Investigation of meson properties with the Belle detector

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Outline

1. New light mesons between 2 and 3 GeV
2. First D state in charmonium family
3. New states in bottomonium
4. Conclusions

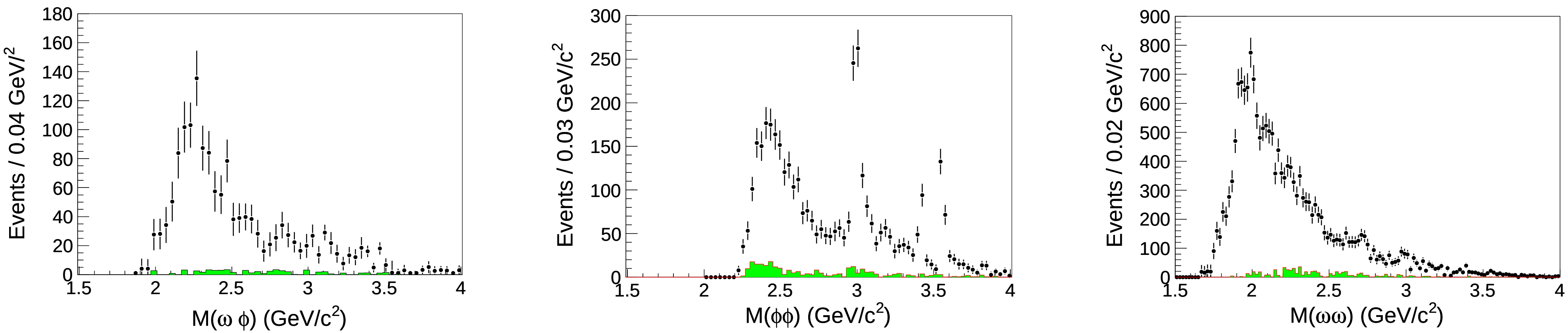
Introduction

- 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 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 $c\bar{c}$
- The combination of these methods/ideas led to spectacular observations in charmonium and bottomonium systems with many new states found, and to 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

$\gamma\gamma \to \omega\phi,\ \phi\phi,\ \omega\omega$ at Belle – I

Belle used a data sample of 870 fb^{-1} taken at $\Upsilon(nS)$, $n = 1, \ldots, 5$, to measure cross sections of $\gamma\gamma \to \omega\phi,\ \phi\phi,\ \omega\omega$

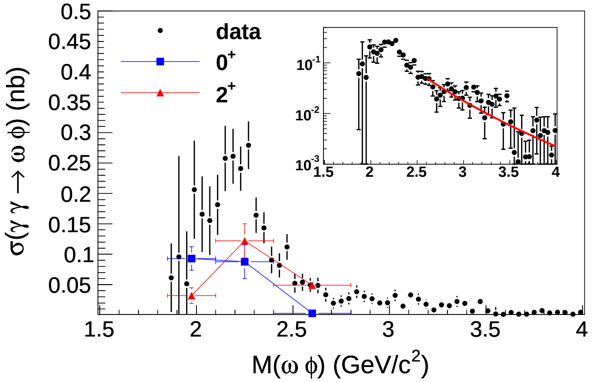
Z.Q. Liu et al., arxiv:1202.5632, PRL

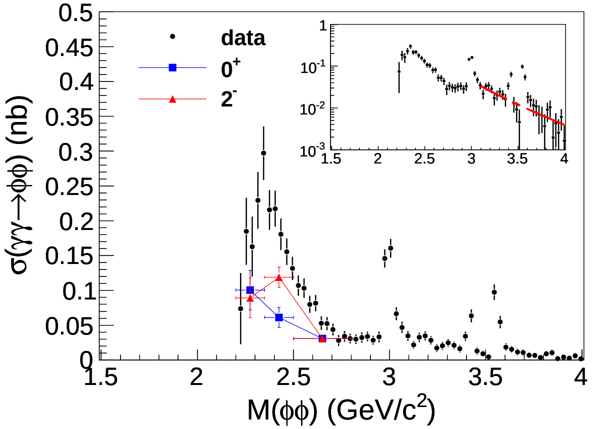


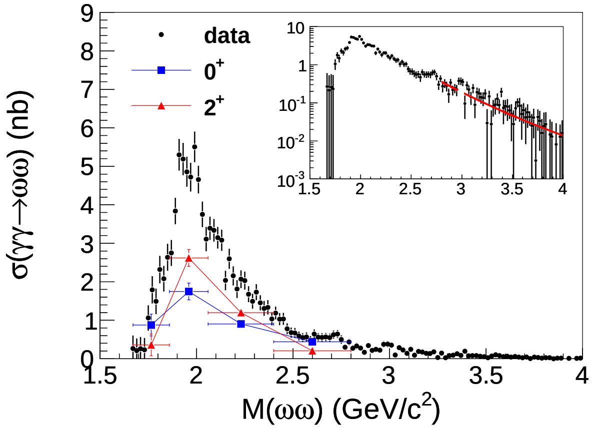
In addition to charmonium signals, obvious structures are seen below 3 GeV

$\gamma\gamma \to \omega\phi,\ \phi\phi,\ \omega\omega$ at Belle – II

2D angular analysis for various $J^P(0^+, 0^-, 2^+, 2^-)$ reveals a mixture of spin-0 and spin-2 components for all modes

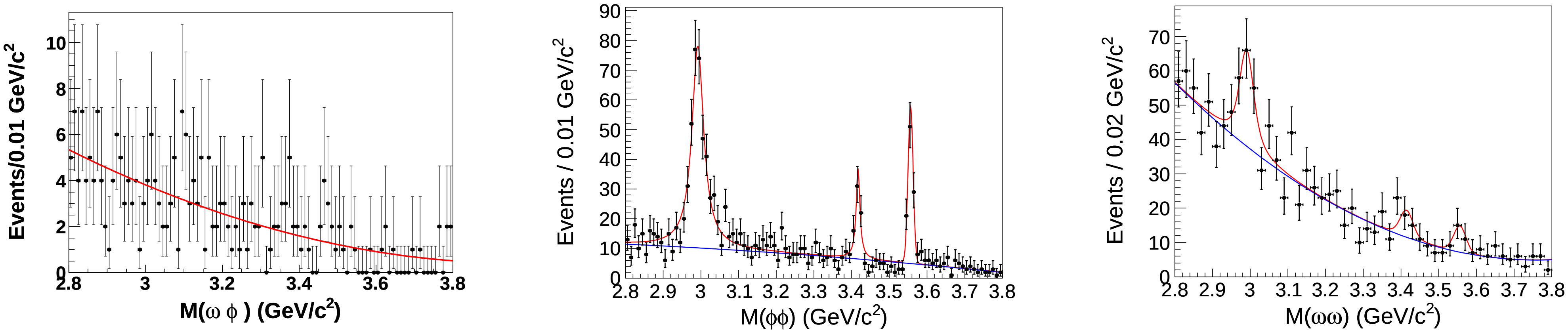






Mode	$\omega\phi$	$\phi\phi$	$\omega\omega$
M, GeV	2.2	2.35	1.91
σ_{peak}, nb	0.27 ± 0.05	0.30 ± 0.04	5.30 ± 0.42

$\gamma\gamma \to \omega\phi,\ \phi\phi,\ \omega\omega$ at Belle – III



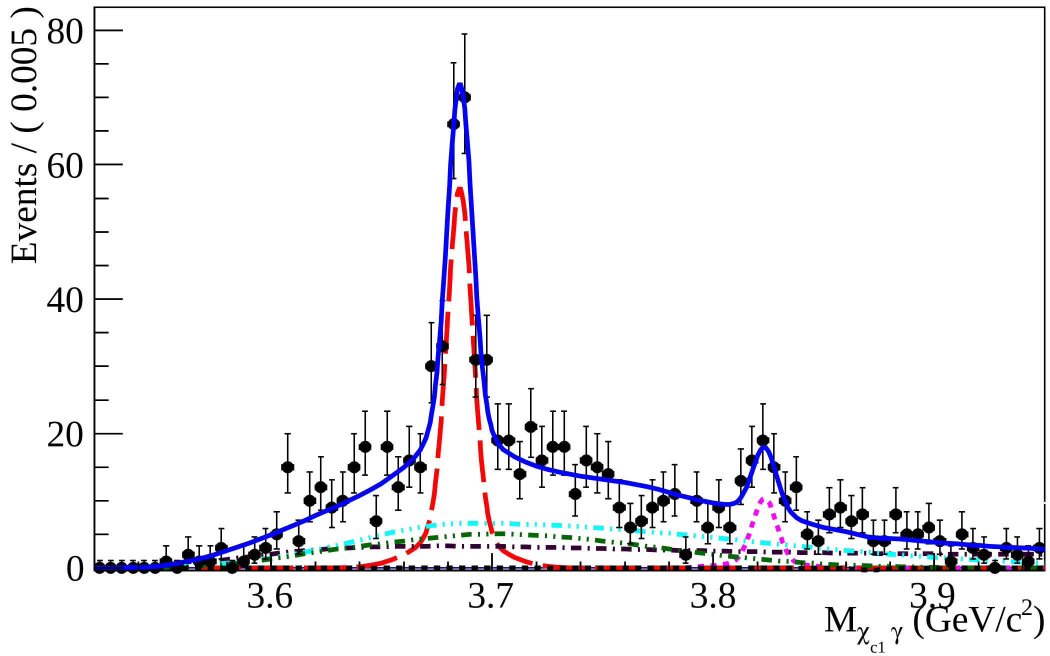
$\Gamma_{\gamma\gamma}\mathcal{B}(R \to VV)$ are measured with improved precision for the $\eta_c,\ \chi_{c0},\ \chi_{c2} \to \phi\phi$, $\eta_c \to \omega\omega$ and upper limits for other decays to $\omega\omega,\ \omega\phi$ are the first measurements

4-quark, t-channel factorization, one-pion exchange models fail to explain the position and height of the peaks

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 $X(3872)$

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 Υ(5S) decays

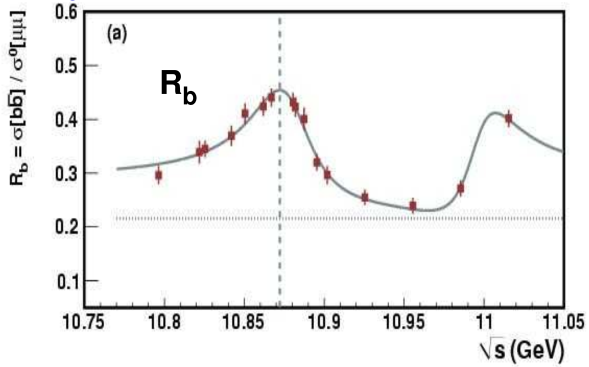
At 21.7 fb^{-1} Υ (5S) ->Υ(nS) $\pi^+\pi^-$ two orders of magnitude larger than in Υ (4S) decay

	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 ⇒

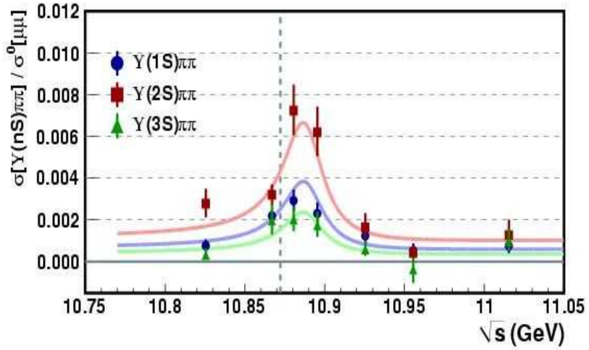
shapes of R_b and σ(Υππ) different (2σ)



-Rescattering Υ(5S)→BBππ→Υ(nS)ππ

Simonov JETP Lett 87,147(2008)

-Exotic resonance Y_b near Υ(5S)



Υ(5S) is very interesting and not yet understood

Finally Belle recorded 121.4fb^{-1} at Υ(5S)

arXiv:1104.2025

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

⇒ Belle search for h_b in Υ(5S) data

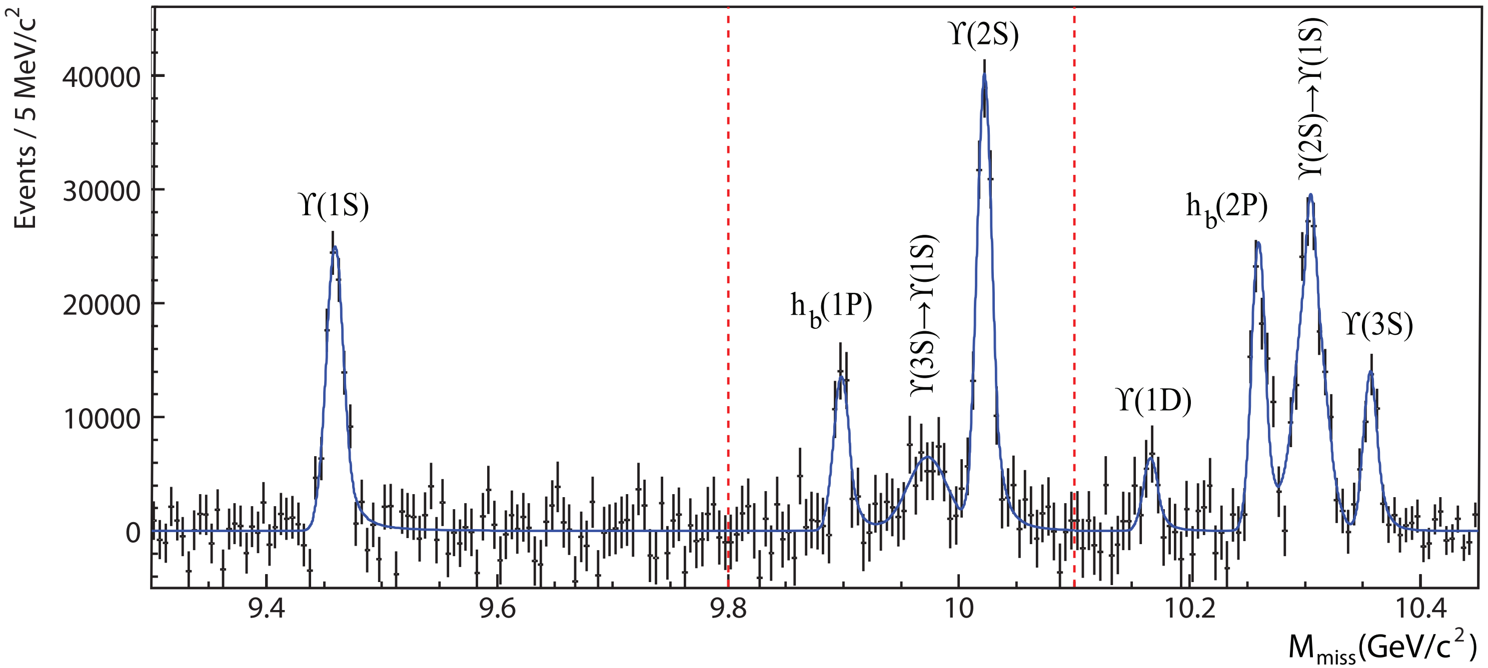
Observation of $h_b(1P)$ and $h_b(2P)$ at Belle – I

- Belle used 121.4 fb^{-1} collected near 10860 MeV to study $\Upsilon(5S) \to X\pi^+\pi^-$, where $X = \Upsilon(1S, 2S, 3S)$ or really new $b\bar{b}$ state, using missing mass to $\pi^+\pi^-$
- 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 $h_b(2P)$
-

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

- 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 – $h_b(nP)$

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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

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

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

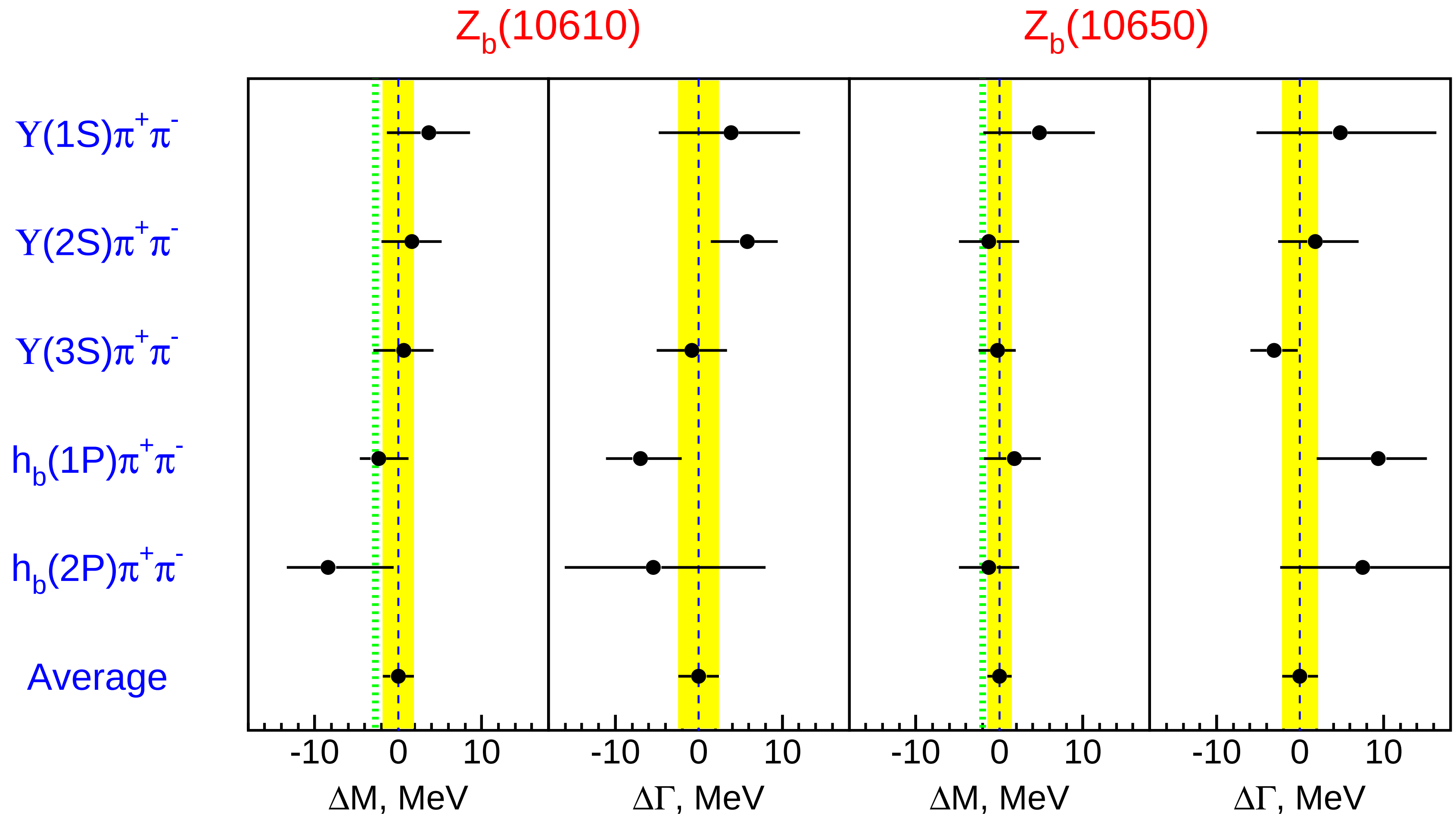
Masses, widths, relative amplitudes are consistent

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

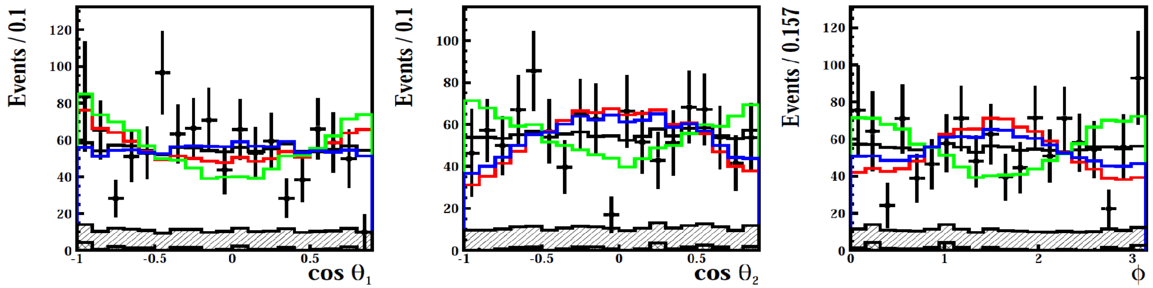
Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – III



Angular analysis

[preliminary]

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



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

<table>
<tr><th rowspan="2">J^P</th><th colspan="3">$Z_b(10610)$</th><th colspan="3">$Z_b(10650)$</th></tr>
<tr><th>$\Upsilon(2S)\pi^+\pi^-$</th><th>$\Upsilon(3S)\pi^+\pi^-$</th><th>$h_b(1P)\pi^+\pi^-$</th><th>$\Upsilon(2S)\pi^+\pi^-$</th><th>$\Upsilon(3S)\pi^+\pi^-$</th><th>$h_b(1P)\pi^+\pi^-$</th></tr>
<tr><td>1^-</td><td>3.6σ</td><td>0.3σ</td><td>0.3σ</td><td>3.7σ</td><td>2.6σ</td><td>2.7σ</td></tr>
<tr><td>2^+</td><td>4.3σ</td><td>3.5σ</td><td rowspan="2">4.3σ</td><td>4.4σ</td><td>2.7σ</td><td rowspan="2">2.1σ</td></tr>
<tr><td>2^-</td><td>2.7σ</td><td>2.8σ</td><td>2.9σ</td><td>2.6σ</td></tr>
</table>

1+ assignment is favorable.

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

1

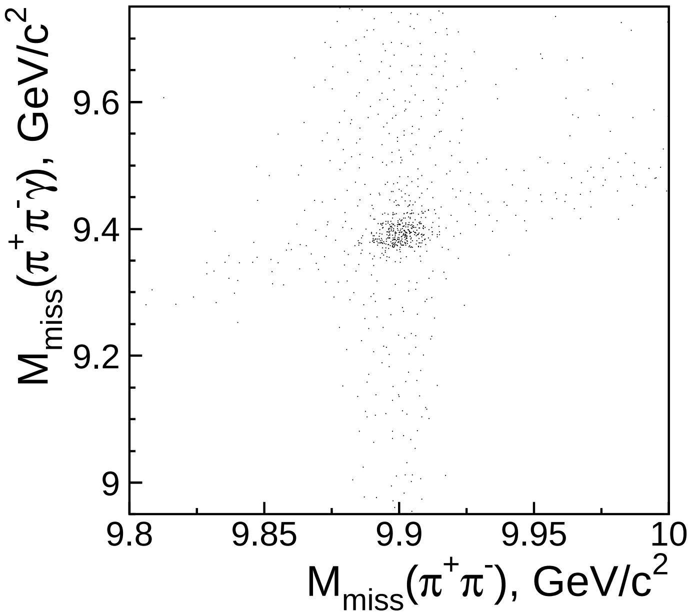
What do we know about the $\eta_b(1S)$?

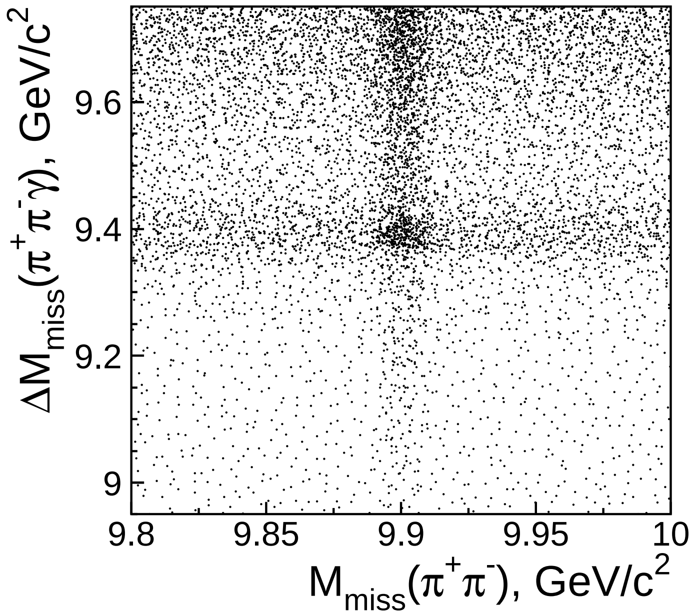
- First claim from ALEPH in 2002 in 200 GeV e^+e^- at $9300 \pm 20 \pm 20$ MeV
- First observations by BaBar (2008, 2009) and CLEO (2010) in $\Upsilon(2S, 3S) \to \eta_b(1S)\gamma$
- World-average mass $M(\eta_b(1S)) = 9390.9 \pm 2.8$ MeV $\Rightarrow$
  Hyperfine mass splitting $\Delta M_{\rm hf} = M(\Upsilon(1S)) - M(\eta_b(1S))$=$69.3 \pm 2.8$ 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 $M(\eta_b)$
- $\Delta M_{\text{miss}}(\pi^+\pi^-\gamma) \equiv M_{\text{miss}}(\pi^+\pi^-\gamma) - M_{\text{miss}}(\pi^+\pi^-) + M(h_b)$
- We fit $M_{\text{miss}}(\pi^+\pi^-)$ spectra in $\Delta M_{\text{miss}}(\pi^+\pi^-\gamma)$ 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

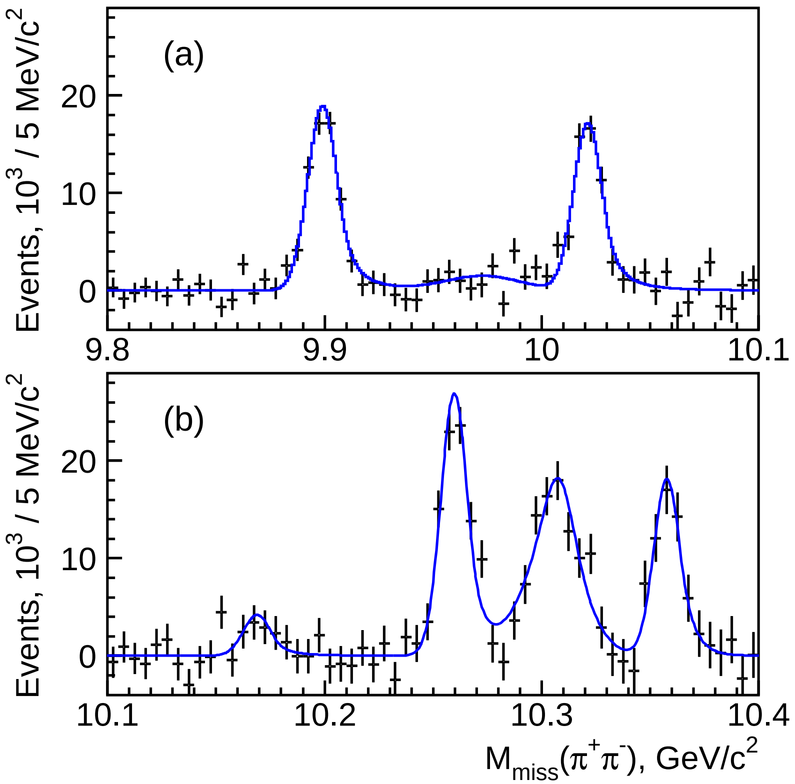
The horizontal band for $\Delta M_{\rm miss}(\pi^+\pi^-\gamma)$ corresponds to η_b, true γ and bg $\pi^+\pi^-$

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 $\eta_b(2S)$,

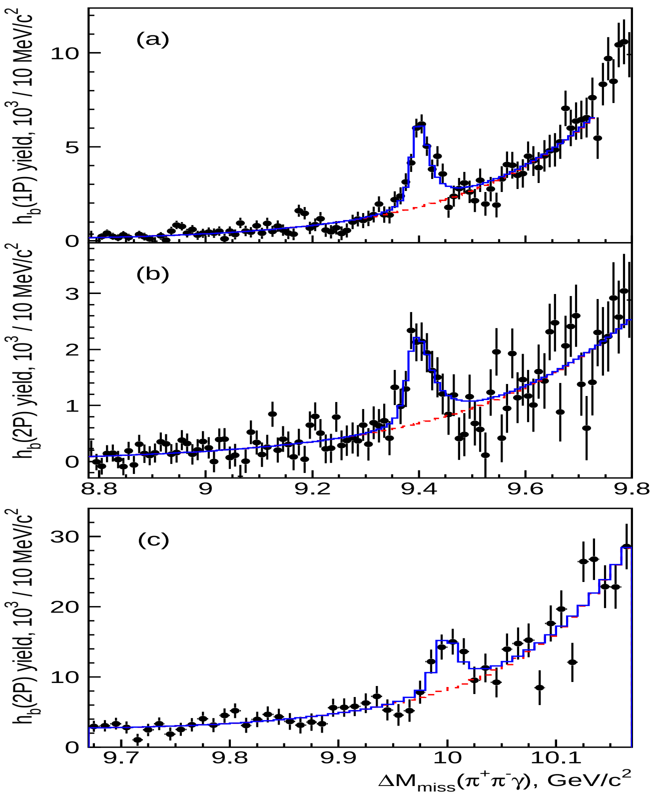
We also update $h_b(1P)$ and $h_b(2P)$ mass measurements



$\pi\pi$ 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

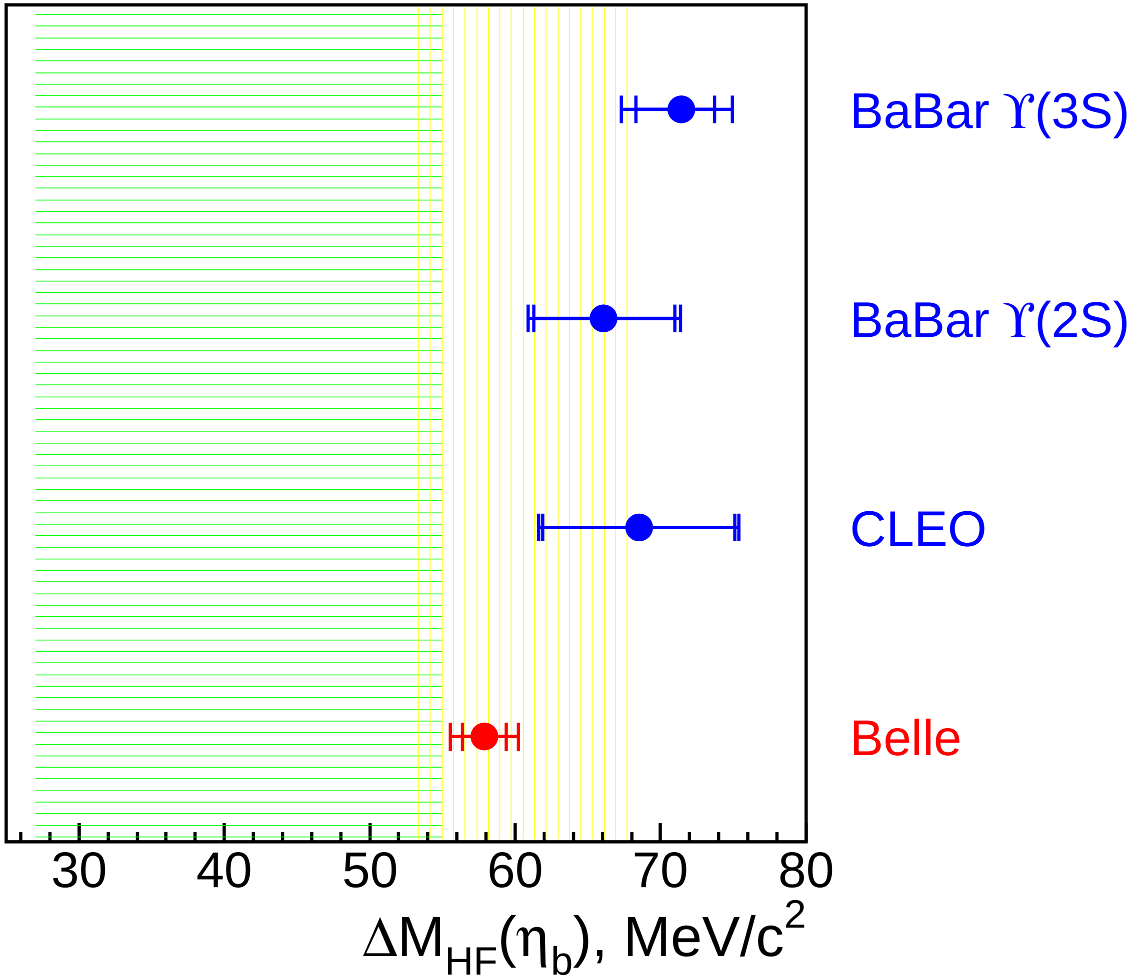
$\mathcal{B}$, %	$1P \to 1S$	$2P \to 1S$	$2P \to 2S$
–	$49.2 \pm 5.7^{+5.6}_{-3.3}$	$22.3 \pm 3.8^{+3.1}_{-3.3}$	$47.5 \pm 10.5^{+6.8}_{-7.7}$

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)

Belle Collaboration, arXiv:1205.6351, submitted to PRL

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)

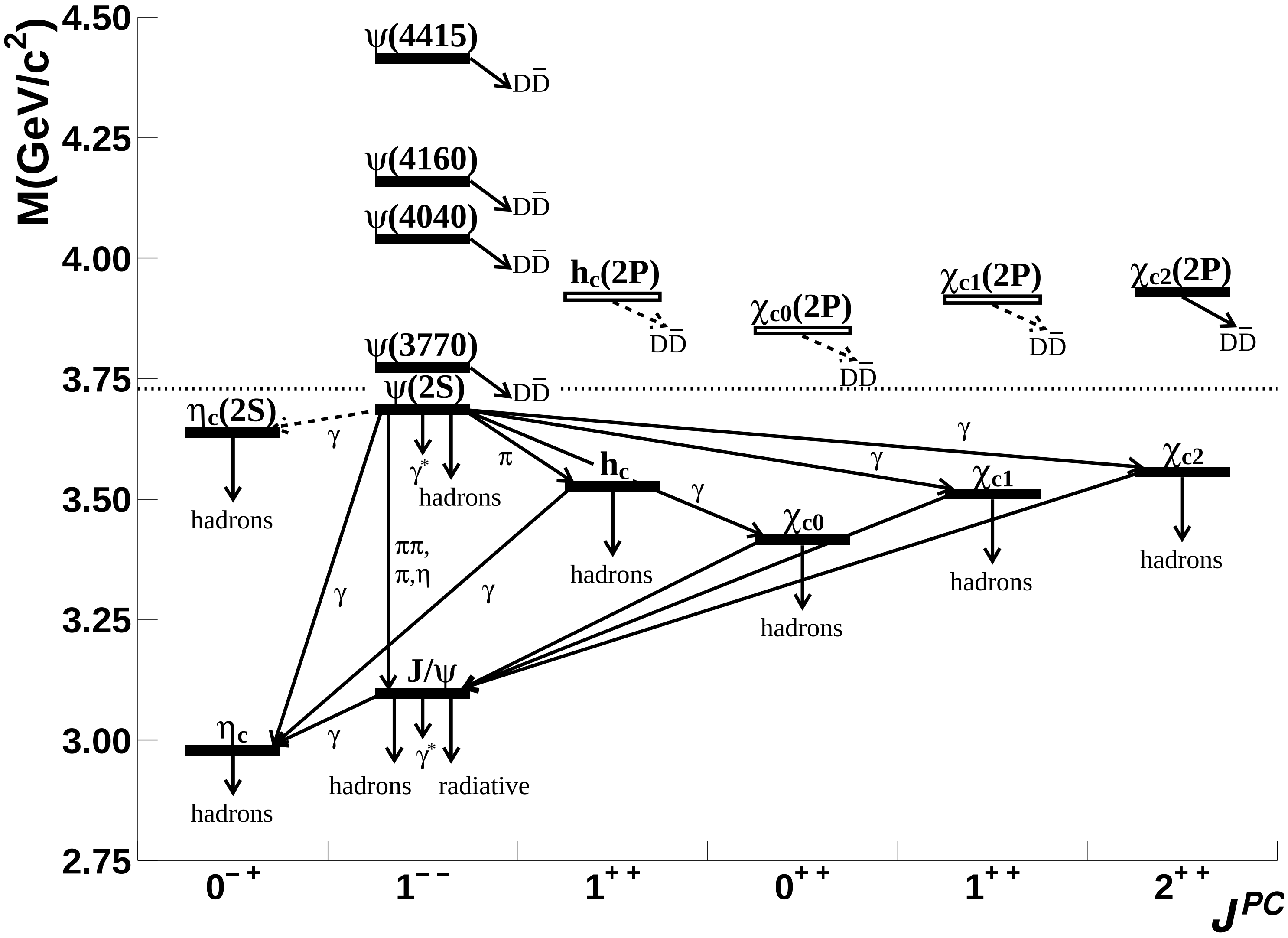
Belle Collaboration, arXiv:1205.6351, submitted to PRL

Conclusions

- Huge data samples collected at B factories together with various methods of analysis give access to rare processes in e^+e^- annihilation, $\gamma\gamma$, B and $\Upsilon(5S)$ decays
- Many new mesons of light and heavy quarks 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
- In many cases detailed analysis of $X_{c\bar{c}}$ is limited by statistics, a breakthrough expected at Super$B$-factories, PANDA and LHC
- Various new states in the $b\bar{b}$ family: $\eta_b(1S)$, $\eta_b(2S)$, $h_b(1P)$, $h_b(2P)$, $Z_b(10610)$, $Z_b(10650)$
- Theoretical interpretation is very far from final and new interesting experimental observations coming

Back-up

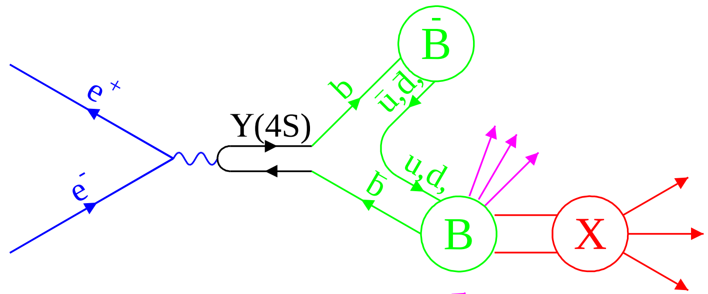
The Charmonium System



Particle Production at B Factories

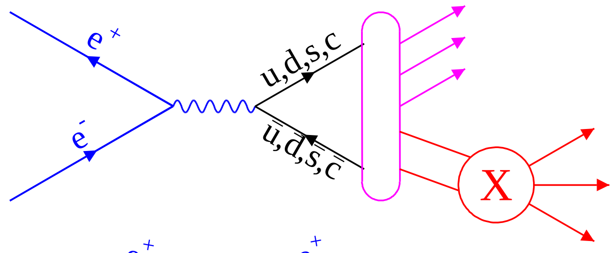
Production from B-decay

(broad D^{**}, D_{sJ}, $X(3872)$, $Y(3940)$)



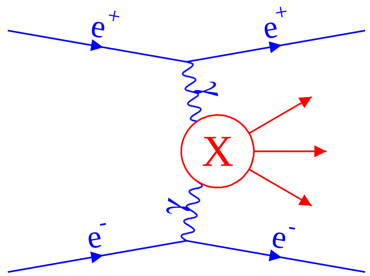
Production from continuum

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



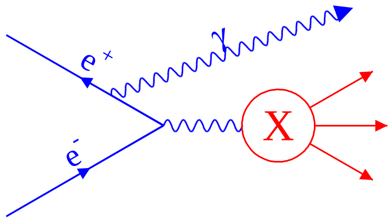
Two-photon production

($\eta_c(2S)$, $\chi_{c2}(2P)$)



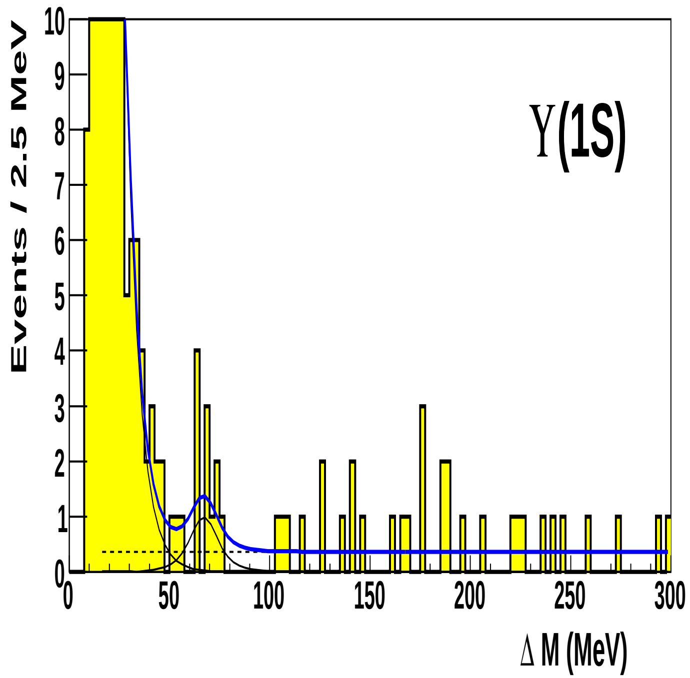
Initial state radiation

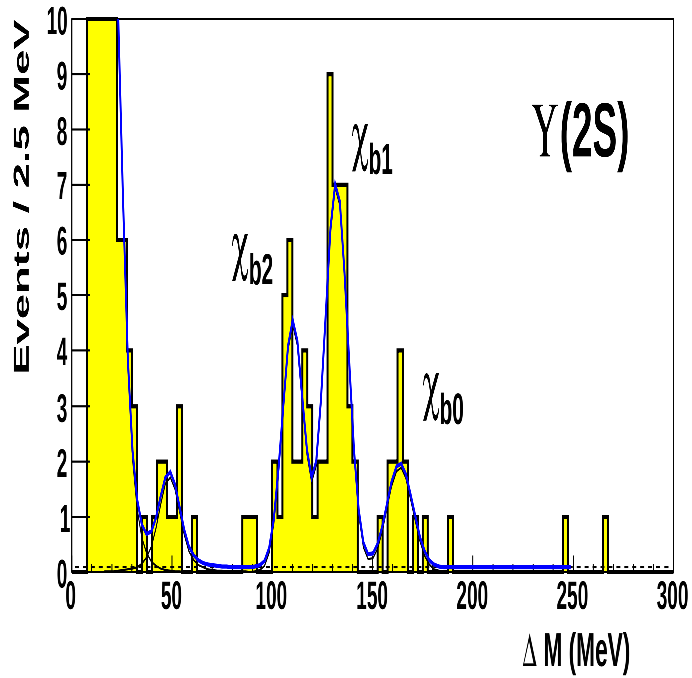
($Y(4260)$, $Y(4360)$, $Y(4660)$)



$\eta_b(1S)$ 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

arxiv:1204.4205 – 5 authors only use CLEO data!

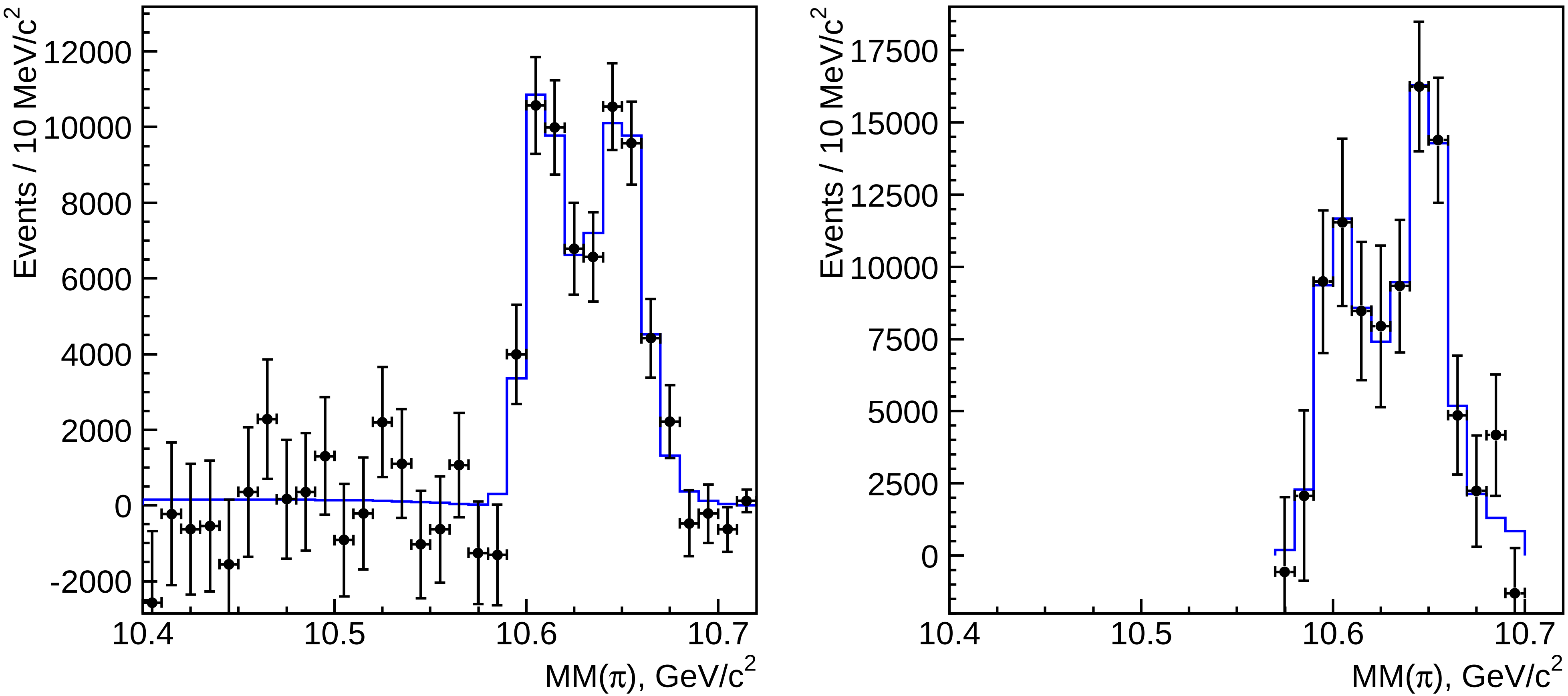
$\eta_b(1S)$ and $\eta_b(2S)$ from CLEO Data – III

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

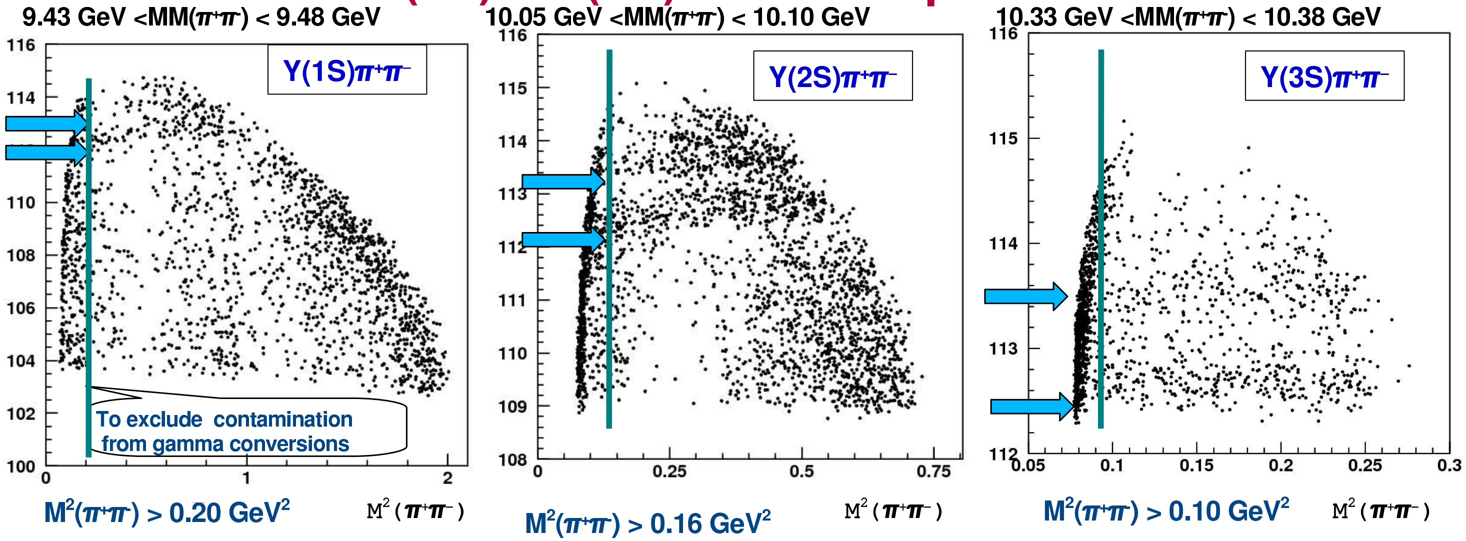
Observation of $\Upsilon(1D)$ at Belle – I

- A 1^3D_J triplet is expected, $J = 1, 2, 3$; $\Gamma \sim 30$ keV, $\Delta M \sim 10$ MeV
- Discovered by CLEO, Phys. Rev. D 70, 032031 (2004) with 10.2σ
- BaBar, Phys. Rev. D 82, 111102 (2010) with 5.8σ;
  $\Upsilon(3S) \to \gamma\chi_{bJ'}(2P)$, $\chi_{bJ'}(2P) \to \gamma\Upsilon(1^3D_J)$, $\Upsilon(1S)\pi^+\pi^-$
- Belle uses $\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-, \Upsilon(1D) \to \chi_b(1P)\gamma, \chi_b(1P) \to \Upsilon(1S)\gamma$

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



$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$ Dalitz plots



$s_i \equiv M^2_{\pi_i \Upsilon}$ **Unbinned fit of DP with signal function:**

Flatte m=950 MeV/c²

D-wave Breit-Wigner

$$S(s_1, s_2) = |A_{Z_{b1}} + A_{Z_{b2}} + A_{NR} + A_{f_0(980)} + A_{f_2(1275)}|^2$$

$$A_{Z_{bi}} = \frac{\sqrt{M_i\Gamma_i}}{M_i^2 - s_1 + iM_i\Gamma_i} + \frac{a_i e^{i\phi_i}\sqrt{M_i\Gamma_i}}{M_i^2 - s_2 + iM_i\Gamma_i}$$

$$A_{NR} = c_1 + c_2 m^2_{\pi\pi}$$

[1] M.B. Voloshin, Prog. Part. Nucl. Phys. 61:455, 2008.

[2] M.B. Voloshin, Phys. Rev. D74:054022, 2006.

1

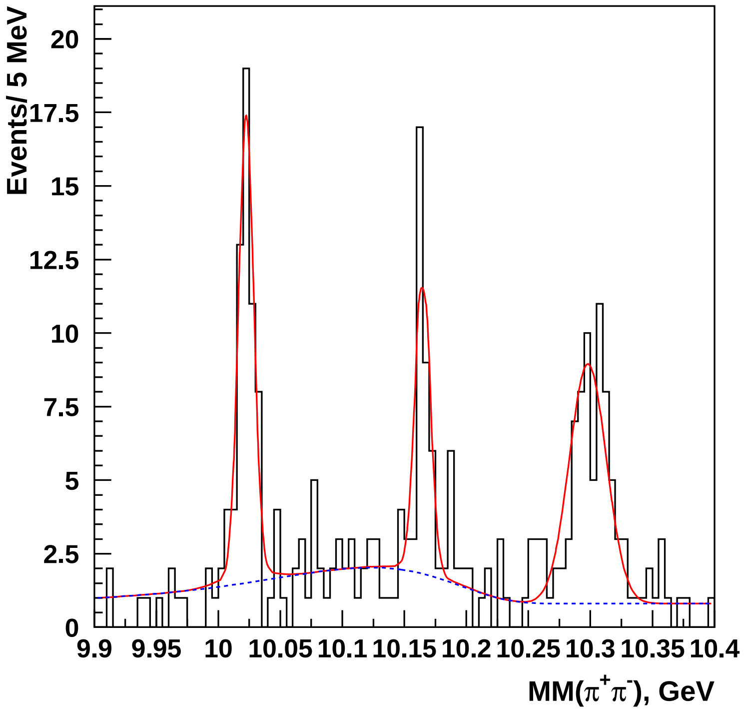
Comparison with Theory

In the non-relativistic approximation the spin-spin interaction $\propto |\psi(0)|^2$.
Then $\Delta M_{\rm HF}(nP) = 0$ in agreement with
0.8 ± 1.1 and 0.5 ± 1.2 MeV

$$\Delta M_{\rm HF}(2S) = \Delta M_{\rm HF}(1S)\frac{\Gamma_{ee}[\Upsilon(2S)]}{\Gamma_{ee}[\Upsilon(1S)]} = (26.5 \pm 1.2)\ \mathrm{MeV} \qquad 24.3^{+4.0}_{-4.5}\ \mathrm{MeV}$$

$$\Gamma[\eta_b(2S)] = \Gamma[\eta_b(1S)]\frac{\Gamma_{ee}[\Upsilon(2S)]}{\Gamma_{ee}[\Upsilon(1S)]} = (4.9^{+2.7}_{-1.9})\ \mathrm{MeV} \qquad < 24\ \mathrm{MeV}$$

Observation of $\Upsilon(1D)$ at Belle



$\Upsilon(1S)[\mu^+\mu^-]\pi^+\pi^-\gamma\gamma$ final state

Three peaks in $MM(\pi^+\pi^-)$:

$\Upsilon(2S)\pi^+\pi^-$

$\Upsilon(1D)\pi^+\pi^-$

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

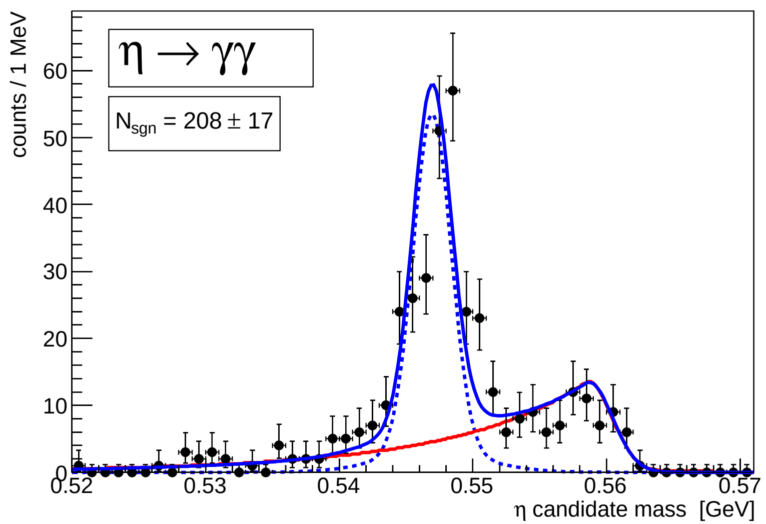
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-)\mathcal{B}(\Upsilon(1D) \to \chi_b(1P)\gamma \to \Upsilon(1S)\gamma\gamma) =$
$(2.0 \pm 0.4 \pm 0.3) \cdot 10^{-4}$ 9σ sign.!

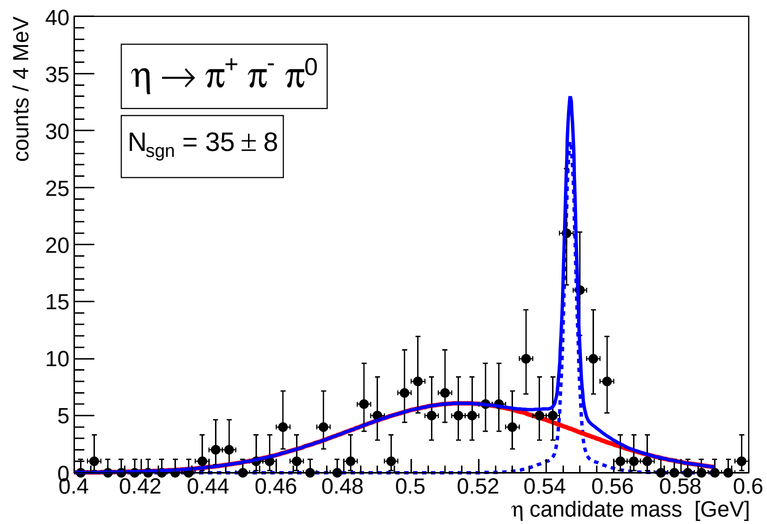
η Transitions in Bottomonium

- η and π^0 transitions in bottomonium are important for theory, between 1^{--} $b\bar{b}$ spin flip of the b, scaling as $1/m_b$
- From $\psi(2S) \to \eta J/\psi$ $\mathcal{B}(\Upsilon(2S) \to \eta\Upsilon(1S)) \sim 8 \cdot 10^{-4}$
- For π^0 $\Gamma(\Upsilon(2S) \to \pi^0\Upsilon(1S)) - 0.16\Gamma(\Upsilon(2S) \to \eta\Upsilon(1S))$
- From BaBar and CLEO, branchings are either unexpectedly large ($\Upsilon(4S)$) or too small ($\Upsilon(2S)$ and $\Upsilon(3S)$)

Study of $\Upsilon(2S) \to \Upsilon(1S)(\eta, \pi^0)$ at Belle

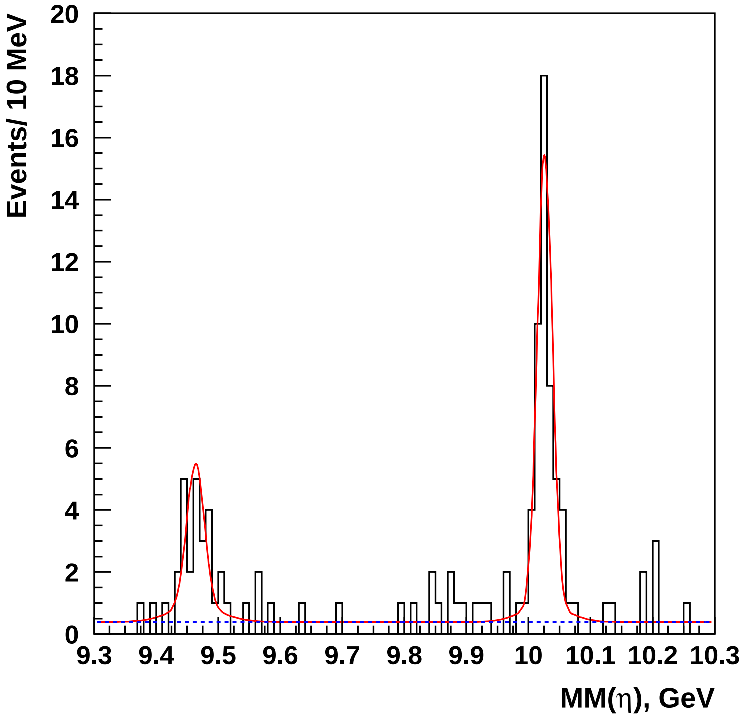
Belle uses 158M $\Upsilon(2S)$ decays

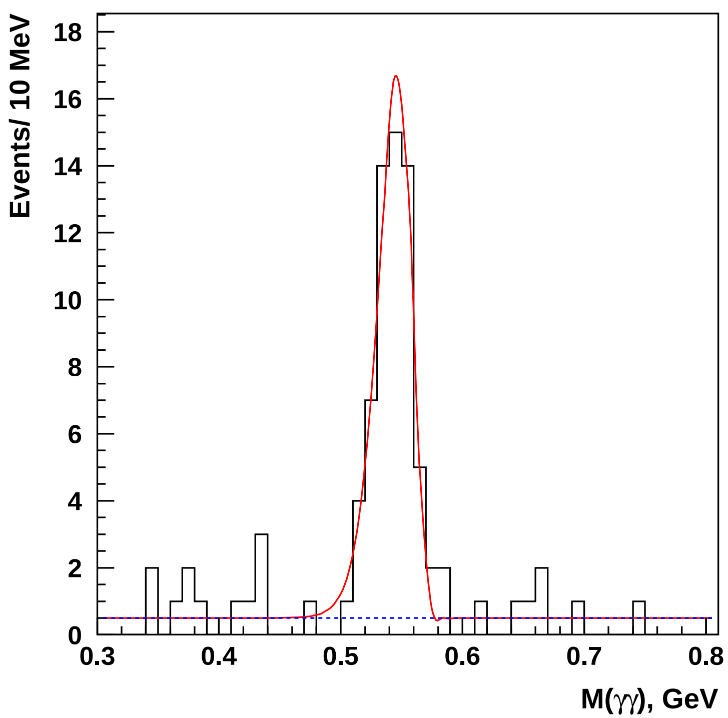




$\mathcal{B}(\Upsilon(2S) \to \Upsilon(1S)\eta) = (3.28 \pm 0.27 \pm 0.35) \cdot 10^{-4}, \quad \mathcal{B}(\Upsilon(2S) \to \Upsilon(1S)\pi^0) < 4.3 \cdot 10^{-5}$

Observation of $\Upsilon(5S) \to \Upsilon(1,2S)\eta$ – I





Observation of $\Upsilon(5S) \to \Upsilon(1,2S)\eta$ – II

Three modes:

- $\Upsilon(5S) \to \Upsilon(1,2S)\eta,\ \Upsilon(1,2S) \to \mu^+\mu^-,\ \eta \to \pi^+\pi^-\pi^0$
- $\Upsilon(5S) \to \Upsilon(2S)\eta,\ \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-,\ \Upsilon(1S) \to \mu^+\mu^-,\ \eta \to \gamma\gamma$
- $\Upsilon(5S) \to \Upsilon(1S)\eta',\ \Upsilon(1S) \to \mu^+\mu^-,\ \eta' \to \eta\pi^+\pi^-$

Results on the branching fractions:

- $\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\eta) = (7.3 \pm 1.6 \pm 0.8) \cdot 10^{-4}$
- $\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\eta) = (38 \pm 4 \pm 5) \cdot 10^{-4}$
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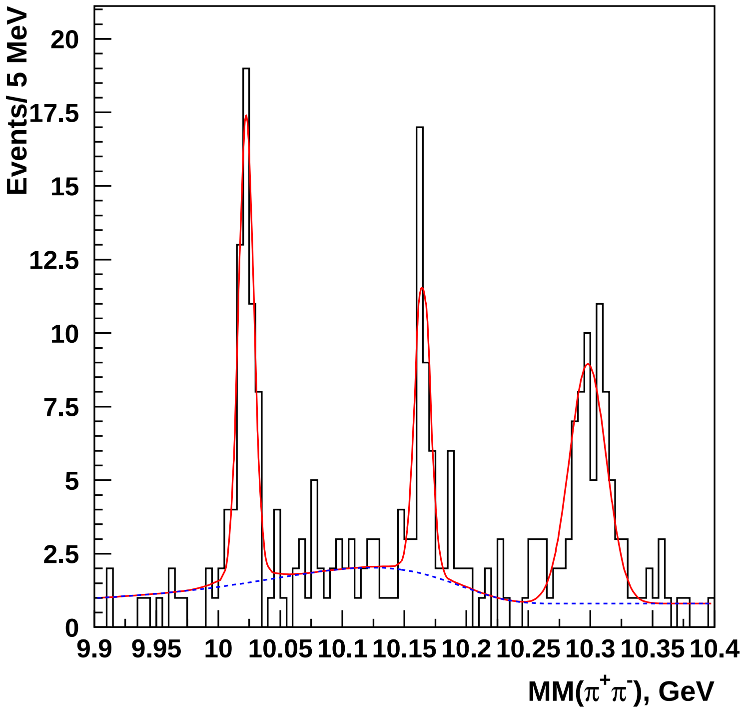

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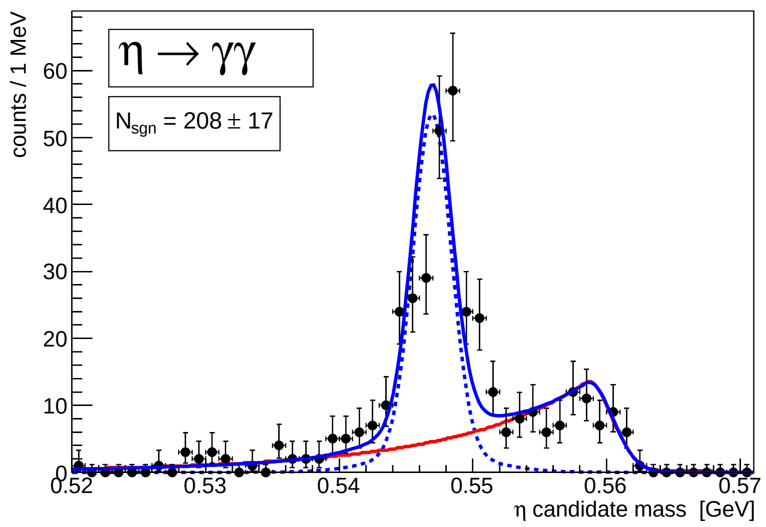

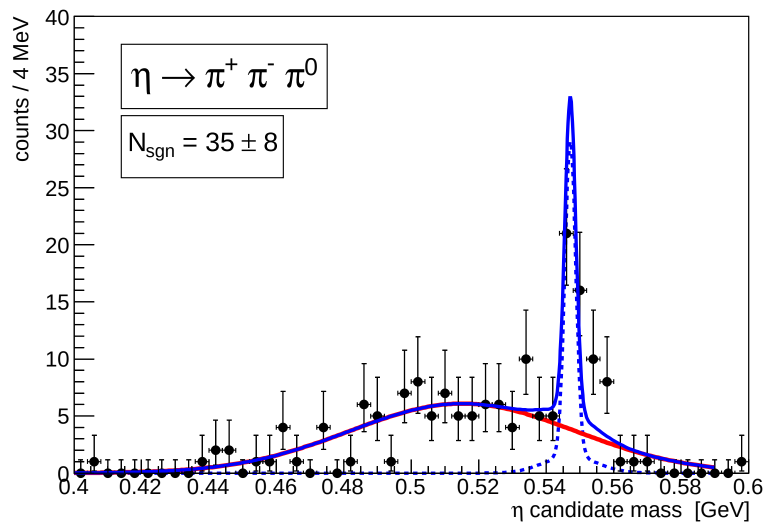

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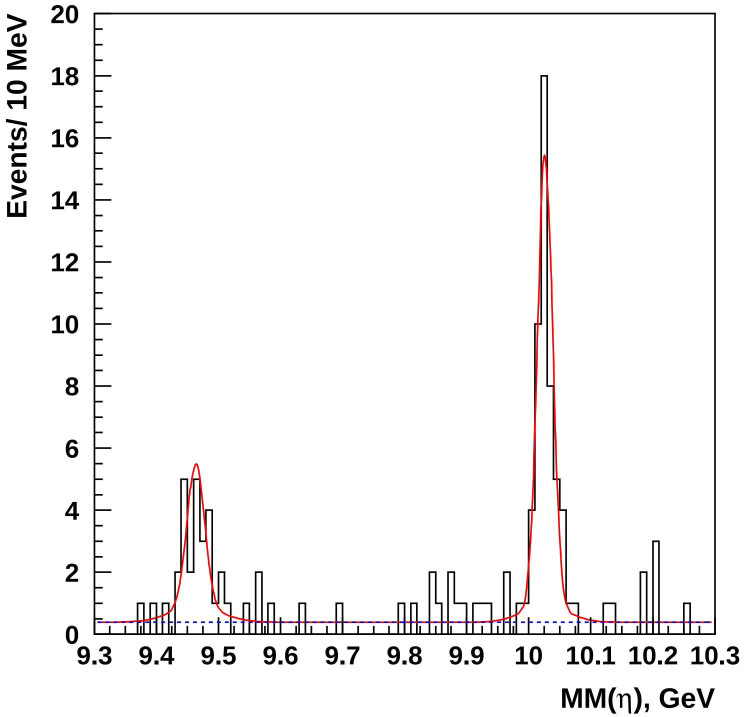
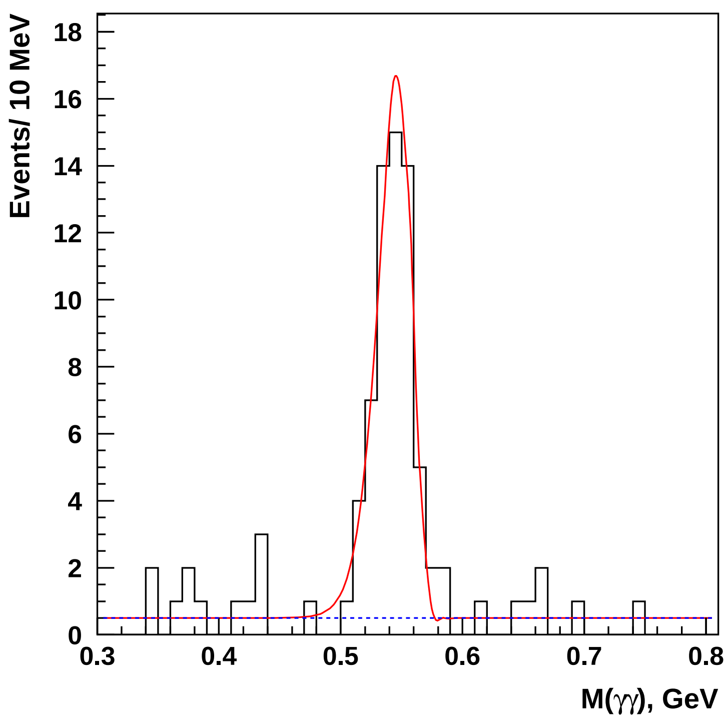
Observation of $\Upsilon(5S) \to \Upsilon(1,2S)\eta$ – I





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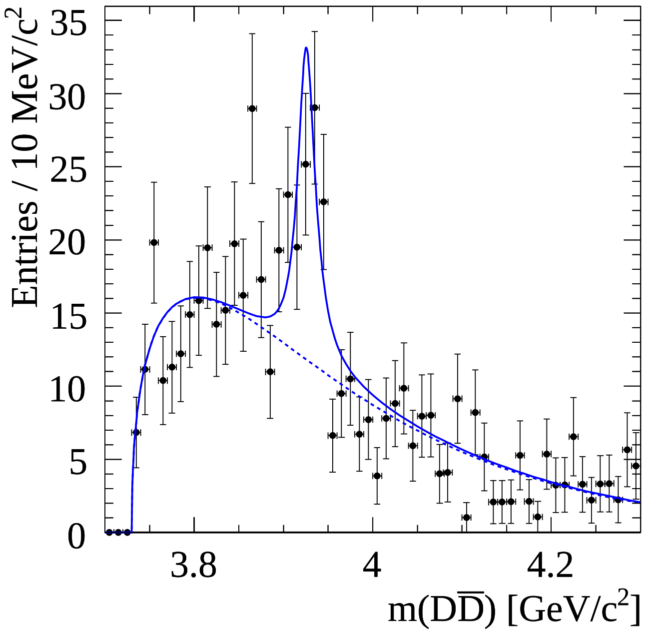
$Z(3930)$ or $\chi_{c2}(2P)$ – I



Discovered by Belle
and confirmed by BaBar,
both in $\gamma\gamma \to D^0\bar{D}^0,\ D^+D^-$

$\mathcal{B}(D^+D^-)/\mathcal{B}(D^0\bar{D}^0) \sim 0.89$

Angular analysis $\Rightarrow$ spin=2

Originally $Z(3930)$, all properties like of the $\chi_{c2}(2P)$, mass 50 MeV below

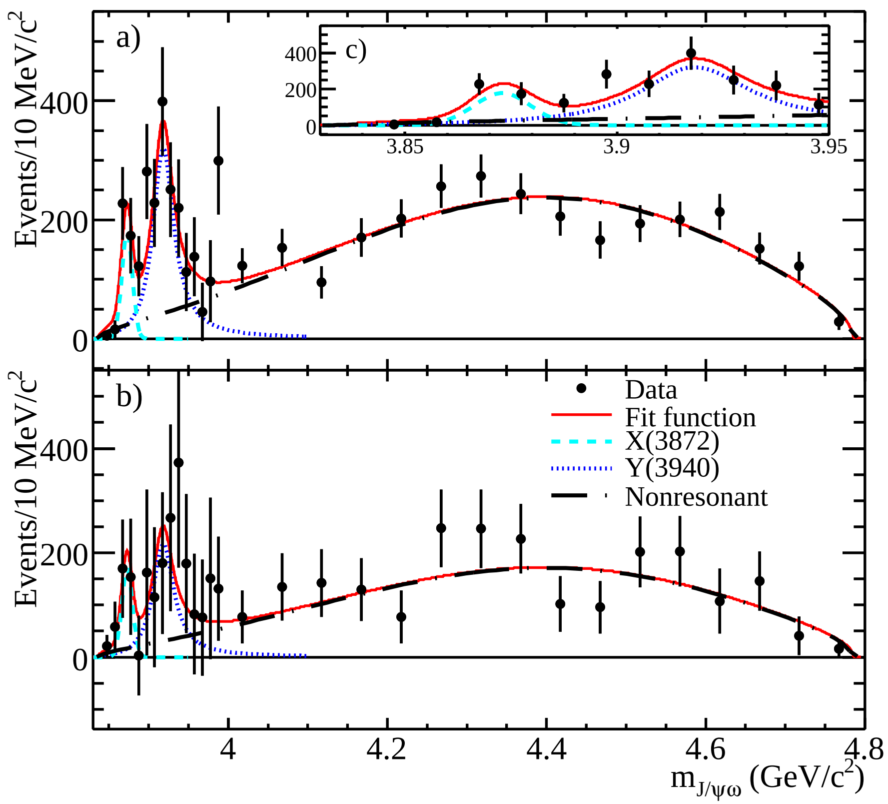
$Z(3930)$ or $\chi_{c2}(2P)$ – II

Group	Mass, MeV	Width, MeV	$\Gamma_{\gamma\gamma}\mathcal{B}_{D\bar{D}}$, keV	Events
Belle	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$	$0.18 \pm 0.05 \pm 0.03$	64
BaBar	$3926.7 \pm 2.7 \pm 1.1$	$21.3 \pm 6.8 \pm 3.6$	$0.24 \pm 0.05 \pm 0.04$	76 ± 17

Belle PRL 96, 082003 (2006)

BaBar PRD 81, 092003 (2010)

$Y(3945)$ at Belle and BaBar – I



$$B \to Y(3945)K,\ Y(3945) \to \omega J/\psi$$

$Y(3945)$ at Belle and BaBar – II

Group	Mass, MeV	Width, MeV	Process	Ref.
Belle	$3943 \pm 11 \pm 13$	$87 \pm 22 \pm 26$	$B \to \omega J/\psi K$	1
BaBar	$3919.1^{+3.8}_{-3.5} \pm 2$	$31^{+10}_{-\ 8} \pm 2$	$B \to \omega J/\psi K$	2
Belle	$3915 \pm 3 \pm 2$	$17 \pm 10 \pm 3$	$\gamma\gamma \to \omega J/\psi$	3

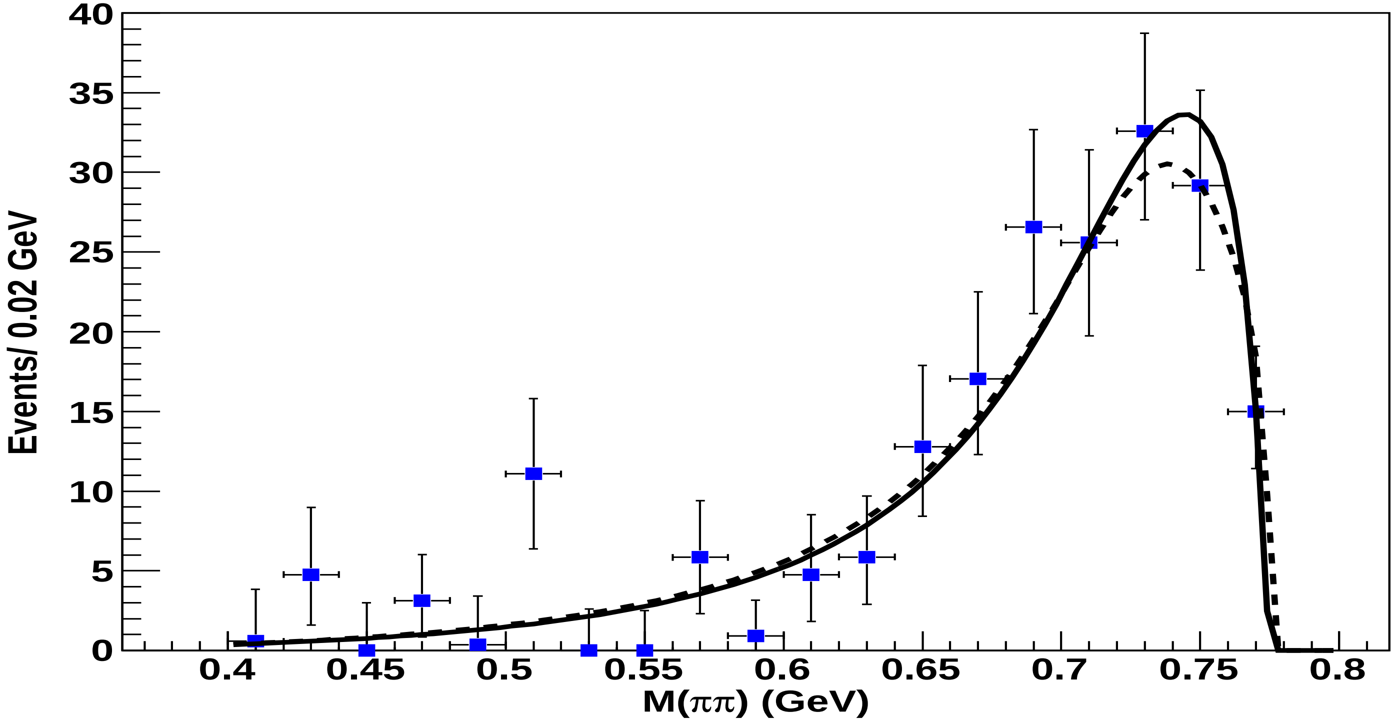
1 Belle PRL 94, 182002 (2005)

2 BaBar PRD 82, 011101 (2010)

3 Belle PRL 104, 092001 (2010)

J^P unknown, but $\omega J/\psi \to C = +1$,
may be the same state as $\chi_{c2}(2P)$

Study of $X(3872) \to \pi\pi J/\psi$ – IV

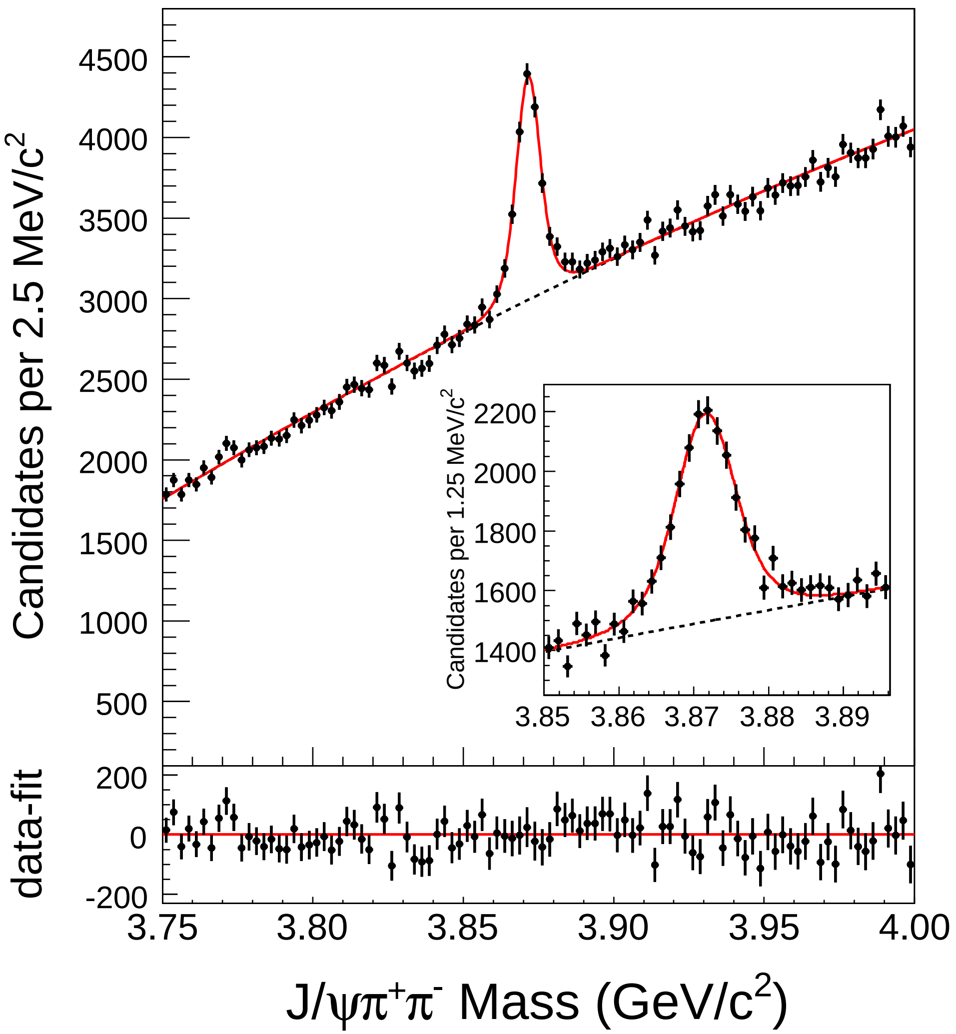


$\rho - \omega$ interference is important

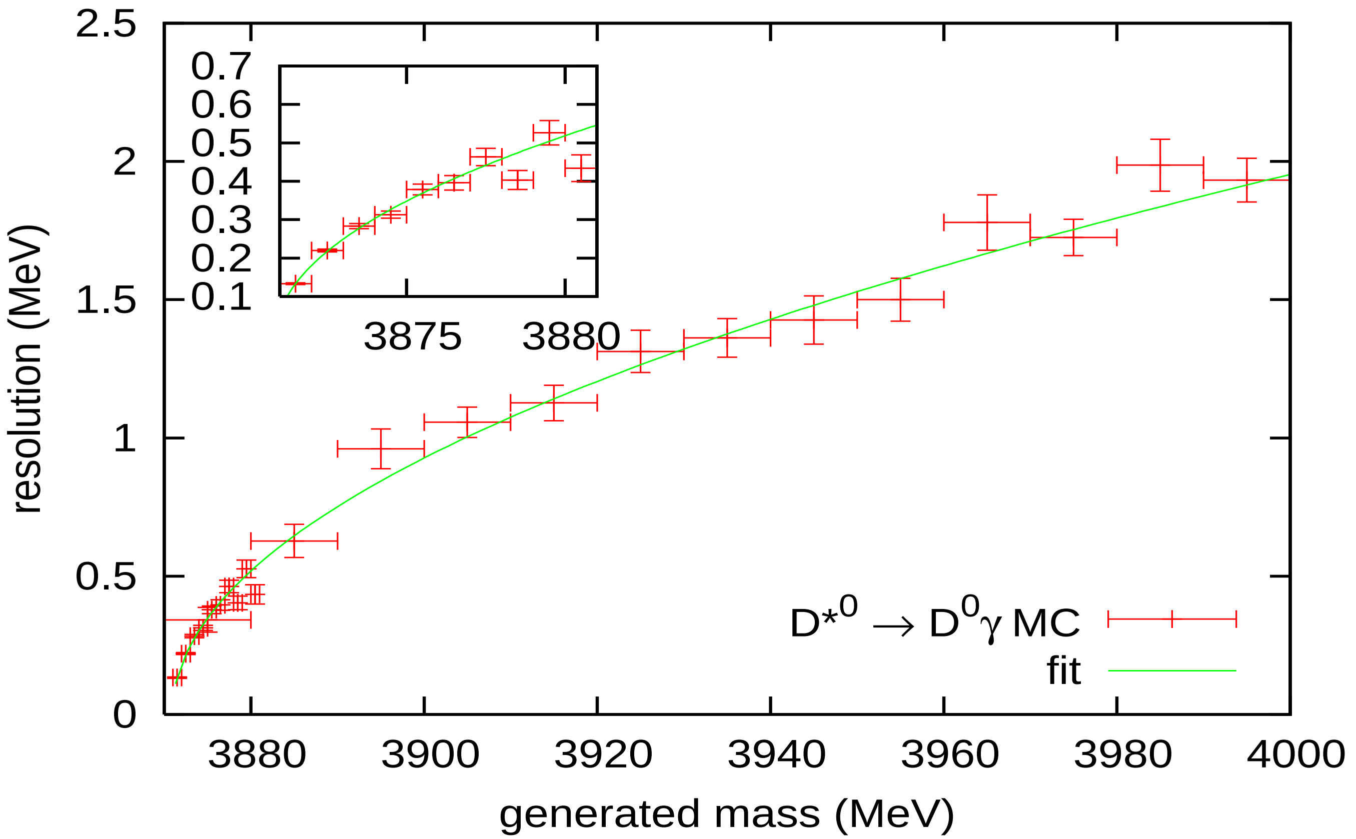
Systematic uncertainties on $M_{X(3872)}$ at LHCb

Group	Source	σ_M, keV
Mass fit:	Natural width	10
	Rad. tail	20
	Resolution	10
	Background model	20
Momentum calibration:	Average scale	100
	η dependence	30
Detector description:	Energy loss	50
Detector alignment	Track slopes	10
	Total	120

Confirmation of $X(3872)$ at CDF

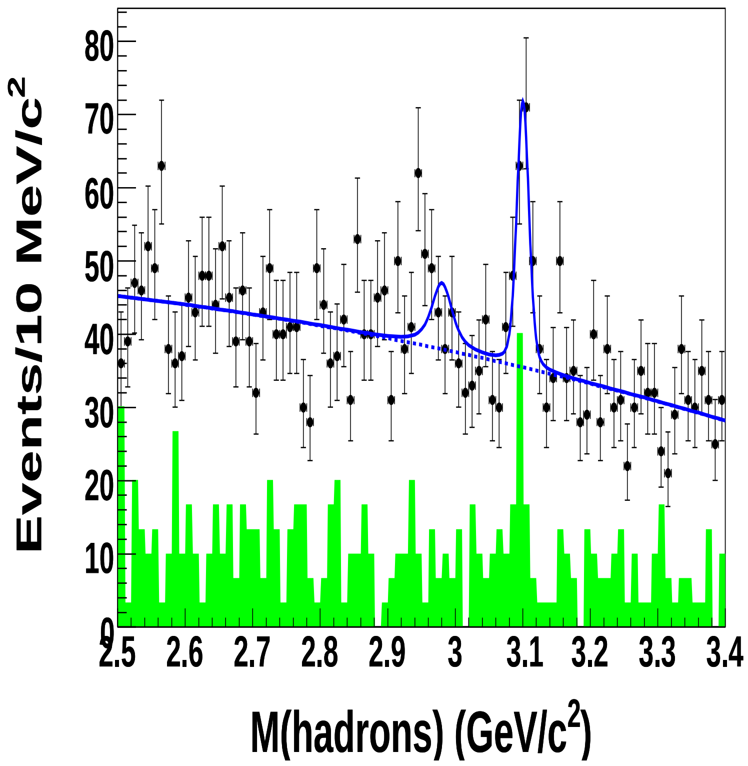


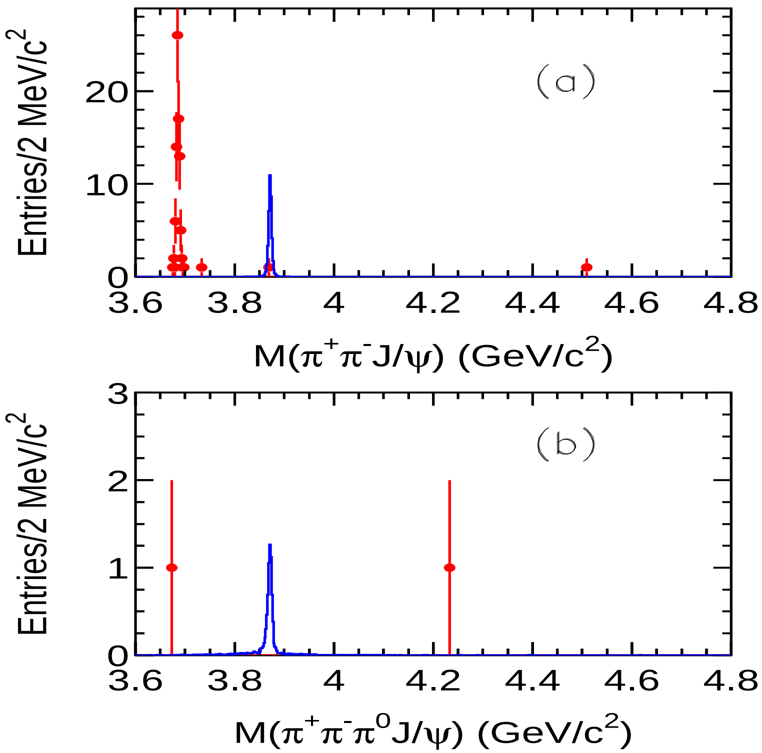
Study of $X(3872) \to D^{*0}\bar{D}^0$



Search for Charmonium(like) States in $\Upsilon(1S)$ Decays – I

Belle searched for $\Upsilon(1S) \to R\gamma$ using 102×10^6 $\Upsilon(1S)$ events





Phys. Rev. D82, 051504 (2010)

Search for Charmonium(like) States in $\Upsilon(1S)$ Decays – II

Upper Limits on $\mathcal{B}(\Upsilon(1S) \to R\gamma)$ at 90%CL

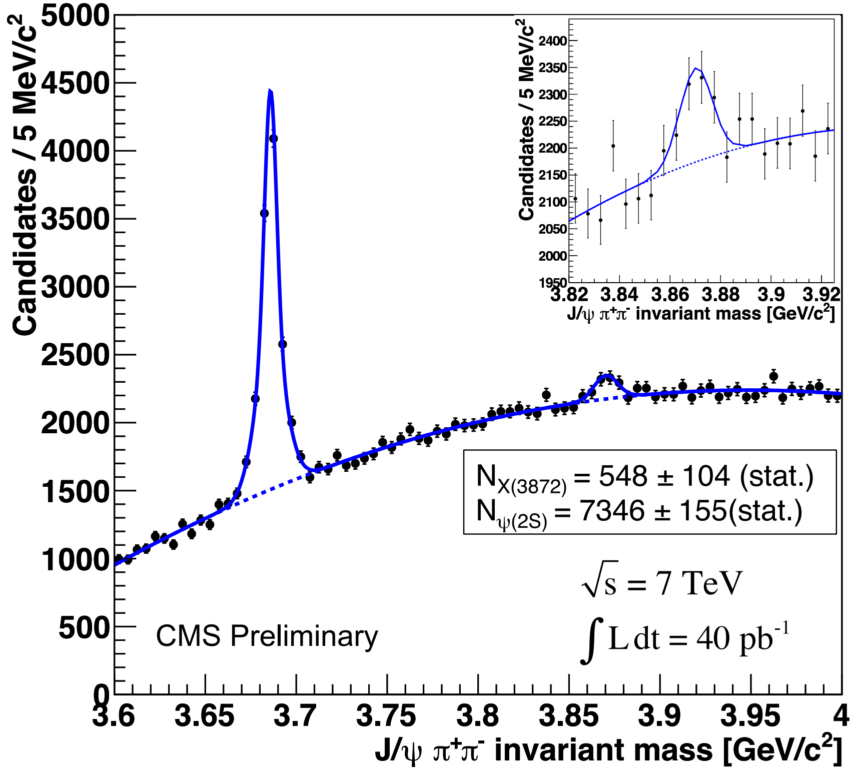
State (R)	$\mathcal{B}_R, 10^{-5}$
χ_{c0} $(J/\psi\gamma)$	65
χ_{c1} $(J/\psi\gamma)$	2.3
χ_{c2} $(J/\psi\gamma)$	0.76
η_c (5 modes)	5.7
$X(3872) \to \pi^+\pi^- J/\psi$	0.16
$X(3872) \to \pi^+\pi^-\pi^0 J/\psi$	0.28
$X(3915) \to \omega J/\psi$	0.30
$Y(4140) \to \phi J/\psi$	0.22

No contradiction with Y.-J. Gao et al., hep-ph/0701009

No excited charmonium states below 4.8 GeV

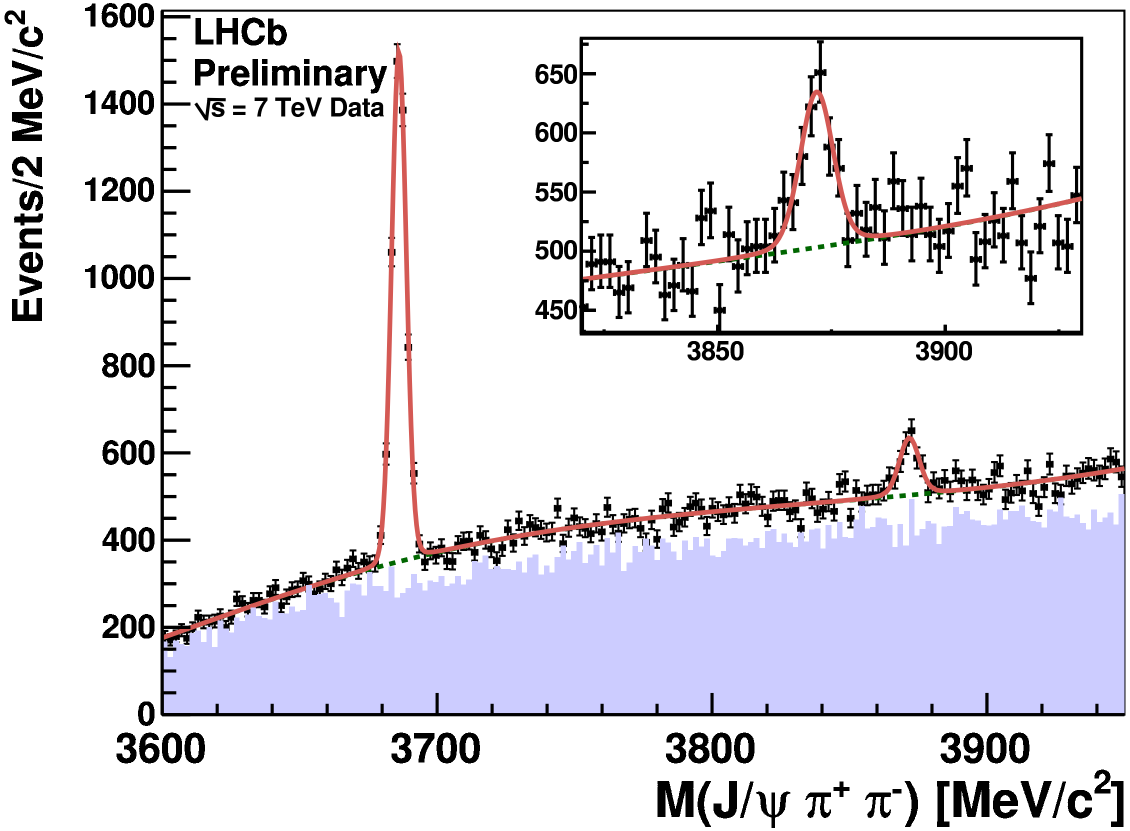
Similar analysis is in progress for 158×10^6 $\Upsilon(2S)$ events

$X(3872)$ at CMS

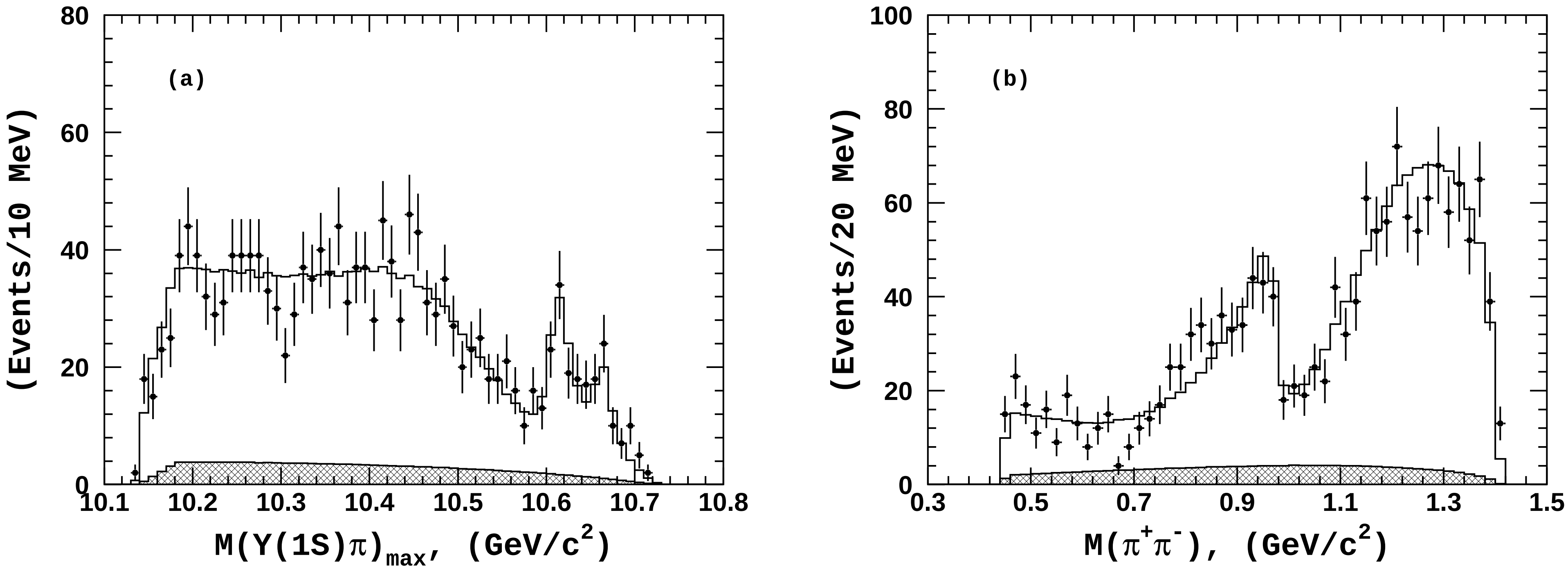


Candidates / 5 MeV/c²
J/ψ π⁺π⁻ invariant mass [GeV/c²]
N_X(3872) = 548 ± 104 (stat.)
N_ψ(2S) = 7346 ± 155(stat.)
√s = 7 TeV
∫ L dt = 40 pb⁻¹
CMS Preliminary

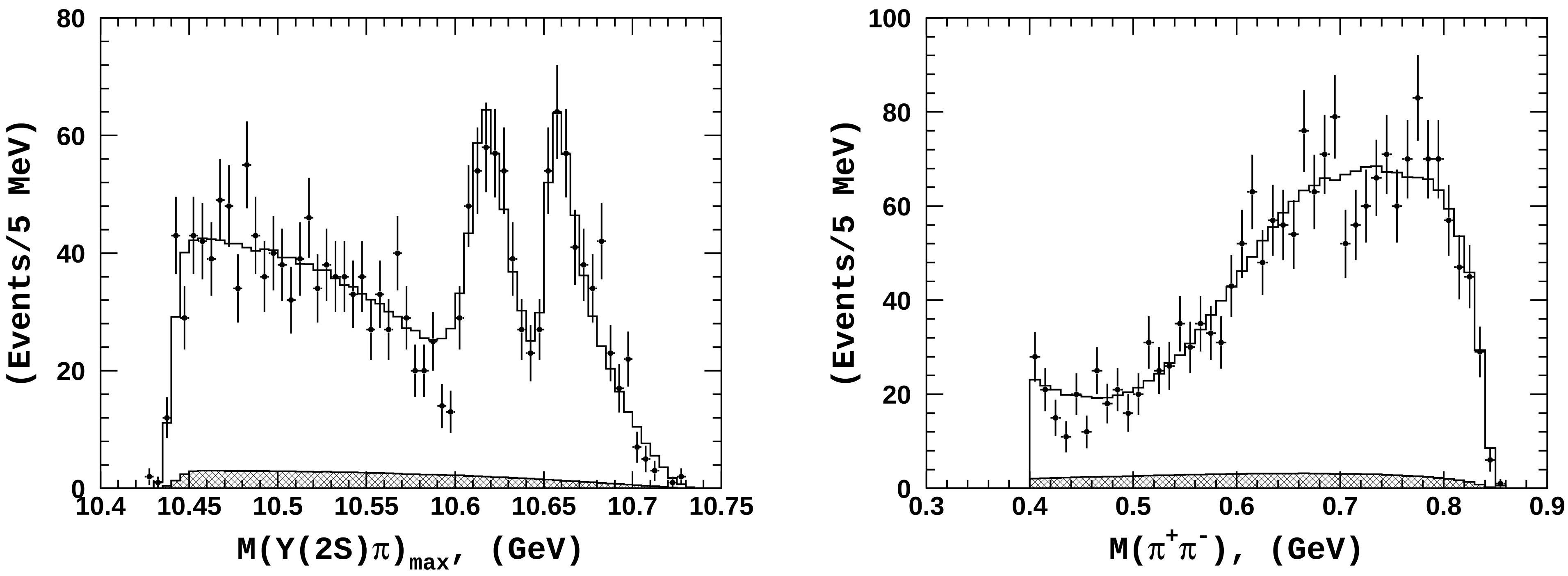
$X(3872)$ at LHCb



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



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



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