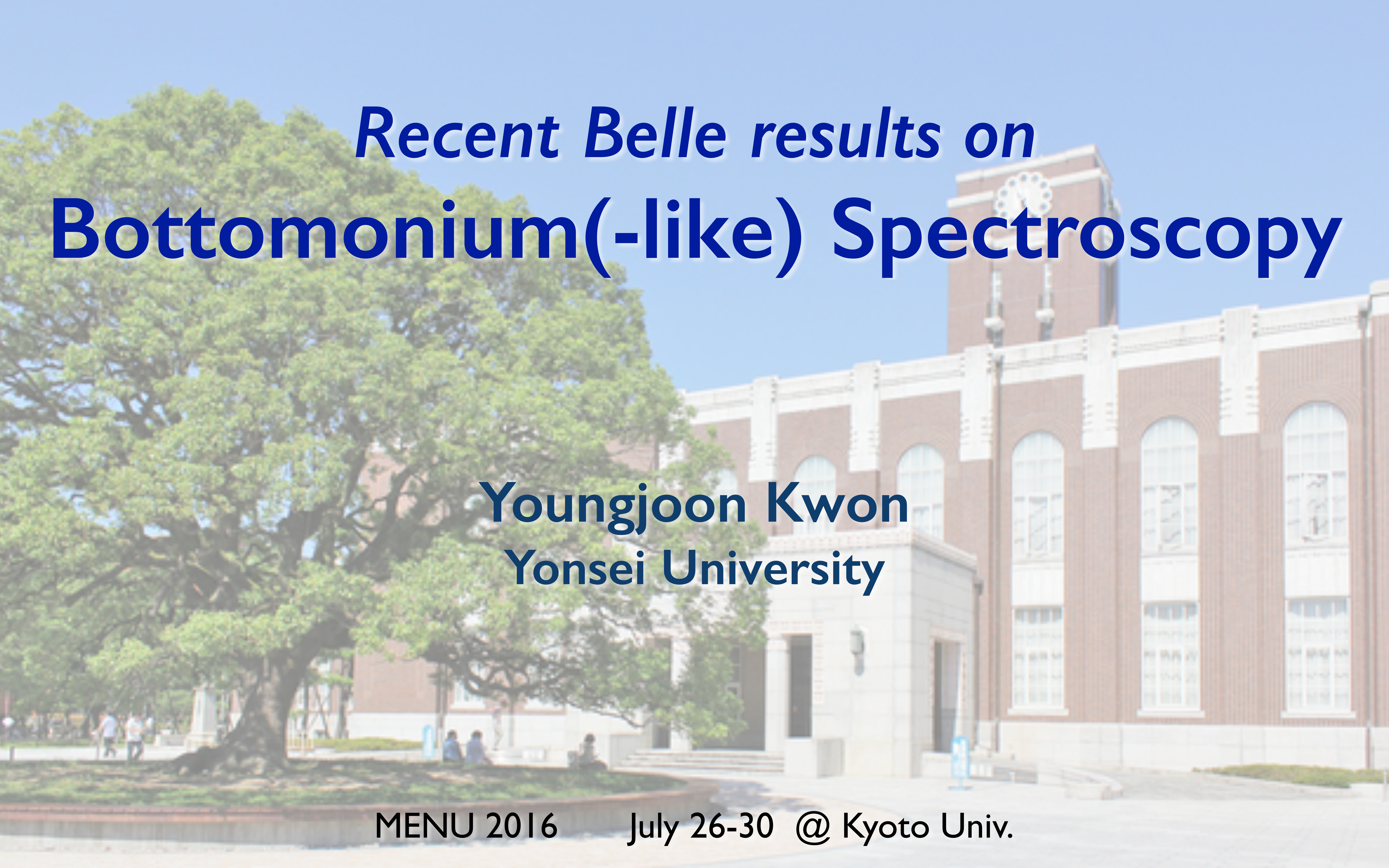

Recent Belle results on

Bottomonium(-like) Spectroscopy

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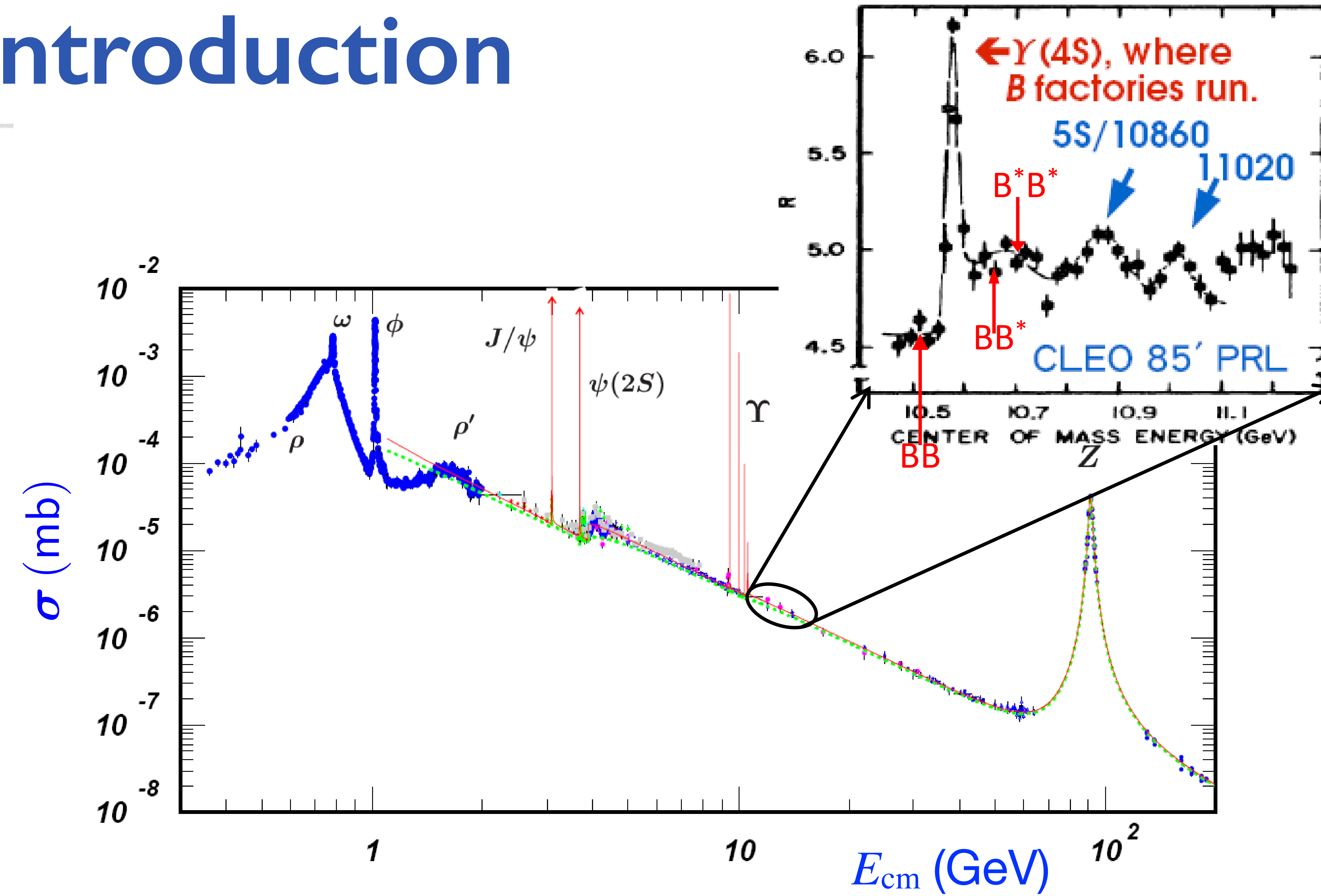
Yonsei University

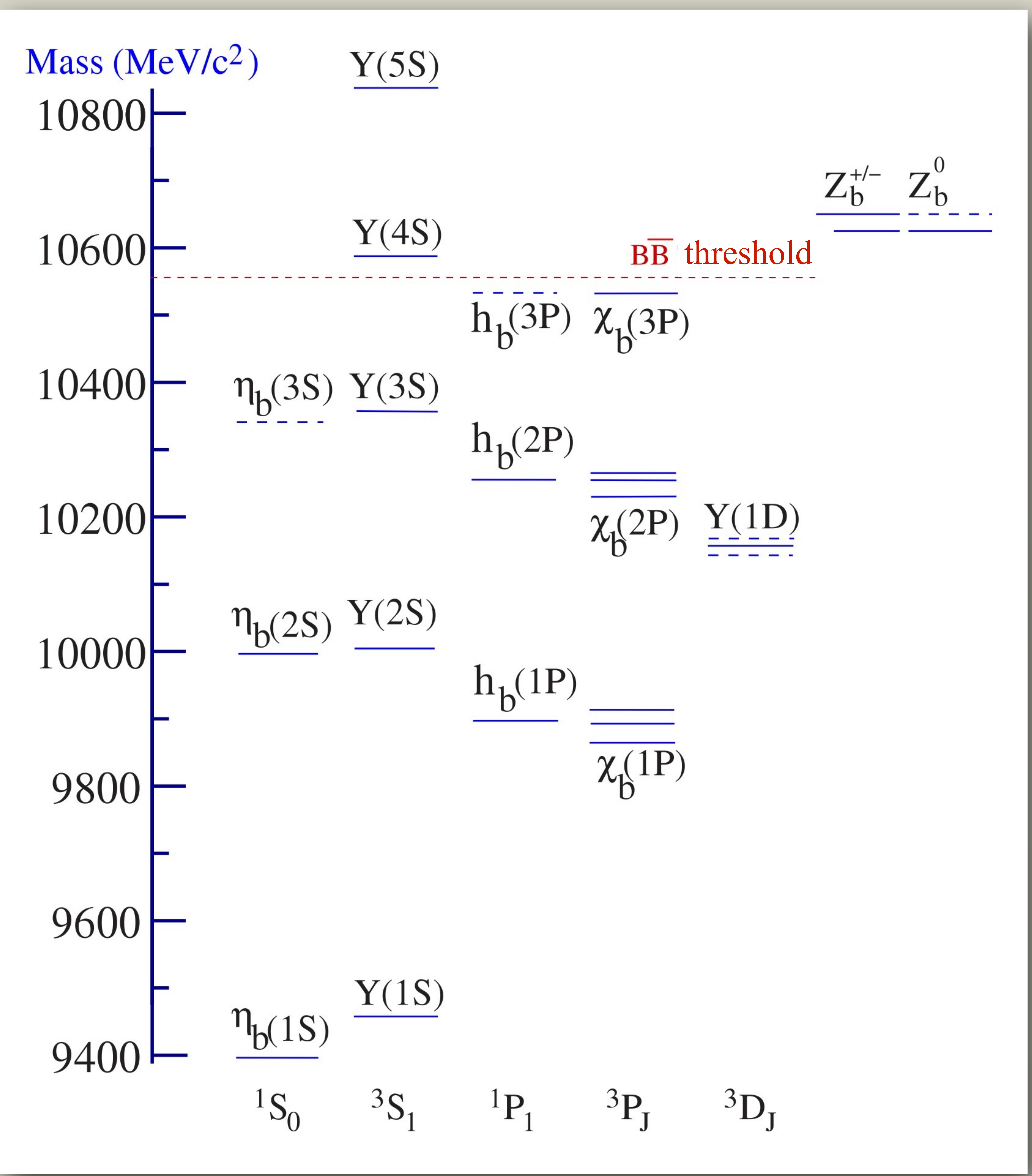
MENU 2016 July 26-30 @ Kyoto Univ.

Overview

- **Introduction**
- **Recent results**
  - Energy scan near Υ(5S) and Υ(6S)
  - Bottomonium(-like) states
- **Summary & Prospects**

Introduction

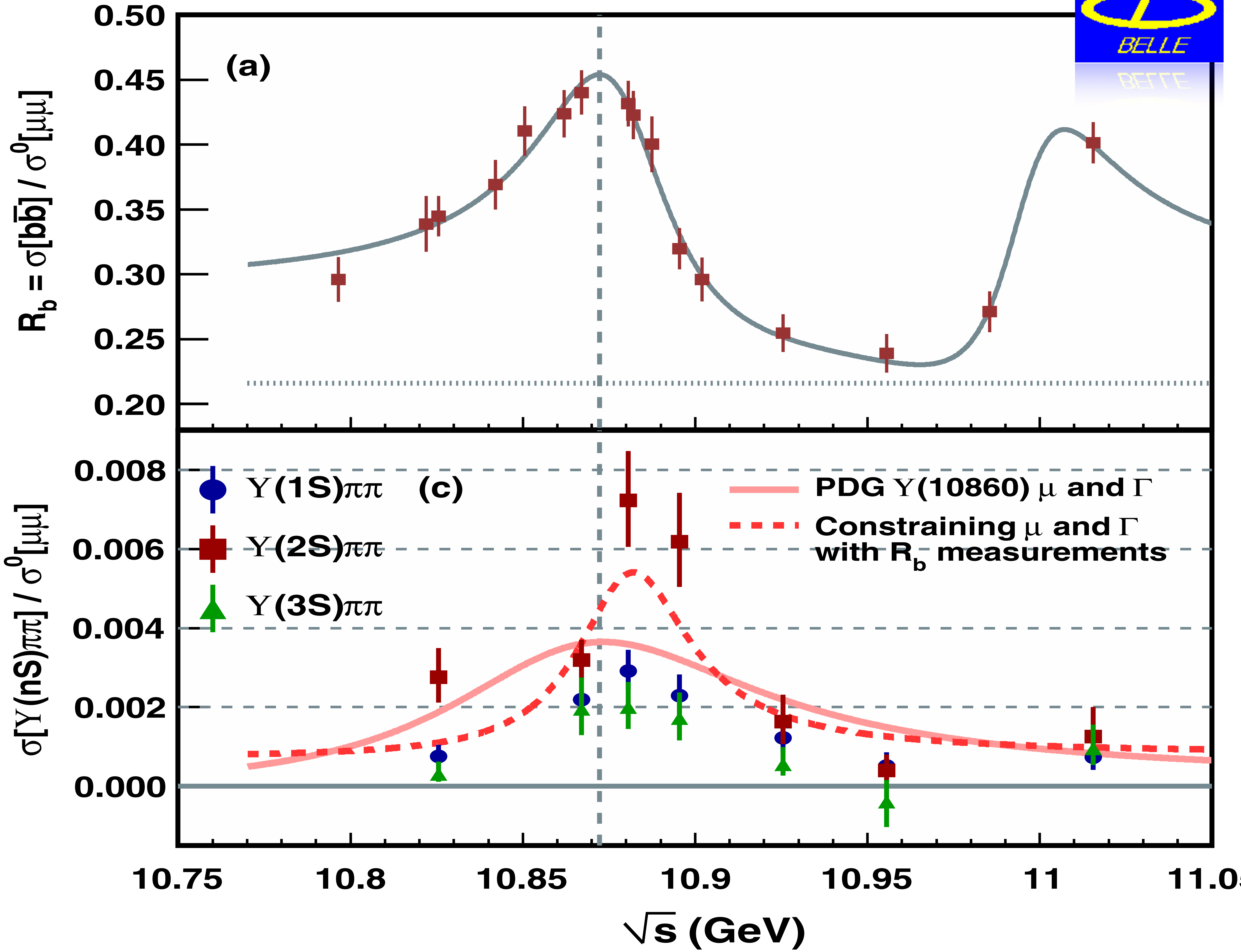




If I could remember the names of all these particles, I'd be a botanist.

- E. Fermi

PHYSICAL REVIEW D **82,** 091106(R) (2010)



$$R_b \equiv \frac{\sigma(b\bar{b})}{\sigma(\mu\mu)}$$

$$\frac{\sigma[\Upsilon(nS)\pi\pi]}{\sigma(\mu\mu)}$$

peak shift?

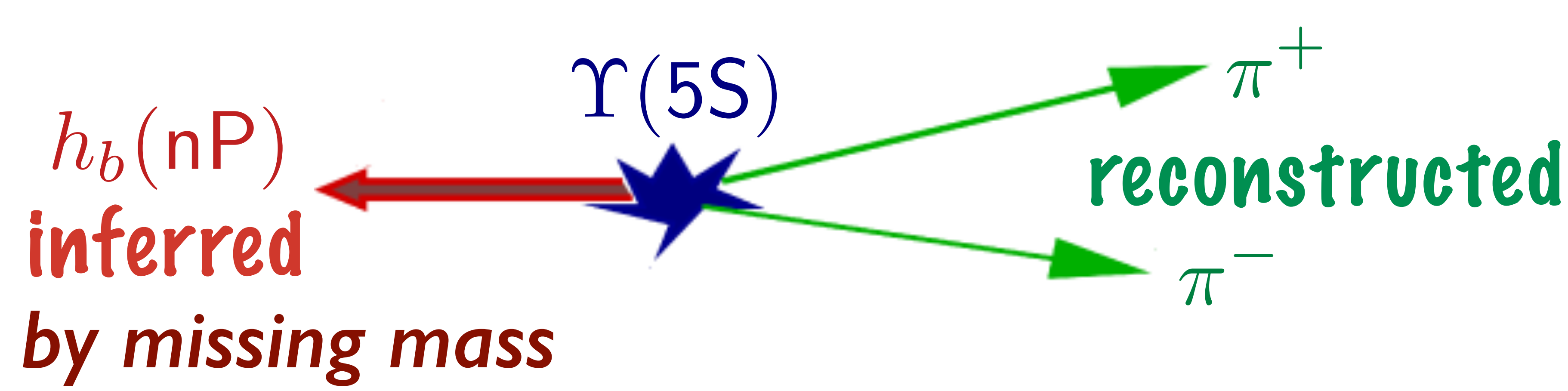
PRL 100, 112001 (2008)

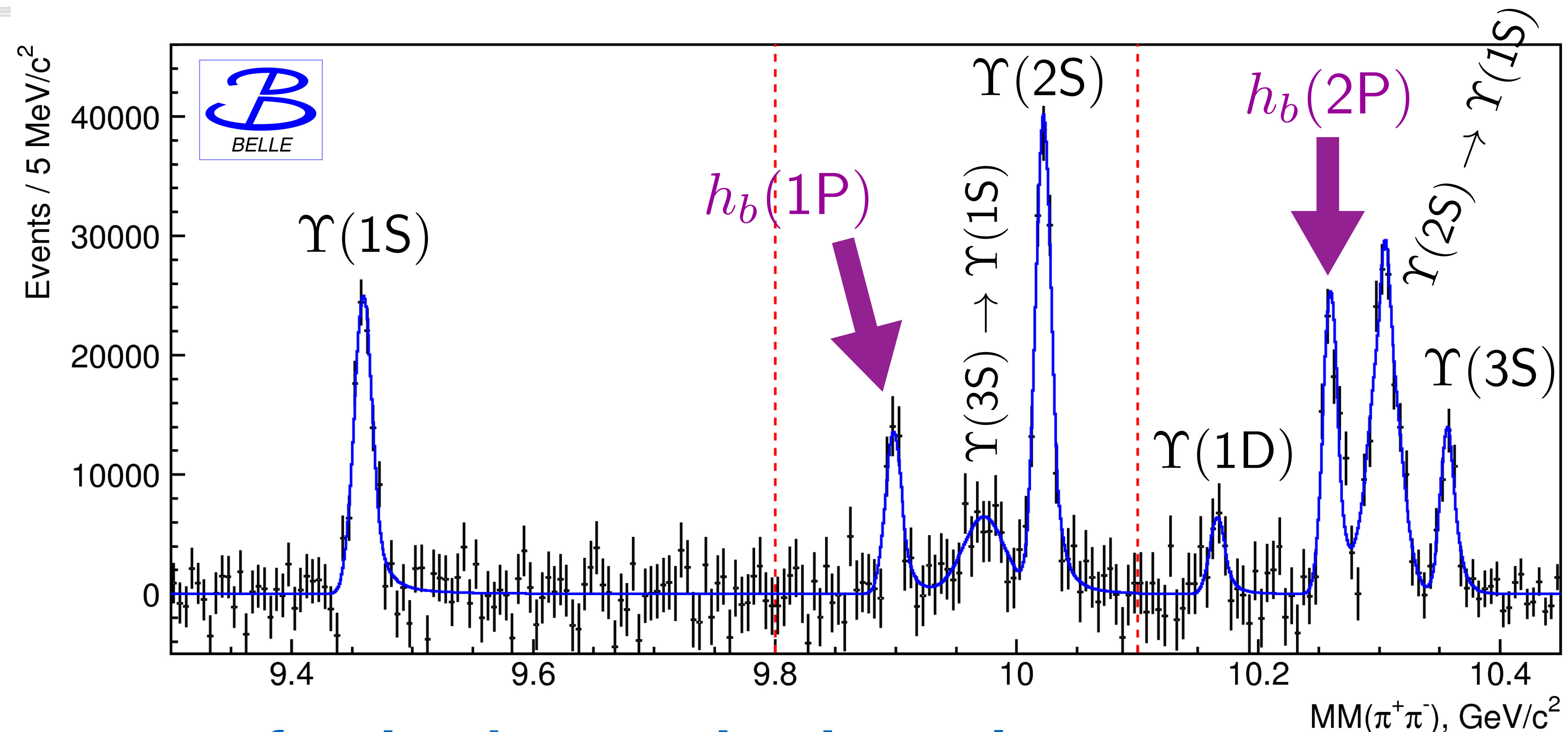
	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$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

bigger by O(10^2)??

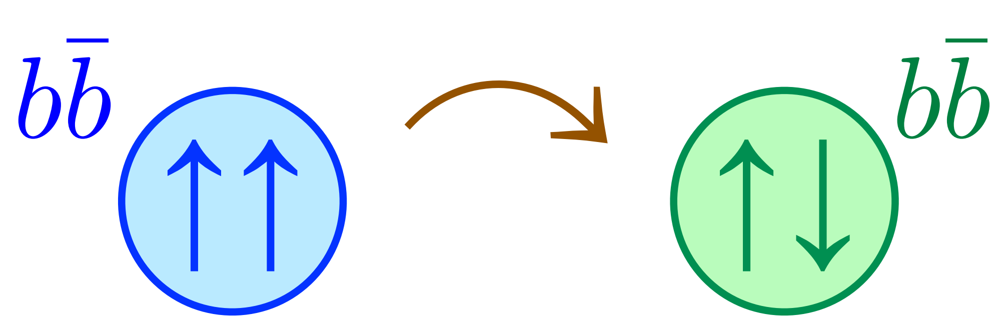
- $\Upsilon(5S)$ has anomalously high rates to $\Upsilon(nS)$, $(n = 1, 2, 3)$
- Perhaps, it is not a pure $b\bar{b}$ but an admixture?

Spin-flip puzzle with $h_b(nP)$





after background subtraction



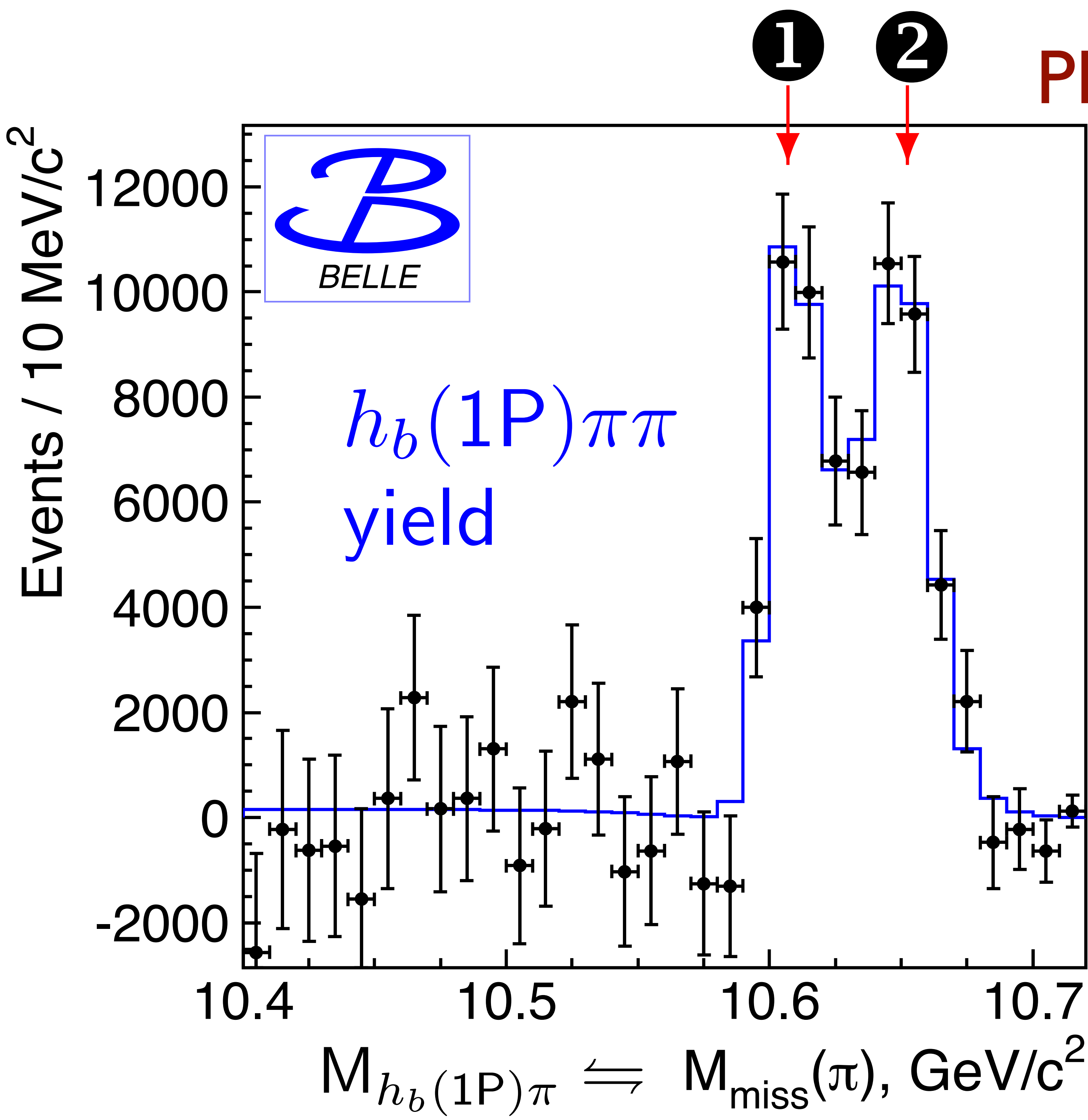
$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08 \pm {}^{0.07}_{0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08 \pm {}^{0.22}_{0.17} & \text{for } h_b(2P) \end{cases}$$

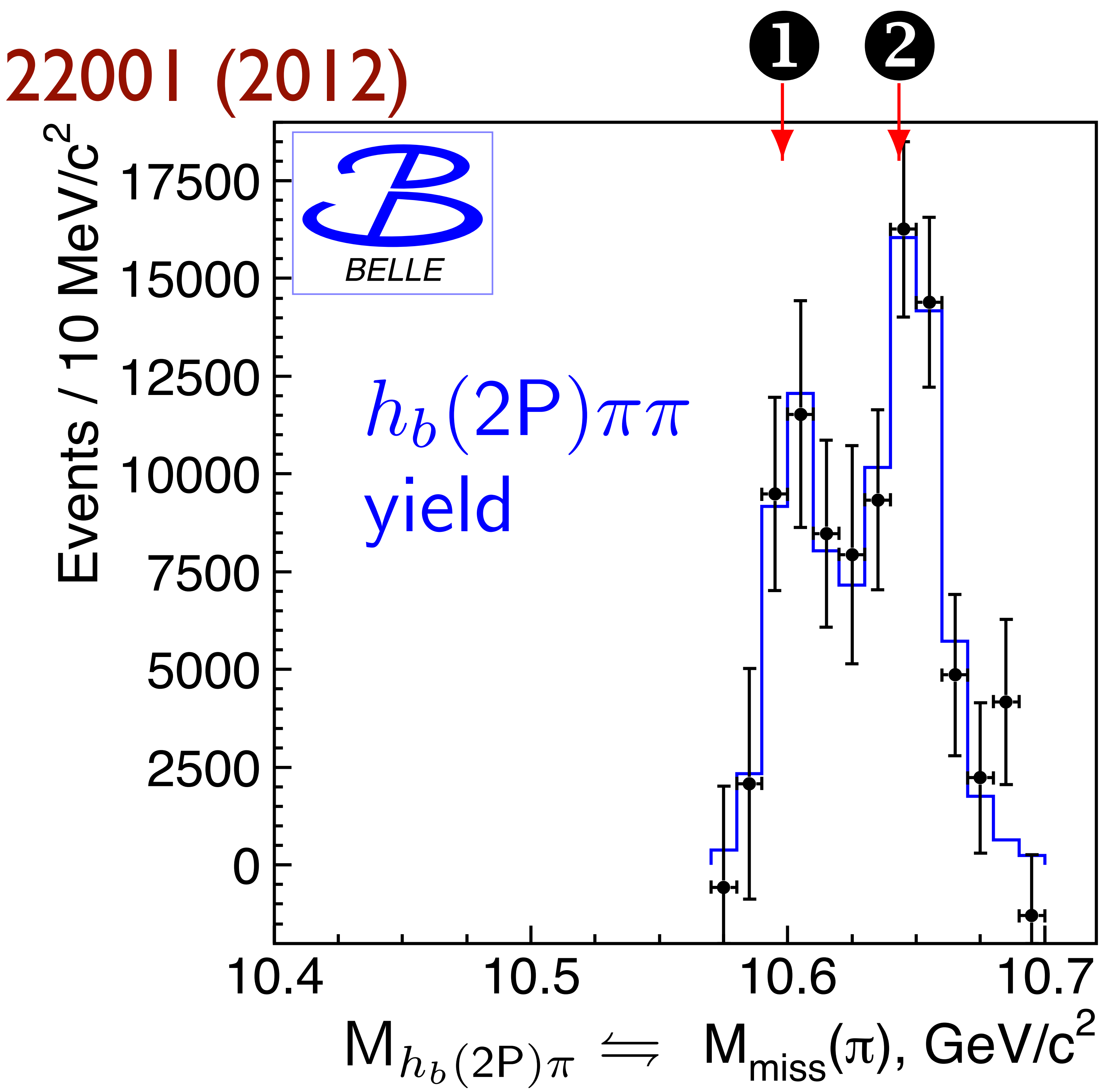
not suppressed as $\sim (\Lambda_{\rm QCD}/m_b)^2$??

Then there are exotic Z_b^+ states

$\Upsilon(5S) \to h_b(\mathrm{nP})\pi^+\pi^-$ proceeds via 2 resonances!

PRL 108, 122001 (2012)

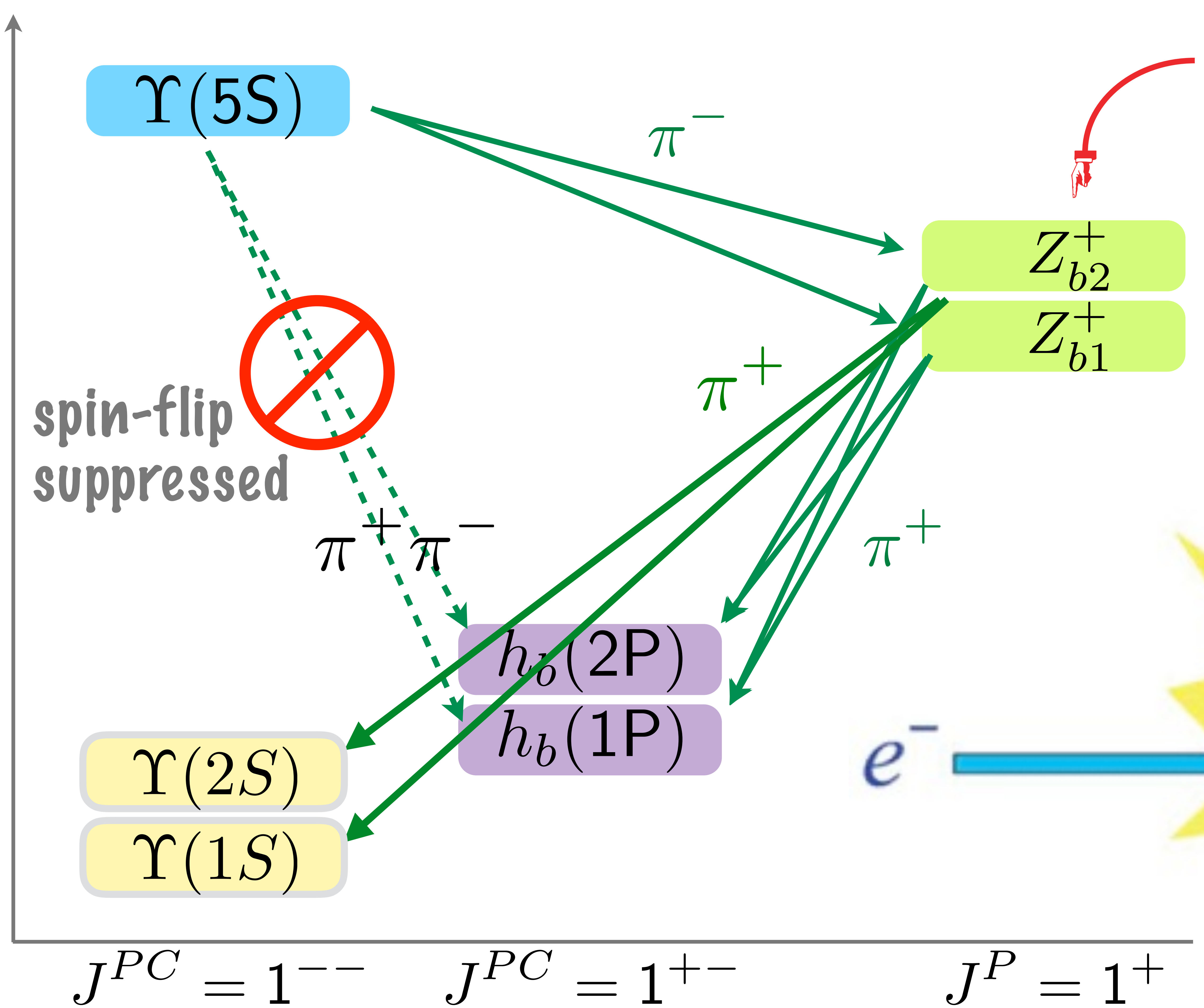


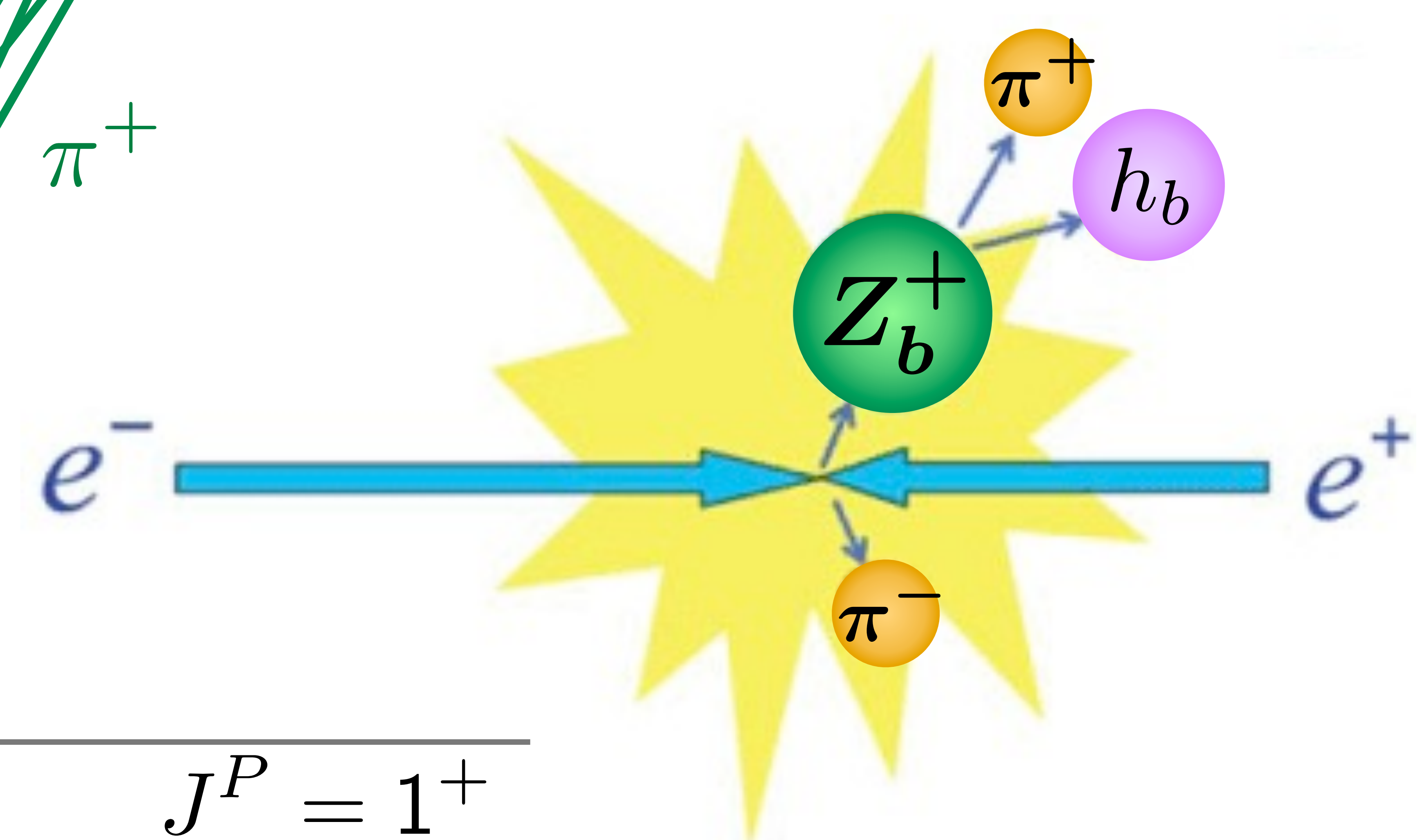


$Z_b(10610)^+$ and $Z_b(10650)^+$

and then we've found neutral counterpart $Z_b(10610)^0$ too

Then there are exotic Z_b^+ states





Recent results

- **Bottomonium transition**

  (1) $\Upsilon(4S) \rightarrow \eta\, h_b(1P)$ & h_b and η_b parameters — PRL 115, 142001 (2015)

- **Energy scan near $\Upsilon(5S)$ and $\Upsilon(6S)$ &**

  (2) via $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ — PRD 93, 0111011(R) (2016)

  (3) via $\sigma(e^+e^- \to h_b(nP)\pi^+\pi^-)$ — 1508.06562 *submitted to* PRL

- **Bottomonium-like exotic states**

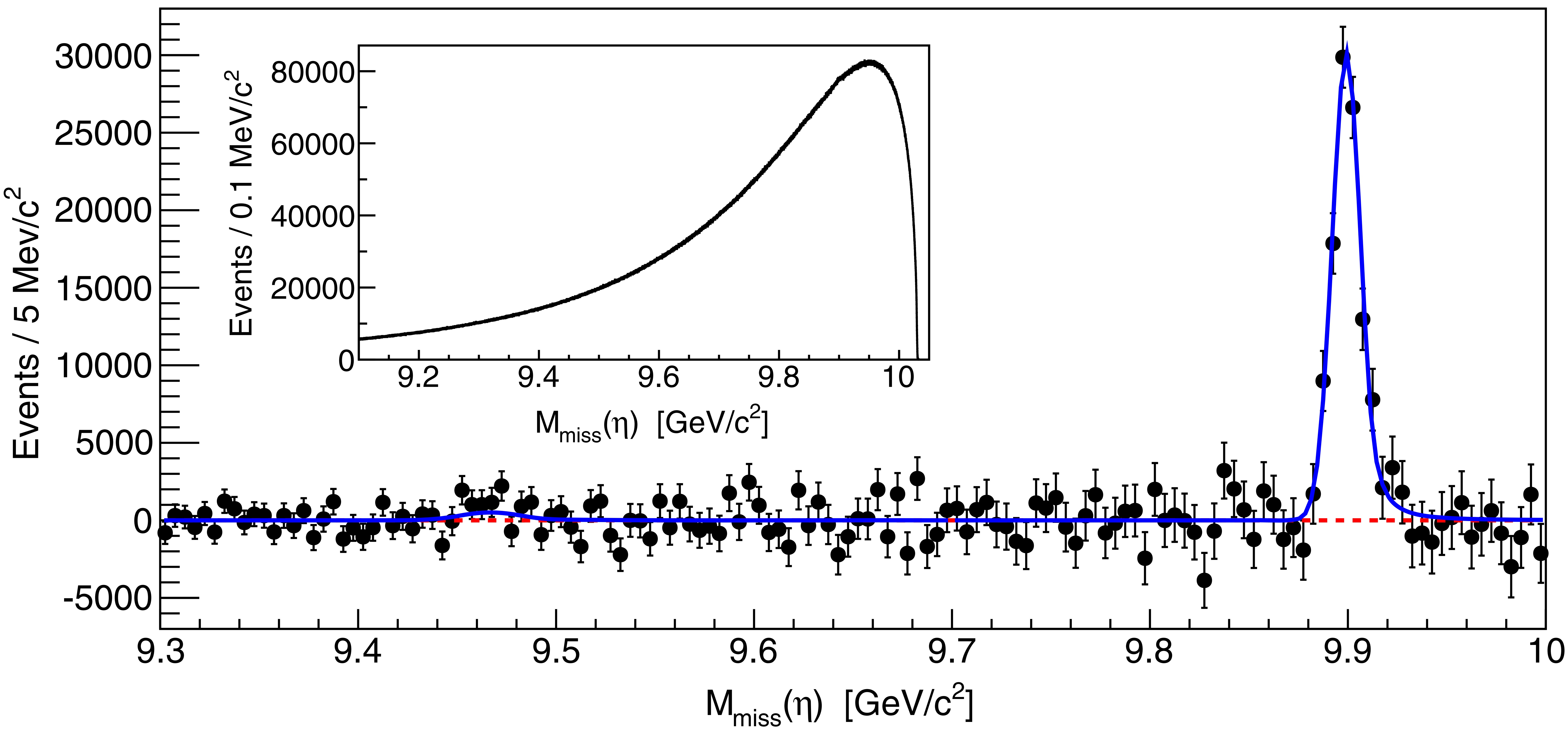
  (4) via amplitude analysis of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ — PRD 91, 072003 (2015)

  (5) $Z_b(10610)$ & $Z_b(10650)$ decaying to B mesons — PRL 116, 212001 (2016)

(1)

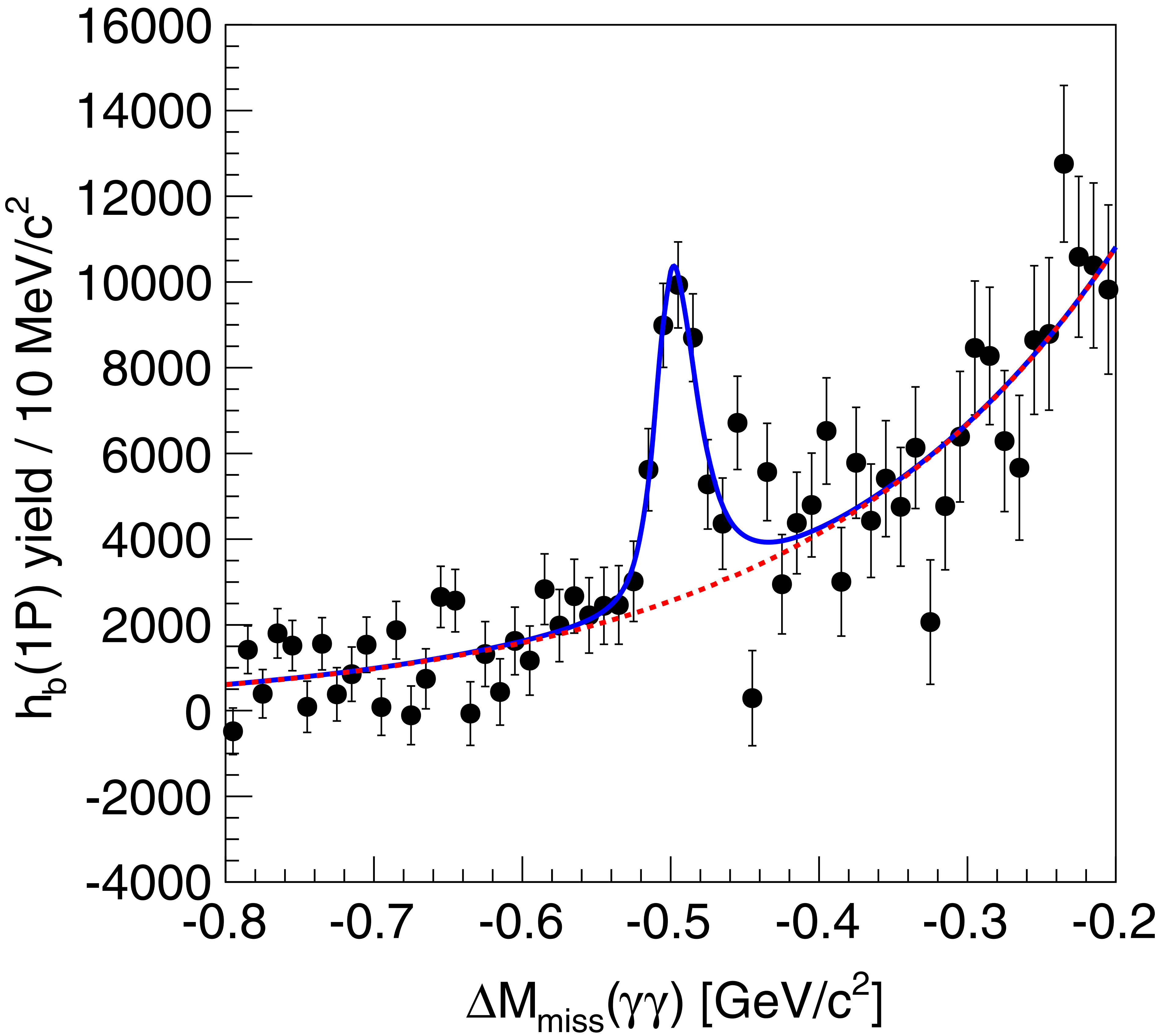
PRL **115,** 142001 (2015) PHYSICAL REVIEW LETTERS week ending 2 OCTOBER 2015

First Observation of the Hadronic Transition $\Upsilon(4S) \rightarrow \eta h_b(1P)$ and New Measurement of the $h_b(1P)$ and $\eta_b(1S)$ Parameters



$$M_{\text{miss}}(\eta) \text{ for } e^+e^- \to \Upsilon(4S) \to \eta h_b(1P)$$

before and after background subtraction



- study $\eta_b(1S)$ by $\Upsilon(4S) \to \eta h_b(1P) \to \eta\gamma\eta_b(1S)$
- main variable: $\Delta M_{\text{miss}} \equiv M_{\text{miss}}(\eta\gamma) - M_{\text{miss}}(\eta)$
- η_b signal shall produce a peak at $m_{\eta_b(1S)} - m_{h_b(1P)}$
- a clean signal of $\eta_b(1S)$; and we measure

$$m_{\eta_b(1S)} - m_{h_b(1P)} = (-498.6 \pm 1.7 \pm 1.2)\ \text{MeV}/c^2$$

TABLE III. Summary of the results of the searches for $\Upsilon(4S) \to \eta h_b(1P)$ and $h_b(1P) \to \gamma \eta_b(1S)$.

Observable	Value
$\mathcal{B}[\Upsilon(4S) \to \eta h_b(1P)]$	$(2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$
$\mathcal{B}[h_b(1P) \to \gamma \eta_b(1S)]$	$(56 \pm 8 \pm 4)\%$
$M_{h_b(1P)}$	$(9899.3 \pm 0.4 \pm 1.0)$ MeV$/c^2$
$M_{\eta_b(1S)} - M_{h_b(1P)}$	$(-498.6 \pm 1.7 \pm 1.2)$ MeV$/c^2$
$\Gamma_{\eta_b(1S)}$	$(8^{+6}_{-5} \pm 5)$ MeV$/c^2$
$M_{\eta_b(1S)}$	$(9400.7 \pm 1.7 \pm 1.6)$ MeV$/c^2$
$\Delta M_{\mathrm{HF}}(1S)$	$(+59.6 \pm 1.7 \pm 1.6)$ MeV$/c^2$
$\Delta M_{\mathrm{HF}}(1P)$	$(+0.6 \pm 0.4 \pm 1.0)$ MeV$/c^2$

η_b parameters: consistent with previous Belle results,
but not consistent with BaBar, CLEO

(2)

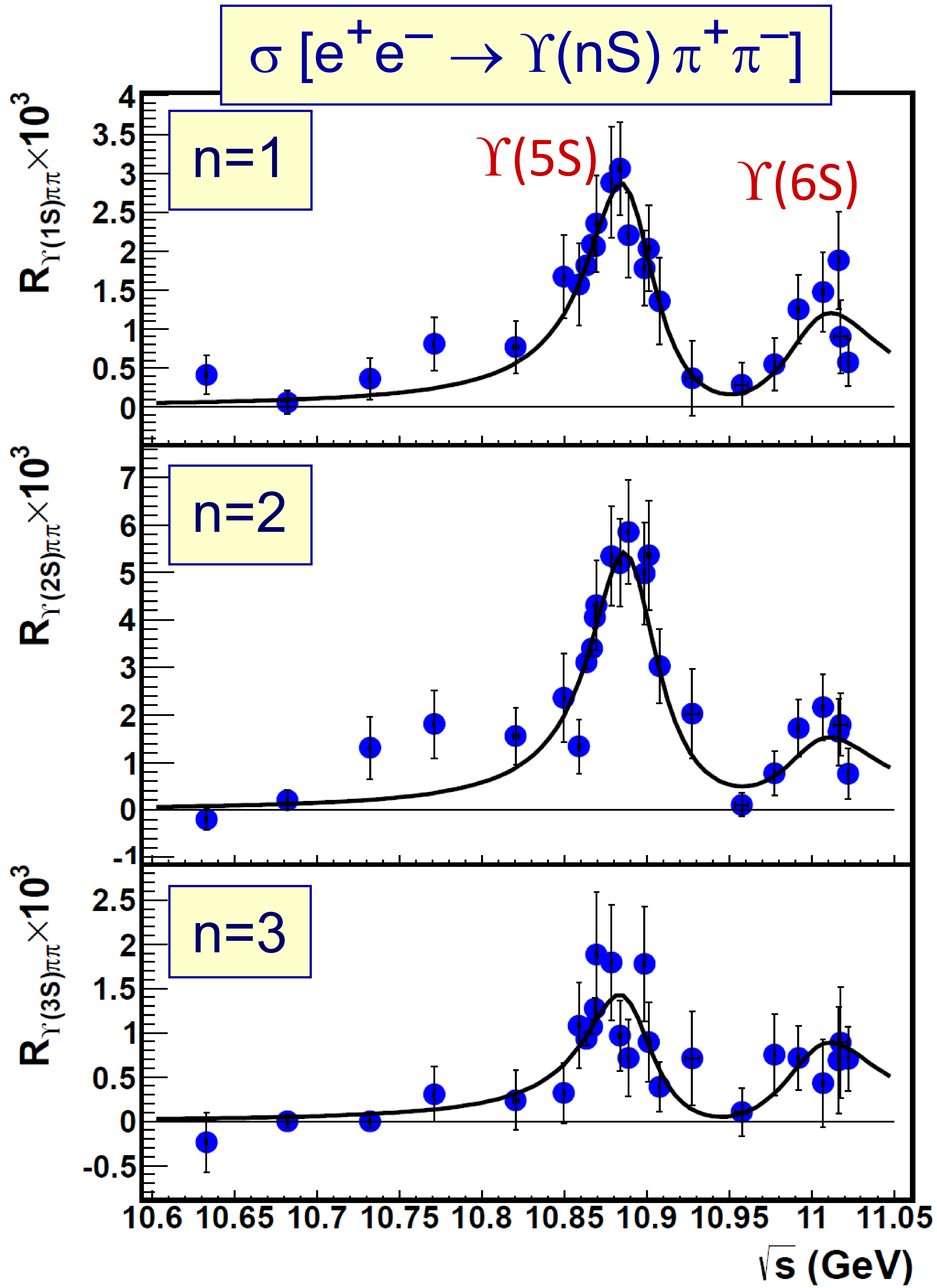
PHYSICAL REVIEW D **93**, 011101(R) (2016)

RAPID COMMUNICATIONS

Measurements of the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances via $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$

Energy scan — motivations

- **Υ(10860) has been interpreted to be a pure S-wave, $J^{PC} = 1^{--}$**
- **But several recent measurements bring questions to this**
    - peak shifts, anomalously high decay rates to $\Upsilon(nS)\pi\pi$, non-suppression of spin-flip process, etc.
- **Moreover, unlike the charmonium cases, all cross sections around Υ(10860) and Υ(11020) show similar structure**
    - Just two peaks — "5S" and "6S"
    - This difference, to charmonia, is not understood

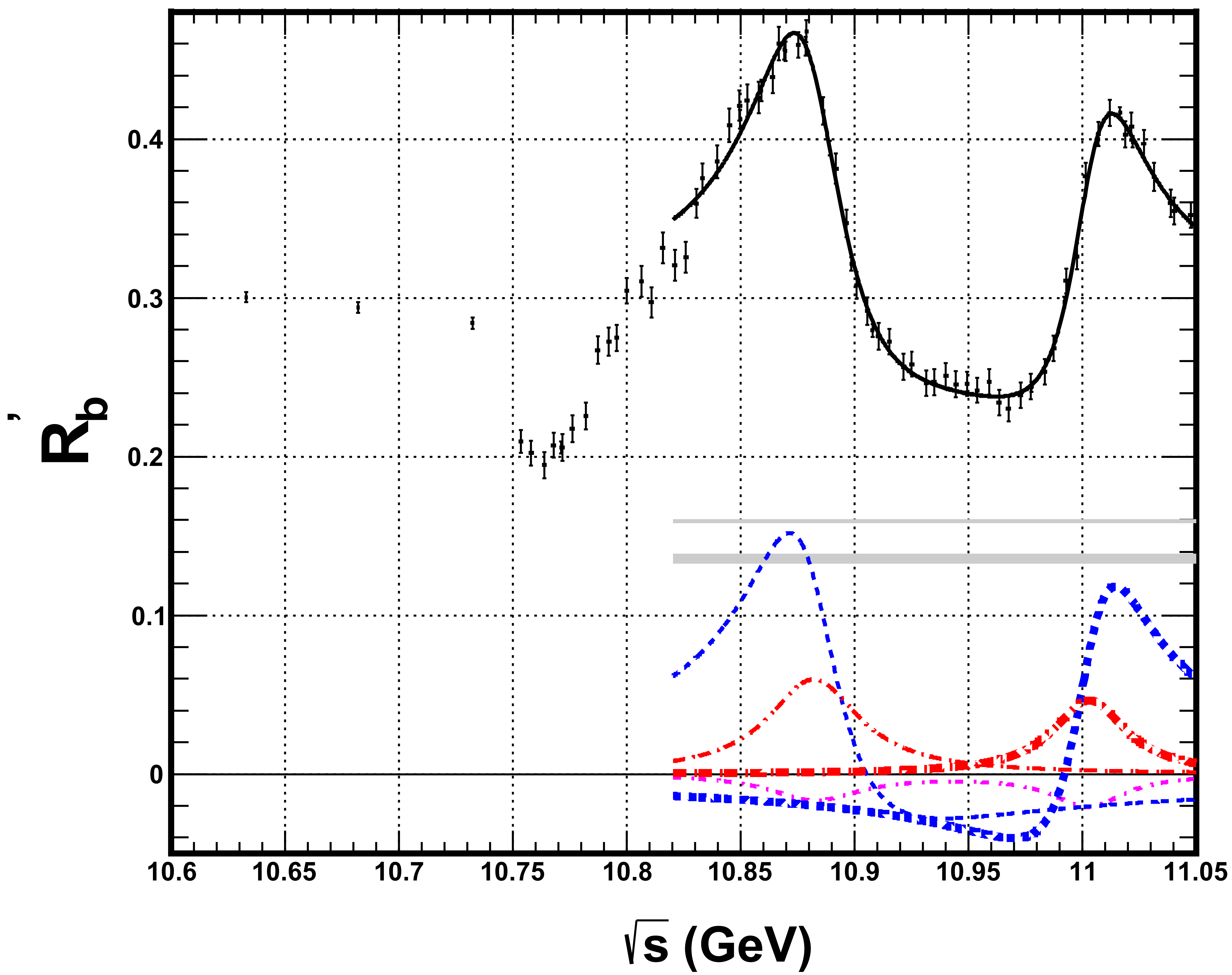


- essentially, no continuum contribution
- Interference between ϒ(5S) and ϒ(6S) is taken into account in the fit

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

- Measure resonance parameters of ϒ(5S) and ϒ(6S) using this cross section

$$R'_{b,i} \equiv R_{b,i} - \sum \sigma_{\mathrm{ISR},i}/\sigma^0_{\mu^+\mu^-,i}$$



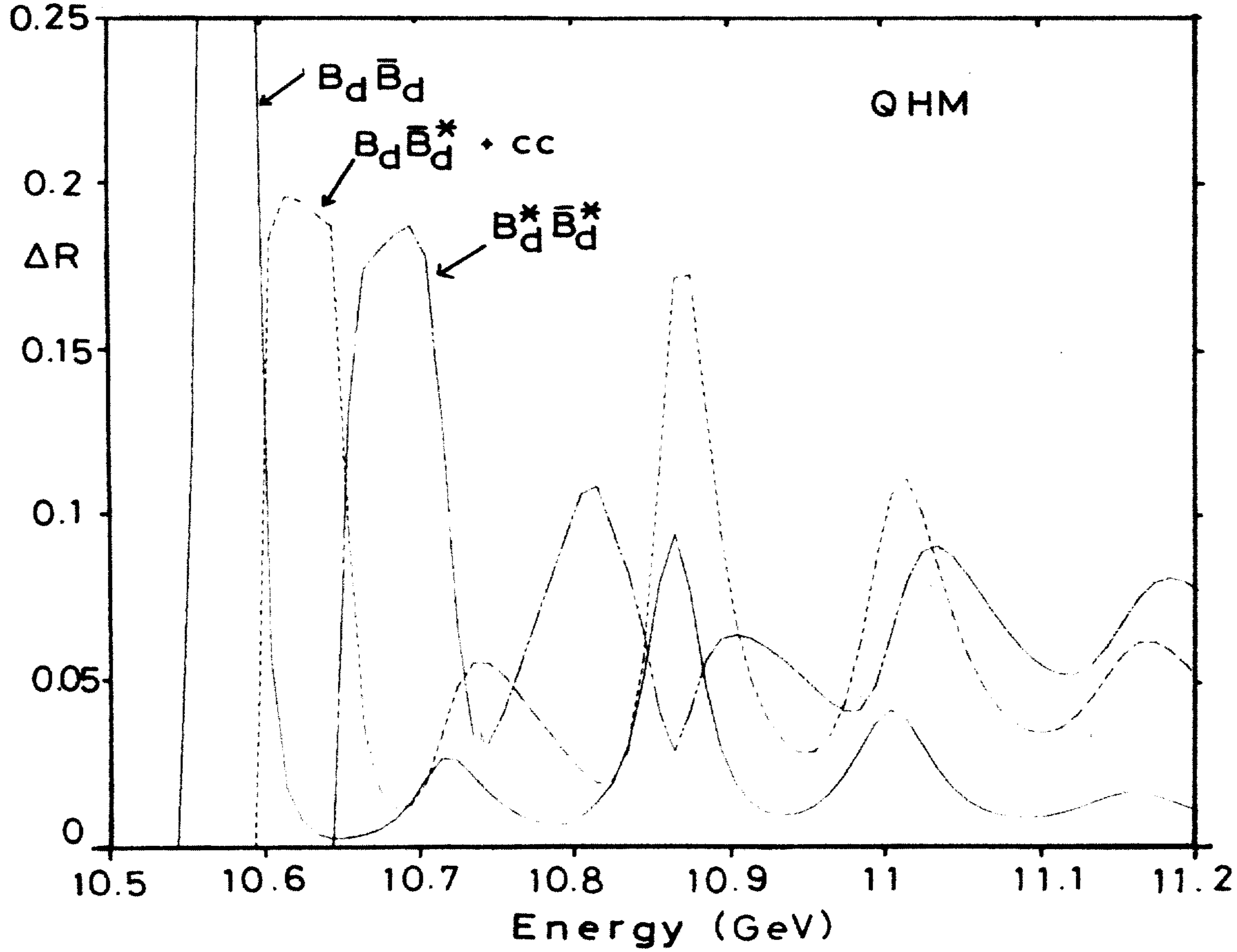
$$\mathcal{F}(\sqrt{s}) = |A_{\mathrm{ic}}|^2 + |A_{\mathrm{c}} + A_{5\mathrm{S}} e^{i\phi_{5\mathrm{S}}} f_{5\mathrm{S}}(\sqrt{s}) + A_{6\mathrm{S}} e^{i\phi_{6\mathrm{S}}} f_{6\mathrm{S}}(\sqrt{s})|^2,$$

- Strong interference between $\Upsilon(5S)$ and continuum
- $\Upsilon(5S)$ peak is saturated by $B^{(*)}B^*\pi,\ \Upsilon(nS)\pi\pi,\ h_b(nP)\pi\pi$

  ➔ leaving nearly no room for other final states ?? e.g. $B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$
- What about large resonance-continuum interference?
- Flat continuum assumption in this region is too much simplistic

by Quarkonium-Hybrid-Mixing (QHM) model

Ono, Sanda, Tornqvist
PRD 34, 186 (1986)



Our (Belle) conclusion is that "masses and widths for the $\Upsilon(10860)$ and $\Upsilon(11020)$ obtained from $R_b^{(\prime)}$ carry unknown systematic uncertainties due to the unknown shape of the continuum and its interaction with the resonance"

	M_{5S} (MeV/c^2)	Γ_{5S} (MeV)	M_{6S} (MeV/c^2)	Γ_{6S} (MeV)
R'_b	$10881.8^{+1.0}_{-1.1} \pm 1.2$	$48.5^{+1.9}_{-1.8}{}^{+2.0}_{-2.8}$	$11003.0 \pm 1.1^{+0.9}_{-1.0}$	$39.3^{+1.7}_{-1.6}{}^{+1.3}_{-2.4}$
$R_{\Upsilon(nS)\pi\pi}$	$10891.1 \pm 3.2^{+0.6}_{-1.7}$	$53.7^{+7.1}_{-5.6}{}^{+1.3}_{-5.4}$	$10987.5^{+6.4}_{-2.5}{}^{+9.0}_{-2.1}$	$61^{+9}_{-19}{}^{+2}_{-20}$

	$\phi_{6S} - \phi_{5S}(\delta)$ (rad)	χ^2/dof
R'_b	$-1.87^{+0.32}_{-0.51} \pm 0.16$	56/50
$R_{\Upsilon(nS)\pi\pi}$	$-1.0 \pm 0.4^{+1.4}_{-0.1}$	51/56

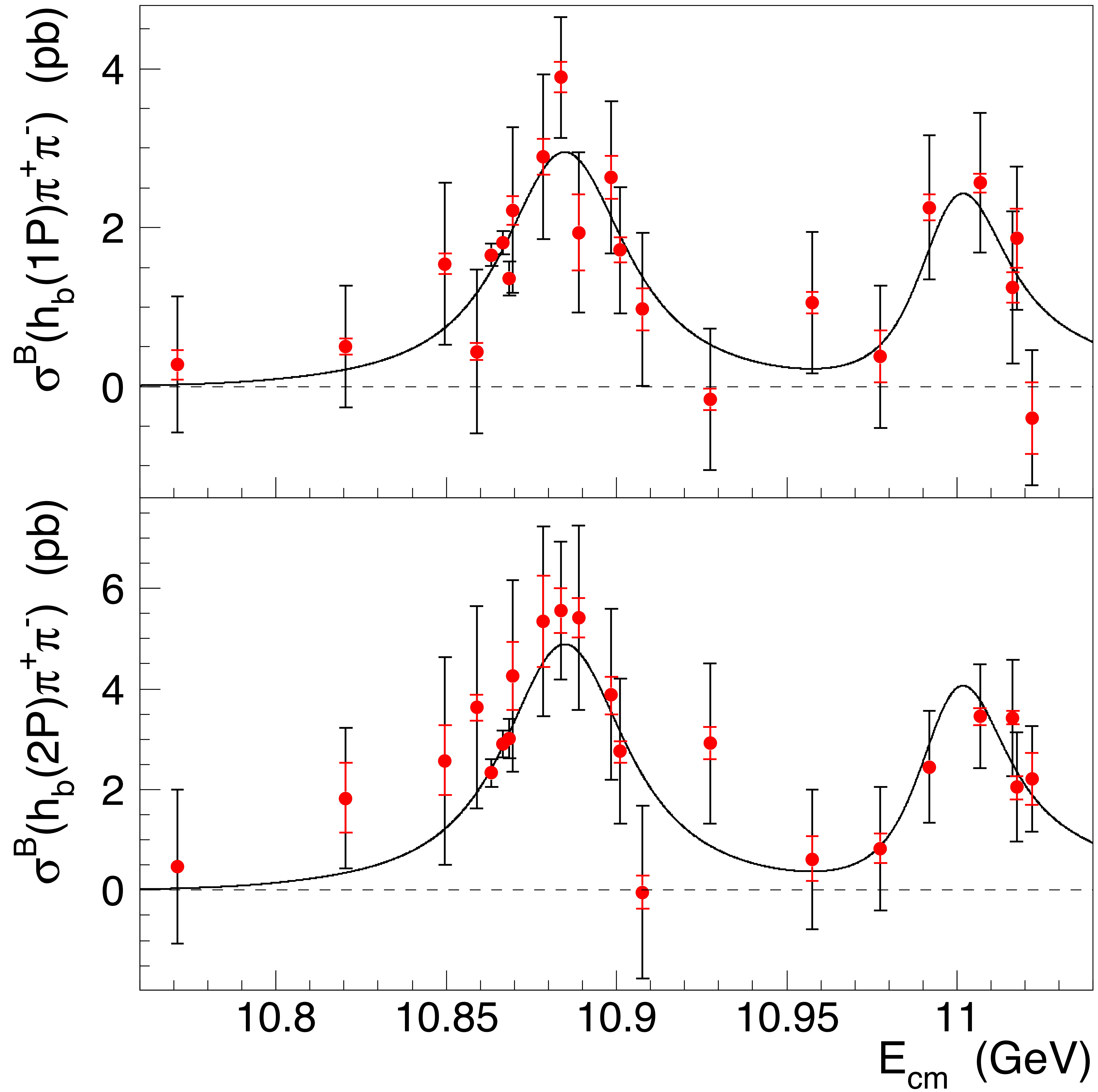
We report only the parameters from $R_{\Upsilon(nS)\pi\pi}$ as our official results.

(3)

1508.06562, ***submitted to PRL***

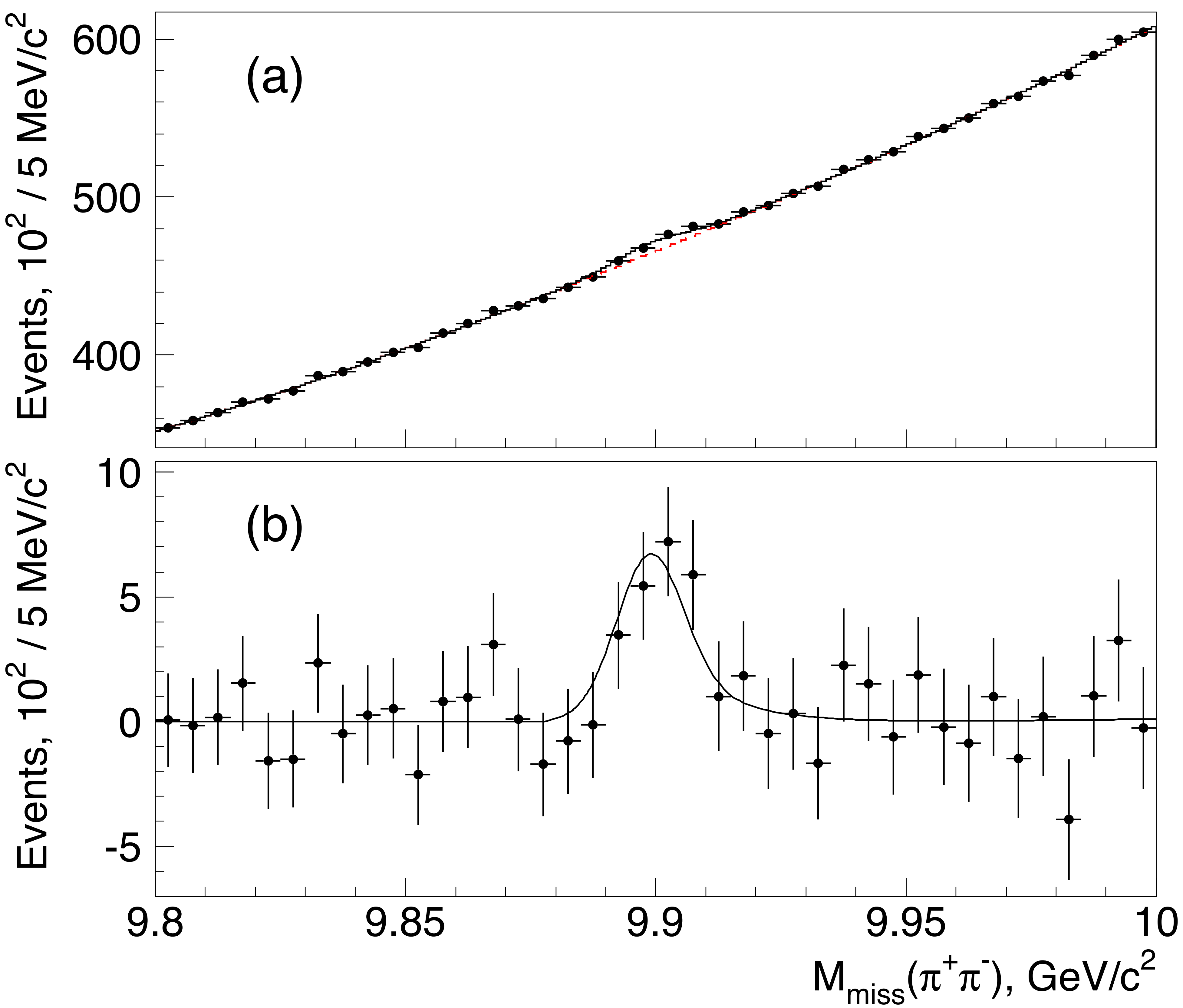
Energy scan of the $e^+e^- \to h_b(nP)\pi^+\pi^-$ $(n = 1, 2)$ cross sections and evidence for $\Upsilon(11020)$ decays into charged bottomonium-like states

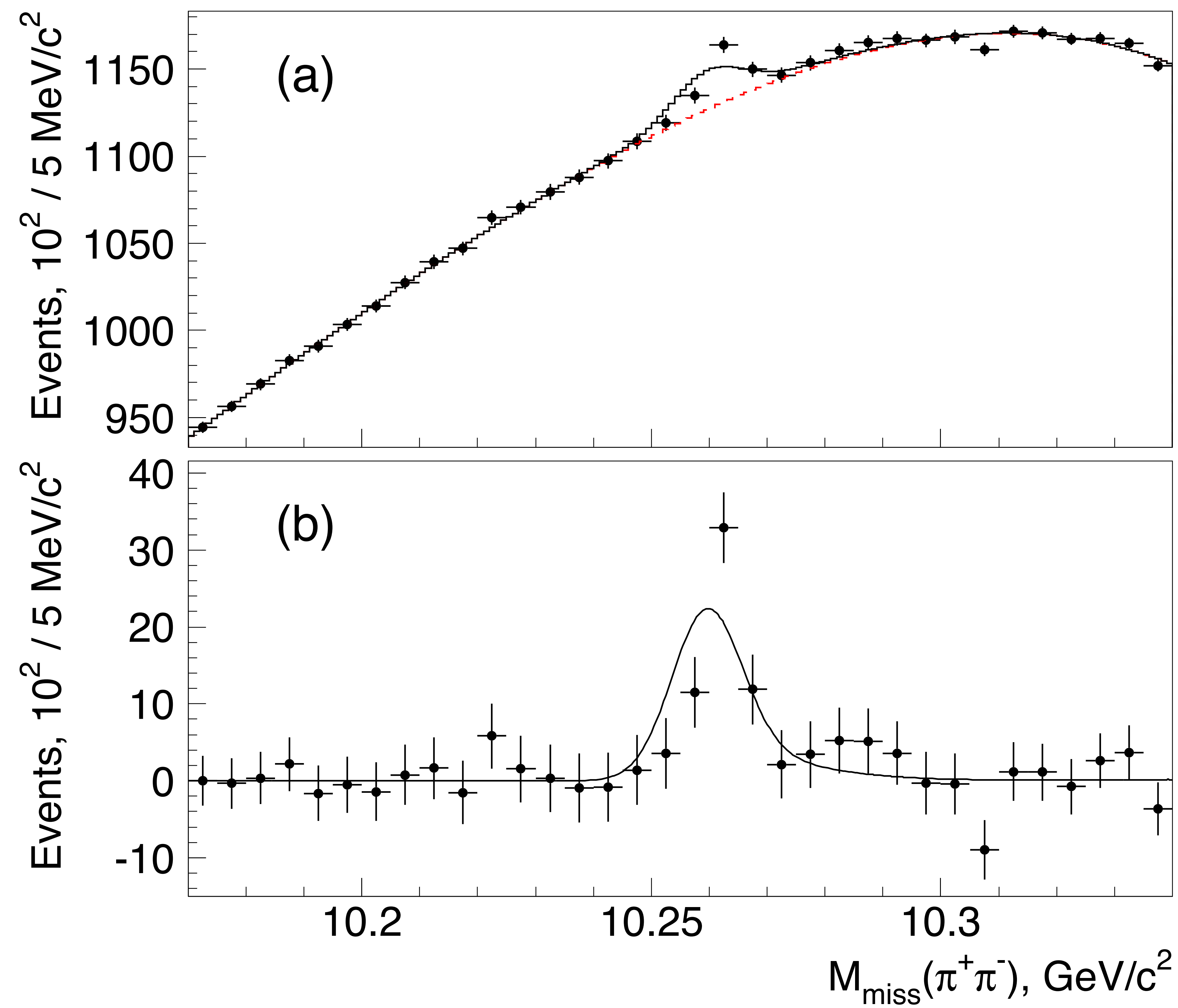
- Energy scan of the $\sigma[e^+e^- \to h_b(nP)\pi^+\pi^-]$ $(n = 1, 2)$
- Evidence for $\Upsilon(11020)$ decays into $Z_b^\pm$ states



Essentially the same structure (two resonances and almost no continuum) as in $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$

h_b(1P) and h_b(2P) from the five data points near ϒ(6S)





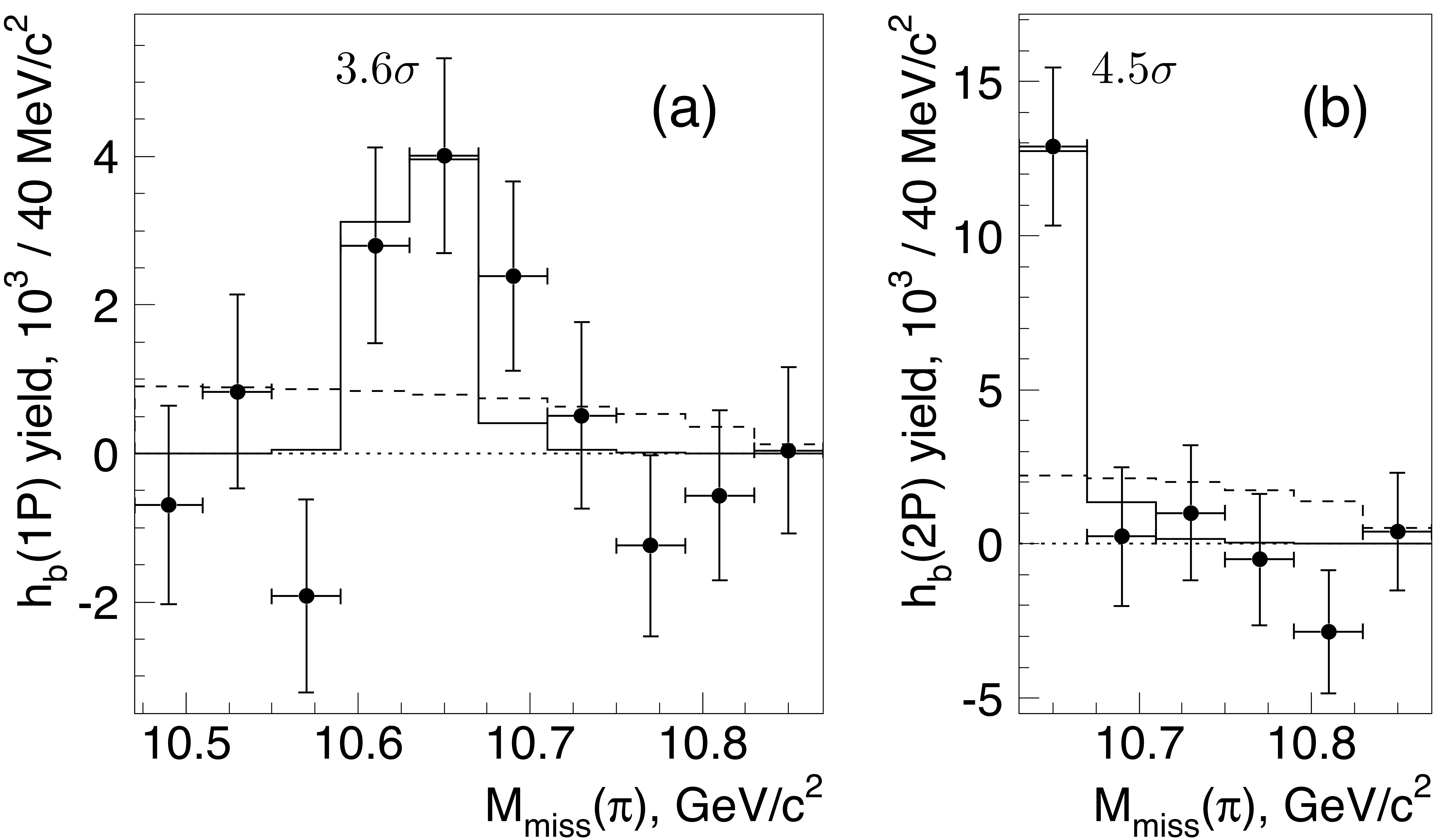
First evidence (S = 3.5σ) of

$$\Upsilon(6S) \to h_b(1P)\pi^+\pi^-$$

First observation (S = 5.3σ) of

$$\Upsilon(6S) \to h_b(2P)\pi^+\pi^-$$

The efficiency-corrected yields of (a) $h_b(1P)\pi^+\pi^-$ and (b) $h_b(2P)\pi^+\pi^-$, as functions of $M_{\rm miss}(\pi)$



single $Z_b(10610)$ hypothesis is excluded at 3.3σ level

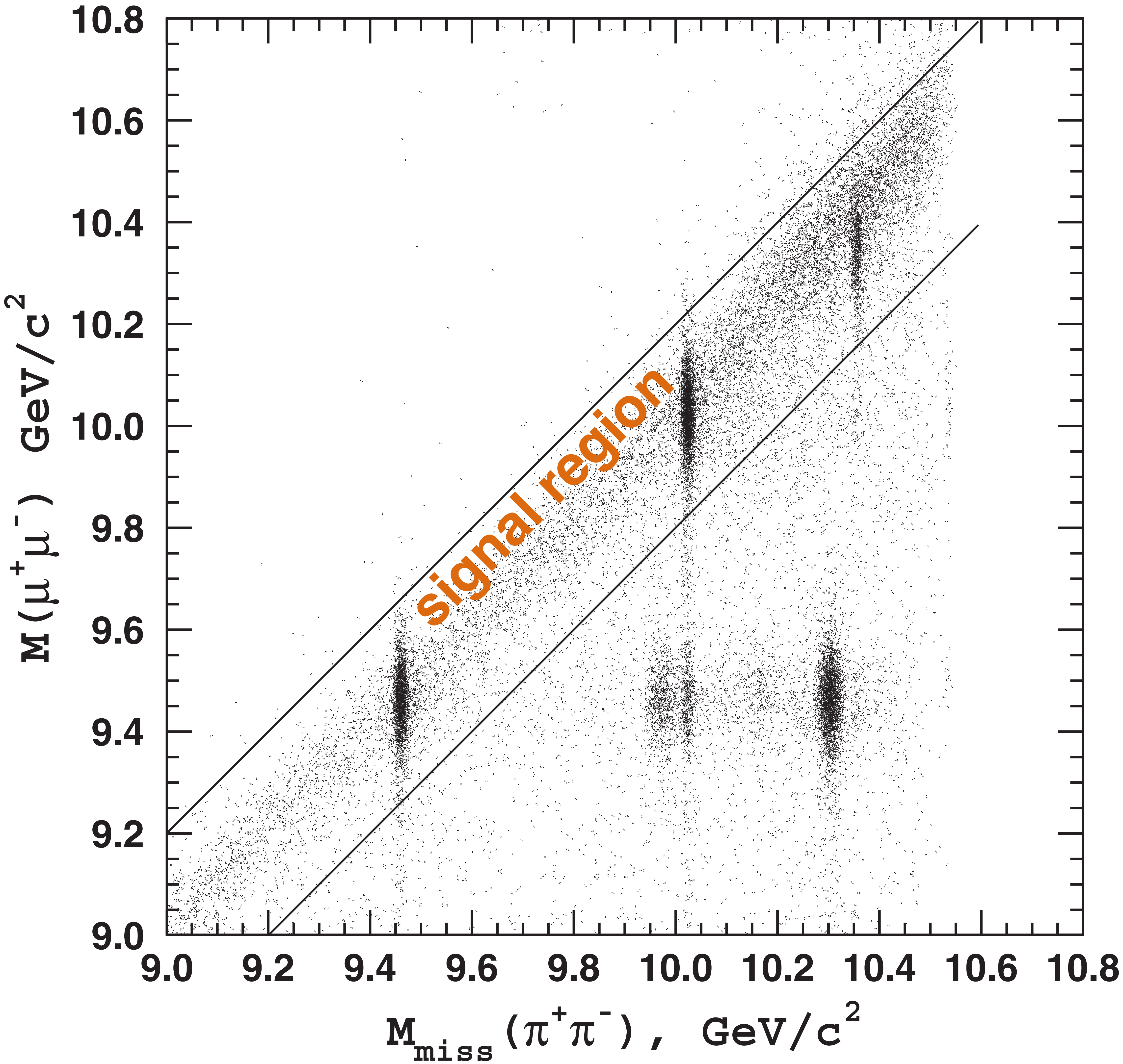
single $Z_b(10650)$ hypothesis is *not* excluded

(4)

PHYSICAL REVIEW D **91,** 072003 (2015)

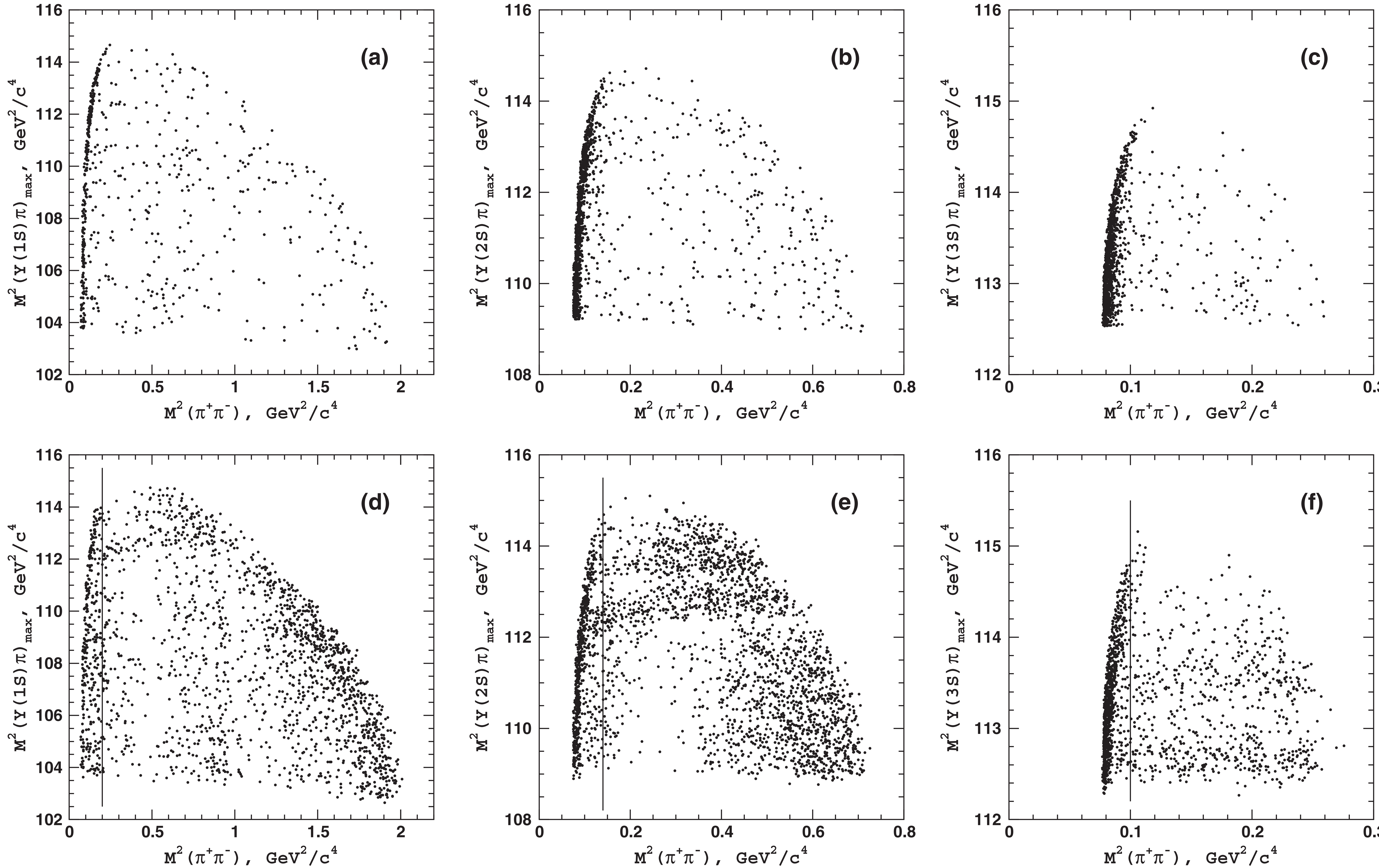
Amplitude analysis of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ at $\sqrt{s} = 10.866$ GeV

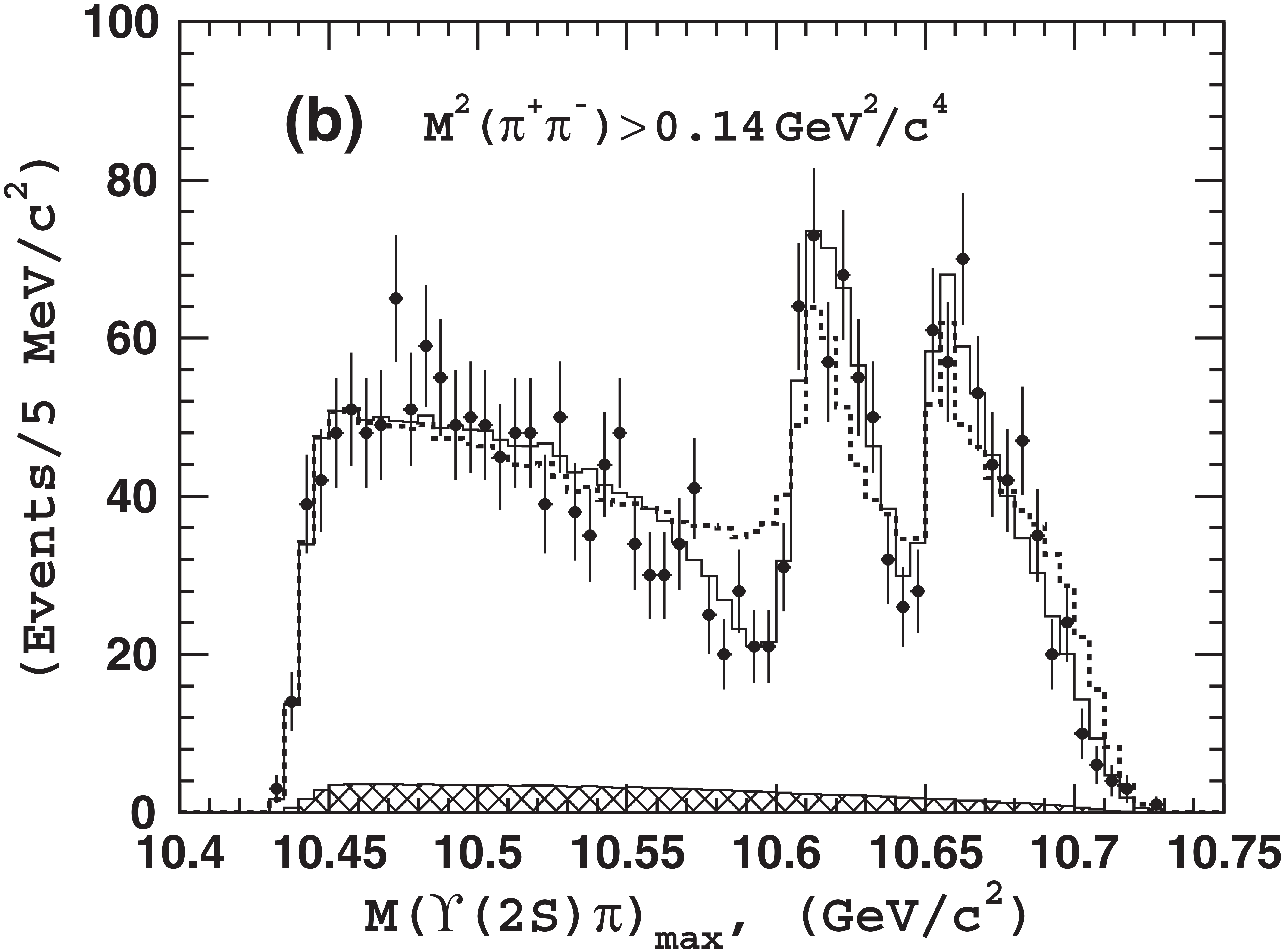
$e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ at $\sqrt{s} = 10.866$ GeV



$e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ at $\sqrt{s} = 10.866$ GeV

Dalitz plots: (top) sideband, (bottom) signal region





See back-up slide for other plots!

nominal model: $J^P = 1^+$ for both Z_b states (solid)

comparison: $J^P = 2^+$ for both Z_b states (dashed)

Fit results for $\Upsilon(2S)\pi\pi[\Upsilon(3S)\pi\pi$ events.
Shown in the table is the difference in $\mathcal{L}$ values.

	$Z_b(10650)$			
$Z_b(10610)$	1^+	1^-	2^+	2^-
1^+	0(0)	60(33)	42(33)	77(63)
1^-	226(47)	264(73)	224(68)	277(106)
2^+	205(33)	235(104)	207(87)	223(128)
2^-	289(99)	319(111)	321(110)	304(125)

TABLE VI. Summary of results of fits to $\Upsilon(nS)\pi^+\pi^-$ events in the signal regions.

Parameter	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$f_{Z_b^\mp(10610)\pi^\pm}$, %	$4.8 \pm 1.2^{+1.5}_{-0.3}$	$18.1 \pm 3.1^{+4.2}_{-0.3}$	$30.0 \pm 6.3^{+5.4}_{-7.1}$
$Z_b(10610)$ mass, MeV/c^2	$10608.5 \pm 3.4^{+3.7}_{-1.4}$	$10608.1 \pm 1.2^{+1.5}_{-0.2}$	$10607.4 \pm 1.5^{+0.8}_{-0.2}$
$Z_b(10610)$ width, MeV	$18.5 \pm 5.3^{+6.1}_{-2.3}$	$20.8 \pm 2.5^{+0.3}_{-2.1}$	$18.7 \pm 3.4^{+2.5}_{-1.3}$
$f_{Z_b^\mp(10650)\pi^\pm}$, %	$0.87 \pm 0.32^{+0.16}_{-0.12}$	$4.05 \pm 1.2^{+0.95}_{-0.15}$	$13.3 \pm 3.6^{+2.6}_{-1.4}$
$Z_b(10650)$ mass, MeV/c^2	$10656.7 \pm 5.0^{+1.1}_{-3.1}$	$10650.7 \pm 1.5^{+0.5}_{-0.2}$	$10651.2 \pm 1.0^{+0.4}_{-0.3}$
$Z_b(10650)$ width, MeV	$12.1^{+11.3+2.7}_{-4.8-0.6}$	$14.2 \pm 3.7^{+0.9}_{-0.4}$	$9.3 \pm 2.2^{+0.3}_{-0.5}$
ϕ_Z, degrees	$67 \pm 36^{+24}_{-52}$	$-10 \pm 13^{+34}_{-12}$	$-5 \pm 22^{+15}_{-33}$
$c_{Z_b(10650)}/c_{Z_b(10610)}$	$0.40 \pm 0.12^{+0.05}_{-0.11}$	$0.53 \pm 0.07^{+0.32}_{-0.11}$	$0.69 \pm 0.09^{+0.18}_{-0.07}$
$f_{\Upsilon(nS)f_2(1270)}$, %	$14.6 \pm 1.5^{+6.3}_{-0.7}$	$4.09 \pm 1.0^{+0.33}_{-1.0}$	–
$f_{\Upsilon(nS)(\pi^+\pi^-)_S}$, %	$86.5 \pm 3.2^{+3.3}_{-4.9}$	$101.0 \pm 4.2^{+6.5}_{-3.5}$	$44.0 \pm 6.2^{+1.8}_{-4.3}$
$f_{\Upsilon(nS)f_0(980)}$, %	$6.9 \pm 1.6^{+0.8}_{-2.8}$	–	–

(cross section) × (BF)

$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(1S)\pi^{\mp}} = 110 \pm 27^{+36}_{-10} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(2S)\pi^{\mp}} = 744 \pm 127^{+190}_{-86} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10610)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(3S)\pi^{\mp}} = 442 \pm 93^{+93}_{-115} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(1S)\pi^{\mp}} = 20 \pm 7^{+4}_{-3} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(2S)\pi^{\mp}} = 167 \pm 49^{+43}_{-21} \text{ fb}$$

$$\sigma_{Z_b^{\pm}(10650)\pi^{\mp}} \times \mathcal{B}_{\Upsilon(3S)\pi^{\mp}} = 196 \pm 54^{+43}_{-25} \text{ fb.}$$

(5)

PRL **116,** 212001 (2016) PHYSICAL REVIEW LETTERS week ending 27 MAY 2016

Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons

Studying Z_b decays to B mesons – *motivations*

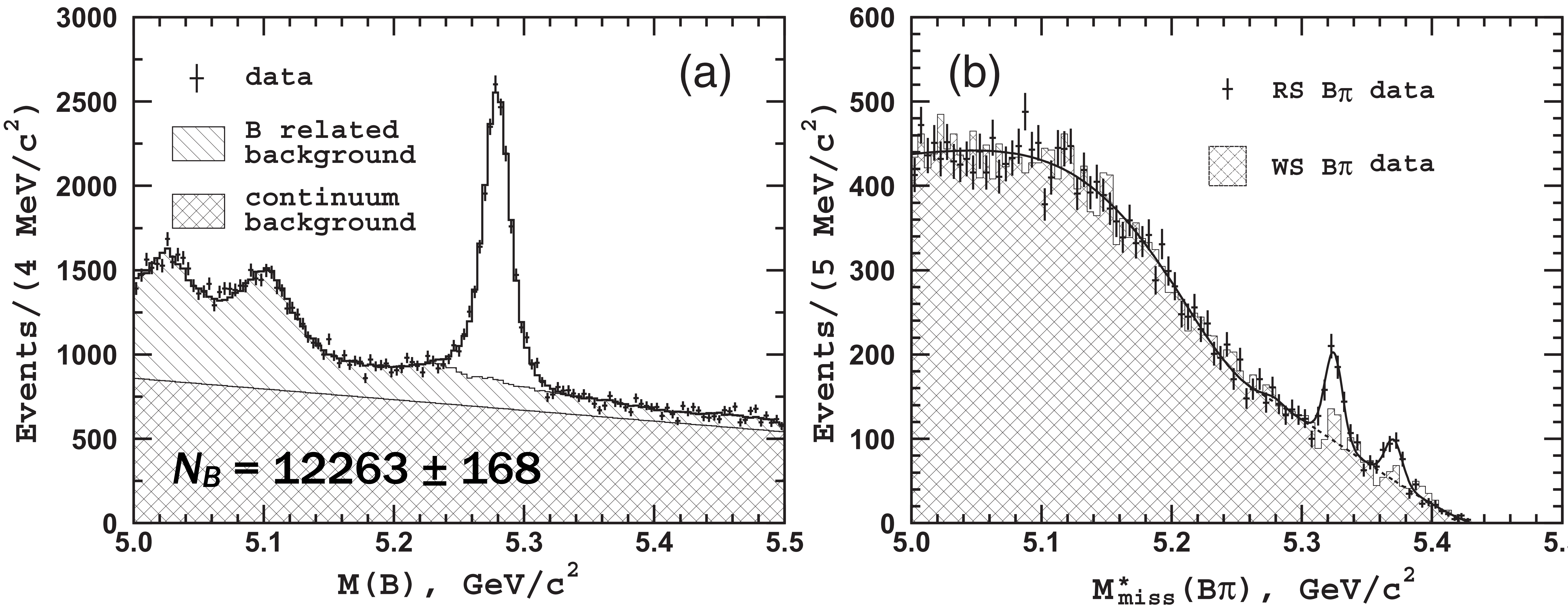
- $Z_b(10610)$ and $Z_b(10650)$ might be loosely bound $B\bar{B}^*$ and $B^*\bar{B}^*$ systems ("molecules") Bondar *et al.*, PRD 84, 054010 (2011)

- Possible alternatives:
  - hadroquarkonia Voloshin, PRD 87, 091501 (2013)
  - tetraquarks Ali *et al.*, PRD 85, 054011 (2012)

- If indeed **molecules**, it is natural to expect Z_b's decay dominantly into its constitutents, i.e. $Z_b(10610) \to B\bar{B}^*$ and $Z_b(10650) \to B^*\bar{B}^*$.

- Study resonant substructure in $\Upsilon(5S) \to (B\bar{B}^* + \text{c.c.})\pi$ and $\Upsilon(5S) \to B^*\bar{B}^*\pi$

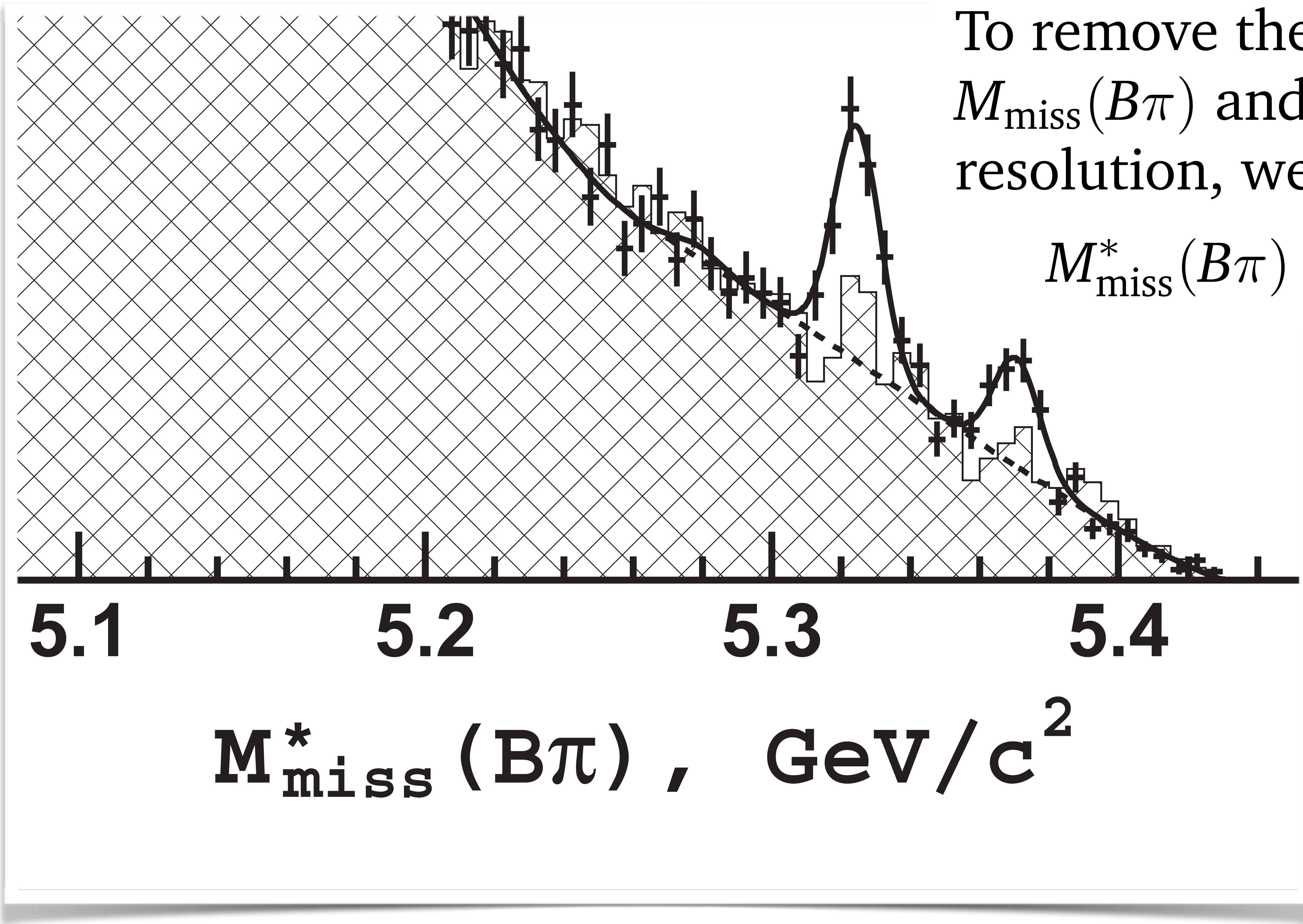
Studying Z_b decays to B mesons – *how-to*



- Reconstruct one B, then look at the recoil mass against $B\pi$

$$B^+ \to J/\psi K^{(*)+},\ \bar{D}^{(*)0}\pi^+$$

$$B^0 \to J/\psi K^{(*)0},\ D^{(*)-}\pi^+$$

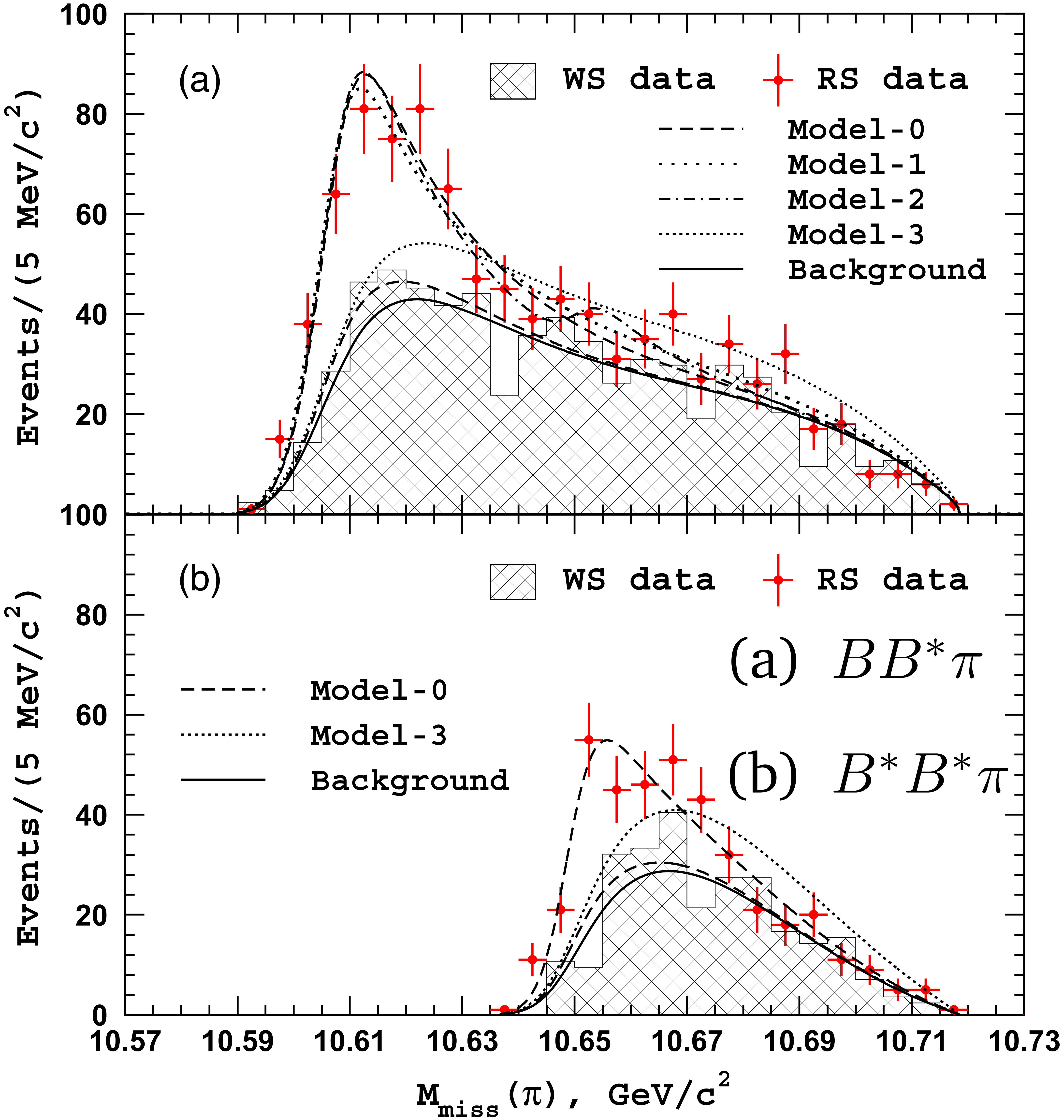


To remove the correlation between $M_{\text{miss}}(B\pi)$ and $M(B)$, and to improve the resolution, we use

$$M^*_{\text{miss}}(B\pi) \equiv M_{\text{miss}}(B\pi) + M(B) - m_B$$

- very little $B\bar{B}\pi$ contribution
- $\sim 10\%$ of signal leak into WS sample due to B^0 oscillations

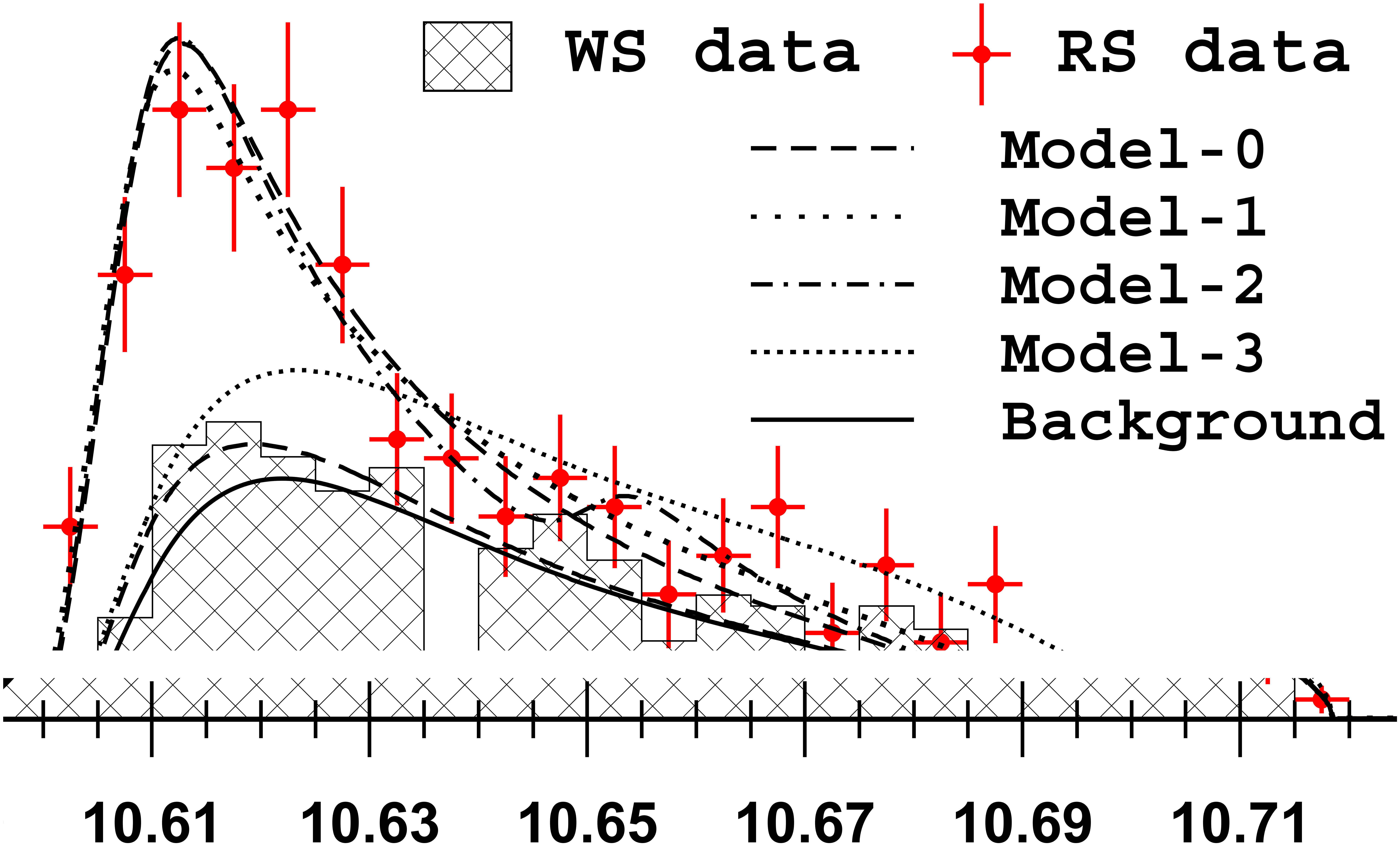
$M_{miss}(\pi)$ distribution

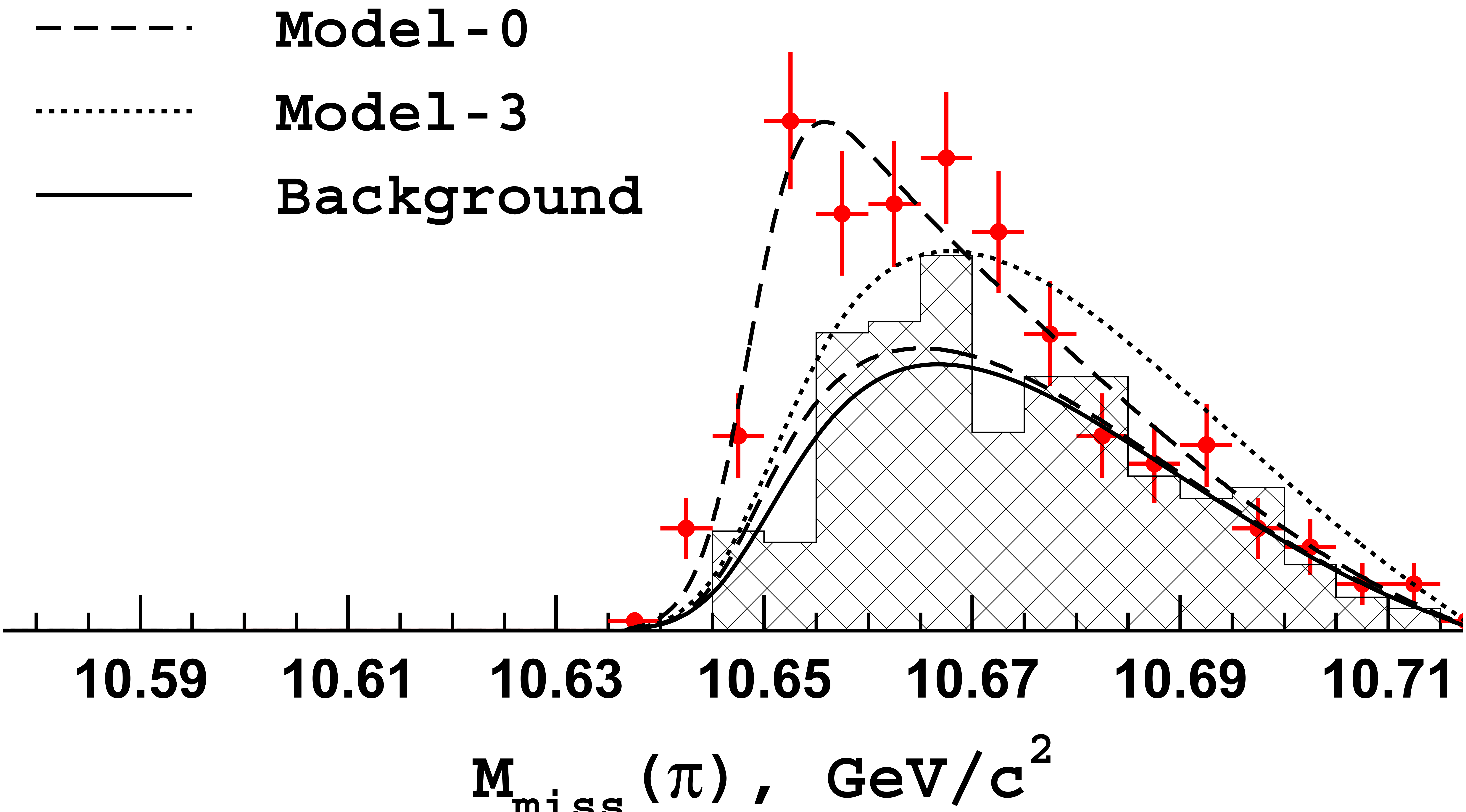


Fit function $\propto$

$$|\mathcal{A}_{Z_b(10610)} + \mathcal{A}_{Z_b(10650)} + \mathcal{A}_{\rm nr}|^2$$

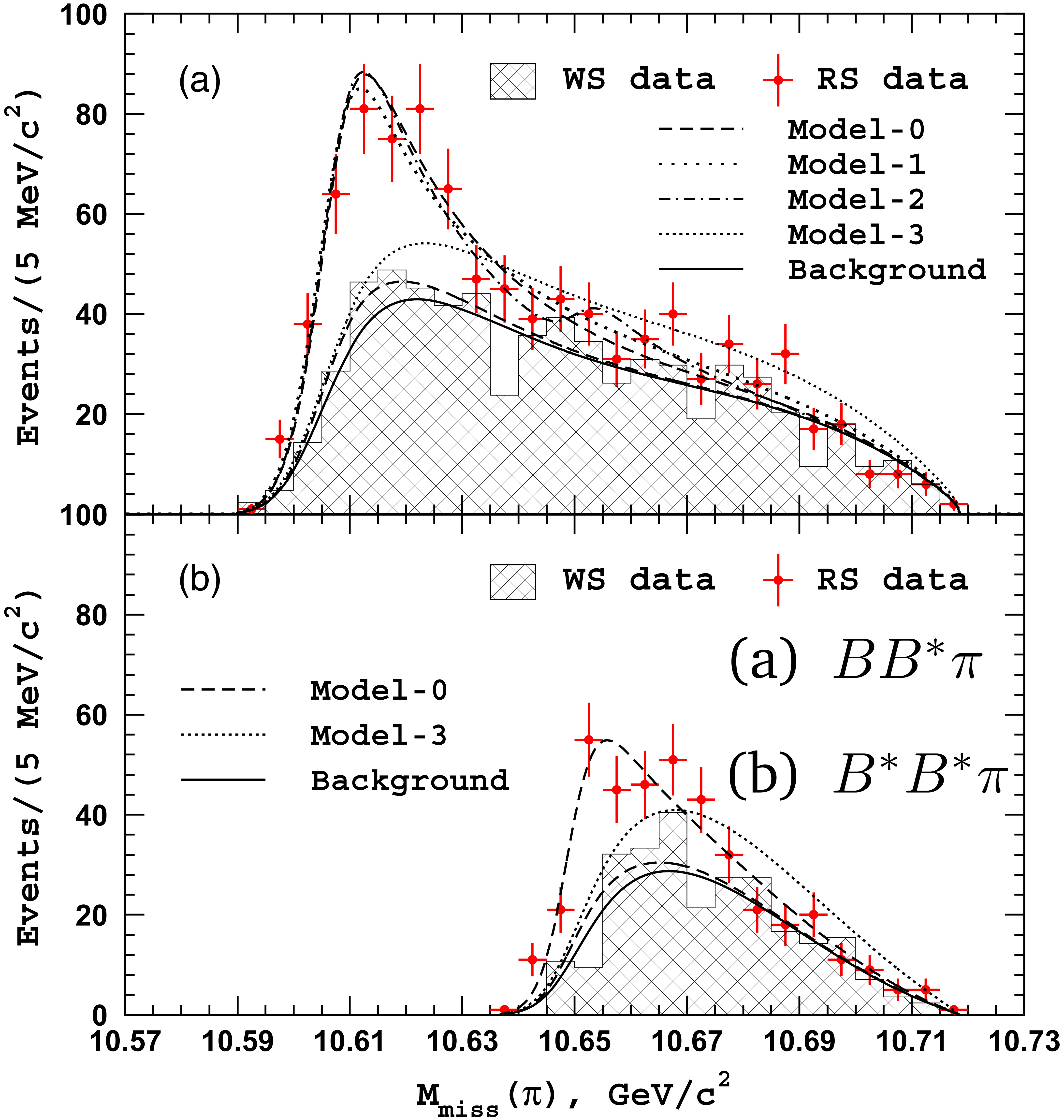
- model 0
  - $Z_b(10610)$ only, for $B\bar{B}^*\pi$
  - $Z_b(10650)$ only, for $B^*\bar{B}^*\pi$
- model 3
  - no Z_b's; non-resonant only
- model 1
  - model 0 + non-resonant
- model 2
  - both Z_b's for $B\bar{B}^*\pi$


WS data
RS data
Model-0
Model-1
Model-2
Model-3
Background
10.61
10.63
10.65
10.67
10.69
10.71



Model-0
Model-3
Background
10.59
10.61
10.63
10.65
10.67
10.69
10.71
$M_{miss}(\pi)$, GeV/c^2

$M_{miss}(\pi)$ distribution



Fit function $\propto$

$$|\mathcal{A}_{Z_b(10610)} + \mathcal{A}_{Z_b(10650)} + \mathcal{A}_{\mathrm{nr}}|^2$$

$B\bar{B}^*\pi$

- $Z_b(10610)$ only vs. PHSH 6.3σ
- need non-resonant? 1.5σ
- need $Z_b(10650)$? 1.3σ

$B^*\bar{B}^*\pi$

- $Z_b(10650)$ only vs. PHSH 5.2σ
- need non-resonant? 0.1σ

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

Dominant decay channels are:

$$Z_b(10610) \to B\bar{B}^*\pi$$

$$Z_b(10650) \to B^*\bar{B}^*\pi$$

a smoking-gun signature of molecular structure

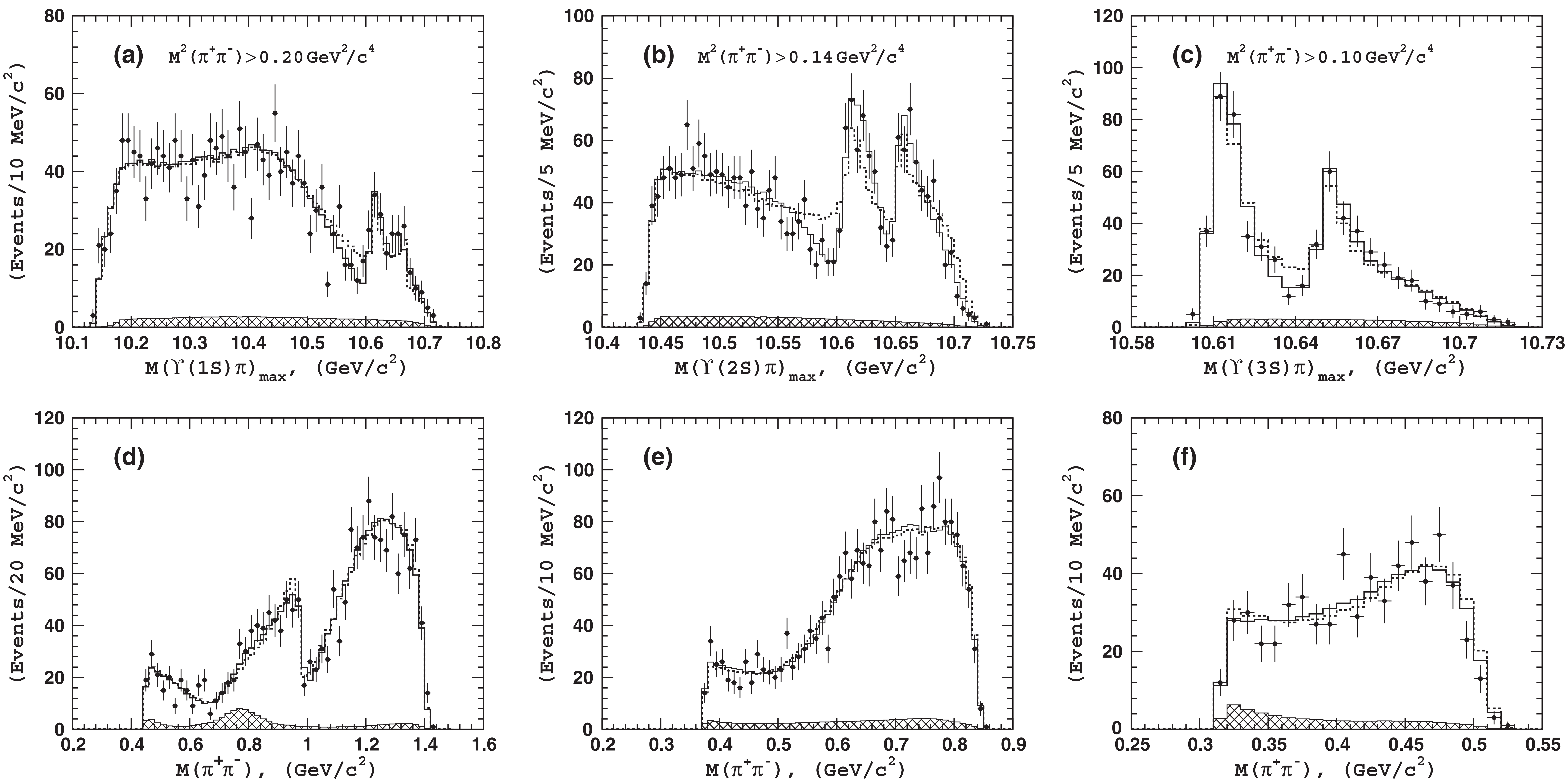
In conclusion,

- Since its discovery of Z_b's in 2012, Belle has added more and more studies/results on their properties
- Belle has updated the energy scan around $\Upsilon(5S)$ and $\Upsilon(6S)$ regions

  ➔ more precise resonance parameters as well as evidence for $\Upsilon(6S)$ decays to Z_b's
- First observation of $\Upsilon(4S) \to \eta\, h_b(1P)$ has been attained
- With Belle II to start in a couple years, we look forward to seeing more exciting and illuminating results

Back-up


AHAJOKES.COM
MY COMPUTER DOESN'T WORK! THE HARD DRIVE CRASHED! WHAT DO I DO?!
DID YOU BACK UP?
WHY? IS IT GONNA BLOW?!
STEINFELD ©96



nominal model: $J^P = 1^+$ for both Z_b states (solid)

comparison: $J^P = 2^+$ for both Z_b states (dashed)

TABLE I. Summary of fit results to the $M_{\rm miss}(\pi)$ distributions for the three-body $BB^*\pi$ and $B^*B^*\pi$ final states.

Mode	Parameter	Model 0	Model 1		Model 2		Model 3
			Solution 1	Solution 2	Solution 1	Solution 2	
$BB^*\pi$	$f_{Z_b(10610)}$	1.0	1.45 ± 0.24	0.64 ± 0.15	1.01 ± 0.13	1.18 ± 0.15	$\cdots$
	$f_{Z_b(10650)}$	$\cdots$	$\cdots$	$\cdots$	0.05 ± 0.04	0.24 ± 0.11	$\cdots$
	$\phi_{Z_b(10650)}$, radians	$\cdots$	$\cdots$	$\cdots$	-0.26 ± 0.68	-1.63 ± 0.14	$\cdots$
	$f_{\rm nr}$	$\cdots$	0.48 ± 0.23	0.41 ± 0.17	$\cdots$	$\cdots$	1.0
	$\phi_{\rm nr}$, radians	$\cdots$	-1.21 ± 0.19	0.95 ± 0.32	$\cdots$	$\cdots$	$\cdots$
	$2\log\mathcal{L}$	-304.7	-300.6	-300.5	-301.4	-301.4	-344.5
$B^*B^*\pi$	$f_{Z_b(10650)}$	1.0	1.04 ± 0.15	0.77 ± 0.22			$\cdots$
	$f_{\rm nr}$	$\cdots$	0.02 ± 0.04	0.24 ± 0.18			1.0
	$\phi_{\rm nr}$, radians	$\cdots$	0.29 ± 1.01	1.10 ± 0.44			$\cdots$
	$2\log\mathcal{L}$	-182.4	-182.4	-182.4			-209.7