Perspectives on spectroscopy study at Belle II

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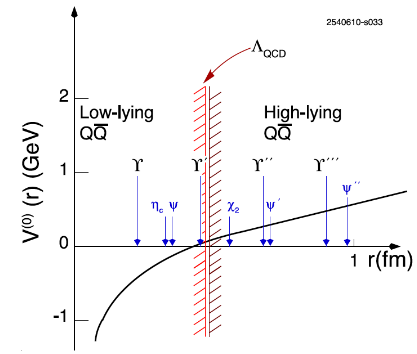
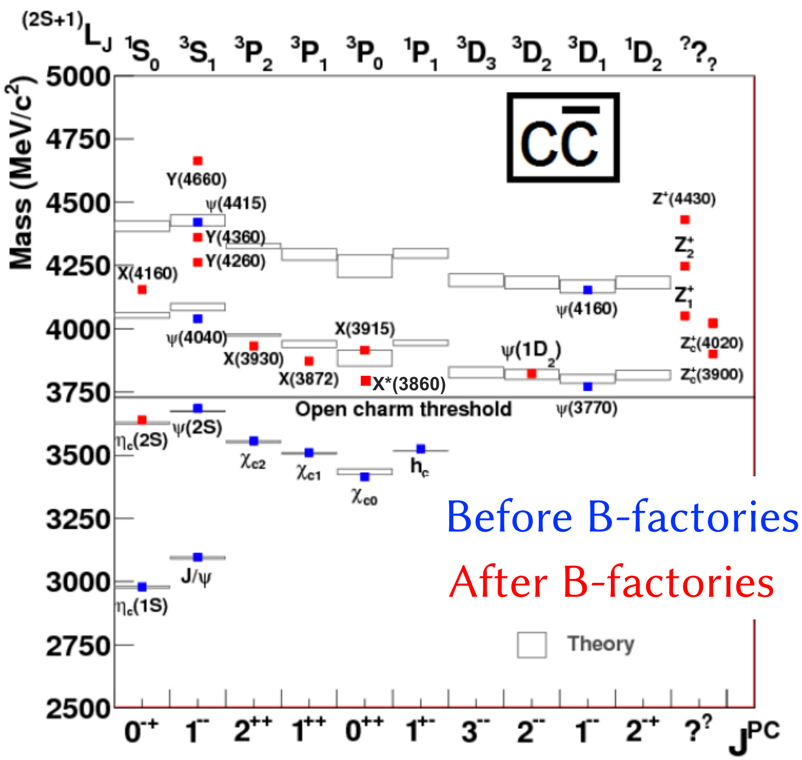
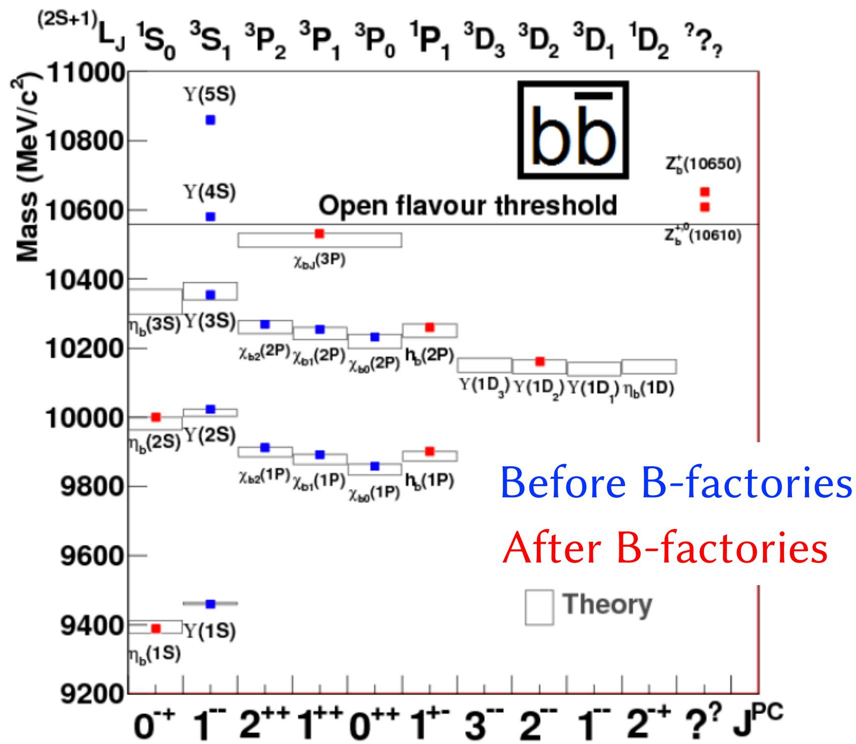
Quarkonium 2017 @ Peking University, 6-10 Nov 2017

Spectroscopy of heavy quarkonia

- Heavy quarkonium: bound states of $c\bar{c}$ or $b\bar{b}$
  - Treated with NRQCD due to the heavy c/b mass
  - Tests of perturbative and non-perturbative QCD
- B-factories did great job in establishing the long awaited states and finding surprises in exotic quarkonium-like states

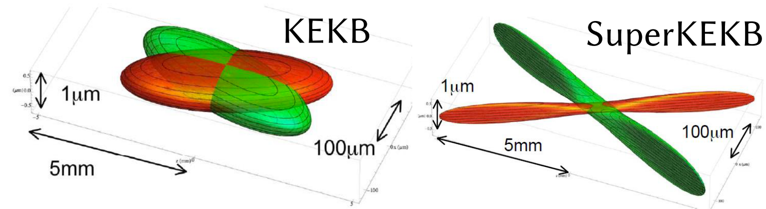


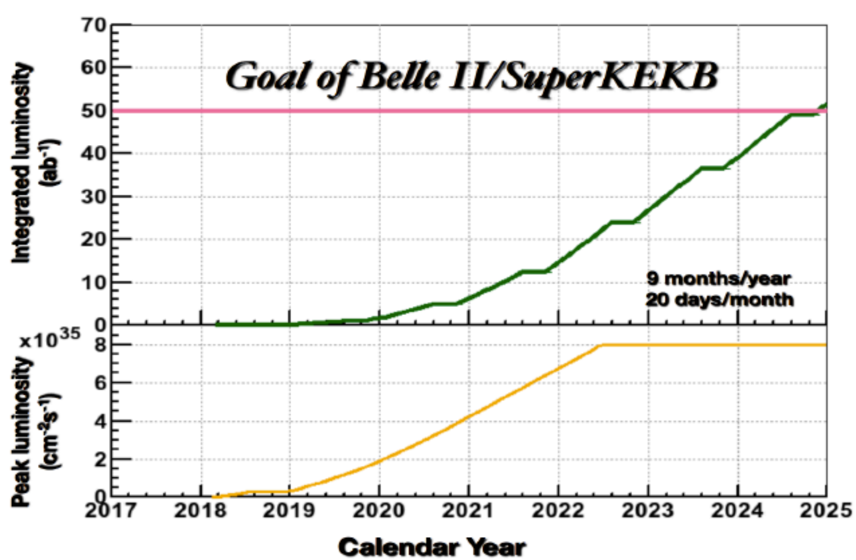


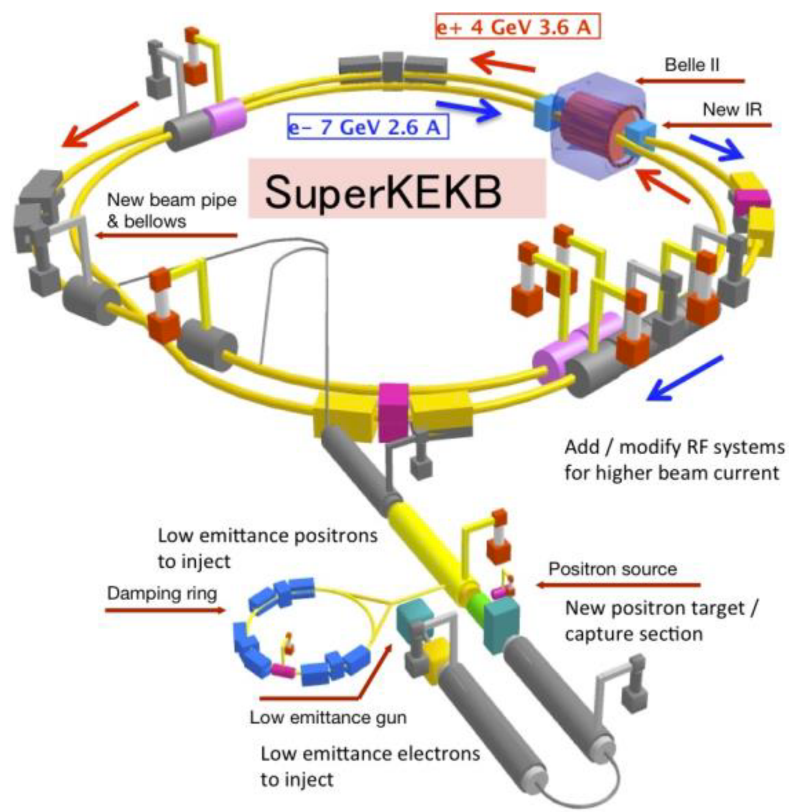


Belle @ KEKB → Belle II @ SuperKEKB

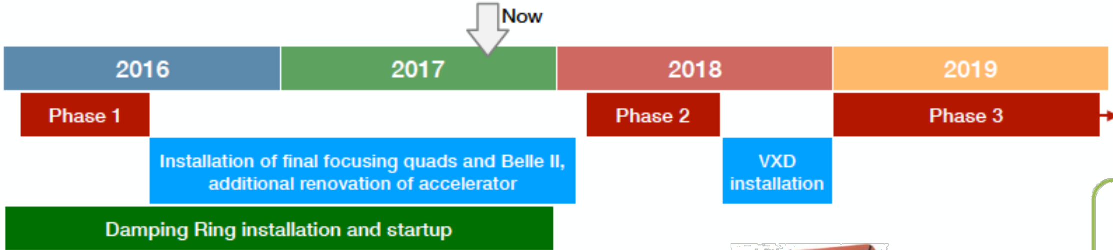
- 40 times increase in luminosity!
  - $2.1 \times 10^{34} \rightarrow 8 \times 10^{35}$ cm^{-2}s^{-1}.
- E(e-) 7.0 GeV, E(e+) 4.0 GeV
- Targeted L_{int} = 50 ab^{-1}. (Belle ~1ab^{-1})

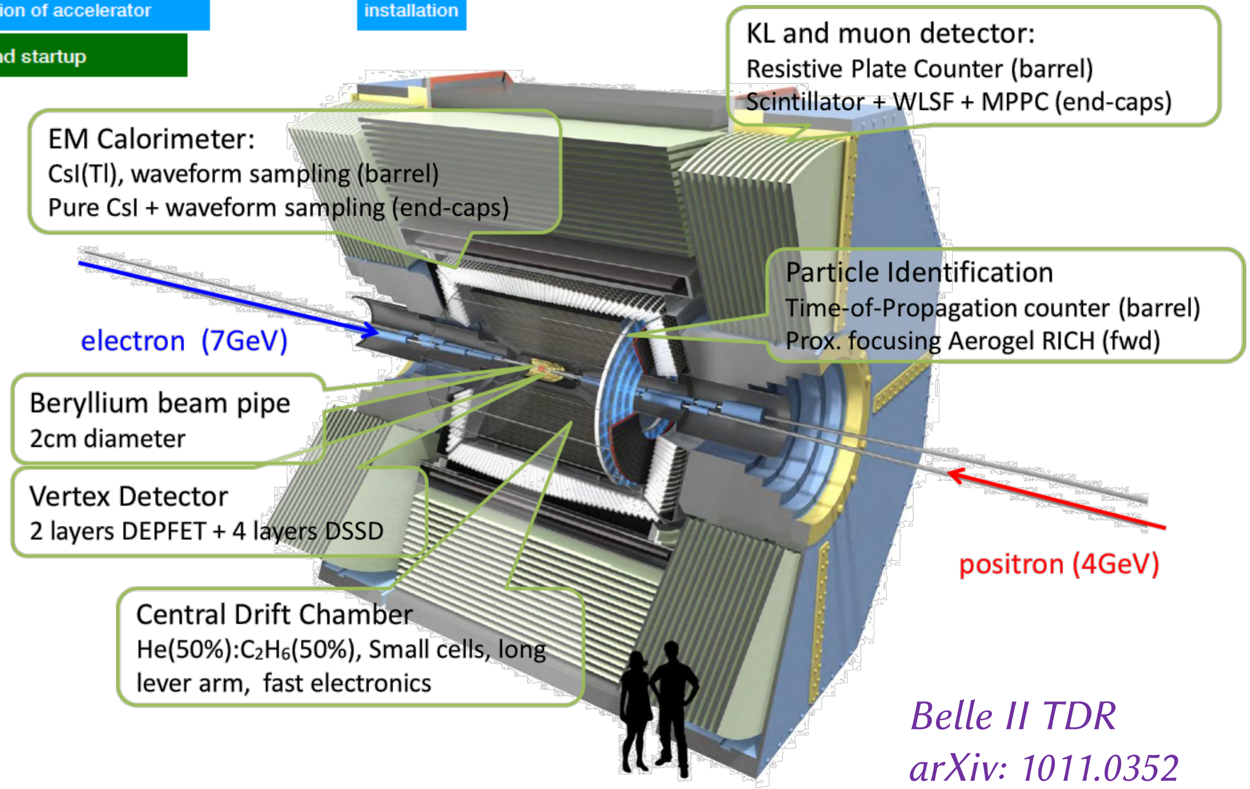






Belle II detector





Belle II TDR
arXiv: 1011.0352

More info & status: YE Hua's talk "Status of Belle II and SuperKEKB"

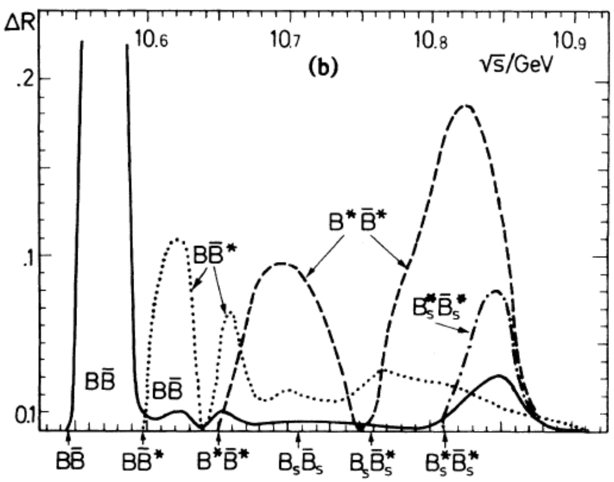
- Better vertexing; Improved PID capability; Fast data-acquisition…

Bottomonia(-like)

Scan above Υ(4S)

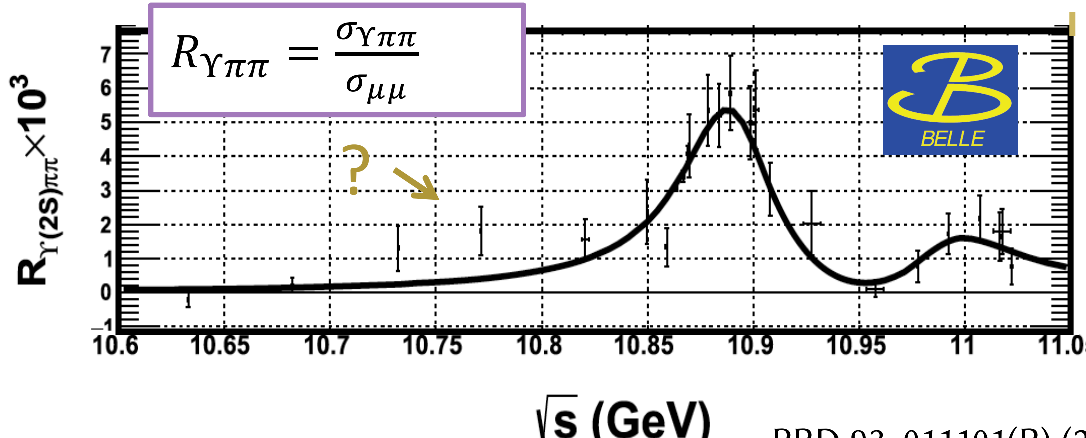
- Total cross-section above BB threshold have been measured in $\Upsilon(nS)\pi\pi$ and $B_s^{(*)}\bar{B}_s^{(*)}$
  - R_b dip vs. $\Upsilon\pi\pi$ bump
  - Sign of Y_b states?
- Expected study: $BB, BB^*, B^*B^*(\pi), \Upsilon\pi\pi, \Upsilon\eta$, especially at 10.65, 10.75 GeV.

$$R_b = \frac{\sigma(ee \to hadron)}{\sigma_{\mu\mu}}$$



Törnqvist, PRL 53, 878 (1984)

$$R_{\Upsilon\pi\pi} = \frac{\sigma_{\Upsilon\pi\pi}}{\sigma_{\mu\mu}}$$

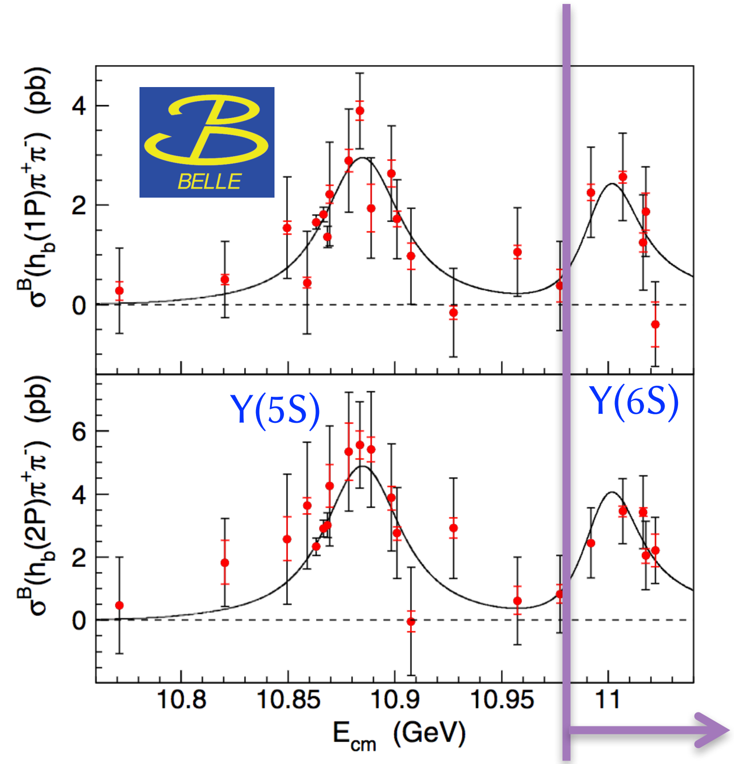


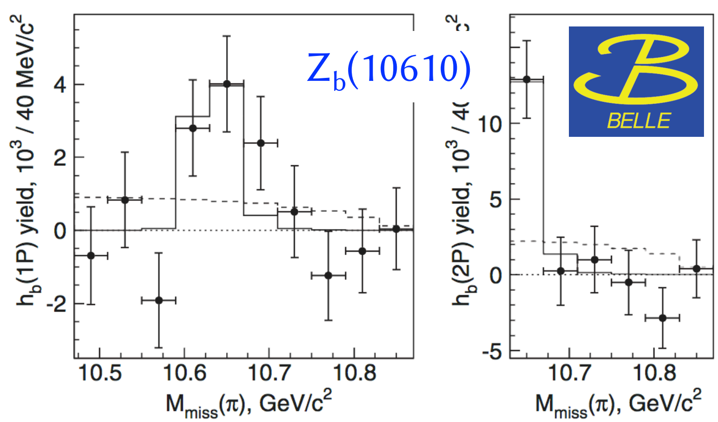
PRD 93, 011101(R) (2016)

Z_b in $\Upsilon(6S)$

- Charged Z_b^+ state is observed in $\Upsilon(5S) \to \pi[\pi\Upsilon]/\pi[\pi h_b]$
- Evidence of $\Upsilon(6S) \to \pi^+\pi^- h_b(nP)$, via $Z_b(10610)$ or $Z_b(10650)$
- Statistics is not large enough to distinguish contributions from the two states

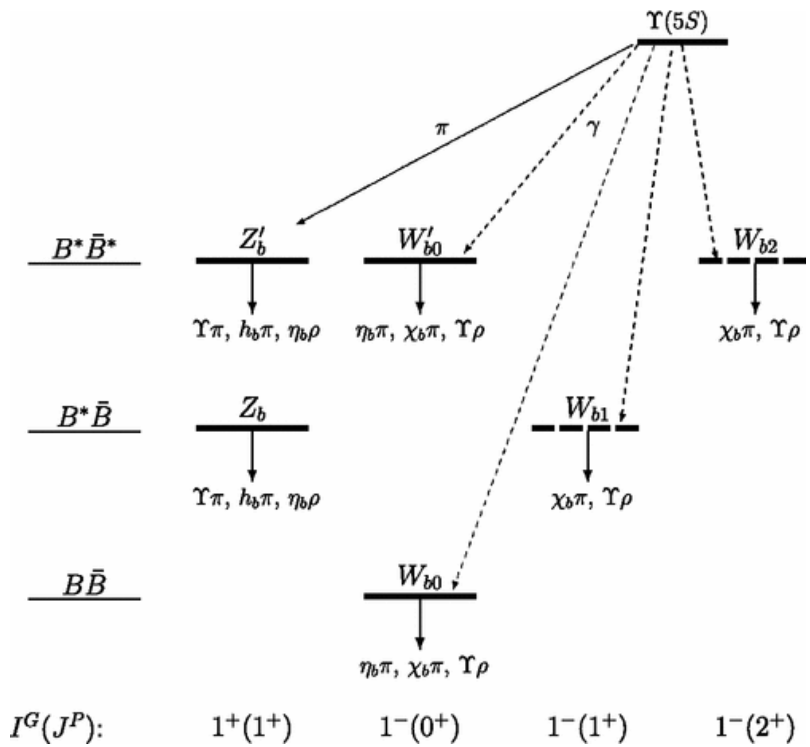
- More data needed for this FS and other possibilities:
  - $\Upsilon(6S) \to \pi^+\pi^-\Upsilon(mS)$, $\pi^+\pi^- h_b(nP)$
  - With $\pi^0\pi^0$





Z_b in $\Upsilon(6S)$

- $Z_b(10610)$ and $Z_b(10650)$ also found in $B\bar{B}^*$ and $B^*\bar{B}^*$ final states, respectively
- For molecular bottomonia interpretation, Z_b has neutral partners W_b
- Potential searches:
  - $\Upsilon(6S) \to \gamma\, W_b$
  - $\Upsilon(6S) \to \pi^+\pi^- W_b / \rho\, W_b$
  - $W_b \to \eta_b \pi,\ \chi_b \pi, \Upsilon\rho$



Voloshin, PRD 84, 031502 (R)

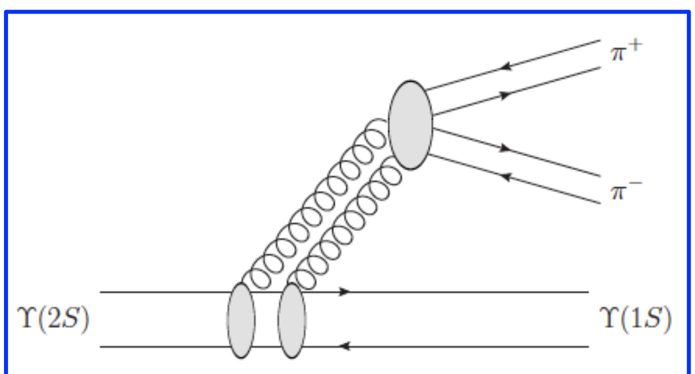
Hadronic transition of Υ(5S) and Υ(6S)

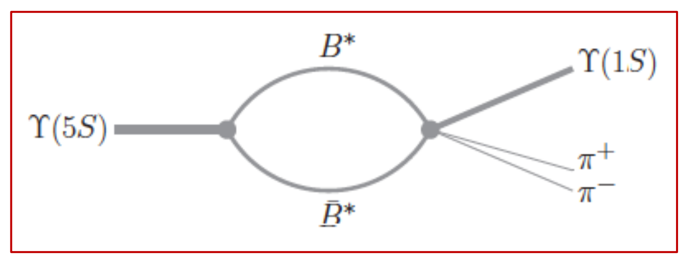
- For bottomonium states above BB threshold, hadronic transitions suppressed by Heavy Quark Spin Symmetry are enhanced

- Could be explained if the Υ states are not pure $b\bar{b}$ but a "molecular" admixture of meson pairs

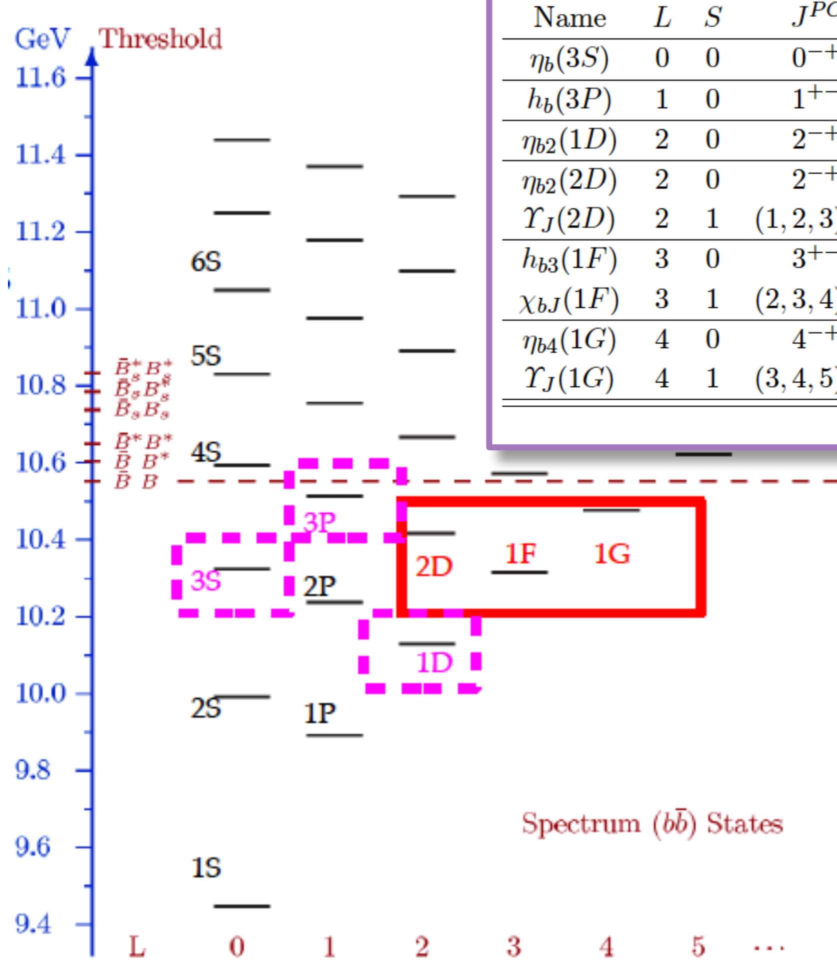
State	Decomposition into $b\bar{b}$ spin eigenstates
$B\bar{B}$	$\frac{1}{2\sqrt{3}}\,\psi_{10} + \frac{1}{2}\,\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\,\psi_{12} + \frac{1}{2}\,\psi_{01}$
$B\bar{B}^*$	$\frac{1}{\sqrt{3}}\,\psi_{10} + \frac{1}{2}\,\psi_{11} - \frac{\sqrt{5}}{2\sqrt{3}}\,\psi_{12}$
$(B^*\bar{B}^*)_{S=0}$	$-\frac{1}{6}\,\psi_{10} - \frac{1}{2\sqrt{3}}\,\psi_{11} - \frac{\sqrt{5}}{6}\,\psi_{12} + \frac{\sqrt{3}}{2}\,\psi_{01}$
$(B^*\bar{B}^*)_{S=2}$	$\frac{\sqrt{5}}{3}\,\psi_{10} - \frac{\sqrt{5}}{2\sqrt{3}}\,\psi_{11} + \frac{1}{6}\,\psi_{12}$

Spin eigenstate	Expected decays
ψ_{10}	$\Upsilon(nS)\,\pi^+\pi^-$, $\Upsilon(nS)\,K^+K^-$ in S wave
ψ_{11}	$\Upsilon(nS)\,\eta$, $\Upsilon(nS)\,\eta'$
ψ_{11}, ψ_{12}	$\Upsilon(nS)\,\pi^+\pi^-$, $\Upsilon(nS)\,K^+K^-$ in D wave
ψ_{01}	$\eta_b(nS)\,\omega$, $\eta_b(nS)\,\phi$, $h_b(nP)\,\eta$, $h_b(nP)\,\eta'$





Missing $b\bar{b}$ states below $B\bar{B}$ threshold

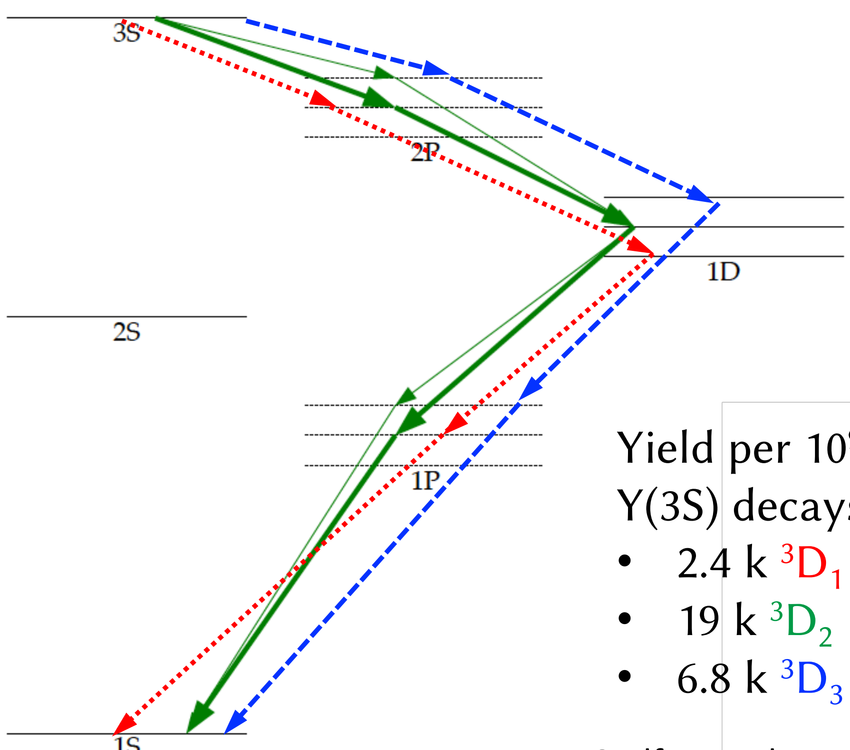


Name	L	S	J^{PC}	Mass, MeV/c^2	Emitted hadrons [Threshold, GeV/c^2]
$\eta_b(3S)$	0	0	0^{-+}	10336	ω [11.12], ϕ [11.36]
$h_b(3P)$	1	0	1^{+-}	10541	$\pi^+\pi^-$ [10.82], η [11.09], η' [11.50]
$\eta_{b2}(1D)$	2	0	2^{-+}	10148	ω [10.93], ϕ [11.17]
$\eta_{b2}(2D)$	2	0	2^{-+}	10450	ω [11.23], ϕ [11.47]
$\Upsilon_J(2D)$	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]

- Υ(6S) data at 11.02 GeV will open the door to some unestablished bottomonium states
  - $\Upsilon(6S) \to \pi\pi h_b(3P)$
  - $\Upsilon(6S) \to \pi\pi\Upsilon(2D)/\ \eta\Upsilon(2D)$
  - 1F triplet 2,3,4++ may be from 2D transition
- $\Upsilon(1D), \Upsilon(2D)$ can be searched in direct scan

Resolving Υ(1D) triplet in Υ(3S) decays

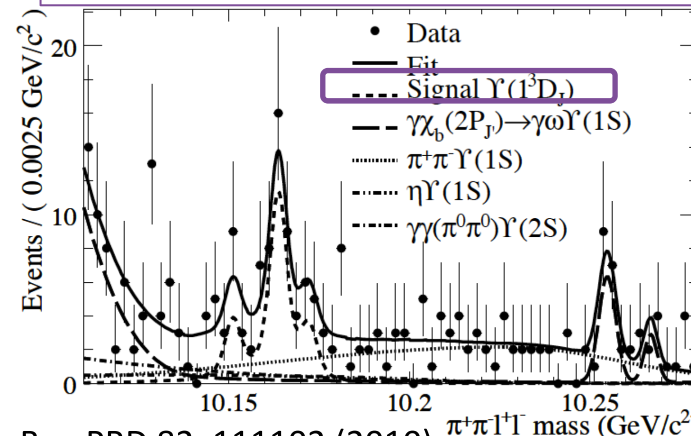
- Υ(1D) produced in Υ(3S) radiative decay
  - Followed by dipion decay to Υ(1S)
  - Four-gamma cascade



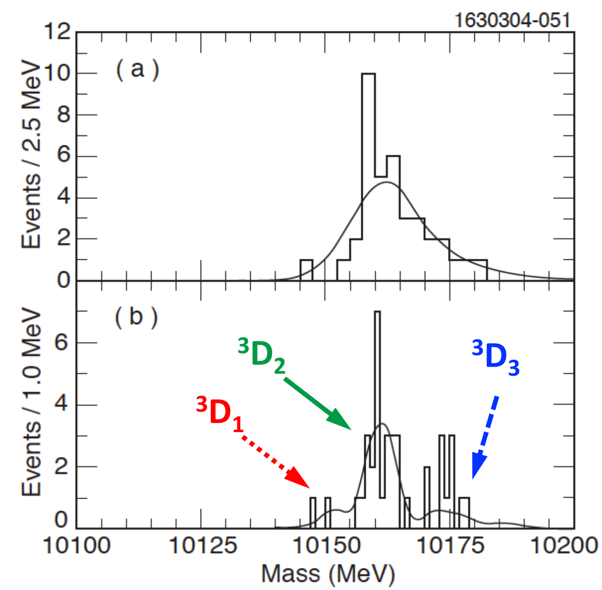
Yield per 10^9 Υ(3S) decays
- 2.4 k $^3D_1$
- 19 k $^3D_2$
- 6.8 k $^3D_3$

Godfrey and Moats, PRD 92, 054034 (2015)

$$\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_J) \to \gamma\gamma\pi^+\pi^-\Upsilon(1S)$$



BaBar, PRD 82, 111102 (2010)



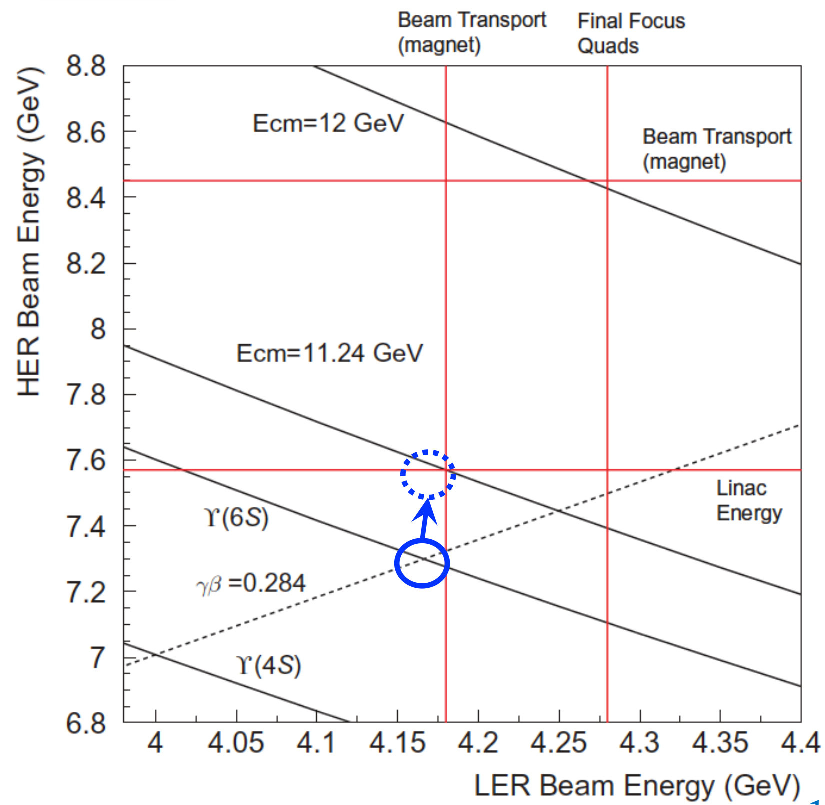
CLEO, PRD 82, 111102 (2010)

Planned data-points

Experiment	Scans Off. Res.	$\Upsilon(6S)$ fb^{-1}	$\Upsilon(5S)$ fb^{-1}	$\Upsilon(5S)$ 10^6	$\Upsilon(4S)$ fb^{-1}	$\Upsilon(4S)$ 10^6	$\Upsilon(3S)$ fb^{-1}	$\Upsilon(3S)$ 10^6	$\Upsilon(2S)$ fb^{-1}	$\Upsilon(2S)$ 10^6	$\Upsilon(1S)$ fb^{-1}	$\Upsilon(1S)$ 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

Y(6S) Yb? Y(2D) Y(1D)

- Above BB threshold
  - Detailed Z_b study at Y(6S) ~ 20/fb
  - Hadronic transition
  - Scan at higher energy (up to 11.24 GeV $\Lambda_b\overline{\Lambda_b}$ threshold)
- Below BB threshold
  - 200~300 /fb at Y(3S)
  - Scan of Y(1D) and Y(2D) regions



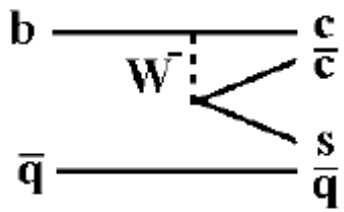
Production:

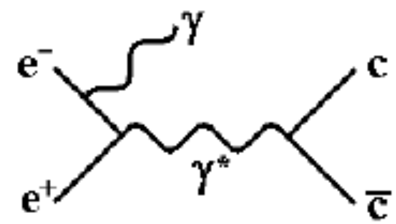
In B decays

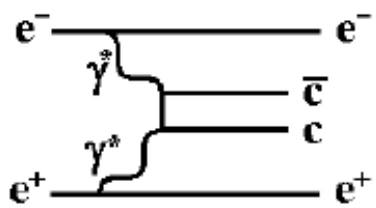
Direct production/ISR

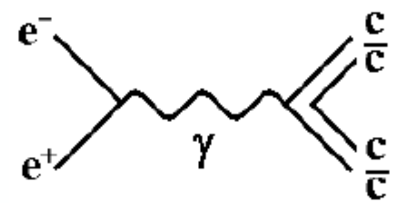
Photon production

Double charmonia production









Charmonium(-like) states

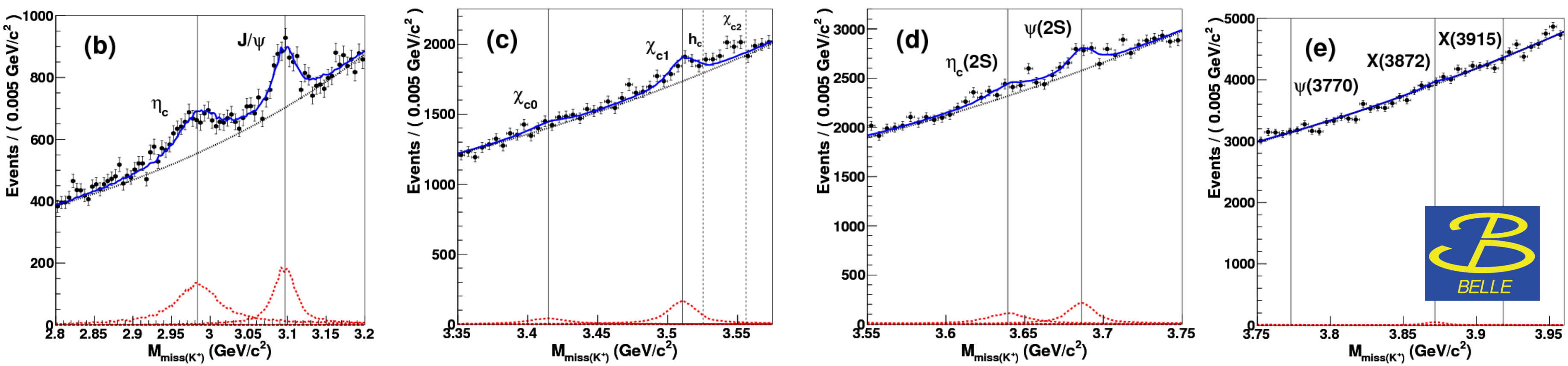
Charmonium-like exotics from B decays

- Amplitude analysis can be performed in B decays, thus the quantum number of exotic states could be determined
- With larger data sample, spin-parity of other exotic states is to be determined, especially for those observed in a single final state:
  - X(3915) in $B \to K\omega J/\psi$ (also interesting for X(3872)!)
  - Zc(4050), Zc(4250) in $B \to K\pi\chi_{c1}$
- Search for open flavour decays, esp. for candidates of molecules
  - $B \to KD\overline{D}, KD^*\overline{D}, KD^*\overline{D}^*$

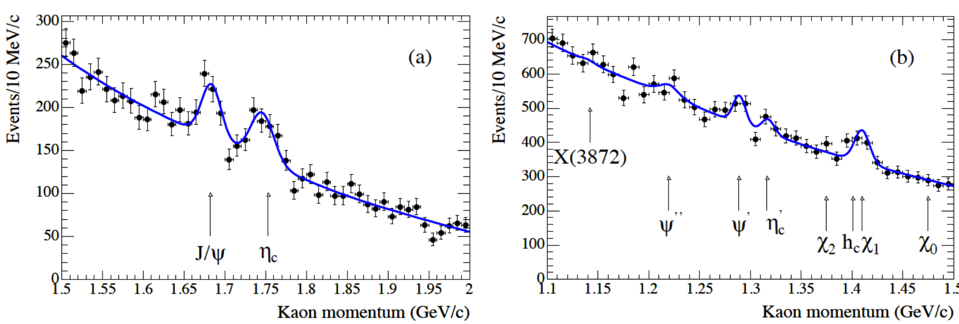
Charmonia in B decay – absolute BF

- Absolute BF of exotic states can be measured in $B \to KX$ via the missing mass recoiling against the kaon
- Initial momentum of the mother B can be determined by fully reconstructing the accompany $\bar{B}$

Unique at ee collider!



Belle, arXiv:1709.06108



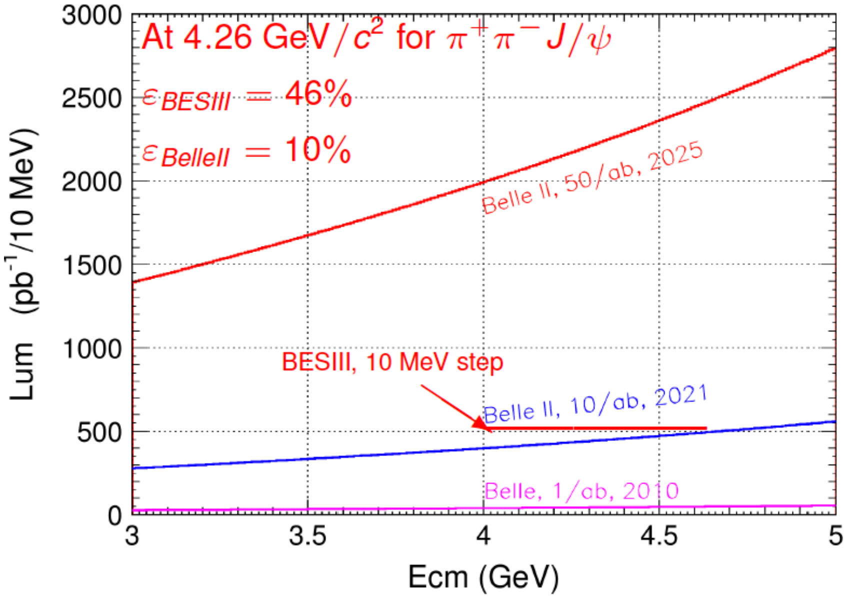
BaBar, PRL 96, 052002 (2006)

ISR

- Coverage of the full energy spectrum (line shape, fine structure…);
- Many simultaneous $\sqrt{s}$, point-to-point systematics small
- Lower efficiency (boost may help)

vs. direct production

- Higher luminosity at fixed $\sqrt{s}$;
- Better resolution;
- Much higher efficiency

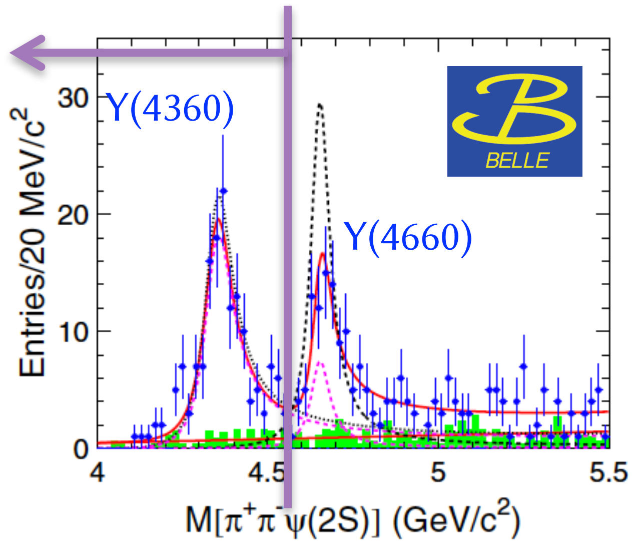


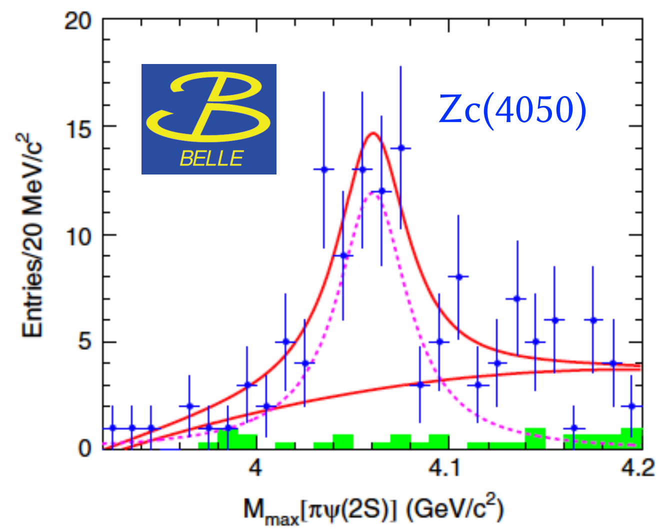
- Belle II can do ISR studies in
  - Charmonium + light hadrons
  - Charm meson pair (+light hadrons)

ISR with increased data sample at Belle II

- Charged Zc search:
  - Evidence of Zc(4050) found in Y(4360) → $\pi^+\pi^-\psi(2S)$, needs confirmation
- ISR production of charmonium + light hadrons in addition to $\pi\pi\psi$:
  - $\gamma X(3872)$; $\psi(4040), \psi(4160)$ into $\eta J/\psi$, $KK\psi$, ...
  - Charm meson pairs: $D\overline{D}, D\overline{D}^*(\pi)$, ...

PRD 91, 112007 (2015)





Golden channels of ISR

10 ab^{-1} by 2020

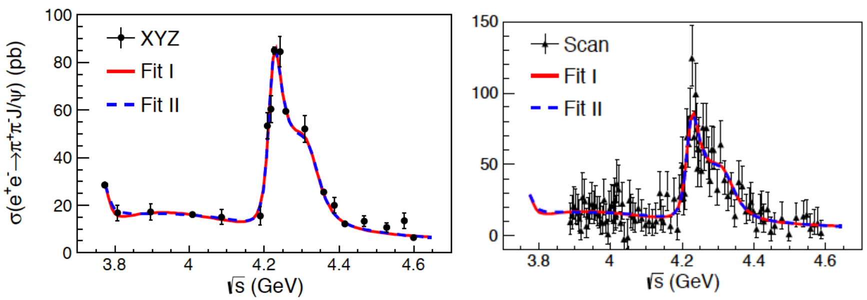
(50 ab^{-1} by 2024)

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)	$Y(4220)$

$e^+e^- \to \pi^+\pi^-J/\psi$:

- Line shape around 4.26 GeV? Confirm Y(4008)?
- Detailed study of charged Zc(3900)

With 10/ab the statistical uncertainty already competitive



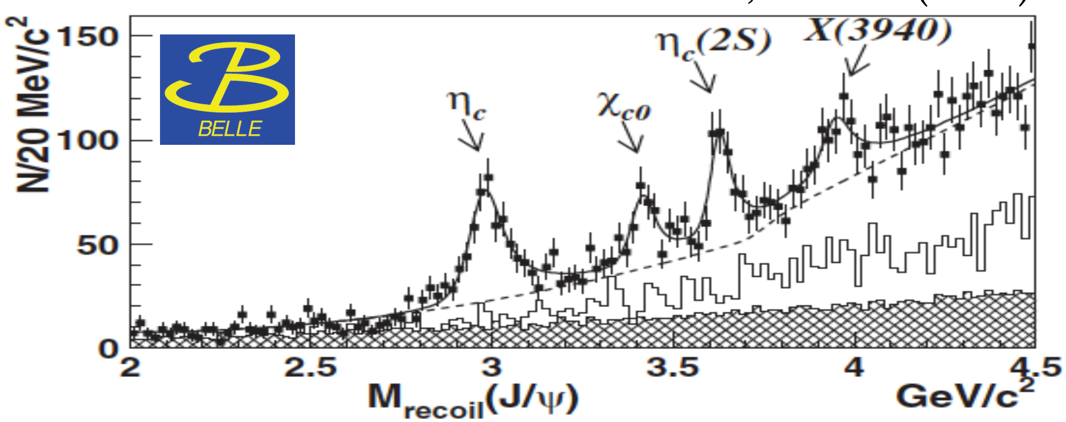
BESIII, PRL 118, 092001 (2017)

Dedicated ISR generator PHOKHARA has been implemented in Belle II framework

Double charmonium production

- $e^+e^- \to J/\psi\, X, X = c\bar{c}$
  - X can be studied using J/ψ recoil, especially for C-even states
  - X = conventional $c\bar{c}$, $\eta_c\,(1S, 2S)$; or = exotics: X(3940), X(4160), X*(3860)…
  - Decays of X can be further studied: $X(3940) \to D\bar{D}^*, X(4160) \to D^*\bar{D}^*$ found in $J/\psi D^*$ recoil

PRD 98, 082001 (2007)



A lot more to do at Belle II:

- Full list of the states accessible, with better accuracy eg. $\chi_{c0}(2P)$
- Angular analyses giving access to the ratio of different L contributions
- $e^+e^- \to \eta_c X$ / $\chi_c X$ … to be explored for the C-odd states!

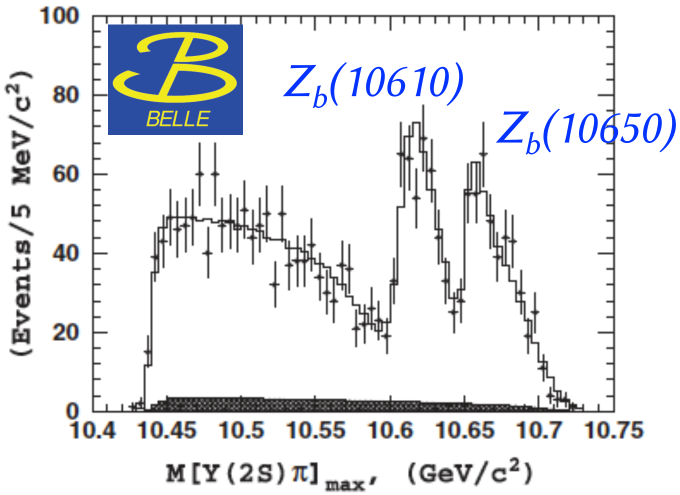
Summary

- Heavy quarkonium spectroscopy is an active field, and many unsolved puzzles on the nature of dozens of exotic states
- SuperKEK and Belle II experiment are on the track for physics data taking in 2018
  - Expecting a x40 higher luminosity and a x50 larger data sample
- Plenty of studies on spectroscopy using Belle II data
  - Bottomonia studies at high energy eg. Y(5S), Y(6S) starting soon in early data-taking
  - 200~300 fb^{-1} Y(3S) data-taking motivated
  - Charmonium(-like) states will be studied comprehensively in B decays, ISR and double production

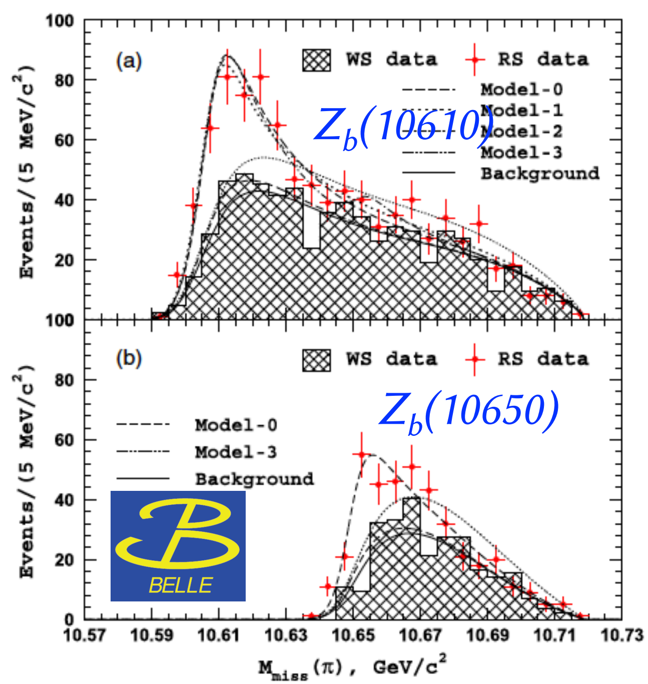
Backup

Observation of Z_b in $\Upsilon(5S)$ at Belle

- Charged Z_b^+ state is observed in $\Upsilon(5S)$
  - $\Upsilon(5S) \rightarrow Z_b^+\pi^- \rightarrow \Upsilon(nS)\pi^+\pi^- \,/\, h_b(mP)\pi^+\pi^-$, n=1,2,3, m=1,2
- Zb(10610) and Zb(10650) also found in $B\bar{B}^*$ and $B^*\bar{B}^*$ final states



PRL 108, 122001 (2012)



PRL 116, 212001 (2016)

Υ(3S) operation

- 200~300 fb^{-1} at or around Υ(3S) will enable many studies like:
  - Rare η transitions
  - Spectroscopy of D and F waves
  - Hindered (M1) radiative transitions
  - Antitritium and He-3 in Υ decays