Recent Results of Bottomonium Studies at Belle

Simon Eidelman

Budker Institute of Nuclear Physics SB RAS
and Novosibirsk State University,
Novosibirsk, Russia

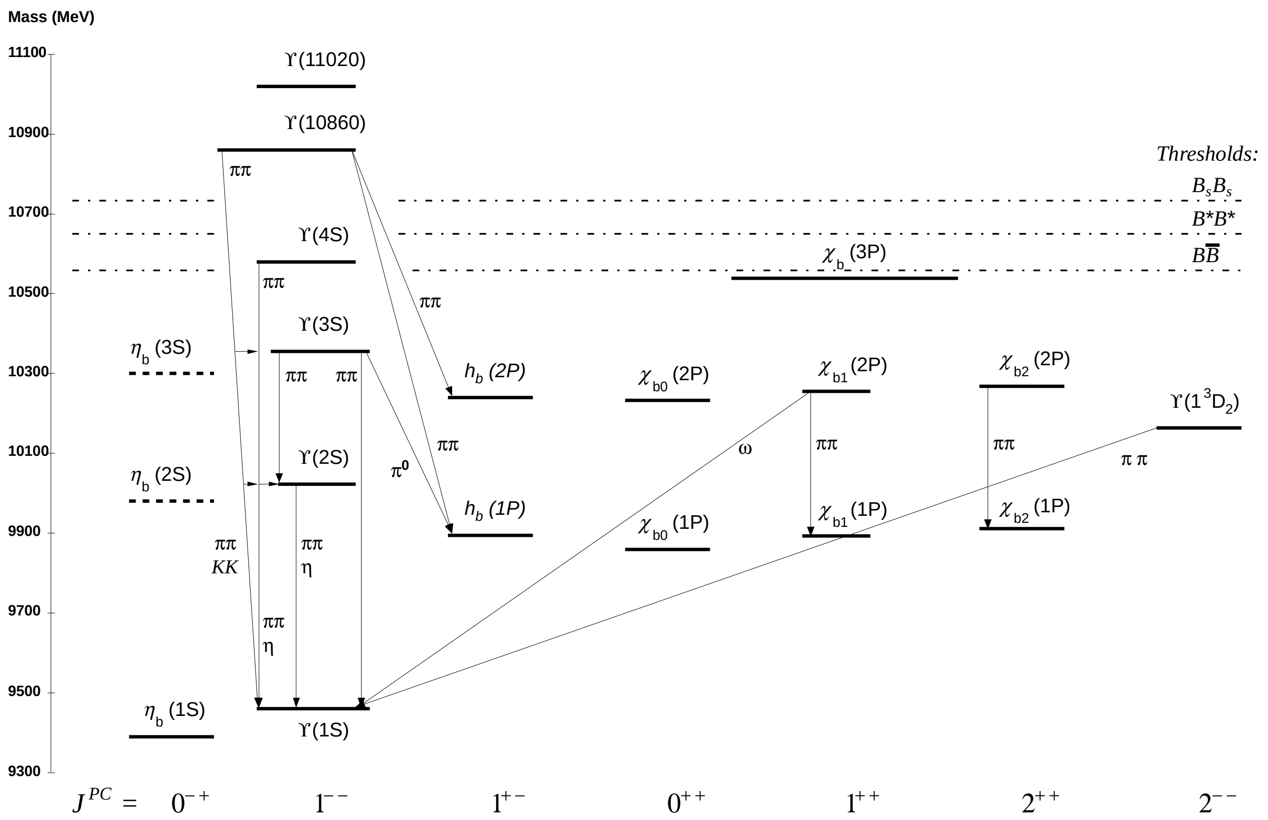
Outline

1. Summary of recent findings
2. Scans above the $\Upsilon(4S)$
3. Conclusions

Introduction – Some History

- Until recently most of the info on bottomonium came from CLEO and CUSB at CESR (80-ies and 90-ies) as well as from ARGUS and Crystal Ball at DESY
- These works followed the discovery of the $\Upsilon(1S)$ at Fermilab in 1977, so by mid-90-ies we knew three narrow and three broad $\Upsilon(nS)$'s plus six $\chi_{bJ}(1P)$ and $\chi_{bJ}(2P)$ states
- Then for a long time CLEO had a monopoly improving precision, which was broken by BaBar and Belle during last 5 years
- In particular, Belle collected $\sim$146 fb^{-1} from 10.63 to 11.05 GeV, two orders of magnitude larger than before
- An important addition to Standard Model tests, providing a lot of information on strong interactions and new (exotic) hadrons

Bottomonium Levels



K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

Summary of Recent Findings

- First observation of $h_b(1P)$ and $h_b(2P)$
  I. Adachi et el., Phys. Rev. Lett. 108, 032001 (2012)
- Reliable observation of $\eta_b(1S)$ and first evidence for $\eta_b(2S)$
  R. Mizuk et el., Phys. Rev. Lett. 109, 232002 (2012)
- Discovery of charged states $Z_b(10610)$ and $Z_b(10650)$
  A. Bondar et el., Phys. Rev. Lett. 108, 122001 (2012)
- Discovery of the neutral state $Z_b(10610)$
  P. Krokovny et al., Phys. Rev. D88, 052015 (2013)
- Amplitude analysis of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ and quantum numbers of Z_b
  A. Garmash et al., Phys. Rev. D91, 072003 (2015)

New Measurement of the $h_b(1P)$ and $\eta_b(1S)$ from $\Upsilon(4S) \to \eta h_b(1P)$

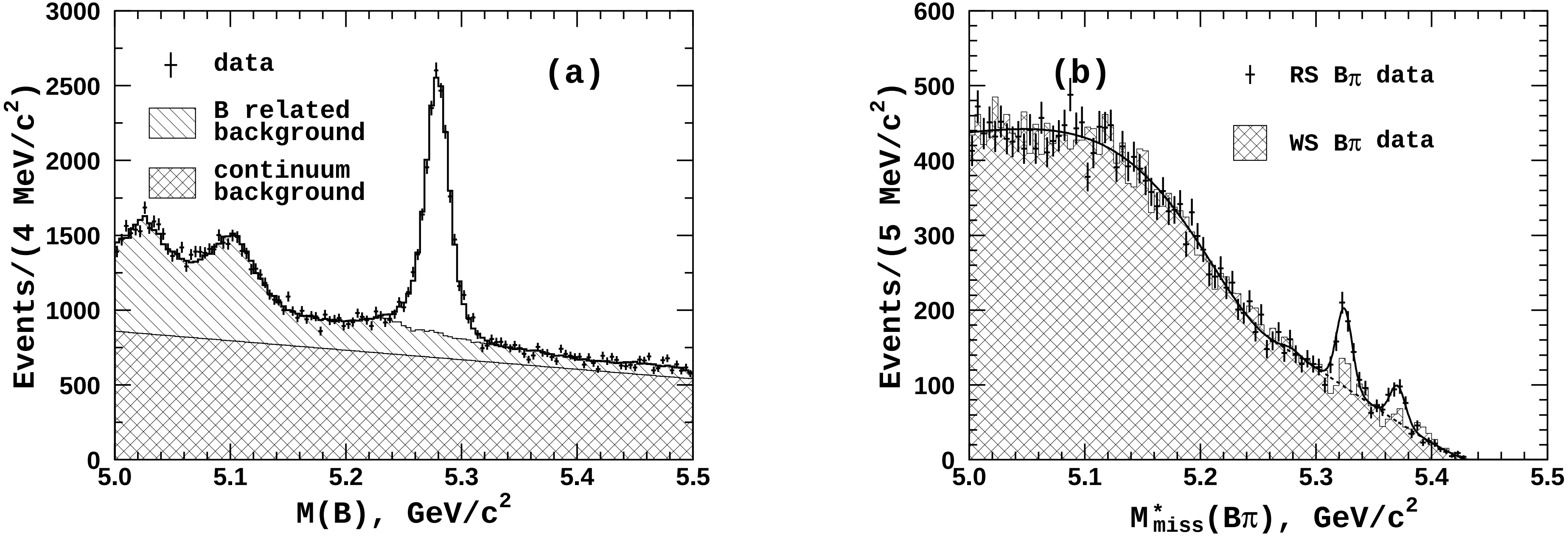
Observable	Value
$\mathcal{B}[\Upsilon(4S) \to \eta h_b(1P)]$	$(2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$
$\mathcal{B}[h_b(1P) \to \gamma\eta_b(1S)]$	$(56 \pm 8 \pm 4)\%$
$M_{h_b(1P)}$	$(9899.3 \pm 0.4 \pm 1.0)$ MeV$/c^2$
$M_{\eta_b(1S)} - M_{h_b(1P)}$	$(-498.6 \pm 1.7 \pm 1.2)$ MeV$/c^2$
$\Gamma_{\eta_b(1S)}$	$(8^{+6}_{-5} \pm 5)$ MeV$/c^2$
$M_{\eta_b(1S)}$	$(9400.7 \pm 1.7 \pm 1.6)$ MeV$/c^2$
$\Delta M_{\mathrm{HF}}(1S)$	$(+59.6 \pm 1.7 \pm 1.6)$ MeV$/c^2$
$\Delta M_{\mathrm{HF}}(1P)$	$(+0.6 \pm 0.4 \pm 1.0)$ MeV$/c^2$

U. Tamponi et al., Phys. Rev. Lett. 115, 142001 (2015)

Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons – I

Belle: $e^+e^- \to B\bar{B}\pi^\pm, B\bar{B}^*\pi^\pm + c.c., B^*\bar{B}^*\pi^\pm$ with 121.4 fb^{-1} at 10.866 GeV

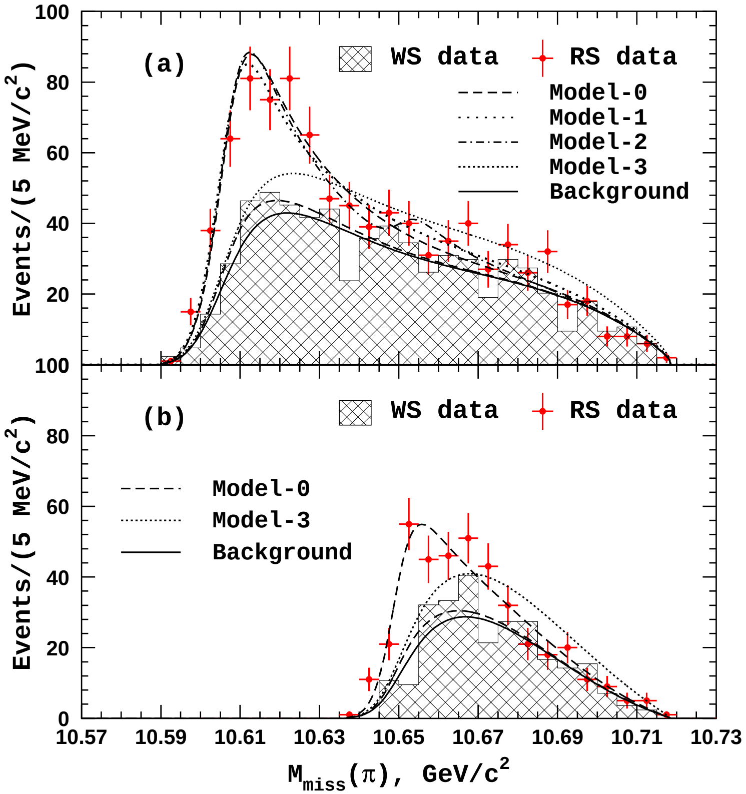
$$M_{\rm miss}(B\pi) = \sqrt{(\sqrt{s} - E_{B\pi})^2 - P^2_{B\pi}}$$



12263 ± 168 fully reconstructed B mesons

A. Garmash et al., Phys. Rev. Lett. 116, 212001 (2016)

Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons – II



13 ± 25 $B\bar{B}\pi$ events

357 ± 30 $B^*\bar{B}\pi$ events

161 ± 21 $B^*\bar{B}^*\pi$ events

$$M_{\rm miss}(\pi) = \sqrt{(\sqrt{s} - E_\pi)^2 - P_\pi^2}$$

A. Garmash et al., Phys. Rev. Lett. 116, 212001 (2016)

Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons – III

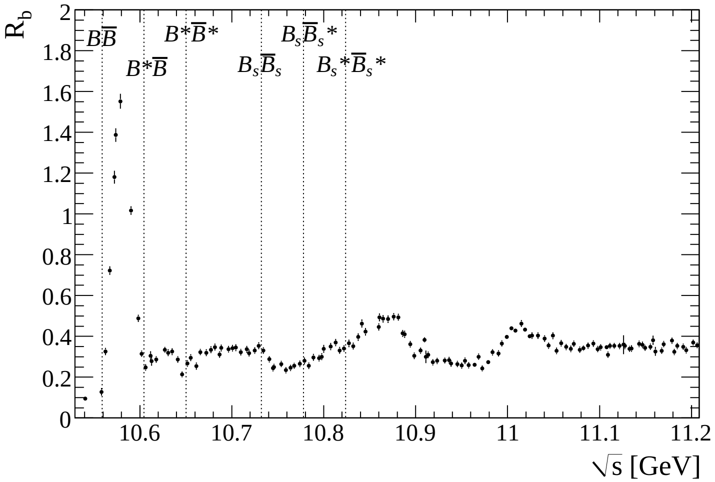
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	–
$B^{*+}\bar{B}^{*0}$	–	$73.7^{+3.4+2.7}_{-4.4-3.5}$

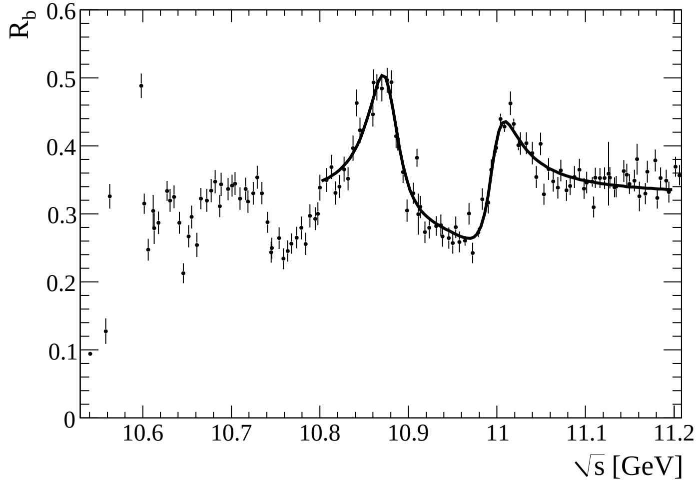
A. Garmash et al., Phys. Rev. Lett. 116, 212001 (2016)

Puzzles of $\Upsilon(10860)$ and $\Upsilon(11020)$

- The rate for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ (n=1,2,3) at $\Upsilon(10860)$ is ~ 100 times that for $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$ (n=2,3,4)
  K.-F.Chen et al. (Belle), Phys.Rev.Lett. 100, 112001 (2008)
- Rates to $h_b(mP)\pi^+\pi^-$ (m=1,2) are of the same order as to $\Upsilon(nS)\pi^+\pi^-$ despite a b-quark spin flip
  I.Adachi et al., Phys.Rev.Lett. 108, 032001 (2012)
- The peak of $R_{\Upsilon(nS)\pi\pi} \equiv \sigma(\Upsilon(nS)\pi^+\pi^-)/\sigma^0_{\mu\mu}$ near $\Upsilon(10860)$ occurs at 9 ± 4 MeV higher than that of $R_b \equiv \sigma(b\bar{b})/\sigma^0_{\mu\mu}$
  K.-F.Chen et al., Phys.Rev. D82, 091106 (2010)
- Is there another peaking structure at 10.9 GeV suggested by data of Belle and BaBar?
  A.Ali et al., Phys. Lett. B684, 28 (2010), Phys. Rev. Lett. 104, 162001 (2010)
- $R'_{b,i} = R_{b,i} - \Sigma\sigma_{\mathrm{ISR,i}}/\sigma^0_{\mu^+\mu^-,i}$

BaBar High-Energy Scan





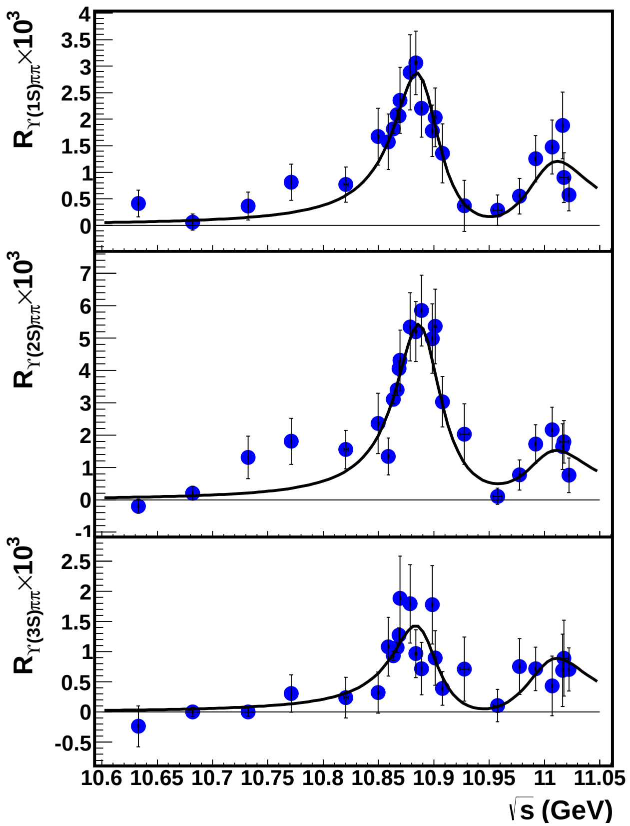
3.3 fb^{-1} from 10.54 to 11.20 GeV + 0.6 fb^{-1} from 10.96 to 11.10 GeV

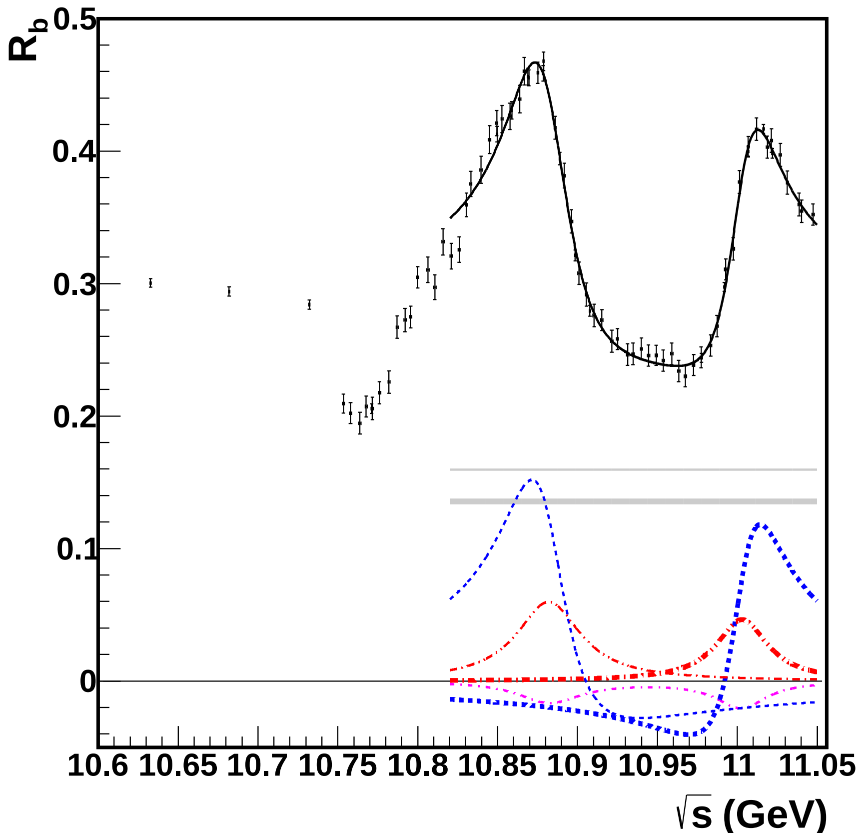
Parameters of the $\Upsilon(5S, 6S)$ are sensitive to the $\sigma(s)$ shape

Clear structures at opening thresholds, a plateau near $B_s^* \bar{B}_s^*$

B. Aubert et al., Phys. Rev. Lett. 102, 012001 (2009)

Belle High-Energy Scans – I





About 146 fb^{-1} from 10.63 to 11.05 GeV, 35 times more than at BaBar

D. Santel et al., Phys. Rev. D93, 011101 (2016)

Belle High-Energy Scans – II

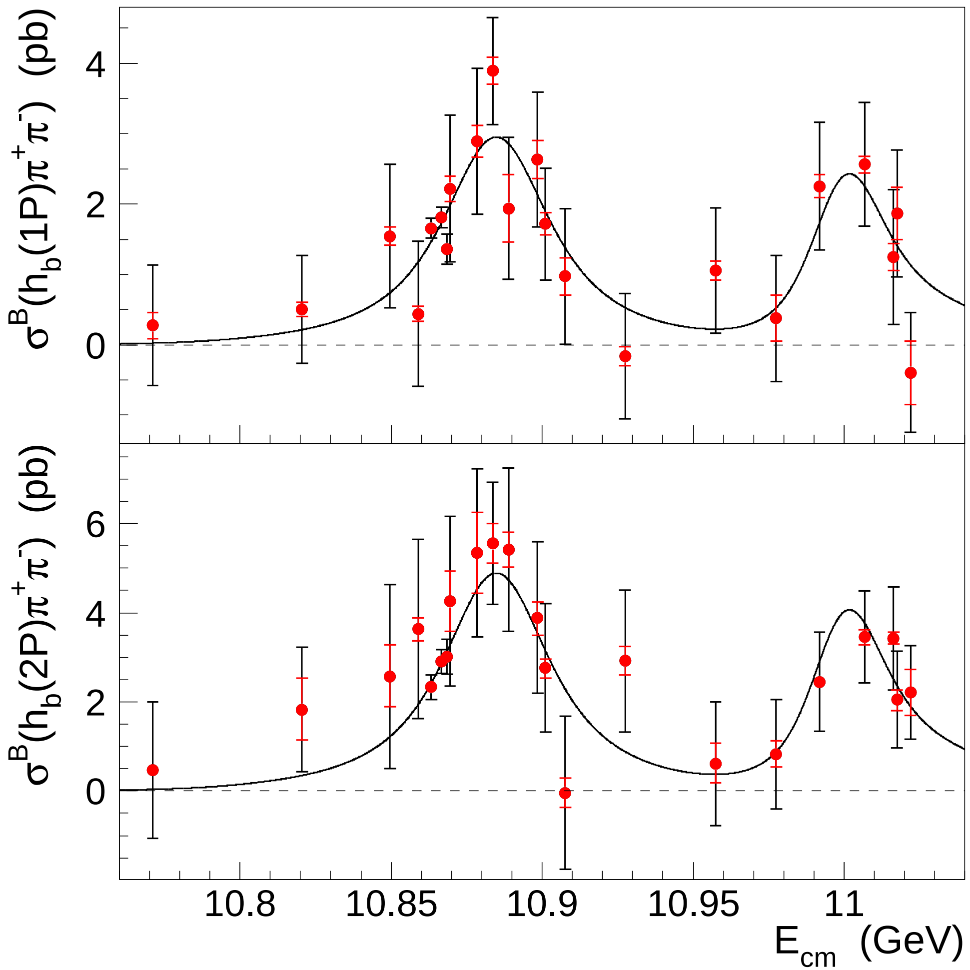
	M_{5S} (MeV)	Γ_{5S} (MeV)	M_{6S} (MeV)	Γ_{6S} (MeV)
R'_b	$10881.8^{+1.0}_{-1.1} \pm 1.2$	$48.5^{+1.9}_{-1.8}{}^{+2.0}_{-2.8}$	$11003.0 \pm 1.1^{+0.9}_{-1.0}$	$39.3^{+1.7}_{-1.6}{}^{+1.3}_{-2.4}$
$R_{\Upsilon\pi\pi}$	$10891.1 \pm 3.2^{+0.6}_{-1.7}$	$53.7^{+7.1}_{-5.6}{}^{+1.3}_{-5.4}$	$10987.5^{+6.4}_{-2.5}{}^{+9.0}_{-2.1}$	$61^{+9}_{-19}{}^{+2}_{-20}$

- M and Γ from R'_b and $R_{\Upsilon\pi\pi}$ are consistent, but the fitted $\mathcal{A}$'s are not and validity of flat continuum for R'_b is doubtful; interference effects
- $\Upsilon\pi\pi$ spectra have little or no nonresonant component, so it makes sense to quote resonance parameters from $R_{\Upsilon\pi\pi}$
- First hadronic transitions $\Upsilon(6S) \to \Upsilon(nS)\pi^+\pi^-$ are observed
- No peaking structure at 10.9 GeV in the R'_b observed, $\Gamma_{ee} < 9$ eV at 90%CL

D. Santel et al., Phys. Rev. D93, 011101 (2016)

Belle High-Energy Scans – III

Belle used ~ 140 fb^{-1} from 10.77 to 11.02 GeV to study $e^+e^- \to h_b(nP)\pi^+\pi^-$



Belle High-Energy Scans – IV

Parameter	$h_b\pi\pi$	$\Upsilon\pi\pi$
M_{5S}, MeV	$10884.7^{+3.6+8.9}_{-3.4-1.0}$	$10891.1 \pm 3.2^{+0.6}_{-1.7}$
Γ_{5S}, MeV	$40.6^{+12.7+\ 1.1}_{-8.0-19.1}$	$53.7^{+7.1+1.3}_{-5.6-5.4}$
M_{6S}, MeV	$10999.0^{+7.3+16.9}_{-7.8-\ 1.0}$	$10987.5^{+6.4+9.0}_{-2.5-2.1}$
Γ_{6S}, MeV	$27^{+27+\ 5}_{-11-12}$	$61^{+\ 9+\ 2}_{-19-20}$

- Results in $h_b\pi\pi$ and $\Upsilon\pi\pi$ modes are consistent
- There is no non-resonant component in $h_b\pi\pi$
- $\Upsilon(11020) \to h_b\pi^+\pi^-$ transitions proceed via $Z_b(10610)$ and/or $Z_b(10650)$

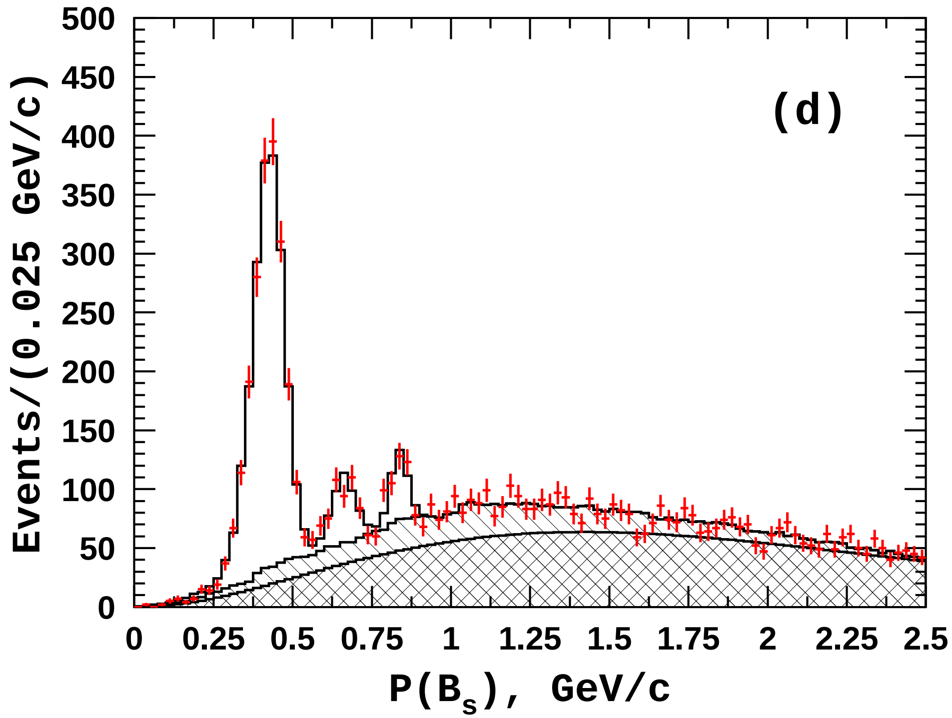
A.Abdessalam et al., arXiv:1508.06562, Phys.Rev.Lett.

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – I

121.4 fb^{-1} near the $\Upsilon(10860)$ peak

2283 ± 63 events from a fit to the $M(B_s)$ distribution

$B_s^*\bar{B}_s^*$, $B_s\bar{B}_s^* + c.c.$, $B_s\bar{B}_s$ expected to peak at 0.43, 0.63, 0.83 GeV/c



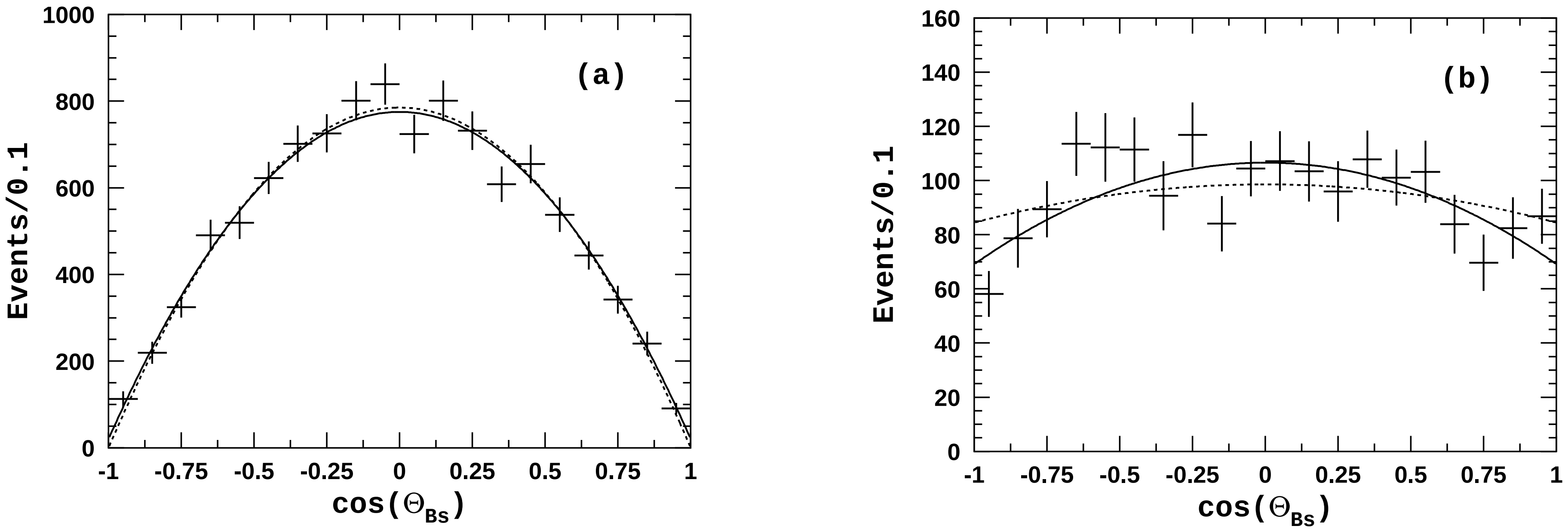
K. Kinoshita, talk at ICHEP-16, preliminary

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – II

	$B_s^*\bar{B}_s^*$	$B_s\bar{B}_s^* + \bar{B}_sB_s^*$	$B_s\bar{B}_s$
$N_{\rm events}$	1824 ± 51	223 ± 27	168 ± 24
Belle	7	$0.856 \pm 0.106 \pm 0.053$	$0.645 \pm 0.094 \pm 0.033$
PDG	7	0.537 ± 0.152	0.199 ± 0.199
HQSS	7	4	1

Heavy Quark Spin Symmetry (HQSS) Approximation considered by
A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. Lett. 38 (1977) 317
is strongly broken near threshold of open flavor for both $c\bar{c}$ and $b\bar{b}$ states
M. Voloshin, Phys. Rev. D 85 (2012) 034024 argues that
strong HQSS breaking near threshold is due to mixing of quarkonium-like states
with pairs of heavy mesons, should be also seen in angular distributions

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – III



MC with $a_2 = 0$

Data

For $e^+e^- \to B_s^* \bar{B}_s^*$ $\quad d\sigma/dcos\theta \sim a_0^2(1 - cos^2\theta) + a_2^2(7 - cos^2\theta)/10$

In HQSS $a_0^2 : a_2^2 = 1 : 20$ or $r = a_0^2/(a_0^2 + a_2^2) = 1 : 21 = 0.048$

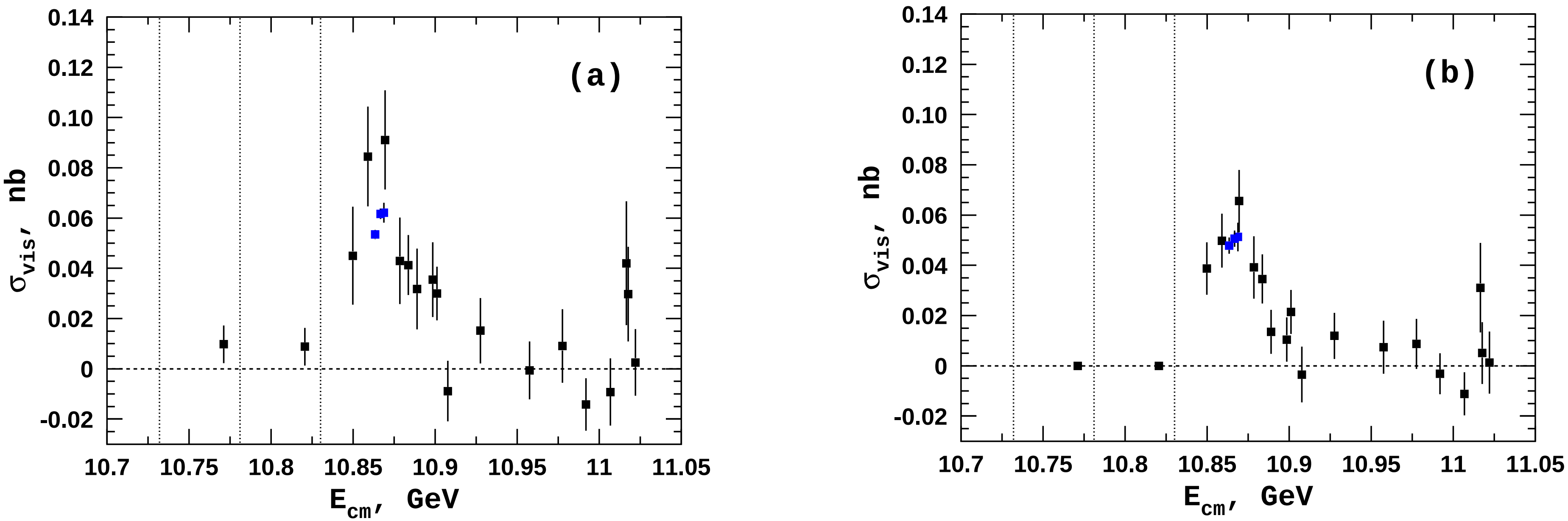
From a fit Belle obtains $r = 0.175 \pm 0.057 \pm 0.020$

or 2.6σ significance for the $S = 0$ component

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – IV

121.4 fb^{-1} near the $\Upsilon(10860)$ (grouped into three points)
and 16.4 fb^{-1} from 10.77 to 11.02 GeV

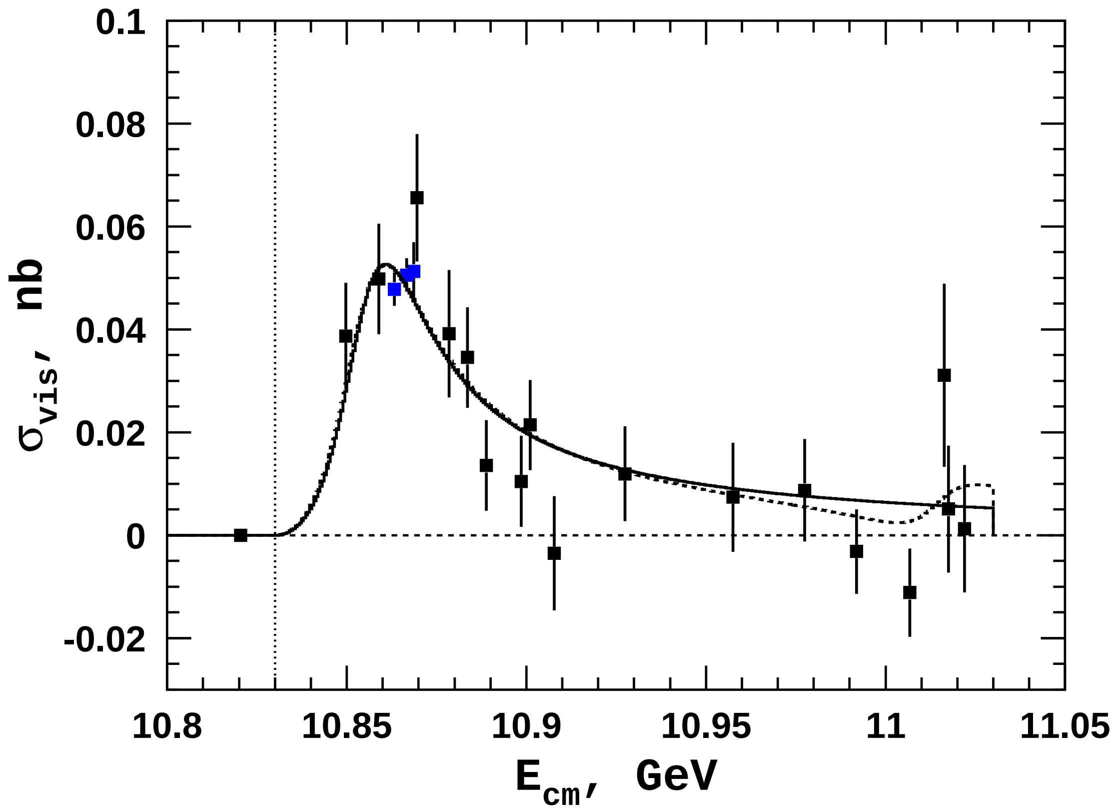
Prominent signals in $M(B_s)$ at three points with large luminosity



$e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ $e^+e^- \to B_s^{*}\bar{B}_s^{*}$

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – V

For $e^+e^- \to B_s^*\bar{B}_s^*$ separate analysis with tighter conditions



K. Kinoshita, talk at ICHEP-16, preliminary

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – VI

$$\sigma \sim (P/P_0)|F_{BW}(s, M_5, \Gamma_5) + aF_{BW}(s, M_6, \Gamma_6)\exp^{i\phi}|^2$$

Parameter	$\Upsilon(10860)$	$\Upsilon(10860)$+$\Upsilon(11020)$
M_5, MeV	10869.1 ± 5.3	10870.8 ± 5.8
Γ_5, MeV	59 ± 22	65 ± 23
M_6, MeV	–	11013.0 ± 8.9
Γ_6, MeV	–	27
a_6	–	0.121 ± 0.072
ϕ/π	–	1.38 ± 0.43
χ^2/ndf	$20.9/17$	$18.5/14$

Parameters of $\Upsilon(10860)$ are close to these in $\Upsilon(nS)(h_b(mP))\pi^+\pi^-$ final states

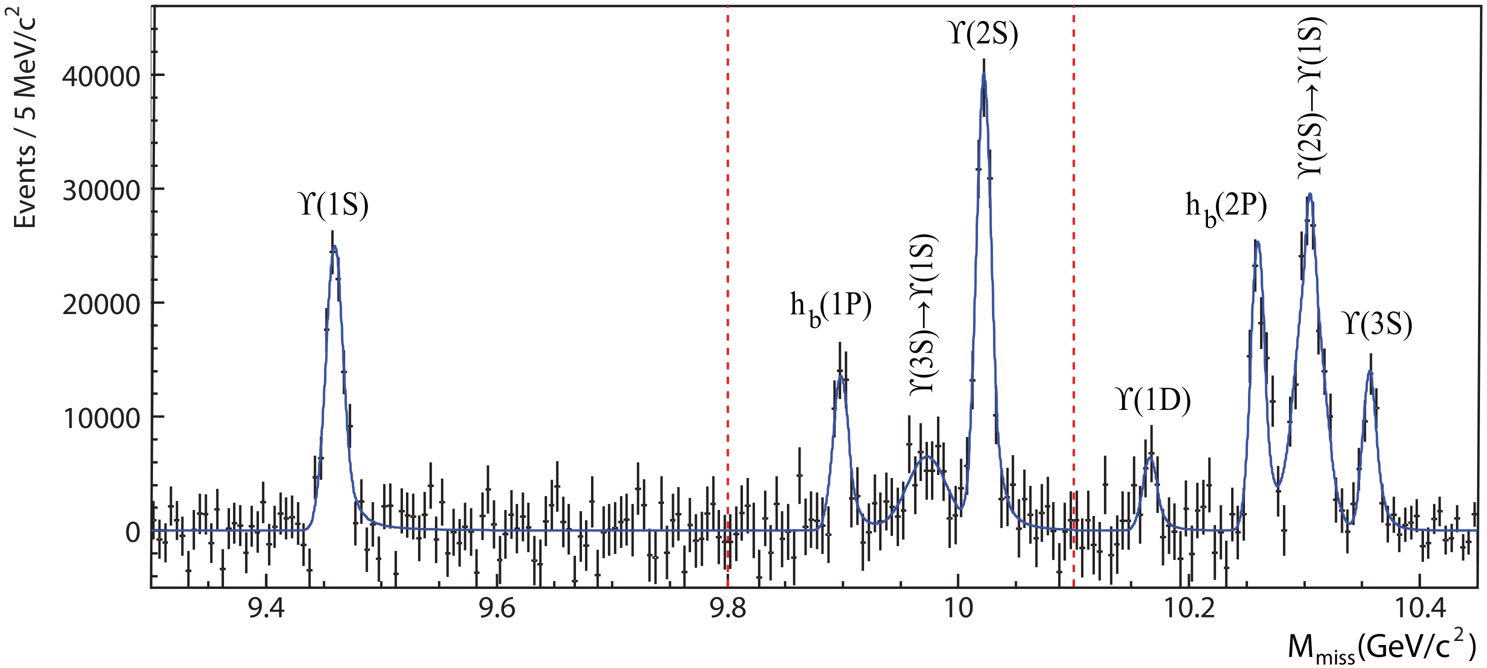
No significant signal of $\Upsilon(11020) \to B_s^*\bar{B}_s^*$

Conclusions and Future

- Various $b\bar{b}$ states have been discovered/remeasured due to new energy domains, high statistics measurements and sophisticated analysis
- Higher $M_{\eta_b(1S)}$ confirmed, smaller tension with theory for $\Delta M_{\mathrm{HF}}(1S)$
- Exotic states (two Z_b's) not fitting the quark model exist, they decay into both hidden ($\Upsilon\pi,\ h_b\pi$) and open beauty ($B^*\bar{B}^*, B\bar{B}^* + c.c.$) states
- Not yet discovered bottomonium analogues of $c\bar{c}$ states likely, the question of analogies with charmonium is of great interest
- $\Upsilon(10860)$ and $\Upsilon(11020)$ decay to $\Upsilon(nS)\pi\pi$ and $h_b(1P)\pi\pi$
- New decay modes of $\Upsilon(10860) \to B_s^{(*)}\bar{B}_s^{(*)}$, no signal at $\Upsilon(11020)$
  $B_s^*\bar{B}_s^* : B_s\bar{B}_s^* + c.c. : B_s\bar{B}_s = 7 : 0.856 \pm 0.119 : 0.645 \pm 0.100$
  Strong breaking of HQSS
- A lot of work for BelleII and LHC experiments in the future

Backup Slides

Observation of $h_b(1P)$ and $h_b(2P)$ at Belle – II

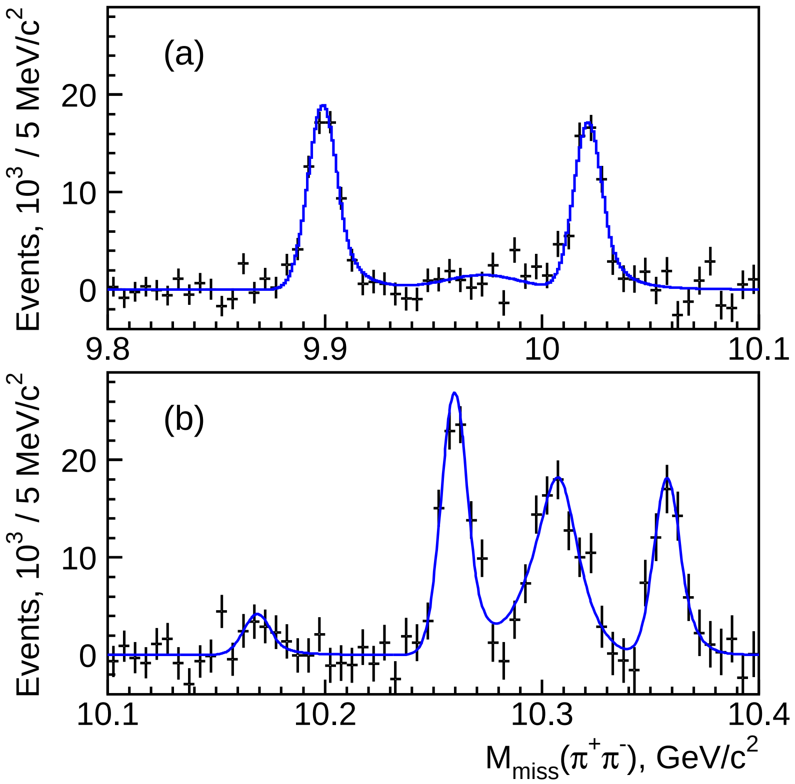


Missing mass distribution clearly shows
a variety of states with different J^P

Results with the Full $\Upsilon(5S)$ Sample – I

Using 133.4 fb^{-1} and this method, Belle updates results on the $\eta_b(1S)$ and reports first evidence for the $\eta_b(2S)$,

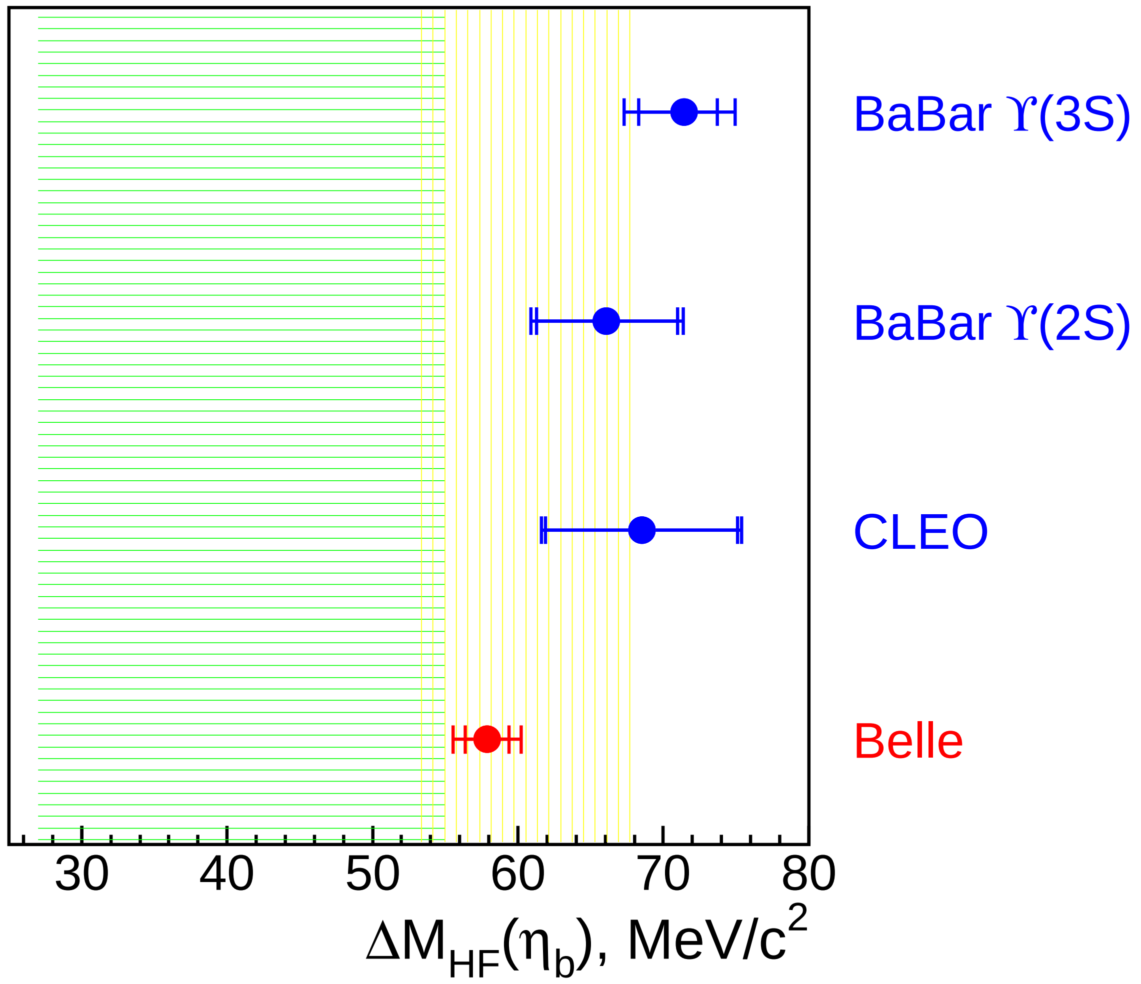
We also update $h_b(1P)$ and $h_b(2P)$ mass measurements



$\pi\pi$ transitions in the $h_b(1P)$ region:
$\Upsilon(5S) \to h_b(1P)$, $\Upsilon(3S) \to \Upsilon(1S)$, $\Upsilon(5S) \to \Upsilon(2S)$

$\pi\pi$ transitions in the $h_b(2P)$ region:
$\Upsilon(5S) \to \Upsilon(1D)$, $\Upsilon(5S) \to h_b(2P)$, $\Upsilon(2S) \to \Upsilon(1S)$, $\Upsilon(5S) \to \Upsilon(3S)$

Comparison of the Mass Measurements with Theory



Summary on the $\eta_b(2S)$

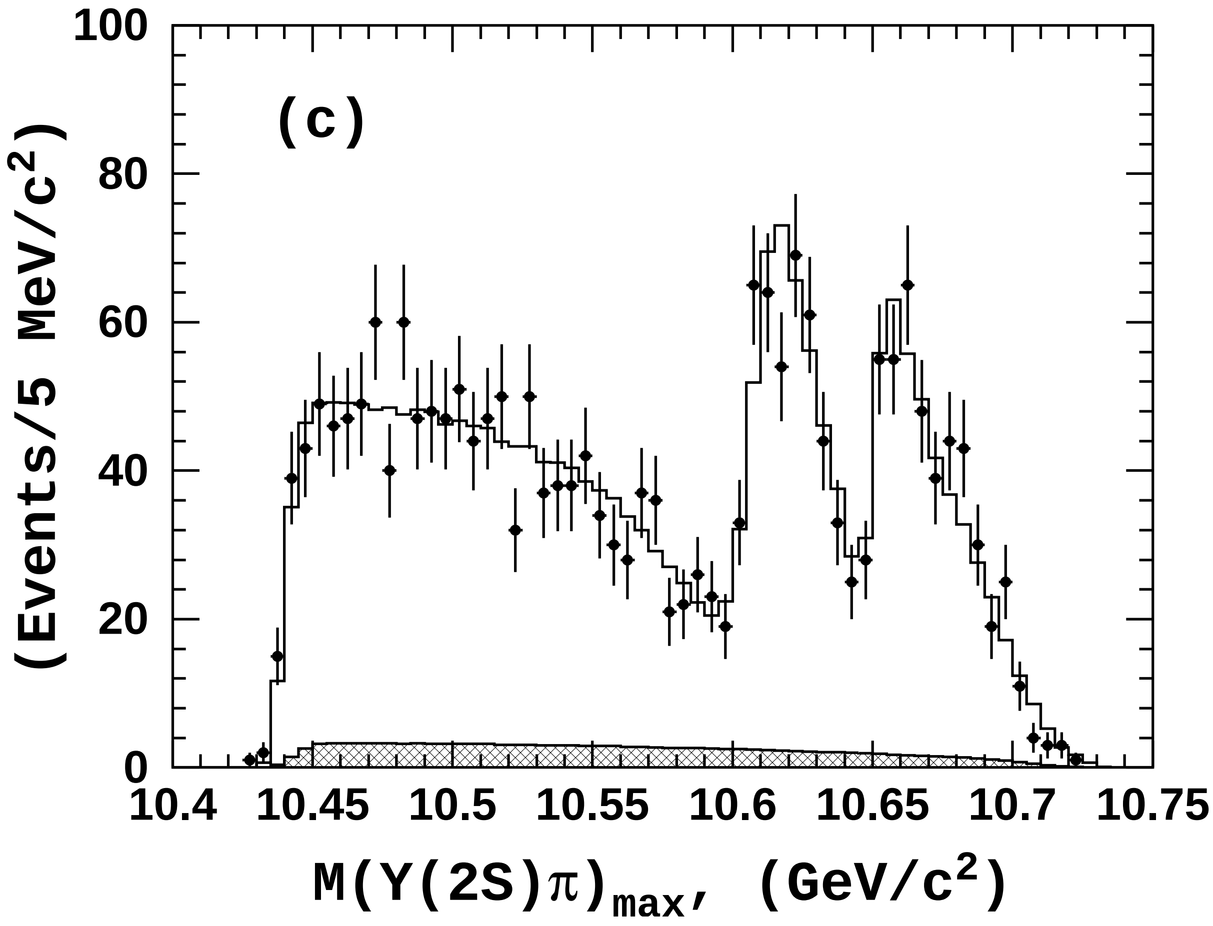
Quantity	Belle, 2012	PDG, 2011	Theory
Mass, MeV	$9999.0 \pm 3.5^{+2.8}_{-1.9}$	–	–
$\Delta M_{\rm hf}$, MeV	$24.3^{+4.0}_{-4.5}$	–	23.5 ± 4.7, Latt.
Width, MeV	< 24	–	4.1 ± 0.7, Potential
$\mathcal{B}(h_b(2P) \to \eta_b(2S)\gamma)$, %	$47.5 \pm 10.5^{+6.8}_{-7.7}$	–	19 (GR, 2002)

R. Mizuk et al., Phys. Rev. Lett. 109, 232002 (2012)

Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – I

- Analysis of $\Upsilon(5S)$ decays to $h_b(1P)\pi^+\pi^-$, $h_b(2P)\pi^+\pi^-$ as well as $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$ shows the resonant structure in $\Upsilon(nS)\pi$, $h_b(mP)\pi$ – Z_b
  A. Bondar et al., Phys. Rev. Lett. 107, 122001 (2012)
- There are two Z_b states at 10610 MeV and 10650 MeV which both decay into $\Upsilon(nS)\pi^\pm$ and $h_b(mP)\pi^\pm$, $n = 1, 2, 3; m = 1, 2$
- $\Upsilon(5S) \to Z_b\pi$, $Z_b \to \Upsilon(nS)\pi$ or $Z_b \to h_b(mP)\pi$
- Two Z_b states are charged and obviously exotic
- M. Karliner and H.J. Lipkin, 0802.0649

Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – II



Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – III

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M(Z_b^1)$, MeV	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma(Z_b^1)$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\ ^{+4.5+2.1}_{-3.9-1.2}$	$13\ ^{+10+9}_{-8-7}$
$M(Z_b^2)$, MeV	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\ ^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma(Z_b^2)$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\ ^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\ ^{+11}_{-7}$
Rel. norm.	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, $^\circ$	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

Masses, widths, relative amplitudes are consistent

Relative phases are swapped for Υ and h_b final states

as expected in the molecular model

State	$Z_b(10610)$	$Z_b(10650)$
M, MeV	10607.2 ± 2.0	10652.2 ± 1.5
Γ, MeV	18.4 ± 2.4	11.5 ± 2.2

Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – IV