B_s and $\Upsilon(5S)$ decays at Belle

きぼう (kibō) means hope

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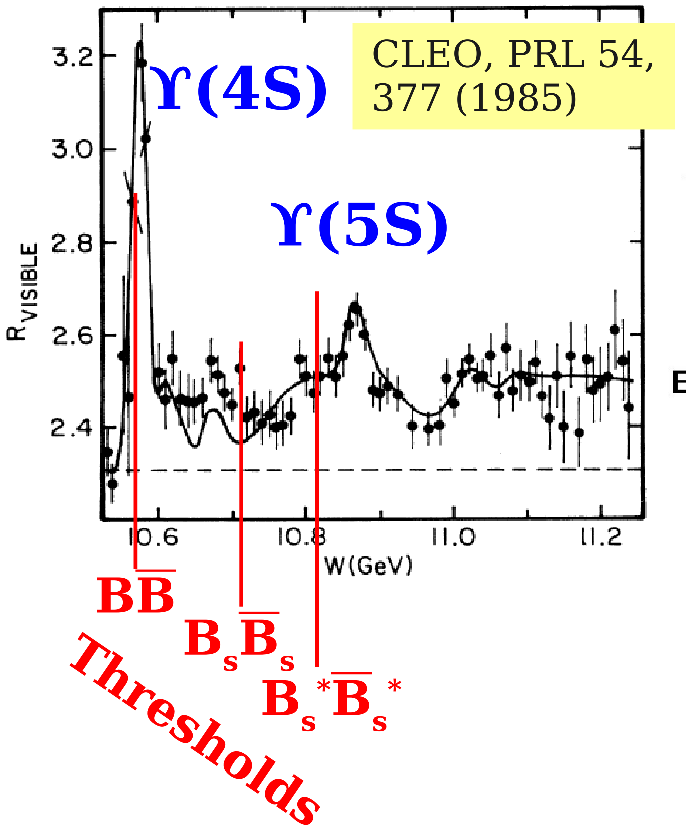
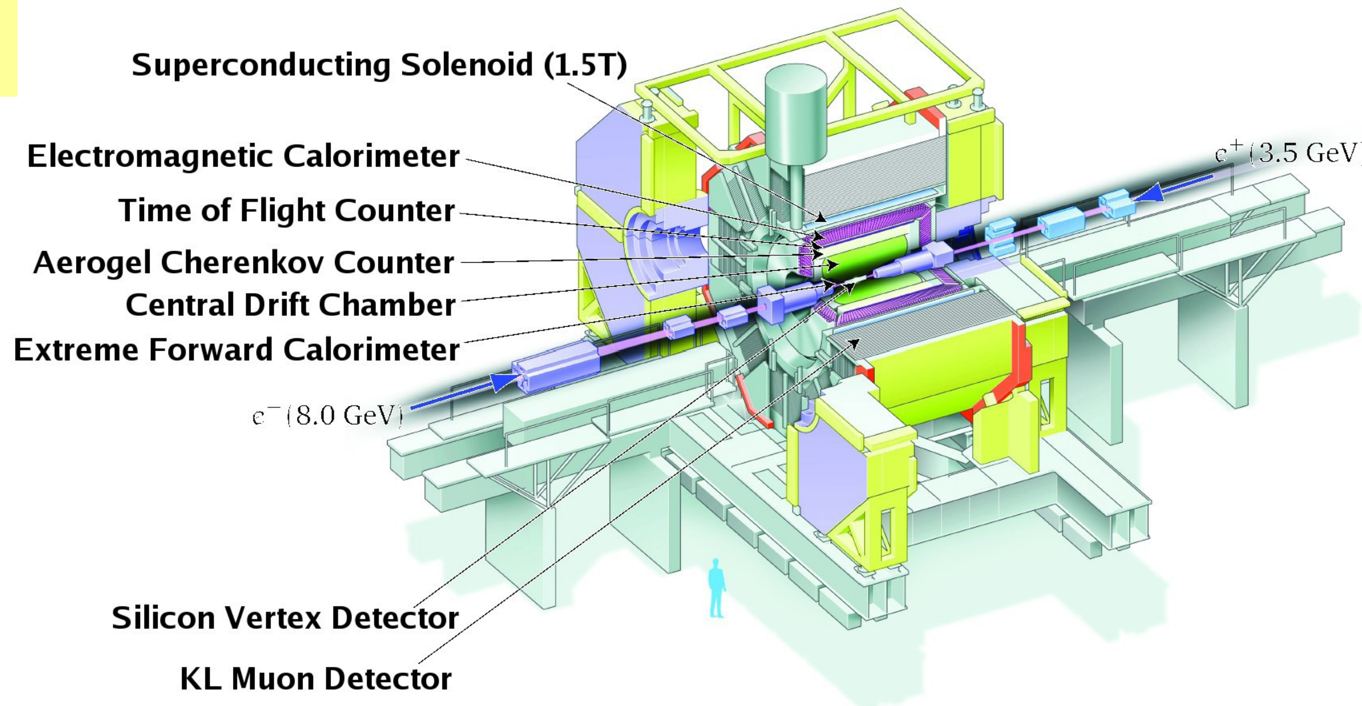
Beauty 2011

April 4th 2011

Data samples at ϒ(5S)





ϒ(5S) above $B_s^{(*)}B_s^{(*)}$ threshold

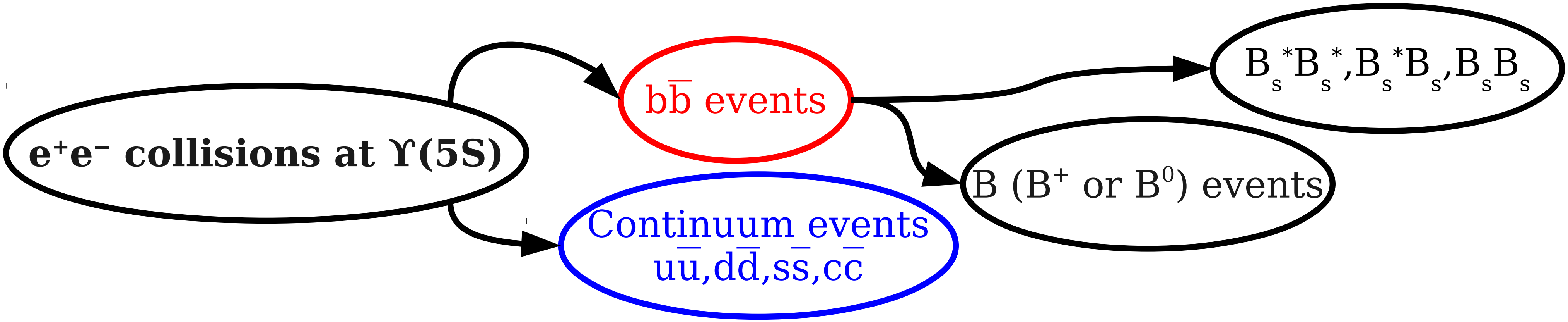
- B_s can be produced and studied at B-factory
  - was established by CLEO
- ϒ(5S) does also of course decay to B^+ and B^0
  - Can be excited and produced with pions
    - ⇒ $B^{(*)}B^{(*)}(n\pi)$
- And to ϒ(nS)ππ, etc...

Belle took about ~140 fb^{-1} around the ϒ(5S)

- **121.4 fb^{-1} at the resonance**
- ~20 fb^{-1} in scans
- Much larger than CLEO, BaBar: <1 fb^{-1}

Compared to 711 fb^{-1} at the ϒ(4S)

Absolute BF measurement



Number of $b\bar{b}$: ϒ(4S) off-resonance data (continuum) subtraction

$$N_{b\bar{b}}^{\Upsilon(5S)} = \frac{1}{\epsilon_{\Upsilon(5S)}^{b\bar{b}}} \left(N_{\text{hadr}}^{\Upsilon(5S)} - N_{\text{hadr}}^{\text{cont}} \frac{\mathcal{L}_{\Upsilon(5S)}}{\mathcal{L}_{\text{cont}}} \frac{E_{\Upsilon(5S)}^2}{E_{\text{cont}}^2} \frac{\epsilon_{\Upsilon(5S)}^{\text{rec}}}{\epsilon_{\text{cont}}^{\text{rec}}} \right)$$

B_s production fraction (f_s)

Take advantage of BF($B_s \to D_s X$) » BF($B \to D_s X$)

$$\mathcal{B}(B_s \to D_s X) = (92 \pm 11)\%$$

$$\mathcal{B}(B \to D_s X) = (8.3 \pm 0.7)\%$$

$$\overbrace{\mathcal{B}(\Upsilon(5S) \to D_s X)}^{\text{We measure with } \Upsilon(5S) \text{ data}}/2 = f_s \times \overbrace{\mathcal{B}(B_s \to D_s X)}^{\text{Theory}} + (1 - f_s) \times \overbrace{\mathcal{B}(B \to D_s X)}^{\text{BaBar@}\Upsilon(4S)}$$

In 121.4 fb^{-1}: 14 million B_s mesons (**~18% uncertainty**)

Reconstruction of B_s

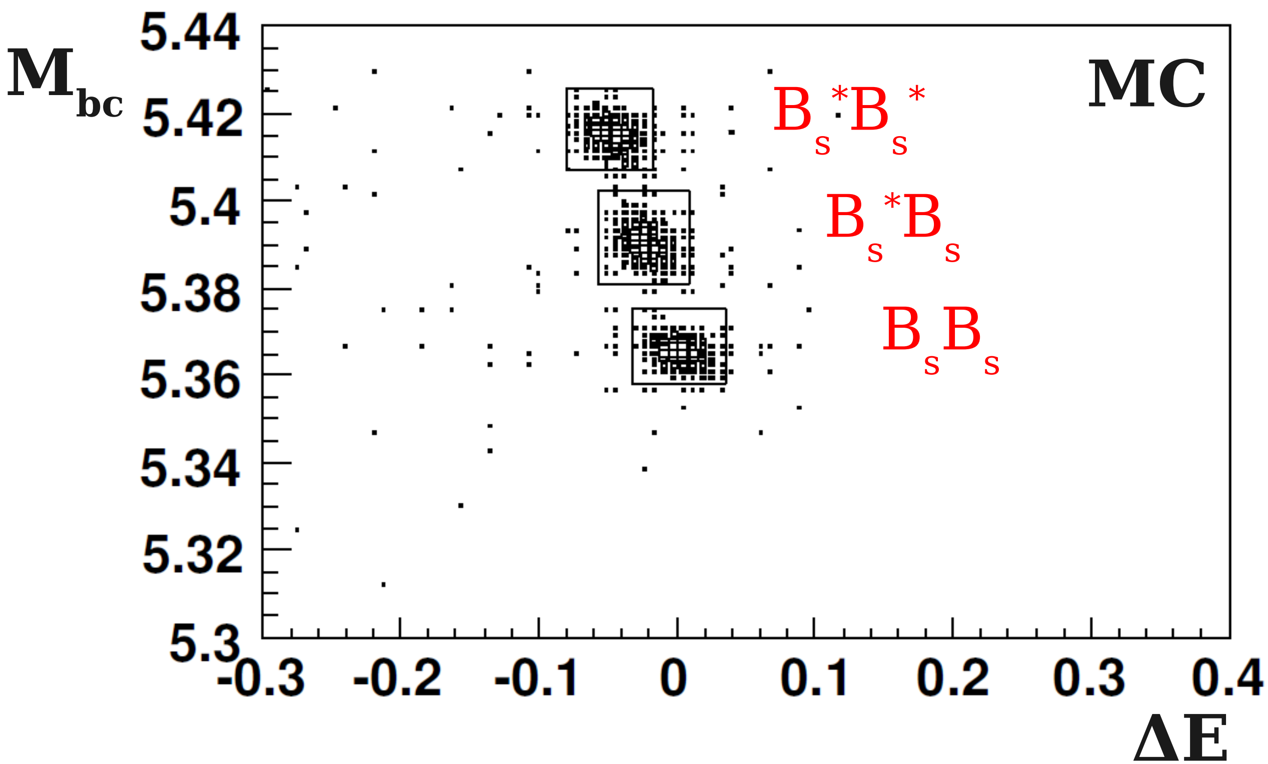
Using well-known M_{bc} and ΔE variables taking advantage of e^+e^- annihilation to two B

$$M_{\mathrm{bc}} = \sqrt{(E_{\mathrm{CM}}/2)^2 - (p_{B_s^0}^{\mathrm{CM}})^2}$$

$$\Delta E = E_{B_s^0}^{\mathrm{CM}} - E_{\mathrm{CM}}/2$$

Three possible ϒ(5S) decays: $B_s^*B_s^*$, $B_s^*B_s$ and B_sB_s

- We don't reconstruct the ~50MeV photon from B_s^* decay to B_s
  - Three regions in M_{bc}-ΔE plane (well separated)



~90% of B_s are produced through $B_s^*B_s^*$

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

PRL 106 121802 (2011)

121.4 fb^{-1}

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

- **Silver mode for LHCb** to measure β_s, the CP-violating phase in the B_s mixing
  Stone et al., arXiv:0909.5442 (2009)
  - BF 2-5 times smaller than $B_s \to J/\psi\ \phi$ BUT $J/\psi\ f_0$ is a **pure CP-eigenstate** (S→VS versus S→VV)
    - **No angular analysis required**
- **Branching fraction**
  - Extrapolation from $B_s \to J/\psi\ \varphi$

$$\frac{\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(B_s^0 \to J/\psi \phi)\mathcal{B}(\phi \to K^+K^-)} \approx 0.2$$

Stone et al., PRD 79, 074024 (2009)

$$= 0.42 \pm 0.11$$

CLEO ($D_s \to f_0 e\nu$), PRD 80, 052009 (2009)

CDF's J/ψ φ ⇉ $\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-) = \boxed{(1.3 - 2.7)10^{-4}}$

  - Theory (QCD@LO)

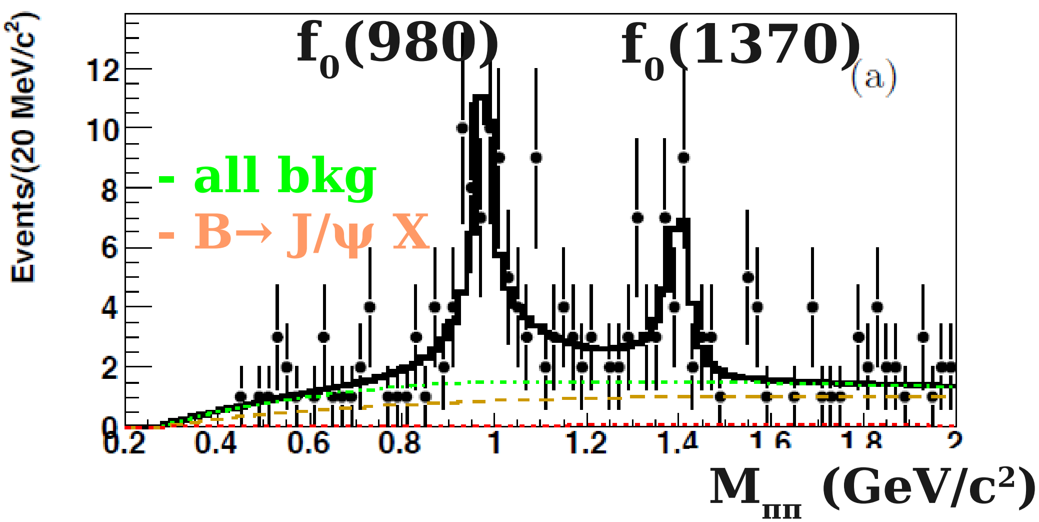
$$\mathcal{B}(B_s^0 \to J/\psi f_0)\mathcal{B}(f_0 \to \pi^+\pi^-) = (3.4 \pm 2.4)10^{-4} \times (50^{+7}_{-9})\%$$

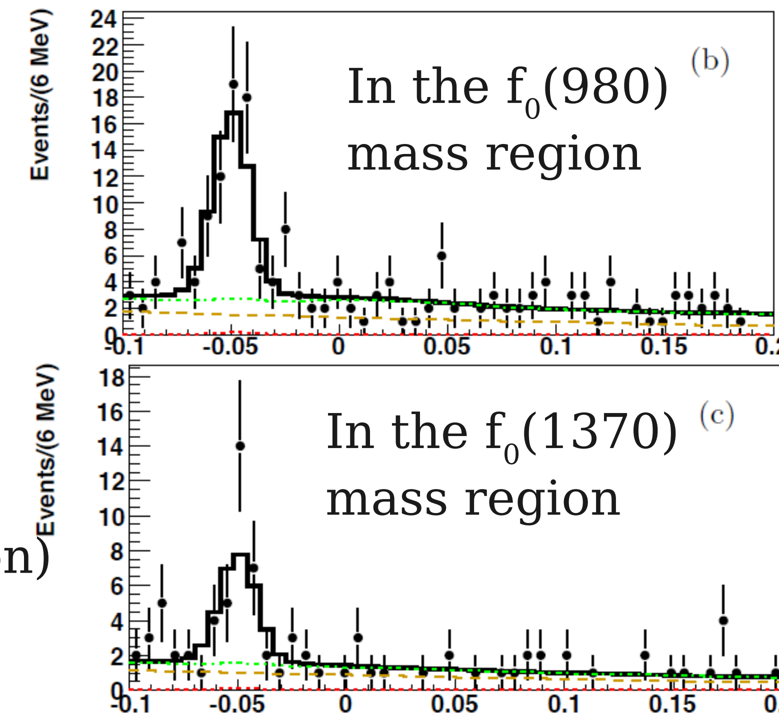
QCD (LO) PRD 81, 074001 (2010) | BES, PRD 80, 052009 (2009)

$$= \boxed{(1.6 \pm 1.3)10^{-4}}$$

$B_s \to J/\psi\ f_0$ results

$J/\psi \to e^+e^-, \mu^+\mu^-$ and $f_0 \to \pi^+\pi^-$; select B_s with M_{bc}; fit $M_{\pi\pi}$ and ΔE distributions





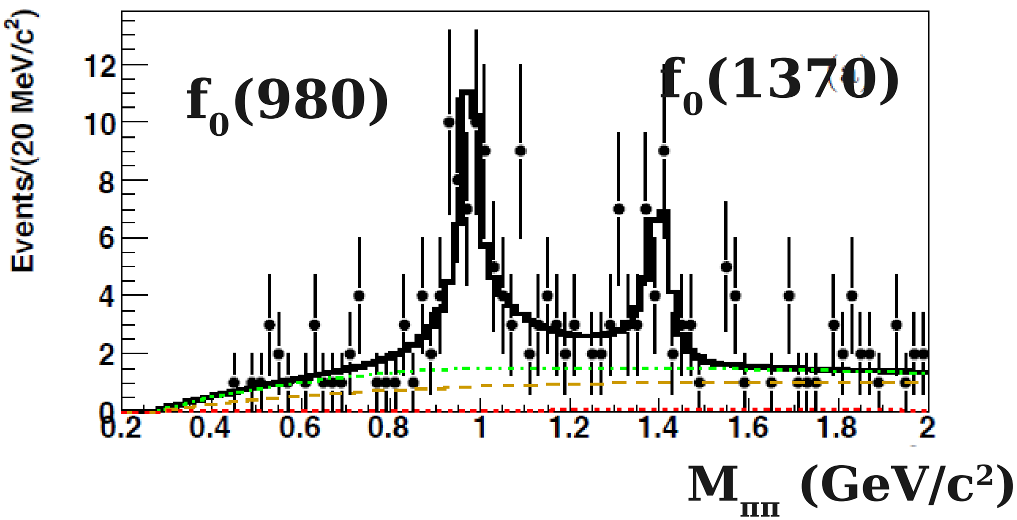
$M_{\pi\pi}$:

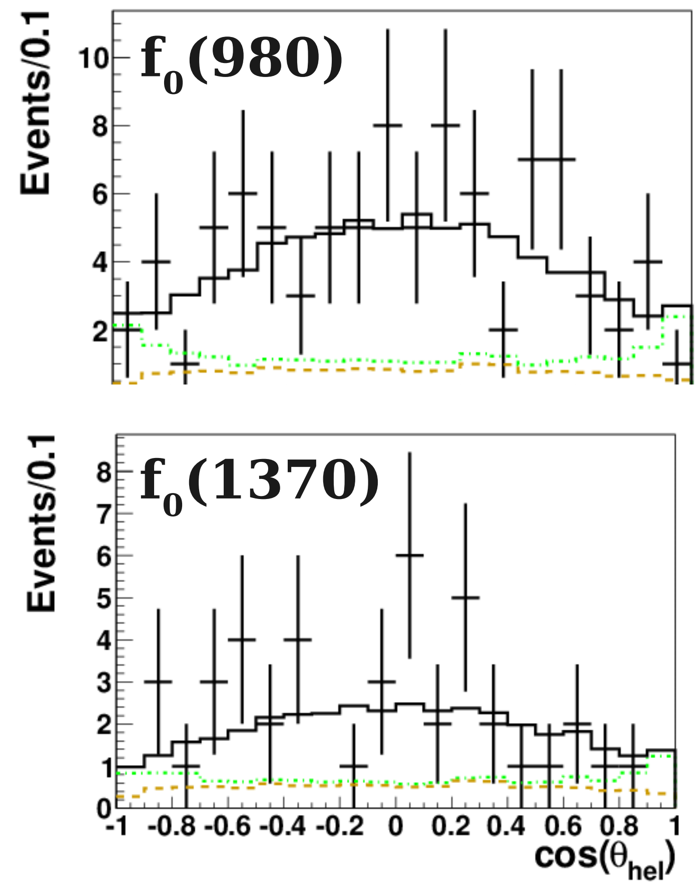
- $f_0(980)$ parameters fixed from BES (Flatté function)
- $f_0(1370)$ parameters floated (BW function)
  - The two f_0 can interfere
- Non-resonant $B \to J/\psi\ \pi^+\pi^-$ signal (non interfering)
- $B \to J/\psi$ X bkg (MC), continuum bkg (sideband data)

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

BF in good agreement with predictions

$B_s \to J/\psi\ f_0$ results





$$M = 1.405 \pm 0.015^{+0.001}_{-0.007}\ \mathrm{GeV/c^2}$$
$$\Gamma = 0.054 \pm 0.033^{+0.014}_{-0.003}\ \mathrm{GeV}$$

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 $B_s \to J/\psi\ f_0(1370)$
LHCb has also observed $J/\psi\ f_0(980)$: PLB 698, 115 (2011)

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

arXiv:1103.3419 [hep-ex]
preliminary
contributed to La Thuile 2011
121.4 fb^{-1}

ϒ(5S)→ϒ(nS)ππ decays

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

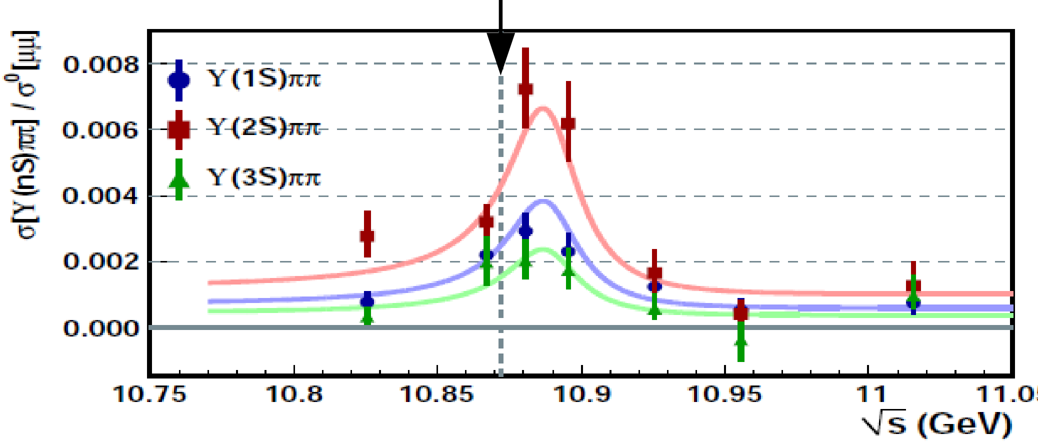
- Anomalously large ϒ(nS)ππ transitions at the ϒ(5S) (on-res)

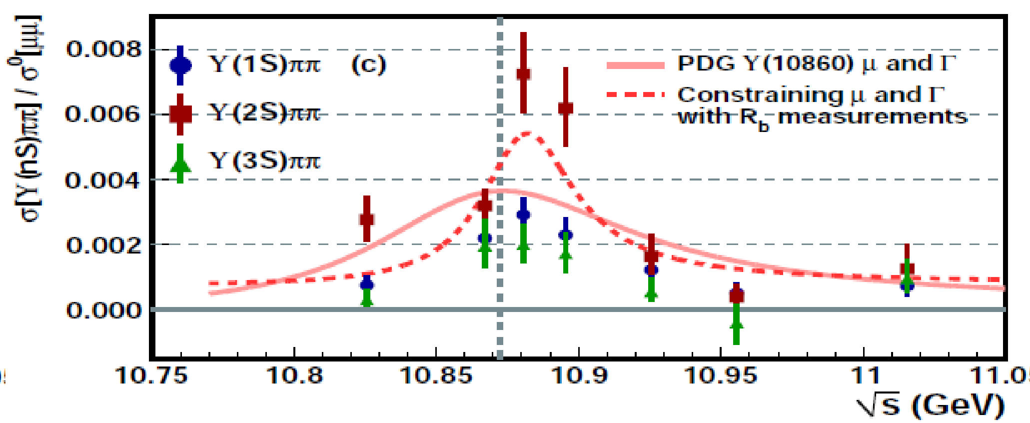
Process	Γ_{total}	$\Gamma_{e^+e^-}$	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032 MeV	0.612 keV	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020 MeV	0.443 keV	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5 MeV	0.272 keV	0.0019 MeV
$\Upsilon(10860)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

>100x larger

- 2007: 6-points scan (~1fb^{-1} per point)

Maximum of hadrons' production





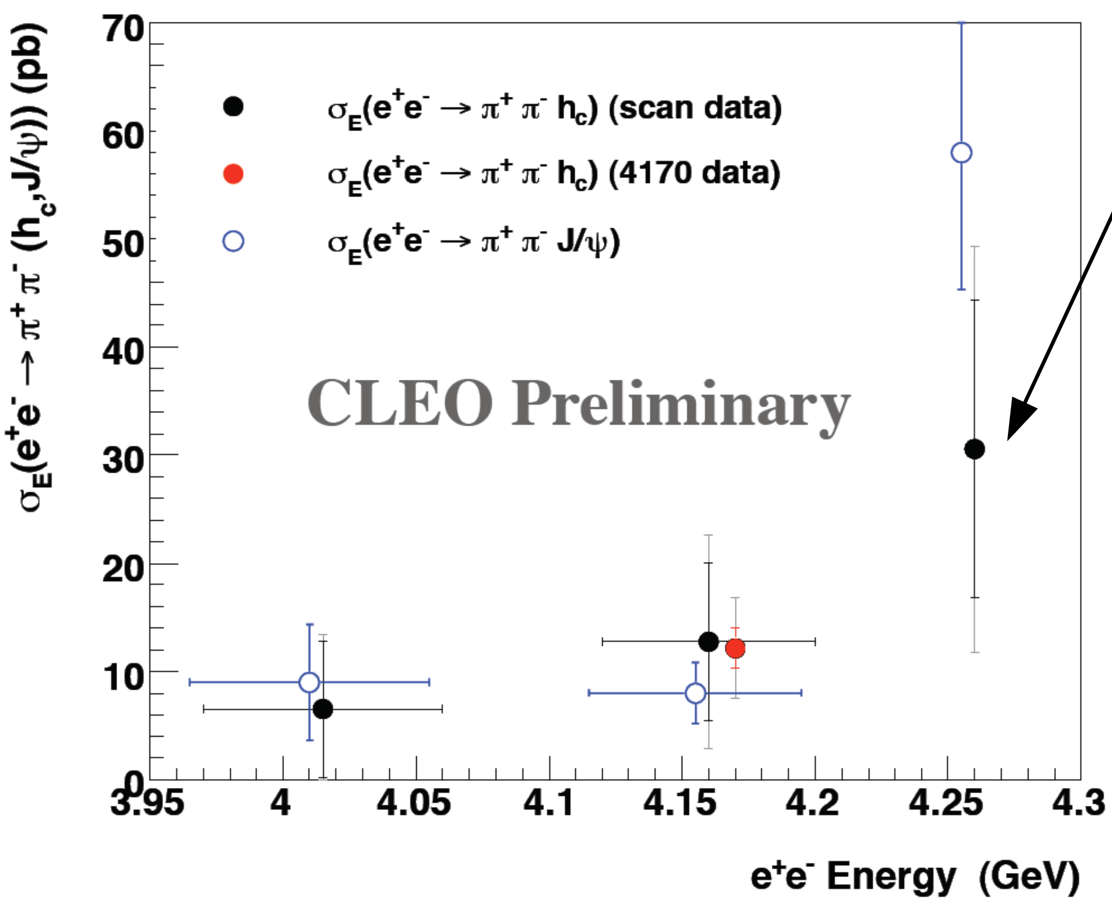
Does not agree well with the conventional ϒ(10860) line shape

1) Y_b particle: analog to Y(4260) that has anomalously large Γ(J/ψππ)

2) Rescattering of ϒ(5S)→BBππ→ϒ(nS)ππ

Discovery of h_c by CLEO

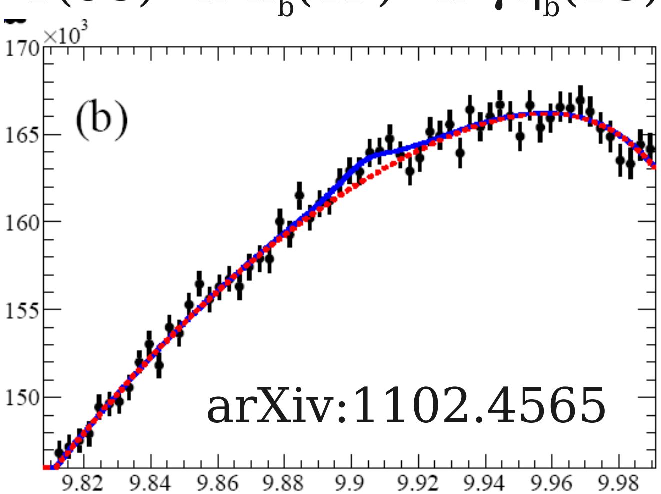
- CLEO observed $e^+e^- \to h_c\, \pi^+ \pi^-$
  - h_c production cross-section seems to be **enhanced near Υ(4260)**

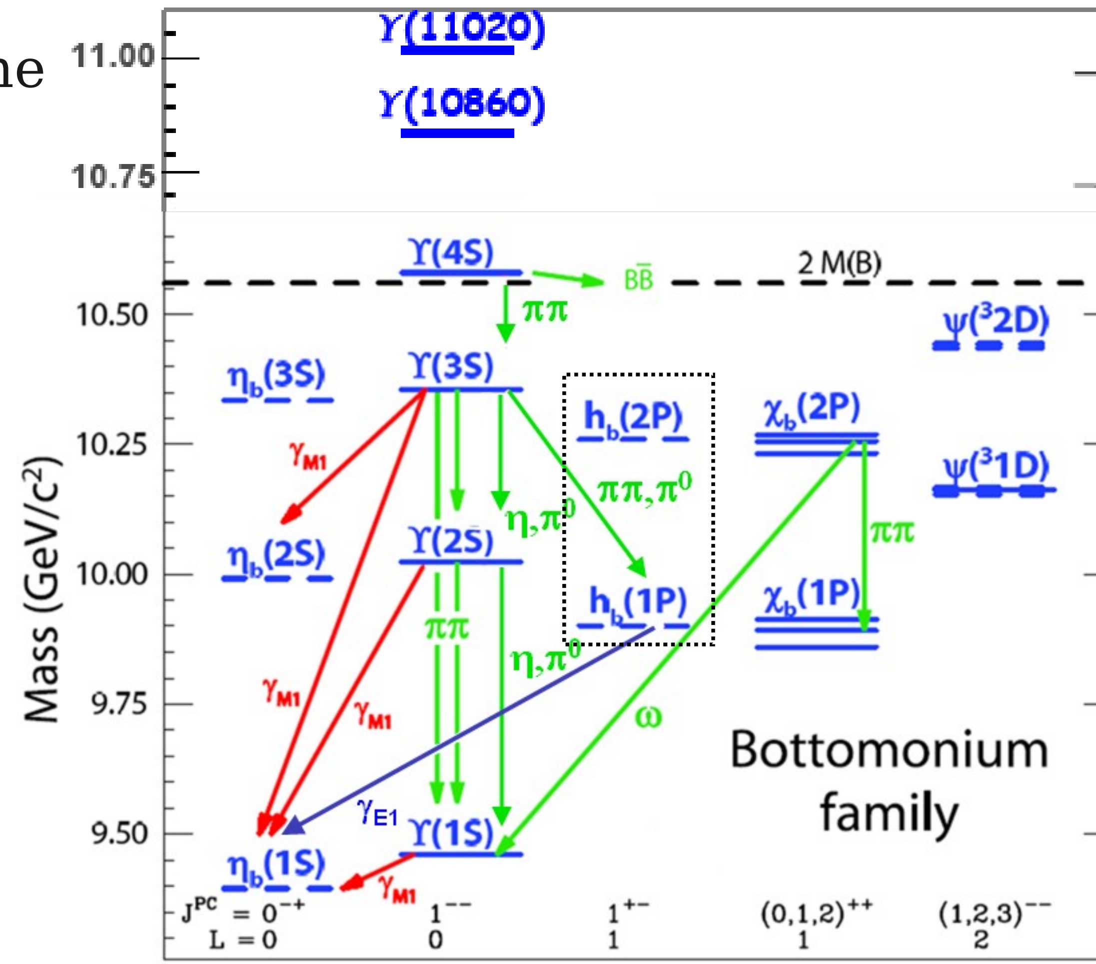


- Do we have more chance of seeing h_b at Υ(5S)?

h_b(nP) properties

- $b\bar{b}$ states, spin 0, L=1, $J^{PC}=1^{+-}$.
- Expected mass of h_b(nP) at the Center of Gravity (CoG) of χ_b states
  - Test of hyperfine splitting
- Radiative transition to η_b(1S)
  - BaBar has obtained evidence (3.0σ) of h_b(1P) in $\Upsilon(3S)\to\pi^0 h_b(1P)\to\pi^0\gamma\eta_b(1S)$





Analysis procedure

- Similar to CLEO's h_c analysis: missing mass (MM) technique
  - Implicit reconstruction of h_b thanks to e^+e^- annihilation
    - $e^+e^- \rightarrow \Upsilon(5S) \rightarrow h_b\, \pi^+\pi^-$

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

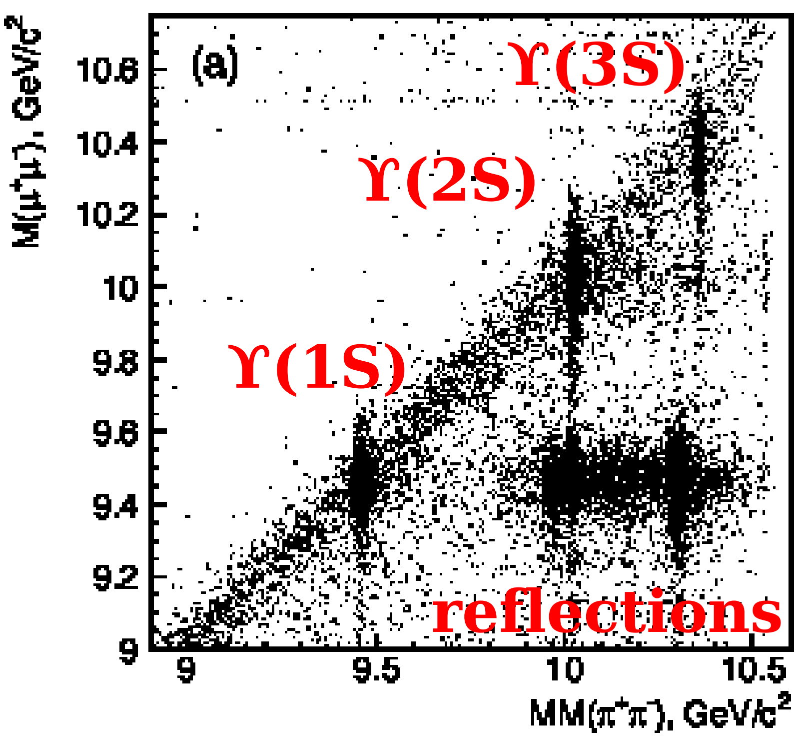
      - $P_{\Upsilon(5S)}$: CM-energy and boost (accelerator information)
      - $P_{\pi+\pi-}$: we reconstruct and measure
  - Search for peaks in MM when h_b(nP), Υ(1-3S), etc... are produced:

$$MM \equiv M_{h_b}$$

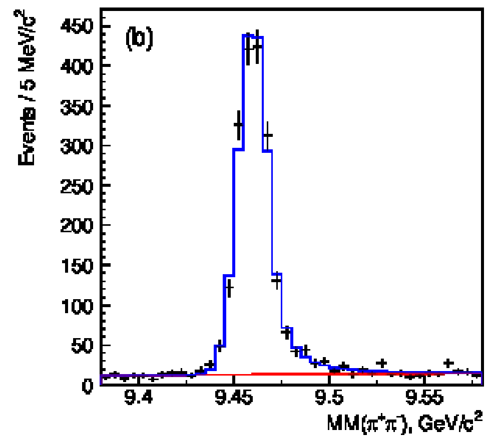
- Selection is simple
  - Pions with opposite charges
    - track originating from IP and particle identification
  - Continuum suppression with event shape

Signal calibration

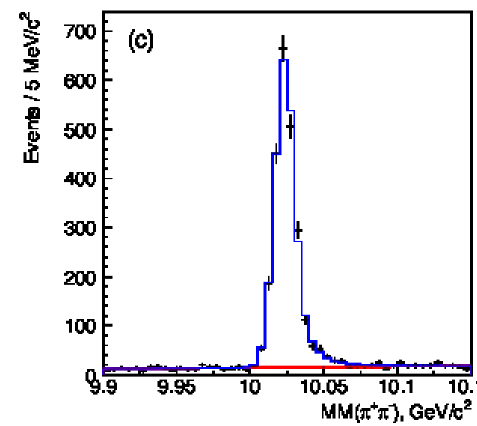
- Use the large exclusive "$\Upsilon(5S) \rightarrow \Upsilon(nS)\ \pi^+\pi^-$ with $\Upsilon(nS) \rightarrow \mu^+\mu^-$" as reference
  - Signal: CrystalBall tail due to ISR
  - Reflections are also calibrated



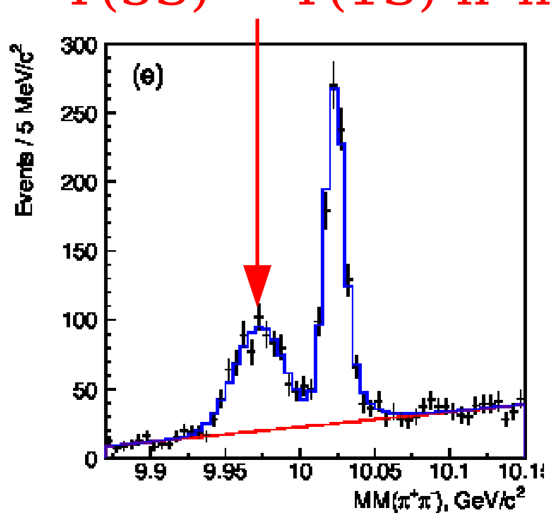
$\Upsilon(5S) \rightarrow \Upsilon(1S)\ \pi^+\pi^-$



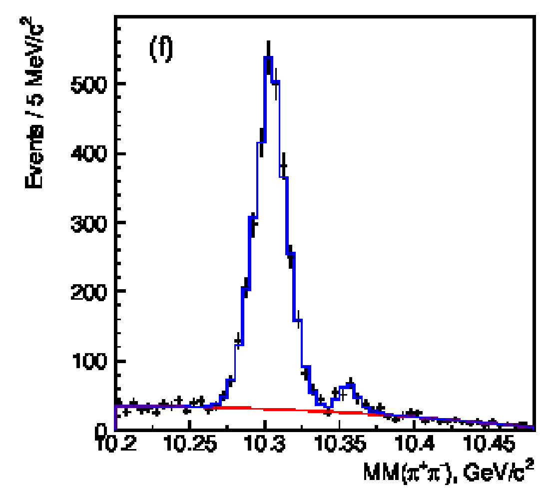
$\Upsilon(5S) \rightarrow \Upsilon(2S)\ \pi^+\pi^-$



$\Upsilon(3S) \rightarrow \Upsilon(1S)\ \pi^+\pi^-$

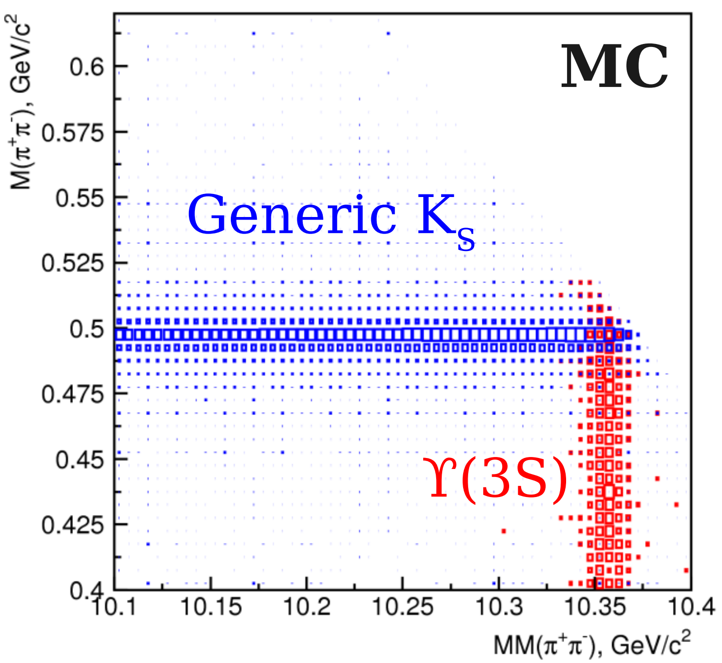


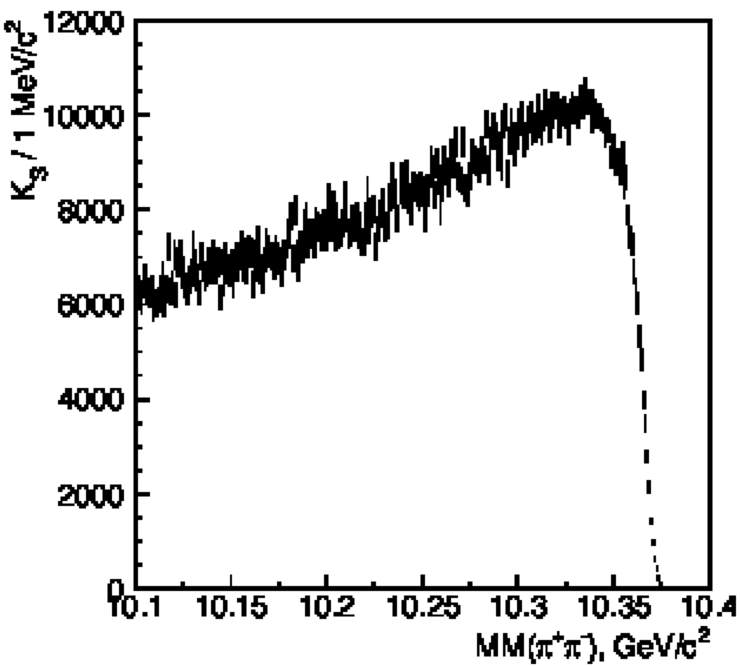
$\Upsilon(2S) \rightarrow \Upsilon(1S)\ \pi^+\pi^-$



Background

- Most background is random combination of pions that can be described by polynomial function
- At MM~$M_{\Upsilon(3S)}$ region: contribution from real $K_S \rightarrow \pi^+\pi^-$ explodes
  - Near threshold: $M_{\Upsilon(3S)} \sim E_{CM} - M_{KS}$

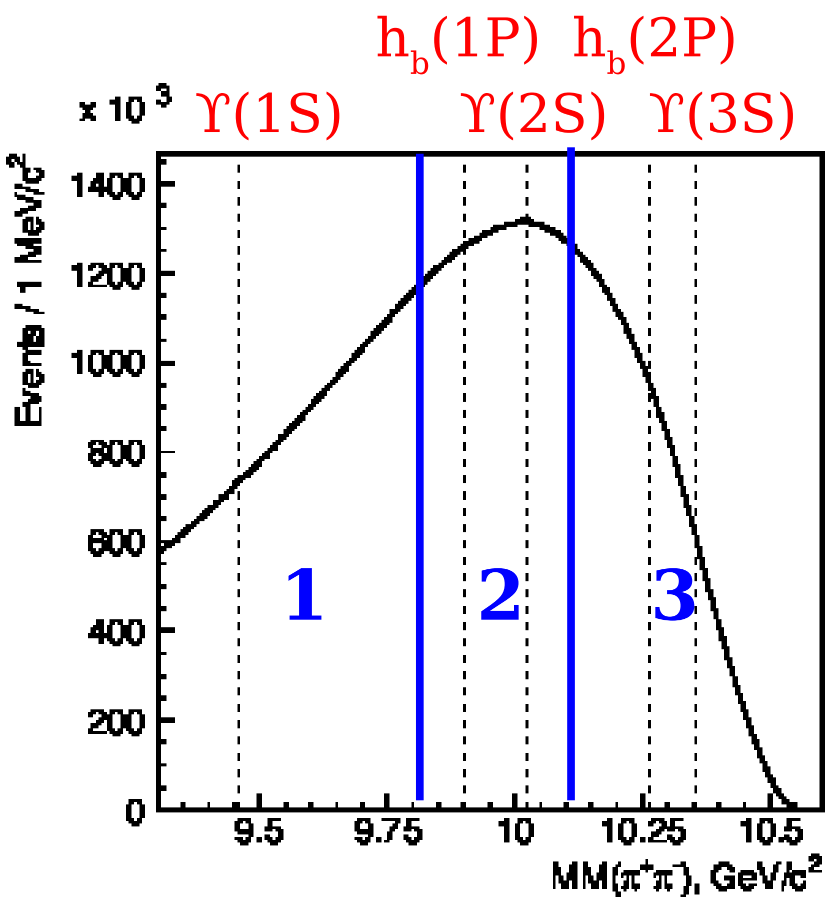


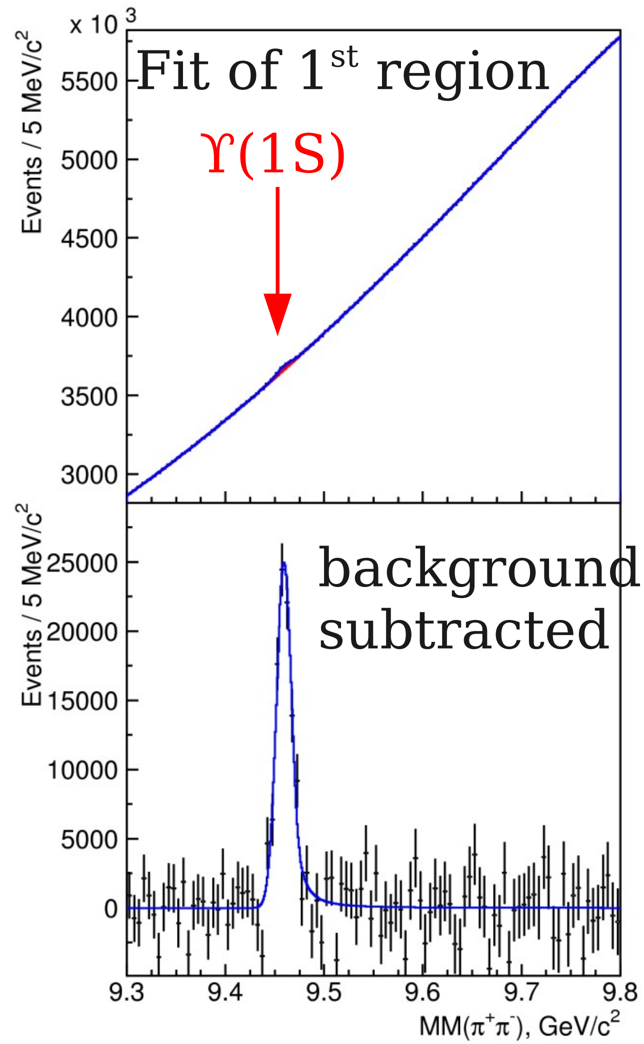


K_S yield fitted in data as a function of MM
Will be used as PDF in the fit

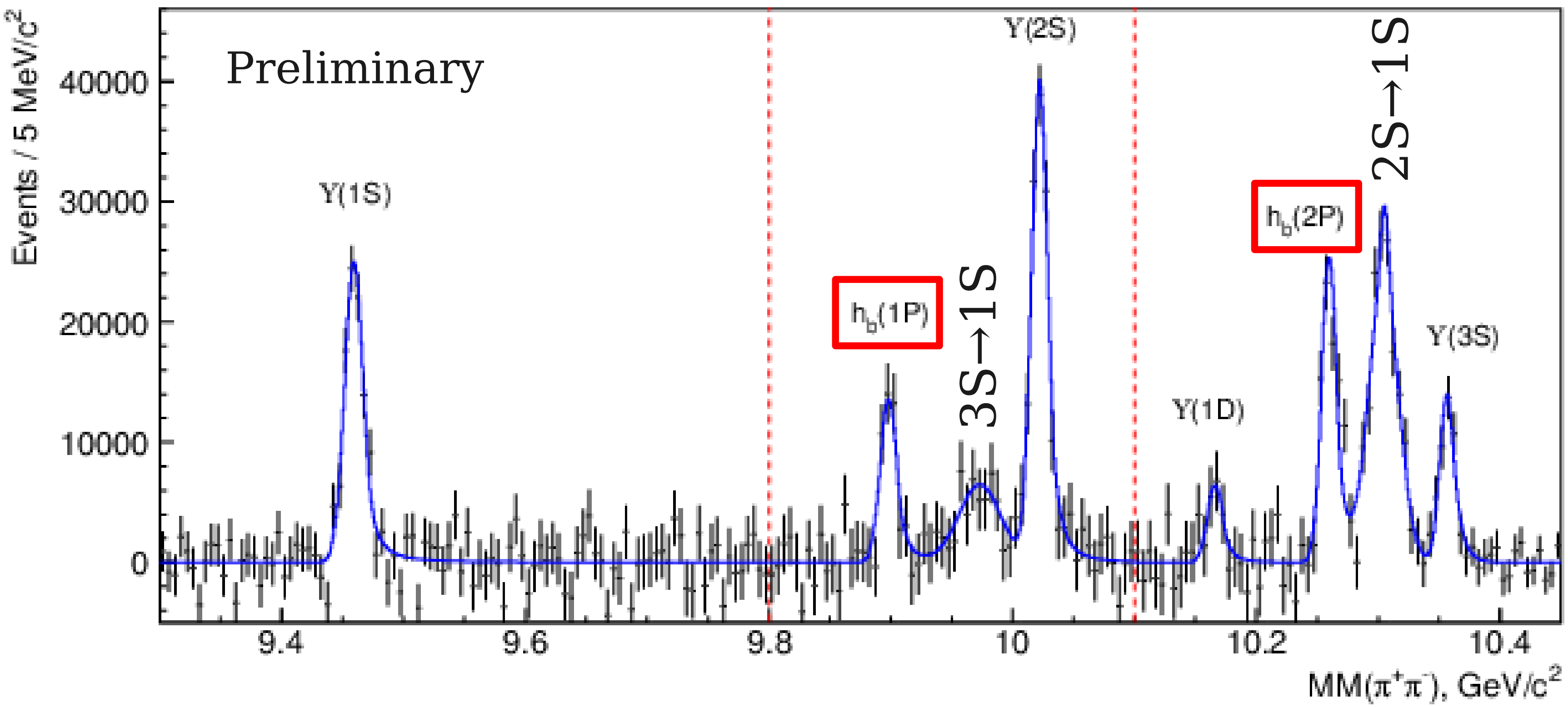
Fit procedure

- Three independent fit are performed to MM distribution
  - signals and reflections (calibrated with exclusive decays)
  - combinatorial background: order of polynomial: max of C.L.
  - K_S background (3^{rd} region only)





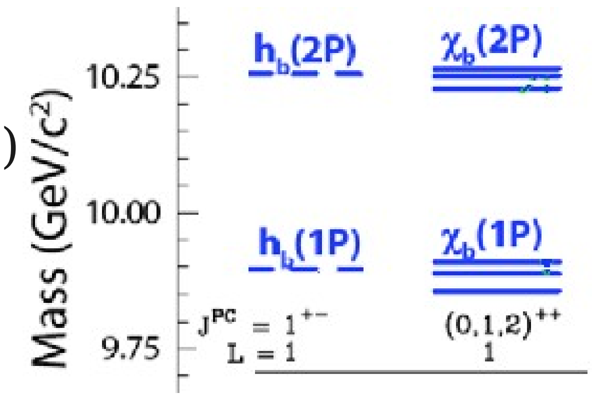
Results



	Yield $[10^3]$	Mass $[\mathrm{MeV/c^2}]$	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.42 \pm 0.53 \pm 1.02$	18.2
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.25 \pm 1.06^{+1.03}_{-1.07}$	5.5
$\Upsilon(3S) \to \Upsilon(1S)$	55 ± 19	9973.01	2.9
$\Upsilon(2S)$	$143.4 \pm 8.7 \pm 6.8$	$10022.25 \pm 0.41 \pm 1.01$	16.6
$\Upsilon(1D)$	22.1 ± 7.8	10166.2 ± 2.4	2.4
$h_b(2P)$	$84 \pm 7^{+23}_{-10}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	11.2
$\Upsilon(2S) \to \Upsilon(1S)$	$151.6 \pm 9.7^{+9.0}_{-20.0}$	$10304.57 \pm 0.61 \pm 1.03$	15.7
$\Upsilon(3S)$	$44.9 \pm 5.1 \pm 5.1$	$10356.56 \pm 0.87 \pm 1.06$	8.5

Results

- Could the observed states be $\chi_{b1}(nP)$? No
  - Measured masses are ~3σ off compared to $\chi_{b1}(nP)$
  - $\Upsilon(5S) \to \chi_{b1}(nP)\pi^+\pi^-$ violates isospin (strong interaction)



- Mass are in very good agreement with CoG of χ_b states
  - $h_b(1P)$: $\Delta M = 1.62 \pm 1.52$ MeV/c^2
  - $h_b(2P)$: $\Delta M = 0.48 \pm 1.57$ MeV/c^2

Consistent with hyperfine interaction

- Ratio of production rate

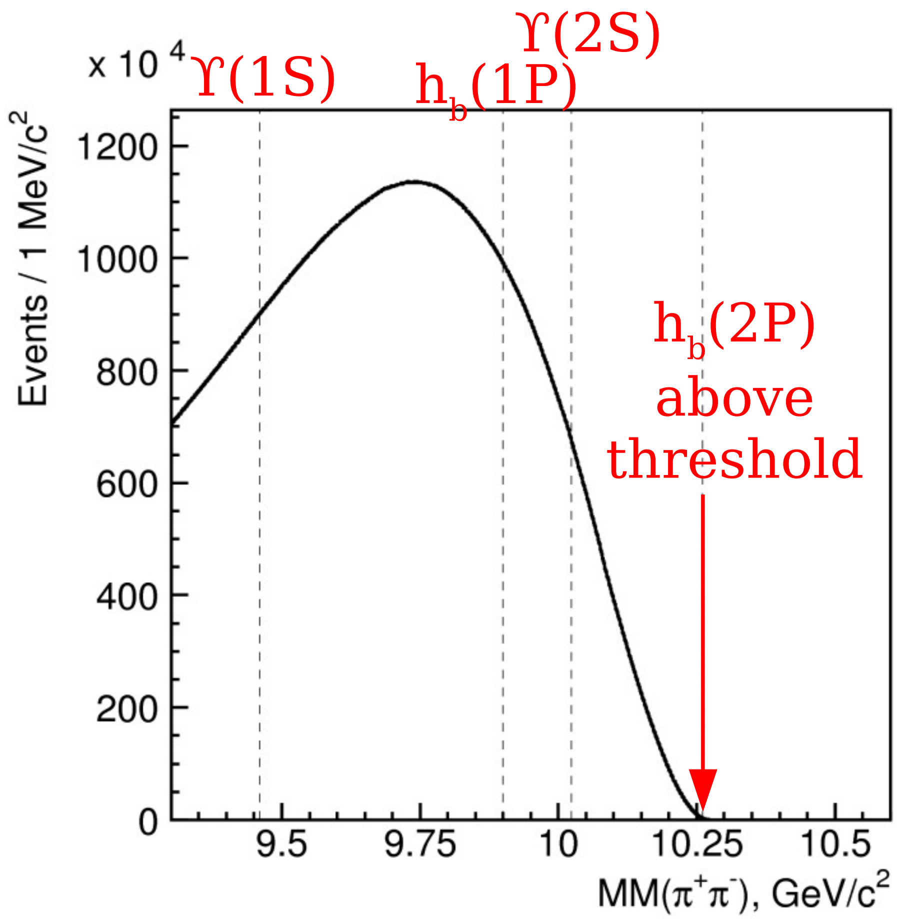
$$\frac{\Gamma(\Upsilon(5S)\to h_b(1P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-)} = 0.407 \pm 0.079^{+0.043}_{-0.076}$$

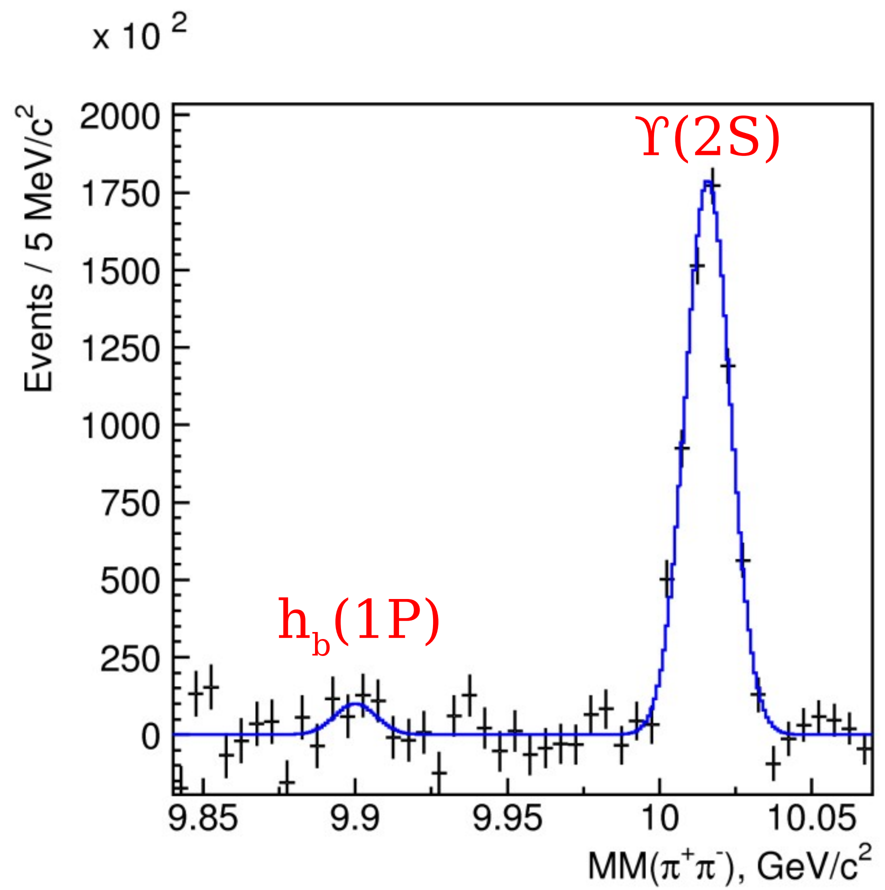
$$\frac{\Gamma(\Upsilon(5S)\to h_b(2P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-)} = 0.78 \pm 0.09^{+0.22}_{-0.10}$$

  - Spin of $h_b(nP)$ is 0 while $\Upsilon(nS)$'s are 1: decays to h_b should be suppressed because of spin-flip.
    - $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ decays seem exotic!

Search for h_b at $\Upsilon(4S)$

- Using all our data: 711 fb^{-1} (ie six times more data than at $\Upsilon(5S)$)





No significant h_b signal
(34±20) 10^3 (1.7σ)

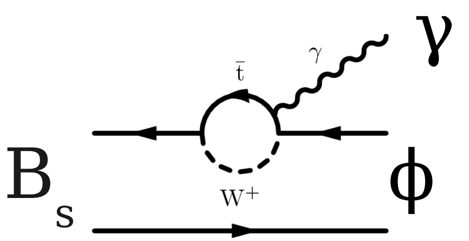
$$\frac{\sigma(e^+e^- \to h_b(1P)\pi^+\pi^-)@\Upsilon(4S)}{\sigma(e^+e^- \to h_b(1P)\pi^+\pi^-)@\Upsilon(5S)} < \mathbf{0.28\ (90\%\ CL)}$$

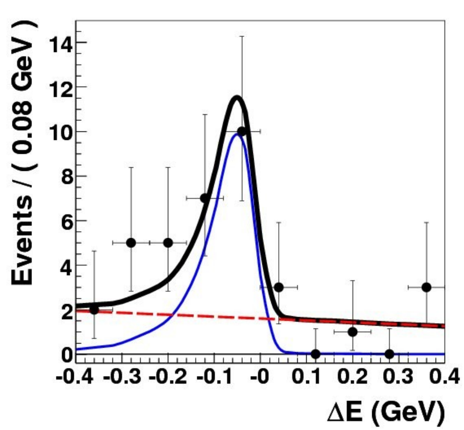
$\Upsilon(4S)$ decay to h_b is not enhanced

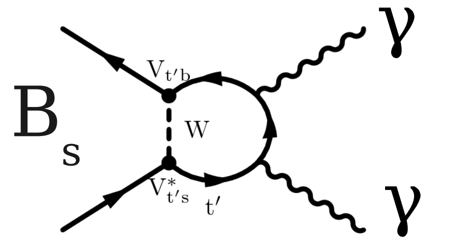
Future plans

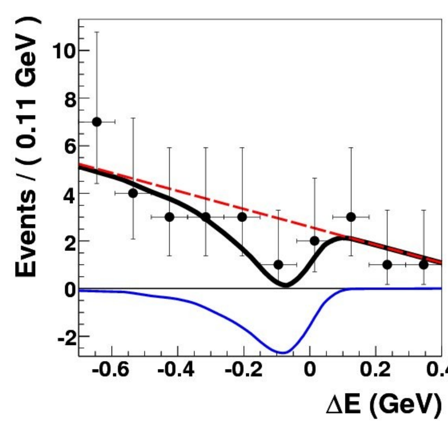
Many results obtained with only one fifth of our data: 23.6 fb^{-1}

$B_s^0 \to$	Type	$\mathcal{B}$	Signif.	Status	Reference
$\phi\gamma$	Radiative penguin	$(53^{+18+12}_{-15-11})\ 10^{-6}$	5.5	1st obs.	PRL 100, 121801
$\gamma\gamma$	Radiative penguin	$< 8.7\ 10^{-6}$	–	Best UL	PRL 100, 121801
$J/\psi\eta$	CP-eigenstate	$(3.3 \pm 0.9 \pm 0.5)\ 10^{-4}$	7.3	1st obs.	arXiv:0912.1434
$J/\psi\eta'$	CP-eigenstate	$(3.1 \pm 1.2 \pm 0.7)\ 10^{-4}$	3.8	1st evid.	arXiv:0912.1434
D_sD_s	CP-eigenstate	$(1.0^{+0.4+0.3}_{-0.3-0.2})$ %	6.2	–	PRL 105, 201802
$D_s^*D_s$	CP-eigenstate	$(2.8^{+0.8}_{-0.7} \pm 0.7)$ %	6.6	1st obs.	PRL 105, 201802
$D_s^*D_s^*$	CP-eigenstate	$(3.1^{+1.2}_{-1.0} \pm 0.8)$ %	3.1	1st evid.	PRL 105, 201802

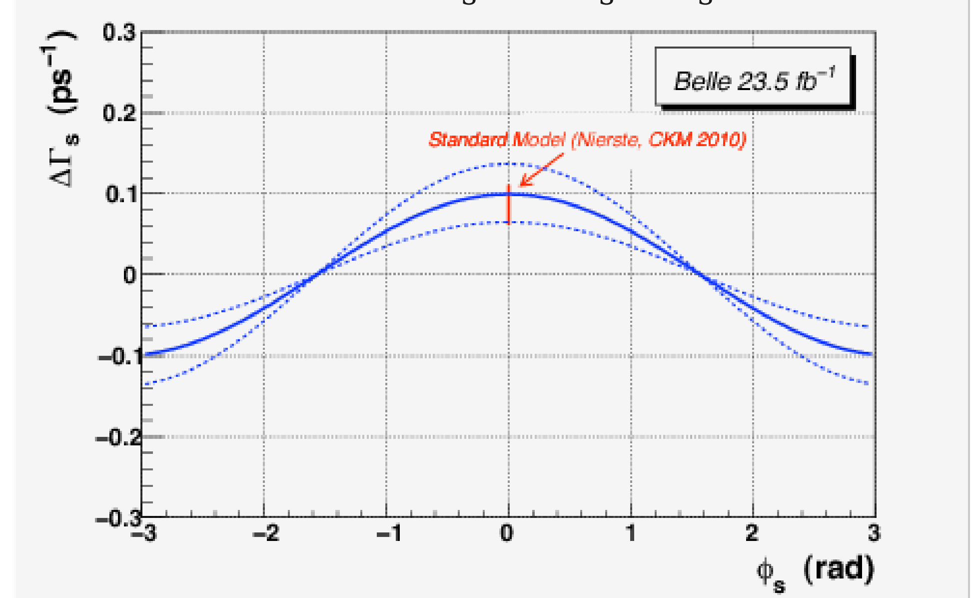








Measurement of $\Delta\Gamma_s$ with $B_s \to D_s^{(*)}D_s^{(*)}$



Need to update!

Future plans

- Measure branching fractions as precisely as possible
  - Important for example for $B_s \to \mu\mu$ BF normalization at LHC
  - Need to improve precision on f_s (fraction of B_s)
    - Using new method: **dileptons**
      - $\Upsilon(5S) \to B_s(\to X^- \mathbf{l^+} \nu)\, \overline{B}_s(\to X^+ \mathbf{l^-} \nu)$
      - B_s oscillate ~40 times faster than B^0

	Lifetime $[10^{-12}\ s]$	$\Delta m\ [10^{12}\ \bar{h}\ s^{-1}]$
B_s^0	1.425 ± 0.041	17.77 ± 0.12
B^0	1.525 ± 0.009	0.507 ± 0.005

      - Ratio of "same sign dileptons" to "opposite sign dileptons" is sensitive to f_s
      - Reach **5% precision** on f_s according to: arXiv:hep-ph/0604201

Summary

- With 121.4 fb^{-1} at $\Upsilon(5S)$
- Observation of $B_s \to J/\psi\ f_0(980)$ and first evidence of $B_s \to J/\psi\ f_0(1370)$
  - CP eigenstates to measure β_s without angular analysis
- First observation of two $b\bar{b}$ states: $h_b(1P)$ and $h_b(2P)$
  - Masses in agreement with expectations (CoG of χ_b)
  - Production ratio of h_b with respect to $\Upsilon(2S)$ is not suppressed as expected due to the spin-flip
    - Production of h_b at $\Upsilon(5S)$ is exotic
  - No evidence of h_b in 711 fb^{-1} at $\Upsilon(4S)$
- Stay tuned for summer results!

Systematics

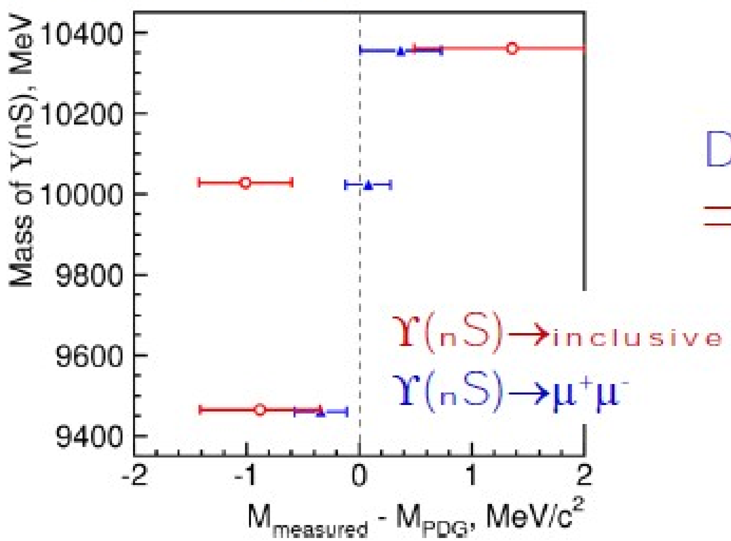
	Polynomial order	Fit range	Signal shape	Selection requirements
$N[h_b]$, 10^3	± 2.4	± 3.6	${}^{+1.2}_{-8.0}$	–
$M[h_b]$, MeV/c^2	$\pm .04$	$\pm .10$	${}^{+0.04}_{-0.20}$	${}^{+.20}_{-.30}$
$N[h_b(2P)]$, 10^3	± 2.2	± 2.6	${}^{+23.}_{-9.0}$	–
$M[h_b(2P)]$, MeV/c^2	$\pm .10$	$\pm .20$	${}^{+1.0}_{-0.0}$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

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?

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