International Workshop on e^+e^- collisions from ϕ to ψ,
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Review of bottomonium studies at Belle

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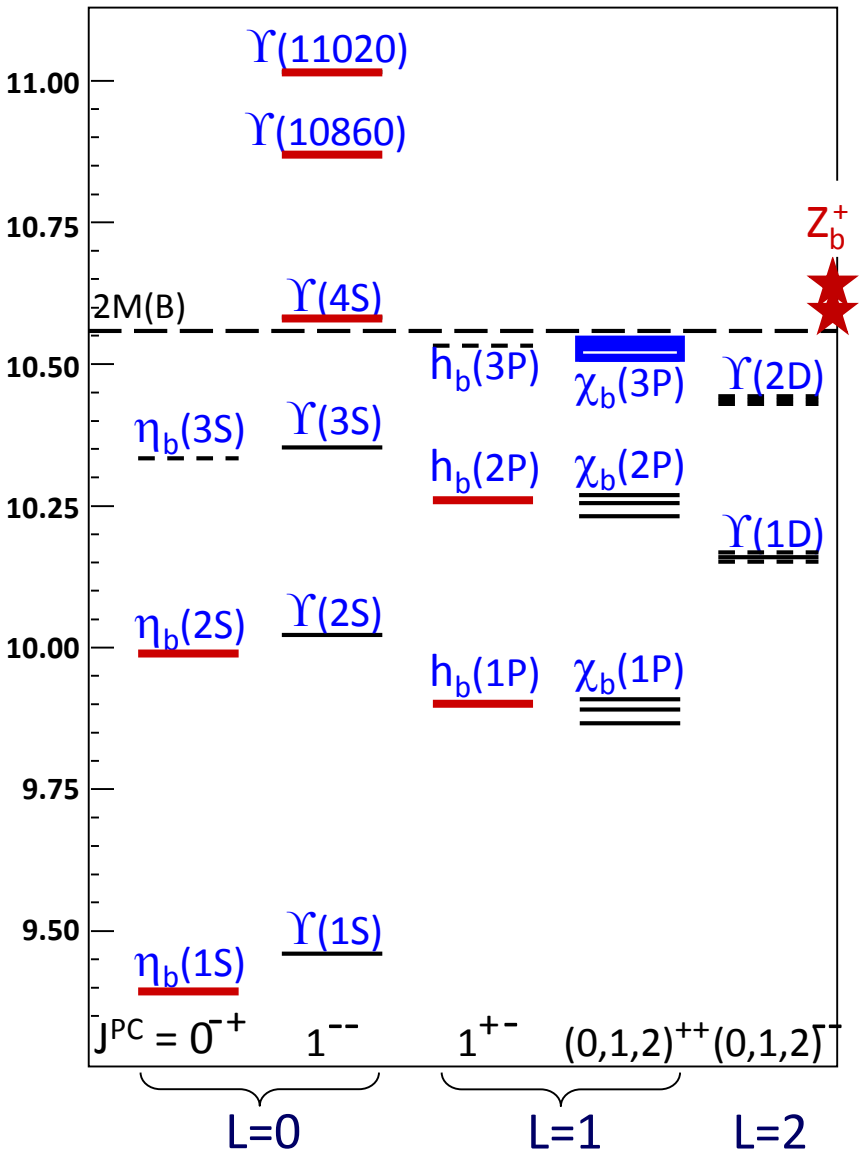
Bottomonium at B-factories



530 fb^{-1}

On resonance:

Υ(4S): 433 fb^{-1}

Υ(3S): 30 fb^{-1}

Υ(2S): 14 fb^{-1}

Off reson./scan :

~54 fb-1

> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

Υ(2S): 24 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan :

~100 fb-1

Main observations:

– $\eta_b(1S)$, $\eta_b(2S)$, $h_b(1P)$, $h_b(2P)$

– $Z_b(10610)$, $Z_b(10650)$

– anomalous transitions from $\Upsilon(4,5,6S)$

My talk:

New measurement of $\eta_b(1S)$ mass

Observation of $\Upsilon(4S) \to \Upsilon(1S)\,\eta'$

Energy scan of $e^+e^- \to \chi_{bJ}(1P)\,\pi^+\pi^-\pi^0$

PRL121,232001(2018)

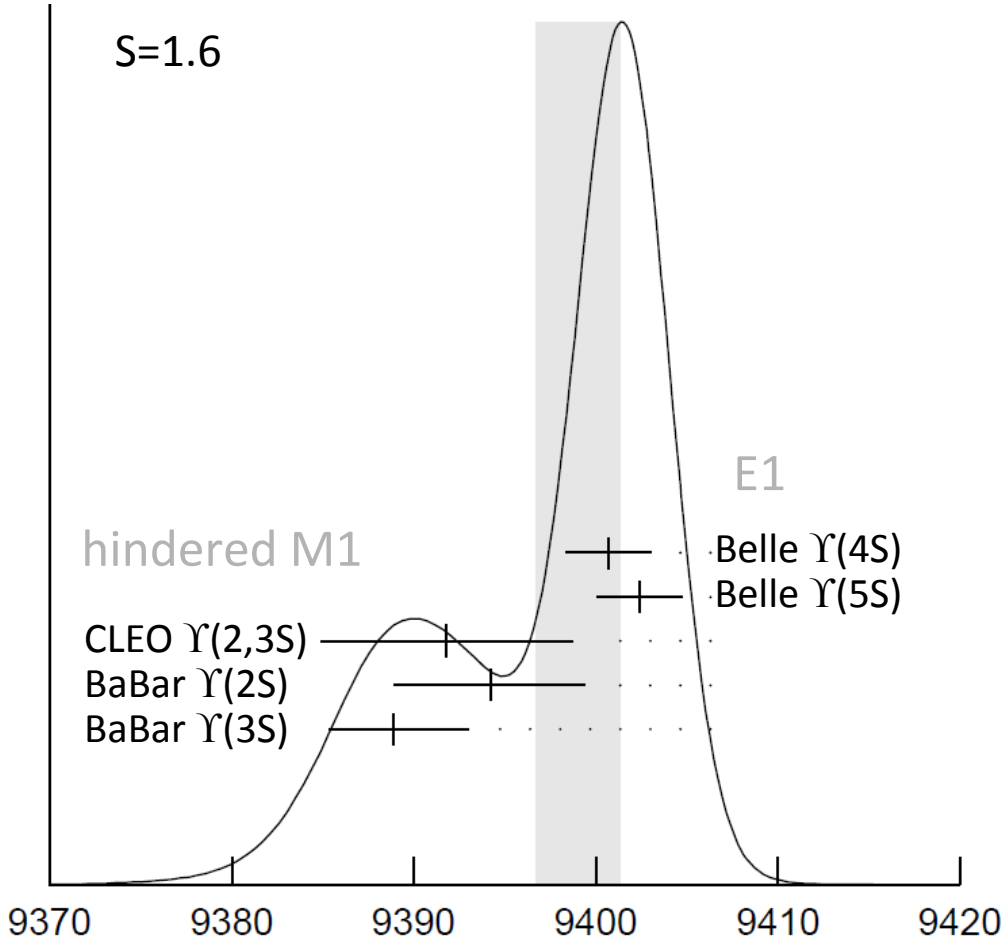
New measurement of $\eta_b(1S)$ mass

$\eta_b(1S)$ mass

BaBar, CLEO: $\Upsilon(2,3S) \to \eta_b(1S)\,\gamma$ hindered M1

Belle: $\Upsilon(4S) \to h_b(1S)\,\eta$
$\Upsilon(5S) \to h_b(1S)\,\pi^+\pi^-$
} $h_b(1P) \to \eta_b(1S)\,\gamma$ E1

PRL101, 071801 (2008)
PRL103, 161801 (2009)
PRD81, 031104 (2010)
PRL 109, 232002 (2012)
PRL 115, 142001 (2015)



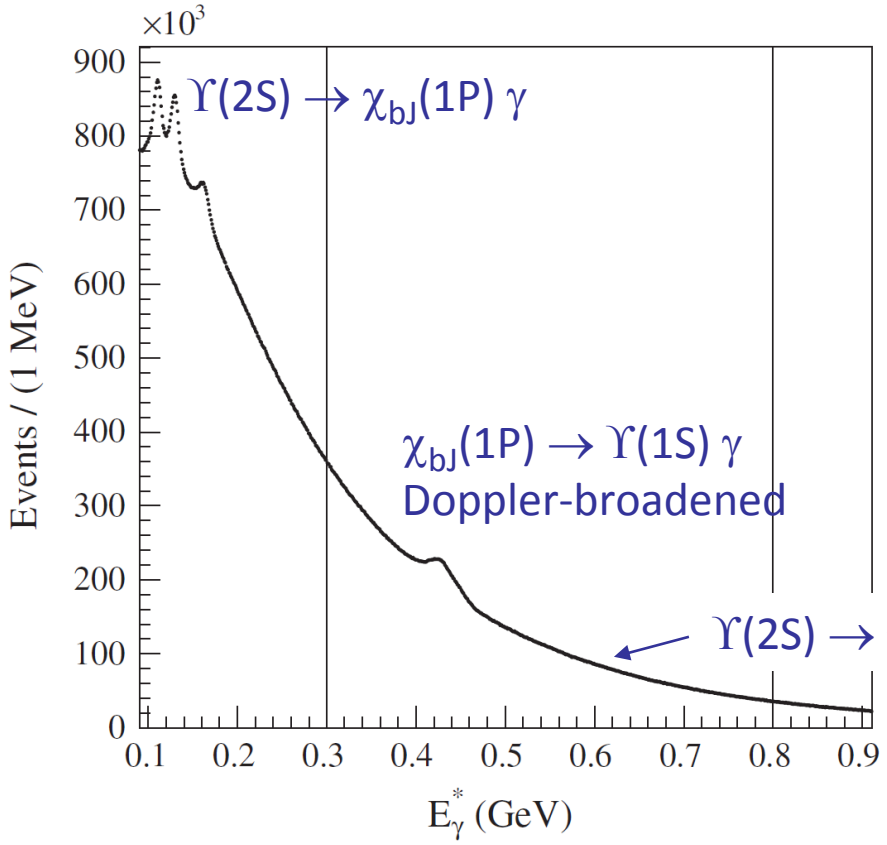
Discrepancy: 3.1σ
– fluctuation?
– experimental systematics?
– different line shapes?

⇒ Study $\Upsilon(2S) \to \eta_b(1S)\gamma$ at Belle

Method

$\Upsilon(2S)$ data: 25 fb^{-1}, 158M $\Upsilon(2S)$ decays c.f. BaBar: 14 fb^{-1}

$\Upsilon(2S) \to \eta_b(1S)\,\gamma$: inclusive reconstruction – study energy spectrum of all photons.



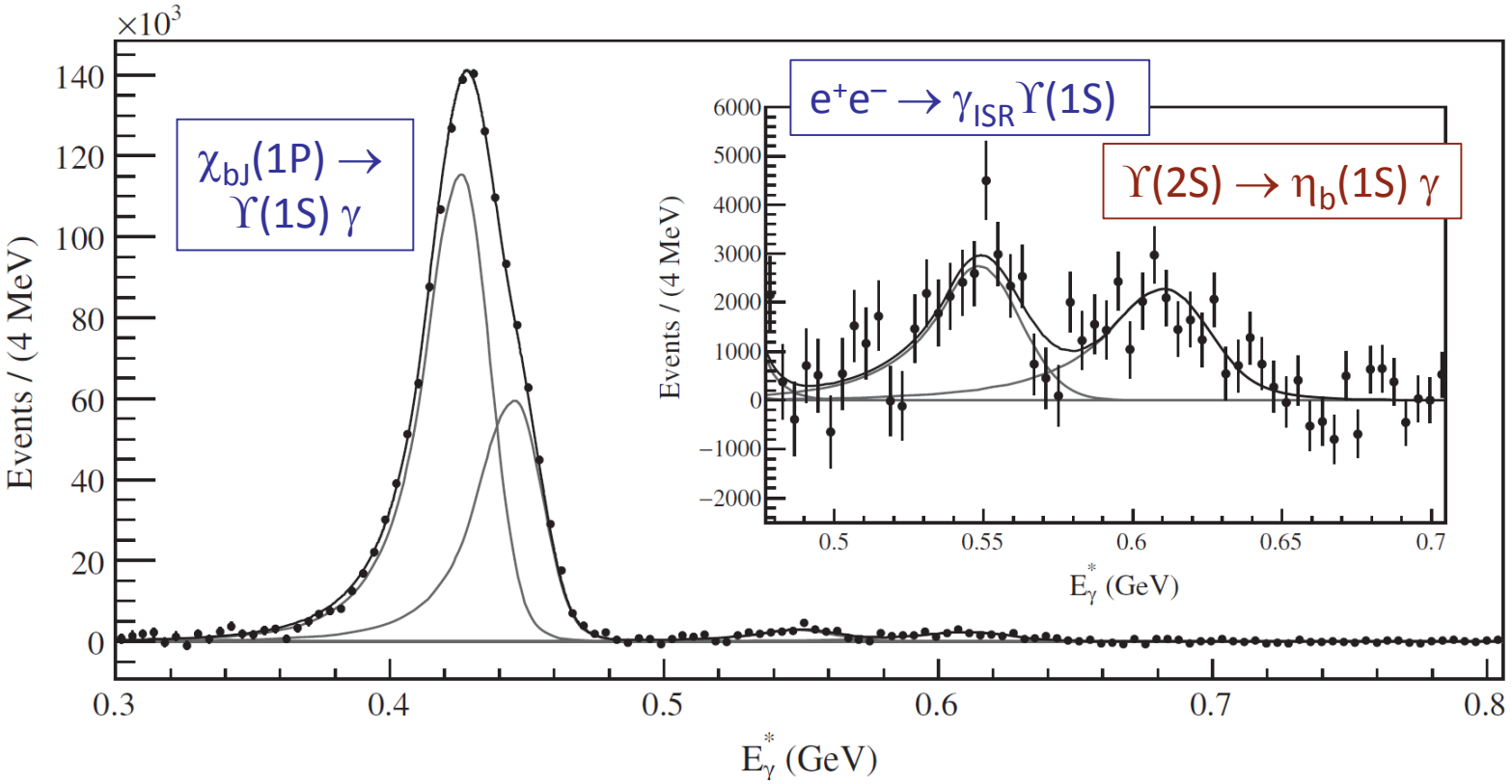
Selection:
– π^0 veto
– event topology to suppress u,d,s,c production

Calibration of MC simulation: $\chi_{bJ}(1P) \to \Upsilon(1S)\,\gamma \to \mu^+\mu^-\,\gamma$, $\eta \to 2\gamma$, $D^{*0} \to D^0\,\gamma$

Fit to E^*_γ spectrum

Combinatorial background: exp × 6th order polynomial

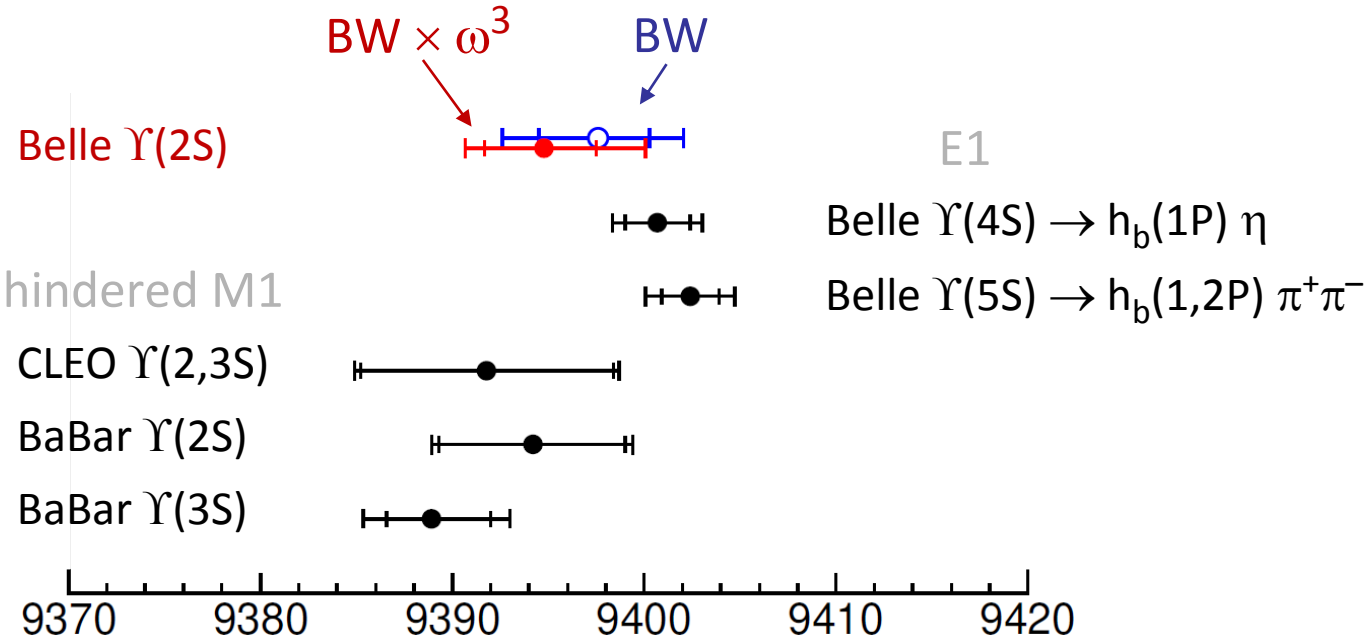
Peaking components: shapes from MC, parametrized by asymmetric Gaussians with power-law tails. Width of $\eta_b(1S)$ is fixed: $\Gamma = 10^{+5}_{-4}$ MeV.



Significance of $\Upsilon(2S) \to \eta_b(1S)\gamma$ exceeds $7\sigma \Rightarrow$ first observation.

Peak positions and yields of $\chi_{bJ}(1P)$ and ISR agree with expectations.

$\eta_b(1S)$ mass: $9394.8^{+2.7+4.5}_{-3.1-2.7}$ MeV



Default parametrization is BW × ω^3, if changed to BW → shift in mass +2.8 MeV.

New result hints that discrepancy is due to a fluctuation. Accuracy is insufficient for firm conclusion. ⇒ Need more data at ϒ(2S) ← BelleII

PRL 121,062001(2018)

Observation of $\Upsilon(4S) \to \Upsilon(1S)\,\eta'$

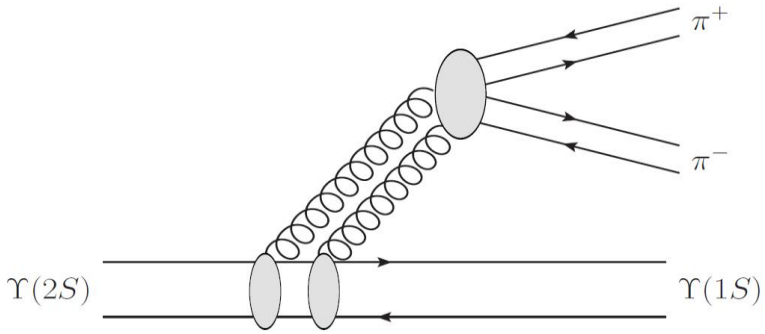
Experimental status

Bondar, RM, Voloshin MPLA32,1750025(2017)

Transition	Partial width (keV)
$\Upsilon(2S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	5.7 ± 0.5
$\Upsilon(1S)\,\eta$	$(9.3 \pm 1.5) \times 10^{-3}$
$\Upsilon(3S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	0.89 ± 0.08
$\Upsilon(1S)\,\eta$	$< 2 \times 10^{-3}$
$\Upsilon(2S)\,\pi^+\pi^-$	0.57 ± 0.06
$\Upsilon(4S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8

$\Leftarrow$ B meson loops?

In bottomonium hadronic transitions are OZI suppressed:



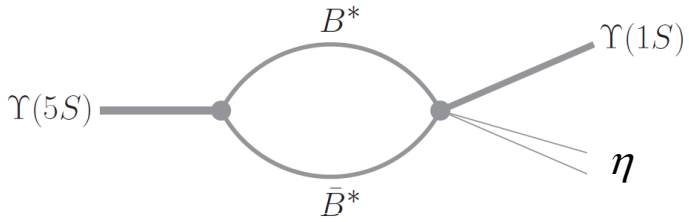
$\pi^+\pi^-$ transitions: E1E1 gluons,
transitions: E1M2 gluons
– Heavy Quark Spin Symmetry suppressed

Prediction:

M. B. Voloshin, Mod. Phys. Lett. A **26**, 773 (2011)

hadron loops: $0.2 \le R_{\eta'/\eta} \le 0.6$

gluons: $R_{\eta'/\eta} \sim 25$



$\Rightarrow$ Search for $\Upsilon(4S) \to \Upsilon(1S)\,\eta'$

Method

496 fb^{-1} of $\Upsilon(4S)$ data

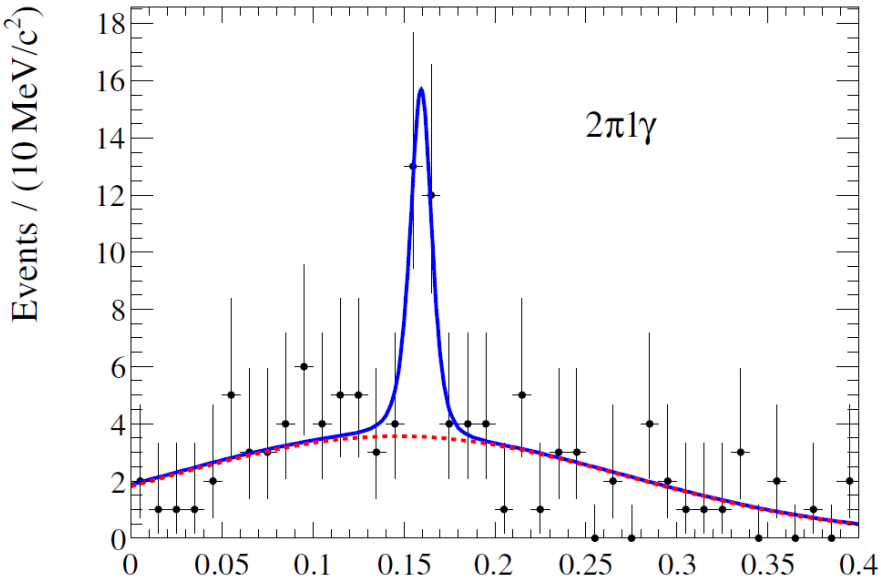
$\Upsilon(4S) \to \Upsilon(1S)\,\eta'$

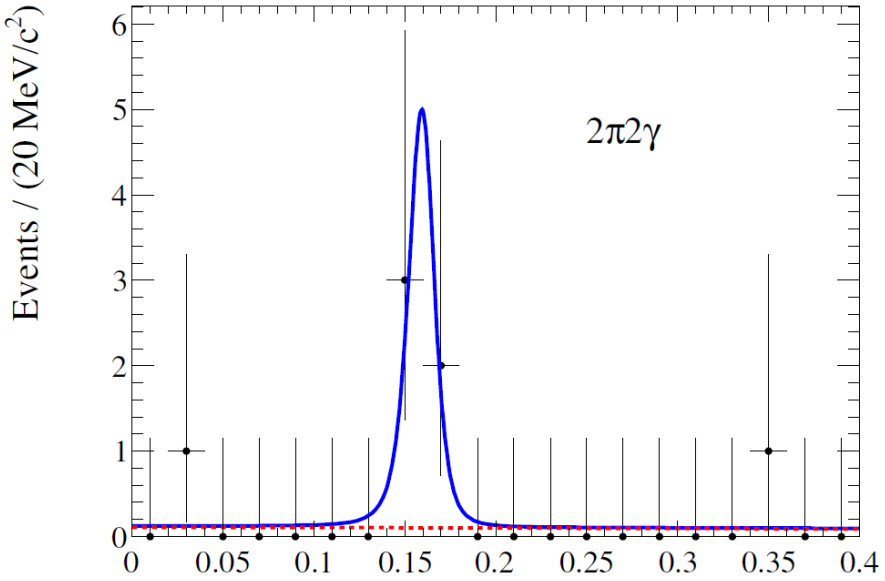
$\Upsilon(1S) \to \mu^+\mu^-$

$\eta' \to \rho\,\gamma \quad \to \pi^+\pi^-\,\gamma$

$\eta' \to \pi^+\pi^-\,\eta \to \pi^+\pi^-\,\gamma\gamma$

$$\Delta M = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$$





Signal shapes: from MC, background: broad Gaussian ($2\pi1\gamma$), linear ($2\pi2\gamma$)

Significances: 4.2σ ($2\pi1\gamma$), 4.1σ ($2\pi2\gamma$), combined: 5.7σ including systematics.

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Bondar, RM, Voloshin MPLA32,1750025(2017)

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$\Upsilon(1S)\,\eta$	$< 2 \times 10^{-3}$
$\Upsilon(2S)\,\pi^+\pi^-$	0.57 ± 0.06
$\Upsilon(4S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8
$\Upsilon(1S)\,\eta'$	0.70 ± 0.18

Results

$$\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S)) =$$
$$(3.43 \pm 0.88(\text{stat.}) \pm 0.21(\text{syst.})) \times 10^{-5}$$

$$R_{\eta'/\eta} = 0.20 \pm 0.06$$

Prediction: M. B. Voloshin, Mod. Phys. Lett. A **26**, 773 (2011)

hadron loops: $0.2 \le R_{\eta'/\eta} \le 0.6$

gluons: $R_{\eta'/\eta} \sim 25$

$\Rightarrow$ Measured $R_{\eta'/\eta}$ agrees with prediction of hadron loops model.

PRD98,091102(2018)

Energy scan of $e^+e^- \to \chi_{bJ}(1P)\ \pi^+\pi^-\pi^0$

Transition	Partial width (keV)
$\Upsilon(2S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	5.7 ± 0.5
$\Upsilon(1S)\,\eta$	$(9.3 \pm 1.5) \times 10^{-3}$
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$\Upsilon(4S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8
$\Upsilon(2S)\,\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)\,\eta$	45 ± 7
$\Upsilon(5S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\,\eta$	39 ± 11
$\Upsilon(1S)\,K^+K^-$	33 ± 11
$\Upsilon(2S)\,\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\,\eta$	204 ± 44
$\Upsilon(3S)\,\pi^+\pi^-$	153 ± 31
$\chi_{b1}(1P)\,\omega$	84 ± 20
$\chi_{b1}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	28 ± 11
$\chi_{b2}(1P)\,\omega$	32 ± 15
$\chi_{b2}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	33 ± 20
$\Upsilon_J(1D)\,\pi^+\pi^-$	~ 60
$\Upsilon_J(1D)\,\eta$	150 ± 48
$Z_b(10610)^\pm\pi^\mp$	2070 ± 440
$Z_b(10650)^\pm\pi^\mp$	1200 ± 300

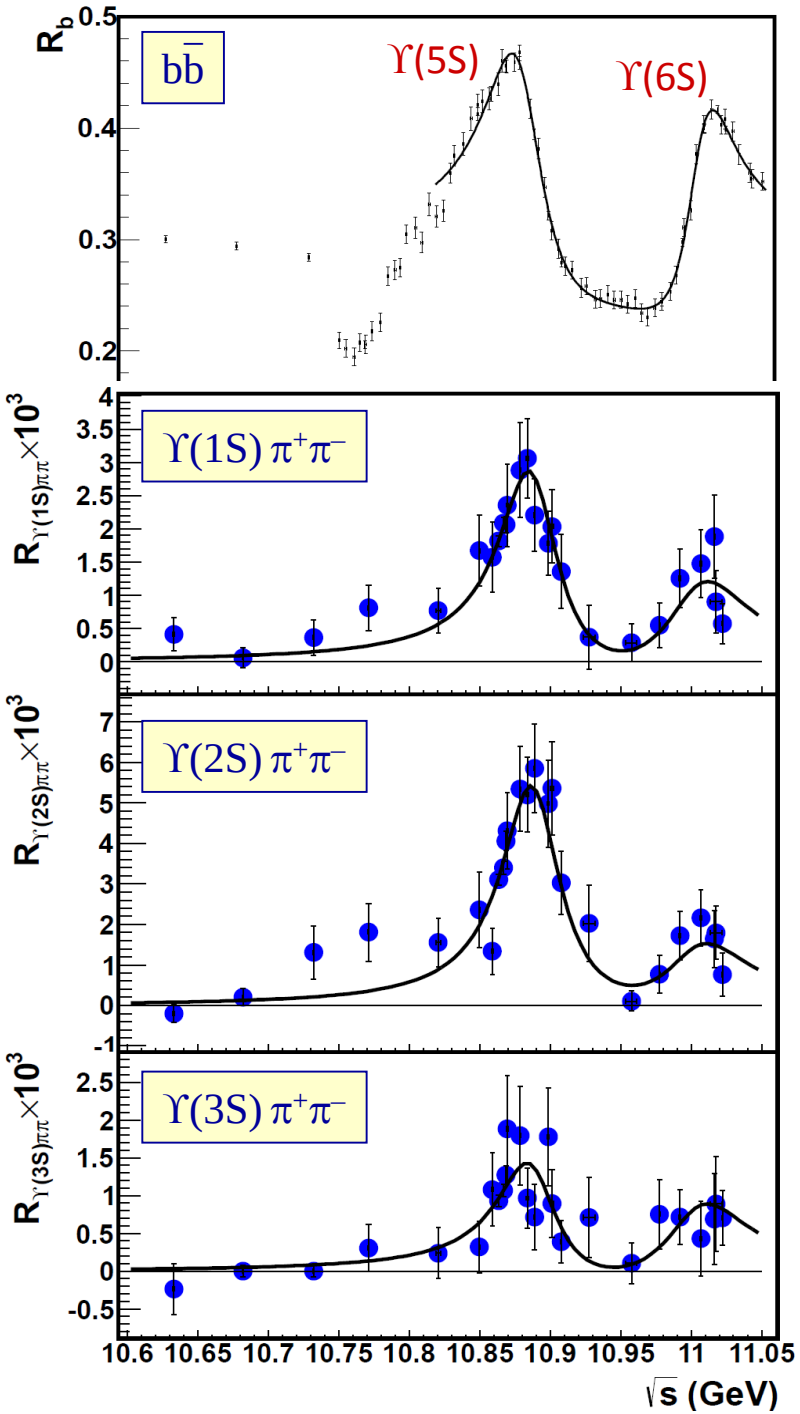
Transitions from Υ(4S), Υ(5S)
violate OZI rule and HQ spin symmetry

Measurements are performed in the peak of each resonance.

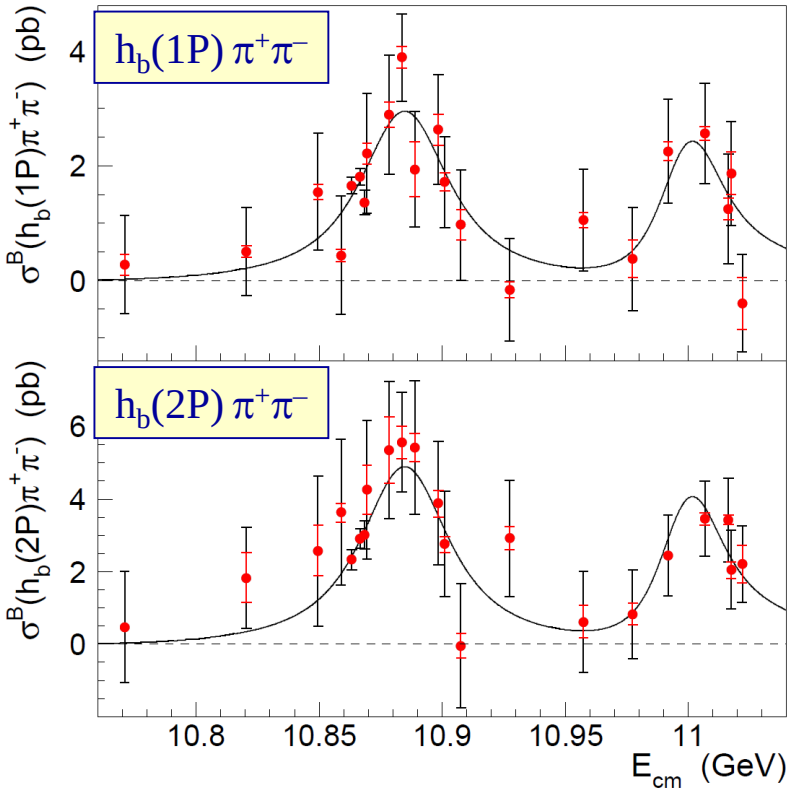
Mechanism: resonant / non-resonant ?

Bondar, RM, Voloshin
MPLA32,1750025(2017)

Belle energy scans



PRL117,142001(2016) PRD93,011101(2016)

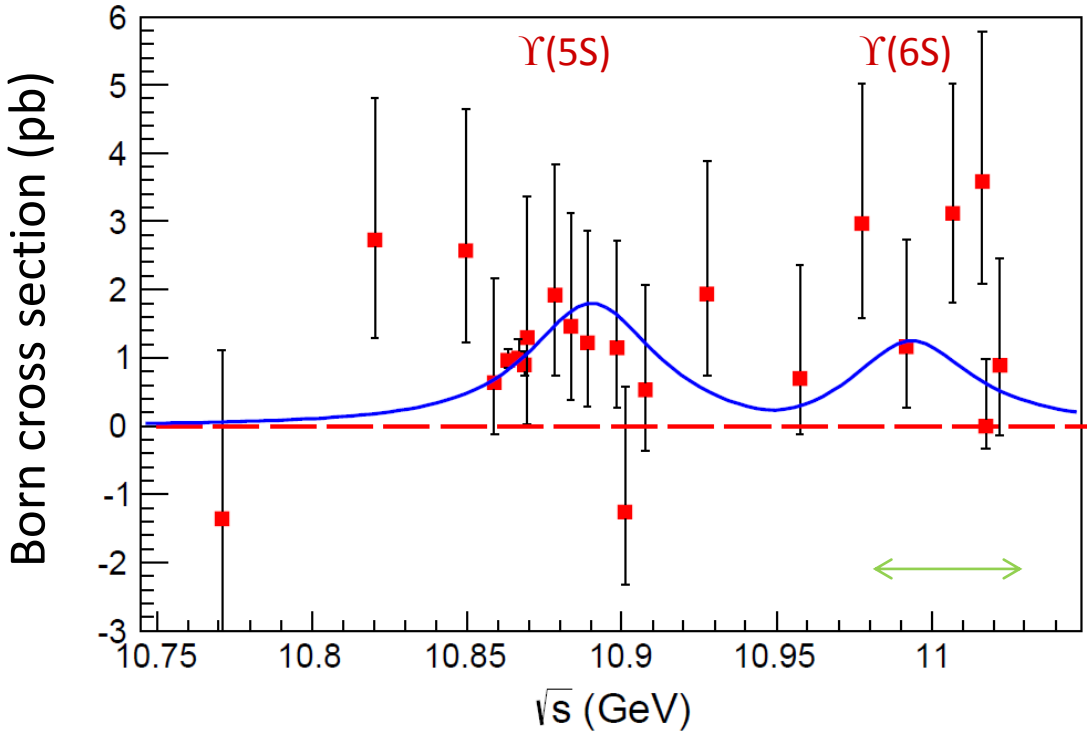


$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ and
$e^+e^- \to h_b(mP)\,\pi^+\pi^-$
proceed via $\Upsilon(5S)$, $\Upsilon(6S)$

Cross section of $e^+e^- \to \chi_{bJ}(1P)\,\pi^+\pi^-\pi^0$

Exclusive reconstruction: $\chi_{bJ}(1P) \to \Upsilon(1S)\,\gamma$ $\Upsilon(1S) \to \mu^+\mu^-$ or e^+e^-

Extraction of signal: 2D fit in $M(\Upsilon(1S)\,\gamma)$ vs. $M(\pi^+\pi^-\pi^0)$

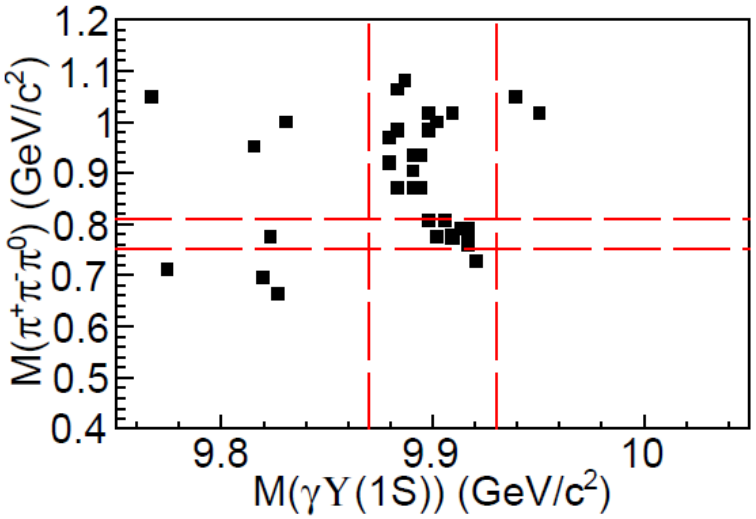


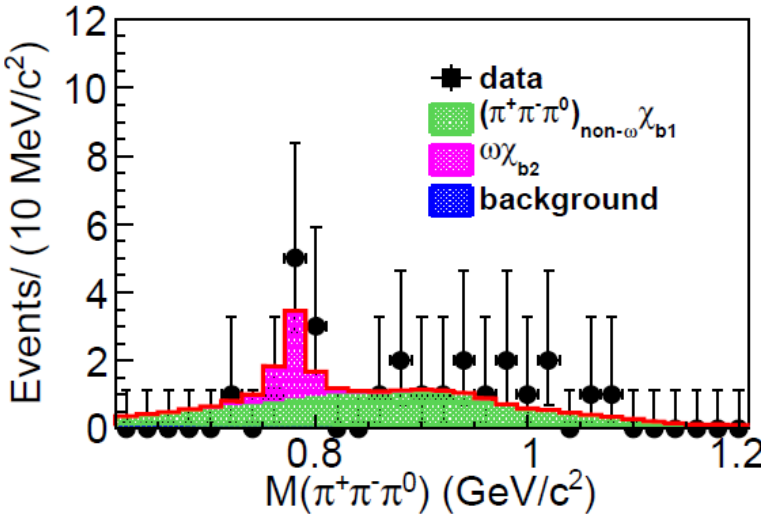
Cross section in scan data is similar to on-resonance measurement.

Non-zero values in the $\Upsilon(6S)$ region.

Accuracy is insufficient to establish production mechanism: via $\Upsilon(5,6S)$ or non-res.

Combined data in the $\Upsilon(6S)$ region





Observation of $e^+e^- \to \chi_{b1}\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$ 5.3σ

Evidence for $e^+e^- \to \chi_{bJ}\,\omega$ 4.0σ

No sign of $e^+e^- \to \chi_{bJ}\,\phi$ $\sigma < 1$pb

Interesting to perform energy scan with more data.

Conclusions

Recent Belle results on bottomonium:

Observation of $\Upsilon(2S) \to \eta_b(1S)\,\gamma$	PRL 121, 232001 (2018)
Observation of $\Upsilon(4S) \to \Upsilon(1S)\,\eta'$	PRL 121, 062001 (2018)
Energy scan of $e^+e^- \to \chi_{bJ}(1P)\,\pi^+\pi^-\pi^0$	PRD 98, 091102 (2018)

On-going Belle analyses:

Energy scan of $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$,.. cross sections

Update on line shape of Z_b states in elastic channels

Search for $\Upsilon(5S) \to W_{bJ}\,\gamma \to (\Upsilon(1S)\pi^+\pi^-)\,\gamma$

Search for $\Upsilon(4S,5S) \to \eta_b(1S,2S)\,\omega$ …

Your wishes on what should (still) be studied at Belle ?