19th Particles and Nuclei International Conference, July 2011

$\Upsilon(5S)$ Results from Belle: Strange Beauty & Other Beasts

- B_s
- $\sin 2\varphi_1 (\sin 2\beta)$
- Bottomonia

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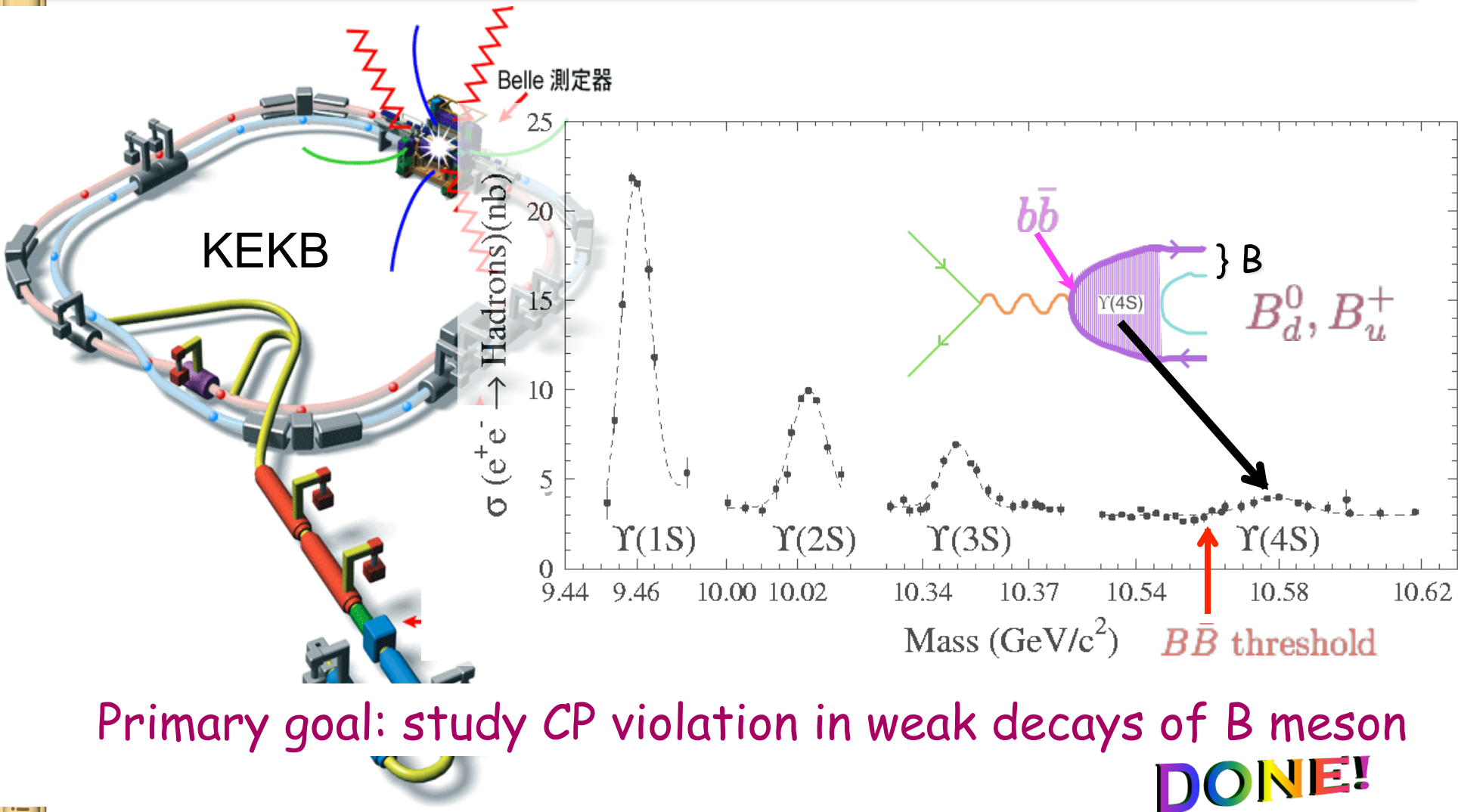
University of Cincinnati
Belle Collaboration

Belle/KEKB: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

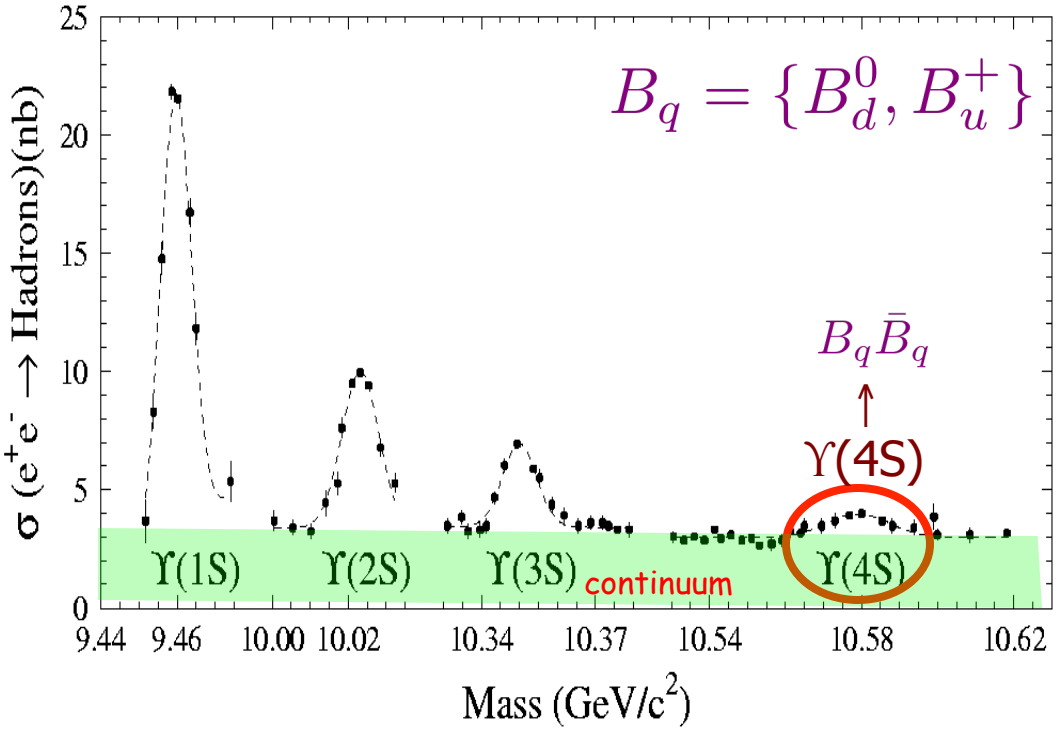


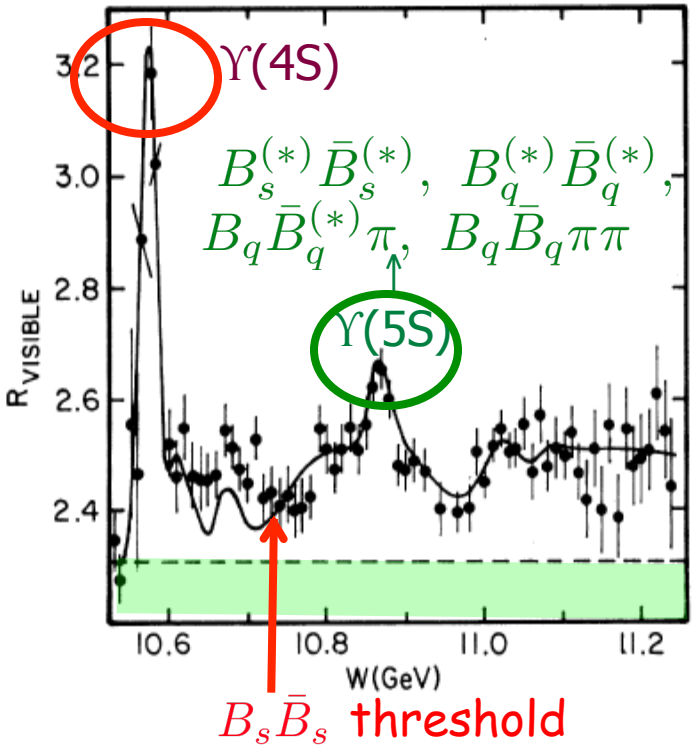
Primary goal: study CP violation in weak decays of B meson

DONE!

711 fb^{-1} = 770M B events recorded at $\Upsilon(4S)$

BUT wait, more …. including Υ(10860), or Υ(5S)



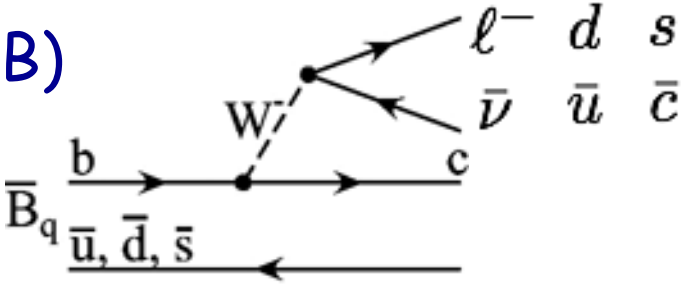


- For B_s studies: More B_s from pp(bar) (FNAL, LHC) but…
  Υ(5S) is competitive for some aspects
  - CLEAN events, energy definition, γ's; ~100% trigger efficiency
    -> absolute BF's, modes w π^0, γ
  - high lum, established detector, Υ(4S) data for B "background"
- Bottomonia above Bbbar threshold – complex structure

Υ(5S) physics

B_s in Standard Model

- CP-asymmetry ~ 0 -> window to New Physics
- $\Delta\Gamma/\Gamma_{CP}/\Gamma$=O(10%)
- Spectator decay (as w non-strange B)
  -> quark-hadron duality



B physics

- a novel tag

spectroscopy

- $B_s^{(*)}$ mass
- $B_{(s)}^{(*)}(\pi)$ event fractions
- bottomonium, bottomonium-like states

Data 2005-10

June 2005: 3-day "engineering" run

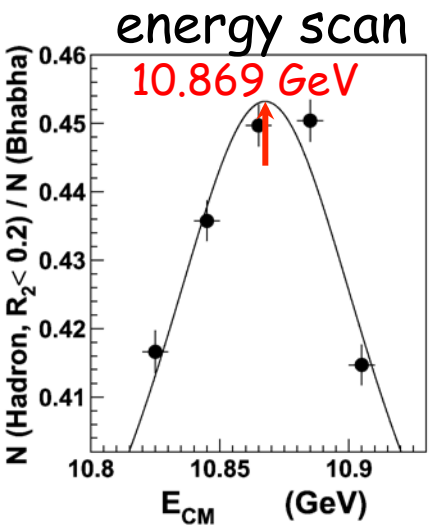
- 1.86 fb^{-1} at peak (10869 MeV)

June 2006: 20 days

- + 21.7 fb^{-1} on resonance

December 2007

- + 7.9 fb^{-1} scan above resonance



A. Drutskoy et al., PRL 98, 052001 (2007)
A. Drutskoy et al., PRD 76, 012002 (2007)
K.F. Chen et al., PRL 100, 112001 (2008)
J. Wicht et al., PRL 100, 121801 (2008)
R. Louvot et al., PRL 102, 021801 (2009)
A. Drutskoy et al., PRD81, 112003 (2010)
R. Louvot et al., PRL 104, 231801 (2010)
J. Li et al., PRL 106, 121802 (2011)
C.-C. Peng et al., PRD 82, 072007 (2010)
S. Esen et al., PRL 105, 201802 (2010)
K.F. Chen et al., PRD82, 091106 (2010)

Oct 2008-Dec 2009: 121.4 fb^{-1} total

- + 97.8 fb^{-1} on resonance

this talk:
I. Adachi et al., arXiv: 1103.3419
I. Adachi et al., arXiv: 1105.4583
Y. Sato et al., BELLE-CONF-1145
L. Solovieva et al., BELLE-CONF-1146

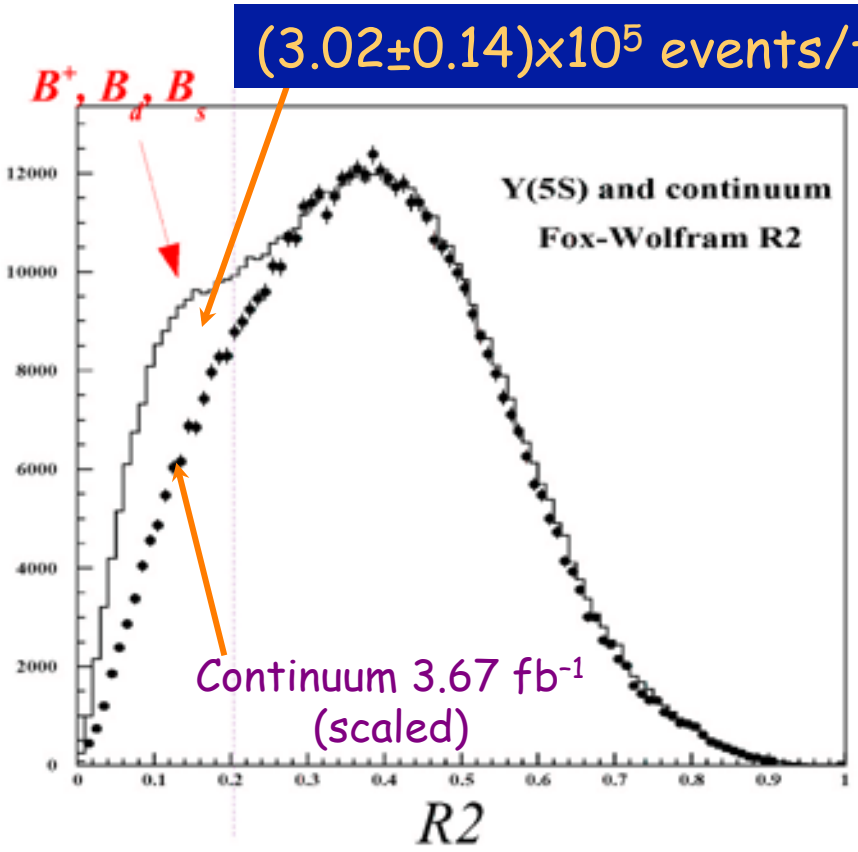
R. Louvot et al., BELLE-CONF-1144
J. Li et al., BELLE-CONF-1101
S. Esen et al., BELLE-CONF-1143

2010: + 20 fb^{-1} scan

fundamentals

Event count

PRD 75, 012002 (CLEO); PRL 98, 052001 (Belle)



$$R_2 = \frac{\sum_{i,j} |p_i||p_j| P_2(\cos\theta)}{\sum_{i,j} |p_i||p_j| P_0(\cos\theta)}$$

Fox-Wolfram moments

- Event types among $b\bar{b}$

$$B_s^{(*)}\bar{B}_s^{(*)},\ B_q^{(*)}\bar{B}_q^{(*)}$$

$$B_q\bar{B}_q^{(*)}\pi,\ B_q\bar{B}_q\pi\pi$$

(~10% initial state radiation)

$$e^+e^- \to \gamma B_q \bar{B}_q X$$

$$B_q = \{B_d^0, B_u^+\}$$

- B_s fraction f_s in Υ(5S) events

inclusive D_s, D^0, φ, B production (Belle, CLEO) arXiv: 1010.1589

$$f_s = (21.5 \pm 3.1)\%$$

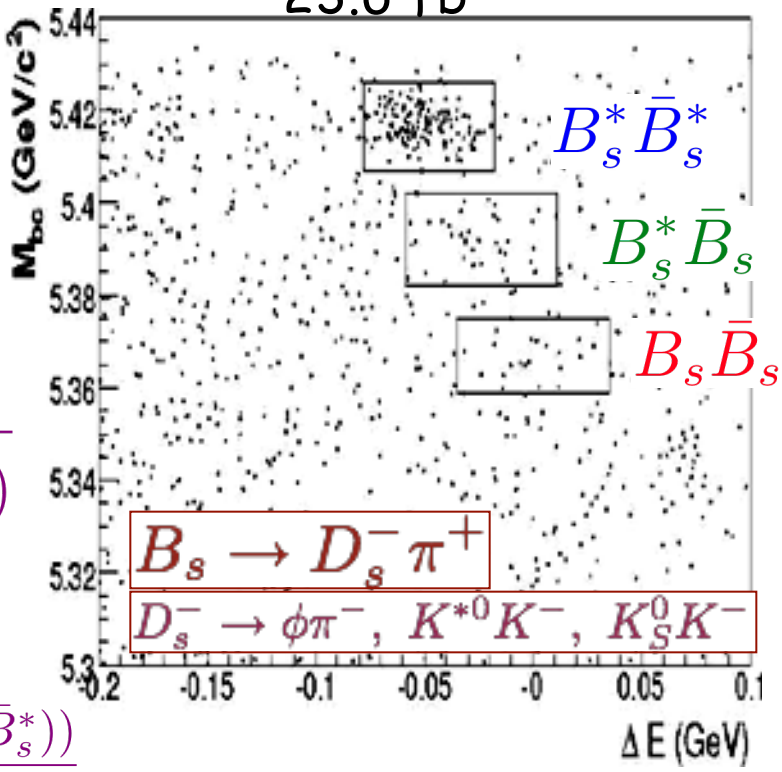
B_s at Υ(5S): $B_s\bar{B}_s + B_s^*\bar{B}_s + \bar{B}_s^* B_s + B_s^*\bar{B}_s^*$

Full reconstruction of B_s candidates: example

[PRL 102, 021801 (2009)]

B_s in 3 event types:
kinematically distinguishable

23.6 fb^{-1}



$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_{cand}^2}$$

$$\Delta E \equiv E_{cand} - E_{beam}$$

Comparing rates:

$$f_{B_s^*B_s^*} \equiv \frac{\sigma(e^+e^- \to B_s^*\bar{B}_s^*)}{\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$$

$$f_{B_s^*B_s} \equiv \frac{\sigma(e^+e^- \to B_s^*\bar{B}_s + B_s\bar{B}_s^*))}{\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})} = (7.3 \pm 0.3 \pm 0.1)\%$$

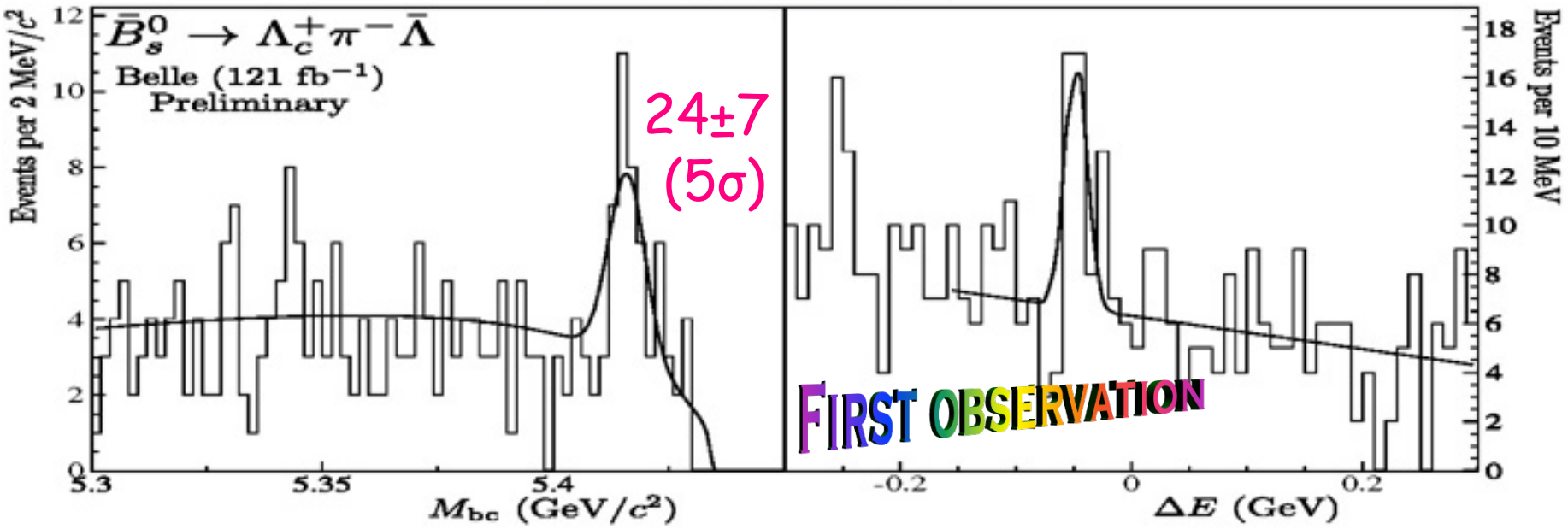
Observation of $\bar{B}_s^0 \to \Lambda_c^+ \pi^- \bar{\Lambda}$

L. Solovieva et al., BELLE-CONF-1146

Observation of

$\bar{B}^0_s \to \Lambda_c^+ \pi^- \bar{\Lambda}$ $\Lambda_c^+ \to pK^-\pi^+$ $\bar{\Lambda} \to \bar{p}\pi^+$

2-d fit in ΔE, M_{bc}



$$\mathcal{B}(\bar{B}^0_s \to \Lambda_c^+ \pi^- \bar{\Lambda}) = (4.8 \pm 1.4(stat.) \pm 0.9(sys) \pm 1.3(\Lambda_c^+)) \times 10^{-4}$$

First observation of a baryonic B_s decay

Compare (PDG): $\mathcal{B}(\bar{B}^- \to \Lambda_c^+ \pi^- \bar{p}) = (2.8 \pm 0.8) \times 10^{-4}$

Measurement of sin2φ_1 (sin2β) with B-π tagging

Y. Sato et al., BELLE-CONF-1145

Events

$$B^{(*)0}B^{(*)-}\pi^+ + c.c.$$

Reconstruct B^0, π; charge of π tags B^0 flavor at t=0

$$A_{BB\pi} \equiv \frac{N_{BB\pi^-} - N_{BB\pi^+}}{N_{BB\pi^-} + N_{BB\pi^+}} = \frac{\mathcal{S}x + \mathcal{A}}{1+x^2}$$

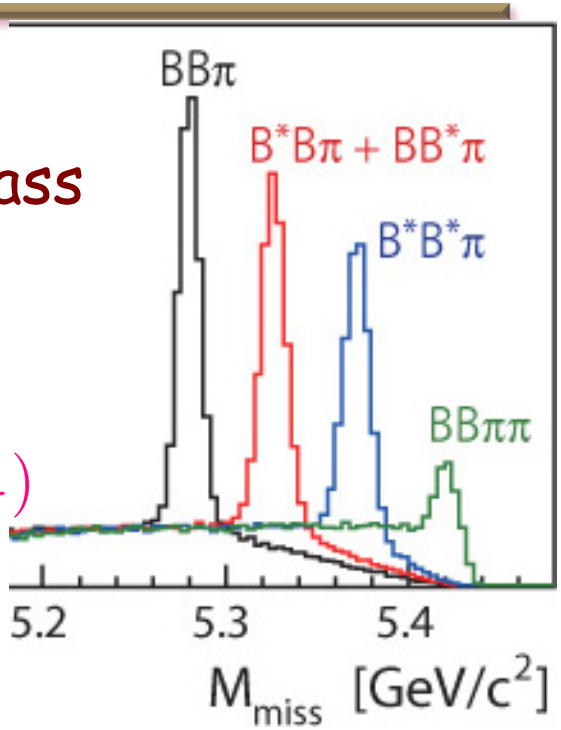
$$\mathcal{S} = -\eta_{CP}\sin 2\phi_1 \qquad x = \Delta m/\Gamma \qquad \mathcal{A} = 0 \text{ (SM)}$$

Time-independent measurement

sin2φ_1 (sin2β) with B-π tagging

Reconstruct B^0, π;
$B^{(*)}$-$B^{(*)0}\pi$ events identified via Missing Mass

$$\underbrace{(E_{beam}, \vec{p}_{beam})}\quad\quad\underbrace{(E_{B\pi}, \vec{p}_{B\pi})}$$
$$\Upsilon(5S) \rightarrow \underbrace{B^{(*)-}\{(\gamma)}\overline{B^0\}}\pi^+$$
$$(E_{miss}, \vec{p}_{miss}) = (E_{beam} - E_{B\pi}, \vec{p}_{beam} - \vec{p}_{B\pi})$$
$$M_{miss} = \sqrt{E_{miss}^2 - p_{miss}^2}$$



sin2φ_1 (sin2β) with B-π tagging

Reconstruct B^0, π;
$B^{(*)}$-$B^{(*)0}\pi$ events identified via Missing Mass

$$\underbrace{(E_{beam}, \vec{p}_{beam})}\quad\quad\underbrace{(E_{B\pi}, \vec{p}_{B\pi})}$$
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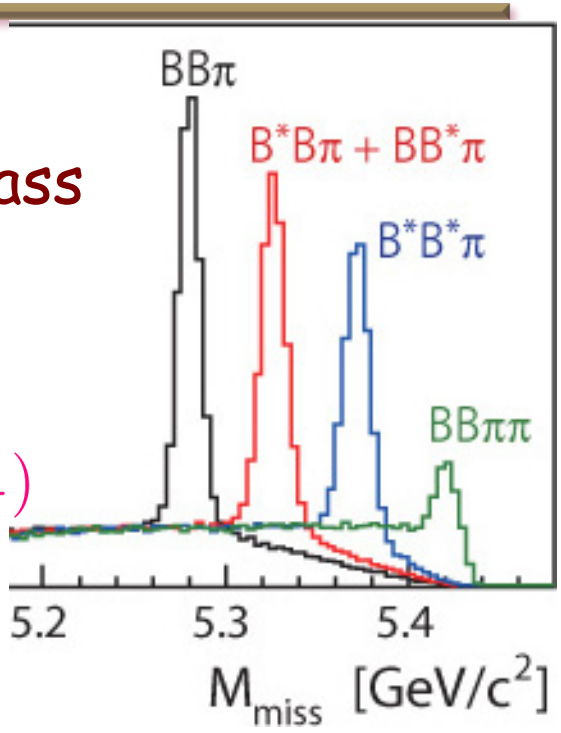
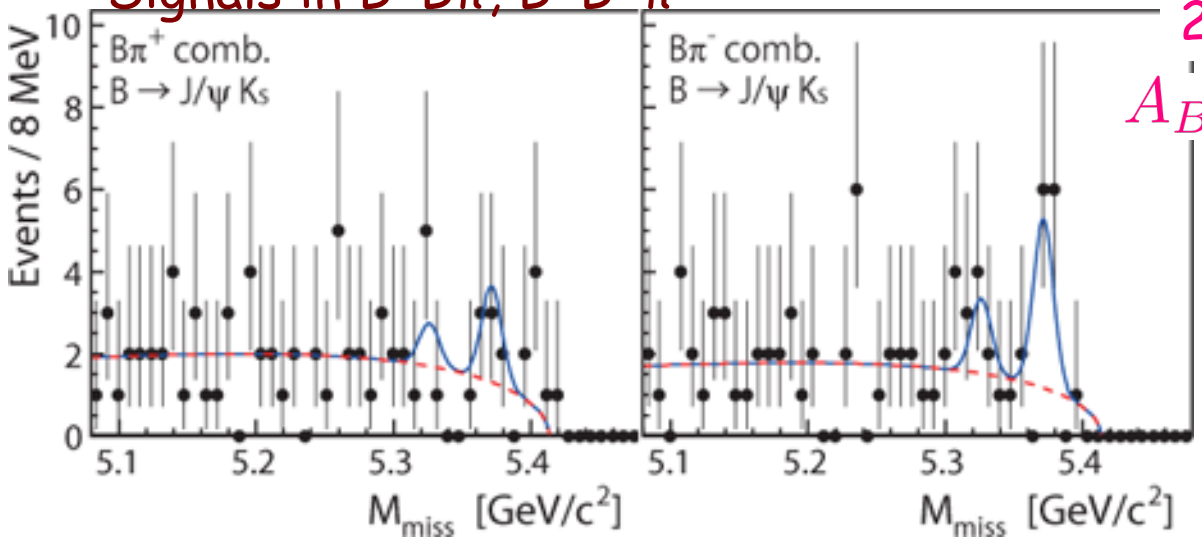


Signals in B*Bπ, B*B*π

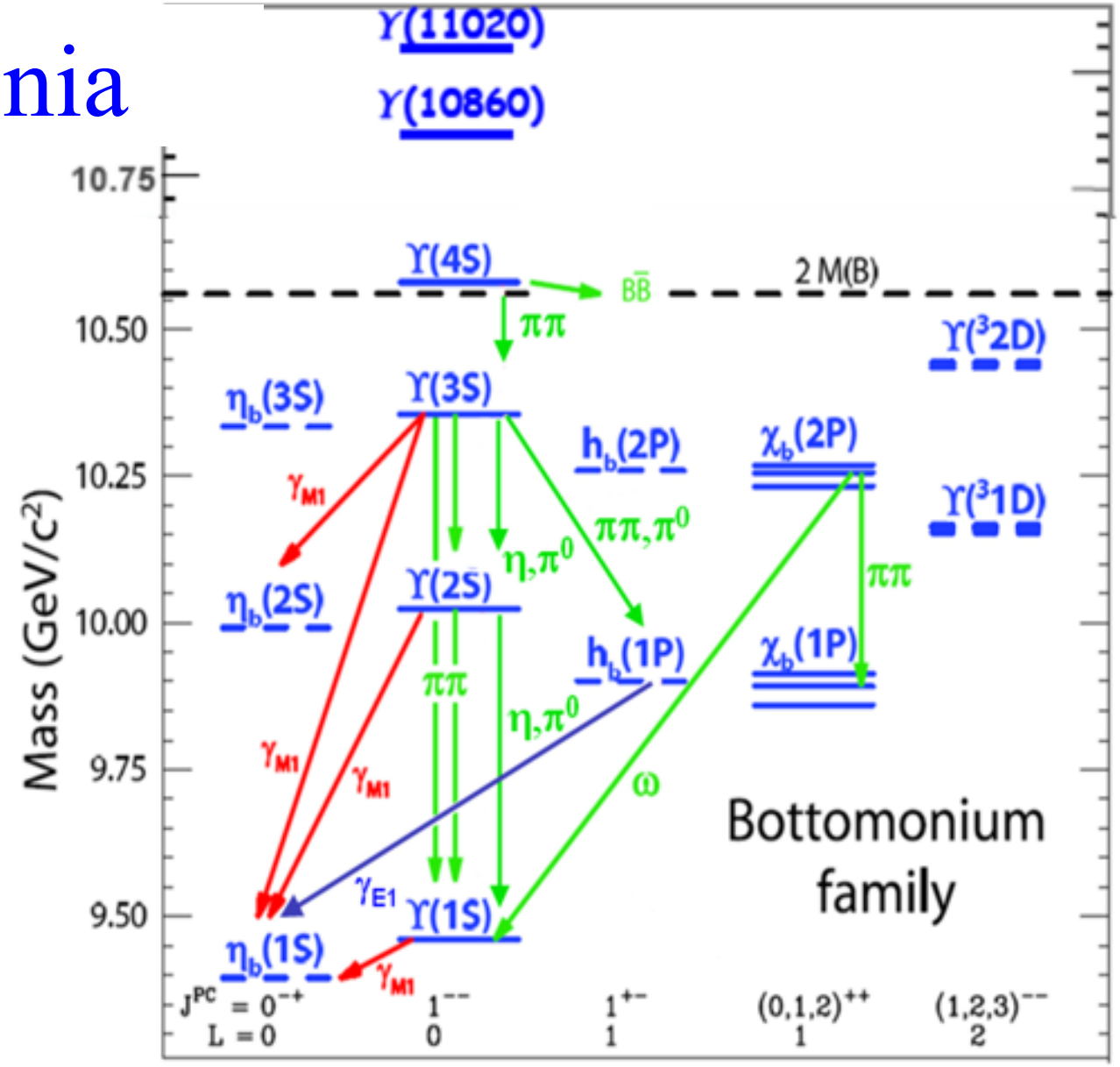


21.5±6.8 total signal

$$A_{BB\pi} = 0.28 \pm 0.28(stat.)$$

$$\sin 2\phi_1 = 0.57 \pm 0.58(stat) \pm 0.06(sys)$$

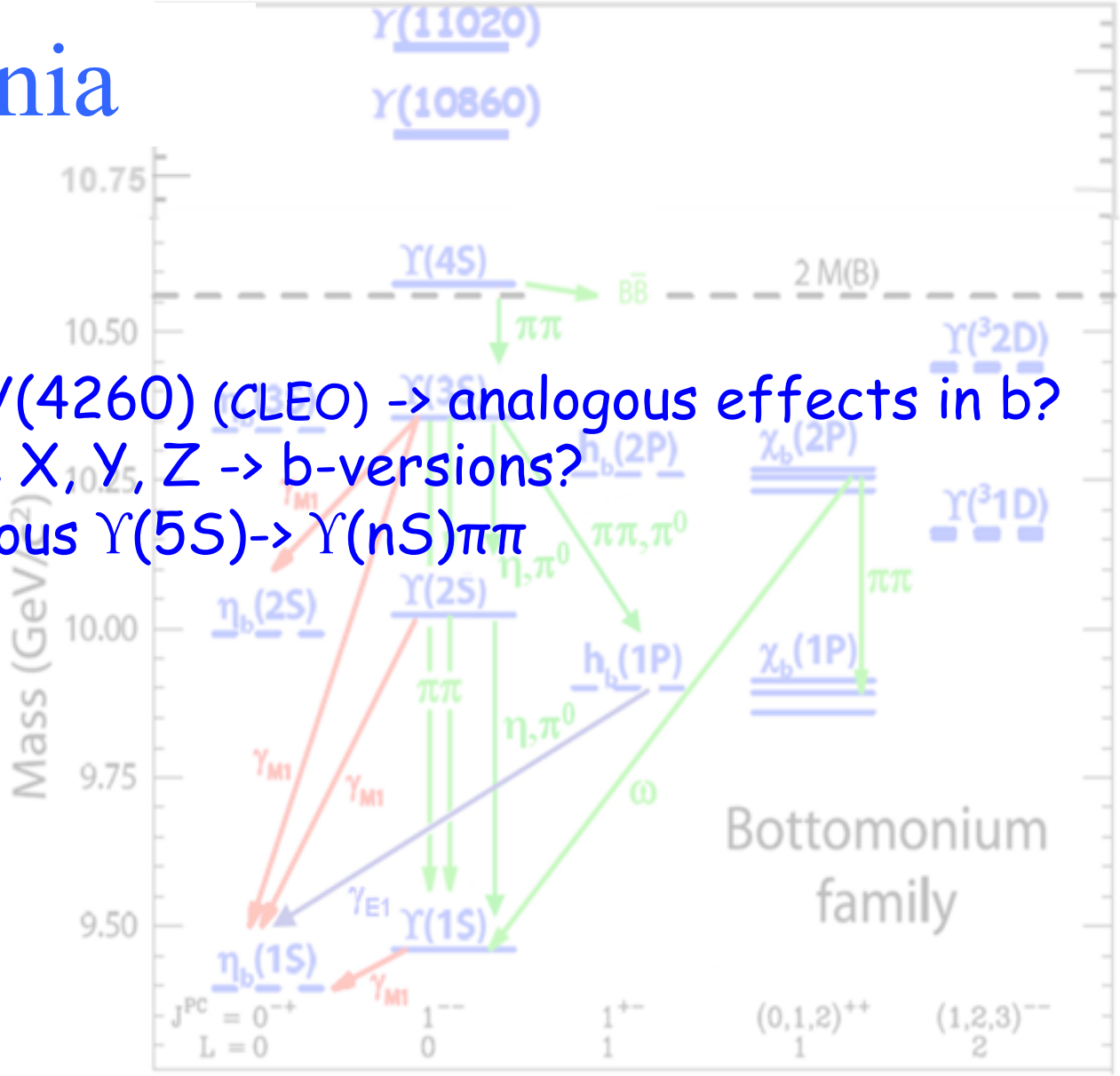
Bottomonia


Υ(11020)
Υ(10860)
10.75
10.50
10.25
10.00
9.75
9.50
Mass (GeV/c²)
Υ(4S)
BB̄
2 M(B)
ππ
Υ(3S)
ηb(3S)
hb(2P)
χb(2P)
Υ(3²D)
γM1
ππ,π0
η,π0
Υ(2S)
ηb(2S)
Υ(3¹D)
ππ
hb(1P)
χb(1P)
ω
Bottomonium
family
γE1
Υ(1S)
ηb(1S)
JPC = 0−+
L = 0
1−−
0
1+−
1
(0,1,2)++
1
(1,2,3)−−
2

Bottomonia

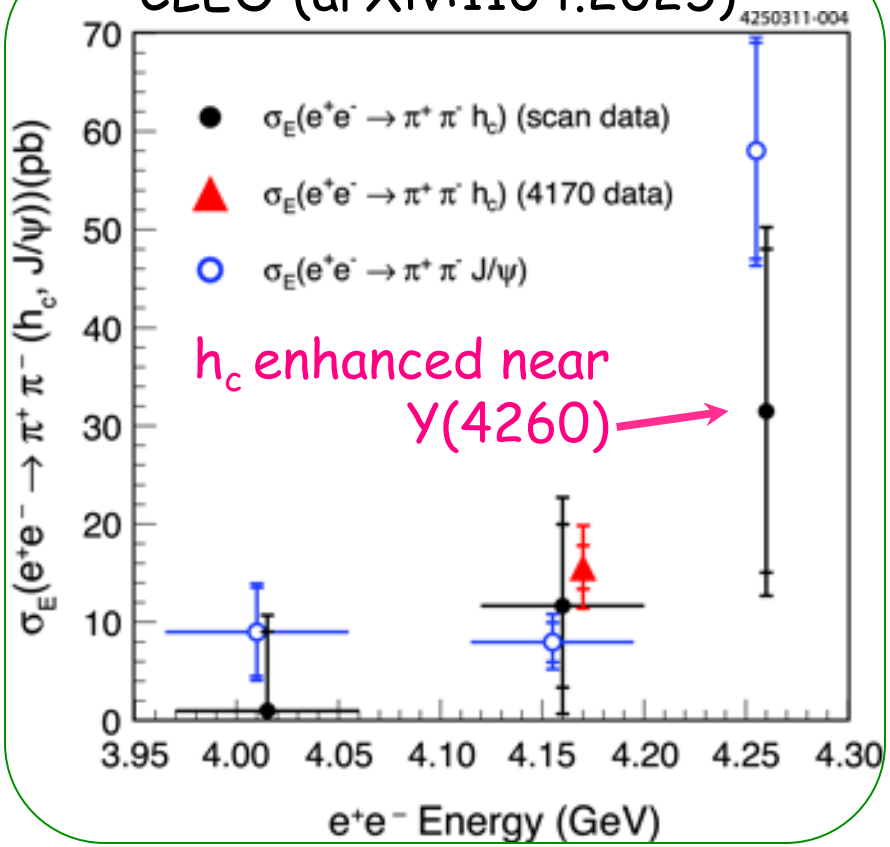
Motivations

- seek/study h_b
- enhanced h_c at Y(4260) (CLEO) -> analogous effects in b?
- charmonium-like X, Y, Z -> b-versions?
- origin of anomalous $\Upsilon(5S)$-> $\Upsilon(nS)\pi\pi$



Previous related results

CLEO (arXiv:1104.2025)

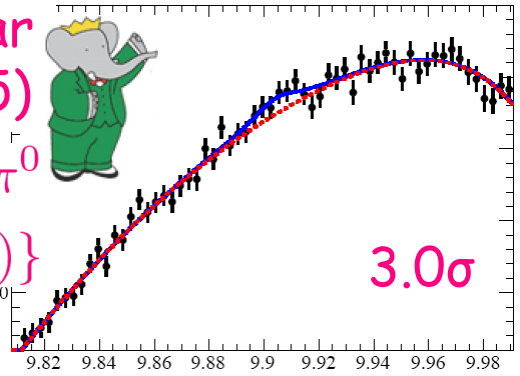


Evidence at Babar (arXiv:1102.4565)

$\Upsilon(3S) \to h_b(1P)\pi^0$

$\{h_b(1P) \to \gamma\eta_b(1S)\}$

3.0σ



from CLEO FPCP 2011

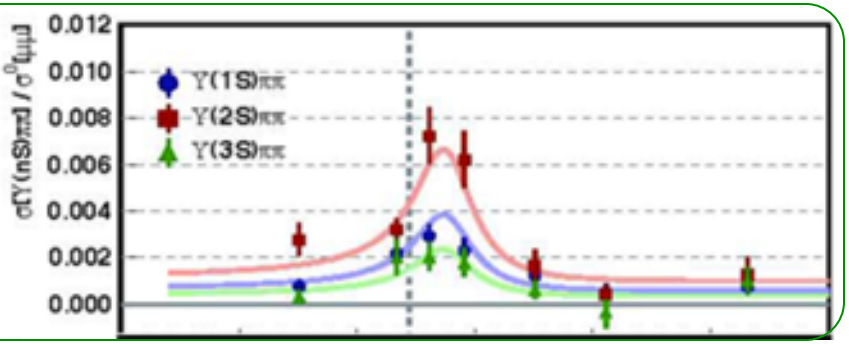
$B(\Upsilon(3S) \to \pi^0 h_b) < 1.6 \times 10^{-3}$ (90% CL)

Belle [PRL 100, 112001 (2008)]:

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$ exceeds rate for $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$ by $O(10^2)$

Belle [PRD82, 091106 (2010)]:

$e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ scan – indicates peak offset from peak of $e^+e^- \to$ hadrons: Y_b?



Observation of h_b in

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

arXiv: 1103.3419

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

Method: missing mass

from accelerator: $(E_{beam}, \vec{p}_{beam})$ — Reconstructed: $(E_{\pi\pi}, \vec{p}_{\pi\pi})$

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

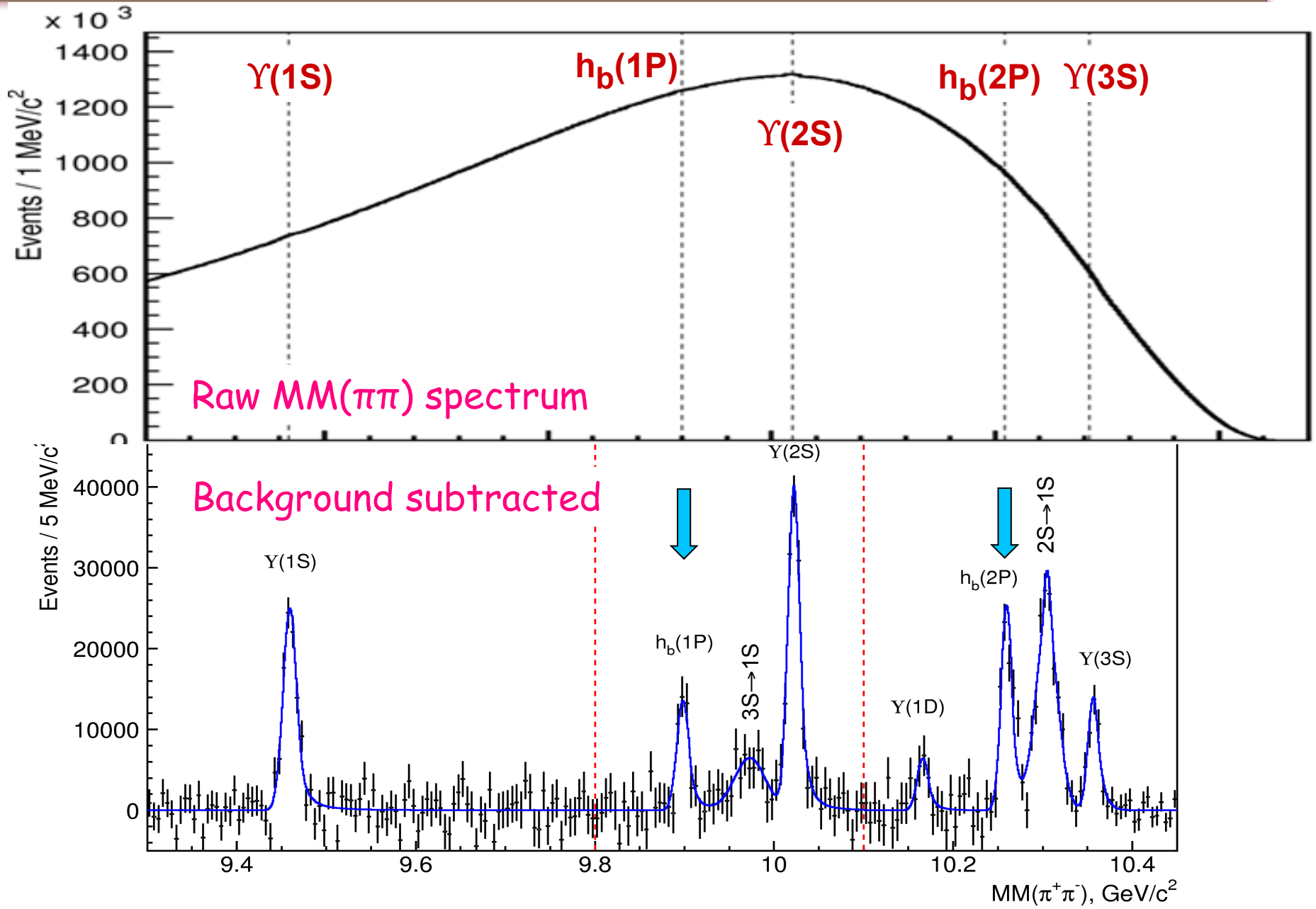
$$(E_{h_b}, \vec{p}_{h_b}) = (E_{beam} - E_{\pi\pi}, \vec{p}_{beam} - \vec{p}_{\pi\pi})$$

$$M_{h_b} = MM(\pi^+\pi^-) = \sqrt{E_{h_b}^2 - p_{h_b}^2}$$

Selection criteria:

- well-identified π^+,π^-
- event shape to disfavor continuum (2-jet)
- blind analysis

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



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

Results

	Yield, 10^3	Mass, MeV/c^2	Signif.	w. Systematics
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.42 \pm 0.53 \pm 1.02$	$18.2\,\sigma$	
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.25 \pm 1.06^{+1.03}_{-1.07}$	$6.2\,\sigma$	5.5σ
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$	FIRST OBSERVATION
$\Upsilon(2S)$	$143.4 \pm 8.7 \pm 6.8$	$10022.25 \pm 0.41 \pm 1.01$	$16.6\,\sigma$	
$\Upsilon(1D)$	22.1 ± 7.8	10166.2 ± 2.4	$2.4\,\sigma$	
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	$12.4\,\sigma$	11.2σ
$2S \to 1S$	$151.6 \pm 9.7^{+9.0}_{-20.}$	$10304.57 \pm 0.61 \pm 1.03$	$15.7\,\sigma$	FIRST OBSERVATION
$\Upsilon(3S)$	$44.9 \pm 5.1 \pm 5.1$	$10356.56 \pm 0.87 \pm 1.06$	$8.5\,\sigma$	

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

Expected mass: spin-weighted average of $\chi_b = (M_{\chi b0} + 3M_{\chi b1} + 5M_{\chi b2})/9$

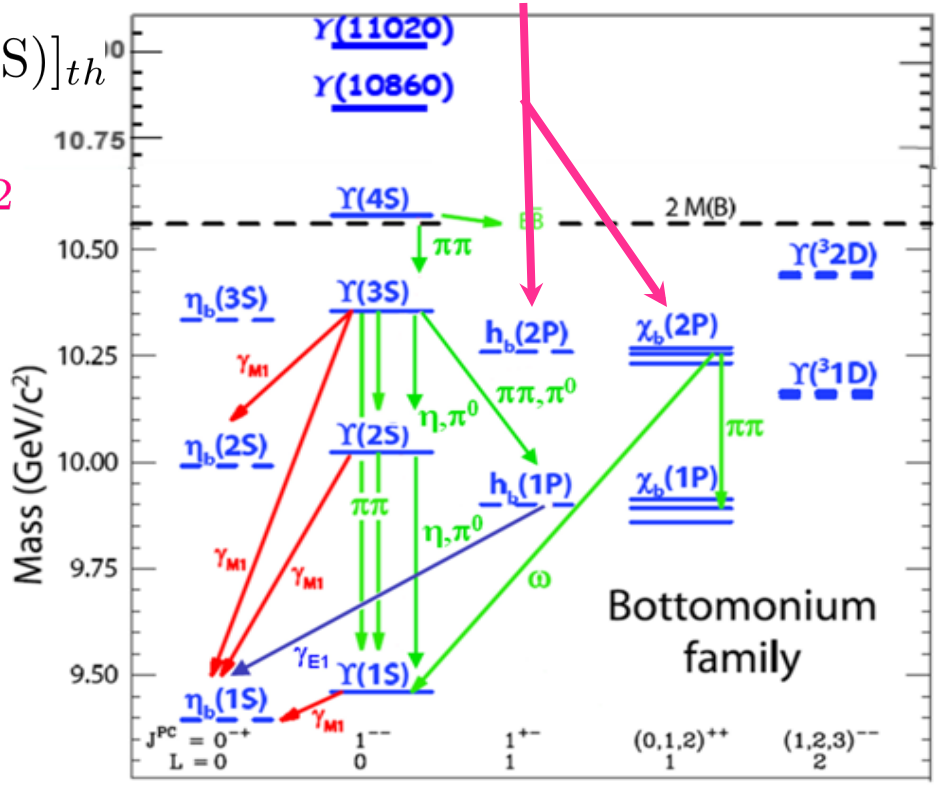
$\Delta M_{HF,n} \equiv M[h_b(nS)]_{meas} - M[h_b(nS)]_{th}$

tests hyperfine interaction

$\Delta M_{HF,1} = 1.62 \pm 1.52\ \mathrm{MeV}/c^2$

$\Delta M_{HF,2} = 0.48^{+1.57}_{-1.22}\ \mathrm{MeV}/c^2$

Consistent with zero



Spin dependence of rate

$$R_n \equiv \frac{\Gamma(\Upsilon(5S) \to h_b(nS)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)}$$

spin flip

no spin flip

Naïve expectation:
spin flip suppressed

$R_1 = 0.407 \pm 0.079^{+0.048}_{-0.076}$

$R_2 = 0.78 \pm 0.09^{+0.22}_{-0.10}$

NOT suppressed -> exotic mechanism?

----- > Look at resonant substructure

Study of resonant substructure in

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

and

Observation of
Two Charged Bottomonium-like Resonances

arXiv: 1105.4583

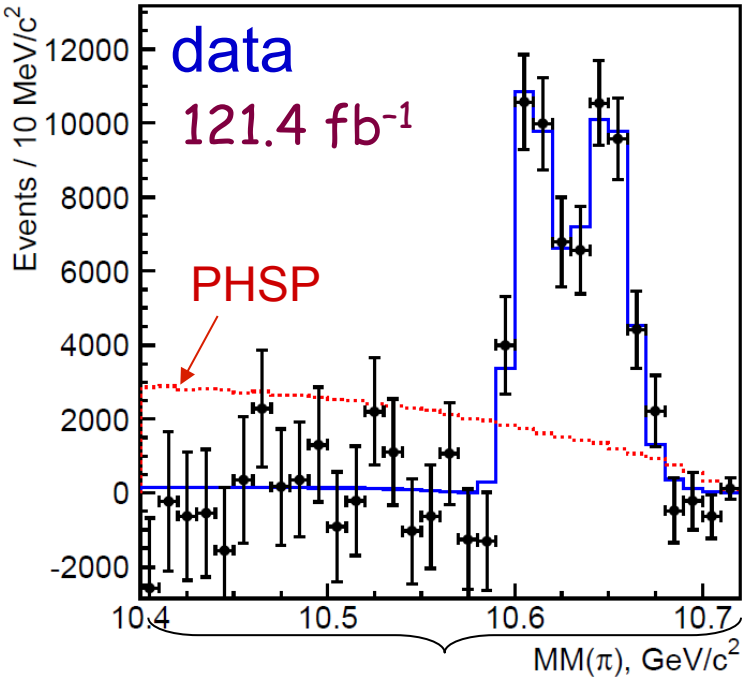
Resonant substructure $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$

probe: missing mass $\Upsilon(5S) \to \underbrace{h_b(nP)\pi^{\pm}}_{\text{"Z"}}\pi^{\mp}$

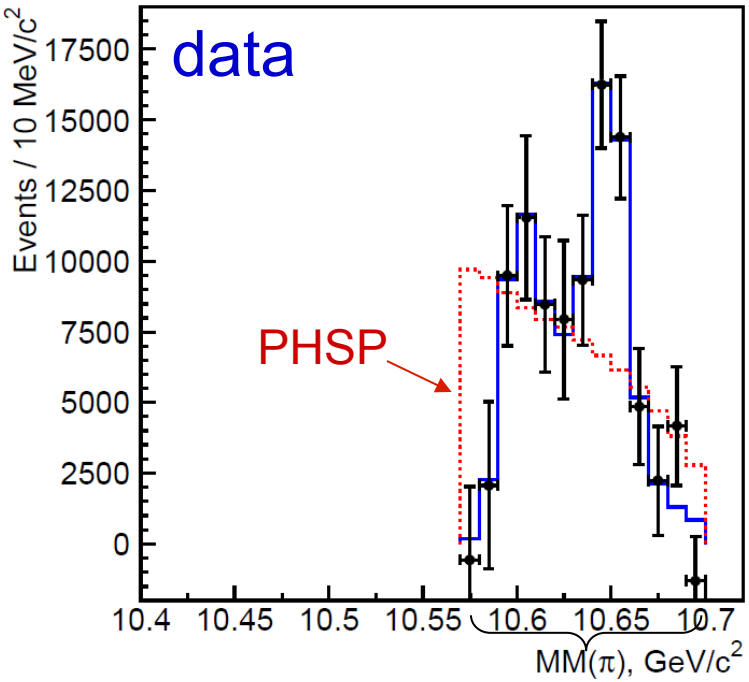
$$M_Z = MM(\pi) = \sqrt{E_Z^2 - p_Z^2}$$

yield in MM(π) bins

$\Upsilon(5S) \to h_b(1P)\pi\pi$



$\Upsilon(5S) \to h_b(2P)\pi\pi$



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

Fit Results

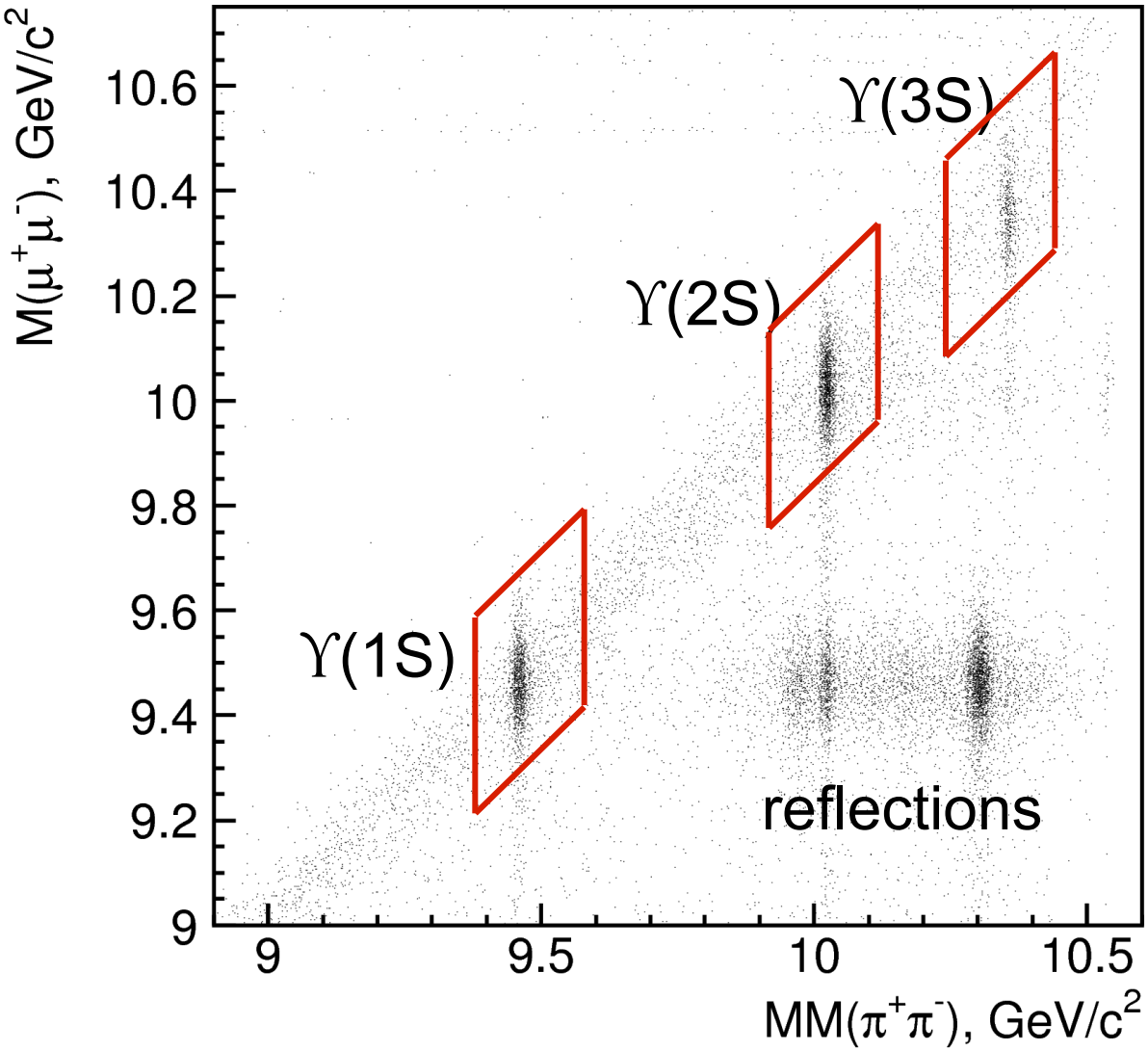
	$h_b(1P)\pi^\pm\pi^\mp$	$h_b(2P)\pi^\pm\pi^\mp$	
M_1 (MeV/c^2)	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$	Z_{b1}
Γ_1 (MeV)	$11.4^{+4.5+2.1}_{-3.9-1.2}$	16^{+16+13}_{-10-14}	
M_2 (MeV/c^2)	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$	Z_{b2}
Γ_2 (MeV)	$20.9^{+5.4+2.1}_{-1.7-5.7}$	$12^{+11+8}_{-9\ -2}$	
a	$1.8^{+1.0+0.1}_{-0.7-0.5}$	$1.3^{+3.1+0.4}_{-1.1-0.7}$	
ϕ (°)	188^{+44+4}_{-58-9}	$255^{+56+12}_{-72-183}$	
b	≈ 0	≈ 0	

- Good agreement between h_b(1P) and h_b(2P)
- Non-resonant part~0: nearly all h_b(nP) produced via

$$\Upsilon(5S) \to Z^\pm\pi^\mp \to h_b(nP)\pi^\pm\pi^\mp$$

Resonant substructure $\Upsilon(5S) \to \Upsilon(nS)\pi^{\pm}\pi^{\mp}$

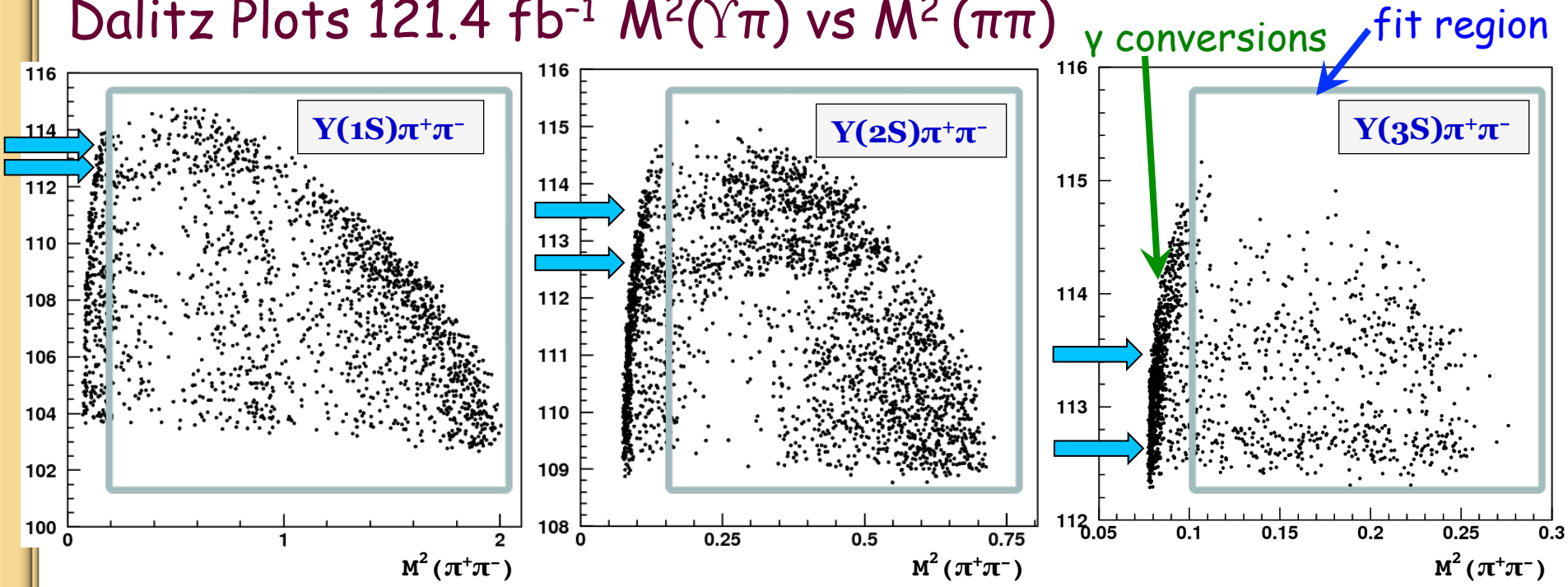
$\Upsilon(5S) \to \Upsilon(nS)\pi^{\pm}\pi^{\mp}$ $\Upsilon(nS) \to \mu^{+}\mu^{-}$



Full reconstruction,
Clean signal
-> Dalitz analysis

Resonant substructure $\Upsilon(5S) \to \Upsilon(nS)\pi^{\pm}\pi^{\mp}$

Dalitz Plots 121.4 fb^{-1} $M^2(\Upsilon\pi)$ vs $M^2(\pi\pi)$



Fit function:

$$S(s_1, s_2) = |A_{Z_{b1}} + A_{Z_{b2}} + A_{\rm NR} + A_{f_0(980)} + A_{f_2(1275)}|^2$$

$$s_i = M^2_{\pi_i \Upsilon} \quad A_{Z_{bk}} = \frac{\sqrt{M_k \Gamma_k}}{M_k^2 - s_1 + iM_k\Gamma_k} + \frac{a_k e^{i\phi_k}\sqrt{M_k\Gamma_k}}{M_k^2 - s_2 + iM_k\Gamma_k}$$

$$A_{\rm NR} = c_1 + c_2 M^2_{\pi\pi}$$

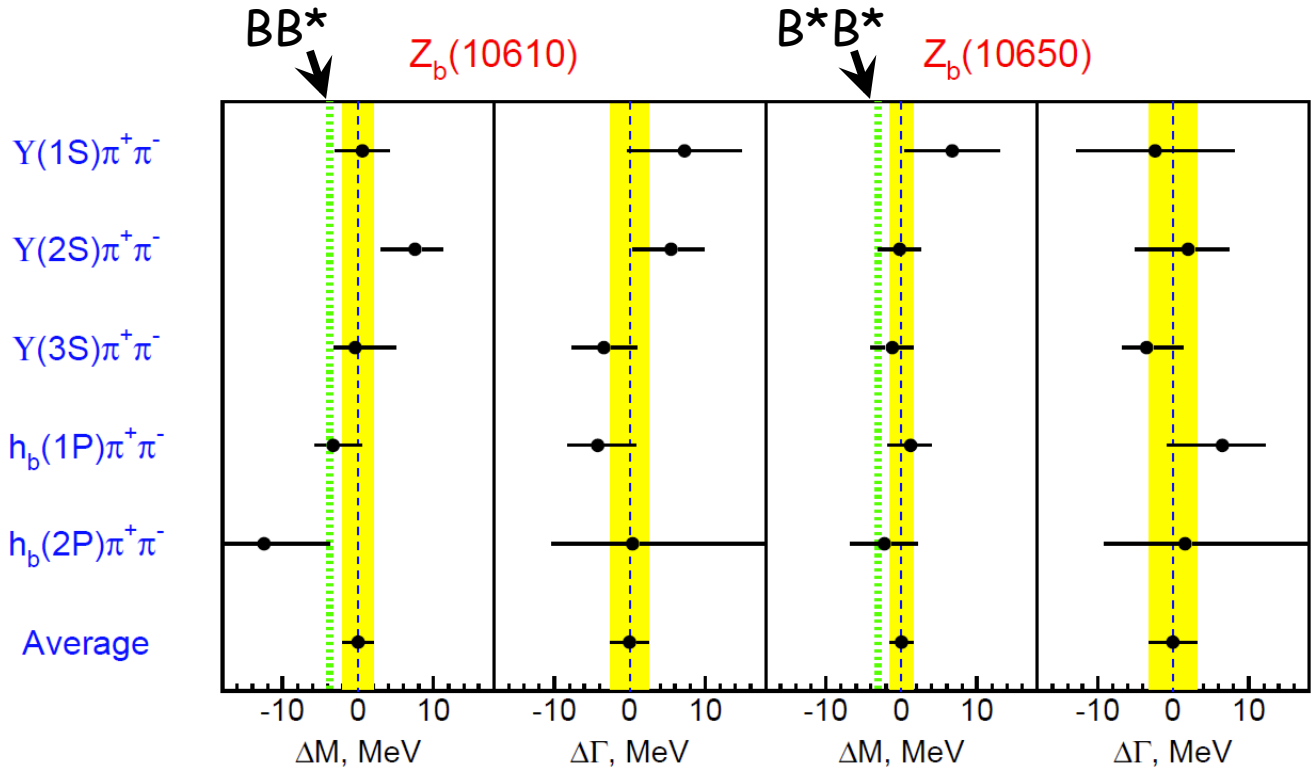
A. Voloshin, PRD74, 054022 (2006);
Prog. Part. Nucl. Phys. 61, 455 (2008)

Fit Results

$\Upsilon(5S) \to \Upsilon(nS)\pi^{\pm}\pi^{\mp}$

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$M(Z_b(10610))$	$10609 \pm 3 \pm 2$	$10616 \pm 2^{+3}_{-4}$	$10608 \pm 2^{+5}_{-2}$
$\Gamma(Z_b(10610))$	$22.9 \pm 7.3 \pm 2$	$21.1 \pm 4^{+2}_{-3}$	$12.2 \pm 1.7 \pm 4$
$M(Z_b(10650))$	$10660 \pm 6 \pm 2$	$10653 \pm 2 \pm 2$	$10652 \pm 2 \pm 2$
$\Gamma(Z_b(10650))$	$12 \pm 10 \pm 3$	$16.4 \pm 3.6^{+4}_{-6}$	$10.9 \pm 2.6^{+4}_{-2}$
Rel. amplitude	$0.59 \pm 0.19^{+0.09}_{-0.03}$	$0.91 \pm 0.11^{+0.04}_{-0.03}$	$0.73 \pm 0.10^{+0.15}_{-0.05}$
Rel. phase,	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$

$Z_b(10610)$, $Z_b(10650)$ summary, 5 modes



$M=10608.4\pm2.0$ MeV/c^2 $\Gamma=15.6\pm2.5$ MeV

$M=10653.2\pm1.5$ MeV/c^2 $\Gamma=14.4\pm3.2$ MeV

- Relative phases: Υ (~0°), h_b (~180°)
- Masses just above B*B and B*B* thresholds
- angular analysis favors $J^P=1^+$

Indicates Z_b's could be molecules

Summary

KEKB and Belle at Υ(5S)+

- 2005-6: 23.6 fb^{-1}, 1.3 M B_s events + scan; 11 papers
- 2005-10: 121.4 fb^{-1}, 7M B_s events; first results

strange beauty

first observation of a B_s baryonic decay

$$\bar{B}_s^0 \to \Lambda_c^+ \pi^- \bar{\Lambda}$$

(more in progress)

nonstrange beauty

Bπ tag: new way to measure $\sin 2\phi_1$

beasts

$h_b(1P)$, $h_b(2P)$ first observation

New states $Z_b^+(10610)$, $Z_b^+(10650)$

in substructure of 5 states:

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