Recent Results on Spectroscopy from Belle

XiaoLong Wang

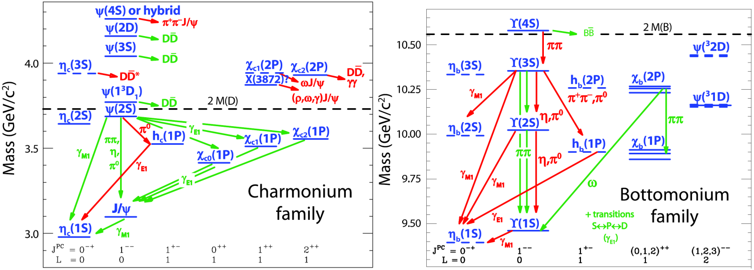
VirginiaTech

(Belle Collaboration)

BEACH, Wichita, Kansas, 07/28/2012

Introduction

- Quarkonia – Both charmonium and bottomonium provide important tests of QCD.
- Charmonia – Many charmonium(-like) states found at the Charm and B factories.
- Bottomonium – BaBar and Belle took data at $\Upsilon(nS)(n = 1, 2, 3, 4, 5)$, studied well on bottomonium(-like) states.
- XYZ particles – Quarkonium-like states with many exotic properties! What is their nature? (QWG, Eur. Phy. J. C71, 1534(2011))



Eichten et al, Rev. Mod. Phys.80,1161(2008)

Contributions to spectroscopy from Belle

Belle's large data samples:

798 fb^{-1} near $\Upsilon(4S)$, 123 fb^{-1} near $\Upsilon(5S)$, 5.7 fb^{-1}@$\Upsilon(1S)$ (102×10^6 $\Upsilon(1S)$ events), 24.7 fb^{-1}@$\Upsilon(2S)$ (158×10^6 $\Upsilon(2S)$ events).

Since X(3872) discovered, Belle has contributed a lot to spectroscopy. NOT only a B factory.

- Productions:

  B decay, double charmonium, initial state radiation (ISR), $\gamma\gamma$ collision, quarkonium transition, $e^+e^- \to \gamma^*$, $\Upsilon(1S, 2S)$ radiative decay,...

- Topics:

  charmonium(-like) states, bottomonium(-like) states, charmed mesons, bottom mesons, $s\bar{s}$...

- States/structures:

  X(3872), $\eta_c(2S)$, $\psi_2(1D)$, X(3915), X(3930), Y(3940), Z(3930), Y(4008), Y(4260), Y(4360), Y(4660), X(4630), $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, Z(4430), Z_1/Z_2,
  Y_b, Z_b, $h_b(1P)$, $h_b(2P)$, $\eta_b(1S)$, $\eta_b(2S)$, $\Upsilon(5S)$,

  Y(2175), χ_{cJ}, D^{**}, D^*_{sJ}, $\eta(')$, ...

Outline

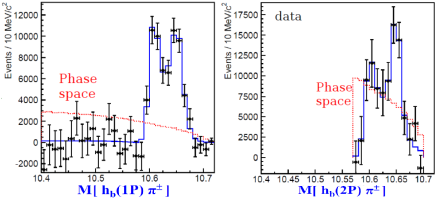
1. Bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$.
    - Charged Z_b states in $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$.
    - Charged Z_b states in $\Upsilon(5S) \to B^* B^{(*)}\pi^\pm$.
    - Neutral Z_b partner in $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$.
2. $h_b(1P, 2P) \to \gamma\eta_b$ and first evidence of $\eta_b(2S)$.
3. Search for X(3872) partners.
4. $\psi_2(1D)$ in $B \to (\chi_{c1}\gamma)K$.
5. $e^+e^- \to \eta J/\psi$ via ISR.

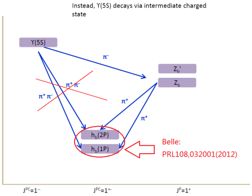
Bottomonium-like States $Z_b(10610)$ and $Z_b(10650)$

($Z_b(10610)$ will be called Z_{b1} in short, and $Z_b(10650)$ will be called Z_{b2})

Charged Z_b's in $\Upsilon(5S) \rightarrow (b\bar{b})\pi^+\pi^-$

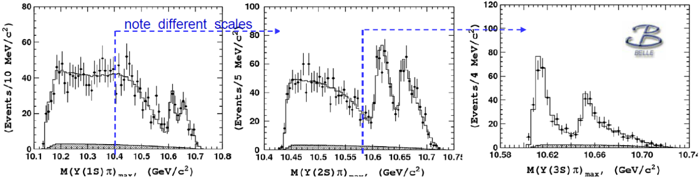
- π^+ and π^- reconstructed only, $M_{miss}(\pi^+\pi^-) \sim b\bar{b}$.
- Structures in $\pi^\pm h_b$ modes: (more on h_b later)




Instead, $\Upsilon(5S)$ decays via intermediate charged state

Belle:
PRL108,032001(2012)

- Structures in $\pi^\pm\Upsilon$ modes:


note different scales

- $Z_b(10610)/Z_b(10650) \rightarrow (b\bar{b}) + \pi^\pm$: PRL108,122001(2012).
  - $Z_b(10610)$: $M_1 = (10607.2 \pm 2.0)$ MeV$/c^2$, $\Gamma_1 = (18.4 \pm 2.4)$ MeV.
  - $Z_b(10650)$: $M_2 = (10652.2 \pm 1.5)$ MeV$/c^2$, $\Gamma_2 = (11.5 \pm 2.2)$ MeV.

Branching Fractions

Using $\sigma(e^+e^- \to \Upsilon(5S)) = 0.340 \pm 0.016$ nb, Belle gets

- $\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-) = [4.45 \pm 0.16(stat.) \pm 0.35(syst.)] \times 10^{-3}$
- $\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-) = [7.97 \pm 0.31(stat.) \pm 0.96(syst.)] \times 10^{-3}$
- $\mathcal{B}(\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-) = [2.88 \pm 0.19(stat.) \pm 0.36(syst.)] \times 10^{-3}$

and fractions of individual sub-modes:

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$Z(10610)\pi^\pm$, %	$2.54^{+0.86+0.13}_{-0.51-0.55}$	$19.6^{+3.5+1.9}_{-3.1-0.6}$	$26.8^{+6.6}_{-3.9} \pm 1.5$
$Z(10650)\pi^\pm$, %	$1.04^{+0.65+0.07}_{-0.31-0.12}$	$5.77^{+1.44+0.27}_{-0.96-1.56}$	$11.0^{+4.2}_{-2.3} \pm 0.7$
$f_2(1270)$, %	$15.6 \pm 1.4 \pm 2.1$	$2.81^{+0.84+0.63}_{-0.56-0.86}$	–
Total $S-$wave, %	$89.2 \pm 3.0 \pm 2.4$	$105.6 \pm 4.1 \pm 2.6$	$45.6 \pm 5.3 \pm 0.8$

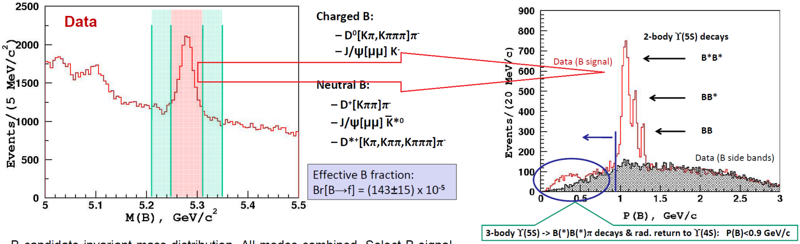
	$h_b(1P)\pi$	$h_b(2P)\pi$
non-resonant, %	3.2 (< 22 at 90% C.L.)	–
$Z_b(10610)$, %	$42.3^{+9.5}_{-12.7}{}^{+6.7}_{-0.8})$	$(35.2^{+15.6}_{-9.4}{}^{+0.1}_{-13.4})\%$
$Z_b(10650)$, %	$60.2^{+10.3}_{-21.1}{}^{+4.1}_{-3.8}$	$(64.8^{+15.2}_{-11.4}{}^{+6.7}_{-15.5})\%$

In $\pi^+\pi^- h_b$, Z_bs dominate!

(A. Bondar's talk at ICHEP2012)

Charged Z_b in $\Upsilon(5S) \to B^* B^{(*)} \pi^{\pm}$

Note:
$M(Z_b(10610)) - (m_B + m_{B^*}) = +2.6 \pm 2.1$ MeV$/c^2$
$M(Z_b(10651)) - 2m_{B^*} = +1.8 \pm 1.7$ MeV$/c^2$
If $Z_b = |b\bar{b}u\bar{d}>$, it can naturally decay to $B^{(*)}B^*$.



Charged B:
- $D^0[K\pi, K\pi\pi\pi]\pi^-$
- $J/\psi[\mu\mu]\ K^-$

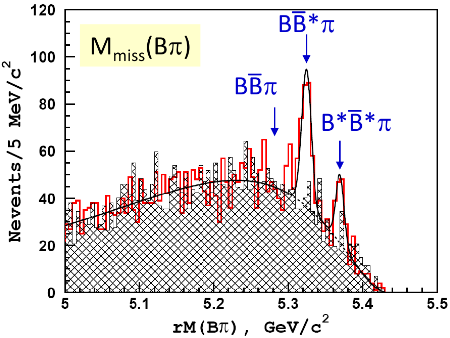
Neutral B:
- $D^+[K\pi\pi]\pi^-$
- $J/\psi[\mu\mu]\ \bar{K}^{*0}$
- $D^{*+}[K\pi\pi, K\pi\pi\pi]\pi^-$

Effective B fraction:
Br[B→f] = (143±15) x 10^{-5}

3-body $\Upsilon(5S)$ -> $B(^*)B(^*)\pi$ decays & rad. return to $\Upsilon(4S)$: P(B)<0.9 GeV/c

B candidate invariant mass distribution. All modes combined. Select B signal within 30-40 MeV (depending on B decay mode) around B nominal mass.

$\Upsilon(5S) \to B^* B^{(*)} \pi^{\pm}$: **recoil of** $B\pi$

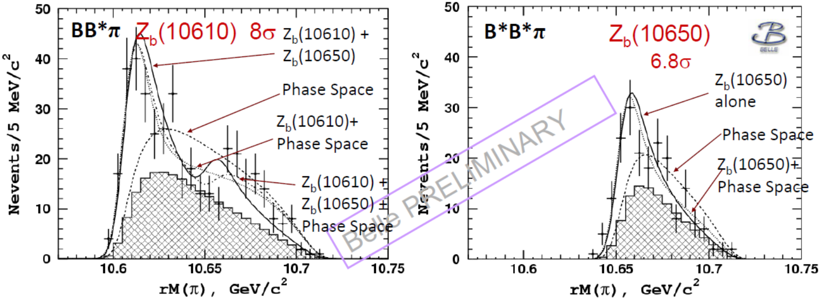


- Red Histogram: right signal $B\pi$ combinations.
- Hatched histogram: wrong signal $B\pi$ combinations.
- Solid line: fit to right signal data.

Fit yields:

$N(BB\pi) = 0.3 \pm 14$, $N(BB^*\pi) = 194 \pm 19\ (9.3\sigma)$, $N(B^*B^*\pi) = 82 \pm 11\ (5.7\sigma)$.

$\Upsilon(5S) \to B^{*}B^{(*)}\pi^{\pm}$: **Signal data**



- Point – right signal $B\pi$ combinations (data);
- Lines – fit to data with various models ($\times$ Phase Space, convolved with resolution (Gaussian) with $\sigma = 6$ MeV).
- Hatched histogram – background component.

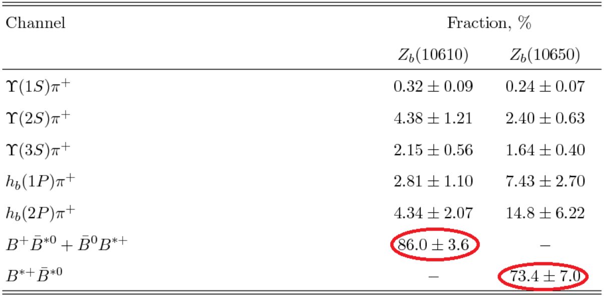
- $B^{*}B^{*}\pi$ signal is well fit to just $Z_b(10650)$ signal alone.
- $BB^{*}\pi$ data fits (almost) equally well to a sum of $Z_b(10610)$ and $Z_b(10650)$ or to a sum of $Z_b(10610)$ and non-resonant.

$\Upsilon(5S) \to B^* B^{(*)} \pi^{\pm}$: Results

Branching fractions of $\Upsilon(5S)$ decays (including neutral modes):

- $BB\pi < 0.60\%$ @ 90% C.L.
- $BB^*\pi = (4.25 \pm 0.44 \pm 0.69)\%$.
- $B^*B^*\pi = (2.12 \pm 0.29 \pm 0.36)\%$.

Assuming Z_b decays are saturated by the already observed $\Upsilon(nS)\pi$, $h_b(mP)\pi$, and $B^{(*)}B^*$ channels, the table of relative branching fractions is:



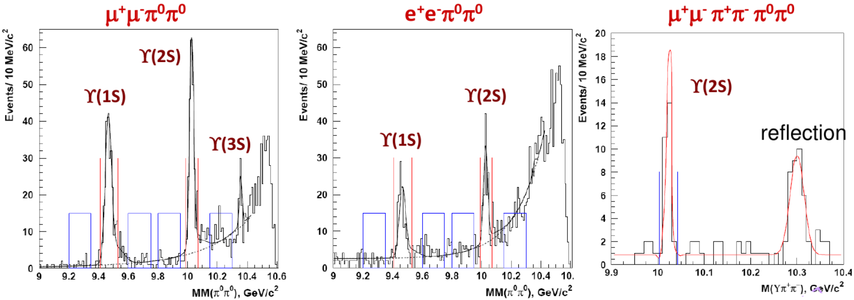
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

$B^{(*)}B^*$ channels dominate!

Is there a neutral partner of the Z_b^+???
Can be searched for in $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$
Belle, arXiv:1207.4345

Neutral Z_b in $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$

- $\Upsilon(1,2,3S) \to e^+e^-/\mu^+\mu^-$, $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$.
- Require energy-momentum balance to improve resolution.



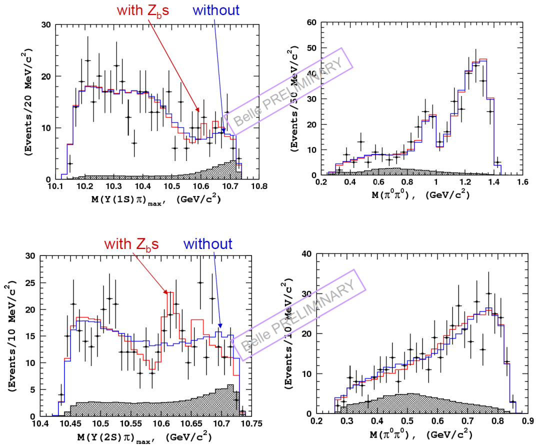
In the first plots, red lines – signal regions, blue boxes – sidebands.

The Branching Fractions Belle got:

- $\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^0\pi^0) = (2.25 \pm 0.11 \pm 0.20) \times 10^{-3}$
- $\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0) = (3.66 \pm 0.22 \pm 0.48) \times 10^{-3}$

in agreement with isospin relations. (c.f. page 7)

$\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$: Structures



- Clear $Z_b^0(10610)$ is seen in $\Upsilon(2S)\pi^0\pi^0$, while both Z_b^0s are not significant in $\Upsilon(1S)\pi^0\pi^0$.
- Significance of $Z_b^0(10610)$ is 5.3σ (4.9σ with systematics), and $M = (10609^{+8}_{-6} \pm 6)$ MeV$/c^2$ in consistence with the mass of $Z_b^\pm(10610)$.
- $Z_b^0(10650)$ is less significant (about 2σ).

$h_b(1P, 2P)$ and $\eta_b(2S)$

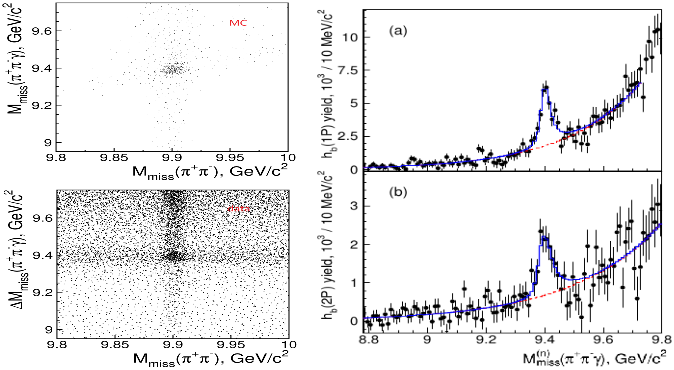
Belle, arXiv: 1205.6351

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

Decay chain: $\Upsilon(5S) \to h_b\pi^+\pi^-,\ h_b \to \gamma\eta_b(1S)$.

Reconstruction: π^+, π^- and γ.

$M(\eta_b) = \Delta M_{miss}(\pi^+\pi^-\gamma) \equiv M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + m_{h_b}$



$\Gamma = 10.8^{+4.0+4.5}_{-3.7-2.0}$ MeV$/c^2$ as expected.

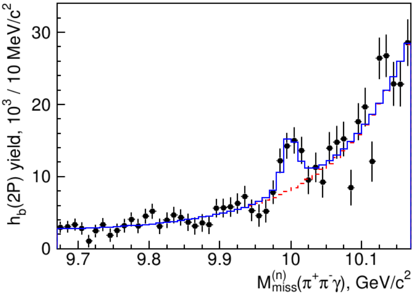
$\mathcal{B}(h_b(1P) \to \gamma\eta_b(1S)) = (49.2 \pm 5.7^{+5.6}_{-3.3})\%$. and $\mathcal{B}(h_b(2P) \to \gamma\eta_b(1S)) = (22.3 \pm 3.8^{+3.1}_{-3.3})\%$.

Hyperfine splitting: $\Delta M_{HF}(\eta_b) = M(\Upsilon(1S)) - M(\eta_b(1S)) = (59.3 \pm 1.9^{+2.4}_{-1.4})$ MeV$/c^2$.

(PDG2012: 69.3 ± 2.8 MeV$/c^2$)

First evidence for $\eta_b(2S)$

Decay chain: $\Upsilon(5S) \to h_b\pi^+\pi^-$, $h_b \to \gamma\eta_b(2S)$. arXiv:1205.6351
Reconstruction: π^+, π^- and γ.



Narrow width: $\Gamma = 4 \pm 8$ MeV$/c^2$ and < 24 MeV$/c^2$ @ 90% C.L.

For Branching fractions:

Branching Fraction	Belle value (%)	Expectation (%)
$h_b(1P) \to \gamma\eta_b(1S)$	$49.2 \pm 5.7^{+5.6}_{-3.3}$	41
$h_b(2P) \to \gamma\eta_b(1S)$	$22.3 \pm 3.8^{+3.1}_{-3.3}$	13
$h_b(2P) \to \gamma\eta_b(2S)$	$47.5 \pm 10.5^{+6.8}_{-7.7}$	19

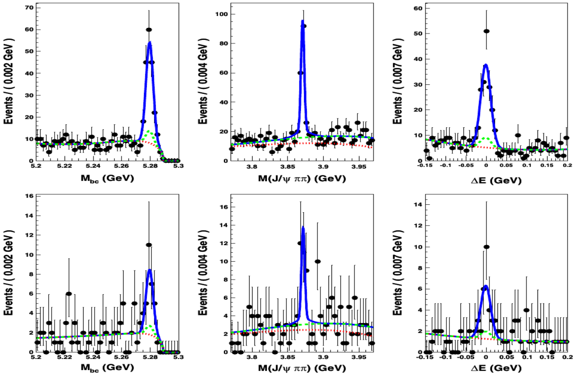
c.f.: BESIII $\mathcal{B}(h_c(1P) \to \gamma\eta_c(1S)) = (54.3 \pm 8.5)\%$, and expectation is 39%.

Expectations: Godfrey Rosner: PRD66, 014012(2002).

Charmonium(-like) States

Update on $X(3872) \to \pi^+\pi^- J/\psi$ at Belle

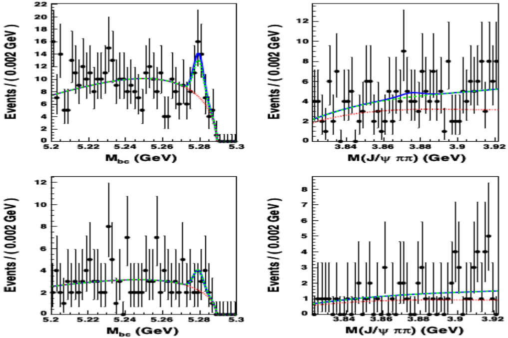
- Discovered by Belle about 10 years ago in $B \to J/\psi\pi^+\pi^- K$. It's the beginning of XYZ field. (Belle: PRL91, 262001(2003))
- The update from Belle (772×10^6 $B\overline{B}$): PRD84, 052004(2011).



- $M_{X(3872)} = 3871.84 \pm 0.27 \pm 0.19$ MeV$/c^2$; $\Gamma_{X(3872)} < 1.2$ MeV @ 90% C.L.
- Mass difference of $X(3872)$ from B^+ and B^0: $\Delta M_{X(3872)} = -0.69 \pm 0.97 \pm 0.19$ MeV$/c^2$.

Search for charged X

- A charged partner could be possible if $X(3872)$ is exotic.
- Charged partner is searched for in $X(3872)^+ \to J/\psi\rho^+(\to \pi^+\pi^0)$.

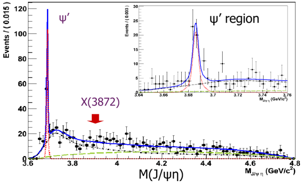


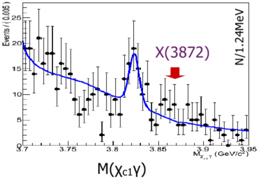
- First row is $\overline{B}^0 \to K^-\rho^+J/\psi$, and the second row is $B^+ \to K^0\rho^+J/\psi$.
- $\mathcal{B}(\overline{B}^0 \to X^+K^-) \times \mathcal{B}(X^+ \to J/\psi\rho^+) < 4.2 \times 10^{-6}$
- $\mathcal{B}(B^+ \to X^+K^0) \times \mathcal{B}(X^+ \to J/\psi\rho^+) < 6.1 \times 10^{-6}$

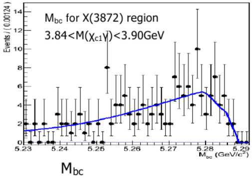
No evidence.

Search for C-odd neutral partner of X in B decays

- Is there a C-odd neutral partner of $X(3872)$ if it's an exotic state?
- Channels: $B \to K + \eta J/\psi$ and $B \to K + \gamma\chi_{c1}$





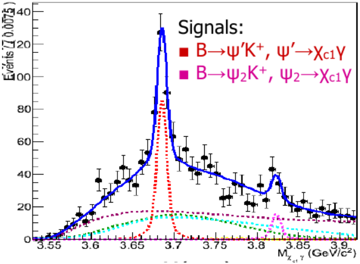


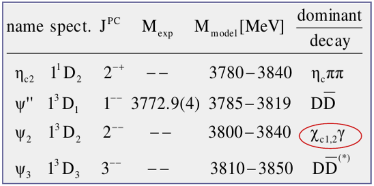
- $B \to K + \eta J/\psi$: only ψ' signal and non-resonant component, no $X(3872)$.
  $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \eta J/\psi) < 3.8 \times 10^{-6}$ @90% C.L.
- $B \to K + \gamma\chi_{c1}$:no $X(3872)$ signal observed, $N_{sig} = -1 \pm 5$.
  $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \gamma\chi_{c1}) < 2.0 \times 10^{-6}$ @ 90% C.L. and
  $\mathcal{B}(X \to \gamma\chi_{c1})/\mathcal{B}(X \to J/\psi\pi^+\pi^-) < 0.26$ @ 90% C.L.,

  according to PRD84, 052004(2011)(Belle):
  $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) = (8.6 \pm 0.8 \pm 0.5) \times 10^{-6}$.
- BUT, what's the peak at $M(\gamma\chi_{c1})$? A new charmonium state observed?

$\psi_2 \to \gamma\chi_{c1}$

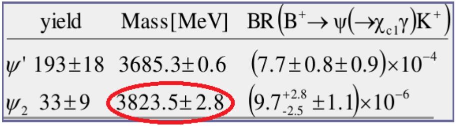
- $\psi_2 \to \gamma\chi_{c1}$ was predicted, $(\Gamma(\psi_2 \to \gamma\chi_{c1}) = 260$ keV).
  Godfrey-Isgur, PRD21,189(1985); Eichten-Lane-Quigg, PRL89, 162002(2002) and PRD69, 094019(2004)





name	spect.	J^{PC}	M_{exp}	M_{model}[MeV]	dominant decay
η_{c2}	1^1D_2	2^{-+}	--	3780−3840	$\eta_c\pi\pi$
ψ''	1^3D_1	1^{--}	3772.9(4)	3785−3819	$D\bar{D}$
ψ_2	1^3D_2	2^{--}	--	3800−3840	$\chi_{c1,2}\gamma$
ψ_3	1^3D_3	3^{--}	--	3810−3850	$D\bar{D}^{(*)}$

- ψ_2 significance 4.2σ w/syst. First evidence from Belle!!!
- $\Gamma(\psi_2) = 4 \pm 6$ MeV$/c^2$ if fitted.



	yield	Mass[MeV]	$BR(B^+ \to \psi(\to\chi_{c1}\gamma)K^+)$
ψ'	193±18	3685.3±0.6	$(7.7\pm0.8\pm0.9)\times10^{-4}$
ψ_2	33±9	3823.5±2.8	$(9.7^{+2.8}_{-2.5}\pm1.1)\times10^{-6}$

Exotic states

An exotic property of charmonium-like states, is the large hardonic transition fractions:

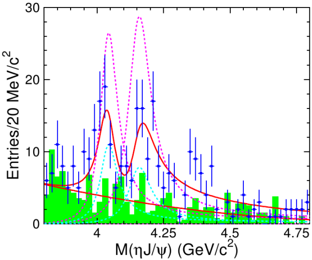
- $2.3\% < \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 6.6\%$.
- $\Gamma(Y(4260) \to J/\psi\pi^+\pi^-) > 0.51$ MeV @ 90% C.L. (X.H. Mo $\mathrm{et\ al}$, PLB640,182(2006)). $Y(4360)$ and $Y(4660)$ are similar.
- $\mathcal{B}(X(3915) \to J/\psi\omega) > (1 \sim 6)\%$, from R. Kass' talk.
- Large $\pi^+\pi^- h_c$ production at 4.17 GeV from CLEOc.
- Large $\pi^+\pi^-\Upsilon$ productions near $\Upsilon(5S)$.
- ...

BUT, the transitions are all related to new XYZ particles, and mostly via emitting $\pi^+\pi^-(\pi^0)$

SO, how about transition with an η? Belle performed the search on $\eta J/\psi$ final states via ISR.

$\eta J/\psi$ via ISR

Belle: Search for hadronic transition via emitting an η. (Preliminary)



Parameters	Solution I	Solution II
$M(\psi(4040))$	4039 (fixed)	
$\Gamma(\psi(4040))$	80 (fixed)	
$\mathcal{B}(\psi(4040) \to \eta J/\psi) \cdot \Gamma_{e^+e^-}$	$5.1 \pm 0.8 \pm 1.1$	$12.4 \pm 1.2 \pm 1.2$
$M(\psi(4160))$	4153 (fixed)	
$\Gamma(\psi(4160))$	103 (fixed)	
$\mathcal{B}(\psi(4160) \to \eta J/\psi) \cdot \Gamma_{e^+e^-}$	$4.1 \pm 0.5 \pm 0.8$	$15.2 \pm 1.2 \pm 1.5$
$\phi(^\circ)$	$-20 \pm 11 \pm 8$	$-110 \pm 4 \pm 3$

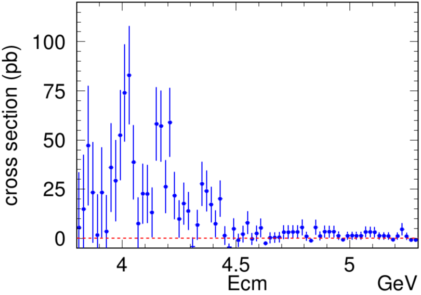
Taking $\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV from PDG →
$\mathcal{B}(\psi(4040) \to \eta J/\psi) = (0.59 \pm 0.11 \pm 0.14)\%$ or
$\mathcal{B}(\psi(4040) \to \eta J/\psi) = (1.44 \pm 0.18 \pm 0.18)\%$.
Taking $\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV from PDG →
$\mathcal{B}(\psi(4160) \to \eta J/\psi) = (0.50 \pm 0.07 \pm 0.11)\%$ or
$\mathcal{B}(\psi(4160) \to \eta J/\psi) = (1.83 \pm 0.21 \pm 0.24)\%$.
The significance of $\psi(4040)$ is 5.8σ, and the one of $\psi(4160)$ is 5.7σ.

$\mathcal{B}$s are at 1% level, corresponding partial widths are all about 1 MeV. They are Large! (c.f. $\mathcal{B}(\psi' \to \eta J/\psi) = (3.28 \pm 0.07)\%$ from PDG'12)

Cross section of $e^+e^- \to \eta J/\psi$

Belle preliminary

$$\sigma_i = \frac{n_i^{\text{obs}} - n_i^{\text{bkg}}}{\varepsilon_i \mathcal{L}_i \mathcal{B}(\eta \to \pi^+\pi^-\pi^0 + \gamma\gamma)\mathcal{B}(J/\psi \to \ell^+\ell^-)}$$



A systematic error of 8.8% to all data points is not shown.

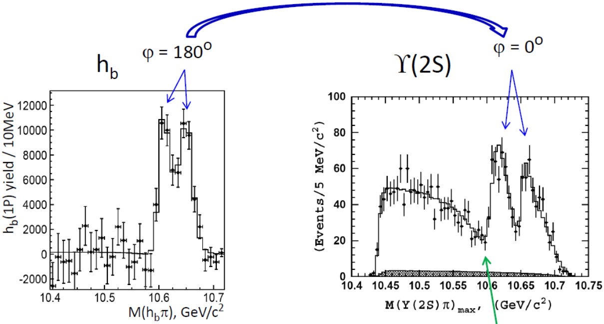
Summary

1. Bottomonium-like $Z_b(10610)$ and $Z_b(10650)$.
   - Charged Z_bs were discovered in $b\bar{b}\pi^{\pm}$ and confirmed in $B^{(*)}B^{*}$.
   - Neutral $Z_b(10610)$ is observed in $\Upsilon(2S)\pi^0\pi^0$.
2. $h_b(1P)$ and $h_b(2P)$ transitions to $\eta_b(1S)$ are observed, and evidence for $\eta_b(2S)$ is obtained for the first time.
3. $X(3872)$:
   - Update on $X(3872) \to \pi^+\pi^- J/\psi$ performed by Belle. More precise results got.
   - No charged partner of $X(3872)$ found in $J/\psi\rho^+$ search. No C-odd partner found in $\gamma\chi_{c1}$ or $\eta J/\psi$.
4. The first evidence of ψ_2 is got in $B \to K + \gamma\chi_{c1}$ search. The significance is 4.2σ.
5. $e^+e^- \to \eta J/\psi$ via ISR is measured for the first time:
   - Obvious $\psi(4040)$ and $\psi(4160)$ signals in the final states, but no Y(4260/4360/4660) state seen in $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi'$.
   - Their branching fractions $\eta J/\psi$ are at 1% level and the partial widths are about 1 MeV.
   - Cross section of $e^+e^- \to \eta J/\psi$ is measured.

Thank you!

Back-up

Projections of $\Upsilon(5S) \to [\Upsilon(nS), h_b(mP)]\pi^+\pi^-$



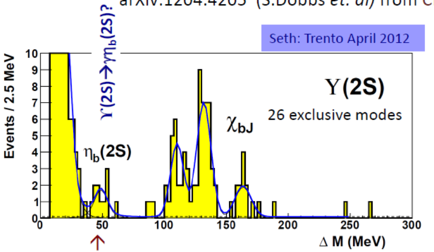
Dip due to destructive interference with non-resonant amplitude.
$\Rightarrow$ Information on J^P of Z_b ?

From J. Li's talk at FPCP2012.

Comparison: $\eta_b(2S)$ “signals"

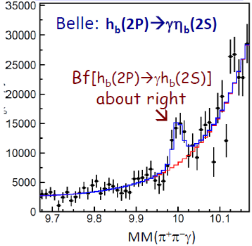
arXiv:1204.4205 (S.Dobbs *et. al)* from CLEO data

Seth: Trento April 2012



↑ anomalously large production rate ($\sim 0.2\times\chi_{b1}$ rate)

Belle: IWHSS’12 April, 2012



$Bf[h_b(2P)\to\gamma h_b(2S)]$ about right

Expt	$\Delta M_{hfs}(2S)$ (MeV)
S. Dobbs	48.7±2.7
Belle	24.3±4.3

← strong disagreement with theory

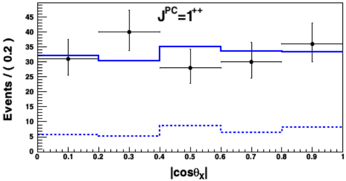
← agrees with theory

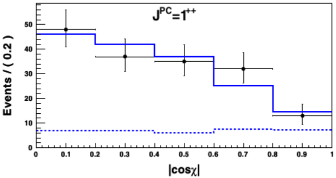
≈5σ discrepancy

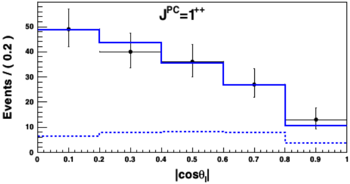
From J. Li’s talk at FPCP2012.

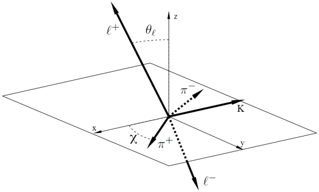
Angular analysis of $X(3872)$ at Belle

- $J^{PC} = 1^{++}$ or 2^{-+} from angular analysis by CDF. (PRL98, 132002(2007)).
- For $X(3872) \to J/\psi\rho \to J/\psi\pi^+\pi^-$ with $J/\psi - \rho$ orbital momentum L and S:
  $J^{PC} = 1^{++}$: L = 0, S = 1 → 1 amplitude; $J^{PC} = 2^{-+}$: L = 1, S = 1 or 2 → 2 amplitudes B_{11} and B_{12}.

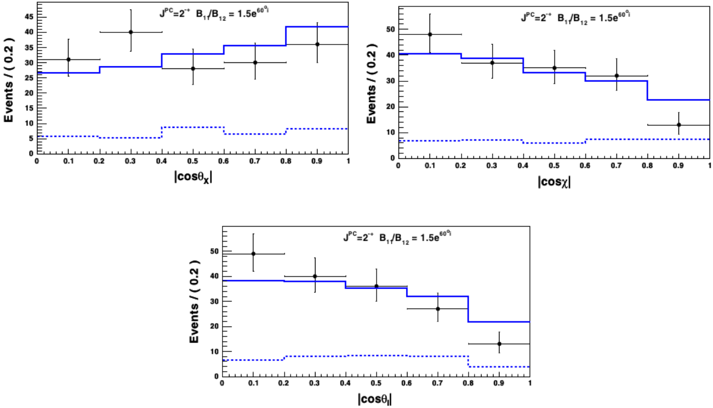








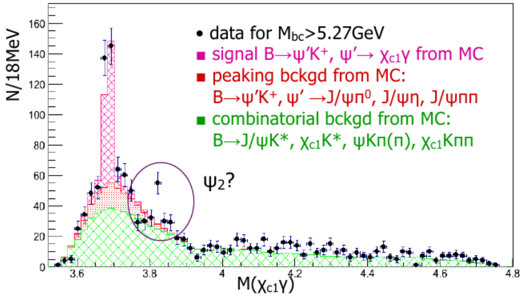
Angular analysis of $X(3872)$ at Belle



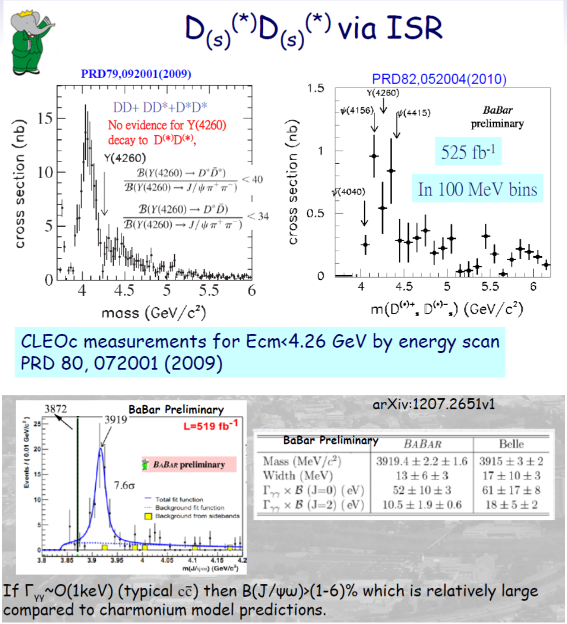
Both $J^{PC} = 1^{++}$ and $J^{PC} = 2^{-+}$ (for certain B_{11}/B_{12}) describe data well.

Study of $\gamma\chi_{c1}$

- $B^+ \to \gamma\chi_{c1}K^+$ with $\chi_{c1} \to \gamma J/\psi$ using 772×10^6 $B\overline{B}$.
- Efficiency and resolution improve with increasing $M_{\gamma\chi_{c1}}$



- $M_{\gamma\chi_{c1}}$ in data agree with inclusive MC simulation, except for the peak at 3.82 GeV$/c^2$.
- Missing $\psi_2(1^3D_2)$ charmonium? Mass agrees with prediction.



$D_{(s)}^{(*)}D_{(s)}^{(*)}$ via ISR

PRD79,092001(2009)

DD+ DD*+D*D*

No evidence for Y(4260) decay to $D^{(*)}D^{(*)}$,

$$\frac{\mathcal{B}(Y(4260)\to D^*\bar{D}^*)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 40$$

$$\frac{\mathcal{B}(Y(4260)\to D^*\bar{D})}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 34$$

PRD82,052004(2010)

BaBar preliminary

525 fb⁻¹

In 100 MeV bins

CLEOc measurements for Ecm<4.26 GeV by energy scan
PRD 80, 072001 (2009)

BaBar Preliminary

L=519 fb⁻¹

arXiv:1207.2651v1

BaBar Preliminary

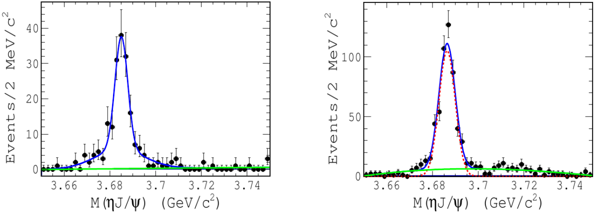
	BABAR	Belle
Mass (MeV/c^2)	$3919.4 \pm 2.2 \pm 1.6$	$3915 \pm 3 \pm 2$
Width (MeV)	$13 \pm 6 \pm 3$	$17 \pm 10 \pm 3$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=0) (eV)	$52 \pm 10 \pm 3$	$61 \pm 17 \pm 8$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=2) (eV)	$10.5 \pm 1.9 \pm 0.6$	$18 \pm 5 \pm 2$

If $\Gamma_{\gamma\gamma}$~O(1keV) (typical $c\bar{c}$) then B(J/ψω)>(1-6)% which is relatively large compared to charmonium model predictions.

R. Kass' talk.

Search on $\eta J/\psi$ via ISR at Belle (Preliminary)

- Reconstructions: $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, $\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$.
- Clear ψ' signals.



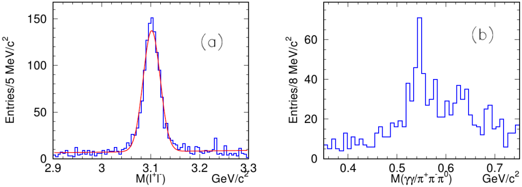
Left is $\eta \to \pi^+\pi^-\pi^0$ mode and right is $\eta \to \gamma\gamma$ mode.
Measurement on cross section of $\sigma(e^+e^- \to \gamma_{\rm ISR}\psi')$ at Belle:

- $\pi^+\pi^-\pi^0$ mode: $n^{sig} = 186 \pm 17$, $\sigma = 13.9 \pm 1.4$ pb.
- $\gamma\gamma$ mode: $n^{sig} = 470 \pm 25$, $\sigma = 14.0 \pm 0.8$ pb.
- Theory calculation: $\sigma = 14.2$ pb.

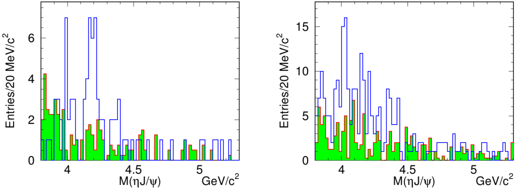
Measurement on ψ' signal is reliable.

$\eta J/\psi$ via ISR at Belle (Preliminary)

The J/ψ signal and η signal at high energy region ($M_{\eta J/\psi} > 3.8$ GeV/c^2):



The $\eta J/\psi$ signals:



The left is $\eta \to \pi^+\pi^-\pi^0$ mode and the right is $\eta \to \gamma\gamma$ mode. Events accumulate around the positions of $\psi(4040)$ and $\psi(4160)$, and no obvious Y states found at $\pi^+\pi^- J/\psi(\psi')$ transitions!