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Future of hadron exotics at Belle II

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Exotic Hadrons and Flavor Physics Workshop
Simons Center for Geometry and Physics
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U.S. DEPARTMENT OF ENERGY

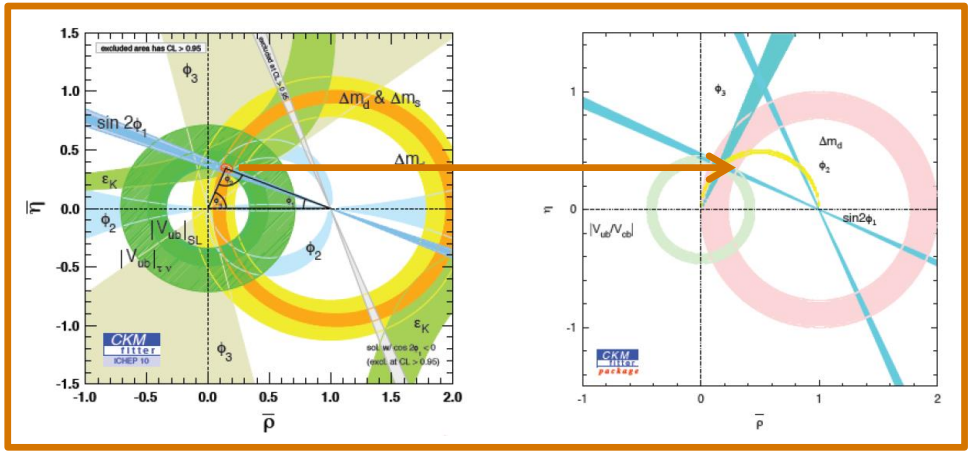
Outline

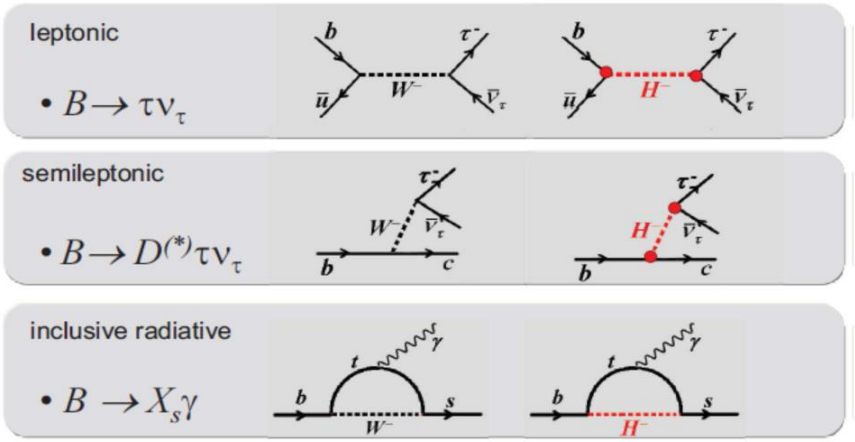
- Belle II: the next generation B Factory
  - Detector / accelerator description
  - Collaboration and plans
  - Early Belle II status
- Future prospects: quarkonium and exotics
  - Charmonium(-like) production
  - Bottomonium(-like): Above $\Upsilon(4S)$
  - Bottomnoium(-like): Below $\Upsilon(4S)$

BELLE II INTRODUCTION

Motivation for a next generation B Factory

- **Search for New Physics via precision measurements**

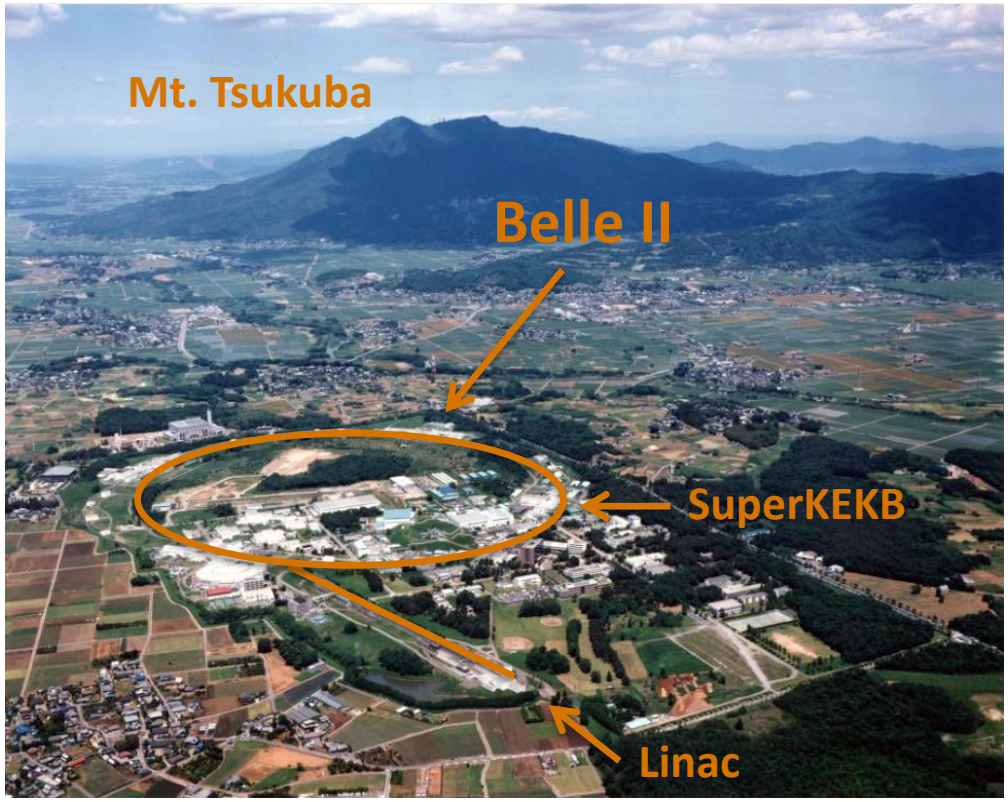




- Belle II Advantages
  - Sensitive to “New Physics” masses above direct production
  - “Clean” experimental environment, full event reconstruction
  - Tau decays and neutrals (γ, π^0, K_L, ν) in final state
  - Beam energy range and luminosity for exotics studies
  - Complementary to LHC

The Belle II Collaboration

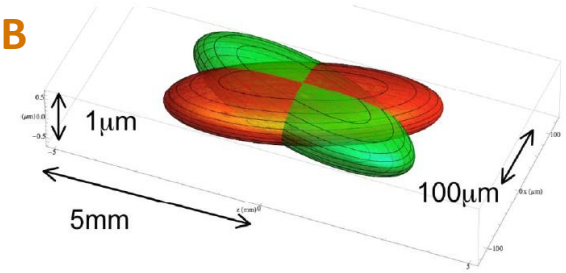
- 800+ members, 108 institutions, 25 countries
- Located at KEK in Tsukuba, Japan



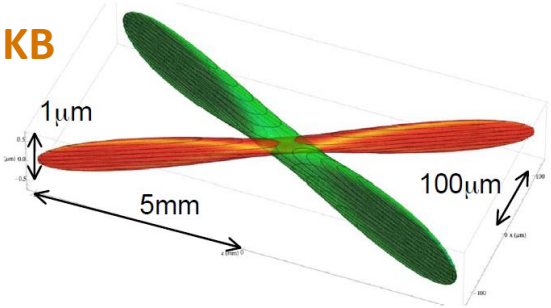
SuperKEKB Accelerator Upgrade

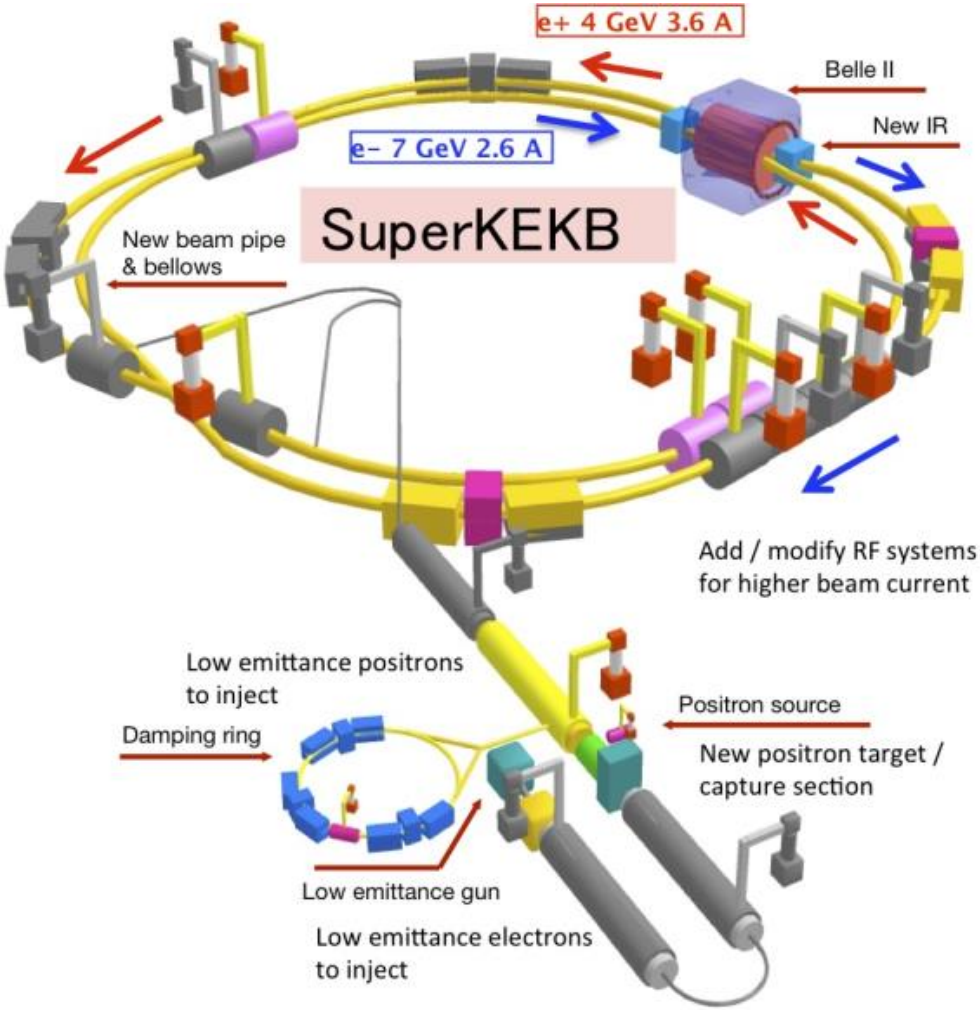
- "Nano-beam" interaction point
- Increase in current
- Factor of 40x increase in luminosity
- Energy: e^- (7 GeV) e^+ (4 GeV)

KEKB



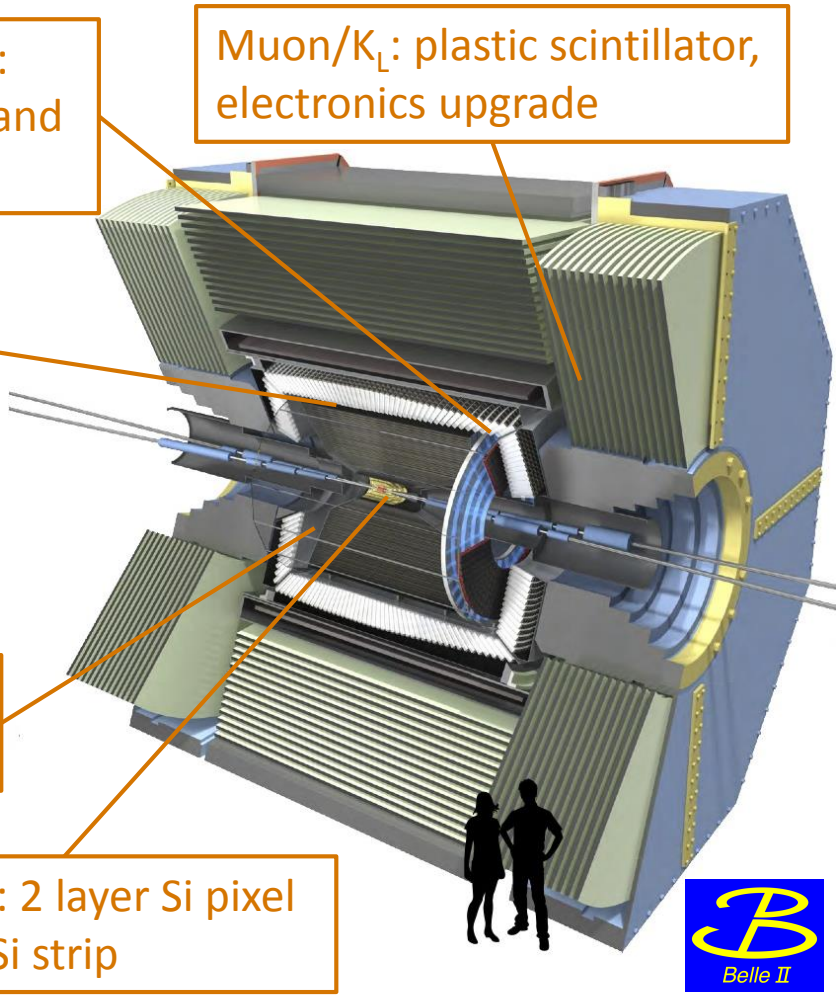
SuperKEKB





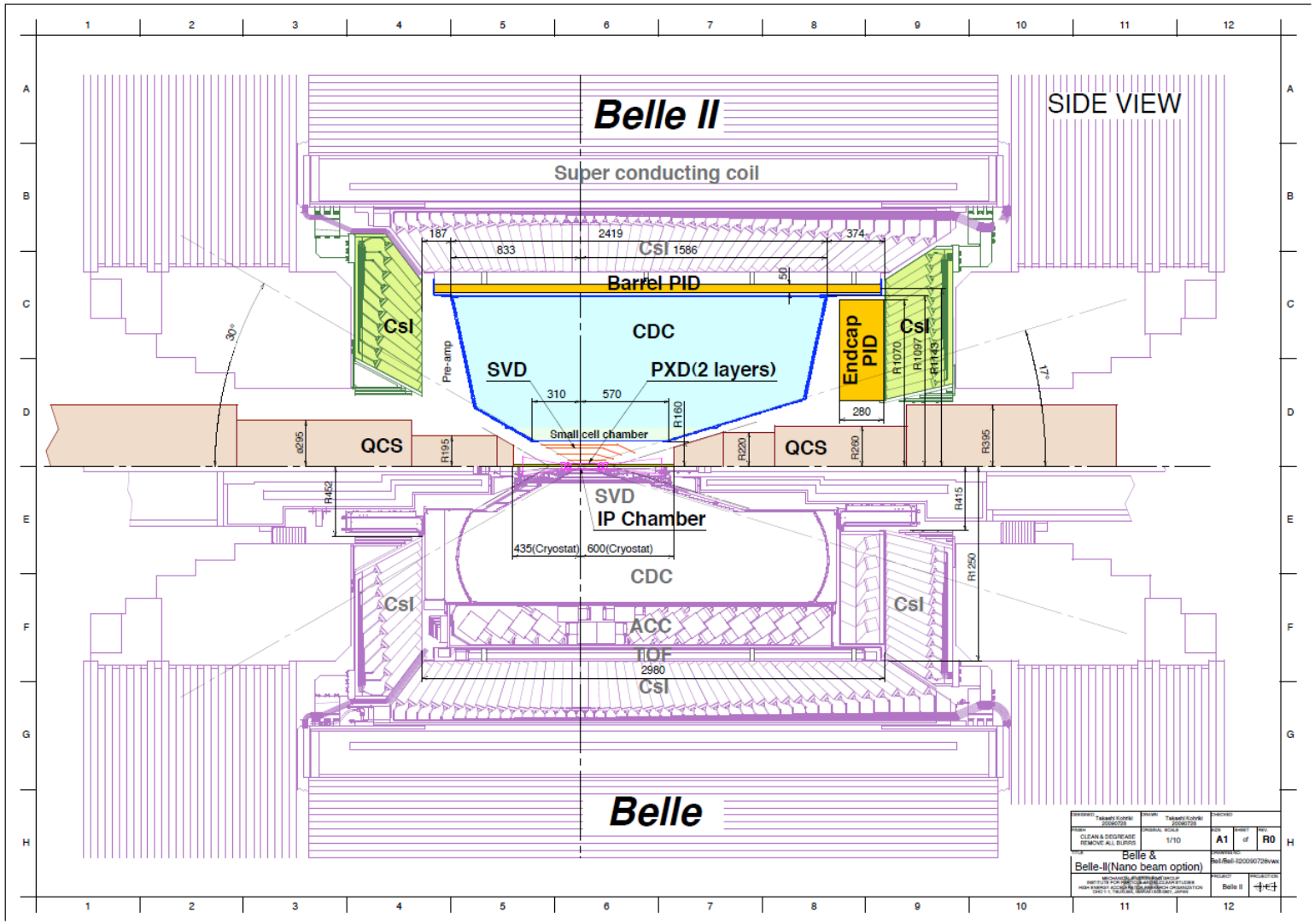
Detector Upgrade

- Order of magnitude luminosity increase means:
  - Higher background
    - Radiation damage
    - Pile-up/ECAL hits
  - Higher event rate
    - Trigger, DAQ, computing
  - Boost change
    - Improve vertexing
- Significant detector upgrades



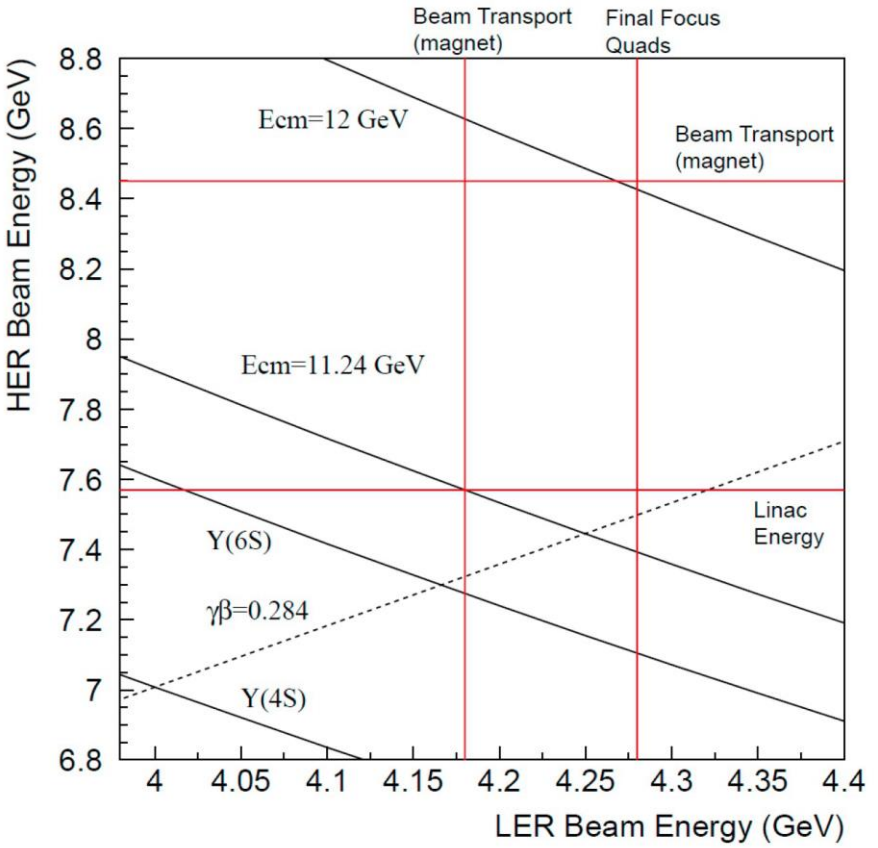
arXiv:1011.0352 (2011)

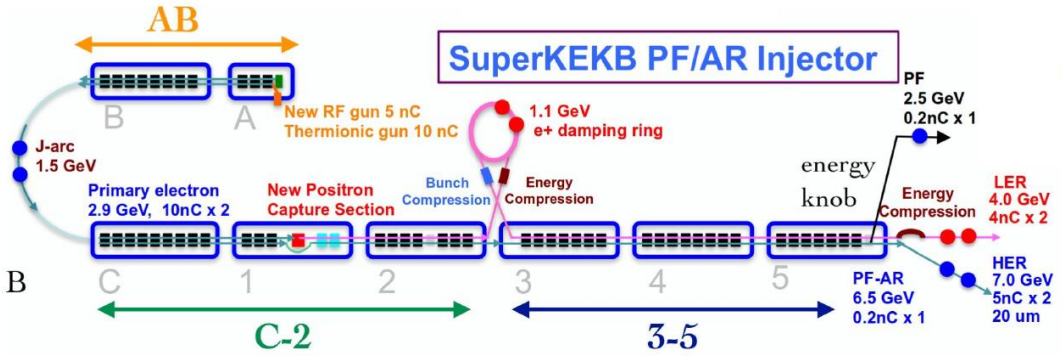
Detector Upgrade



Machine Capability

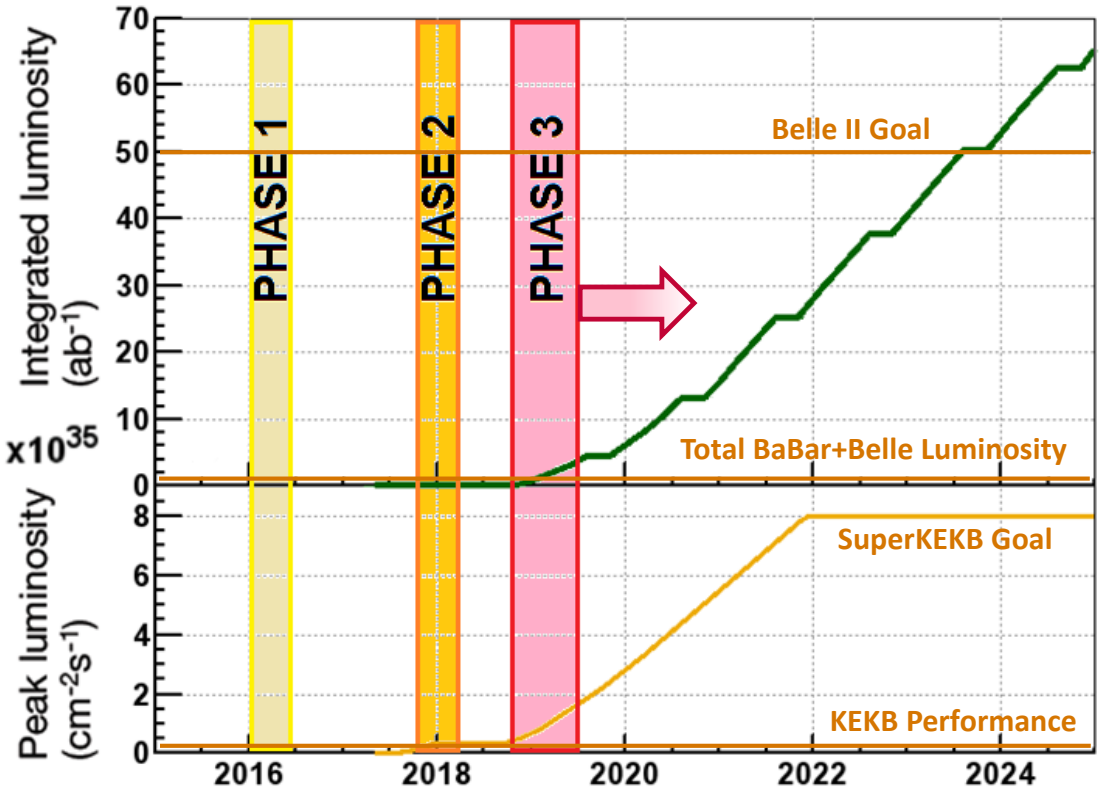
- Luminosity
  - Belle: 2 x 10^{34} $cm^{-2}s^{-1}$
  - Belle II: 8 x 10^{35} $cm^{-2}s^{-1}$
- Energy
  - Nominal: 10.58 GeV
  - Present Maximum: 11.02 GeV
  - Potential Maximum: 11.24 GeV





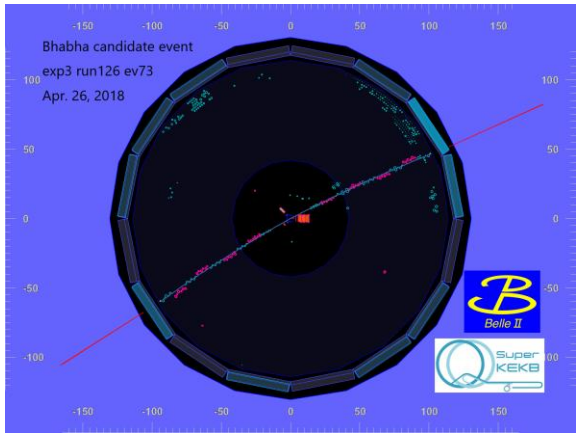
Belle II Schedule and Plans

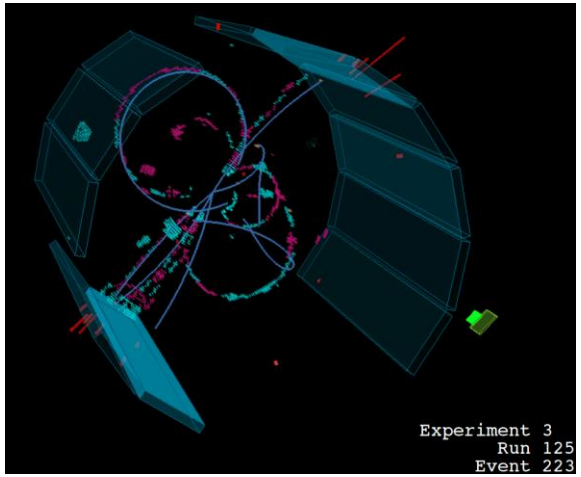
- Phase 1 (completed 2016)
  - Accelerator commissioning
- Detector roll-in: April 2017
- Phase 2 (2017/18)
  - First collisions (10±10 fb^{-1})
  - Partial detector
  - Background study
  - Physics possible
- Phase 3 (2018/19)
  - Nominal Belle II start
- **Ultimate goal: 50 ab^{-1}**

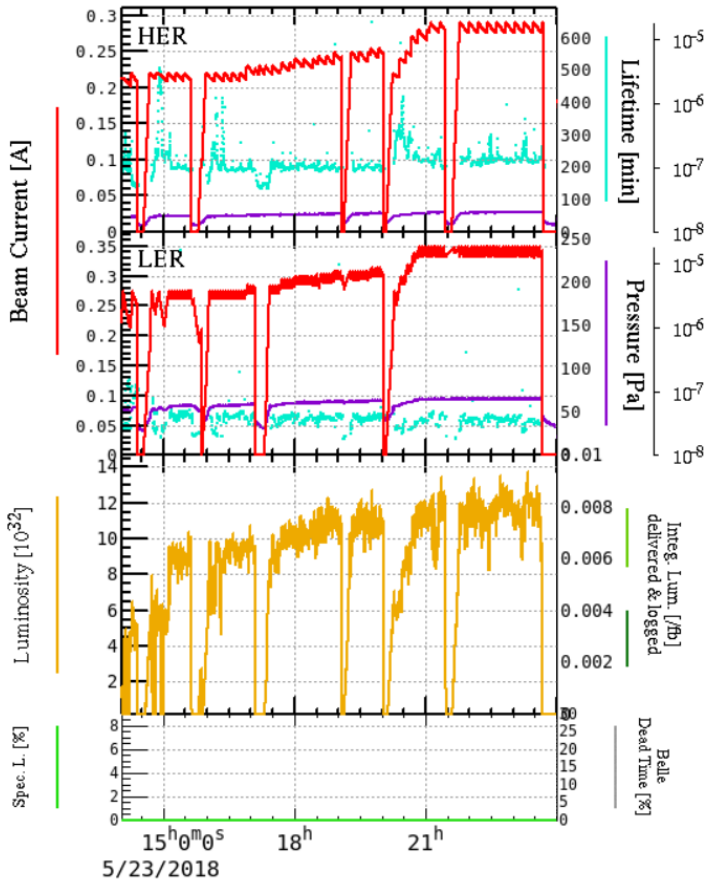


Recent Status

- First collisions: Apr. 26, 2018



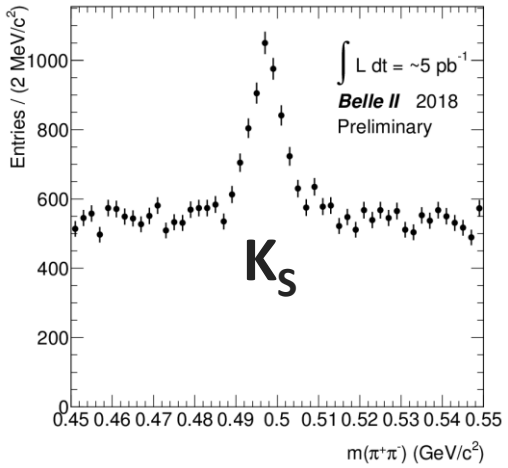


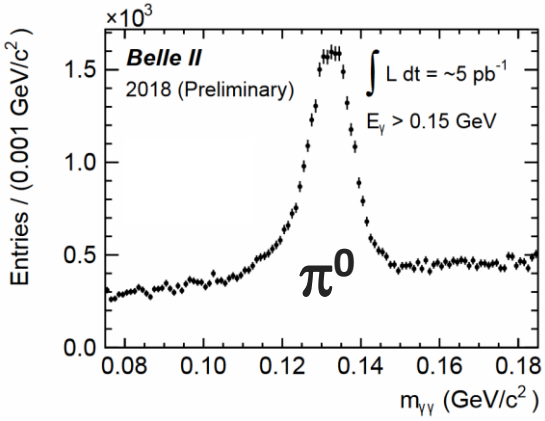


- Recent SuperKEKB status

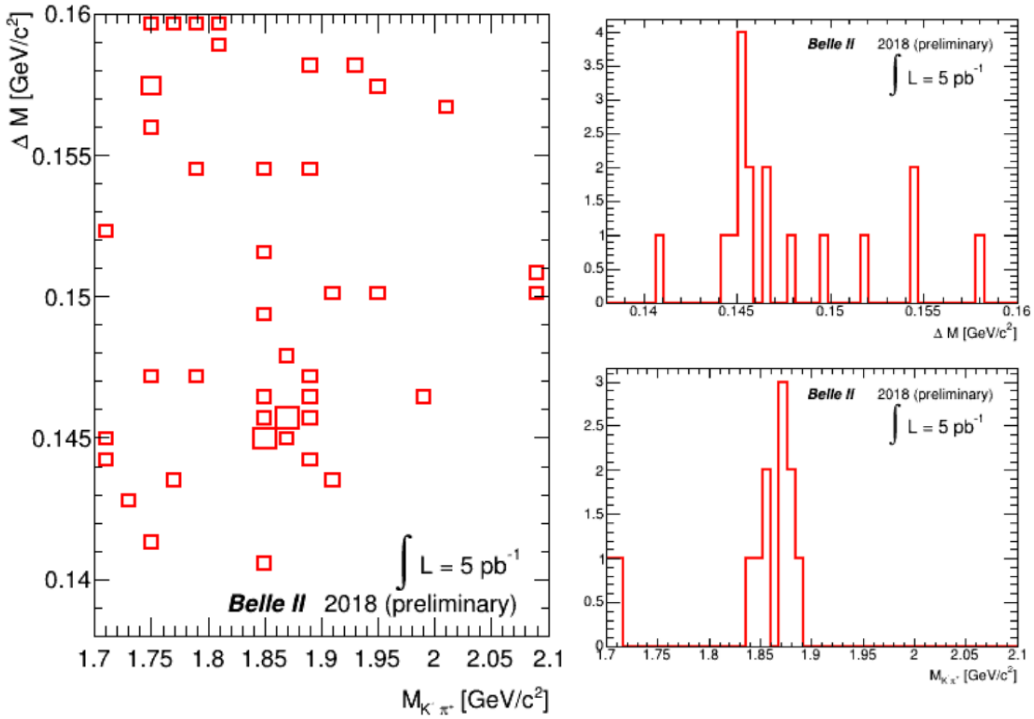
First signs of physics

- Beginning “rediscovery” of expected particles





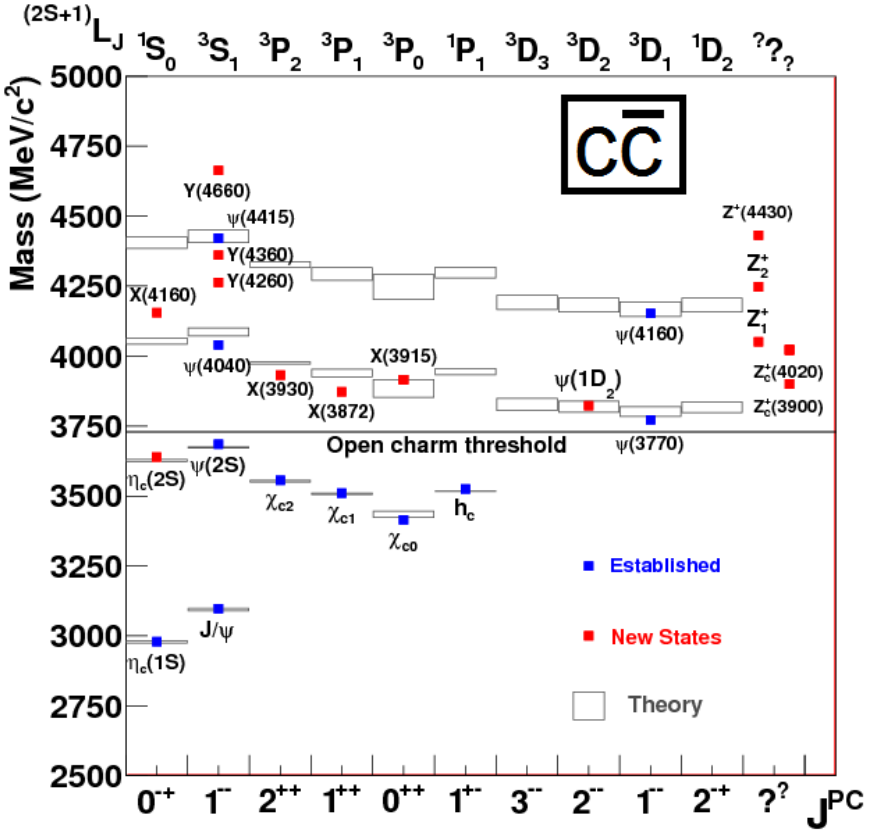
$D^* \rightarrow \pi^{\pm} D^0(K^{\mp}\pi^{\pm})$

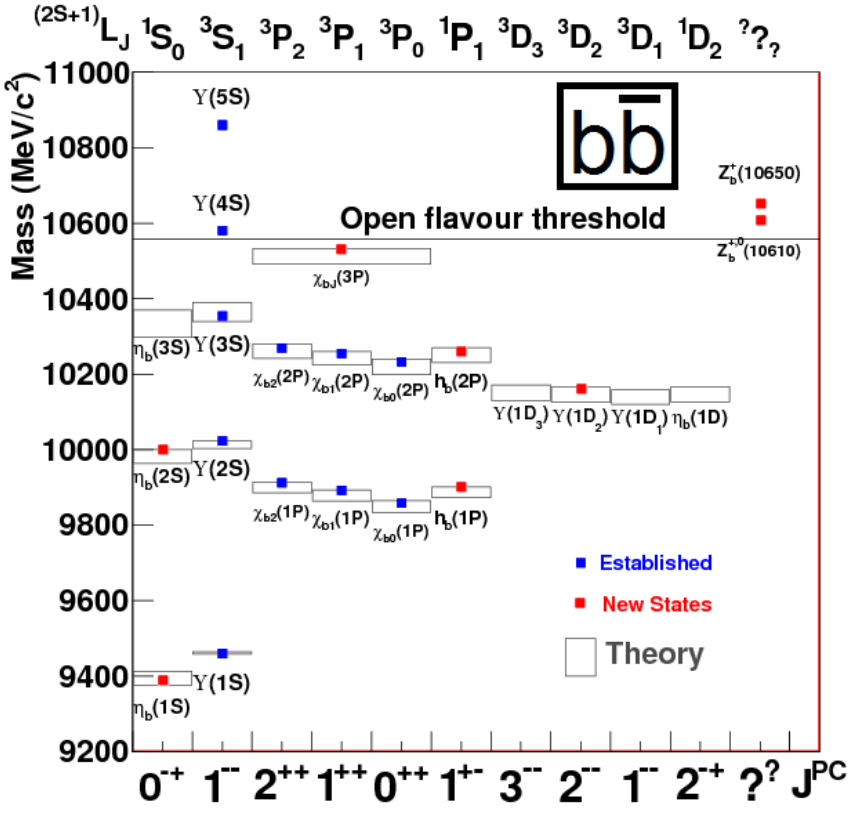


- Also indications for η, Λ, K*, ϕ, ...

QUARKONIUM AND EXOTICS

Quarkonium Spectroscopy Progress

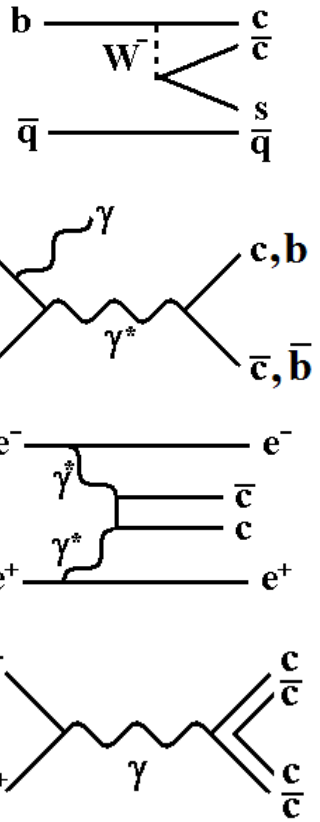




- First discoveries of long-predicted conventional quarkonia
- Many discoveries are difficult to explain by quarkonium model
- Several states have non-zero charge, cannot be a $c\bar{c}$/$b\bar{b}$ pair

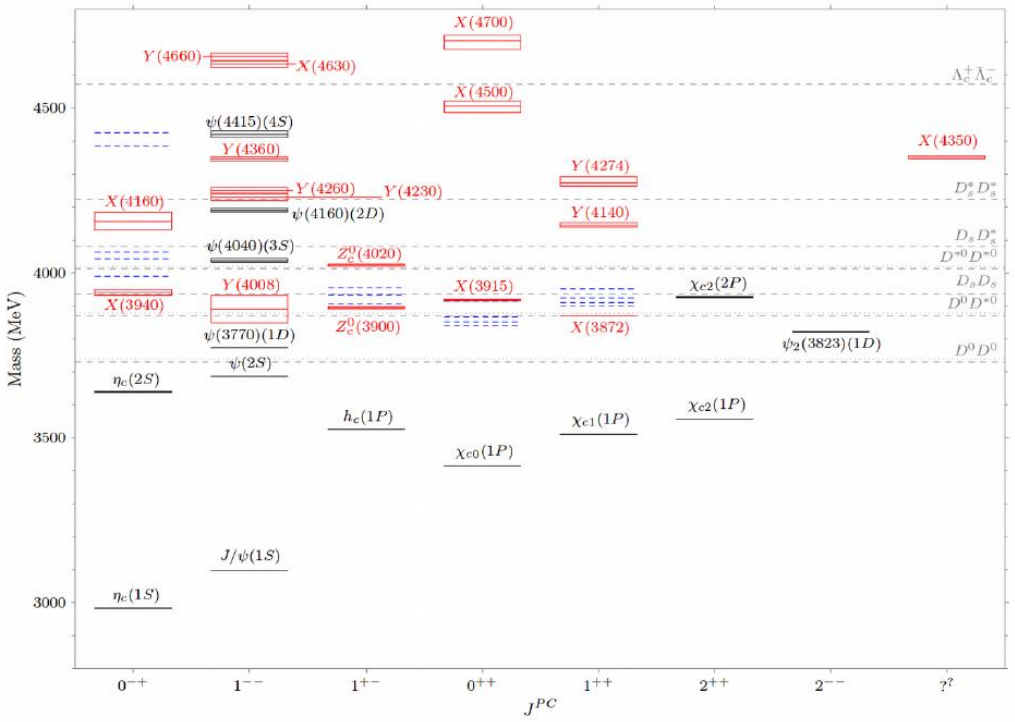
Quarkonium production at e^+e^- colliders

- B decays
  - Charmonium only
  - All quantum numbers available
- Direct production / Initial State Radiation (ISR)
  - E_{CM} or below
  - $J^{PC}=1^{--}$
- Two-photon interaction
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$
- Double charmonium production
  - Seen for $J^{PC}=1^{--}$ (J/ψ, $\psi(2S)$) plus J=0 states
- Quarkonium transitions
  - Hadronic/radiative decays between states



Charmonium(-like) Overview

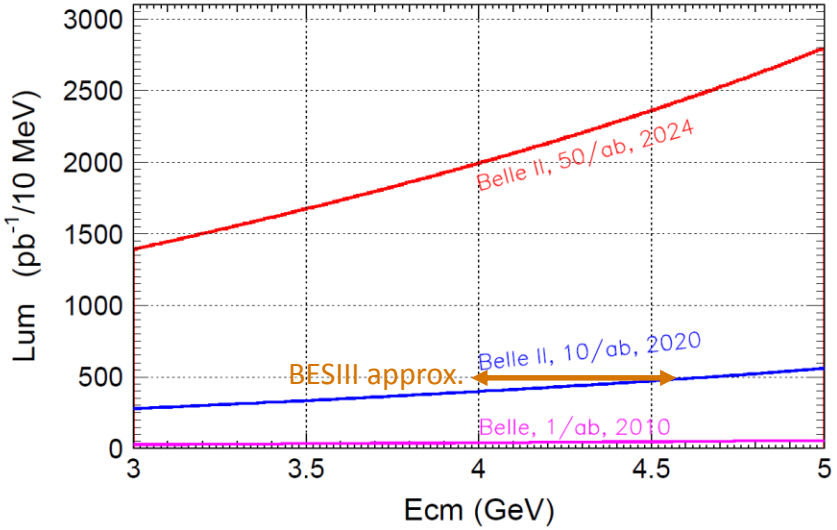
- Charmonium system
  - Many states/overpopulation
  - Several in one process/mode
  - Limited statistics

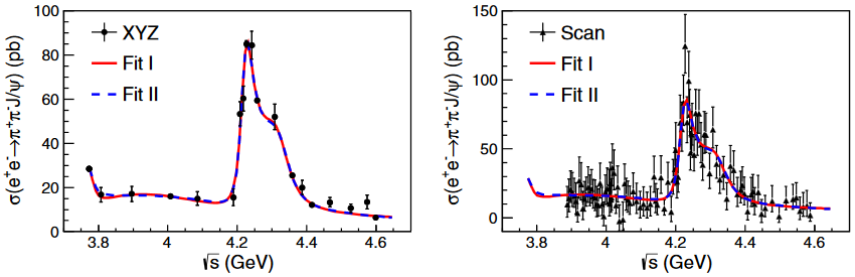


- Belle II prospects
  - Competition from LHCb (B decays) and BESIII (scans for 1^{--} states)
  - Exploit unique production methods: ISR, double charmonium, two-photon
  - Require large statistics samples
  - Not necessarily restricted by E_{CM}

ISR Charmonium

- ISR gives access to: lineshape of vector states, decays of vector exotica
  - Y(4220), Y(4320), Y(4360), Y(4660): many nearby peaks and final states





BESIII, PRL 118, 092001 (2017)

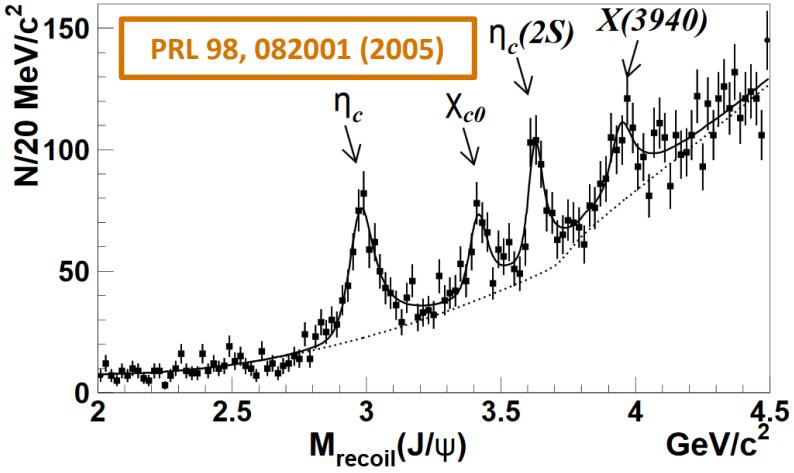
- Belle II @ 50ab^{-1}
  - Wider range of energies
  - Y(4260) lineshape
  - Strange partner of Z_c

- Modes of interest

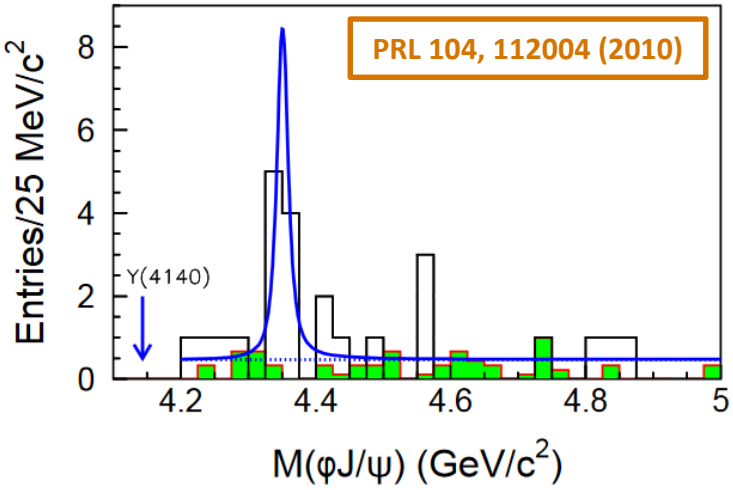
Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^- \psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$,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

Other Charmonium Production

- Measureable only at Belle II
- Double charmonium
  - $e^+e^- \to c\bar{c}\ (0^{+/-})\ c\bar{c}\ (1^{-/+})$



- Two-photon fusion
  - $e^+e^- \to c\bar{c}\ (0^{-/+}, 2^+)\ e^+e^-$



- Belle II prospects
  - angular distributions, production
  - probe for new states
  - χ_c and η_c recoil to study 1^{--}
  - Disentangle $\phi J/\psi$ states
  - $\chi_{c0,2}(2P)$ properties

Bottomonium(-like) Overview

- Important past B-Factory contributions
  - Bottomonium spectroscopy: discovery of η_b, h_b
  - Anomalous $\pi\pi$ and η transitions
  - Discovery of Z_b, exotic nature of above-threshold Υ states
- Most results from operation at non-$\Upsilon(4S)$ energies

Existing datasets in fb^{-1} (M events)

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5

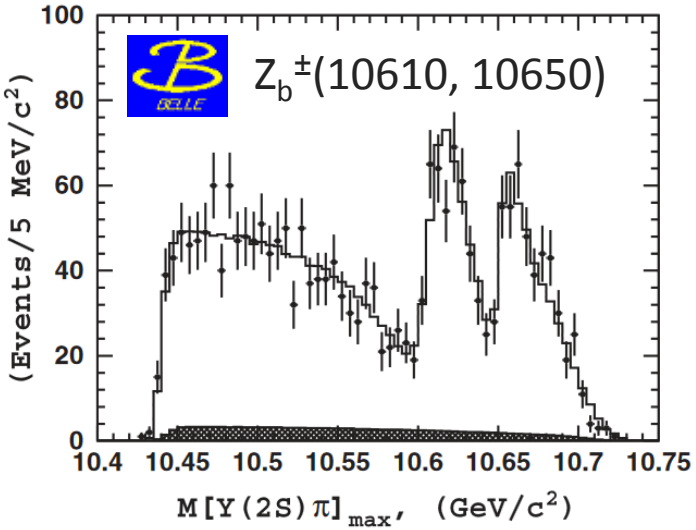
- Expect additional samples to be collected at Belle II
- Existing B-Factories ~1.5 ab^{-1} @ $\Upsilon(4S)$: opportunity for non-B physics results in early operation?

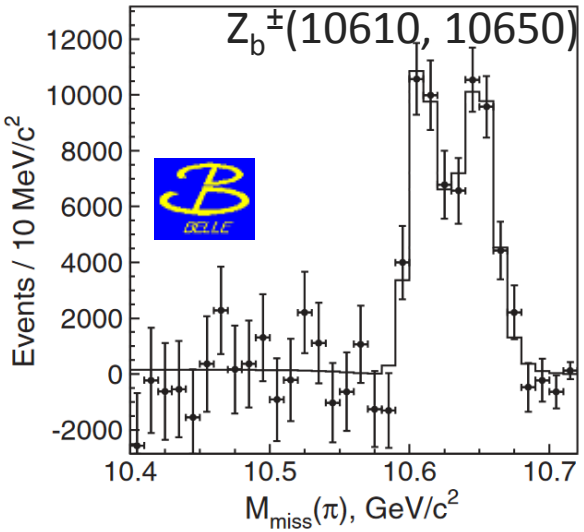
Potential Belle II Bottomonium Scenarios

- Above $\Upsilon(4S)$
  - Study of exotic four-quark states
  - $<6 fb^{-1}$ accumulated by Belle at $E_{CM}=\Upsilon(6S)$
  - $1\ ab^{-1}$ @ $\Upsilon(5S)$ = order of magnitude increase (also B_s physics)
  - $100\ fb^{-1}$ @ $\Upsilon(6S)$ plus ~$400\ fb^{-1}$ scan
- Below $\Upsilon(4S)$
  - Bottomonium search/study
  - New Physics in decays
  - Scan for direct production of $\Upsilon(n^3D_1)$
  - $300 fb^{-1}$ @ $\Upsilon(3S)$ = order of magnitude increase
- Dedicated operation <5% of total luminosity

$Z_b^{\pm}$ states in the bottomonium system

- Anomalous dipion transition rate: $\Upsilon(5S) \to \pi\pi\, b\bar{b}$
- Discovery of $h_b(1P, 2P)$, $\eta_b(2S)$, **indication of charged $Z_b^{\pm}$ states**
- $\Upsilon(5S) \to \pi^{\mp} Z_b^{\pm} \to \pi^{\pm}\Upsilon(1S,2S,3S)$ and $Z_b^{\pm} \to \pi^{\pm} h_b(1P,2P)$
- **Analogous to Y(4260) decays and $Z_c^{\pm}$ in charmonium system!**



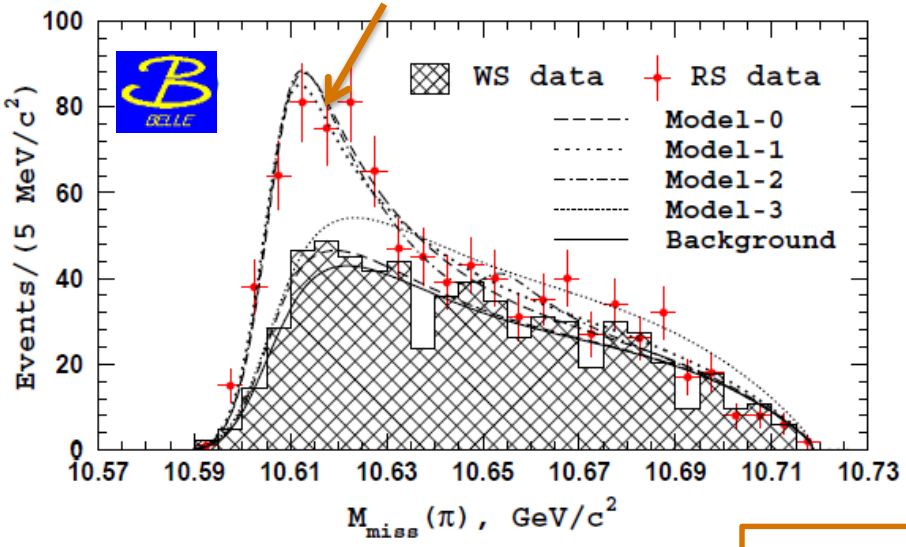


PRL 108, 122001 (2012)

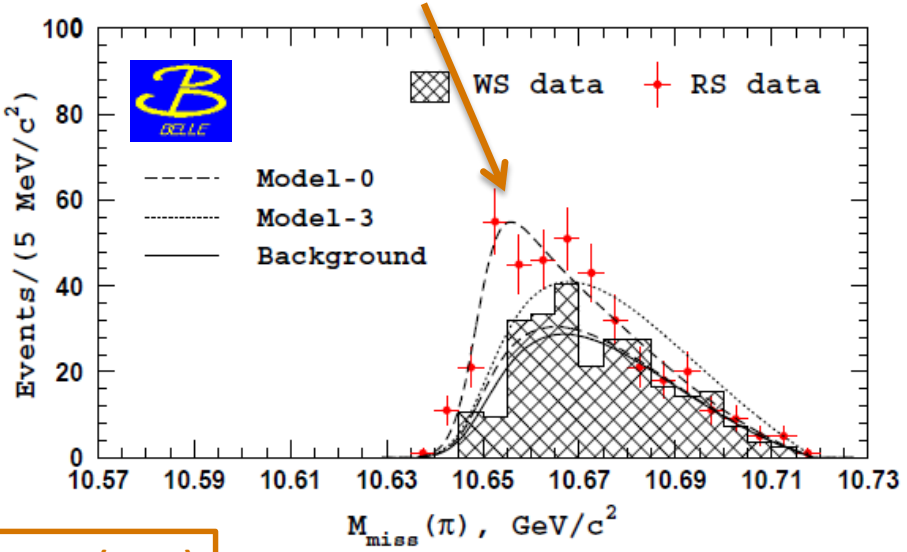
$Z_b^{\pm}$ states in the bottomonium system

- Decays to $B^{(*)}B^*$ dominate

$Z_b(10610) \to B\bar{B}^*$



$Z_b(10650) \to B^*\bar{B}^*$



PRL 116, 212001 (2016)

- Z_b masses ~equal to $B^{(*)}B^*$ thresholds?

$Z_b^{\pm}$ states from $\Upsilon(6S)$ decays

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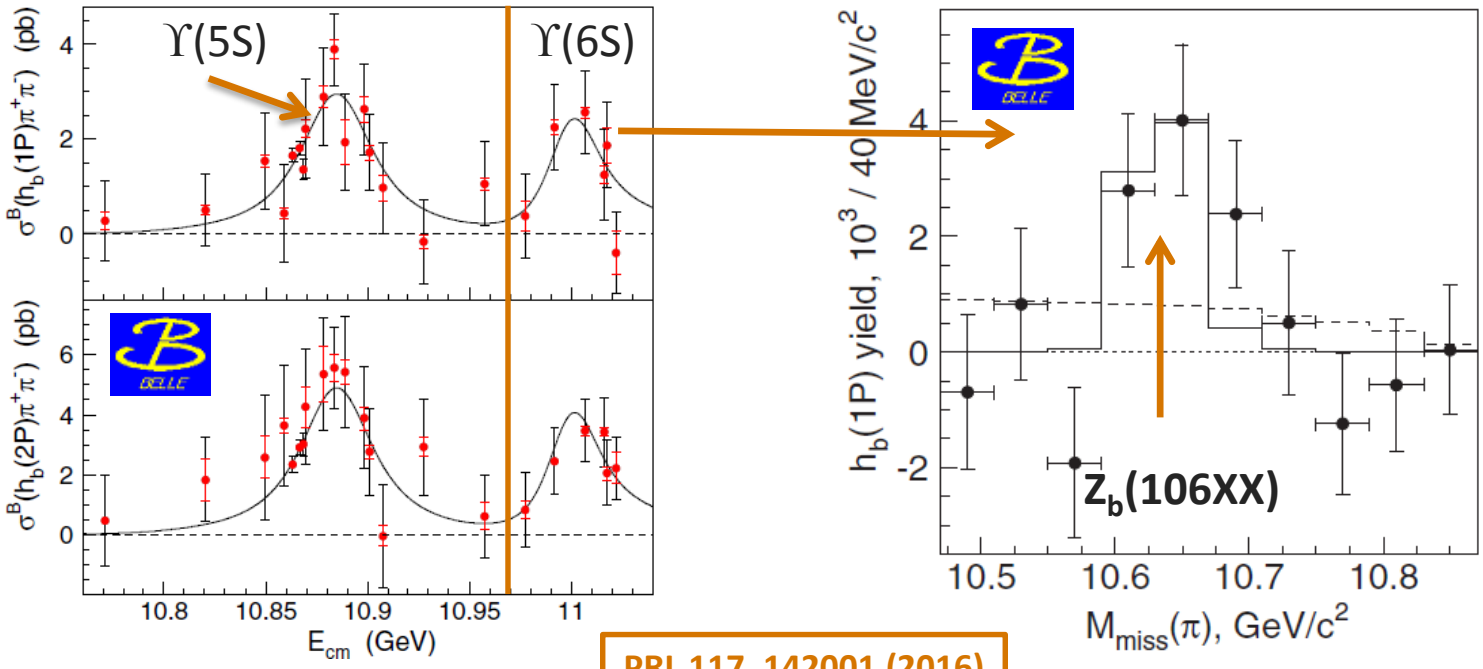
- Belle energy scan up to $\Upsilon(6S)$, search for $\Upsilon(6S) \to \pi^+\pi^- h_b(1P,2P)$ decays



- Enhanced transition rate, similar to $\Upsilon(5S)$ scenario
- Observation of $Z_b(106XX)$ states, but unable to resolve them

Υ(6S): Belle II Objectives

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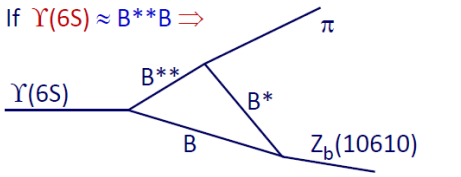
"New States"

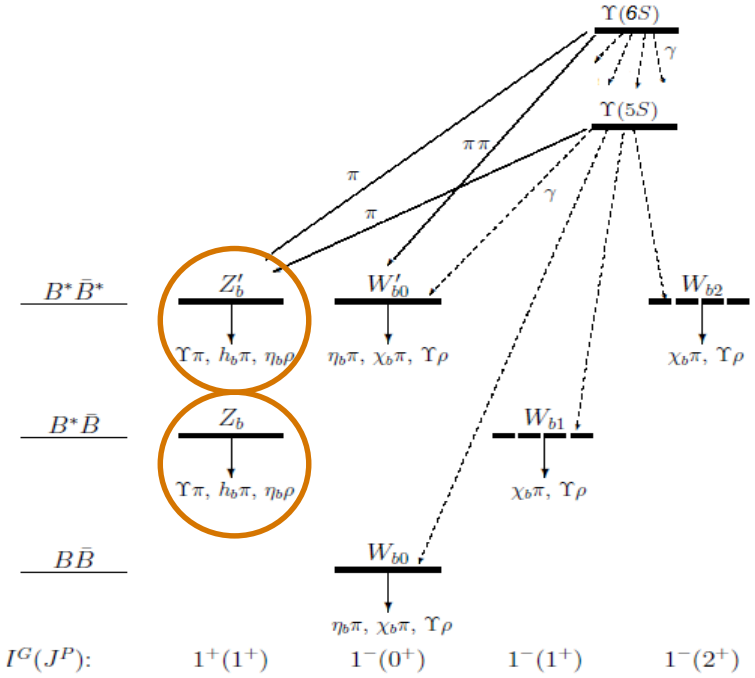
- Understand $\Upsilon(6S) \rightarrow Z_b$ decay
  - $\Upsilon(6S) \rightarrow \pi^+\pi^- h_b(1P,2P)$
  - $\Upsilon(6S) \rightarrow \pi^+\pi^- \Upsilon(1S,2S,3S)$ (+ $\ell^+\ell^-$ exclusive)
  - Also with $\pi^o\pi^o$?

- Evidence Z_b is a molecular state
- Should have partners ("W_b")
- Potential searches
  - $\Upsilon(5S, 6S) \rightarrow \gamma\, W_{b0}$
  - $\Upsilon(6S) \rightarrow \pi^+\pi^-(\rho)\, W_{b0}$ possible?
  - $W_{b0} \rightarrow \eta_b\pi,\ \chi_b\pi,\ \Upsilon\rho$

Voloshin, PRD 84, 031502 (2011)



no way to produce B*B* molecule = $Z_b(10650)$



Υ(6S): Belle II Objectives

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Quarkonia Transitions

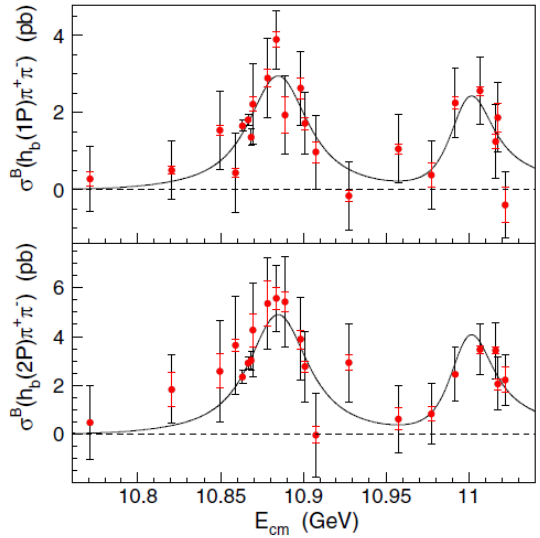
- Analogies to Υ(5S) evidence/observations at Belle
  - $\Upsilon(6S) \to \pi^+\pi^- \Upsilon(n^3D_J)$ (n=1 or 2)
  - $\Upsilon(6S) \to \eta\, \Upsilon(pS)$ and $\eta\, \Upsilon(n^3D_J)$ (n=1)
  - $\Upsilon(6S) \to \omega\, \chi_b(1P)$
  - $\Upsilon(6S) \to K^+K^- \Upsilon(1S)$
  - Inclusive and exclusive searches for all of the above
- Understand the nature of above-threshold Υ(mS) states

Bottomonium Discovery

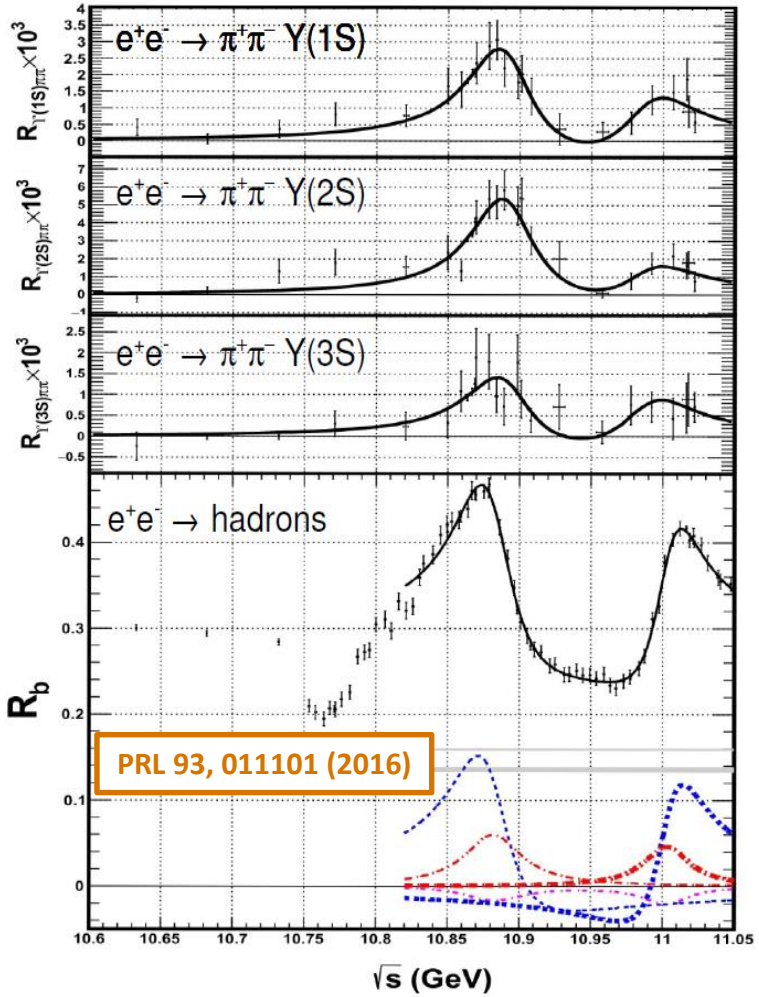
- Υ(6S) phase space opens possibility for first discovery:
  - h_b(3P): $\Upsilon(6S) \to \pi^+\pi^- h_b(3P)$
  - Y(2D): $\Upsilon(6S) \to \pi^+\pi^- \Upsilon(2D)$ or $\to \eta\, \Upsilon(2D)$
  - 1F bottomonium multiplet via dipion transition?

Above $\Upsilon(4S)$ Scan

- Other $B^{(*)}\overline{B}^{(*)}$ thresholds show potential
  - R_b dip versus $\pi\pi\Upsilon$ rise
  - Similar features as charm thresholds?
  - Sign of "Y_b" state near ~10.75 GeV?
- Previous scans <1 fb^{-1} per point



PRL 117, 142001 (2016)

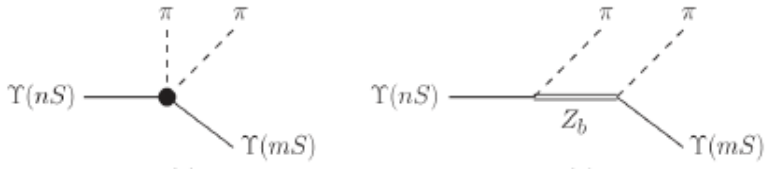


PRL 93, 011101 (2016)

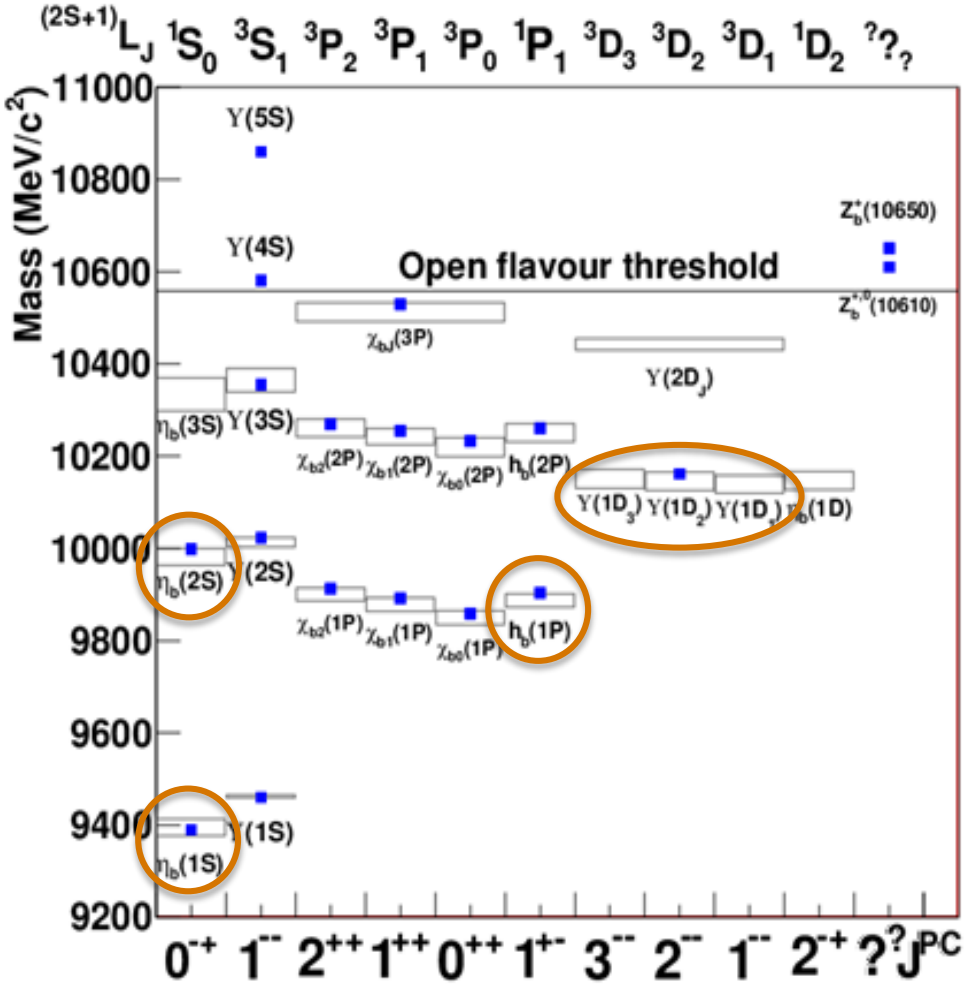
- 10MeV steps of 10 fb^{-1} to understand entire region, measure final state σ

Υ(3S) On-Resonance: Bottomonium physics

- **300fb^{-1} ~10xBaBar (Phase 3+)**
- Focus on conventional $b\bar{b}$ physics
  - $\Upsilon(1^3D_J)$ triplet: discover J=1,3
  - η_b(1S,2S): confirm m(η_b(1S,2S))
  - Hadronic (π^0,$\pi^+\pi^-$,η, ω) decays
  - Radiative transitions
- Z_b^+ exotic contributions?



- BSM physics
  - Υ(1S, 2S) $\rightarrow$ invisible
  - $\chi_{b0} \rightarrow \tau\tau$ light Higgs search
  - Dark sector $\gamma\chi\bar{\chi}$ decays



CONCLUSIONS

Conclusions

- SuperKEKB / Belle II upgrade status
  - Accelerator commissioning ongoing, collisions are happening!
  - Nominal start early 2019
- Next generation flavor factory
  - At least 50 times more data and improved detector capabilities
  - Search for New Physics via high-statistics precision measurement
- Potential for understanding exotic hadrons and quarkonium
  - Unique production methods to probe charmonium(-like) system
  - Only experiment able to address nature of bottomonium(-like) states

Conclusions

- SuperKEKB / Belle II upgrade status
  - Accelerator commissioning ongoing, collisions are happening!
  - Nominal start early 2019
- Next generation flavor factory
  - At least 50 times more data and improved detector capabilities
  - Search for New Physics via high-statistics precision measurement
- Potential for understanding exotic hadrons and quarkonium
  - Unique production methods to probe charmonium(-like) system
  - Only experiment able to address nature of bottomonium(-like) states

Thank you for your attention, and stay tuned!