Seminar, Krakow, POLAND, April 5, 2013

Strange Beauty and Other Beasts in the Υ(5S) Neighborhood at Belle

- Belle/KEKB: B-factory
  - Υ(4S) Resonance, B meson
- Υ(5S) Resonance and B_s
  - motivation
  - data, selected results
  - prospects

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Belle Collaboration

The people

Belle collaboration

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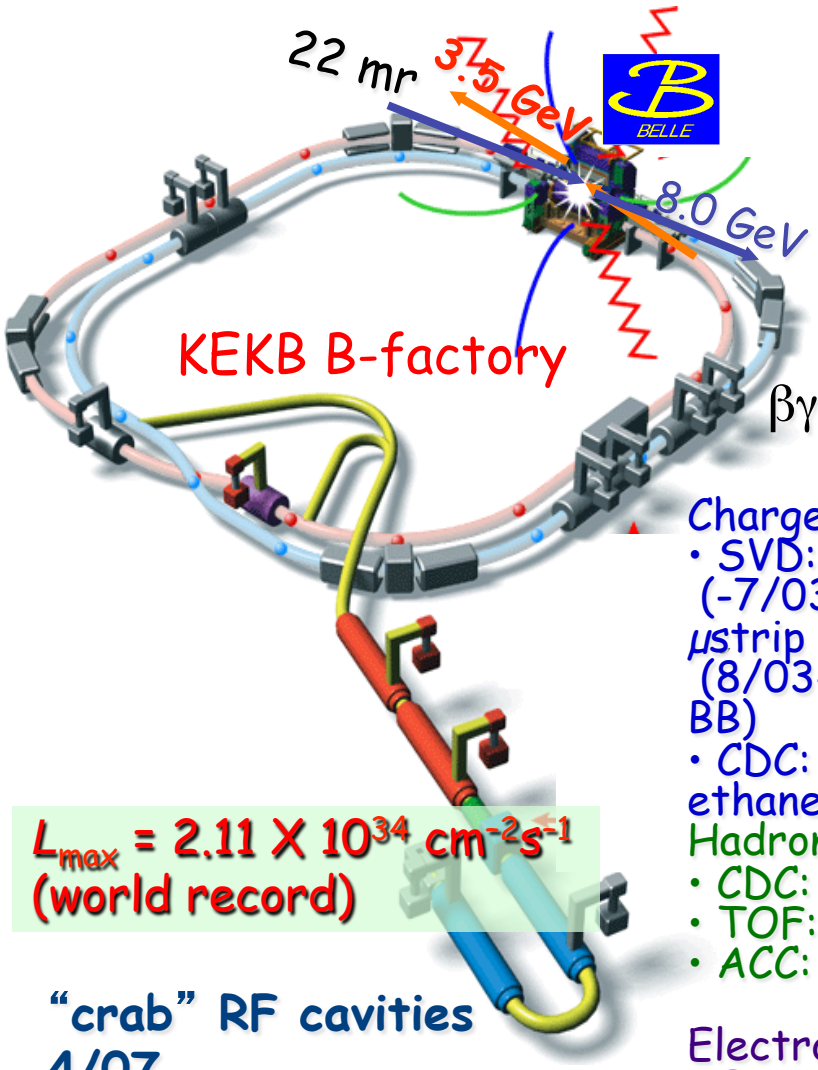
~14 nations, 55 institutes, ~400 collaborators

(authors vary, each paper)

... the hardware



$\beta\gamma = 0.425$

$L_{max} = 2.11 \times 10^{34}\ cm^{-2}s^{-1}$
(world record)

"crab" RF cavities
4/07-

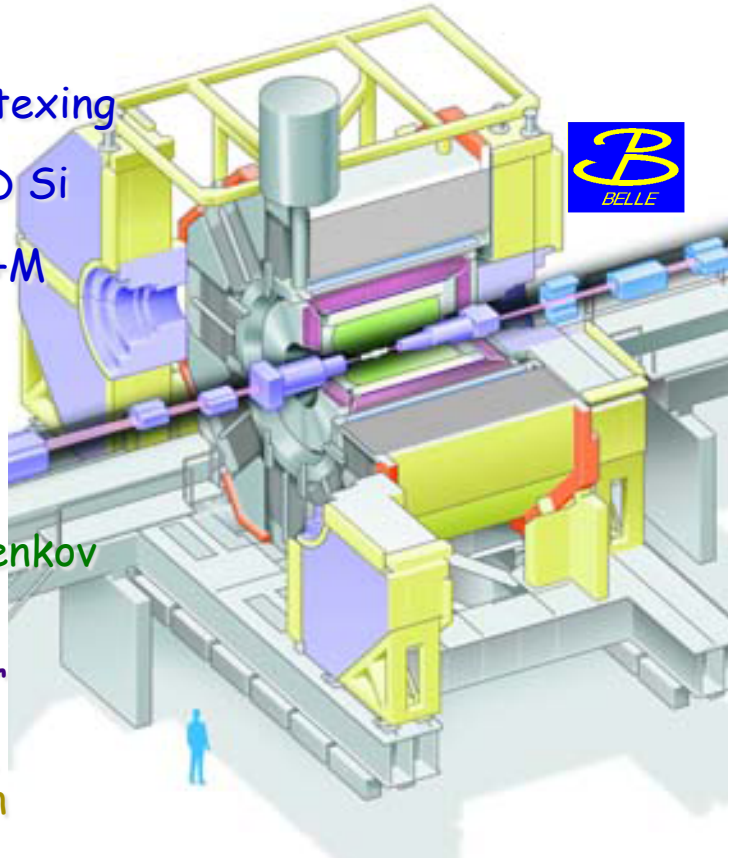
4/07- COPPER pipelined DAQ system

Charged tracking/vertexing
- SVD:
  (-7/03) 3-layer DSSD Si μstrip (152M B pairs)
  (8/03-) 4-layer (550+M BB)
- CDC: 50 layers (He-ethane)

Hadron identification
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon
- ECL: CsI calorimeter

Muon/K_L
- KLM: Resistive plate counter/iron



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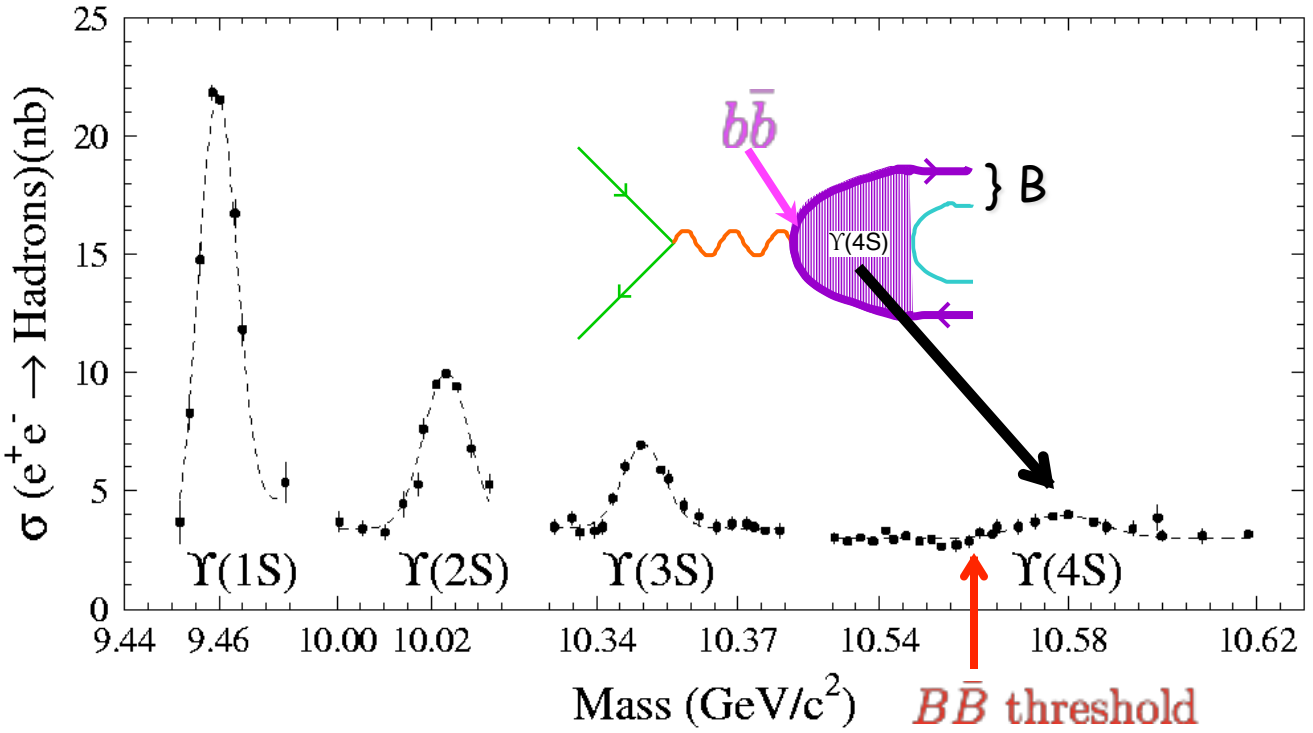
... the Physics $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ (mostly)



CMS energy

"B-factory"

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

DONE! (2001)

and more....

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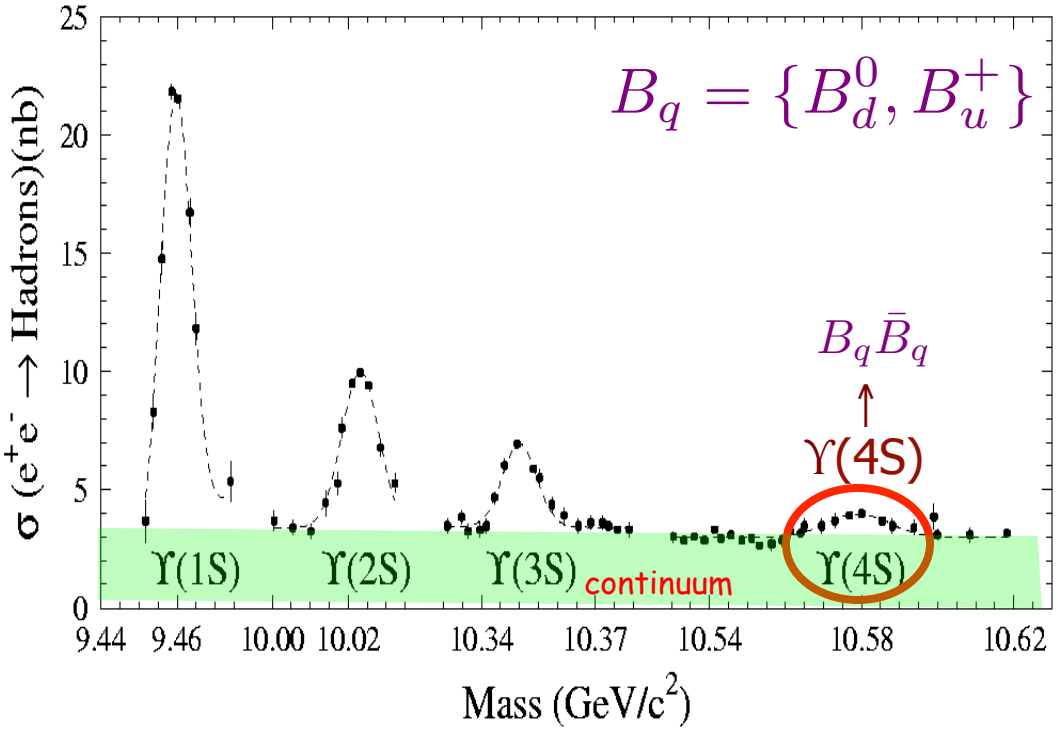
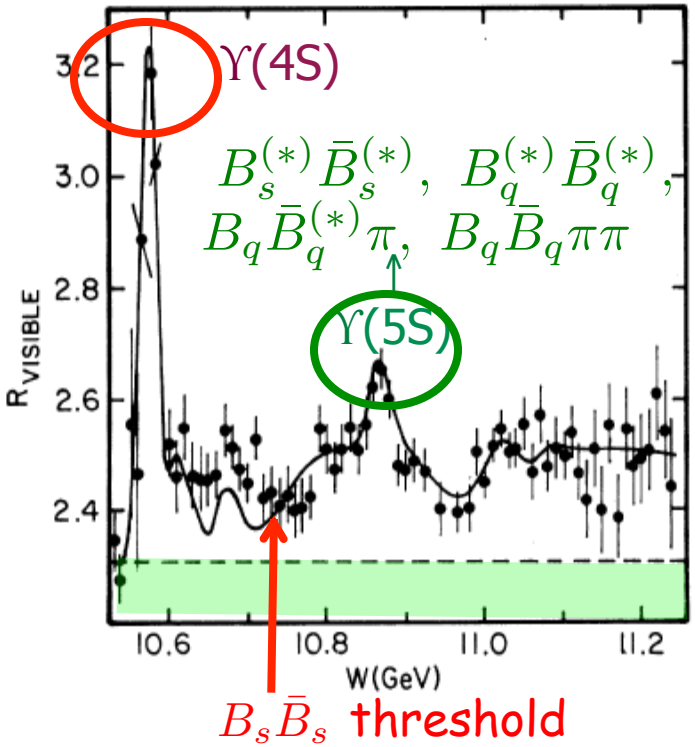
Υ(10860), or Υ(5S)





B_s physics with Belle at the Υ(5S)

- CLEAN events, energy definition, γ's; ~100% trigger efficiency
- high luminosity, established detector, Υ(4S) data for comparison
- resonance – # events measured directly -> absolute BF's

Upsilon Spectroscopy

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Belle experiment

~382 papers published/in press (since 3/2001)
http://belle.kek.jp/bdocs/b_journal.html

Highlights

- Constraints on CKM; precision sin $2\varphi_1$, $|V_{cb}|$, $|V_{ub}|$
- overconstraints on CKM; limits/hints on New Physics
- evidence for D^0 mixing
- new charmonium-like states Z(4430), Y(4660), Y(4008), X(4160), Y(3940), X(3872)
- new bottomonia, bottomonium-like $Z_b(10610)$, $Z_b(10650)$
- Kobayashi & Maskawa 2008 Nobel

Next: KEKB Upgrade/Belle II
- approved 6/2010

Data (1999-2010)

> 1 ab^{-1} recorded by Belle

$\int L dt$ since 6/1999

- $\Upsilon(4S)$ 711 fb^{-1}
- sub-$\Upsilon(4S)$ continuum ~100 fb^{-1}
- $\Upsilon(5S)$ ~121 fb^{-1}
- $\Upsilon(3S)$, $\Upsilon(2S)$, $\Upsilon(1S)$ ~34fb^{-1}
- $\Upsilon(5S)$+ scan ~31 fb^{-1}

- B pairs (7.7 x 10^8 events)
- charm (1.1 x 10^9 events)
- tau (~8 x 10^8 events)
- 2-photon events
- B_s (~7 x 10^6 events)
- $\Upsilon(5S)$ (~4 x 10^7 events)

Data at $\Upsilon(5S)$

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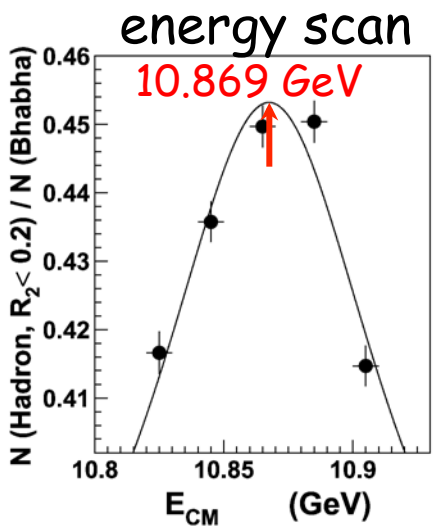
June 2005: 3-day "engineering" run

- basic $\Upsilon(5S)$, $B_s^{(*)}$ properties,
- test KEKB at $\Upsilon(5S)$ - L_{max}~$1.39 \times 10^{34} cm^{-2} s^{-1}$
- 1.86 fb^{-1} at peak (10869 MeV)
  = 4 x largest previous sample (CLEO)

A. Drutskoy et al., PRL 98, 052001 (2007)
A. Drutskoy et al., PRD 76, 012002 (2007)



June 2006: 20-day run

- + 21.7 fb^{-1} on resonance

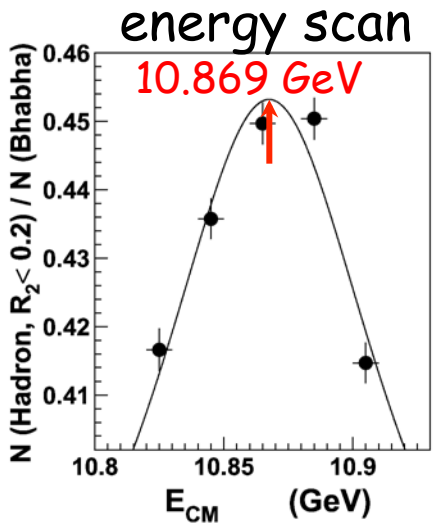
K.F. Chen et al., PRL 100, 112001 (2008)
J. Wicht et al., PRL 100, 121801 (2008)
R. Louvot et al., PRL 102, 021801 (2009)
A. Drutskoy et al., PRD 81, 112003(R)(2010)
R. Louvot et al., PRL 104, 231801 (2010)
C.-C. Peng et al., Phys. Rev. D 82, 072007 (2010)
S. Esen et al., Phys. Rev. Lett. 105, 201802 (2010)
J. Li et al., Phys. Rev. Lett. 106, 121802 (2011)

Data at $\Upsilon(5S)$

December 2007: scan 6 pts

- + 7.9 fb^{-1} above resonance

  K.F. Chen, W.S. Hou et al., Phys. Rev. D82, 091106 (2010)



Oct 2008-Dec 2010

Extended $\Upsilon(5S)$/scan

- ~100 fb–1 on resonance

  R. Mizuk, D. Asner, T. Pedlar, A. Bondar et al., PRL 108, 032001 (2012)

  A. Bondar, A. Garmash, R. Mizuk, D. Santel, K. Kinoshita, et al. PRL 108, 122001 (2012)

  Y. Sato et al., PRL 108, 171801 (2012)

  J. Li, et al. PRL 108, 181808 (2012)

  R. Mizuk et al., PRL 109, 232002 (2012)

  S. Esen, A. Schwartz et al., Phys. Rev. D 87, 031101 (2013)

  C. Oswald, P. Urquijo, J. Dingfelder et al., arXiv:1212.6400 [hep-ex]

  F. Thorne, C. Schwanda et al., BELLE-CONF-1249

  A. Garmash, R. Mizuk et al., arXiv:1209.6450 [hep-ex]

  P. Krokovny et al., arXiv:1207.4345 [hep-ex]

- ~23 fb–1 scan

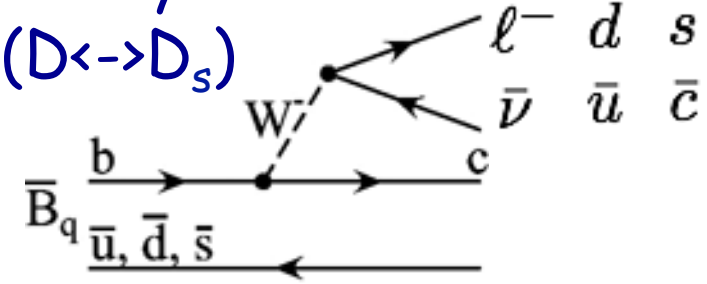
  Y.P. Yang et al., Belle-CONF- 1250

  D. Santel, PRELIMINARY

Υ(5S) physics

B_s decay in Standard Model

- similar to non-strange B
  spectator decay -> quark-hadron duality
  correspondence btw final particle (D<->D_s)
- dissimilarities
  $\Delta\Gamma/\Gamma_{CP}/\Gamma$=O(10%)
  CP-asymmetry ~ 0



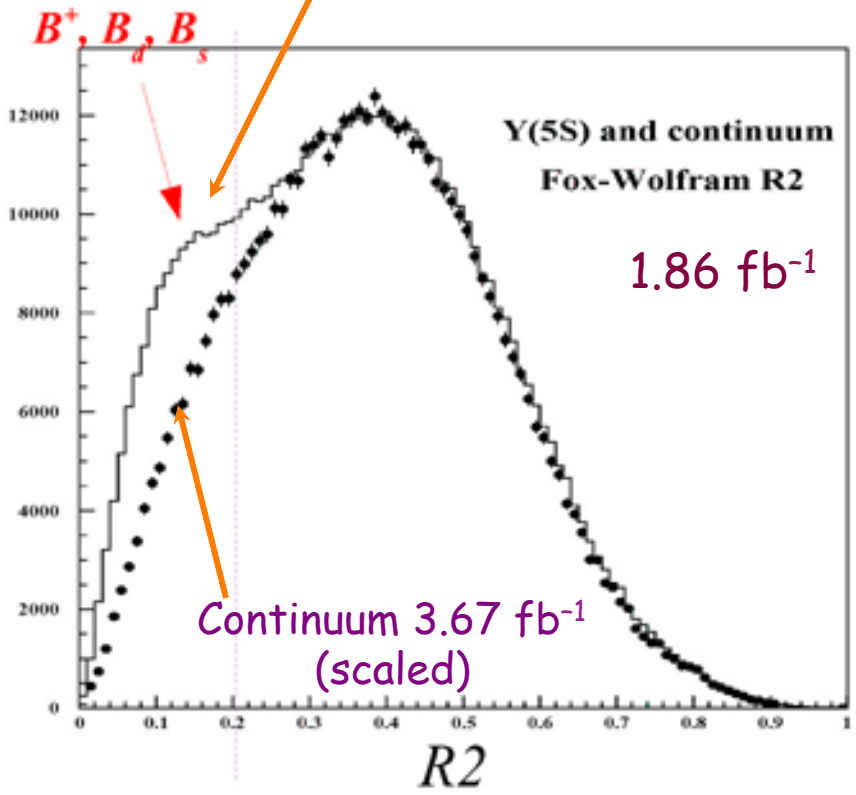
spectroscopy

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

Fundamentals

Event count

$(3.40\pm0.16)\times10^5$ events/fb^{-1} (121.4 fb^{-1})



Event shape parameter
(Fox-Wolfram moments)

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

$3x^2-1$

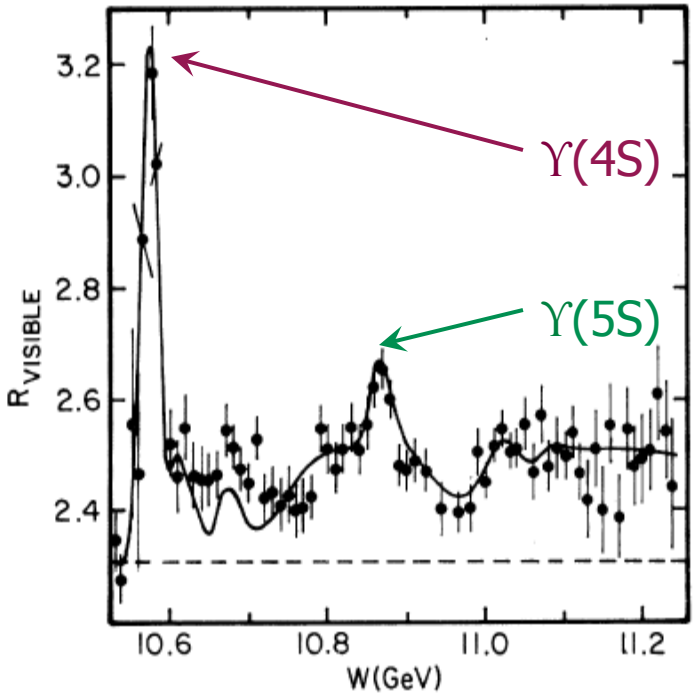
1

2-jet $e^+e^- \to q\bar{q}$ R_2->1

$e^+e^- \to B\bar{B}$ R_2->0

Question in the Υ(5S) region

- above $B_{(s)}^{(*)}$ thresholds –
  complex bottomonium(-like) resonances possible
  mixing/interference?



Is the Υ(10860) purely Υ(5S)?

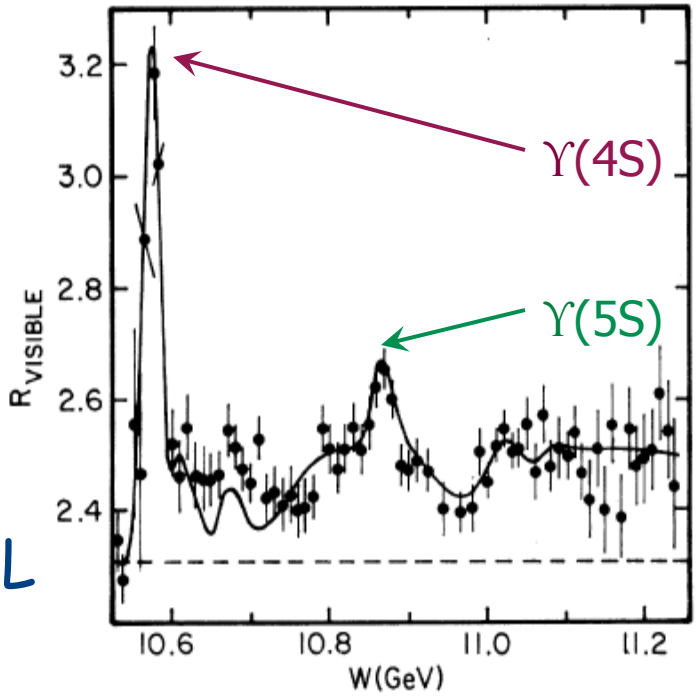
- Y: charmonium-like particle at 4260 GeV found in

$$e^+e^- \to \gamma_{ISR}\,\pi^+\pi^- J/\psi \qquad e^+e^- \to \pi^+\pi^- J/\psi$$

Babar PRL 95, 142001 (2005)
Belle PRD 77, 011105 (R) (2008)
CLEO PRD 74, 091104(R) (2006)

$$Y(4260) \to \pi^+\pi^- J/\psi$$

+ many more!



recent: Observation of Z(3895)+
arXiv:1304.0121; submitted to PRL

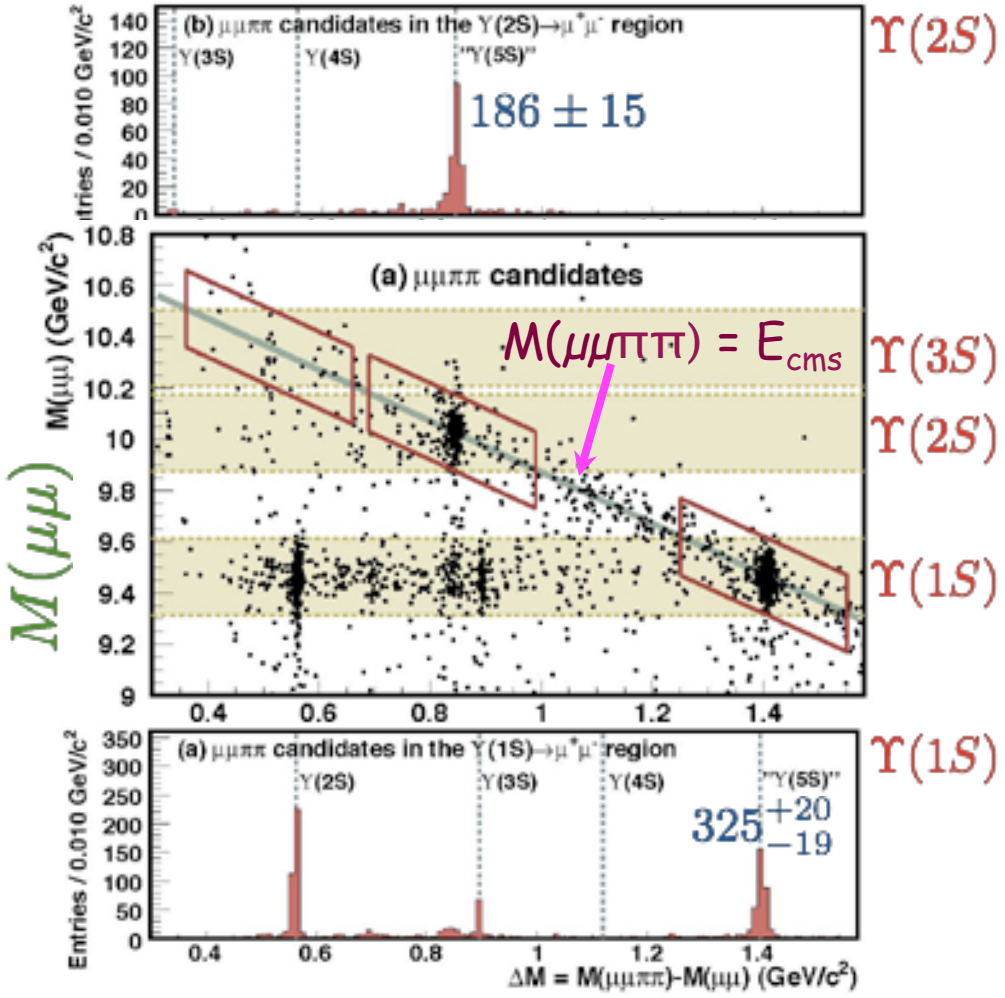
Does(do) analogous state(s) exist in Upsilon region?
[W.S. Hou, PRD 74, 017504 (2006)]

Is the Υ(10860) purely Υ(5S)?

-> look for: $\mu^+\mu^- h^+ h^-$

$$e^+e^- \to \Upsilon(1S)\pi^+\pi^- X$$

$$e^+e^- \to \Upsilon(2S)\pi^+\pi^- X$$



$$\Delta M = M(\mu\mu\pi\pi) - M(\mu\mu)$$

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Is the Υ(10860) purely Υ(5S)?

4 modes seen $\Upsilon(10860) \to \Upsilon(nS)h^+h^-$

Process	σ(pb)	$\mathcal{B}$(%)	Γ(MeV)
$\Upsilon(1S)\pi^+\pi^-$	$1.61 \pm 0.10 \pm 0.12$	$0.53 \pm 0.03 \pm 0.05$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	$2.35 \pm 0.19 \pm 0.32$	$0.78 \pm 0.06 \pm 0.11$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$1.44^{+0.55}_{-0.45} \pm 0.19$	$0.48^{+0.18}_{-0.15} \pm 0.07$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$0.185^{+0.048}_{-0.041} \pm 0.028$	$0.061^{+0.016}_{-0.014} \pm 0.010$	$0.067^{+0.017}_{-0.015} \pm 0.013$

Expectation: Υ(5S) width comparable to Υ(2S/3S/4S)

Process	Γ_{total}	$\Gamma_{e^+e^-}$	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032 MeV	0.612 keV	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020 MeV	0.443 keV	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5 MeV	0.272 keV	0.0019 MeV
$\Upsilon(10860) \to \Upsilon(1S)\pi^+\pi^-$	110 MeV	0.31 keV	0.59 MeV

larger by > 10^2

K.-F. Chen, W.-S. Hou, M. Shapkin, A. Sokolov, et al. PRL 100, 112001 (2008)

Conclusion: <u>not</u> pure Υ(5S)?

12/07: energy scan, measure $e^+e^- \to \Upsilon(nS)h^+h^-$

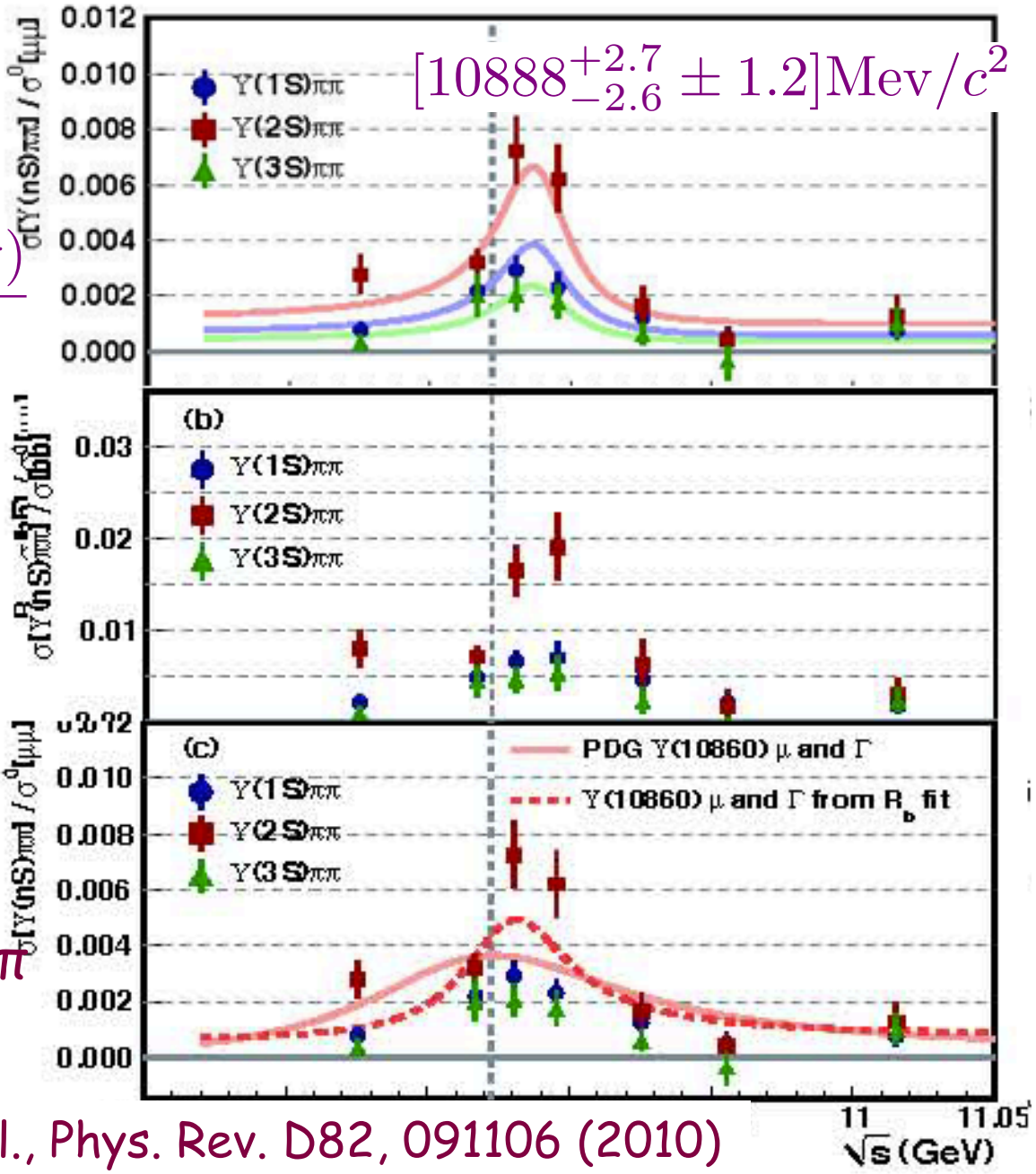
Followup: scan above $\Upsilon(5S)$ in 2007

$\sqrt{s}$(GeV)	$\mathcal{L}$(fb^{-1})
10.8275	1.68
10.8825	1.83
10.8975	1.41
10.9275	1.14
10.9575	1.01
11.0175	0.86

$$\frac{\sigma(\Upsilon(\mathrm{nS})\pi\pi)}{\sigma_{\mu\mu}}$$

$$\frac{\sigma(\Upsilon(\mathrm{nS})\pi\pi)}{\sigma(b\bar{b})}$$

$$\frac{\sigma(\Upsilon(\mathrm{nS})\pi\pi)}{\sigma_{\mu\mu}}$$



Conclusion:
Peaks hadronic vs $\Upsilon\pi\pi$ offset ~2σ

K.F. Chen, W.S. Hou et al., Phys. Rev. D82, 091106 (2010)

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

PRL 108, 122001 (2012)

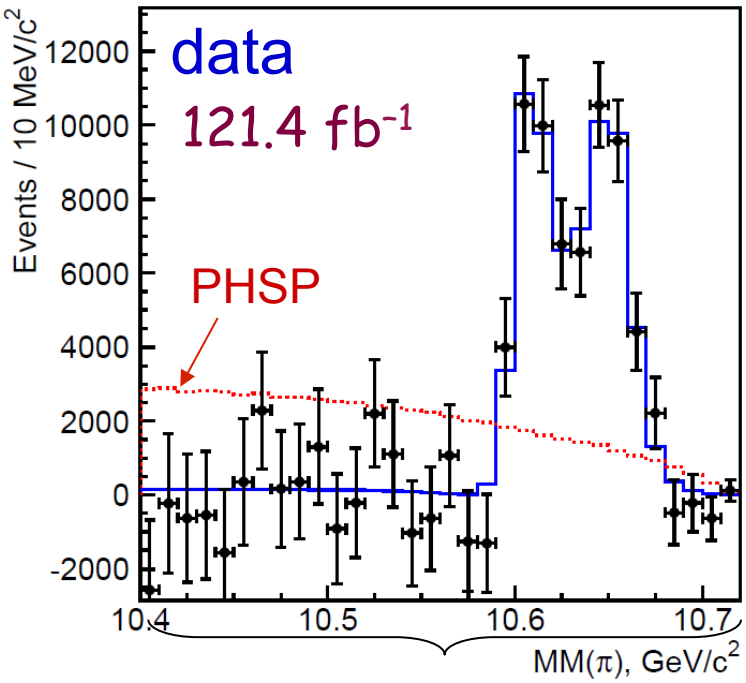
Resonant substructure $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$

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

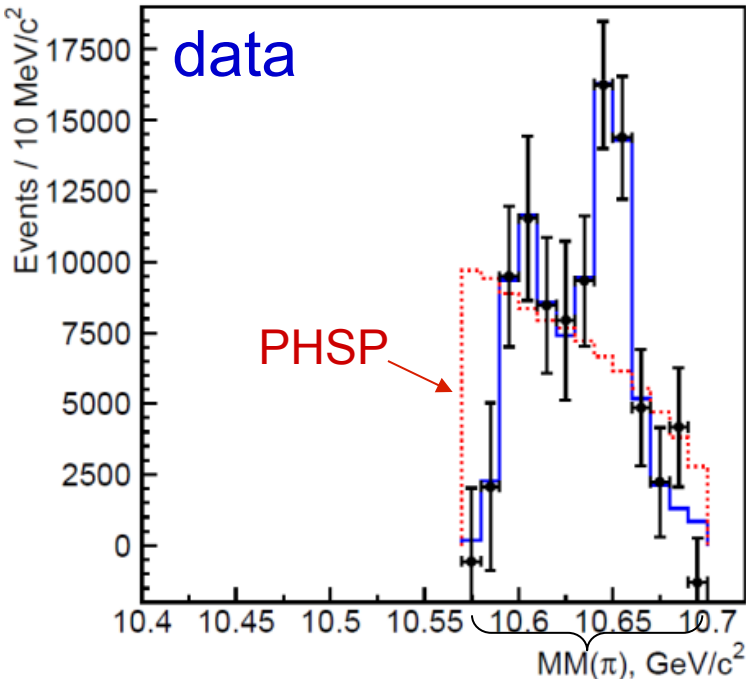
$$M_Z = MM(\pi) = \sqrt{E_Z^2 - p_Z^2}$$

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

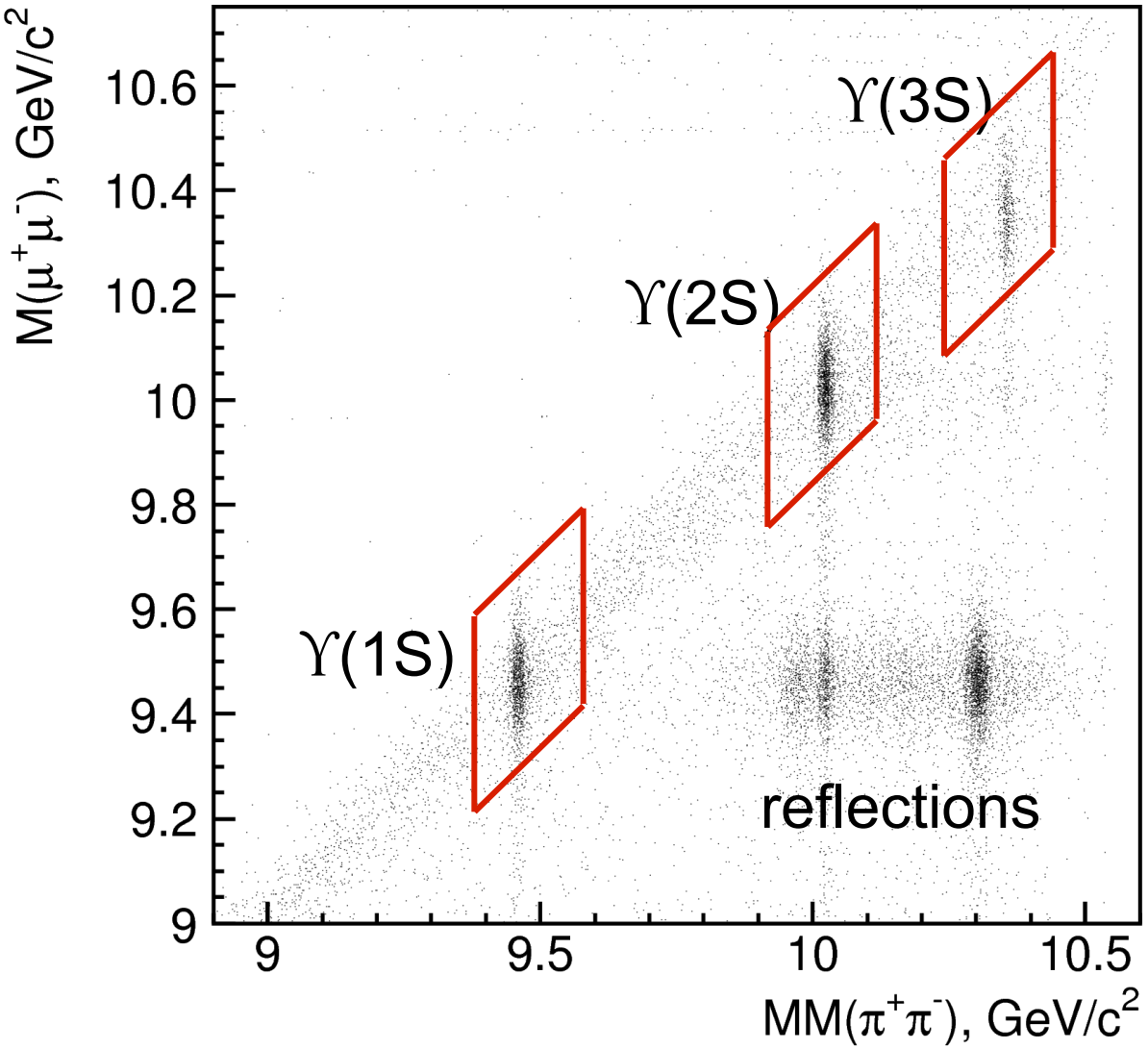
	$h_b(1P)\pi^\pm\pi^\mp$	$h_b(2P)\pi^\pm\pi^\mp$	
M_1 (MeV/c^2)	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$	Z_{b1}
Γ_1 (MeV)	$11.4^{+4.5+2.1}_{-3.9-1.2}$	16^{+16+13}_{-10-14}	
M_2 (MeV/c^2)	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$	Z_{b2}
Γ_2 (MeV)	$20.9^{+5.4+2.1}_{-1.7-5.7}$	$12^{+11+8}_{-9\ -2}$	
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

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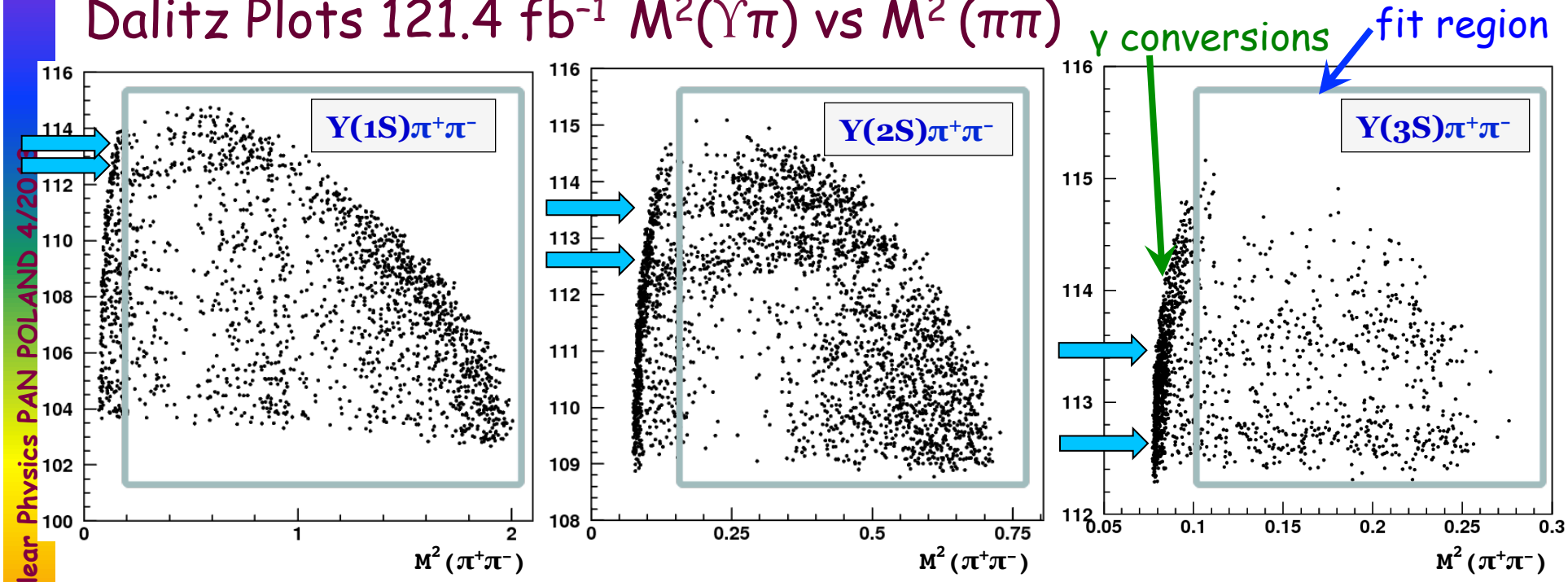
Resonant substructure $\Upsilon(5S) \to \Upsilon(nS)\pi^{\pm}\pi^{\mp}$

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)

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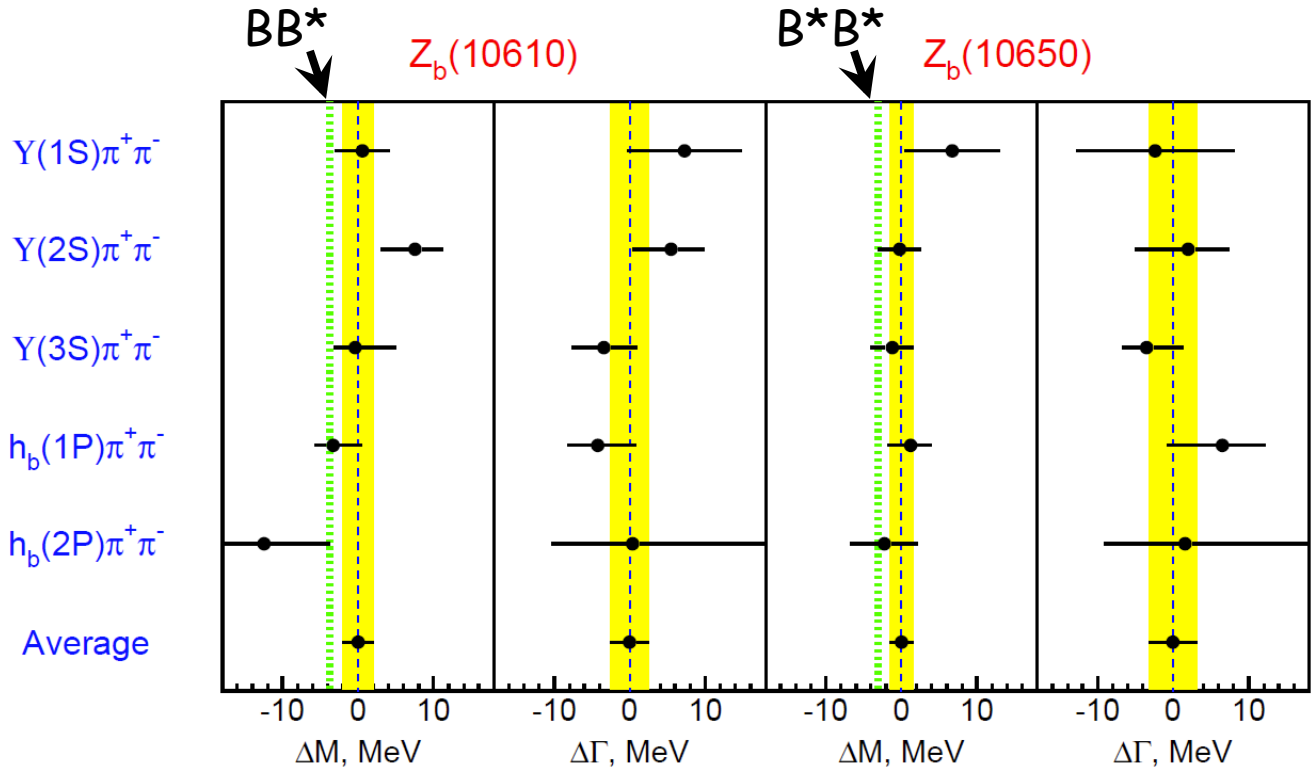
$\Upsilon(5S) \to \Upsilon(nS)\pi^{\pm}\pi^{\mp}$

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

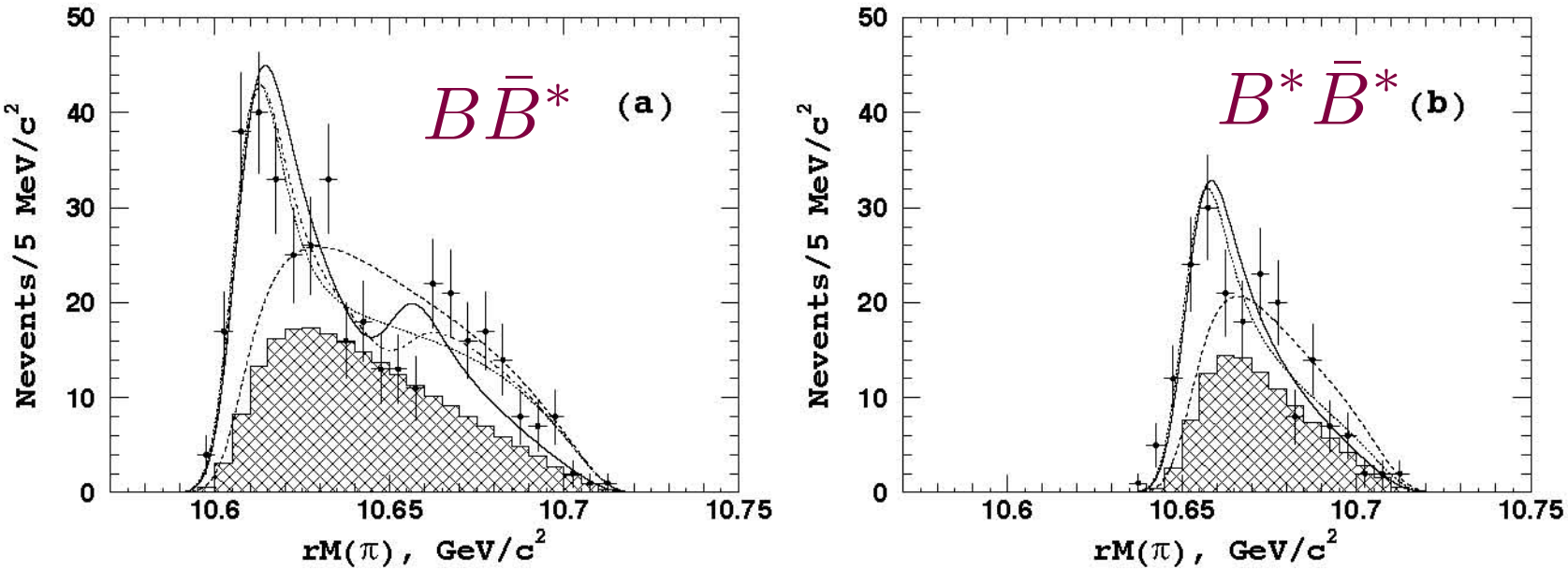
$\Gamma=15.6\pm2.5$ MeV $\Gamma=14.4\pm3.2$ MeV

- 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

Further evidence

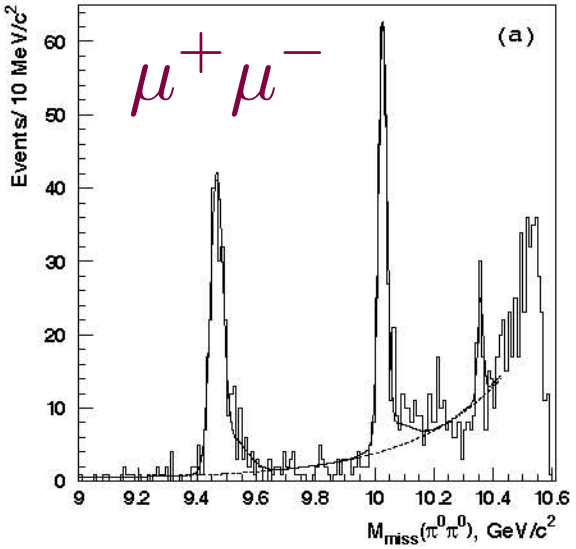
121.4 fb^{-1}

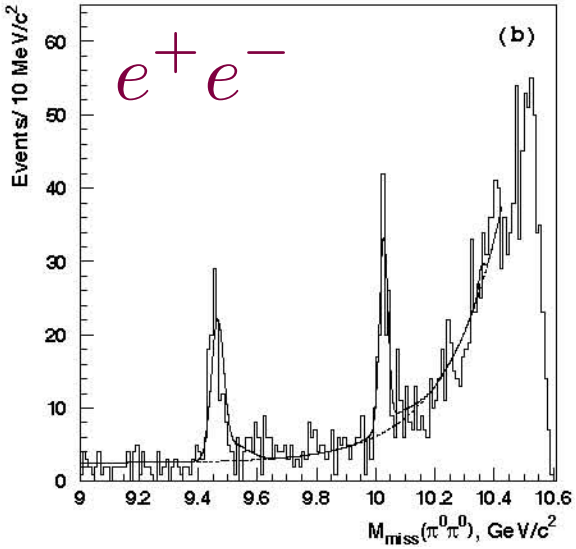


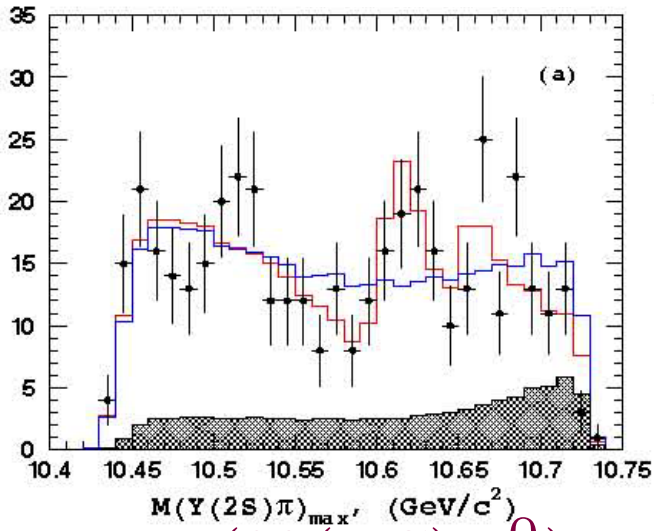
arXiv:1209.6450 [hep-ex]

Further evidence

121.4 fb^{-1}







$M(\Upsilon(2S)\pi^0)$

$\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ $\quad$ $Z_b^0 \to \Upsilon(nS)\pi^0$

arXiv:1207.4345 [hep-ex]

Followup: scan above/below $\Upsilon(5S)$ in 2009-10

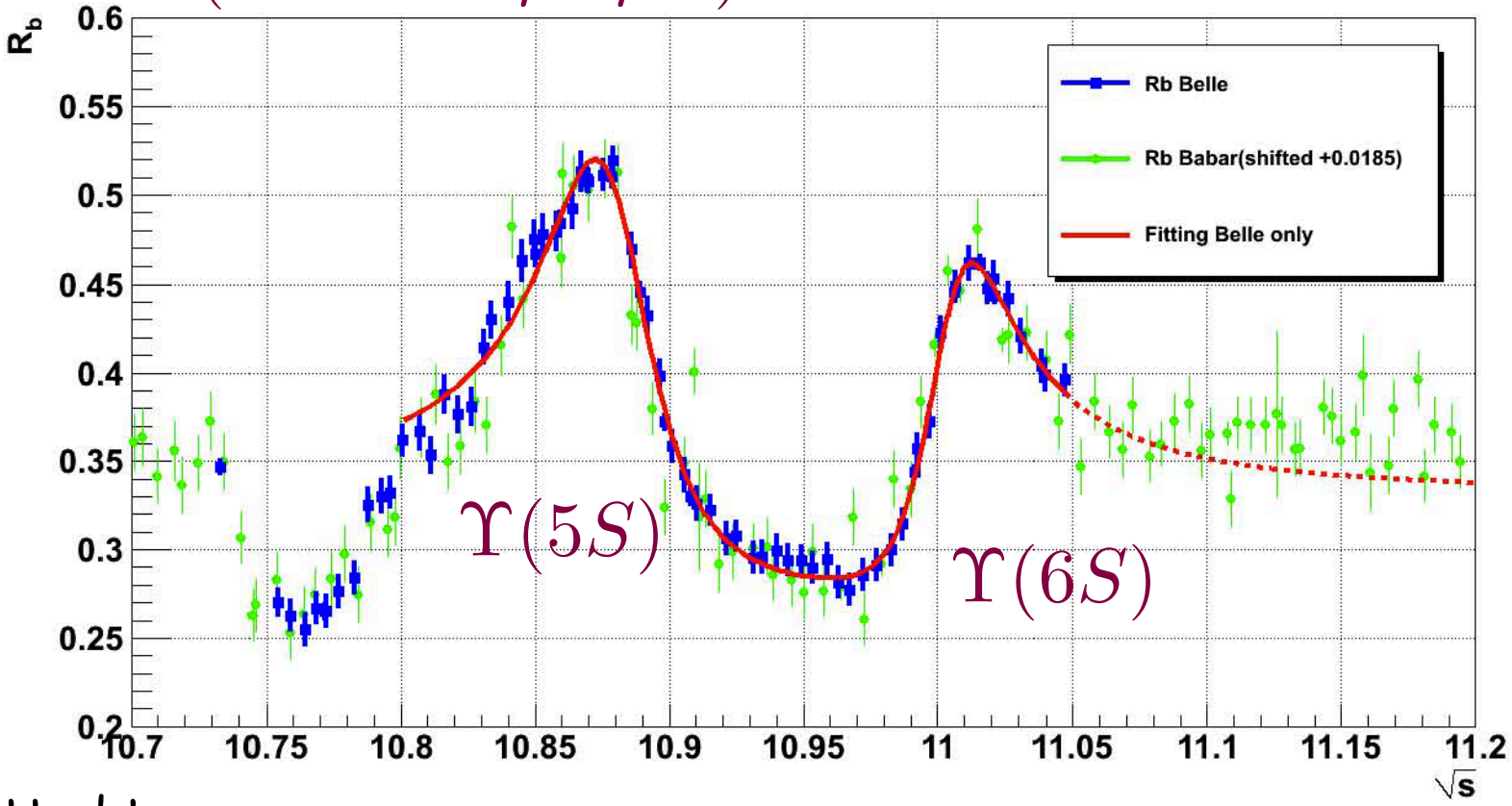
15 additional ~1 fb^{-1} points, 121.4 fb^{-1} total on resonance
+ 61 ~50 pb^{-1} points for R_b measurement

Experiment	Calibrated CM Energy (GeV)	Luminosity (fb^{-1})	Experiment	Calibrated CM Energy (GeV)	Luminosity (fb^{-1})
e73	10.6828	0.95	e73	11.0158	0.77
e73	10.7328	0.95	e73	11.0214	0.98
e73	10.7715	0.96	e53+e43	10.8667	23.6
e73	10.8498	0.99	e67	10.8667	27.29
e73	10.8590	0.99	e69	10.8633	47.65
e73	10.8696	0.98	e71	10.8686	22.94
e73	10.8785	0.98	Includes average 30% data loss		
e73	10.8889	0.99	e61	10.8255	1.164
e73	10.8984	0.98	e61	10.8805	1.27
e73	10.9076	0.98	e61	10.8955	.873
e73	10.9771	1.00	e61	10.9255	.667
e73	10.9914	0.99	e61	10.9555	.851
e73	11.0062	0.98	e61	11.0155	0.849

Measurement of $e^+e^- \to b\bar{b}$

$$R_b \equiv \frac{\sigma(e^+e^- \to b\bar{b})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Belle-CONF- 1250



Fitted to

$$|A_{NR}|^2 +$$

$$|A_R + A_{5S}e^{i\phi_{5S}}BW(M_{5S},\Gamma_{5S}) + A_{6S}e^{i\phi_{6S}}BW(M_{6S},\Gamma_{6S})|^2$$

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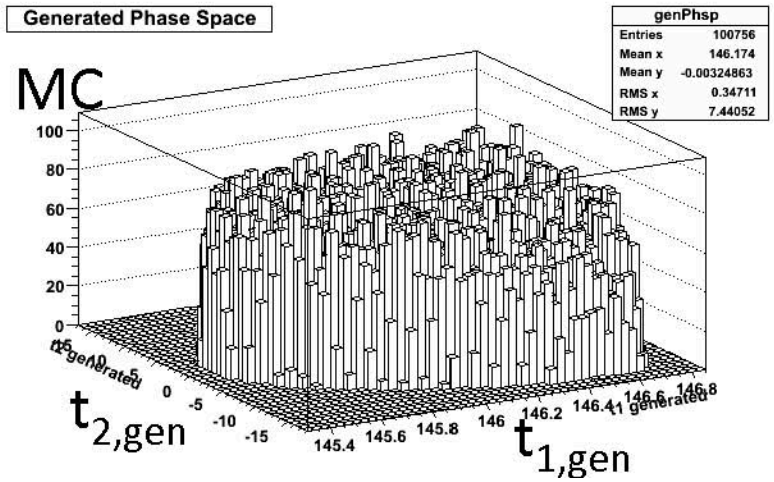
Measurement of $e^+e^- \to b\bar{b}$

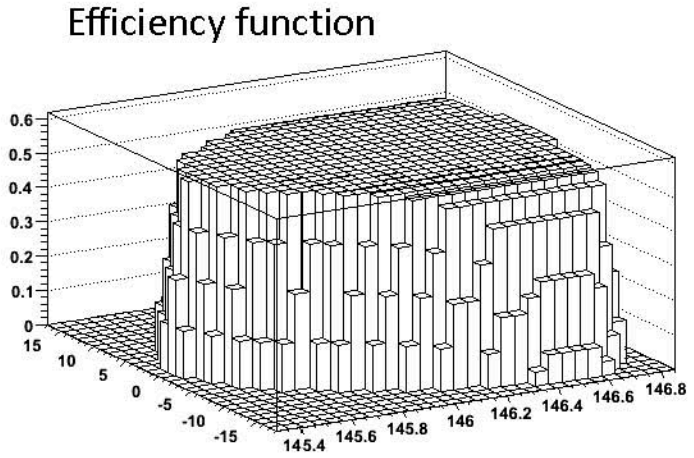
Results: masses, widths

	parameter	Belle	Babar	PDG(2012)
continuum	A_{nr}	0.42 ± 0.01	-	-
	A_r	0.38 ± 0.01	-	-
$\Upsilon(5S)$	$A(5S)$	0.23 ± 0.04	-	-
	$M(5S)$ (MeV)	10880.4 ± 0.9	10876 ± 2	10876 ± 11
	$\Gamma(5S)$ (MeV)	51 ± 2	43 ± 4	55 ± 28
	$\phi(5S)$ (Rad)	2.26 ± 0.05	2.11 ± 0.12	-
$\Upsilon(6S)$	$A(6S)$	0.20 ± 0.02	-	-
	$M(6S)$ (MeV)	11004 ± 1	10996 ± 2	11019 ± 8
	$\Gamma(6S)$ (MeV)	40 ± 2	37 ± 3	79 ± 16
	$\phi(6S)$ (Rad)	0.61 ± 0.07	0.12 ± 0.07	-

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

- Event selection: similar to KF Chen et al.
- New: event-by-event efficiency correction over Dalitz space, reduce model-dependence





$$t_1 \equiv [m^2_{\Upsilon\pi+} + m^2_{\Upsilon\pi-}]/\sqrt{2}$$

$$t_2 \equiv [m^2_{\Upsilon\pi+} - m^2_{\Upsilon\pi-}]/\sqrt{2}$$

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

- New: reduce ISR – veto conversions without cutting on Dalitz space: vertex of $\pi^+\pi^-$ candidates (>90% eff)

$$e^+e^- \to e^+e^-\{\to \mu^+\mu^-\}\gamma\{\to e^+e^-\}$$

- event-by-event sideband subtraction
- fitted to same shape as R_b

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

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- fit function

$$PHSP(E_{CM}) \times (|A_{NR}|^2 + |A_R + A_{5S}e^{i\phi_{5S}}BW(M_{5S},\Gamma_{5S}) + A_{6S}e^{i\phi_{6S}}BW(M_{6S},\Gamma_{6S})|^2)$$

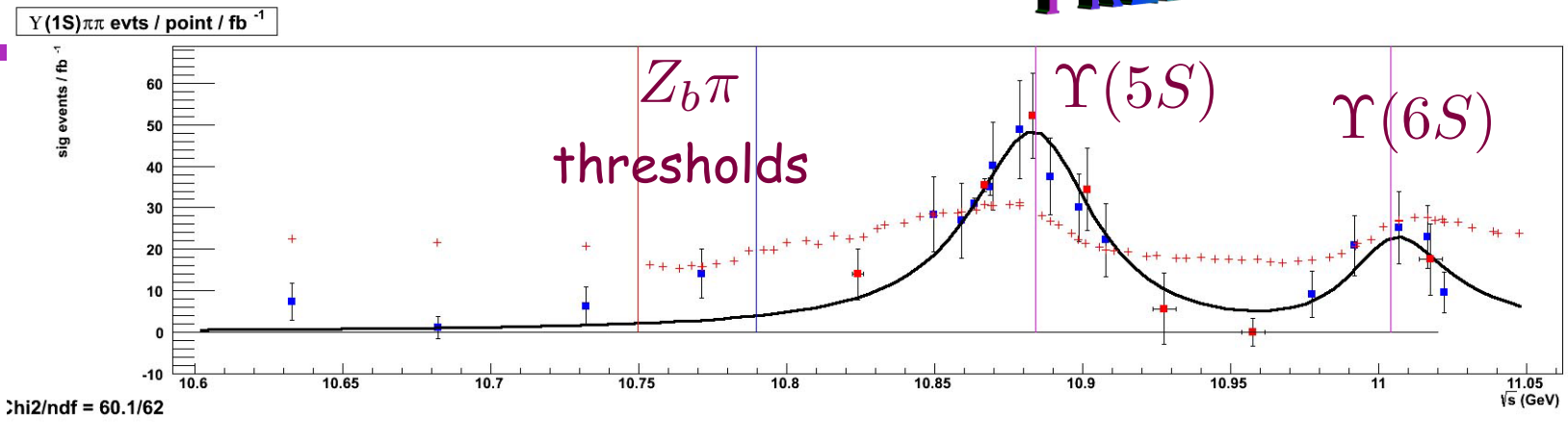
- correlation: relative phase, Υ(6S) mass; insufficient data at Υ(6S) => fix Υ(6S) mass, relative phase
  float: amplitudes, Υ(5S) mass, width [simultaneous for Υ(1S), Υ(2S), Υ(3S)]
- result

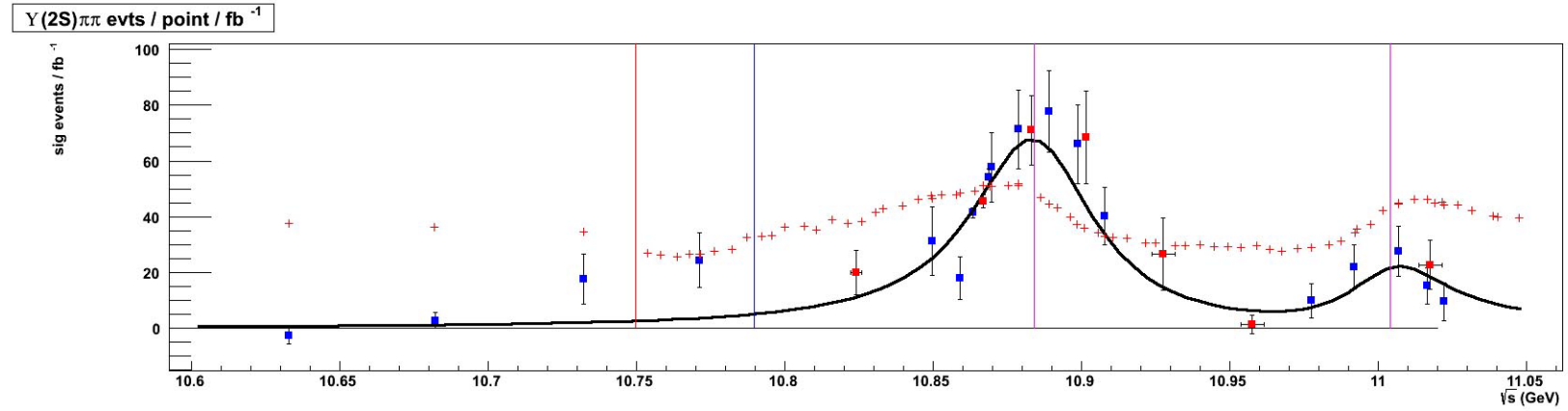
PRELIMINARY

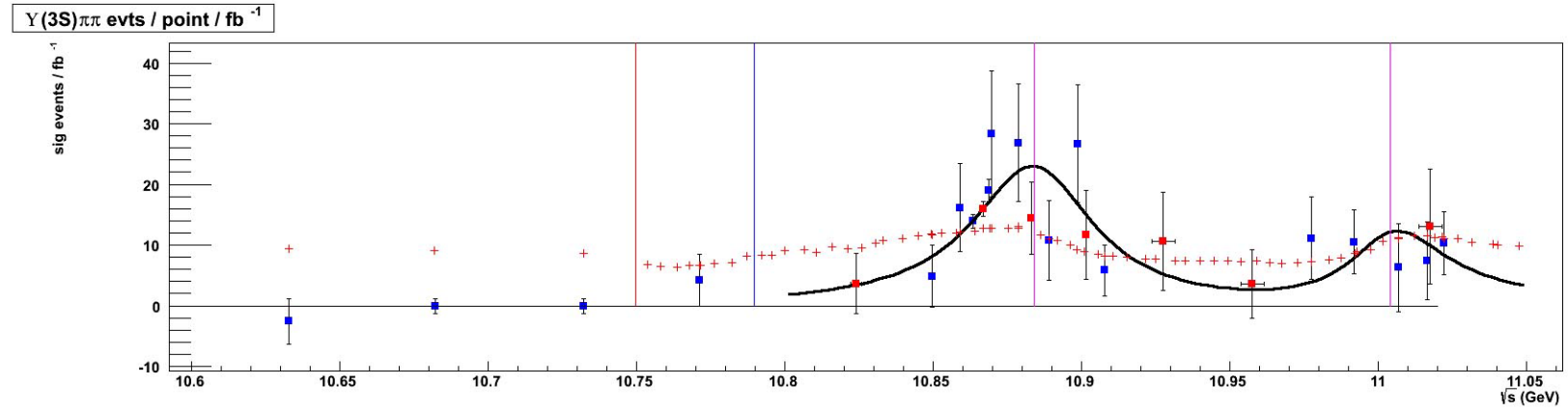
χ^2/ndf	M_{5S} (GeV)	Γ_{5S} (GeV)	ϕ_{6S-5S} (Rad)	A_{nr}	A_r
57.8/60.0	10.8851 ± 0.0018	0.047 ± 0.005	-1.6500	1.4 ± 0.6	0.4 ± 0.4

- systematics: VERY preliminary

PRELIMINARY







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

- systematics: in progress
  fitting effects: float Υ(5S) width, relative phase
  vary fitting range
  Dalitz structure dependence
  energy calibration
- VERY preliminary: <±2 MeV

Preliminary conclusion

- fit yields

$$M_{\Upsilon(5S)}(\Upsilon(nS)\pi\pi) - M_{\Upsilon(5S)}(R_b) = (4.7 \pm 2.0)\mathrm{MeV//c^2}$$

- but data fit with masses, widths from R_b fit give reasonable chisquare/DOF (67.4/62)

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Summary

KEKB and Belle at Υ(5S)+

- multiple new questions raised by behavior of

$$\Upsilon(5S) \to \{b\bar{b}\}\pi\pi$$

  New states $Z_b^+(10610)$, $Z_b^+(10650)$
  Seen to decay to BB*, B*B*
  Evidence for neutral Z_b

- compare parameters to results from R_b
  preliminary: consistent Υ(5S) mass