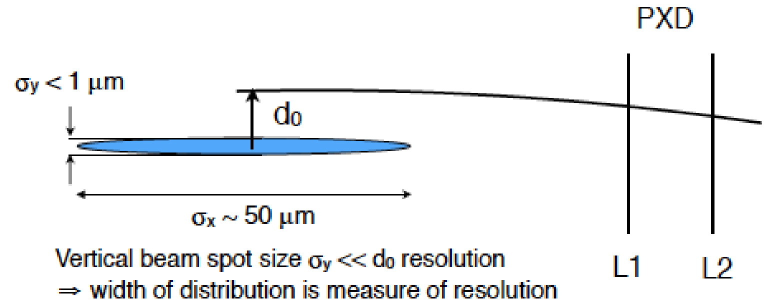
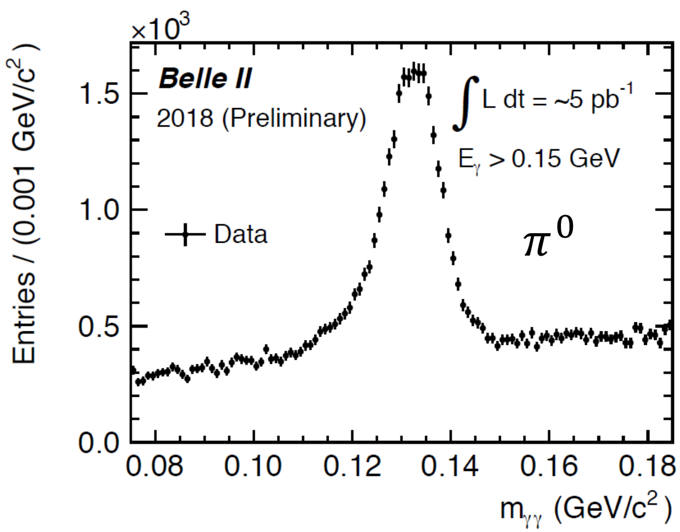
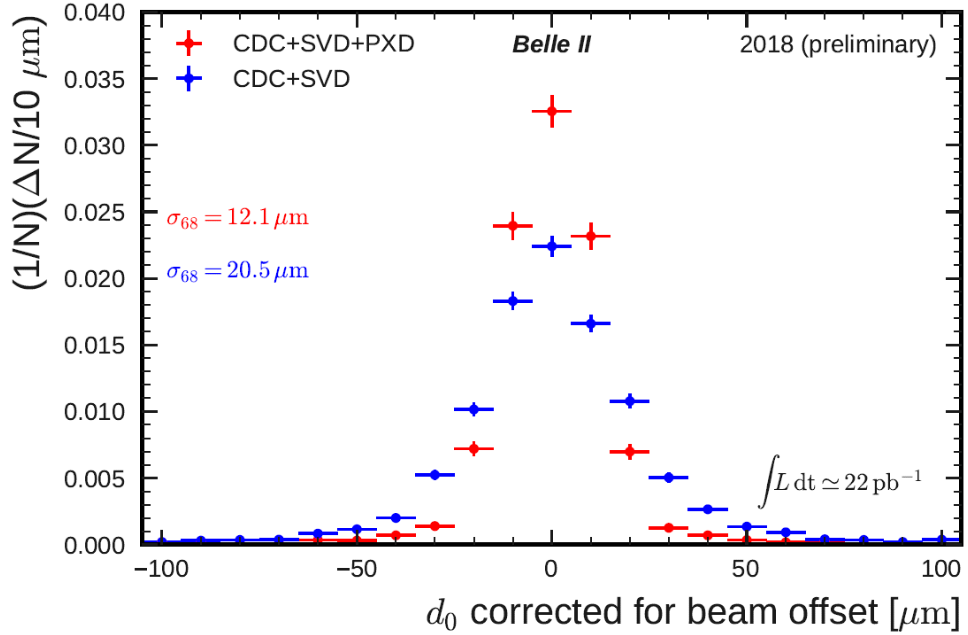


Results from Phase 2 – Detector Performance

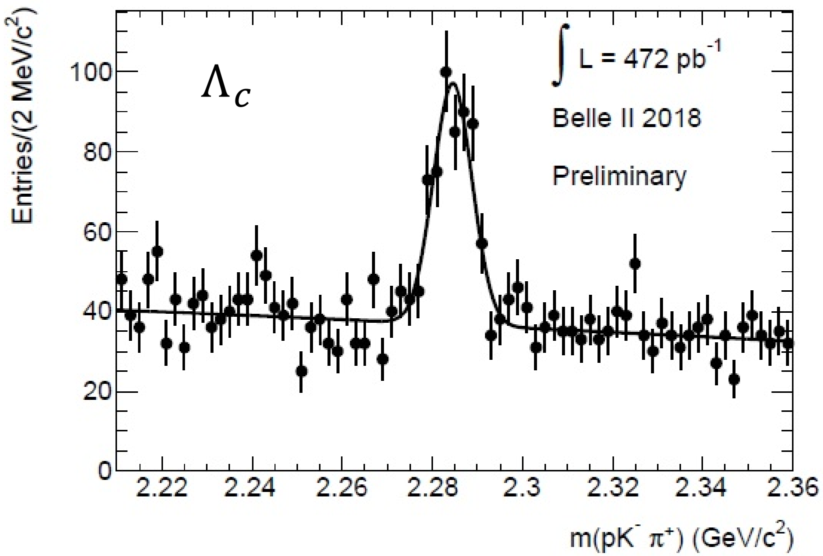


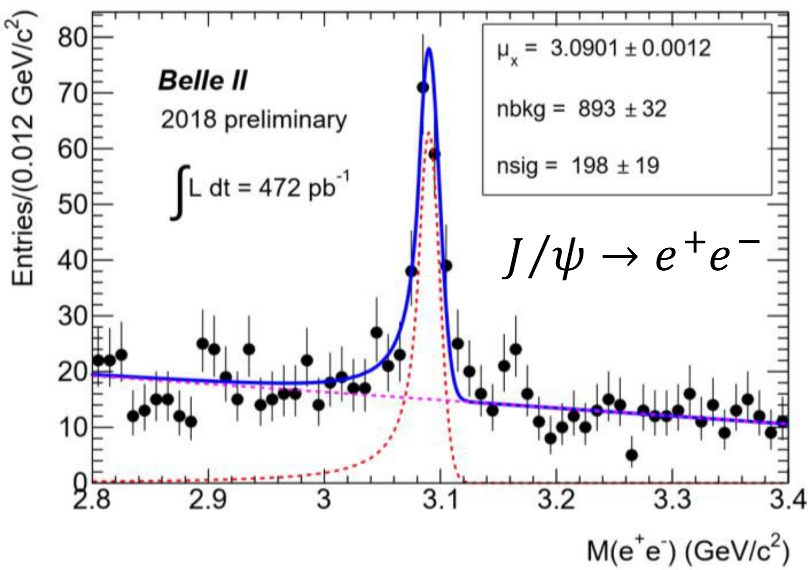


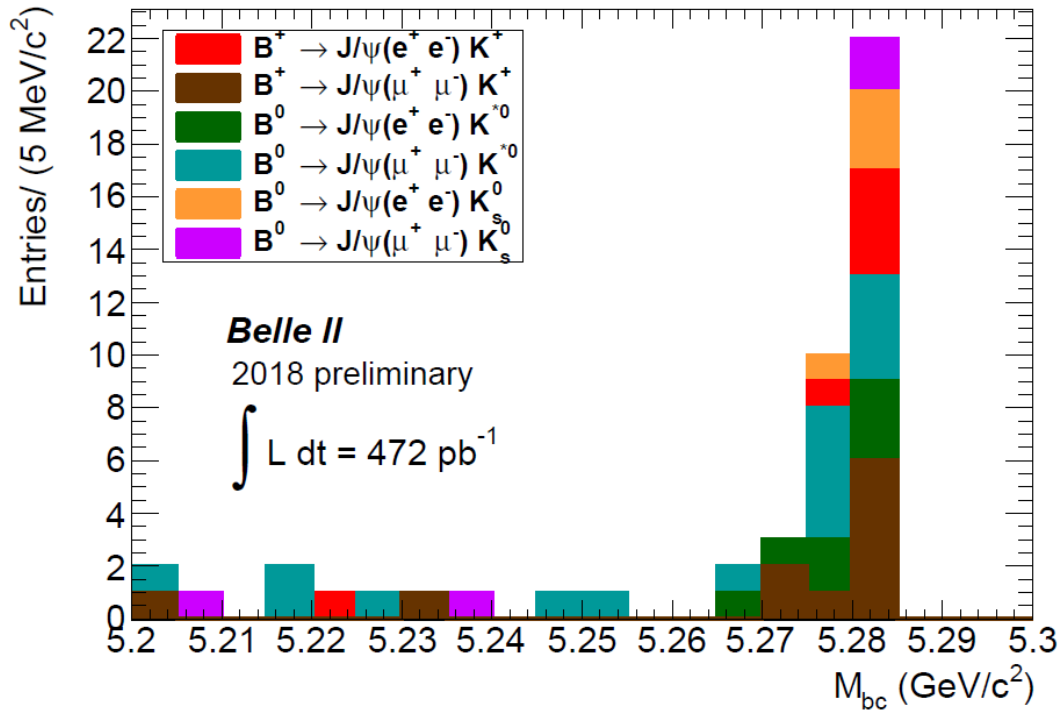




Results from Phase 2 – 'Rediscoveries'







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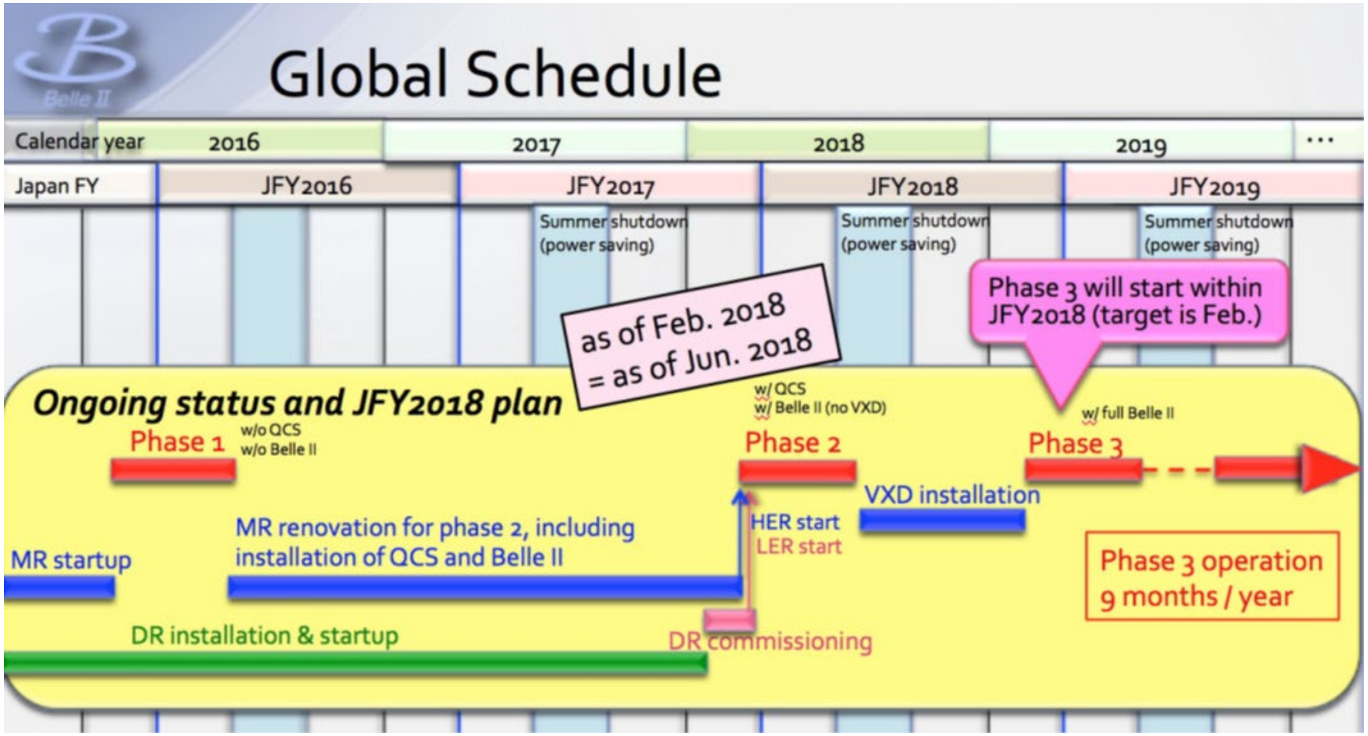
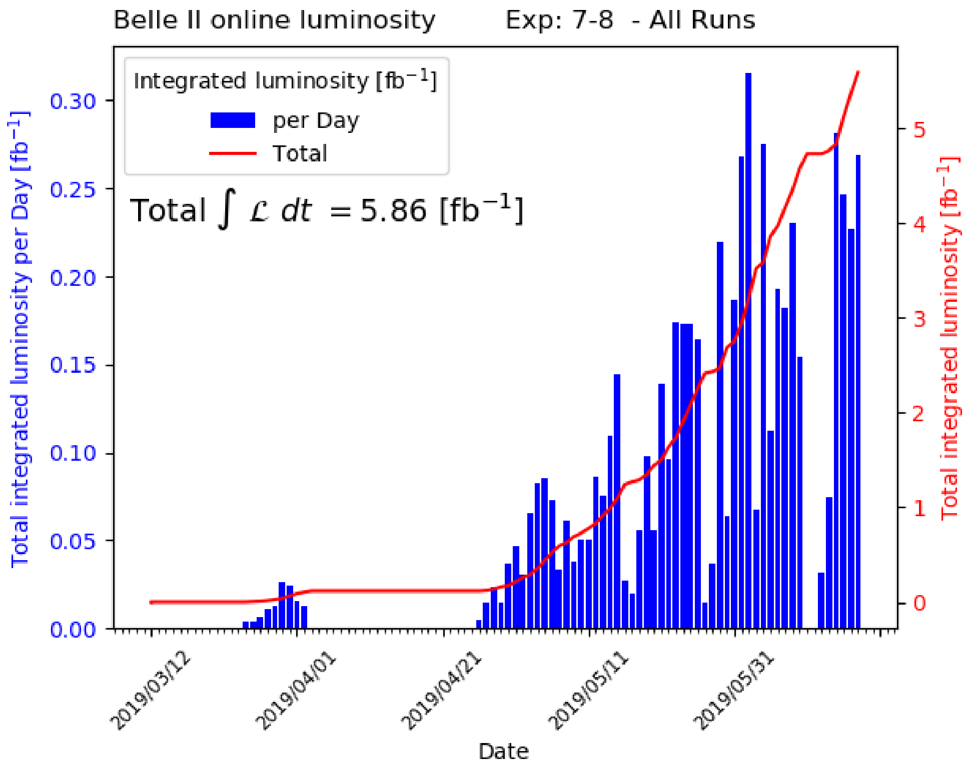
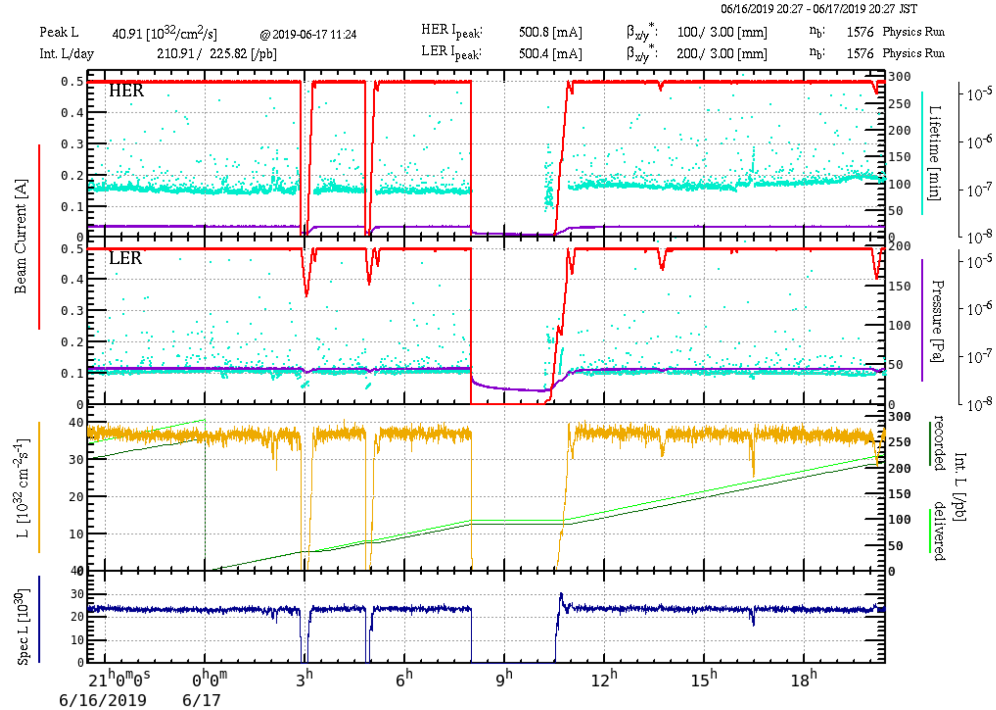
- ❑ Beam optimization
- ❑ Background studies
- ❑ Detector Calibration

Phase 3
- ❑ Belle II Detector w full Vertex Detector
- ❑ Physics Run



Belle II - Commissioning





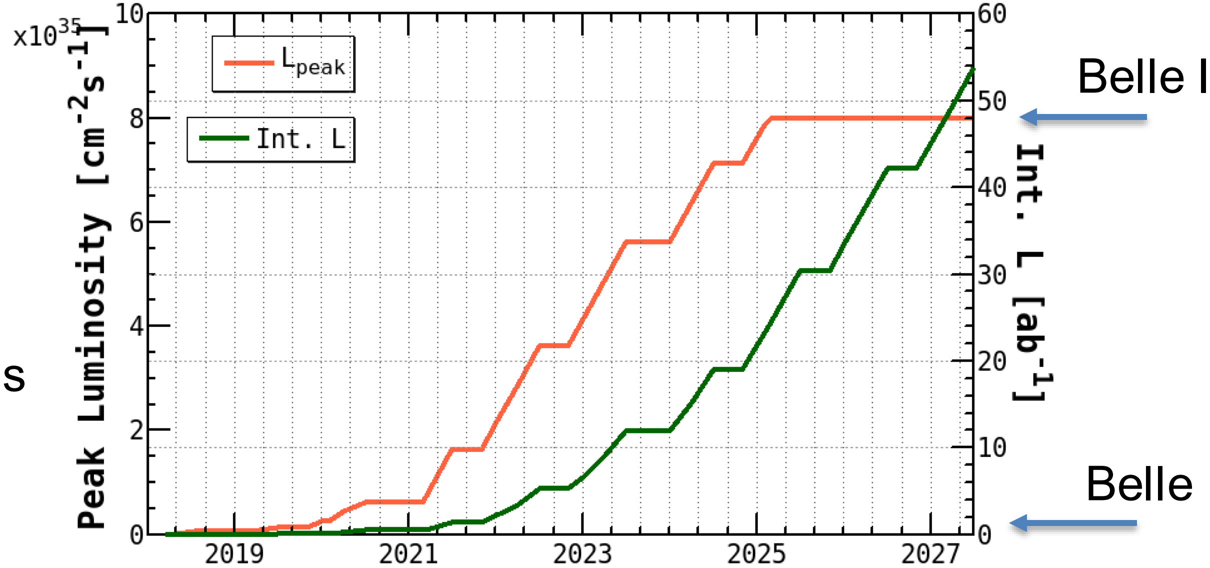
Phase 3
- ❑ Belle II Detector w full Vertex Detector
- ❑ Physics Run

- ❑ Beam current $0.5\ A$ in both rings
- ❑ $L_{peak} \sim 4 \times 10^{33} cm^{-2} s^{-1}$
- ❑ $\sim 250\ \text{pb}^{-1}$ per day achieved
- ❑ Routine data taking

Belle II Physics Plan

50 × the Belle's $B\bar{B}$ sample by 2027

- ❑ Rare B decays, New Physics
- ❑ CP violation
- ❑ τ physics
- ❑ Bottomonium (Only Belle II can do it!)
- ❑ Charmonium and Charmed baryons
- ❑ Hyperons
- ☞ See Belle II Physics Book *(arXiv:1808.10567 [hep-ex])*

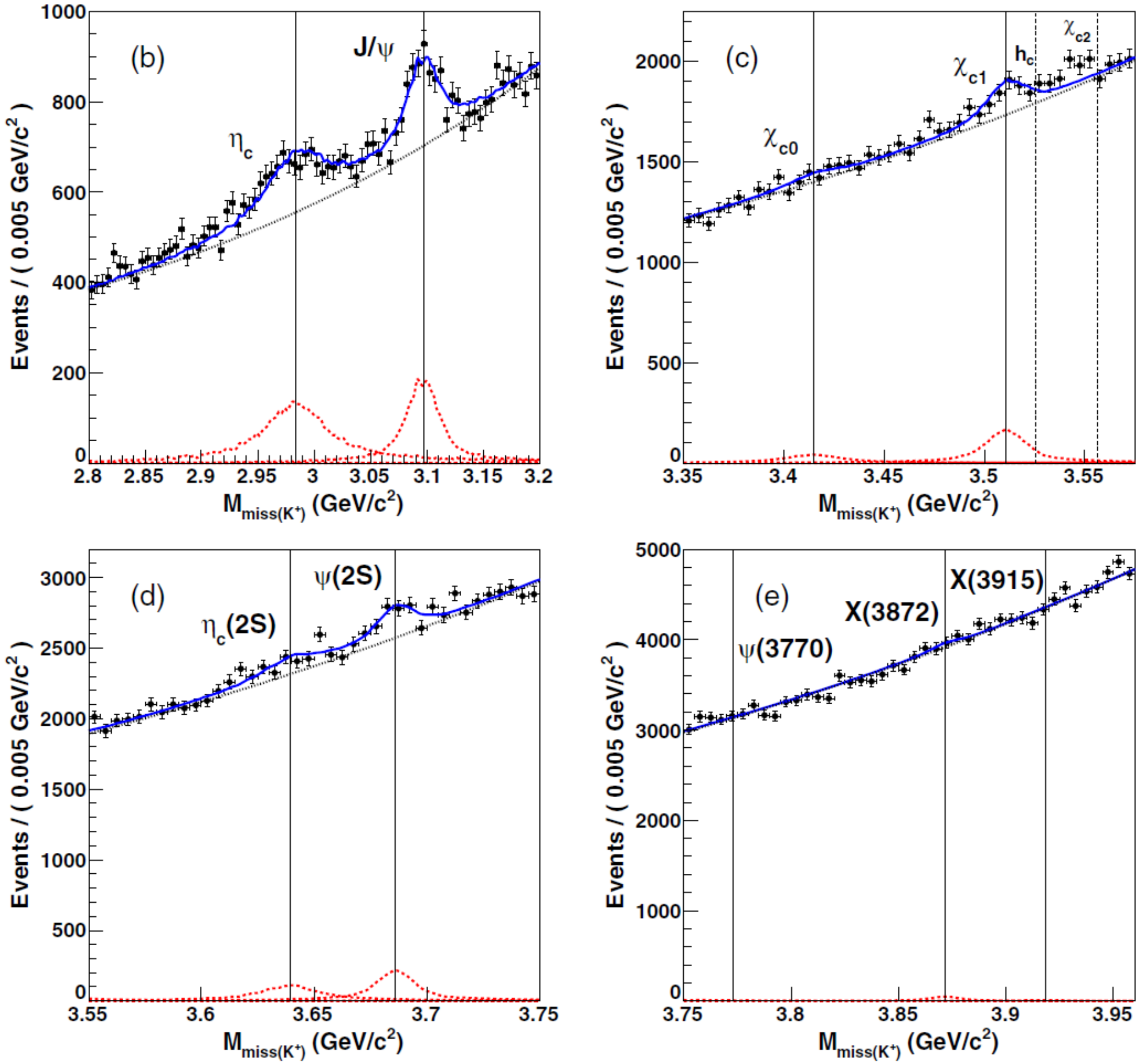


Current samples in fb^{-1} (millions of events), and the proposal for Belle II

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%

Running at $\Upsilon(4S)$ – B to $K(c\bar{c})$

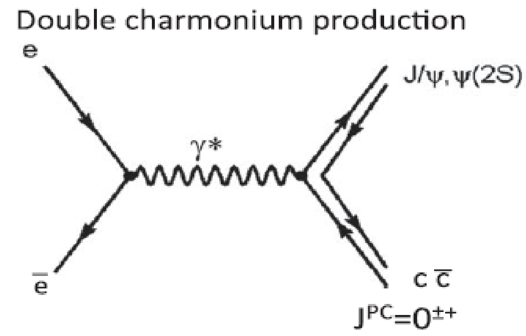
- Uniquely done in e^+e^- B-factories
- All quantum numbers available
- Allows to calculate absolute *BR*
- Competitive with LHCb
- Allows reconstruction of
  - hadronic transitions with π^0, η, ω in final state
  - states decaying with large multiplicities
- Further developments:
  - $K\gamma$ recoils (search for the spin singlet $1\ ^1D_2$)
  - Comprehensive study of $KD^{(*)}\bar{D}^{(*)}$ *and* $KD^{(*)}\bar{D}^{**}$

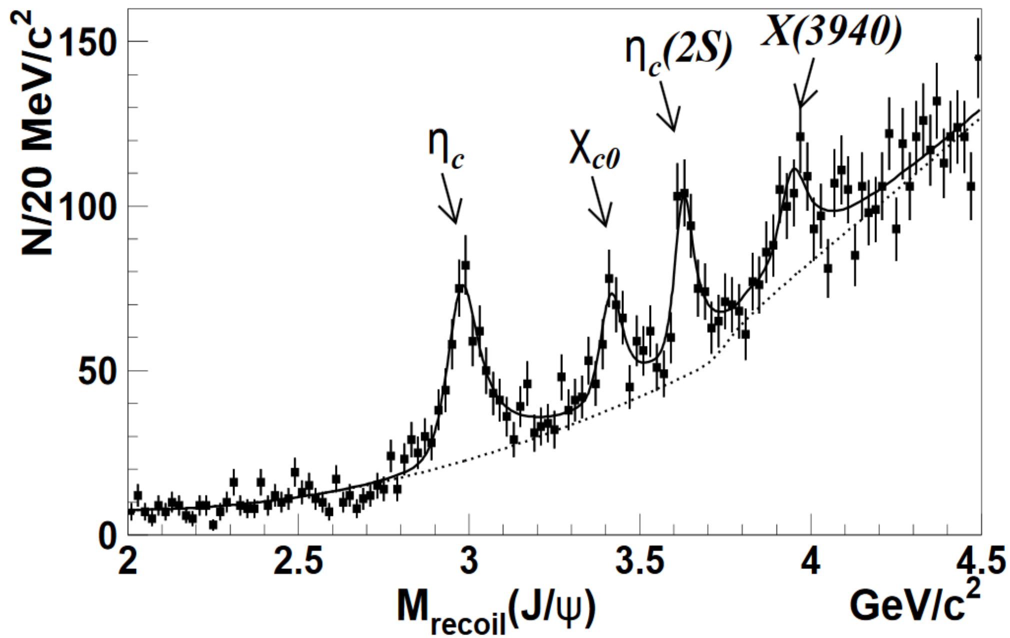


[PRD 97, 012005 (2018)]

Running at $\Upsilon(4S)$ – Double Charmonium

- Absolute *BR* and cross sections
- The legacy of previous generation (mostly Belle) :
- $e^+e^- \rightarrow\ c\bar{c}(1^-)\ c\bar{c}(0^\pm)$
  - $J/\psi, \psi'$ recoils
- Most recent result: the discovery of $\chi_{c0}(2P)$ (studying the $J/\psi\ D$ recoil) *[Phys.Rev. D95 (2017) 112003]*
- Future prospects, with larger statistics (>5 ab^{-1}):
- $e^+e^- \rightarrow\ c\bar{c}(0^\pm)\ c\bar{c}(1^-\ \mathrm{or}\ 1^+)$
  - η_c or χ_{c0} recoils
- Study of angular distributions:
  - to decouple overlapping states
  - to do cross checks on J^{PC}
- Study on double charmonium from $\Upsilon(3S)$
  - Belle has evidence of $J/\psi, \chi_{c1}$ from $\Upsilon(1{,}2S)$ *[PRD90,112008(2014)]*



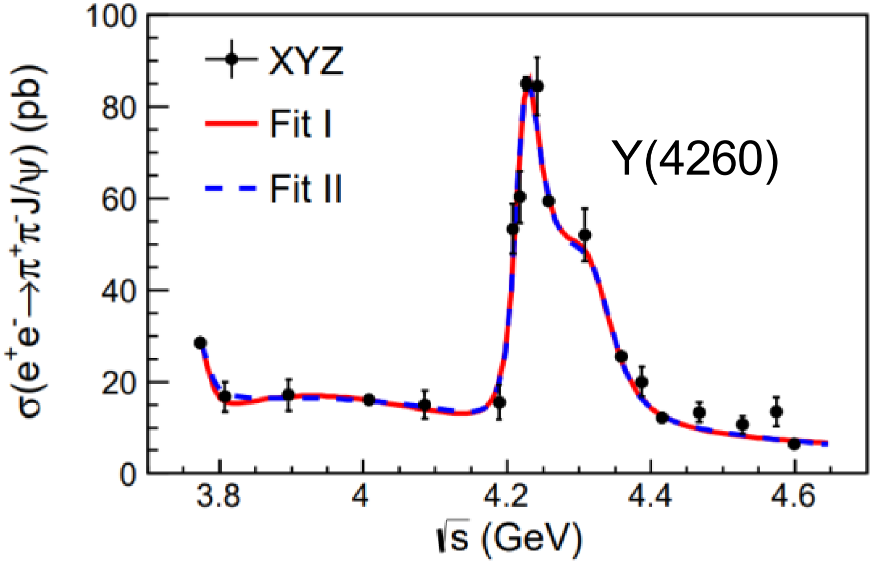


[Belle, PRL 98, 082001 (2007)]

Running at $\Upsilon(4S)$ – Initial State Radiation

- Access to line shape of vector states
- $Y(4230), Y(4260), Y(4360)$ could all be explored
- Unexpected $Y(4260)$ line-shape measured at BESIII, inconsistent among different modes. Could explore w ISR
- Cross sections of exclusive $(c\bar{c})$ + hadrons
- Search for strange partner of $Z(3900)$ in K^+K^-J/ψ

[BES III, PRL 118, 092001 (2017)]

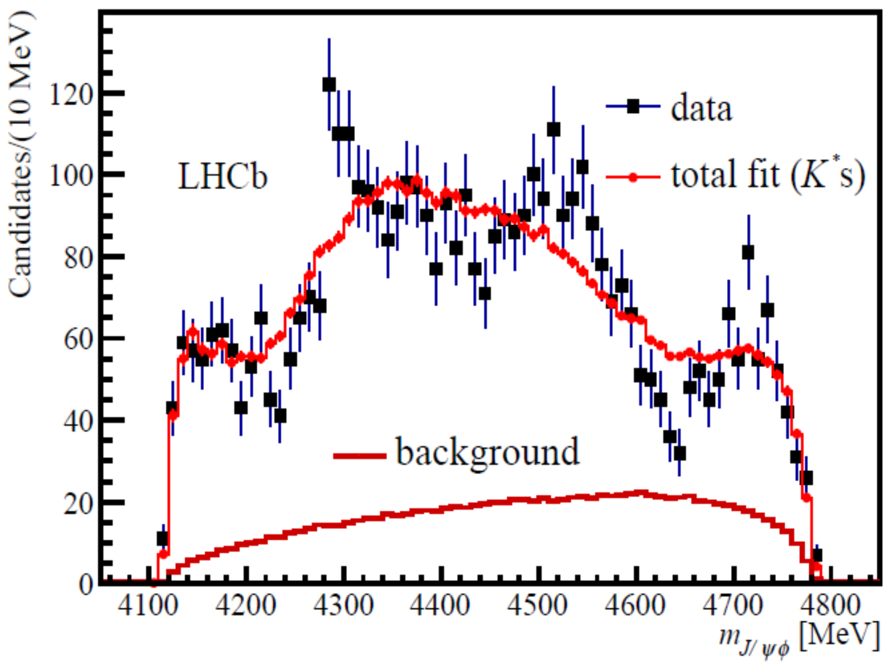


Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^-J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
K^+K^-J/ψ	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^-h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$,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

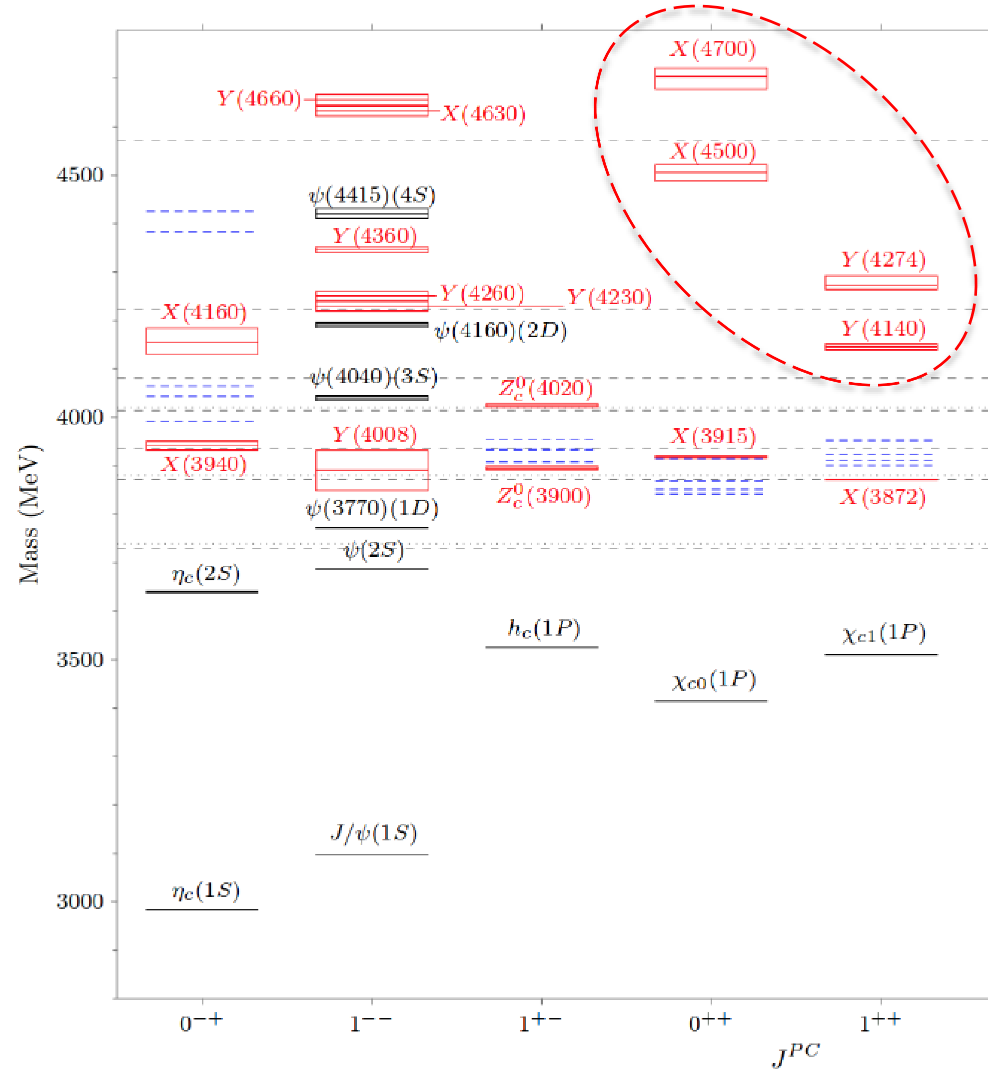
$10ab^{-1}$ ($50ab^{-1}$)

Running at Υ(4S) – Two Photon Interactions

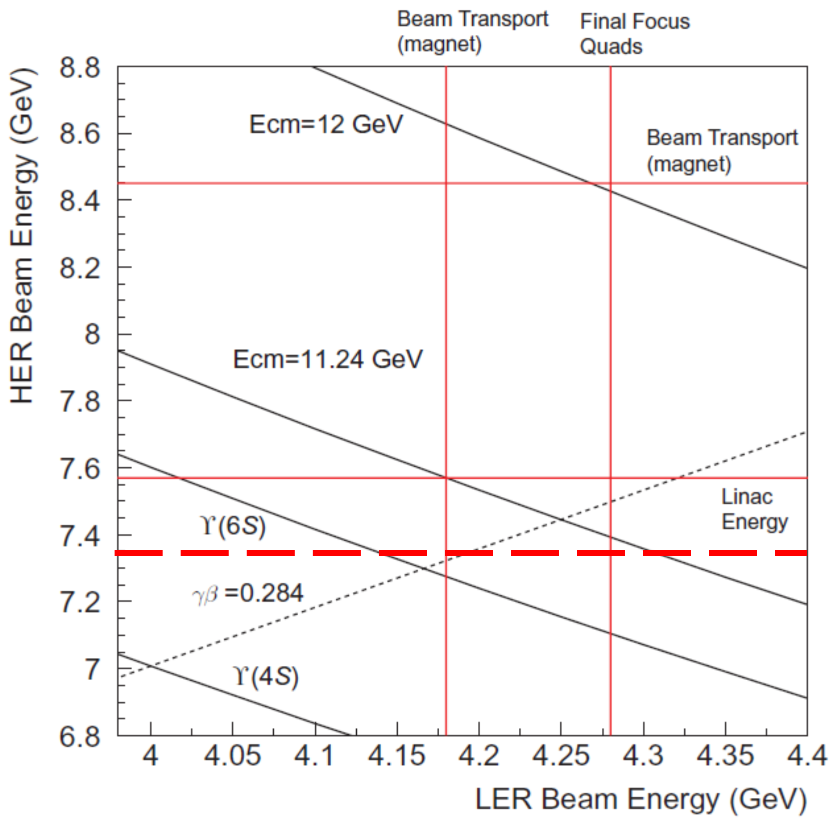
- ❑ $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$
- ❑ Also uniquely measurable at Belle II.
- ❑ Could disentangle two of the four states seen by LHCb in $\phi\, J/\psi$
- ❑ need >10 ab^{-1} to confirm the scalar states found by LHCb



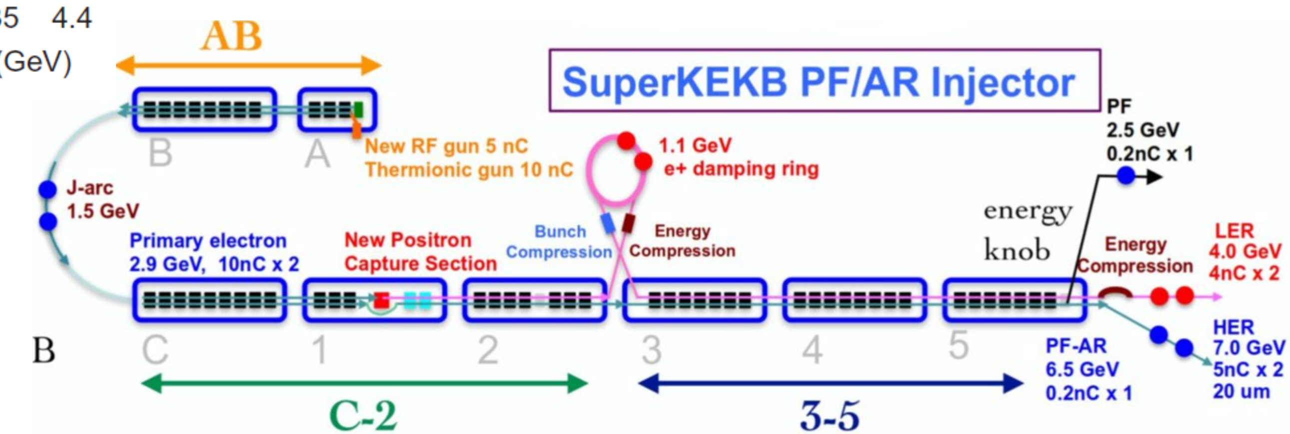
[PRL 118, 022003 (2017)]



Running above Υ(4S) – Accelerator Limits

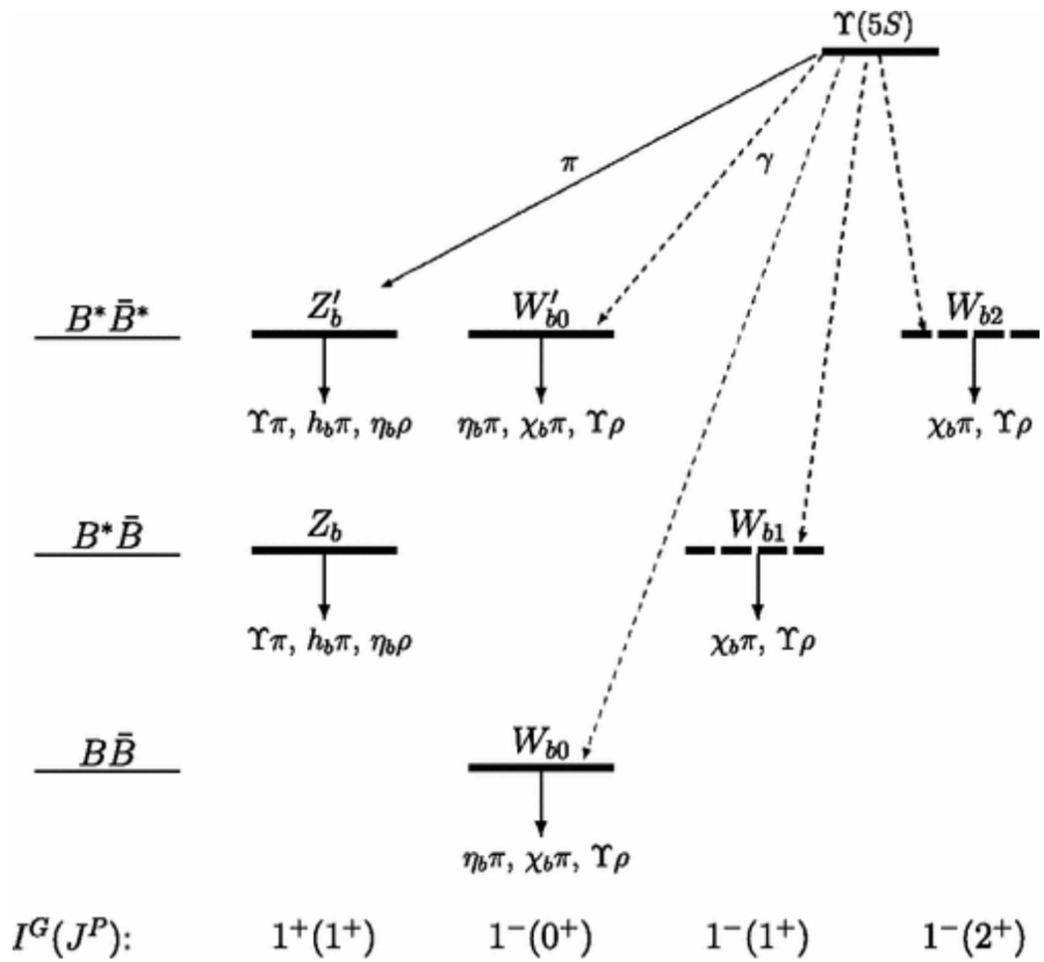


- Current machine limits:
  - Present max $E_{cm} \sim 11.02\ GeV$, a bit above $\Upsilon(6S)$
  - Possible max $E_{cm} \sim 11.24 GeV$, at $\Lambda_b \overline{\Lambda}_b$ threshold (J-arc upgrade)
- Not enough spare cavities to run safely at $\Upsilon(6S)$
- Major modifications required for running above $\Upsilon(6S)$



Running at $\Upsilon(5S)$

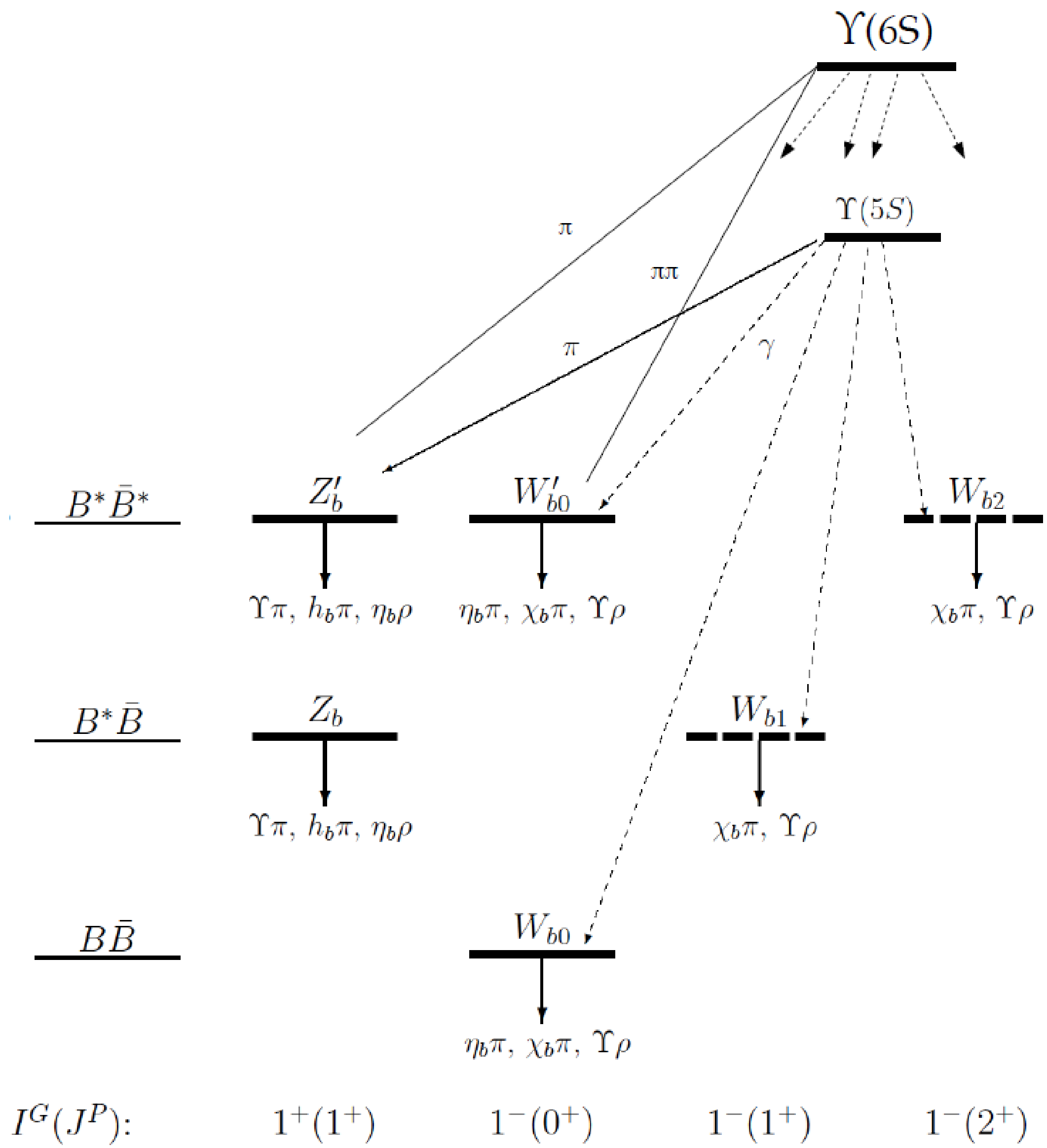
- $\Upsilon(5S)$: $1\ \mathrm{ab}^{-1}$ “high statistics” run
- Settle nature of $\Upsilon(5S)$
- $\Upsilon(5S)$ line shapes
  - Apparent discrepancies in shape in $\pi\pi\Upsilon$ modes vs. $\pi\pi h$ modes
- Precision Z_b measurements
  - Z_b above or below open flavour threshold
- Exotica discovery



Voloshin, PRD 84, 031502 (2011)

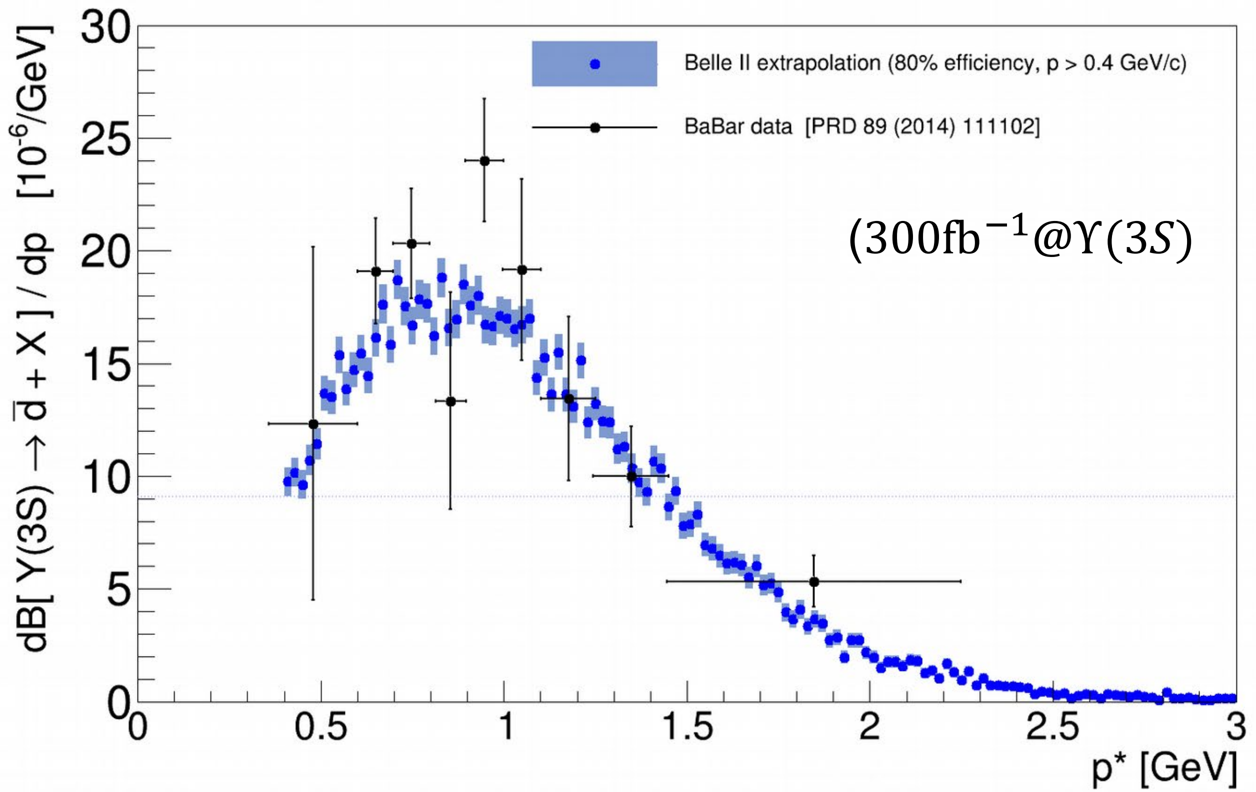
Running at $\Upsilon(6S)$ – Accelerator Upgrade needed

- $\Upsilon(6S)$: 100 fb^{-1} exploratory run
- Comparing $\Upsilon(5S)$ and $\Upsilon(6S)$ decay rates
- Di-pion transitions for discovery of more Z_b states?
- Molecular model for Z_b predicts neutral partners (W_b), should be reachable via radiative transitions
- Further hadronic transitions to W_b states are expected above 11.3 GeV, unreachable at present.
- η transition to $\Upsilon(2D)$



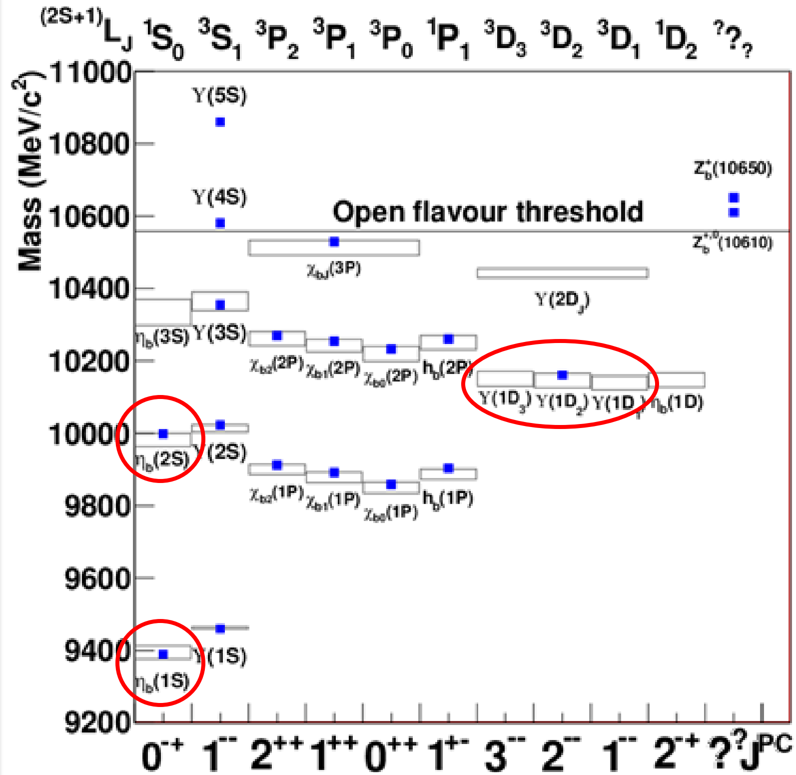
Running at $\Upsilon(3S)$ – (Anti)Deuteron Production

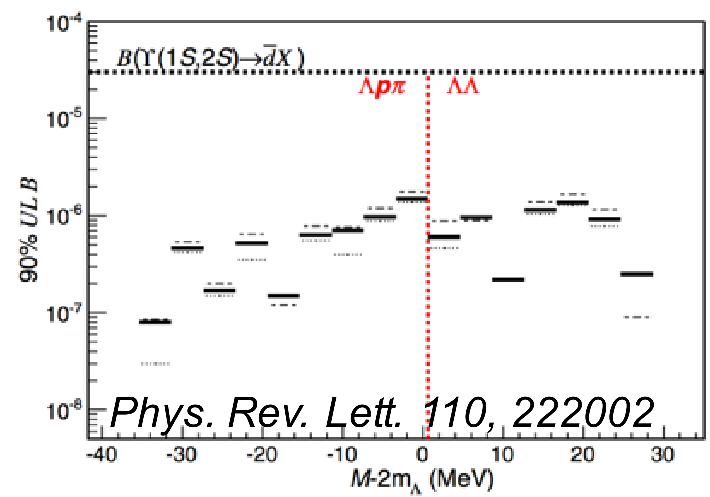
- $\bar{d}$ in cosmic ray have long since been considered a probe for supersymmetric relics in the galactic halo
- $\bar{d}$ production described with coalescence models tuned on HEP data
  - need of further constraints in the production model
- CLEO and Babar measured the $\bar{d}$ spectrum (no dedicated PID or tracking)
- Belle II:
  - dedicated tracking and PID
  - collect $\sim 3 \times 10^4$ $\bar{d}$
- World best estimate of coalescence parameter



Running at $\Upsilon(3S)$ – Quarkonia and Exotics

- Could collect 10-fold BaBar data set at $\Upsilon(3S)$ resonance
- Focus on conventional $b\bar{b}$ physics
  - $\Upsilon(1\,^3D_J\,)$ triplet: discover $J = 1{,}3$
  - $\eta_b(1S, 2S)$: confirm $m(\eta_b(1S, 2S))$
  - Hadronic $(\pi^0, \pi^+\pi^-, \eta, \omega)$ decays
  - Radiative transitions
- Search for H-dibaryon in missing mass $(\Upsilon(3S) \to H\ X, H \to \Lambda\Lambda \text{ or } \Lambda p\pi^-)$
  - high statistics study near threshold
- Rough extrapolation for $300\ \text{fb}^{-1}\ \Upsilon(3S)$
  - ~60 Million events with one Λ or $\bar{\Lambda}$
  - ~3 Million events with one $\Lambda\bar{\Lambda}$ pair





Phys. Rev. Lett. 110, 222002

Outlook

- Upgrade of SuperKEKB finished
- Belle II started to take data
- Goal is to integrate 50 × Belle data by 2027
- Unique production methods to probe charmonium(-like) systems
- $\Upsilon(3S)$ peak: if high luminosity running does not spoil the beam energy spread, at least $300\ \mathrm{fb}^{-1}$ data taking is planned
- $\Upsilon(5S)$ peak: at least $1\ \mathrm{ab}^{-1}$ is envisaged, to have impactful new results
- $\Upsilon(6S)$ peak: a pilot run of $10\ \mathrm{fb}^{-1}$, then up to $100\ \mathrm{fb}^{-1}$
- Scan of the high energy region (10.5 to 11 GeV): $400\ \mathrm{fb}^{-1}$?