

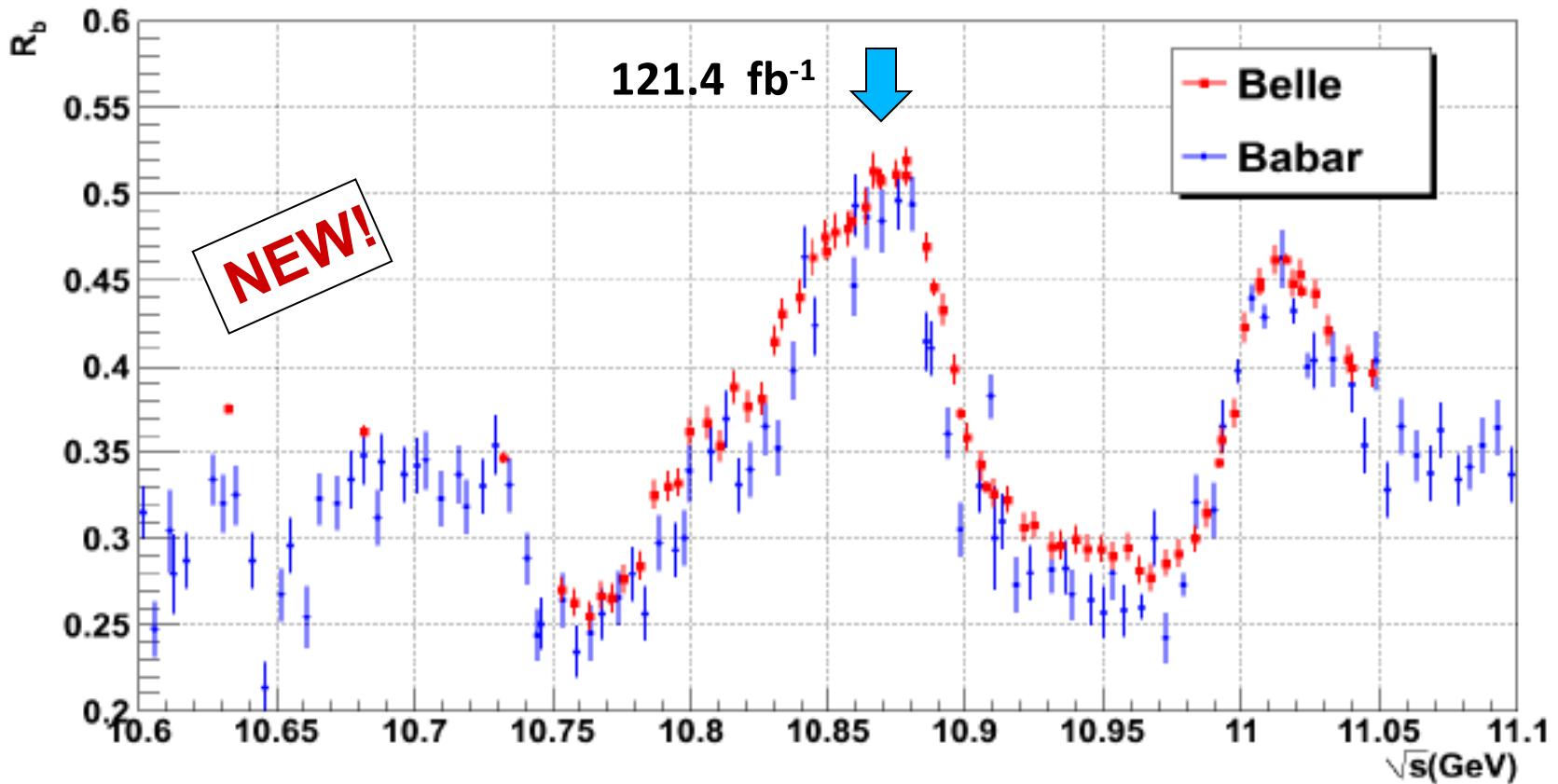
Y(5S) spectroscopy at Belle

Alex Bondar
BINP, Novosibirsk
(On behalf of Belle Collaboration)



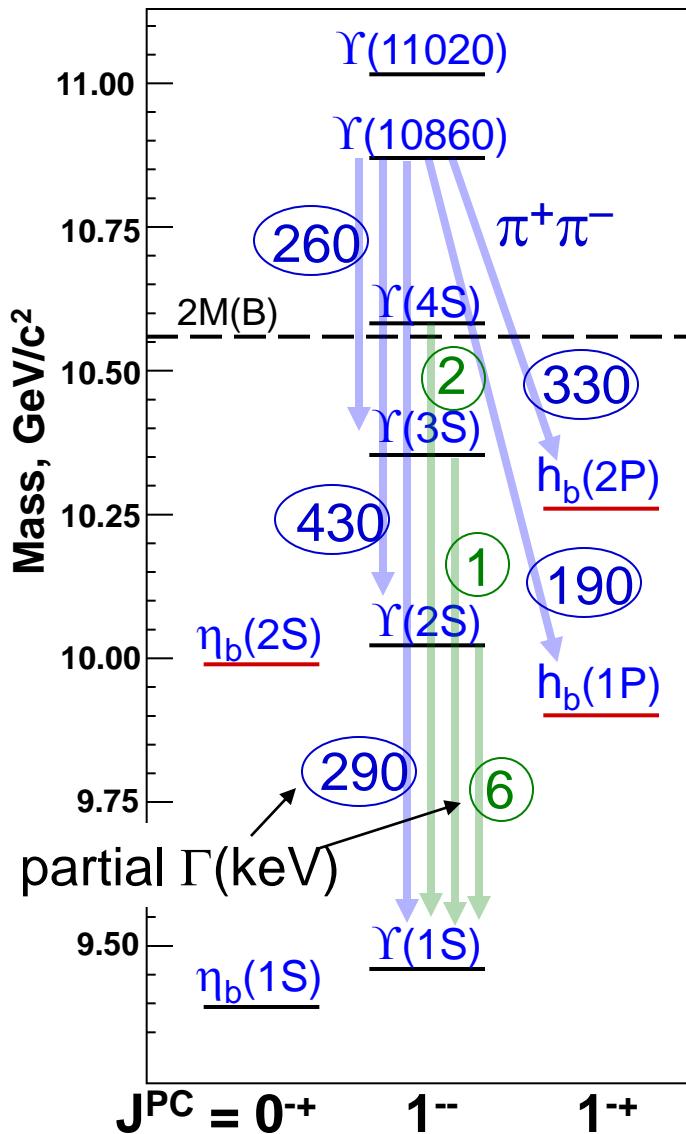
**International Conference on High Energy Physics,
4 - 11, July, 2012, Melbourne, Australia**

R_b Measurements



- Better statistic errors, but covers a smaller energy range compared to Babar
- R_b is slightly higher by 0.0185
- No Ali's Y_b(10900) (Phys.Lett. B 684, 28-39 2010) $\Gamma_{ee} < 36 \text{ eV}$

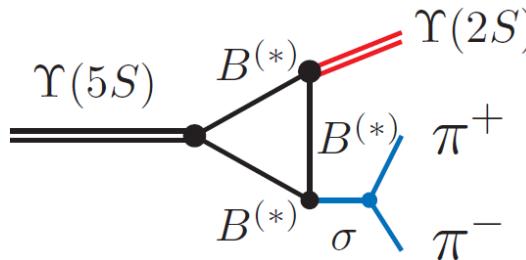
Anomalies in $\Upsilon(5S) \rightarrow (b\bar{b})\pi^+\pi^-$ transitions



Belle: PRL100, 112001 (2008) ~ 100

$\Gamma[\Upsilon(5S) \rightarrow \Upsilon(1,2,3S)\pi^+\pi^-] \gg \Gamma[\Upsilon(4,3,2S) \rightarrow \Upsilon(1S)\pi^+\pi^-]$

\Leftarrow Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



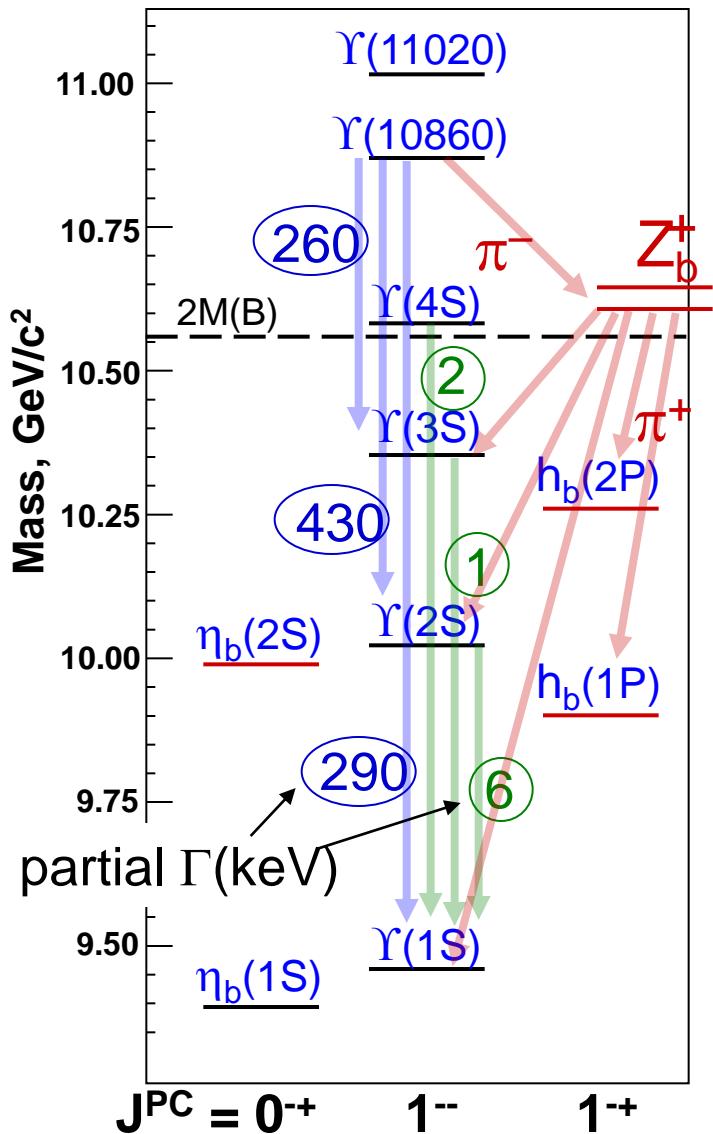
Belle: PRL108, 032001 (2012)



expect suppression $\sim \Lambda_{\text{QCD}}/m_b$
Heavy Quark Symmetry

$\Upsilon(5S) \rightarrow h_b(1,2P)\pi^+\pi^-$ are not suppressed

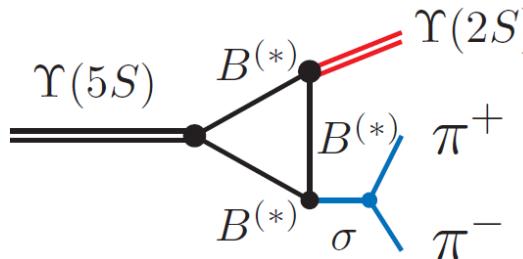
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⇐ Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



Belle: PRL108, 032001 (2012)



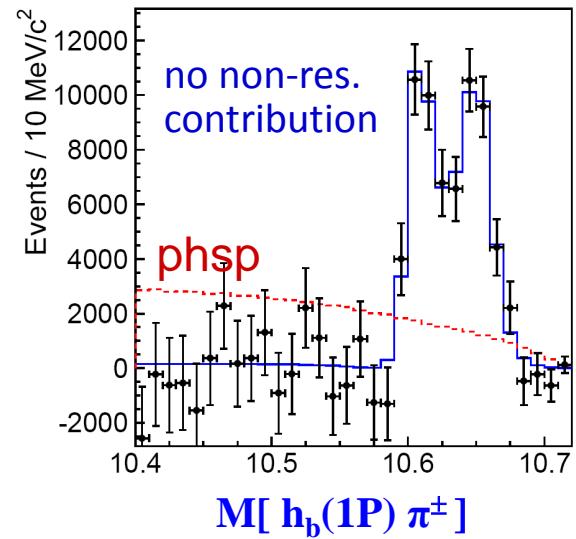
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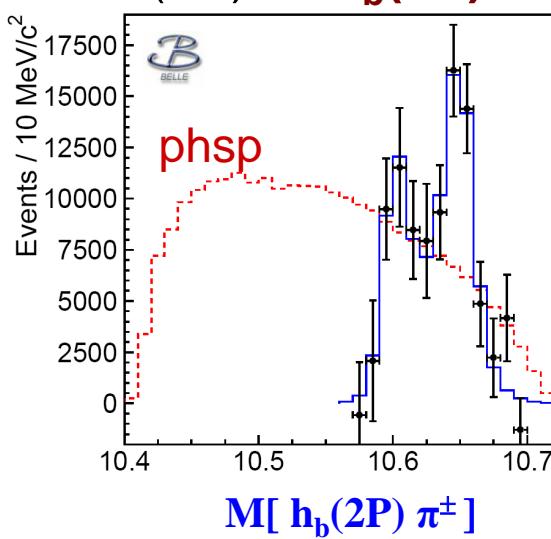
h_b production mechanism? \Rightarrow Study resonant structure in $h_b(mP)\pi^+\pi^-$

Resonant structure of $\Upsilon(5S) \rightarrow (b\bar{b})\pi^+\pi^-$

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



$\Upsilon(5S) \rightarrow h_b(2P)\pi^+\pi^-$



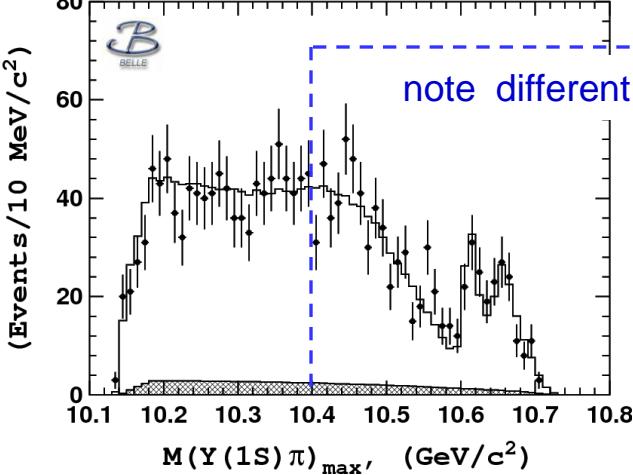
Two peaks are observed
in all modes!

Belle: PRL108, 232001 (2012)

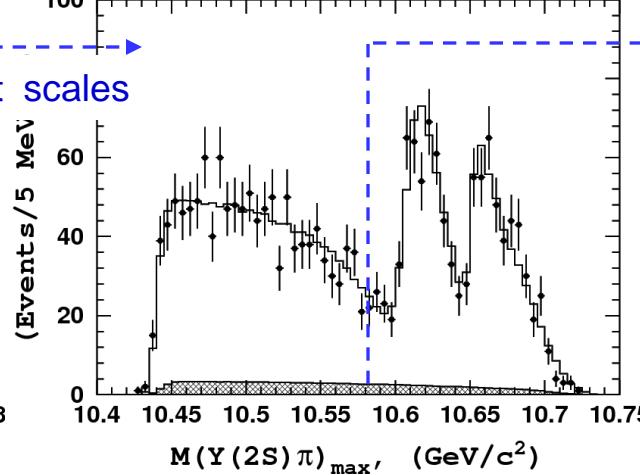
$Z_b(10610)$ and $Z_b(10650)$
should be multiquark states

Dalitz plot analysis

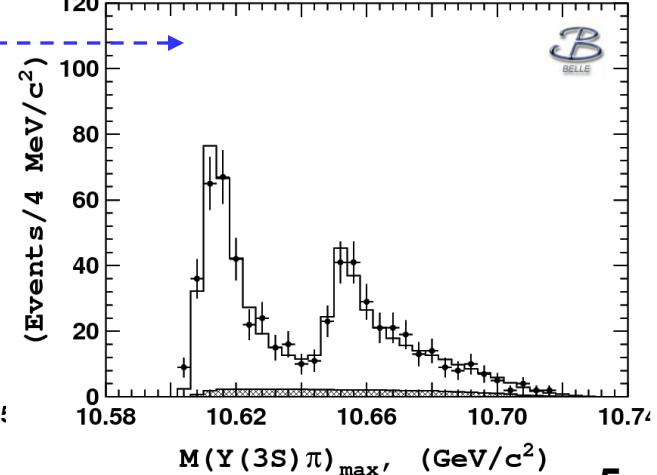
$\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-$



$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$



$\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^-$



Branching Fractions

Using $\Upsilon(10860)$ production cross section of $\sigma[e^+e^- \rightarrow \Upsilon(10860)] = 0.340 \pm 0.016 \text{ nb}$:

$$\text{Br}(\Upsilon(10860) \rightarrow \Upsilon(1S) \pi^+ \pi^-) = [4.45 \pm 0.16(\text{stat.}) \pm 0.35(\text{syst.})] \times 10^{-3}$$

$$\text{Br}(\Upsilon(10860) \rightarrow \Upsilon(2S) \pi^+ \pi^-) = [7.97 \pm 0.31(\text{stat.}) \pm 0.96(\text{syst.})] \times 10^{-3}$$

$$\text{Br}(\Upsilon(10860) \rightarrow \Upsilon(3S) \pi^+ \pi^-) = [2.88 \pm 0.19(\text{stat.}) \pm 0.36(\text{syst.})] \times 10^{-3}$$

Fractions of individual sub-modes:

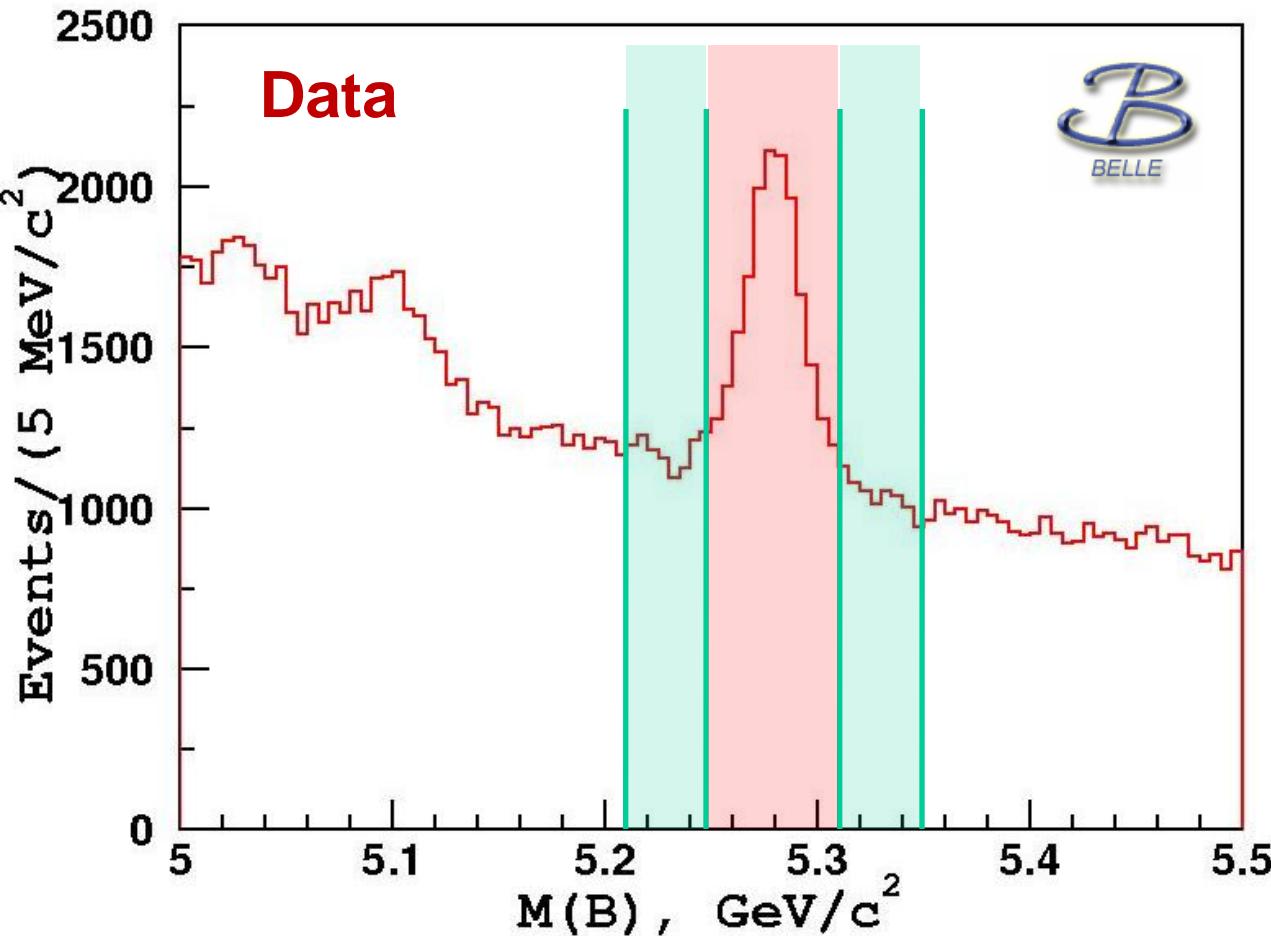
NEW!

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

Belle PRELIMINARY

$$\Upsilon(5S) \rightarrow Z_b(10610)\pi^+ \rightarrow BB^*\pi^+$$
$$Z_b(10650)\pi^+ \rightarrow B^*B^*\pi^+$$

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



Charged B:

- $D^0[\bar{K}\pi, K\pi\pi]\pi^-$
- $J/\psi[\mu\mu] K^-$

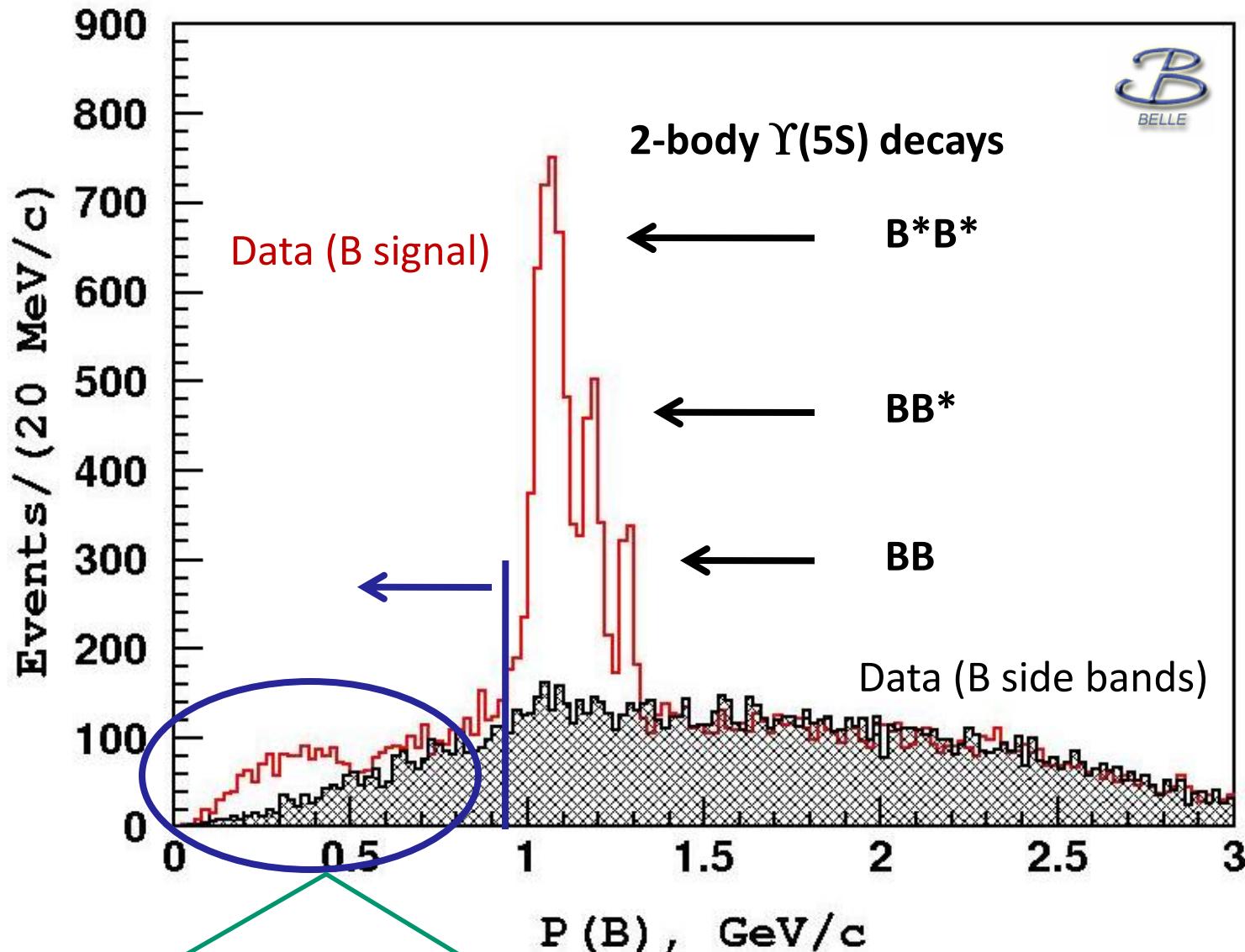
Neutral B:

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

Effective B fraction:
 $\text{Br}[B \rightarrow f] = (143 \pm 15) \times 10^{-5}$

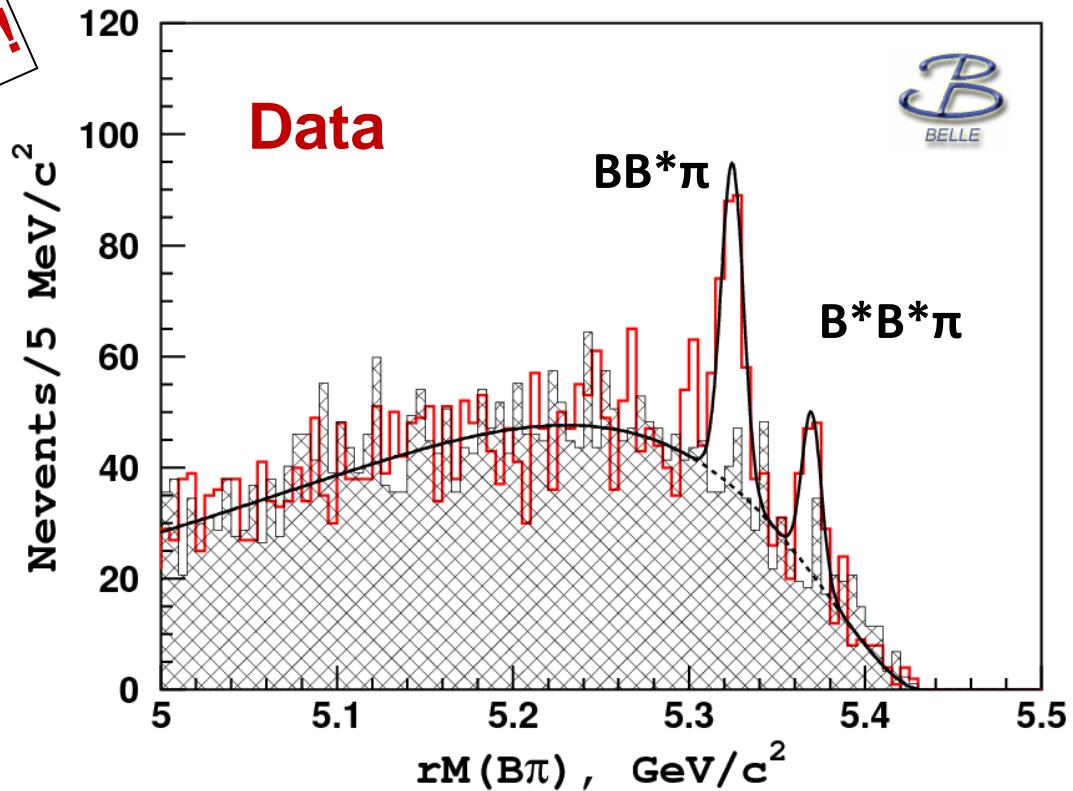
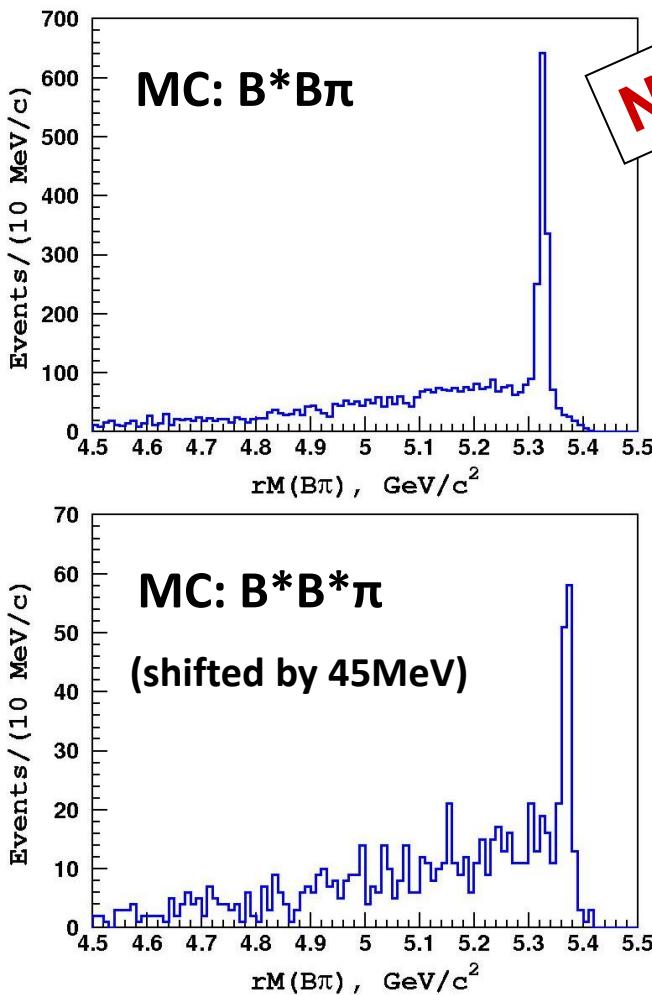
B candidate invariant mass distribution. All modes combined. Select B signal within 30-40 MeV (depending on B decay mode) around B nominal mass.

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



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

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



Red histogram – right sign $B\pi$ combinations;
 Hatched histogram – wrong sign $B\pi$ combinations;
 Solid line – fit to right sign data.

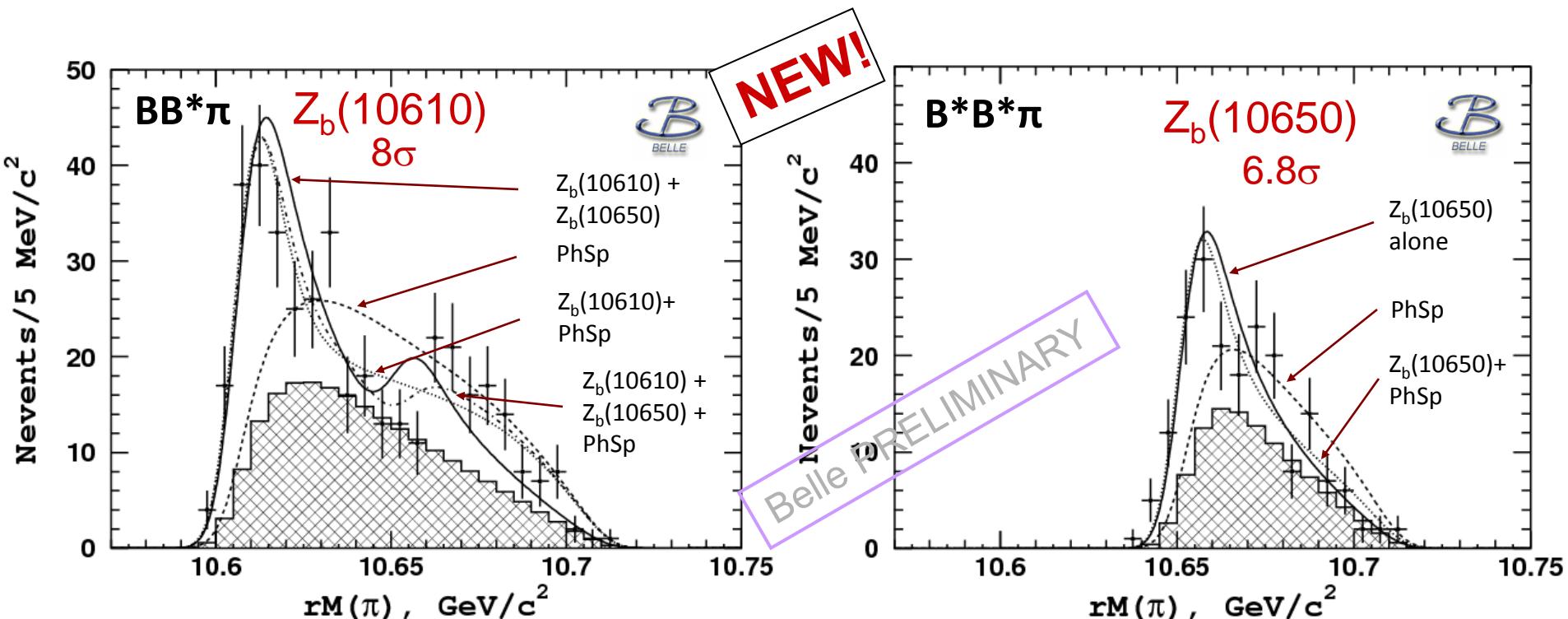
Fit yields: $N(BB\pi) = 0.3 \pm 14$

$N(BB^*\pi) = 184 \pm 19$ (9.3σ)

$N(B^*B^*\pi) = 82 \pm 11$ (5.7σ)

Belle PRELIMINARY

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



points – right sign $B\pi$ combinations (data);

lines – fit to data with various models (times PHSP, convolved with resolution function = Gaussian with $\sigma=6\text{MeV}$).

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.

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

Branching fractions of $\Upsilon(10680)$ decays (including neutral modes):

$$\begin{aligned} BB\pi &< 0.60\% \text{ (90%CL)} \\ BB^*\pi &= 4.25 \pm 0.44 \pm 0.69\% \\ B^*B^*\pi &= 2.12 \pm 0.29 \pm 0.36\% \end{aligned}$$

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

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

Belle PRELIMINARY

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

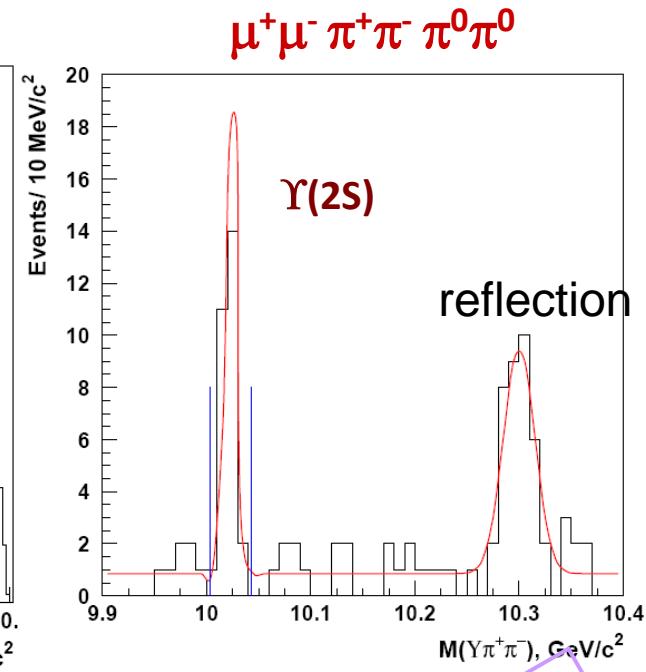
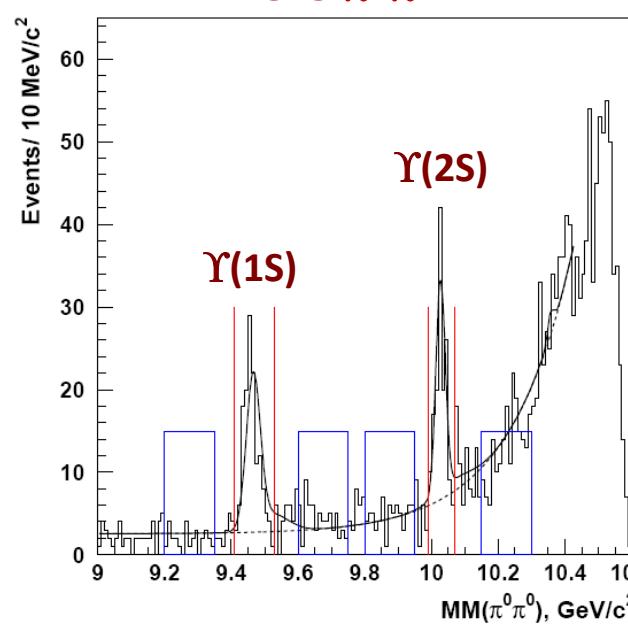
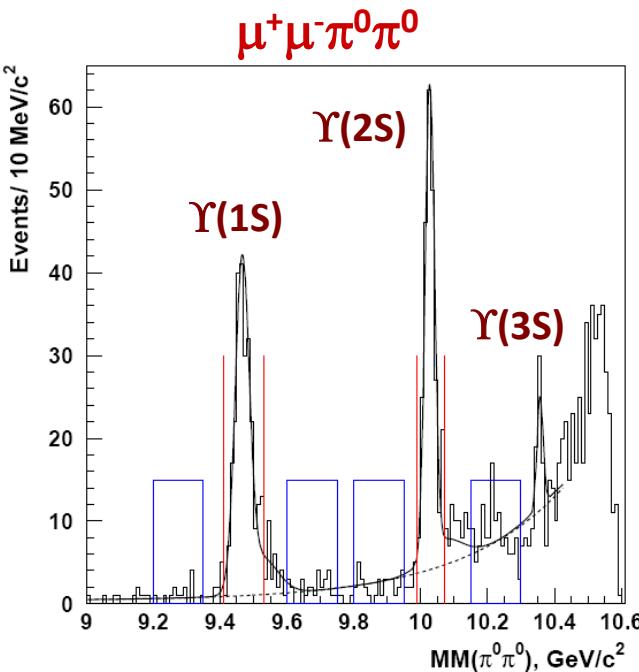
Resonant structure of $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$

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

NEW!

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

Require energy-momentum balance to improve resolution



signal and sidebands regions

$$BF[\Upsilon(10680) \rightarrow \Upsilon(1S)\pi^0\pi^0] = (2.25 \pm 0.11 \pm 0.20) \cdot 10^{-3}$$

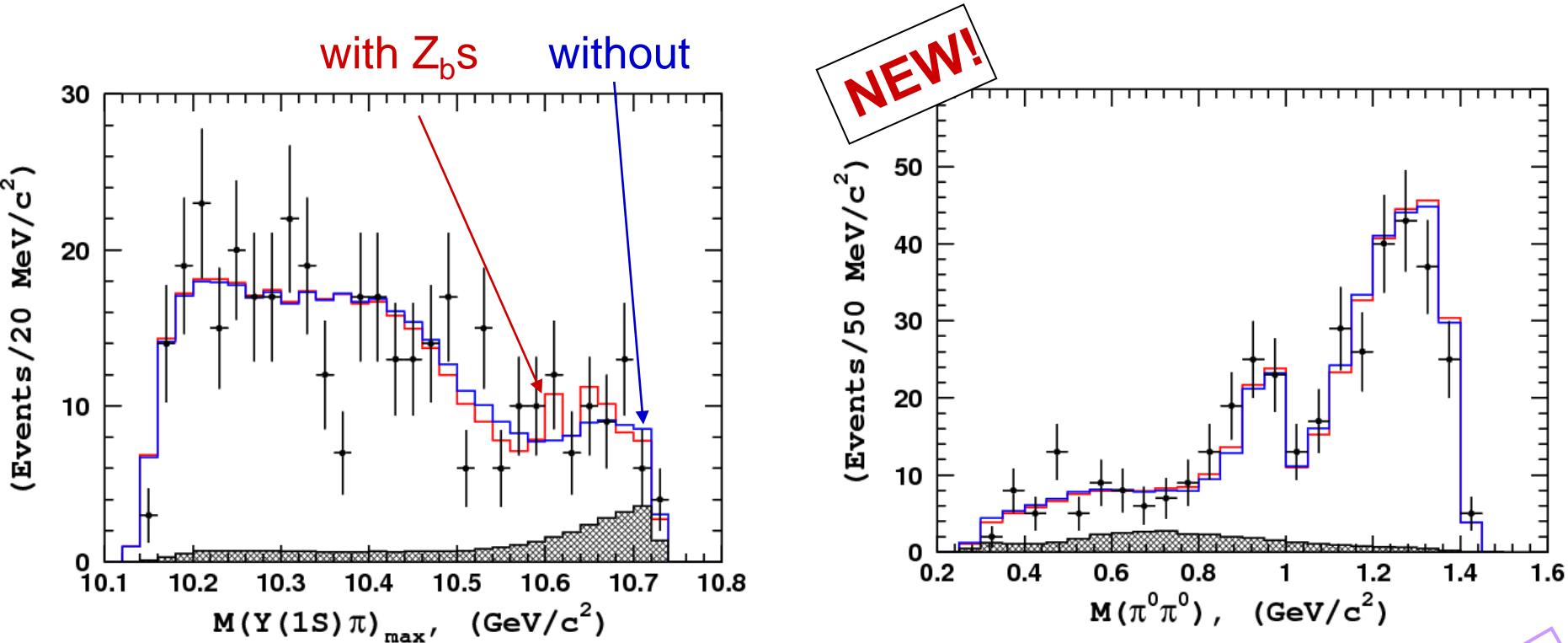
$$BF[\Upsilon(10680) \rightarrow \Upsilon(2S)\pi^0\pi^0] = (3.79 \pm 0.24 \pm 0.49) \cdot 10^{-3}$$

in agreement with isospin relations

Belle PRELIMINARY

Resonant structure of $\Upsilon(1S)\pi^0\pi^0$

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

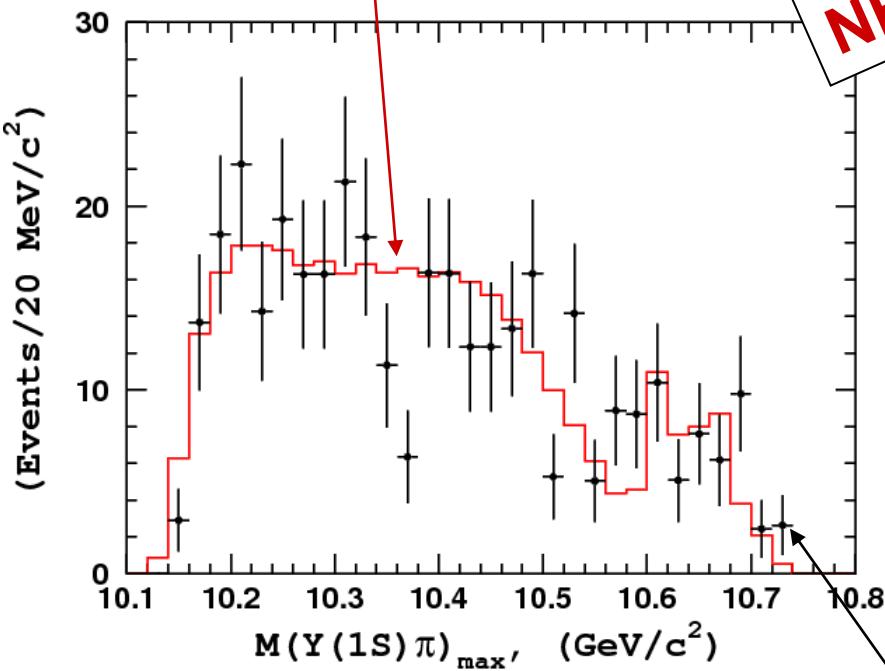


- Signals of both Z_b^0 s are not significant

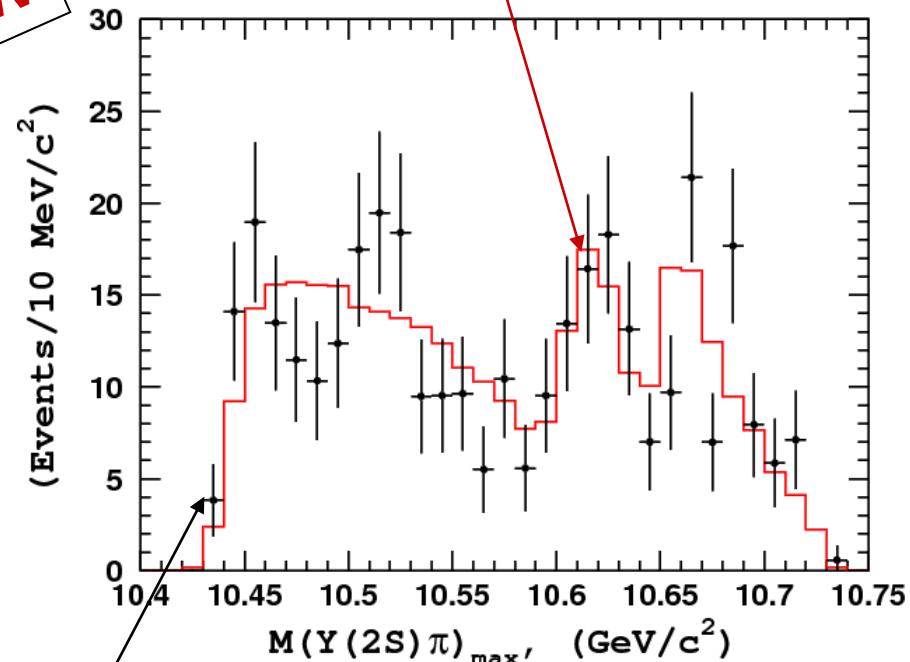
Belle PRELIMINARY

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

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



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

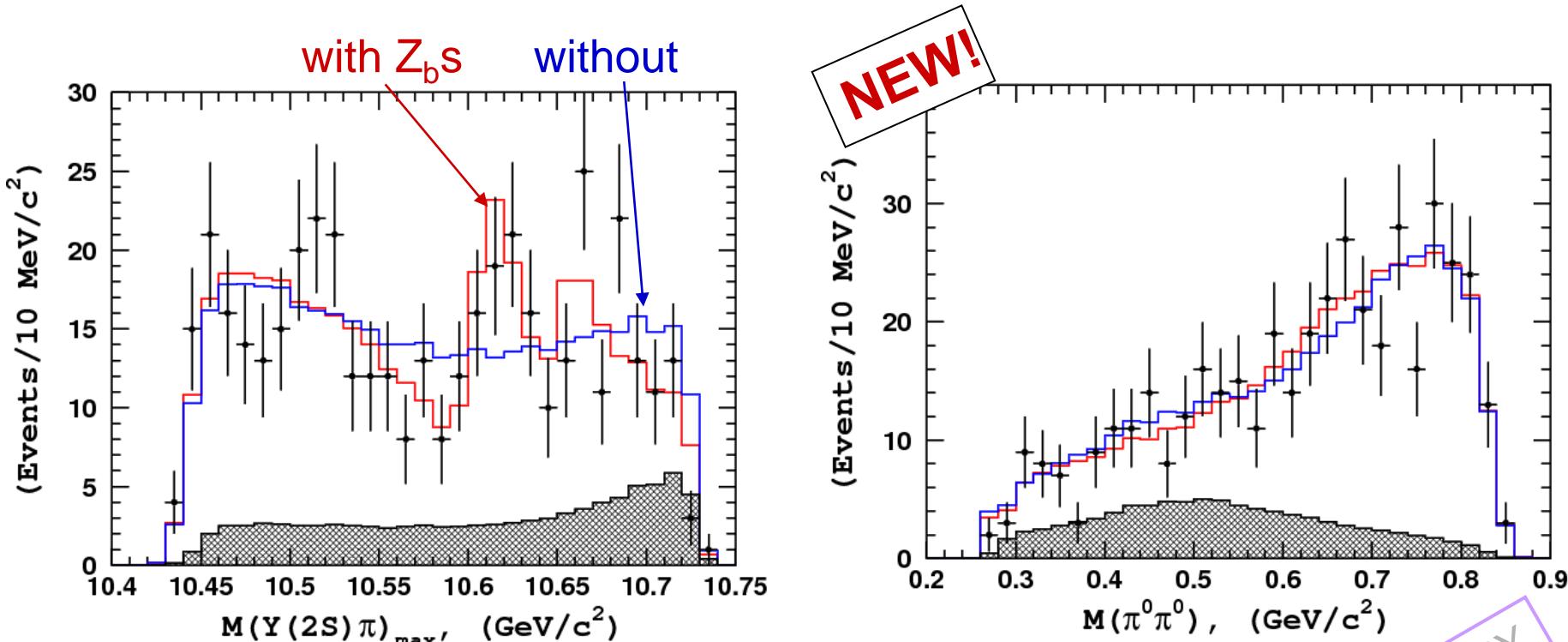


Background subtracted $\Upsilon(nS)\pi^0\pi^0$ data

Belle PRELIMINARY

Resonant structure of $\Upsilon(2S)\pi^0\pi^0$

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



- Clear Z_b^0 s signals are seen in $\Upsilon(2S)\pi^0\pi^0$
- Significance of $Z_b^0(10610)$ is 5.3σ (4.9σ with systematics)
- $Z_b^0(10650)$ is less significant ($\sim 2\sigma$)
- Fit to the $Z_b^0(10610)$ mass gives $M=10609 \pm 8 \pm 6$ MeV
 $M(Z_b^+) = 10607.2 \pm 2.0$ MeV

Summary

■ New R_b measurements

From 10750 MeV to 11050 MeV with extra 3 points @ lower energies.
No bump at 10900 MeV

■ Branching fractions of the two charged bottomonium-like Z_b^+ resonances decays $\Upsilon(1S)\pi^+$, $\Upsilon(2S)\pi^+$, $\Upsilon(3S)\pi^+$, $h_b(1P)\pi^+$, $h_b(2P)\pi^+$

■ First observation of Z_{bs} decays to BB^* and B^*B^* final states

$Z_b(10610)$ dominantly decays to BB^* , but $Z_b(10650)$ to B^*B^*
Decay fraction of $Z_b(10650)$ to BB^* is currently not statistically significant,
but at least less than to B^*B^*

■ First observation of $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$

■ First evidence for the neutral partners of $Z_b(10610)/Z_b(10650)$

Fit to the $Z_b^0(10610)$ mass gives $M = 10609 \pm 8 \pm 6$ MeV

Z_b s properties well fit the “molecular” hypothesis

Back up slides

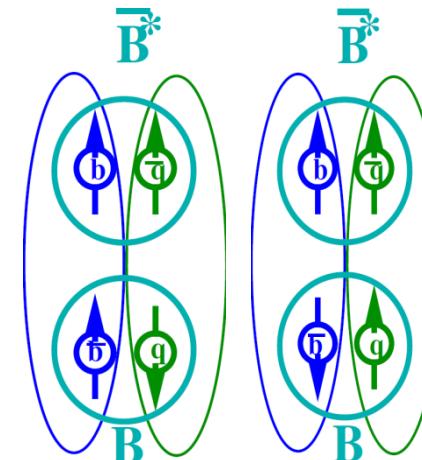
Heavy quark structure in Z_b

A.B.,A.Garmash,A.Milstein,R.Mizuk,M.Voloshin PRD84 054010 (arXiv:1105.4473)

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

$$|\tilde{Z}_b\rangle = \frac{1}{\sqrt{2}} \bar{Q}_b \otimes \mathbf{I} - \frac{1}{2} \mathbf{I} \otimes \bar{Q}_b$$

$$|\tilde{Z}_b\rangle = \frac{1}{\sqrt{2}} \bar{Q}_b \otimes \mathbf{I} + \frac{1}{2} \mathbf{I} \otimes \bar{Q}_b$$



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.Karlener, H.Lipkin, arXiv:0802.0649)

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

Introduction to η_b

Expected decays of h_b

Godfrey & Rosner, PRD66 014012 (2002)

$h_b(1P) \rightarrow ggg$ (57%), $\eta_b(1S)\gamma$ (41%), γgg (2%)

$h_b(2P) \rightarrow ggg$ (63%), $\eta_b(1S)\gamma$ (13%), $\eta_b(2S)\gamma$ (19%), γgg (2%)

Large $h_b(mP)$ samples give opportunity to study $\eta_b(nS)$ states.

Experimental status of η_b

$\Upsilon(3S) \rightarrow \eta_b(1S) \gamma$

$M[\eta_b(1S)] = 9390.9 \pm 2.8$ MeV (BaBar + CLEO)

$M[\Upsilon(1S)] - M[\eta_b(1S)] = 69.3 \pm 2.8$ MeV

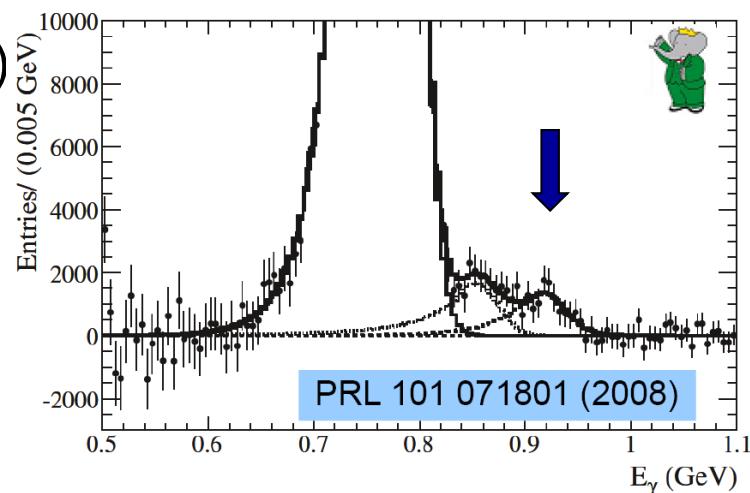
pNRQCD: 41 ± 14 MeV

Kniehl et al., PRL92,242001(2004)

Lattice: 60 ± 8 MeV

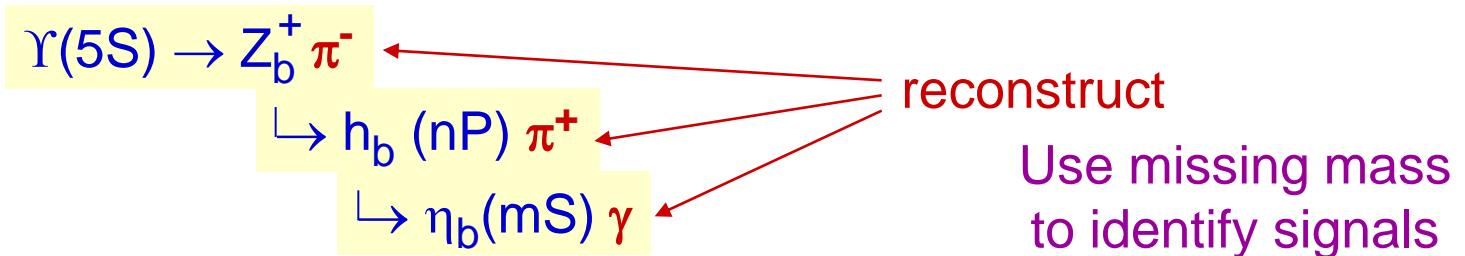
Meinel, PRD82,114502(2010)

Width of $\eta_b(1S)$: no information

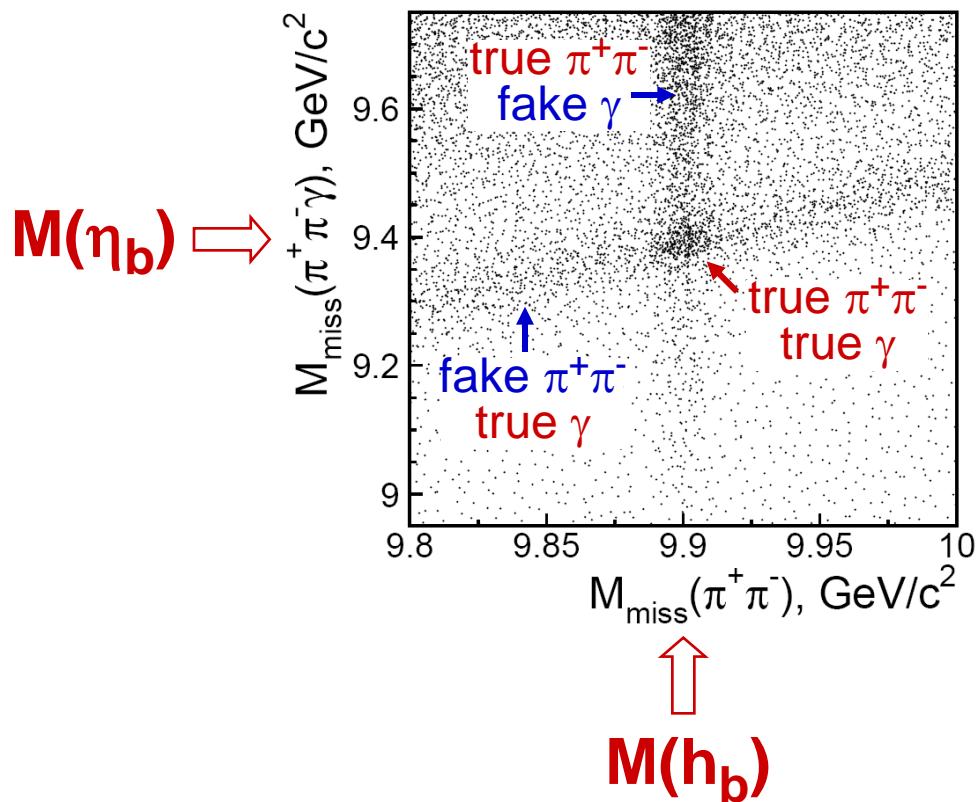


Method

Decay chain

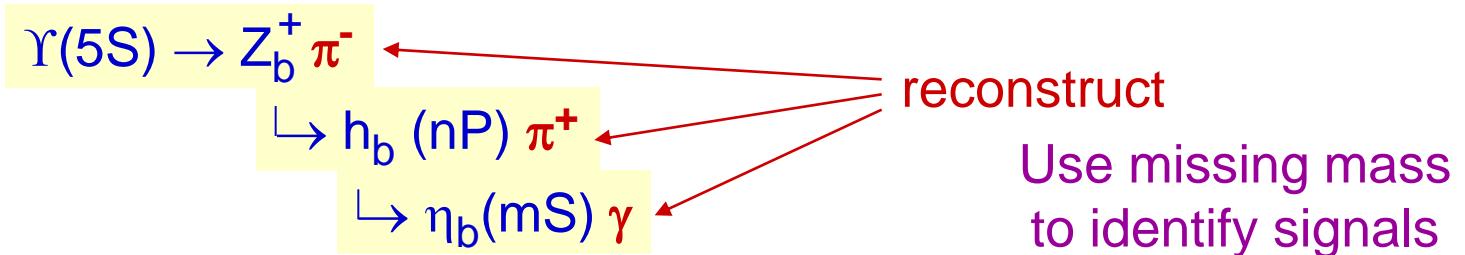


MC simulation

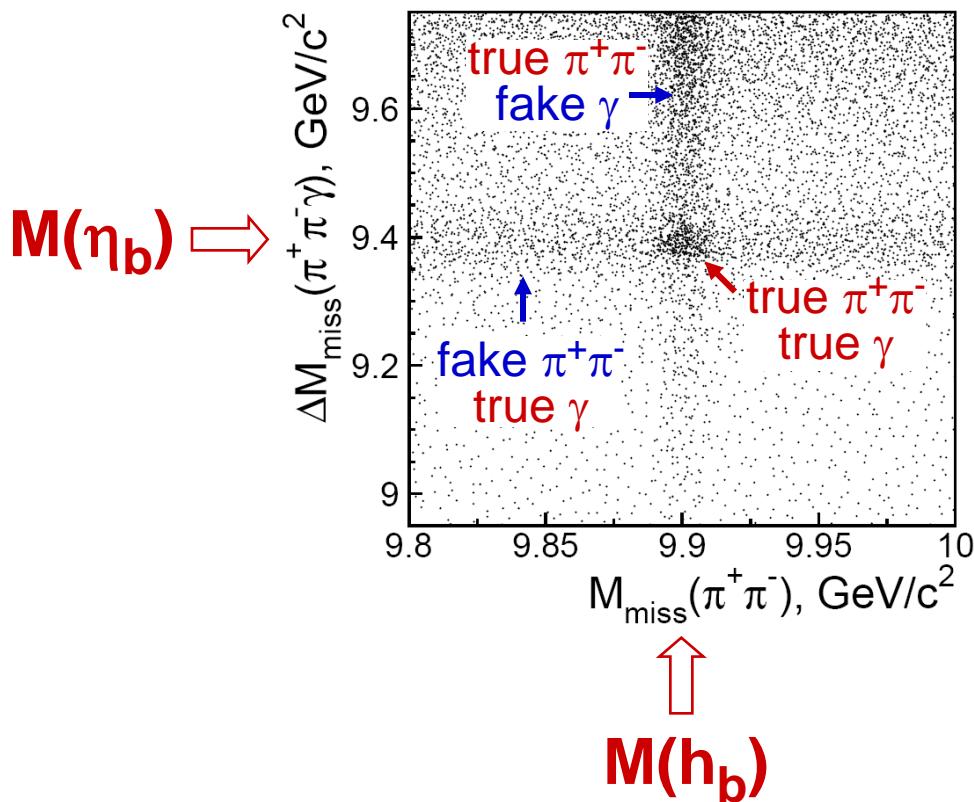


Method

Decay chain



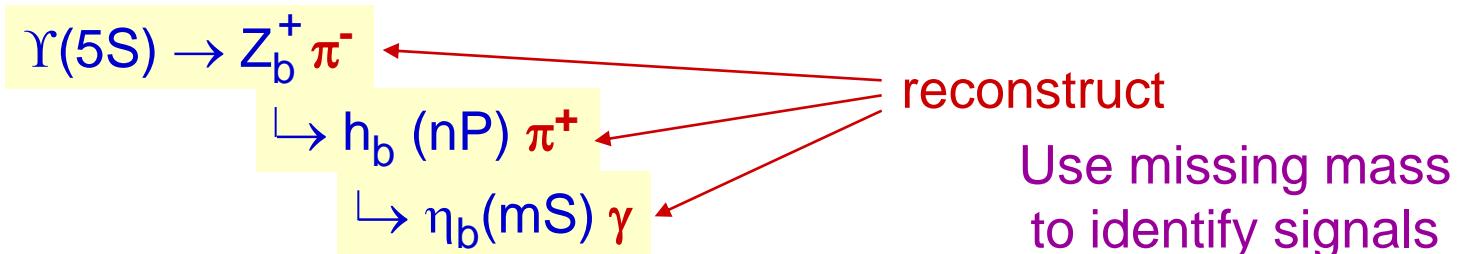
MC simulation



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

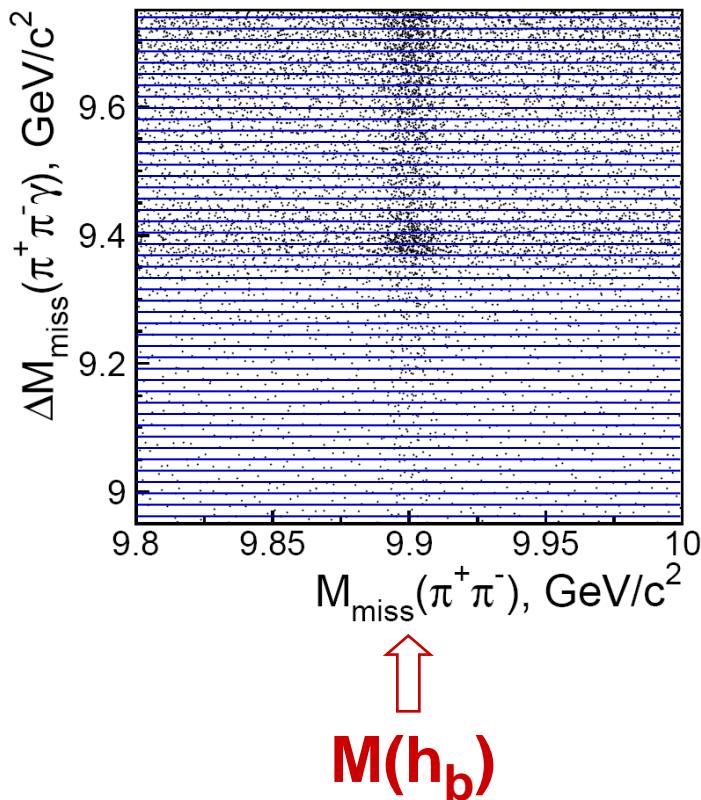
Method

Decay chain



MC simulation

$M(\eta_b)$



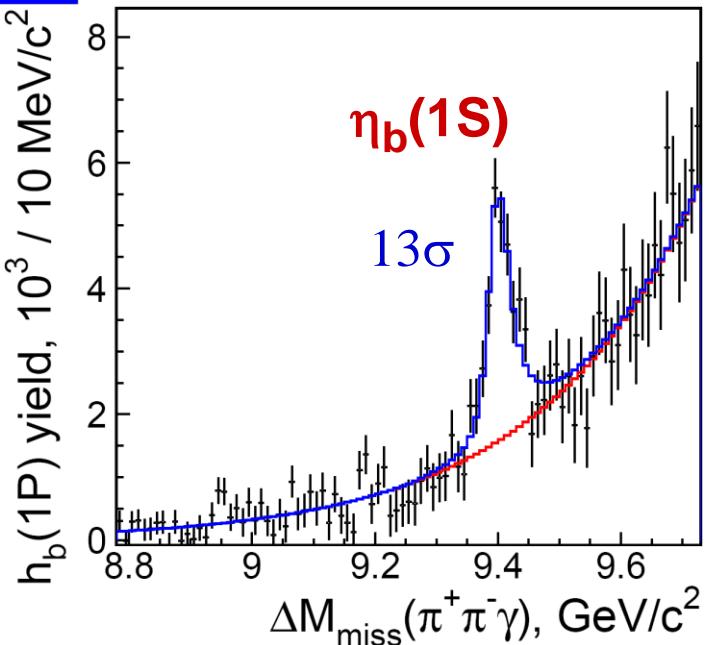
$$\Delta M_{\text{miss}}(\pi^+\pi^-\gamma) \equiv M_{\text{miss}}(\pi^+\pi^-\gamma) - M_{\text{miss}}(\pi^+\pi^-) + M[h_b]$$

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

Results

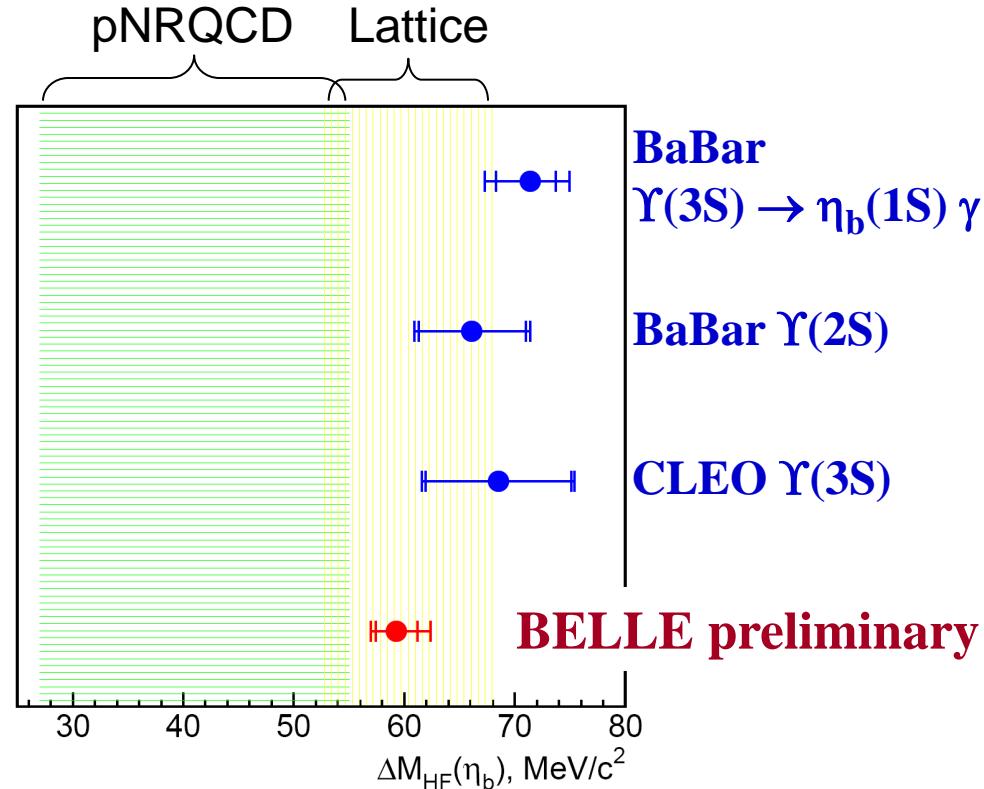


$$M[\eta_b(1S)] = (9401.0 \pm 1.9^{+1.4}_{-2.4}) \text{ MeV}/c^2$$

$$\Delta M_{\text{HF}} [\eta_b(1S)] = 59.3 \pm 1.9^{+2.4}_{-1.4} \text{ MeV}/c^2$$

$$\Gamma[\eta_b(1S)] = (12.4^{+5.5+11.5}_{-4.6-3.4}) \text{ MeV}$$

N.Brambilla et al., Eur.Phys.J.
C71(2011) 1534 (arXiv:1010.5827)



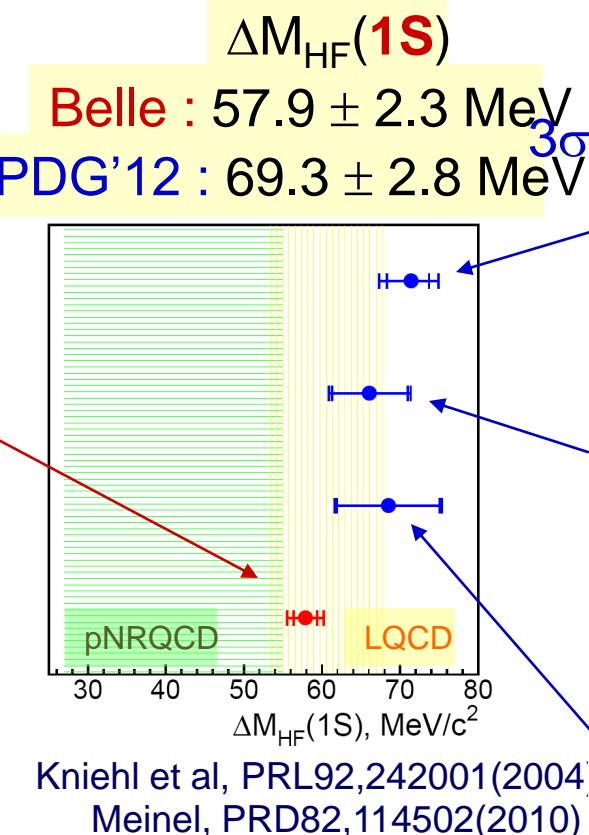
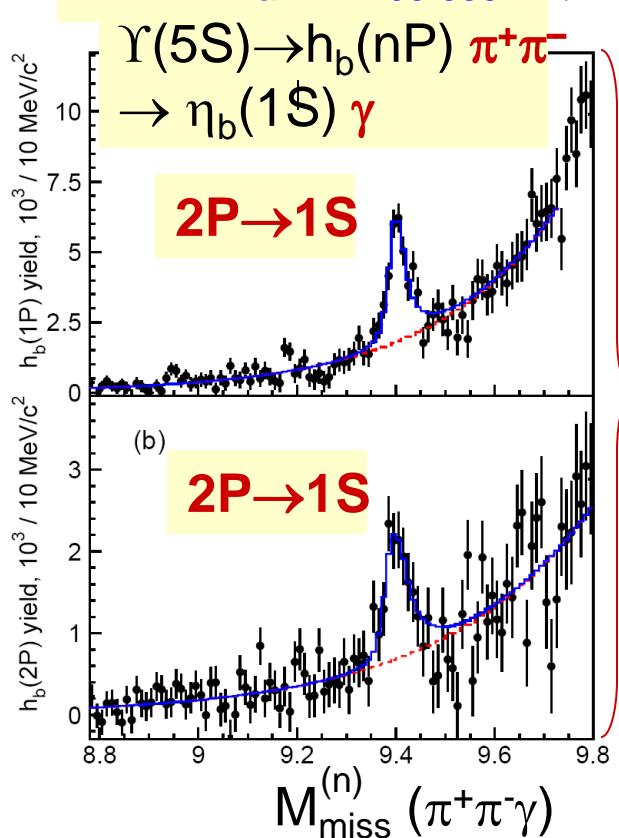
$$\mathcal{B}[h_b(1P) \rightarrow \eta_b(1S)\gamma] = (49.8 \pm 6.8^{+10.9}_{-5.2})\% \quad \text{Godfrey \& Rosner : BF = 41\%}$$

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

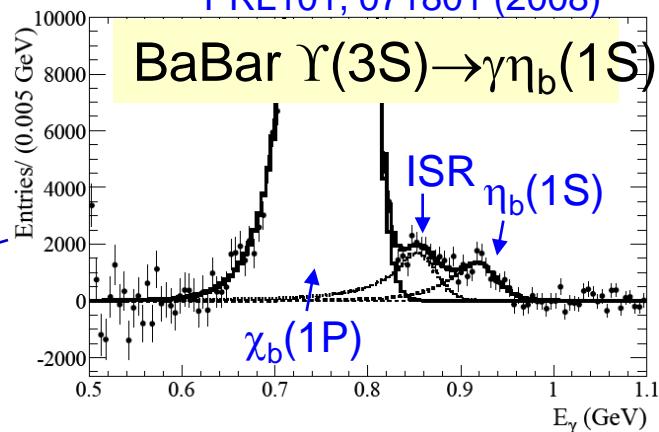
PRL101, 071801 (2008)

Belle

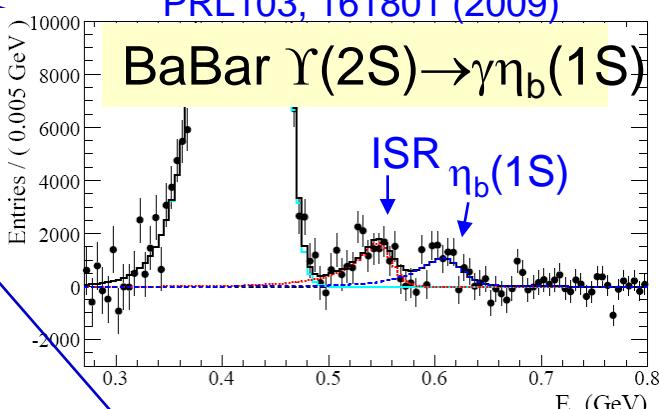
arxiv:1205.6351 → PRL



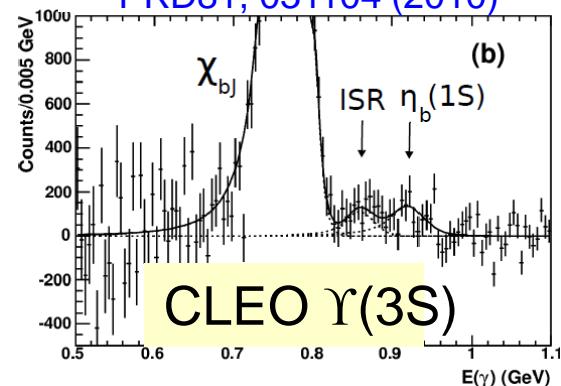
Kniehl et al, PRL92,242001(2004)
Meinel, PRD82,114502(2010)



PRL103, 161801 (2009)



PRD81, 031104 (2010)

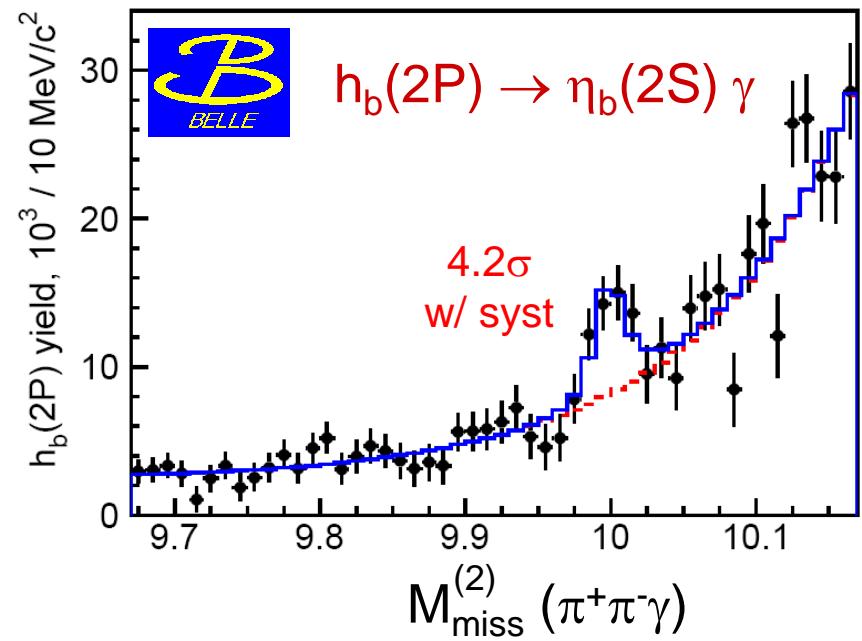


Belle: no peaks close to $\eta_b(1S)$ region
Belle result decreases tension with theory

First measurement $\Gamma = 10.8^{+4.0}_{-3.7}{}^{+4.5}_{-2.0} \text{ MeV}$
as expected

First evidence for $\eta_b(2S)$

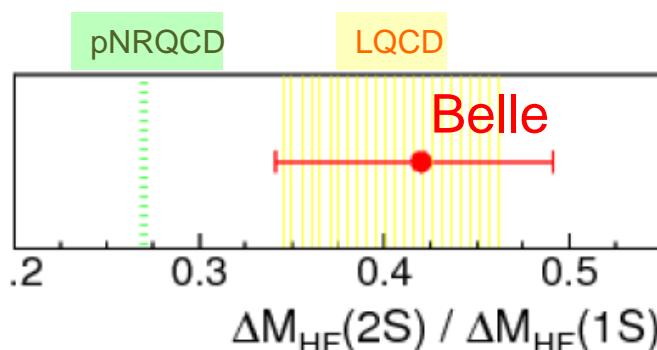
arxiv:1205.6351 →PRL



Belle

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

First measurement



In agreement with theory

$$\Gamma(2S) = 4 \pm 8 \text{ MeV}, < 24 \text{ MeV @ 90% C.L.} \\ \text{expect } \sim 4 \text{ MeV}$$

Branching fractions

$$\text{BF}[h_b(1P) \rightarrow \eta_b(1S)\gamma] = 49.2_{-3.3}^{+5.7+5.6} \% \times 1.2$$

$$\text{BF}[h_b(2P) \rightarrow \eta_b(1S)\gamma] = 22.3_{-3.3}^{+3.8+3.1} \% \times 1.7 \text{ w.r.t. expectations}$$

$$\text{BF}[h_b(2P) \rightarrow \eta_b(2S)\gamma] = 47.5_{-7.7}^{+10.5+6.8} \% \times 2.5$$

Godfrey Rosner PRD66,014012(2002)

c.f. BESIII $\text{BF}[h_c(1P) \rightarrow \eta_c(1S)\gamma] = 54.3 \pm 8.5 \% \times 1.4$



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

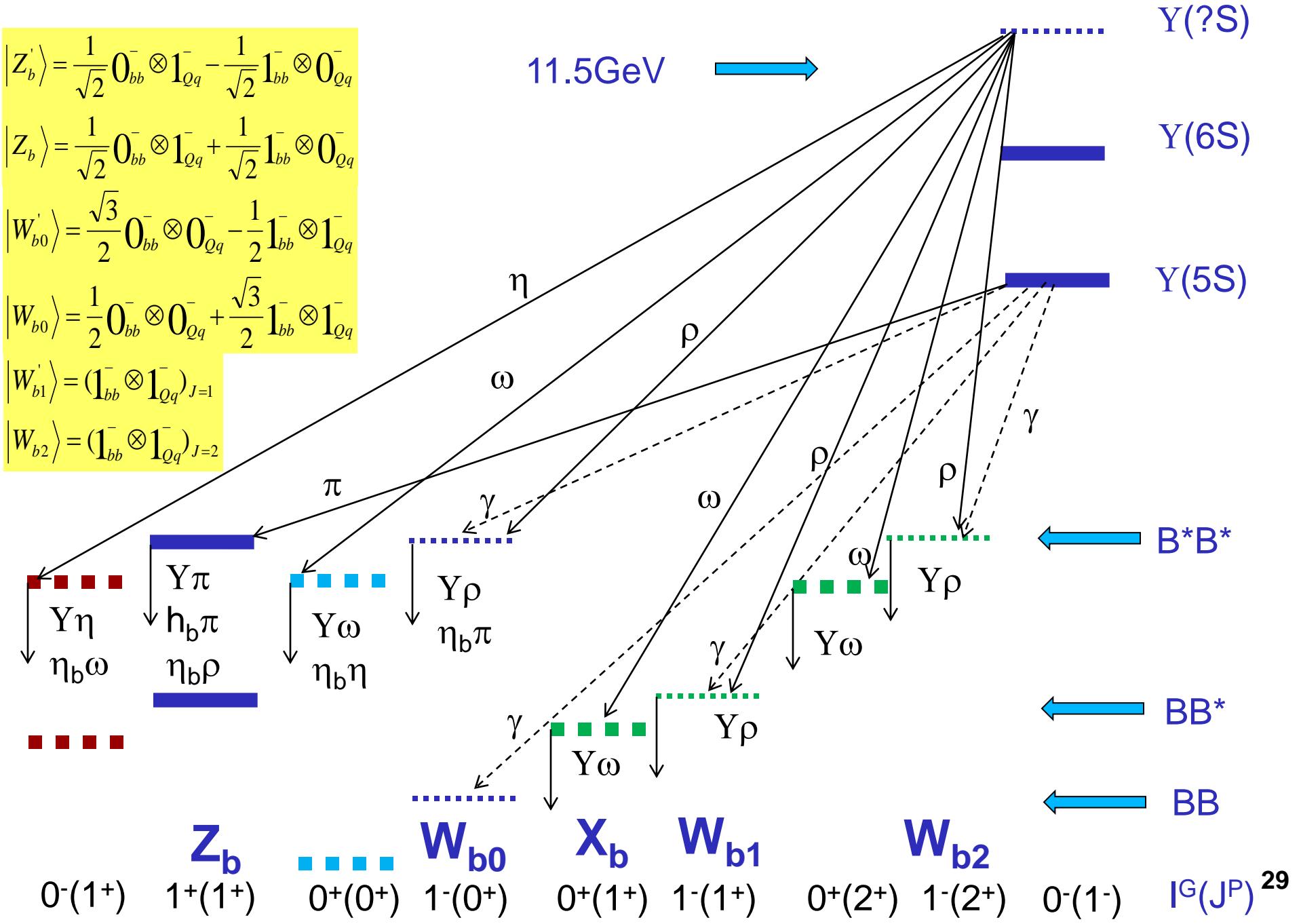
$$\left| Z_b' \right\rangle = \frac{1}{\sqrt{2}} \mathbf{0}_{bb}^- \otimes \mathbf{1}_{Qq}^- + \frac{1}{\sqrt{2}} \mathbf{1}_{bb}^- \otimes \mathbf{0}_{Qq}^-$$

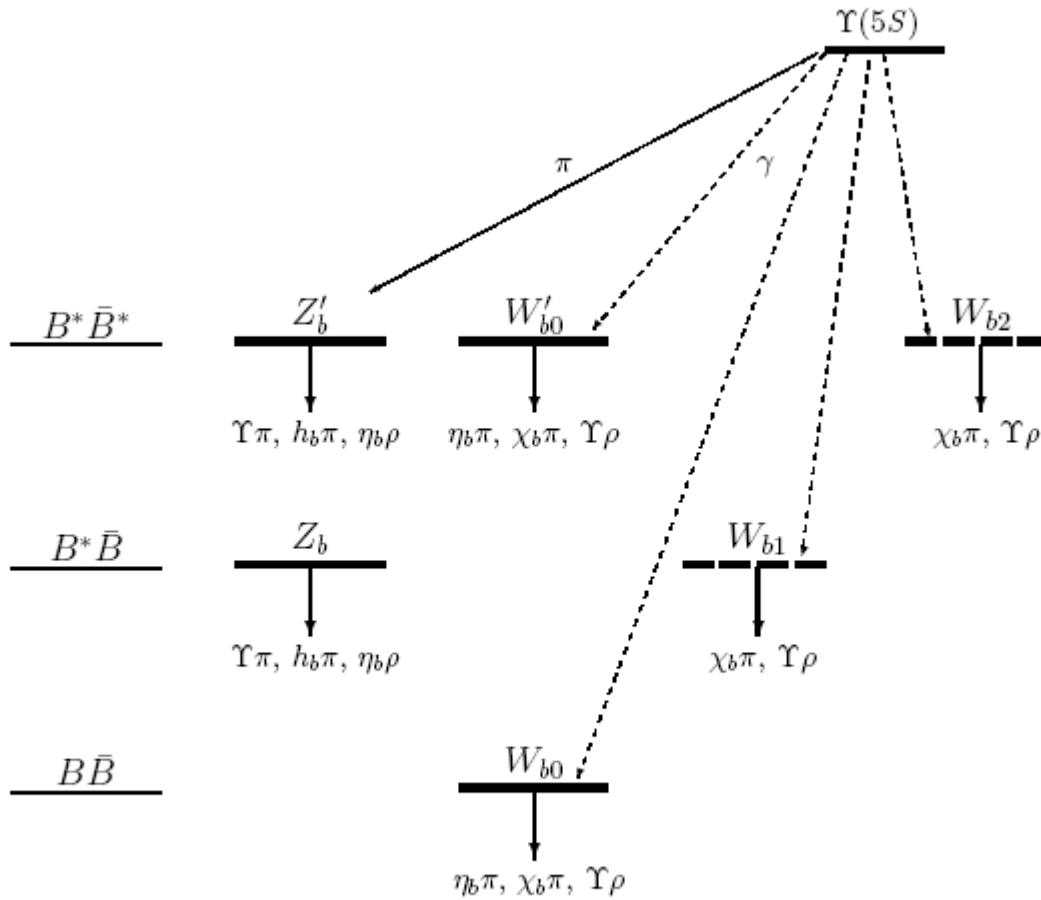
$$\left| W_{b0} \right\rangle = \frac{\sqrt{3}}{2} \mathbf{0}_{bb}^- \otimes \mathbf{0}_{Qq}^- - \frac{1}{2} \mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-$$

$$\left| W_{b0}' \right\rangle = \frac{1}{2} \mathbf{0}_{bb}^- \otimes \mathbf{0}_{Qq}^- + \frac{\sqrt{3}}{2} \mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-$$

$$\left| W_{b1} \right\rangle = (\mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-)_{J=1}$$

$$\left| W_{b2} \right\rangle = (\mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-)_{J=2}$$





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

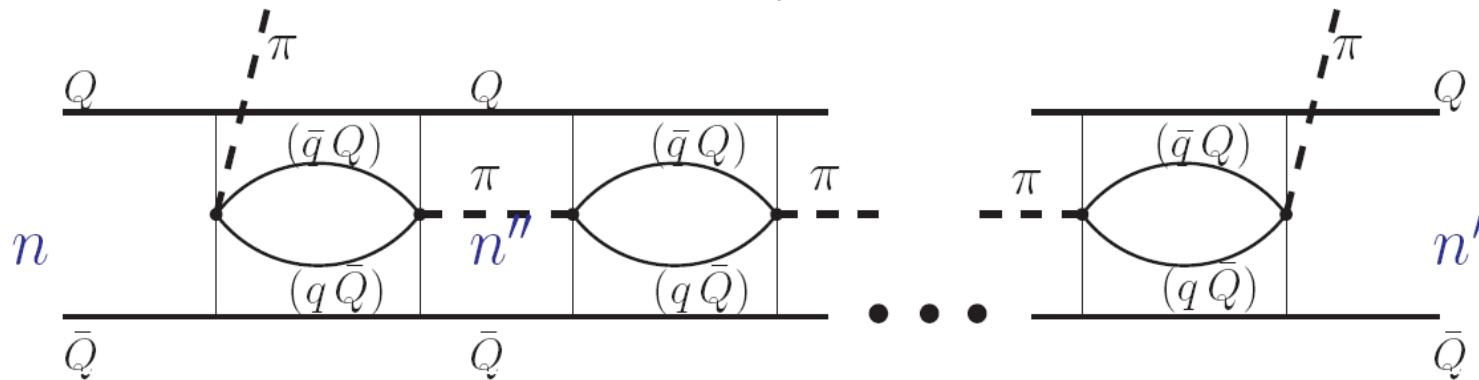
$$|Z_b\rangle = \frac{1}{\sqrt{2}} \mathbf{0}_{bb}^- \otimes \mathbf{1}_{Qq}^- + \frac{1}{\sqrt{2}} \mathbf{1}_{bb}^- \otimes \mathbf{0}_{Qq}^-$$

$$|W'_{b0}\rangle = \frac{\sqrt{3}}{2} \mathbf{0}_{bb}^- \otimes \mathbf{0}_{Qq}^- - \frac{1}{2} \mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-$$

$$|W_{b0}\rangle = \frac{1}{2} \mathbf{0}_{bb}^- \otimes \mathbf{0}_{Qq}^- + \frac{\sqrt{3}}{2} \mathbf{1}_{bb}^- \otimes \mathbf{1}_{Qq}^-$$

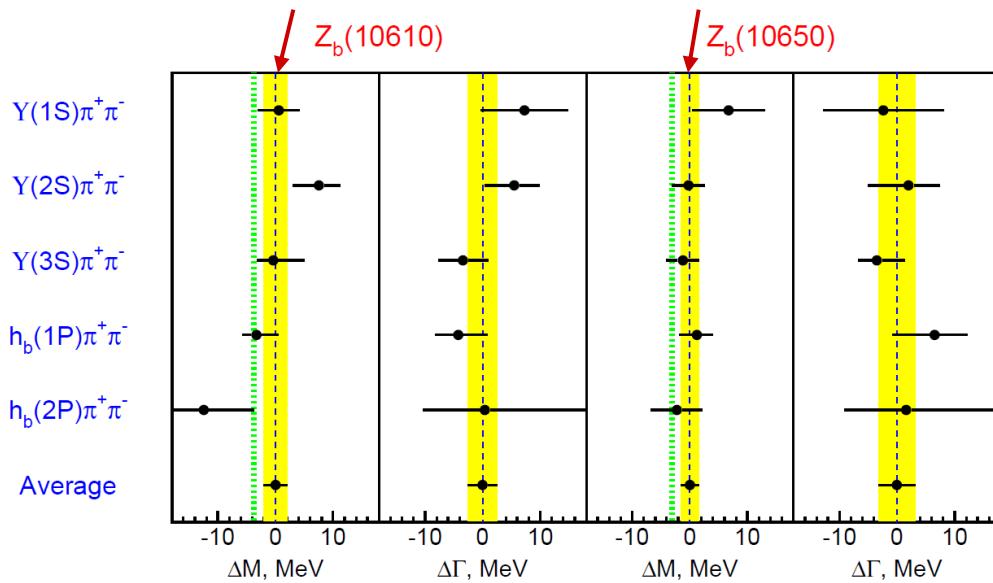
Coupled channel resonance?

I.V.Danilkin, V.D.Orlovsky, Yu.Simonov arXiv:1106.1552



No interaction between $B(*)B^*$ or $\Upsilon\pi$ is needed to form resonance

No other resonances predicted

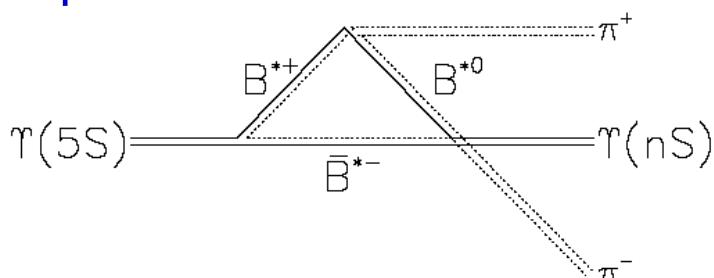


$B(*)B^*$ interaction switched on \Rightarrow individual mass in every channel?

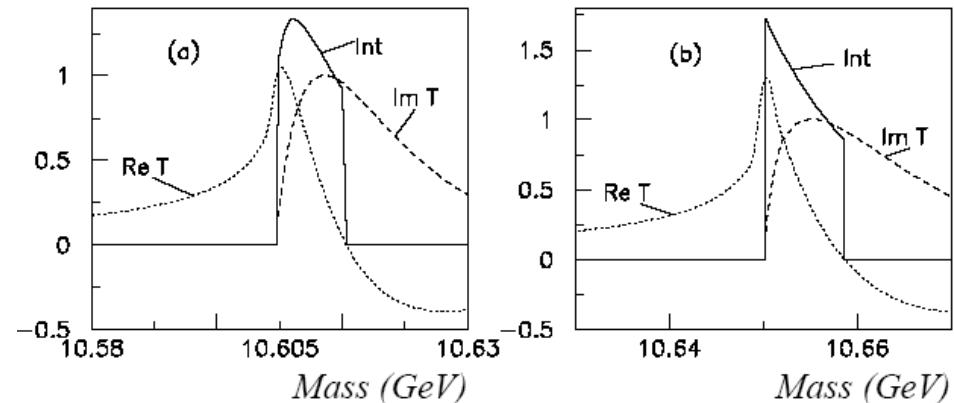
Cusp?

D.Bugg Europhys.Lett.96 (2011) (arXiv:1105.5492)

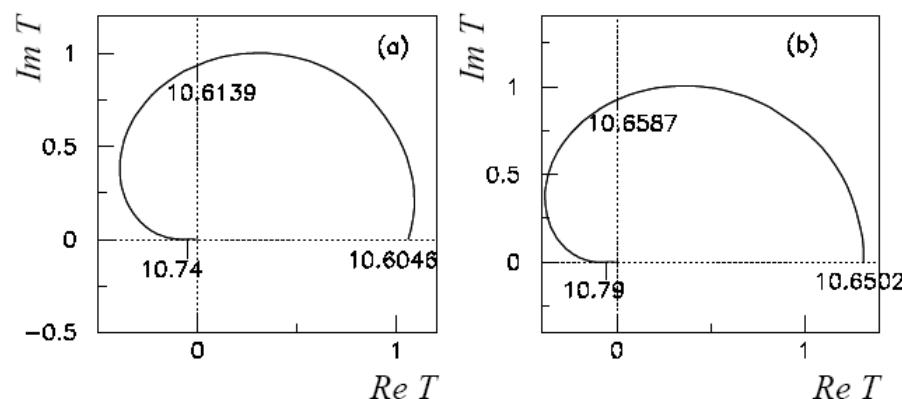
Amplitude



Line-shape



Not a resonance



Tetraquark?

M ~ 10.2 – 10.3 GeV

Ying Cui, Xiao-lin Chen, Wei-Zhen Deng,
Shi-Lin Zhu, High Energy Phys.Nucl.Phys.31:7-13, 2007
(hep-ph/0607226)

M ~ 10.5 – 10.8 GeV

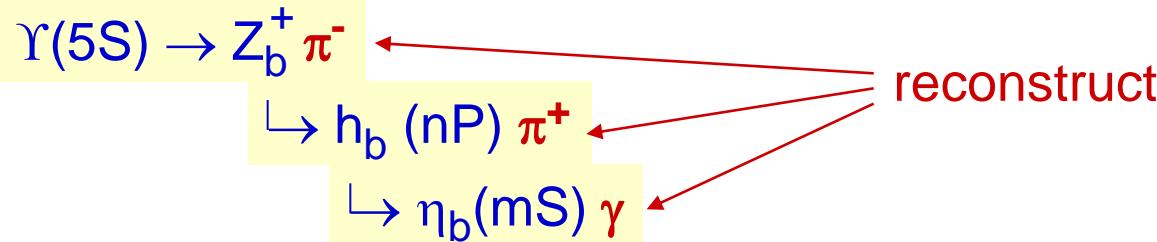
Tao Guo, Lu Cao, Ming-Zhen Zhou, Hong Chen, (1106.2284)

M ~ 9.4, 11 GeV

M.Karliner, H.Lipkin, (0802.0649)

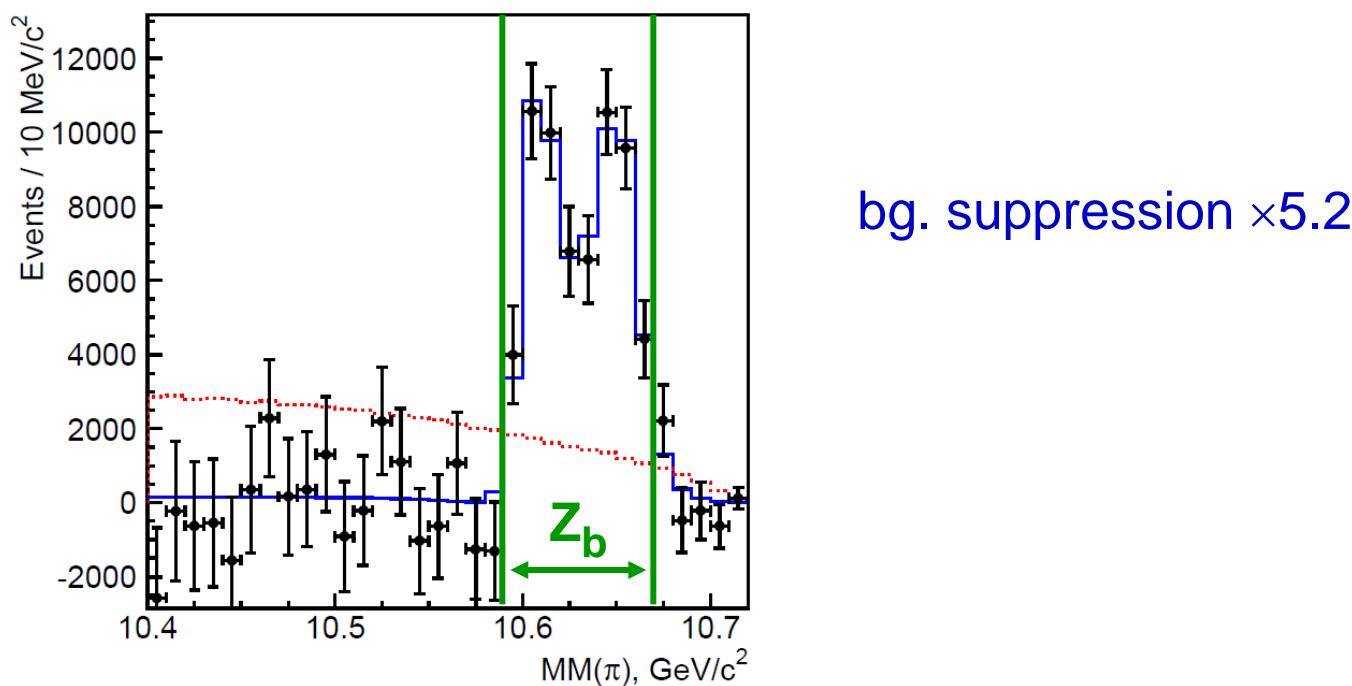
Selection

Decay chain



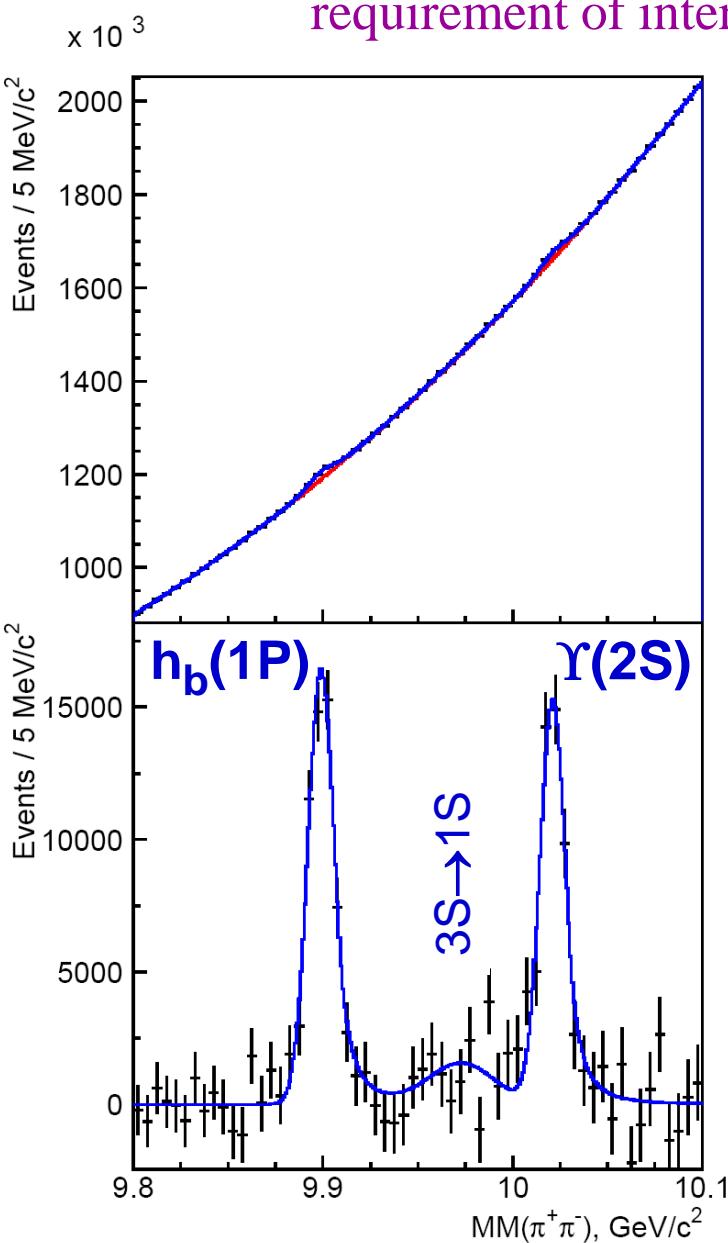
$R_2 < 0.3$
Hadronic event selection; continuum suppression using event shape; π^0 veto.

Require intermediate Z_b : **10.59 < MM(π) < 10.67 GeV**



$M_{\text{miss}}(\pi^+\pi^-)$ spectrum

requirement of intermediate Z_b



Update of $M [h_b(1P)]$:

$$(9899.0 \pm 0.4 \pm 1.0) \text{ MeV}/c^2$$

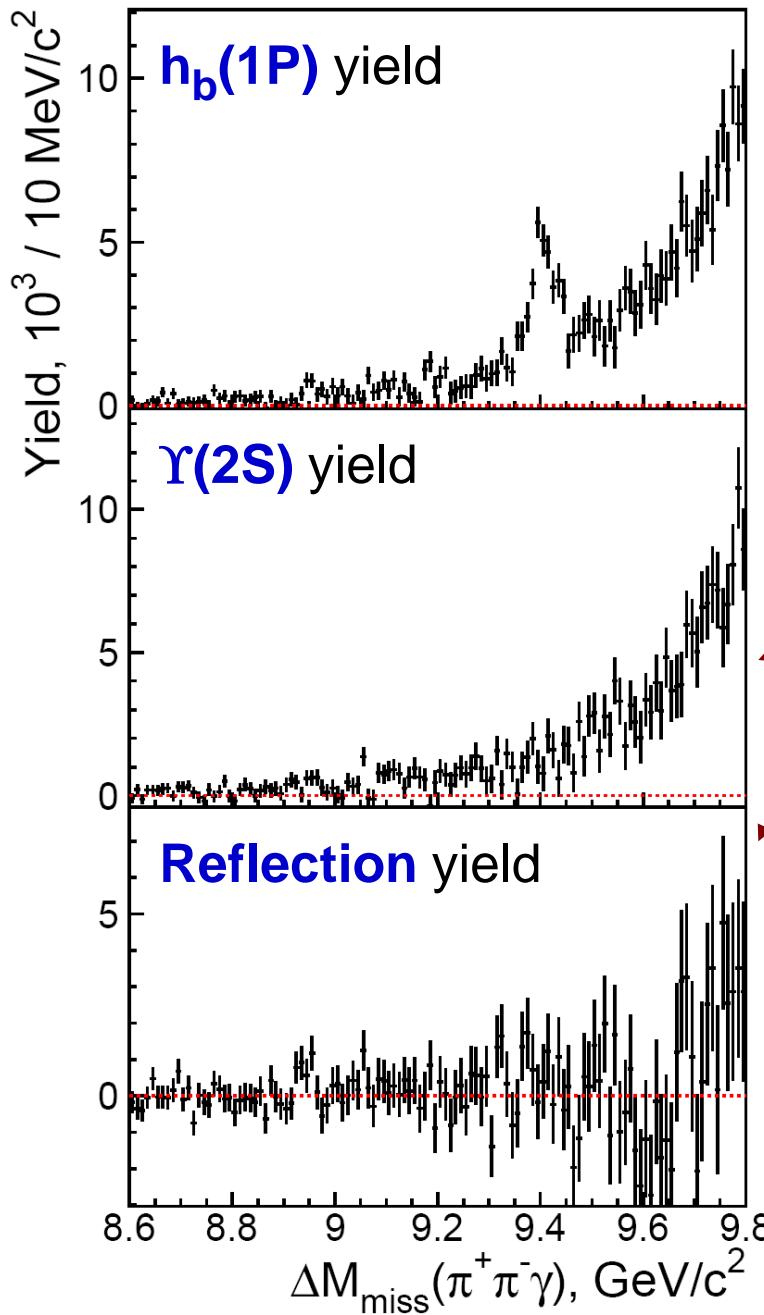
$$\Delta M_{\text{HF}} [h_b(1P)] = (+0.8 \pm 1.1) \text{ MeV}/c^2$$

Previous Belle meas.: arXiv:1103.3411

$$(9898.3 \pm 1.1^{+1.0}_{-1.1}) \text{ MeV}/c^2$$

$$\Delta M_{\text{HF}} [h_b(1P)] = (+1.6 \pm 1.5) \text{ MeV}/c^2$$

Results of fits to $M_{\text{miss}}(\pi^+\pi^-)$ spectra



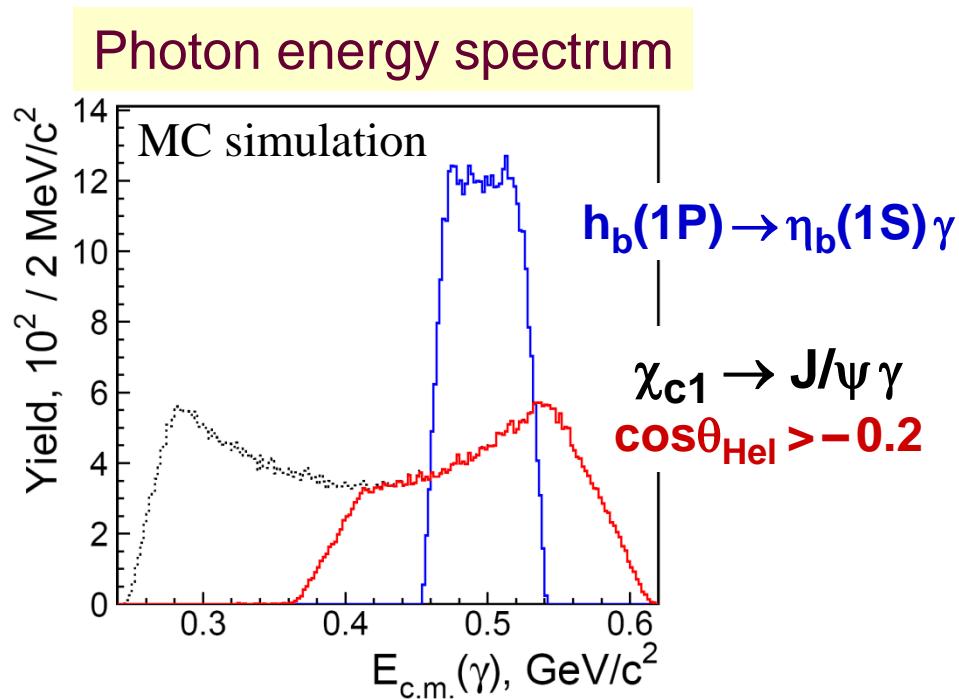
$\eta_b(1S)$

Peaking background?
MC simulation \Rightarrow none.

no significant
structures

Calibration

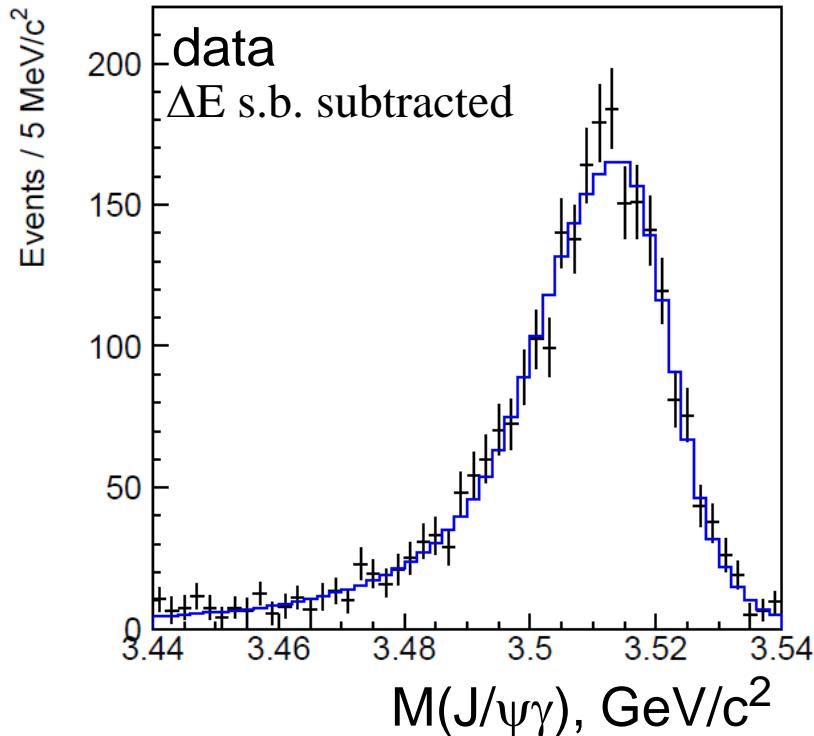
Use decays $B^+ \rightarrow \chi_{c1} K^+ \rightarrow (J/\psi \gamma) K^+$



$\cos\theta_{\text{Hel}}(\chi_{c1}) > -0.2 \Rightarrow$ match γ energy of **signal** & **calibration** channels

Calibration (2)

Resolution: double-sided CrystalBall function with asymmetric core

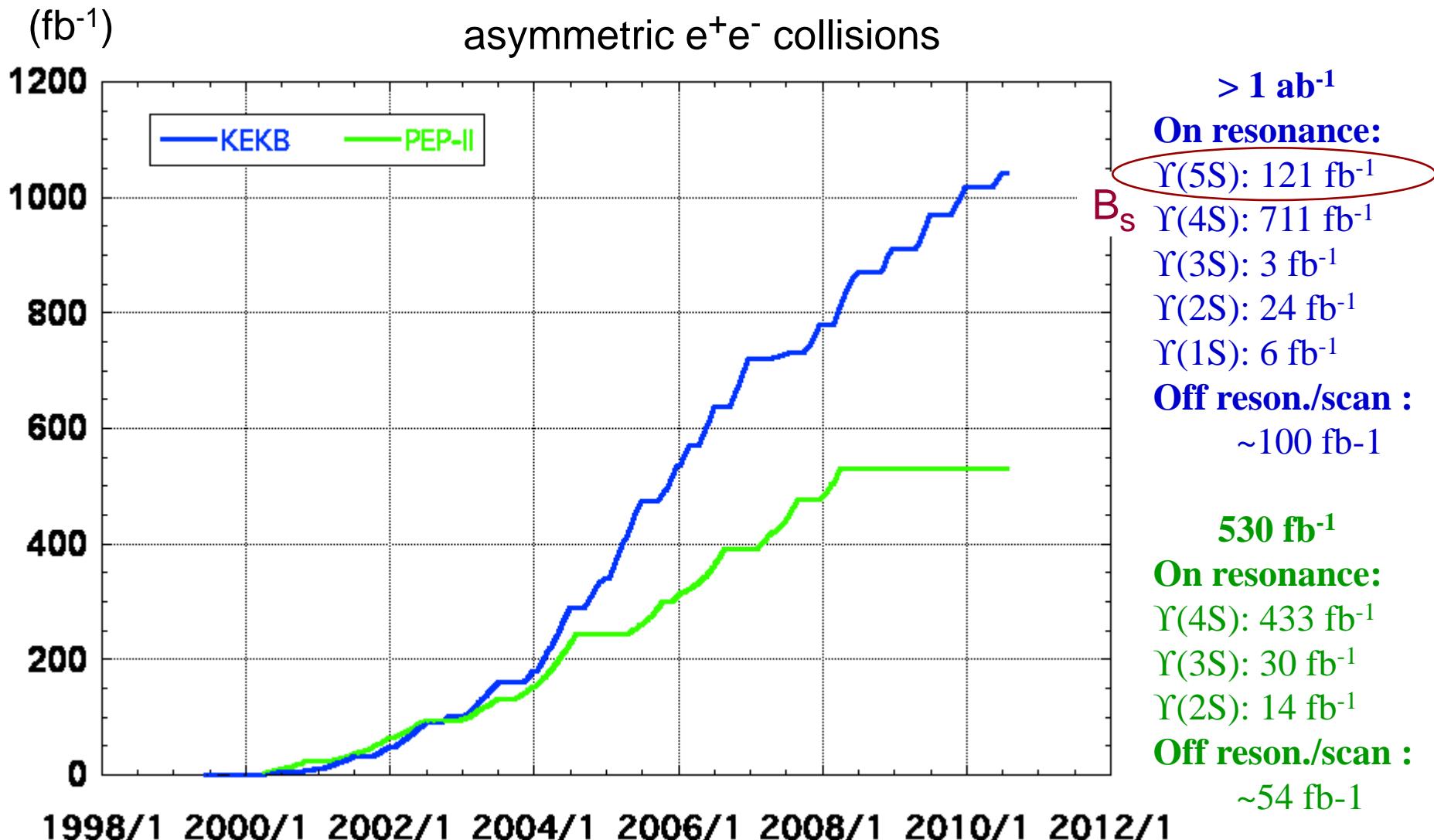


⇒ Correction of MC

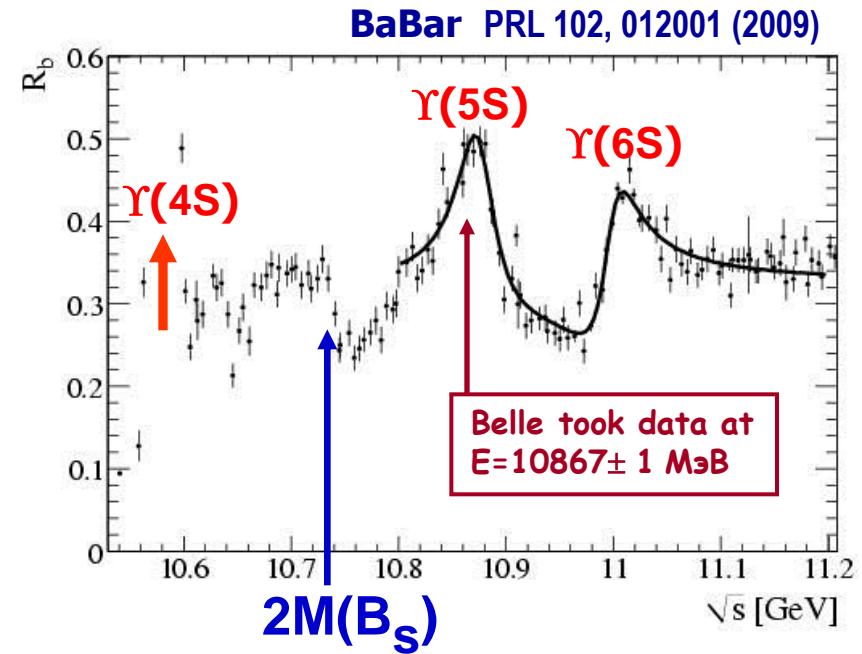
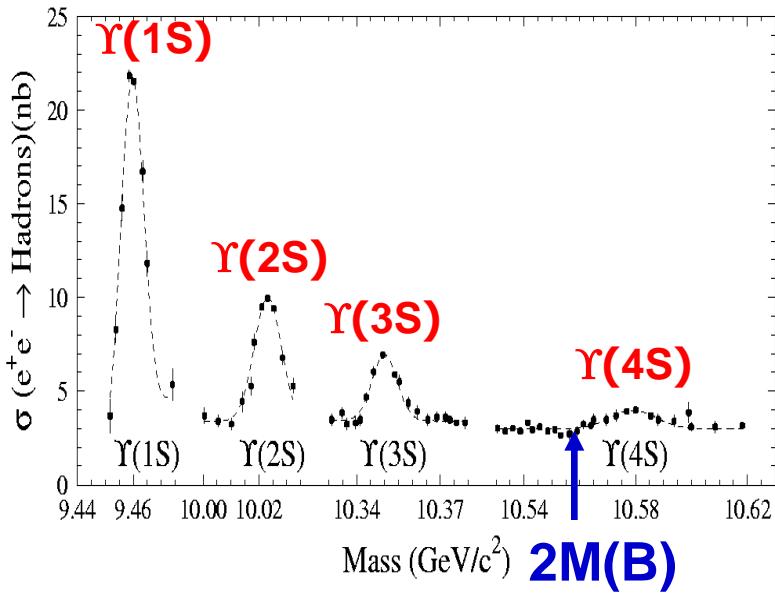
mass shift $-0.7 \pm 0.3 {}^{+0.2}_{-0.4} \text{ MeV}$

fudge-factor
for resolution $1.15 \pm 0.06 \pm 0.06$

Integrated Luminosity at B-factories

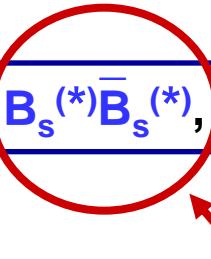


e⁺e⁻ hadronic cross-section



$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, where B is B^+ or B^0

$e^+ e^- \rightarrow b\bar{b}$ ($\Upsilon(5S)$) $\rightarrow B^{(*)}\bar{B}^{(*)}$, $B^{(*)}\bar{B}^{(*)}\pi$, $B\bar{B}\pi\pi$, $B_s^{(*)}\bar{B}_s^{(*)}$, $\Upsilon(1S)\pi\pi$, $\Upsilon X \dots$

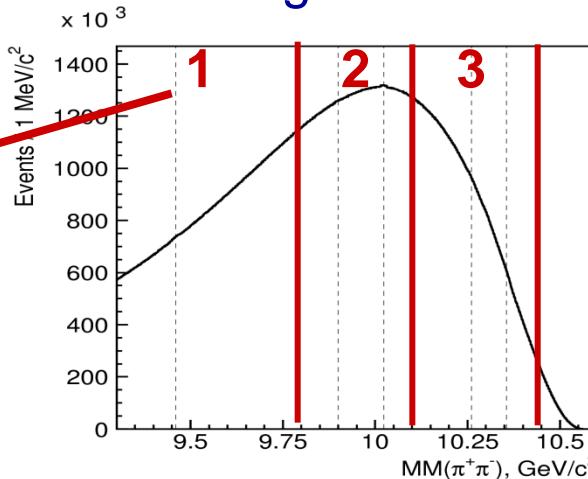
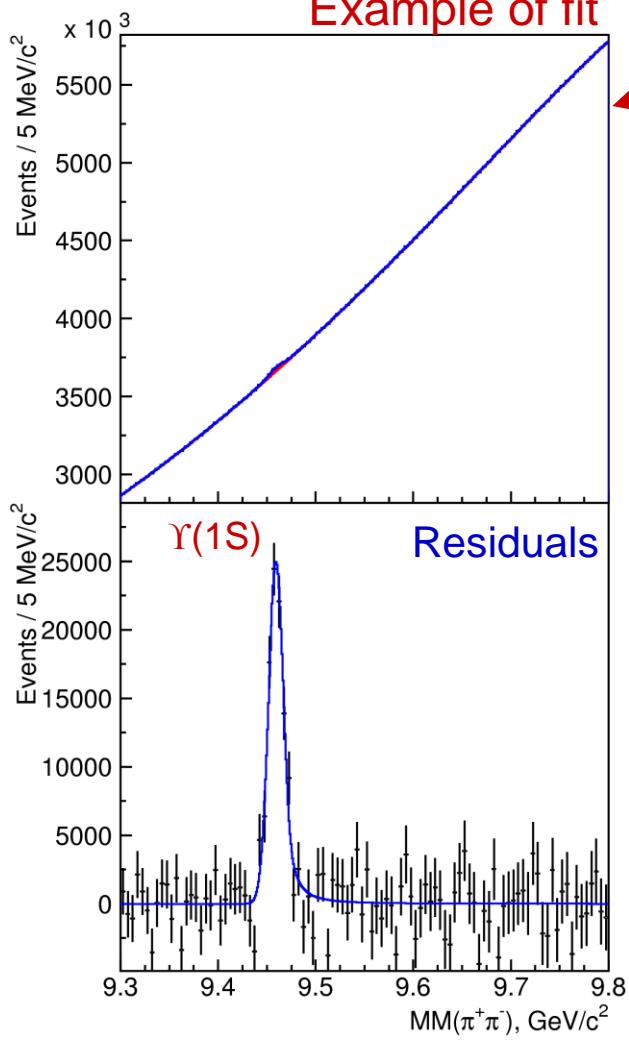


main motivation
for taking data at $\Upsilon(5S)$

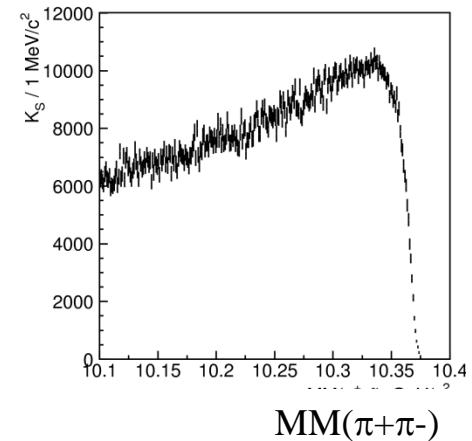
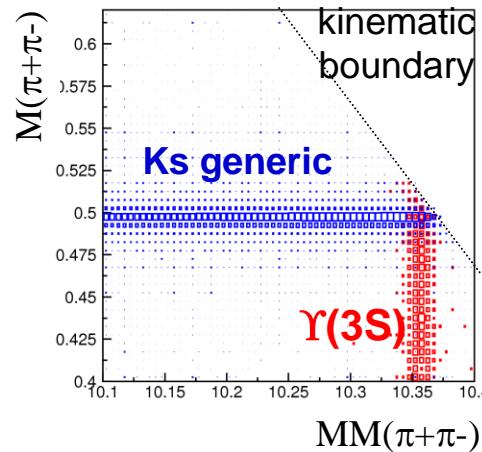
Description of fit to MM($\pi^+\pi^-$)

Three fit regions

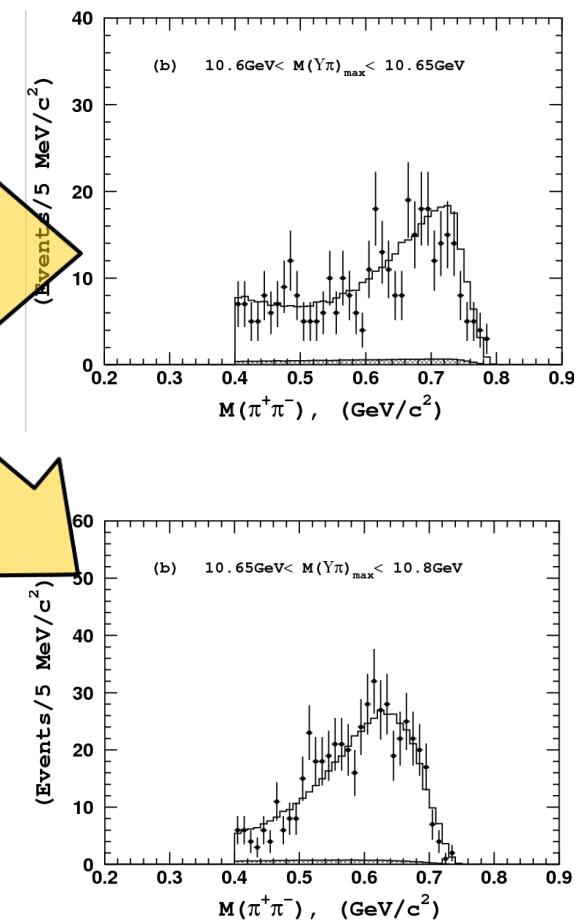
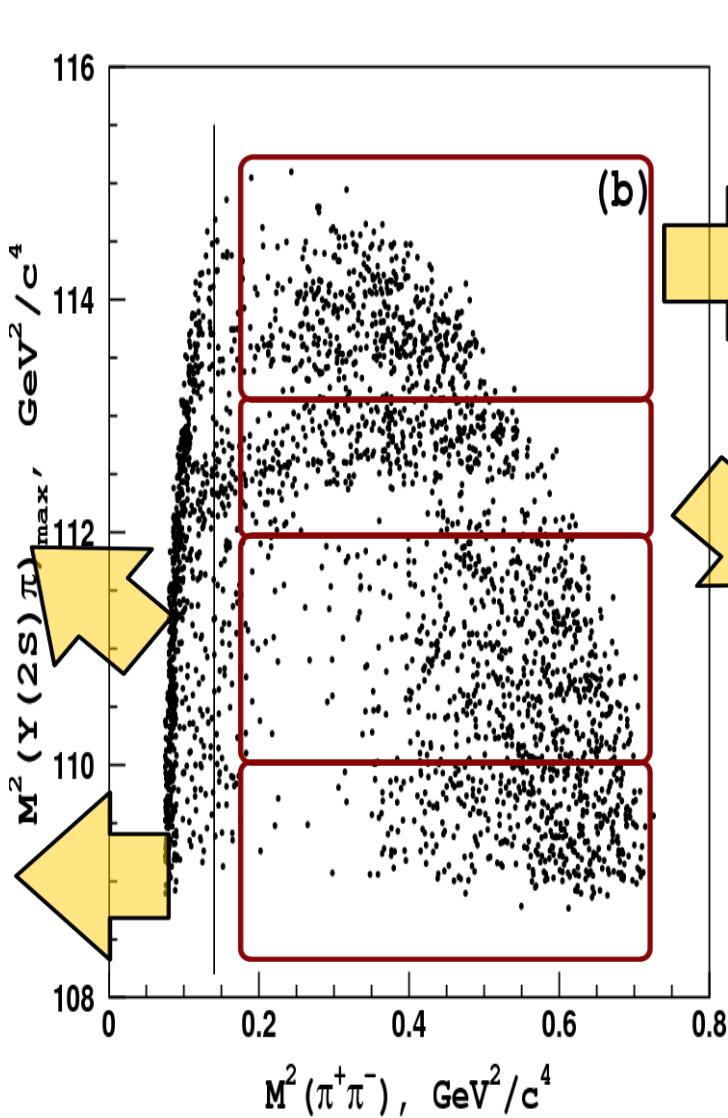
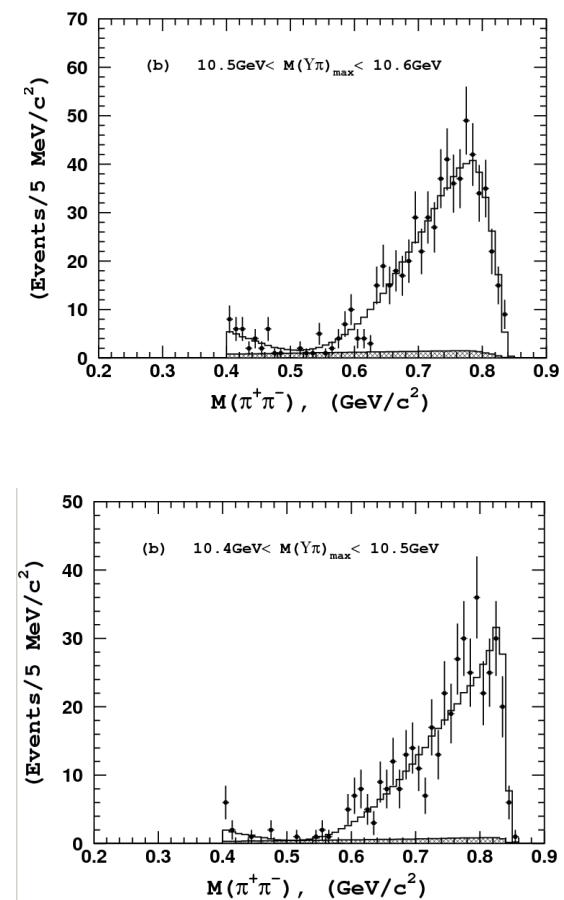
Example of fit



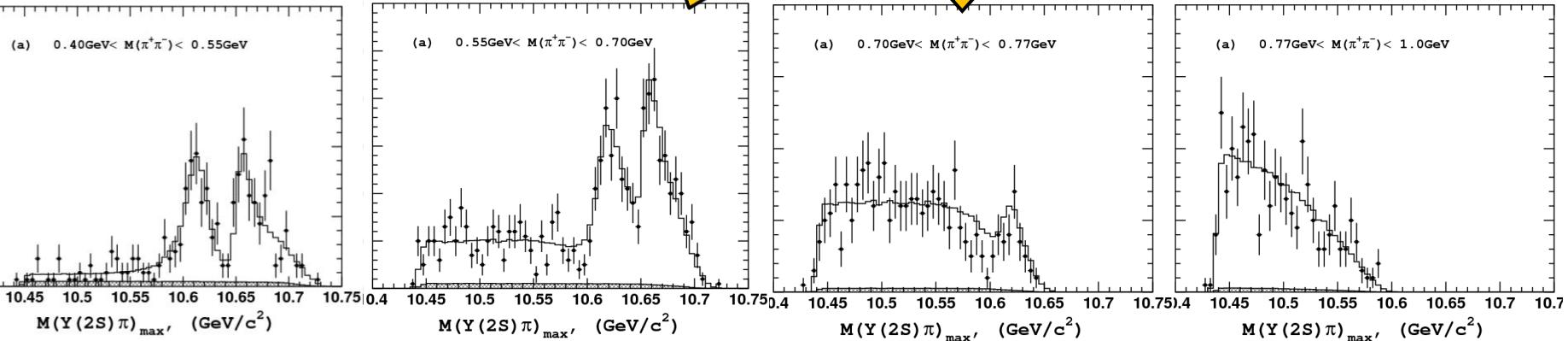
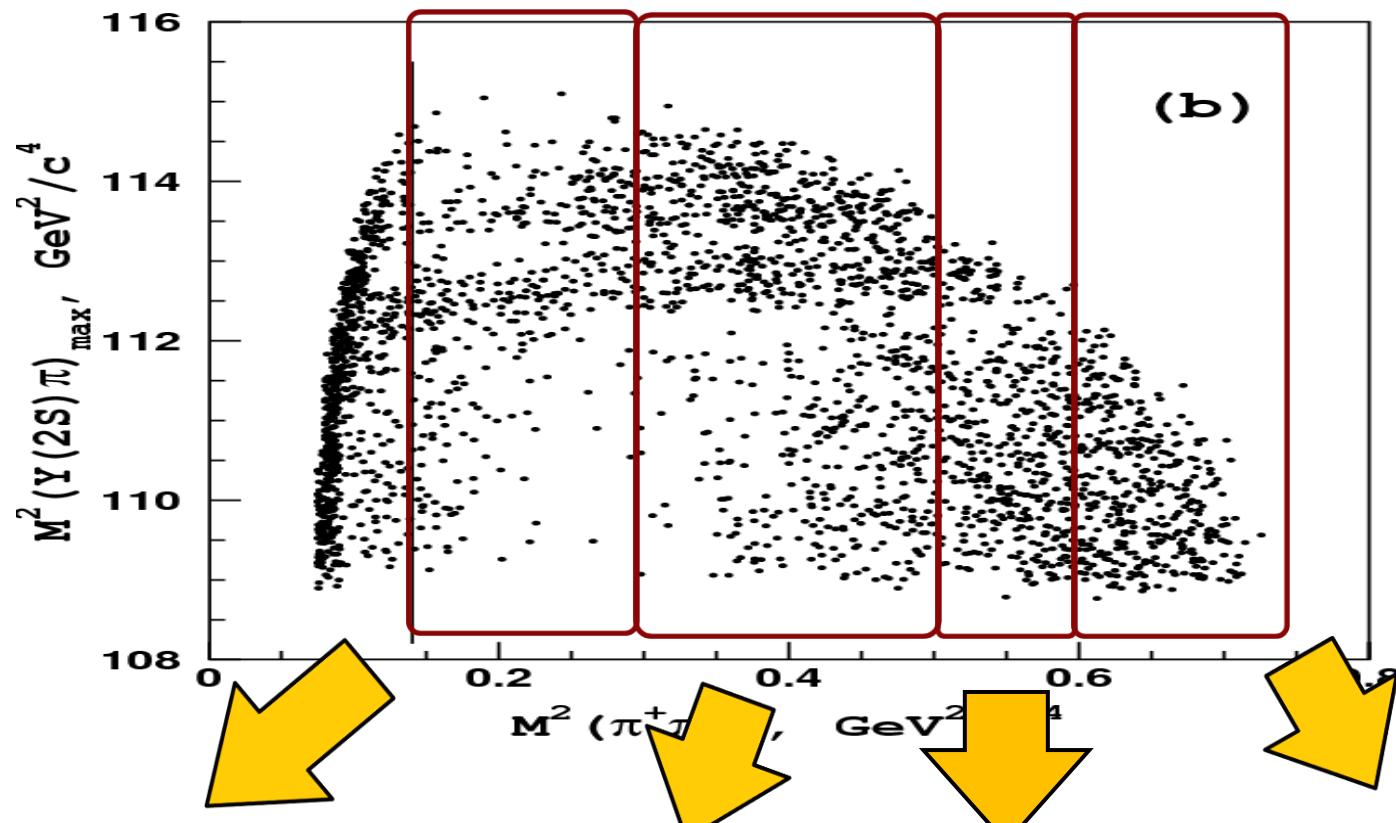
BG: Chebyshev polynomial, 6th or 7th order
 Signal: shape is fixed from $\mu^+\mu^-\pi^+\pi^-$ data
 “Residuals” – subtract polynomial from data points
 K_S contribution: subtract bin-by-bin



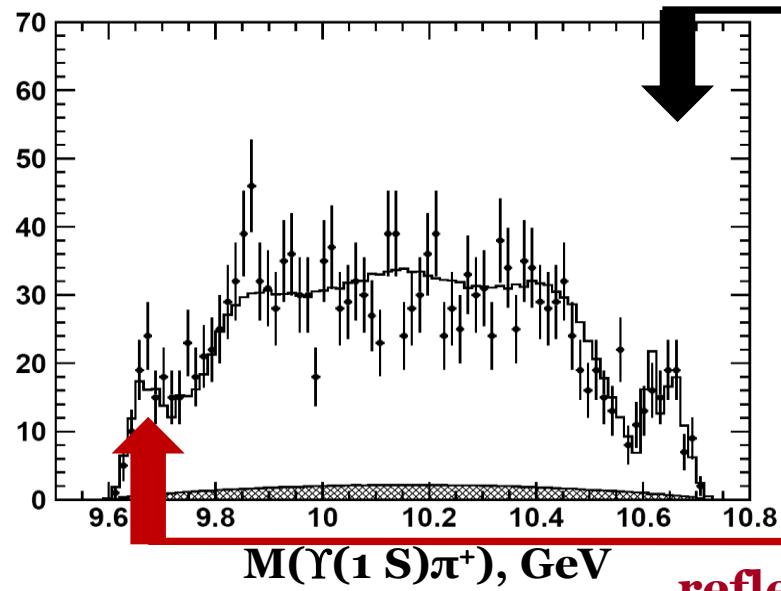
Results: $Y(5S) \rightarrow Y(2S)\pi^+\pi^-$



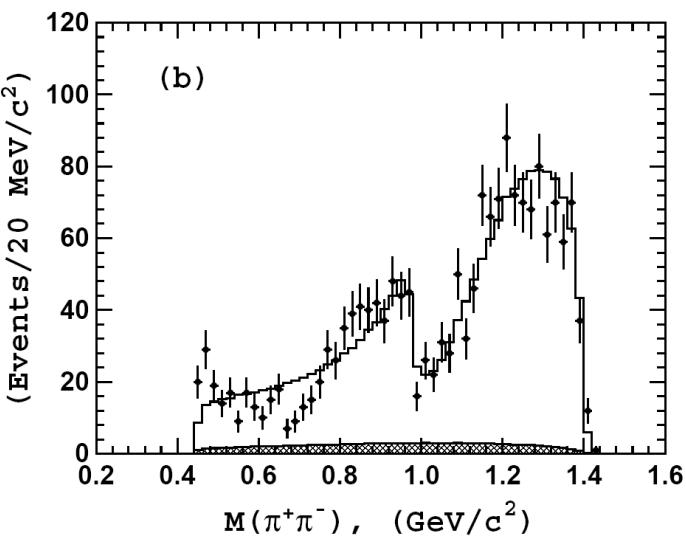
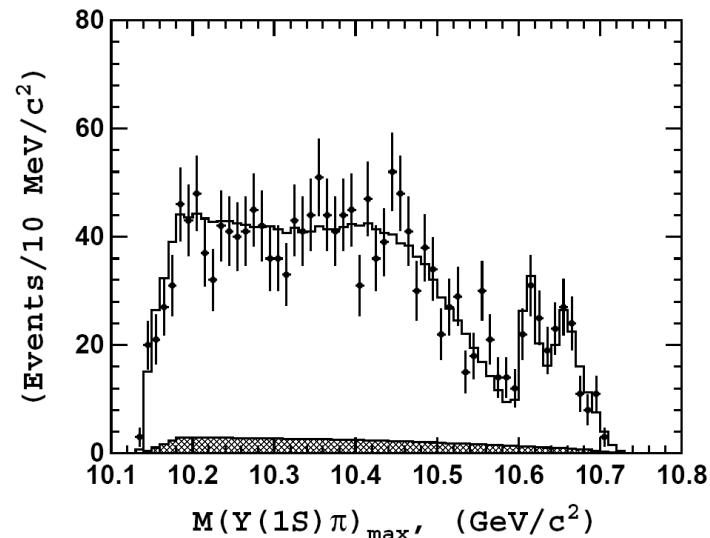
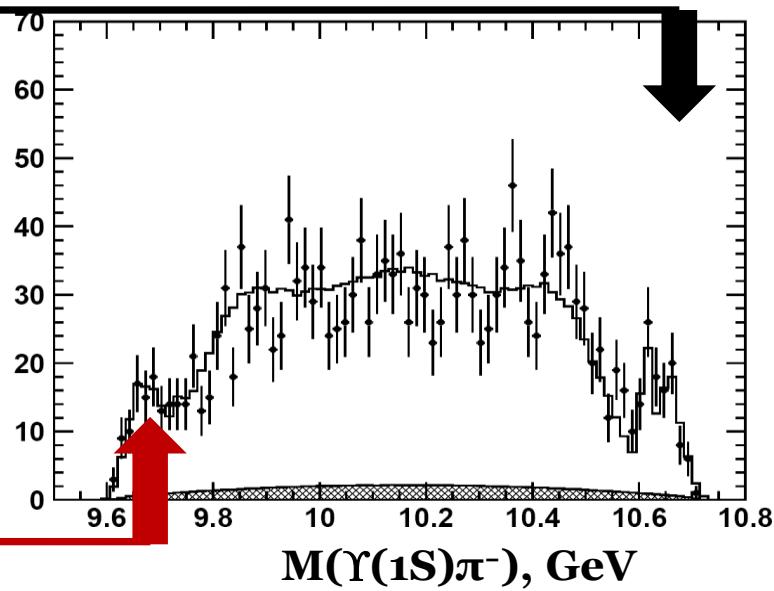
Results: $\text{Y}(5\text{S}) \rightarrow \text{Y}(2\text{S})\pi^+\pi^-$



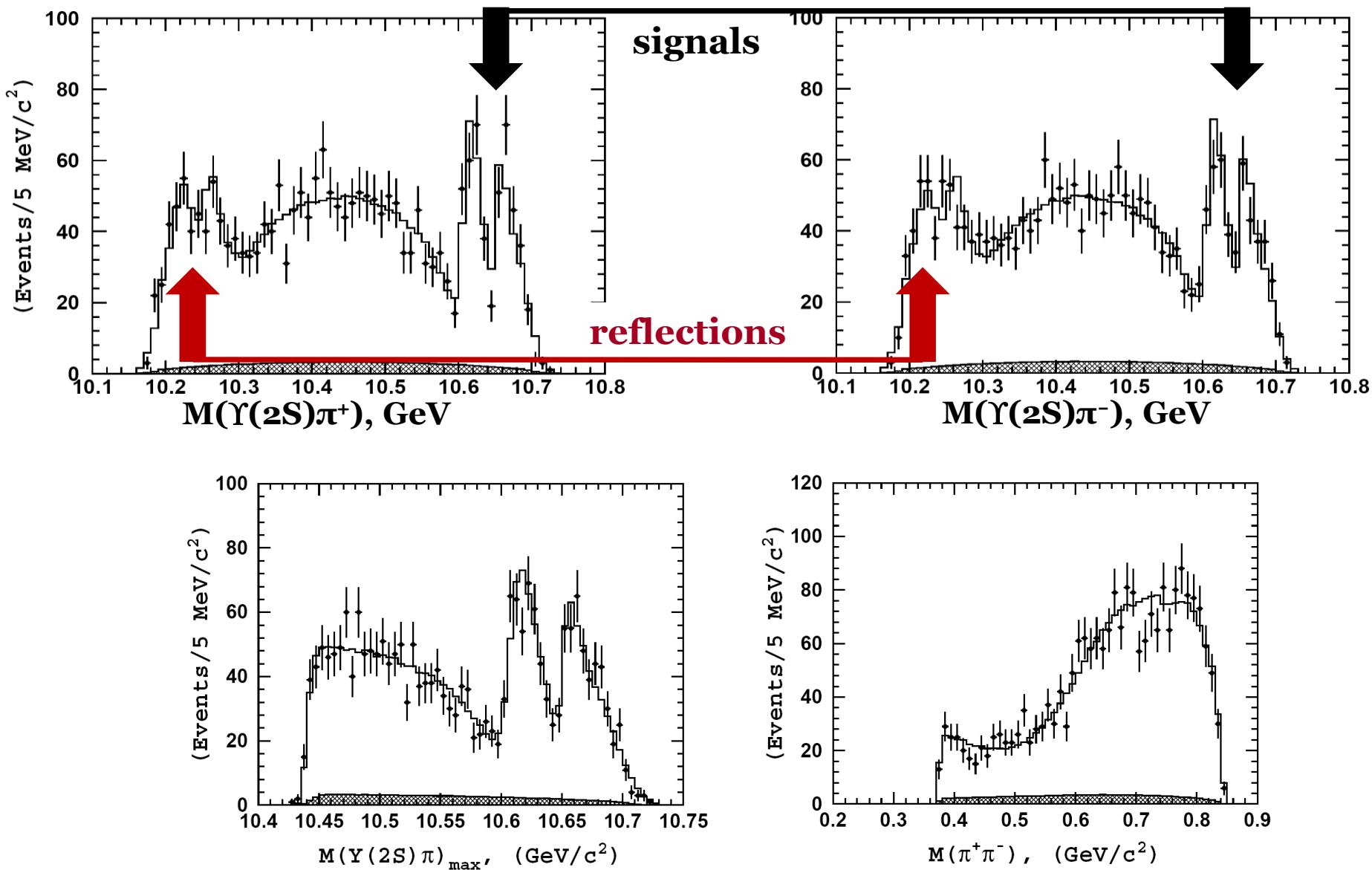
Results: $\Upsilon(1S)\pi^+\pi^-$



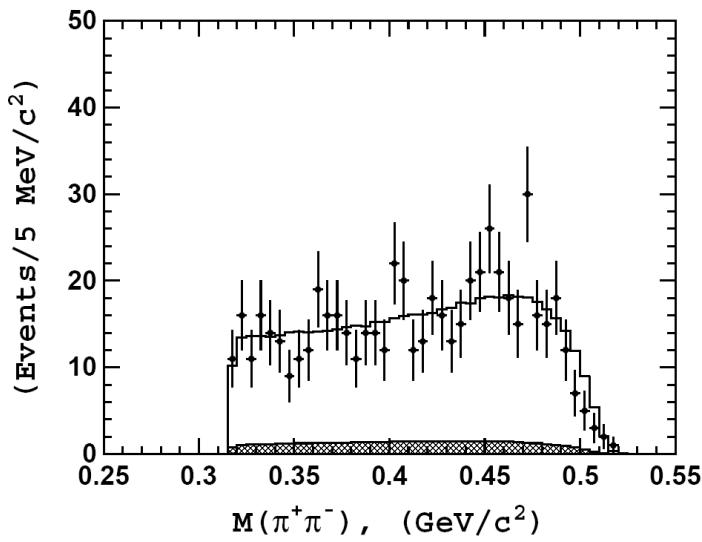
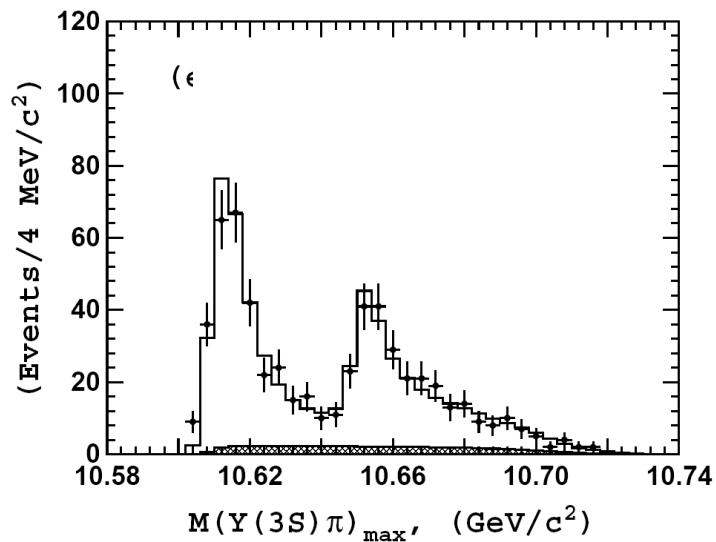
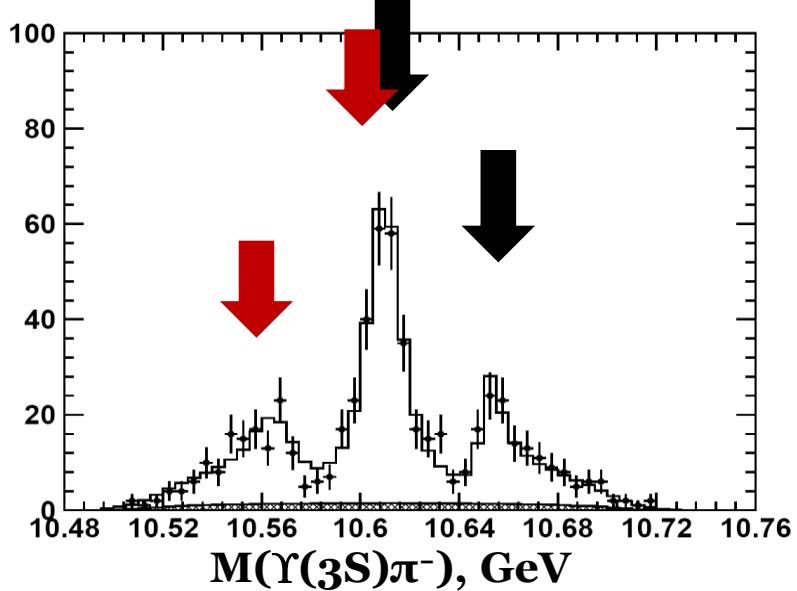
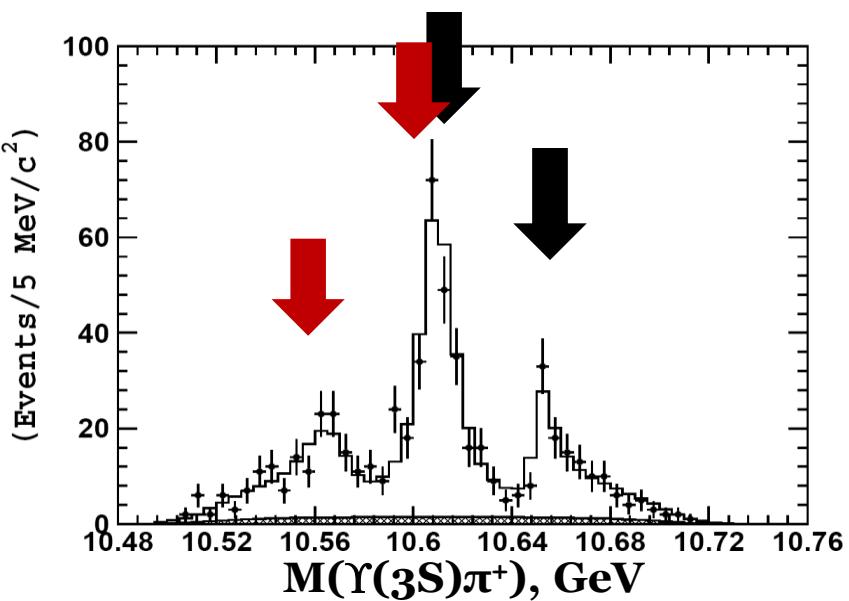
signals
reflections



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



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



Summary of Z_b parameters

$Z_b(10610)$

$Z_b(10650)$

Average over 5 channels

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

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

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

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

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

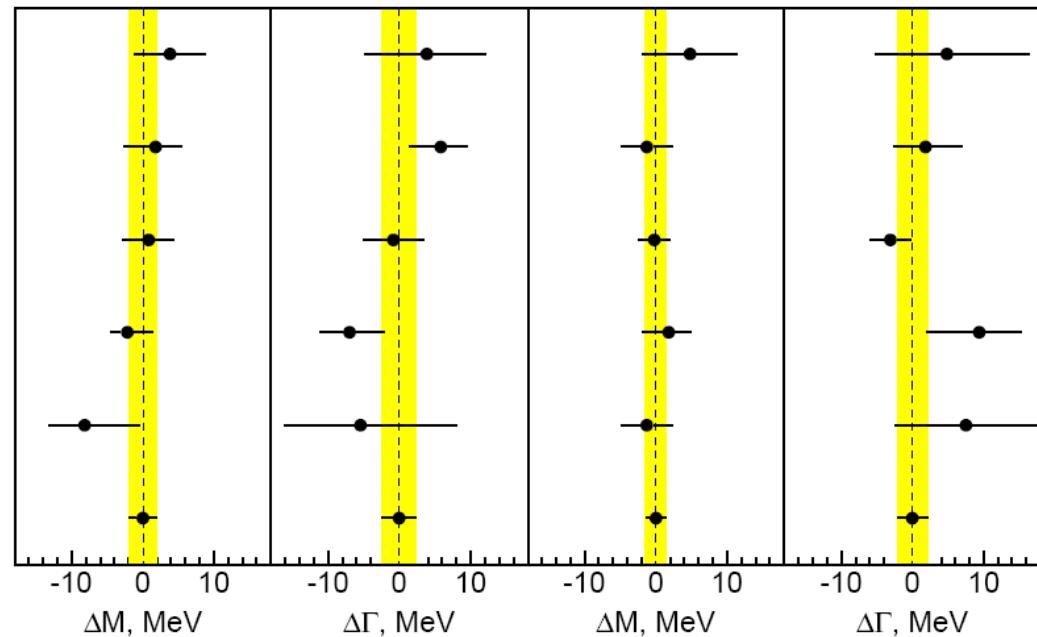
$\Upsilon(2S)\pi^+\pi^-$

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

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

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

Average



Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, 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}	$181^{+65+74}_{-105-109}$

$Z_b(10610)$ yield $\sim Z_b(10650)$ yield in every channel
 Relative phases: 0° for $\Upsilon\pi\pi$ and 180° for $h_b\pi\pi$

Summary of Z_b parameters

$Z_b(10610)$

$Z_b(10650)$

Average over 5 channels

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

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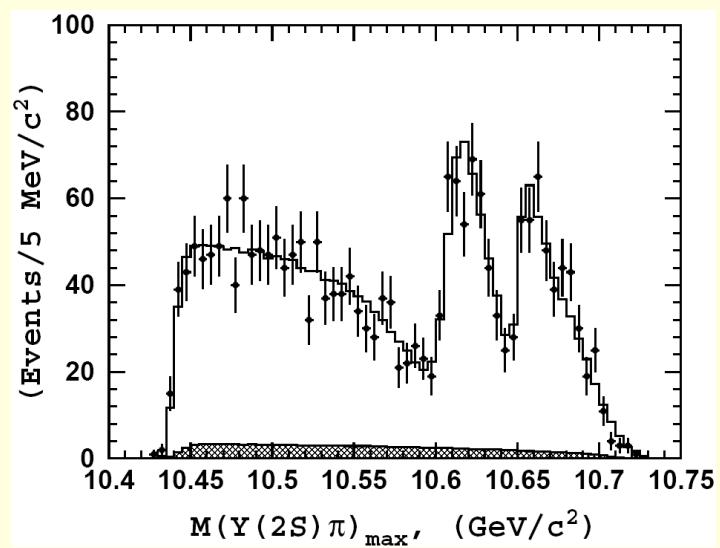
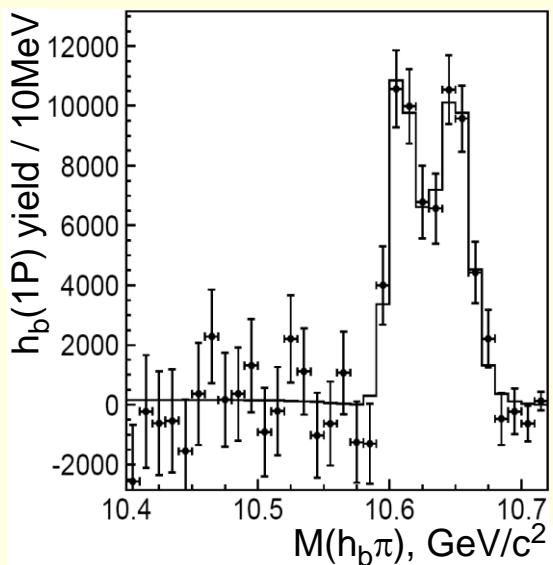
$Y(1S)\pi^+\pi^-$

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

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

$\varphi = 180^\circ$

$\varphi = 0^\circ$



$Z_b(10610)$ yield $\sim Z_b(10650)$ yield in every channel
 Relative phases: 0° for $\gamma\pi\pi$ and 180° for $h_b\pi\pi$

Angular analysis

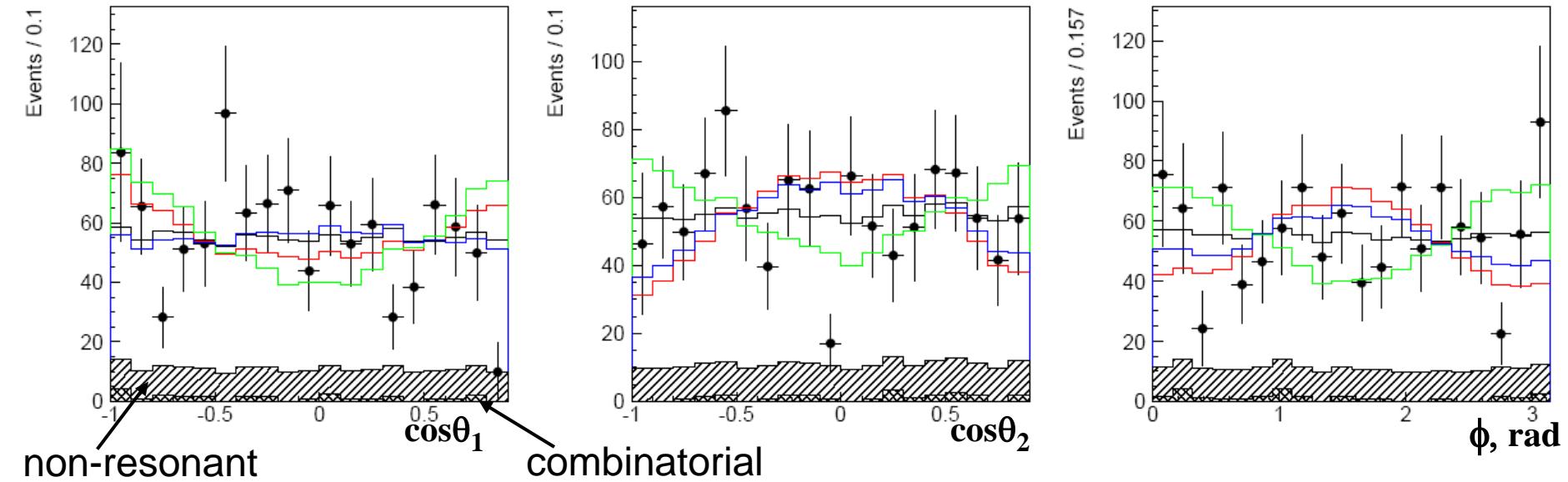
Angular analysis



Definition of angles

$$\theta_i = \angle(\pi_i, e^+), \phi = \angle[\text{plane}(\pi_1, e^+), \text{plane}(\pi_1, \pi_2)]$$

Example : $\Upsilon(5S) \rightarrow Z_b^+(10610) \pi^- \rightarrow [\Upsilon(2S)\pi^+] \pi^-$



Color coding: $J^P = \textcolor{lightblue}{1^+}$ **1⁻** **2⁺** **2⁻** (0^\pm is forbidden by parity conservation)

Best discrimination: **cosθ₂** for **1⁻** (3.6σ) and **2⁻** (2.7σ);
cosθ₁ for **2⁺** (4.3σ)

Summary of angular analysis

All angular distributions are consistent with $J^P=1^+$ for $Z_b(10610)$ & $Z_b(10650)$.

All other J^P with $J \leq 2$ are disfavored at typically 3σ level.

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

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

Preliminary:

procedure to deal with non-resonant contribution is approximate,
no mutual cross-feed of Z_b 's