Recent Progress in Heavy Quarkonium Studies

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Outline

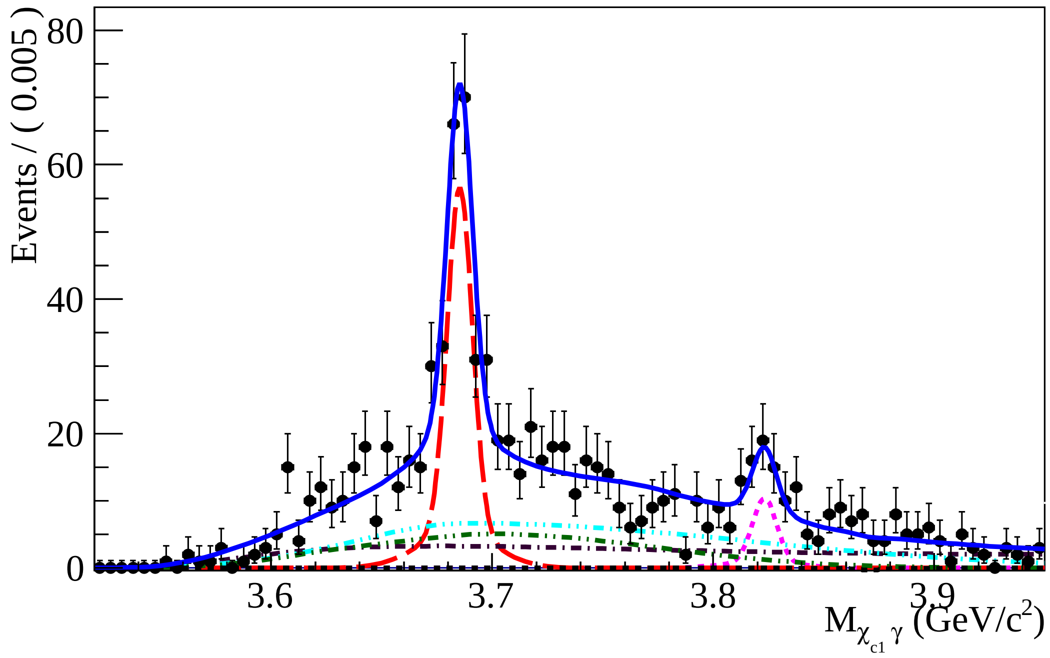
1. Overview of $c\bar{c}$ states
2. Bottomonium studies at Belle
3. Heavy quarkonium at hadronic colliders
4. Conclusions

Introduction

- B factories were designed to study CP violation in $B\bar{B}$ at $\Upsilon(4S)$
- From ARGUS and CLEO times it was known that much richer physics in other energy domains was accessible with special methods of analysis: $\gamma\gamma \to$ light and heavy quark mesons, τ leptons, charm, narrow Υ
- Huge statistics collected by BaBar ($\sim$550 fb^{-1}) and Belle ($\sim$1030 fb^{-1}) strengthened that and resulted in principally new studies, e.g., $\gamma\gamma \to c\bar{c}$, initial-state radiation to $q\bar{q}$ and $c\bar{c}$, and spectacular observations in $c\bar{c}$ and $b\bar{b}$ with new states found, as well as detailed studies of various mesons of light quarks
- Progress of experiment stimulated theory resulting in many models: tetraquark, hybrid, molecules, hadrocharmonium or, alternatively, effects of close thresholds, coupled channels and rescattering
- Results from hadronic colliders coming in parallel

New Charmonium State at Belle – I

Using a full data sample of $772 \cdot 10^6$ $B\bar{B}$ pairs at $\Upsilon(4S)$
Belle studies $B^+ \to \chi_{c1}\gamma K^+$ scanning a broad mass range



A new state at 3820 MeV seen in addition to $\psi(2S)$!

There is no signal at 3872 MeV

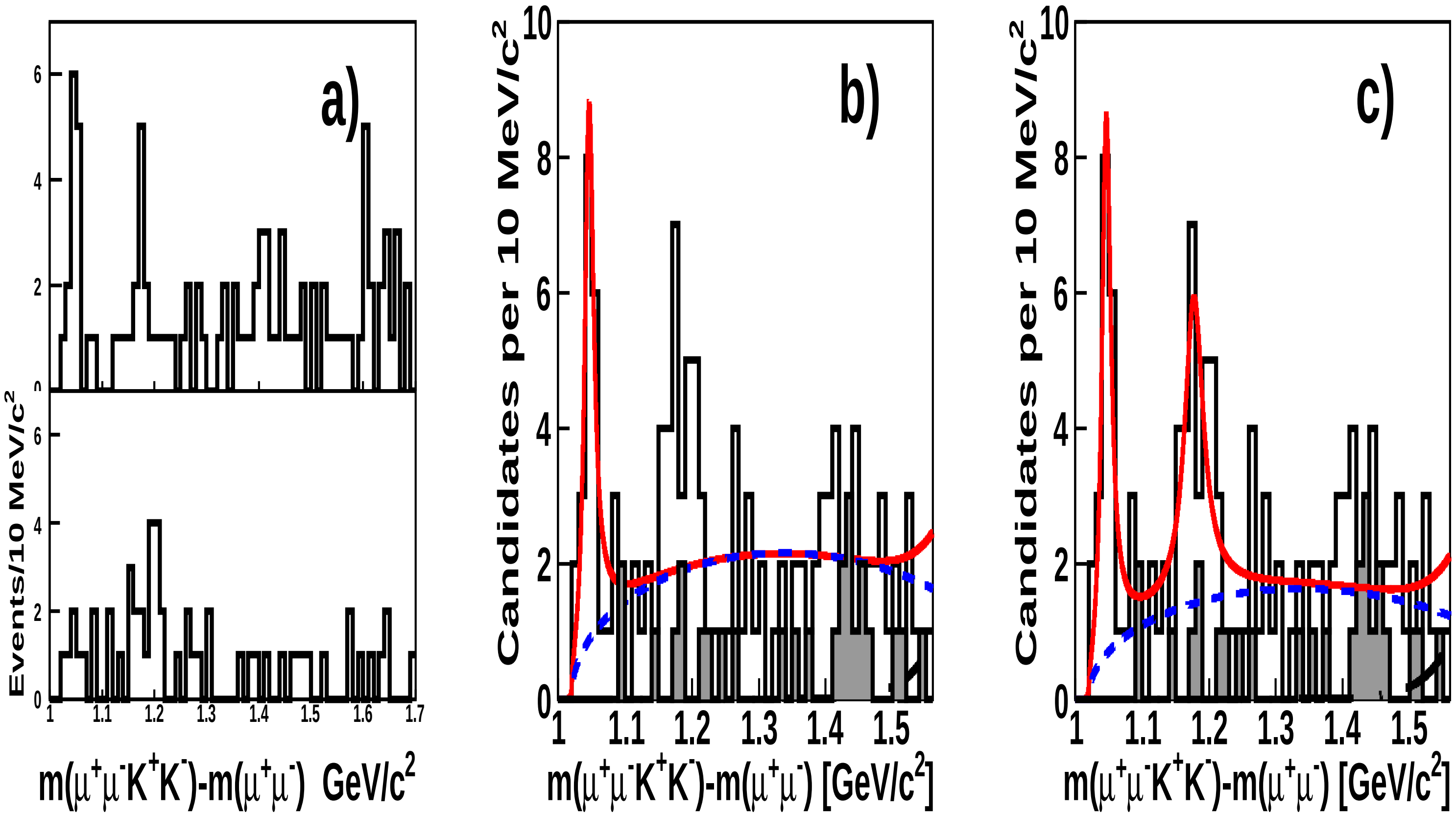
New Charmonium State at Belle – II

- There is 4.2σ evidence for a new state at 3823.5 ± 2.8 MeV
- $\mathcal{B}(B^+ \to X(3820)K^+)\mathcal{B}(X \to \chi_{c1}\gamma) = (9.7^{+2.8+1.1}_{-2.5-1.0}) \cdot 10^{-4}$
- It could be a $^3D_2$ or $\psi(1D)$ state expected at 3810-3840 MeV
- For $X(3872)$ $\mathcal{B}\mathcal{B} < 1.9 \cdot 10^{-4} \Rightarrow$
  $\Gamma(X(3872) \to \chi_{c1}\gamma)/\Gamma(X(3872) \to J/\psi\pi^+\pi^-) < 0.26$
  setting a constraint on the C-odd partner of $X(3872)$

$Y(4140)$ at CDF – I

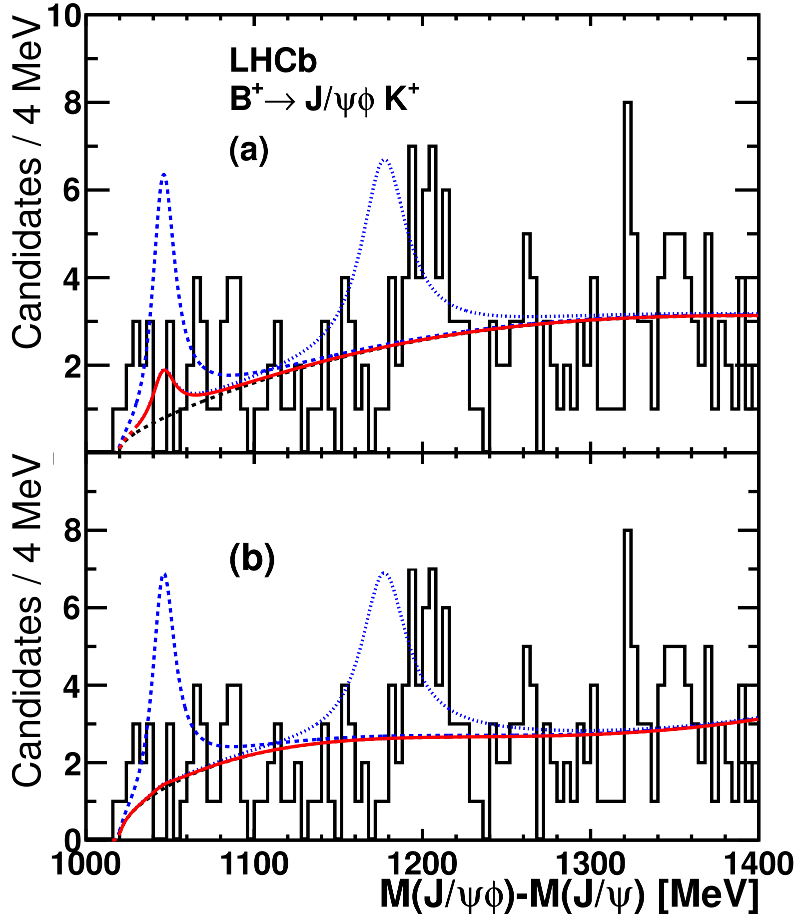
- First evidence (3.8σ) from CDF as $B^+ \to Y(4140)K^+,\ Y(4140) \to J/\psi\phi$, $N = 14 \pm 5,\ M = (4143.0 \pm 2.9 \pm 1.2)$ MeV, $\Gamma = (11.7^{+8.3}_{-5.0} \pm 3.7)$ MeV, T.Aaltonen et al., PRL 102, 242002 (2009)
- Belle searched for $Y(4140)$ in B decays with a negative, but not inconsistent with CDF result, J.Brodzicka, LP-09
- Belle also didn't see $Y(4140)$ in $\gamma\gamma$, but found evidence for $Y(4350)$ with 3.2σ significance
- In 1101.0658 CDFII reports x2.2 (6 fb^{-1}) and confirms $Y(4140)$
- As before, they use $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$
- The first state of two heavy quarkonia - $c\bar{c}s\bar{s}$

$Y(4140)$ at CDF – II



Two significant structures seen: at 4143 MeV (5.0σ) and at 4274 MeV (3.1σ) with 19 ± 7 and 22 ± 8 events

Search for $Y(4140)$ at LHCb – I



R. Aaij et al. (LHCb Collab.), Phys. Rev. D85, 091103 (2012)

Search for $Y(4140)$ at LHCb – II

- LHCb observes 382 ± 22 events of $B^+ \to J/\psi\phi K^+$ with 115 ± 12 at CDF
- LHCb: < 16 events of $B^+ \to X(4140)K^+$ with $35 \pm 9 \pm 6$ expected from CDF, 2.4σ disagreement
- LHCb: $\frac{\mathcal{B}(B^+ \to X(4140)K^+)\mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.07$ at 90%CL
- CDF: $\frac{\mathcal{B}\mathcal{B}}{\mathcal{B}} = 0.149 \pm 0.039 \pm 0.024$
- For $X(4274)$, LHCb: < 24 events, 53 ± 19 expected from CDF
- LHCb: $\frac{\mathcal{B}\mathcal{B}}{\mathcal{B}} < 0.08$, with 0.17 ± 0.06 at CDF

New Charmonium(like) States from B Factories – I

State	J^{PC}	Process
$\eta_c(2S, 3639)$	0^{-+}	$B \to K(K_S K \pi)$
$\psi(3820)$	2^{--}	$B \to \chi_{c1}\gamma K$
$X(3872)$	$1^{++}/2^{-+}$	$B \to K(J/\psi\pi^+\pi^-)$
$G(3900)$	1^{--}	$e^+e^- \to \gamma(D\bar{D})$
$X(3915)$	$0/2^{?+}$	$B \to K(J/\psi\omega)$
$\chi_{c2}(2P, 3927)$	2^{++}	$\gamma\gamma \to D\bar{D}$
$X(3940)$	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Y(4008)$	1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$
$Z_1(4050)^+$	?	$B \to K(\chi_{c1}(1P)\pi^+)$

New Charmonium(like) States from B Factories – II

State	J^{PC}	Process
$X(4160)$	$?^{?+}$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$
$Z_2(4250)^+$	?	$B \to K(\chi_{c1}(1P)\pi^+)$
$Y(4260)$	1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$
$X(4350)$	$0/2^{++}$	$\gamma\gamma \to J/\psi\phi$
$Y(4360)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$
$Z(4430)^+$	?	$B \to K(\psi(2S)\pi^+)$
$Y(4630)$	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$

PRL100,112001(2008)

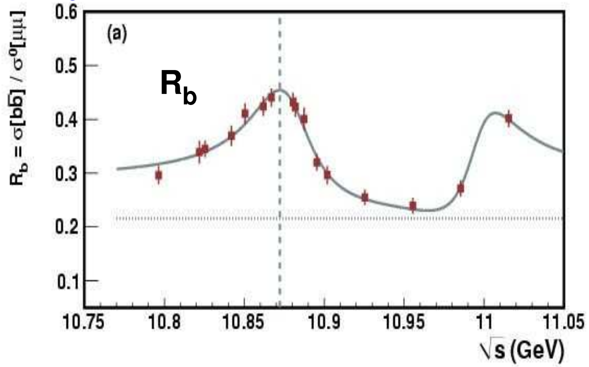
Puzzles of $\Upsilon(5S)$ decays

At 21.7 fb^{-1} $\Upsilon(5S)$ $\to \Upsilon(nS)\pi^+\pi^-$ two orders of magnitude larger than in $\Upsilon(4S)$ decay

	Γ(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

PRD82,091106R(2010)

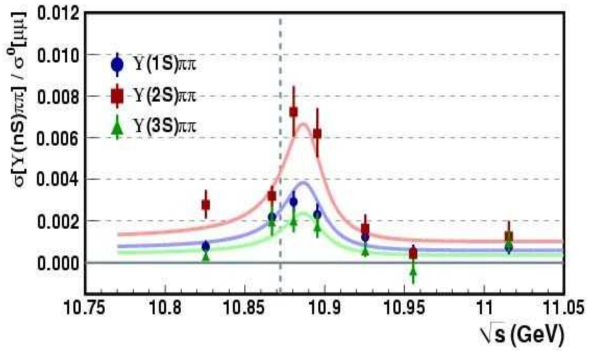
Dedicated energy scan $\Rightarrow$
shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (2σ)



-Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$

Simonov JETP Lett 87,147(2008)

-Exotic resonance Y_b near $\Upsilon(5S)$



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

Finally Belle recorded 121.4fb^{-1} at $\Upsilon(5S)$

arXiv:1104.2025

Observation of $e^+e^- \to \pi^+\pi^- h_c$ by CLEO

$\Rightarrow$ Belle search for h_b in $\Upsilon(5S)$ data

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

- $\Upsilon(5S) \to X\pi^+\pi^-$ decays, $X = \Upsilon(1S, 2S, 3S)$, or a new $b\bar{b}$ state, were studied with 121.4 fb^{-1} near 10860 MeV, using MM($\pi^+\pi^-$)
- In addition to $\Upsilon(1S, 2S, 3S)$, they observe $3S \to 1S$ and $2S \to 1S$ transitions, << see >> $\Upsilon(1D)$ (2.4σ) and discover $h_b(1P)$ and $h_b(2P)$
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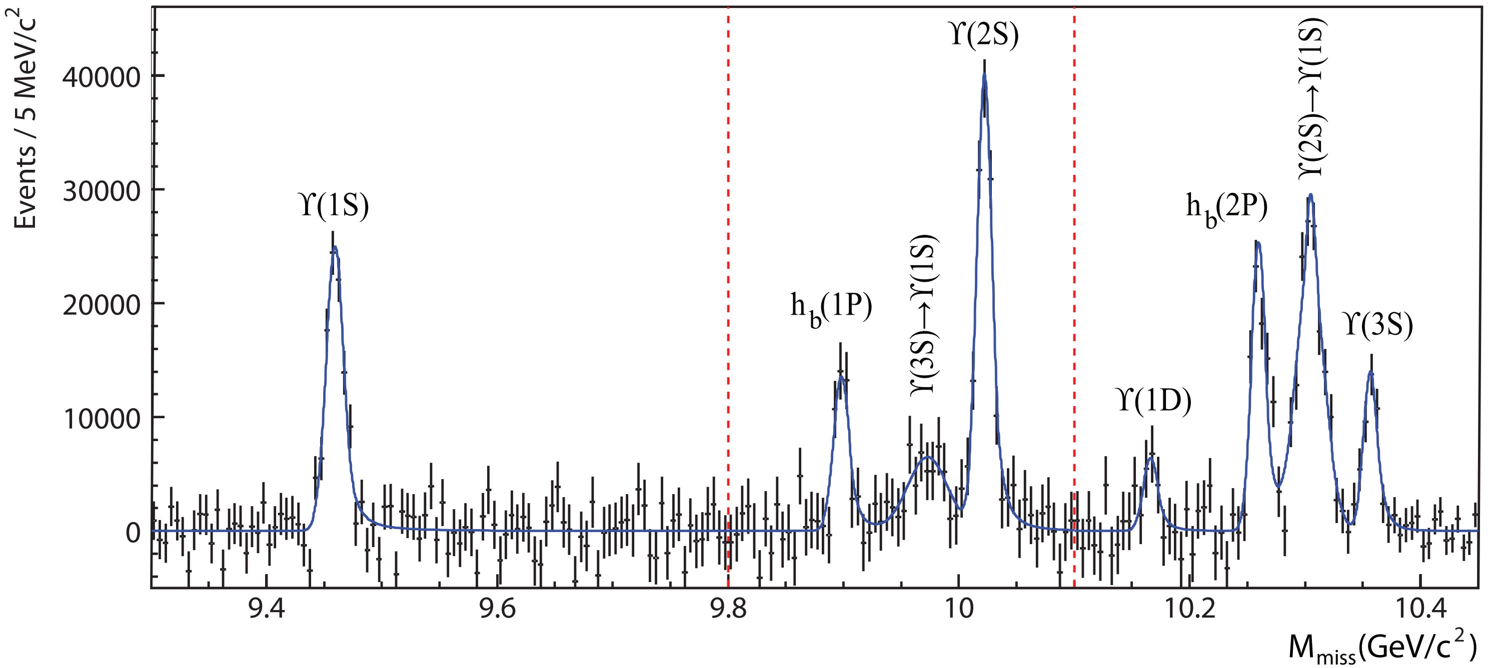
State	Yield, 10^3	Mass, MeV	Sign.
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.6}_{-1.1}$	5.5σ
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	11.2σ

- No complete reconstruction with huge statistics instead
- Belle, PRL 108, 032001 (2012)

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

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

- The hyperfine splitting $\Delta M_{\rm HF} =< M(n^3P_J) > -M(n^1P_1)$, where $< M(n^3P_J) >$ – spin-weighted average mass of the P-wave triplet states, triplet n^3P_J – $\chi_{bJ}(nP)$, singlet n^1P_1 – $h_b(nP)$
-

State	$h_b(1P)$	$h_b(2P)$
$\Delta M_{\rm HF}$, MeV	1.6 ± 1.5	$+0.5^{+1.6}_{-1.2}$

compared to 0.00 ± 0.15 MeV for the $h_c(1P)$

-

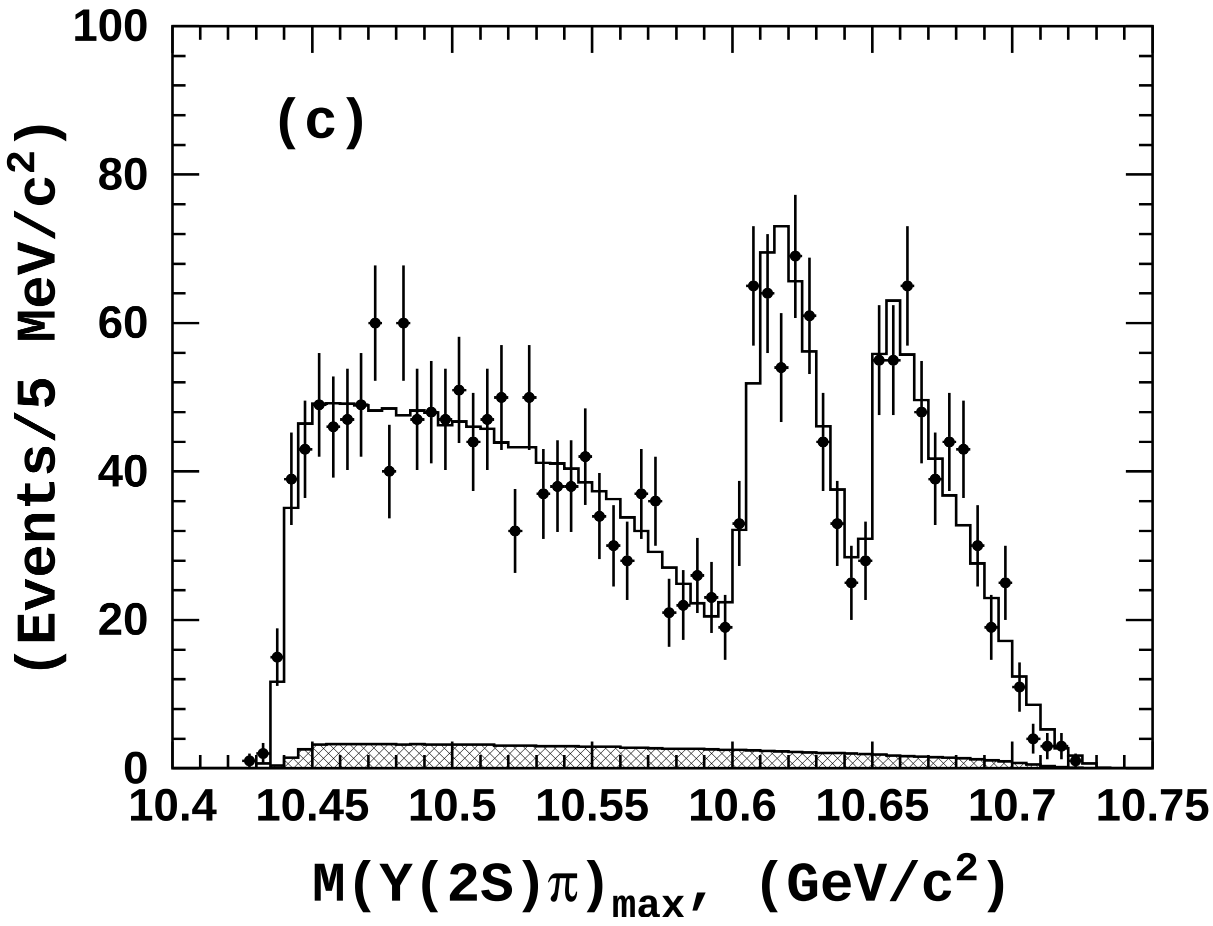
State	$h_b(1P)$	$h_b(2P)$
$\frac{\sigma(h_b(nP)\pi^+\pi^-)}{\sigma(\Upsilon(2S)\pi^+\pi^-)}$	$0.46 \pm 0.08^{+0.07}_{-0.12}$	$0.77 \pm 0.08^{+0.22}_{-0.17}$

i.e., a spin flip of the b quark is not suppressed

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
  PRL 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}	$181^{+65+74}_{-105-109}$

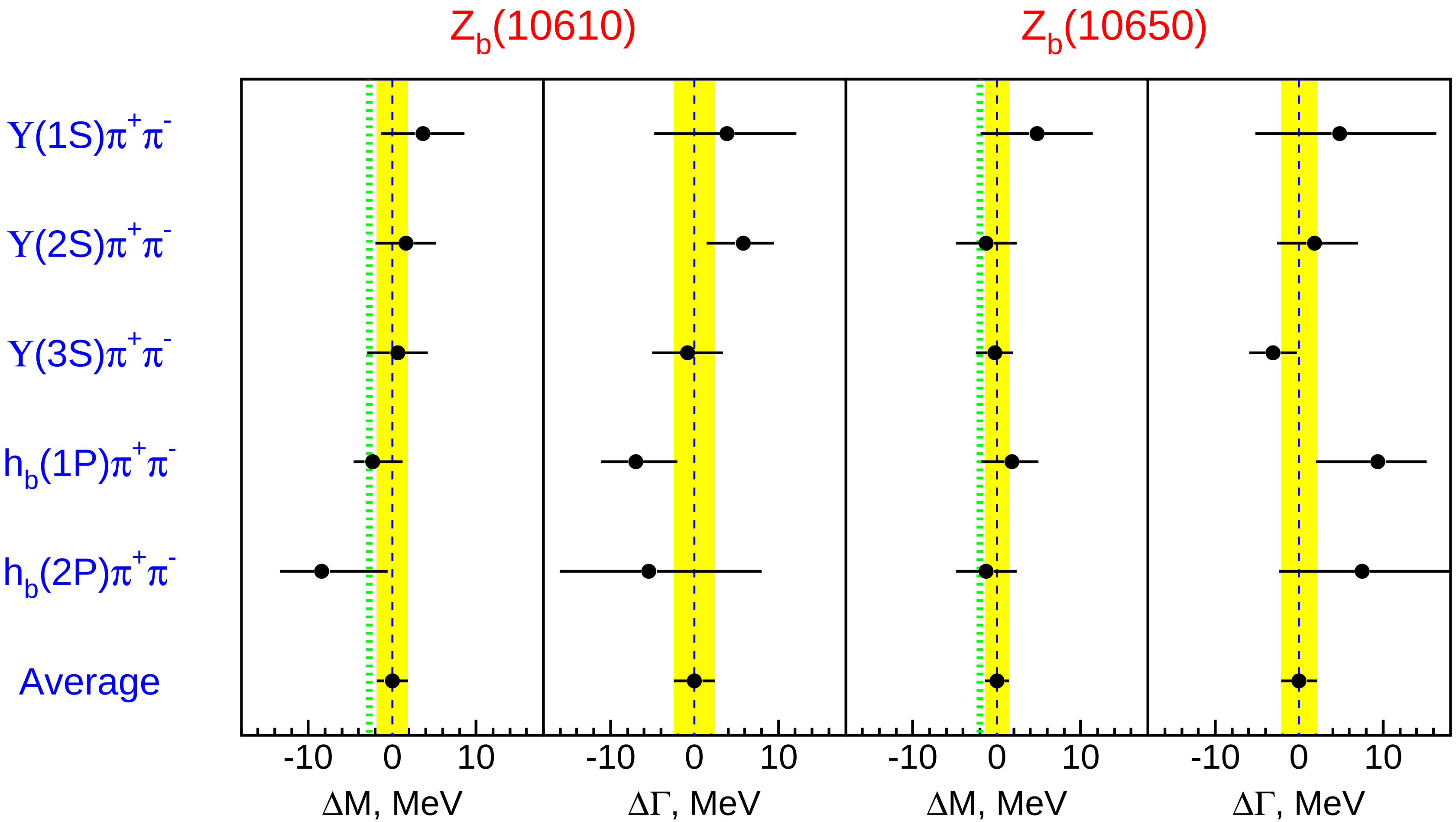
Masses, widths, relative amplitudes are consistent

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

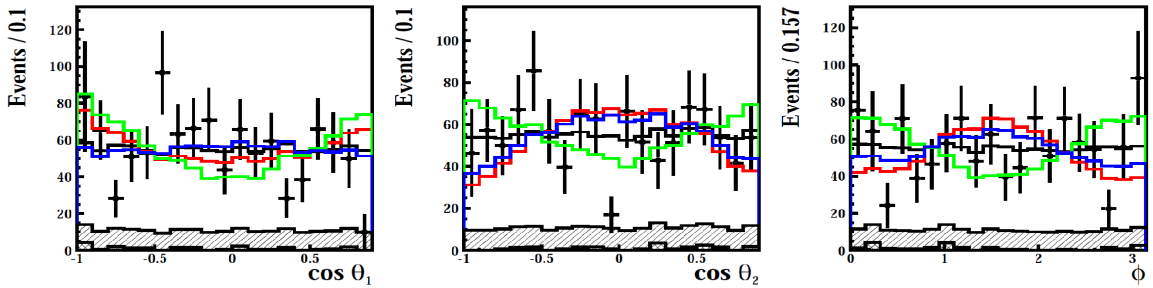
Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – IV



Angular analysis

[preliminary]

J^P= 1^+ 1^- 2^+ 2^-



Probabilities at which different J^P hypotheses are disfavored compared to 1^+

J^P	$Z_b(10610)$			$Z_b(10650)$		
	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$
1^-	$3.6\,\sigma$	$0.3\,\sigma$	$0.3\,\sigma$	$3.7\,\sigma$	$2.6\,\sigma$	$2.7\,\sigma$
2^+	$4.3\,\sigma$	$3.5\,\sigma$	$4.3\,\sigma$	$4.4\,\sigma$	$2.7\,\sigma$	$2.1\,\sigma$
2^-	$2.7\,\sigma$	$2.8\,\sigma$		$2.9\,\sigma$	$2.6\,\sigma$	

1+ assignment is favorable.

1-, 2+ ,2- are disfavored at typically 3σ level.

1

Search for $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ – I

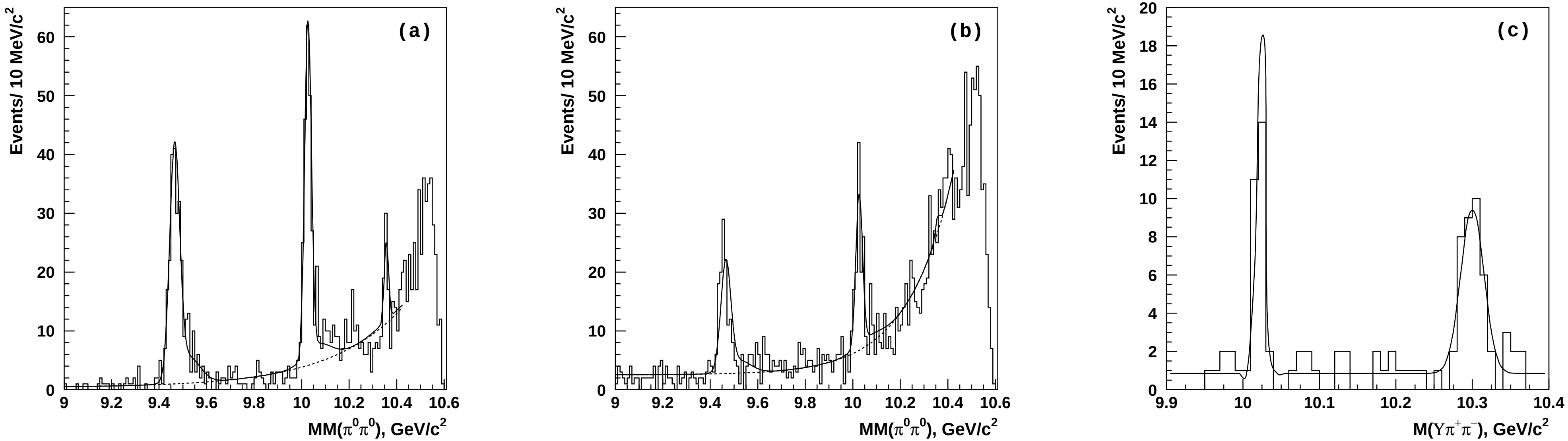
A search for $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ from 121.4 fb^{-1} at $\Upsilon(5S)$ (arXiv:1207.4345)

$\Upsilon(5S)$ are formed from $\Upsilon(1,2S)\pi^0\pi^0$ combinations

with $\Upsilon(1,2S) \to e^+e^-, \mu^+\mu^-$ and $\Upsilon(2S) \to \Upsilon(1S)[e^+e^-, \mu^+\mu^-]\pi^+\pi^-$

$\Upsilon(nS)[l^+l^-]\pi^0\pi^0$ decays are selected by missing mass $MM(\pi^0\pi^0)$;

$\Upsilon(2S) \to \Upsilon(1S)[e^+e^-, \mu^+\mu^-]\pi^+\pi^-$ – by the invariant mass $M(\Upsilon(1S)\pi^+\pi^-)$



Search for $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ – II

The $\Upsilon(nS)$ signal yields are obtained from the fits

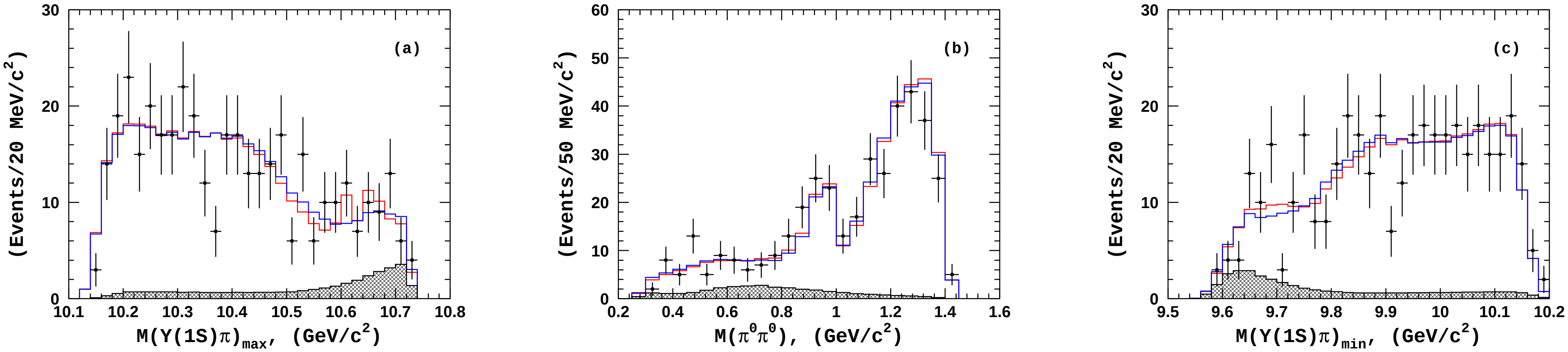
Final state	Yield	$\mathcal{B}, 10^{-3}$
$\Upsilon(1S) \to \mu^+\mu^-$	261 ± 17	2.28 ± 0.13
$\Upsilon(1S) \to e^+e^-$	123 ± 13	2.15 ± 0.23
$\Upsilon(2S) \to \mu^+\mu^-$	241 ± 18	3.77 ± 0.28
$\Upsilon(2S) \to e^+e^-$	108 ± 13	3.84 ± 0.46
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	24 ± 5	2.85 ± 0.60

Search for $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ – III

Decay Mode	$\mathcal{B}, 10^{-3}$
$\Upsilon(1S)\pi^+\pi^-$	$5.30 \pm 0.30 \pm 0.50$
$\Upsilon(1S)\pi^0\pi^0$	$2.25 \pm 0.11 \pm 0.20$
$\Upsilon(2S)\pi^+\pi^-$	$7.80 \pm 0.60 \pm 1.10$
$\Upsilon(2S)\pi^0\pi^0$	$3.66 \pm 0.22 \pm 0.48$

The $\mathcal{B}(\Upsilon(nS)\pi^+\pi^-)/\mathcal{B}(\Upsilon(nS)\pi^0\pi^0)$ ratio is consistent with 2:1, with $\pi^+\pi^-$ transitions studied in PRL 100, 112001 (2008)

Search for $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ – IV

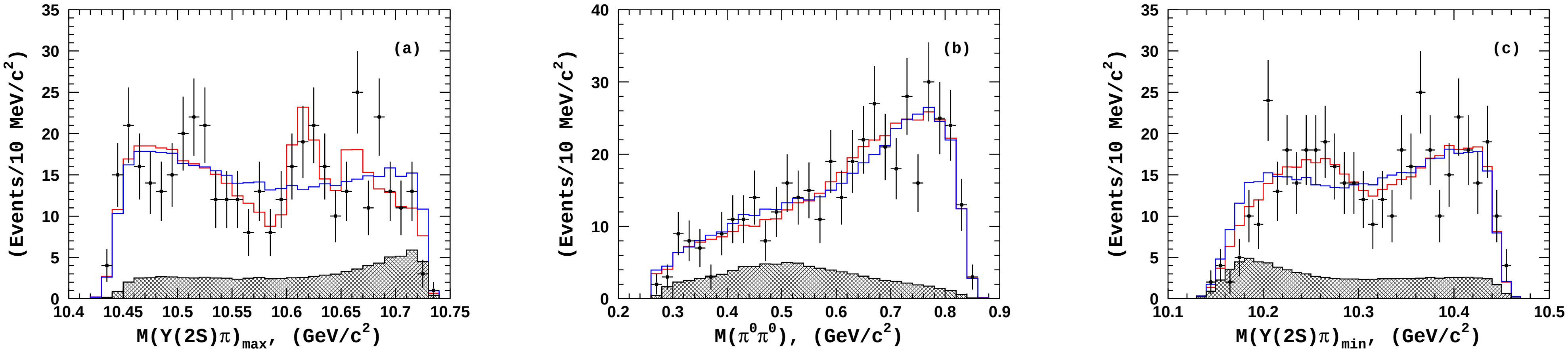


Fits with (red) and without Z_b's (blue)

don't show a significant signal in the $\Upsilon(1S)\pi^0\pi^0$;

The $\pi^0\pi^0$ system shows $f_0(980)$ and $f_2(1270)$

Search for $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ – V



In the $\Upsilon(2S)\pi^0\pi^0$ there is a significant signal of $Z_b^0(10610)$ with $M = 10609^{+8}_{-6} \pm 6$ MeV, consistent with 10607.2 ± 2.0 MeV for the $Z_b^{\pm}(10610)$

The $Z_b^0(10650)$ is not significant in either $\Upsilon(1S)\pi^0\pi^0$ or $\Upsilon(2S)\pi^0\pi^0$, data do not contradict the $Z_b^0(10650)$, but too small statistics

Study of Three-body Decays $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ – I

Belle used 121.4 fb^{-1} collected near 10860 MeV or $\Upsilon(5S)$ to study three-body decays to $B\bar{B}\pi,\ B\bar{B}^*\pi,\ B^*\bar{B}^*\pi$

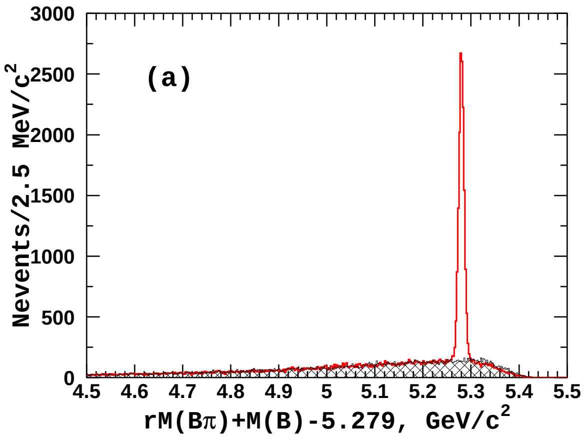
$B\bar{B}\pi$ is $B^+\bar{B}^0\pi^- + B^-B^0\pi^+$,
$B\bar{B}^*\pi$ is $B^+\bar{B}^{*0}\pi^- + B^-B^{*0}\pi^+ + B^0B^{*-}\pi^+ + \bar{B}^0B^{*+}\pi^-$,
$B^*\bar{B}^*\pi$ is $B^{*+}\bar{B}^{*0}\pi^- + B^{*-}B^{*0}\pi^+$

B decays are reconstructed in the following channels:
$B^+ \to J/\psi K^+,\ \bar{D}^0\pi^+;\ B^0 \to J/\psi K^{*0},\ D^-\pi^+,\ D^{*-}\pi^+$

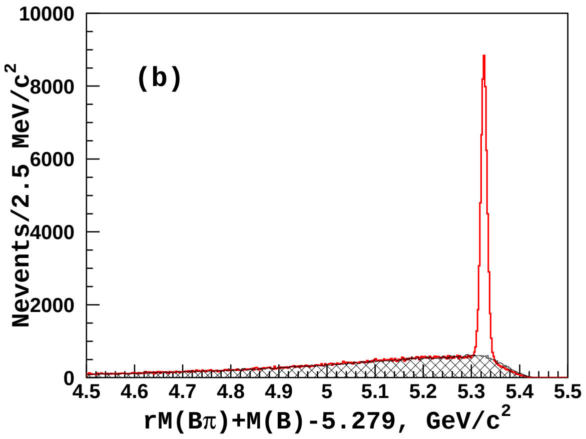
Reconstructed $B^+(B^0)$ candidates are combined with a π^-, a recoil mass to the $B\pi$, $rM(B\pi) = \sqrt{E^2_{\rm cm} - p^2_{B\pi}}$

Study of Three-body Decays $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ – II

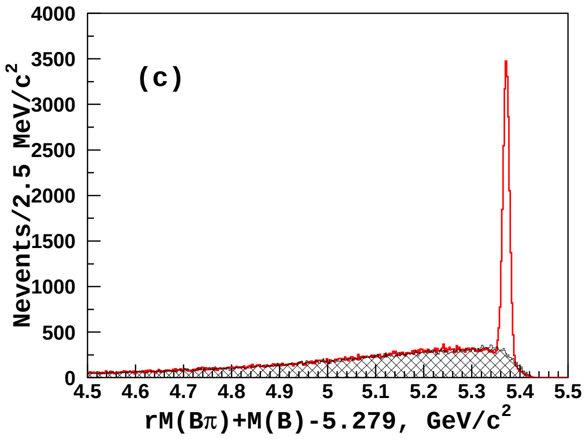
Results of MC simulation



$B\bar{B}\pi$

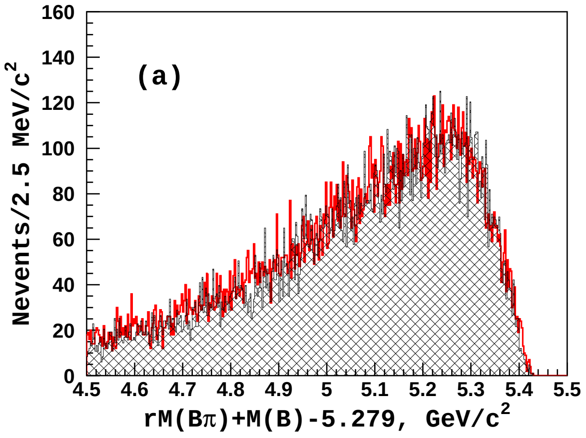


$B\bar{B}^*\pi$

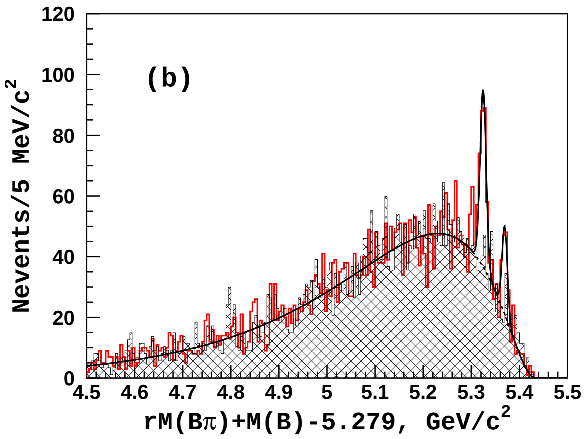


$B^*\bar{B}^*\pi$

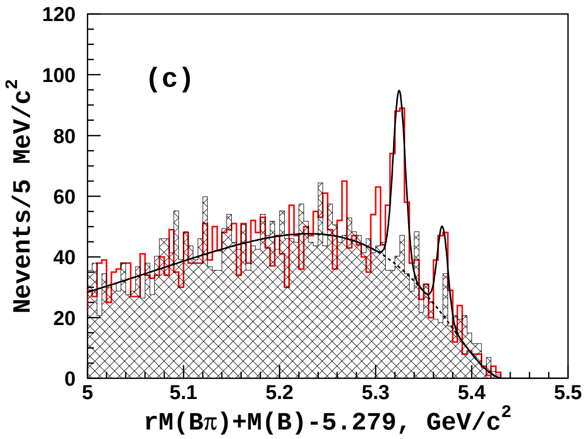
Study of Three-body Decays $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ – III



MC w/o $B^{(*)}\bar{B}^{(*)}\pi$



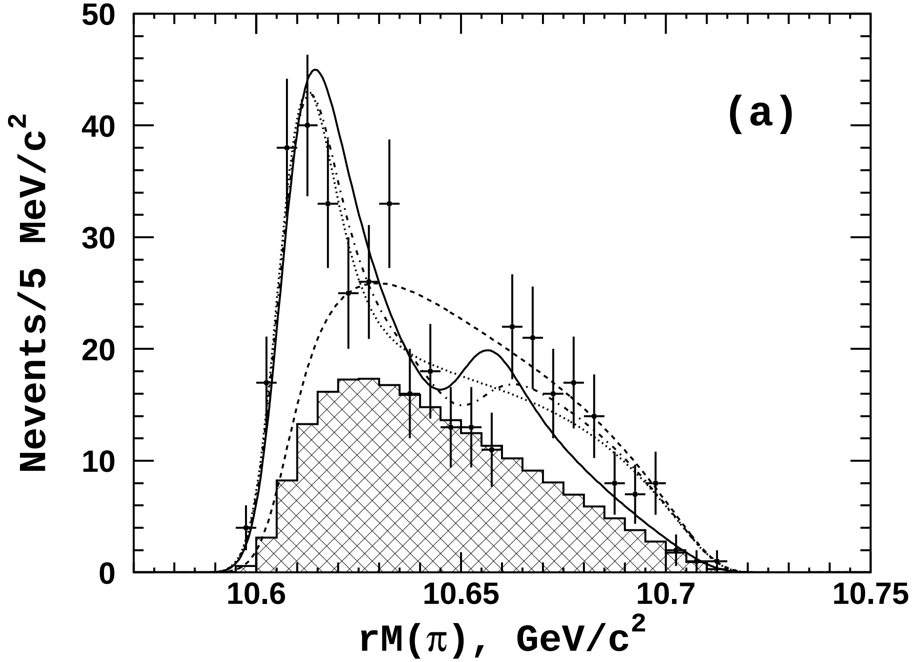
Data



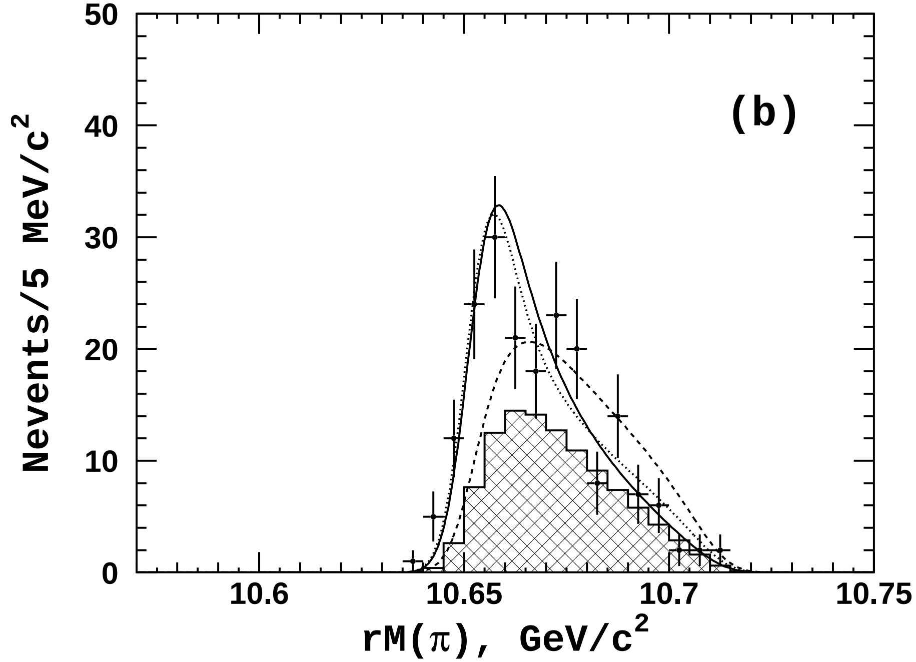
Data-zoom

Study of Three-body Decays $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ – IV

Results of the fits



$B\bar{B}^*\pi$



$B^*\bar{B}^*\pi$

Study of Three-body Decays $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ – V

Channel	$B\bar{B}\pi$	$B\bar{B}^*\pi$	$B^*\bar{B}^*\pi$
N	0	38	5
$\mathcal{B}$, %	$0.0 \pm 1.2 \pm 0.3$	$7.3^{+2.3}_{-2.1} \pm 0.8$	$1.0^{+1.4}_{-1.3} \pm 0.4$
N	0.3 ± 14.0	184 ± 19	82 ± 11
$\mathcal{B}$, %	< 0.4 @90%CL	$2.83 \pm 0.29 \pm 0.46$	$1.41 \pm 0.19 \pm 0.24$

In black results of the older (23.6 fb^{-1}) analysis, PRD 81, 112003 (2010)

Study of Three-body Decays $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ – VI

Channel	$Z_b(10610)$, %	$Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.707
$h_b(2P)\pi^+$	4.34 ± 2.07	14.80 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

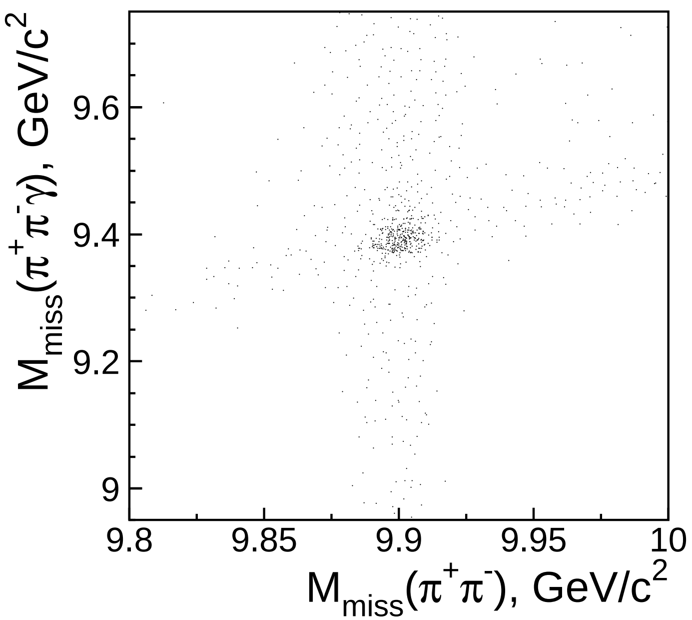
What do we know about the $\eta_b(1S)$?

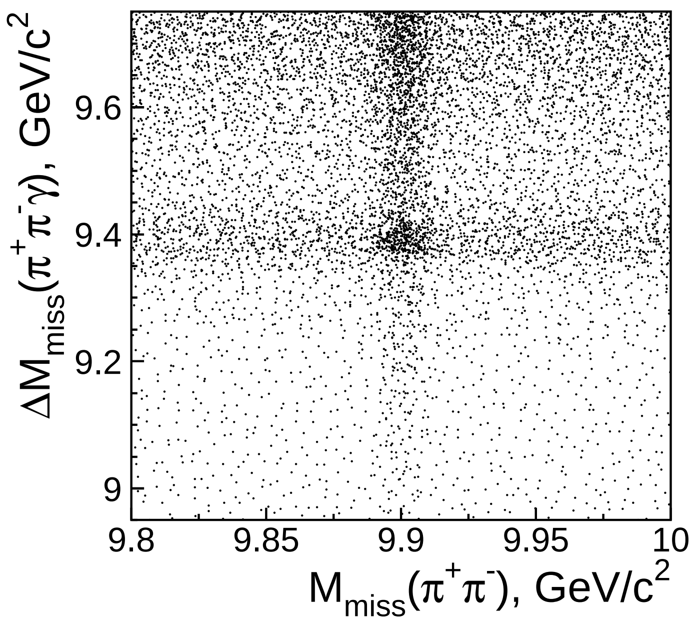
- First claim from ALEPH in 2002 in 200 GeV e^+e^- at $9300 \pm 20 \pm 20$ MeV
- First observations by BaBar (2008, 2009) and CLEO (2010) in $\Upsilon(2S, 3S) \to \eta_b(1S)\gamma$
- World-average mass $M(\eta_b(1S)) = 9390.9 \pm 2.8$ MeV $\Rightarrow$
  Hyperfine mass splitting $\Delta M_{\rm hf} = M(\Upsilon(1S)) - M(\eta_b(1S))$=$69.3 \pm 2.8$ MeV,
  compared to 41 ± 14 MeV in pNRQCD and 60 ± 8 MeV on the lattice
- No measurements of its width exist
- It is tempting to search for $h_b(nP) \to \eta_b(mS)\gamma$
  with 50k of $h_b(1P)$ and 84k of $h_b(2P)$ at Belle
  for which theory predicts sizable branchings
- Belle did that first with 121.4 fb^{-1} and observed the $\eta_b(1S)$ (arxiv:1110.3934),
  then the analysis of the full data sample of 133.4 fb^{-1} gave first evidence
  for the $\eta_b(2S)$!, arxiv:1205.6351, submitted to PRL

Method – I

- Decay chain $\Upsilon(5S) \to Z_b^+ \pi^-$
$$\hookrightarrow \quad h_b(nP)\pi^+$$
$$\hookrightarrow \quad \eta_b(mS)\gamma$$
- We reconstruct π^-, π^+, γ and use missing masses to identify signal
- Missing mass to π^- is $M(Z_b^+)$,
missing mass to $\pi^+\pi^-$ is $M(h_b)$,
and missing mass to $\pi^+\pi^-\gamma$ is $M(\eta_b)$
- $\Delta M_{\rm miss}(\pi^+\pi^-\gamma) \equiv M_{\rm miss}(\pi^+\pi^-\gamma) - M_{\rm miss}(\pi^+\pi^-) + M(h_b)$
- We fit $M_{\rm miss}(\pi^+\pi^-)$ spectra in $\Delta M_{\rm miss}(\pi^+\pi^-\gamma)$ bins

Method – II





In the ideal world all events group in the center,

in reality there is resolution as well as background π and γ

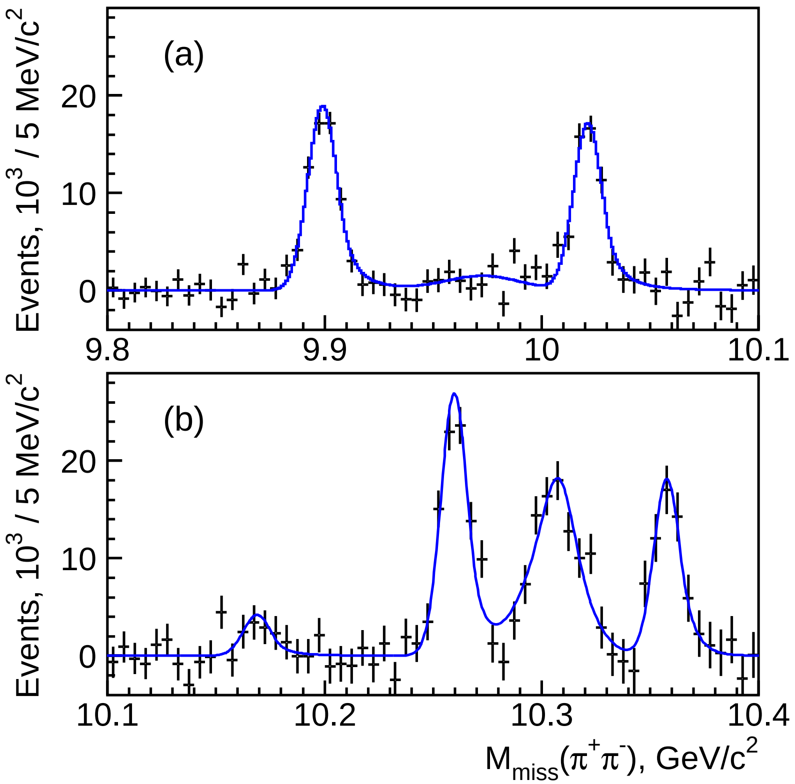
The horizontal band for $\Delta M_{\rm miss}(\pi^+\pi^-\gamma)$ corresponds to η_b, true γ and bg $\pi^+\pi^-$

The vertical band for $M_{\rm miss}(\pi^+\pi^-)$ corresponds to h_b, true $\pi^+\pi^-$ and bg γ

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 $\eta_b(2S)$,

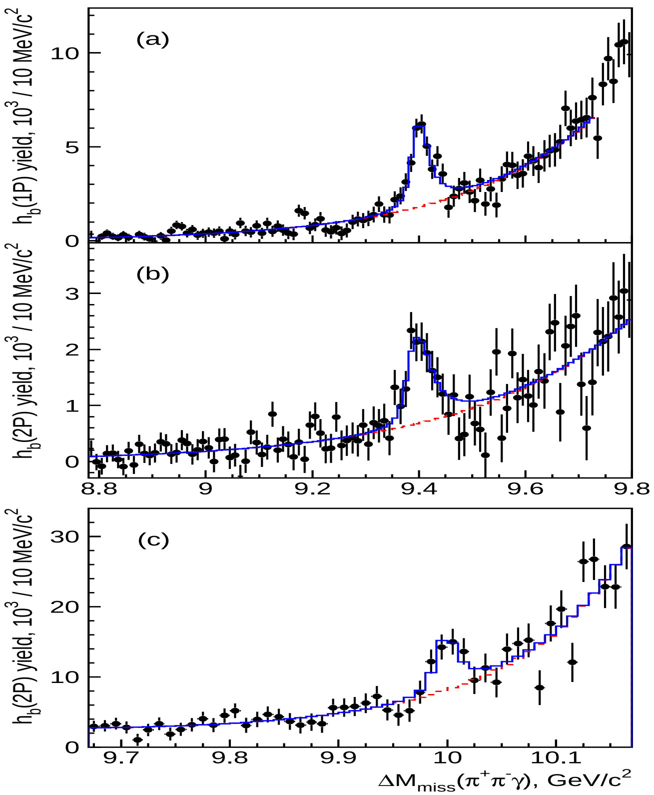
We also update $h_b(1P)$ and $h_b(2P)$ mass measurements



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

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



$h_b(1P) \to \eta_b(1S)\gamma$

$(23.5 \pm 2.0) \cdot 10^3$ events

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

$(10.3 \pm 1.3) \cdot 10^3$ events

$h_b(2P) \to \eta_b(2S)\gamma$

$(25.8 \pm 4.9) \cdot 10^3$ events

A simultaneous fit of $h_b(1P) \to \eta_b(1S)$ and $h_b(2P) \to \eta_b(1S)$!

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

State	Mass, MeV	Width, MeV	$\Delta M_{\rm hf}$, MeV
$\eta_b(1S)$	$9402.4 \pm 1.5 \pm 1.8$	$10.8^{+4.0+4.5}_{-3.7-2.0}$	57.9 ± 2.3
$\eta_b(2S)$	$9999.0 \pm 3.5^{+2.8}_{-1.9}$	< 24	$24.3^{+4.0}_{-4.5}$
$h_b(1P)$	$9899.1 \pm 0.4 \pm 1.0$	–	0.8 ± 1.1
$h_b(2P)$	$10259.8 \pm 0.5 \pm 1.1$	–	0.5 ± 1.2

Branching fractions of $h_b(nP) \to \eta_b(mS)$ transitions

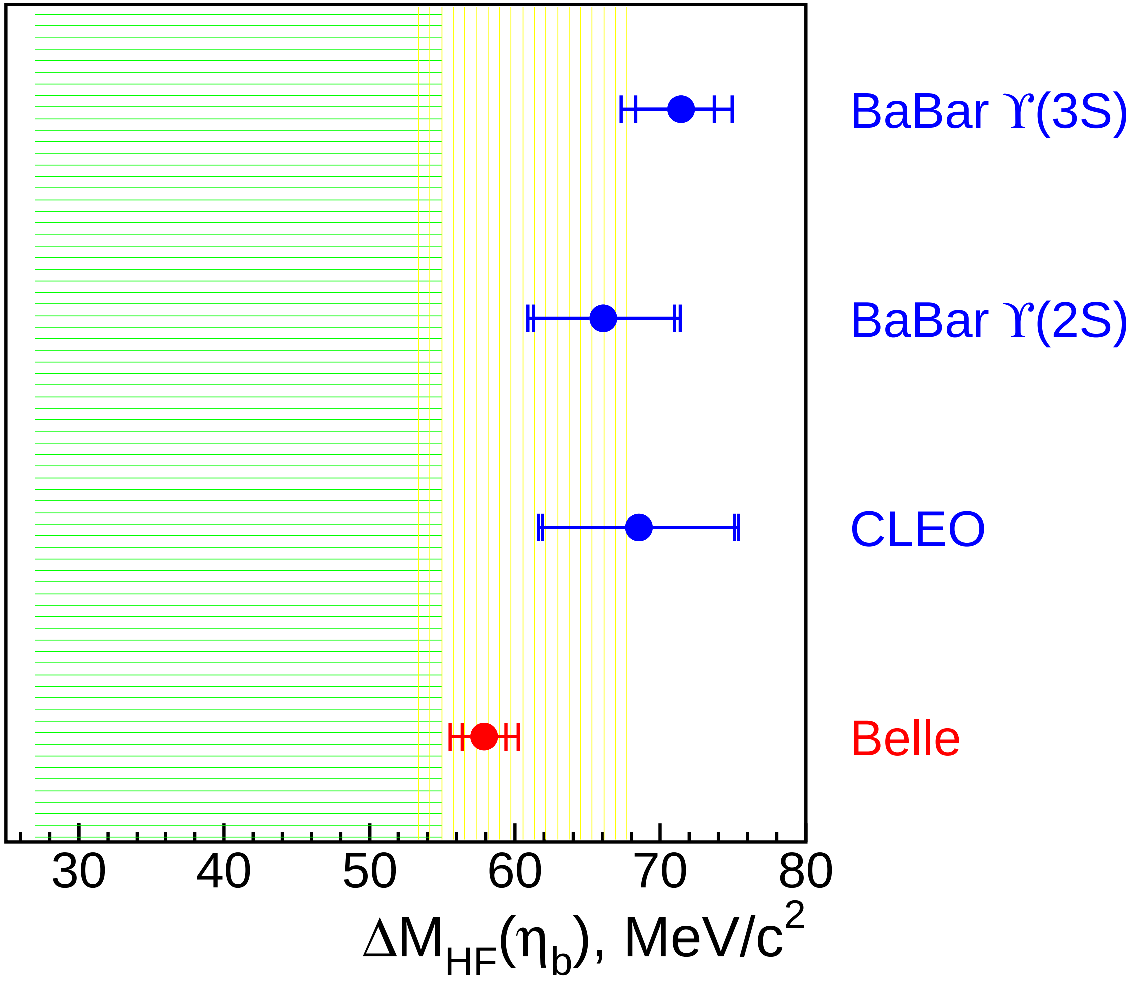
$\mathcal{B}$, %	$1P \to 1S$	$2P \to 1S$	$2P \to 2S$
–	$49.2 \pm 5.7^{+5.6}_{-3.3}$	$22.3 \pm 3.8^{+3.1}_{-3.3}$	$47.5 \pm 10.5^{+6.8}_{-7.7}$

Summary on the $\eta_b(1S)$

Quantity	Belle, 2012	PDG, 2011	Theory
Mass, MeV	$9402.4 \pm 1.5 \pm 1.8$	9390.9 ± 2.8	–
$\Delta M_{\rm hf}$, MeV	57.9 ± 2.3	69.3 ± 2.8	40-60, Latt.
Width, MeV	$10.8^{+4.0+4.5}_{-3.7-2.0}$	–	4-20, Potential
$\mathcal{B}(h_b(1P) \to \eta_b(1S)\gamma)$, %	$49.2 \pm 5.7^{+5.6}_{-3.3}$	–	41 (GR, 2002)

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

Comparison of the Mass Measurements with Theory

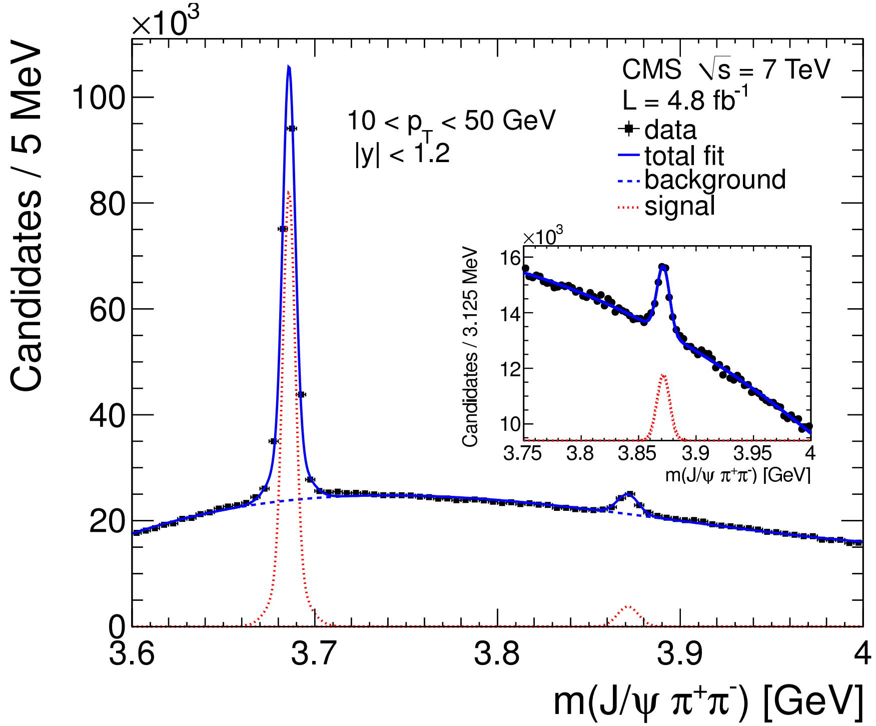


Summary on the $\eta_b(2S)$

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. (Belle Collab.), Phys. Rev. Lett. 109, 232002 (2012)

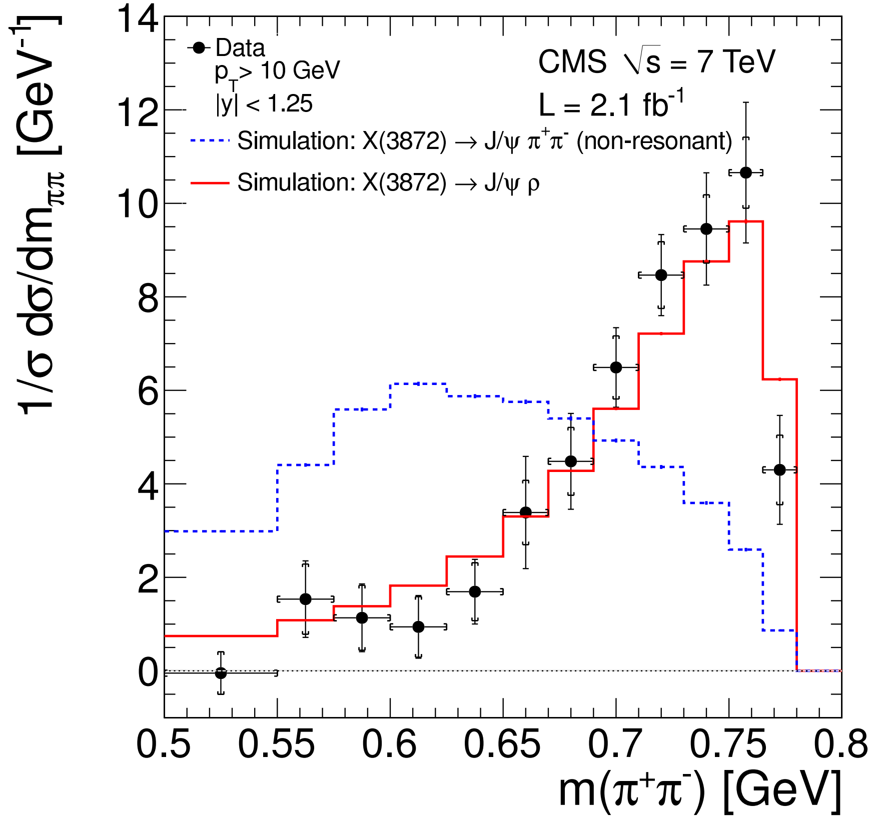
$X(3872)$ at CMS – I



CMS: 4.8 fb^{-1} at 7 TeV, $N_X = 11910 \pm 490$ $X(3872) \to J/\psi\pi^+\pi^-$ events

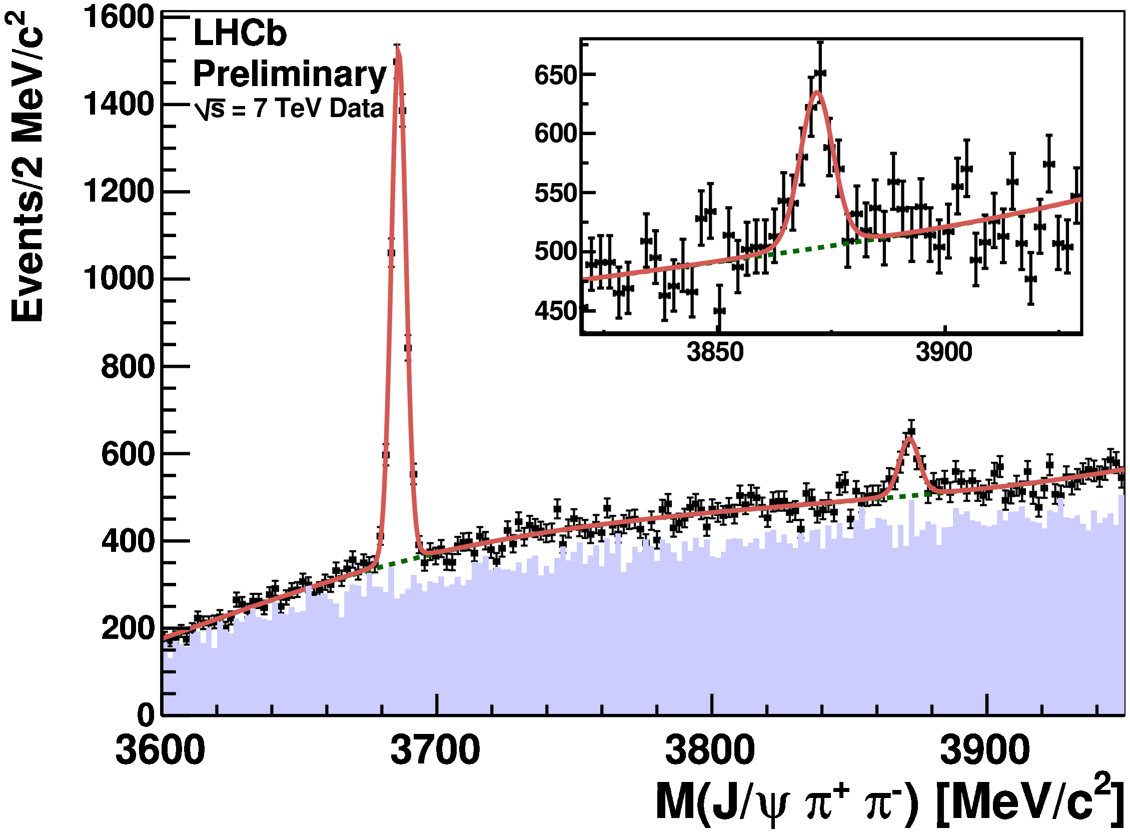
S. Chatrchyan et al., arxiv:1302.3968, subm. to JHEP

$X(3872)$ at CMS – II



2.1 fb^{-1} at 7 TeV, $N_X = 6302 \pm 346$ events are used to study the $\pi^+\pi^-$ mass spectrum and show that it clearly favors an intermediate ρ^0 state

$X(3872)$ at LHCb – I



From a small data sample at LHCb in 2010, $\sqrt{s} = 7$ TeV, $\int Ldt = 34.7$ pb^{-1}

$X(3872)$ at LHCb – II

State	$\psi(2S)$	$X(3872)$
N_{ev}	3998 ± 83	565 ± 62
Mass (LHCb), MeV	$3686.12 \pm 0.06 \pm 0.10$	$3871.95 \pm 0.48 \pm 0.12$
Mass (PDG-11), MeV	3686.09 ± 0.04	3871.57 ± 0.25
Mass (PDG-12), MeV	$3686.109^{+0.012}_{-0.014}$	3871.68 ± 0.17

$$\sigma(pp \to X + anything)\mathcal{B}(X \to J/\psi\pi^+\pi^-) = (5.4 \pm 1.3 \pm 0.8)\ \text{nb}$$

R. Aaij et al. (LHCb Collab.), Eur. Phys. J. 72, 1972 (2012)

$X(3872)$ in e^+e^- and in $p\bar{p}$, pp

Detector	$\sqrt{s}$, GeV	$\int Ldt$, fb^{-1}	Events	Mass, MeV	Ev./fb^{-1}
LHCb	7000	0.035	585 ± 74	$3871.96 \pm 0.46 \pm 0.10$	≈ 17000
CDF	1960	2.4	≈ 6000	$3871.64 \pm 0.16 \pm 0.19$	≈ 2500
Belle	10.58	711	173 ± 16	$3871.84 \pm 0.46 \pm 0.19$	0.24

Obvious advantages of high-energy measurements in $p\bar{p}$, pp collisions

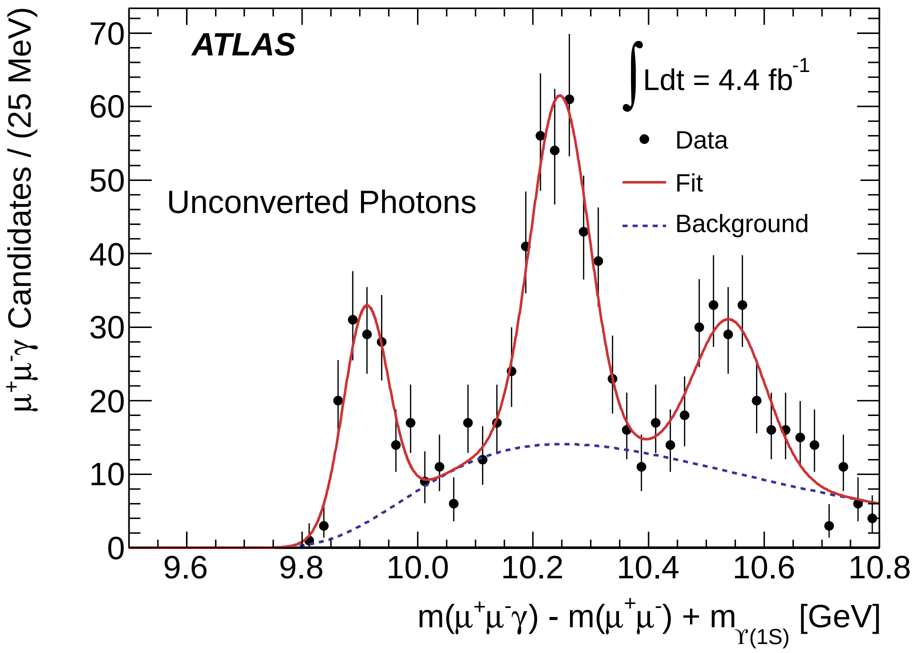
Mass very close to $m_{D^0} + m_{D^{*0}} = 3871.73 \pm 0.20$ MeV

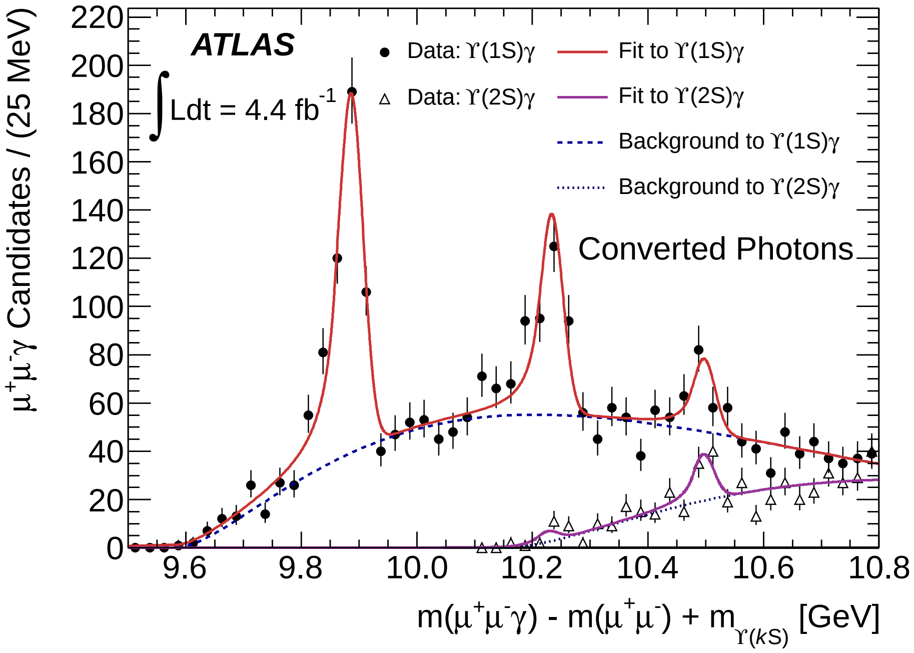
Discovery of $\chi_b(3P)$ at ATLAS – I

ATLAS uses 4.4 fb^{-1} at 7 TeV to study

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

with $\gamma \to e^+e^-$ conversion or direct detection





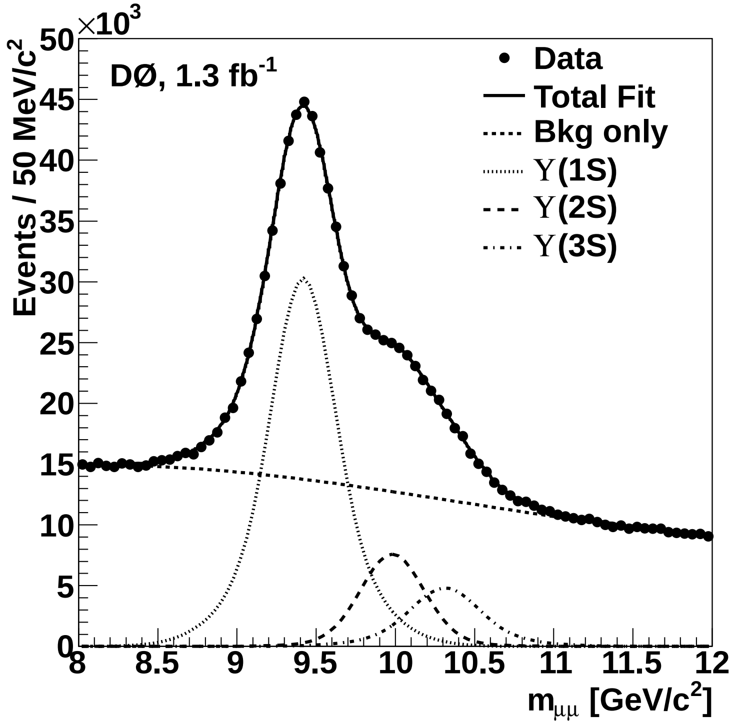
Discovery of $\chi_b(3P)$ at ATLAS – II

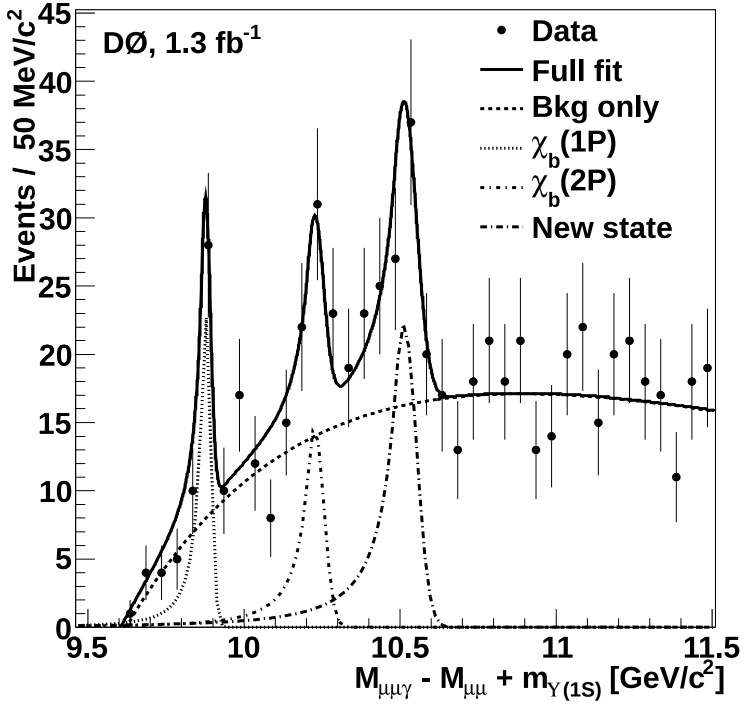
State	Theory	Unconverted γ	Converted γ
$\chi_b(1P)$	9900	$9910 \pm 6 \pm 11$	Fixed
$\chi_b(2P)$	10260	$10246 \pm 5 \pm 18$	Fixed
$\chi_b(3P)$	10525	$10541 \pm 11 \pm 30$	$10539 \pm 4 \pm 8$

G. Aad et al. (ATLAS Collab.), Phys. Rev. Lett. 108, 152001 (2012)

Confirmation of $\chi_b(3P)$ at D0

D0, 1.3 fb^{-1} at 1.96 TeV: $\chi_b(nP) \to \Upsilon(1S)\gamma,\ \Upsilon(1S) \to \mu^+\mu^-$ with $\gamma \to e^+e^-$





V.M. Abazov et al. (D0 Collab.), Phys. Rev. 86, 031103 (2012)

Comparison of ATLAS and D0 Results on $\chi_b(3P)$

Group	ATLAS	D0
M, MeV	$10539 \pm 4 \pm 8$	$10551 \pm 14 \pm 17$
Sign., σ	> 6	5.6
Resol., MeV	16–20	–

The hyperfine splitting is $\sim$ 12 MeV

Conclusions

- Huge data samples collected at B factories together with various methods of analysis give access to rare decays and transitions in the $c\bar{c}$ and $b\bar{b}$
- Many new decays and states were discovered, some expected and many with surprising or even exotic properties
- Impressive progress in the charmonium family studies, about 20 new mesons observed, but 2-3 only understood
- Various new states in the $b\bar{b}$ family: $\eta_b(1S),\ \eta_b(2S),\ h_b(1P),\ h_b(2P), Z_b(10610),\ Z_b(10650)$
- Detailed analysis of $c\bar{c}$ and $b\bar{b}$ is often limited by statistics, first promising results from pp and $p\bar{p}$ $(\chi_b(3P))$, a breakthrough expected at Super$B$-factories, PANDA and LHC
- Theoretical interpretation is very far from final and new interesting experimental observations coming

Back-up

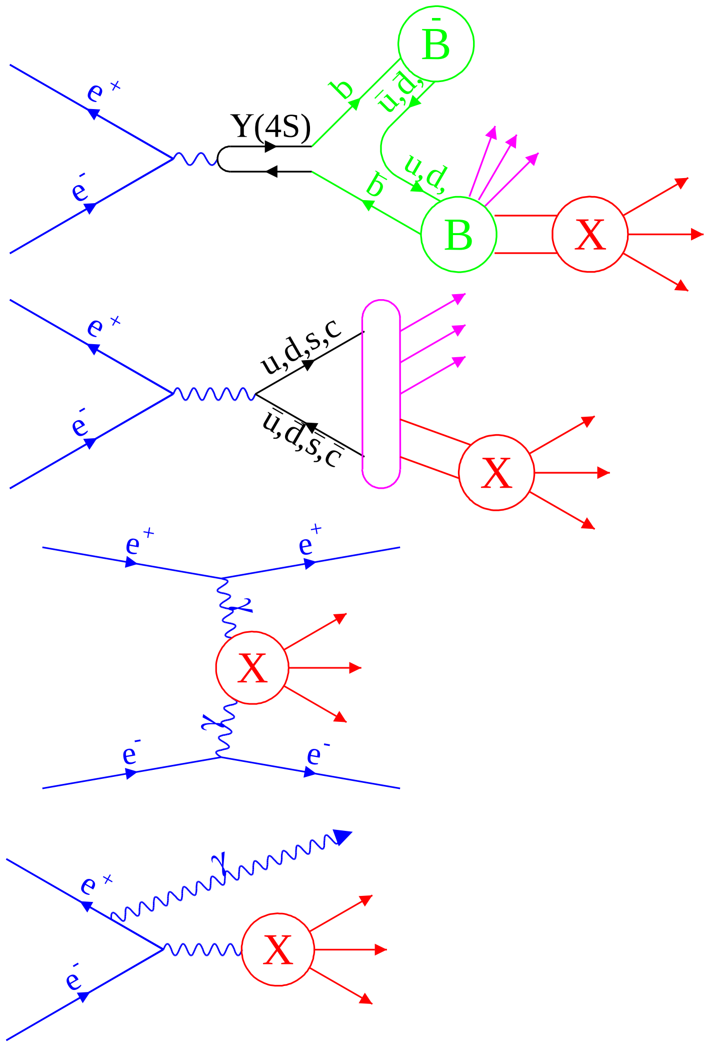
Particle Production at B Factories

Production from B-decay
(broad D^{**}, D_{sJ}, $X(3872)$, $Y(3940)$)

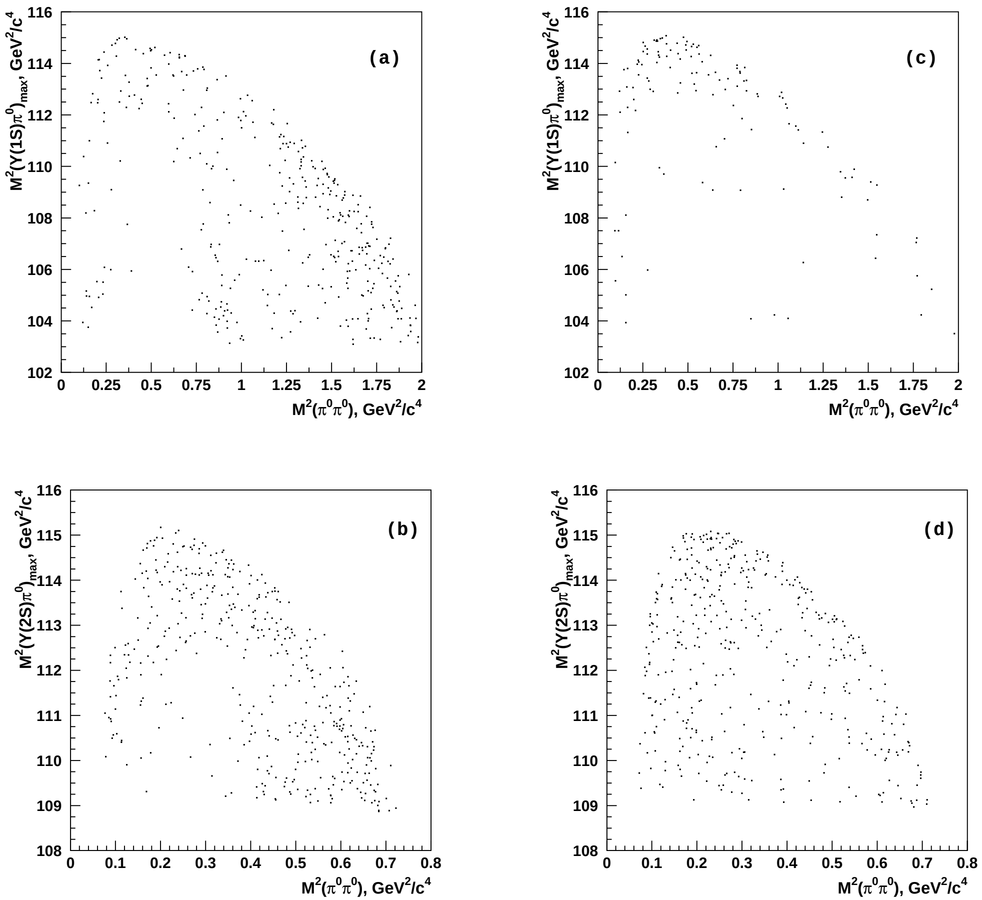
Production from continuum
(D_{sJ}, $\eta_c(2S)$, $X(3940)$, $\Sigma(2800)$)

Two-photon production
($\eta_c(2S)$, $\chi_{c2}(2P)$)

Initial state radiation
($Y(4260)$, $Y(4360)$, $Y(4660)$)

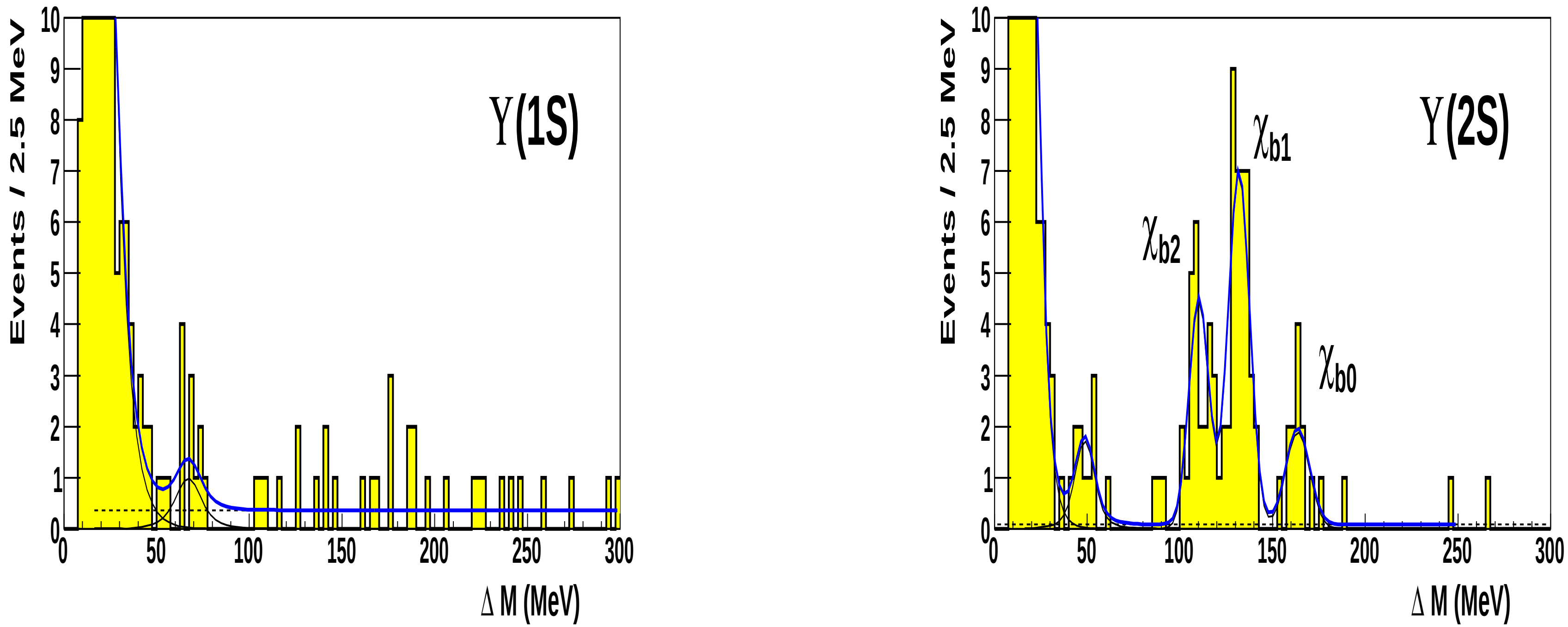


Search for $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ – IV



$\eta_b(1S)$ and $\eta_b(2S)$ from CLEO Data – I

Based on $20.9M$ $\Upsilon(1S)$ and 9.3 $\Upsilon(2S)$ decays from CLEO data
the group of K. Seth looks for $\eta_b(1,2S)$ in $\Upsilon(nS) \to \eta_b(nS)\gamma,\ \eta_b(nS) \to X$



$\eta_b(1S)$ and $\eta_b(2S)$ from CLEO Data – II

State	Events	Mass, MeV	$\Delta M_{\rm HF}$	Sign., σ
$\eta_b(1S)$	$10.3^{+4.9}_{-4.1}$	$9393.2 \pm 3.4 \pm 2.3$	$67.1 \pm 3.4 \pm 2.3$	3.1
$\eta_b(2S)$	$11.4^{+4.3}_{-3.5}$	$9974.6 \pm 2.3 \pm 2.1$	$48.7 \pm 2.3 \pm 2.1$	4.9

PRL 109, 082001 (2012) – 5 authors only use CLEO data!

$\eta_b(1S)$ and $\eta_b(2S)$ from CLEO Data – III

Group	State	Events	Mass, MeV	$\Delta M_{\rm HF}$	Sign., σ
K. Seth	$\eta_b(1S)$	$10.3^{+4.9}_{-4.1}$	$9393.2 \pm 3.4 \pm 2.3$	$67.1 \pm 3.4 \pm 2.3$	3.1
Belle	–	$(23.5 \pm 2.0)k$	$9402.4 \pm 1.5 \pm 1.8$	57.9 ± 2.3	15
–	–	$(10.3 \pm 1.3)k$	–	–	9
K. Seth	$\eta_b(2S)$	$11.4^{+4.3}_{-3.5}$	$9974.6 \pm 2.3 \pm 2.1$	$48.7 \pm 2.3 \pm 2.1$	4.9
Belle	–	$(25.8 \pm 4.9)k$	$9999.0 \pm 3.5^{+2.8}_{-1.9}$	$24.3^{+4.0}_{-4.5}$	4.2