Belle Results at $\Upsilon(5S)$

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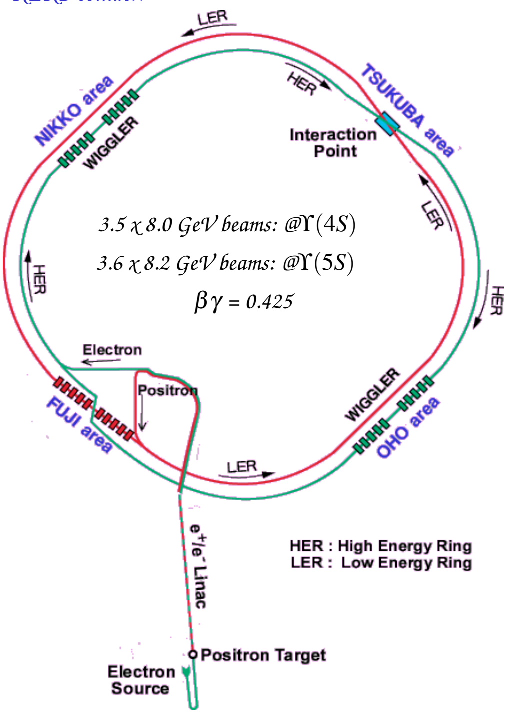
Outline

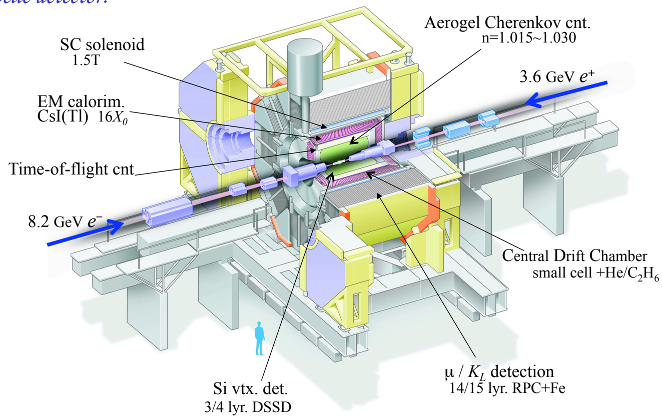
- The Belle Experiment
- Physics at $\Upsilon(5S)$
- CP-eigenstate B_s^0 decays
- Bottomonia searches
- Summary

KEKB Collider and Belle Detector

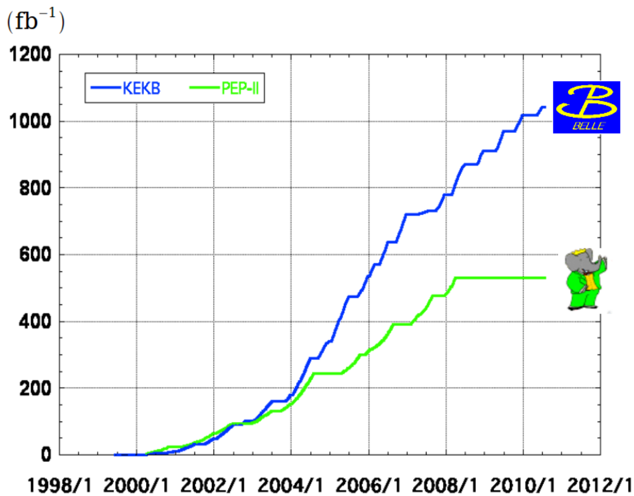
KEKB collider:



Belle detector:



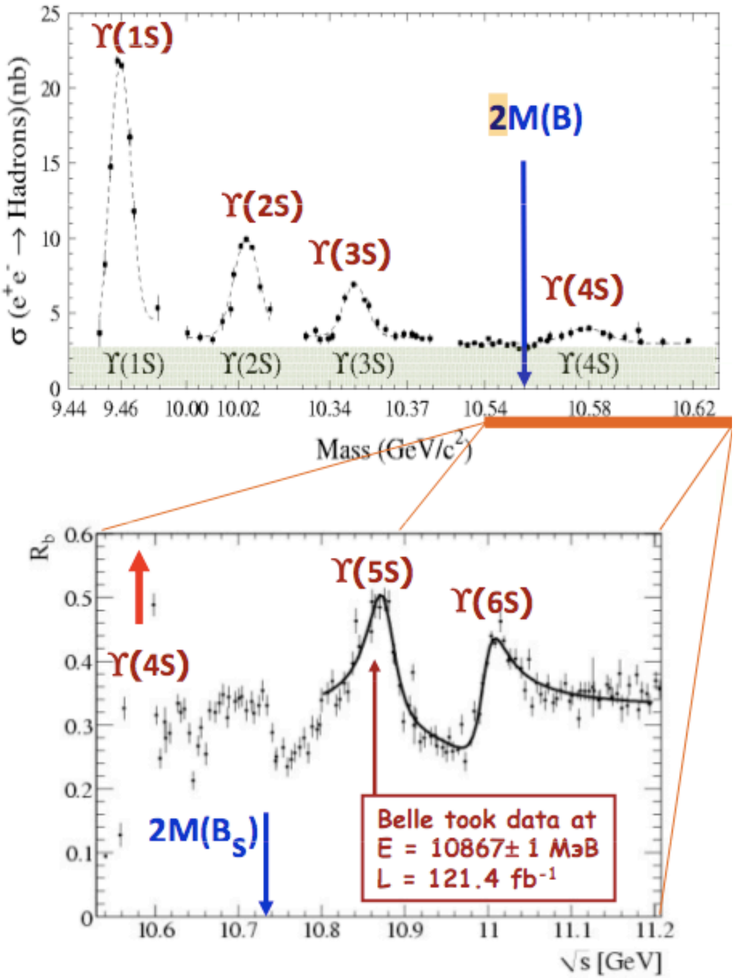
Integrated luminosity of B factories



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Physics at $\Upsilon(5S)$



beyond $\Upsilon(4S) \Rightarrow \Upsilon(5S)$

- $B^{(*)}B^{(*)}(\pi\pi), B_s^{(*)}\bar{B}_s^{(*)}, \Upsilon(nS)\pi\pi, \ldots$
- *above* $B_s^*\bar{B}_s^*$ *threshold :*
  14 million B_s^0 *at Belle*
- *Bottomonia above* $B^*\bar{B}$ *threshold*

Reconstruction of B_s^0

B_s^0 production fraction:

$$\mathcal{B}(\Upsilon(5S) \to D_s X)/2 = f_s \times \mathcal{B}(B_s \to D_s X) + (1 - f_s) \times \mathcal{B}(B \to D_s X)$$

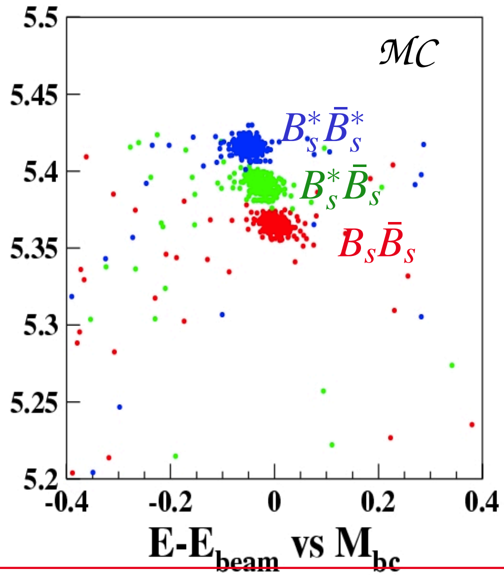
we measure with $\Upsilon(5S)$ data — $(92 \pm 11)\%$ Model-dependent — $(8.3 \pm 0.7)\%$ BaBar@$\Upsilon(4S)$

- Full reconstruction using observables :
  - Beam-constrained mass: $M_{bc} = \sqrt{E_b^{*2} - p_{B_s^0}^{*2}}$
  - Energy difference: $\Delta E = E_{B_s^0}^* - E_b^*$
- 3 production modes:

  $\Upsilon(5S) \to B_s^* \bar{B}_s^*, B_s^* \bar{B}_s$ and $B_s \bar{B}_s$

  $f_{B_s^* \bar{B}_s^*} = (87.0 \pm 1.7)\%$ measured w/ $B_s \to Ds\pi$
- $B_s^* \to B_s^0 \gamma$

  low momentum γ is not reconstructed



$B_s^0 \to J/\psi f_0$

- *Motivation:*
  - Promising mode for LHCb to measure β_s, the CP-violating phase in the B mixing
  - pure CP-odd eigenstate: no angular analysis needed

Stone et al., arXiv:0909.5442 (2009)

- *Event selection*
  - full reconstruction $J/\psi \to e^+e^-$ or $\mu^+\mu^-$ modes
  - Two f_0 resonances: $f_0(980)$ and $f_0(1370)$ with $f_0 \to \pi^+\pi^-$
  - select B_s^0 with M_{bc}; fit $M_{\pi\pi}$ and ΔE distributions
  - Backgrounds from continuum and other J/ψ modes.

- *Results:*

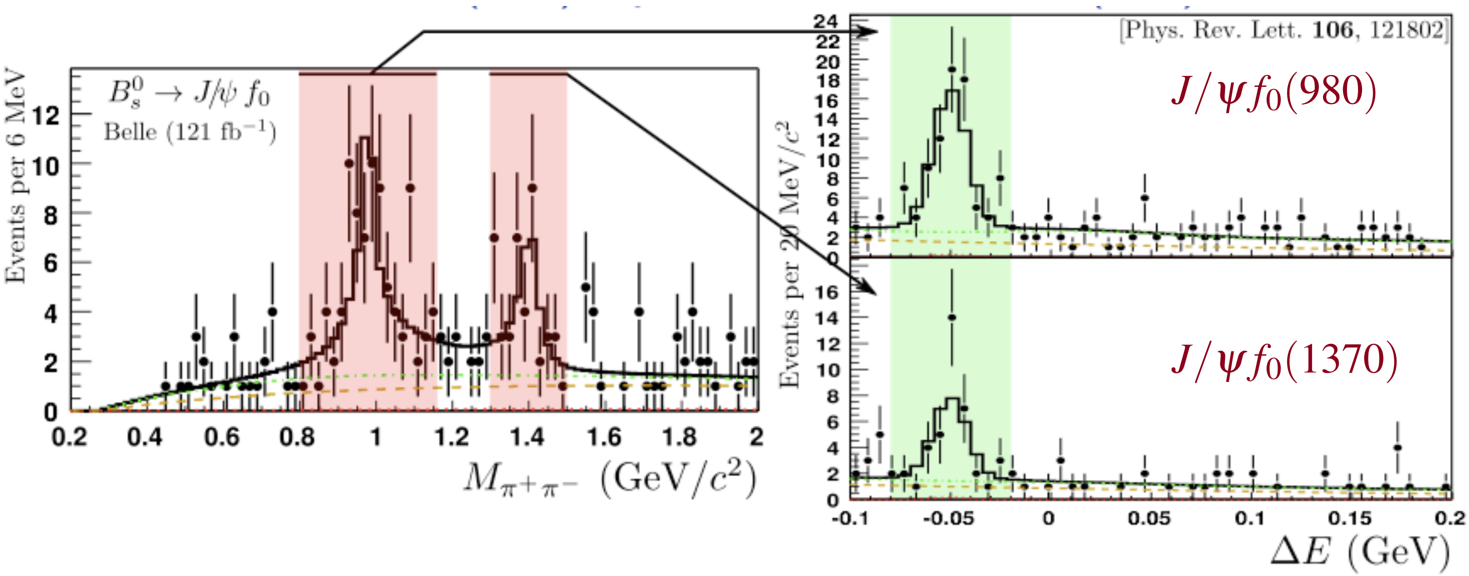
Observation of 63^{+16}_{-10} $B_s^0 \to J/\psi f_0(980)$ events (8.4σ incl. syst.)

First evidence for 19^{+6}_{-8} $B_s^0 \to J/\psi f_0(1370)$ events (4.2σ incl. syst.)

$B_s^0 \to J/\psi f_0$ PRL 106, 121802 (2011)

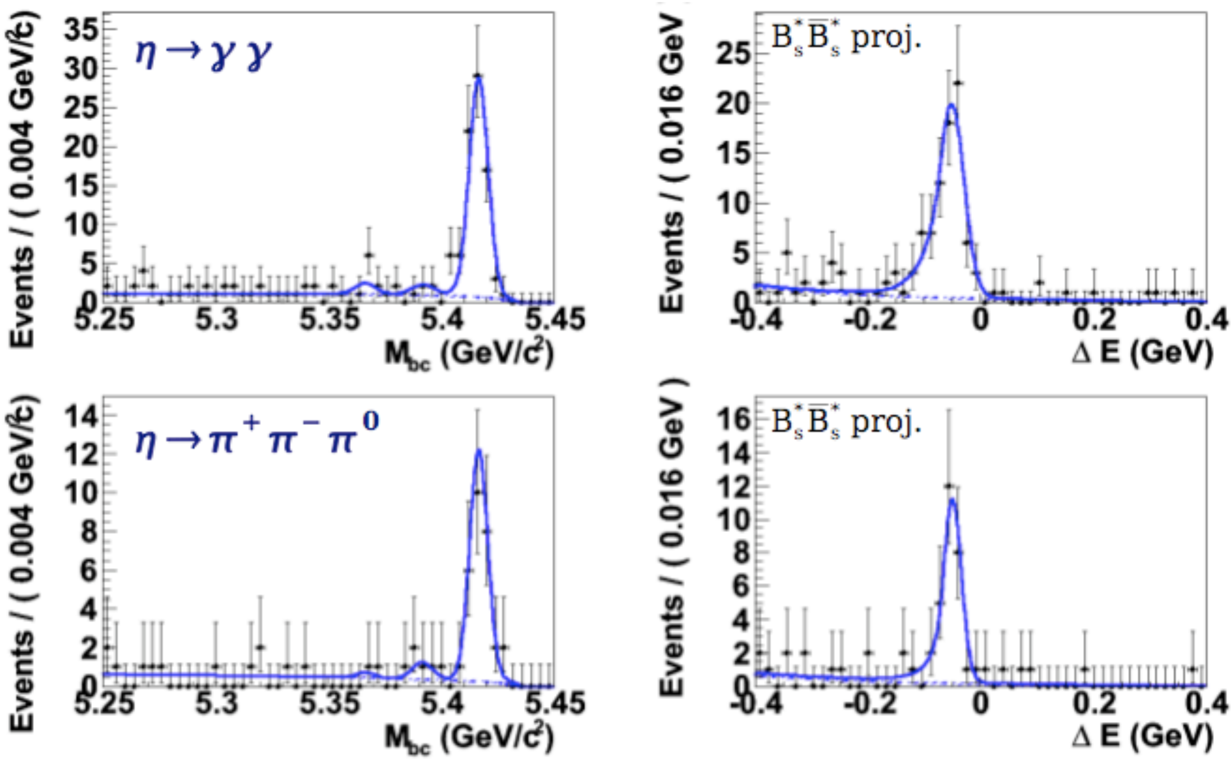
- $\mathcal{B}(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-) = [1.16^{+0.31}_{-0.19}(stat.)^{+0.15}_{-0.17}(syst.)^{+0.26}_{-0.18}(N(B_s^0))] \times 10^{-4}$
  $\mathcal{B}(B_s^0 \to J/\psi f_0(1370); f_0(1370) \to \pi^+\pi^-) = [0.34^{+0.11}_{-0.14}(stat.)^{+0.03}_{-0.02}(syst.)^{+0.08}_{-0.05}(N(B_s^0))] \times 10^{-4}$

- *Comparable results with LHCb [PLB 698, 115], CDF [arXiv: 1106.3682] and D0 [conf. note 6152]*

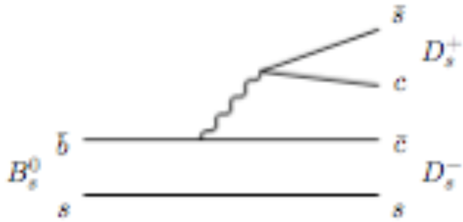


Observation of $B_s^0 \to J/\psi\eta$

- reconstruct $B_s^0 \to J/\psi\eta$ with $\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$
- two simultaneous fits to $\Delta E - M_{bc}$ distributions for η sub-modes
- Branching Fraction = $(5.11 \pm 0.50(stat.) \pm 0.35(syst.) \pm 0.68(fs)) \times 10^{-4}$



$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$ *decays and* $\Delta\Gamma_s$



- *CP-even final states*
  - $D_s^+ D_s^-$ *pure CP-even*
  - $D_s^* D_s^{(*)}$ *predominantly CP-even*
- *In the heavy quark limit, while* $(m_b - 2m_c) \to 0$ *and* $N_c \to \infty$
  - $b \to c\bar{c}s$ *processes contribute constructively to* $\Delta\Gamma_s$
  - $\Gamma[B_s^0(CP+) \to D_s^{(*)-} D_s^{(*)+}]$ *saturates* $\Delta\Gamma_s^{CP}$
  - *assuming negligible CP violation, we can estimate* $\Delta\Gamma_s/\Gamma_s$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \frac{2\mathcal{B}(B_s^0 \to D_s^{(*)-} D_s^{(*)+})}{1 - \mathcal{B}(B_s^0 \to D_s^{(*)-} D_s^{(*)+})}$$

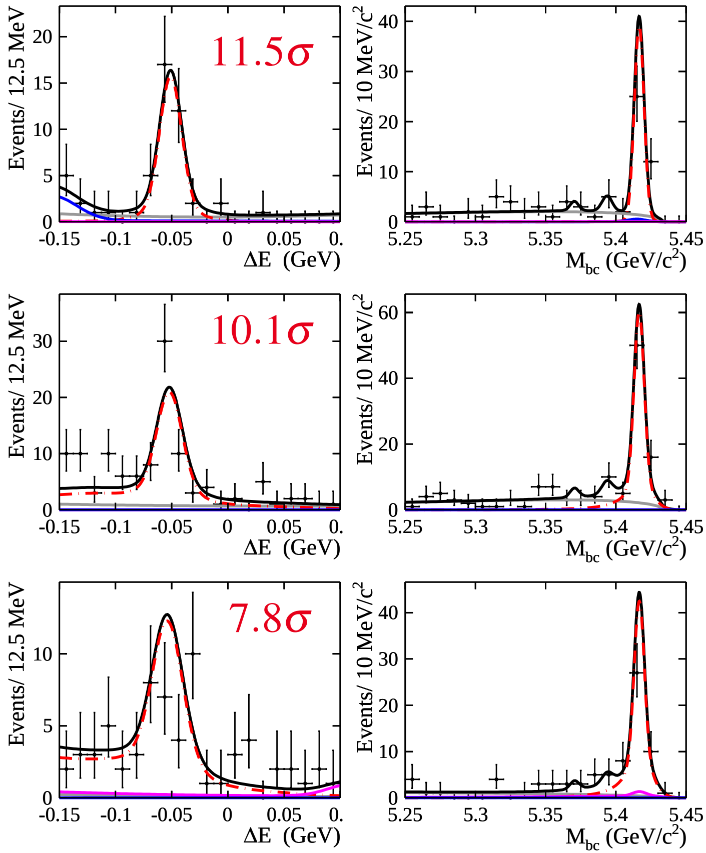
Aleksan et. al., PLB 316, 567 (1993) , Dunietz et. al. , PRD 63, 114015 (2001)

some theoretical uncertainty

- ≻ *3-body* $D_s D_s X$ *and* $D_{sJ} D_s$ *final states are not included*
- ≻ $D_s^{*+} D_s^{*-}$ *modes may have a CP-odd component* $\Rightarrow$ *we will measure this*

$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$ *arXiv:1110.2099*

signal region projections
$\Delta E[-0.1, 0.0]$ *and* $M_{bc}[5.4, 5.43]$



- *Event selection:*
  - *reconstruct six* D_s^- *decays:*

    $\phi\pi^-, K_sK^-, K^{*0}K^-, \phi\rho^-, K^{*-}K_s^+, K^{*0}K^{*-}$
  - *simultaneous fit of three* B_s *modes*
  - *2D unbinned ML fit to* ΔE *and* M_{bc}
- *Results:*

Mode	$\mathcal{Y}$ *(events)*	$\mathcal{B}$ *(%)*
$D_s^+D_s^-$	$33.1^{+6.0}_{-5.4}$	$0.58^{+0.11}_{-0.09} \pm 0.13$
$D_s^{*\pm}D_s^{\mp}$	$44.5^{+5.8}_{-5.5}$	$1.8 \pm 0.2 \pm 0.40$
$D_s^{*+}D_s^{*-}$	$24.4^{+4.1}_{-3.8}$	$1.98 \pm 0.3 \pm 0.5$
Sum	$102.0^{+9.3}_{-8.6}$	$4.3 \pm 0.4 \pm 1.0$
$\Delta\Gamma_s/\Gamma_s$	$(9.0 \pm 0.9 \pm 2.2)$ %	

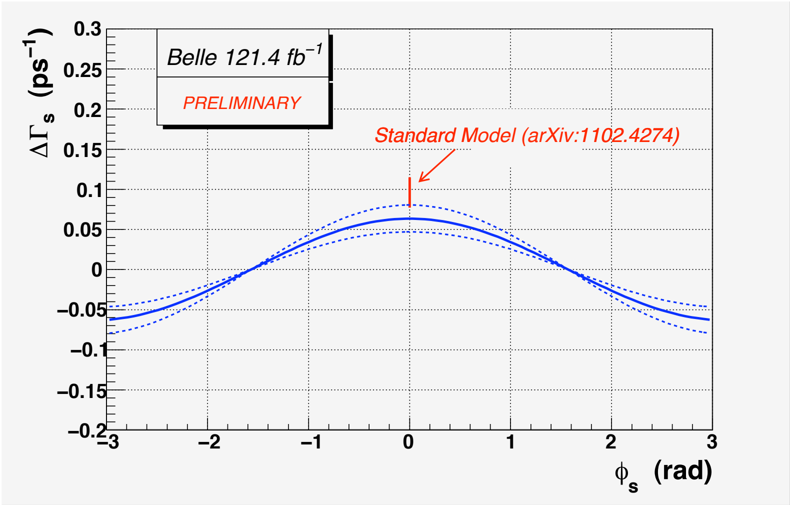
PDG $: 9.2^{+5.1}_{-5.4}$*% (w/o LHCb* $J/\psi\phi$ *mesurement)*

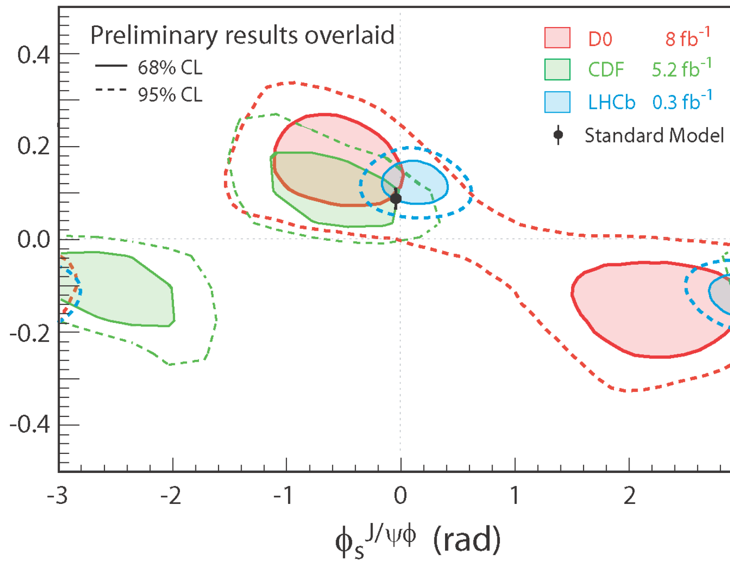
$\Delta\Gamma_s$ *with CPV*

$$4\,\mathcal{B}(B_s \to D_s D_s) = \left(\frac{\Delta\Gamma}{\cos\varphi}\right)\left[\frac{1+\cos\varphi}{1+\Delta\Gamma/2} + \frac{1-\cos\varphi}{1-\Delta\Gamma/2}\right]$$

$$\text{where } \varphi = \text{Arg}\left(\frac{M_{12}}{\Gamma_{12}}\right)$$

Dunietz, Fleischer, Nierste, PRD 63, 114015 (2001)





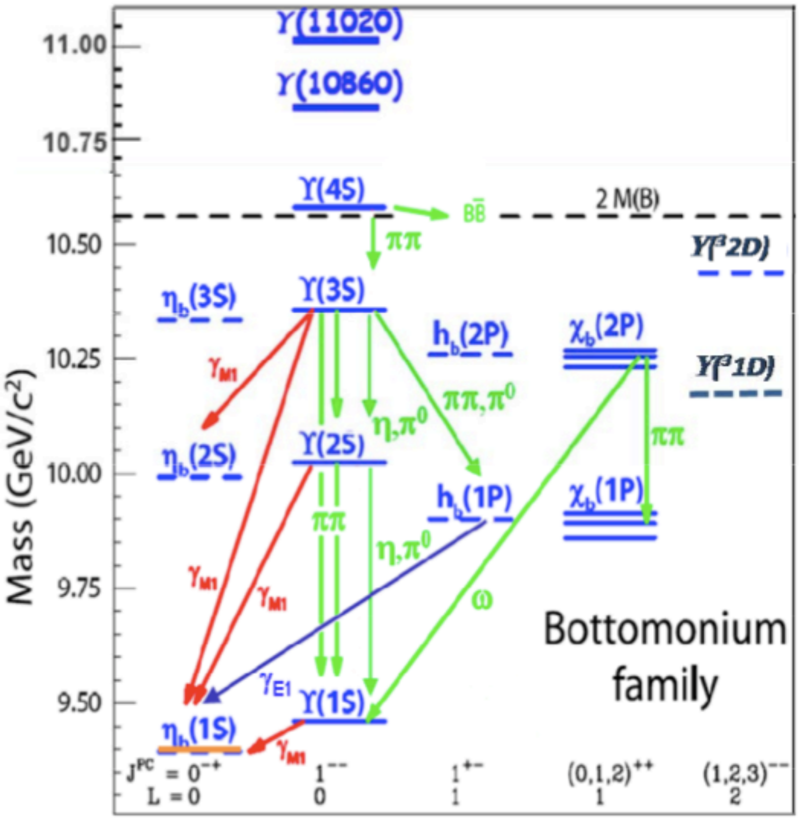
Bottomonia

Motivation

- *seek/study h_b*
- *search for b-versions of charmonium-like X, Y, Z states*
- *origin of anomalous*

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

  K.F. Chen et al. (Belle) PRL 100, 112001 (2008); PRD 82, 091106(R) (2010)



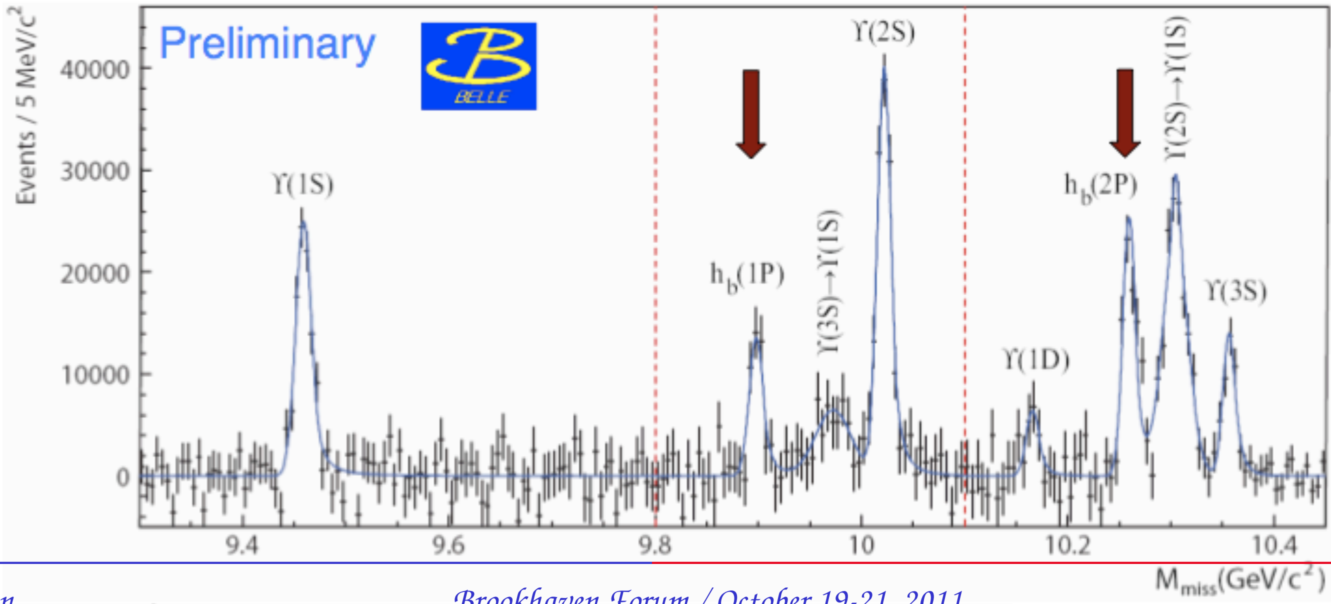
First Observation of $h_b(nP)$ arXiv:1103.3419

- *Use missing mass method:*

  $M_{h_b} = MM(\pi^+\pi^-) = \sqrt{(P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2}$

- $\pi^{\pm}$ *: good track quality consistent PID information*

	Yield, 10^3	Mass, MeV$/c^2$	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$



Observation of $h_b(nP)$: what we learned

- Masses are in very good agreement with CoG of χ_b states

$$h_b(1P) : \Delta M = 1.6 \pm 1.5 MeV/c^2$$

$$h_b(2P) : \Delta M = 0.5^{+1.6}_{-1.2} MeV/c^2$$

Consistent with hyperfine interaction

- Ratio of production rate :

$$\frac{\Gamma(\Upsilon(5S) \to h_b(1P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = 0.46 \pm 0.08^{+0.07}_{-0.12}$$

$$\frac{\Gamma(\Upsilon(5S) \to h_b(2P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = 0.77 \pm 0.08^{+0.22}_{-0.17}$$

Process with spin flip is not suppressed in $\Upsilon(5S)$ as expected

- search for $h_b(1P)$ at $\Upsilon(4S)$:

$$\frac{\sigma(e^+e^- \to h_b(1P)\pi^+\pi^-)@\Upsilon(4S)}{\sigma(e^+e^- \to h_b(1P)\pi^+\pi^-)@\Upsilon(5S)} < 0.28(90\% CL)$$

$\Upsilon(4S)$ decay to h_b is not enhanced

$\Rightarrow h_b$ through exotic mechanism?

Source of h_b : Z_b arXiv:1110.2251

- Inspect the mass of $h_b\pi$: look at the missing mass of a single pion
- Masses, widths and relative amplitudes from five channels are consistent

$Z_b(10610)$:

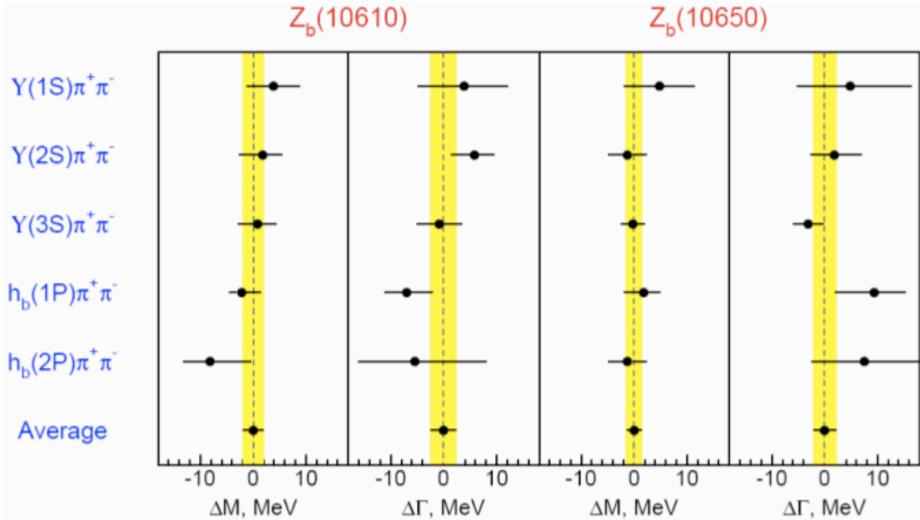
$M = 10607.2 \pm 2.0 MeV/c^2$

$\Gamma = 18.4 \pm 2.4 MeV$

$Z_b(10650)$:

$M = 10652.2 \pm 1.5 MeV/c^2$

$\Gamma = 11.5 \pm 2.2$ MeV



- Relative phases are swapped for final states $\Upsilon(\approx 0^\circ)$ and $h_b(\approx 180^\circ)$ explains why $\Upsilon(5S) \to h_b\pi\pi$ are not suppressed compare to $\Upsilon\pi\pi$
- Masses of Z_b are close to $B^*B^{(*)}$ thresholds

$h_b(1P) \to \eta_b(1S)\gamma$ *arXiv:1110.3934*

- *Expected decays of h_b*

$$h_b(1P) \to ggg(57\%), \eta_b(1S)\gamma(41\%), \gamma gg(2\%)$$

$$h_b(2P) \to ggg(63\%), \eta_b(1S)\gamma(13\%), \eta_b(2S)\gamma(19\%), \gamma gg(2\%)$$

- *method:*

– *reconstruct π^+, π^- and γ from decay chain:*

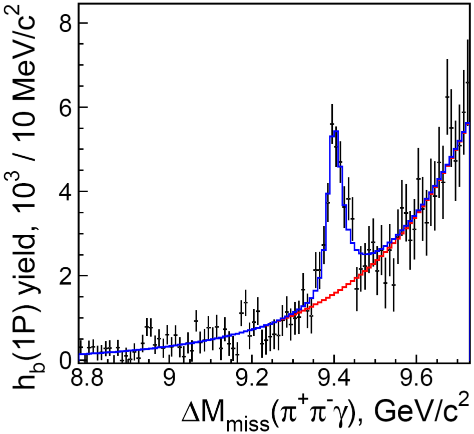
$$\Upsilon(5S) \to Z_b^+ \pi^-, Z_b^+ \to h_b(1P)\pi^+, h_b(1P) \to \eta_b(1S)\gamma$$

– *fit $MM(\pi^+\pi^-)$ spectra in $\Delta M_{miss}(\pi^+\pi^-\gamma)$ bins*

$$\Delta M_{miss}(\pi^+\pi^-\gamma) = MM(\pi^+\pi^-\gamma) - MM(\pi^+\pi^-) + M(h_b)$$

– *Require intermediate Z_b :*

$$10.59 < MM(\pi) < 10.67 \ GeV$$



- *results:*

$$M(\eta_b(1S)) = 9401.0 \pm 1.9^{+1.4}_{-2.4} MeV/c^2$$

$$\Gamma(\eta_b(1S)) = 12.4^{+5.5+11.5}_{-4.6-3.4} MeV$$

$$\mathcal{B}(h_b(1P) \to \eta_b(1S)\gamma) = 49.8 \pm 6.8^{+10.9}_{-5.2} \%$$

Summary

- Belle collected 121.4 fb^{-1} data at the $\Upsilon(5S)$
- Observation of $B_s^0 \to J/\Psi f_0(980)$ and first evidence of $B_s^0 \to J/\Psi f_0(1370)$
- improved branching fraction measurement of $B_s^0 \to D_s^{(*)} D_s^{(*)}$
  - constraint on $\Delta\Gamma_s/\Gamma_s$
- First observation of two $b\bar{b}$ states: $h_b(1P)$ and $h_b(2P)$
  - masses are consistent with expectation (COG) arXiv:1103.3419
- First observation of two charged bottomonia resonances
  - seen in 5 final states with consistent parameters
  - masses are close B^*B and B^*B^*
- First observation of $h_b(1P) \to \eta_b(1S)\gamma$
  - first measurement of $\eta_b(1S)$ width
  - BF, mass, width in agreement with theoretical expectations
- more is coming!

BACKUP

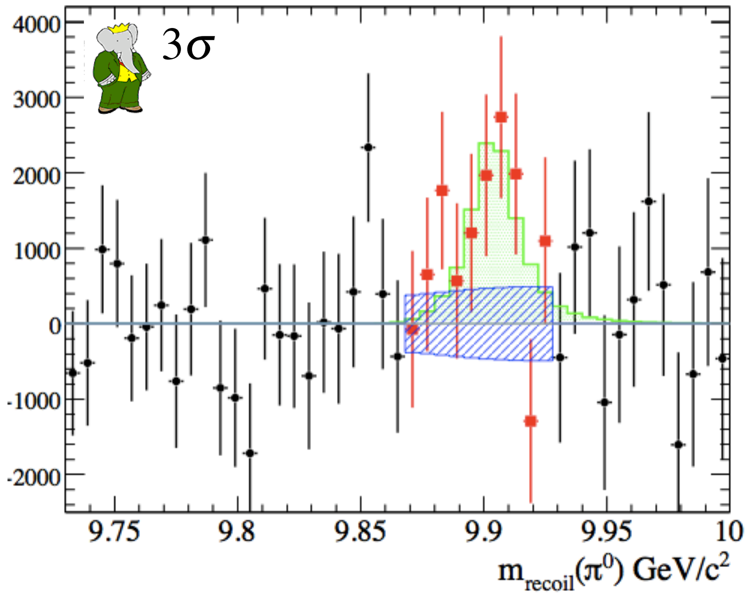
Properties of $h_b(nP)$

- $b\bar{b}$ *states with spin 0,* $L = 1, J^{PC} = 1^{+-}$
  $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ *decays should be suppressed due to spin-flip*

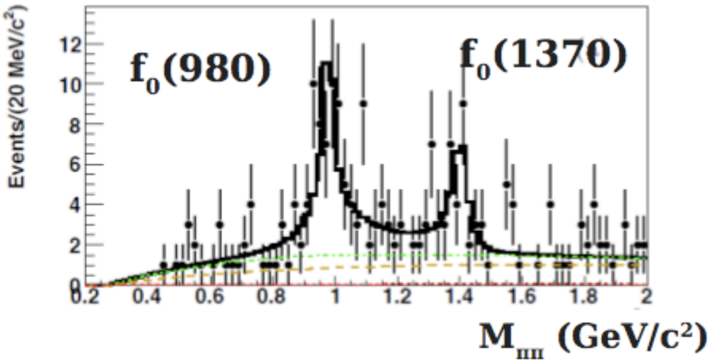
- *expected mass (CoG of* χ_{bJ}) : $M_{h_b} \approx (M_{\chi_{b0}} + 3M_{\chi_{b1}} + 5M_{\chi_{b2}})/9$
  $\Delta M_{HF} \Rightarrow$ *test of hyperfine interaction*

- *Radiative transition to* $\eta_b(nS)$

- *Evidence from BaBar (arXiv:1102.4565)*
  $\Upsilon(3S) \to \pi^0 h(1P) \to \pi^0 \gamma \eta_b(1S)$



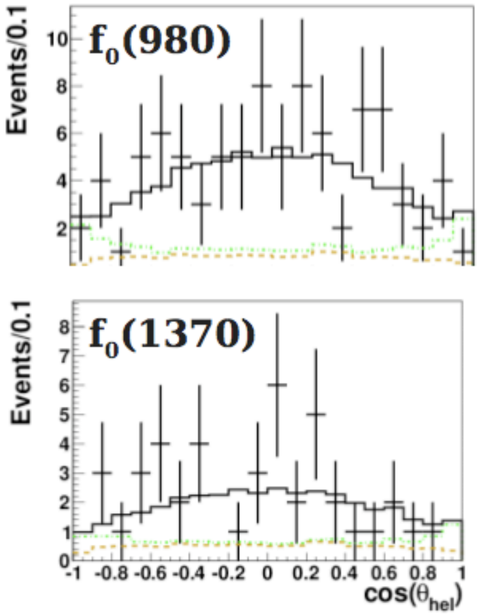
$B_s^0 \to J/\psi f_0$



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

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

Mass and width of $f_0(1370)$ in good agreement with PDG



Helicity angle distribution is consistent with f_0 being scalars

Observation of $B_s \to J/\psi\ f_0(980)$

First evidence of $B_s \to J/\psi\ f_0(1370)$