Bottomonium and Exotic Meson Spectroscopy

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with thanks to the BaBar and BELLE Collaborations

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BABAR

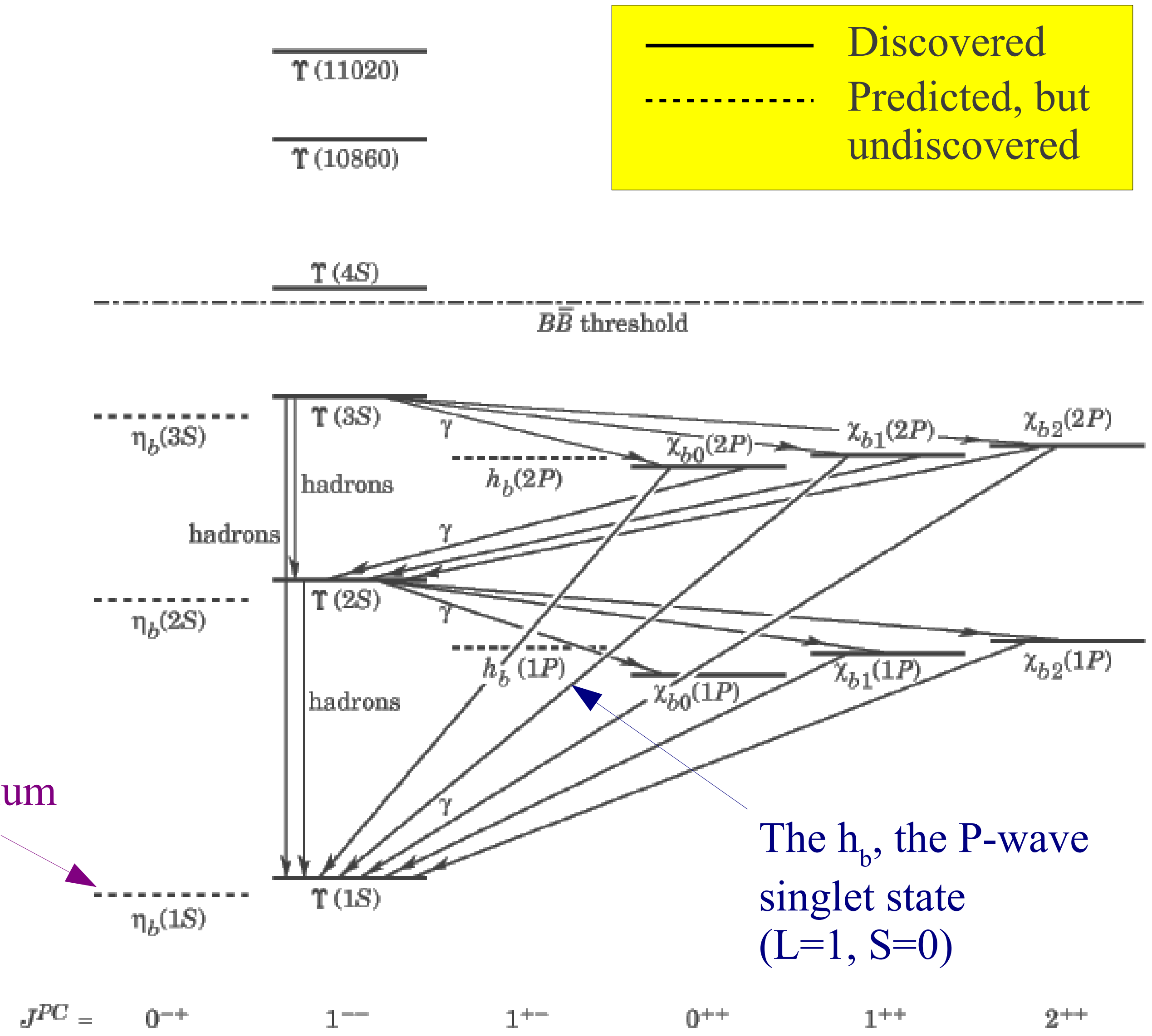
SMU

Programme

- The bottomonium spectrum
  - opportunities for discovery
- The B-factories
- Recent measurements
  - "Useful History" - the η_b
  - Radiative transitions from the Υ(3S) and Υ(2S)
  - The h_b saga and exotic bottomonium
- Conclusions and Outlook

The Bottomonium Spectrum

Spectrum: circa 2007



—— Discovered

- - - - Predicted, but undiscovered

The bottomonium ground state (L=0, S=0)

The h_b, the P-wave singlet state (L=1, S=0)

Theoretical Predictions - η_b

The bottomonium ground state: η_b

- The Υ(1S) mass is well-known experimentally: $m_{\Upsilon(1S)} = 9460.30 \pm 0.26$ MeV/c^2 (average from PDG 2010)

- QCD calculations predict the mass splitting between the η_b and the Υ(1S) using potential models, lattice QCD, etc.
  - **these predictions ranged between 36-100 MeV/c^2**

- Experimentally favored production and decay mode:
  - $\Upsilon(nS) \rightarrow \gamma\, \eta_b$, $\eta_b \rightarrow$ hadrons (where n = 1, 2, 3)
  - Branching fraction for this decay anticipated to be between 10^{-4}-10^{-3} . . . this implies needing *many millions* of Υ(nS) mesons in order to see a signal on top of multi-hadronic backgrounds.

Theoretical Predictions – P-wave States

The P-wave spin-singlet: h_b

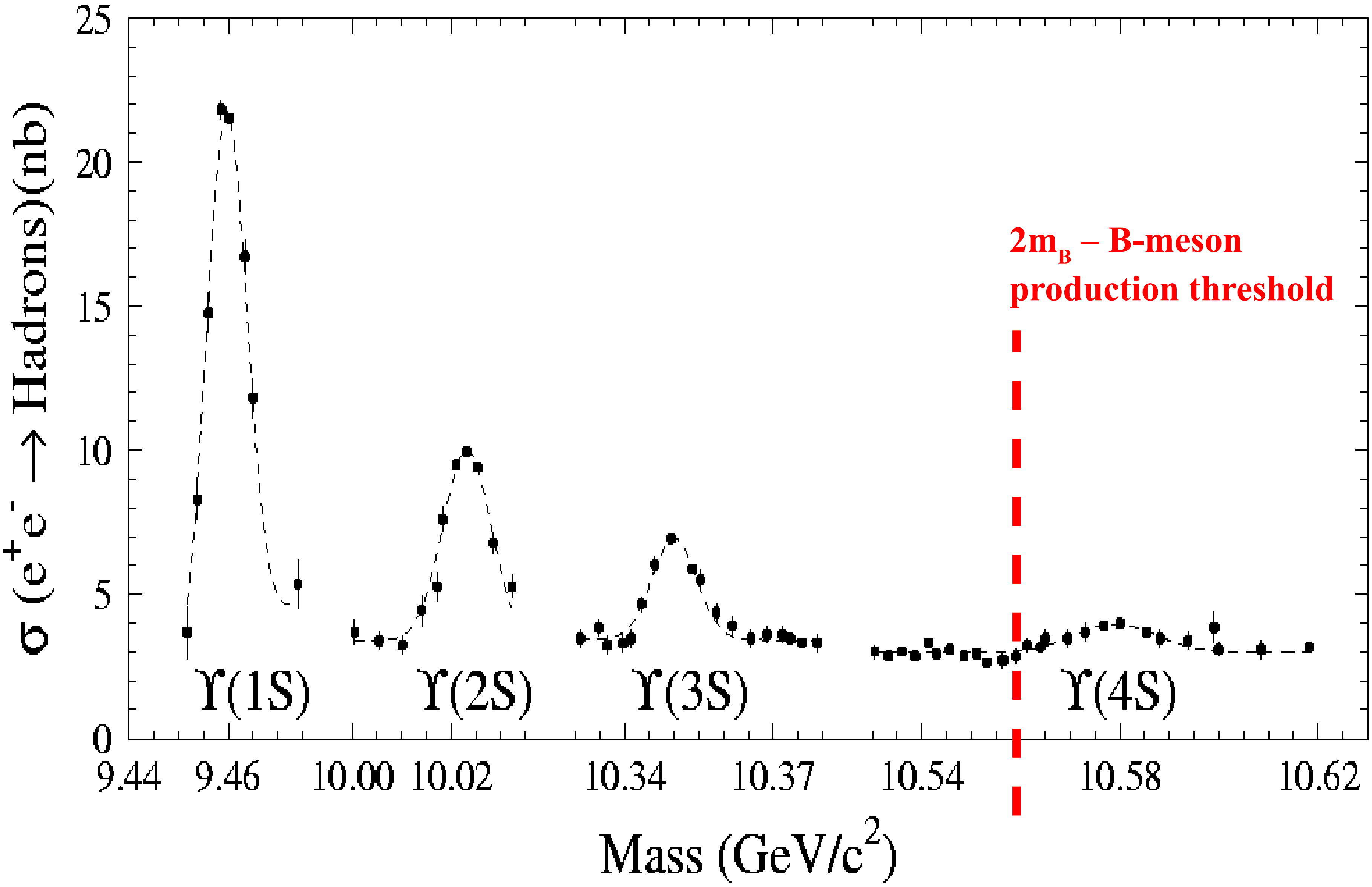
- The partner of the P-wave $\chi_{bJ}(1P)$ states (J=0, 1, 2)
- Its mass is estimated from the spin-weighted center of gravity of the $\chi_{bJ}(1P)$ states Stubbe & Martin, PLB 271 208 (1991)
  - **$m_{hb} = 9899.87 \pm 0.27$ MeV/c^2 (predicted)**
- Experimentally favored discovery modes (n=1,2,3):
  - **$\Upsilon(nS) \rightarrow \pi^0 h_b$, $h_b \rightarrow \gamma \eta_b$, BF ~ (0.001) × (0.5)**
  - **$\Upsilon(nS) \rightarrow \pi^+\pi^- h_b$, $h_b \rightarrow$ hadrons, BF ~ 10^{-4}**

The P-wave spin-triplet: $\chi_{bJ}(nP)$

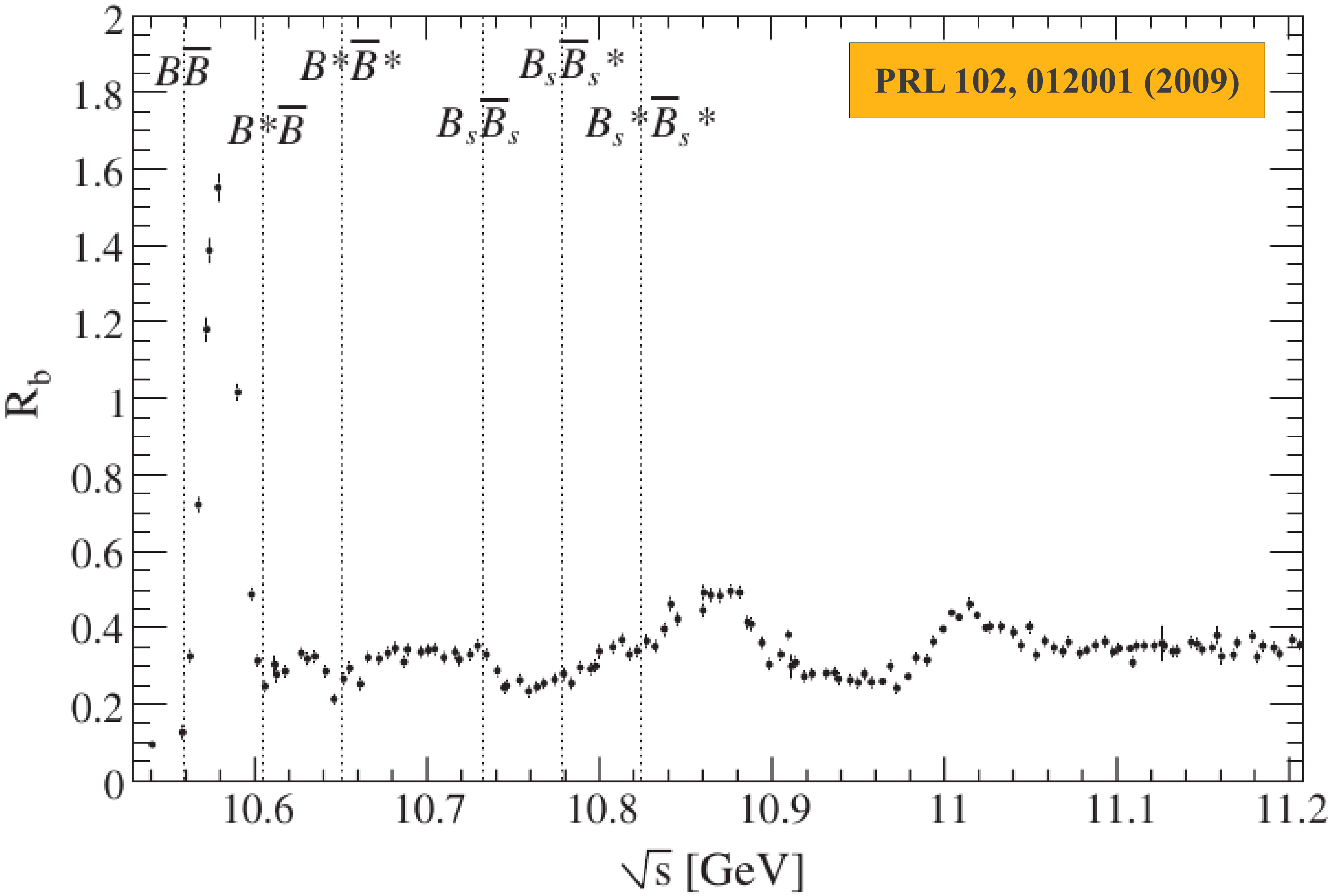
- Experimental measurements of radiative transitions to and from $\chi_{bJ}(nP)$ states effective potential models for heavy quarks

The B-Factories

Υ(4S) and Below

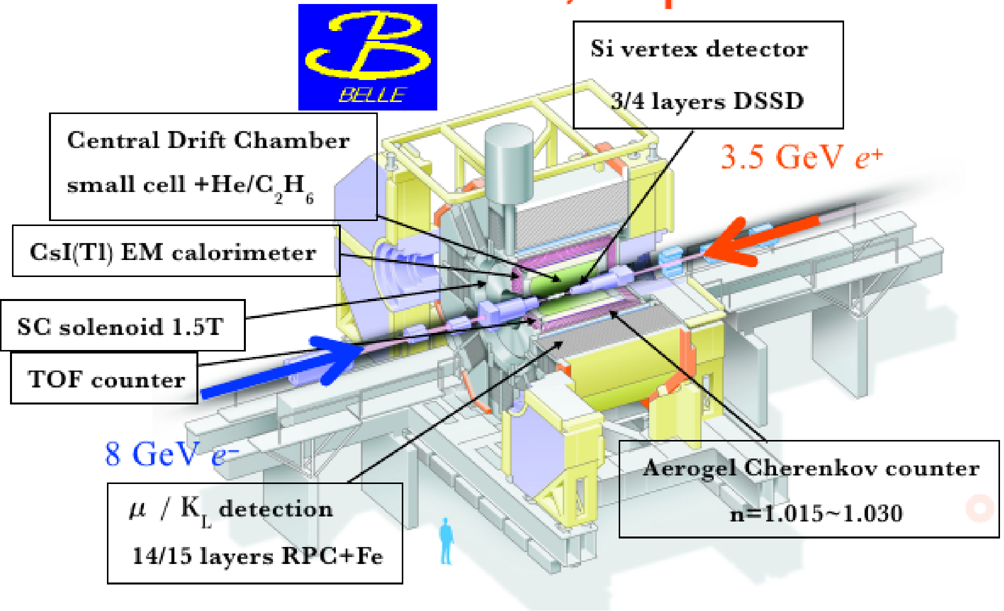


Υ(4S) and above

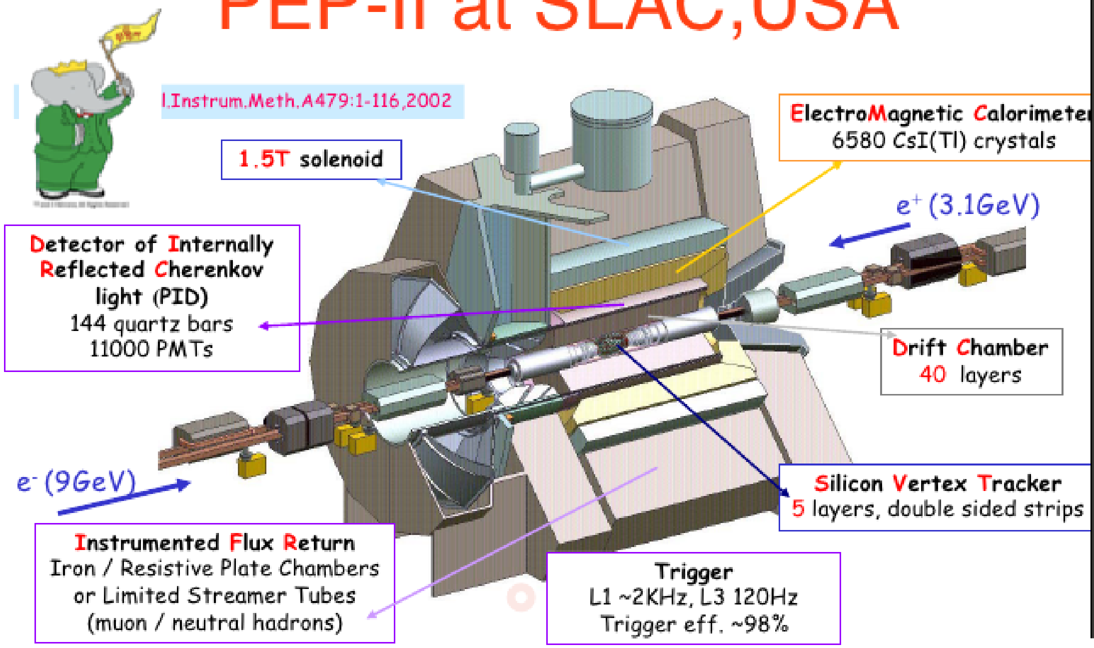


PRL 102, 012001 (2009)

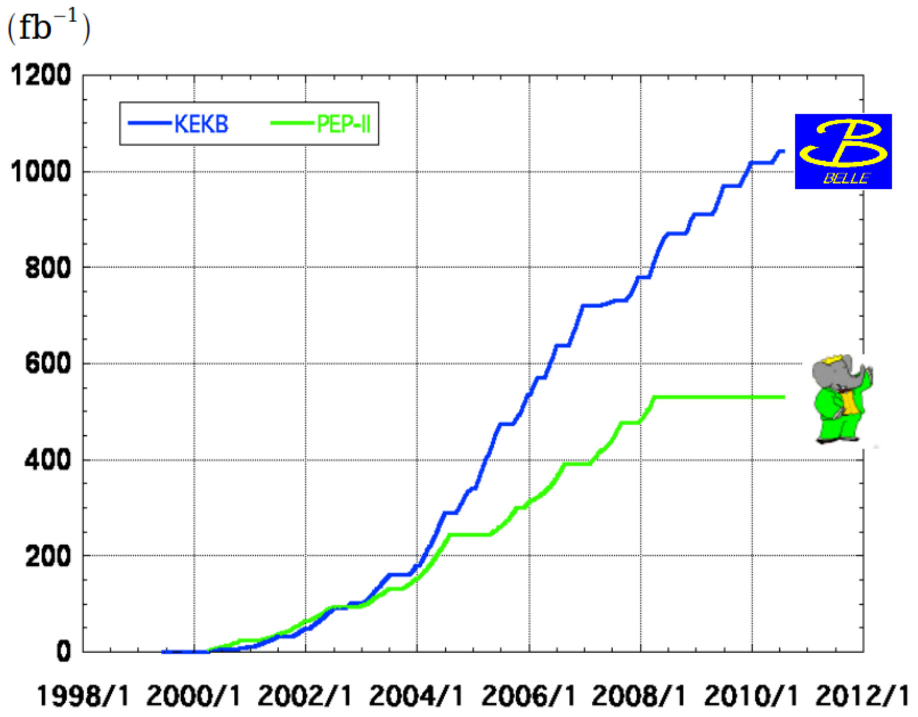
KEKB at KEK,Japan



PEP-II at SLAC,USA



Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

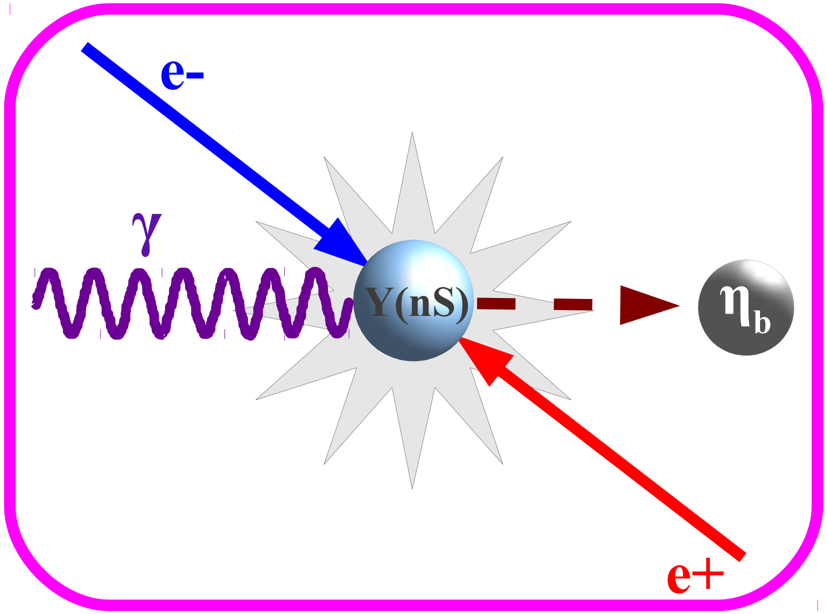
~ 54 fb^{-1}

- Multi-purpose detectors with large solid-angle coverage, excellent momentum and energy resolution and particle identification systems
- Colliders operated routinely above design specifications and ran at various center-of-mass (CM) energies
- Data collected at both facilities for nearly a decade

Experimental Results

η_b – archetypal search strategy

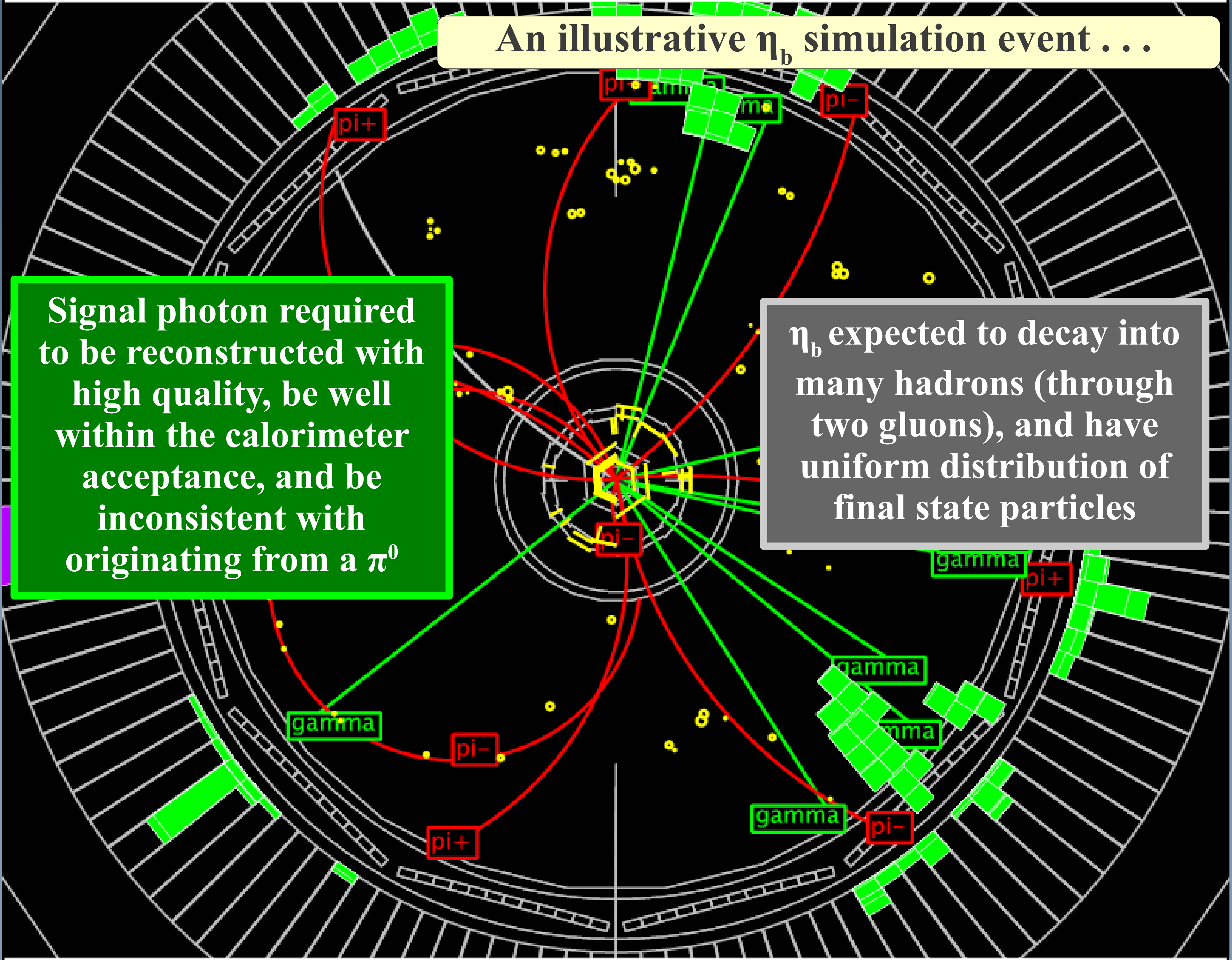
$$E_{\gamma}^{*}=\frac{m_{\Upsilon(3S)}^{2}-m_{\eta_b}^{2}}{2\,m_{\Upsilon(3S)}}$$



Search for monochromatic photon “recoiling” against η_b

- **fit energy spectrum for signal/background(s)**
- **this search is a good example of how all other searches are conducted; what typically differs is the particle(s) “tagging” the transition**

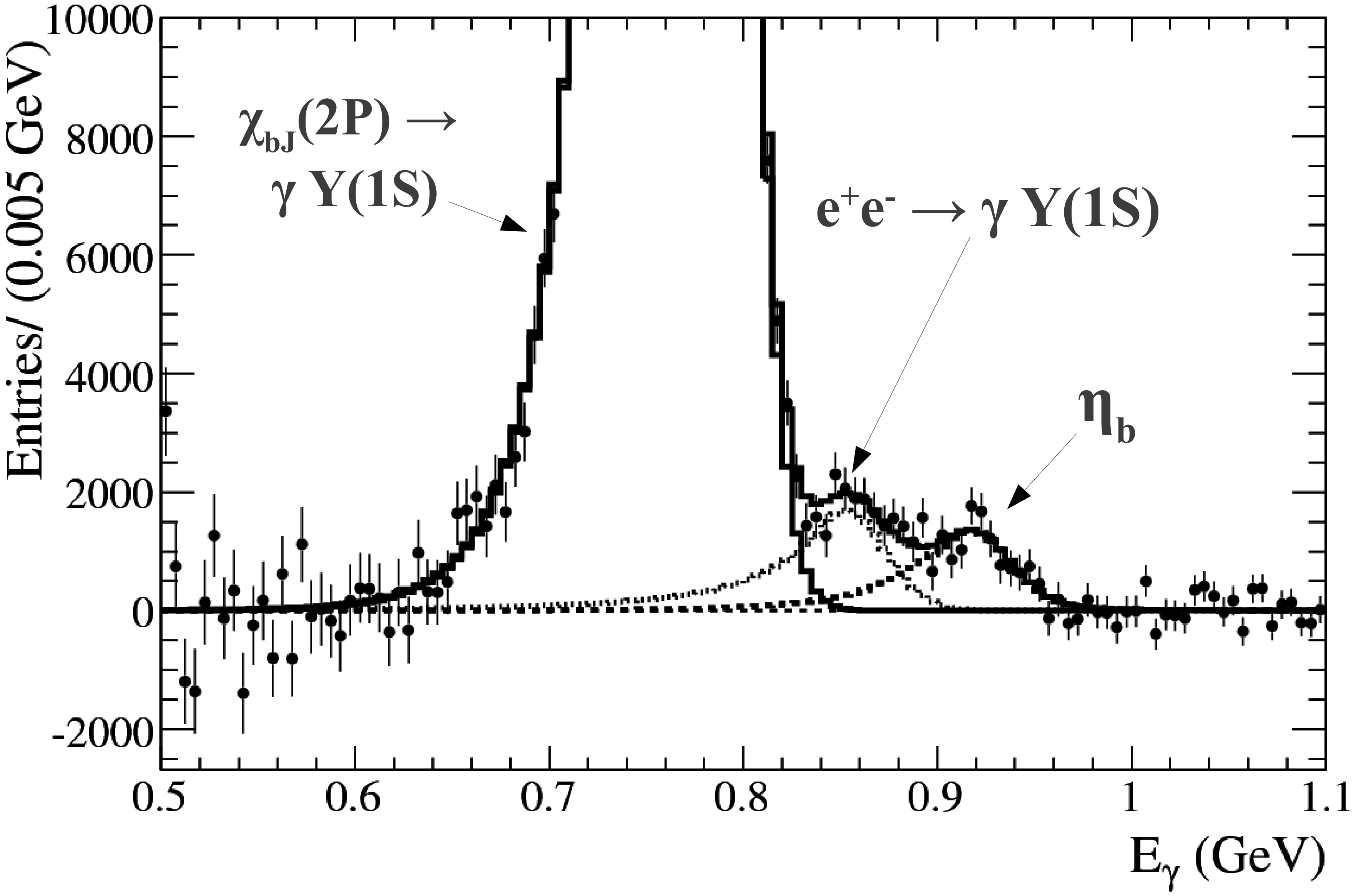
An illustrative η_b simulation event . . .



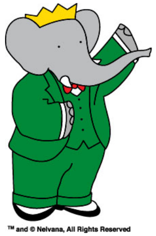
Signal photon required to be reconstructed with high quality, be well within the calorimeter acceptance, and be inconsistent with originating from a π^0

η_b expected to decay into many hadrons (through two gluons), and have uniform distribution of final state particles

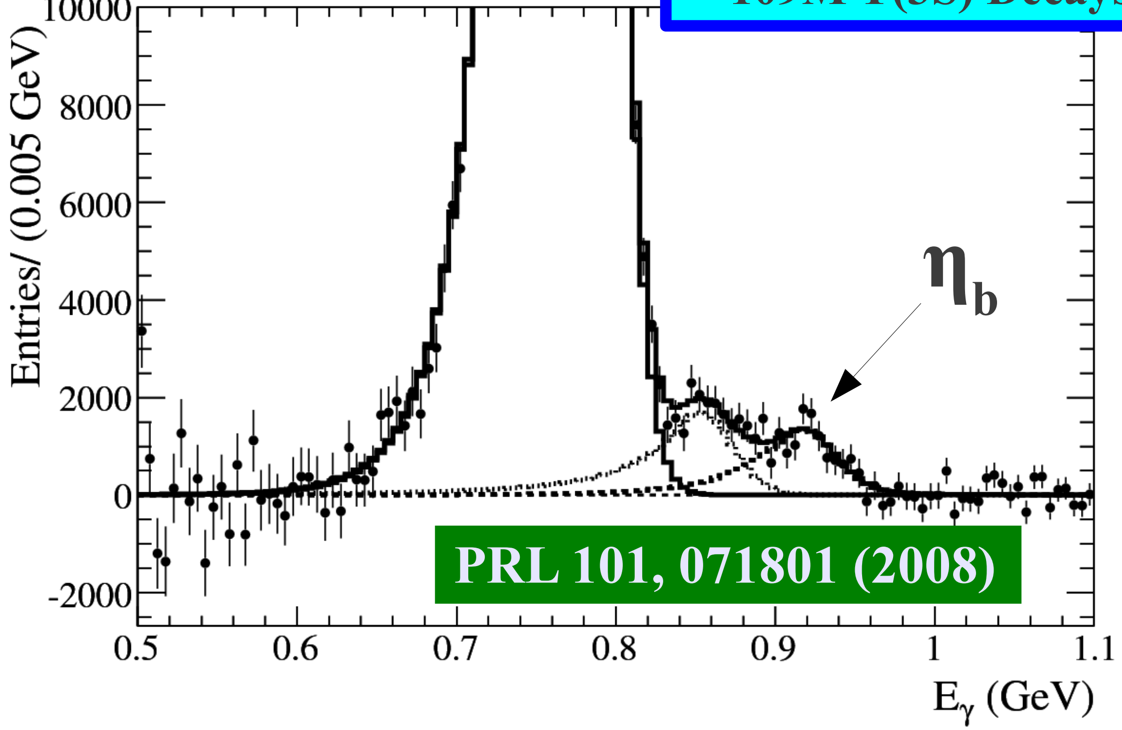
Discovery: $\Upsilon(3S) \rightarrow \gamma\, \eta_b$



Discovery: $\Upsilon(3S) \rightarrow \gamma\,\eta_b$



109M Y(3S) Decays



PRL 101, 071801 (2008)

Fitted signal yield:

19200 ± 2000 (stat.) ± 2100 (syst.)

Branching Fraction:

$(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$

Fitted Mean: $E_\gamma = 921.2^{+2.1}_{-2.8} \pm 2.4\,\mathrm{MeV}$

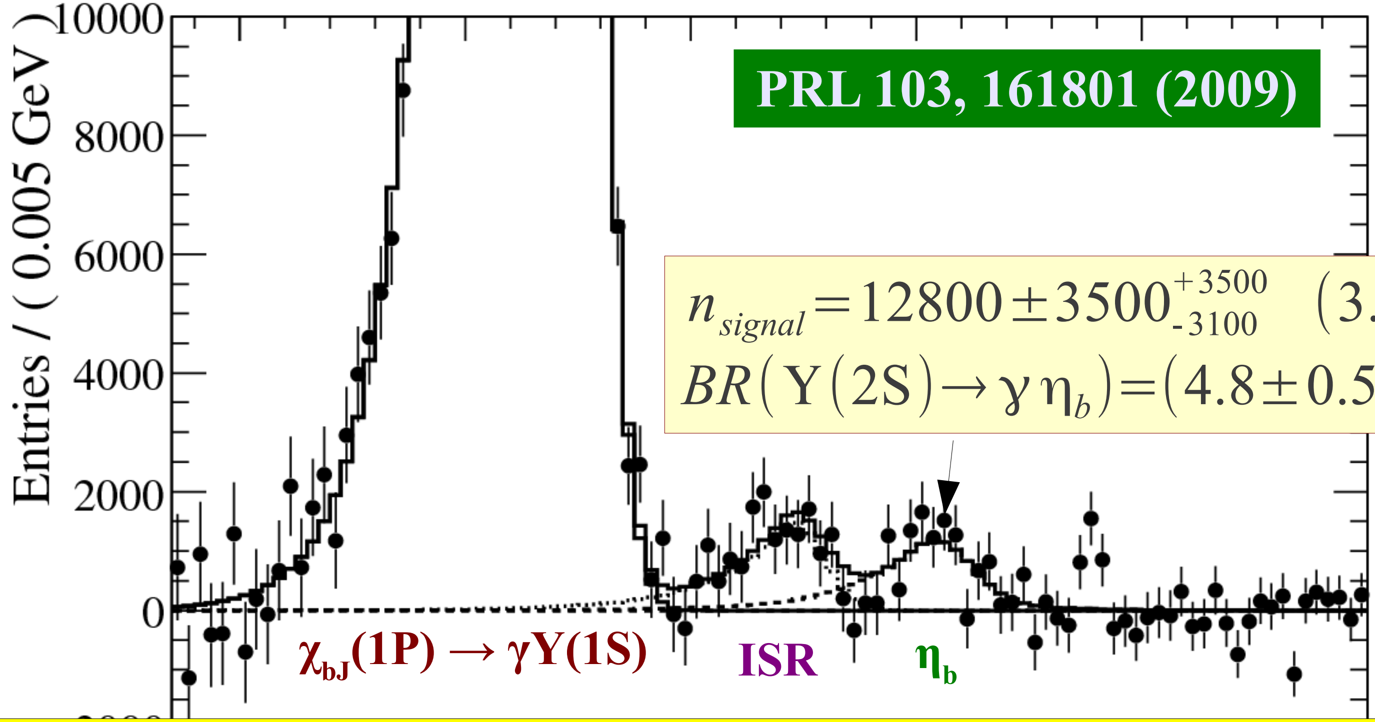
Mass: $9388.9^{+2.3}_{-3.1} \pm 2.7\,\mathrm{MeV}/c^2$

Hyperfine Splitting: $71.4^{+2.3}_{-3.1} \pm 2.7\,\mathrm{MeV}/c^2$

Most consistent with lattice QCD predictions of the η_b properties

Confirmation: $\Upsilon(2S) \rightarrow \gamma\, \eta_b$

91.6M Υ(2S) Decays



PRL 103, 161801 (2009)

$$n_{signal} = 12800 \pm 3500^{+3500}_{-3100} \quad (3.0\sigma)$$

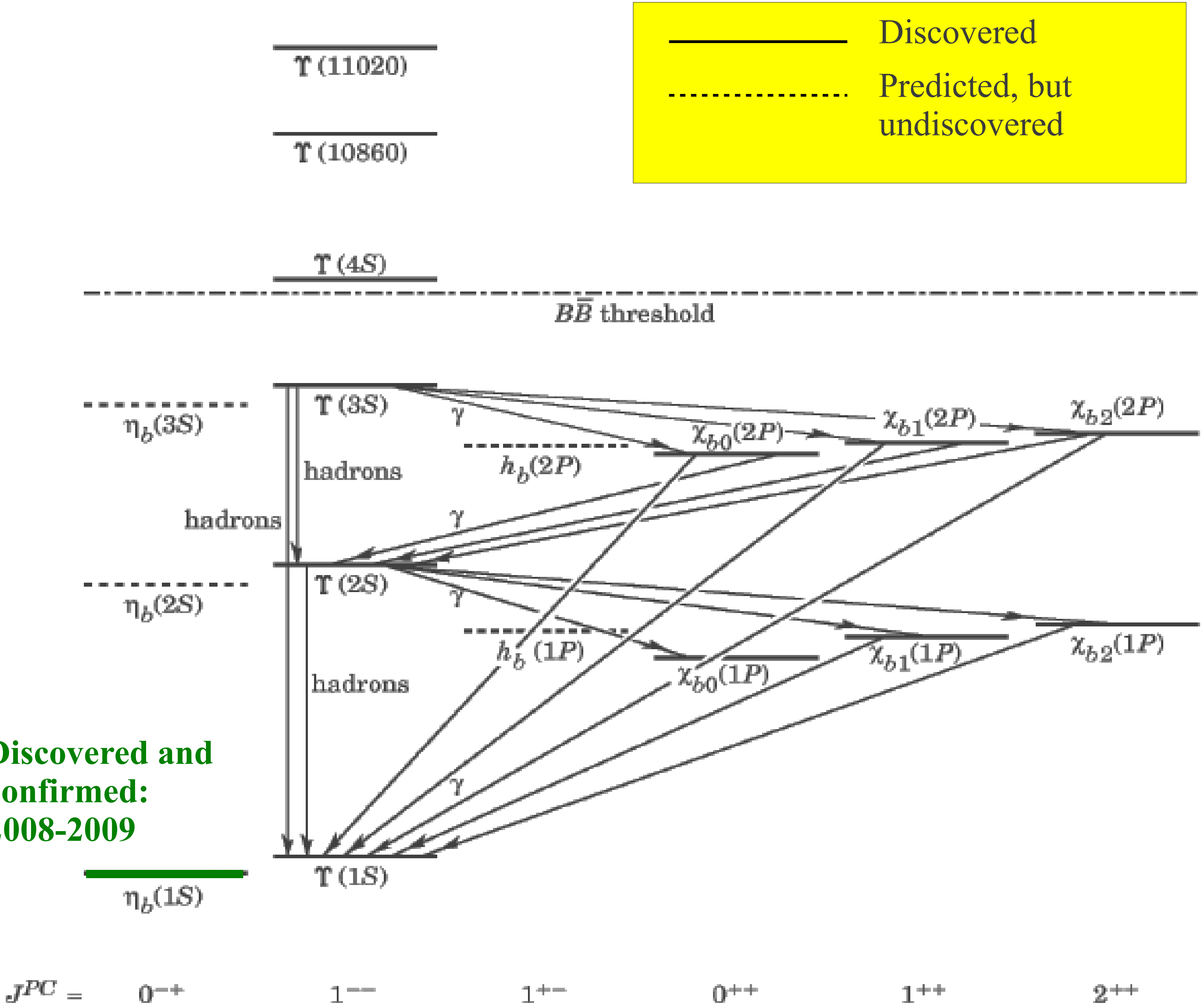
$$BR(\Upsilon(2S) \rightarrow \gamma\eta_b) = (4.8 \pm 0.5 \pm 0.6) \times 10^{-4}$$

Fitted Mean: $E_\gamma = 609.3^{+4.6}_{-4.5} \pm 1.9\,\text{MeV}$

Mass: $9394.2^{+4.8}_{-4.9} \pm 2.0\,\text{MeV}/c^2$

Hyperfine Splitting: $66.1^{+4.9}_{-4.8} \pm 2.0\,\text{MeV}/c^2$

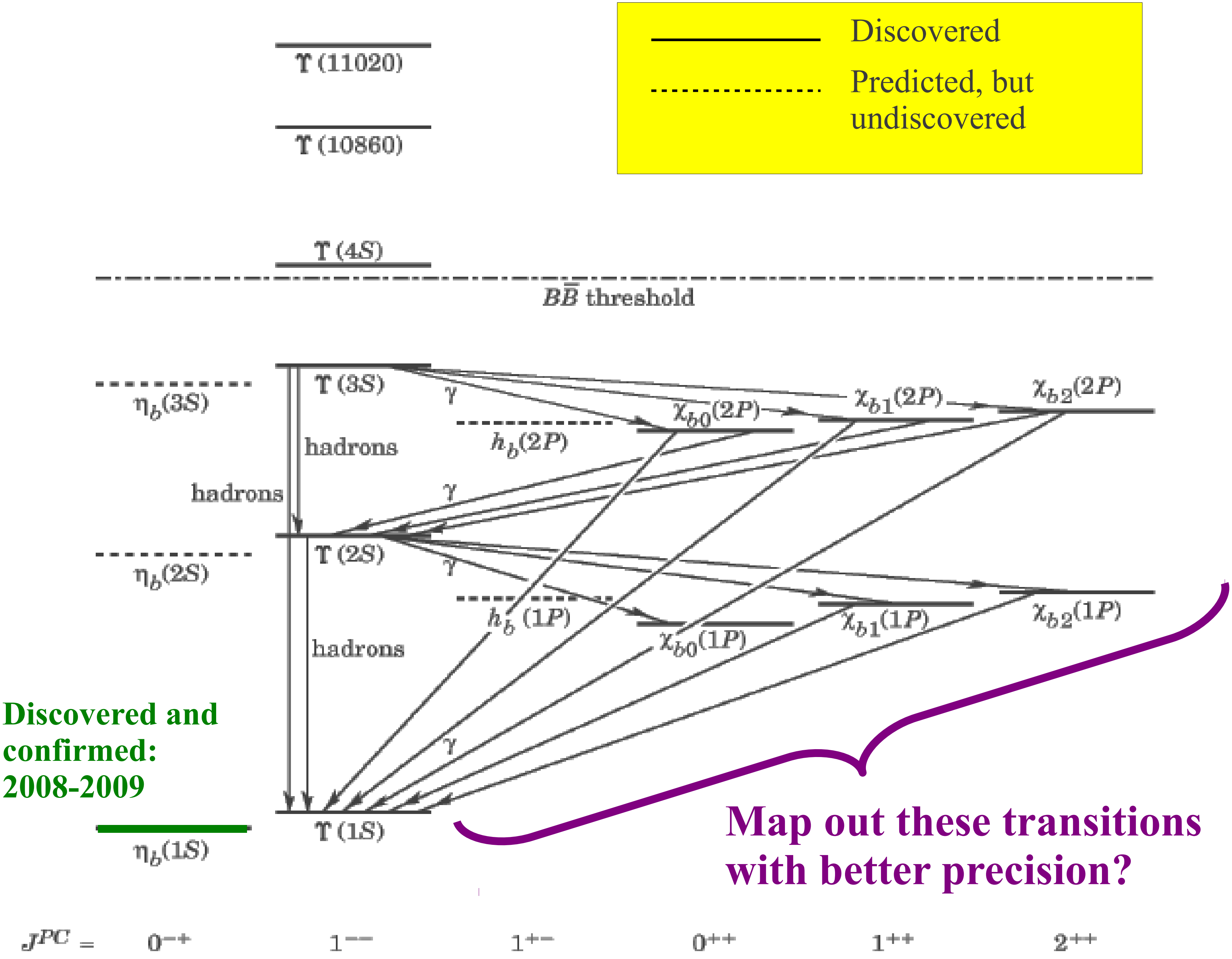
Consistent with the Υ(3S)-based measurement!



—— Discovered

-------- Predicted, but undiscovered

Discovered and confirmed: 2008-2009

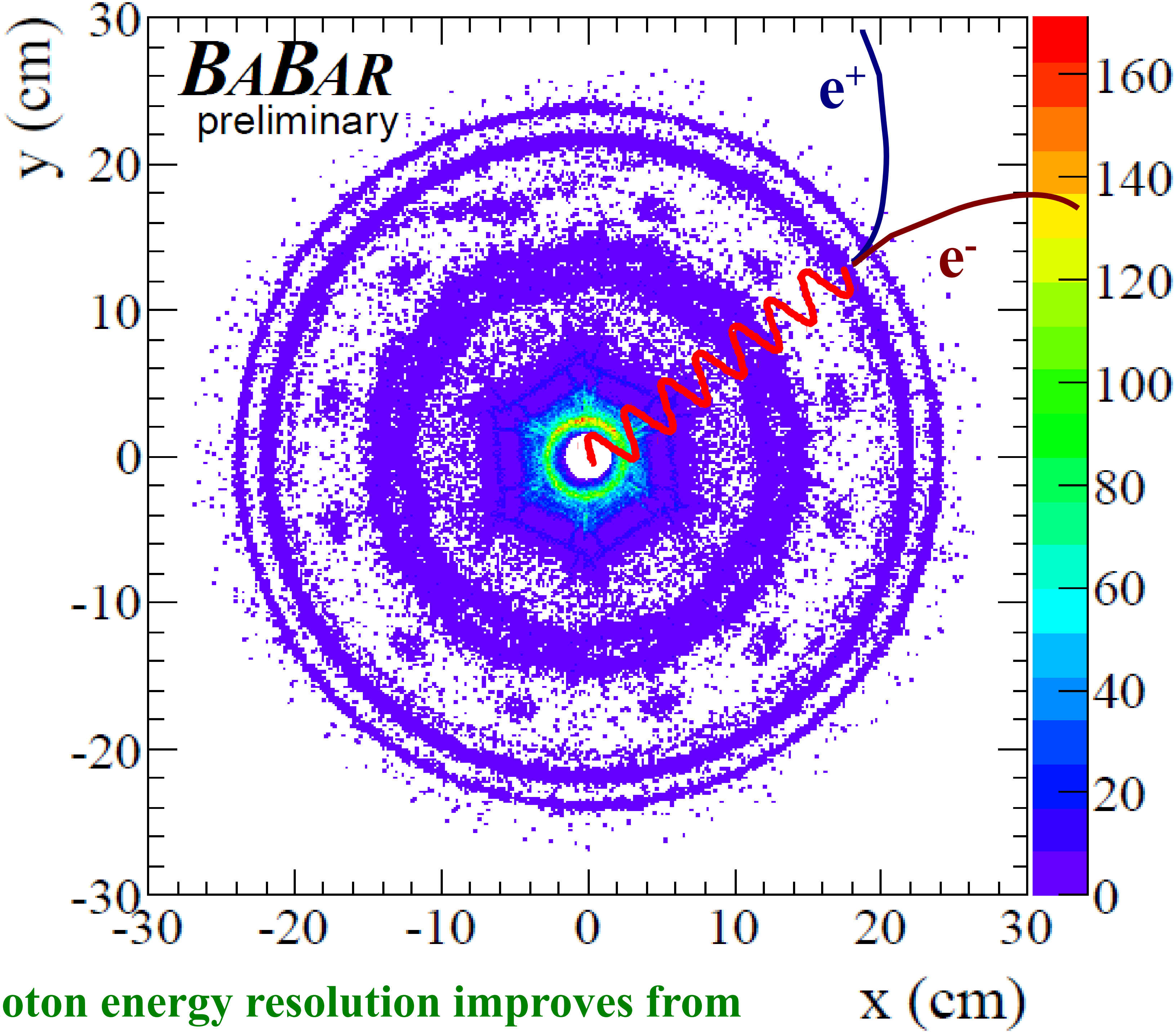


Discovered and confirmed: 2008-2009

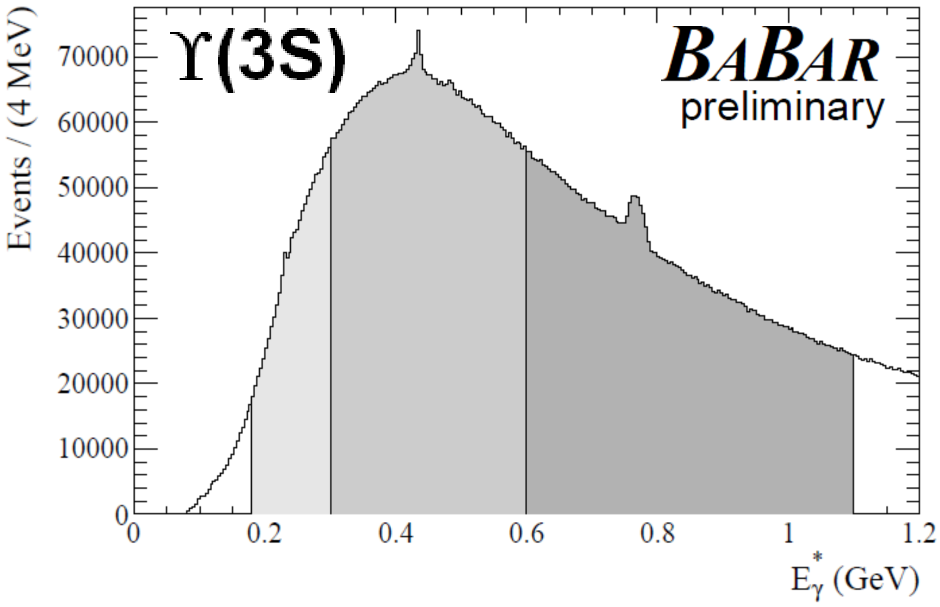
Map out these transitions with better precision?

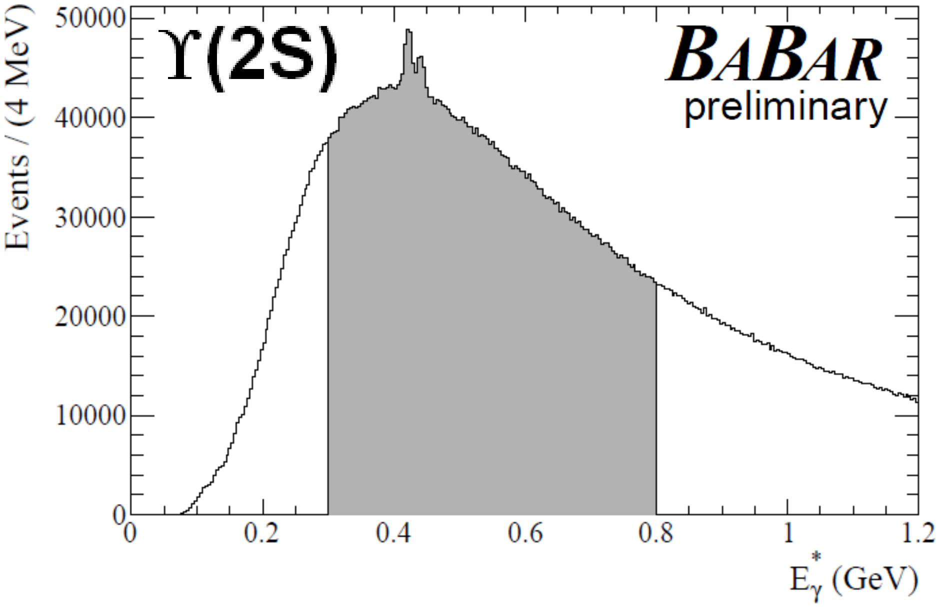
Further Study of Radiative Transitions

- Bottomonium has a rich radiative transition structure
  - energy resolution limited by calorimeter
  - difficult to resolve nearby transitions, e.g. $\chi_{bJ}(2P) \rightarrow \gamma\ \Upsilon(1S)$
- Transition rates a generally well-predicted
  - test the predictions with direct measurements
  - improve on existing measurements where possible
  - look for $\eta_b(1S)$ and $\eta_b(2S)$ using an independent technique
- Method: use converted photons ($\gamma \rightarrow e^+ e^-$)



Photon energy resolution improves from about 25 MeV to 5 MeV





Events are selected where . . .

- the reconstructed particle multiplicity and distribution is consistent with a multi-hadronic event
- there is a good photon conversion candidate, based on fit χ^2, mass, and the conversion vertex radius

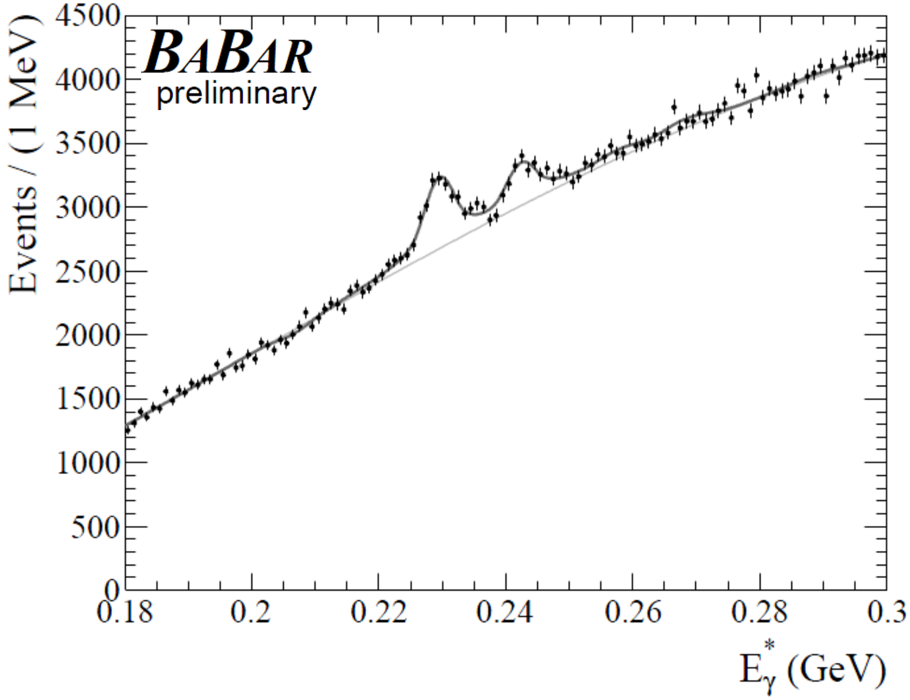
The data is subdivided according to CM photon energy (E*)

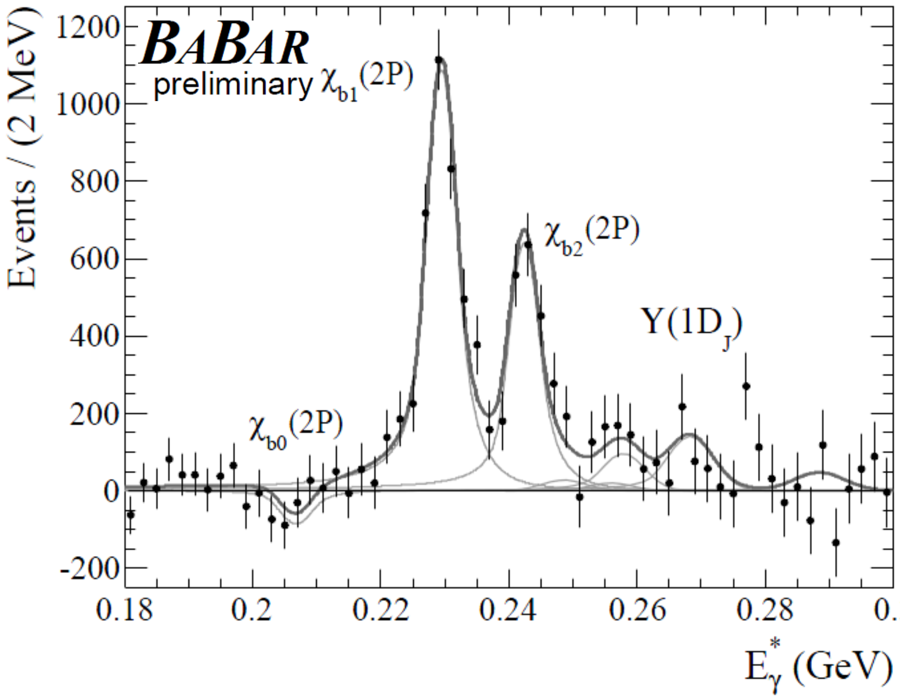
- regions defined based on expected transition content
- Y(3S) events: E^*_γ = [180,300], [300,600], and [600,1100] MeV
- Y(2S) events: E^*_γ = [300,800] MeV

arXiv 1104.5254 (2011)

Υ(3S): E^*_γ = [180, 300] MeV

This region contains expected transitions from $\chi_{bJ}(2P) \rightarrow \gamma \Upsilon(2S)$ and six transitions from D-wave bottomonium states, $\Upsilon(1D_J) \rightarrow \gamma\, \chi_{bJ}(1P)$



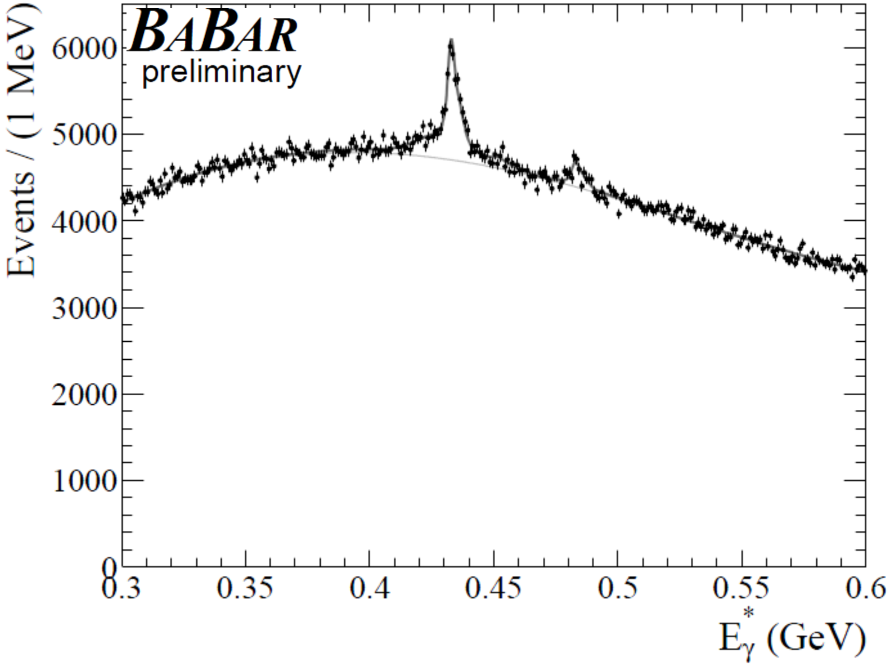


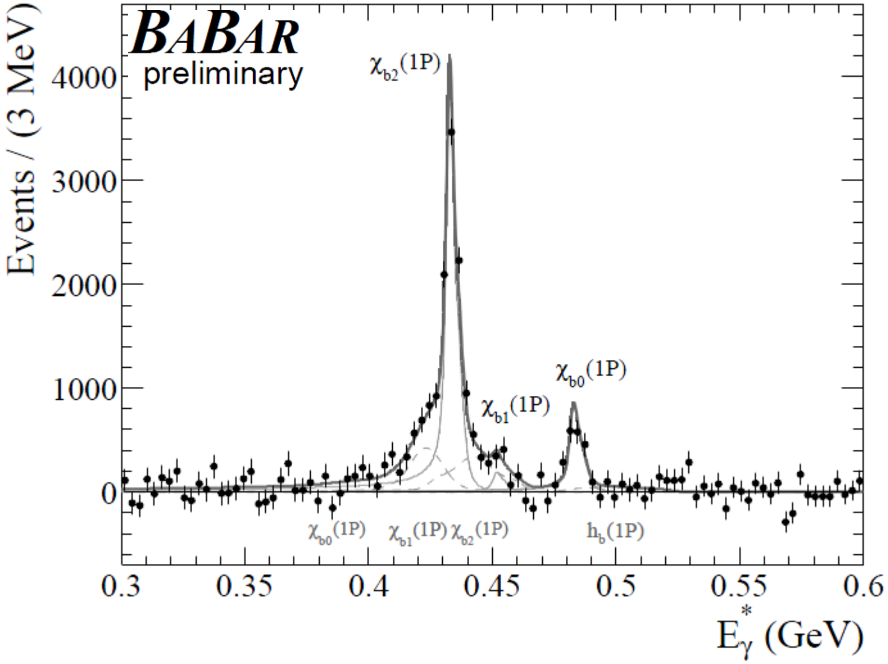
Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CUSB	CLEO
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.9 \pm 2.9^{+0.7}_{-0.8} \pm 0.5\ (< 2.9)$	3.6 ± 1.6	< 5.2
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$19.5 \pm 1.1^{+1.1}_{-1.0} \pm 1.9$	13.6 ± 2.4	21.1 ± 4.5
$\chi_{b2}(2P) \rightarrow \gamma\Upsilon(2S)$	242.3	2462 ± 243	0.190	$8.6^{+0.9}_{-0.8} \pm 0.5 \pm 1.1$	10.9 ± 2.2	9.9 ± 2.7

arXiv 1104.5254 (2011)

Y(3S): E^*_γ = [300,600] MeV

Complicated region with many possible transitions. Some of the highlights are: Y(3S) → $\gamma\ \chi_{bJ}(1P)$ overlap with subsequent $\chi_{bJ}(1P)$ → Y(1S) transitions; $h_b(1P) \rightarrow \gamma\ \eta_b(1S)$ could appear here.





Observations and precision measurements:

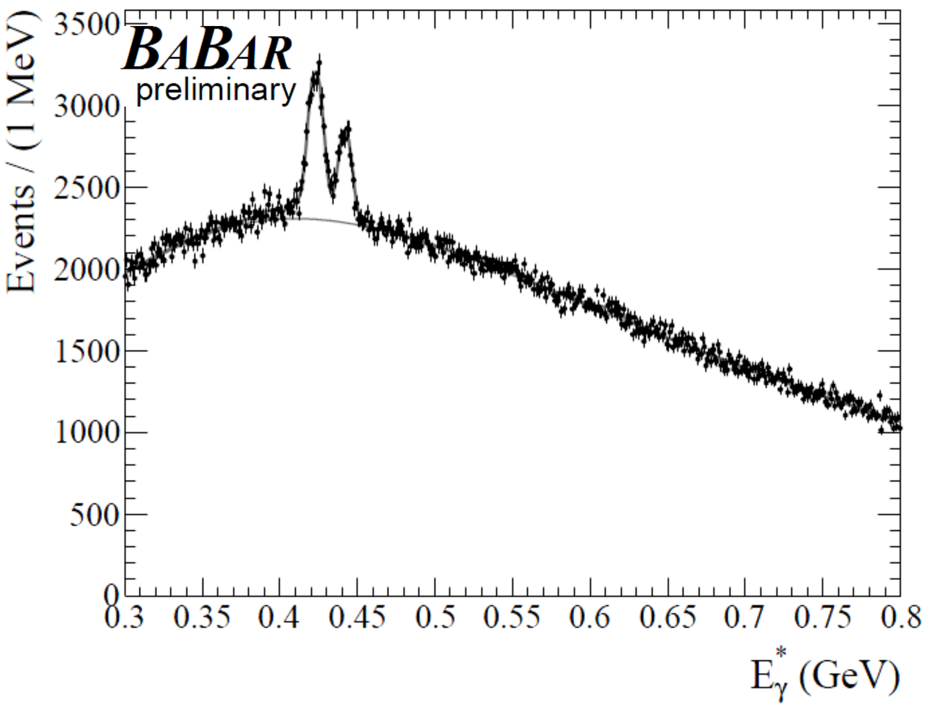
Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction ($\times 10^{-3}$) BABAR	CLEO
$\Upsilon(3S) \rightarrow \gamma\chi_{b2}(1P)$	433.1	9699 ± 318	0.794	$10.6 \pm 0.3 \pm 0.6$	7.7 ± 1.3
$\Upsilon(3S) \rightarrow \gamma\chi_{b1}(1P)$	452.2	483 ± 315	0.818	$0.5 \pm 0.3^{+0.2}_{-0.1}$ (< 1.1)	1.6 ± 0.5
$\Upsilon(3S) \rightarrow \gamma\chi_{b0}(1P)$	483.5	2273 ± 307	0.730	$2.7 \pm 0.4 \pm 0.2$	3.0 ± 1.1

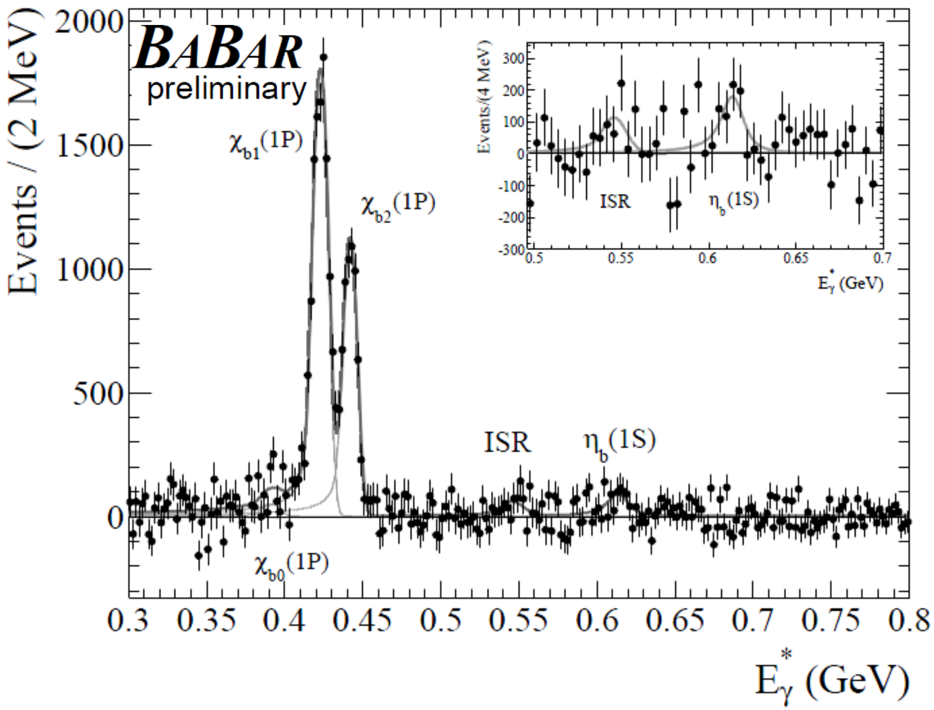
Transitions rates to $\chi_{bJ}(1P)$ are unusual for quarkonium (J=2>0>1)

arXiv 1104.5254 (2011)

Y(2S): E^*_γ = [300,800] MeV

Measure $\chi_{bJ}(1P) \rightarrow \gamma\, Y(1S)$ and search for $Y(2S) \rightarrow \gamma\eta_b(1S)$:





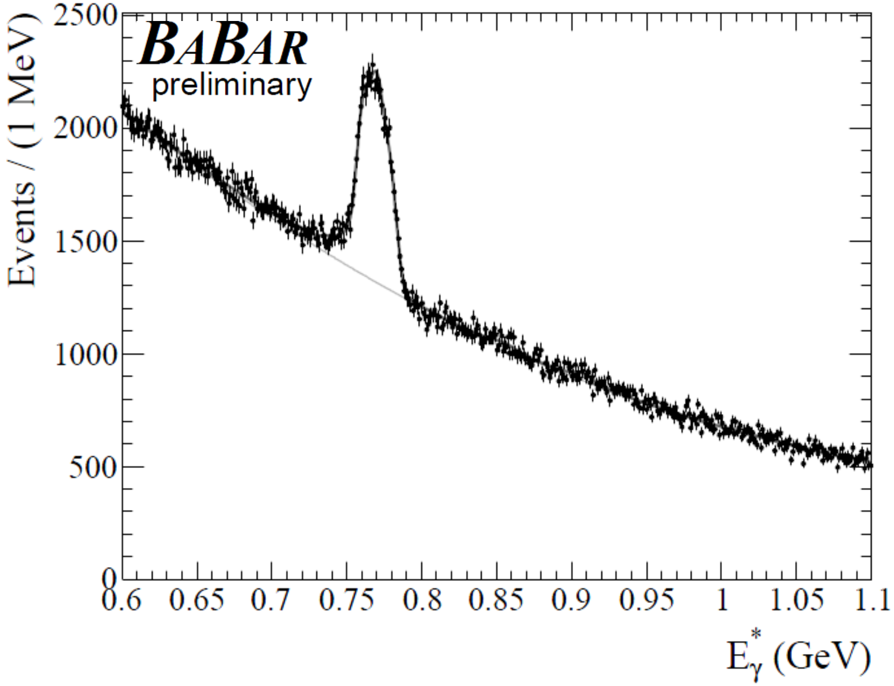
Due to high background and low efficiency, no evidence for $\eta_b(1S)$.

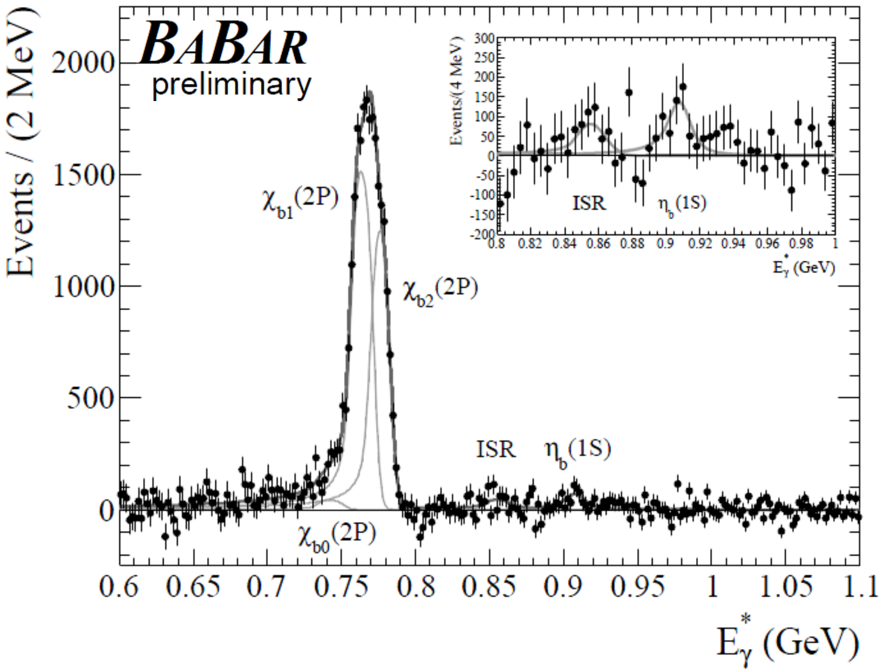
Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CB	CUSB	CLEO
$\chi_{b0}(1P) \rightarrow \gamma\Upsilon(1S)$	391.5	391 ± 267	0.496	$2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2\ (< 4.6)$	< 5	< 12	1.7 ± 0.4
$\chi_{b1}(1P) \rightarrow \gamma\Upsilon(1S)$	423.0	12604 ± 285	0.548	$36.2 \pm 0.8 \pm 1.7 \pm 2.1$	34 ± 7	40 ± 10	33.0 ± 2.6
$\chi_{b2}(1P) \rightarrow \gamma\Upsilon(1S)$	442.0	7665^{+270}_{-272}	0.576	$20.2 \pm 0.7^{+1.0}_{-1.4} \pm 1.0$	25 ± 6	19 ± 8	18.5 ± 1.4
$\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$	$613.7^{+3.0+0.7}_{-2.6-1.1}$	1109 ± 348	1.050	$0.11 \pm 0.04^{+0.07}_{-0.05}\ (< 0.22)$	-	-	-

arXiv 1104.5254 (2011)

Y(3S): E^*_γ = [600,1100] MeV

Measure $\chi_{bJ}(2P) \rightarrow \gamma\, Y(1S)$ and search for $Y(3S) \rightarrow \gamma\eta_b(1S)$:





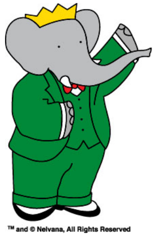
Photon energy for $\eta_b(1S)$ production is lower than expected, but the result is also only ~2.7σ significant → more data needed to fully utilize this conversion-based approach.

Transition	E^*_γ (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) BABAR	CUSB	CLEO
$\chi_{b0}(2P) \rightarrow \gamma\Upsilon(1S)$	742.7	469^{+260}_{-259}	1.025	$0.7 \pm 0.4^{+0.2}_{-0.1} \pm 0.1$ (< 1.2)	< 1.9	< 2.2
$\chi_{b1}(2P) \rightarrow \gamma\Upsilon(1S)$	764.1	14965^{+381}_{-383}	1.039	$9.9 \pm 0.3 \pm 0.4 \pm 0.9$	7.5 ± 1.3	10.4 ± 2.4
$\chi_{b2}(2P) \rightarrow \gamma\Upsilon(1S)$	776.4	11283^{+384}_{-385}	1.056	$7.1 \pm 0.2 \pm 0.3 \pm 0.9$	6.1 ± 1.2	7.7 ± 2.0
$\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$	$907.9 \pm 2.8 \pm 0.9$	933^{+263}_{-262}	1.388	$0.059 \pm 0.016^{+0.014}_{-0.016}$	-	-

Search for the h_b(1P)

- Finding the η_b and h_b were primary goals of the B-factories' bottomonium efforts
- BaBar and BELLE both set out to find the h_b
  - BaBar Approach:
    - Use the Y(3S) sample and look for π^0 or dipion ($\pi^+\pi^-$) transitions down to the h_b
  - BELLE Approach:
    - Y(5S) has observed dipion transitions with rates larger than expected (e.g. to Y(nS) states with n=1,2,3)
    - Use the Y(5S) sample and look for a dipion transition down to the h_b

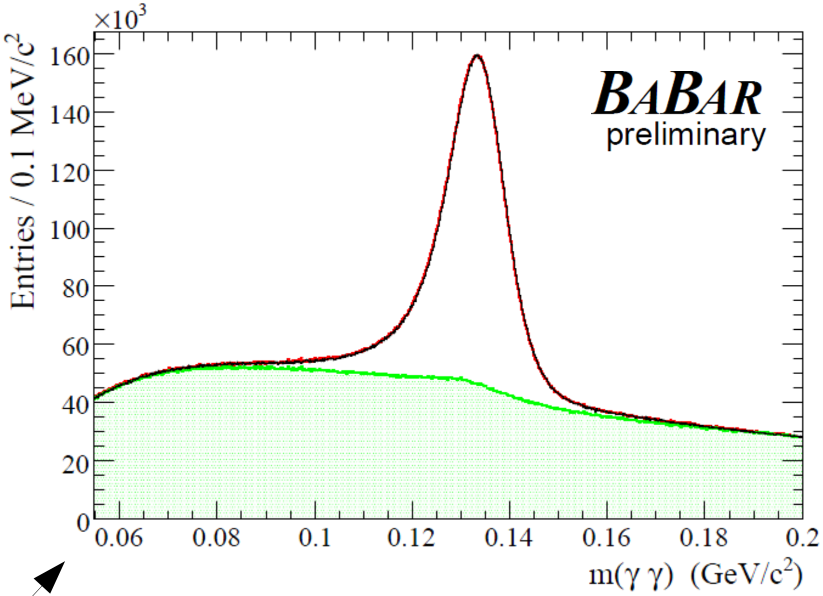
arXiv 1102.4565 (2011)



$\Upsilon(3S) \rightarrow \pi^0 h_b$

Event Selection

- Reconstruct $\pi^0(\gamma_1\gamma_2) + \gamma$
  - 3^{rd} photon required to be consistent with $h_b \rightarrow \gamma\eta_b$
  - Assume $BR(h_b \rightarrow \gamma\eta_b) \sim 41\%$ [PRD 66, 014012 (2002)]



Shown above is the fit to m(γγ) in full range of m.m.(π^0). Background model taken from MC simulation.

Signal Selection

- Define "π^0 recoil mass"

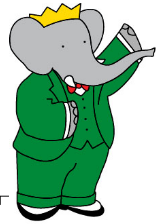
$$m^2_{\mathrm{recoil}}(\pi^0) \equiv \left(E_{\mathrm{beam}} - E^*_{\pi^0}\right)^2 - p^{*2}_{\pi^0}$$

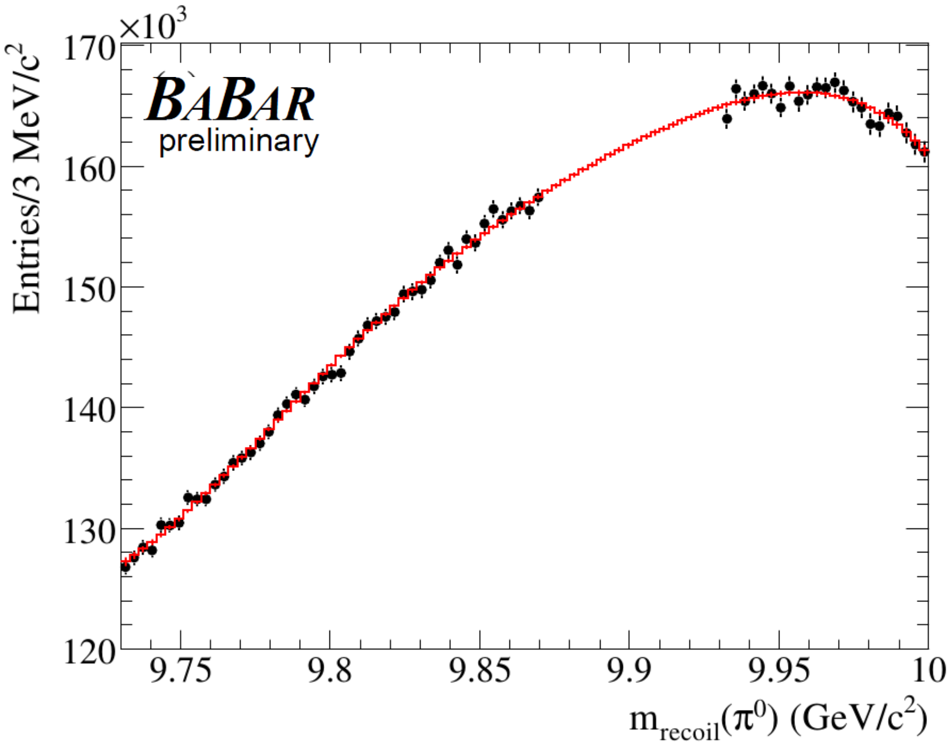
- Fit for the number of π^0 candidates in each bin of recoil mass
- Perform χ^2 fit to recoil mass spectrum

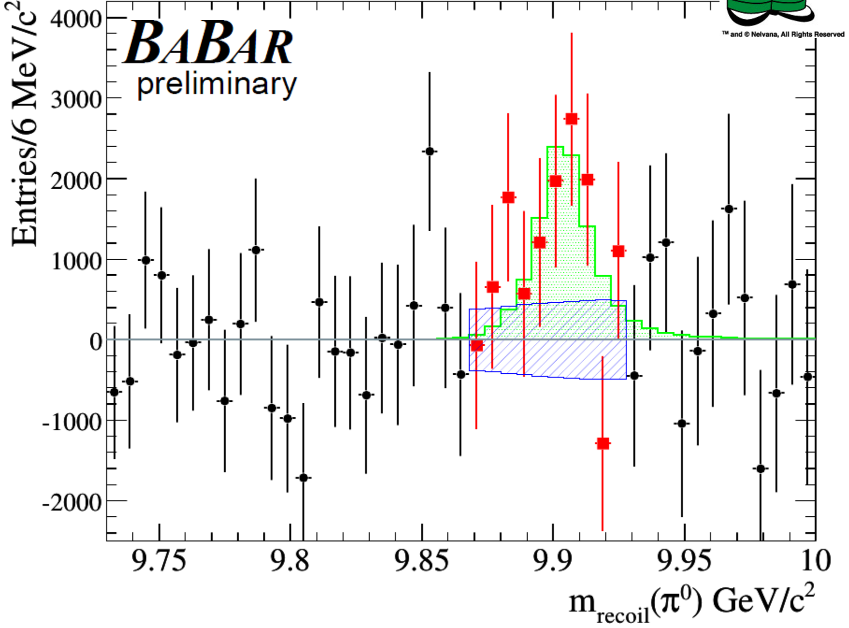
Signal: use Crystal Ball Function (Gaussian with low-side power-law tail)

Background: 6th-order polynomial

arXiv 1102.4565 (2011)







Property	Value
Yield	10814±2813±1652 evts.
Significance	3.3 σ
M [h_b(1P)]	9902±4±2 MeV/c^2
BF(Υ(3S)→$\pi^o h_b$) x BF($h_b \to \gamma \eta_b$)	(4.3±1.1±0.9) x 10^{-4}

- **Measured mass agrees with spin-weighted center-of-gravity of χ_{bJ}(1P) states: ~9900 MeV**
- **Branching fraction consistent with theoretical expectation.**

Voloshin, Sov J Nucl Phys 43 1011 (1986)

- **First evidence for the existence of this state**

arXiv 1103.3419 (2011)

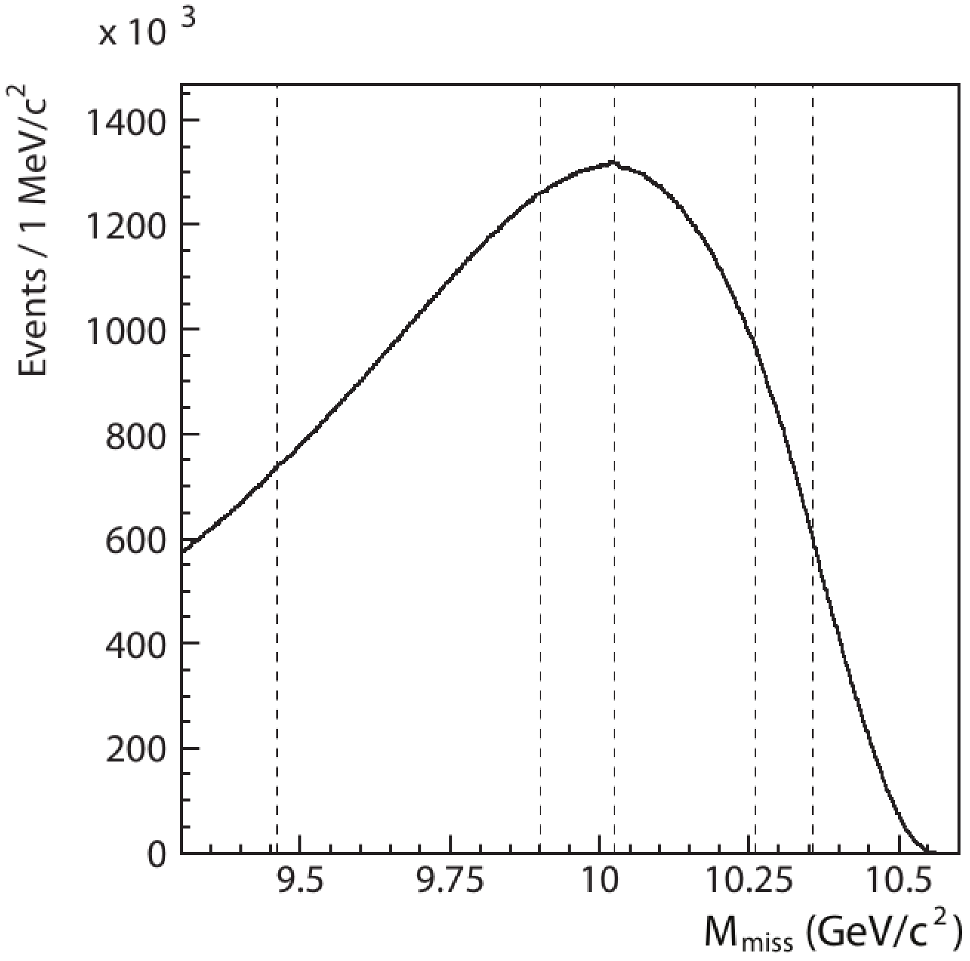
Y(5S) Dipion Recoil Search

Event Selection

- Reconstruct $\pi^+\pi^-$
  - Goal: observe Y(5S) → $\pi^+\pi^- h_b$

Signal Selection

- Define “Missing Mass” (see below)
- Fit the missing mass spectrum for evidence of “recoil” against a resonance

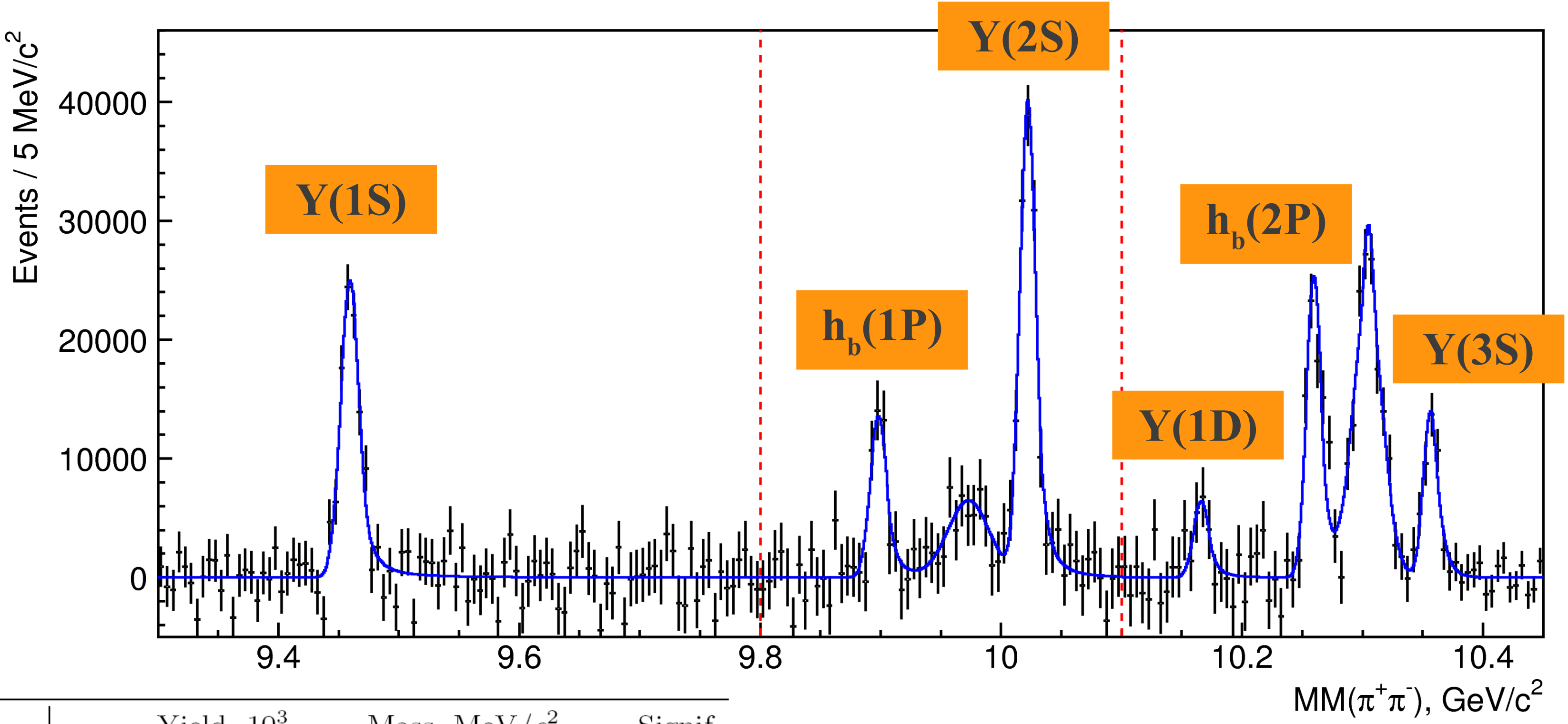


$$M_{miss} \equiv \sqrt{(E_{\Upsilon(5S)} - E^*_{\pi\pi})^2 - p^2_{\pi\pi}}$$

arXiv 1103.3419 (2011)

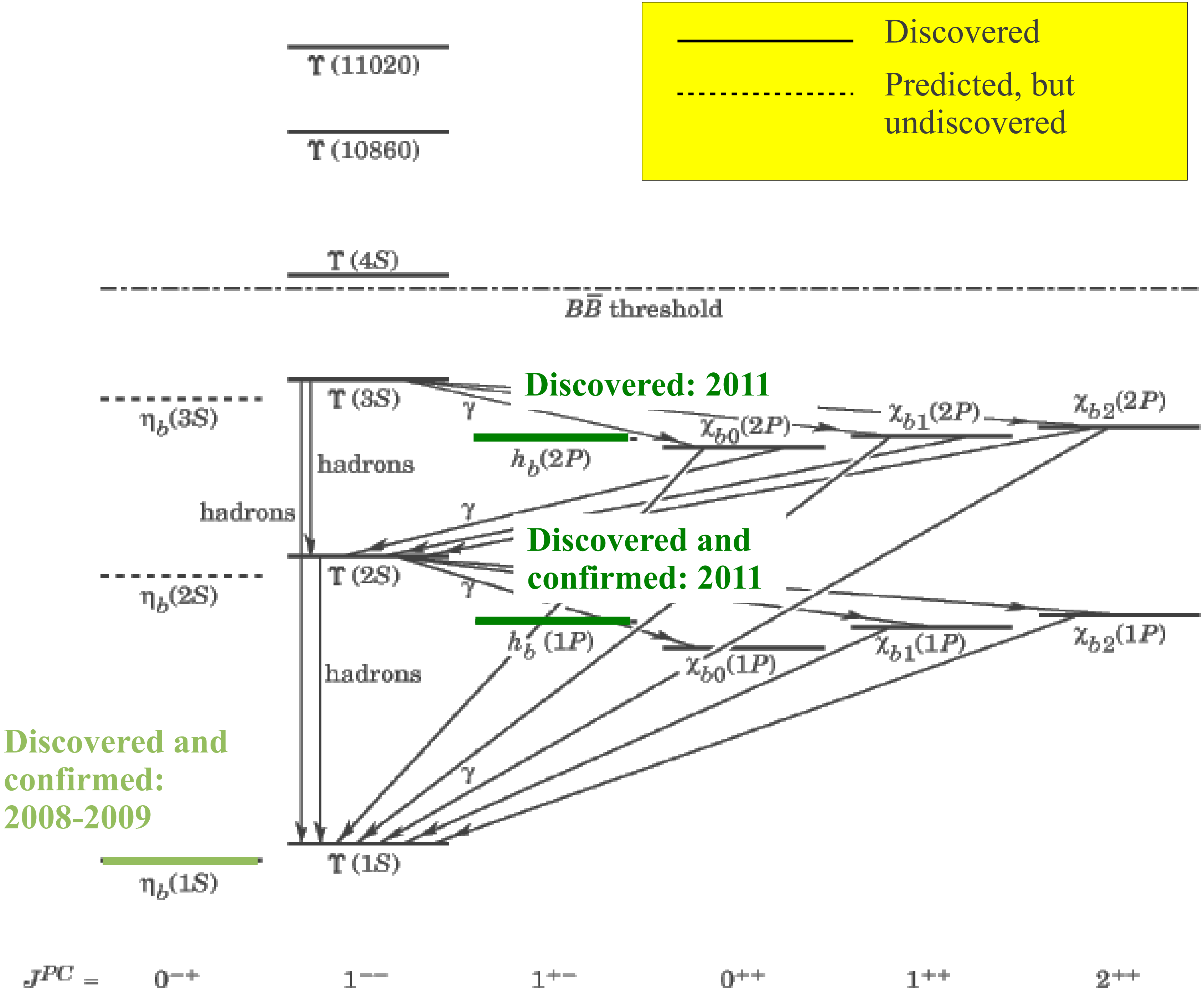
Y(5S) Recoil Search (cont.)

Background-subtracted fit to the data:



	Yield, 10^3	Mass, MeV$/c^2$	Signif.
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.42 \pm 0.53 \pm 1.02$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.25 \pm 1.06^{+1.03}_{-1.07}$	$6.2\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.4 \pm 8.7 \pm 6.8$	$10022.25 \pm 0.41 \pm 1.01$	$16.6\,\sigma$
$\Upsilon(1D)$	22.1 ± 7.8	10166.2 ± 2.4	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	$12.4\,\sigma$
$2S \to 1S$	$151.6 \pm 9.7^{+[illegible]}_{-20.}$	$10304.57 \pm 0.61 \pm 1.03$	$15.7\,\sigma$
$\Upsilon(3S)$	$44.9 \pm 5.1 \pm 5.1$	$10356.56 \pm 0.87 \pm 1.06$	$8.5\,\sigma$

First observations of BOTH the h_b(1P) and the h_b(2P) states! Masses consistent with prediction. Rate much larger from Y(5S) than is expected from n=1,2,3 states.



——— Discovered

- - - - - Predicted, but undiscovered

Discovered: 2011

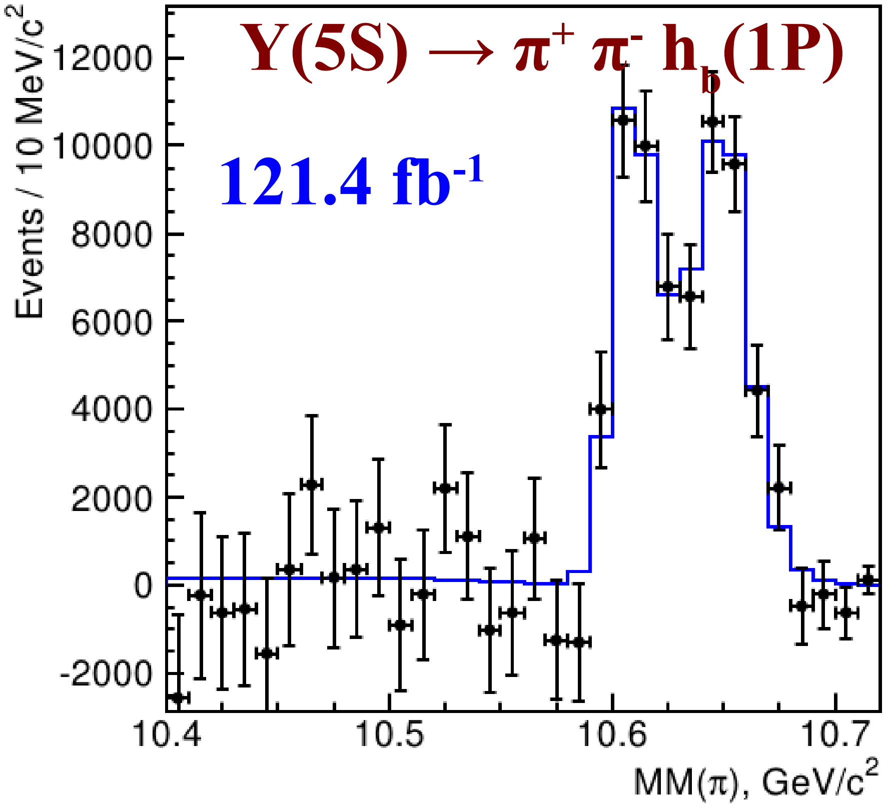
Discovered and confirmed: 2011

Discovered and confirmed: 2008-2009

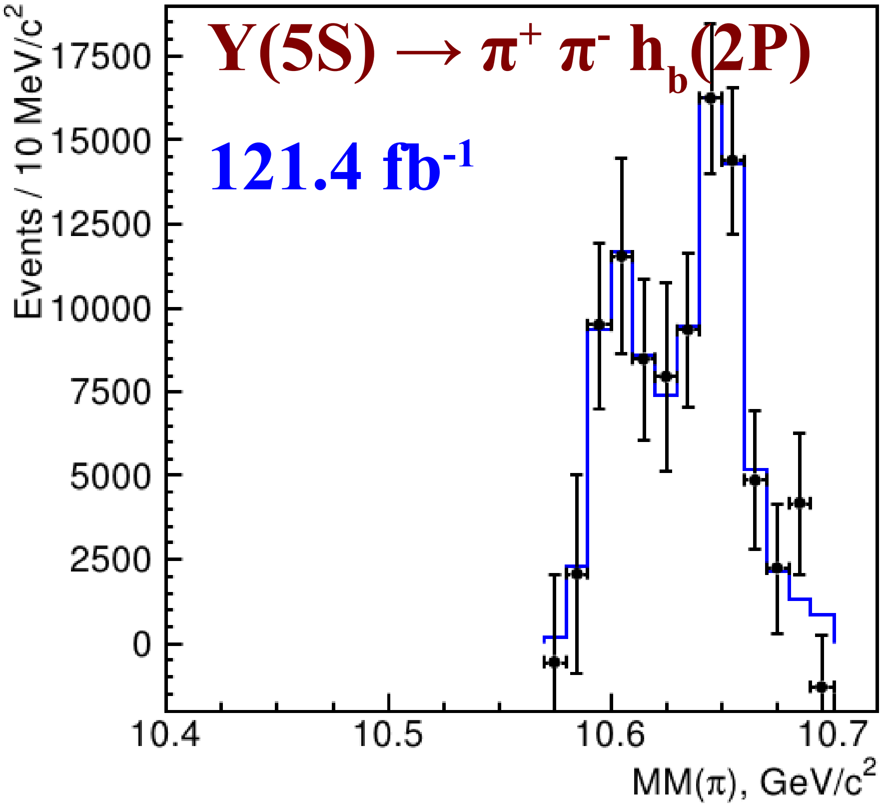
arXiv 1105.4583 (2011)

h_b(nP) spinoff

BELLE has gone on to look for resonant substructure in the transition $\Upsilon(5S) \rightarrow \pi^+ \pi^- h_b(nP)$



$\Upsilon(5S) \rightarrow \pi^+ \pi^- h_b(1P)$



$\Upsilon(5S) \rightarrow \pi^+ \pi^- h_b(2P)$

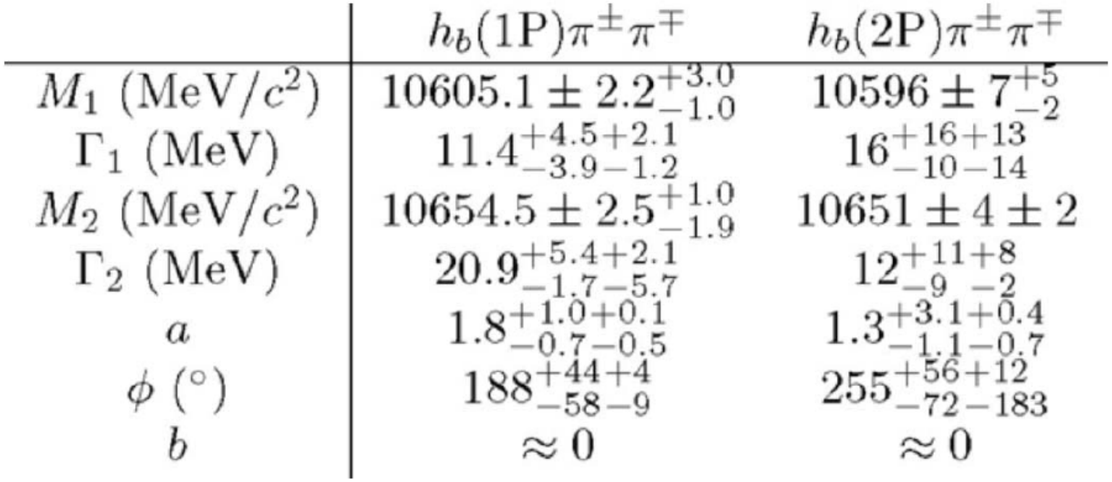
BELLE Interpretation of the data:

Using Energy/Momentum conservation, construct the mass of the $h_b \pi^+$ system – this is also the missing mass recoiling against the π^-. Model using sum of non-resonant component and two resonant components (P-wave Breit-Wigner Functions).

arXiv 1105.4583 (2011)

Interpretation

Results of the fit to the data, done separately in $h_b(1P)$ and $h_b(2P)$ events:



	$h_b(1P)\pi^\pm\pi^\mp$	$h_b(2P)\pi^\pm\pi^\mp$
M_1 (MeV/c^2)	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$
Γ_1 (MeV)	$11.4^{+4.5+2.1}_{-3.9-1.2}$	16^{+16+13}_{-10-14}
M_2 (MeV/c^2)	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$
Γ_2 (MeV)	$20.9^{+5.4+2.1}_{-1.7-5.7}$	$12^{+11+8}_{-9\ -2}$
a	$1.8^{+1.0+0.1}_{-0.7-0.5}$	$1.3^{+3.1+0.4}_{-1.1-0.7}$
ϕ (°)	188^{+44+4}_{-58-9}	$255^{+56+12}_{-72-183}$
b	≈ 0	≈ 0

Consistent results are obtained from the $h_b(1P)$ and $h_b(2P)$

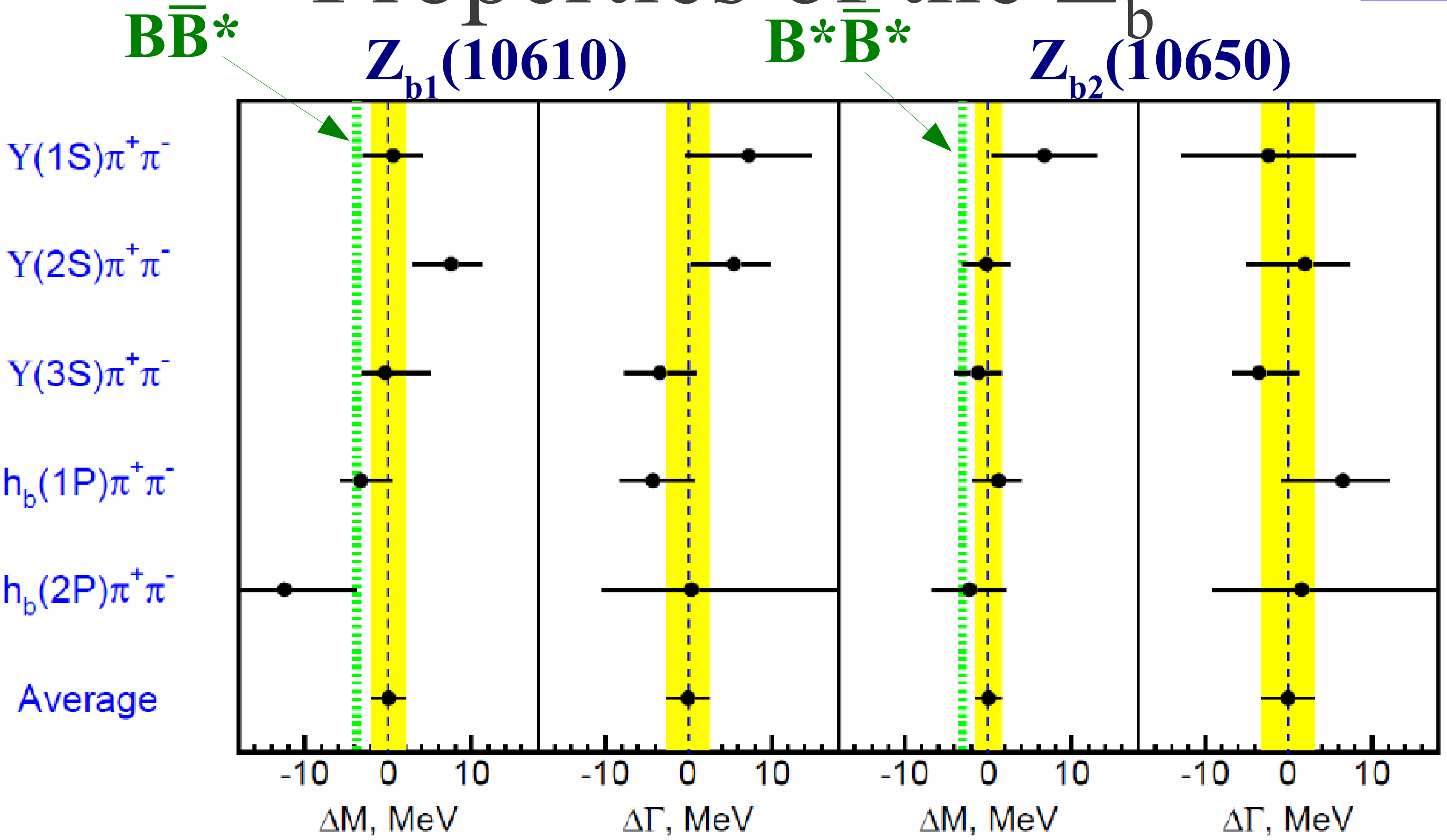
The mass of the Z_{b1} is just around the threshold for $B\bar{B}^*$ production and the mass of the Z_{b2} is just around the threshold for $B^*\bar{B}^*$ production.

Properties of the Z_b states, averaged over all observations (includes dipion transitions to Y(nS), n=1,2,3)

$$M_{Z_{b1}} = 10608.4 \pm 2.0 \text{ MeV}$$
$$\Gamma_{Z_{b1}} = 15.6 \pm 2.5 \text{ MeV}$$
$$M_{Z_{b2}} = 10653.2 \pm 1.5 \text{ MeV}$$
$$\Gamma_{Z_{b2}} = 14.4 \pm 3.2 \text{ MeV}$$

arXiv 1105.4583 (2011)

Properties of the Z_b

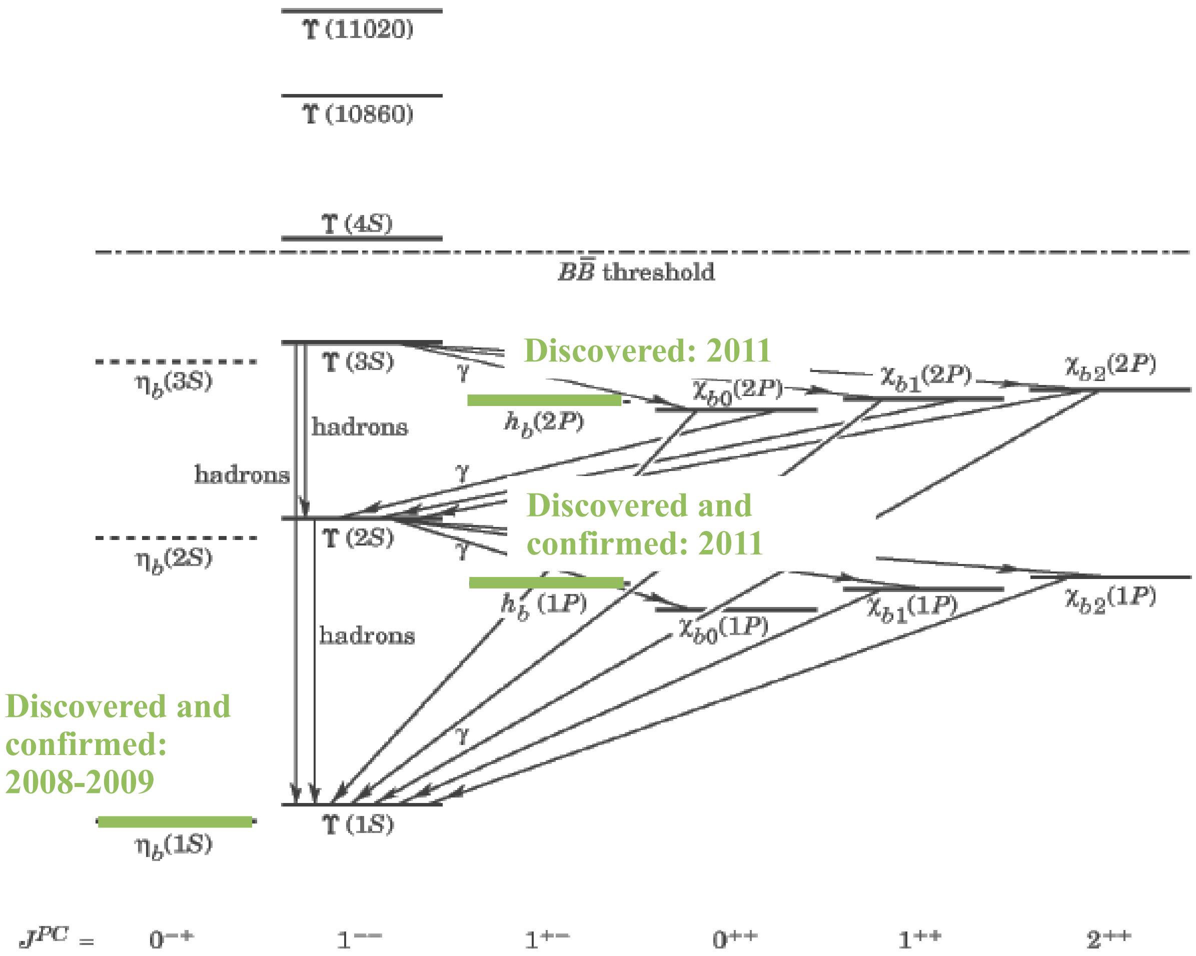


An angular analysis favors the interpretation that $J^P = 1^+$

→ ***Independent interpretations agree on their apparent correlation with the noted thresholds but disagree on their true nature (e.g. cusp/coupled channel effect ala. arXiv:1105.5492; molecular states ala arXiv:1105.5829 or arXiv:1105.5935; tetraquark states ala arXiv:1108.2197)***

——— Discovered

- - - - - - - Predicted, but undiscovered



Discovered: 2011

Discovered and confirmed: 2011

Discovered and confirmed: 2008-2009

Substructure in transitions:

$Z_{b2}(10650)$
$Z_{b1}(10610)$ [2011]

Understanding these states is an active and ongoing effort. Different interpretations do offer different predictions about the properties of these states as well as possible unobserved related states

Conclusions

An Exciting Time for Spectroscopy

- An era of discoveries in the bottomonium sector
  - The $\eta_b(1S)$ in 2008 and the $h_b(nP)$ [n=1,2] and Z_b in 2011
  - Measured properties so far consistent with theory
- Experimental observations call for more theoretical understanding
  - decay rates to lower-mass bottomonium states from Υ(5S) are higher than would be expected from Υ(nS), n=1,2,3,4
  - The pattern of transition rates from Υ(3S) → $\chi_{bJ}(1P)$ system are not as expected between the J=0,1,2 states
- Too many topics to cover in one talk
  - more dipion transition studies; searches for D-wave bottomonium; The Υ_b state; searches for physics beyond the Standard Model (e.g. low-mass Higgs bosons, low-mass dark matter, tests of lepton universality and lepton flavor violation)

Outlook

- More measurements
  - even years after closing out their data sets, BaBar and BELLE are both producing excellent results
  - expect this to continue as more measurements come to completion
- Discoveries and Puzzles?
  - The charmonium and bottomonium sectors continue to deliver discoveries . . .
  - . . . and puzzles!
  - Makes for an exciting interplay of theory and experiment

BACKUP SLIDES