QWG8, GSI, 5 October 2011

Observation of the $h_b(1P)$, $h_b(2P)$ and Z_b's at Belle

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for the BELLE Collaboration

Contents

$\Upsilon(5S) \to \left\{ \begin{array}{l} Z_b(10610)^+ \pi^- \\ Z_b(10650)^+ \pi^- \end{array} \right\} \to \left\{ \begin{array}{l} \Upsilon(1S)\pi^+ \pi^- \\ \Upsilon(2S)\pi^+ \pi^- \\ \Upsilon(3S)\pi^+ \pi^- \\ h_b(1P)\pi^+ \pi^- \\ h_b(2P)\pi^+ \pi^- \end{array} \right.$

multiquark states

Observation of $h_b(1P)$ and $h_b(2P)$

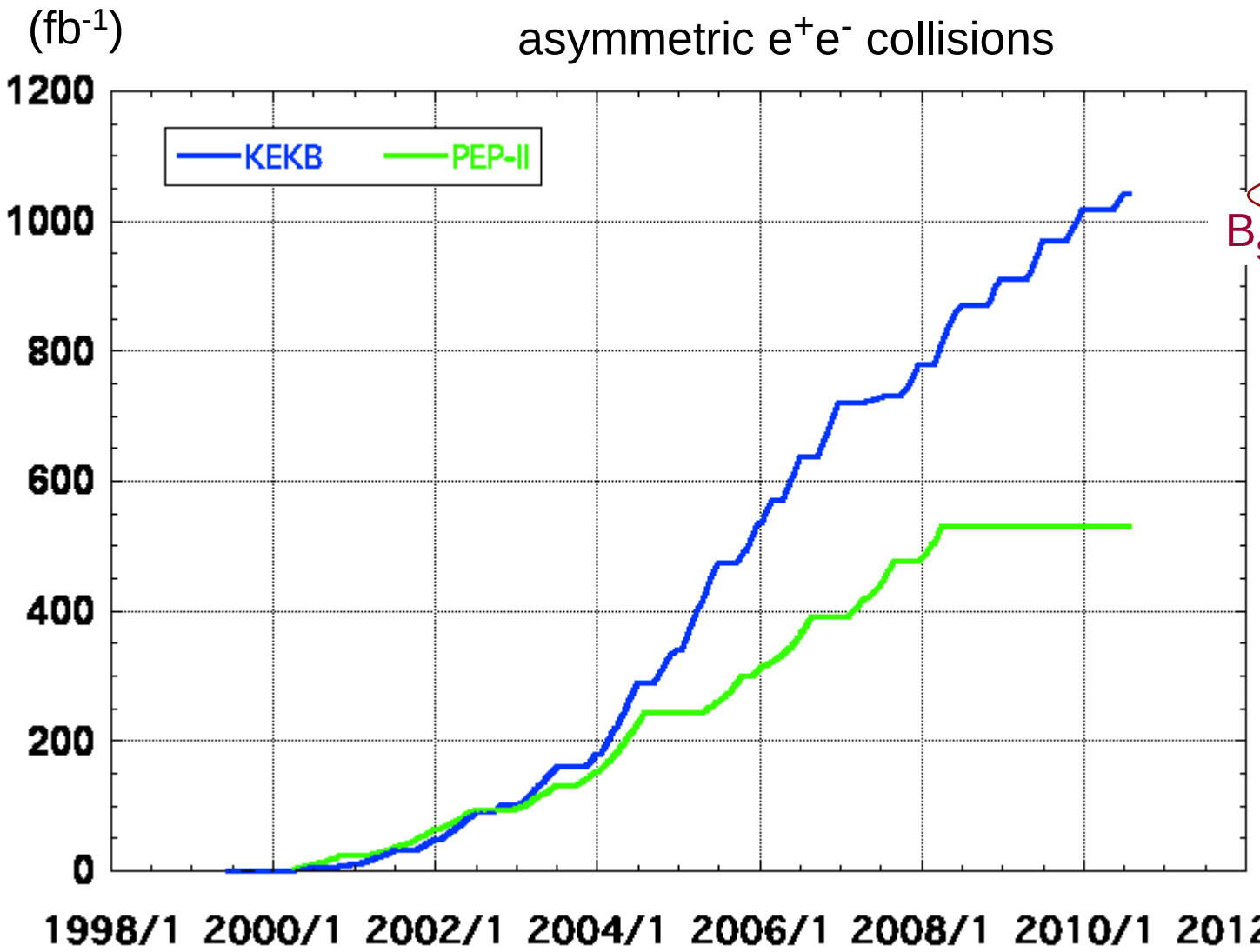
Observation of $Z_b^{\pm}$

- $h_b(nP)\pi^+\pi^-$ final state
- $\Upsilon(nS)\pi^+\pi^-$ final state
- Angular analysis

arXiv:1103.3419
submitted to PRL

update of
arXiv:1105.4583
to be submitted to PRL

Integrated Luminosity at B-factories



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

B_s Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

Υ(2S): 24 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan :

~100 fb-1

530 fb^{-1}

On resonance:

Υ(4S): 433 fb^{-1}

Υ(3S): 30 fb^{-1}

Υ(2S): 14 fb^{-1}

Off reson./scan :

~54 fb-1

Nature of $\Upsilon(5S)$

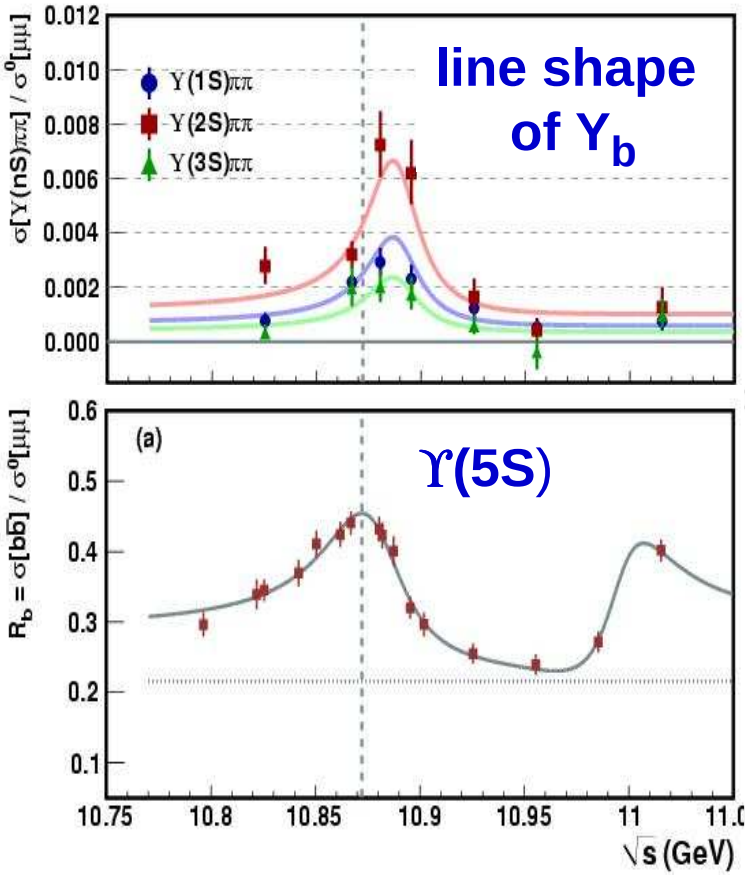
Anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$

PRL100,112001(2008)

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

PRD82,091106R(2010)



Simonov JETP Lett 87,147(2008)

1. Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$?

2. Similar effect in charmonium?

   Y(4260) with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$

   $\Rightarrow$ assume $\exists$ Y_b close to $\Upsilon(5S)$

to distinguish $\Rightarrow$ energy scan

$\Rightarrow$ shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (2σ)

Nature of $\Upsilon(5S)$ is puzzling and not yet understood

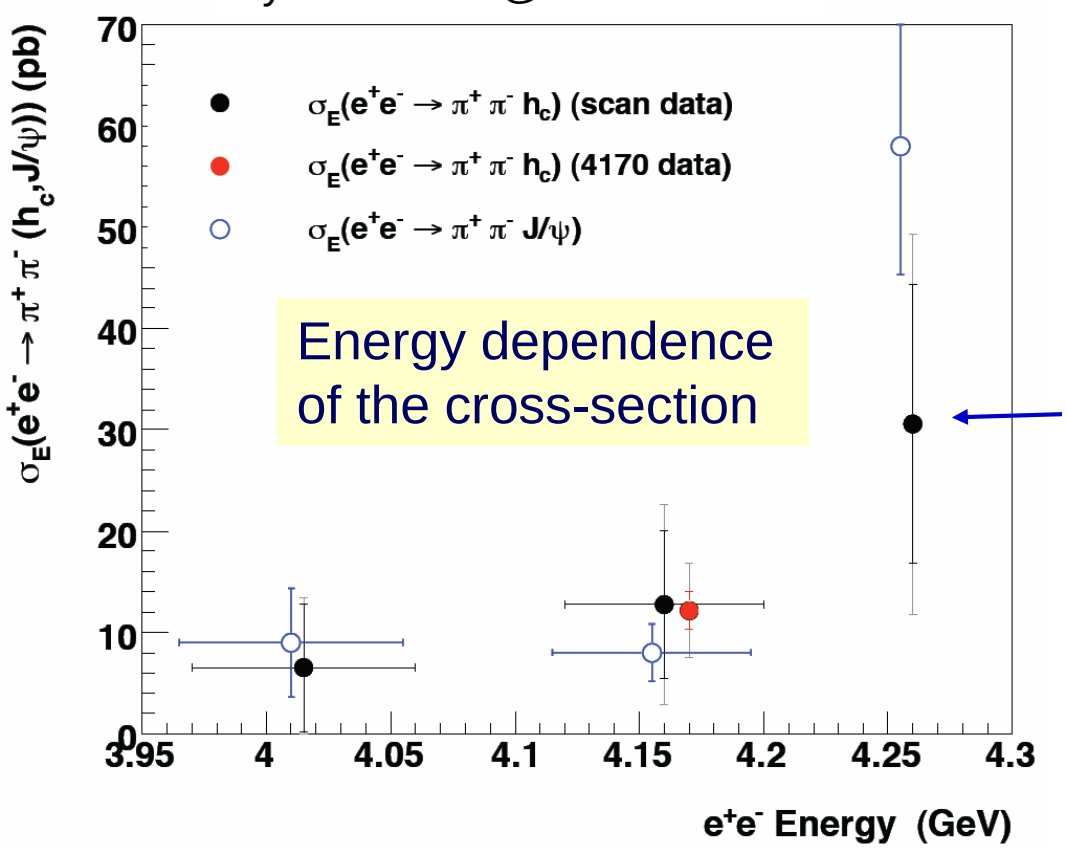
Observation of

$h_b(1P)$ & $h_b(2P)$

Trigger

Observation of $e^+e^- \to \pi^+\pi^- h_c$ above $D\bar{D}$ threshold by CLEO

Ryan Mitchell @ CHARM2010



Production of h_c is unsuppressed relative to J/ψ.

Enhancement @ Y(4260)?

Belle sees $\Upsilon(5S) \to \Upsilon\pi^+\pi^- \Rightarrow$ should search for $\Upsilon(5S) \to h_b\pi^+\pi^-$

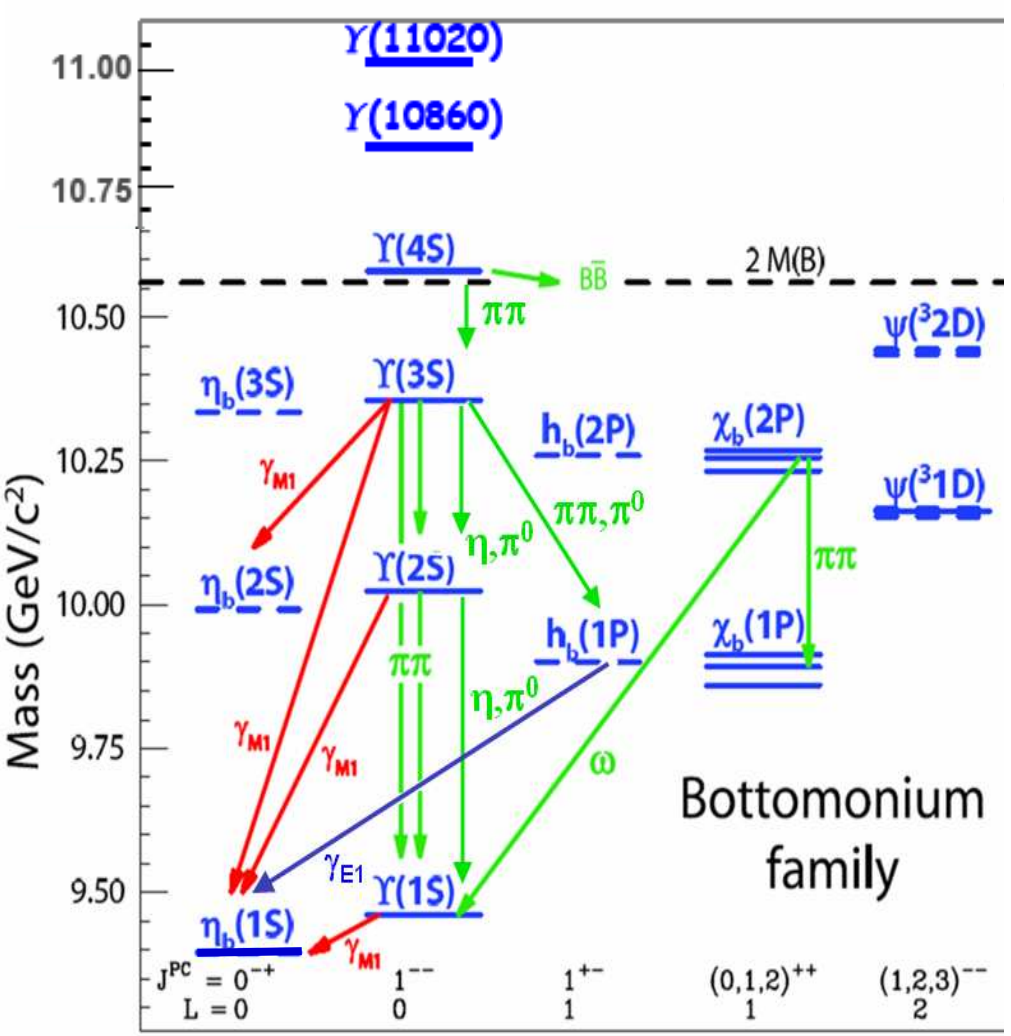
Introduction to h_b(nP)

$(b\bar{b})$: S=0 L=1 $J^{PC}=1^{+-}$

Expected mass
$\approx (M\chi_{b0} + 3\,M\chi_{b1} + 5\,M\chi_{b2}) / 9$

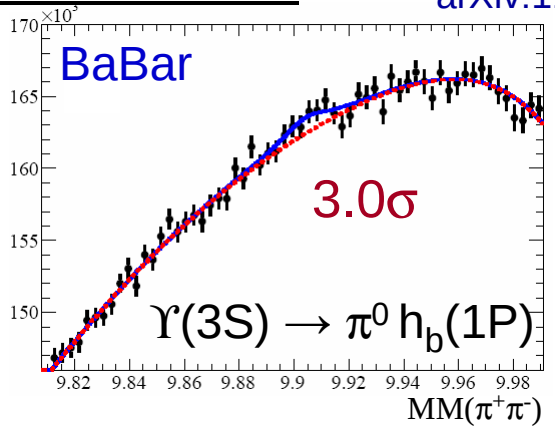
$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

For h_c $\Delta M_{HF} = -0.12 \pm 0.30$ MeV,
expect smaller deviation for h_b(nP)



Previous search

arXiv:1102.4565



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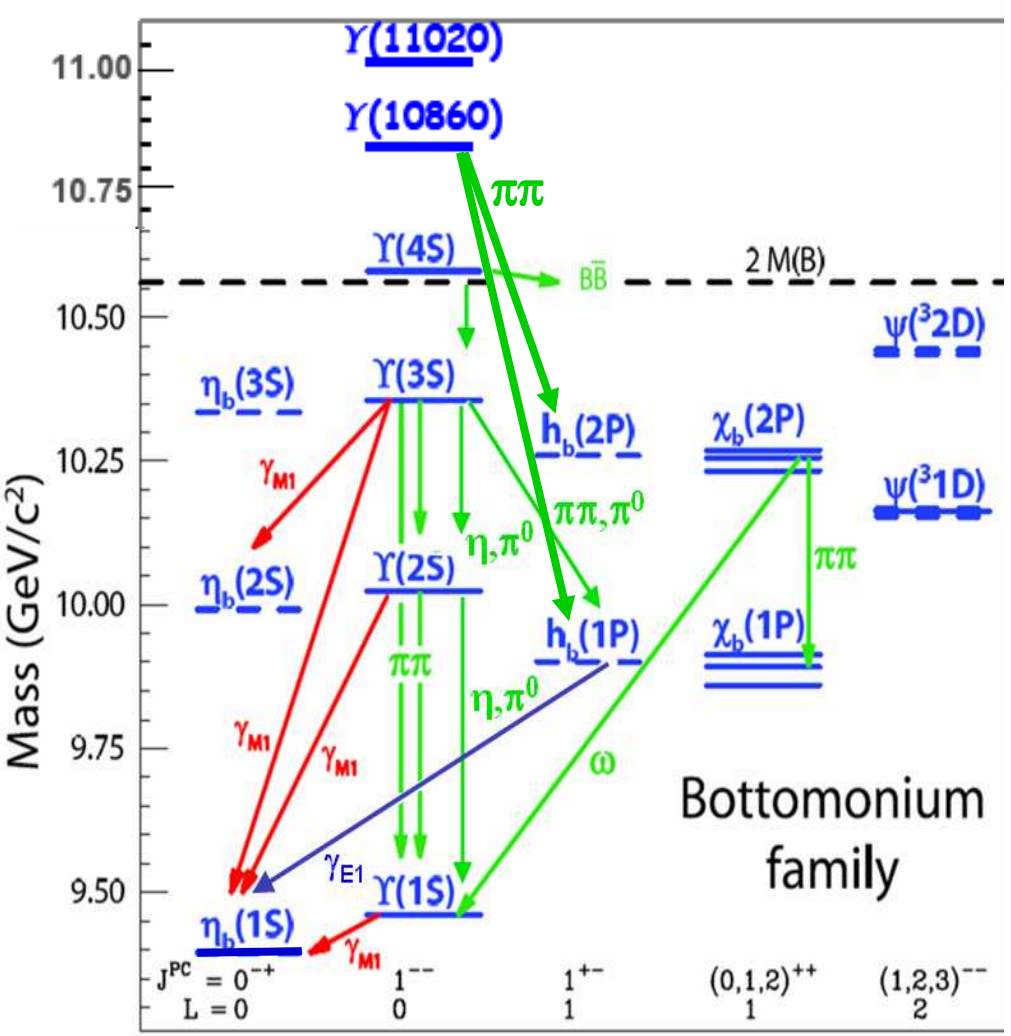
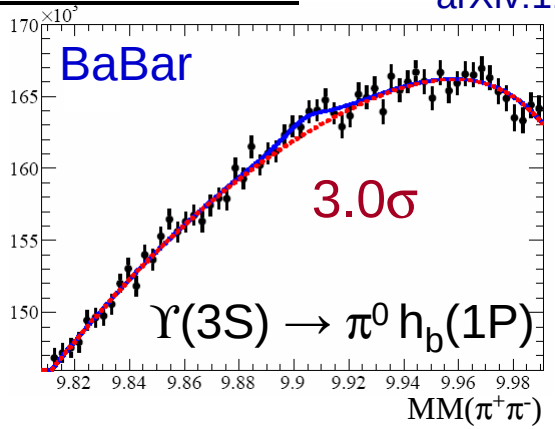


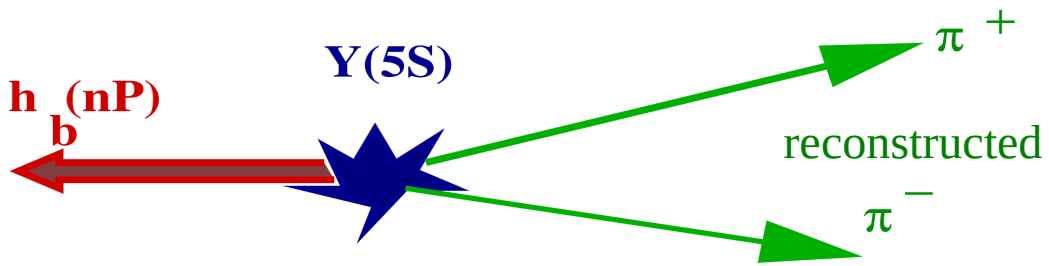
Previous search

arXiv:1102.4565

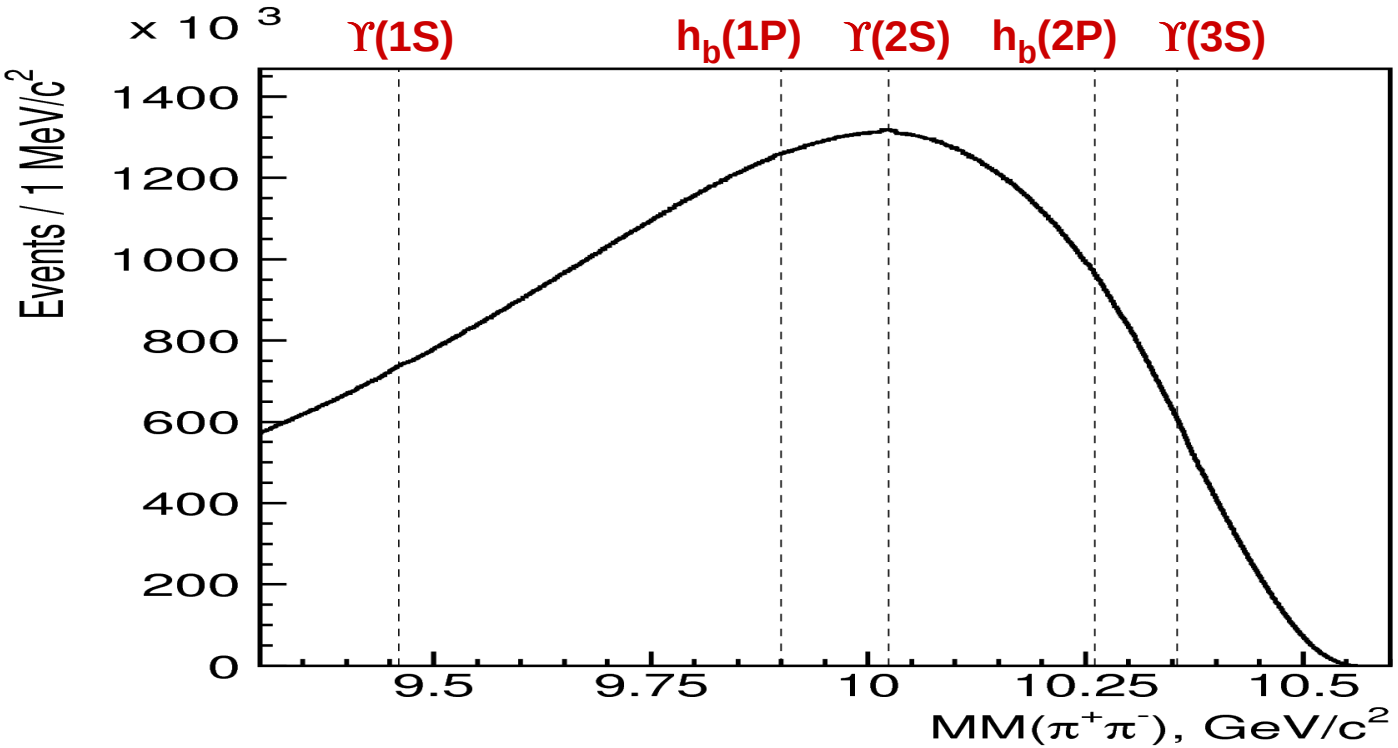


$\Upsilon(5S) \to h_b\,\pi^+\pi^-$ reconstruction

$h_b \to ggg,\ \eta_b\gamma \ \Rightarrow$ no good exclusive final states

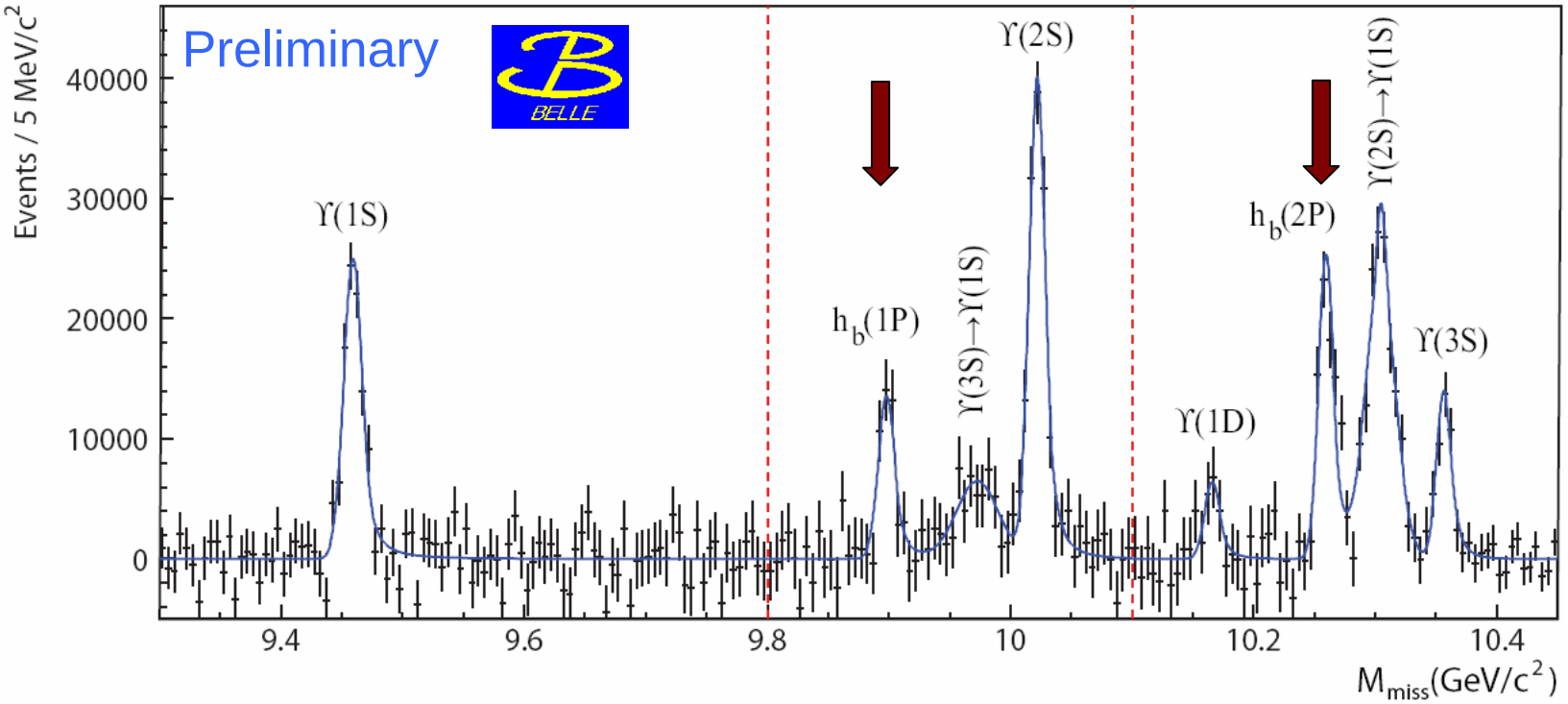


"Missing mass" $\quad \mathbf{M(h_b)} = \sqrt{(E_{c.m.} - E^*_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}} \equiv \mathbf{M_{miss}(\pi^+\pi^-)}$



Results

121.4 fb^{-1}



	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

Significance w/ systematics

$h_b(1P)$ 5.5σ

$h_b(2P)$ 11.2σ

Hyperfine splitting

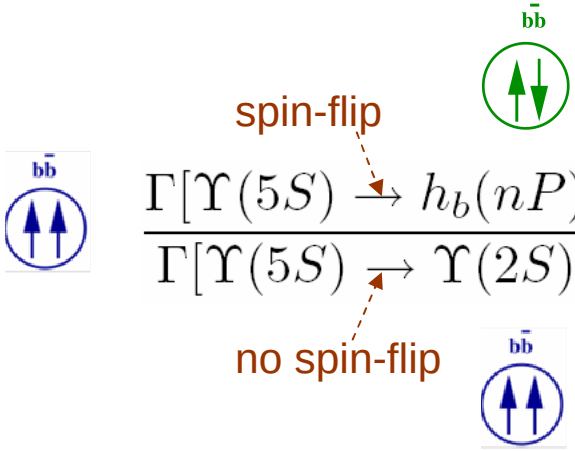
Deviations from CoG of χ_{bJ} masses

$h_b(1P)$ (1.6 ± 1.5) MeV/c^2

$h_b(2P)$ $(0.5\ ^{+1.6}_{-1.2})$ MeV/c^2

} consistent with zero, as expected

Ratio of production rates



$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

Process with spin-flip of heavy quark is not suppressed

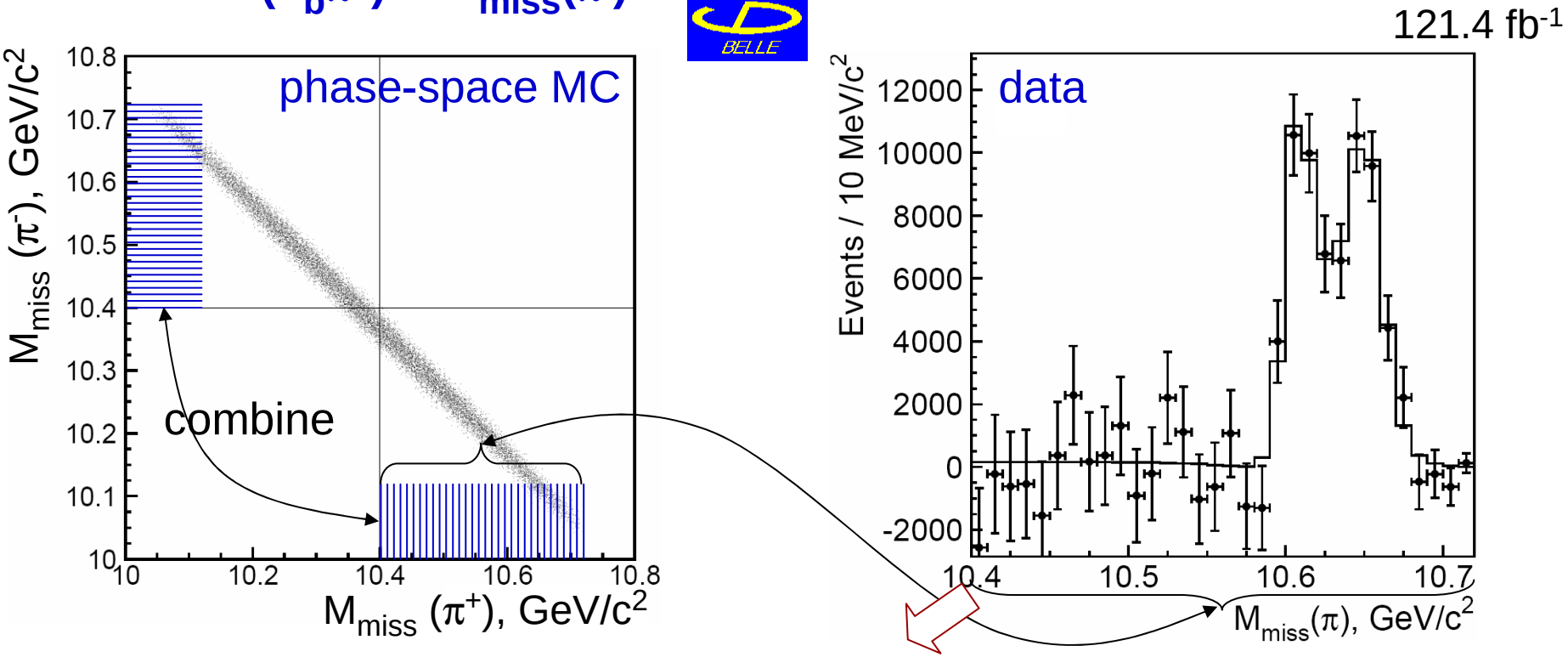
⇒ **Mechanism of Υ(5S) → h_b(nP) $\pi^+\pi^-$ decay is exotic**

Observation of $Z_b^{\pm}$

$h_b(nP)\,\pi^+\pi^-$ final state (n=1,2)

Resonant substructure of $\Upsilon(5S) \to h_b(1P)\,\pi^+\pi^-$

$M(h_b\pi^+) \equiv M_{miss}(\pi^-)$



Fit function $|BW(s,M_1,\Gamma_1) + ae^{i\phi}BW(s,M_2,\Gamma_2) + be^{i\psi}|^2\ \frac{qp}{\sqrt{s}}$

Results

$M_1 = 10605 \pm 2^{+3}_{-1}$ MeV/c² ~B$\bar{B}$* threshold

$\Gamma_1 = 11.4\ ^{+4.5+2.1}_{-3.9-1.2}$ MeV

$a = 1.39 \pm 0.37^{+0.05}_{-0.15}$

$M_2 = 10654 \pm 3\ ^{+1}_{-2}$ MeV/c² ~B*$\bar{B}$* threshold

$\Gamma_2 = 20.9\ ^{+5.4+2.1}_{-4.7-5.7}$ MeV

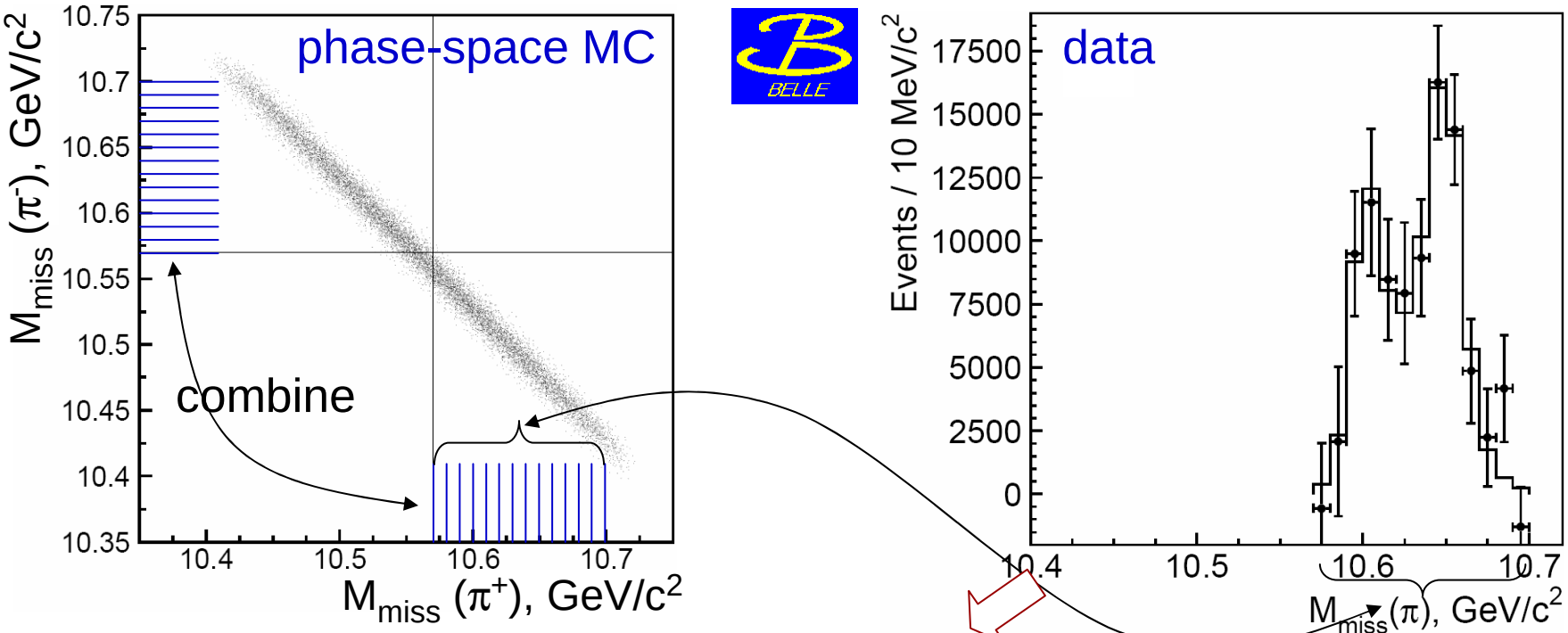
non-res.~0

$\varphi = 187^{+44+3}_{-57-12}$ degree

Significances

18σ (16σ w/ syst)

Resonant substructure of $\Upsilon(5S) \to h_b(2P)\,\pi^+\pi^-$



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

$M_1 = 10605 \pm 2^{+3}_{-1}$ MeV/c^2

$\Gamma_1 = 11.4\ ^{+4.5+2.1}_{-3.9-1.2}$ MeV

$M_2 = 10654 \pm 3\ ^{+1}_{-2}$ MeV/c^2

$\Gamma_2 = 20.9\ ^{+5.4+2.1}_{-4.7-5.7}$ MeV

$a = 1.39 \pm 0.37^{+0.05}_{-0.15}$

$\varphi = 187^{+44+3}_{-57-12}$ degree

non-res.~0

consistent

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

10599^{+6+5}_{-3-4} MeV/c^2

$13\ ^{+10+9}_{-8-7}$ MeV

10651^{+2+3}_{-3-2} MeV/c^2

$19 \pm 7\ ^{+11}_{-7}$ MeV

$1.6^{+0.6+0.4}_{-0.4-0.6}$

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

non-res. set to zero

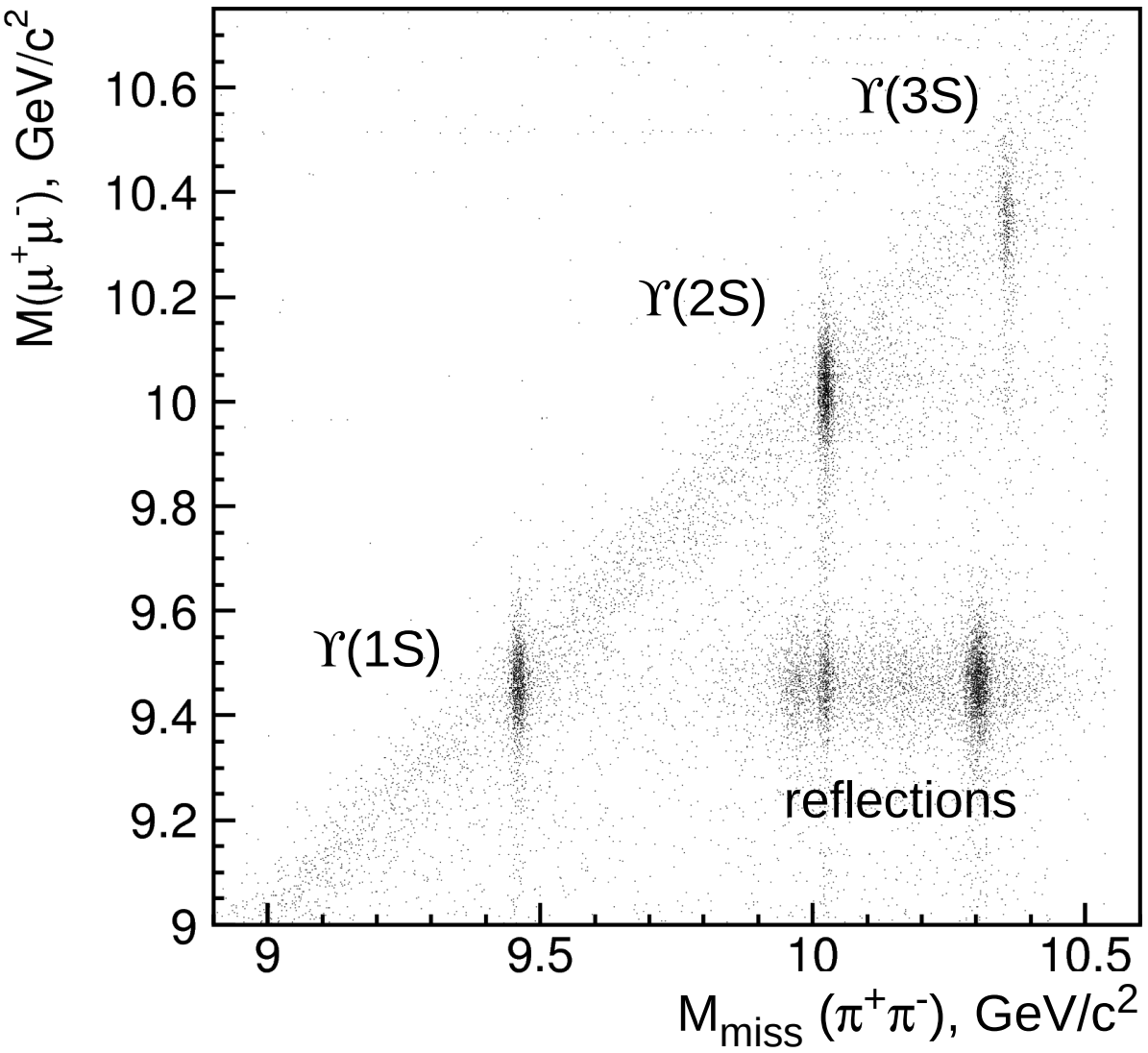
Significances

6.7σ (5.6σ w/ syst)

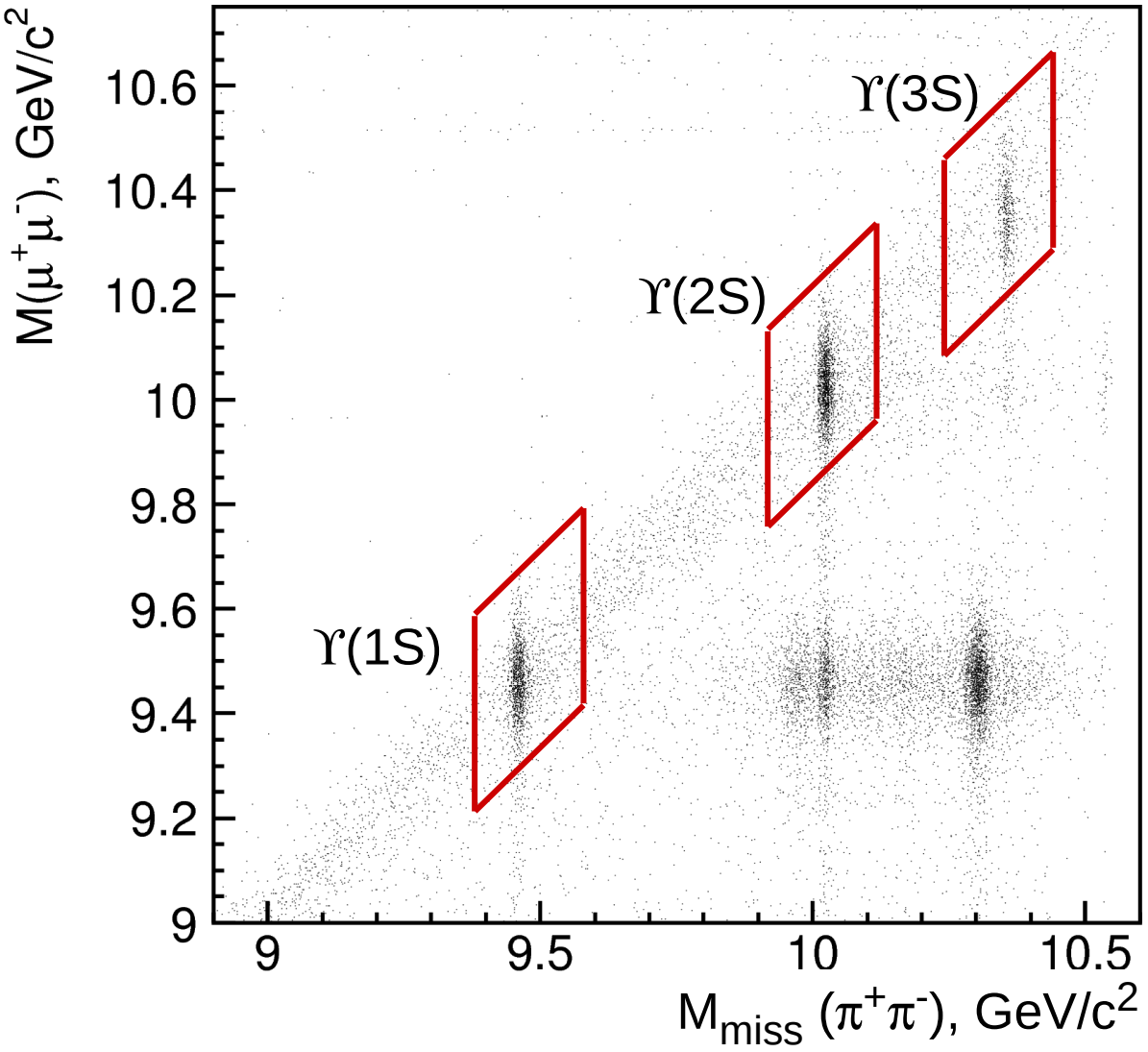
Observation of $Z_b^{\pm}$

$\Upsilon(nS)\,\pi^+\pi^-$ final state (n=1,2,3)

$\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$
$\Upsilon(nS) \to \mu^+\mu^-$ (n = 1,2,3)

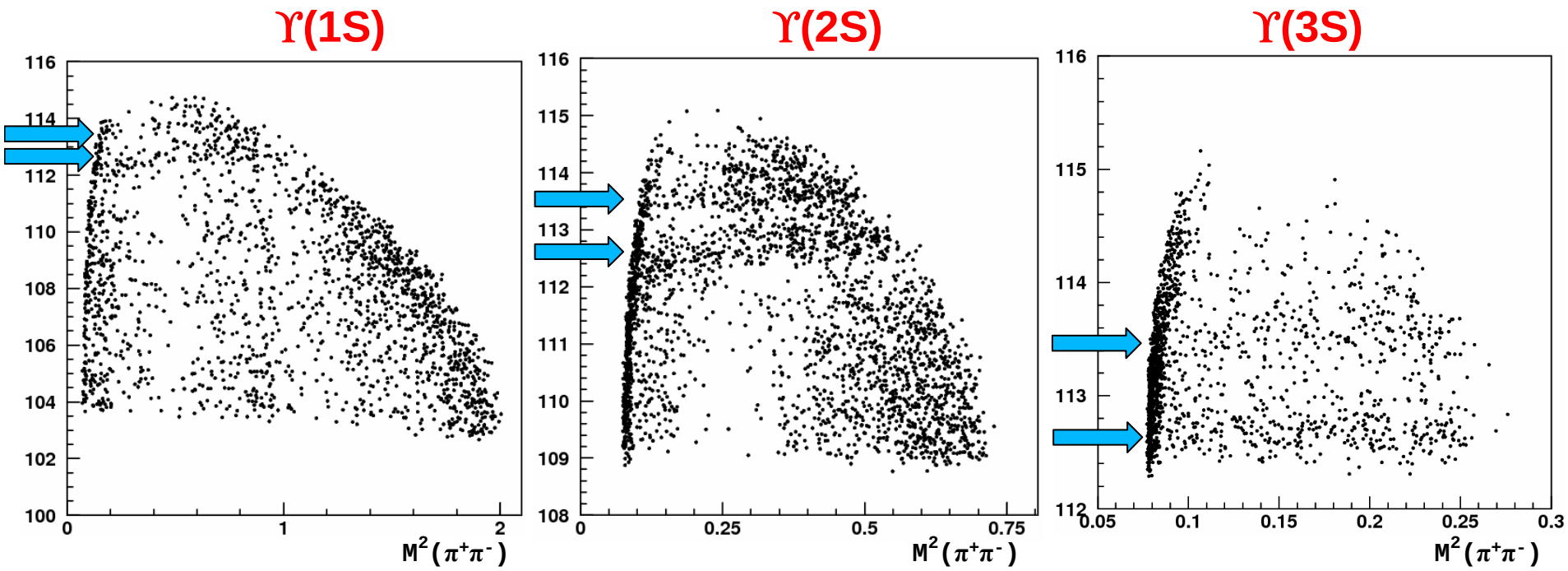


$\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$
$\Upsilon(nS) \to \mu^+\mu^-$
(n = 1,2,3)



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

121.4 fb^{-1}



⇒ Two resonances

⇒ Clear signs of interference ⇒ amplitude analysis is required

Fitting the Dalitz plots

Angular analysis favors $J^P=1^+$

$\Upsilon(5S) \xrightarrow{\text{S-wave}} Z_b\pi$, $Z_b \xrightarrow{\text{S-wave}} \Upsilon(nS)\pi$ – no spin orientation change

Spins of $\Upsilon(5S)$ and $\Upsilon(nS)$ can be ignored

Signal amplitude parameterization:

$$S(s1,s2) = A(Z_{b1}) + A(Z_{b2}) + A(f_0(980)) + A(f_2(1275)) + A_{NR}$$

$$A_{NR} = C_1 + C_2 \cdot m^2(\pi\pi)$$

Parameterization of the non-resonant amplitude is discussed in

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

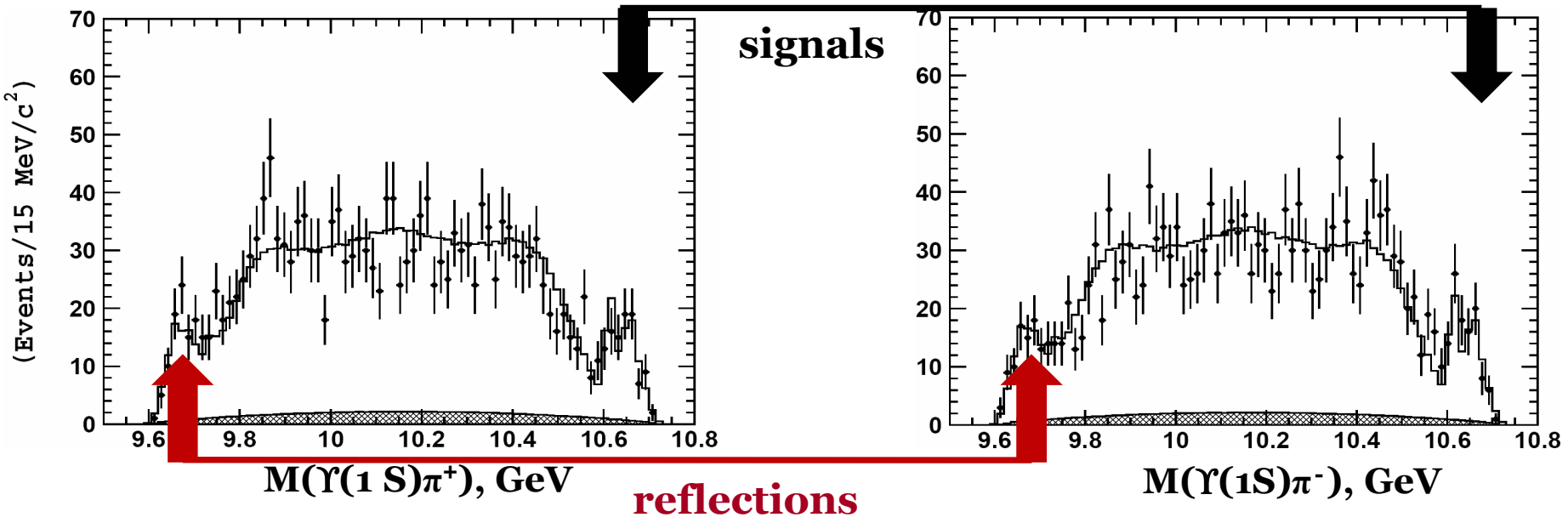
[2] M.B. Voloshin, Phys. Rev. D74:054022, 2006.

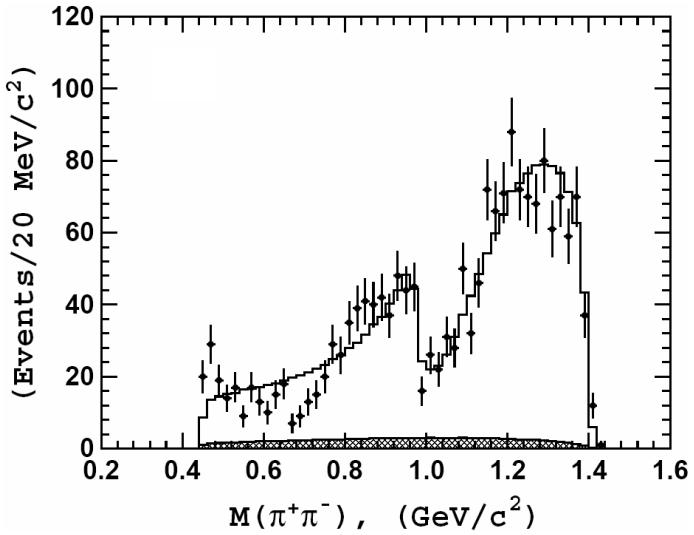
$A(Z_{b1}) + A(Z_{b2}) + A(f_2(1275))$ – Breit-Wigner

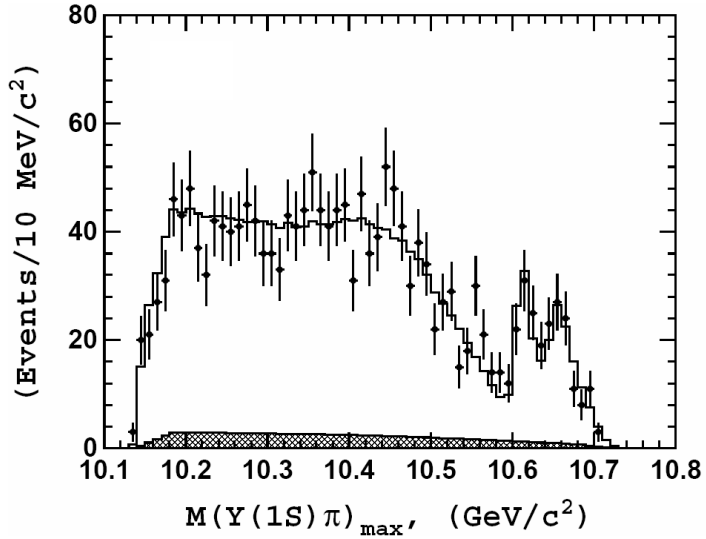
$A(f_0(980))$ – Flatte

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

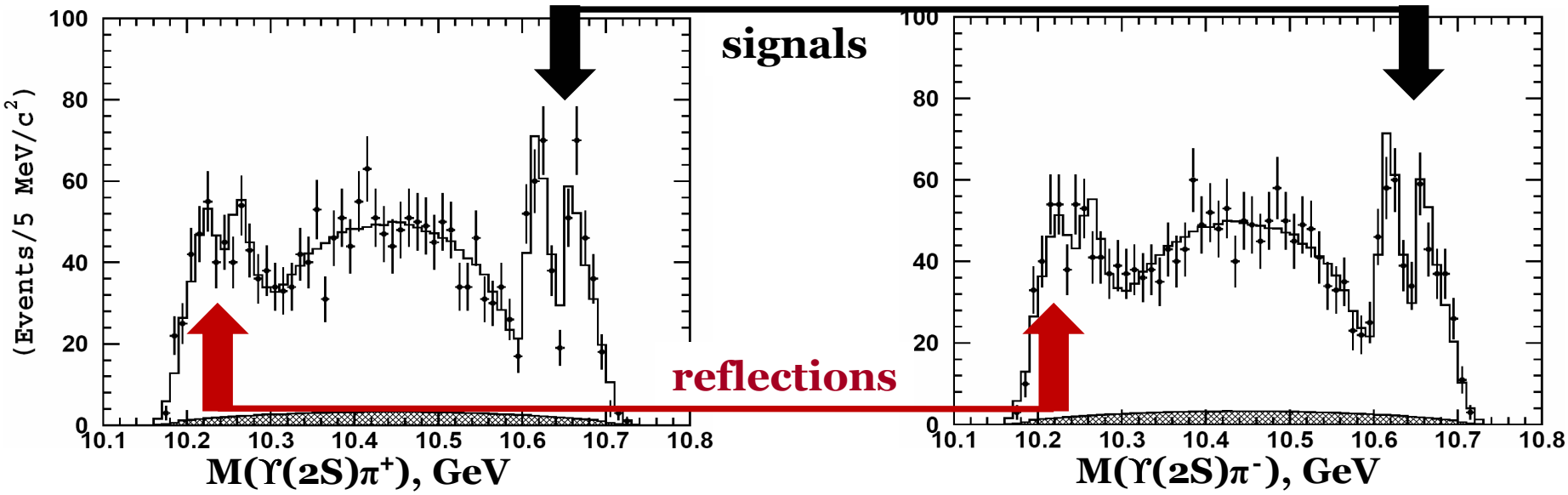
121.4 fb^{-1}

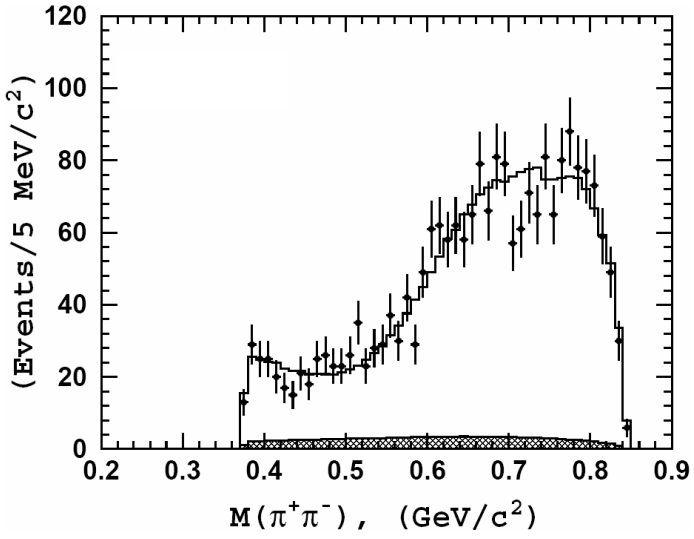


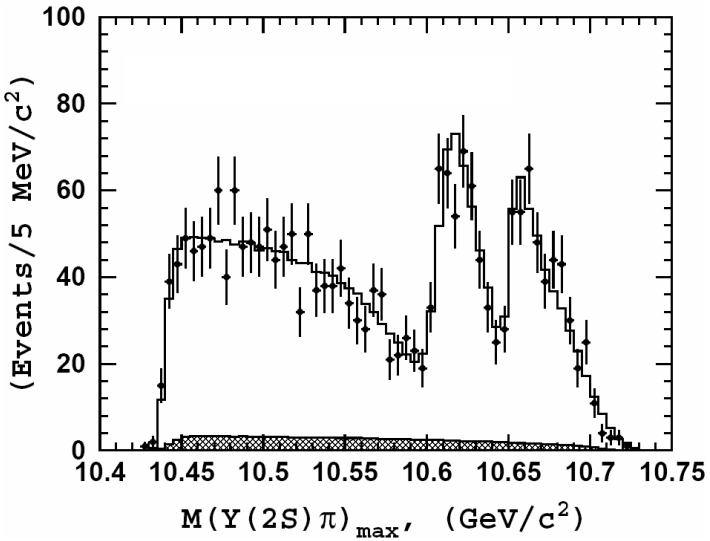




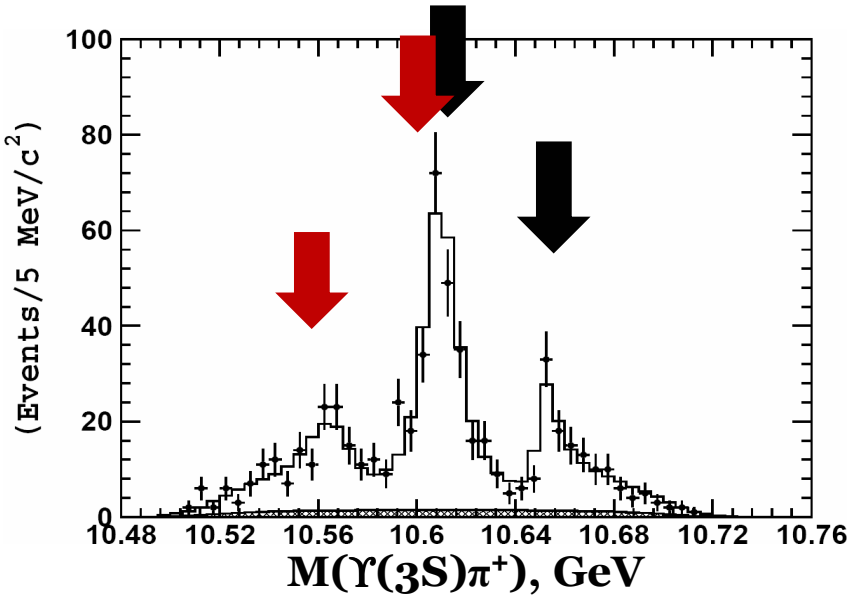
Results: $\Upsilon(2S)\pi^+\pi^-$

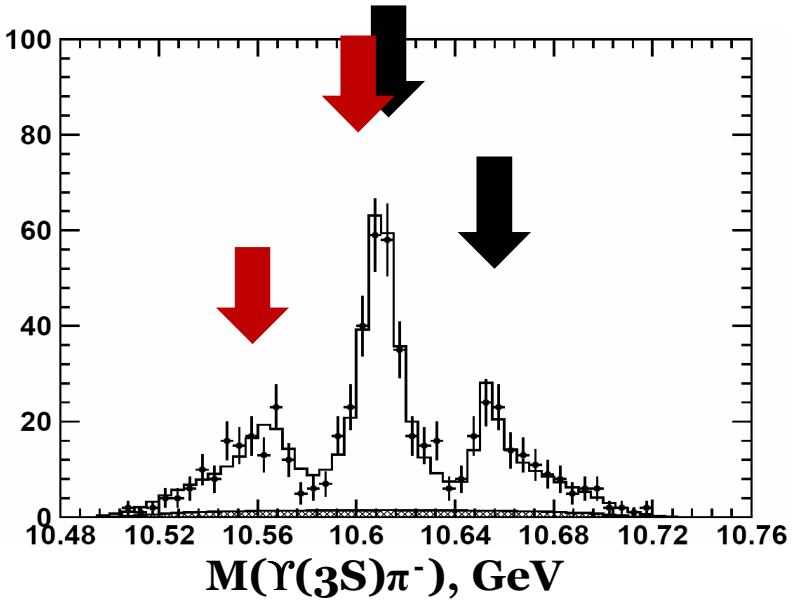


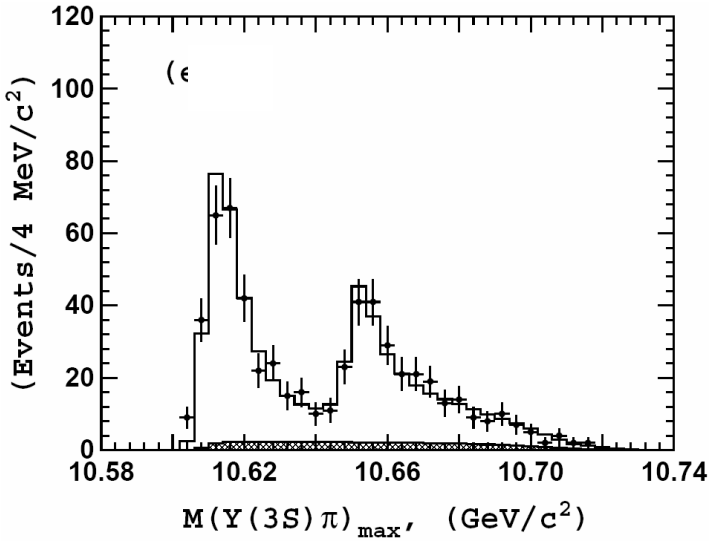


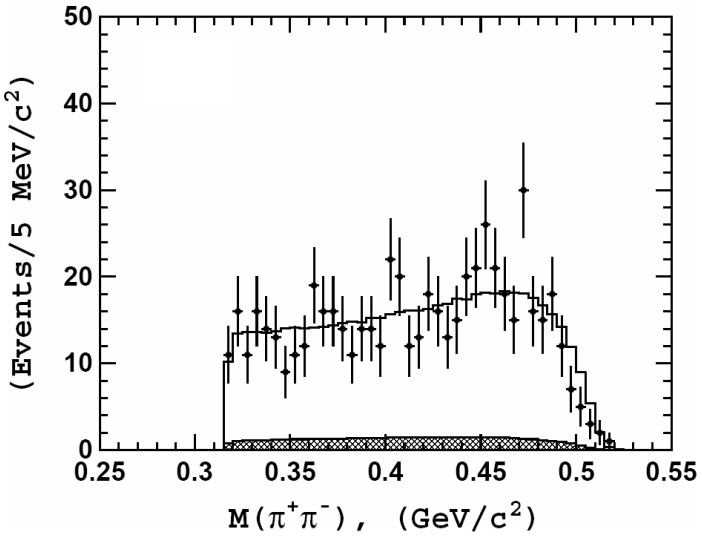


Results: $\Upsilon(3S)\pi^+\pi^-$

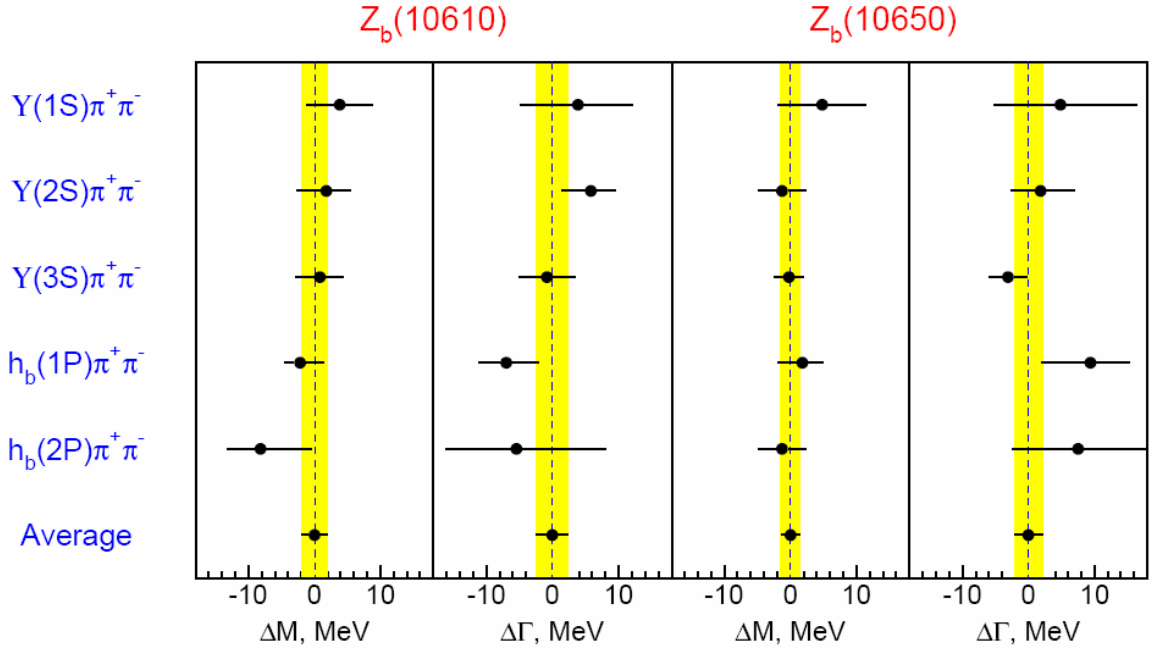








Summary of parameters of charged Z_b states



$Z_b(10610)$

M=10607.2±2.0 MeV

Γ=18.4±2.4 MeV

$Z_b(10650)$

M=10652.2±1.5 MeV

Γ=11.5 ± 2.2 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}	$181^{+65+74}_{-105-109}$

Masses and width are consistent

Relative yield of $Z_b(10610)$ and $Z_b(10650)$ ~ 1

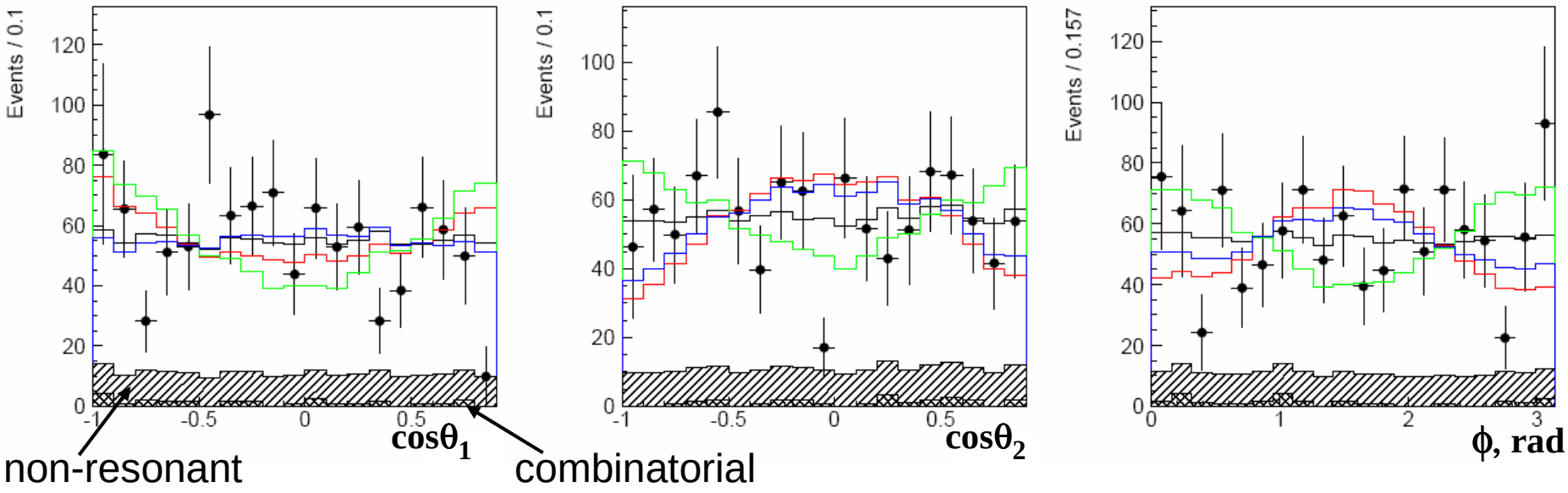
Relative phases are swapped for Υ and h_b final states

Angular analyses

Angular analyses

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

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



Color coding: $J^P = (1^+)\ 1^-\ 2^+\ 2^-$ ($0^\pm$ is forbidden by parity conservation)

Best discrimination: $\cos\theta_2$ for 1^- (3.6σ) and 2^- (2.7σ);
$\cos\theta_1$ for 2^+ (4.3σ)

Summary of angular analyses

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^-	$3.6\,\sigma$	$0.3\,\sigma$	$0.3\,\sigma$	$3.7\,\sigma$	$2.6\,\sigma$	$2.7\,\sigma$
2^+	$4.3\,\sigma$	$3.5\,\sigma$	$4.3\,\sigma$	$4.4\,\sigma$	$2.7\,\sigma$	$2.1\,\sigma$
2^-	$2.7\,\sigma$	$2.8\,\sigma$		$2.9\,\sigma$	$2.6\,\sigma$	

Preliminary:

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

Summary

First observation of $\mathbf{h_b(1P)}$ and $\mathbf{h_b(2P)}$

arXiv:1103.3419
submitted to PRL

Hyperfine splitting consistent with zero, as expected
Anomalous production rates

Observation of two charged bottomonium-like resonances in 5 final states

$\Upsilon(1S)\pi^+$, $\Upsilon(2S)\,\pi^+$, $\Upsilon(3S)\pi^+$, $h_b(1P)\pi^+$, $h_b(2P)\pi^+$

update of
arXiv:1105.4583,
to be submitted to PRL

$Z_b(10610)$ $\quad$ $M = 10607.2 \pm 2.0$ MeV
$\Gamma = 18.4 \pm 2.4$ MeV

$Z_b(10650)$ $\quad$ $M = 10652.2 \pm 1.5$ MeV
$\Gamma = 11.5 \pm 2.2$ MeV

Masses are close to BB* and B*B* thresholds – molecule?

Angular analyses favour $J^P = 1^+$, decay pattern $\Rightarrow I^G = 1^+$

Back up

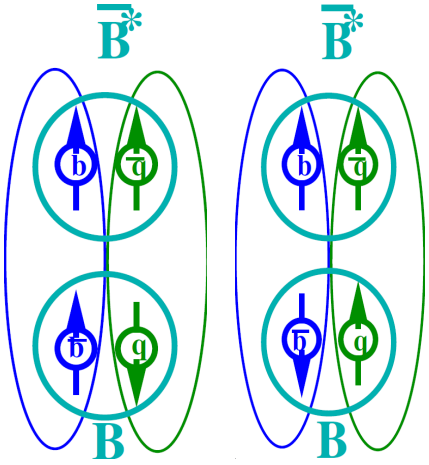
Heavy quark structure in Z_b

arXiv:1105.4473

Wave func. at large distance – free 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

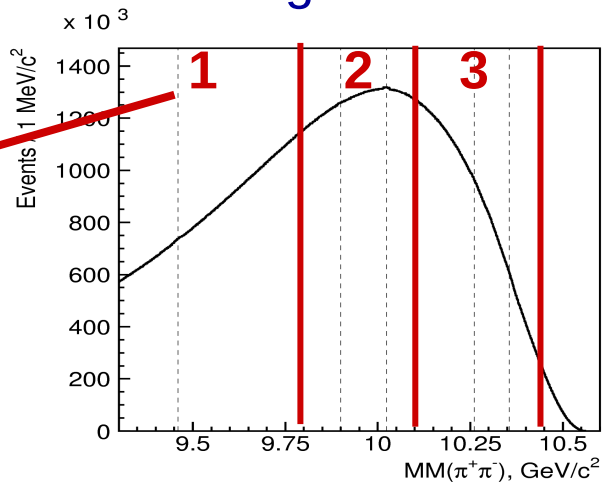
- Why $h_b\pi\pi$ is unsuppressed relative to $\Upsilon\pi\pi$
- Relative phase ~0 for Υ and ~180^0 for h_b
- Production rates of $Z_b(10610)$ and $Z_b(10650)$ are similar
- Widths –"–

Predicts

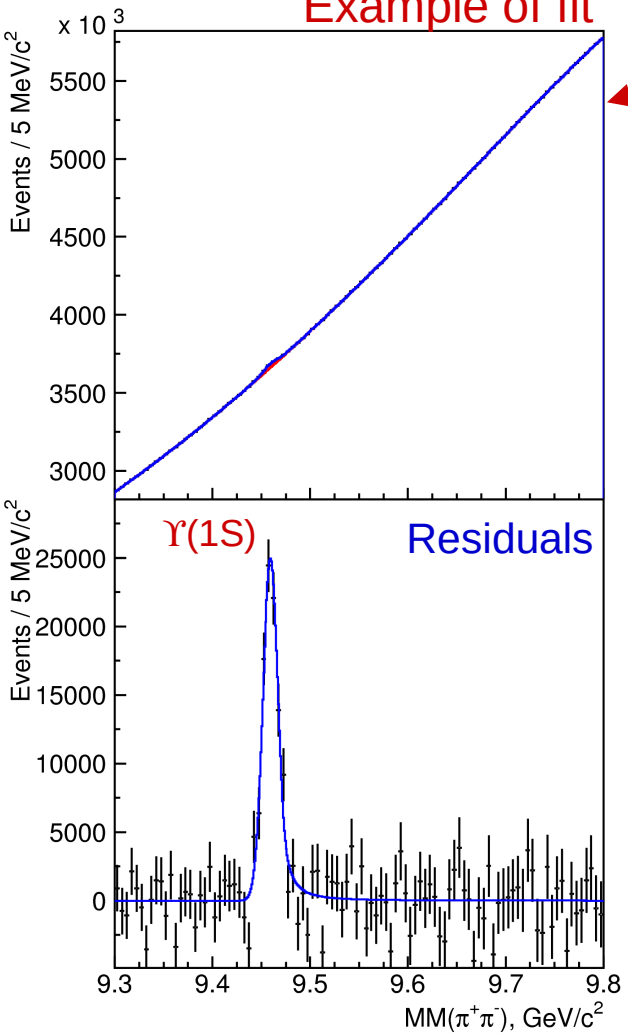
- Existence of other similar states

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