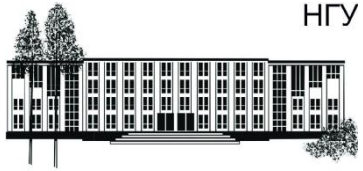

Recent results on bottomonium studies at Belle

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on behalf of the Belle collaboration

Budker Institute of Nuclear Physics
and Novosibirsk State University

Introduction

Bottomonium system yielded many surprises.

$$R \equiv \frac{\sigma(h_b(nP)\pi^+\pi^-)}{\sigma(\Upsilon(2S)\pi^+\pi^-)} \sim 1$$

for $h_b(1P)$ and $h_b(2P)$.

$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ } similar

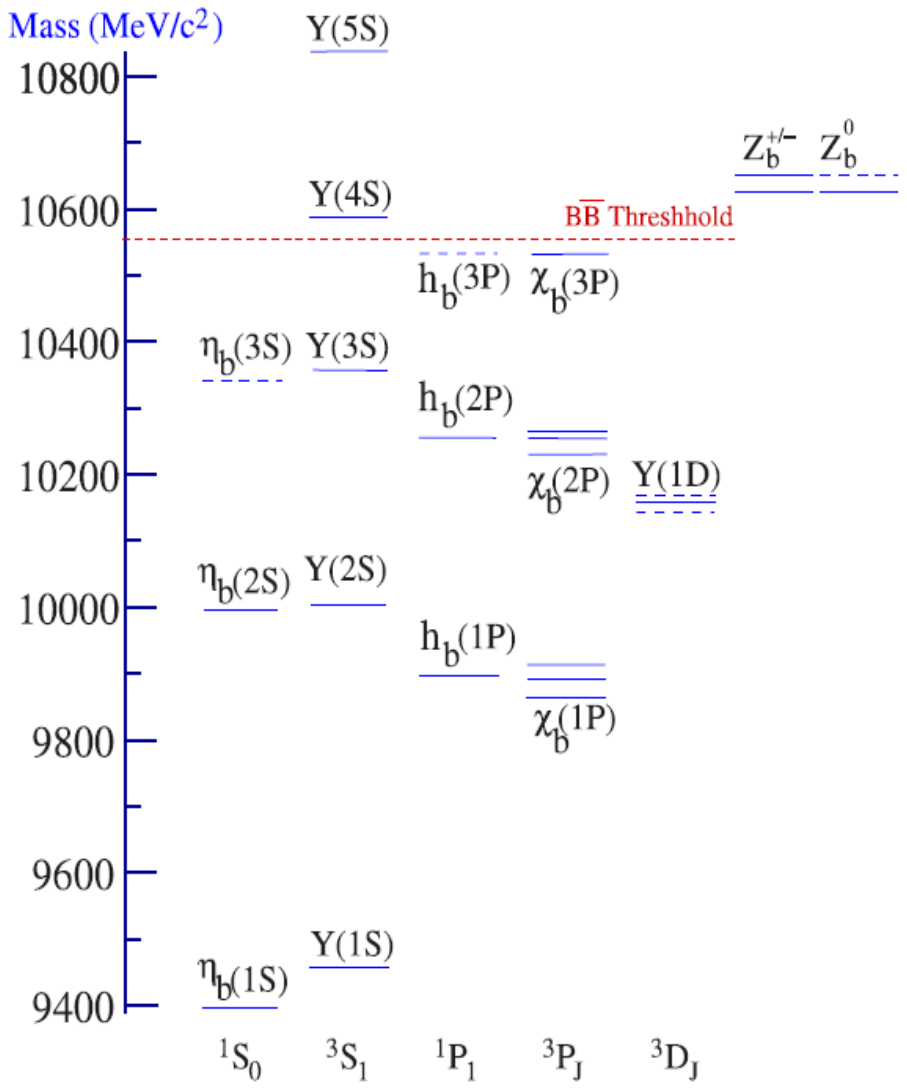
$\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ } rates

requires spin flip

- discoveries of $\eta_b(2S)$ and $h_b(1P,2P)$
- exotic bottomonium-like states Z_b

This talk:

- three energy scans
  - $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$
  - $e^+e^- \to h_b(nP)\pi^+\pi^-$
  - $e^+e^- \to B^{(*)}B^{(*)}\pi^\pm$
- η transition
  - $\Upsilon(4S) \to \eta h_b(1P)$



$e^+e^- \to Y(nS)\pi^+\pi^-$ & $e^+e^- \to b\bar{b}$ I

Data:

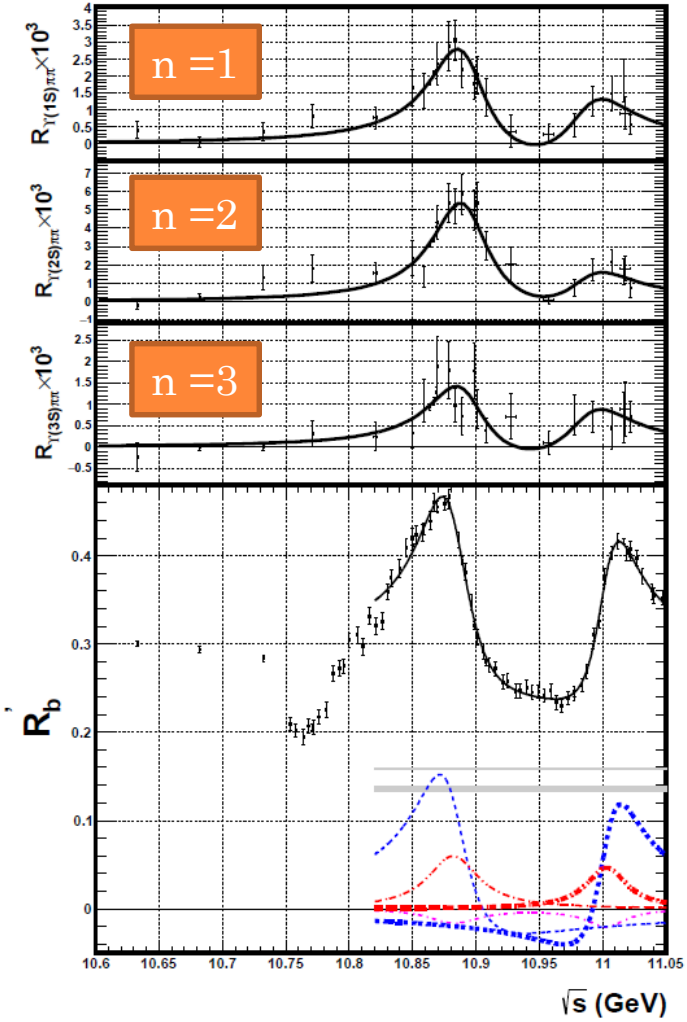
- 10.63 – 11.02 GeV;
- 121.4 fb^{-1} at Y(5S) (3 energy points);
- 26 fb^{-1} scan (19 energy points for $e^+e^- \to Y(nS)\pi^+\pi^-$,
  74 energy points for $e^+e^- \to b\bar{b}$).

Selection:

- $Y(nS) \to \mu^+\mu^-$;
- $\pi^+\pi^-\mu^+\mu^-$ and no other tracks;
- $M(\pi^+\pi^-\mu^+\mu^-)$ consistent with $\sqrt{s}$;
- $\Delta M = M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)$ consistent with $\sqrt{s} - M_{Y(nS)}$.

D. Santel et al. (PRD 93, 011101(R))

$e^+e^-\to Y(nS)\pi^+\pi^-$ & $e^+e^-\to b\bar{b}$ II



$$\mathbf{R_{Y(nS)\pi\pi} = \sigma(Y(nS)\pi^+\pi^-)/\sigma^0_{\mu\mu}}$$

$$\mathcal{F}'_n(\sqrt{s}) = PHSP(\sqrt{s})\cdot\{|A_{5S,n}f_{5S}|^2 + |A_{6S,n}f_{6S}|^2 + 2k_nA_{5S,n}A_{6S,n}\Re[e^{i\delta_n}f_{5S}f^*_{6S}]\}.$$

$$f_{nS} = BW(M_{nS},\Gamma_{nS})$$

$$\mathbf{R_b = \sigma(bb)/\sigma^0_{\mu\mu}}$$

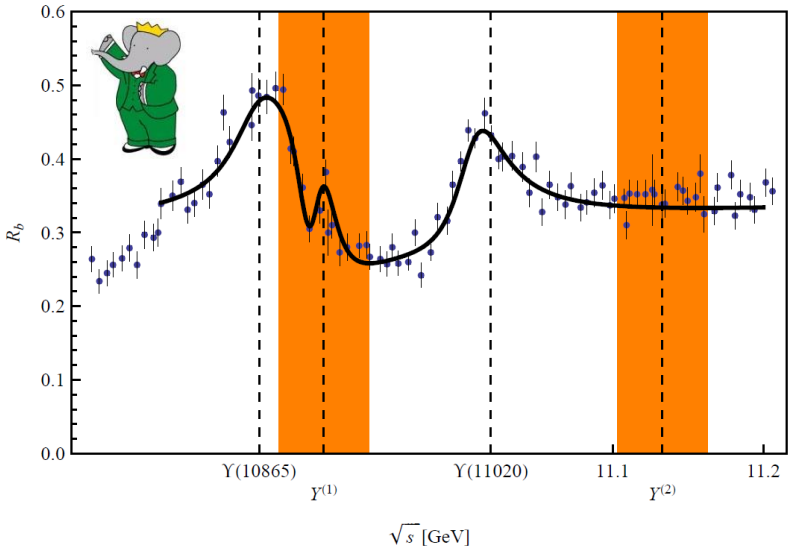
$$\mathcal{F}(\sqrt{s}) = |A_{ic}|^2 + |A_c + A_{5S}e^{i\phi_{5S}}f_{5S}(\sqrt{s}) + A_{6S}e^{i\phi_{6S}}f_{6S}(\sqrt{s})|^2,$$

resonant
interference of resonances with continuum
interference of two resonances
continuum (coherent & incoherent)

	M_{5S} (MeV/c^2)	Γ_{5S} (MeV)	M_{6S} (MeV/c^2)	Γ_{6S} (MeV)	ϕ_{6S}-ϕ_{5S} (δ) (rad)	χ^2/dof
R'_b	$10881.8^{+1.0}_{-1.1}\pm1.2$	$48.5^{+1.9\ +2.0}_{-1.8\ -2.8}$	$11003.0\pm1.1^{+0.9}_{-1.0}$	$39.3^{+1.7\ +1.3}_{-1.6\ -2.4}$	$-1.87^{+0.32}_{-0.51}\pm0.16$	56/50
$R_{\Upsilon(nS)\pi\pi}$	$10891.1\pm3.2^{+0.6}_{-1.7}$	$53.7^{+7.1\ +1.3}_{-5.6\ -5.4}$	$10987.5^{+6.4\ +9.0}_{-2.5\ -2.1}$	$61^{+9\ +2}_{-19\ -20}$	$-1.0\pm0.4^{+1.4}_{-0.1}$	51/56

$e^+e^- \to Y(nS)\pi^+\pi^-$ & $e^+e^- \to b\bar{b}$ III

- Difference in Y(5S) and Y(6S) parameters determined from fits to $R_{Y(nS)\pi\pi}$ and R_b may be caused by the complexity of R_b data (continuum shape, proximity of $B^{(*)}B^{(*)}$ thresholds & their interaction with resonances).
- Measurements from $R_{Y(nS)\pi\pi}$ are more reliable.
- No peaking structure near 10.9 GeV suggested in 2010 by A. Ali et al. (*PLB* ***684*** *28*) based on the BaBar measurement of R_b.



$e^+e^- \to h_b(nP)\pi^+\pi^-$ I

$e^+e^- \to h_b(nP)\pi^+\pi^-$ (n = 1,2) is the next highest statistics channel after $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$

Data:

- 10.63 – 11.02 GeV;
- 121.4 fb^{-1} at Y(5S) (3 energy points);
- 26 fb^{-1} scan (19 energy points).

Selection:

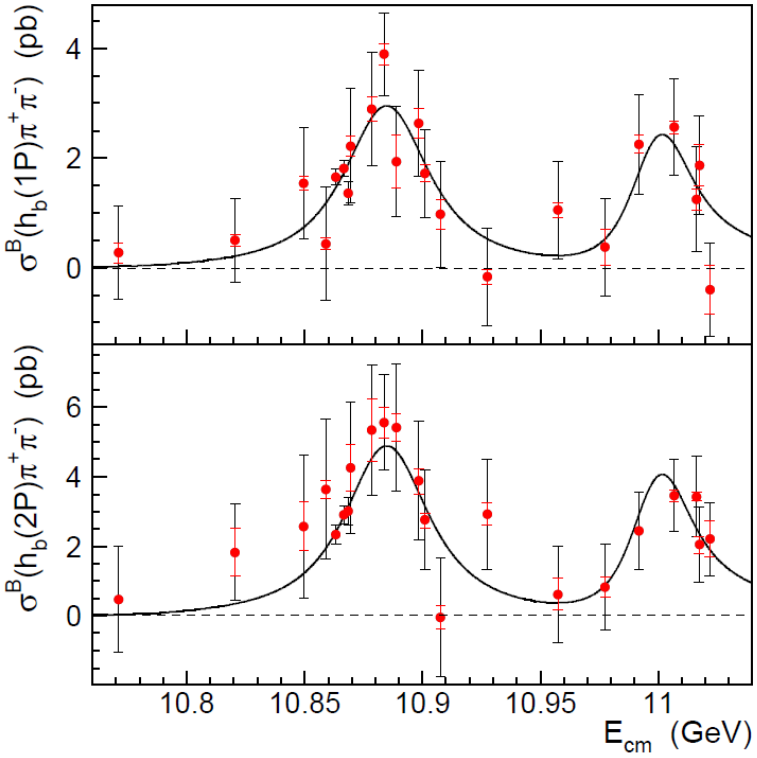
- consider all $\pi^+\pi^-$ pairs
- $R_2 < 0.3$;
- $10.59 < M_{miss}(\pi) < 10.67$ GeV (Z_b region).

  Assumption: $e^+e^- \to Z_b\pi \to h_b(nP)\pi\pi$ (based on Y(5S) decays)

R. Mizuk et al. (to be submitted to PRL)

$e^+e^- \to h_b(nP)\pi^+\pi^-$ II

- Cross sections of $e^+e^- \to h_b(nP)\pi^+\pi^-$ and $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ look very similar and give consistent resonance parameters with no continuum contribution.
- **Charmonium:** difference between $e^+e^- \to h_c\pi^+\pi^-$ and $e^+e^- \to J/\psi\pi^+\pi^-$ shapes is much more pronounced (possible new peaks and non-res contribution).



$$N_1 \left| BW(M_5,\Gamma_5) + A_2 \exp\{iP_2\} BW(M_6,\Gamma_6) \right|$$

$N_1 = (2.1 \pm 0.4)\ 10^3$
$N_2 = (3.2 \pm 0.7)\ 10^3$

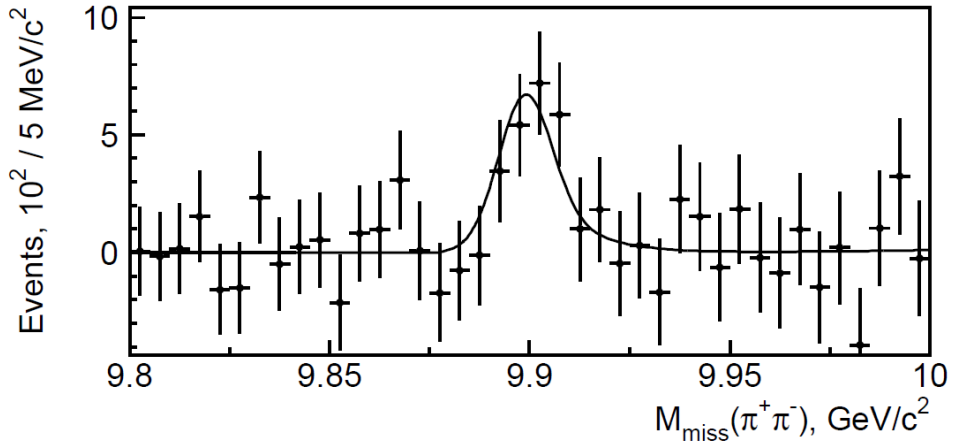
$M_5 = 10\,887 \pm 3$ MeV
$\Gamma_5 = 36 \pm 6$ MeV
$M_6 = 11\,001 \pm 4$ MeV
$\Gamma_6 = 29 \pm 11$ MeV

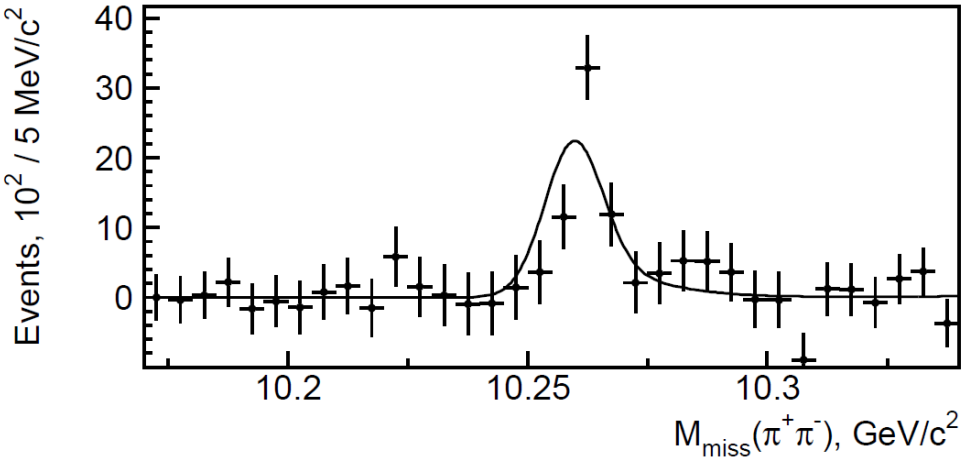
$A_2 = 0.85 \pm 0.14$
$P_2 = (0.14 \pm 0.31)\ \pi$

$e^+e^- \to h_b(nP)\pi^+\pi^-$ III

$\Upsilon(6S) \to h_b(nP)\pi^+\pi^-$

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





5 energy points

first evidence (3.6 σ) for $\Upsilon(6S) \to h_b(1P)\pi^+\pi^-$

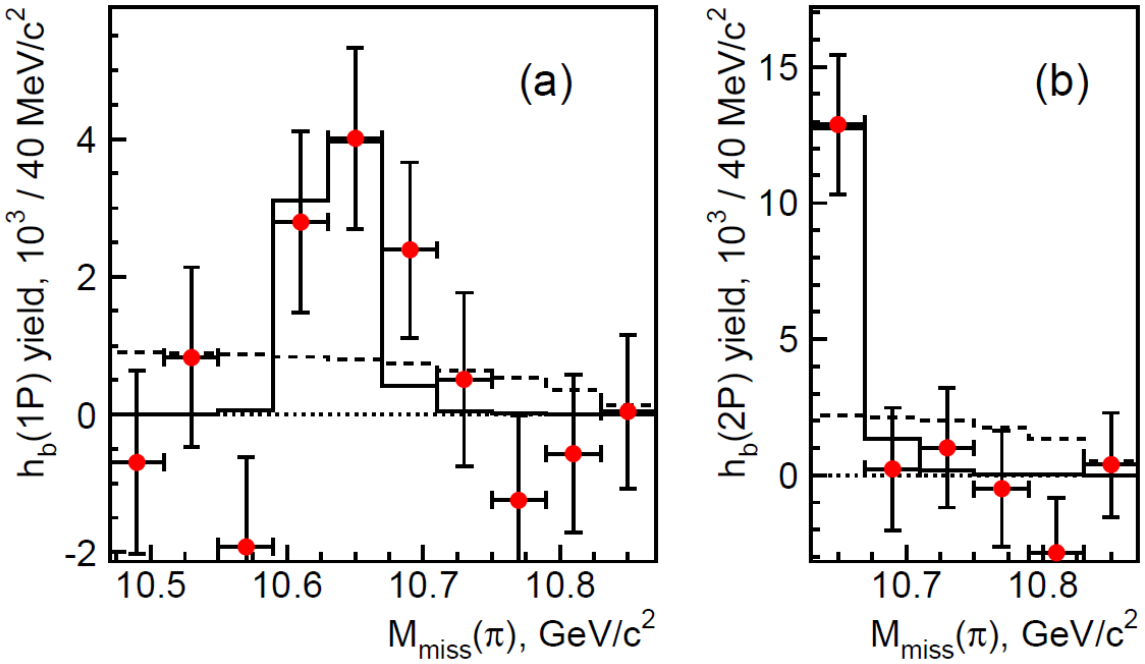
first observation (5.4 σ) of $\Upsilon(6S) \to h_b(2P)\pi^+\pi^-$

$\Upsilon(6S) \to h_b(nP)\pi^+\pi^-$

$M_{miss}(\pi)$ data do not follow phase space distribution, but populate **Z_b mass region**.

Hypotheses:

- Both $Z_b(10610)$ & $Z_b(10650)$ (———)
- Phase space (– – – – -) excluded at level 3.6 σ ($h_b(1P)$) and 4.5 σ ($h_b(2P)$)
- Single $Z_b(10610)$ excluded at level 3.3 σ ($h_b(1P)$)
- Single $Z_b(10650)$ cannot be excluded at significant level



$e^+e^- \to B^{(*)}\bar{B}^{(*)}\pi^{\pm}$ I

- $Z_b(10610)$ & $Z_b(10650)$ contain at least four quarks (including $b\bar{b}$).
- One of the models: loosely bound $B^{(*)}\bar{B}^*$ systems.
- Decay rates of $Z_b \to B^{(*)}\bar{B}^*$ are expected to be significant.
- Evidence for $\Upsilon(5S) \to B\bar{B}^*\pi$ was reported by Belle (23.6 fb^{-1}).

Data:

- 121.4 fb^{-1} at $\Upsilon(5S)$ resonance;

Selection:

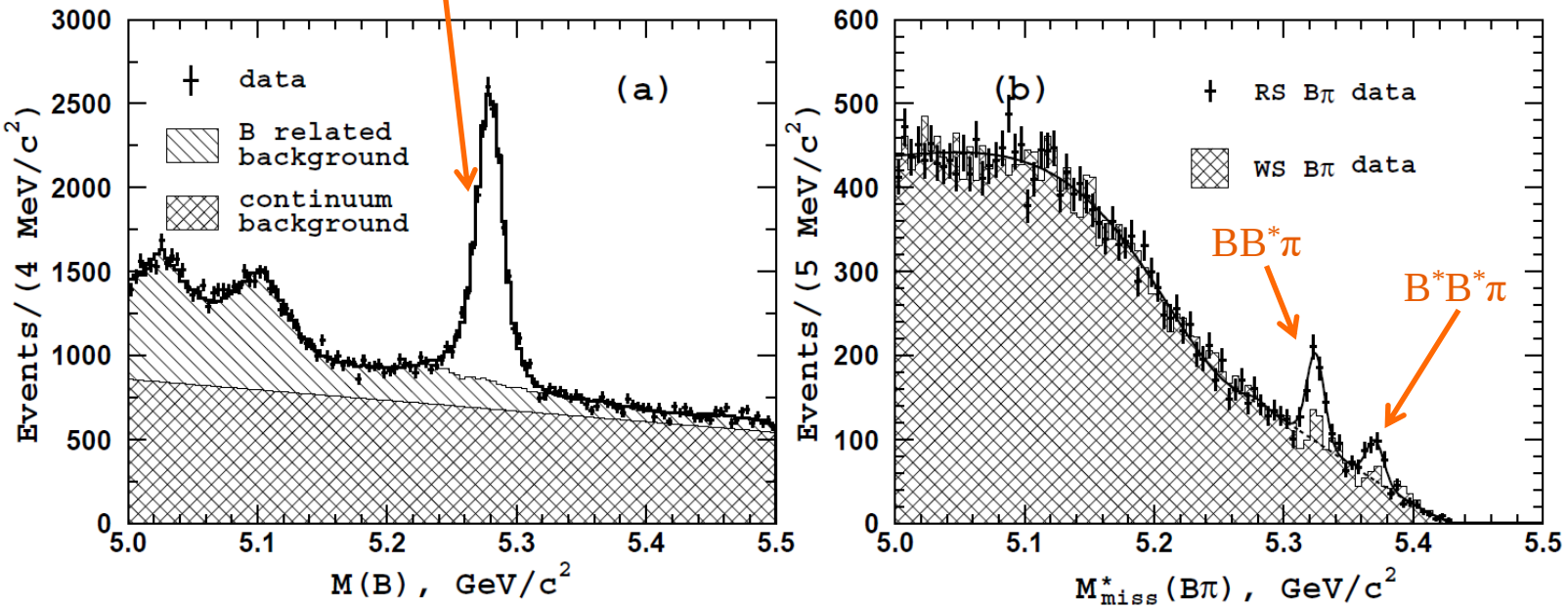
- one B meson from 16 decay modes ($J/\psi K^{(*)}$ & $D^{(*)}\pi$);
- $\cos\theta_{thrust} < 0.8$;
- momentum $P(B) < 1.35$ GeV;
- invariant mass consistent with B meson.

A. Garmash et al. (arXiv:1512.07419, accepted at PRL)

$e^+e^- \to B^{(*)}\bar{B}^{(*)}\pi^{\pm}$ II

B meson reconstruction

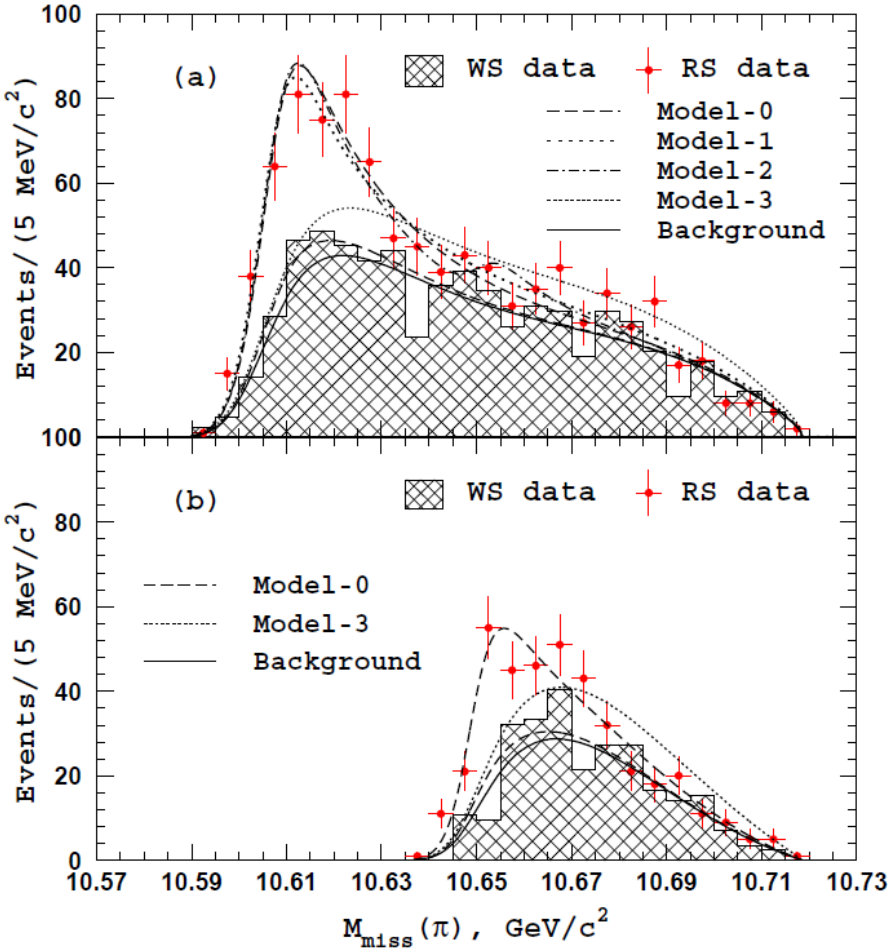
B^+ and B^0 combination with $\pi^{-(+)}$ form Right (Wrong) Sign data



$e^+e^- \to B^{(*)}\bar{B}^{(*)}\pi^\pm$ III

After selecting $B\bar{B}^*\pi$ and $B^*\bar{B}^*\pi$ events we perform $M_{miss}(\pi)$ fit.

- Simultaneous fit of RS and WS samples.
- WS data are used to estimate background.
- Z_b parameters are fixed from $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ decays.



Model 0: single Z_b amplitude

Model 1: + non-res component
(no significant improvement compared to Model 0)

Model 2: + another Z_b amplitude
(no significant improvement compared to Model 0)

Model 3: pure non-res amplitude
(fit is significantly worse)

$e^+e^- \to B^{(*)}\bar{B}^{(*)}\pi^\pm$ IV

Born cross sections are $\sigma(e^+e^- \to [B\bar{B}^* + \text{c.c.}]^\pm\pi^\mp) = (17.4 \pm 1.6 \pm 1.9)$ pb

$\sigma(e^+e^- \to [B^*\bar{B}^*]^\pm\pi^\mp) = (8.75 \pm 1.15 \pm 1.04)$ pb

$\sigma(e^+e^- \to [B\bar{B}]^\pm\pi^\mp) < 2.9$ pb

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	–
$B^{*+}\bar{B}^{*0}$	–	$73.7^{+3.4+2.7}_{-4.4-3.5}$

Z_b decays are dominated by $B^{(*)}\bar{B}^*$ channels

$\Upsilon(4S) \to \eta h_b(1P)$ I

- QCD multipole expansion (low m, n): $\Upsilon(nS) \to \Upsilon(mS)(gg)$ — E1E1 → $\pi\pi$; E1M2 → η suppressed due to spin flip
- Above BB threshold spin-flip processes are not suppressed due to presence of exotic bottomonium.
- Branching of $\Upsilon(4S) \to \eta h_b(1P)$ is predicted to be 10^{-3} (*PRL* ***105*** *162001*).

Data:

- 711 fb^{-1} at $\Upsilon(4S)$ resonance.

Selection:

- $R_2 < 0.3$;
- $\eta \to \gamma\gamma$;
- $\cos\theta_{hel} < 0.9$;
- π^0 veto.

U. Tamponi et al. (PRL 115, 142001)

$\Upsilon(4S) \to \eta h_b(1P)$ II

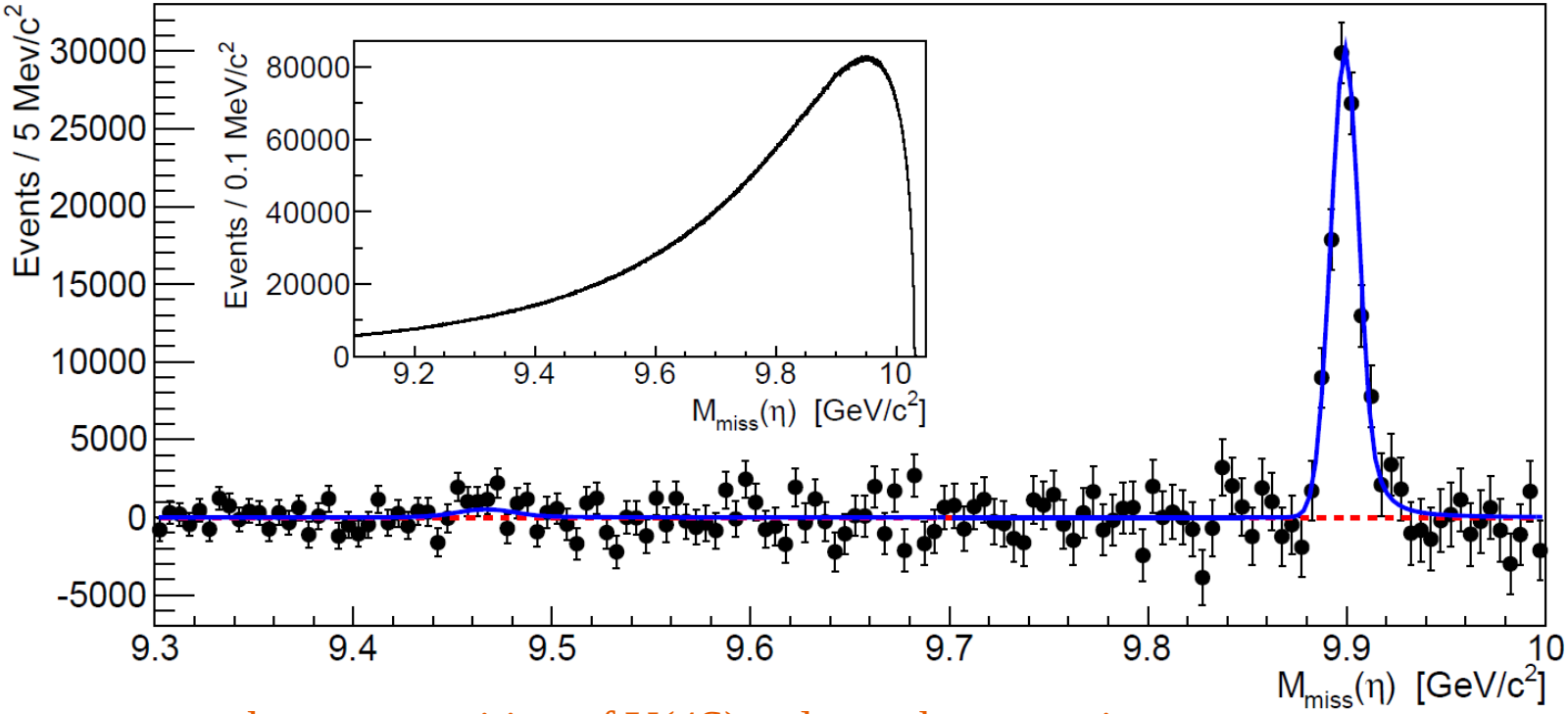
$$M_{h_b(1P)} = (9899.3 \pm 0.4 \pm 1.0)\ \text{MeV}$$

$$\mathcal{B}[\Upsilon(4S) \to \eta h_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$$

$$\mathcal{B}[\Upsilon(4S) \to \eta \Upsilon(1S)] < 2.7 \times 10^{-4}$$ 90% CL (agreement with BaBar)

1P hyperfine splitting $\Delta M_{HF}(1P) = m(h_b(1P)) - m^{sa}(\chi_{bJ}(1P))$

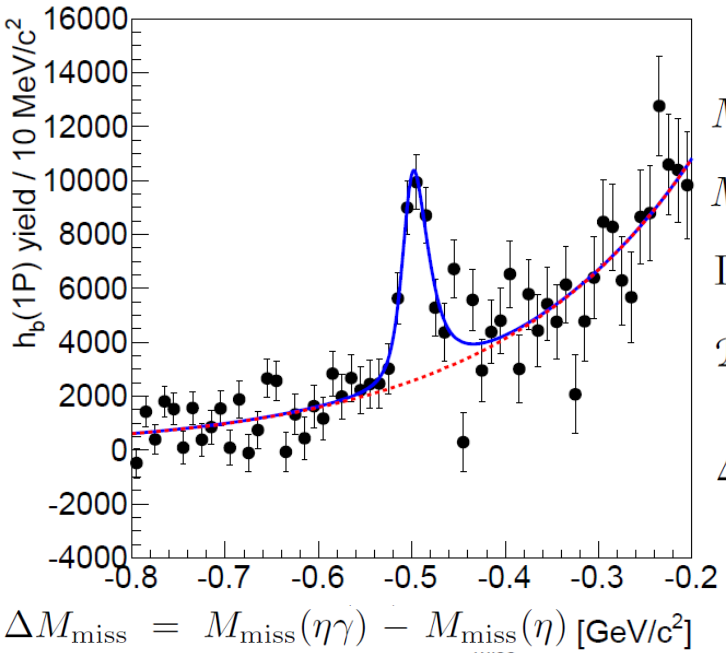
$$\Delta M_{HF}(1P) = (+0.6 \pm 0.4 \pm 1.0)\ \text{MeV}$$ (no sizeable spin-spin interactions)



strongest known transition of Y(4S) to lower bottomonium

$\Upsilon(4S)\to\eta h_b(1P)$ III

$\Upsilon(4S)\to\eta h_b(1P)\to\eta\gamma\eta_b(1S)$



$$M_{\eta_b(1S)} - M_{h_b(1P)} = (-498.6 \pm 1.7 \pm 1.2)\ \text{MeV}$$

$$M_{\eta_b(1S)} = M_{h_b(1P)} + \Delta M_{\rm miss} = (9400.7 \pm 1.7 \pm 1.6)\ \text{MeV}$$

$$\Gamma_{\eta_b(1S)} = (8^{+6}_{-5} \pm 5)\ \text{MeV}$$

$$\mathcal{B}[h_b(1P) \to \gamma\eta_b(1S)] = \frac{N_{\eta_b(1S)}\epsilon_{\eta h_b(1P)}}{N_{h_b(1P)}\epsilon_{\eta\gamma\eta_b(1S)}} = (56 \pm 8 \pm 4)\%$$

$$\Delta M_{\rm HF}(1S) = (59.6 \pm 1.7 \pm 1.6)\ \text{MeV}$$

M(η_b(1S))

- in agreement with $\Upsilon(5S)\to\pi^+\pi^- h_b(1P)\to\pi^+\pi^-\gamma\eta_b(1S)$:
  - (9402.4 ± 1.5 ± 1.8) MeV (*PRL* ***109***, *232002*);
- in discrepancy with $\Upsilon(2S,3S)\to\gamma\eta_b(1S)$:
  - (9388.9 $^{+3.1}_{-2.3}$ ± 2.7) MeV (*PRL* ***101*** *071801)*,
  - (9390.8 ± 3.2) MeV (*PRL* ***103*** *161801*),
  - (9391.8 ± 6.6 ± 2.0) MeV (*PRD* ***81*** *031104*).

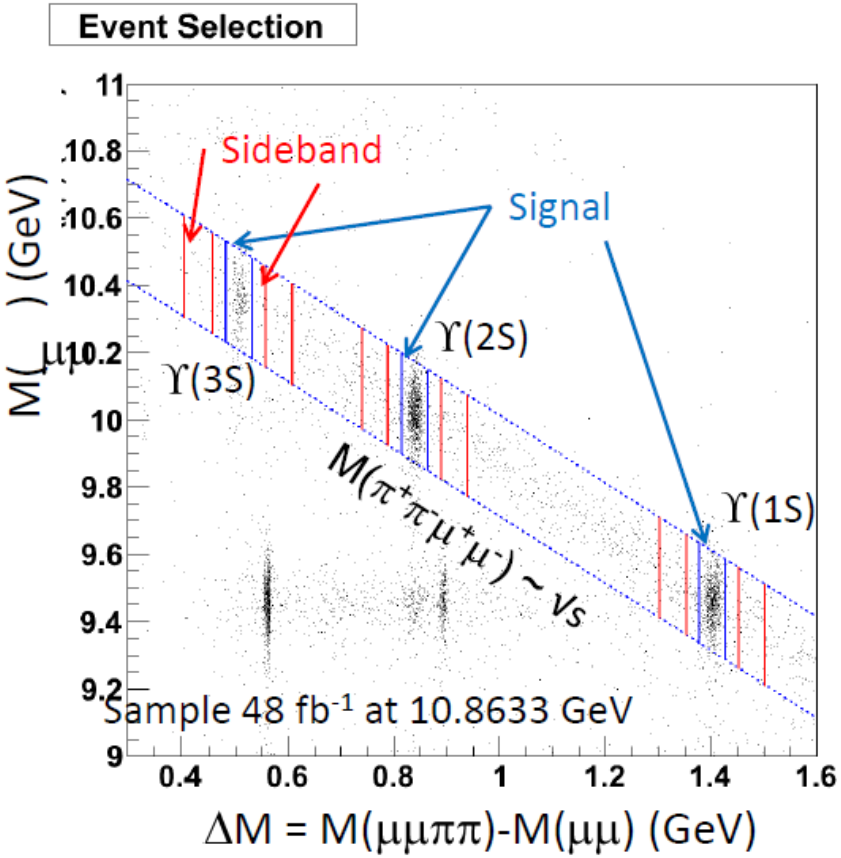
Summary

- $ee \to Y(nS)\pi\pi$ (n = 1, 2, 3) & $ee \to b\bar{b}$
  - We have measured the cross sections $e^+e^- \to Y(nS)\pi^+\pi^-$ (n = 1, 2, 3) and $e^+e^- \to b\bar{b}$ in the region $\sqrt{s}$ = 10.8 – 11.05 GeV to determine masses and widths for Y(5S) and Y(6S).
  - $R_{Y(nS)\pi\pi}$ is dominated by the two resonances with no continuum.
  - R_b fit is not reliable enough.
  - No peaking structure is seen at 10.9 GeV.
- $ee \to h_b(nP)\pi\pi$
  - We have measured the $e^+e^- \to h_b(nP)\pi^+\pi^-$ cross section and determined the parameters of Y(10860) and Y(11020).
  - First evidence for $Y(6S) \to h_b(1P)\pi^+\pi^-$.
  - First observation of $Y(6S) \to h_b(2P)\pi^+\pi^-$.
  - These transitions proceed either through one or two Z_b's.
- $ee \to B^{(*)}\bar{B}^{(*)}\pi$
  - First observations of $e^+e^- \to B\bar{B}^*\pi$ and $e^+e^- \to B^*\bar{B}^*\pi$ and cross sections measurement.
  - Upper limit on $e^+e^- \to B\bar{B}\pi$.
  - These processes are dominated by $e^+e^- \to Z_b\pi$.
- $Y(4S) \to \eta h_b(1P)$
  - First observation of $Y(4S) \to \eta h_b(1P)$ and branching measurement.
  - New measurement of $h_b(1P)$ mass and calculation of 1P hyperfine splitting.
  - Branching measurement of $h_b(1P) \to \gamma\eta_b(1S)$.
  - New measurement of the $\eta_b(1S)$ width and $h_b(1P) - \eta_b(1S)$ mass difference and calculation of $\eta_b(1S)$ mass and 1S hyperfine splitting.

Backup

Selection of $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$

$\hookrightarrow \mu^+\mu^-$



Similar event selection to PRD 82, 091106(R) 2010

- $\pi^+\pi^-\mu^+\mu^-$ & no other tracks
- $M(\pi^+\pi^-\mu^+\mu^-)$ consistent with $\sqrt{s}$
- $\Delta M = M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)$ consistent with $\sqrt{s} - M_{\Upsilon(nS)}$

Data : $e^+e^- \to \Upsilon(nS)[\mu^+\mu^-]\pi^+\pi^-$

- 10.63-11.02 GeV
- 22 ~1 fb^{-1} scan points
- 121 fb^{-1} on-resonance at Y(10860)

More detail in BN1307

Method

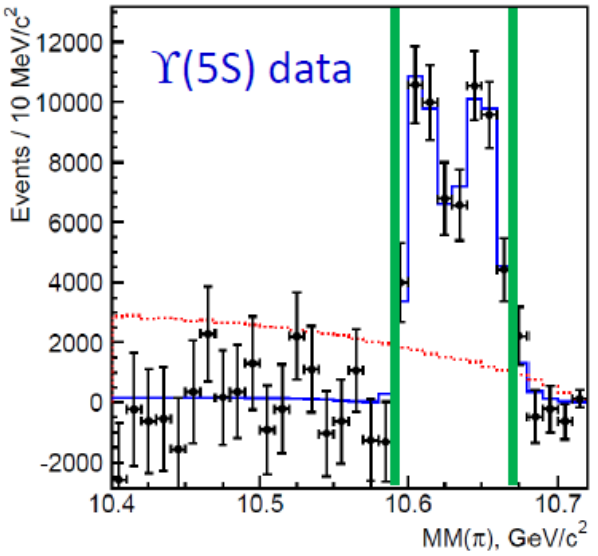
Consider all $\pi^+\pi^-$ pairs, fit $M_{miss}(\pi^+\pi^-)$ spectrum.

Use energy calibration by Yuan-Pao Yang and Dan Santel.

Selection

Same as in h_b, η_b papers.

HadronB skim
dr<0.3cm, dz<2cm
$L(\pi/K)>0.1$, $L(\pi/p)>0.1$, e veto: $P_e<0.9$
R2<0.3
Z_b mass window: $10.59<M_{miss}(\pi)<10.67$ GeV

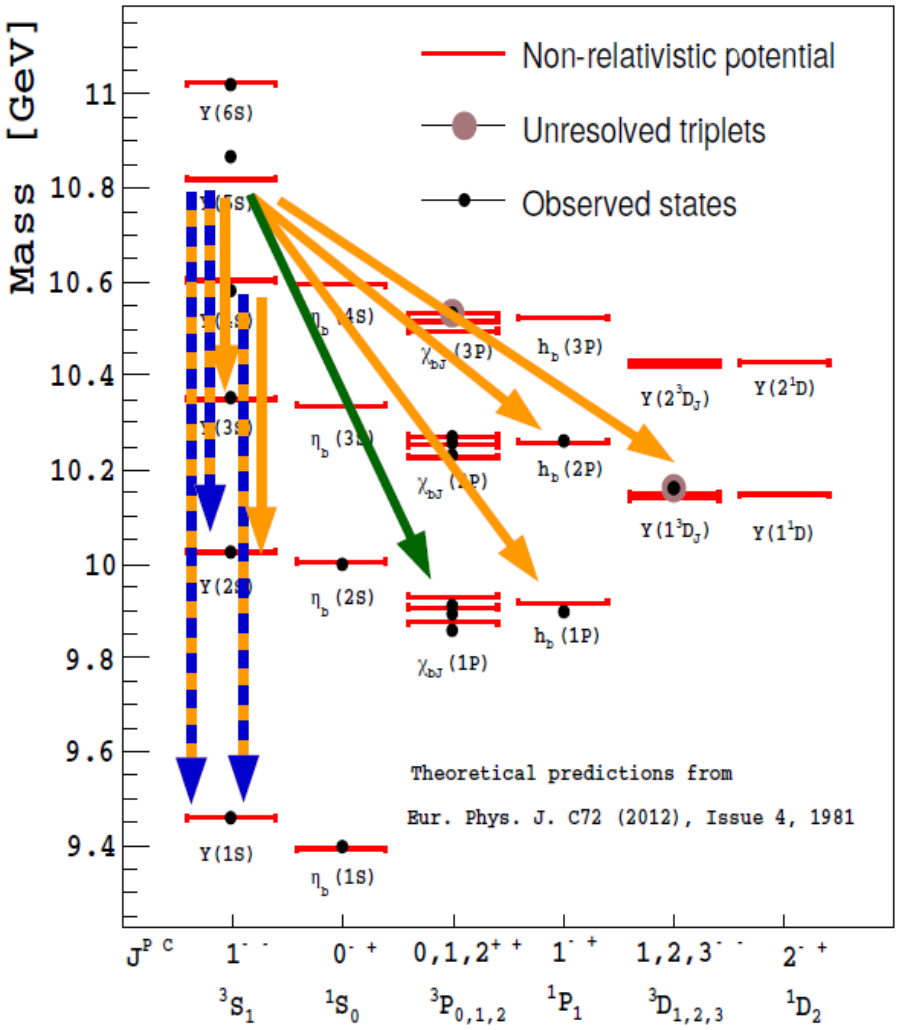


B candidates are reconstructed in the following decay modes:

$B^- \to D^0\pi^-$	$D^0 \to K^-\pi^+;\ K^-\pi^+\pi^0; K^-\pi^-\pi^+\pi^+$
$D^{*0}\pi^-$	$D^{*0} \to D^0\pi^0$ $\hookrightarrow\ D^0 \to K^-\pi^+; K^-\pi^-\pi^+\pi^+$
$J/\psi K^-$	$J/\psi \to \mu^+\mu^-; e^+e^-$
$\bar{B}^0 \to D^+\pi^-$	$D^+ \to K^+\pi^-\pi^-$
$D^{*+}\pi^-$	$D^{*+} \to D^0\pi^+$ $\hookrightarrow\ D^0 \to K^-\pi^+;\ K^-\pi^+\pi^0; K^-\pi^-\pi^+\pi^+$ $D^{*+} \to D^+\pi^0$ $\hookrightarrow\ D^+ \to K^+\pi^-\pi^-$
$J/\psi K_S^0$	$J/\psi \to \mu^+\mu^-; e^+e^-$ $K_S^0 \to \pi^+\pi^-$
$J/\psi \bar{K}^{*0}$	$J/\psi \to \mu^+\mu^-; e^+e^-$ $\bar{K}^{*0} \to K^-\pi^+$

16 decay modes in total

Y(4,5S) hadronic transitions

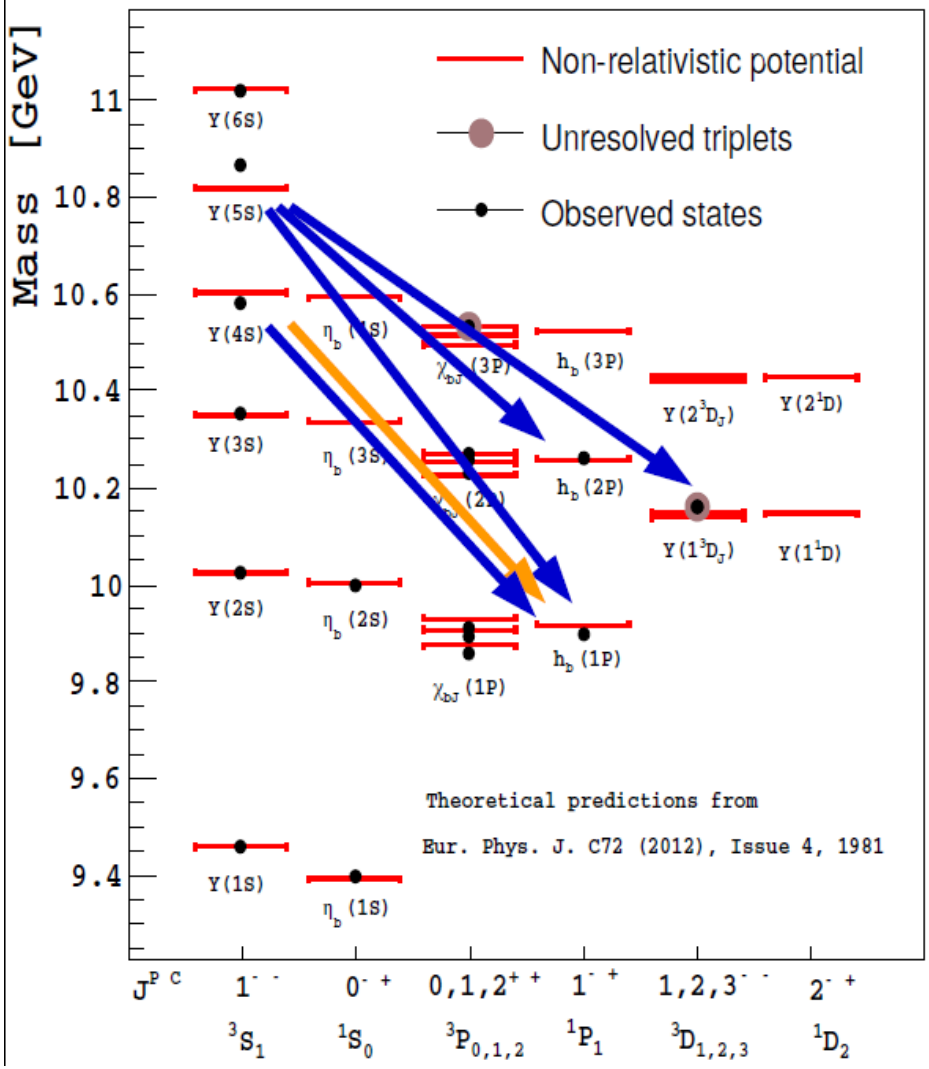


What we have measured from Y(4,5S):

$Y(5S) \to \eta/\pi\pi\ Y(1S)$
$Y(5S) \to \eta/\pi\pi\ Y(2S)$
$Y(5S) \to \pi\pi\ Y(3S)$
$Y(5S) \to \pi\pi$ hb(1P)
$Y(5S) \to \pi\pi$ hb(2P)
$Y(5S) \to \eta/\pi\pi\ Y(^3 1D)$
$Y(5S) \to \omega\ \chi_b(1P)$

$Y(4S) \to \eta/\pi\pi\ Y(1S)$
$Y(4S) \to \pi\pi\ Y(2S)$

Y(4,5S) Missing hadronic transitions



What we are missing:

$\Upsilon(5S) \rightarrow \eta$ hb(1P)

$\Upsilon(5S) \rightarrow \eta$ hb(2P)

$\Upsilon(5S) \rightarrow \eta$ Υ(1D)

$\Upsilon(4S) \rightarrow \pi\pi$ hb(1P)

$\Upsilon(4S) \rightarrow \eta$ hb(1P)

$\Upsilon(4S) \rightarrow \eta h_b(1P)$ Guo, PRL 105

Predicted as large as 10^{-3} (2010) 162001

$\Upsilon(5S) \rightarrow \eta h_b(1P)$

$\Upsilon(5S) \rightarrow \eta h_b(2P)$

No predictions

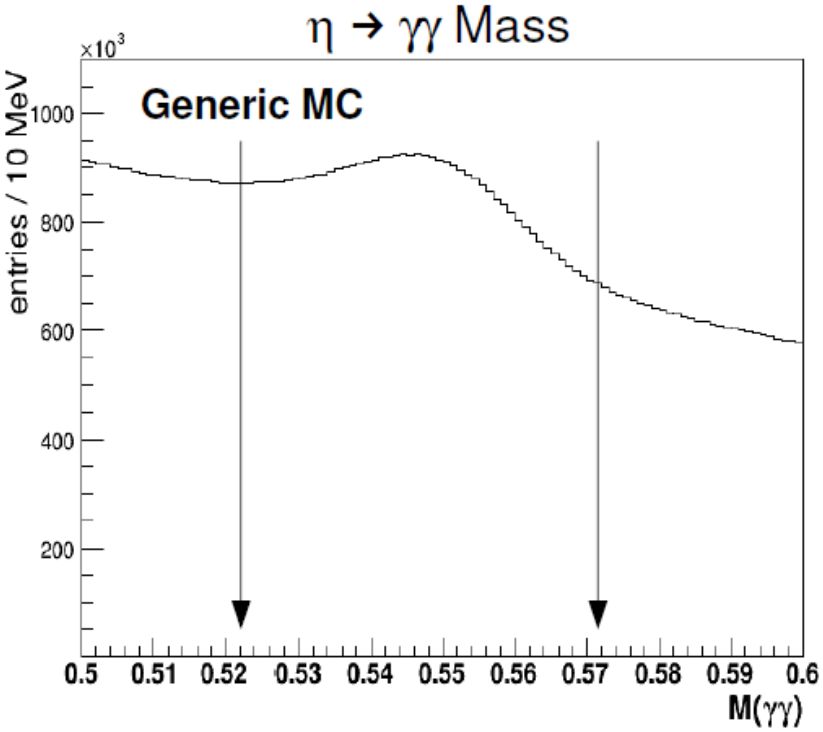
$\eta \to \gamma\gamma$ reconstruction

Event reconstruction

Inclusive $\eta \to \gamma\gamma$ reconstruction
Fit of MM(η)

Selection Criteria

Good photon quality
→ shower containment
→ E > 50 MeV
cos(helicity angle) < 0.9
π^0 veto
$|M(\gamma\gamma) - M(\eta)| < 0.026$ GeV
Kinematic fit with mass constrair



Continuum suppression

R2 < 0.3