# Bottomonia & charmonia at B-factories

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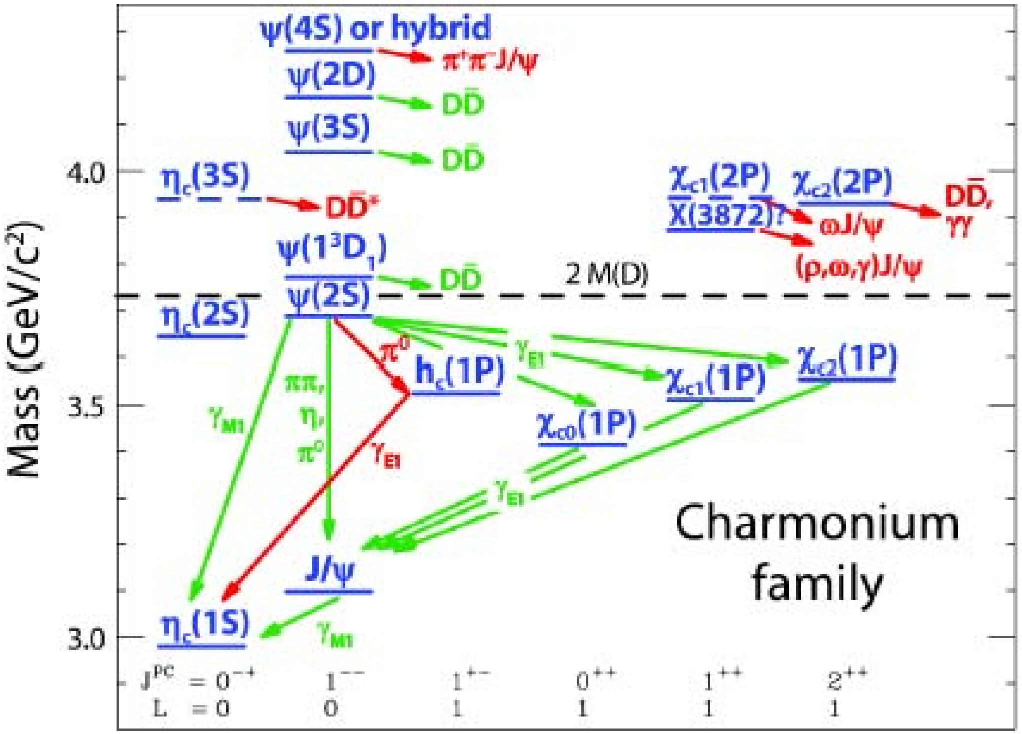
- Introduction
- Bottomonium states
    - $Z_b(10610)$ and $Z_b(10650)$
- Charmonium states
    - Study of X, Y, Z states
    - Evidence for $\psi_2$
- Summary

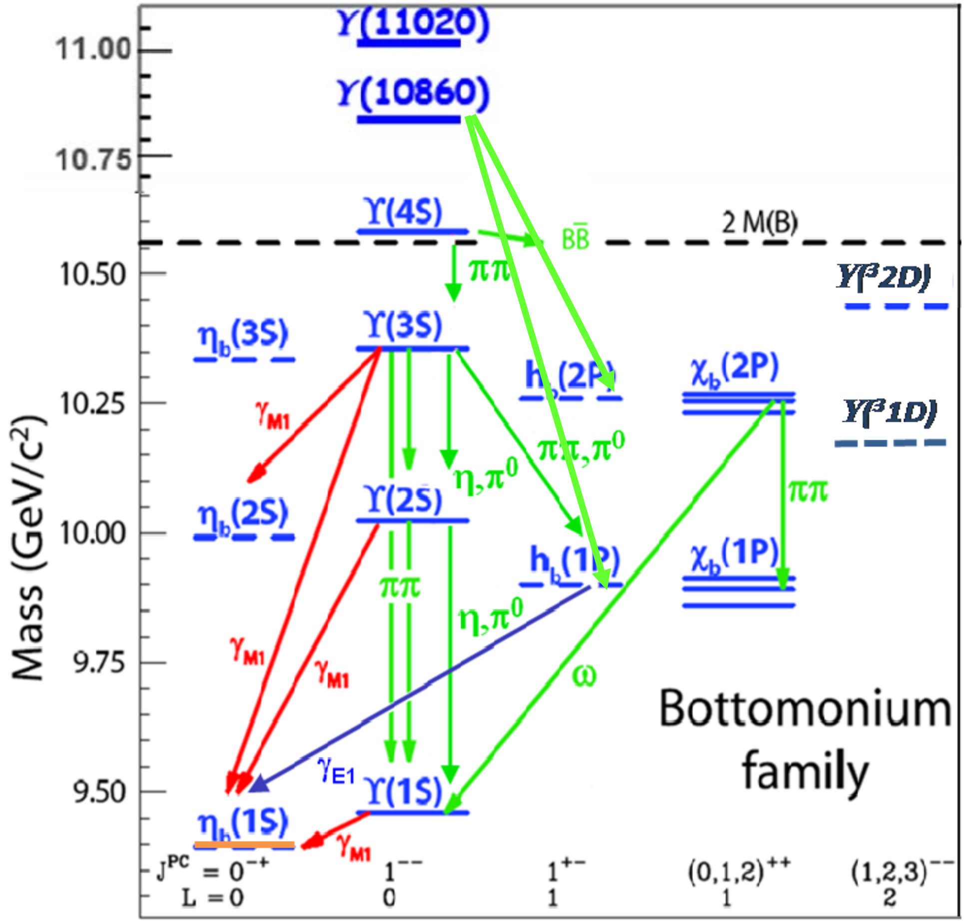
**QFTHEP 2013**

# 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$^{-1}$

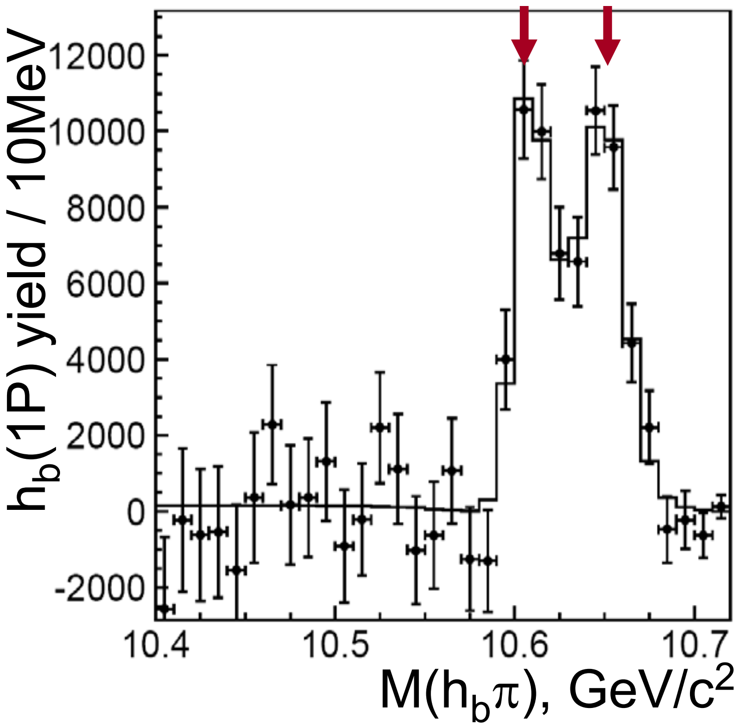


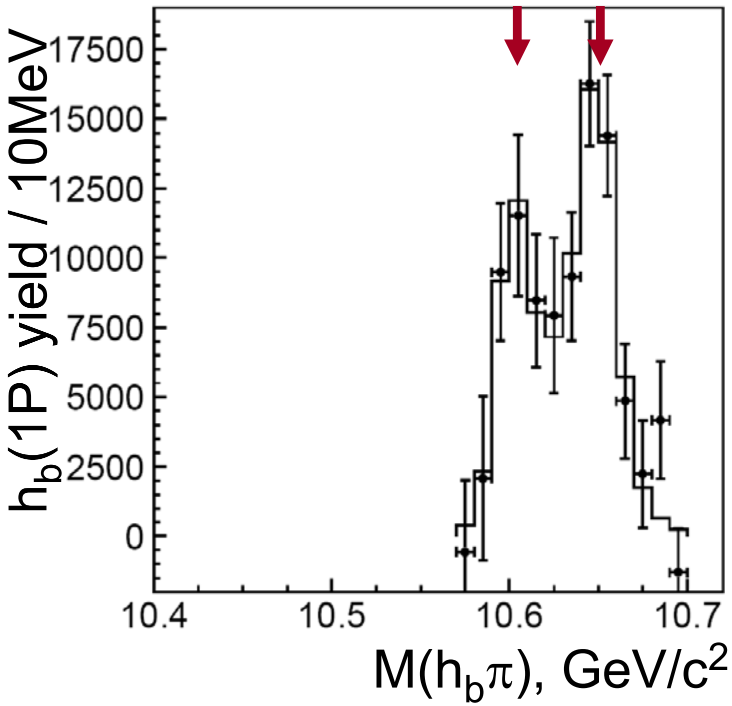




Heavy Quarkonia are ideal tool for testing QCD

# Discovery of $Z_b$

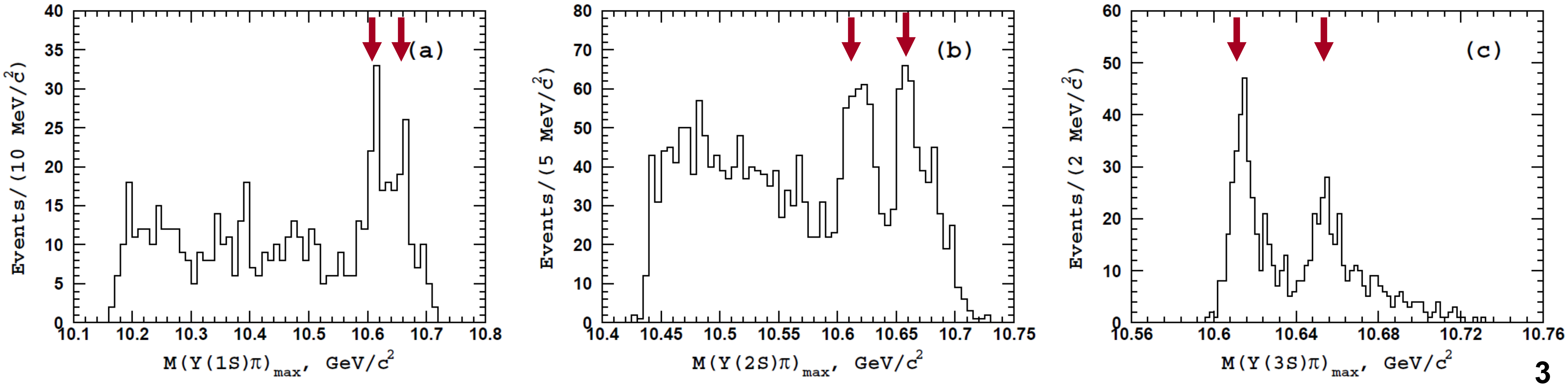
## In analysis of $\Upsilon(5S)\to h_b(mP)\pi^+\pi^-$ and $\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-$




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

PRL 108, 122001 (2012)



# Summary of $Z_b$ parameters

Average over 5 channels

**$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV**

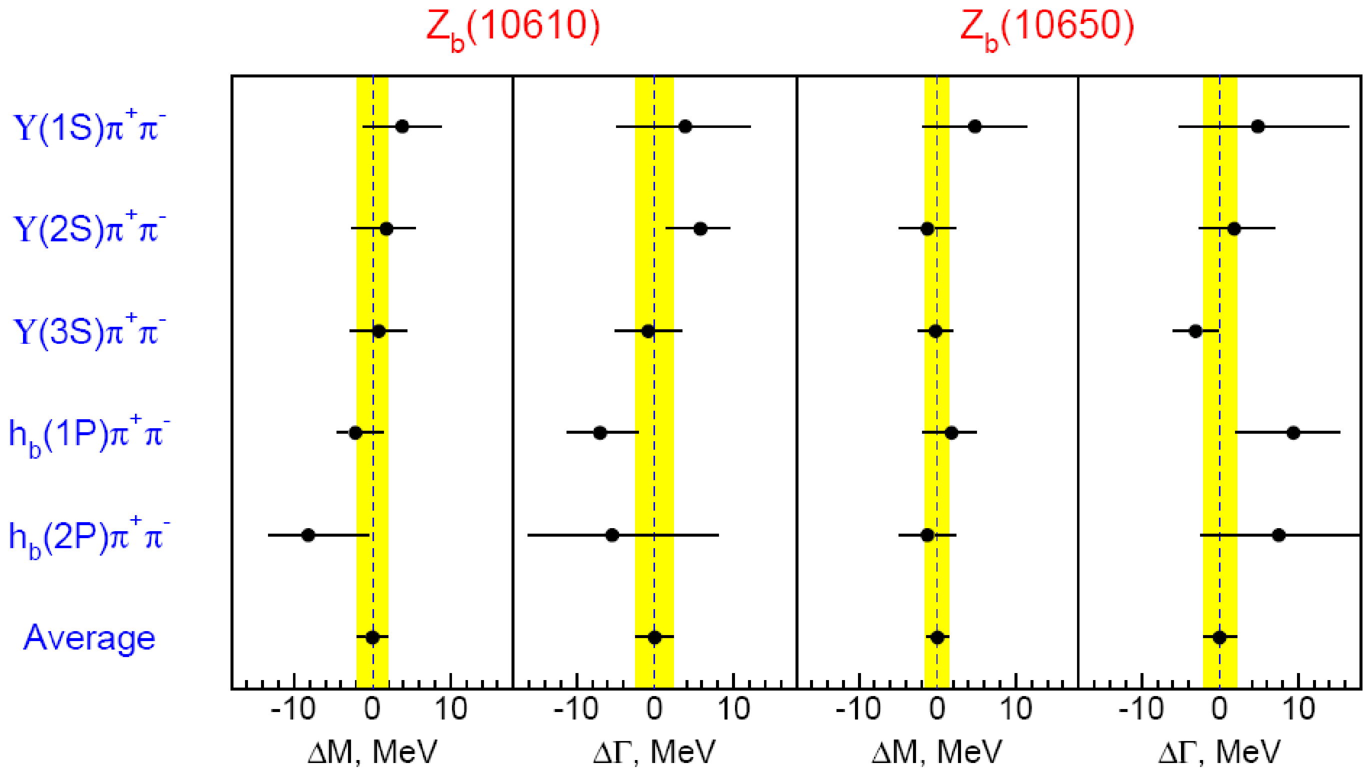
**$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV**

M(BB*)=10604.8 ± 0.4 MeV

**$\langle M_2 \rangle = 10652.2 \pm 1.5$ MeV**

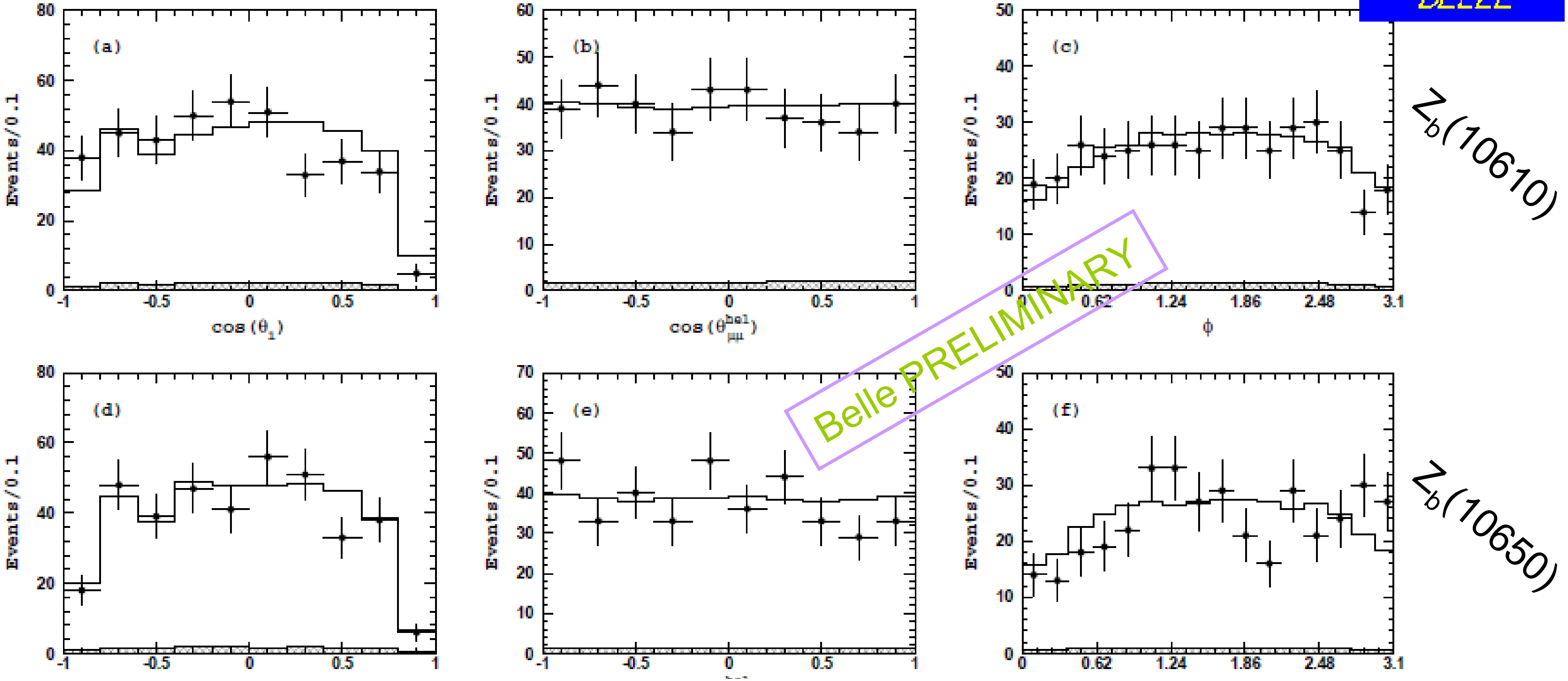
**$\langle \Gamma_2 \rangle = 11.5 \pm 2.2$ MeV**

M(B*B*)=10650.4 ± 0.8 MeV




| Final state | $\Upsilon(1S)\pi^+\pi^-$ | $\Upsilon(2S)\pi^+\pi^-$ | $\Upsilon(3S)\pi^+\pi^-$ | $h_b(1P)\pi^+\pi^-$ | $h_b(2P)\pi^+\pi^-$ |
|---|---|---|---|---|---|
| $M[Z_b(10610)]$, MeV/$c^2$ | $10611 \pm 4 \pm 3$ | $10609 \pm 2 \pm 3$ | $10608 \pm 2 \pm 3$ | $10605 \pm 2^{+3}_{-1}$ | $10599^{+6+5}_{-3-4}$ |
| $\Gamma[Z_b(10610)]$, MeV | $22.3 \pm 7.7^{+3.0}_{-4.0}$ | $24.2 \pm 3.1^{+2.0}_{-3.0}$ | $17.6 \pm 3.0 \pm 3.0$ | $11.4\,^{+4.5+2.1}_{-3.9-1.2}$ | $13\,^{+10+9}_{-8-7}$ |
| $M[Z_b(10650)]$, MeV/$c^2$ | $10657 \pm 6 \pm 3$ | $10651 \pm 2 \pm 3$ | $10652 \pm 1 \pm 2$ | $10654 \pm 3\,^{+1}_{-2}$ | $10651^{+2+3}_{-3-2}$ |
| $\Gamma[Z_b(10650)]$, 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




Angle between prompt pion and beam axis

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

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

| $J^P$ \ 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 |

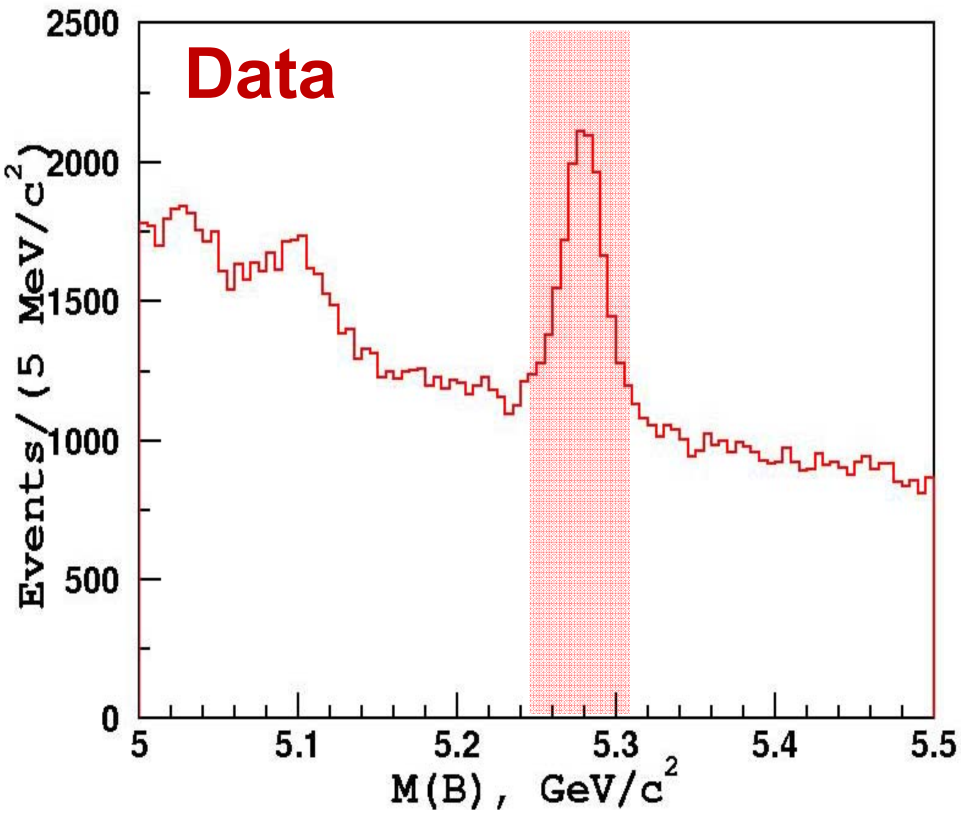
Confirms $J^P=1^+$ hypothesis

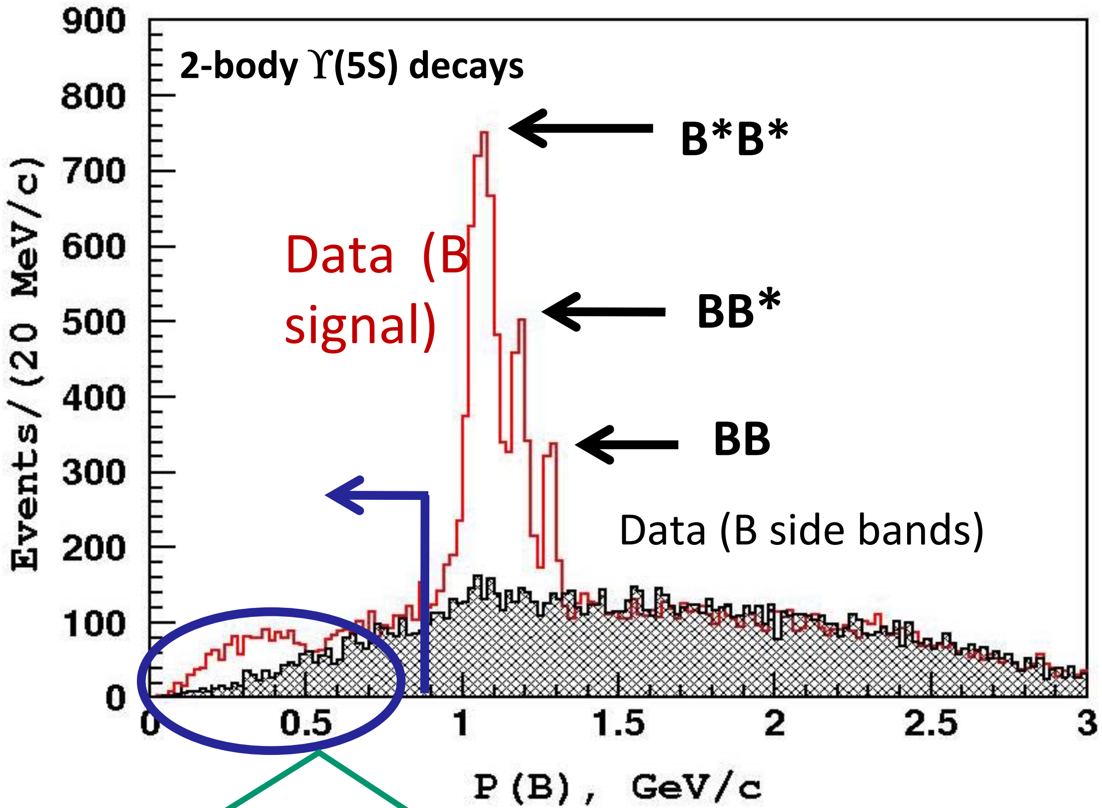
6D amplitude analysis of decays $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

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

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

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




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

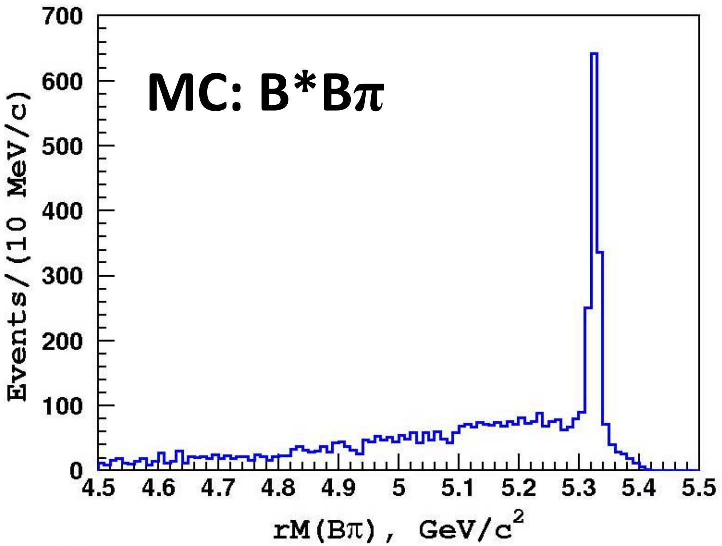
Effective B fraction:
$Br[B\to f] = 1.4 \times 10^{-3}$

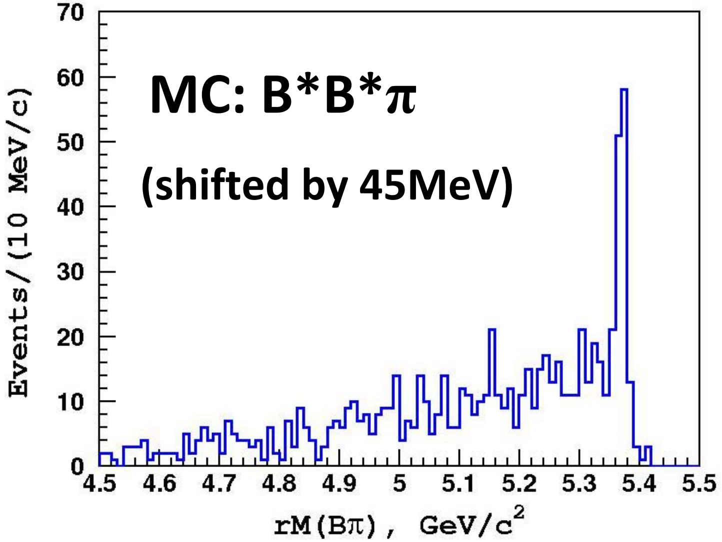
Charged B: $D^0[K\pi, K\pi\pi\pi]\pi^-$, $J/\psi[\mu\mu]\ K^-$

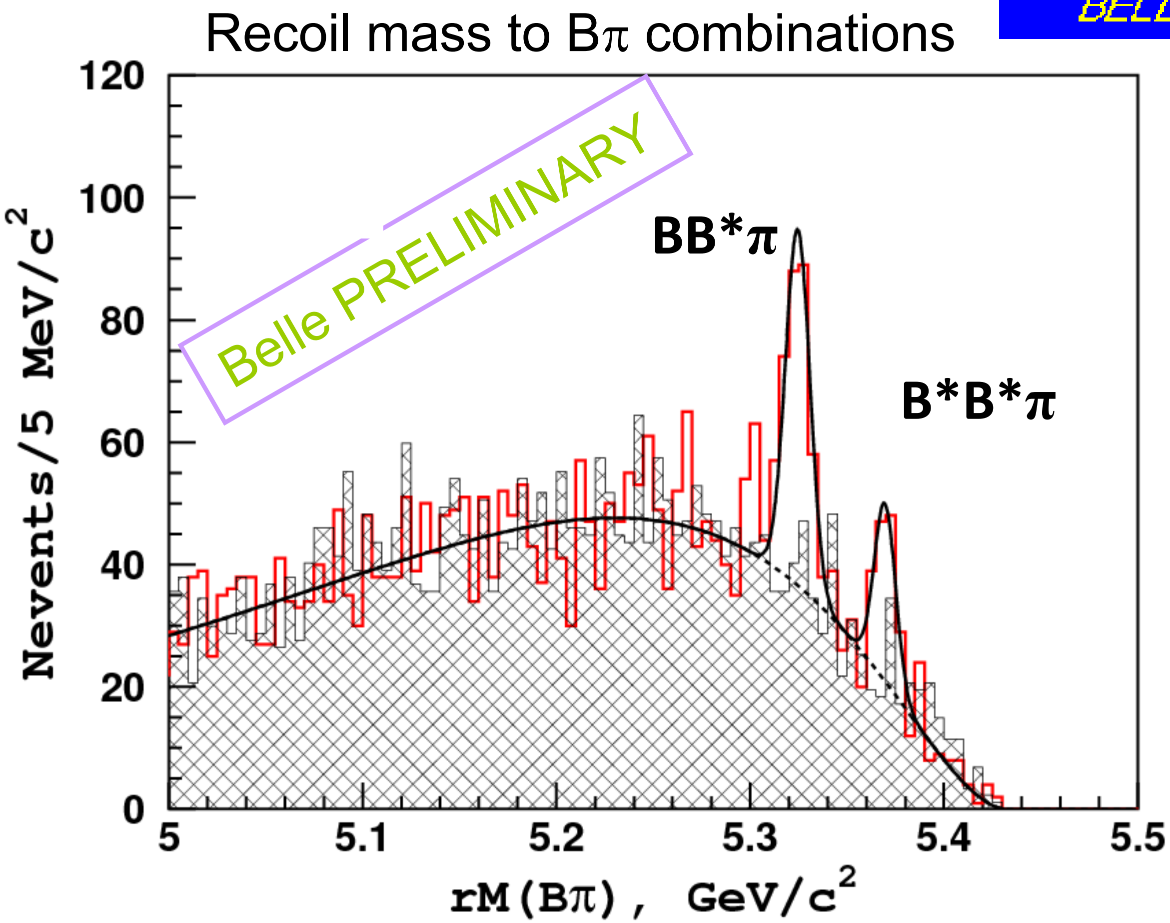
Neutral B: $D^+[K\pi\pi]\pi^-$, $J/\psi[\mu\mu]\ K^{*0}$, $D^{*+}[K\pi, K\pi\pi^0, K\pi\pi\pi]\pi^-$

Belle PRELIMINARY

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



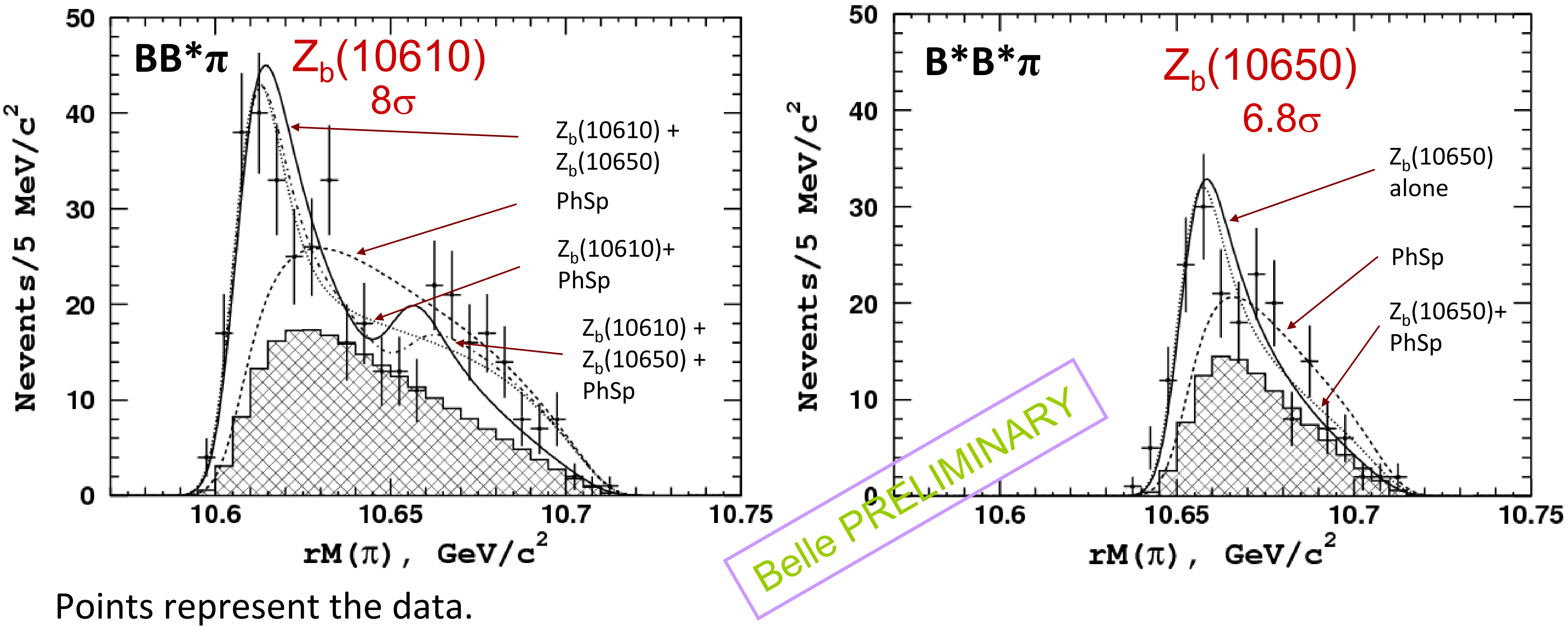

Red histogram: right charge combination Bπ;
Hatched histogram: wrong charge combination;
The curve show the fit to the data.

arXiv:1209.6450

**Fit yields:** **N(BBπ) = 0.3 ± 14**

**N(BB*π) = 184 ± 19 (9.3σ)** **N(B*B*π) = 82 ± 11 (5.7σ)**

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




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

arXiv:1209.6450

$B^*B^*\pi$ candidates are well described by $Z_b(10650)$ only contribution.
$BB^*\pi$ can be described by two models:

- $Z_b(10610) + Z_b(10650)$;
- $Z_b(10610)$ + non-resonant amplitude.

# $Z_b$ branching fractions

$\Upsilon(5S)$ branching fractions:

BB$\pi$ < 0.60% (90%CL)

BB*$\pi$ = 4.25 ± 0.44 ± 0.69%

B*B*$\pi$ = 2.12 ± 0.29 ± 0.36%

To be compared with PRD 81 (2010)
f(BB*$\pi$) = (7.3±2.2±0.8)%
f(B*B*$\pi$) = (1.0±1.4±0.4)%

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

arXiv:1209.6450

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

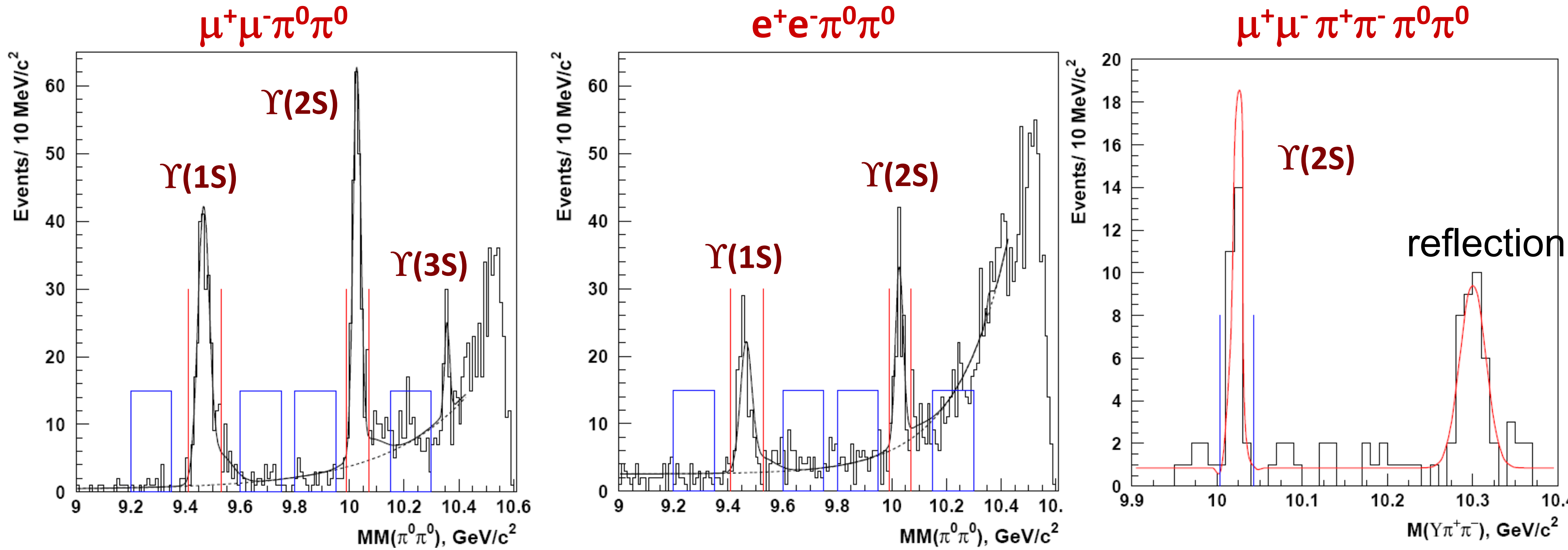
Belle PRELIMINARY

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

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

arXiv:1207.4345

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




**BF[$\Upsilon(5S)\to\Upsilon(1S)\pi^0\pi^0$] = $(2.25\pm0.11\pm0.20)\ 10^{-3}$**

**BF[$\Upsilon(5S)\to\Upsilon(2S)\pi^0\pi^0$] = $(3.79\pm0.24\pm0.49)\ 10^{-3}$**

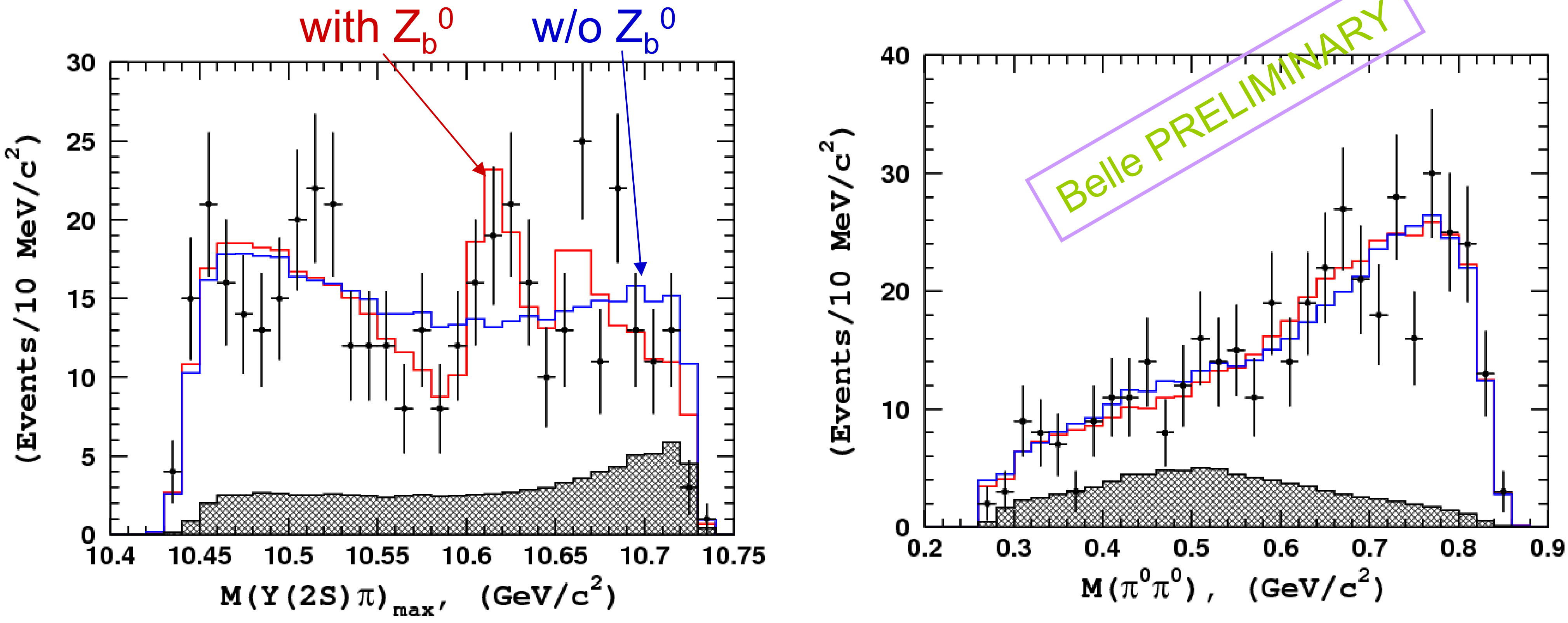
Consistent with ½ of $Y(nS)\pi^+\pi^-$

Belle PRELIMINARY

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

arXiv:1207.4345

$$M(s_1, s_2) = A_{Z1} + A_{Z2} + A_{f_0} + A_{f_2} + A_{NR}$$

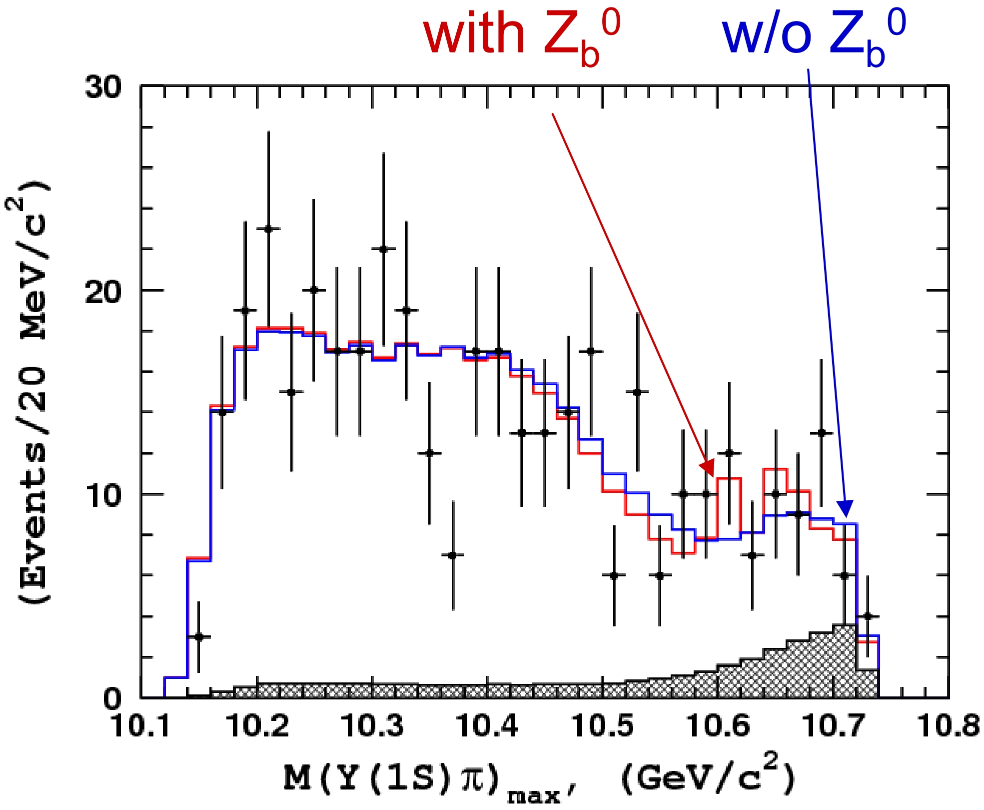


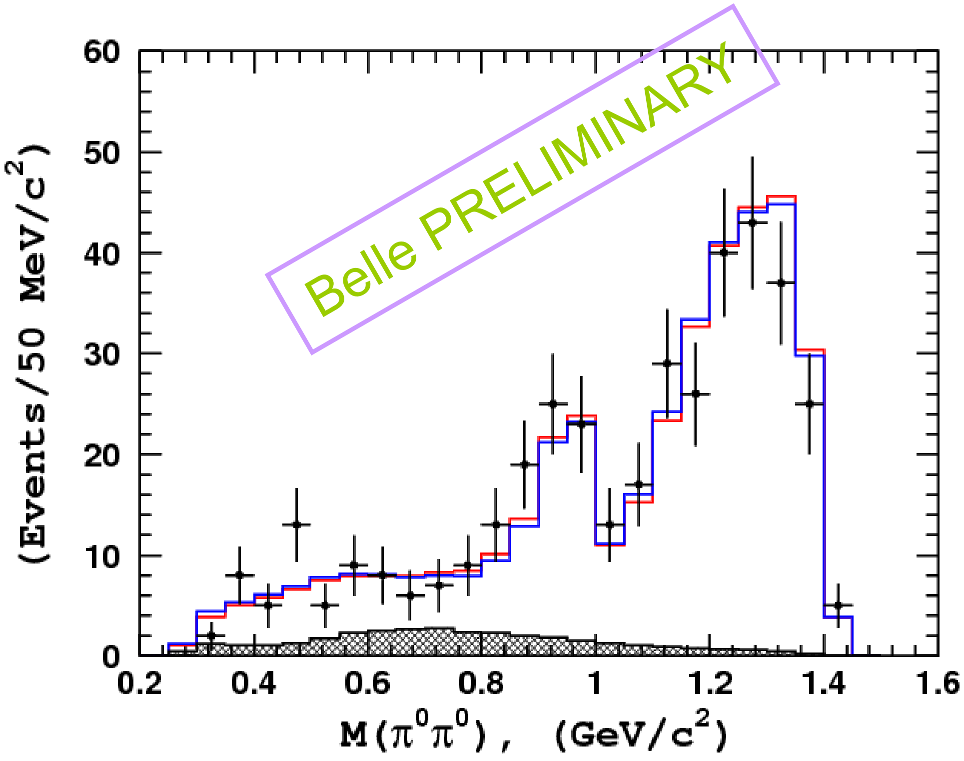

- $Z_b^0$ resonant structure is observed in $\Upsilon(2S)\pi^0\pi^0$
- Statistical significance of $Z_b^0(10610)$ signal is 5.3σ (4.9σ with systematics)
- $Z_b^0(10650)$ signal is not significant (~2σ), not contradicting with its existence
- $Z_b^0(10610)$ mass from the fit M=10609 ± 8 ± 6 MeV/$c^2$

$M(Z_b^+)$=10607±2 MeV/$c^2$

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

Dalitz analysis $$M(s_1, s_2) = A_{Z1} + A_{Z2} + A_{f_0} + A_{f_2} + A_{NR}$$



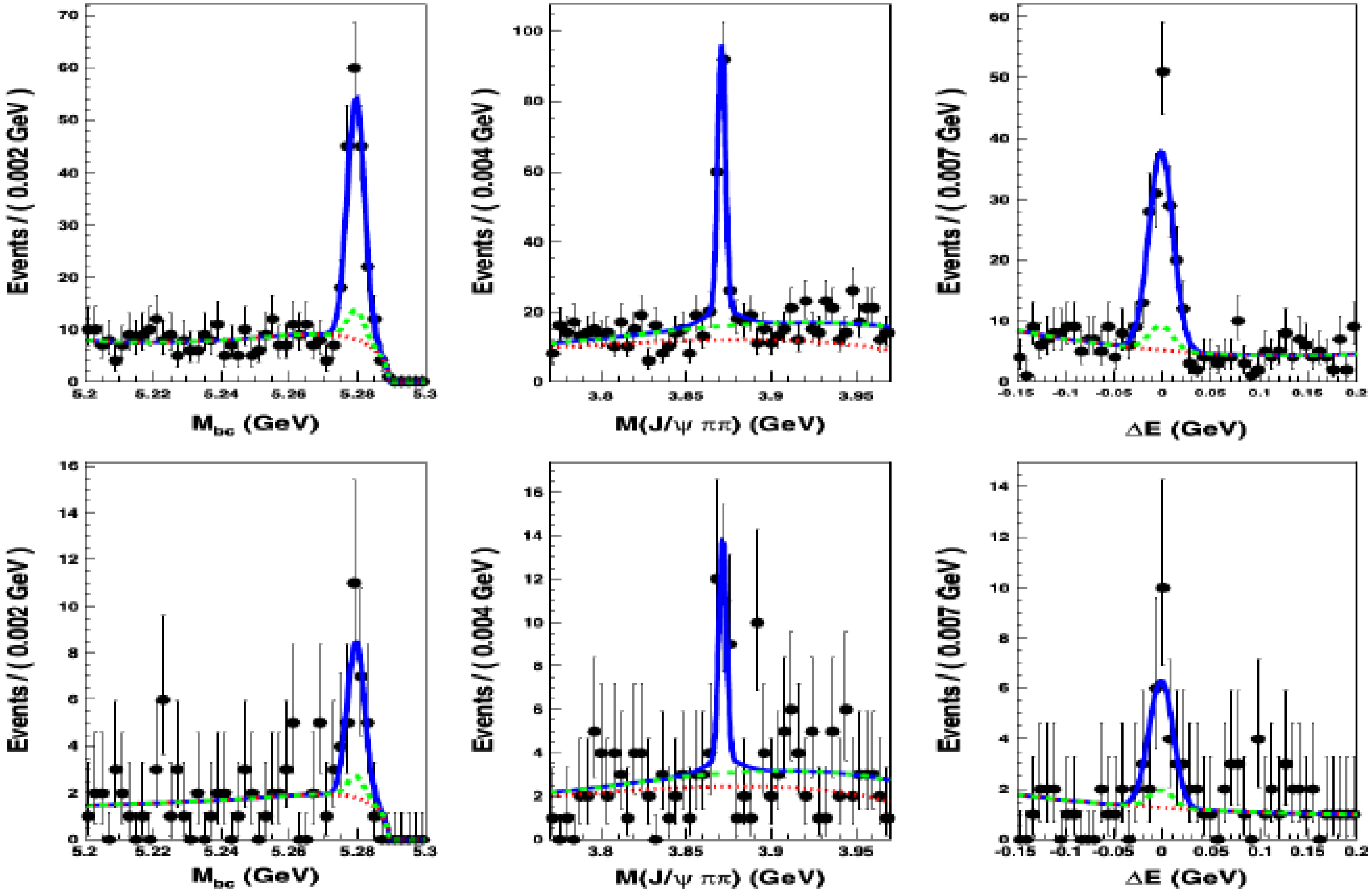

Signals of both $Z_b^0$ are not significant. Data is not contradicting with their existence.

arXiv:1207.4345

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

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

Update using 772 $10^6$ $B\bar{B}$ PRD 84, 052004 (2011)

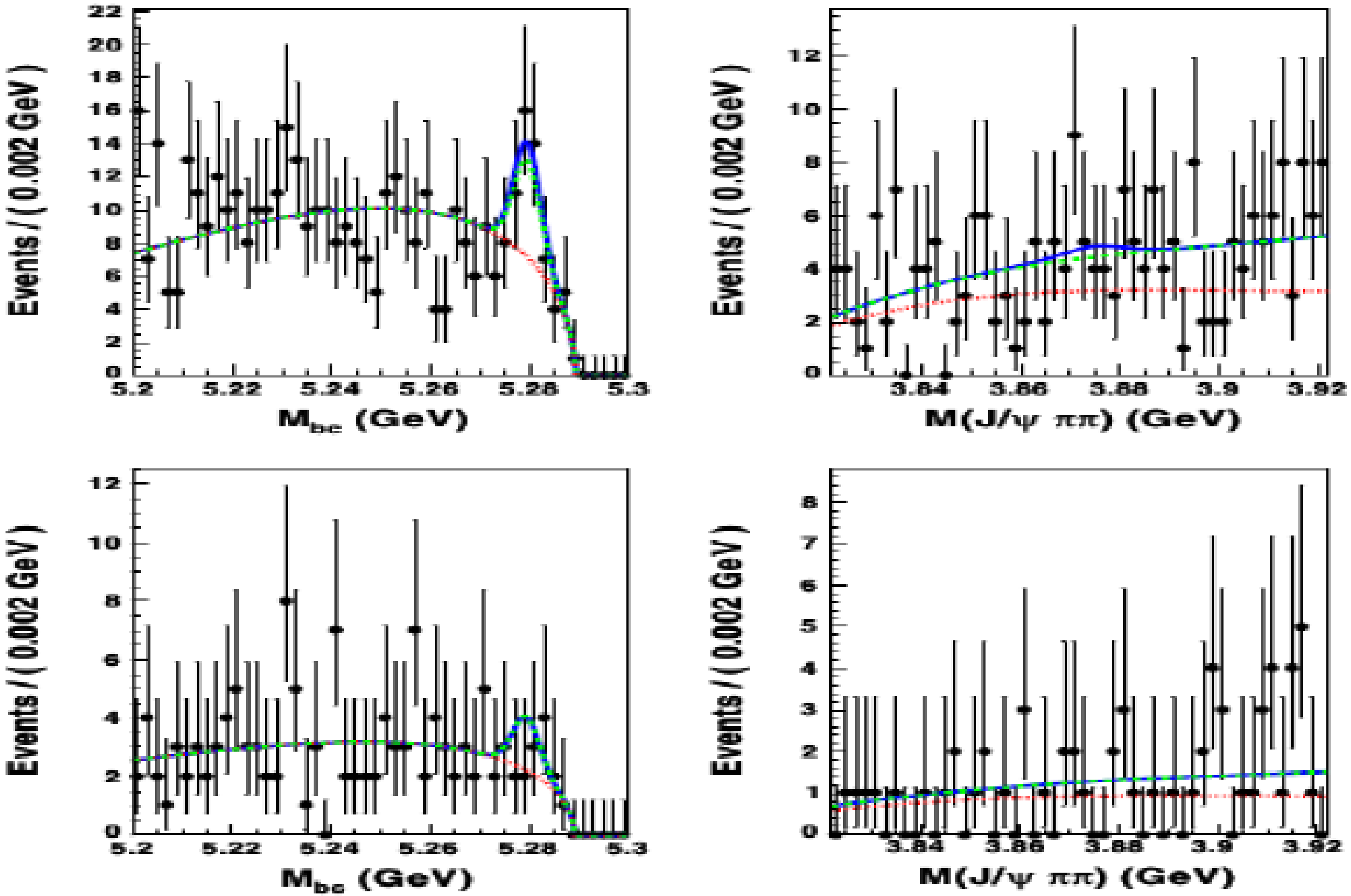



M(3872)=3871.84 ± 0.27 ± 0.19 MeV/$c^2$; Γ(3872)<1.2 MeV @ 90% CL

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

# Search for charged X

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




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

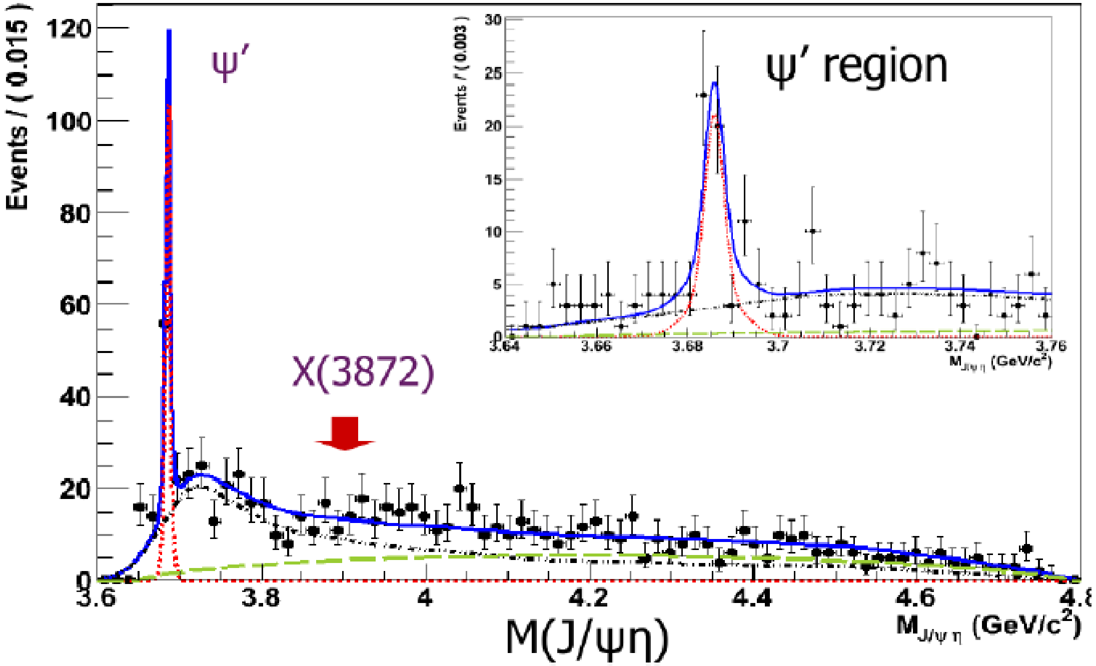
$B^+ \rightarrow K^0 \rho^+ J/\psi$

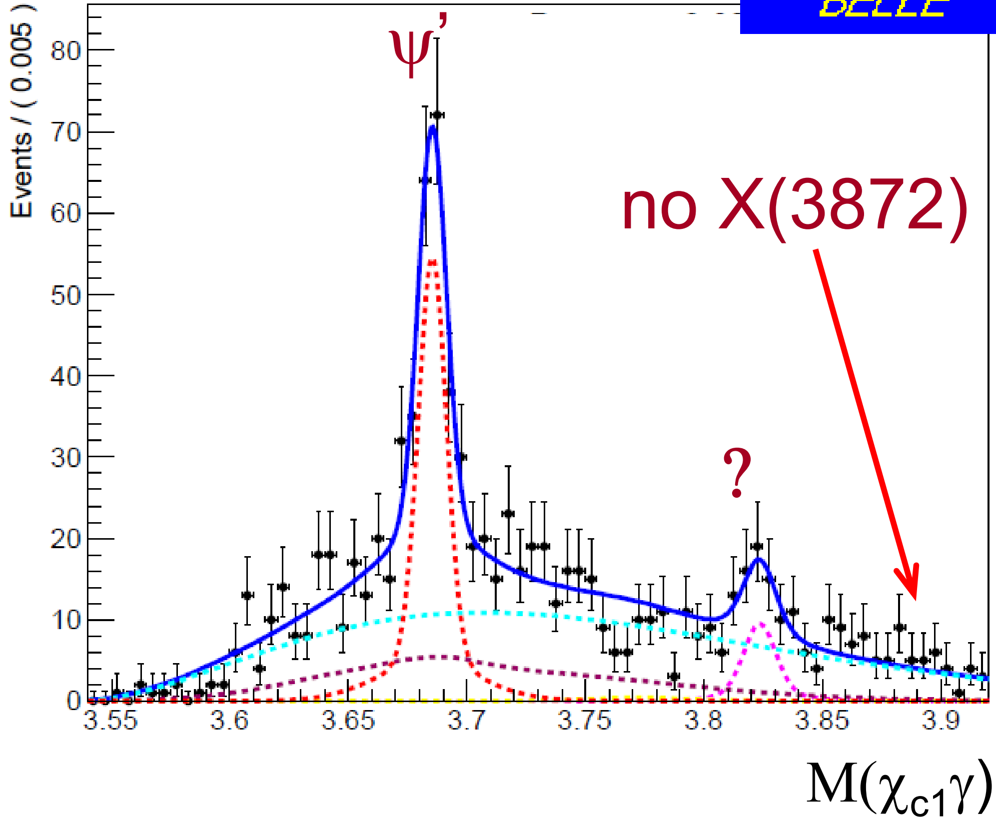
$B(\overline{B}^0 \rightarrow X^+K^-) \times B(X^+ \rightarrow J/\psi\rho^+) < 4.2\ 10^{-6}$

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

PRD 84, 052004 (2011)

# Search for C-odd partner of X(3872)




- $B \to K + \eta J/\psi$: only $\psi'$ 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):

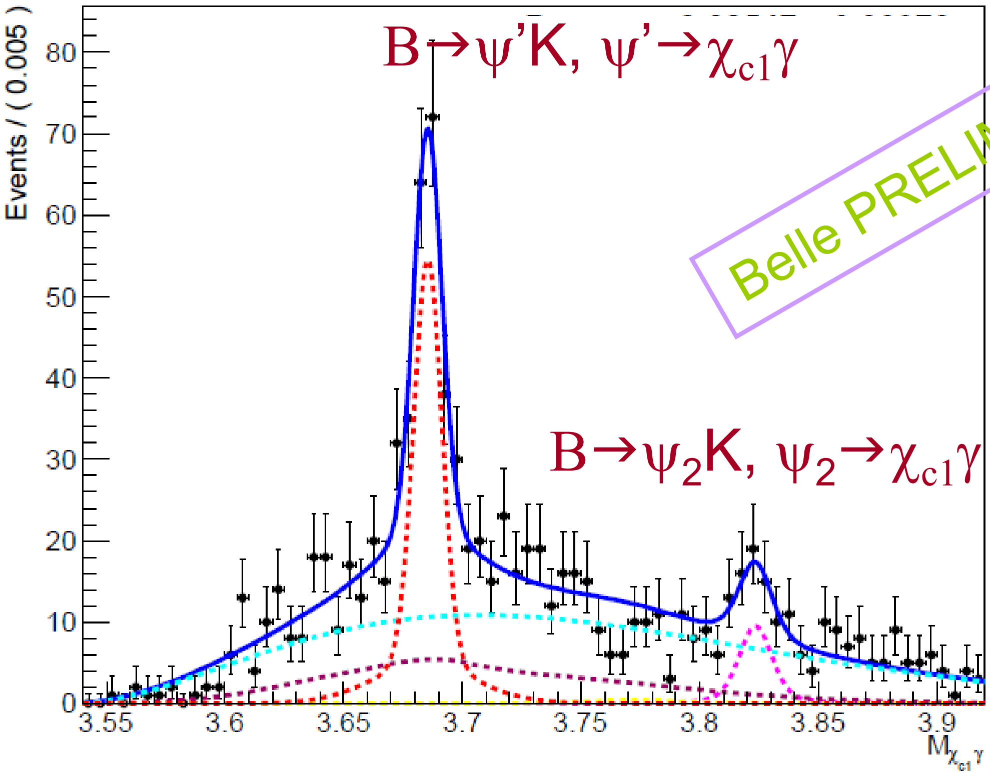
  $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) = (8.6 \pm 0.8 \pm 0.5) \times 10^{-6}$.
- BUT, what's the peak at $M(\gamma\chi_{c1})$? A new charmonium state observed?

# Evidence for $\psi_2 \to \chi_{c1}\gamma$

$\psi_2 \to \chi_{c1}\gamma$ was predicted, $\Gamma(\psi_2 \to \chi_{c1}\gamma)$=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 |
|---|---|---|---|---|---|
| $\eta_{c2}$ | $1^1D_2$ | $2^{-+}$ | -- | 3780–3840 | $\eta_c \pi\pi$ |
| $\psi''$ | $1^3D_1$ | $1^{--}$ | 3772.9(4) | 3785–3819 | $D\bar{D}$ |
| $\psi_2$ | $1^3D_2$ | $2^{--}$ | -- | 3800–3840 | $\chi_{c1,2}\gamma$ |
| $\psi_3$ | $1^3D_3$ | $3^{--}$ | -- | 3810–3850 | $D\bar{D}^{(*)}$ |

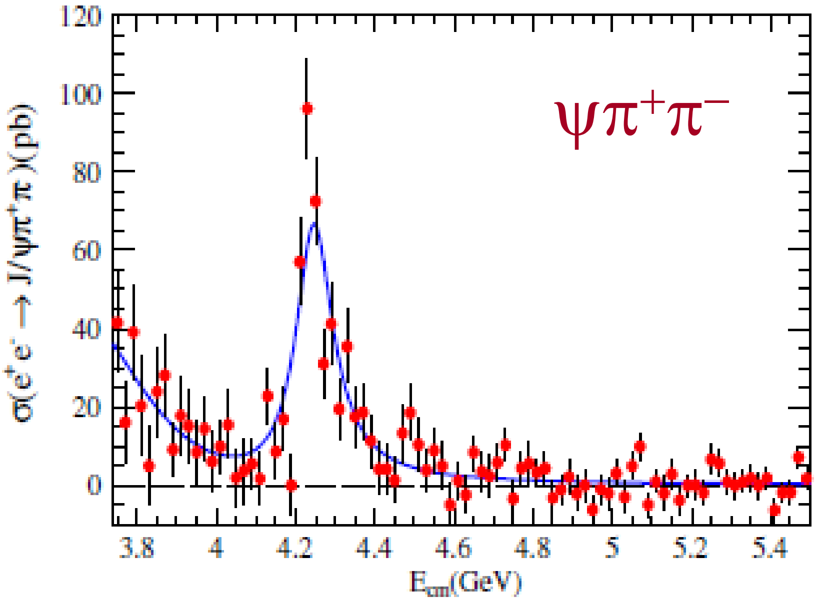
| | yield | Mass[MeV] | $BR(B^+ \to \psi(\to \chi_{c1}\gamma)K^+)$ |
|---|---|---|---|
| $\psi'$ | $193 \pm 18$ | $3685.3 \pm 0.6$ | $(7.7 \pm 0.8 \pm 0.9) \times 10^{-4}$ |
| $\psi_2$ | $33 \pm 9$ | $3823.5 \pm 2.8$ | $(9.7^{+2.8}_{-2.5} \pm 1.1) \times 10^{-6}$ |

First $\psi_2$ evidence

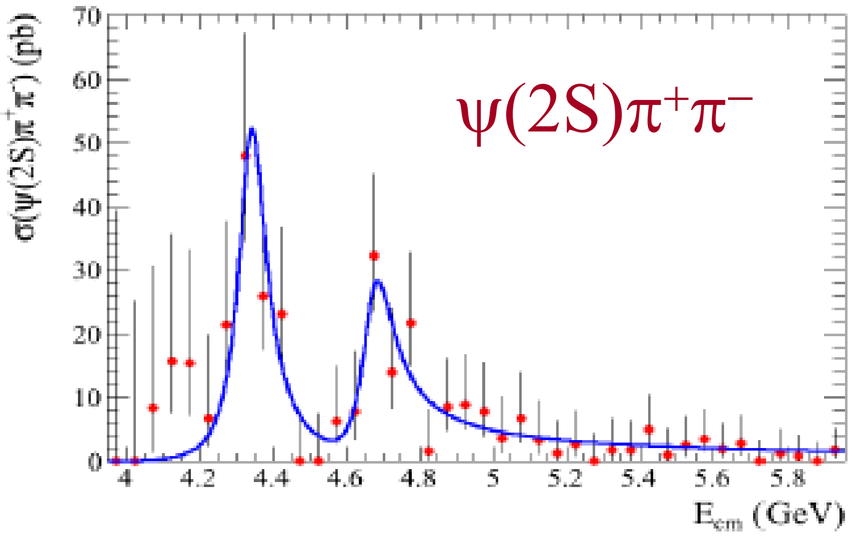
$\psi_2$ significance is 4.2$\sigma$ including systematics

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

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




PRD 86 051102 (2012)




arXiv: 1211.6271

Y(4260): M = 4245 ± 5 ± 4 MeV/c$^2$

$\Gamma$ = 114 ± 15 ± 7 MeV

Y(4360): M = 4340 ± 16 ± 9 MeV/c$^2$

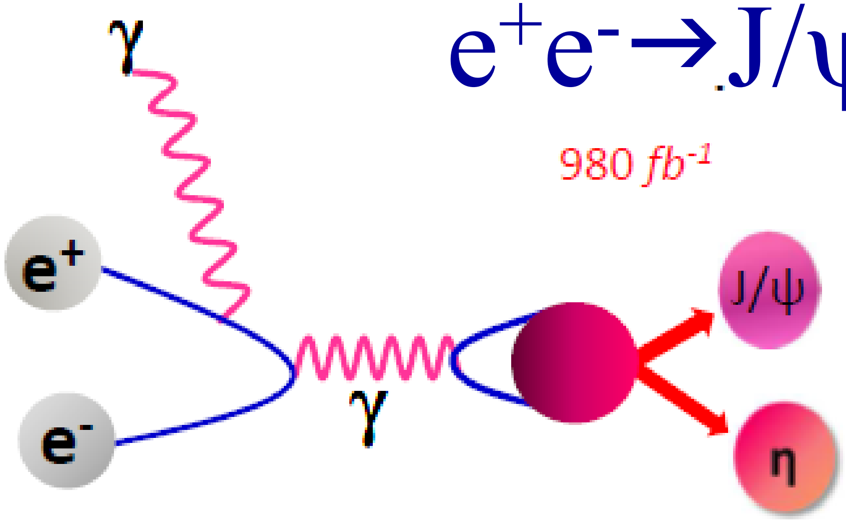
$\Gamma$ = 94 ± 32 ± 13 MeV

Y(4660): M = 4669 ± 21 ± 3 MeV/c$^2$

$\Gamma$ = 104 ± 48 ± 10 MeV

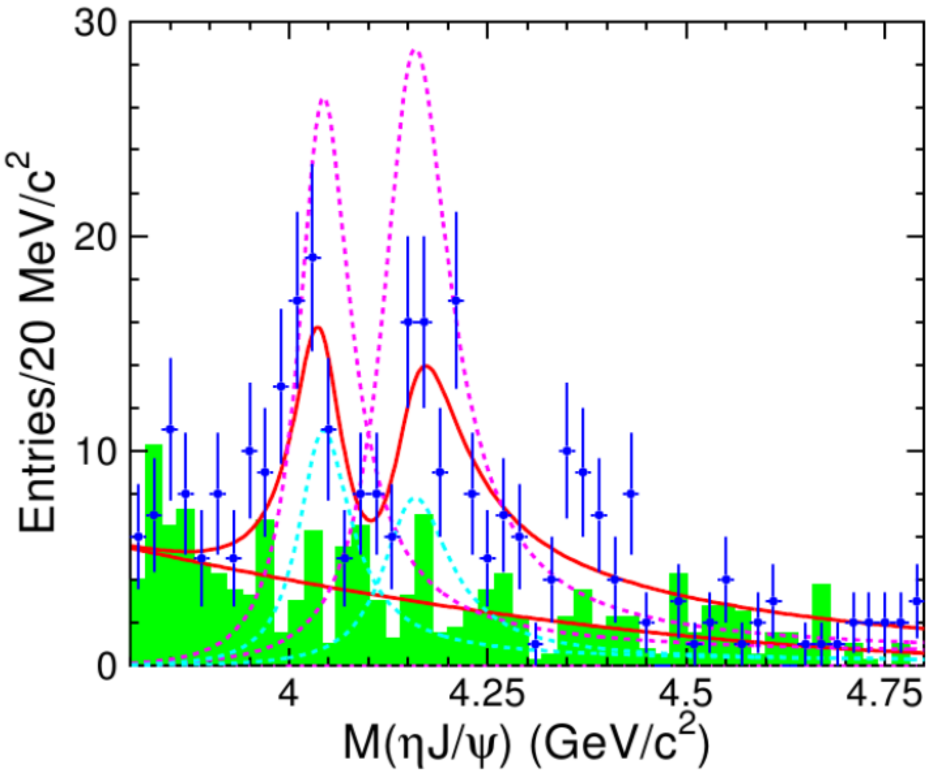
Consistent with previous Belle results

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




980 $fb^{-1}$

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

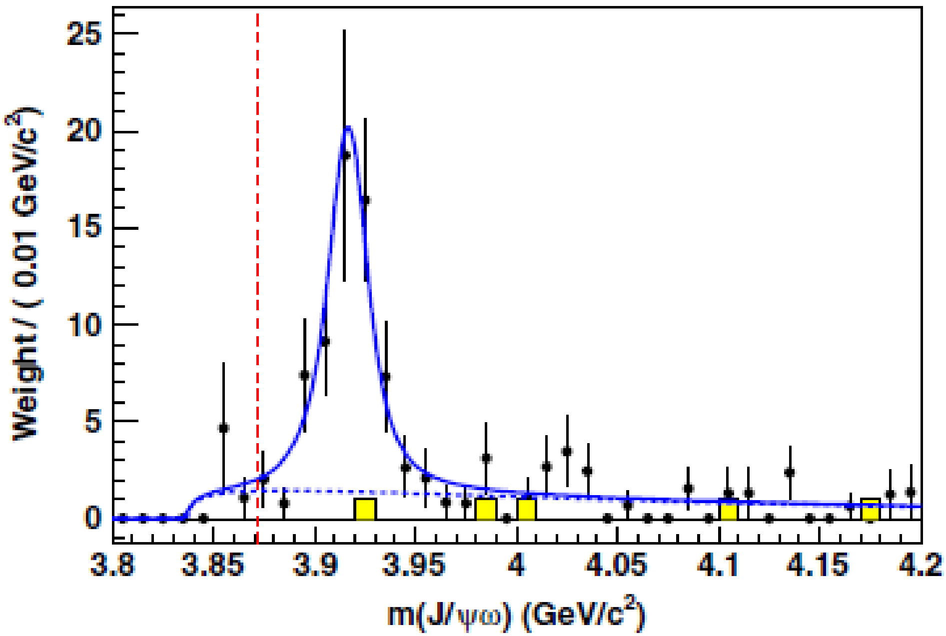



First time ψ(4040) and ψ(4160) have been observed in final states not involving charm meson pair.

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

arXiv:1210.7550

# $X(3915)\to J/\psi\omega$ in two-photons collisions



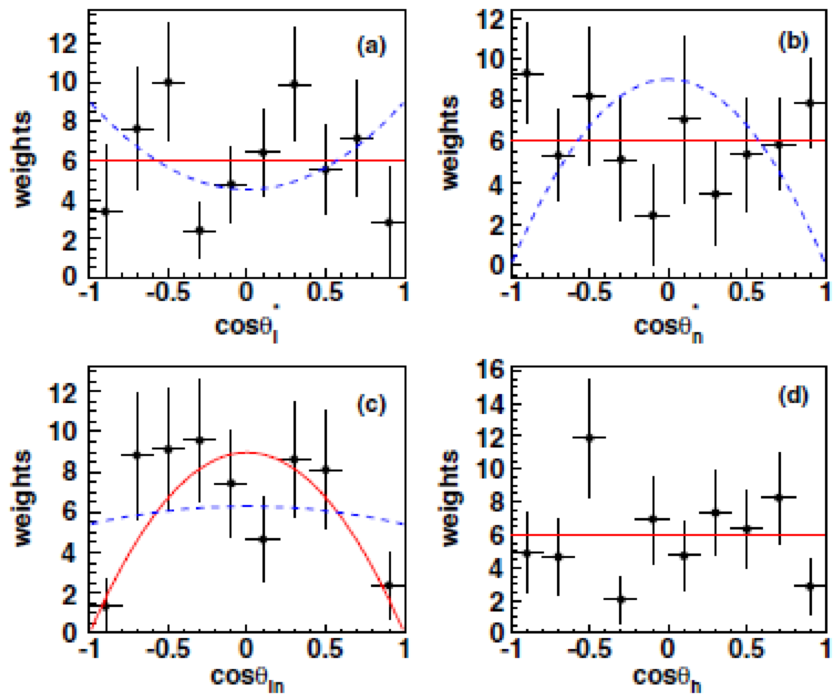

7.6σ significance

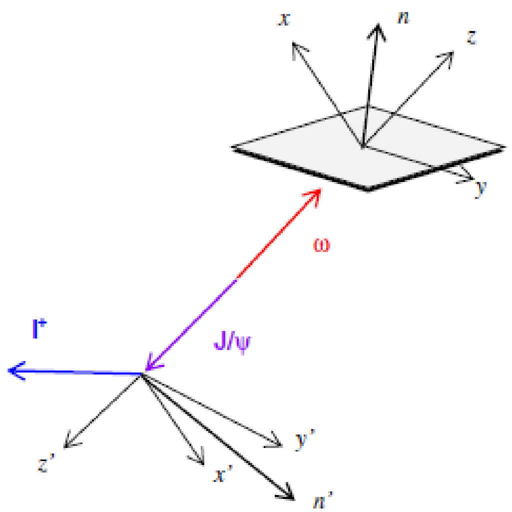
$M = 3919.4 \pm 2.2 \pm 1.6$ MeV/$c^2$

$\Gamma = 13 \pm 6 \pm 3$ MeV

$J^P=0^+$

Consistent with older studies by BaBar & Belle




PRD 86 072002 (2012)

# 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 $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ confirmed $J^P=1^+$ for both $Z_b$

- Evidence for neutral partner $Z_b(10610)$ in analysis of $\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0$
  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 $\psi_2$ is obtained in $B \to K\chi_{c1}\gamma$ decay

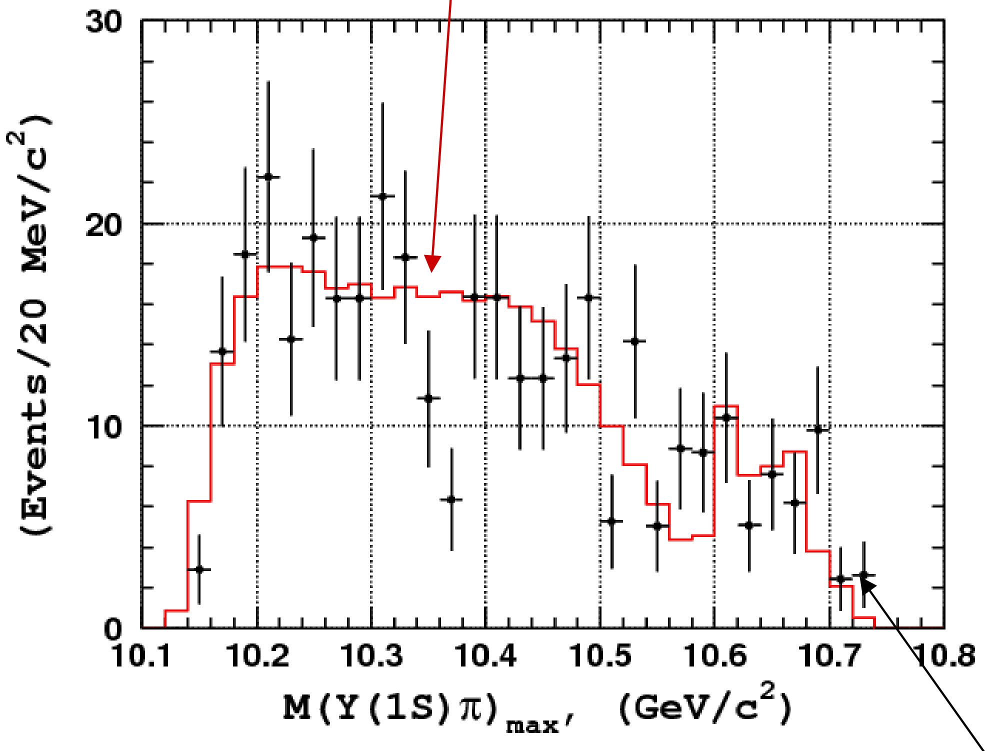
- Y(4260/4360/4660) are seen in $\psi(1,2S)\pi^+\pi^-$, however no evidence in $J/\psi\eta$

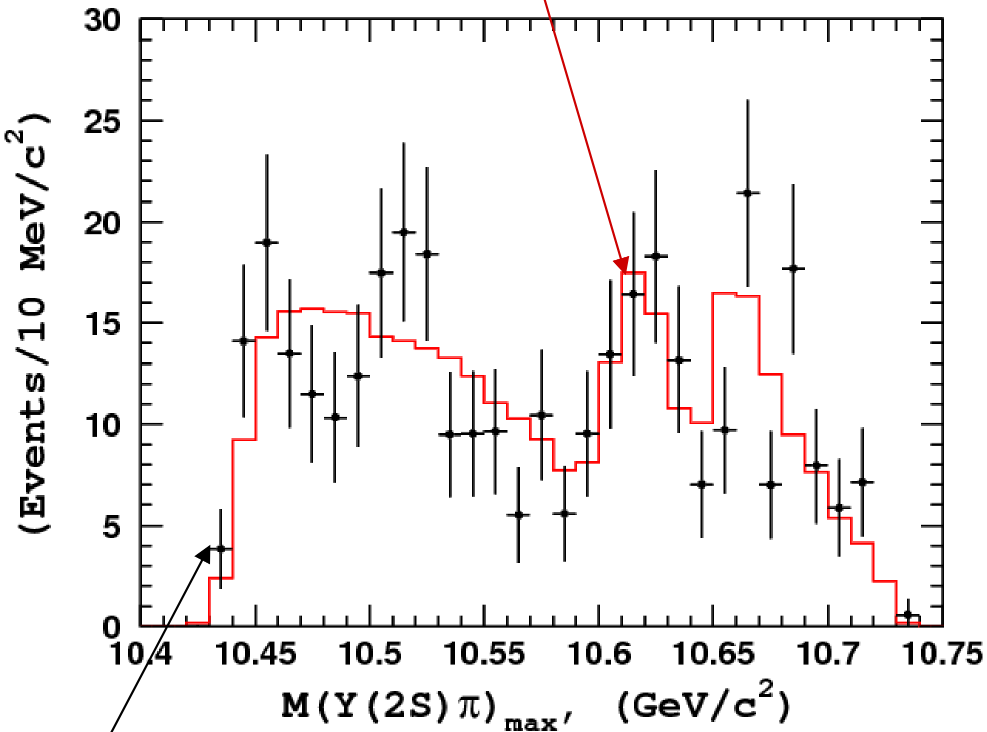
# Back up

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

Fit to the $Y1S\pi^+\pi^-$ data

Fit to the $Y2S\pi^+\pi^-$ data




Background subtracted $YnS\pi^0\pi^0$ data

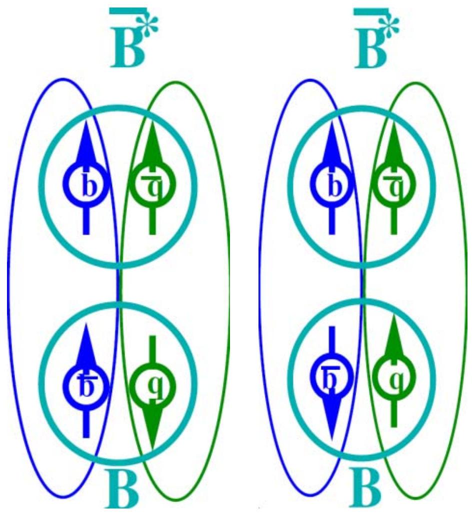
# Heavy quark structure in $Z_b$

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

Wave func. at large distance – B(*)B*

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$




Explains

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

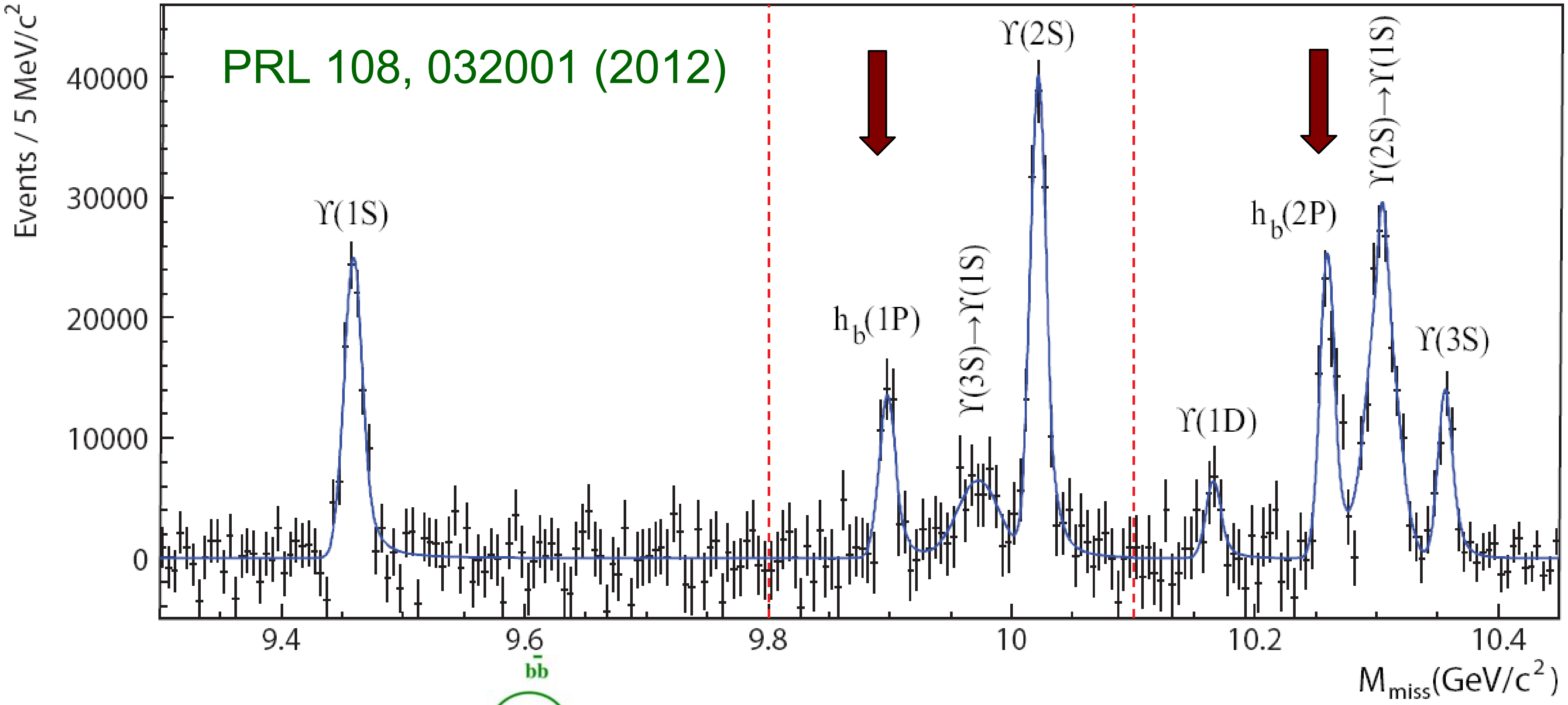
Predicts

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





spin-flip


$$\frac{\Gamma[\Upsilon(5S)\to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S)\to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.45\pm0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77\pm0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no spin-flip


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

# Search for decay $h_b \to \eta_b \gamma$

Decay chain

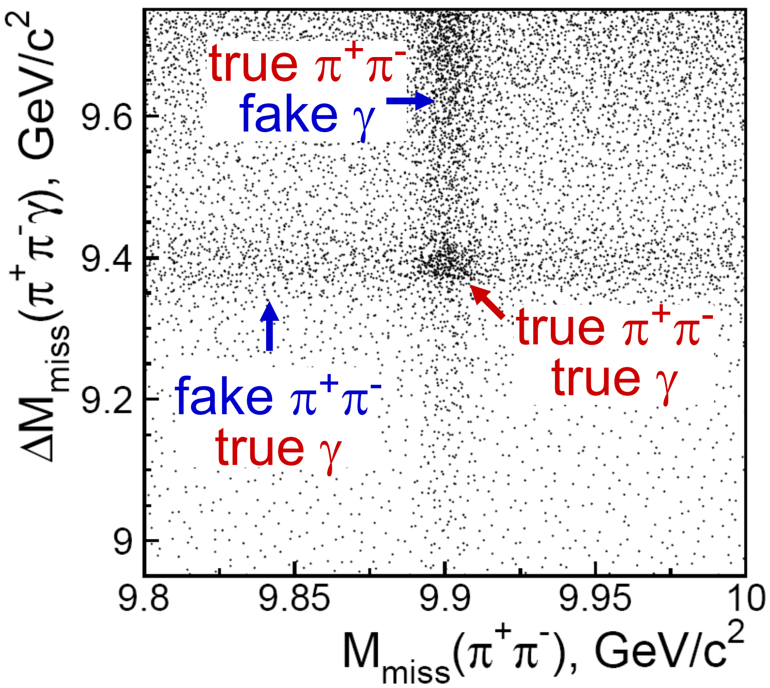
$\Upsilon(5S) \to Z_b^+ \pi^-$
$\quad \hookrightarrow h_b(nP)\, \pi^+$
$\quad\quad \hookrightarrow \eta_b(mS)\, \gamma$

reconstruct

Use missing mass
to identify signals

MC simulation

$M(\eta_b) \Rightarrow$




$\Uparrow$
$M(h_b)$

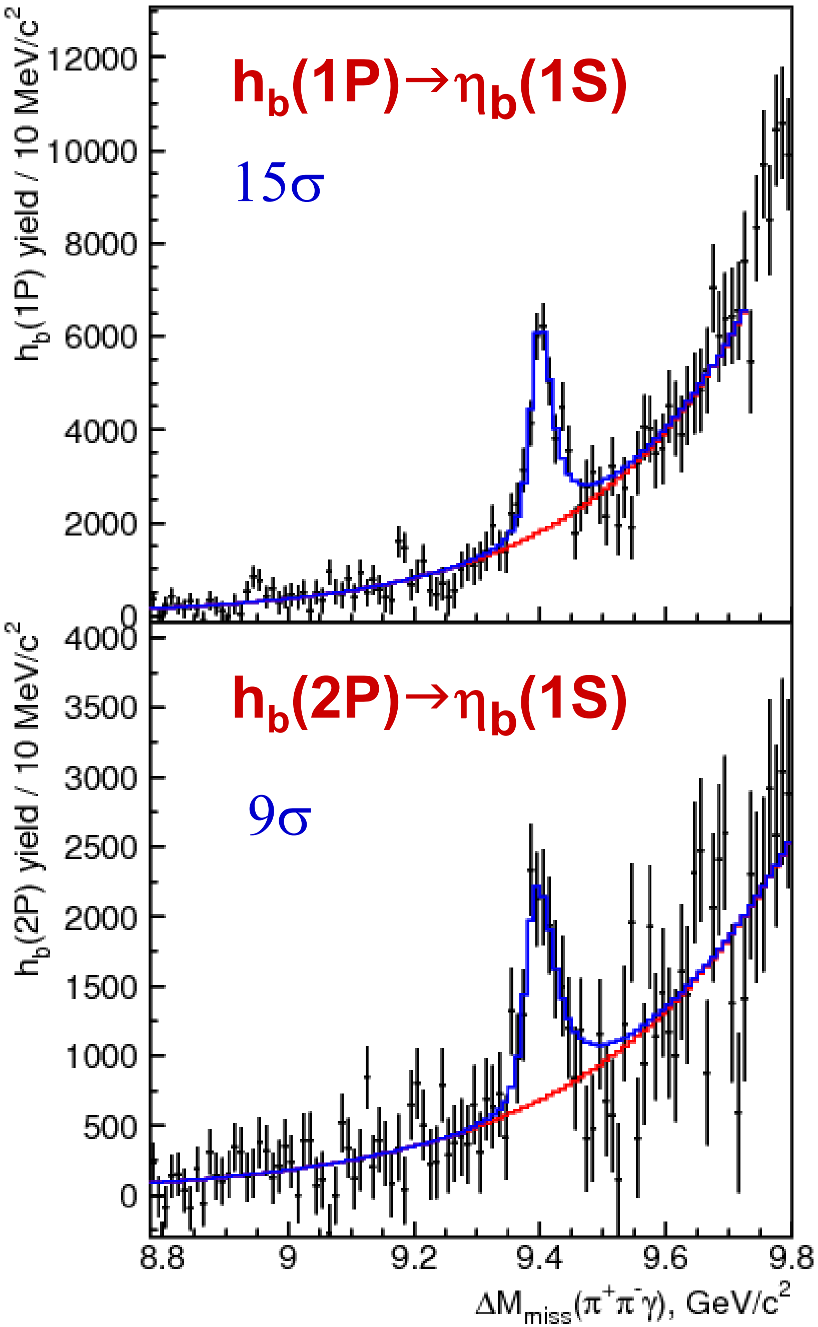
$\Delta M_{miss}(\pi^+\pi^-\gamma) \equiv$
$M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + M[h_b]$

*Approach:*

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

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

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




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

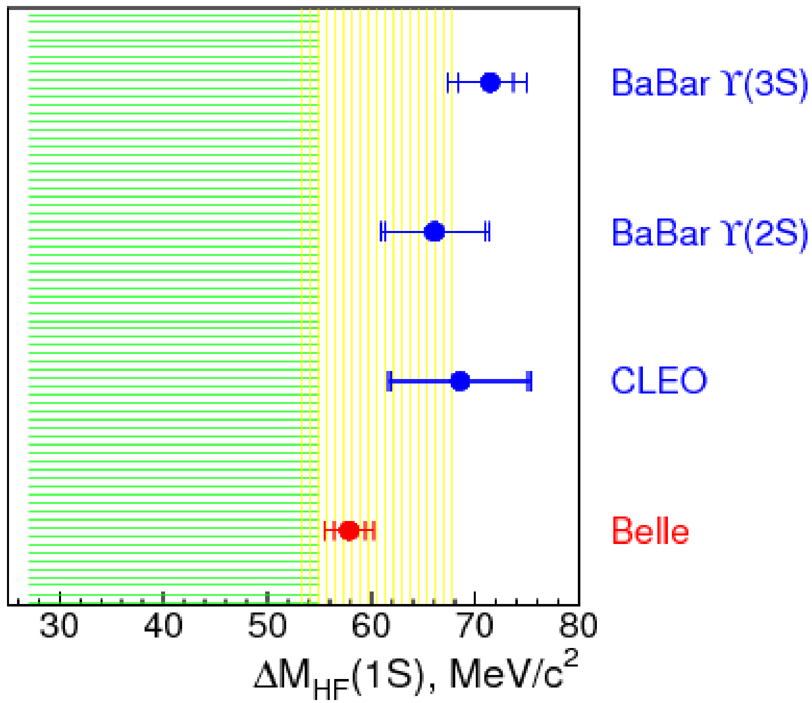
$\Gamma[\eta_b(1S)] = 10.8^{+4.0+4.5}_{-3.7-2.0}\ \text{MeV}$

potential models : $\Gamma$ = 5 – 20 MeV

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

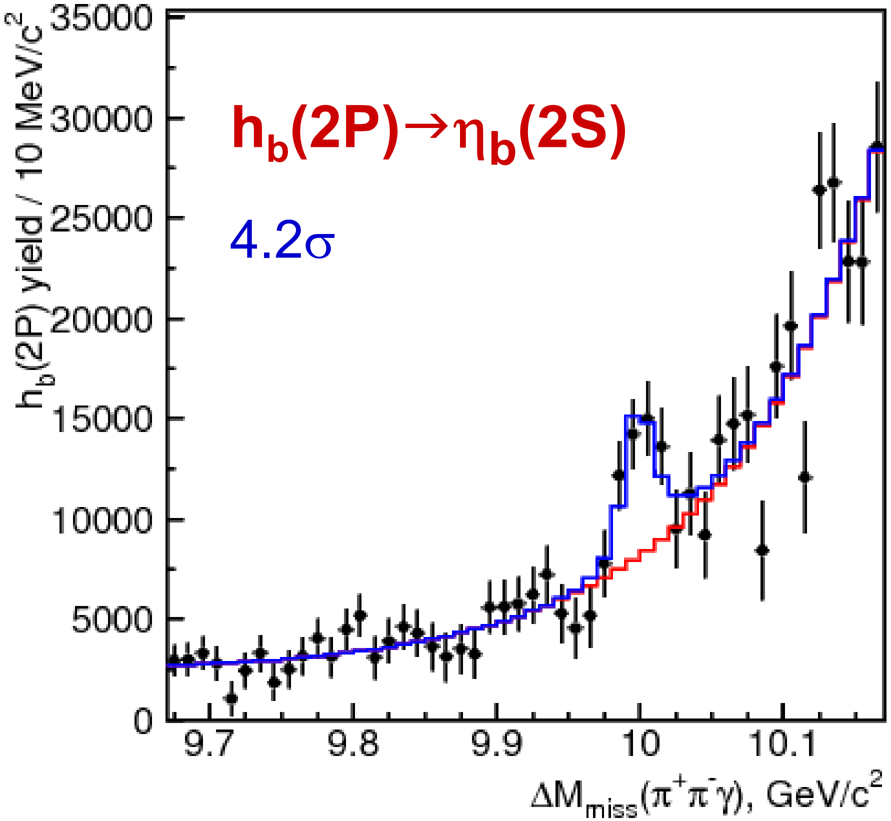
Godfrey & Rosner : BF = 41%

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




PRL 109, 232002 (2012)

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




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

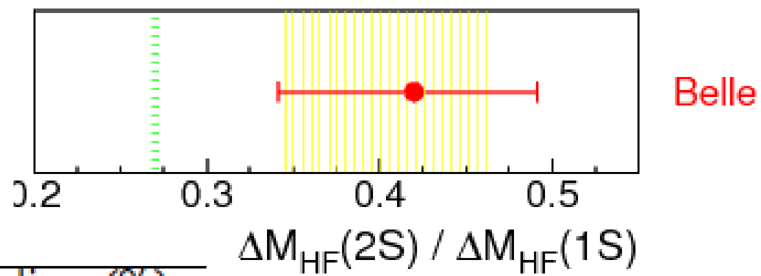
$$\Gamma[\eta_b(2S)] = 10.8^{+4.0+4.5}_{-3.7-2.0}\ \ \mathrm{MeV}$$

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

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

$\Delta M_{HF}$ = 23.5 ±4.7 MeV

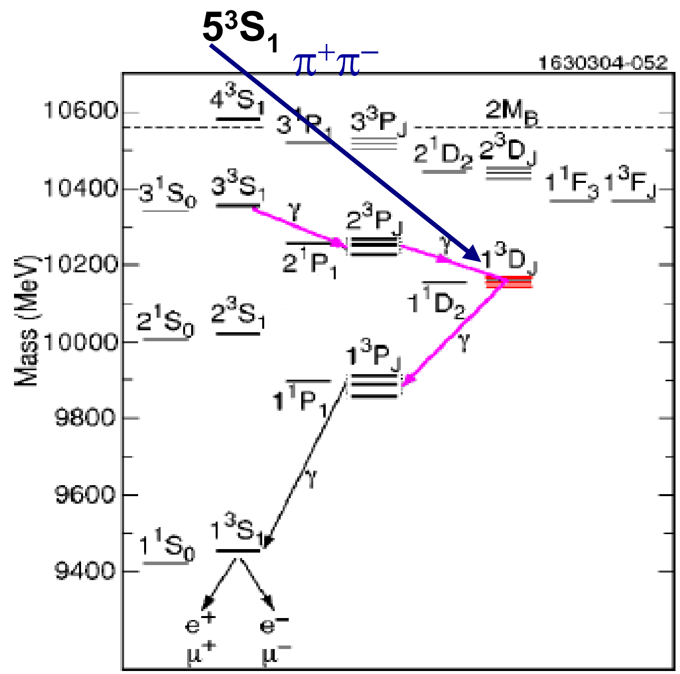
Lattice Meinel PRD82,114502(2010)




**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 |

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

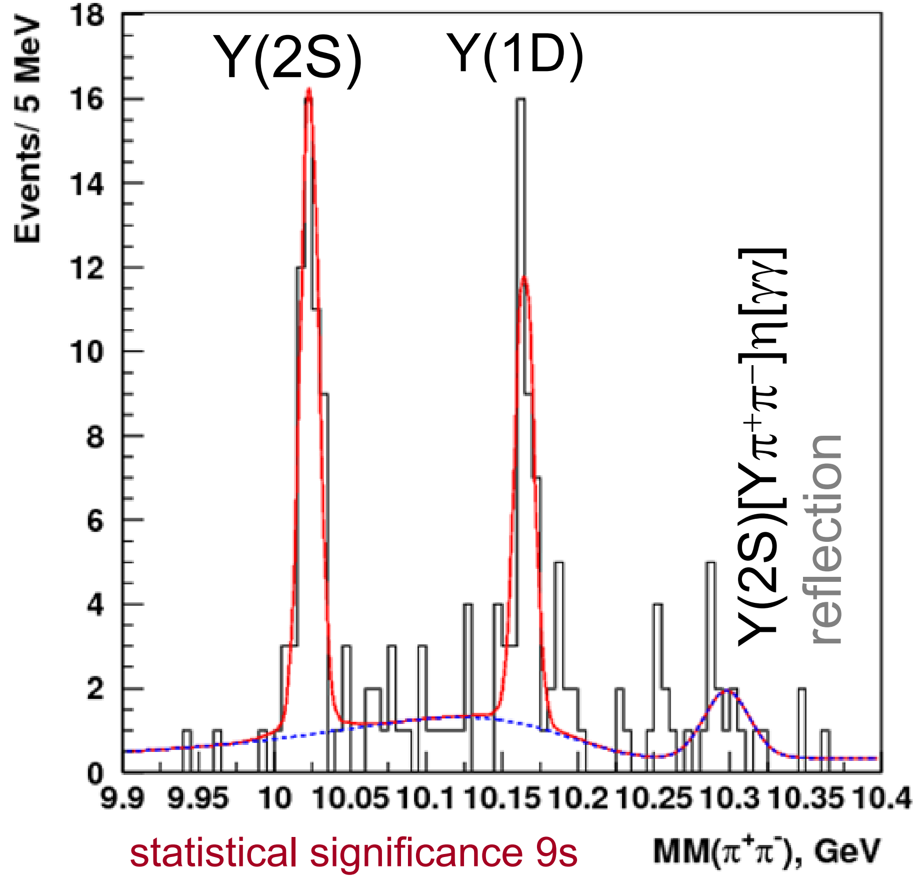



- First and only one $L$=2 state found in radiative decay chain CLEO(2004):
  $\Upsilon(3S)\to\chi_b(2P)\gamma\to\Upsilon(1D)\gamma\gamma\to\chi_b(1P)\gamma\gamma\gamma\to\Upsilon(1S)\gamma\gamma\gamma\gamma$

- Belle measured a new production chain
  $\Upsilon(5S)\to\Upsilon(1D)\pi^+\pi^-\to\chi_b(1P)\gamma\pi^+\pi^-\to\Upsilon(1S)\gamma\gamma\pi^+\pi^-$

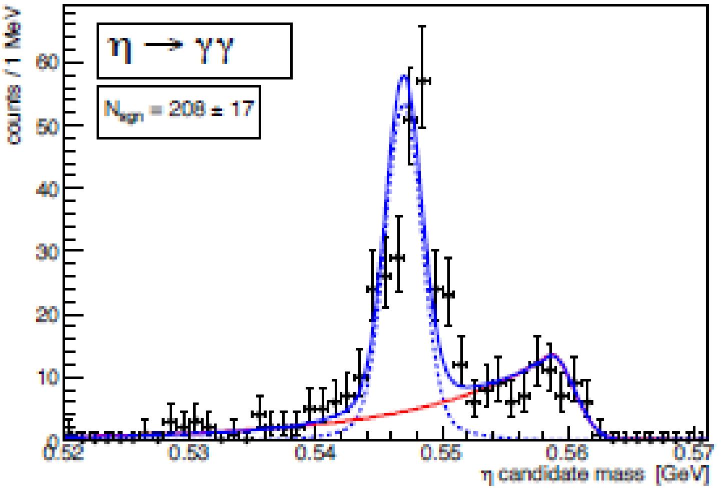
CLEO
$M$ = 10161.1±0.6±1.6 MeV
$B[\Upsilon(3S)\to\Upsilon(1D)\gamma\gamma\to\Upsilon(1S)\gamma\gamma\gamma\gamma]$ =
$(2.5\pm0.5\pm0.5)\times10^{-5}$

Belle preliminary
$B[\Upsilon(5S)\to\Upsilon(1D)\pi^+\pi\to\Upsilon(1S)\gamma\gamma\pi^+\pi^-]$ =
$(2.0\pm0.4\pm0.3)\times10^{-4}$

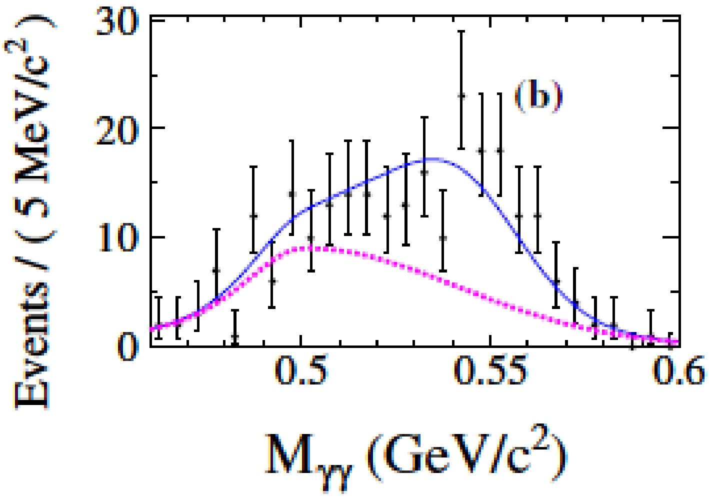


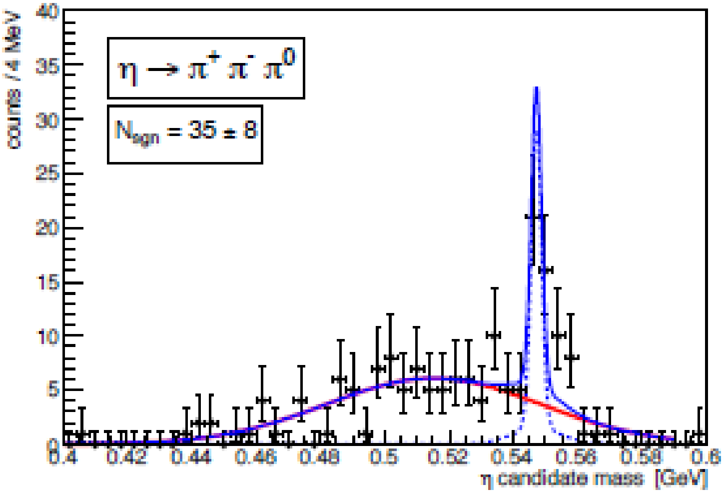

statistical significance 9s

# $\Upsilon(2S)\to\Upsilon(1S)\eta$

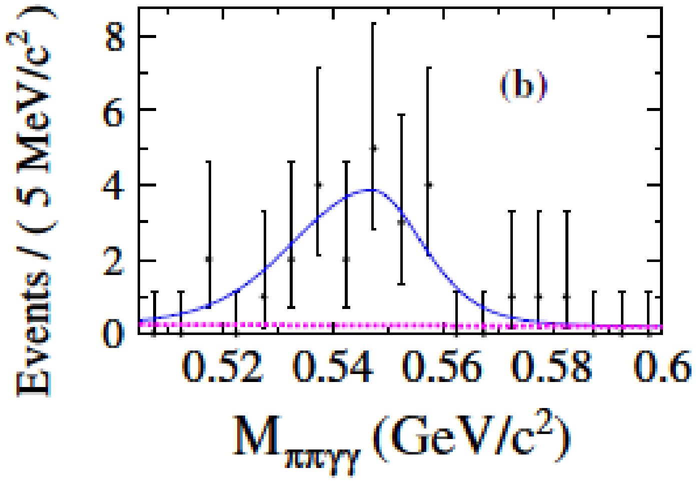



$\eta\to\gamma\gamma$




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




**Phys.Rev.D 84 092003**

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

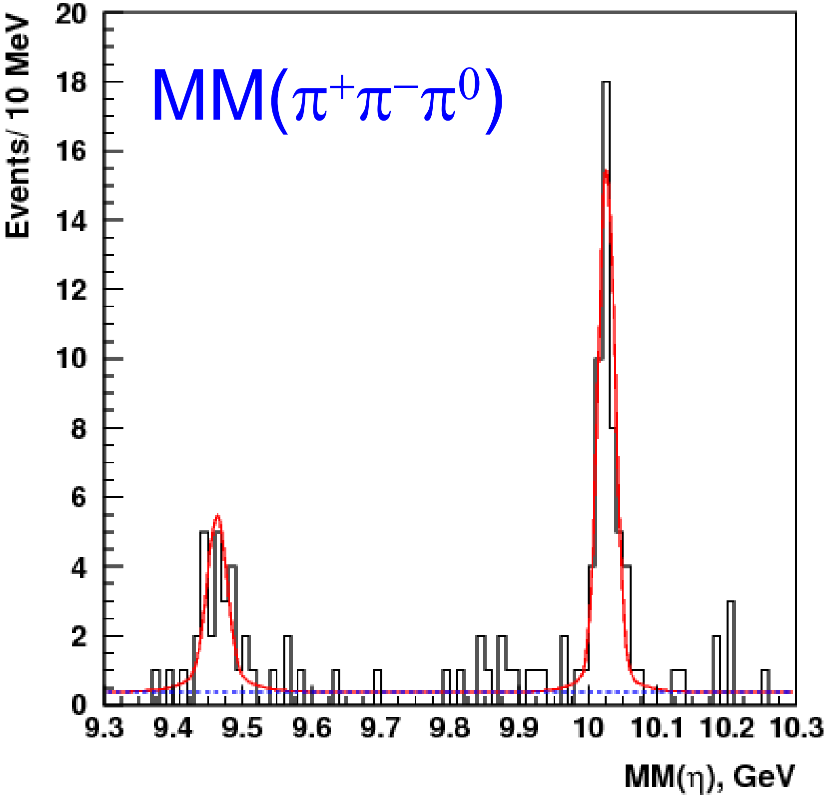
$B[\Upsilon(2S)\to\Upsilon(1S)\pi^0] < 4.3\ 10^{-5}$

PRD 87, 011104(R) (2013)

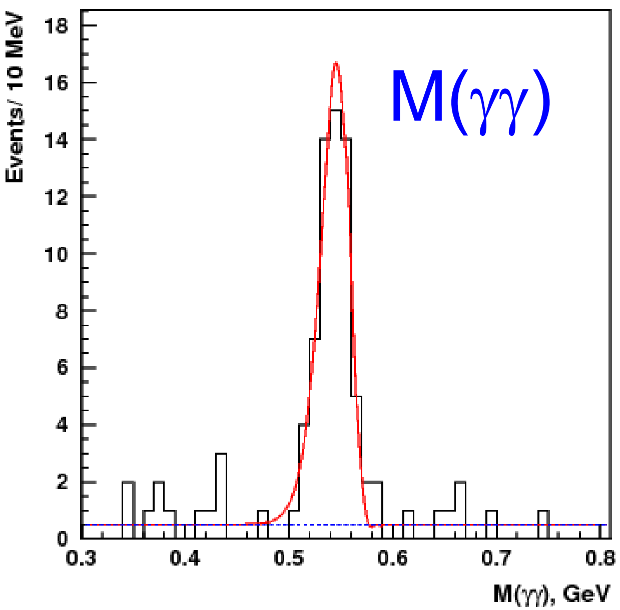
$B[\Upsilon(2S)\to\Upsilon(1S)\eta]=(2.39 \pm 0.31 \pm 0.14)\ 10^{-4}$

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

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




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




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

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

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

preliminary