Quarkonium 2013

Bottomonium Spectroscopy at Belle

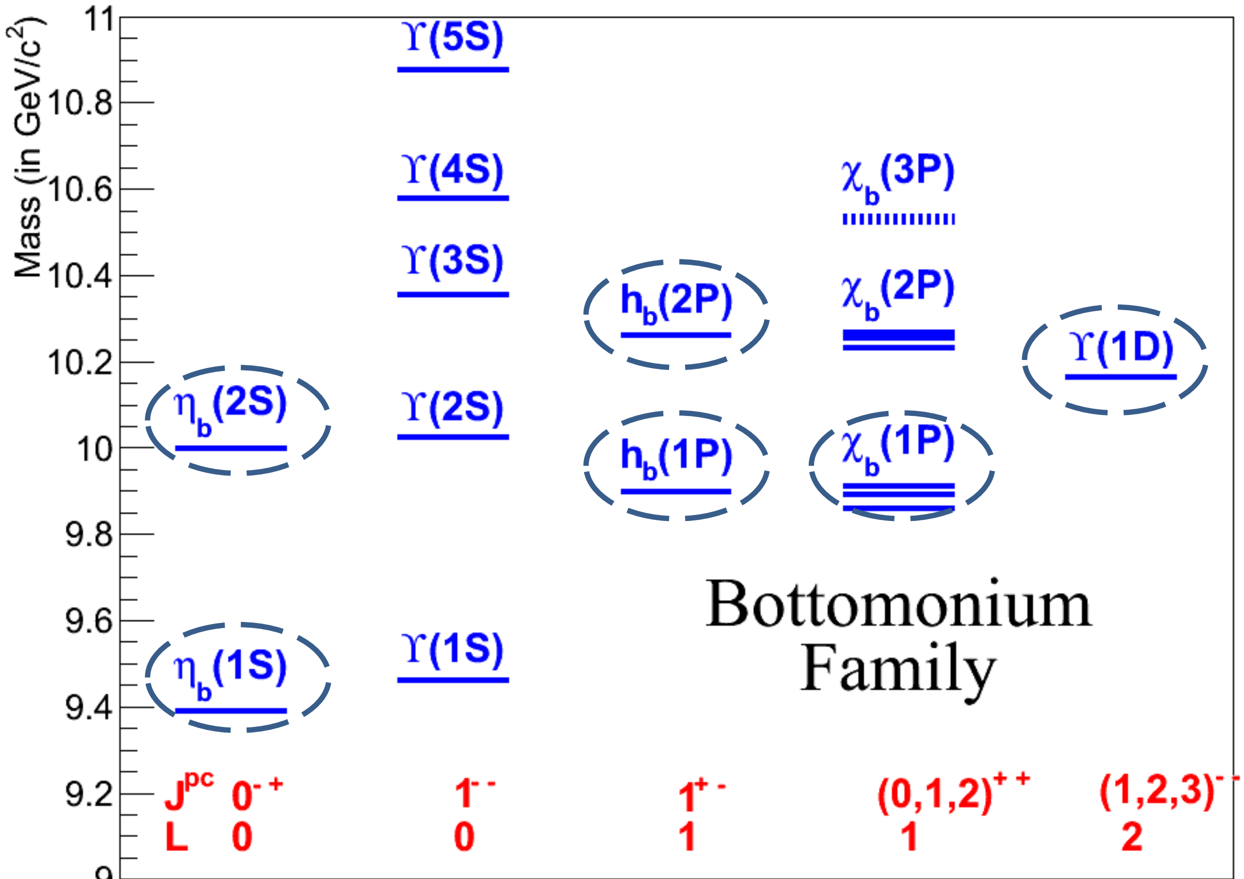
April 22- 26, 2013, IHEP, Beijing

Saurabh Sandilya
TIFR, Mumbai
(On behalf of the Belle Collaboration)

Outline

- $h_b(nP) \to \eta_b(mS)\gamma$
- Radiative $\Upsilon(2S)$ decay NEW
- $\Upsilon(1D)$ mass NEW
- R_b Scan
- Summary

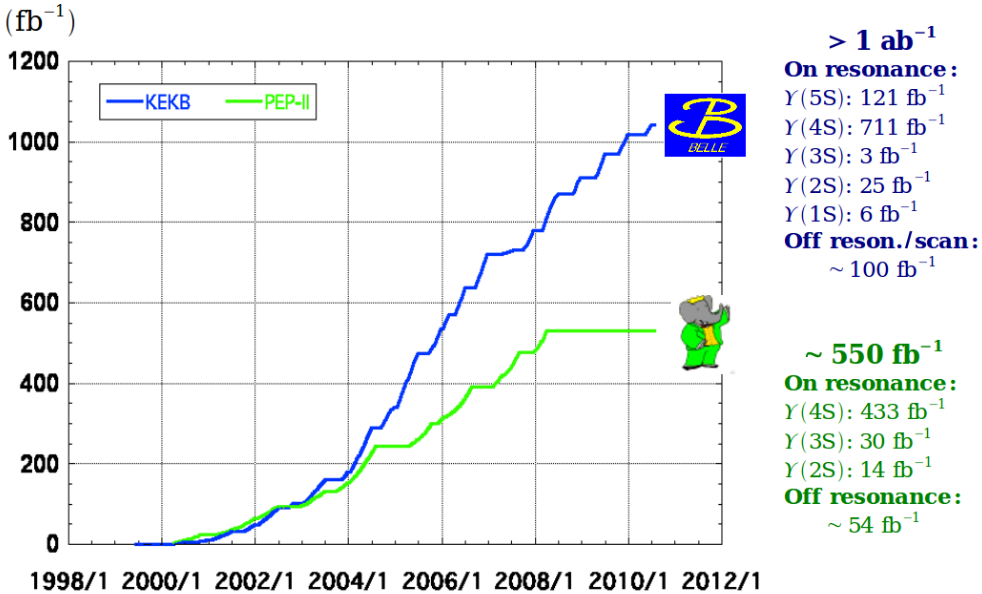
Introduction



*(J. Beringer et al. (PDG), Phys. Rev. D86,010001(2012))

- My talk is a tour of some of the bottomonium states, indicated by studied using the unique data set of Belle

Belle datasets



Resonance	Data Collected @ Belle (June 30, 2010)
Y(1S)	6 fb^{-1} Largest
Y(2S)	24.7 fb^{-1} Largest
Y(3S)	3 fb^{-1}
Y(4S)	711 fb^{-1} Largest
Y(5S)	121 fb^{-1} Largest

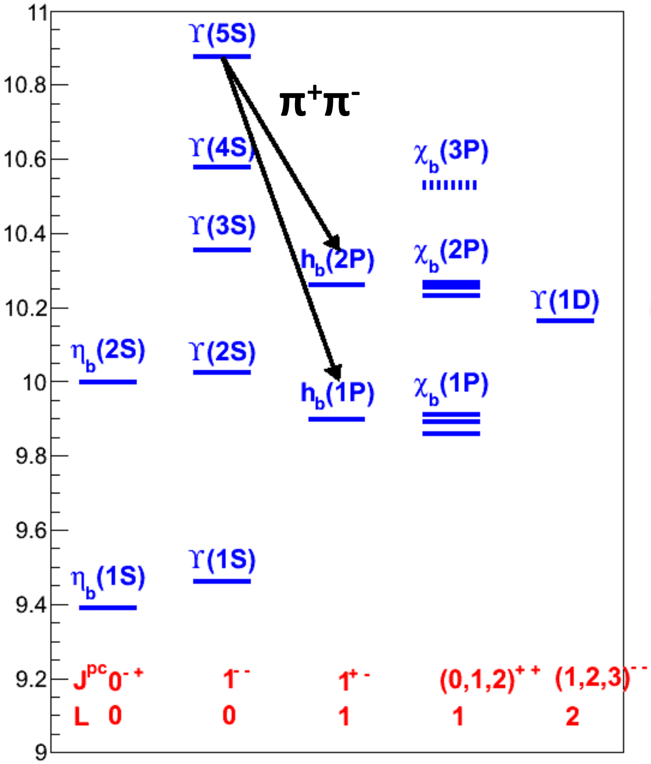
- Belle has collected most of its data at the Y(4S) resonance
  - To study various aspects of B-meson decays
  - Most celebrated result has been “CP violation in B-meson decays”

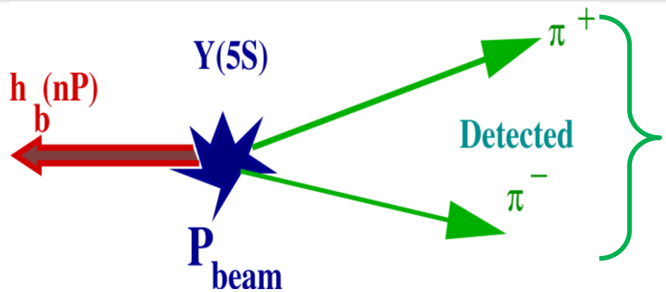
- *e+e−* colliders produce a particularly clean environment to study properties of the ϒ states.
- The entire collision energy of the initial *e+e−* system turns into the ϒ rest mass.

Observation of $h_b(nP)$

Looking for h_b(nP)

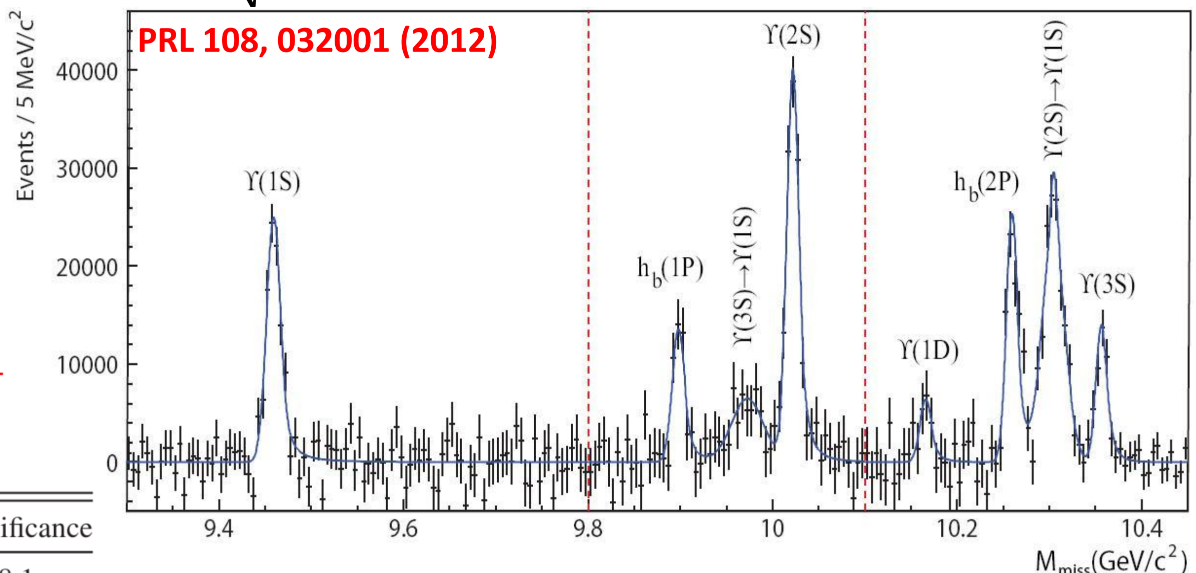
$\Upsilon(5S) \to h_b\pi^+\pi^-$ reconstruction





Reconstructed, use $M_{miss}(\pi^+\pi^-)$

$$M(h_b) = \sqrt{(E_{CM} - E^*_{\pi^+\pi^-})^2 - {E^*_{\pi^+\pi^-}}^2} \equiv M_{miss}(\pi^+\pi^-)$$



	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$104.9 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	18.1σ
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	6.1σ
$3S \to 1S$	55 ± 19	9973.01	2.9σ
$\Upsilon(2S)$	$143.7 \pm 8.7 \pm 6.8$	$10\,022.2 \pm 0.4 \pm 1.0$	17.1σ
$\Upsilon(1D)$	22.4 ± 7.8	$10\,166.1 \pm 2.6$	2.4σ
$h_b(2P)$	$83.9 \pm 6.8^{+23.}_{-10.}$	$10\,259.8 \pm 0.6^{+1.4}_{-1.0}$	12.3σ
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10\,304.6 \pm 0.6 \pm 1.0$	15.7σ
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10\,356.7 \pm 0.9 \pm 1.1$	8.5σ

$\Delta M_{HF}(1P) = +0.8 \pm 1.1\mathrm{MeV}$
$\Delta M_{HF}(2P) = +0.5 \pm 1.2\mathrm{MeV}$
consistent with zero, as expected.

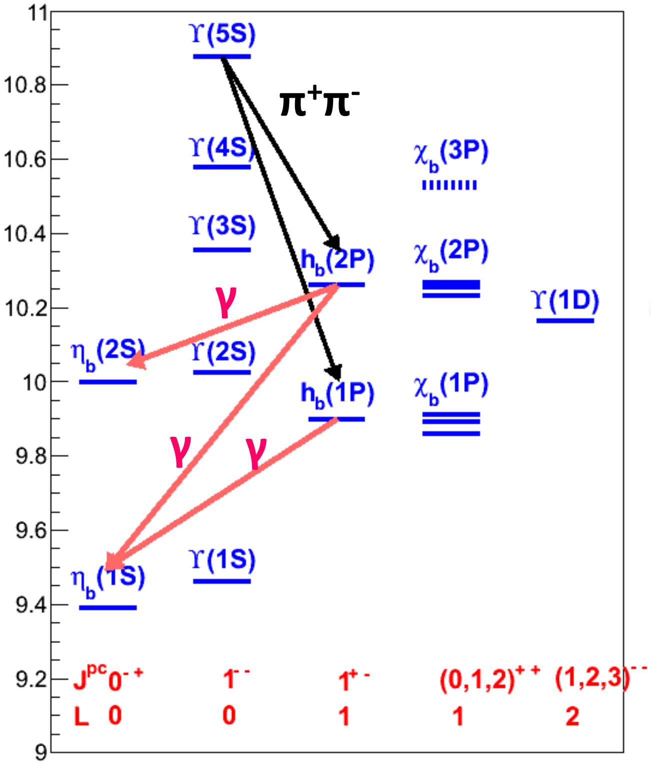
large h_b(1,2P) production rate => Z_b^+ Discovery

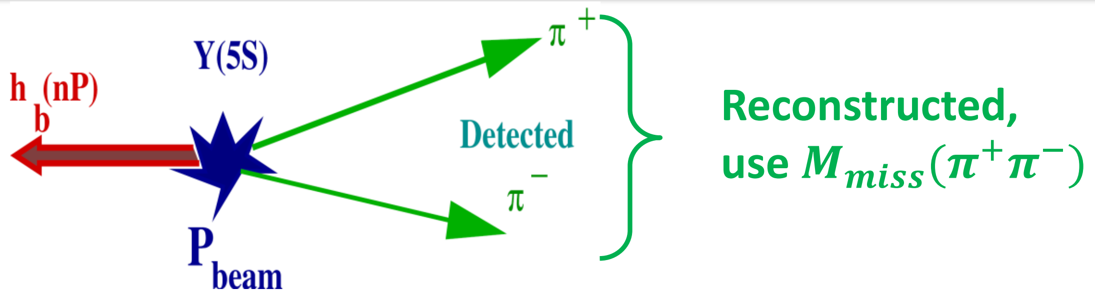
See R. Mizuk's talk, on 26th April

Observation of $h_b(nP)$

Looking for $h_b(nP)$

$Y(5S) \to h_b \pi^+\pi^-$ reconstruction





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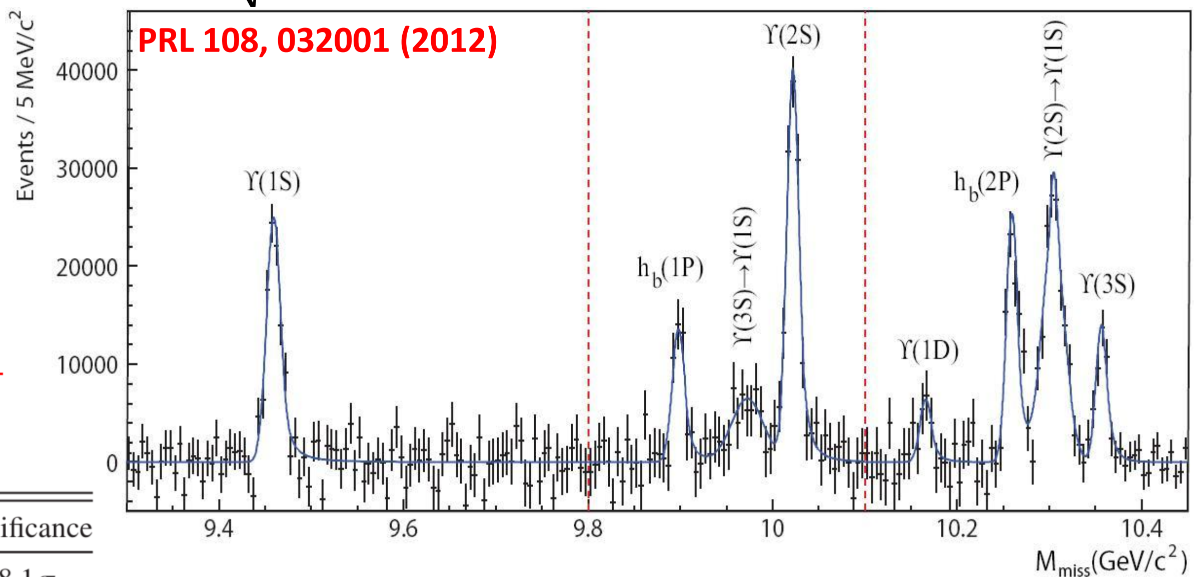

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High yield of $h_b(nP)$ opens new perspective to study $\eta_b(mS)$!!

Observation of $h_b(nP) \to \eta_b(mS)\gamma$

Decay chain

$\Upsilon(5S) \to Z_b\, \pi^{\pm}$
$\quad \hookrightarrow h_b(nP)\, \pi^{+}$
$\quad\quad \hookrightarrow \eta_b(mS)\, \gamma$

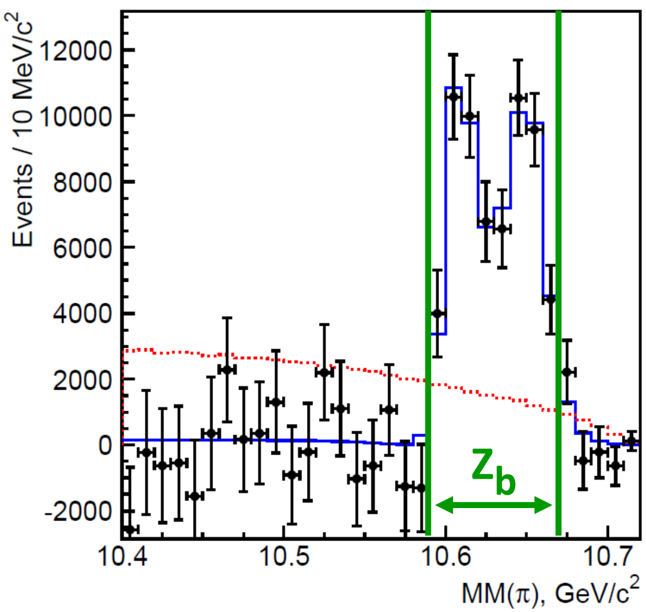
reconstruct

Use missing mass to identify signals

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

Hadronic event selection;
continuum suppression using event shape;
π^0 veto.
Require intermediate Z_b : **10.59 < MM(π) < 10.67 GeV**

- rectangular bg bands
- no correlation

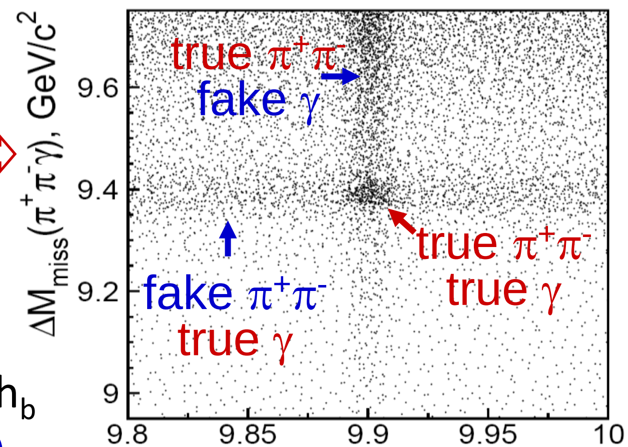


Approach:

Signal is a cluster in the 2D plane and we determine the h_b yield in bins of $\Delta M_{miss}(\pi^+\pi^-\gamma)$

MC simulation

$M(\eta_b) \Rightarrow$



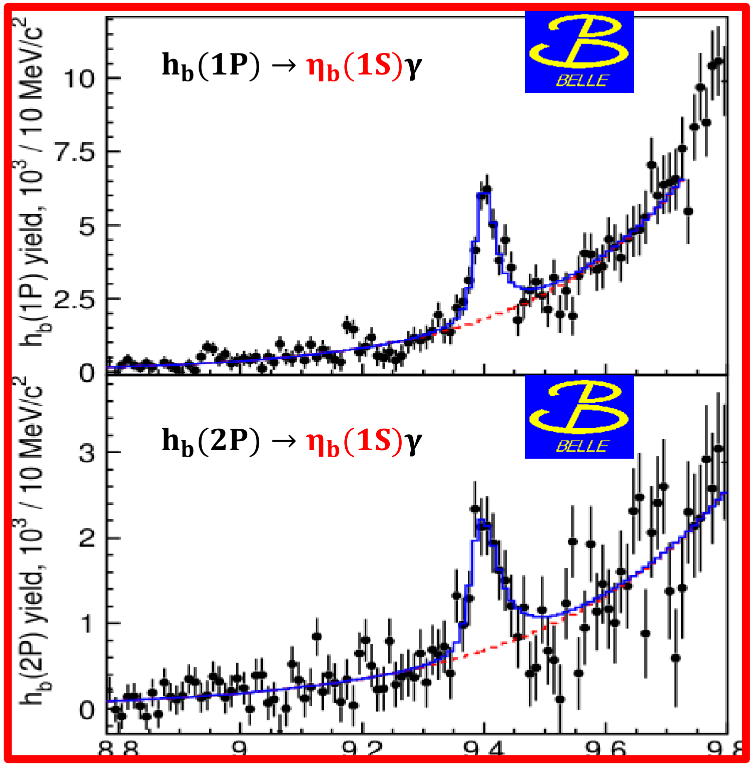
$M(h_b) \Rightarrow M_{miss}(\pi^+\pi^-)$, GeV/c^2

133.4 fb^{-1} Data used at $\Upsilon(5S)$ resonance

fit $M_{miss}(\pi^+\pi^-)$ spectra in $\Delta M_{miss}(\pi^+\pi^-\gamma)$ bins

Re-Discovery of $\eta_b(1S)$ at Belle

PRL **109**,232002 (2012)

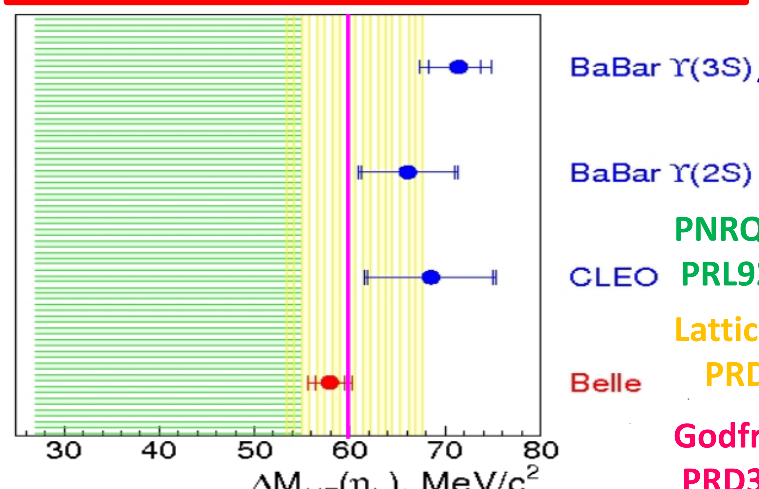


$m_{\eta_b(1S)} = 9402.4 \pm 1.5 \pm 1.8$ MeV/c²

First measurement of $\Gamma = 10.8^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV/c²

B.F. $[h_b(1P) \to \eta_b(1S)\gamma] = (49.2 \pm 5.7^{+5.6}_{-3.3})\%$
B.F. $[h_b(2P) \to \eta_b(1S)\gamma] = (22.3 \pm 5.7^{+5.6}_{-3.3})\%$

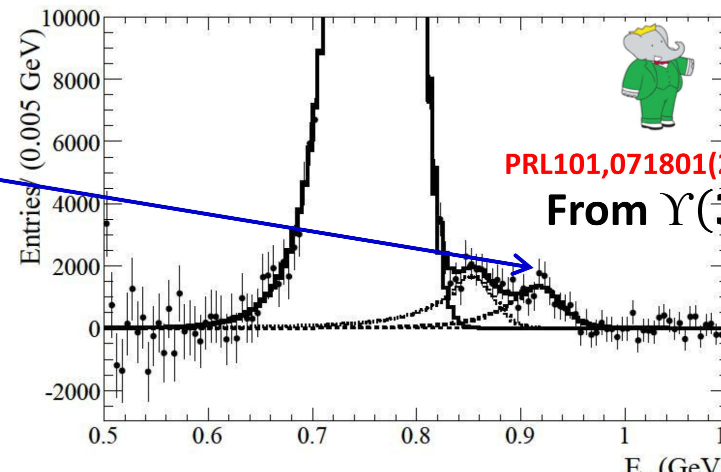
More precise than PDG 2012 (avg)[9391.0 ± 2.8 MeV], decreases tension with theory



PNRQCD@NLL
PRL92,242001(2004)

Lattice QCD
PRD82,114502(2010)

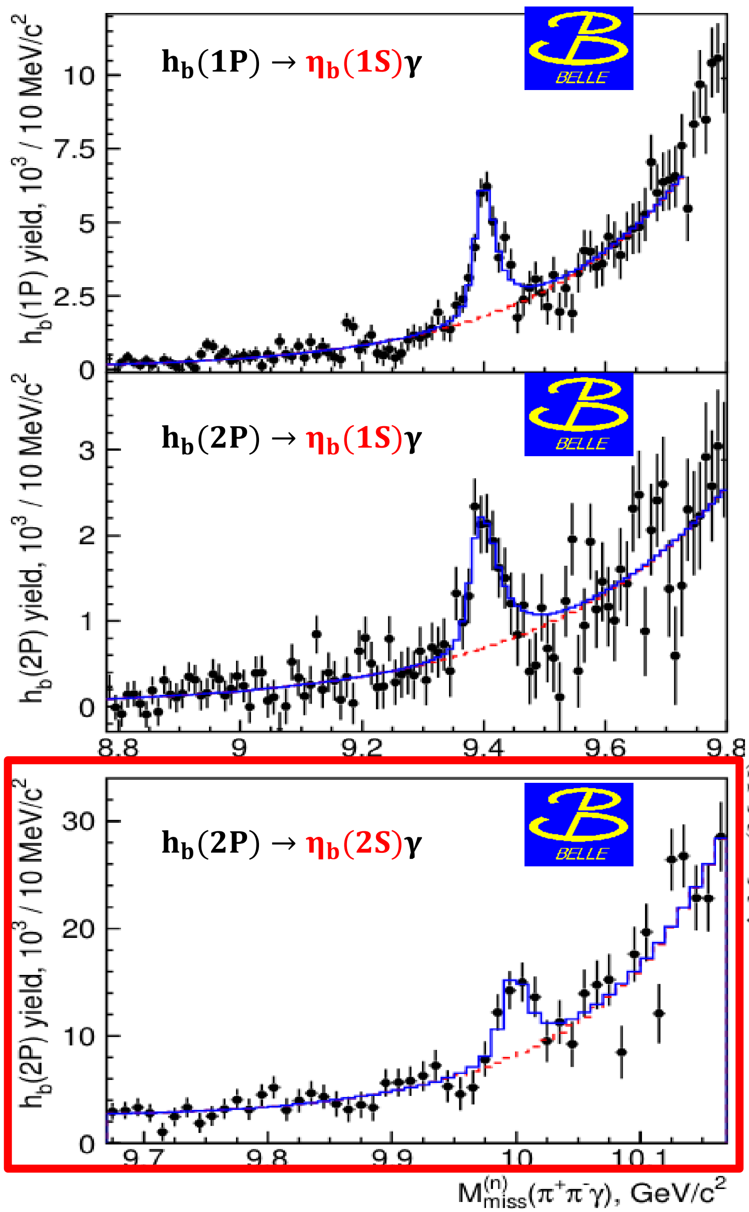
Godfrey-Isgur
PRD32,189(1985)



PRL101,071801(2008)

From $\Upsilon(3S)$

First evidence of $\eta_b(2S)$ at Belle

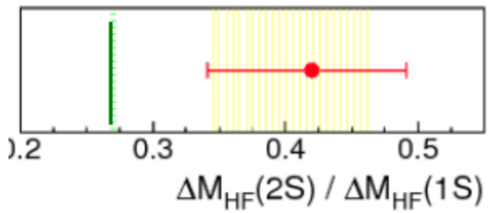


PRL **109**,232002 (2012)

$m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-1.9}$ MeV/c^2

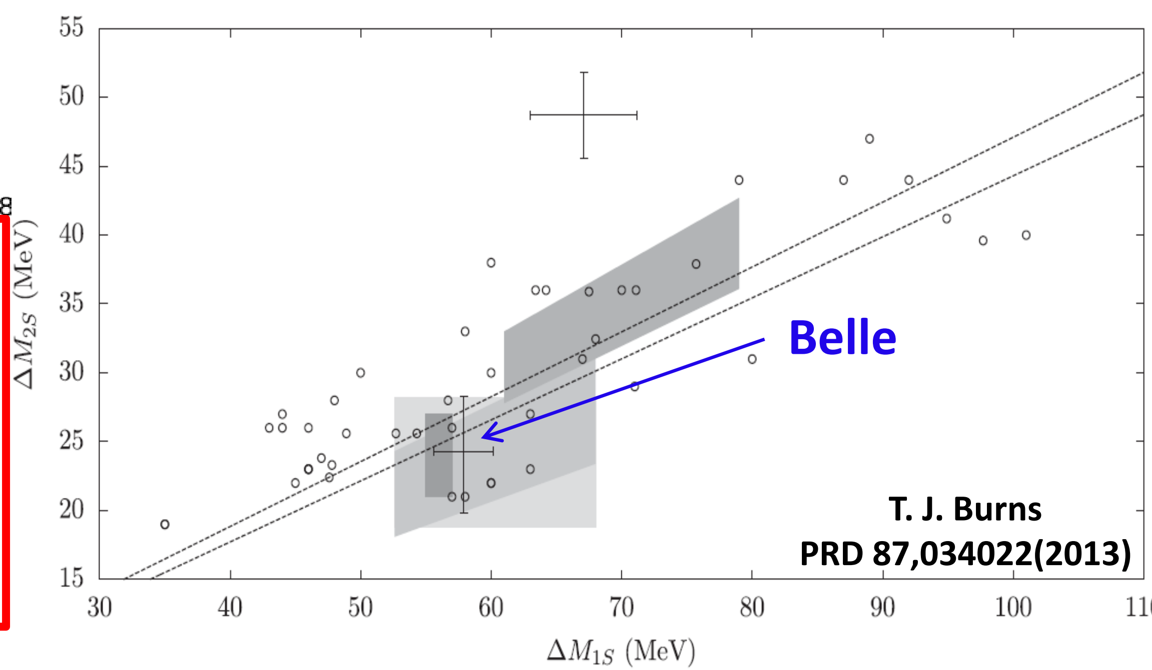
with significance (including sys.)at 4.2σ

B.F. $[h_b(2P) \to \eta_b(2S)\gamma] = (47.5 \pm 10.5^{+6.8}_{-7.7})\%$



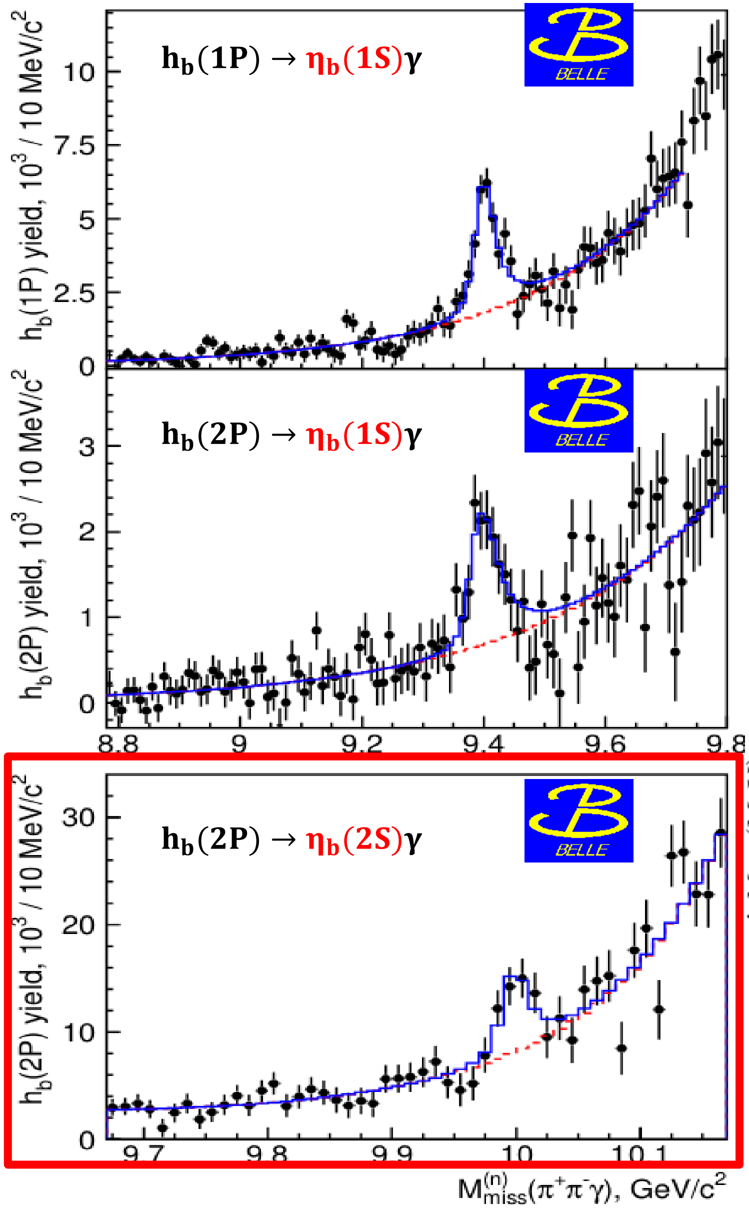
ΔM_{HF} (2S) = $24.3^{+4.0}_{-4.5}$ MeV/c^2

Belle



First evidence of $\eta_b(2S)$ at Belle

PRL **109**,232002 (2012)



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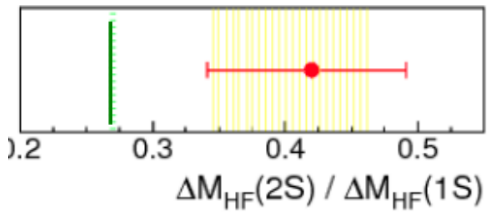

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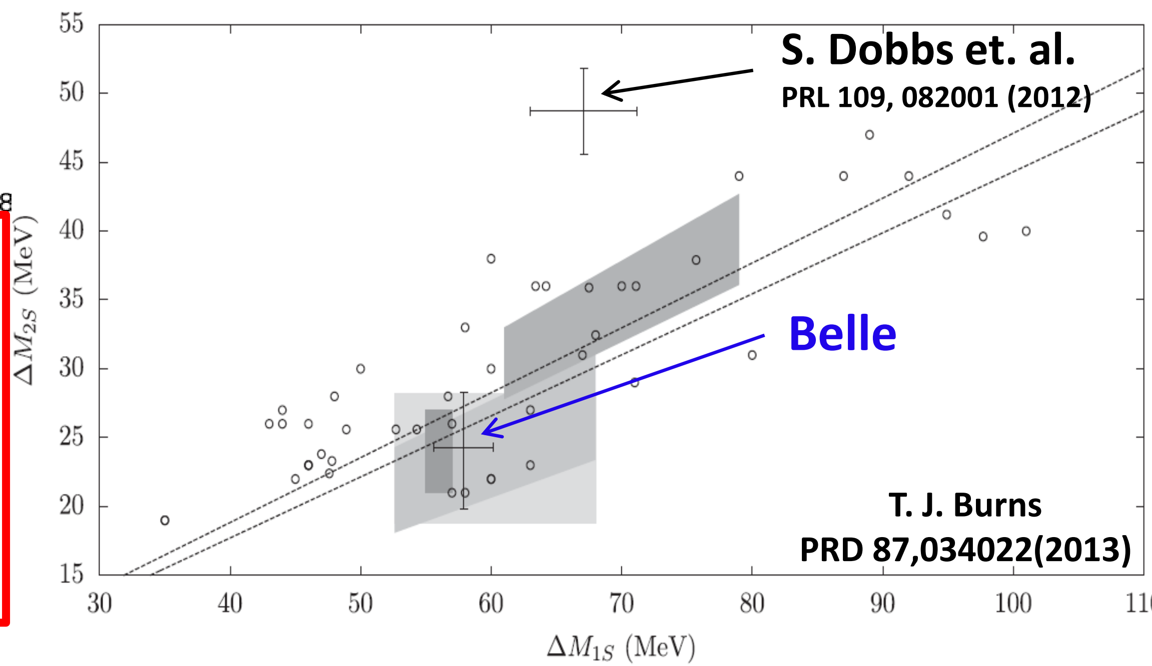


η_b(2S) claim based on CLEO-c data

Observation of the $\eta_b(2S)$ Meson in $\Upsilon(2S) \to \gamma\eta_b(2S)$, $\eta_b(2S) \to$ Hadrons and Confirmation of the $\eta_b(1S)$ Meson

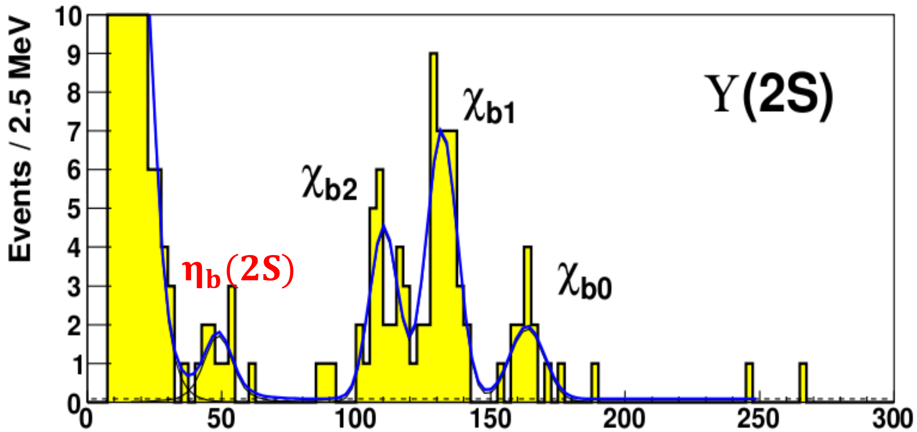
PRL 109, 082001 (2012)

S. Dobbs, Z. Metreveli, A. Tomaradze, T. Xiao, and Kamal K. Seth

Northwestern University, Evanston, Illinois 60208, USA

(Received 18 April 2012; published 24 August 2012)

The data for 9.3 million $\Upsilon(2S)$ and 20.9 million $\Upsilon(1S)$ taken with the CLEO III detector have been used to study the radiative population of states identified by their decay into 26 different exclusive hadronic final states. In the $\Upsilon(2S)$ decays, an enhancement is observed at a $\sim 5\sigma$ level at a mass of $9974.6 \pm 2.3(\text{stat}) \pm 2.1(\text{syst})$ MeV. It is attributed to $\eta_b(2S)$ and corresponds to the $\Upsilon(2S)$ hyperfine splitting of $48.7 \pm 2.3(\text{stat}) \pm 2.1(\text{syst})$ MeV. In the $\Upsilon(1S)$ decays, the identification of $\eta_b(1S)$ is confirmed at a $\sim 3\sigma$ level with $M[\eta_b(1S)]$ in agreement with its known value.



ΔM = M[Υ(2S)] – M[$(b\bar{b})$]

The measurement is carried out in 26 exclusive decays of the η_b(2S) into charged hadrons.

$$\mathcal{B}_1 \times \mathcal{B}_2 \equiv \mathcal{B}_1[\Upsilon(nS) \to \gamma\eta_b(nS)] \times \sum_{i=1}^{26} \mathcal{B}_{2i}[\eta_b(nS) \to h_i]$$

$$\mathcal{B}_1 \times \mathcal{B}_2(\eta_b(2S)) = (46.2 \pm^{+29.7}_{-14.2} \pm 10.6) \times 10^{-6}$$

Reminder: Our ΔM_{HF} (2S) = $24.3^{+4.0}_{-4.5}$ MeV/c²

S. Dobbs's $\eta_b(2S)$ signal is not consistent with theory as well as our measurement

$\Upsilon(2S) \rightarrow \gamma\,(b\bar{b})$

- Study is performed using the 25 fb^{-1} data (157.8×10^6 $\Upsilon(2S)$ events) .

- **~17 times more data than CLEO-c's $\Upsilon(2S)$ sample**

- We study $\Upsilon(2S) \rightarrow \gamma\,(b\bar{b})$; where $(b\bar{b})$ decays hadronically (same 26 exclusive hadronic final states as mentioned in S. Dobbs et. al.)

$\mathbf{X_i}$: $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $4(\pi^+\pi^-)$, $5(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-2(\pi^+\pi^-)$, $K^+K^-3(\pi^+\pi^-)$, $K^+K^-4(\pi^+\pi^-)$, $2(K^+K^-)$, $2(K^+K^-)\pi^+\pi^-$, $2(K^+K^-)2(\pi^+\pi^-)$, $2(K^+K^-)3(\pi^+\pi^-)$, $p\bar{p}\pi^+\pi^-$, $p\bar{p}2(\pi^+\pi^-)$, $p\bar{p}3(\pi^+\pi^-)$, $p\bar{p}4(\pi^+\pi^-)$, $p\bar{p}K^+K^-\pi^+\pi^-$, $p\bar{p}K^+K^-2(\pi^+\pi^-)$, $p\bar{p}K^+K^-3(\pi^+\pi^-)$, $K_S^0K^\pm\pi^\mp$, $K_S^0K^\pm\pi^\mp\pi^+\pi^-$, $K_S^0K^\pm\pi^\mp2(\pi^+\pi^-)$, $K_S^0K^\pm\pi^\mp3(\pi^+\pi^-)$, $2K_S^0\pi^+\pi^-$, $2K_S^02(\pi^+\pi^-)$, $2K_S^03(\pi^+\pi^-)$.

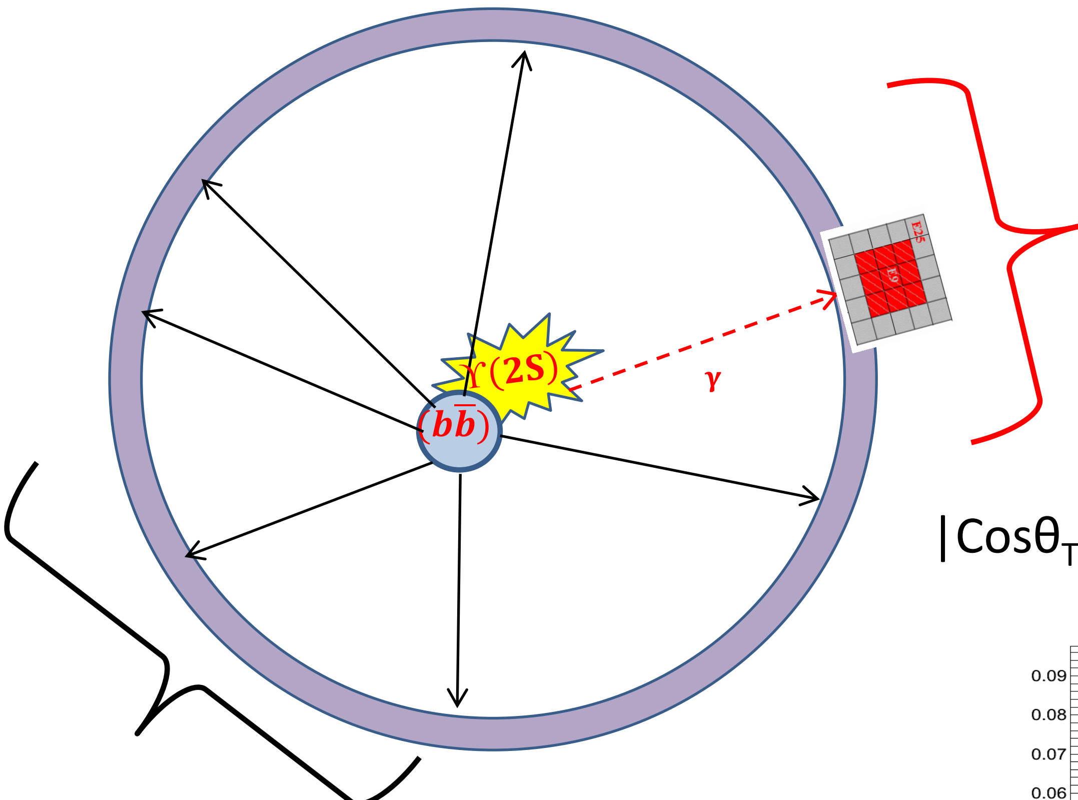
- Following decay channels are good control samples

$$\Upsilon(2S) \rightarrow \gamma\,\chi_{bJ} \quad (J = 0, 1, 2)$$

and χ_{bJ} can decay to the hadronic modes (comprising charged pions, kaons, protons and K_s mesons)

- Off-resonance $\Upsilon(4S)$ data [89.5 fb^{-1} ~4 times larger than our $\Upsilon(2S)$ data] used for background shape study.

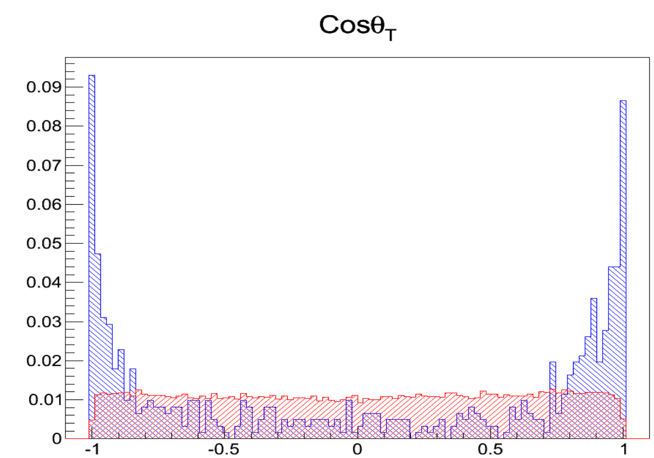
$\Upsilon(2S) \rightarrow \gamma\,(b\bar{b})$



<u>γ - selection</u>

- Isolated cluster
- Energy of gamma > 22 MeV
- E9/E25 > 0.85
- Exclude endcaps

$|\mathrm{Cos}\theta_T| < 0.8$: Continuum - Suppression



<u>$(b\bar{b})$ reconstruction</u>:

- Impact parameter cuts
- Number of charged tracks
- Particle identification (pion, kaon, proton)

Simple and Straightforward !!

$\Upsilon(2S) \rightarrow \gamma\,(b\bar{b})$

- More variables exploited to suppress backgrounds :
  - **ΔE**

    $E^*_{\Upsilon(2S)} - E_{CM}$

    should peak around 0.

    [ΔE > -0.04 GeV & ΔE < 0.05 GeV]
  - **$P^*_{\Upsilon(2S)}$**

    momentum of the ϒ(2S) candidate in the center-of-mass.

    should peak around 0.

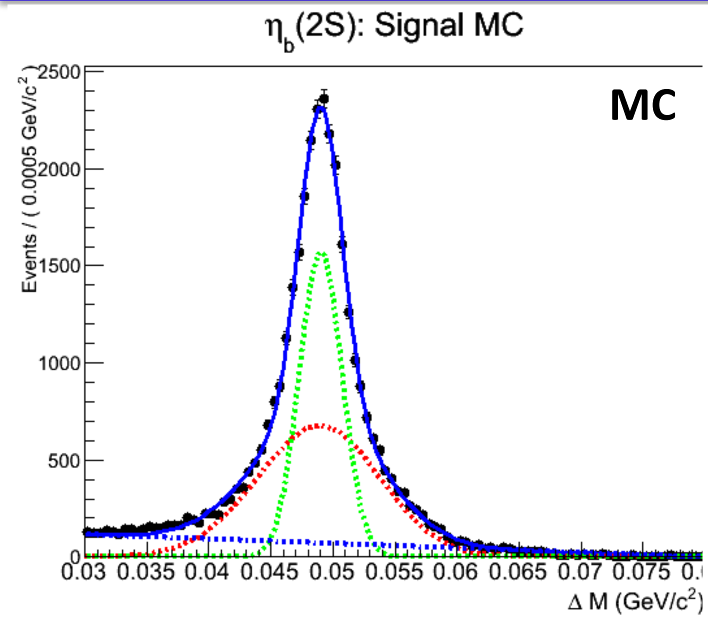
    [$P^*_{\Upsilon(2S)}$ < 0.03 GeV/c]
  - **$\theta_{\gamma(bb)}$**

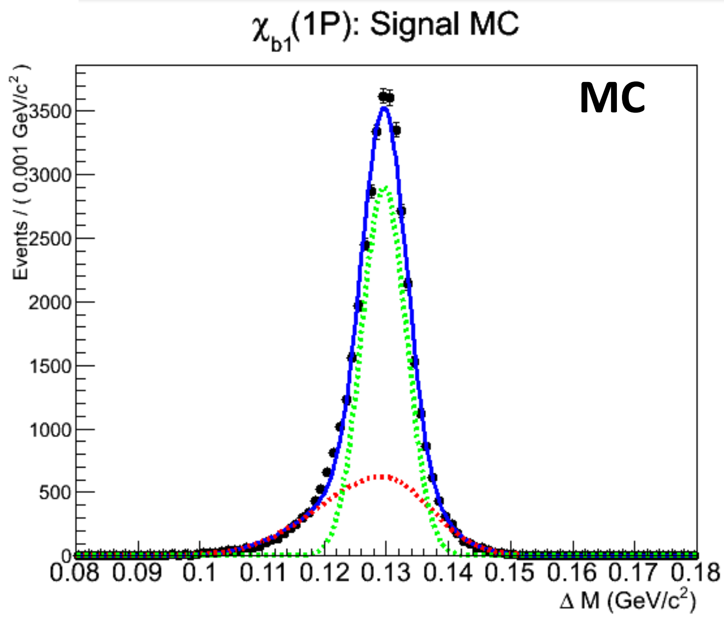
    Angle between γ candidate and $(b\bar{b})$ in the CM Frame.

    should peak around 180^0.

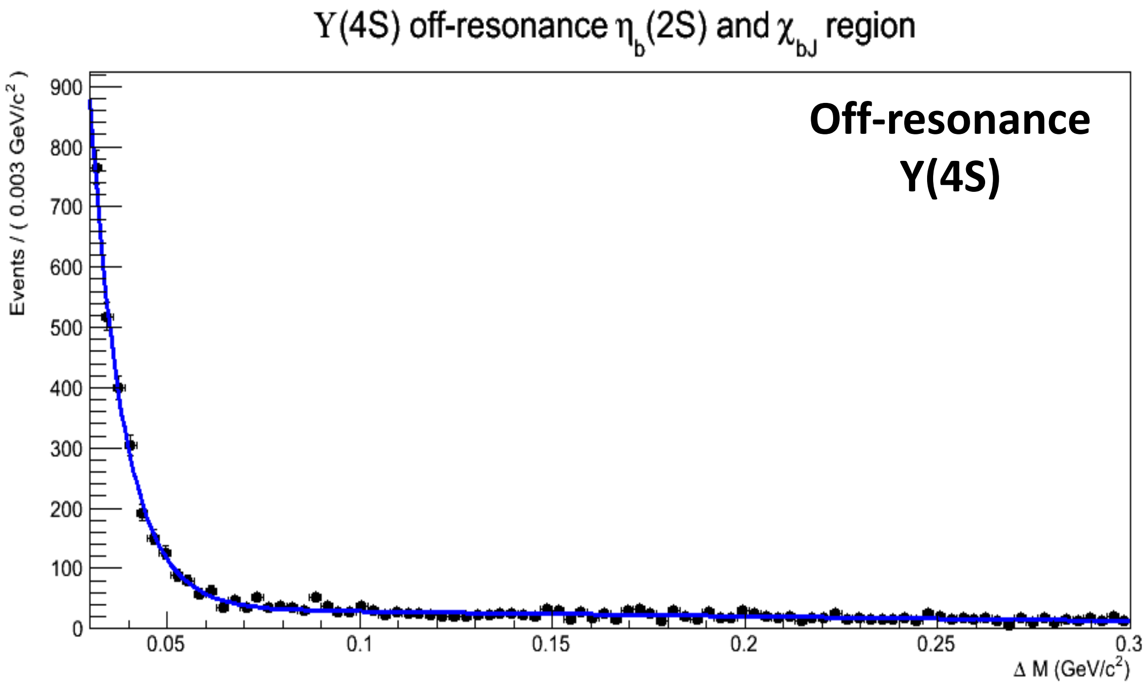
    [$\theta_{\gamma(bb)} > 150^0$]
- Cut values obtained from optimization (assuming S. Dobbs et. al. B. F.)
- Multiple Candidates found at this stage is 8-10% .
- Energy-Momentum constrained kinematic fit (4C)is used to improve the resolution as well as for the best candidate selection.

$\Upsilon(2S) \rightarrow \gamma\,(b\bar{b})$



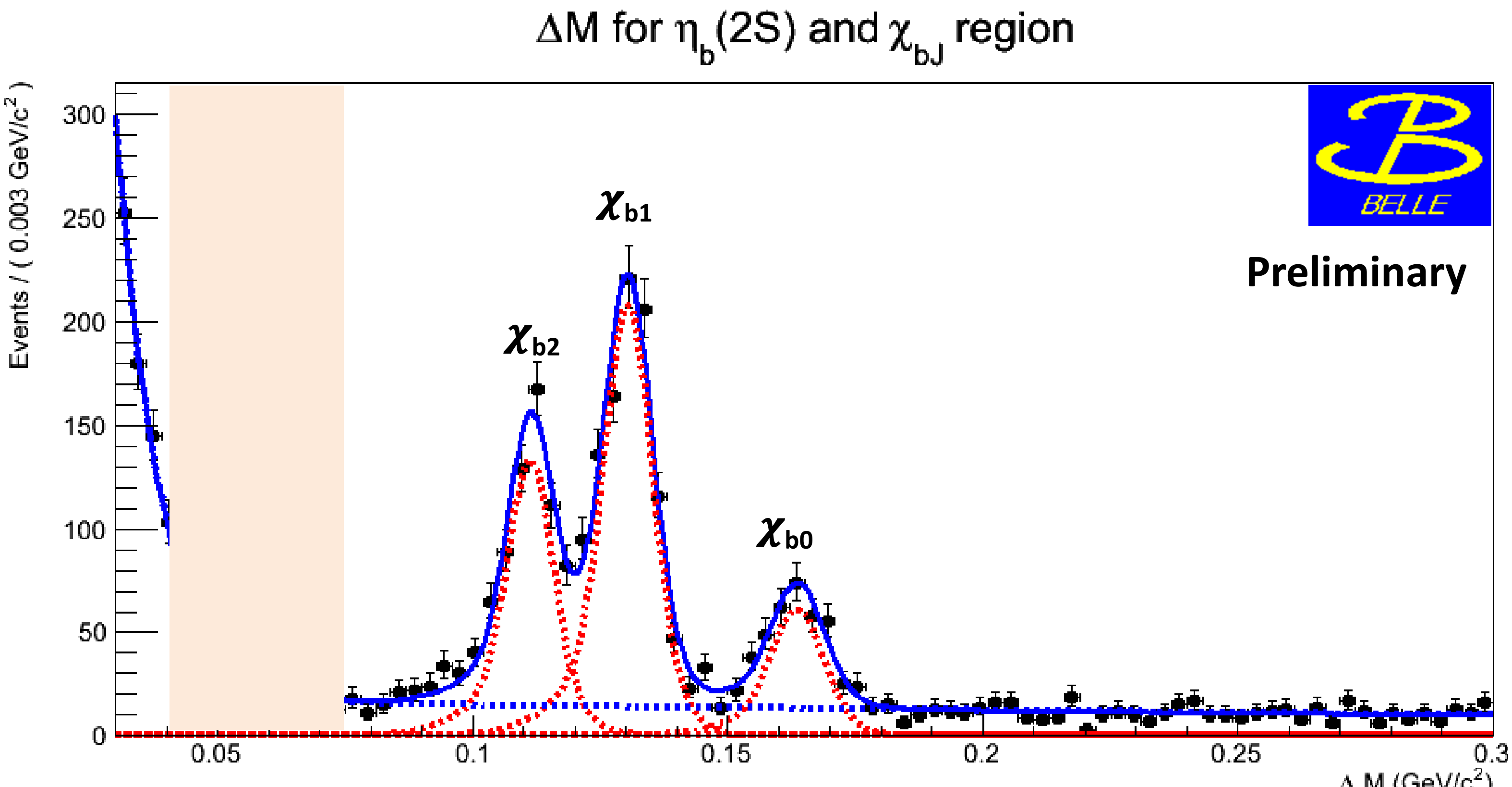


Signal MC is fitted with double gauss [Bifur gauss+gauss]



The background at low energy is mainly coming from beam-background, which is exponential in nature and has long tail.
(To demonstrate this, we fitted Y(4S) [89.5 fb^{-1}] off-resonance)
[exponential+chebyshev pol.]

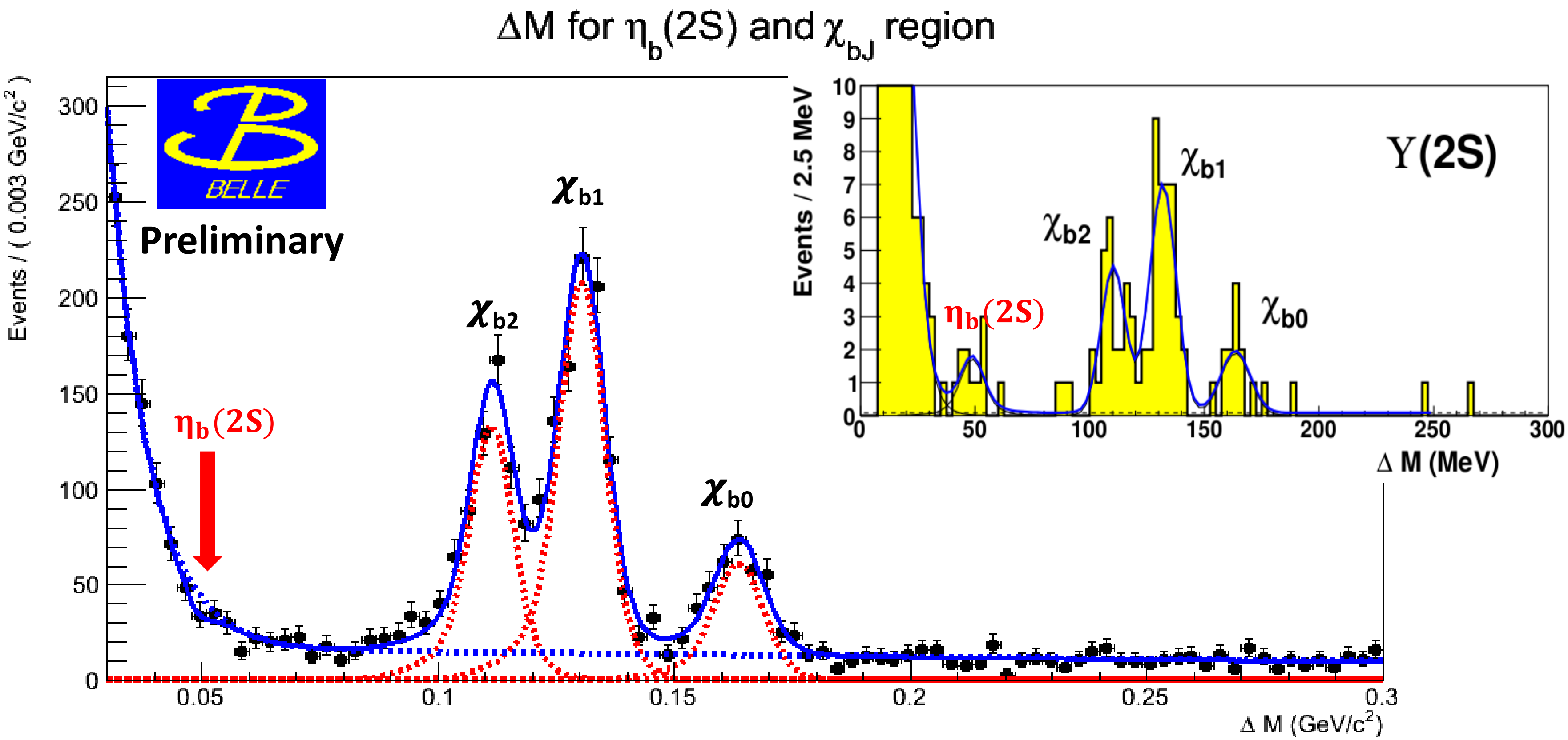
$\Upsilon(2S) \to \gamma\,(b\bar{b})$



Large statistics available in our sample for χ_{bJ} (300-950 candidates) allows to determine precisely the χ_{bJ} masses. (with an accuracy competitive with PDG 2012).

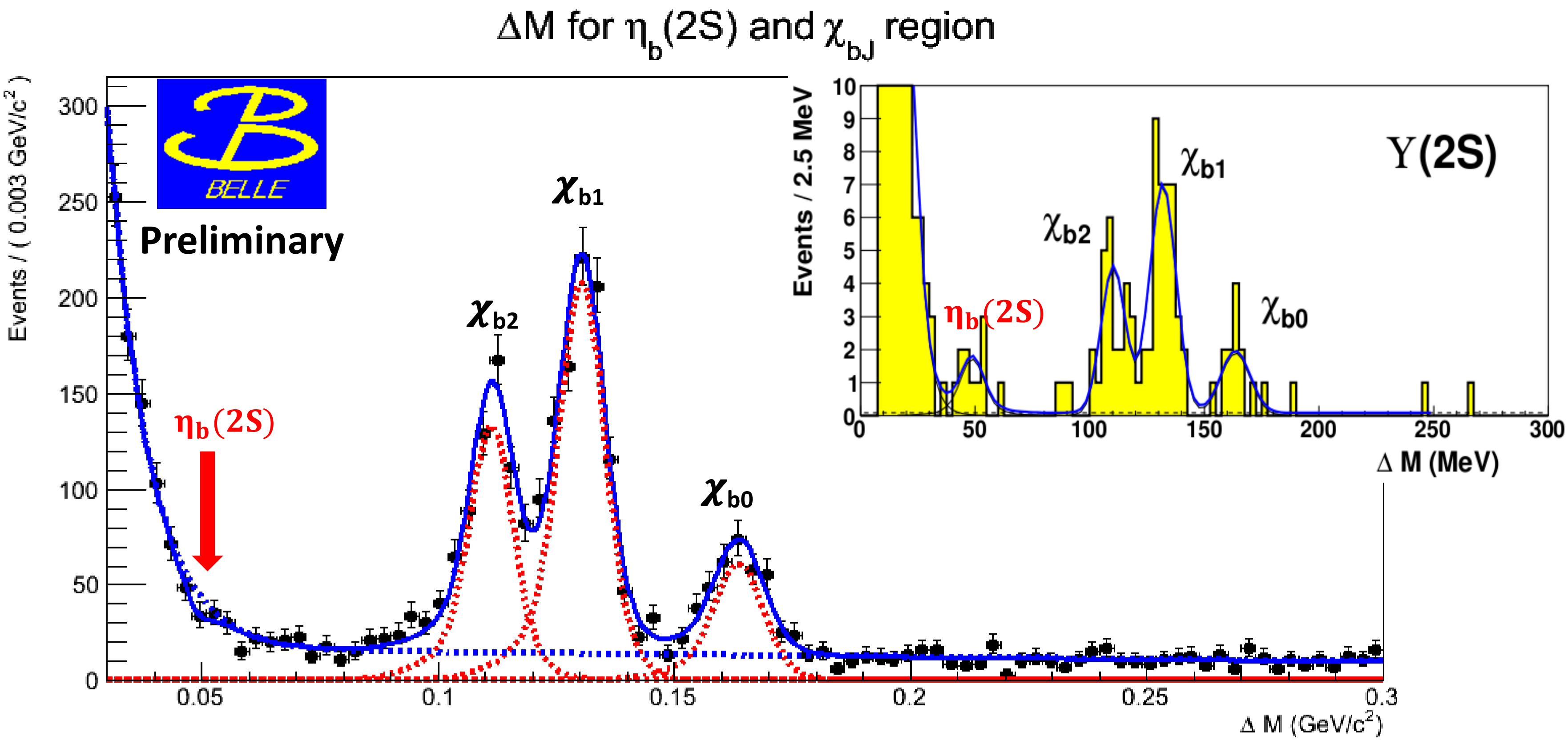
	Mass (MeV/c^2)	Mass PDG (MeV/c^2)
χ_{b0}(1P)	9859.63 ± 0.49	$9859.42 \pm 0.42 \pm 0.31$
χ_{b1}(1P)	9892.83 ± 0.23	$9892.78 \pm 0.26 \pm 0.31$
χ_{b2}(1P)	9912.00 ± 0.34	$9912.21 \pm 0.26 \pm 0.31$

$\Upsilon(2S) \rightarrow \gamma\, (b\bar{b})$



We did not find any signal corresponding to S. Dobbs et. al. $\eta_b(2S)$ candidate !!
N[$\eta_b(2S)$] candidate = -29.6$\pm$19 (negative signal yield).

$\Upsilon(2S) \to \gamma\,(b\bar{b})$



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$$\mathcal{B}_1 \times \mathcal{B}_2 \equiv \mathcal{B}_1[\Upsilon(nS) \to \gamma\eta_b(nS)] \times \sum_{i=1}^{26} \mathcal{B}_{2i}[\eta_b(nS) \to h_i]$$

The Upper Limit on the B.F. (90% C.L.) $< 5.1 \times 10^{-6}$ (with sys.)

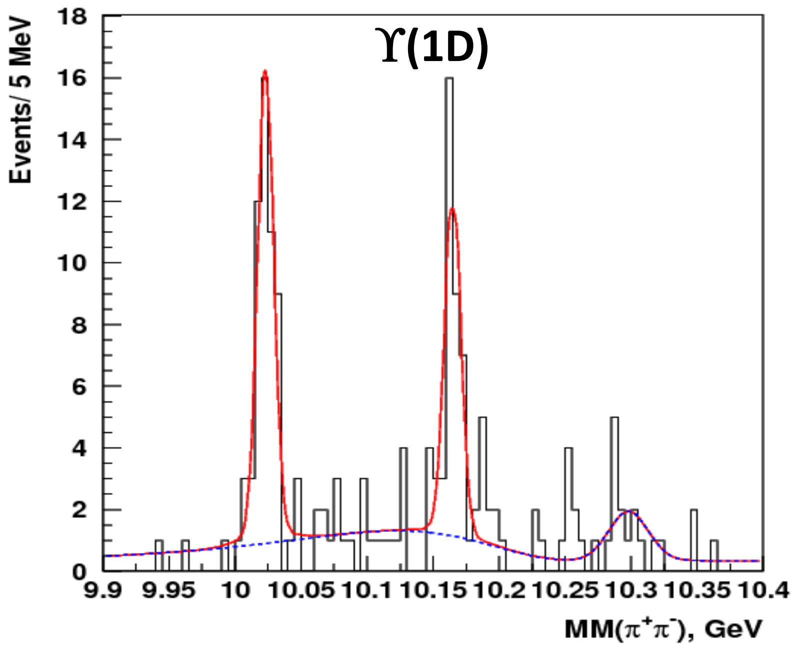
Reminder: $(46.2 \pm^{+29.7}_{-14.2} \pm 10.6) \times 10^{-6}$ S. Dobbs et. al.

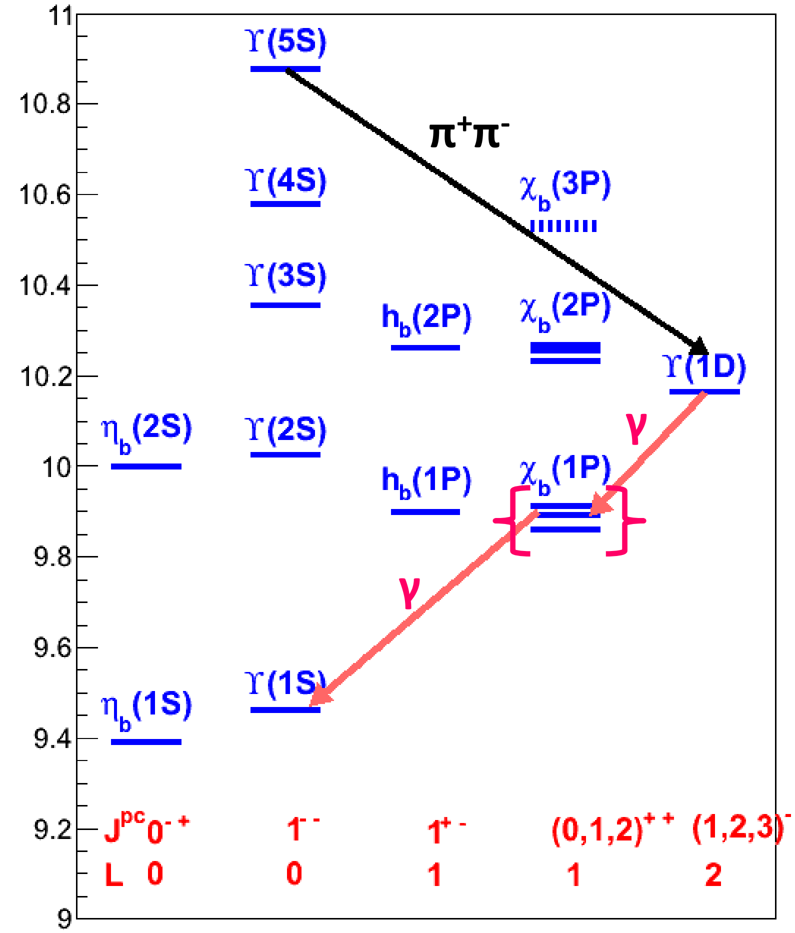
$\Upsilon(1D)$ Mass

$\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$

$\hookrightarrow \chi_{bJ}(1P)\gamma$

$\hookrightarrow \Upsilon(1S)\,\gamma$





$m_{\Upsilon(1D)} = 10164.7 \pm 1.4 \pm 1.0$ MeV/c²

$m_{\Upsilon(2S)} = 10023.2 \pm 1.0$ MeV/c² coincides with PDG value 10023.26 ± 0.31 MeV/c²

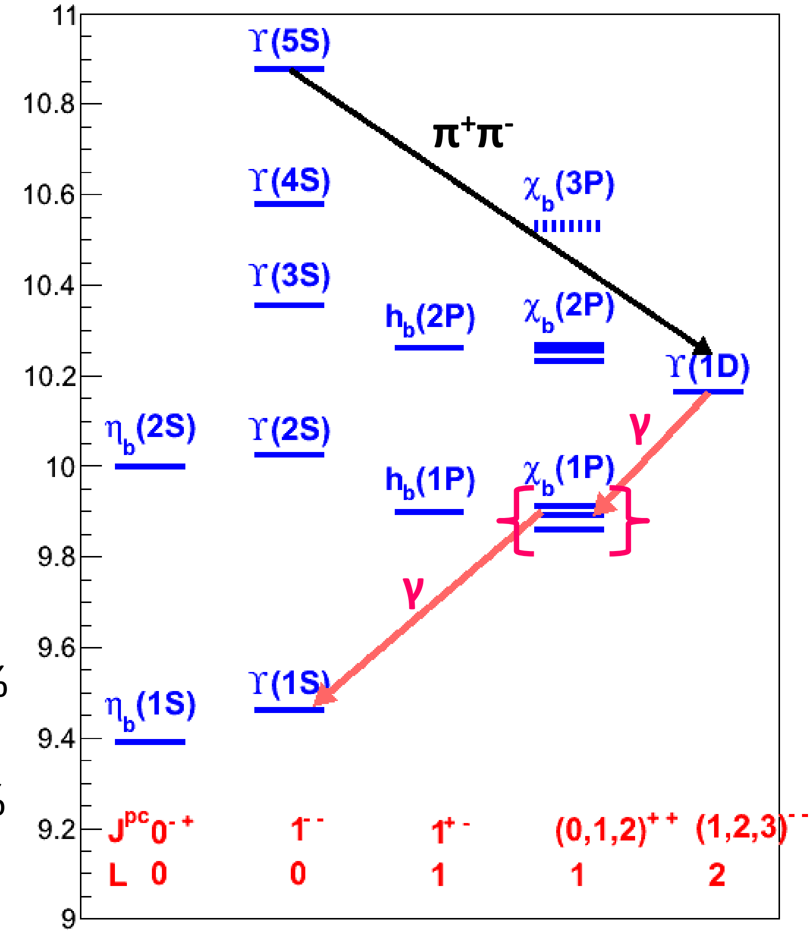
Babar [PRD82(2010)111102]: $m_{\Upsilon(1D)} = 10164.5 \pm 0.8 \pm 0.5$ MeV/c²

Cleo [PRD70(2004)032001]: $m_{\Upsilon(1D)} = 10161.1 \pm 0.6 \pm 1.6$ MeV/c²

Υ(1D) Mass

$\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$
$\quad\hookrightarrow \chi_{bJ}(1P)\gamma$
$\quad\quad\hookrightarrow \Upsilon(1S)\,\gamma$

- Three Υ(1D) states are predicted by theory
  L=2, S=1 => J =1, 2 and 3
- We assume production of Υ_1(1D), Υ_2(1D) and Υ_3(1D) proportional to (2J+1) i.e. 3: 5:7.
- Use B.F.s of $\Upsilon_1(1D) \rightarrow \chi_{b0}\gamma$, $\Upsilon_2(1D) \rightarrow \chi_{b1}\gamma$ and $\Upsilon_3(1D) \rightarrow \chi_{b2}\gamma$ from Kwong, Rosner
  PRD 38, 279 (1998)
- $\mathcal{B}\left(\chi_{b0,1,2} \rightarrow \Upsilon(1S)\,\gamma\right) = 1.76\%, 33.9\%$ and 19.1% respectively from PDG-2012.
- N $\Upsilon_1(1D)$: N $\Upsilon_2(1D)$: N $\Upsilon_3(1D)$: = 10%:49%:41%
- Assuming only $\Upsilon_2(1D)$ and $\Upsilon_3(1D)$ contribute , (conservative assumption) we can fit the distribution to two peaks with fixed relative yields.



Splitting between J=2 and J=3 is ΔM < 10 MeV at 90% CL (with sys.)

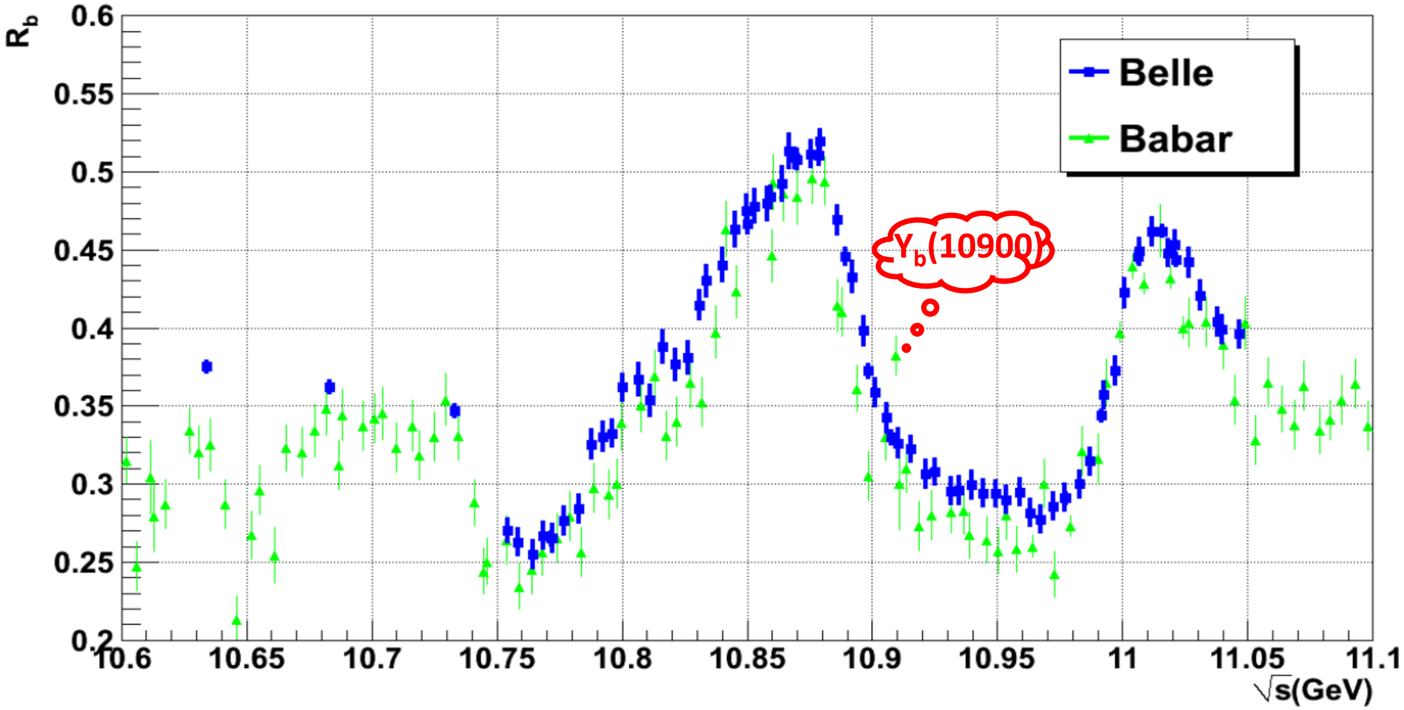
Potential model expectations: 4-11MeV

Search for Ali's $Y_b(10900)$

By definition R_b is given by:

$$R_b(s) \equiv \frac{\sigma_{b\bar{b}(\gamma)}(s)}{\sigma^0_{\mu\mu}(s)}$$

61 points from 10.750 GeV to 11.050GeV with a step 5MeV around 50pb^{-1} for each energy point



- Better statistical errors, but covers a smaller energy range compared to Babar
- R_b is slightly higher by 0.0185
- No Ali's $Y_b(10900)$ (Phys. Lett. B 684, 28-39 2010)

Summary

- $h_b(nP) \rightarrow \eta_b(mS)\gamma$

  $m_{\eta_b(1S)} = 9402.4 \pm 1.5 \pm 1.8$ MeV/c^2 $\Gamma = 10.8^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV/c^2

  $m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-1.9}$ MeV/c^2

- $\Upsilon(2S) \rightarrow \gamma\,(b\bar{b})$

  no signal found similar to S. Dobbs et. al. [attributed to η_b(2S)] . NEW

  Upper Limit on the B.F. (90% C.L.) $< 5.1\ \times 10^{-6}$

- $\Upsilon(1D)$ NEW

  $m_{\Upsilon(1D)} = 10164.7 \pm 1.4 \pm 1.0$ MeV/c^2

  Splitting between J=2 and J=3, ΔM < 10 MeV at 90% CL.

- No Ali's Y_b(10900) found in R_b scan.

Backup

S. Dobbs signal MC embedded