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PNNL-SA-93521

Bottomonium(-like) State Spectroscopy at B-Factories

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Rencontres de Physique de la Vallee d'Aoste
February 26, 2013

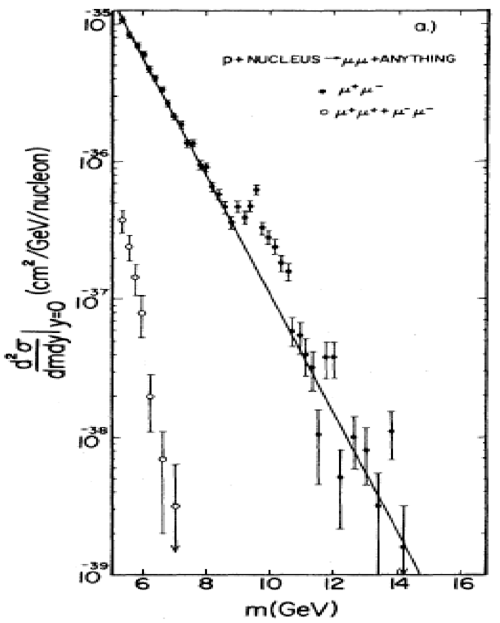
Introduction

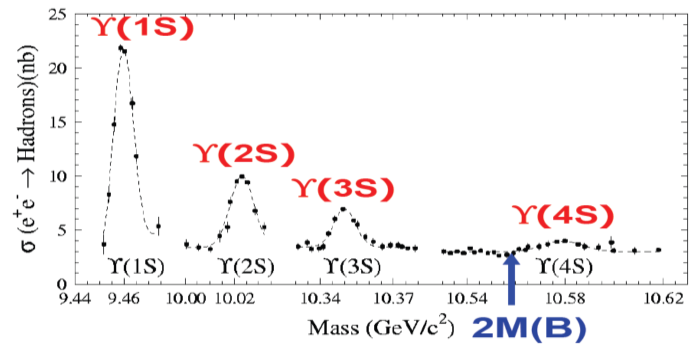
- The ϒ system was discovered in 1977. These resonances were identified as bound states of $b\bar{b}$ quark pairs. The existence of these states was confirmed in the *e+e−* → ϒ process.
- In the *e+e−* → ϒ process, the entire collision energy of the initial *e+e−* turns into the rest mass of the ϒ state. The beam energy must be matched to the resonance mass.

Annu. Rev. Nucl. Part. Sci., 43, 333 (1993)

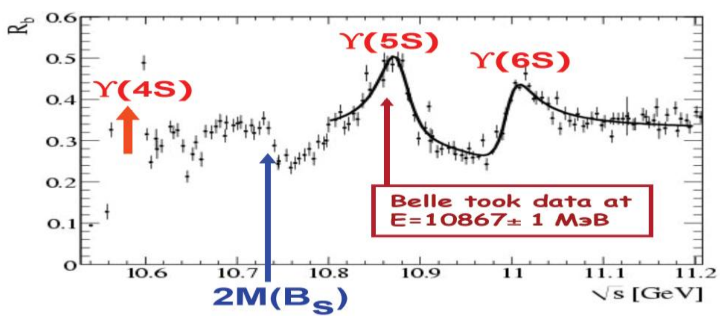
arXiv:1212.6552

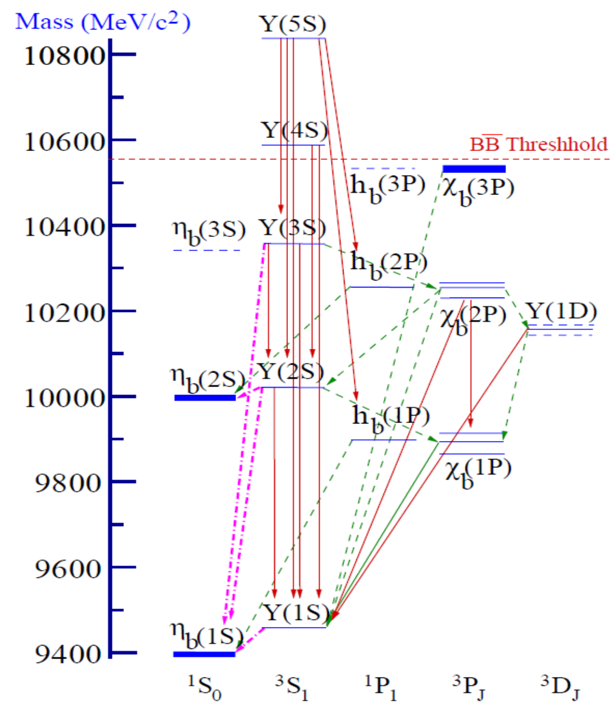
PRL39, 253 (1977)





PRL102, 012001 (2009)





Heavy quarkonium is an ideal tool to study the “meson” which carries spin & angular momentum and described by (mostly non-relativistic) QCD. Godfrey-Isgur, PRD32,169(1985)

Belle and BaBar Experiments

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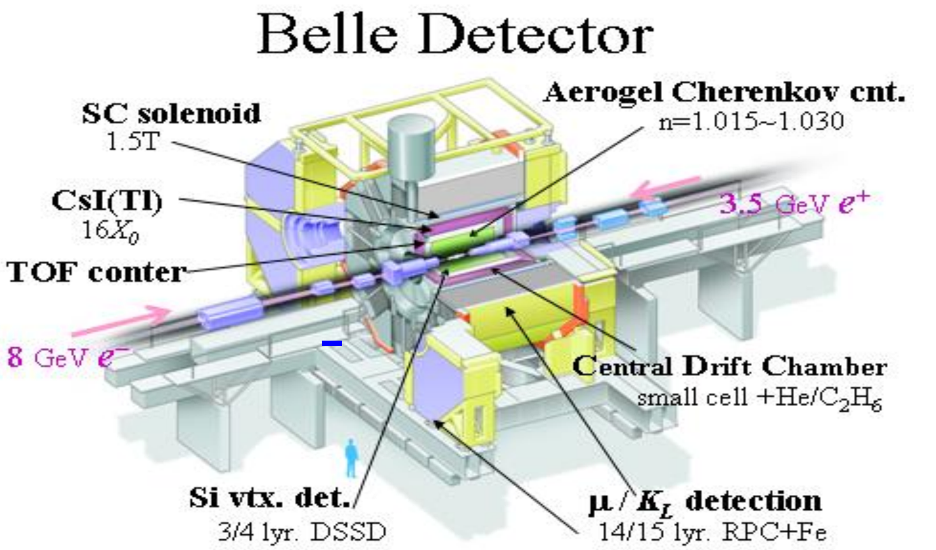
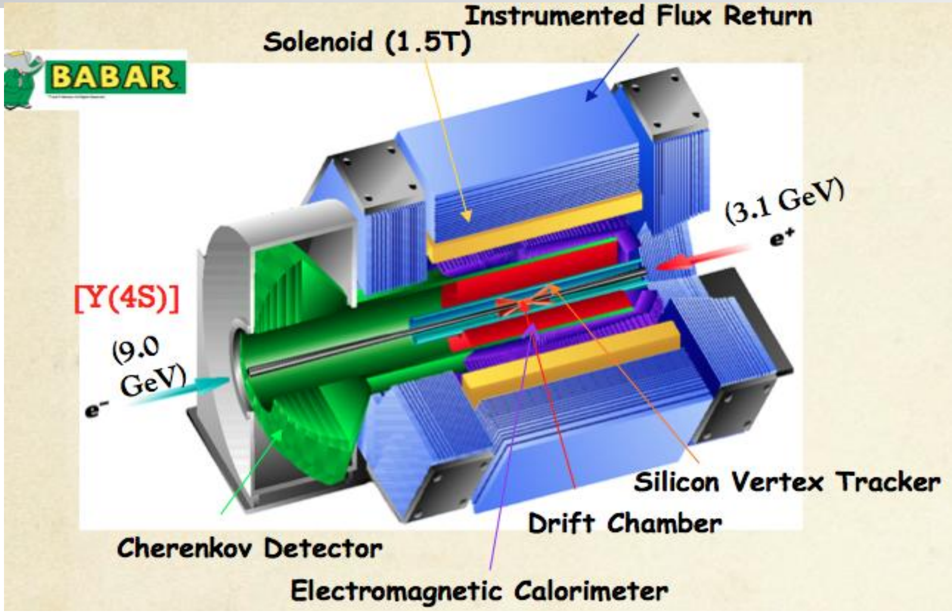
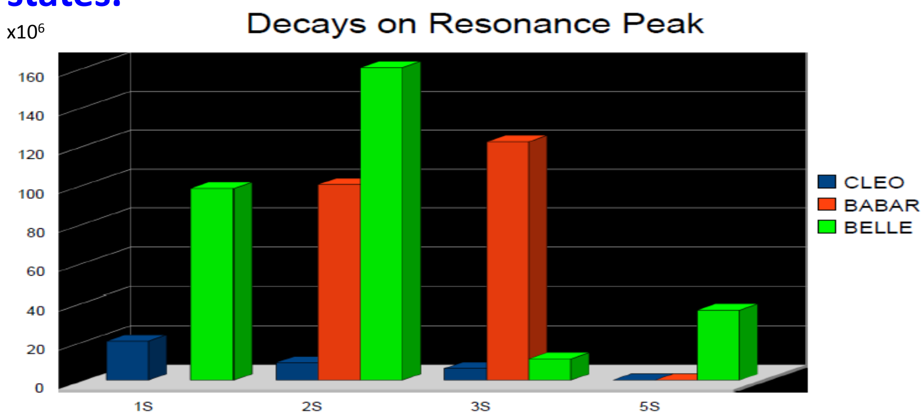
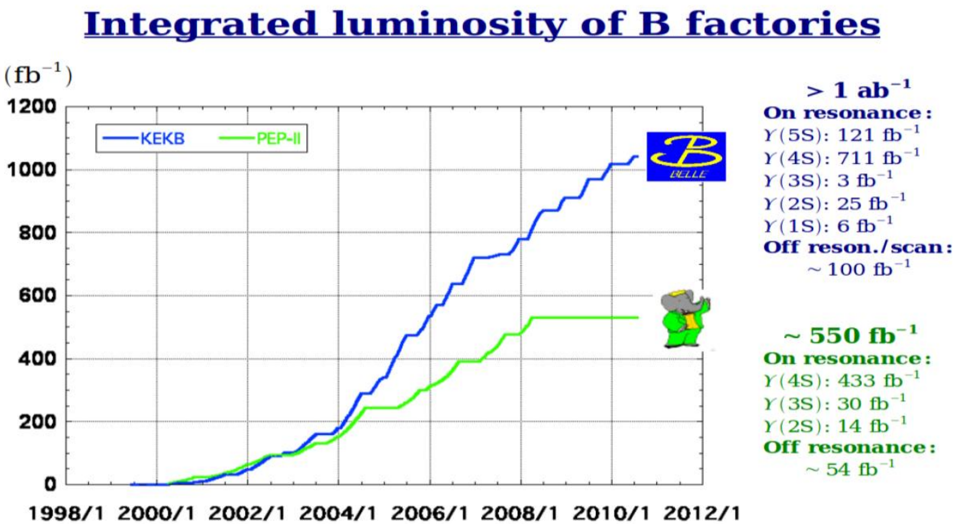




***e+e−* colliders produces a particularly clean environment for studies of the properties of the ϒ states.**





Puzzles of $\Upsilon(5S)$ Decays

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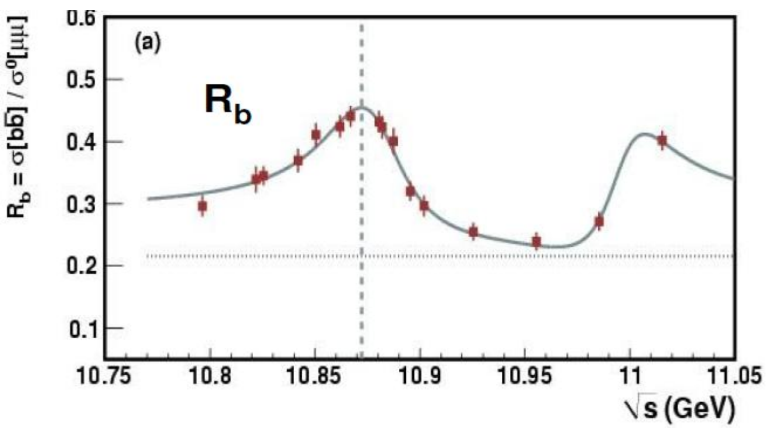
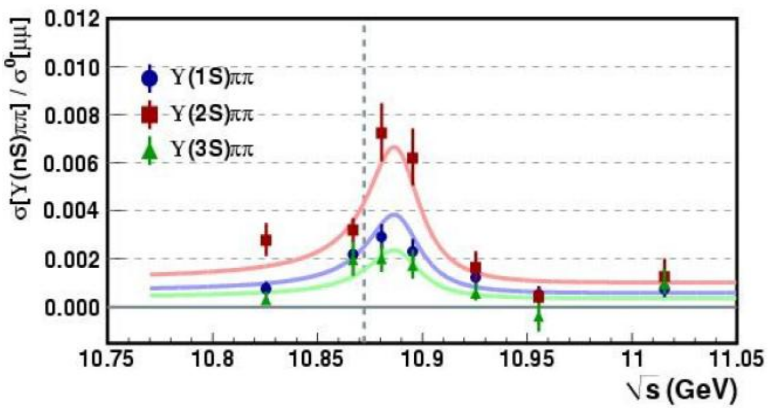
Anomalously large $\Upsilon(nS)\pi\pi$ transitions were observed at the $\Upsilon(5S)$ by Belle with 21 fb^{-1}.

PRD82, 091106R(2010) **PRL100, 112001(2008)**

R_b and $\sigma(\Upsilon(nS)\pi\pi)$ shapes are different (2σ).





	$\Gamma(\text{MeV})$
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

- **Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$**
  JETP Lett 87, 147 (2008)
  PRD78, 034022 (2008)
- **Exotic resonance Y_b near $\Upsilon(5S)$ analogue of Y(4260) resonance with $\Gamma(J/\psi\ \pi\pi)$**
  PRD74, 017504 (2006)
  PRL104, 162001 (2010)
- **Tetraquarks**
  Eur. Phys. J. C61, 411 (2009)
  Eur. Phys. J. C71, 1534 (2011)

$\Upsilon(5S)$ is very interesting and not yet understood.

Evidence for the $h_b(1P)$

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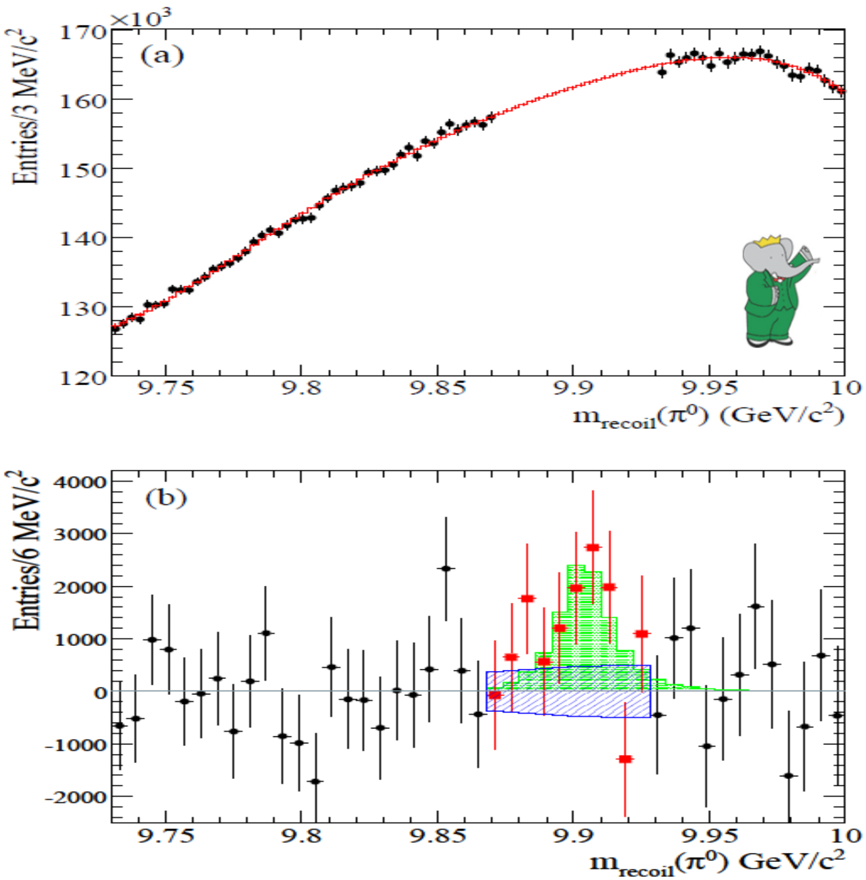
Evidence from BaBar: PRD 84, 091101(R) (2011)
Using a sample of 122 x 10^6 $\Upsilon(3S)$ events only weak signal of $h_b(1P)$ – spin-singlet partner of the P-wave $\chi_{bJ}(1P)$ states was observed.



In the sequential decay:

$\Upsilon(3S) \rightarrow \pi^0 h_b(1P) \rightarrow \gamma \eta_b(1S)$

3.1 σ excess of events above background
M = 9902 ± 4(stat.) ± 2(syst.) MeV/c^2

$B(\Upsilon(3S) \rightarrow \pi^0 h_b) \times B(h_b \rightarrow \gamma \eta_b) =$
$= (4.3 \pm 1.1 \pm 0.9) \times 10^{-4}$

h_b(1P, 2P) from Υ(5S)

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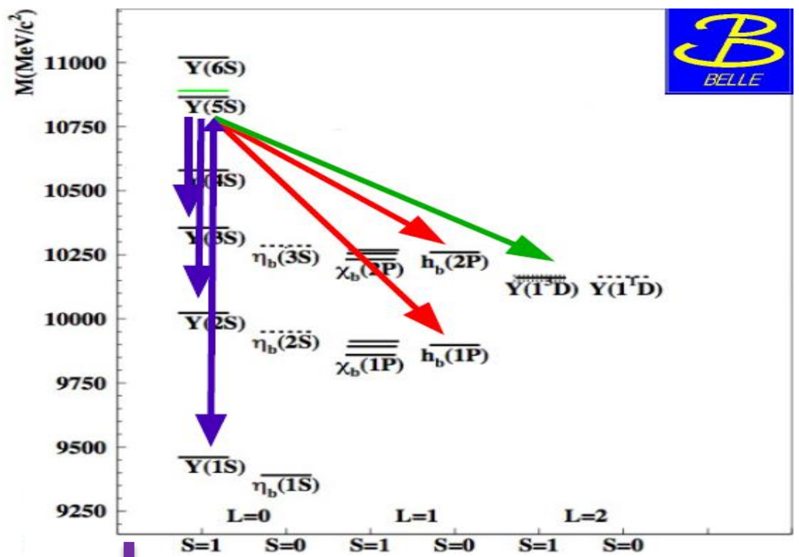
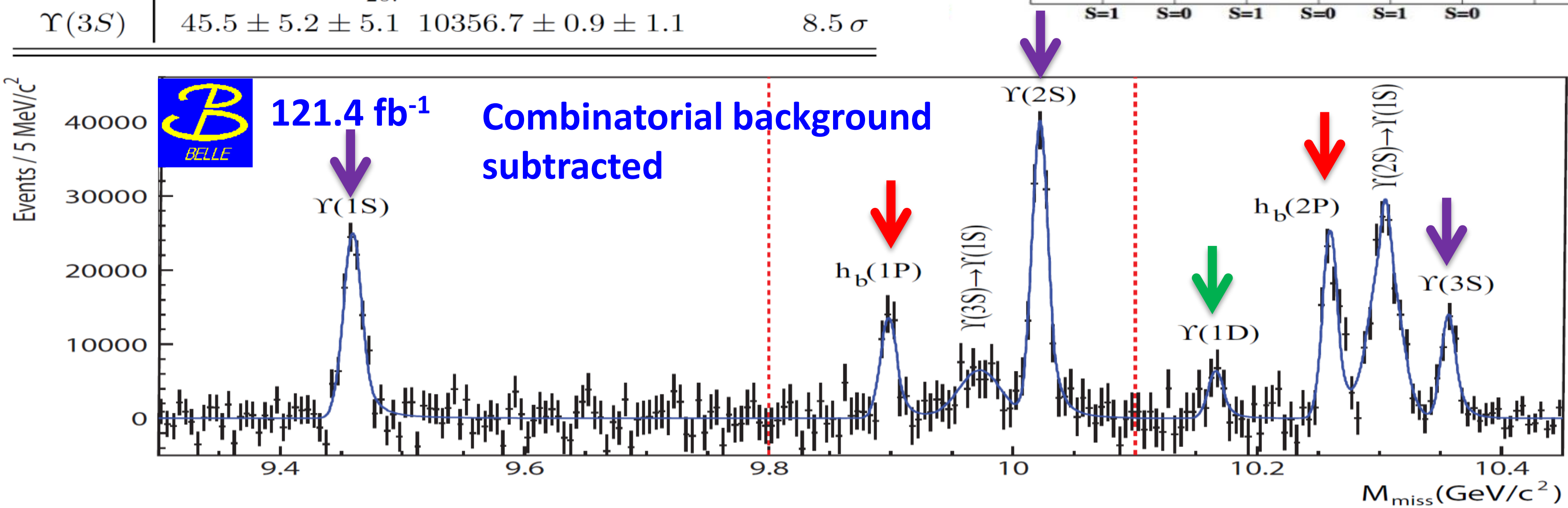
Belle: Inclusive search e+e- $\to$ Υ(5S) $\to$ $\pi^+\pi^-$ + …

Simultaneous discovery of h_b(1P) and h_b(2P)

PRL 108, 032001 (2012)

	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$105.0 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.1\,\sigma$
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	$6.1\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.8 \pm 8.7 \pm 6.8$	$10022.2 \pm 0.4 \pm 1.0$	$17.1\,\sigma$
$\Upsilon(1D)$	22.4 ± 7.8	10166.1 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.0 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.3\,\sigma$
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$





h_b Results

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- $h_b(nP)$ is the singlet partner of $\chi_{bJ}(nP)$. Hyperfine Splitting: M(singlet)-M(triplet).
  - $M_{swa}(\chi_{bJ}(nP)) = (M\chi_{b0} + 3M\chi_{b1} + 5M\chi_{b2}) / 9$
  - Deviations from Spin Weighted Average of χ_{bJ} masses consistent with zero (PRL 109, 232002 (2012)).
  - $\Delta M_{HF} = M(h_b(nP)) - M_{swa}(\chi_{bJ}(nP))$

$\Delta M_{HF} = (+0.8 \pm 1.1)$ MeV/c^2 for 1P states

$\Delta M_{HF} = (+0.5 \pm 1.2)$ MeV/c^2 for 2P states

- The heavy quark spin flip is predicted to suppress the $\pi^+\pi^- h_b$ transition.

Spin flip

$$R = \frac{\Gamma(\Upsilon(5S) \to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(2S)\to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.46 \pm 0.08 \,^{+0.07}_{-0.12} & \text{for the } h_b(1P) \\ 0.77 \pm 0.08 \,^{+0.22}_{-0.17} & \text{for the } h_b(2P) \end{cases}$$

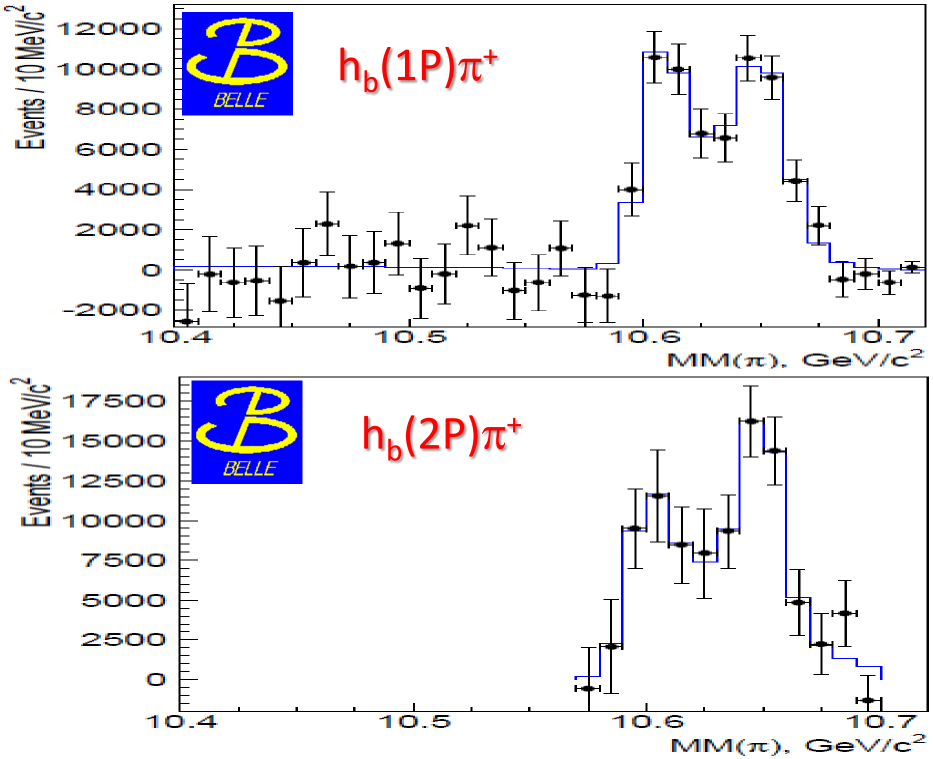
No Spin flip

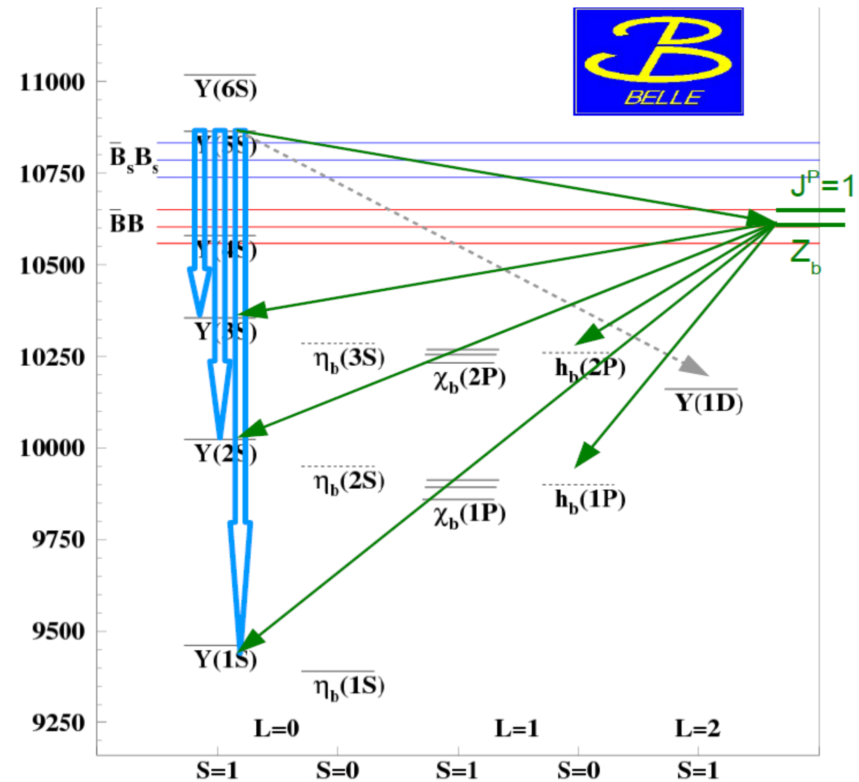
No suppression

- $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ decays seem exotic.

Observation of Z_b in $h_b(1P, 2P)\pi^+\pi^-$ Final States

Belle has discovered two charged bottomonium-like resonances **PRL 108, 122001 (2012)**





- $MM(\pi^{+/-})$ to look at $h_b\pi^{-/+}$.
- $\Upsilon(5S)\to h_b(1P)\pi^+\pi^-$ is saturated with Z_{b1} and Z_{b2} (zero consistent non-resonant amplitude).
- $\Upsilon(5S)\to h_b(2P)\pi^+\pi^-$ has very limited phase space but consistent with Z_{b1} and Z_{b2}.

$\Upsilon(5S)\rightarrow\Upsilon(1S, 2S, 3S)\pi^+\pi^-$ Through Z_b

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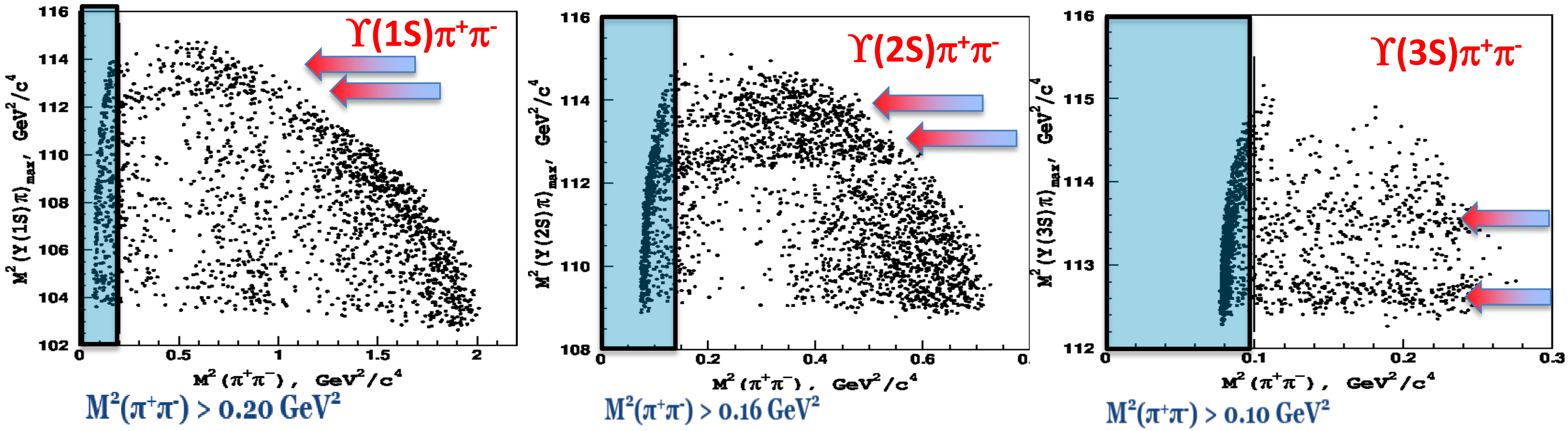
Belle: Charged Z_b states are observed in 5 final states. PRL 108, 122001 (2012)



Region with large backgrounds from photon conversions were excluded

Signal amplitude parameterization:

$$S(s1,s2) = A(Z_{b1}) + A(Z_{b2}) + A(f_0(980)) + A(f_2(1275)) + A_{NR}$$
$$A_{NR} = C_1 + C_2\cdot m^2(\pi\pi)$$

Parameterization of the NR-amplitude: PRD74, 054022 (2006)

Z_b amplitudes are parameterized by Breit-Wigner functions and symmetrized with respect to interchange of the two pions: $A(Z_b) = BW(s_1,M_Z,\Gamma_Z) + BW(s_2,M_Z,\Gamma_Z)$

$A(f_0(980))$ - Flatte function

$A(f_2(1275))$ - Breit-Wigner function

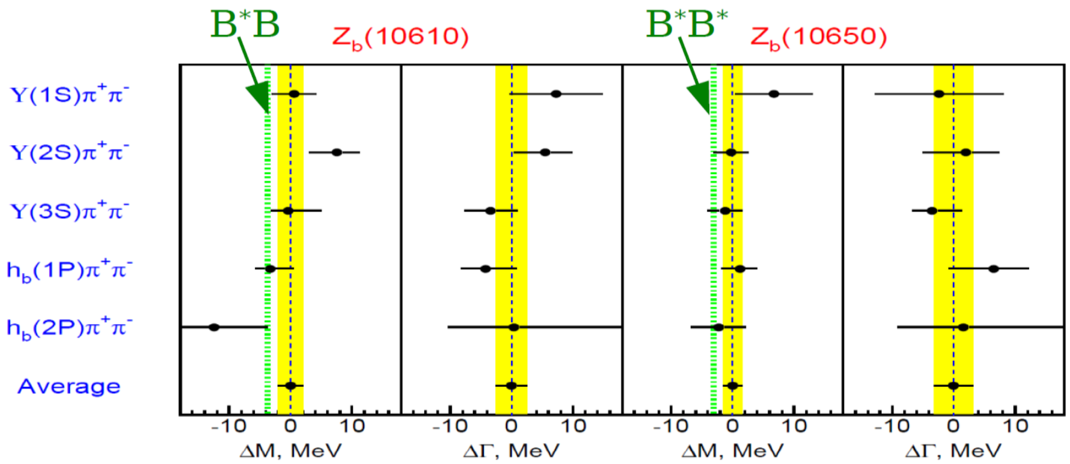
Charged $Z_b(10610)$ and $Z_b(10650)$ Parameters

Belle analyses results:

$\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$, (m=1,2) — **PRL 108, 032001 (2012)**

$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$, (n=1, 2, 3) — **PRL 108, 122001 (2012)**

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$ (MeV/c^2)	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$ (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}
$M[Z_b(10650)]$ (MeV/c^2)	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$ (MeV)	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7^{+11}_{-7}$
Relative normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Relative phase (deg)	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$



- **Parameters consistent between all five studied final states.**
- **Masses just above $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds.**
- **Relative phases are swapped for Υ(~0°) and h_b (~180°) final states (expectation from a 'molecular' model)**

Evidence for a $Z_b^0(10610)$ in $\Upsilon(5S)\to\Upsilon(1S, 2S)\pi^0\pi^0$ Decays

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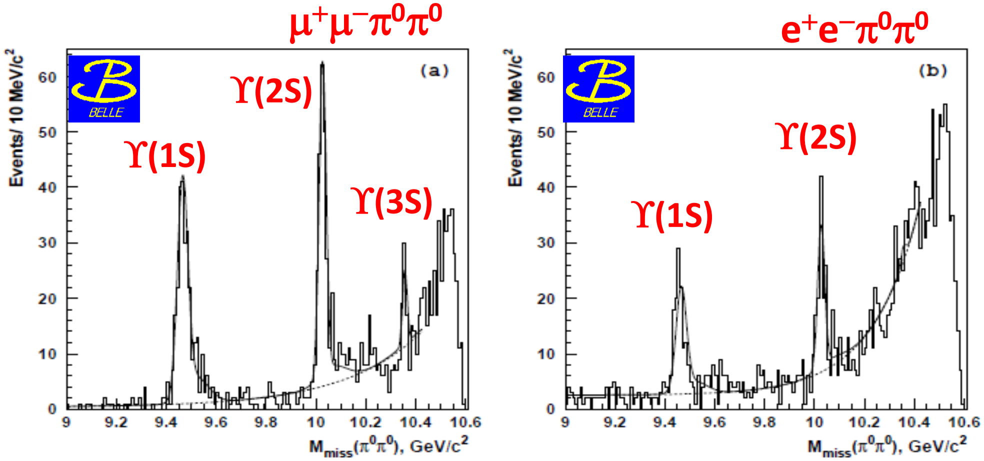
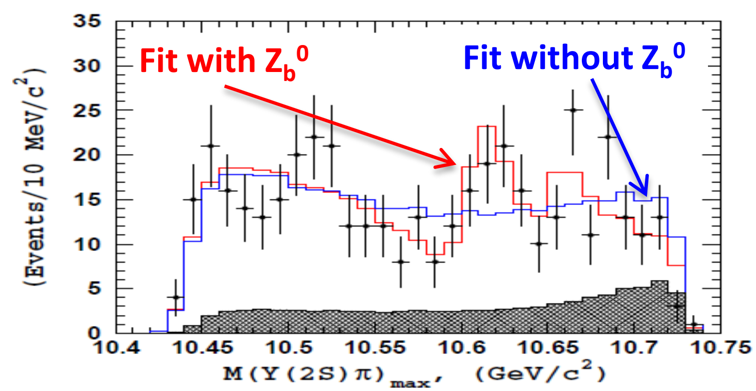
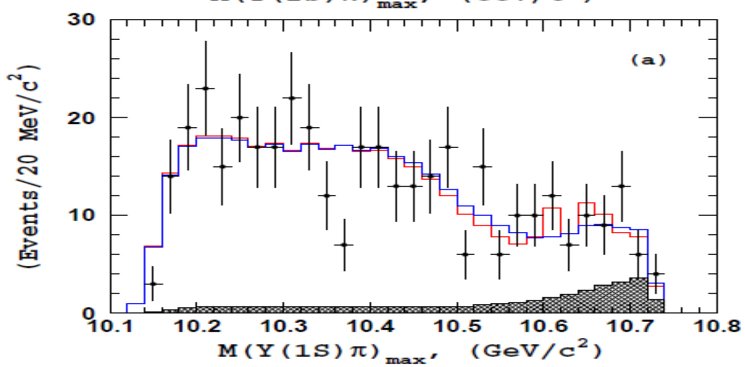
Observation of charged $Z_b^{\pm}$ states motivated search for a neutral partner of these states in the resonant substructure of $\Upsilon(5S)\to\Upsilon(nS)\pi^0\pi^0$.

Belle reported evidence for the $Z_b^0(10610)$ state (arXiv: 1207.4345).
In a Dalitz plot analysis of $\Upsilon(5S)\to\Upsilon(2S)\pi^0\pi^0$ decays 4.9σ evidence of $Z_b^0(10610)$ signal was found.







- **Observation of $\Upsilon(5S)\to\Upsilon(1S, 2S)\pi^0\pi^0$ decays.**
  - **$B[\Upsilon(5S)\to\Upsilon(1S)\pi^0\pi^0] = (2.25\pm0.11\pm0.20)\times 10^{-3}$**
  - **$B[\Upsilon(5S)\to\Upsilon(2S)\pi^0\pi^0] = (3.66\pm0.22\pm0.48)\times 10^{-3}$**
- **$M(Z_b^0(10610)) = 10609^{+8}_{-6} \pm 6$ MeV/c^2**

Observation of η_b(1S) State

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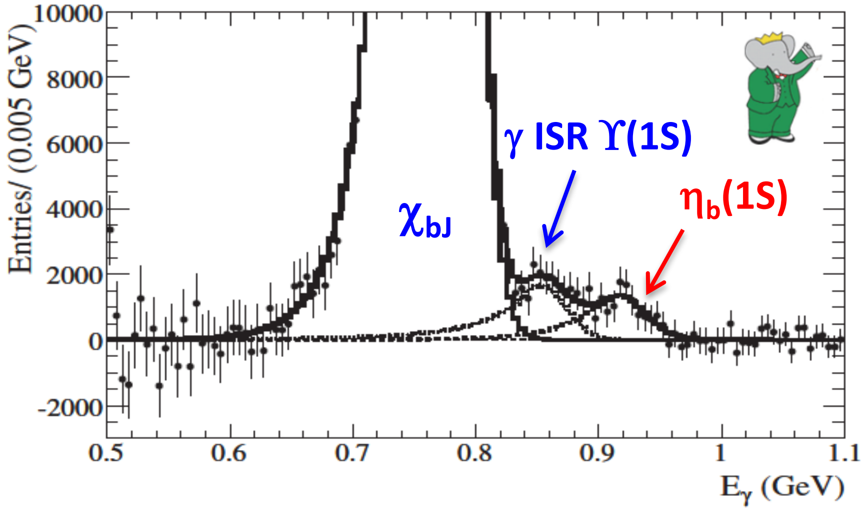
BaBar observed the bottomonium ground state η_b(1S) in radiative transitions from Υ(3S).

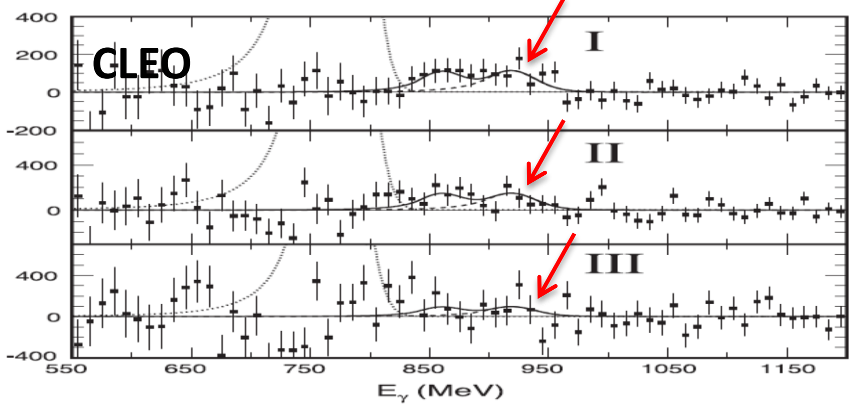
PRL 101, 071801 (2008)



- Υ(3S) sample – 109 x 10^6
- 10σ signal of η_b(1S) at $E\gamma = 921^{+2.1}_{-2.8} \pm 2.4$ MeV corresponds $M(\eta_b(1S)) = 9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV/c^2
- $\Delta M_{HF} = 71.4^{+2.3}_{-3.1} \pm 2.7$ MeV/c^2
- $B[\Upsilon(3S) \rightarrow \eta_b(1S)\gamma] = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$

Weakly confirmed by CLEO with 6×10^6 Υ(3S)

PRD 81, 031104(R) (2010)



- Υ(3S) sample – 6 x 10^6
- $M(\eta_b(1S)) = 9391.8 \pm 6.6 \pm 2.0$ MeV/c^2
- $\Delta M_{HF} = 68.5 \pm 6.6 \pm 2.0$ MeV/c^2
- $B[\Upsilon(3S) \rightarrow \eta_b(1S)\gamma] = (7.1 \pm 1.8 \pm 1.3) \times 10^{-4}$

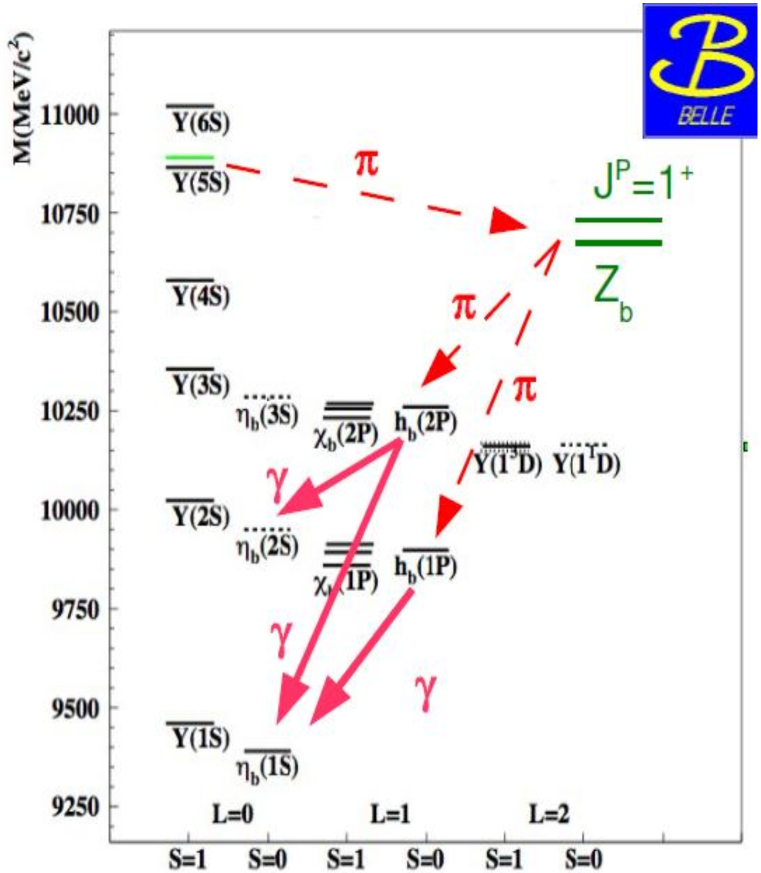
$h_b(1P, 2P) \rightarrow \gamma\eta_b(1S, 2S)$

- $h_b(1P, 2P)$ are predicted to have large BF for radiative decays to $\eta_b(1S, 2S)$ (PRD 66, 014062 (2002)).
  - $h_b(1P) \rightarrow \gamma\eta_b(1S) = 41\%$
  - $h_b(2P) \rightarrow \gamma\eta_b(1S) = 13\%$
  - $h_b(2P) \rightarrow \gamma\eta_b(2S) = 19\%$
- Belle observed $(50 \pm 7.8\ ^{+4.5}_{-1.9}) \times 10^3$ $h_b(1P)$ and $(84 \pm 6.8\ ^{+30}_{-10}) \times 10^3$ $h_b(2P)$.
- Large samples of $h_b(1P, 2P)$ allowed Belle to provide a search for $\eta_b(1S, 2S)$ states.

Decay Chain:

$\Upsilon(5S) \rightarrow Z^+_b\ \pi^-$
 $\hookrightarrow h_b(nP)\ \pi^+$
  $\hookrightarrow \eta_b(mS)\ \gamma$

Reconstructed



Observation of $h_b(1P, 2P) \to \gamma\eta_b(1S, 2S)$

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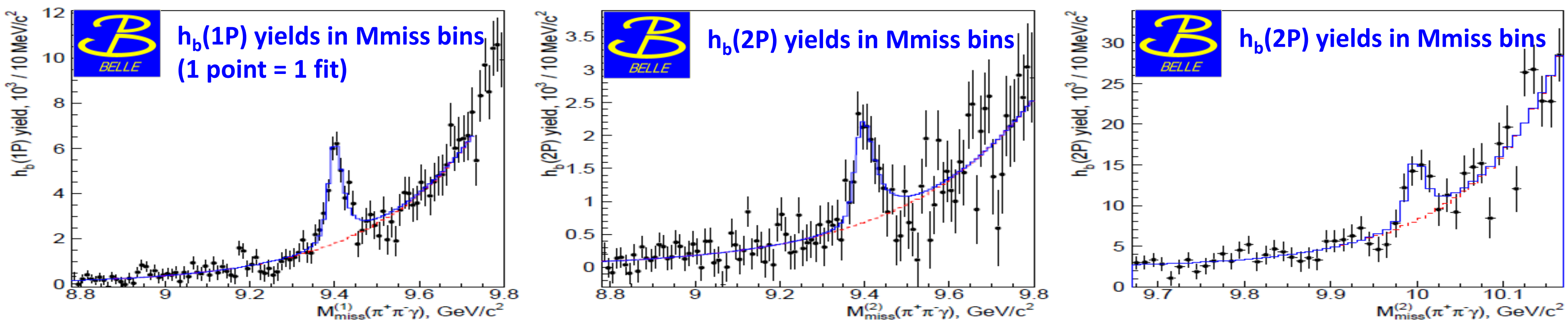
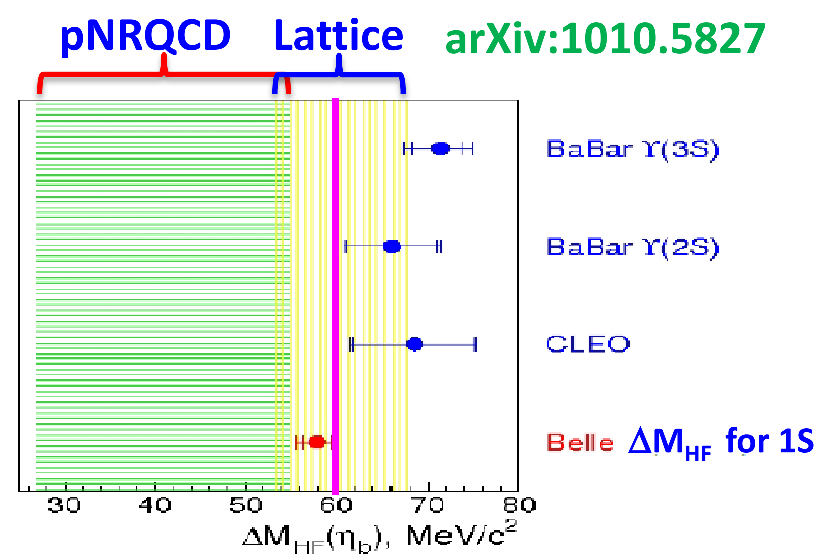
Missing mass technique was used to identify signals:

$\Delta M_{miss}(\pi^+\pi^-\gamma) \equiv M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + M[h_b]$

PRL 109, 232002 (2012)



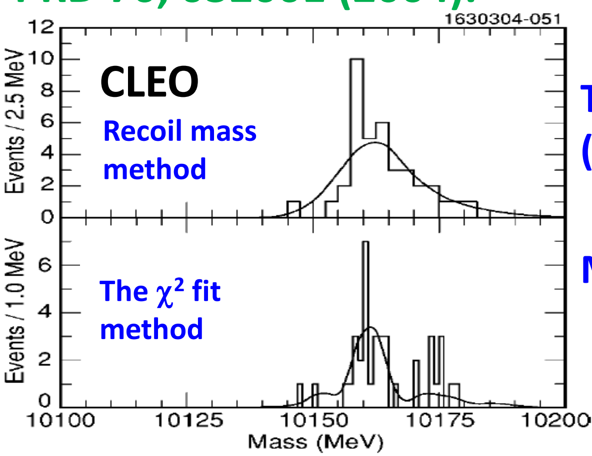
- $M(\eta_b(1S))$=9402.4 ± 1.5± 1.8 MeV/c^2
- ΔM_{HF} = 57.9 ± 2.3 MeV/c^2 for 1S
- $M(\eta_b(2S))$=9999.0 ± 3.5 $^{+2.8}_{-1.9}$ MeV/c^2
- ΔM_{HF} = 24.3 $^{+2.8}_{-1.9}$ MeV/c^2 for 2S



Observation of Υ(1D)

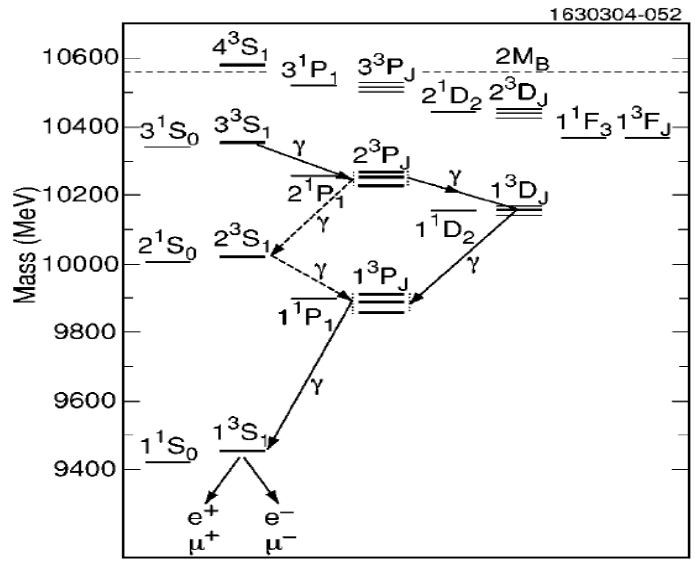
CLEO found first and only one L=2 state in radiative decay chain: $\Upsilon(3S)\rightarrow\chi_b(2P)\gamma\rightarrow\Upsilon(1D)\gamma\gamma\rightarrow\chi_b(1P)\gamma\gamma\gamma\rightarrow\Upsilon(1S)\gamma\gamma\gamma\gamma$

PRD 70, 032001 (2004).



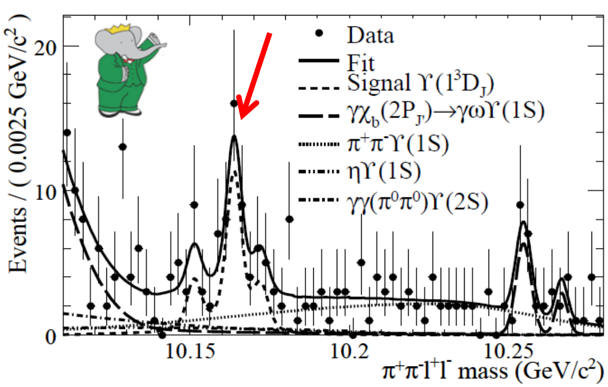
The product branching ratio:
$(2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$

Mass = $(10161.1 \pm 0.6 \pm 1.6)$ MeV



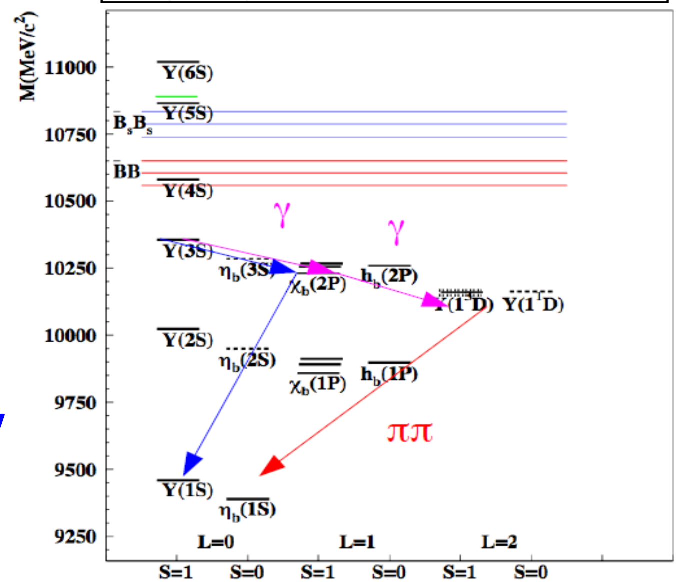
BaBar $\Upsilon(3S)\rightarrow\gamma\gamma\Upsilon(1D)\rightarrow\gamma\gamma\pi\pi\Upsilon(1S)$

PRD 82, 111102 (2010) .



Υ(1D) was produced in transition:
$\Upsilon(3S)\rightarrow\gamma\chi_{bJ}(2P)\rightarrow\gamma\gamma\Upsilon(1D)$.

Mass = $(10164.5 \pm 0.8 \pm 0.5)$ MeV



Observation of $\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$

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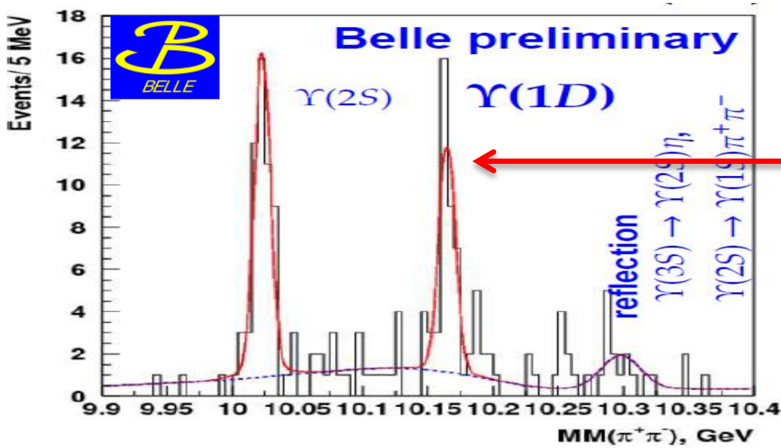
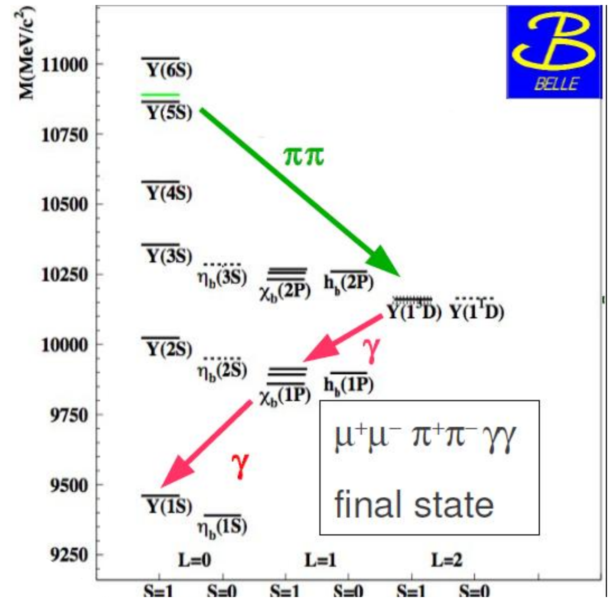
Belle measured a new production chain:

$\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^- \rightarrow \chi_b(1P)\gamma\pi^+\pi^- \rightarrow \Upsilon(1S)\gamma\gamma\pi^+\pi^-$

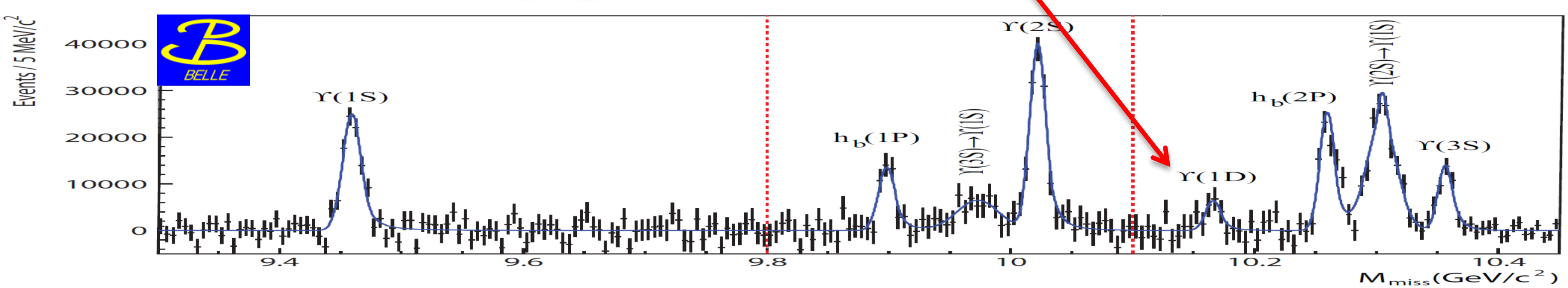




Significance:

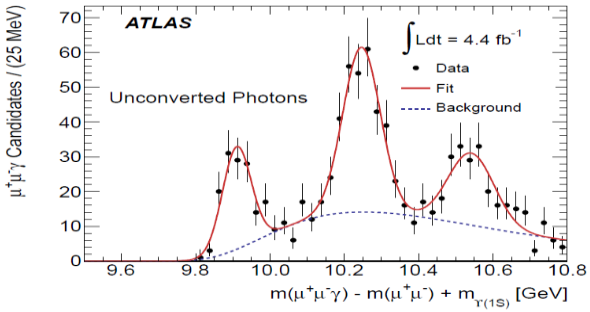
Exclusive - 9σ

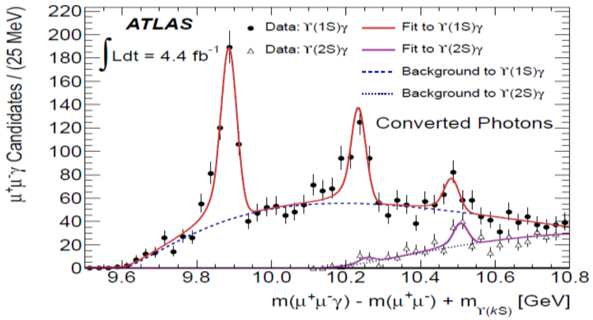
Inclusive - 2.4σ

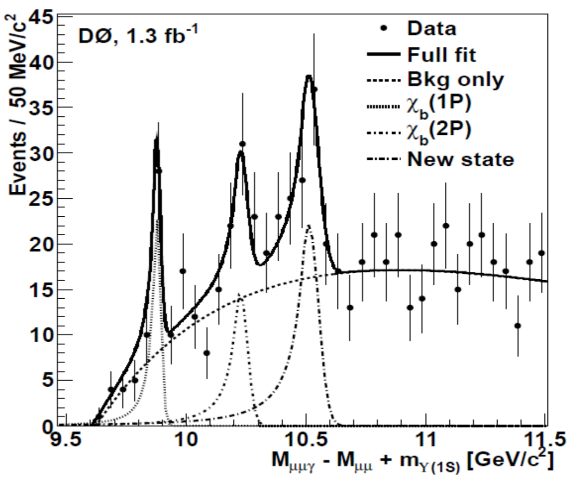


Belle Preliminary: Product B = (2.0 ±0.4 ±0.3) x 10^{-4}

Observation of χ_b(3P) States







ATLAS. **PRL 108, 152001 (2012)**

χ_b quarkonium states were reconstructed with the ATLAS detector. pp collisions @ $s^{1/2}$ = 7.0 TeV. The data used corresponds to 4.4 fb^{-1} of integrated luminosity.

Decay modes:

$\chi_b(nP) \to \gamma\ \Upsilon(1S,2S) \to \mu+\mu-$

Photon was identified from oppositely charged tracks intersecting at a conversion vertex.

χ_b(3P) state was observed @ $10.530 \pm 0.005(stat.) \pm 0.009(syst.)$ GeV/c^2 for converted photon and @ $10.541 \pm 0.011(stat.) \pm 0.030(syst.)$ GeV/c^2 for unconverted photon.

Experiment D0. **PRD 86 031103(R) (2012)**

Υ(1S) was detected by its decay into $\mu+\mu-$.

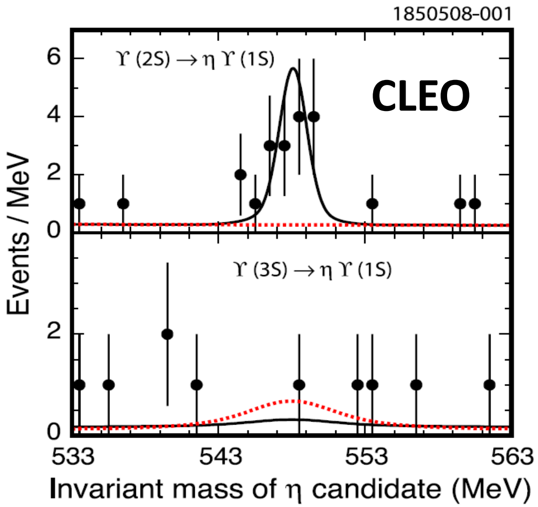
χ_b(3P) state (65 $\pm$ 11 events) was observed @ $10.551 \pm 0.014(stat.) \pm 0.017(syst.)$ GeV/c^2

η Transitions: $\Upsilon(nS) \to \Upsilon(mS)\eta$

arXiv: hep-ph/0601044v2

- QCD multipole expansion model predicts suppression transitions between bottomonia via η meson with respect to di-pion (η – transition requires a spin flip).

CLEO observed $\Upsilon(2S) \to \Upsilon(1S)\eta$ with a branching fraction $B=(2.1^{+0.7}_{-0.6} \pm 0.3) \times 10^{-4}$
PRL 101, 192001 (2008)



η – transitions were observed by BaBar experiment.
PRD 84, 092003 (2011), PRD 78, 112002 (2008)

BaBar: $B(\Upsilon(2S) \to \Upsilon(1S)\eta) = (2.39 \pm 0.31 \pm 0.14) \times 10^{-4}$
BaBar: $B(\Upsilon(3S) \to \Upsilon(1S)\eta) < 1 \times 10^{-4}$

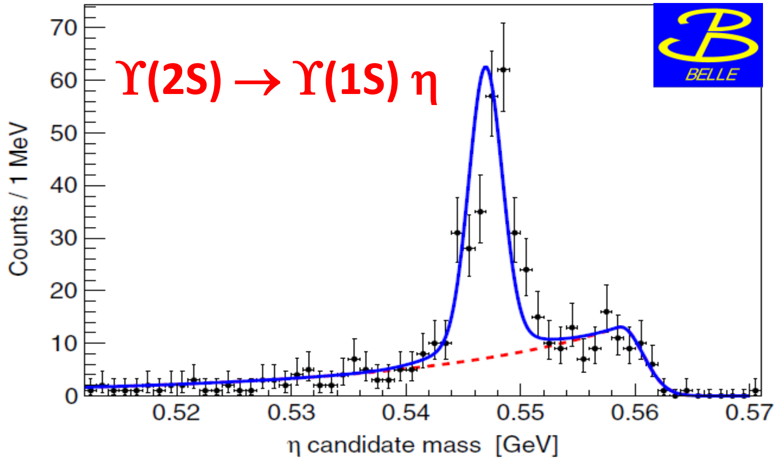
BaBar: $B(\Upsilon(4S) \to \Upsilon(1S)\eta) = (1.96 \pm 0.06 \pm 0.09) \times 10^{-4}$
BaBar: $B(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (0.80 \pm 0.064 \pm 0.027) \times 10^{-4}$

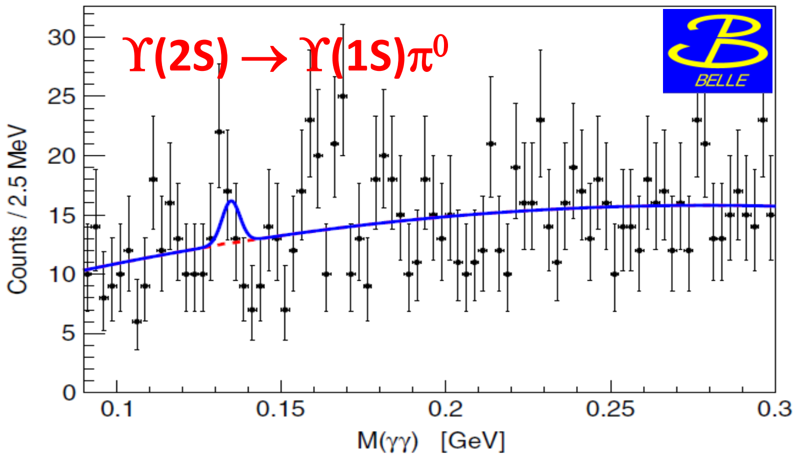
The branching fraction for the $\Upsilon(4S) \to \Upsilon(1S)\eta$ decay is larger than the branching fraction for $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$, which is unexpected when compared to all other known charmonium and bottomonium transitions.

Transitions of $\Upsilon(2S) \to \Upsilon(1S)\ \eta, \pi^0$

Belle measured a transition $\Upsilon(2S) \to \Upsilon(1S)\ \eta, \pi^0$

PRD 87, 011104(R) (2013)





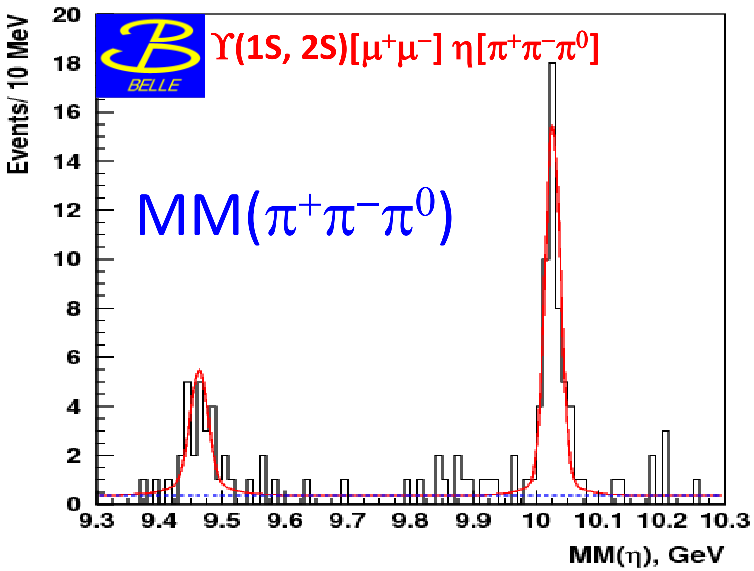
arXiv:1212.6552		CLEO	BaBar	Belle
$\Upsilon(2S)$	$N(\Upsilon)\ (10^6)$	9.32 ± 0.14	98.6 ± 0.9	158 ± 4
	$\to \eta\Upsilon(1S)$	$2.1^{+0.7}_{-0.6} \pm 0.3$	$2.39 \pm 0.31 \pm 0.14$	$3.57 \pm 0.25 \pm 0.21$
	$\to \pi^0\Upsilon(1S)$	< 1.8	–	0.41
$\Upsilon(3S)$	$N(\Upsilon)\ (10^6)$	5.88 ± 0.10	121.8 ± 1.2	–
	$\to \eta\Upsilon(1S)$	< 1.8	< 1.0	–
	$\to \pi^0\Upsilon(1S)$	< 0.7	–	–
	$\to \pi^0\Upsilon(2S)$	< 5.1	–	–

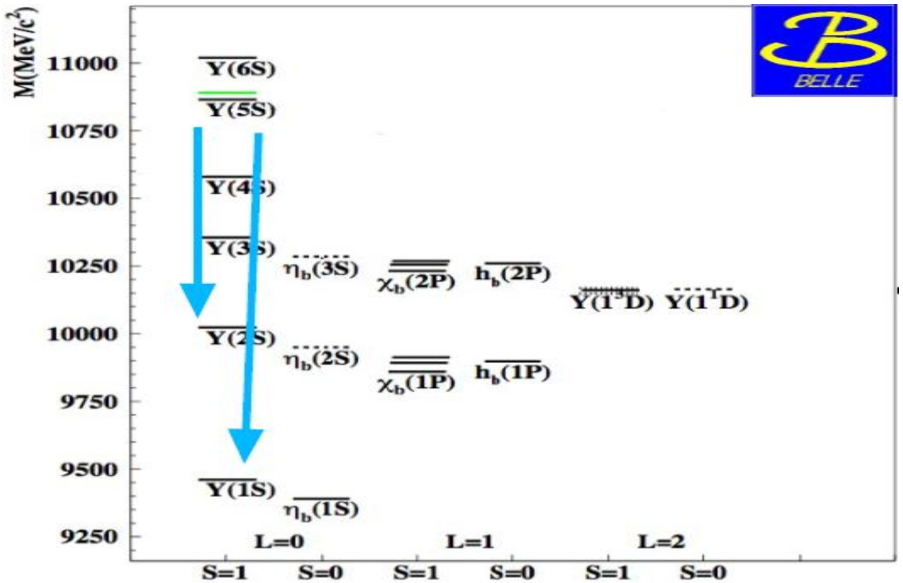
x 10^{-4}

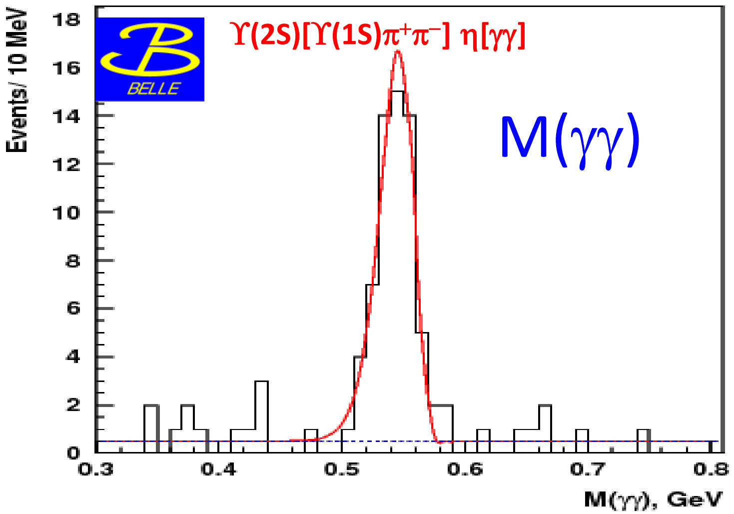
Higher than CLEO and BaBar results.

Still 50% of Theoretical Prediction.

η Transitions: $\Upsilon(5S) \to \Upsilon(1S, 2S)\eta$







- $\Upsilon(1S, 2S)[\mu^+\mu^-]\ \eta[\pi^+\pi^-\pi^0]$
- $\Upsilon(2S)[\Upsilon(1S)\pi^+\pi^-]\ \eta[\gamma\gamma]$

$B(\Upsilon(5S)\to \Upsilon(1S)\eta) = (7.3 \pm 1.6 \pm 0.8) \times 10^{-4}$

$= 0.25 \times B(\Upsilon(5S)\to \Upsilon(1S)\pi\pi)$

$B(\Upsilon(5S)\to \Upsilon(2S)\eta) = (38 \pm 4 \pm 5) \times 10^{-4}$

$= B(\Upsilon(5S)\to \Upsilon(2S)\pi\pi)$

Summary

- h_b and η_b missing pieces of bottomonia family were found.
- Above $B\bar{B}$ threshold charged and neutral bottomonium-like resonances $Z_b(10610)$ and $Z_b(10650)$ were observed.
- η transitions will help understanding the nature of states above threshold.