

Bottomonia & charmonia at B-factories

Pavel Krokovny

Budker Institute of Nuclear Physics,
Novosibirsk, Russia

- Introduction
- Bottomonium states
 - $Z_b(10610)$ and $Z_b(10650)$
- Charmonium states
 - Study of X, Y, Z states
 - Evidence for ψ_2
- Summary

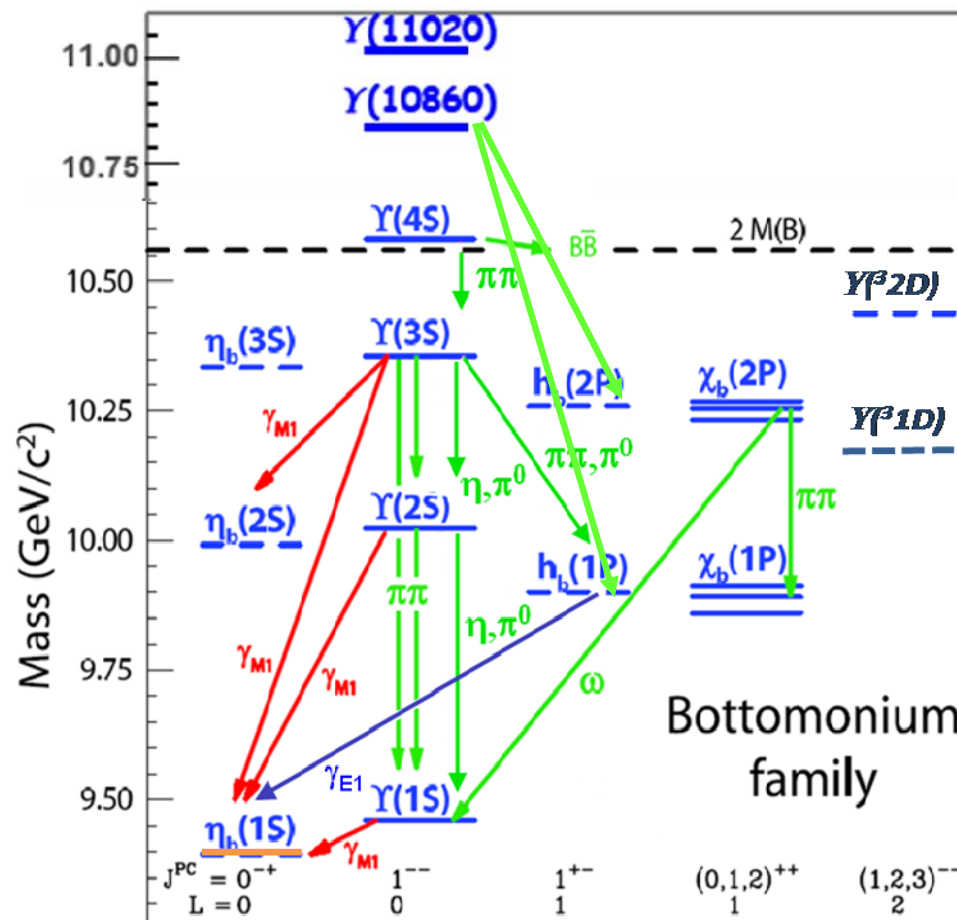
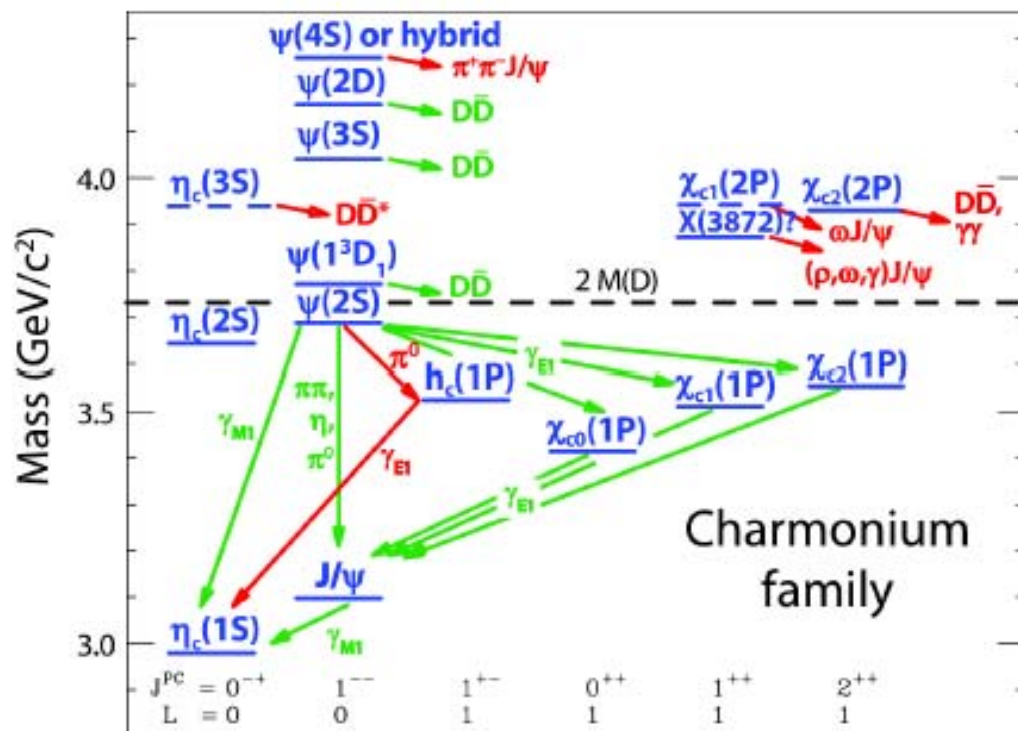


Introduction



$\Upsilon(4S)$: 433 fb⁻¹
 $\Upsilon(3S)$: 30 fb⁻¹
 $\Upsilon(2S)$: 14 fb⁻¹

$\Upsilon(5S)$: 121 fb⁻¹
 $\Upsilon(4S)$: 703 fb⁻¹

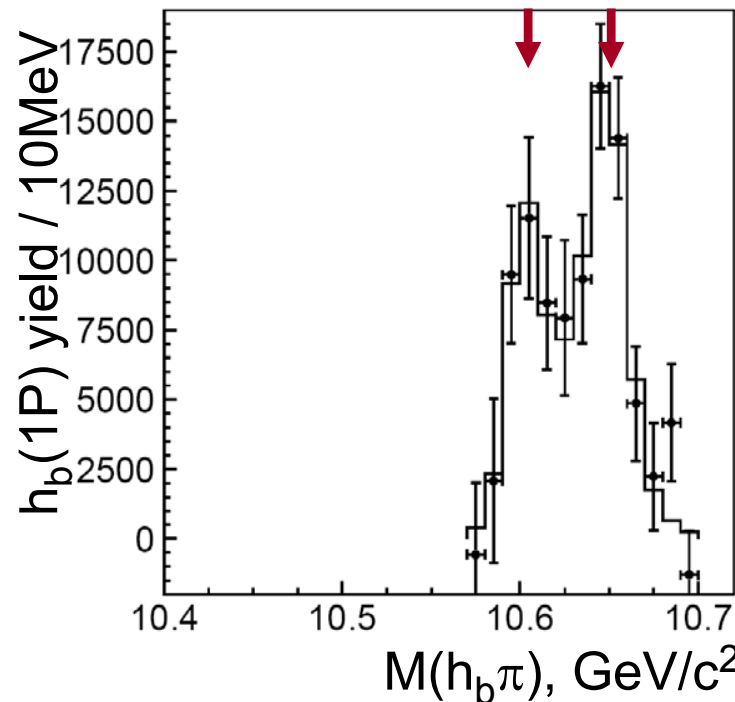
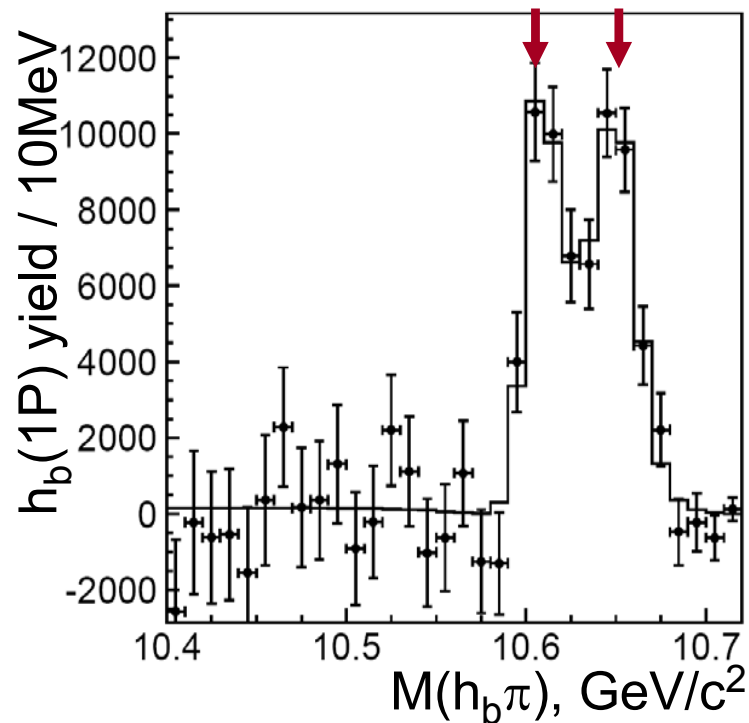


Heavy Quarkonia are ideal tool for testing QCD

Discovery of Z_b

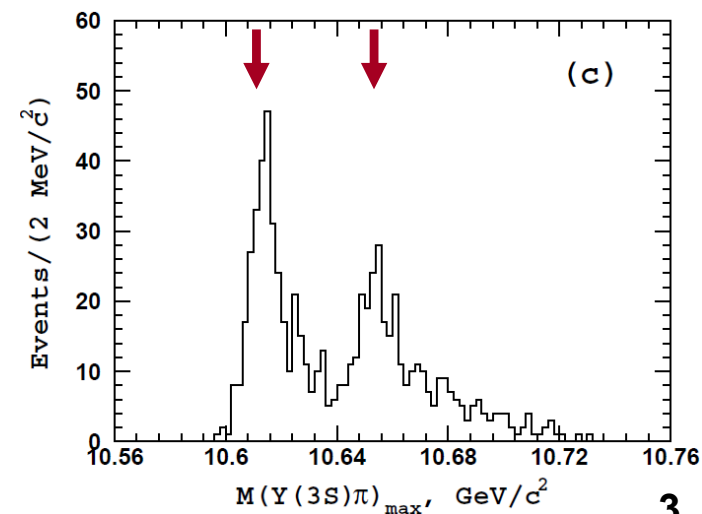
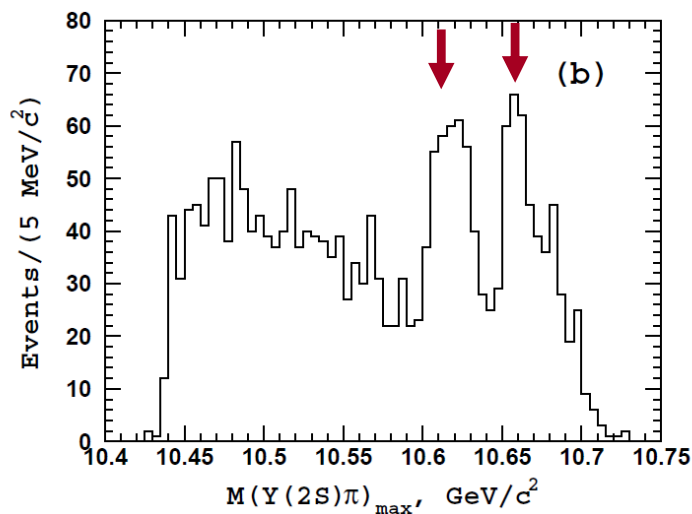
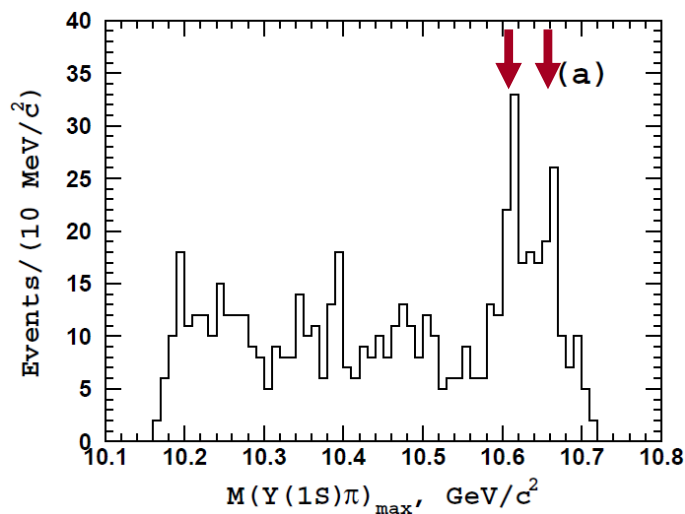


In analysis of $\Upsilon(5S) \rightarrow h_b(mP)\pi^+\pi^-$ and $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$



fit $M_{\text{miss}}(\pi^+\pi^-)$
in $M(h_b\pi)$ bins

PRL 108, 122001
(2012)



Summary of Z_b parameters



Average over 5 channels

$$\langle M_1 \rangle = 10607.2 \pm 2.0 \text{ MeV}$$

$$\langle \Gamma_1 \rangle = 18.4 \pm 2.4 \text{ MeV}$$

$$M(BB^*) = 10604.8 \pm 0.4 \text{ MeV}$$

$$\langle M_2 \rangle = 10652.2 \pm 1.5 \text{ MeV}$$

$$\langle \Gamma_2 \rangle = 11.5 \pm 2.2 \text{ MeV}$$

$$M(B^*B^*) = 10650.4 \pm 0.8 \text{ MeV}$$

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

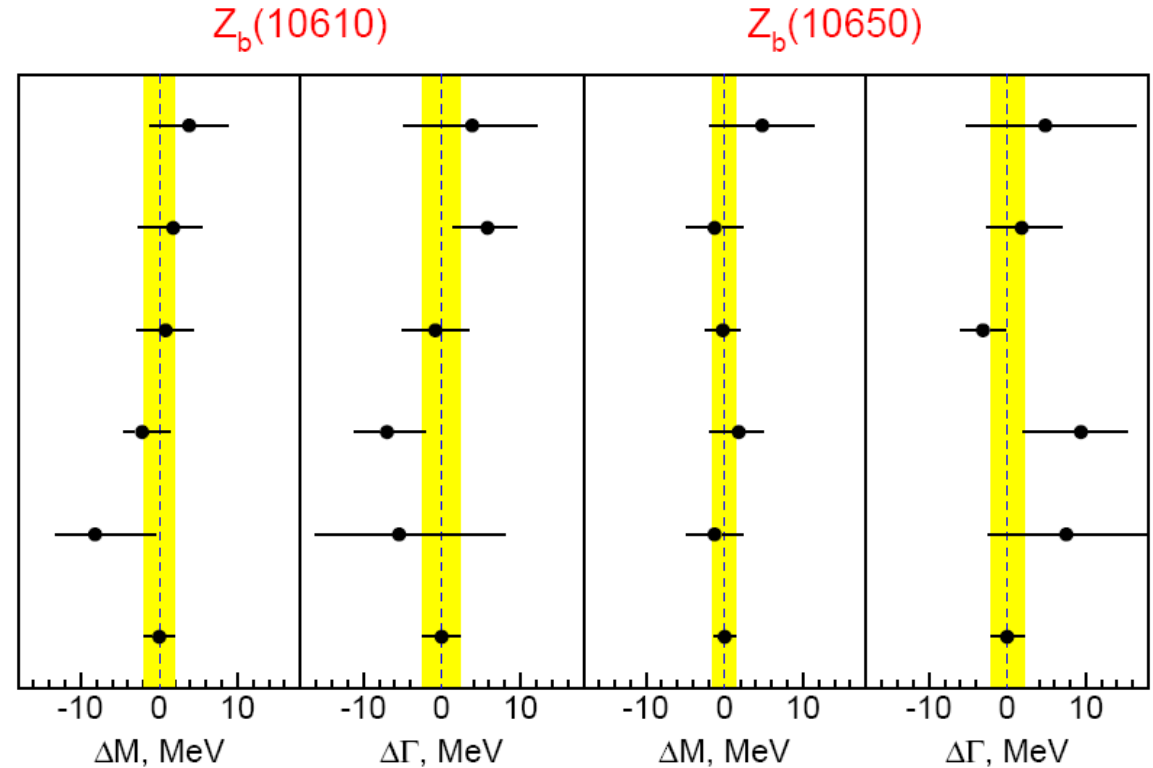
$\Upsilon(2S)\pi^+\pi^-$

$\Upsilon(3S)\pi^+\pi^-$

$h_b(1P)\pi^+\pi^-$

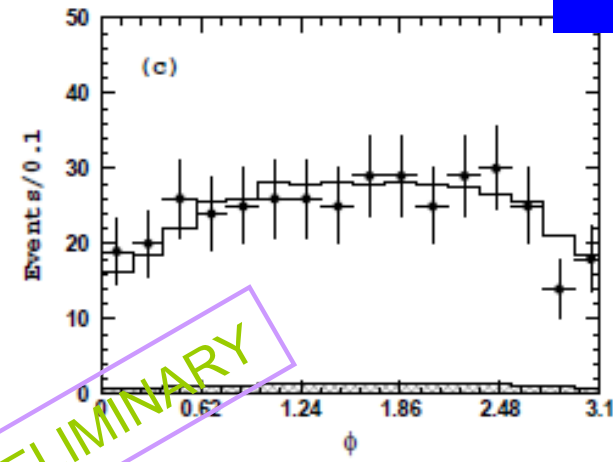
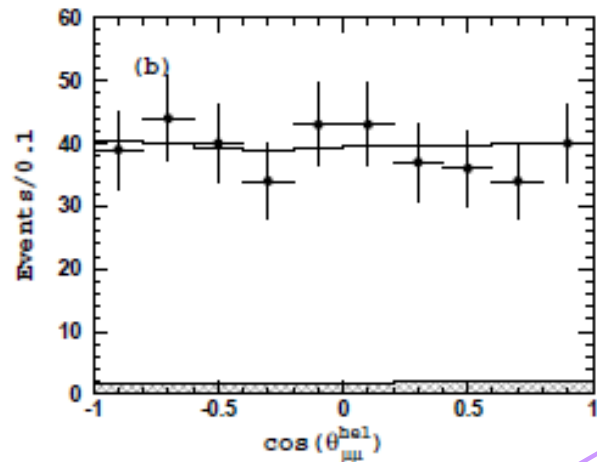
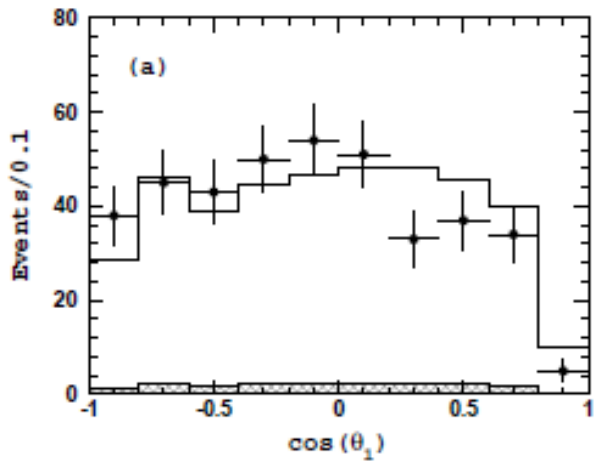
$h_b(2P)\pi^+\pi^-$

Average

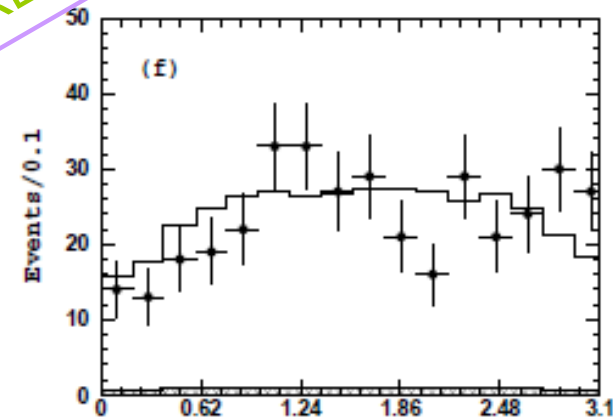
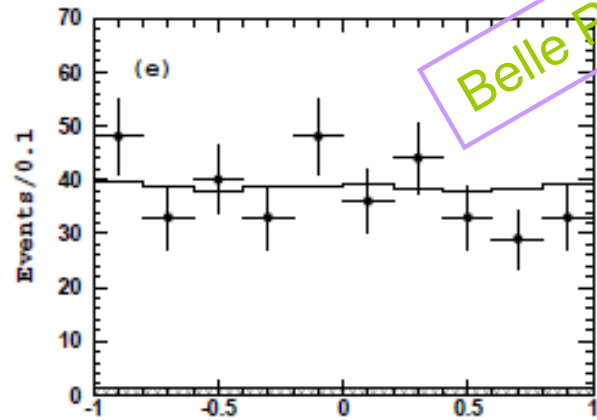
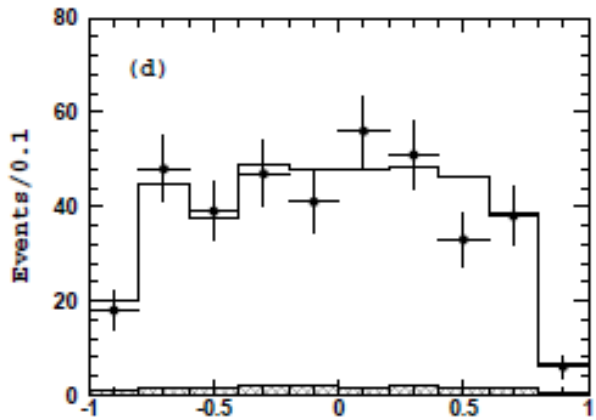


Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)], \text{ MeV}/c^2$	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)], \text{ MeV}$	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	13^{+10+9}_{-8-7}
$M[Z_b(10650)], \text{ MeV}/c^2$	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)], \text{ MeV}$	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

Z_b angular analysis



$Z_b(10610)$



$Z_b(10650)$

Belle PRELIMINARY

Angle between prompt pion and beam axis

$\Upsilon \rightarrow \mu^+ \mu^-$ helicity angle

Angle between planes formed by $(\pi^+ \pi^-)$ and $(\Upsilon, \text{beam axes})$

$J^P \setminus \text{Mode}$	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
1^+	0	0	0
1^-	64	264	73
2^+	41	207	87
2^-	59	304	125

Confirms $J^P=1^+$ hypothesis

6D amplitude analysis of

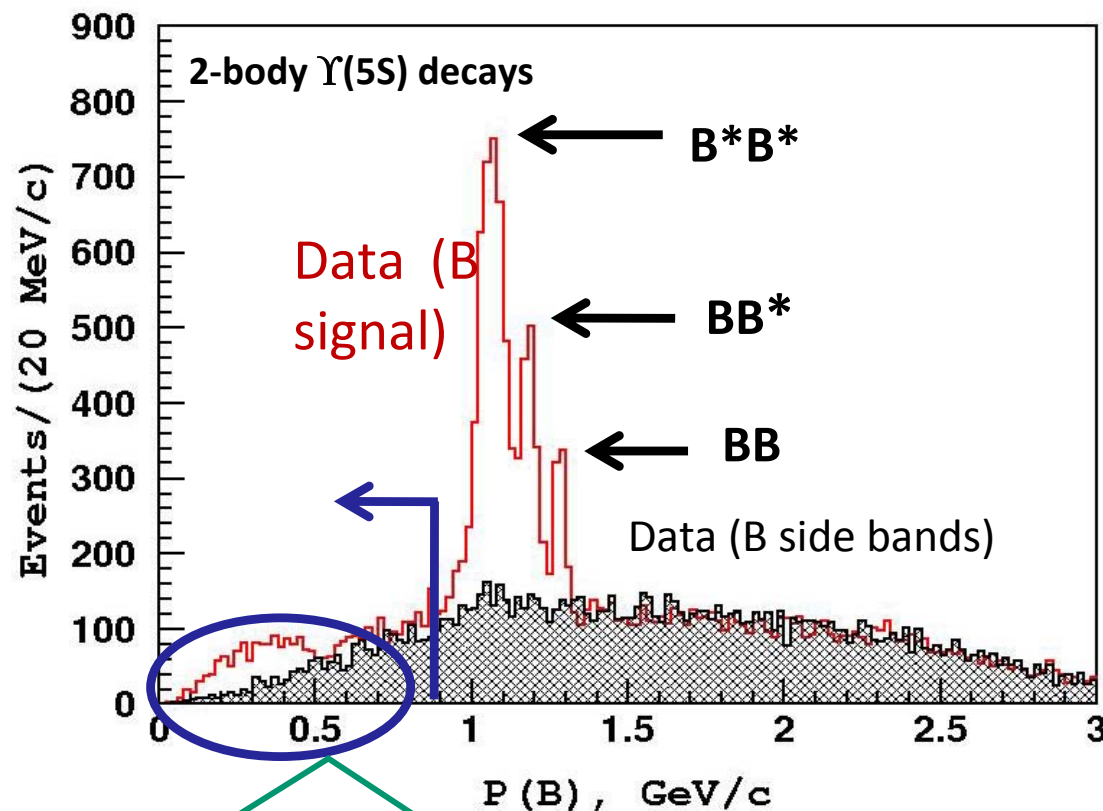
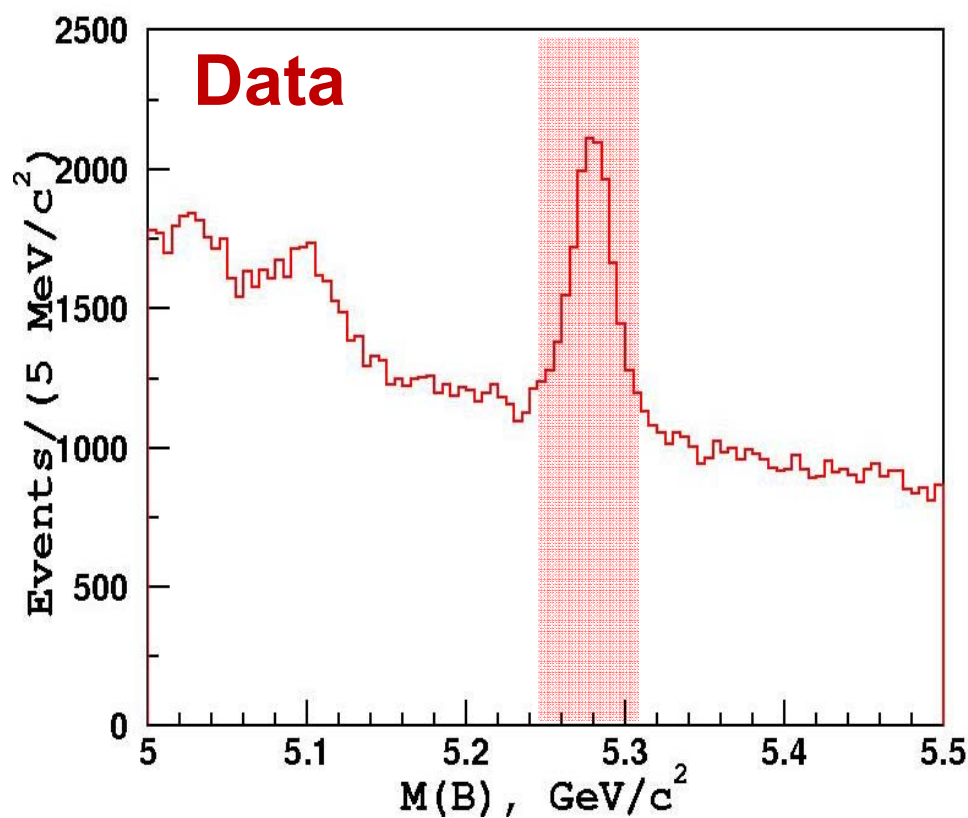
decays $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$

$\Upsilon(5S) \rightarrow B^* B^{(*)} \pi$: Selection



Masses of $Z_b(10610)$ and $Z_b(10650)$ are close to BB^* and B^*B^* threshold.

Search for $\Upsilon(5S) \rightarrow Z_b \pi$ decay with $Z_b \rightarrow B^{(*)} B^*$; reconstruct only one B and prompt pion



Effective B fraction:
 $\text{Br}[B \rightarrow f] = 1.4 \times 10^{-3}$

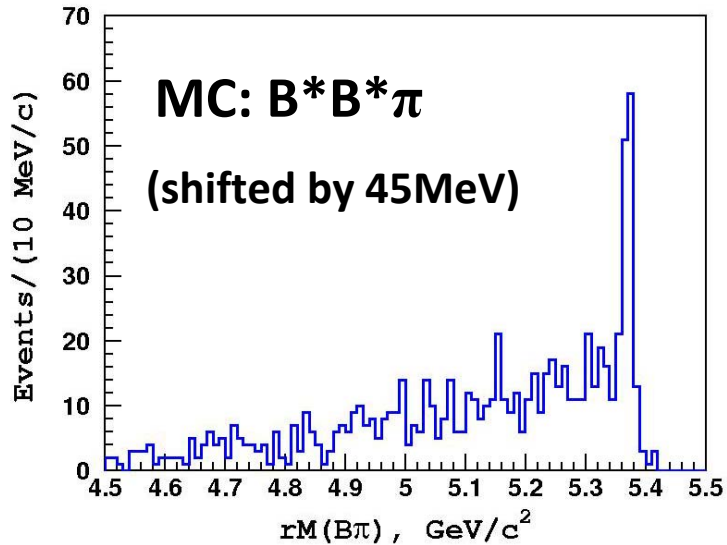
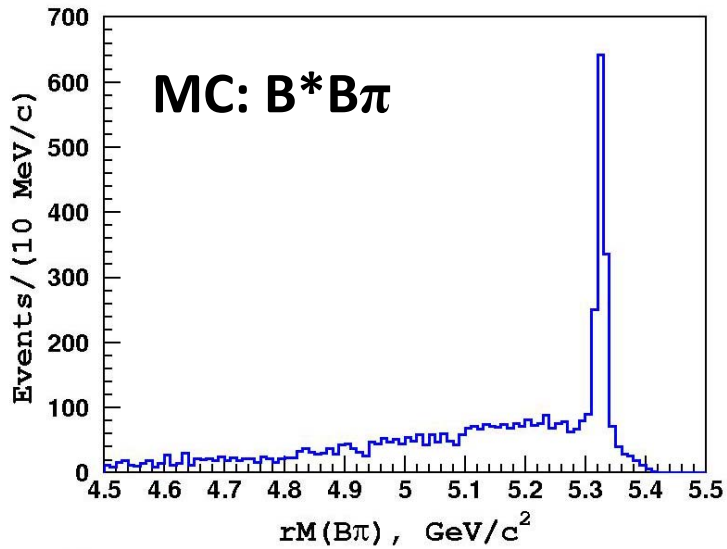
3-body $\Upsilon(5S) \rightarrow B^{(*)} B^{(*)} \pi$ decays & ISR to $\Upsilon(4S)$.
 $P(B) < 0.9 \text{ GeV}/c$

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

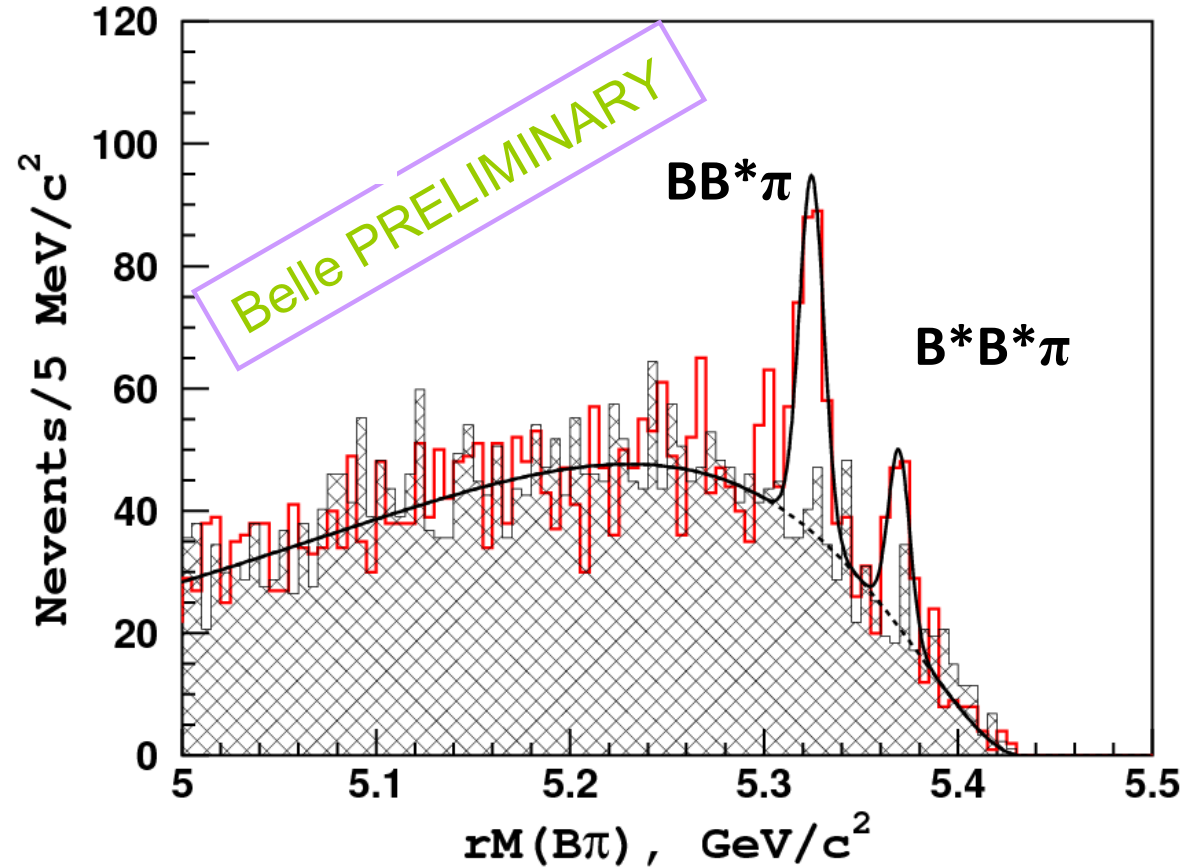
Neutral B: $D^+[K\pi\pi]\pi^-, J/\psi[\mu\mu] K^{*0}, D^{*+}[K\pi, K\pi\pi^0, K\pi\pi\pi]\pi^-$

Belle PRELIMINARY

$\Upsilon(5S) \rightarrow B^* B^{(*)} \pi$: Fit



Recoil mass to $B\pi$ combinations



Red histogram: right charge combination $B\pi$;
Hatched histogram: wrong charge combination;
The curve show the fit to the data.

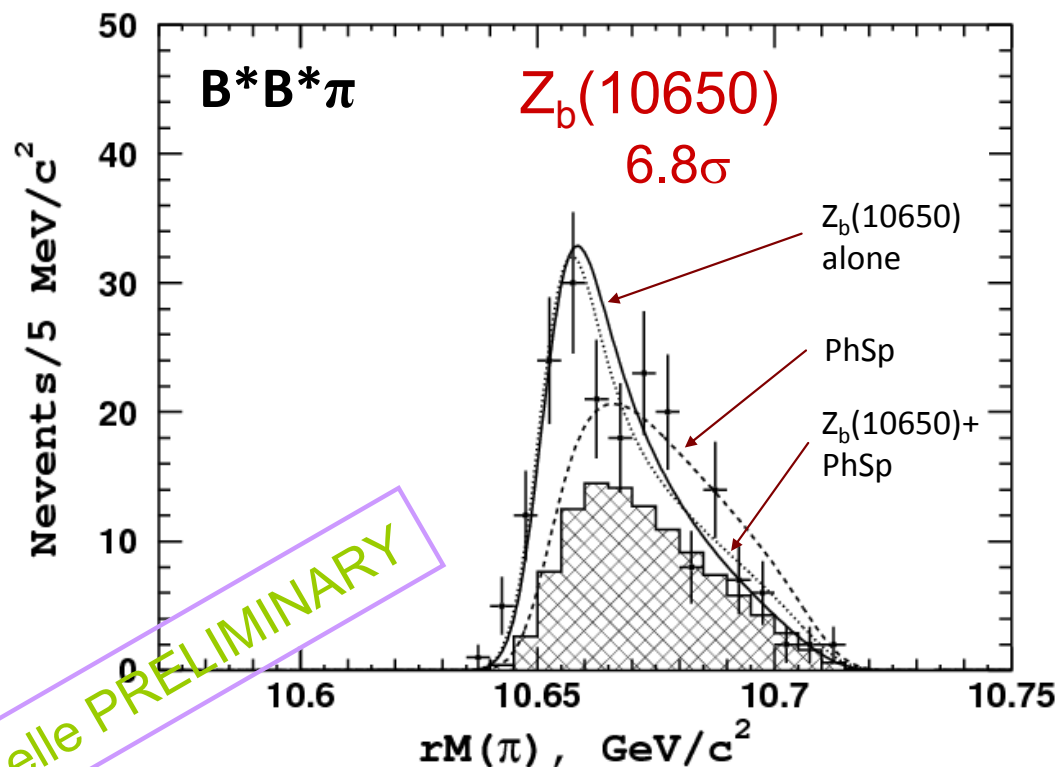
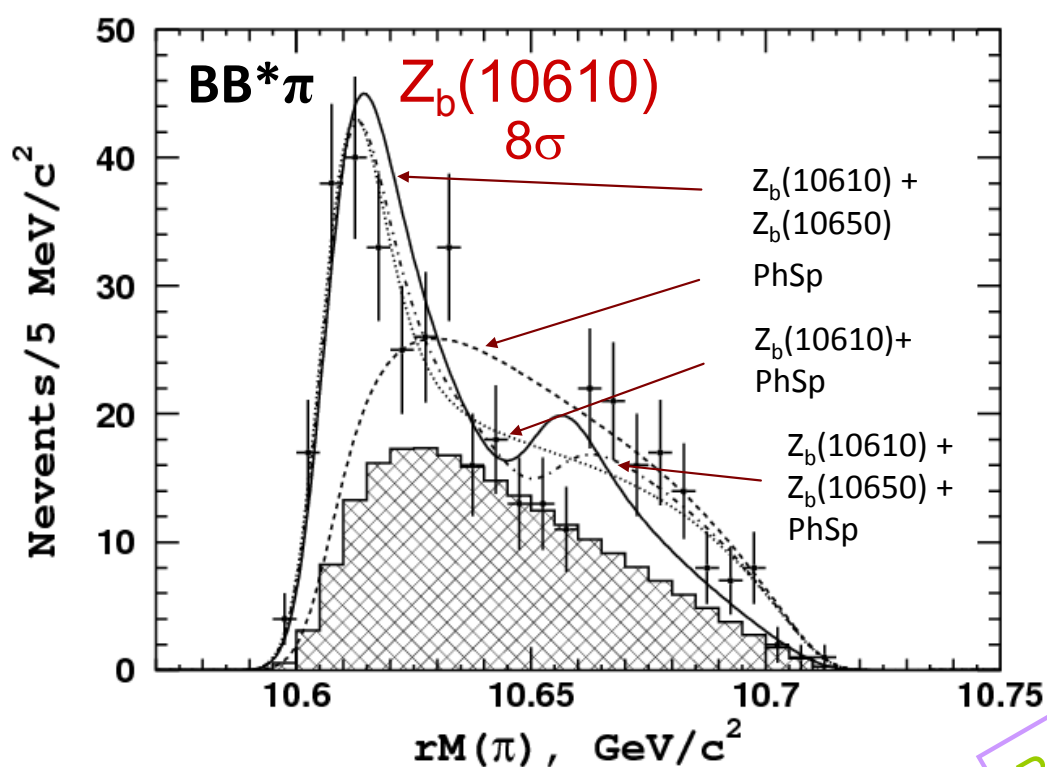
Fit yields: $N(BB\pi) = 0.3 \pm 14$

$N(BB^*\pi) = 184 \pm 19$ (9.3σ)

$N(B^*B^*\pi) = 82 \pm 11$ (5.7σ)

arXiv:1209.6450

$\Upsilon(5S) \rightarrow B^* B^{(*)} \pi$: Search for Z_b



Belle PRELIMINARY

Points represent the data.
Curves show the fit with various models.
Hatched histogram is the background contribution.

[arXiv:1209.6450](https://arxiv.org/abs/1209.6450)

$B^* B^* \pi$ candidates are well described by $Z_b(10650)$ only contribution.

$BB^* \pi$ can be described by two models:

$Z_b(10610) + Z_b(10650)$;

$Z_b(10610) + \text{non-resonant amplitude}$.

Z_b branching fractions



$\Upsilon(5S)$ branching fractions:

$$BB\pi < 0.60\% \text{ (90\%CL)}$$

$$BB^*\pi = 4.25 \pm 0.44 \pm 0.69\%$$

$$B^*B^*\pi = 2.12 \pm 0.29 \pm 0.36\%$$

To be compared with PRD 81 (2010)

$$f(BB^*\pi) = (7.3 \pm 2.2 \pm 0.8)\%$$

$$f(B^*B^*\pi) = (1.0 \pm 1.4 \pm 0.4)\%$$

Assuming Z_b decaying to $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B(^*)B^*$ only:

[arXiv:1209.6450](https://arxiv.org/abs/1209.6450)

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
$B^+\bar{B}^{*0} + \bar{B}^0B^{*+}$	86.0 ± 3.6	—
$B^{*+}\bar{B}^{*0}$	—	73.4 ± 7.0

Belle PRELIMINARY

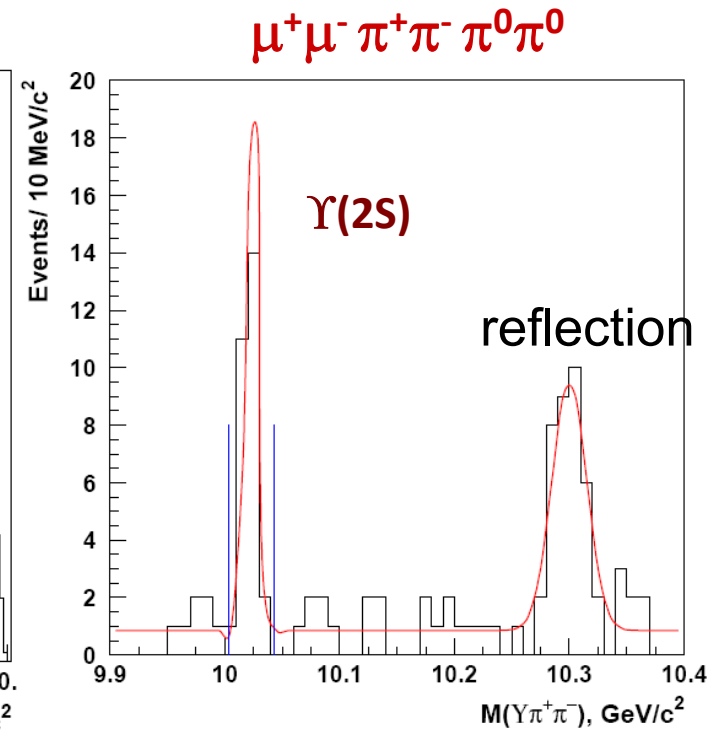
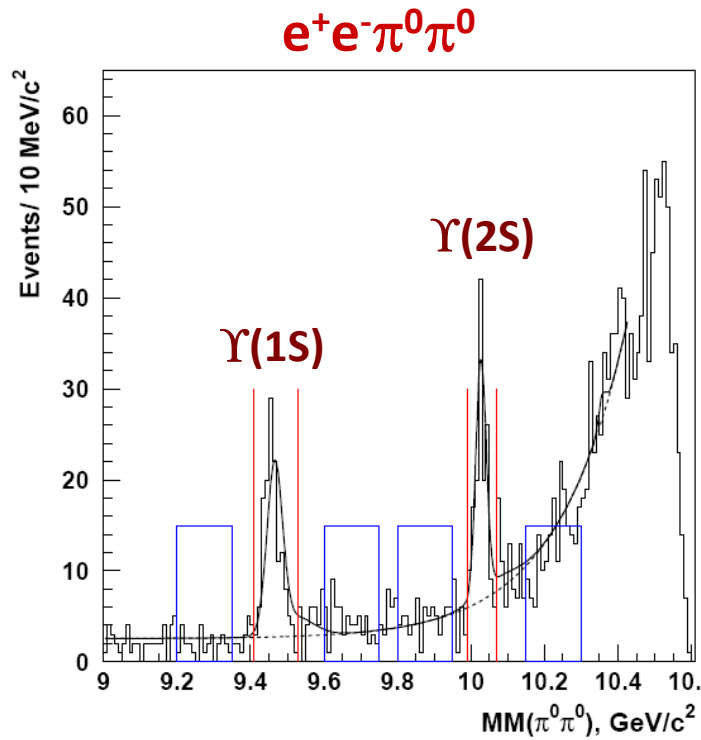
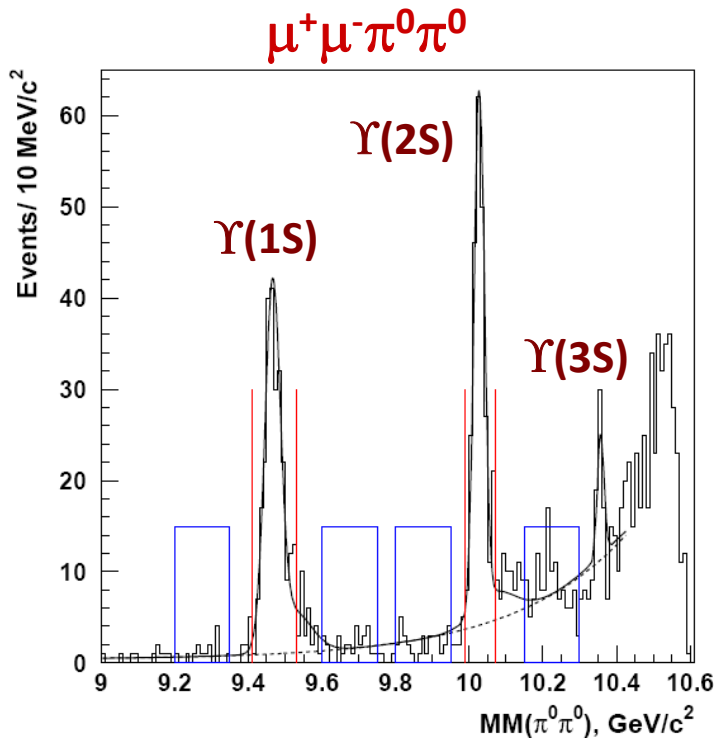
$B(^*)B^*$ - is the dominant mode of Z_b decays

$\Upsilon(5S) \rightarrow \Upsilon(nS) \pi^0 \pi^0$



arXiv:1207.4345

$\Upsilon(1,2,3S) \rightarrow \mu^+ \mu^-, e^+ e^-, \Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$



$$BF[\Upsilon(5S) \rightarrow \Upsilon(1S) \pi^0 \pi^0] = (2.25 \pm 0.11 \pm 0.20) 10^{-3}$$

$$BF[\Upsilon(5S) \rightarrow \Upsilon(2S) \pi^0 \pi^0] = (3.79 \pm 0.24 \pm 0.49) 10^{-3}$$

Consistent with $\frac{1}{2}$ of $\Upsilon(nS) \pi^+ \pi^-$

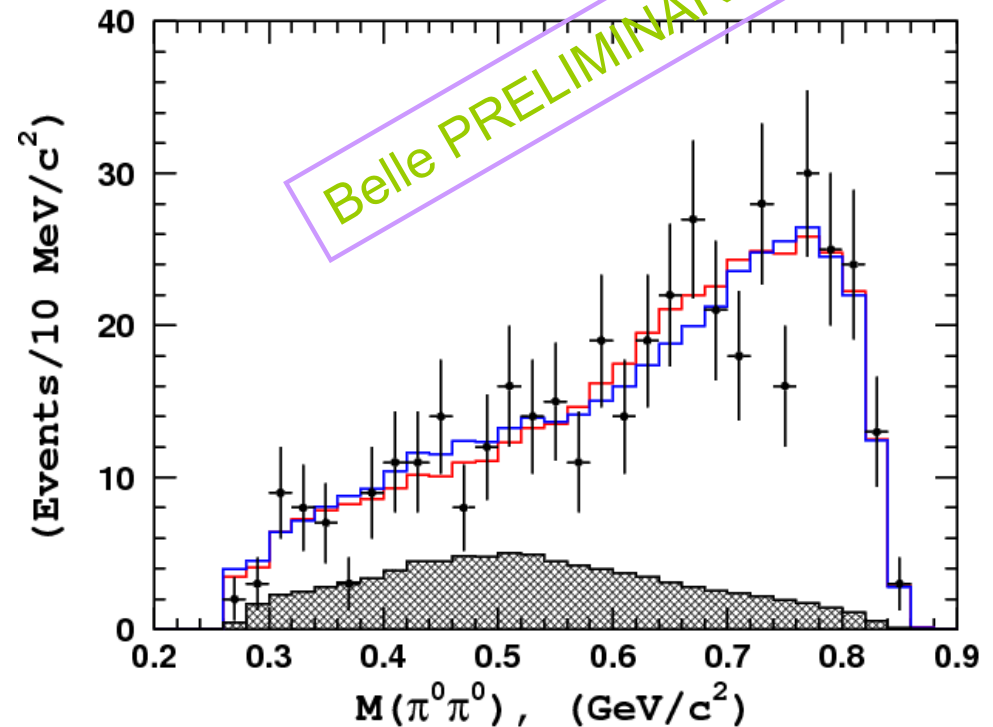
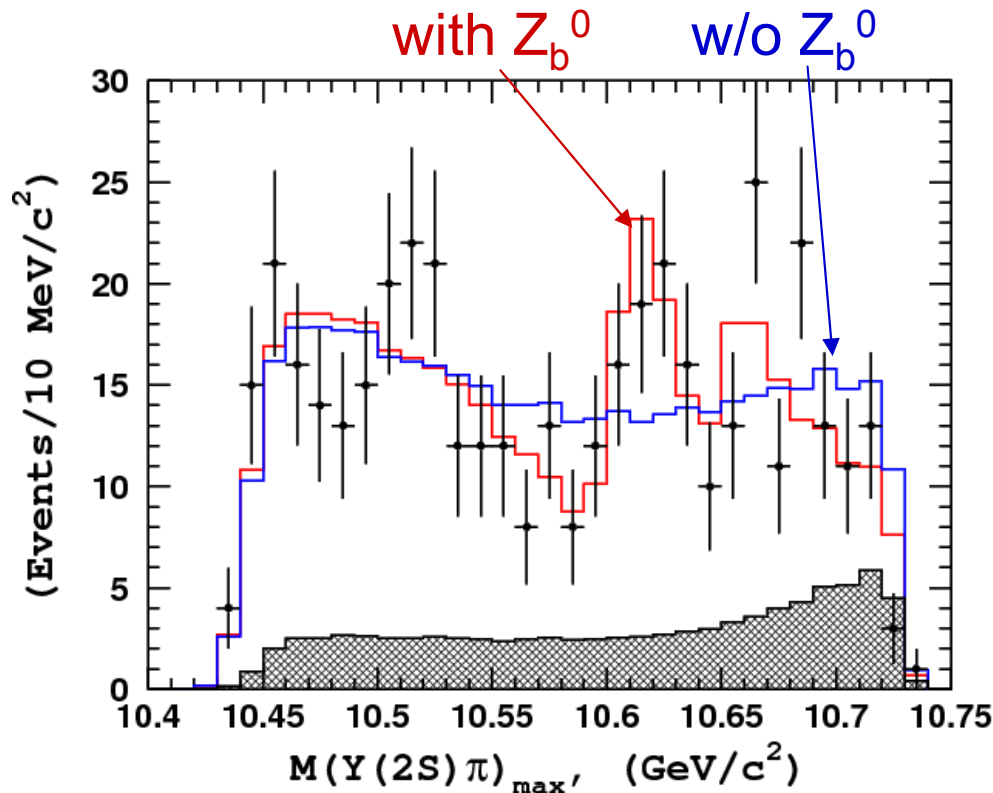
Belle PRELIMINARY

$\Upsilon(2S)\pi^0\pi^0$ Dalitz analysis



arXiv:1207.4345

$$M(s_1, s_2) = A_{Z_1} + A_{Z_2} + A_{f_0} + A_{f_2} + A_{NR}$$



- Z_b^0 resonant structure is observed in $\Upsilon(2S)\pi^0\pi^0$
- Statistical significance of $Z_b^0(10610)$ signal is 5.3σ (4.9σ with systematics)
- $Z_b^0(10650)$ signal is not significant ($\sim 2\sigma$), not contradicting with its existence
- $Z_b^0(10610)$ mass from the fit $M = 10609 \pm 8 \pm 6 \text{ MeV}/c^2$ $M(Z_b^+) = 10607 \pm 2 \text{ MeV}/c^2$

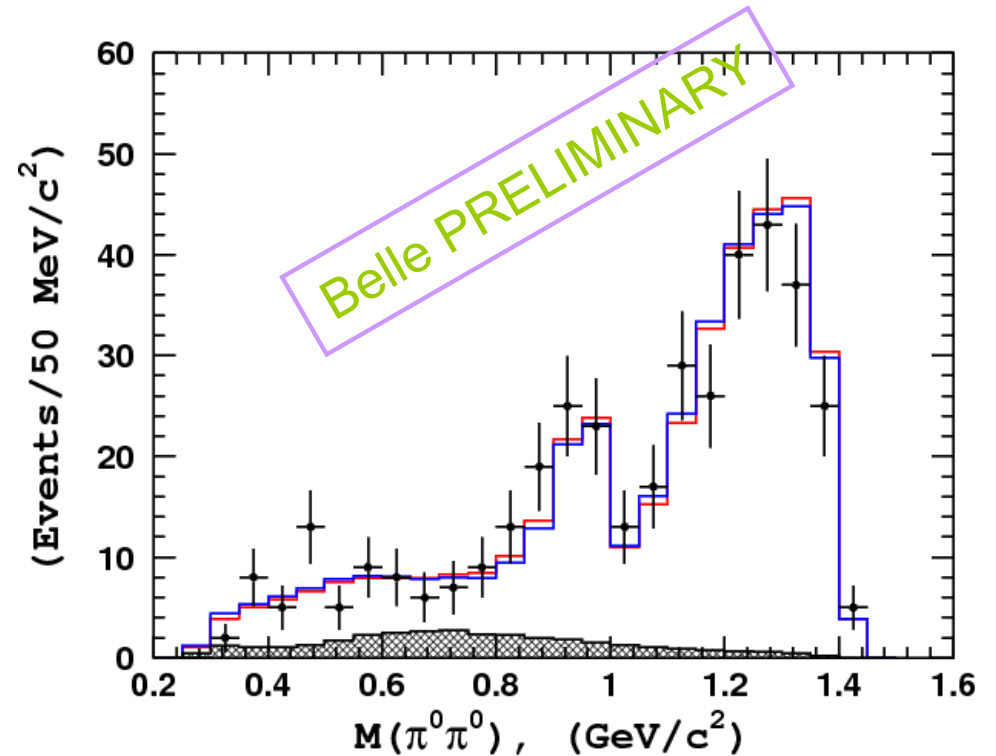
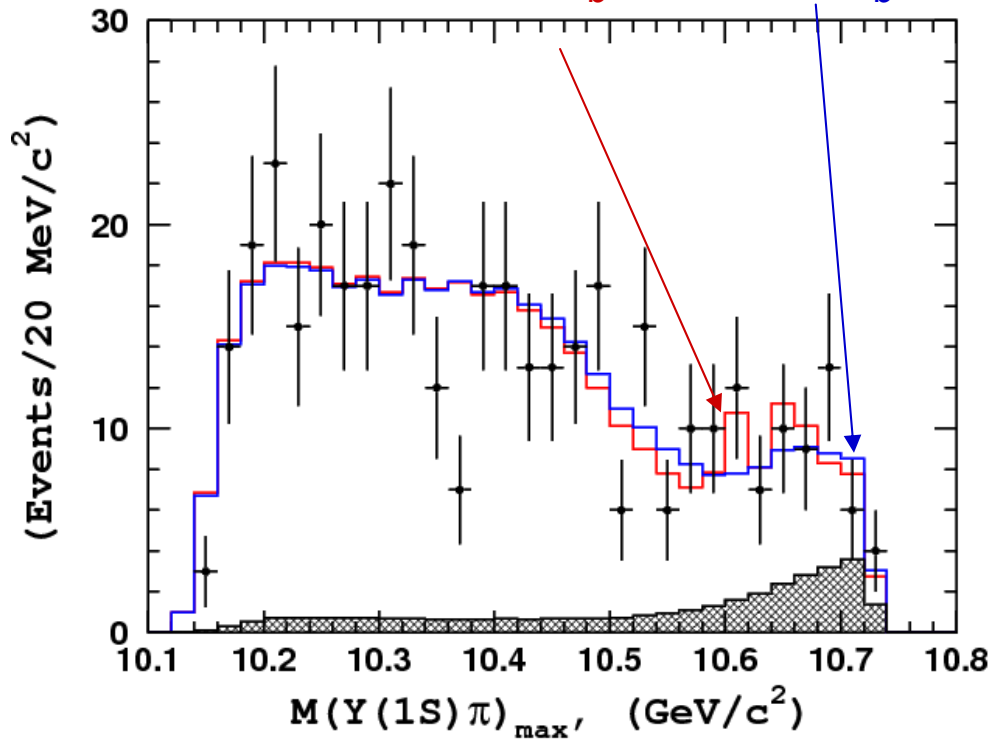
$\Upsilon(1S)\pi^0\pi^0$ Dalitz analysis



Dalitz analysis

$$M(s_1, s_2) = A_{Z_1} + A_{Z_2} + A_{f_0} + A_{f_2} + A_{NR}$$

with Z_b^0 w/o Z_b^0



Signals of both Z_b^0 are not significant. Data is not contradicting with their existence.

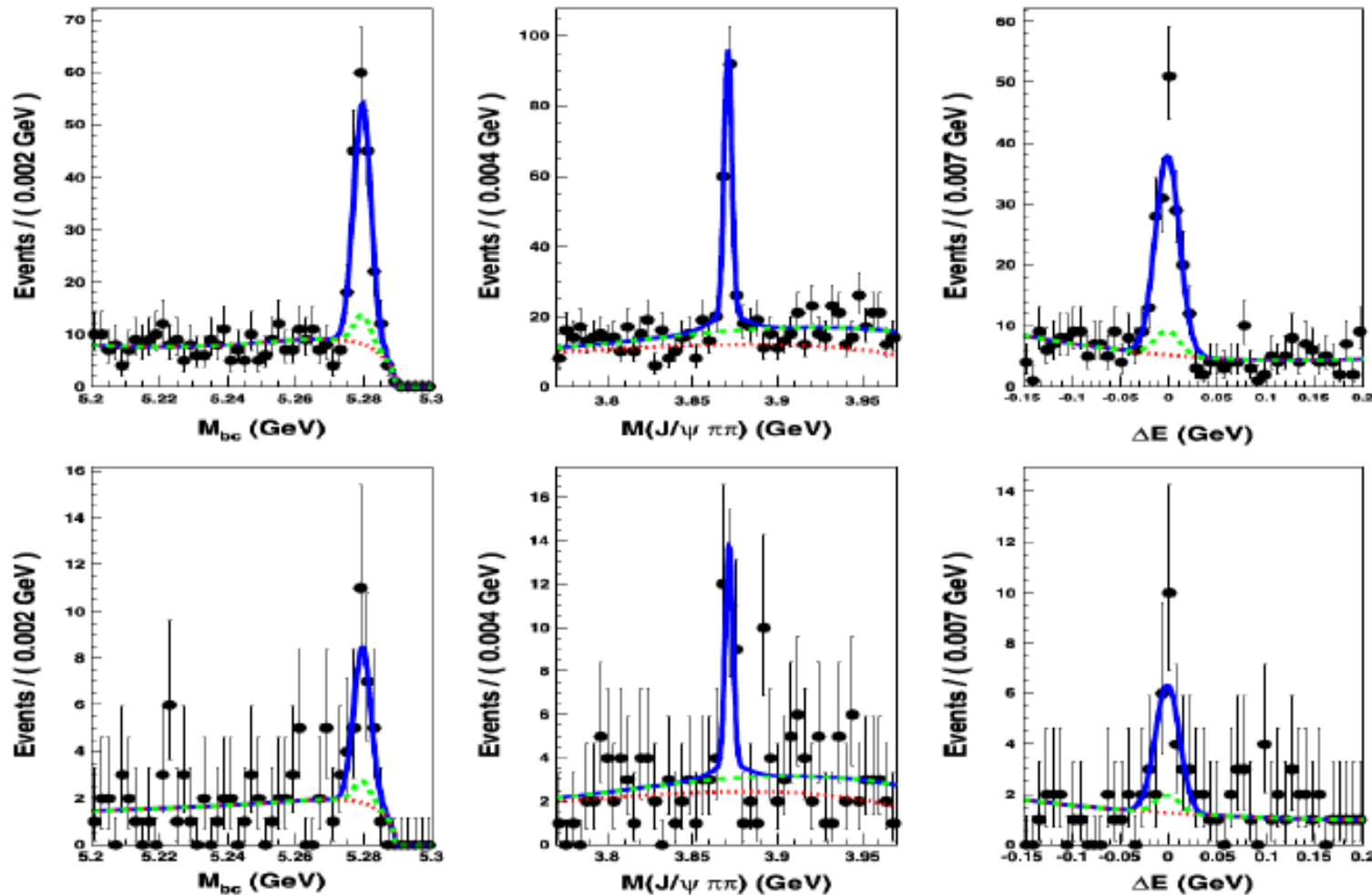
Update of $X(3872) \rightarrow J/\psi \pi^+ \pi^-$



Observed 10 years ago by Belle in $B \rightarrow J/\psi \pi^+ \pi^- K$ PRL 91, 262001 (2003)

Update using $772 \cdot 10^6 \text{ BB}^{\bar{}}$

PRD 84, 052004 (2011)



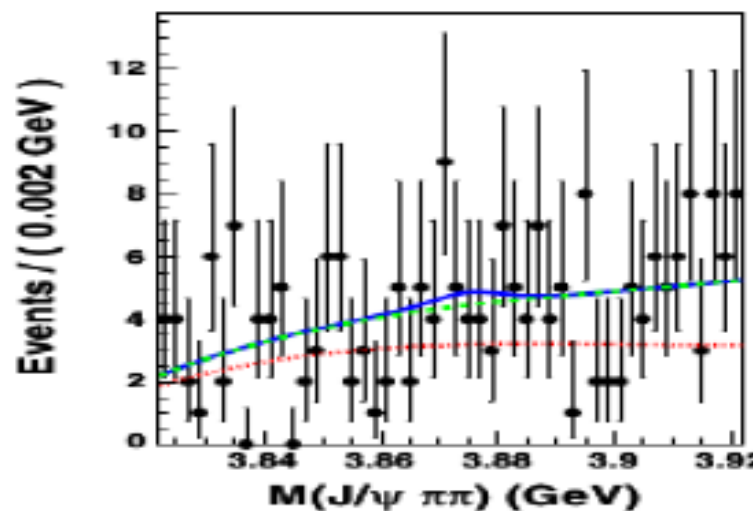
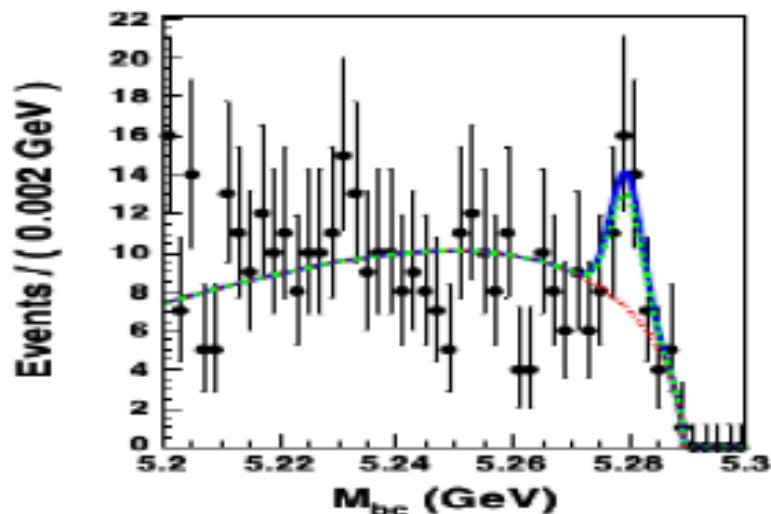
$M(3872) = 3871.84 \pm 0.27 \pm 0.19 \text{ MeV}/c^2$; $\Gamma(3872) < 1.2 \text{ MeV} @ 90\% \text{ CL}$

Mass difference of $X(3872)$ from B^+ and B^0 : $\Delta M = -0.69 \pm 0.97 \pm 0.19 \text{ MeV}/c^2$

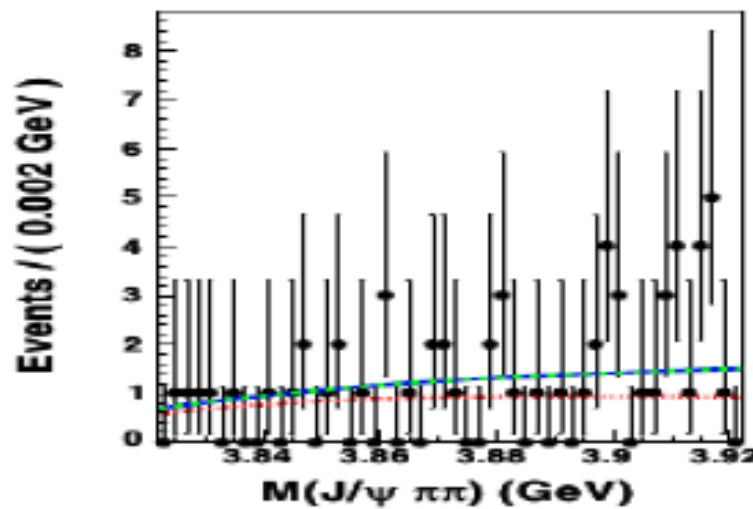
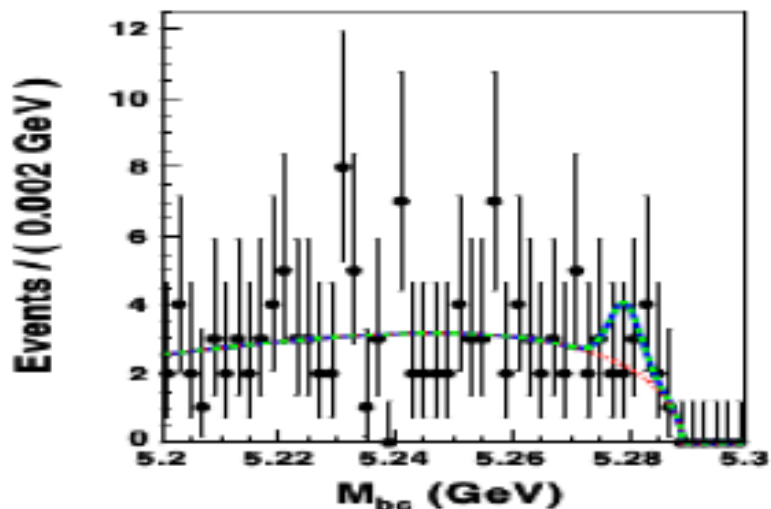
Search for charged X



Charged partner can exist if X(3872) is exotic. Search for $X(3872)^+$ in $J/\psi\rho^+$



$\bar{B}^0 \rightarrow K^- \rho^+ J/\psi$



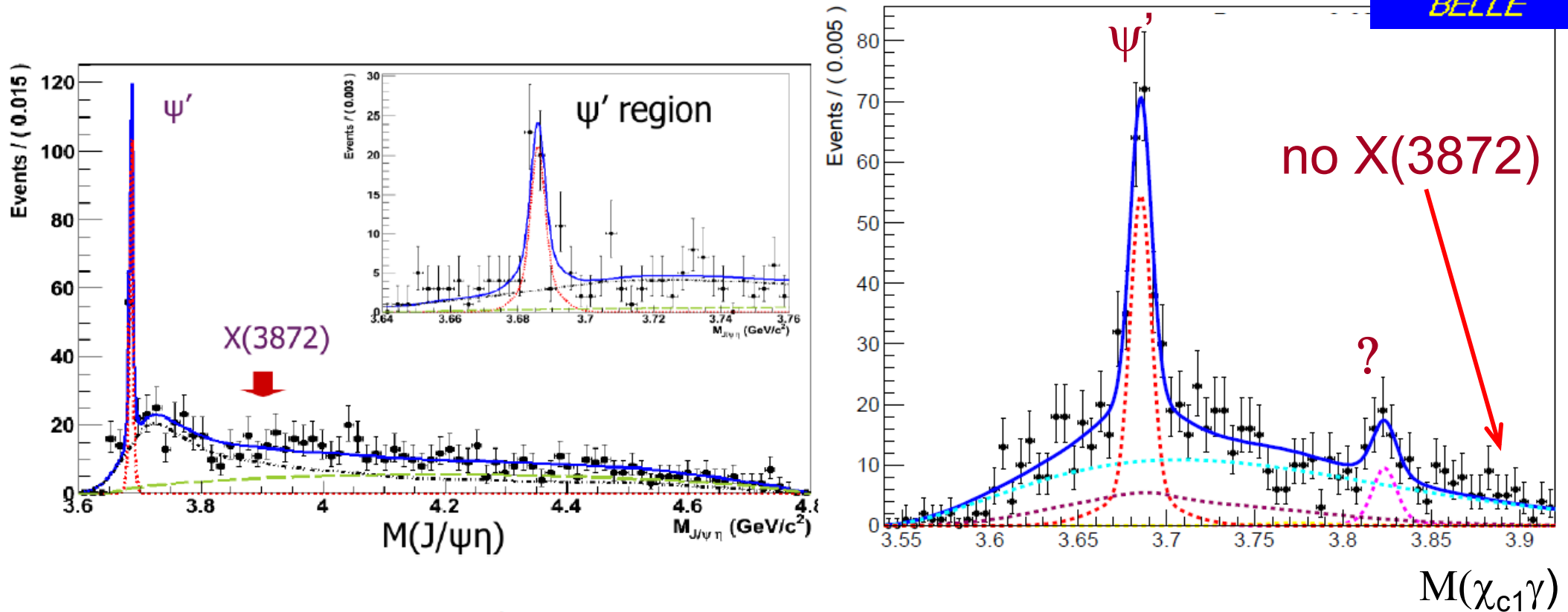
$B^+ \rightarrow K^0 \rho^+ J/\psi$

$$B(\bar{B}^0 \rightarrow X^+ K^-) \times B(X^+ \rightarrow J/\psi \rho^+) < 4.2 \cdot 10^{-6}$$

$$B(B^+ \rightarrow X^+ K^0) \times B(X^+ \rightarrow J/\psi \rho^+) < 6.1 \cdot 10^{-6}$$

PRD 84, 052004 (2011)

Search for C-odd partner of X(3872)



- $B \rightarrow K + \eta J/\psi$: only ψ' signal and non-resonant component, no X(3872).

$$\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X \rightarrow \eta J/\psi) < 3.8 \times 10^{-6} \text{ @90\% C.L.}$$

- $B \rightarrow K + \gamma \chi_{c1}$: no X(3872) signal observed, $N_{sig} = -1 \pm 5$.

$$\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X \rightarrow \gamma \chi_{c1}) < 2.0 \times 10^{-6} \text{ @ 90\% C.L. and}$$

$$\mathcal{B}(X \rightarrow \gamma \chi_{c1}) / \mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-) < 0.26 \text{ @ 90\% C.L.,}$$

according to PRD84, 052004(2011)(Belle):

$$\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X \rightarrow \pi^+ \pi^- J/\psi) = (8.6 \pm 0.8 \pm 0.5) \times 10^{-6}.$$

- BUT, what's the peak at $M(\gamma \chi_{c1})$? A new charmonium state observed?

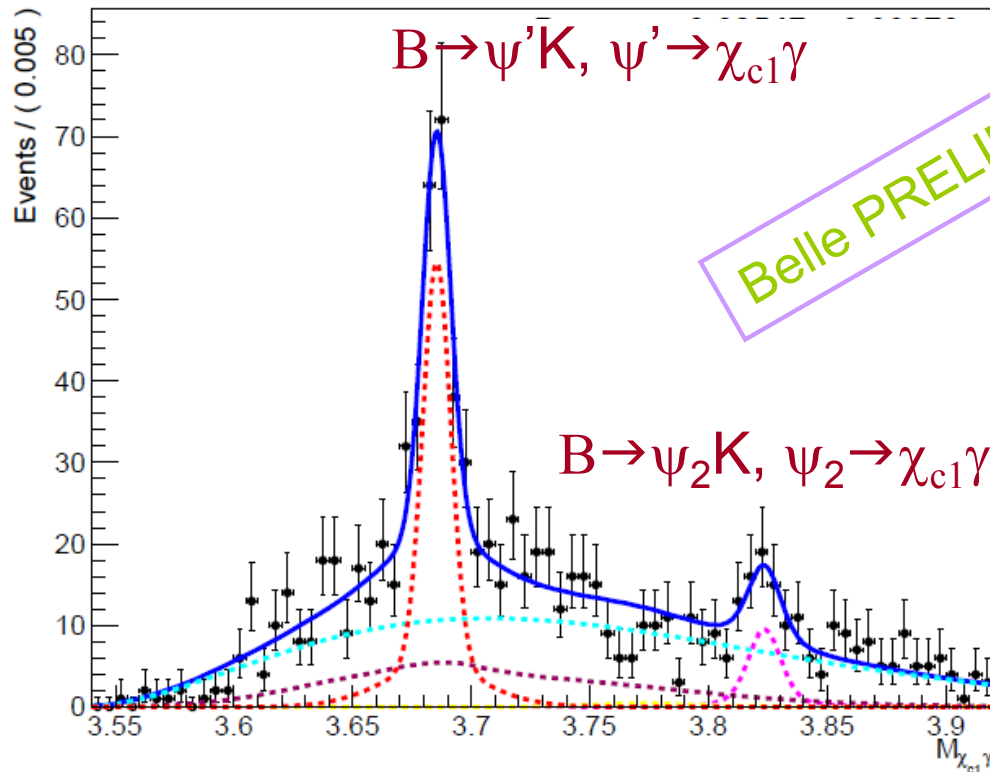
Evidence for $\psi_2 \rightarrow \chi_{c1} \gamma$



$\psi_2 \rightarrow \chi_{c1} \gamma$ was predicted, $\Gamma(\psi_2 \rightarrow \chi_{c1} \gamma) = 260$ KeV

Godfrey & Isgur, PRD 21, 189 (1985);

Eichten, Lane & Quigg, PRL 89 16202 (2002) & PRD 69, 094019 (2004)



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

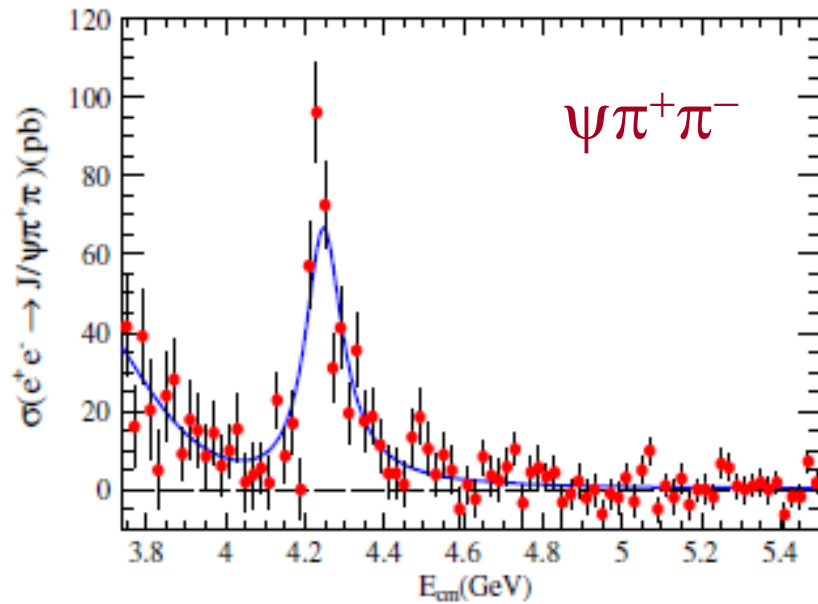
	yield	Mass [MeV]	BR ($B^+ \rightarrow \psi(\rightarrow \chi_{c1} \gamma) K^+$)
ψ'	193 ± 18	3685.3 ± 0.6	$(7.7 \pm 0.8 \pm 0.9) \times 10^{-4}$
ψ_2	33 ± 9	3823.5 ± 2.8	$(9.7^{+2.8}_{-2.5} \pm 1.1) \times 10^{-6}$

First ψ_2 evidence

ψ_2 significance is 4.2σ including systematics

$\Gamma(\psi_2) = 4 \pm 6$ MeV from the fit

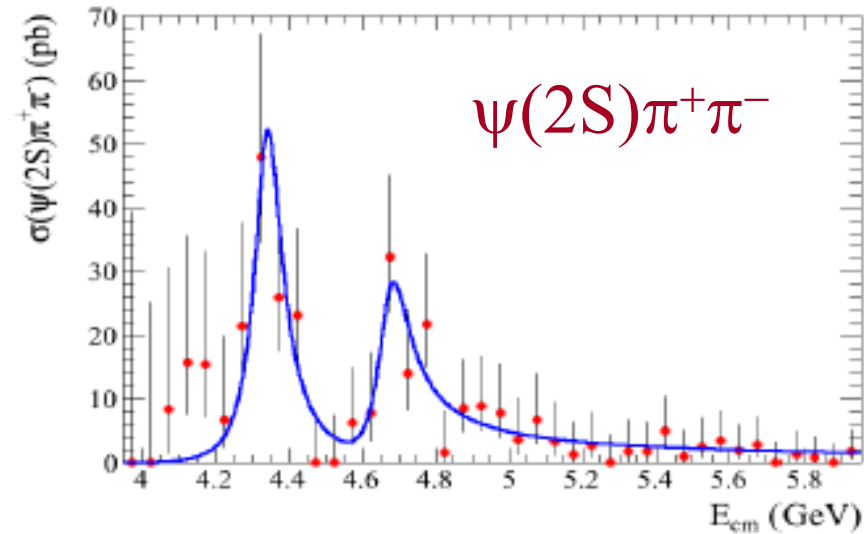
$e^+e^- \rightarrow J/\psi\pi^+\pi^-$ and $\psi(2S)\pi^+\pi^-$ by ISR



PRD 86 051102 (2012)

$Y(4260): M = 4245 \pm 5 \pm 4 \text{ MeV}/c^2$

$\Gamma = 114 \pm 15 \pm 7 \text{ MeV}$



arXiv: 1211.6271

$Y(4360): M = 4340 \pm 16 \pm 9 \text{ MeV}/c^2$

$\Gamma = 94 \pm 32 \pm 13 \text{ MeV}$

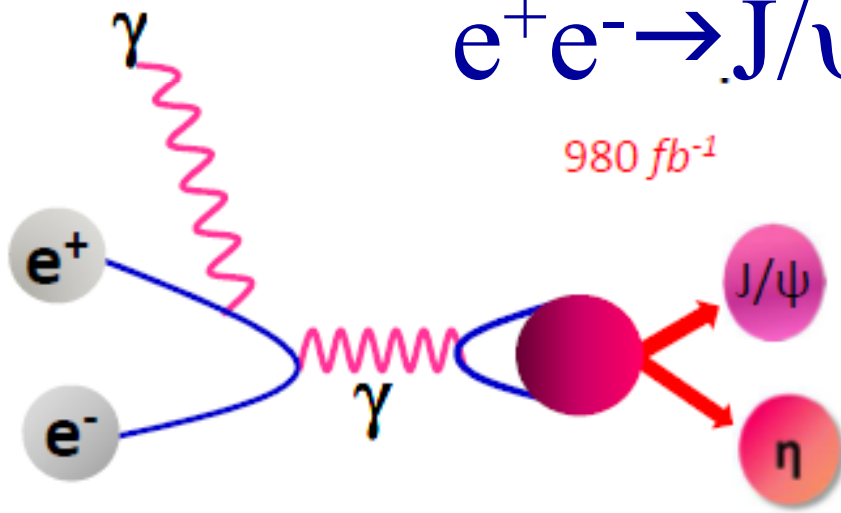
$Y(4660): M = 4669 \pm 21 \pm 3 \text{ MeV}/c^2$

$\Gamma = 104 \pm 48 \pm 10 \text{ MeV}$

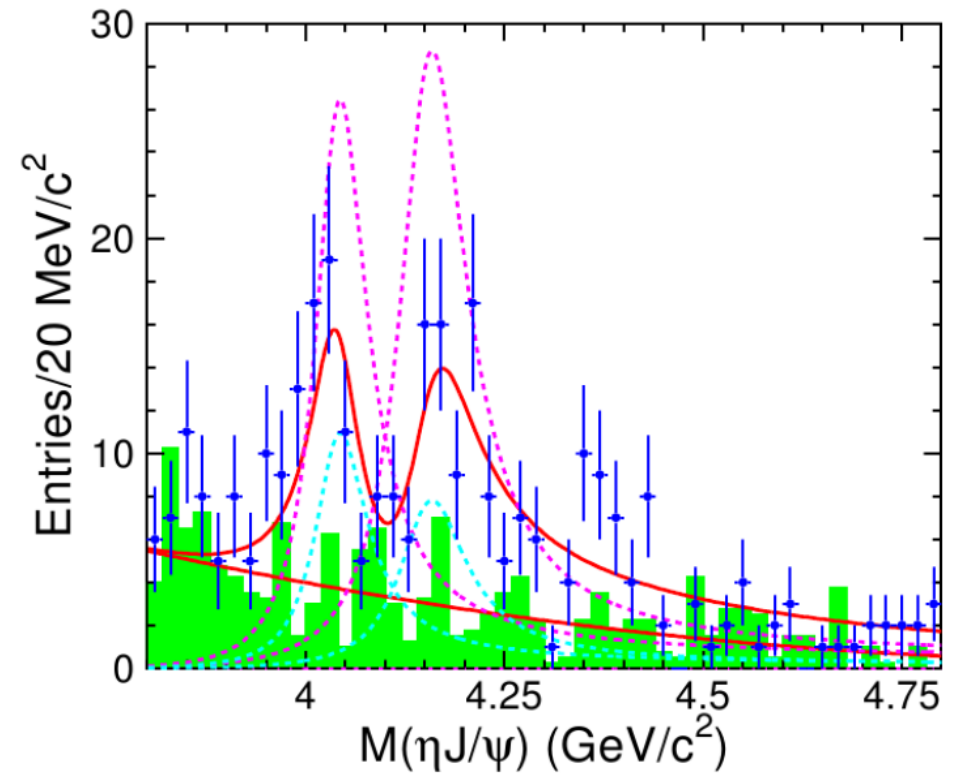
Consistent with previous Belle results

$e^+e^- \rightarrow J/\psi \eta$ by ISR

980 fb⁻¹



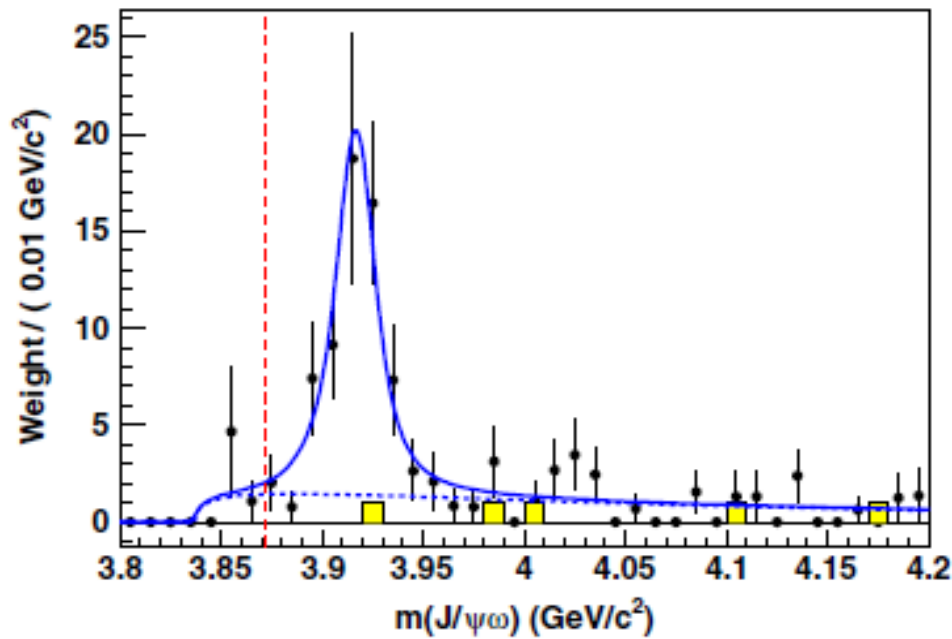
Parameters	Solution I	Solution II
$M_{\psi(4040)}$	4039 (fixed)	
$\Gamma_{\psi(4040)}$	80 (fixed)	
$B. \Gamma_{e^+e^-}^{\psi(4040)}$	$4.8 \pm 0.9 \pm 1.4$	$11.2 \pm 1.3 \pm 1.9$
$M_{\psi(4160)}$	4153 (fixed)	
$\Gamma_{\psi(4160)}$	103 (fixed)	
$B. \Gamma_{e^+e^-}^{\psi(4160)}$	$4.0 \pm 0.8 \pm 1.4$	$13.8 \pm 1.3 \pm 2.0$
ϕ	$336 \pm 12 \pm 14$	$251 \pm 4 \pm 7$



First time $\psi(4040)$ and $\psi(4160)$ have been observed in final states not involving charm meson pair.

No signal from $Y(4260/4360/4660)$.

$X(3915) \rightarrow J/\psi \omega$ in two-photon collisions



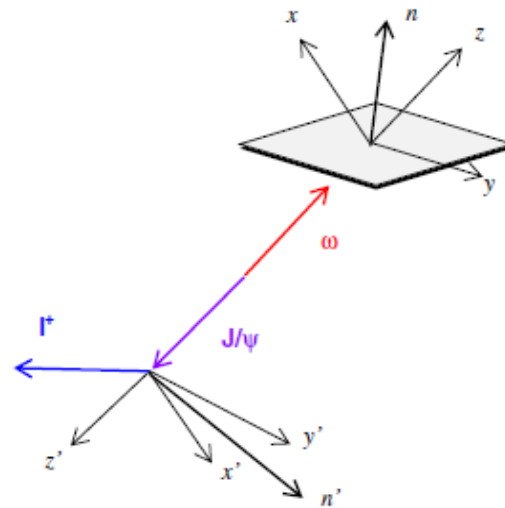
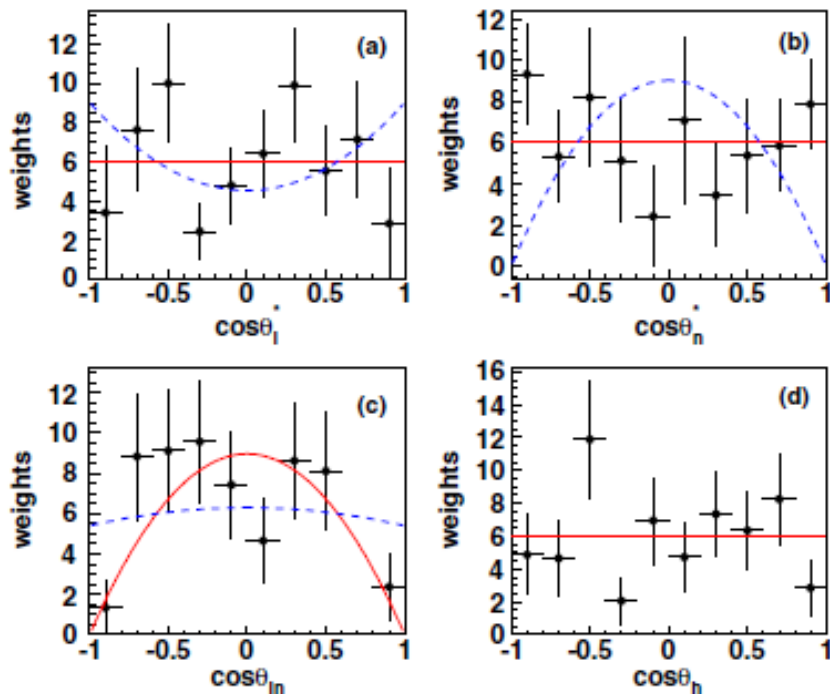
7.6 σ significance

$$M = 3919.4 \pm 2.2 \pm 1.6 \text{ MeV}/c^2$$

$$\Gamma = 13 \pm 6 \pm 3 \text{ MeV}$$

$$J^P = 0^+$$

Consistent with older studies by BaBar & Belle



Summary

New results on bottomonium states come from B factories:

- Observation of $Z_b^+(10610)$ and $Z_b^+(10650)$ decays to BB^* and B^*B^* main decay mode, supporting “molecular” hypothesis
- 6D amplitude analysis of $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ confirmed $J^P=1^+$ for both Z_b
- Evidence for neutral partner $Z_b(10610)$ in analysis of $\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^0\pi^0$ consistent with expectation from isospin

... and on charmonium states:

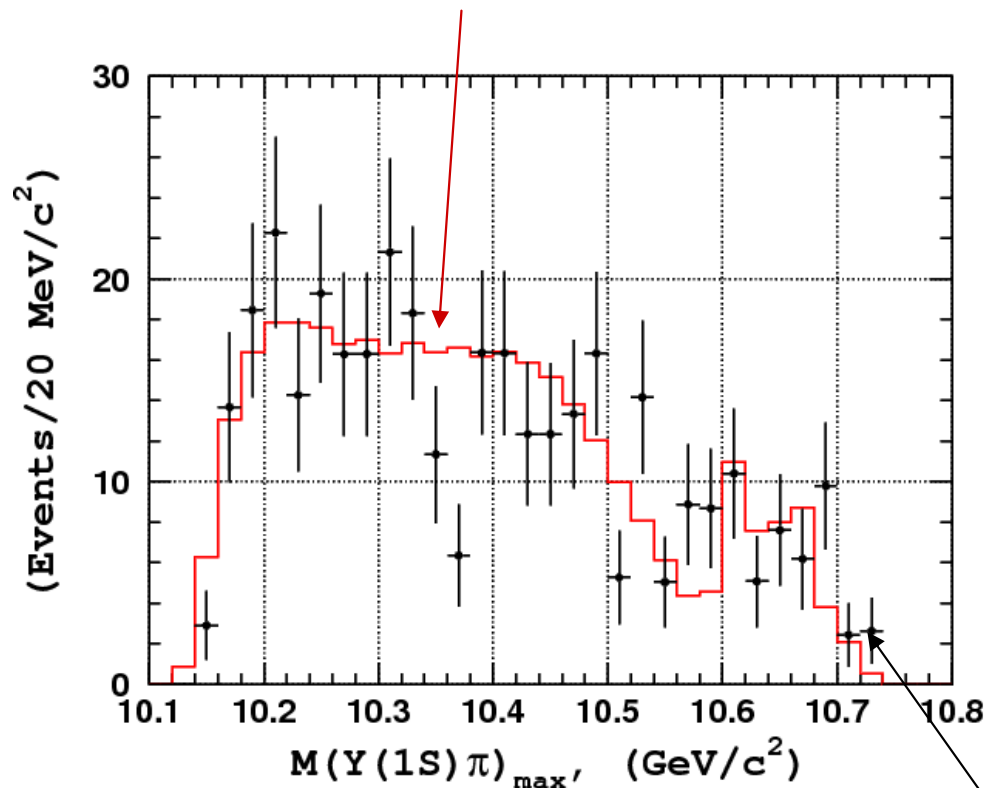
- No charged or C-odd partners of $X(3872)$ have been found
- A first evidence of ψ_2 is obtained in $B \rightarrow K\chi_{c1}\gamma$ decay
- $Y(4260/4360/4660)$ are seen in $\psi(1,2S)\pi^+\pi^-$, however no evidence in $J/\psi\eta$

Back up

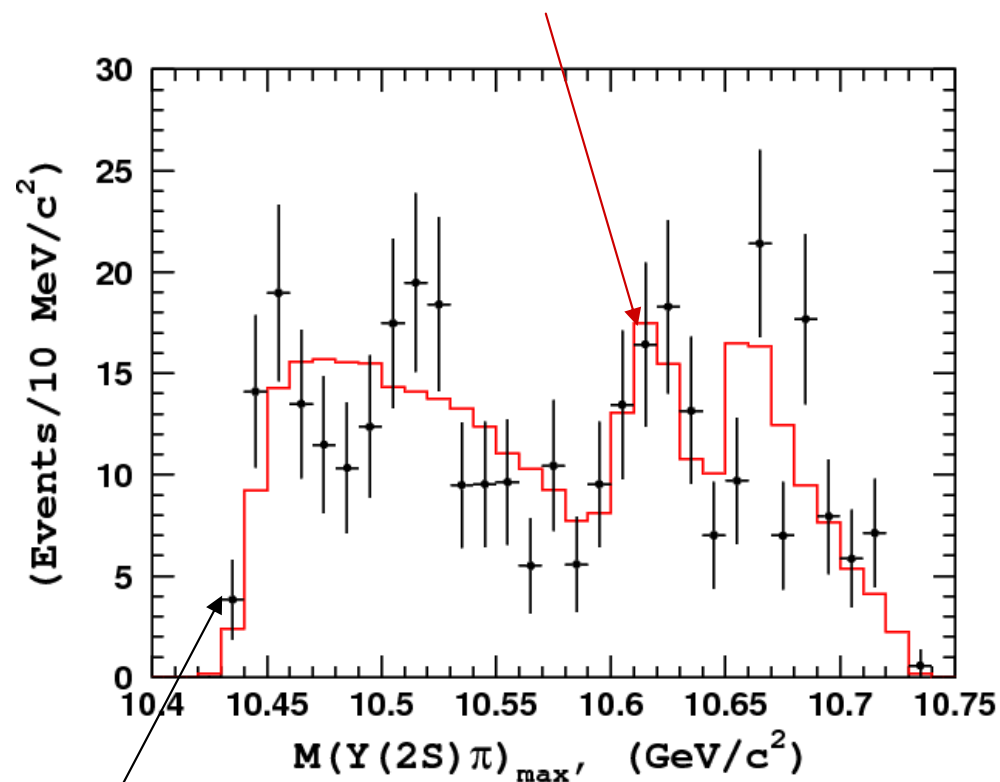
Comparison with $\Upsilon(nS)\pi^+\pi^-$



Fit to the $\Upsilon(1S)\pi^+\pi^-$ data



Fit to the $\Upsilon(2S)\pi^+\pi^-$ data



Background subtracted $\Upsilon nS\pi^0\pi^0$ data

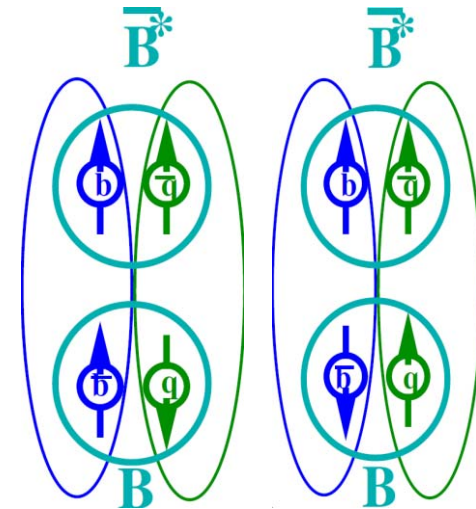
Heavy quark structure in Z_b

Bondar, Garmash, Milstein, Mizuk, Voloshin Phys.Rev.D 84 054010

Wave func. at large distance – $B^{(*)}B^*$

$$|Z'_b\rangle = \frac{1}{\sqrt{2}} 0_{bb}^- \otimes 1_{Qq}^- - \frac{1}{\sqrt{2}} 1_{bb}^- \otimes 0_{Qq}^-$$

$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0_{bb}^- \otimes 1_{Qq}^- + \frac{1}{\sqrt{2}} 1_{bb}^- \otimes 0_{Qq}^-$$



Explains

- Why $h_b \pi \pi$ is unsuppressed relative to $\Upsilon \pi \pi$
- Relative phase ~ 0 for Υ and $\sim 180^\circ$ for h_b
- Production rates of $Z_b(10610)$ and $Z_b(10650)$ are similar
- Widths –”–

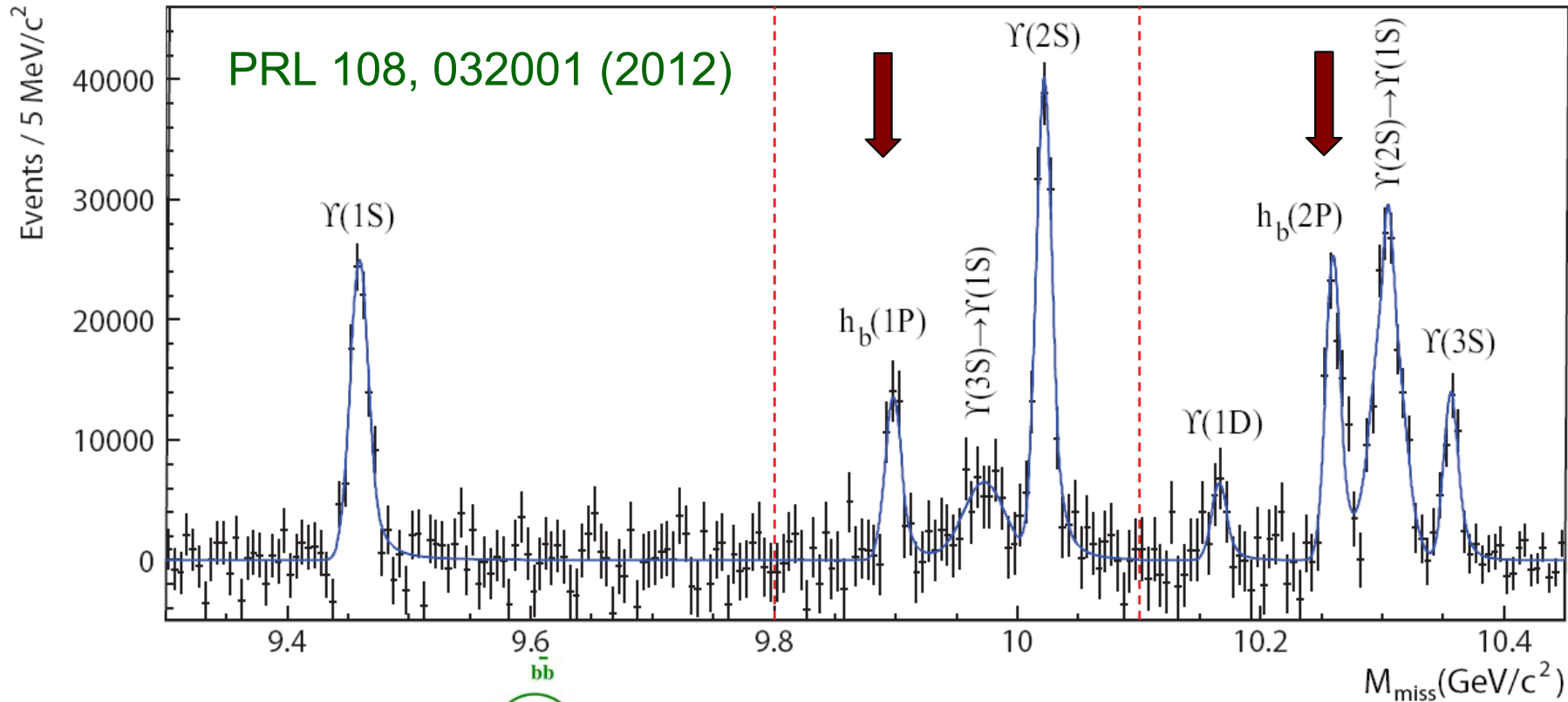
Predicts

- Existence of other similar states

Other Possible Explanations

- Coupled channel resonances (I.V.Danilkin et al, arXiv:1106.1552)
- Cusp (D.Bugg Europhys.Lett.96 (2011), arXiv:1105.5492)
- Tetraquark (M.Karliner, H.Lipkin, arXiv:0802.0649)

Observation of $\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-$



spin-flip



$$\frac{\Gamma[\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-]}{\Gamma[\Upsilon(5S) \rightarrow \Upsilon(2S) \pi^+ \pi^-]} =$$

$$= \begin{cases} 0.45 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no spin-flip

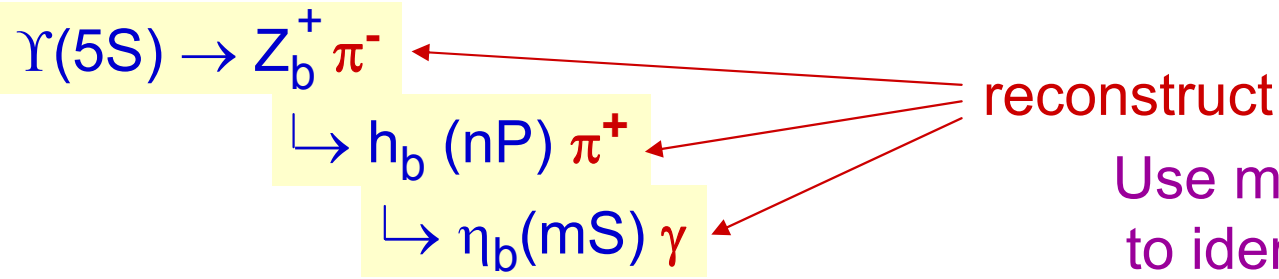


Process with spin flip of heavy quark is not suppressed: mechanism of $\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-$ decay violates Heavy Quark Spin Symmetry

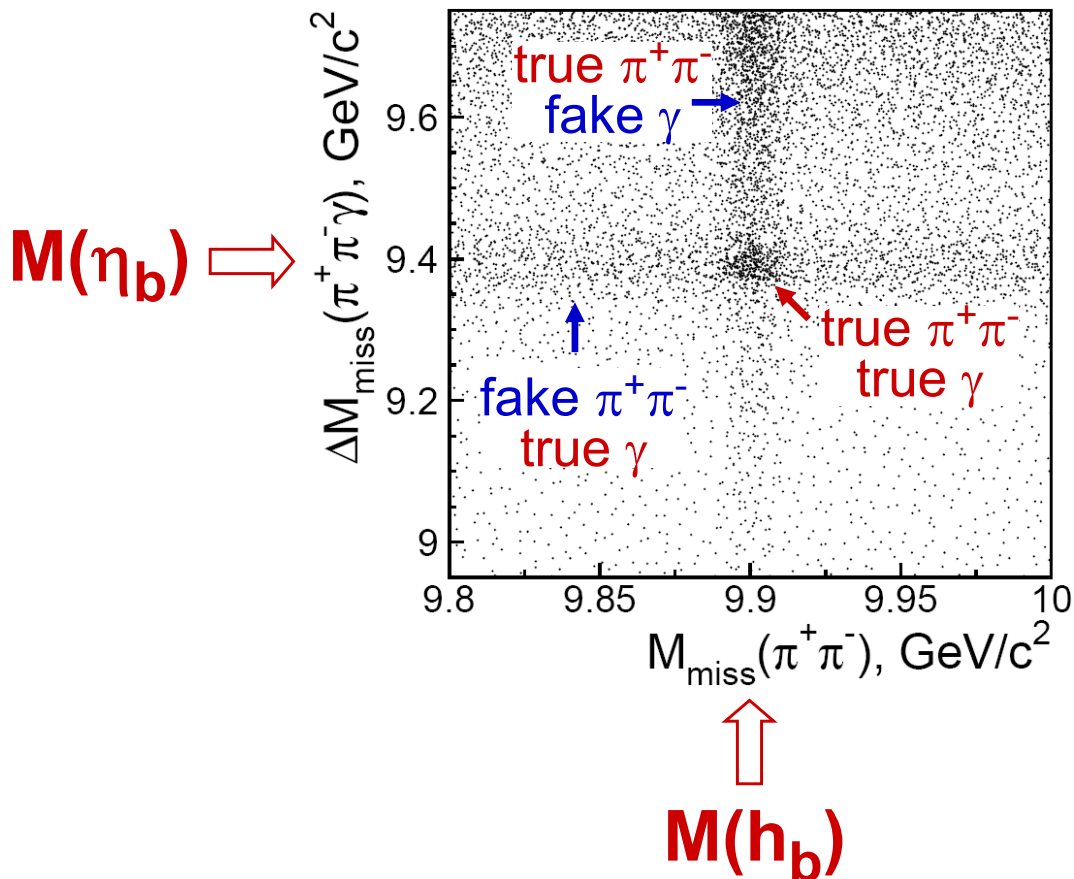
Search for decay $h_b \rightarrow \eta_b \gamma$



Decay chain



MC simulation



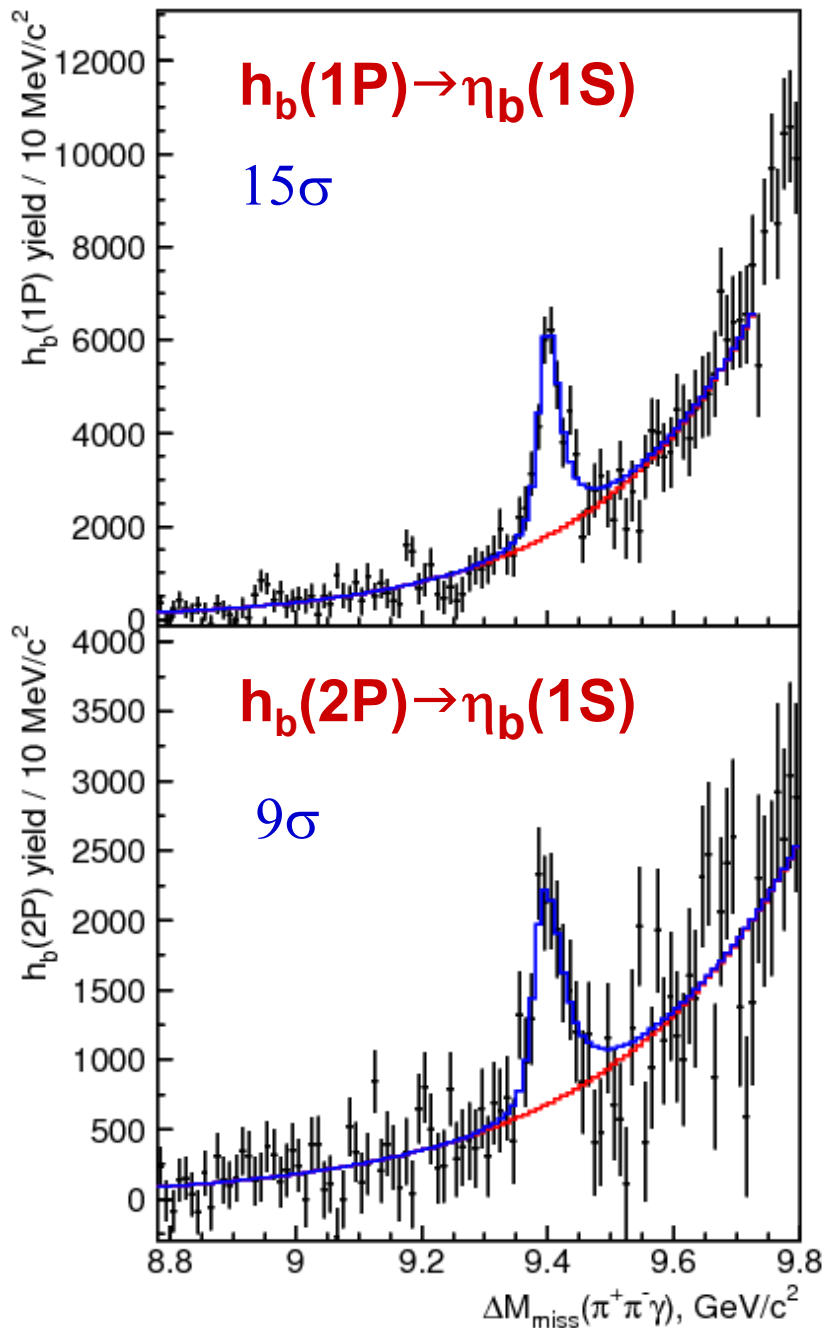
$$\Delta M_{\text{miss}}(\pi^+ \pi^- \gamma) \equiv M_{\text{miss}}(\pi^+ \pi^- \gamma) - M_{\text{miss}}(\pi^+ \pi^-) + M[h_b]$$

Approach:

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

- $\Rightarrow h_b(1P)$ yield vs. $\Delta M_{\text{miss}}(\pi^+ \pi^- \gamma)$
- \Rightarrow search for $\eta_b(1S)$ signal

Observation of $h_b \rightarrow \eta_b(1S) \gamma$



$$M[\eta_b(1S)] = 9402.4 \pm 1.5 \pm 1.8 \text{ MeV}/c^2$$

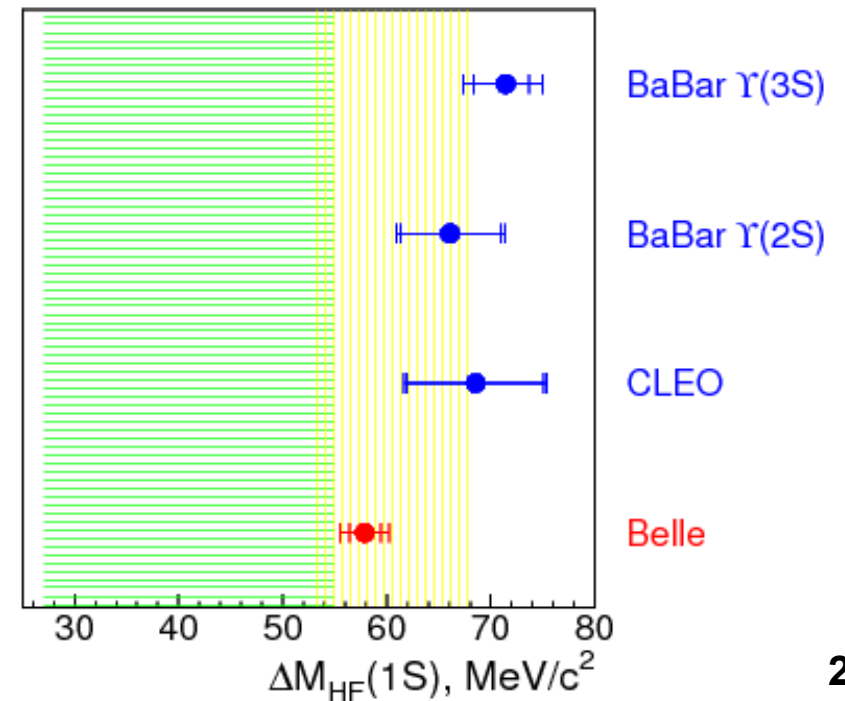
$$\Gamma[\eta_b(1S)] = 10.8^{+4.0+4.5}_{-3.7-2.0} \text{ MeV}$$

potential models : $\Gamma = 5 - 20 \text{ MeV}$

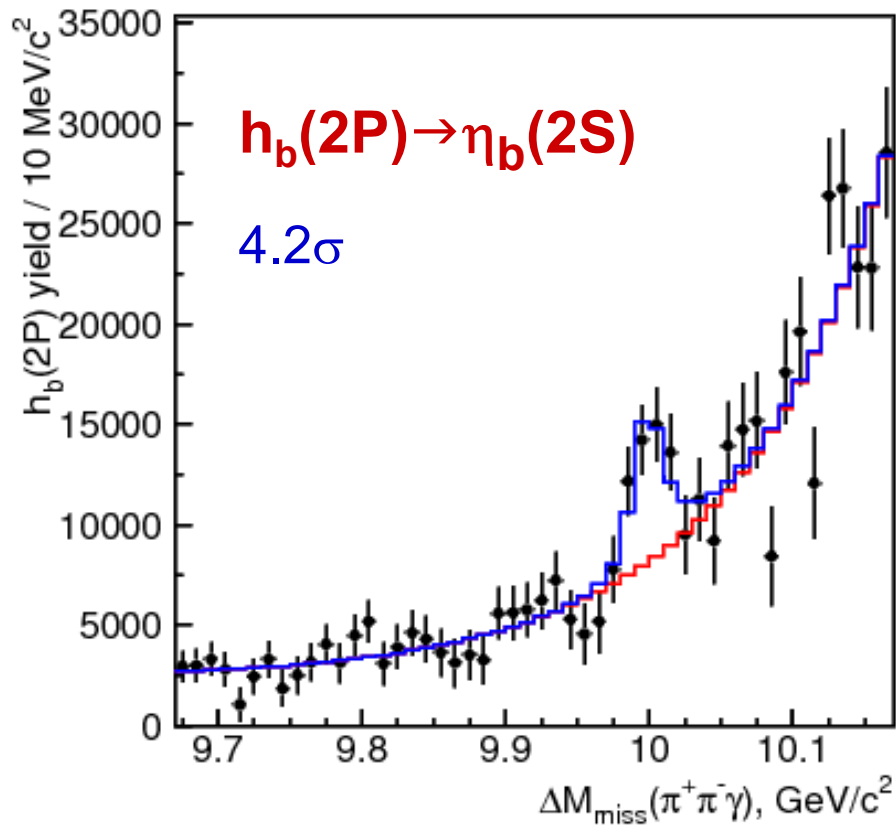
$$B[h_b(1P) \rightarrow \eta_b(1S)\gamma] = (49.2 \pm 5.7^{+5.6}_{-3.3}) \%$$

Godfrey & Rosner : BF = 41%

$$\Delta M_{\text{HF}}[\eta_b(1S)] = 57.9 \pm 2.3 \text{ MeV}/c^2$$



Evidence of $h_b \rightarrow \eta_b(2S) \gamma$



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

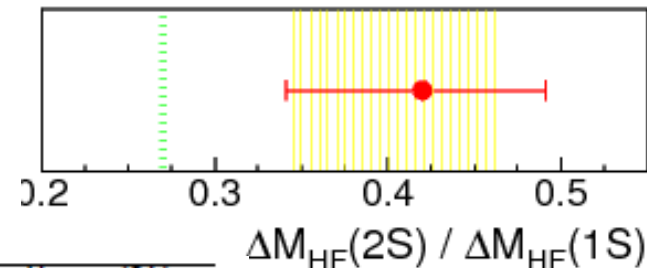
$$\Gamma[\eta_b(2S)] = 10.8^{+4.0+4.5}_{-3.7-2.0} \text{ MeV}$$

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

$$\Delta M_{\text{HF}}[\eta_b(2S)] = 24.3^{+4.0}_{-4.5} \text{ MeV}/c^2$$

$$\Delta M_{\text{HF}} = 23.5 \pm 4.7 \text{ MeV}$$

Lattice Meinel PRD82,114502(2010)



Belle

PRL 109, 232002 (2012)

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



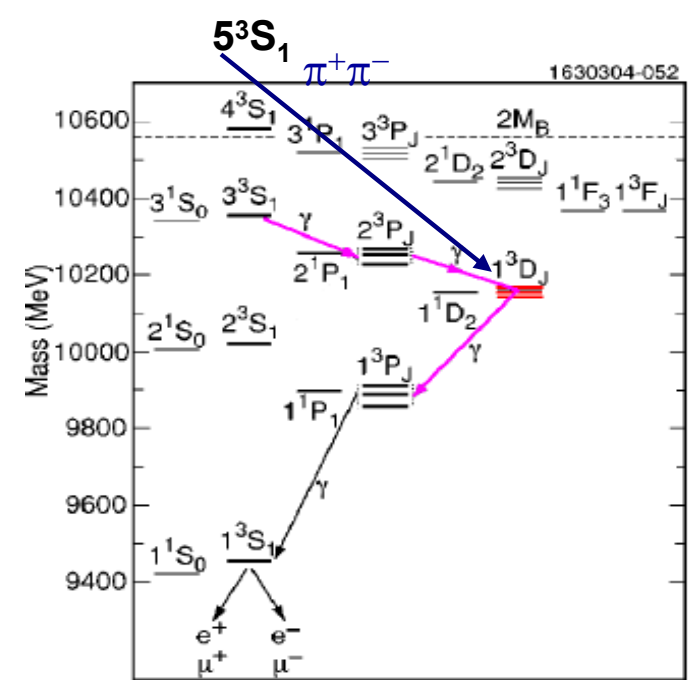
$$\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$$

- First and only one $L=2$ state found in radiative decay chain CLEO(2004):

$$\Upsilon(3S) \rightarrow \chi_b(2P)\gamma \rightarrow \Upsilon(1D)\gamma\gamma \rightarrow \chi_b(1P)\gamma\gamma\gamma \rightarrow \Upsilon(1S)\gamma\gamma\gamma$$

- Belle measured a new production chain

$$\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^- \rightarrow \chi_b(1P)\gamma\pi^+\pi^- \rightarrow \Upsilon(1S)\gamma\gamma\pi^+\pi^-$$



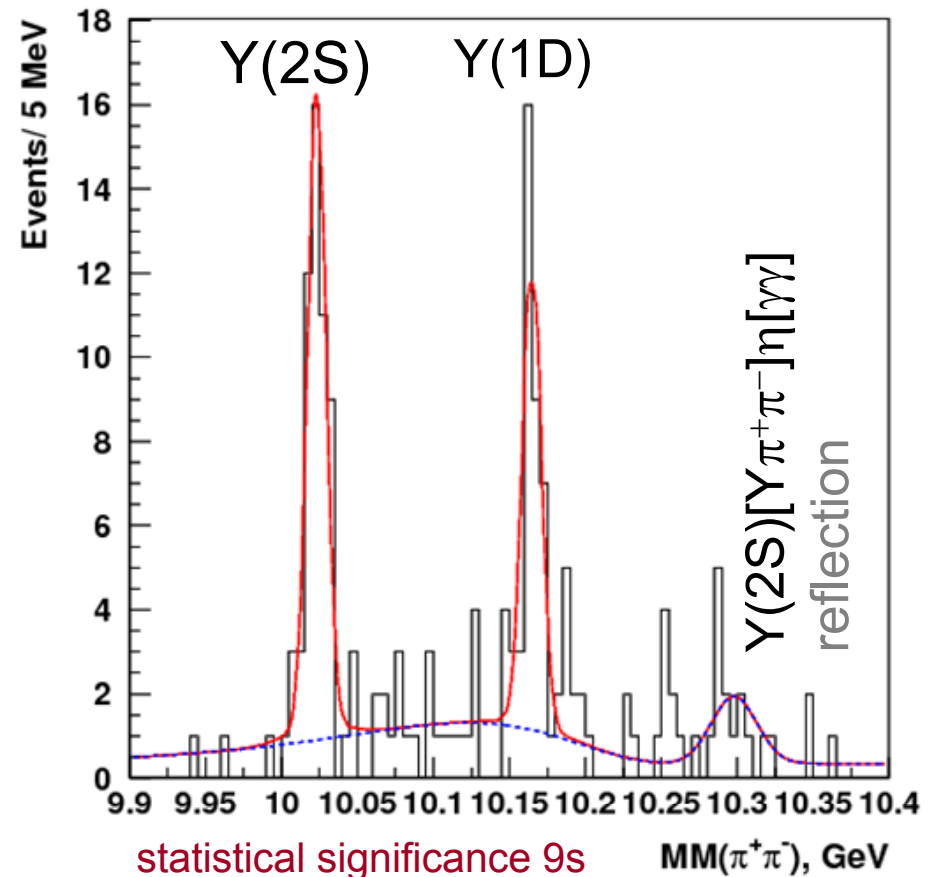
CLEO

$$M = 10161.1 \pm 0.6 \pm 1.6 \text{ MeV}$$

$$B[\Upsilon(3S) \rightarrow \Upsilon(1D)\gamma\gamma \rightarrow \Upsilon(1S)\gamma\gamma\gamma] = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$$

Belle preliminary

$$B[\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^- \rightarrow \Upsilon(1S)\gamma\gamma\pi^+\pi^-] = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4}$$

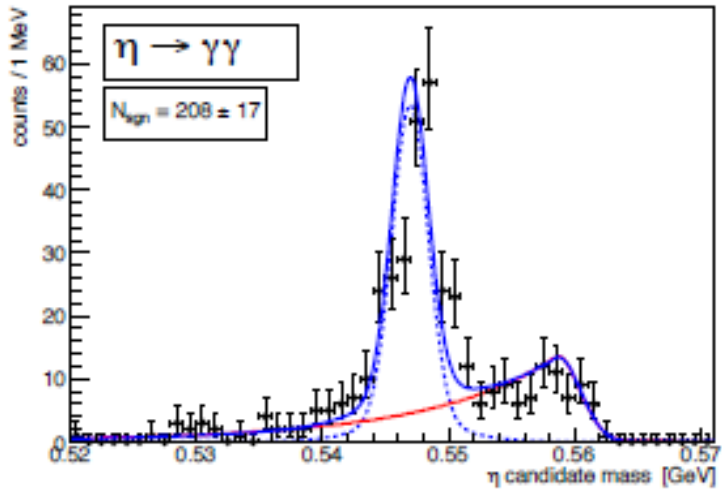


statistical significance 9s

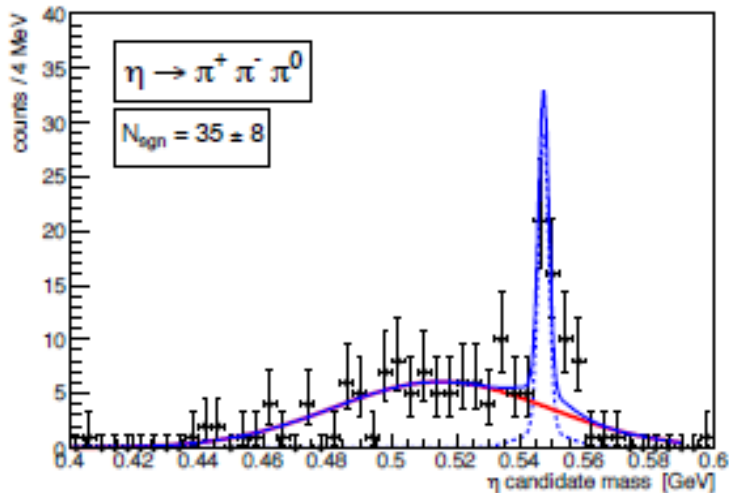
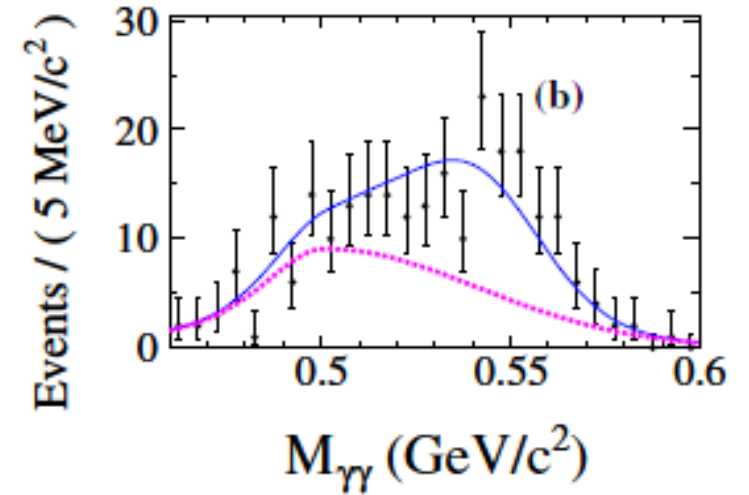
MM($\pi^+\pi^-$), GeV



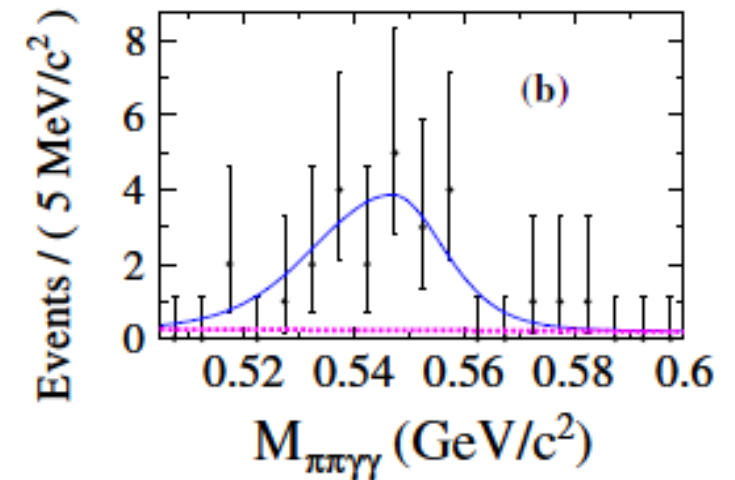
$\Upsilon(2S) \rightarrow \Upsilon(1S)\eta$



$\eta \rightarrow \gamma\gamma$



$\eta \rightarrow \pi^+\pi^-\pi^0$



Phys.Rev.D 84 092003

$$B[\Upsilon(2S) \rightarrow \Upsilon(1S)\eta] = (3.41 \pm 0.37 \pm 0.35) 10^{-4}$$

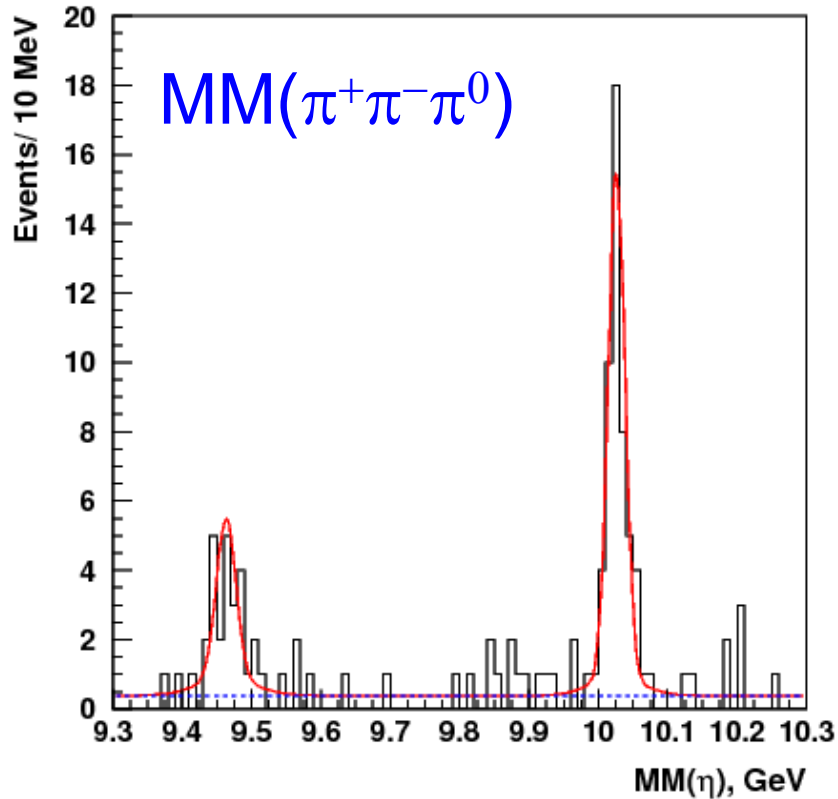
$$B[\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0] < 4.3 10^{-5}$$

PRD 87, 011104(R) (2013)

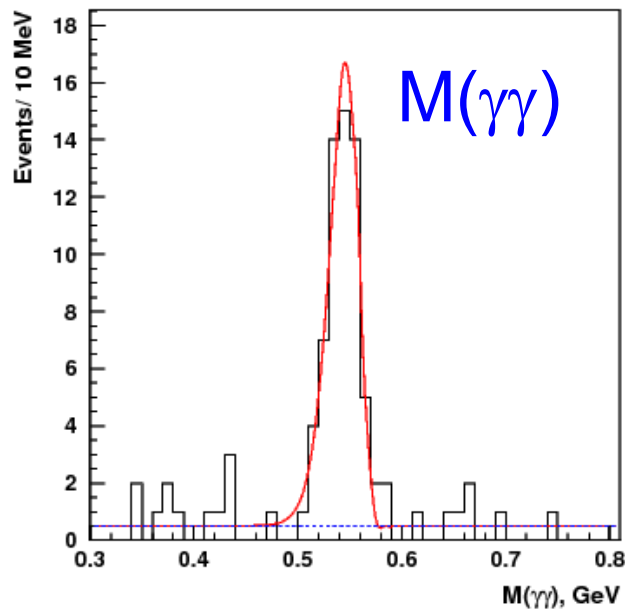
$$B[\Upsilon(2S) \rightarrow \Upsilon(1S)\eta] = (2.39 \pm 0.31 \pm 0.14) 10^{-4}$$

$$B[\Upsilon(3S) \rightarrow \Upsilon(1S)\eta] < 1.0 10^{-4}$$

Observation of $\Upsilon(5S) \rightarrow \Upsilon(1,2S)\eta$



- Three modes:
 - $\Upsilon(1,2S)[\mu^+\mu^-] \eta[\pi^+\pi^-\pi^0]$
 - $\Upsilon(2S)[\Upsilon(1S)\pi^+\pi^-] \eta[\gamma\gamma]$
 - $\Upsilon(1S)[\mu^+\mu^-] \eta'[\eta\pi^+\pi^-]$



$$B[\Upsilon(5S) \rightarrow \Upsilon(1S)\eta] = (7.3 \pm 1.6 \pm 0.8) 10^{-4}$$

$$B[\Upsilon(5S) \rightarrow \Upsilon(2S)\eta] = (38 \pm 4 \pm 5) 10^{-4}$$

$$B[\Upsilon(5S) \rightarrow \Upsilon(1S)\eta'] < 1.2 10^{-4}$$

preliminary