La Thuile 2011, March 2 2010

Physics at $\Upsilon(5S)$

Roman Mizuk
ITEP, Moscow

for the BELLE Collaboration

Contents

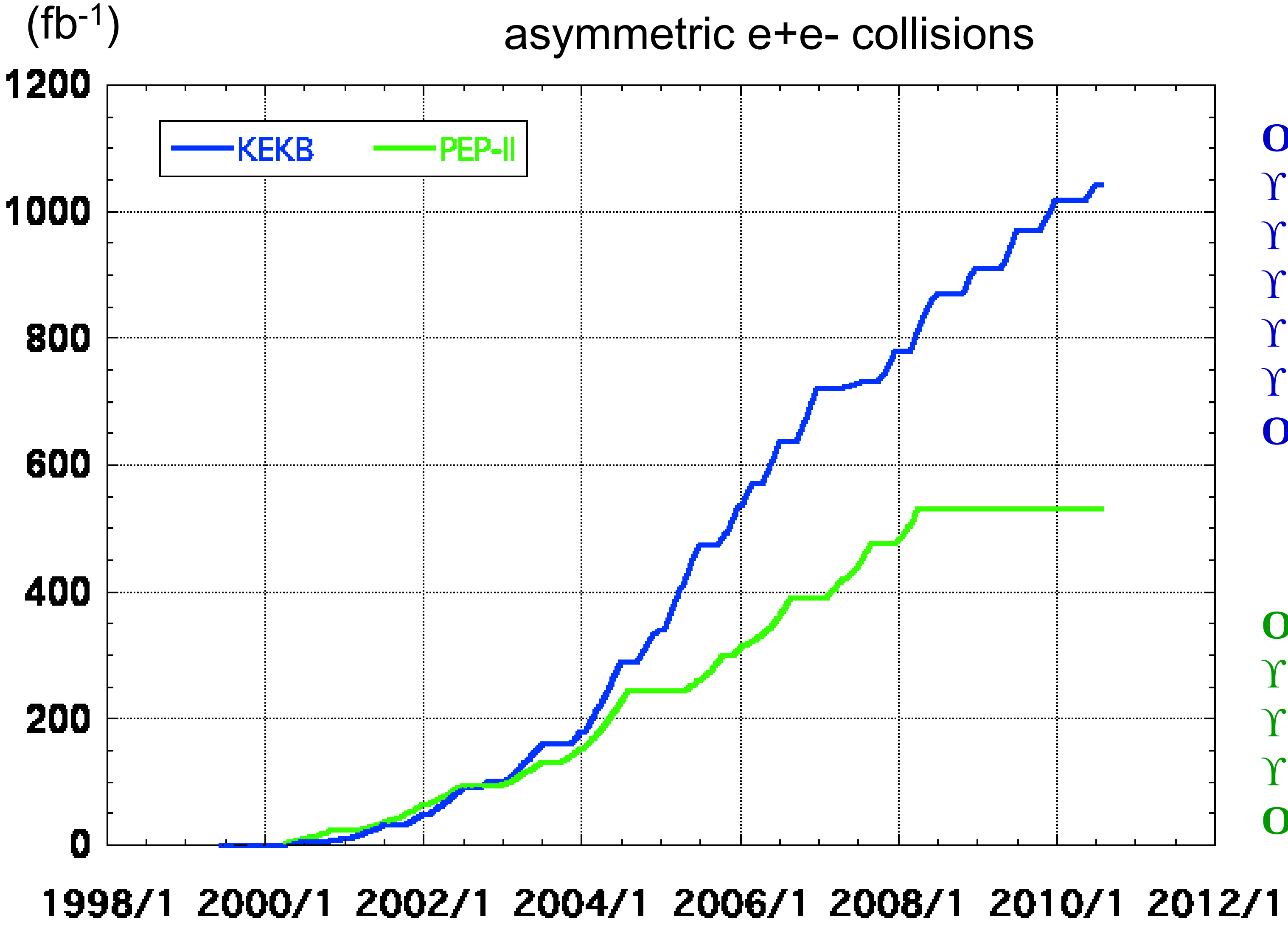
Observation of $B_s \to J/\psi\ f_0(980)$ and evidence for $B_s \to J/\psi\ f_0(1370)$

arXiv:1102.2759, submitted to PRL

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

Results are preliminary

Integrated Luminosity at B-factories



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}
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

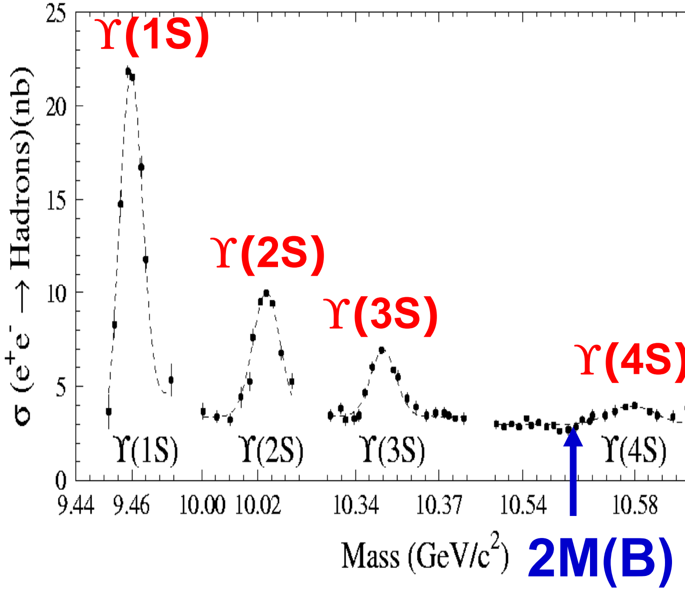
530 fb^{-1}

On resonance:

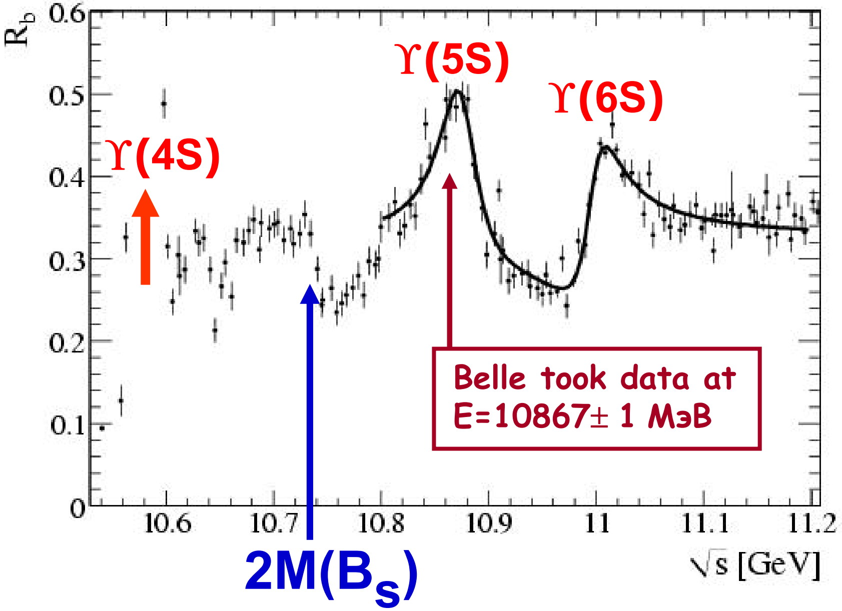
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}

Off reson./scan :
~54 fb-1

e^+e^- hadronic cross-section



BaBar PRL 102, 012001 (2009)



Belle took data at
E=10867± 1 МэВ

$e^+ e^-$ -> $\Upsilon(4S)$ -> $B\bar{B}$, where B is B^+ or B^0

$e^+ e^-$ -> $b\bar{b}$ ($\Upsilon(5S)$) -> $B^{(*)}\bar{B}^{(*)}$, $B^{(*)}\bar{B}^{(*)}\pi$, $B\bar{B}\pi\pi$, $B_s^{(*)}\bar{B}_s^{(*)}$, $\Upsilon(1S)\pi\pi$, ΥX …

study

Measurements of B_s decays at Belle

L= 23.6 fb^{-1}

Before Belle less then 10 decays were known

B_s^0 Decay	Branching Fraction, 10^{-3}	B^0 decay	Branching fraction, 10^{-3}
$B_s^0 \to D_s^- \pi^+$	$3.67\ ^{+0.35}_{-0.33}\ ^{+0.43}_{-0.42} \pm 0.49\,(f_s)$	$B^0 \to D^- \pi^+$	2.68 ± 0.13
> $B_s^0 \to D_s^{*-} \pi^+$	$2.4\ ^{+0.5}_{-0.4} \pm 0.3 \pm 0.4\,(f_s)$	$B^0 \to D^{*-} \pi^+$	2.76 ± 0.13
> $B_s^0 \to D_s^- \rho^+$	$8.5\ ^{+1.3}_{-1.2} \pm 1.1 \pm 1.3\,(f_s)$	$B^0 \to D^- \rho^+$	7.6 ± 1.3
> $B_s^0 \to D_s^{*-} \rho^+$	$11.9\ ^{+2.2}_{-2.0} \pm 1.7 \pm 1.8\,(f_s)$	$B^0 \to D^{*-} \rho^+$	6.8 ± 0.9
$B_s^0 \to D_s^{-/+} K^{+/-}$	$0.24\ ^{+0.12}_{-0.10} \pm 0.03 \pm 0.03\,(f_s)$	$B^0 \to D^{-/+} K^{+/-}$	0.20 ± 0.06
> $B_s^0 \to \phi \gamma$	$(\,5.7\ ^{+1.8}_{1.5}\ ^{+1.2}_{1.1}\,) \times 10^{-2}$	$B^0 \to K^*(892)^0 \gamma$	$(\,4.01 \pm 0.20\,) \times 10^{-2}$
$B_s^0 \to K^+ K^-$	$(3.8\ ^{+1.0}_{-0.9} \pm 0.5 \pm 0.5\,(f_s)) \times 10^{-2}$	$B^0 \to K^+ \pi^-$	$(\,1.94 \pm 0.06\,) \times 10^{-2}$
$B_s^0 \to D_s^+ D_s^-$	$(1.03\ ^{+0.39}_{-0.32}\ ^{+0.26}_{-0.25}\,) \times 10$	$B^0 \to D_s^+ D^-$	$(\,0.72 \pm 0.08\,) \times 10$
> $B_s^0 \to D_s^{*+} D_s^-$	$(2.75\ ^{+0.83}_{-0.71} \pm 0.69\,) \times 10$	$B^0 \to D_s^{*+} D^-$	$(\,0.80 \pm 0.11\,) \times 10$
> $B_s^0 \to D_s^{*+} D_s^{*-}$	$(3.08\ ^{+1.22}_{-1.04}\ ^{+0.85}_{-0.86}) \times 10$	$B^0 \to D_s^{*+} D^{*-}$	$(\,1.77 \pm 0.14\,) \times 10$
> $B_s^0 \to J/\psi\, \eta$	$(3.32 \pm 0.87\ ^{+0.32}_{-0.28} \pm 0.42(f_s)) / 10$	$B^0 \to J/\psi\, K^0$	$(\,8.71 \pm 0.32\,) / 10$ [/3]
> $B_s^0 \to J/\psi\, \eta'$	$(3.1 \pm 1.2\ ^{+0.5}_{-0.6} \pm 0.38(f_s))\ / 10$	$B^0 \to J/\psi\, K^0$	$(\,8.71 \pm 0.32\,) / 10$ [/3]
> $B_s^0 \to X^- \ell^+ \nu$	$(10.2 \pm 0.8 \pm 0.9\,) \times 10$	$B^0 \to X^- \ell^+ \nu$	$(\,10.33 \pm 0.28\,) \times 10$

Properties of B_s^0 and B^0 seem to be consistent with SU(3)

Today: first results with 121.4 fb^{-1}

Observation of $B_s \rightarrow J/\psi\ f_0(980)$ and evidence for $B_s \rightarrow J/\psi\ f_0(1370)$

Motivation

$B_s \rightarrow J/\psi\ f_0$

CP eigenstate , f_0 is scalar ⇒ no angular analysis is required to measure $\Delta\Gamma/\Gamma$ and CPV phase β_s

sensitivity to β_s can be comparable to “golden” $J/\psi\phi$

Stone et al. PRD79,074024(2009)

$\exists\ f_0 \rightarrow K^+K^-$

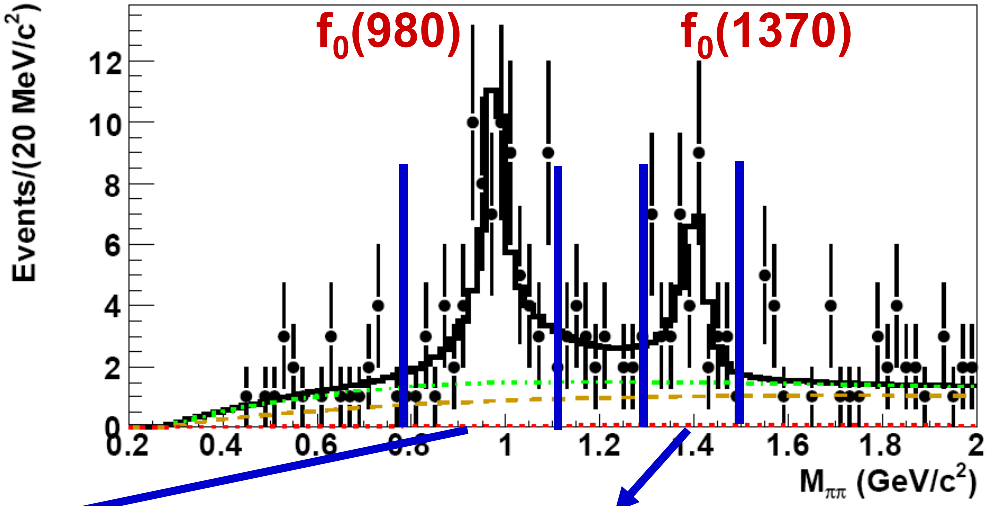
⇒ S-wave polution in $J/\psi\phi$ mode

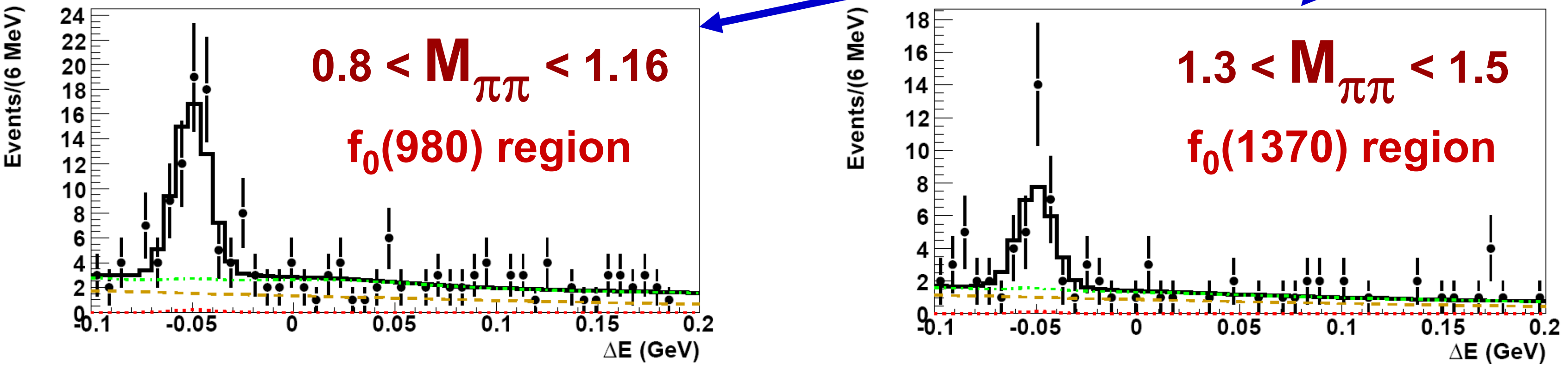
$B_s \to J/\psi\ f_0(980)$ / $f_0(1370)$ Signals

Select $B_s^*B_s^*$ region in M_{bc}
2D fit to ΔE vs. $M(\pi^+\pi^-)$

PDF = |Flatté + a $e^{i\theta}$ RBW|
+ non-res $J/\psi\pi^+\pi^-$ + other BG

Fit projections





	Yield	Significance	$\mathcal{B}(B_s^0 \to J/\psi F; F \to \pi^+\pi^-)$
$f_0(980)$	63^{+16}_{-10}	8.4σ	$1.16^{+0.31}_{-0.19}(\text{stat.})^{+0.15}_{-0.17}(\text{syst.})^{+0.26}_{-0.18}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4}$
$f_0(1370)$	19^{+6}_{-8}	4.2σ	$0.34^{+0.11}_{-0.14}(\text{stat.})^{+0.03}_{-0.02}(\text{syst.})^{+0.08}_{-0.05}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4}$

non-res $J/\psi\pi^+\pi^-$ 4±12

consistent with expectation : $(1.3–3.2)\times10^{-4}$

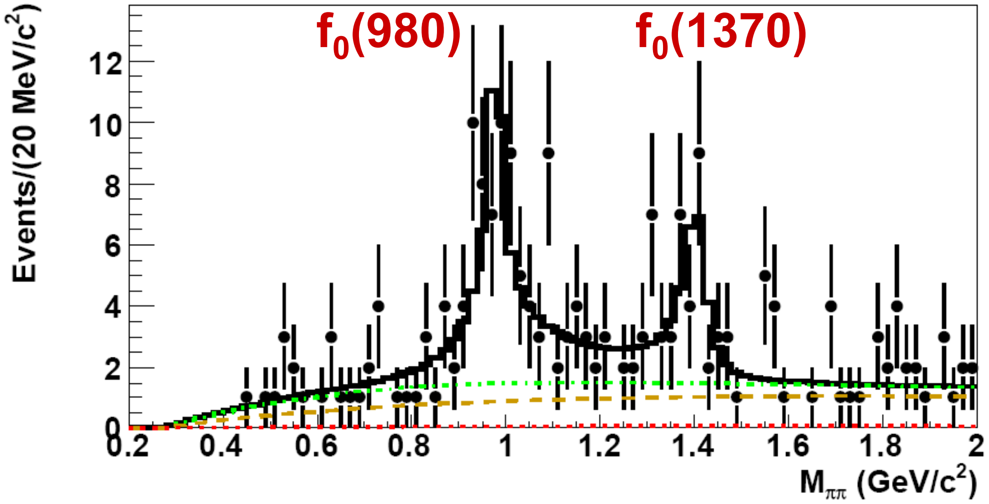
$B_s \rightarrow J/\psi\, f_0(980)$ / $f_0(1370)$ Signals

$f_0(1370)$ mass, width

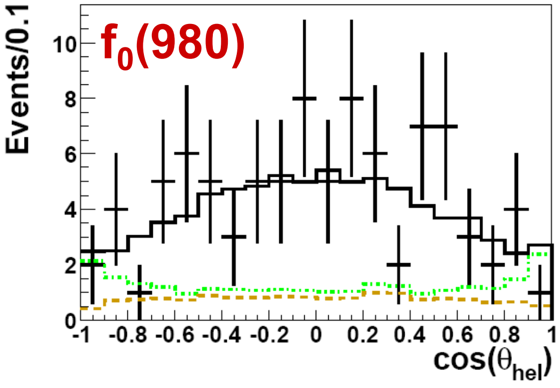
$$m_0 = 1.405 \pm 0.015^{+0.001}_{-0.007}\ \mathrm{GeV}/c^2$$

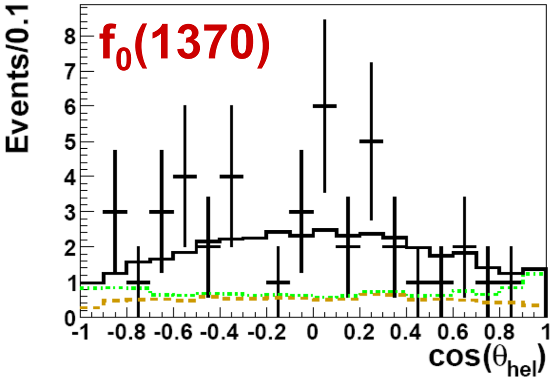
$$\Gamma_0 = 0.054 \pm 0.033^{+0.014}_{-0.003}\ \mathrm{GeV}$$

⇒ compatible with PDG results



J/ψ helicity angle is consistent with expectations for scalar resonance





⇒ Observation of $B_s \rightarrow J/\psi\, f_0(980)$ and evidence for $B_s \rightarrow J/\psi\, f_0(1370)$

Observation of **$B_s \rightarrow J/\psi\, f_0(980)$** is also reported by LHCb and CDF

arXiv:1102.0206

Observation of

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

Puzzles of Υ(5S) decays

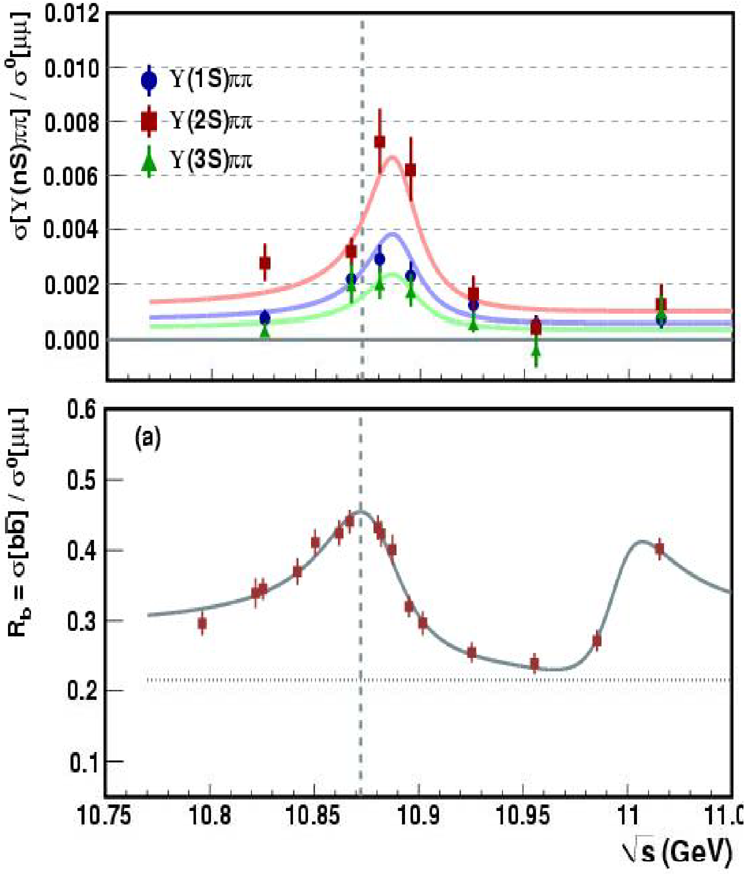
1. Anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$

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) Exotic resonance Y_b near Υ(5S)

analog of Y(4260) resonance

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

Energy scan ⇒

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

PRD81,112003(2010)

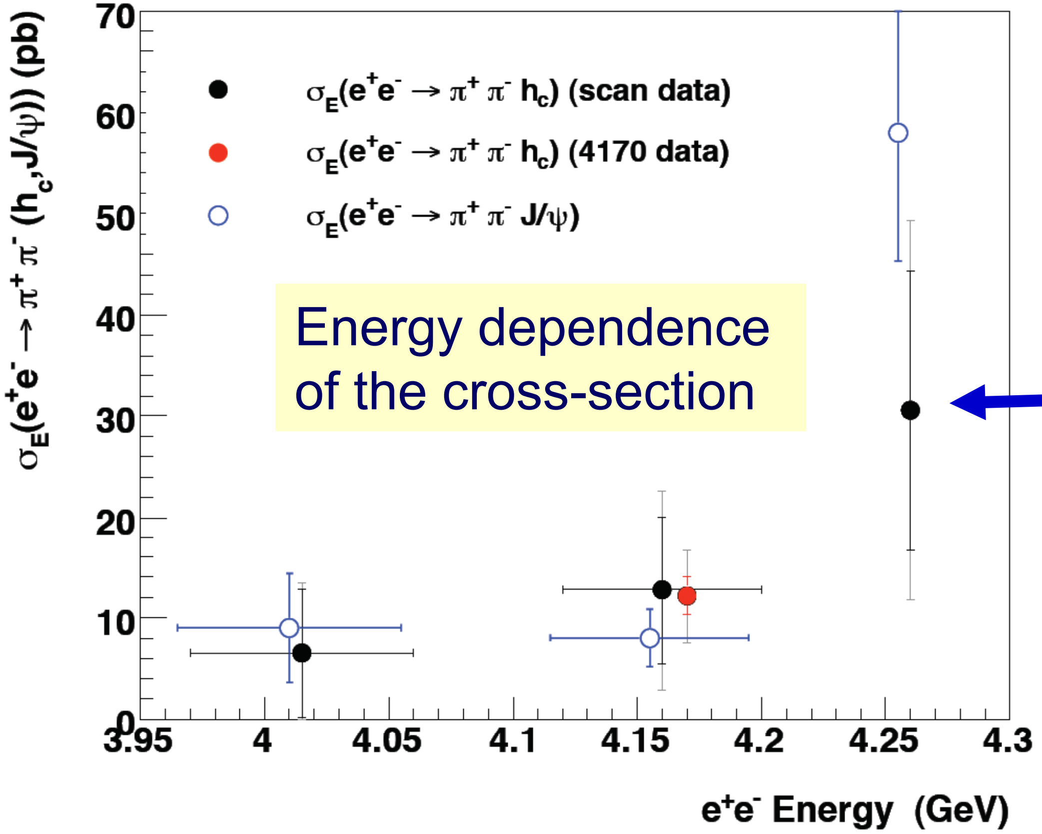
2. $\mathrm{BF}[\Upsilon(5S) \to B^*\overline{B}\pi] = (7.3\ ^{+2.3}_{-2.1} \pm 0.8)\ \%$ *>10 times higher than expectations*

Υ(5S) is very interesting and not yet understood region

Trigger

Observation of **$e^+e^- \to \pi^+\pi^- h_c$** by CLEO

Ryan Mitchell @ CHARM2010



Energy dependence of the cross-section

Enhancement of $\sigma(h_c\,\pi^+\pi^-)$
@ Y(4260)

⇓

$\sigma(h_b\,\pi^+\pi^-)$ is enhanced @ Y_b

⇒ Search for h_b in $\Upsilon(5S)$ data

Introduction to $h_b(nP)$

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

Expected mass

≈ ($M\chi_{b0}$ + 3 $M\chi_{b1}$ + 5 $M\chi_{b2}$) / 9

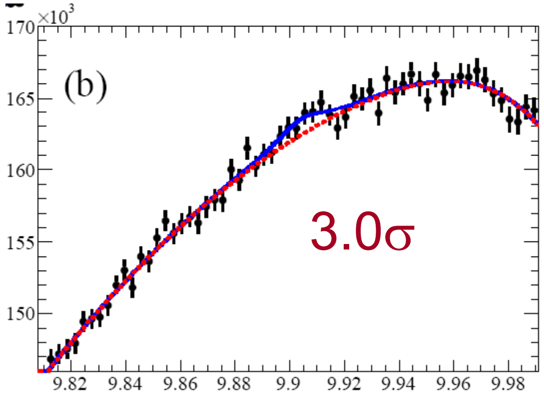
$\Delta M_{CoG} \Rightarrow$ test of hyperfine interaction

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

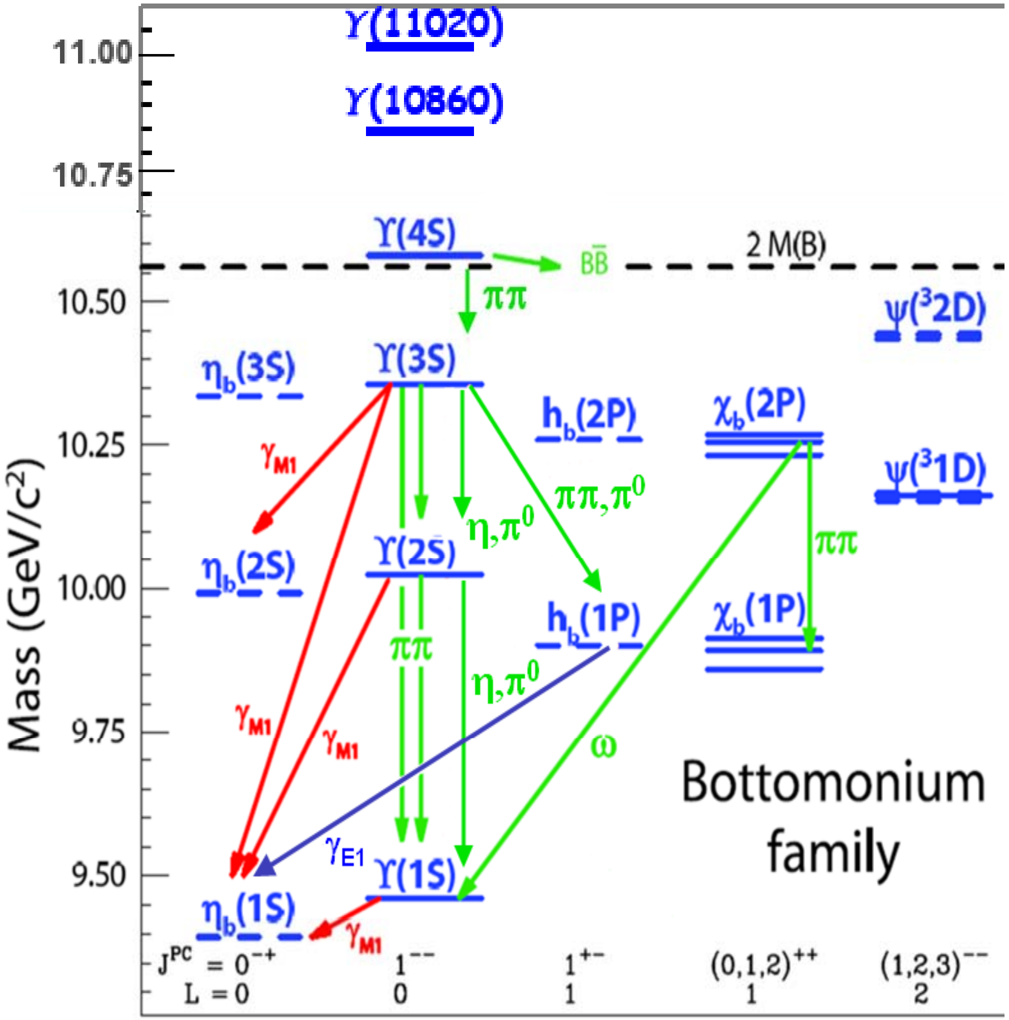
arXiv:1102.4565

Evidence from BaBar

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



3.0σ



Bottomonium family

Method : missing mass technique

Search for signal $\boxed{\Upsilon(5S)} \to h_b(nP)\,\boxed{\pi+\pi-}$

$\underline{P}_{\Upsilon(5S)}$ is given by
c.m. energy and boost
accelerator information

$\underline{P}_{\pi+\pi-}$ is measured
reconstructed

$\underline{P}_{\Upsilon(5S)} - \underline{P}_{\pi+\pi-}$

Method : missing mass technique

Search for signal $\boxed{\Upsilon(5S)} \to h_b(nP) \boxed{\pi+\pi-}$

$\underline{P}_{\Upsilon(5S)}$ is given by
c.m. energy and boost
accelerator information

$\underline{P}_{\pi+\pi-}$ is measured
reconstructed

$$M_{hb(nP)} = \sqrt{(\, \underline{P}_{\Upsilon(5S)} - \underline{P}_{\pi+\pi-})^2} \equiv MM(\pi+\pi-)$$

⇒ Search for h_b(nP) peaks in MM($\pi^+\pi^-$) spectrum

Simple selection :

$\pi^+\pi^-$: good quality, positively identified

Continuum events have jet-like shape ⇒ cut on sphericity variable R2<0.3
R2 = ratio of Fox-Wolfram moments

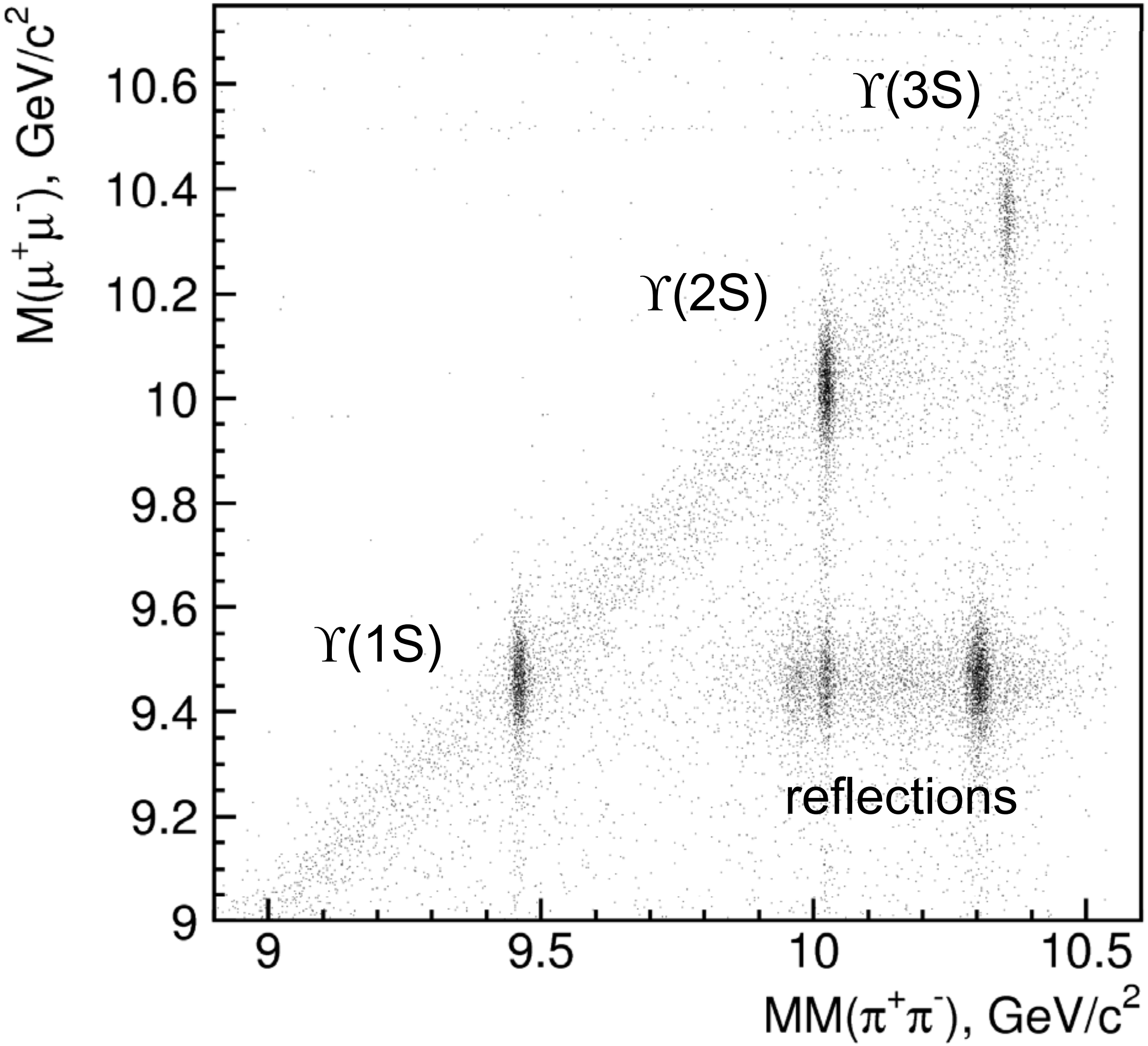
“blind analysis”

Calibration channels

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

$\Upsilon(nS) \to \mu^+\mu^-$

(n = 1,2,3)

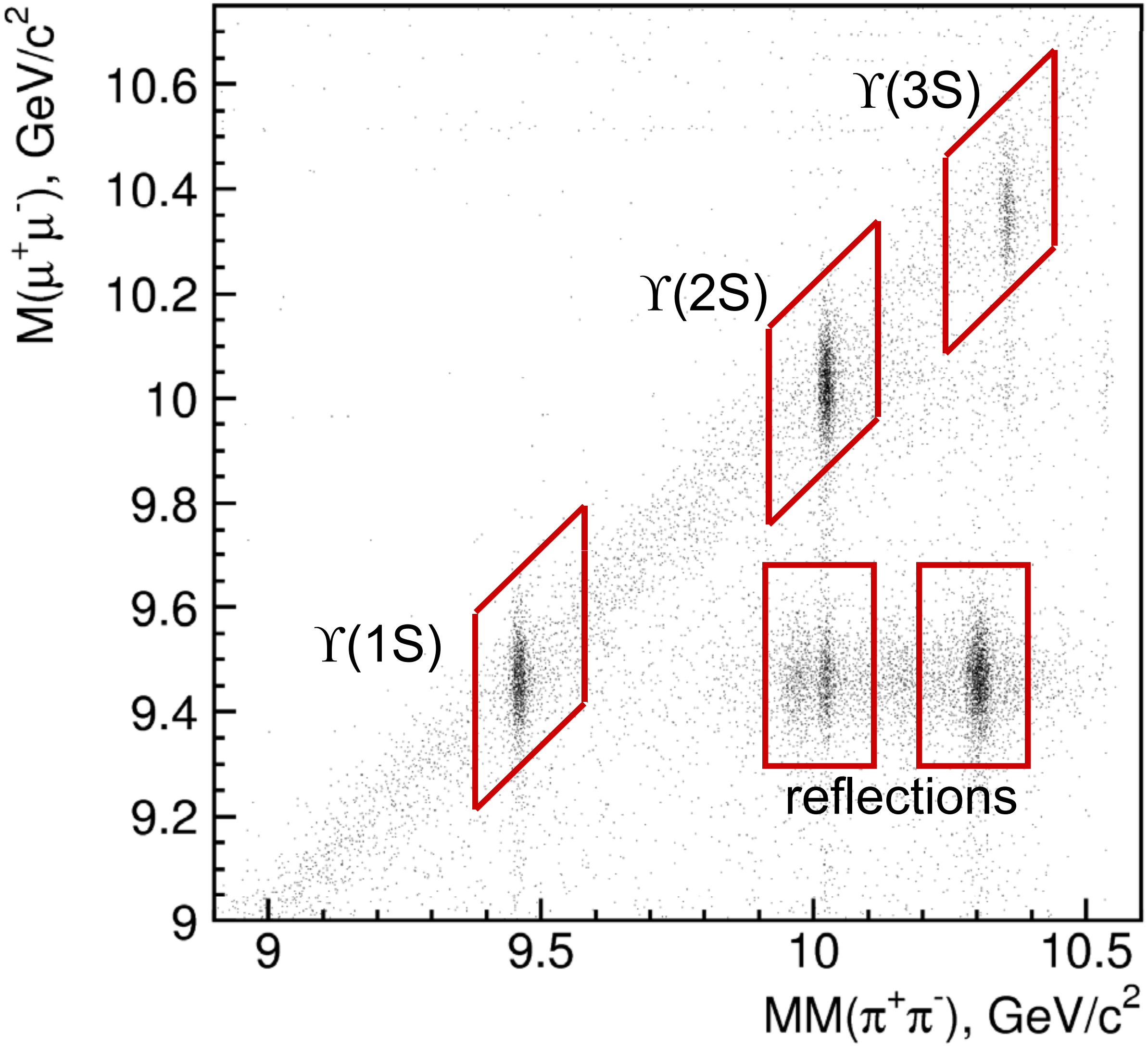


Calibration channels

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

$\Upsilon(nS) \to \mu^+\mu^-$

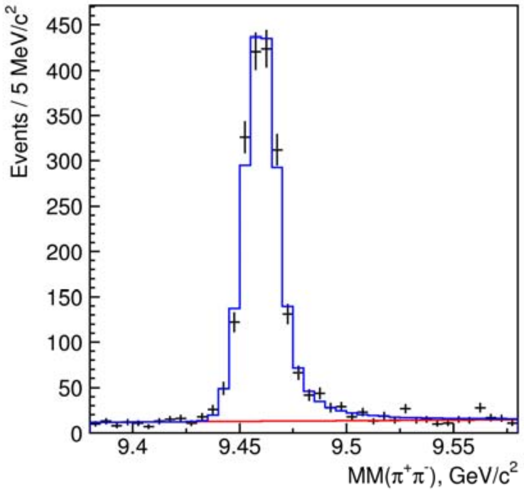
(n = 1,2,3)



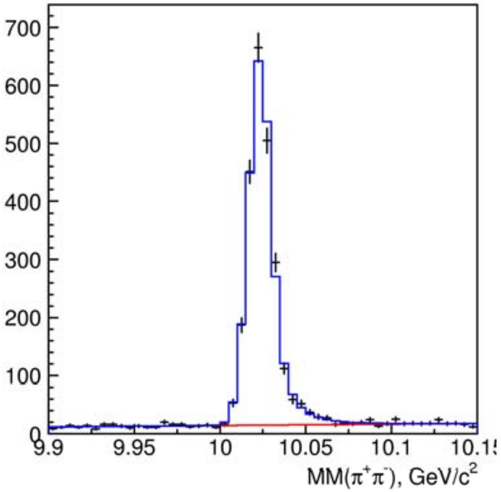
Calibration channels

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

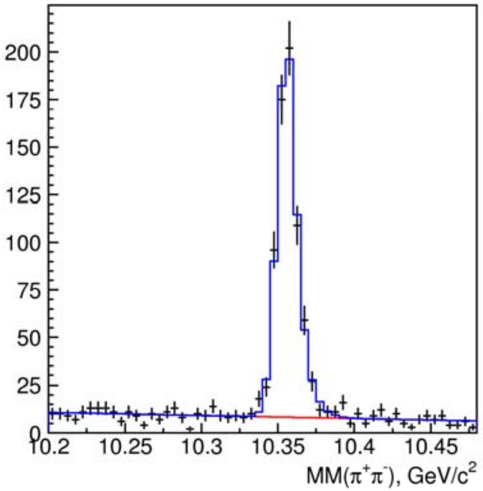
$\Upsilon(5S) \to \Upsilon(1S)\ \pi\pi$

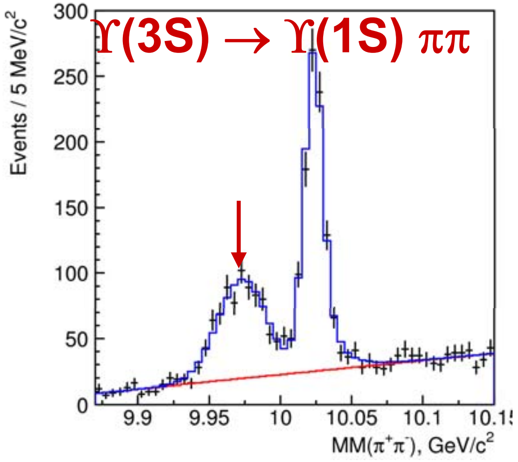


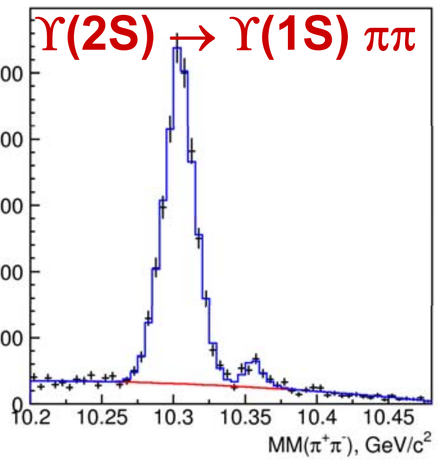
$\Upsilon(5S) \to \Upsilon(2S)\ \pi\pi$



$\Upsilon(5S) \to \Upsilon(3S)\ \pi\pi$




$\Upsilon(3S) \to \Upsilon(1S)\ \pi\pi$


$\Upsilon(2S) \to \Upsilon(1S)\ \pi\pi$

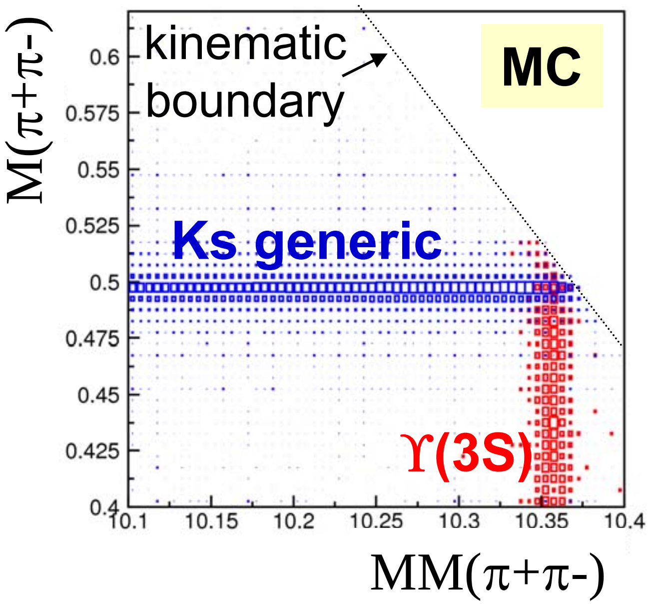
⇒ Shapes of signals

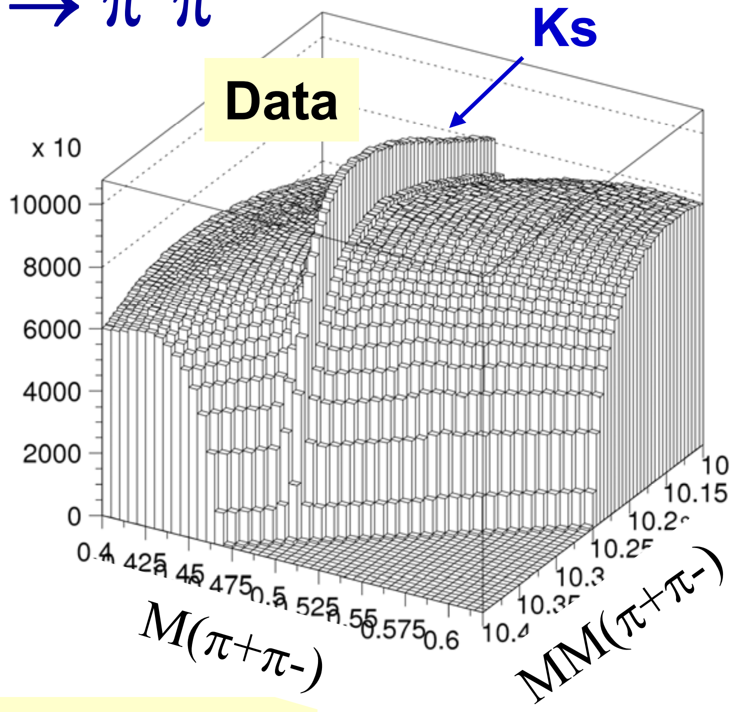
CrystalBall function

tail (8%) – ISR of soft γ
σ = 5.7 – 7.5 MeV

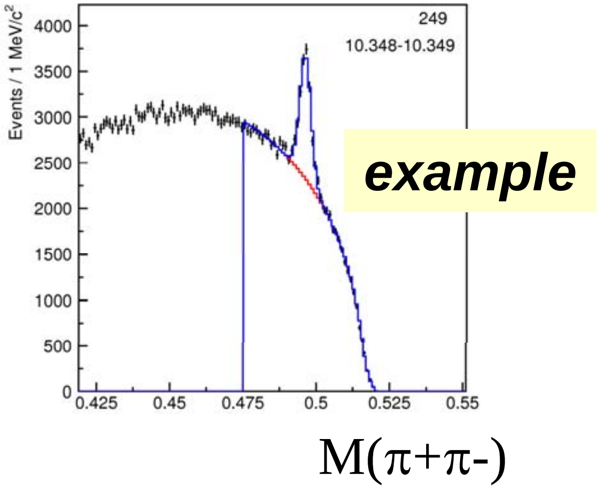
⇒ Shapes of reflections

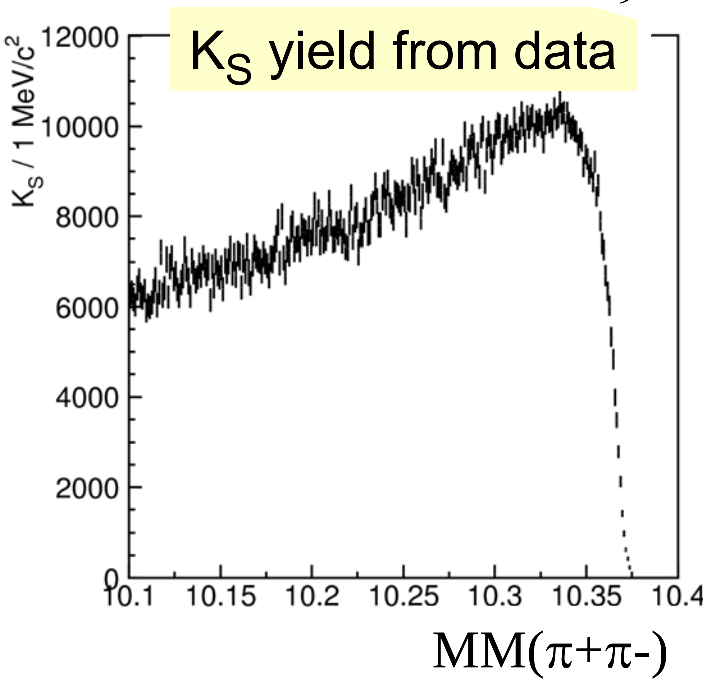
Reflection from $K_S \to \pi^+\pi^-$





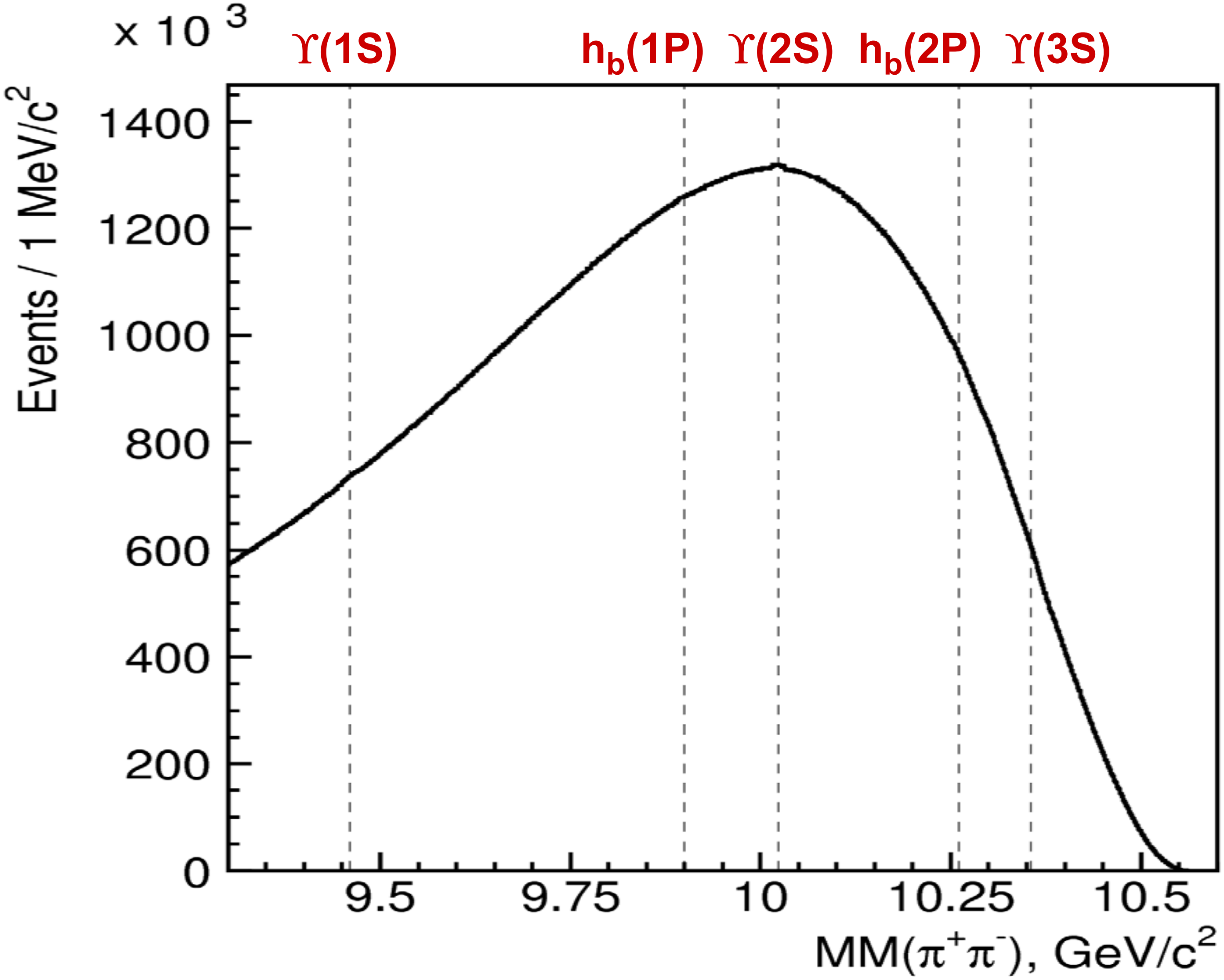
Fit to $M(\pi^+\pi^-)$ in $MM(\pi^+\pi^-)$ bins ⇒





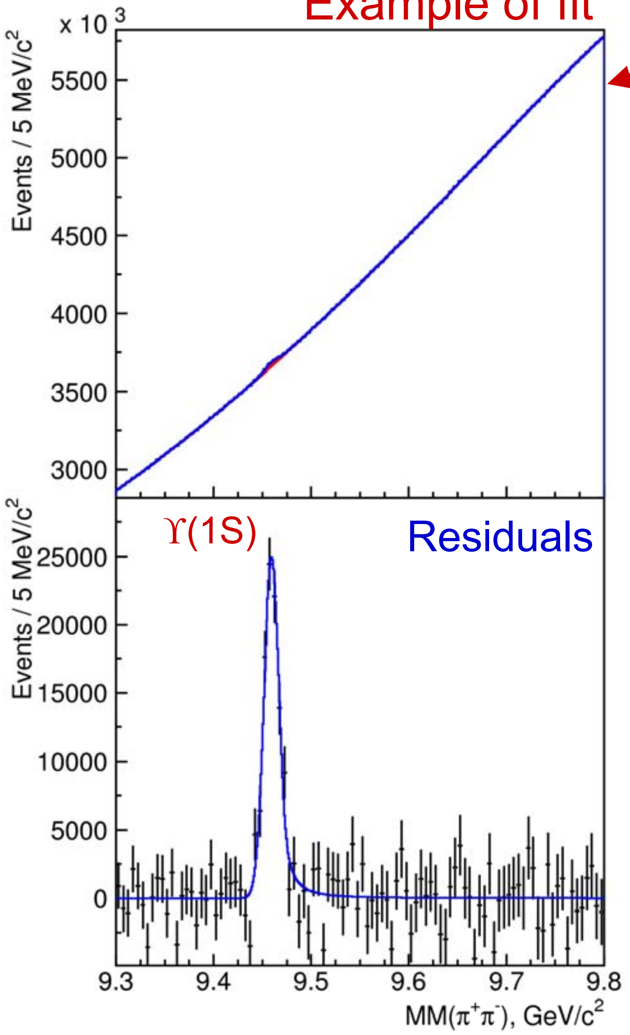
MM($\pi^+\pi^-$) spectrum

121.4 fb^{-1}

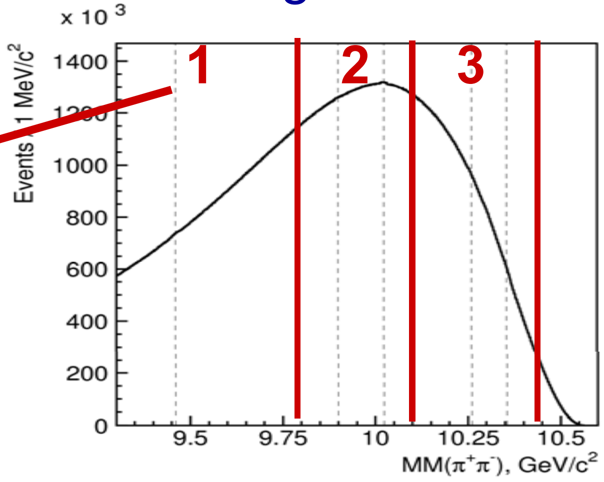


Description of fit to MM($\pi^+\pi^-$)

Example of fit



Three fit regions



BG: Chebyshev polynomial, order: max C.L. of fit

6th or 7th order

Signal: shape is fixed from $\mu^+\mu^-\pi^+\pi^-$ data

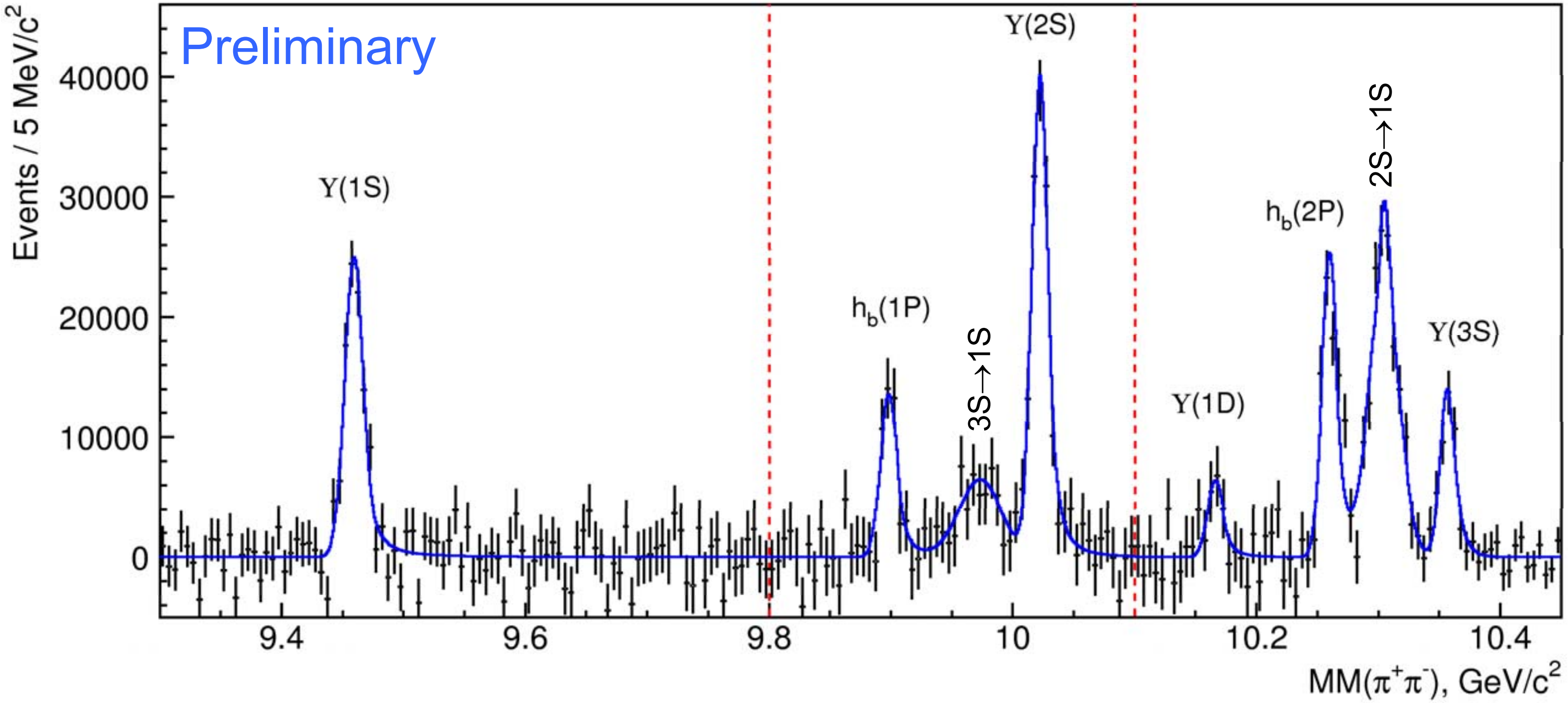
"Residuals" – subtract polynomial from data points

K_S contribution: subtract bin-by-bin

in region #3 only

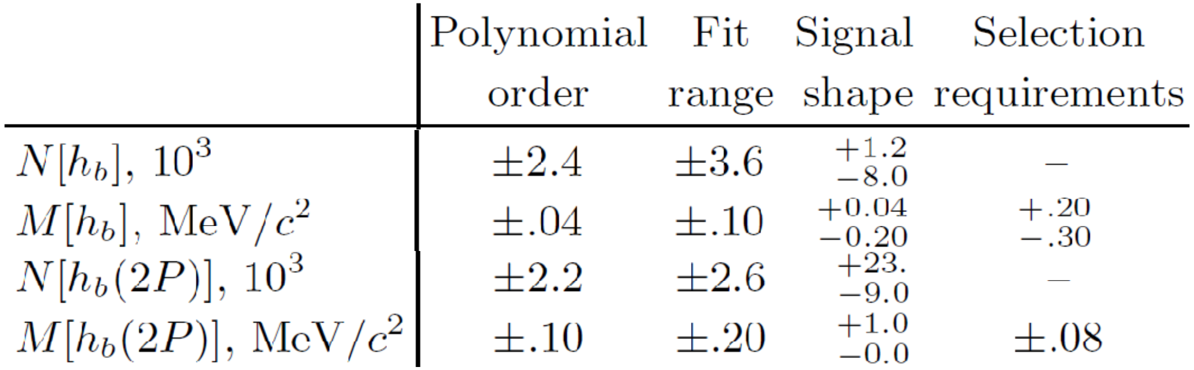
Results

121.4 fb^{-1}



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

Systematics



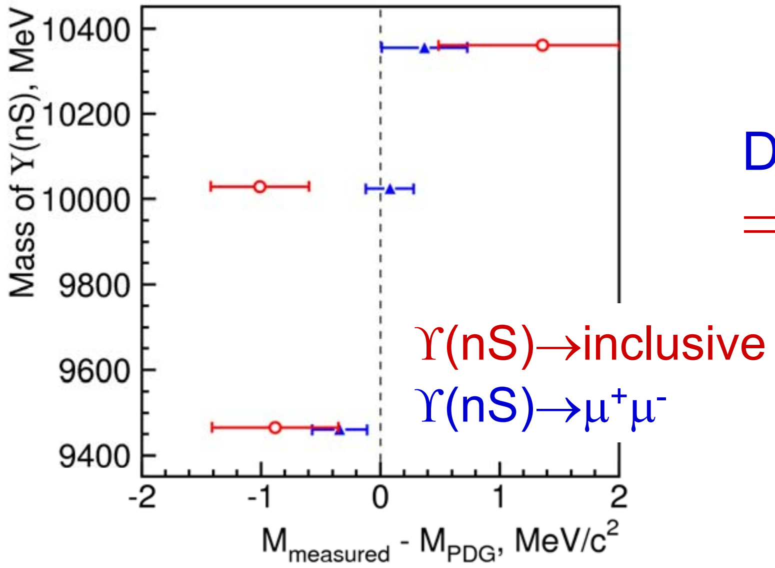
	Polynomial order	Fit range	Signal shape	Selection requirements
$N[h_b]$, 10^3	± 2.4	± 3.6	$^{+1.2}_{-8.0}$	–
$M[h_b]$, MeV$/c^2$	$\pm .04$	$\pm .10$	$^{+0.04}_{-0.20}$	$^{+.20}_{-.30}$
$N[h_b(2P)]$, 10^3	± 2.2	± 2.6	$^{+23.}_{-9.0}$	–
$M[h_b(2P)]$, MeV$/c^2$	$\pm .10$	$\pm .20$	$^{+1.0}_{-0.0}$	$\pm .08$

Results are stable

Significance w/ systematics

$h_b(1P)$	5.5σ
$h_b(2P)$	11.2σ

$M_{measured} - M_{PDG}$ for reference channels



Deviations of reference channels from PDG

⇒ additional uncertainty ±1MeV

local variations of background shape?

Mass measurements

Results

$h_b(1P)$ $9898.25 \pm 1.06^{+1.03}_{-1.07}\,\mathrm{MeV}/c^2$

$h_b(2P)$ $10259.76 \pm 0.64^{+1.43}_{-1.03}\,\mathrm{MeV}/c^2$

Deviations from CoG of χ_{bJ} masses

$$\left.\begin{array}{ll} h_b(1P) & 1.62 \pm 1.52\ \mathrm{MeV/c^2} \\ h_b(2P) & 0.48\ ^{+1.57}_{-1.22}\ \mathrm{MeV/c^2} \end{array}\right\}$$

consistent with zero, as expected

Why do we think these are $h_b(nP)$ and not $\chi_{b1}(nP)$?

- The strong decay $\Upsilon(5S) \to \chi_{b1}\,\pi^+\pi^-$ violates isospin conservation
- Masses are significantly different:

$$\Delta M(1P) = -5.47 \pm 1.56 \quad (3.5\sigma)$$

$$\Delta M(2P) = -4.30 \pm 1.35 \quad (3.2\sigma)$$

⇒ Observed states are $h_b(nP)$

Ratio of production rates

Calibrate MC using data

Efficiency of R2<0.3 from data

Matrix element *vs.* ($m_{\pi\pi}$, $\cos\theta_{Hel}$) ⇒ for $\Upsilon(nS)$ – from $\mu^+\mu^-\pi^+\pi^-$ data,
for $h_b(1P)$ [$h_b(2P)$] – same as for $\Upsilon(2S)$ [$\Upsilon(3S)$]
+ *variations for systematics*

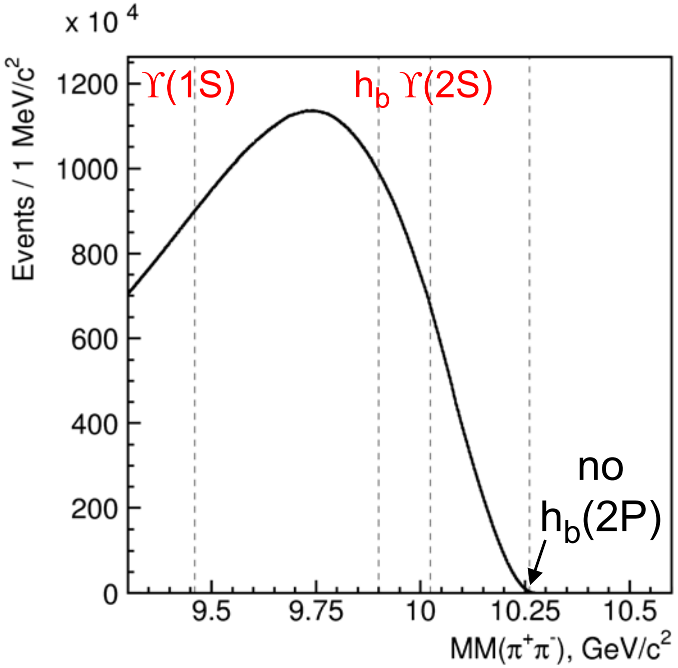
$$\frac{\Gamma[\Upsilon(5S)\to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S)\to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.407\pm0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78\pm0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

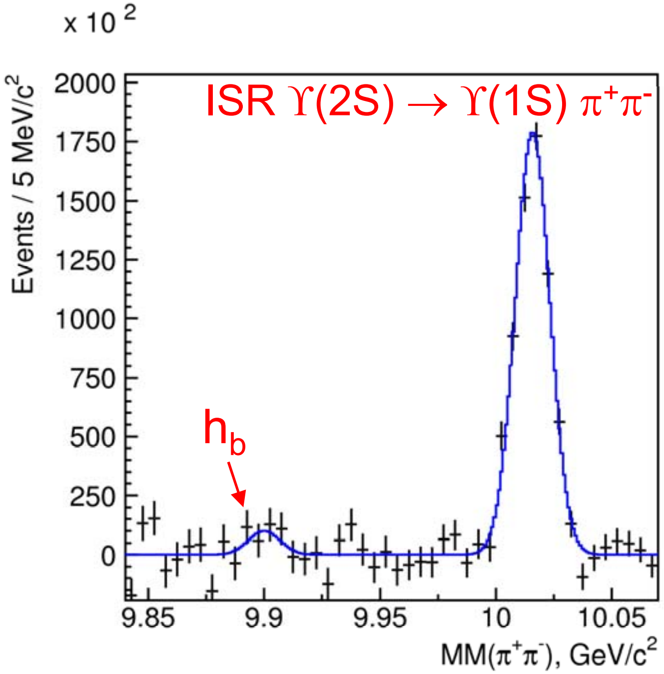
Spin h_b = 0 ⇒ spin-flip
no spin-flip

Process with spin-flip of heavy quark is not suppressed

⇒ Mechanism of $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ decay is exotic

Search in Υ(4S) data





L = 711fb^{-1} [×6 Υ(5S) sample]

No significant signal of h$_b$(1P): $(34 \pm 20) \times 10^3$ (1.7σ)

$$\frac{\sigma[e^+e^- \to h_b(1P)\,\pi^+\pi^-]\ @\ \Upsilon(4S)}{\sigma[e^+e^- \to h_b(1P)\,\pi^+\pi^-]\ @\ \Upsilon(5S)} < 0.28 \text{ at } 90\%\text{C.L.}$$

⇒ Υ(4S) does not show anomalous properties

Conclusions

Primary purpose of taking data at $\Upsilon(5S)$ – studies of B_s decays

Observation of **$B_s \to J/\psi\ f_0(980)$**, evidence for **$J/\psi\ f_0(1370)$**

CP eigenstate , f_0 is scalar $\Rightarrow$ no angular analysis is required to measure $\Delta\Gamma/\Gamma$ and CPV phase β_s

Nature is favorable : $\Upsilon(5S)$ is a rich source of unexpected QCD phenomena

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

Masses consistent with CoG of χ_{bJ} states, as expected
Anomalous production rate