BELLE

Belle physics results at the Υ(5*S*):

studying B_s decays at an e^+e^- collider

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- introduction
- results from 1.8 fb^{-1} engineering run:
  - measurement of inclusive B_s production (hep-ex/0608015 →PRL)
  - measurement of exclusive CF B_s decays ($D_s^{+(*)}\pi$, $\psi\eta$) (hep-ex/0610003)
  - search for rarer B_s decays (K^+K^-, $D_s^{+(*)}D_s^{+(*)}$, $\phi\gamma$, $\gamma\gamma$)
- future B_s physics program

Why study the B_s at an e^+e^- machine?

There are advantages over a hadronic machine:

- *much lower background*

- *high trigger efficiency, negligible trigger bias*

- *measure absolute branching fractions, inclusive branching fractions, branching fractions of CP eigenstates*

- *excellent π^0 identification, and thus ρ^+, ω, η, η', K^{*+}, a_1, etc.*
  - ⇒ *many more final states reconstructed*

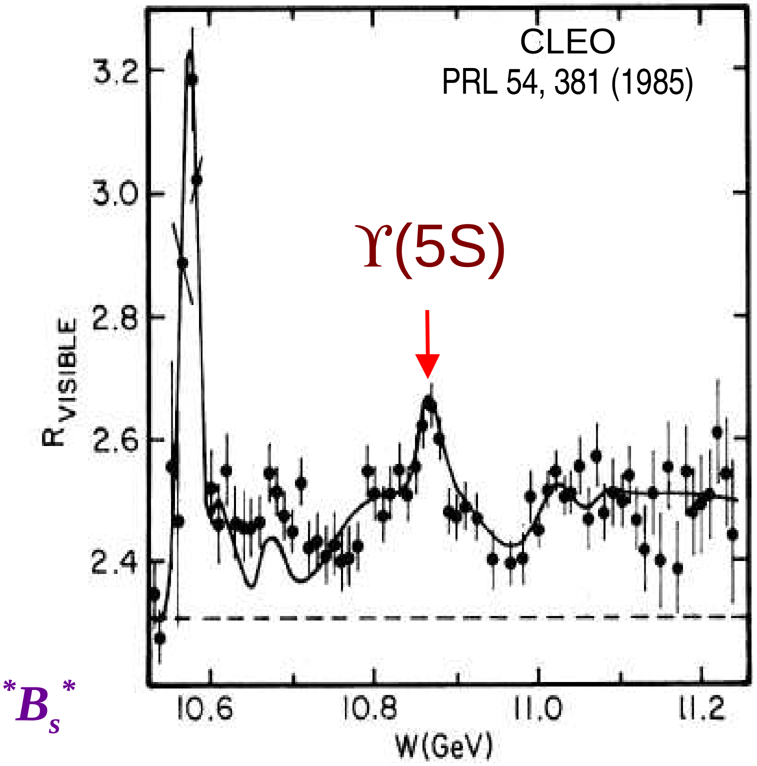
- *excellent K/π separation*

- *many analysis tools/techniques developed for use at the Y(4S) can be applied to analyses at Y(5S): m_{bc}, ΔE, Fox-Wolfram moments for $q\bar{q}$ suppression, flavor tagging methods, vertex fitters, control samples*

Expected rate of B_s production

World sample: four runs

1985 CLEO	~0.1 fb^{-1}
2003 CLEOIII	0.42 fb^{-1} → PRL 95, 261801 (2005)
► 2005 Belle	1.9 fb^{-1}
2006 Belle	21.7 fb^{-1}



CLEO
PRL 54, 381 (1985)

$\sigma\ [e^+e^-\to\Upsilon(5S)] = 0.30\ \mathrm{nb}$ (CLEO 85, 05, Belle)

$\Rightarrow$ 300000 $\Upsilon(5S)$ per fb^{-1}

$\Upsilon(5S) \to BB,\ B^*B,\ B^*B^*,\ BB\pi,\ BB\pi\pi,\ B_sB_s,\ B_s^*B_s,\ B_s^*B_s^*$

$(B^*\to B\gamma\ ,\ B_s^*\to B_s\gamma\ )$

CLEO 05 measured inclusive D_s yield. Assuming $B(B_s \to D_s X) = 0.92$ implies

$\Gamma(\Upsilon(5S) \to B_s^{(*)}B_s^{(*)})/\Gamma(\Upsilon(5S) \to \mathrm{all}) = (16 \pm 6)\%$

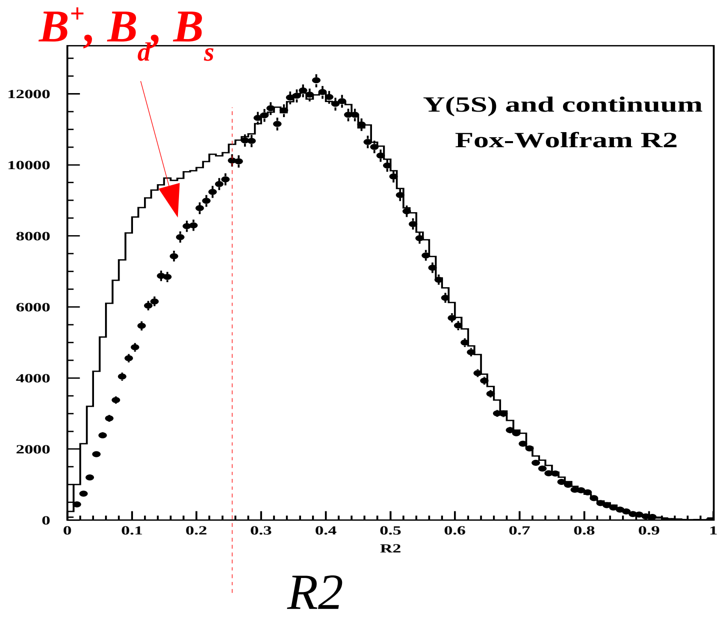
$\Rightarrow$ $\boxed{96000\ \ B_s \text{ per } \mathrm{fb}^{-1}}$

Υ(5S) Engineering run in June 2005

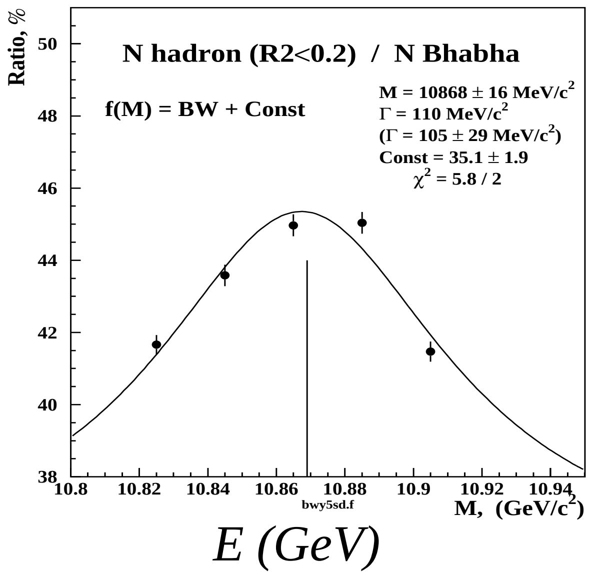
Data set:

- first took ~0.030 fb^{-1} at five points: E = 10.825, 10.845, 10.865, 10.885, 10.905 GeV
- shifted to E=10.869 GeV [beam energy 2.7% higher than at Υ(4S)], took 1.86 fb^{-1}
- by end of run $\mathcal{L} = 1.4 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (like Υ(4S) running)
- also took 3.67 fb^{-1} at energy 60 MeV below Υ(4S) (qq sample)

Fox-Wolfram moment R2:



Energy scan:



fixing width to PDG value (Γ = 110 MeV)

$m_{Υ(5S)}$ = 10868 ± 6 ± 14 MeV/c^2 (PDG: 10865 ±8)

Υ(5S)/cont = 1/3.5

$\Rightarrow \sigma_{Υ(5S)}/\sigma_{Υ(4S)} = 0.25$

Inclusive analysis: $\Upsilon(5S)\rightarrow D_s X$ (hep-ex/0608015 →PRL)

number of $e^+e^-\rightarrow\Upsilon(5S)\rightarrow bb$ events:

- count hadronic events
- subtract qq ($u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}$) contribution by scaling from qq sample:

$$N_{cont}(5S) = N_{cont}(E{=}10.519)\ \mathcal{L}(5S)\,/\,\mathcal{L}(E{=}10.519)\ \ (E_{cont}/E_{5S})^2\ (\varepsilon_{5S}/\varepsilon_{cont})$$

$$N_{bb} = 561000 \pm 3000 \pm 29000$$

fraction of $B_s B_s$ events:

- reconstruct $D_s\rightarrow\phi\pi$ decays, divide by N_{bb}:

$$\mathcal{B}(\Upsilon(5S)\rightarrow D_s X)\,/2\ =\ (23.6 \pm 1.2 \pm 3.6)\ \%$$

- calculate $f_s = (B_s B_s)/bb$ ratio via:

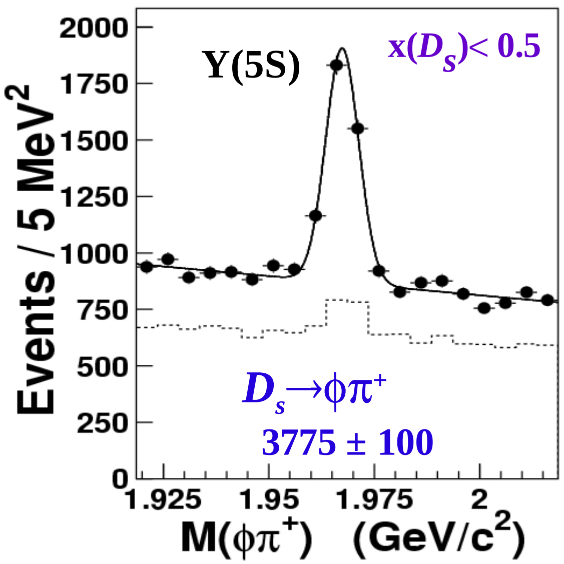
$$\mathcal{B}(\Upsilon(5S)\rightarrow D_s X)\,/2\ =\ f_s\ \mathcal{B}(B_s\rightarrow D_s X) + (1- f_s)\ \mathcal{B}(B\rightarrow D_s X)$$

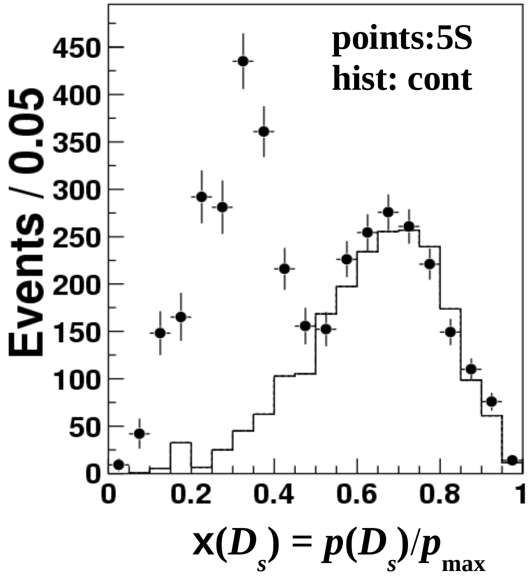
(92 ± 11)%
(theory estimate, CLEO 05)

(8.7 ± 1.2)%
(PDG06, CLEO 05)

$$\Rightarrow\ \boxed{f_s = (17.9 \pm 1.4 \pm 4.1\ )\%}$$

NOTE: $\mathcal{B}(D_s\rightarrow\phi\pi^+) = (4.4 \pm 0.6)\%$ is the dominant systematic





Inclusive analysis: Y(5S)→D^0 X *(hep-ex/0608015 →PRL)*

fraction of B_sB_s events:

- **reconstruct $D^0\to K^-\pi^+$ decays, divide by N_{bb}:**

$$\mathcal{B}(\Upsilon(5S)\to D^0 X)\,/2 \;=\; (53.8 \pm 2.0 \pm 3.4)\ \%$$

- **calculate $f_s = (B_sB_s)/bb$ ratio via:**

$$\mathcal{B}(\Upsilon(5S)\to D^0 X)\,/2 \;=\; f_s\,\mathcal{B}(B_s\to D^0 X) + (1-f_s)\,\mathcal{B}(B\to D^0 X)$$

(8 ± 7)%
(theory estimate, CLEO 05)

(64.0 ± 3.0)%
(PDG06)

$$\Rightarrow\quad \boxed{f_s = (18.1 \pm 3.6 \pm 7.5)\%}$$

NOTE: **$\mathcal{B}(D^0\to K^-\pi^+) = (3.80 \pm 0.07)\%$ well-measured,**

N_{bb} is the dominant systematic

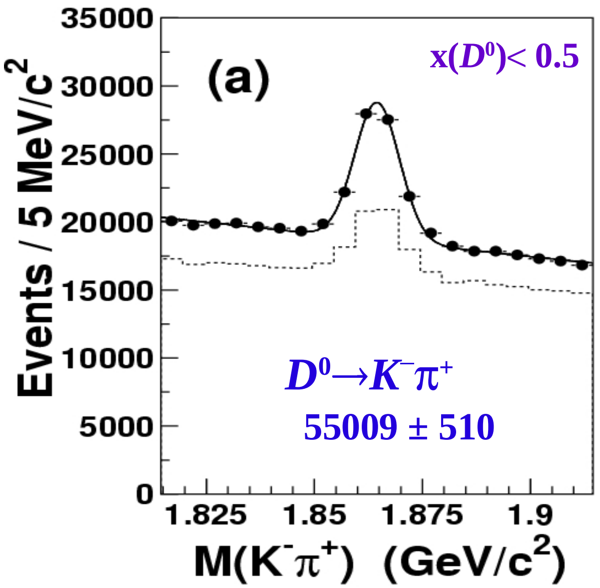
using f_s above in $\Upsilon(5S)\to D_s X$ calculation,

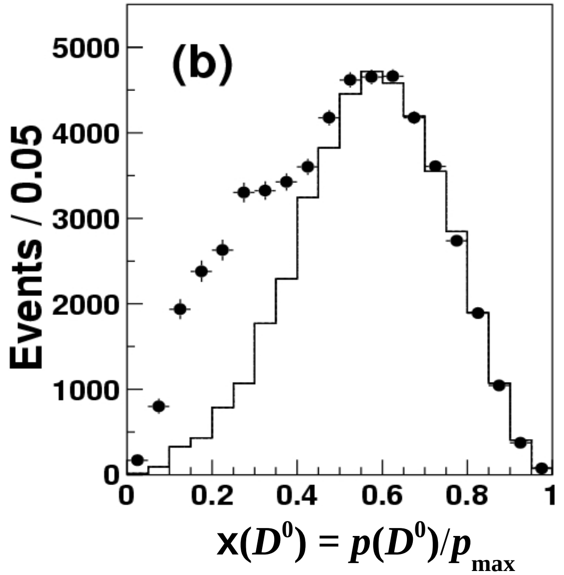
$\mathcal{B}(B_s\to D_s X) = (91 \pm 45)\%$, in agreement with theor. estimate

Combining* Y(5S)→D^0 X *and* Y(5S)→D^0 X *results gives:

$$\boxed{f_s = (18.0 \pm 1.3 \pm 3.2)\%}$$

CLEO 05: (16.0 ± 2.6 ± 5.8)%





Inclusive analysis: $\Upsilon(5S)\to J/\psi\, X$ (hep-ex/0608015 →PRL)

fraction of $B_s B_s$ events:

- reconstruct $J/\psi\to\mu^-\mu^+$ decays, divide by N_{bb}:

$$\mathcal{B}(\Upsilon(5S)\to J/\psi\, X)\,/2 \;=\; (1.030 \pm 0.080 \pm 0.067)\%$$

This can be compared with

$$\mathcal{B}(B\to J/\psi\; X) = (1.094 \pm 0.032)\% \quad \text{(PDG06)}$$

since $(B_s\to J/\psi\; X) / \mathcal{B}(B\to J/\psi\; X) = 1.00 \pm 0.10$ (theory).

Note that the formula

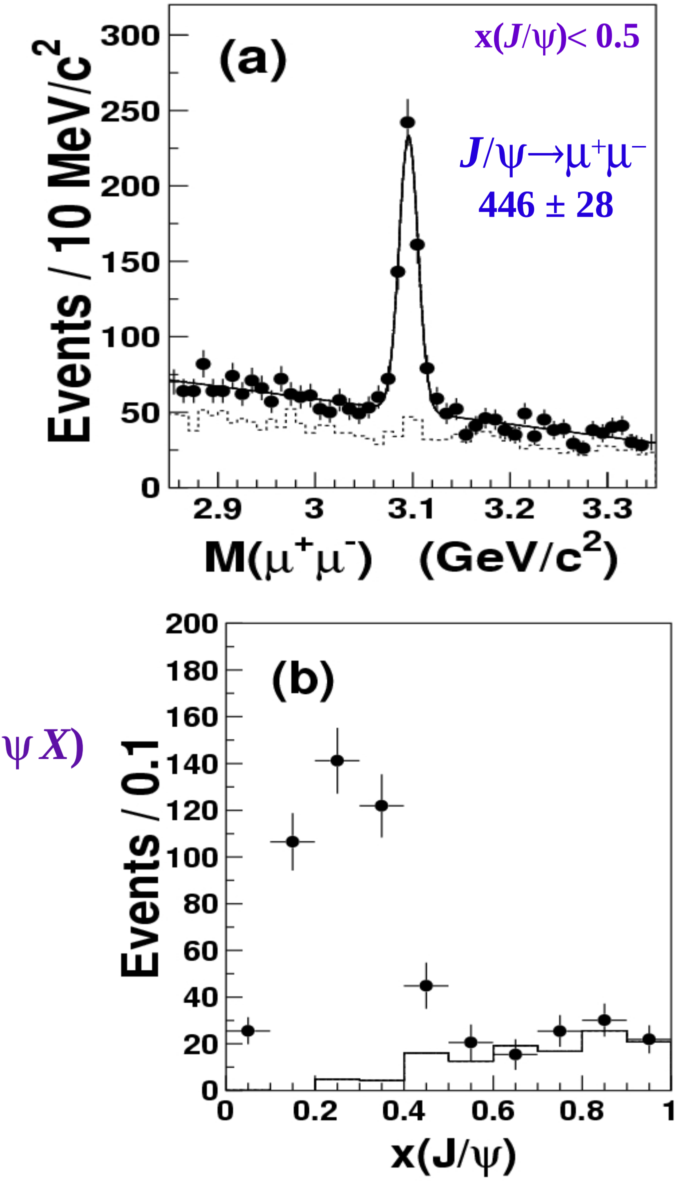
$$\mathcal{B}(\Upsilon(5S)\to J/\psi\, X)\,/2 \;=\; f_s\, \mathcal{B}(B_s\to J/\psi\; X) + (1-f_s)\, \mathcal{B}(B\to J/\psi\, X)$$

cannot be used to determine f_s. However, assuming

$\mathcal{B}\left(B_s\to J/\psi\; X\right) = \mathcal{B}(B\to J/\psi\; X)$ allows one to calculate N_{bb}

(cross-check)

other input: $\mathcal{B}(J/\psi\to\mu^-\mu^+) = (5.88 \pm 0.10)\%$ (PDG06)



Exclusive analysis: B_s reconstruction

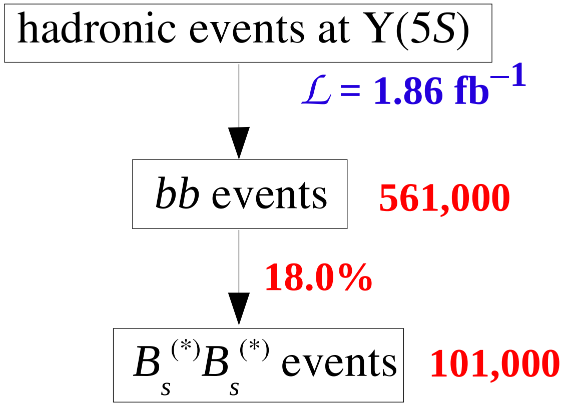
12 Search modes:

Cabibbo favored

- $B_s \to D_s^{(*)+}\pi^-$ $\quad D_s^{*+} \to D_s^+\gamma \quad D_s^+ \to \phi\pi^+,\ K^{*0}K^+,\ K_S K^+$
- $B_s \to D_s^{(*)+}\rho^-$ $\quad \rho^- \to \pi^-\pi^0$
- $B_s \to J/\psi\,\phi$ $\quad J/\psi \to \mu^+\mu^-$ or e^+e^-, $\quad \phi \to K^+K^-$
- $B_s \to J/\psi\,\eta$ $\quad \eta \to \gamma\gamma$
- $B_s \to D_s^{(*)+}D_s^{(*)-}$

$b \to s$ rare

- $B_s \to K^+K^-$
- $B_s \to \phi\gamma$
- $B_s \to \gamma\gamma$



hadronic events at $\Upsilon(5S)$

$\mathcal{L} = 1.86\ \mathrm{fb}^{-1}$

$b\bar{b}$ events **561,000**

18.0%

$B_s^{(*)}\bar{B}_s^{(*)}$ events **101,000**

Selection:

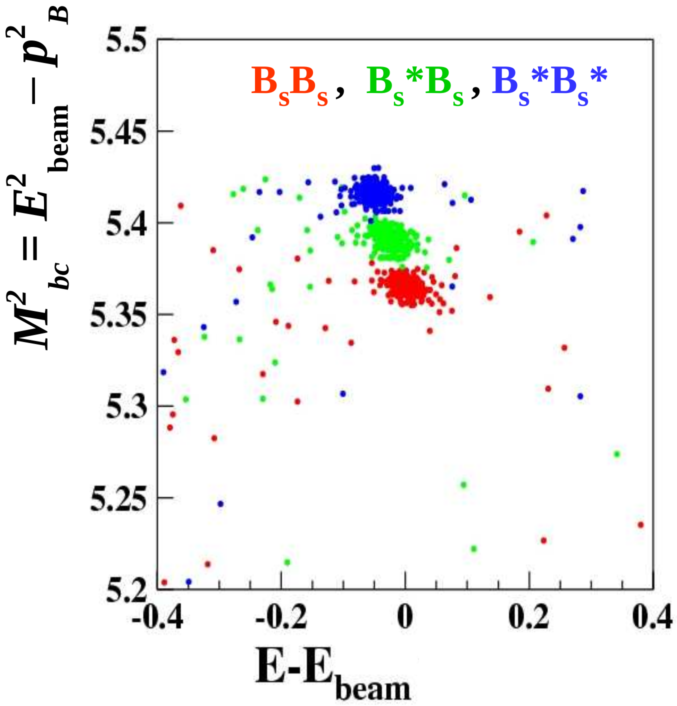
- K identification using time-of-flight, aerogel Cerenkov counter, dE/dx in central tracker
- mass windows are 2σ, 2.5σ, 3σ
- continuum events rejected via Fox-Wolfram $R_2 < 0.3, 0.4$
- B_s : $|\cos\theta| < 0.6 - 0.9$
- D_s^+: $|\cos\theta_{\mathrm{helicity}}| > 0.25$
- $p_\gamma > 50$ or 150 MeV

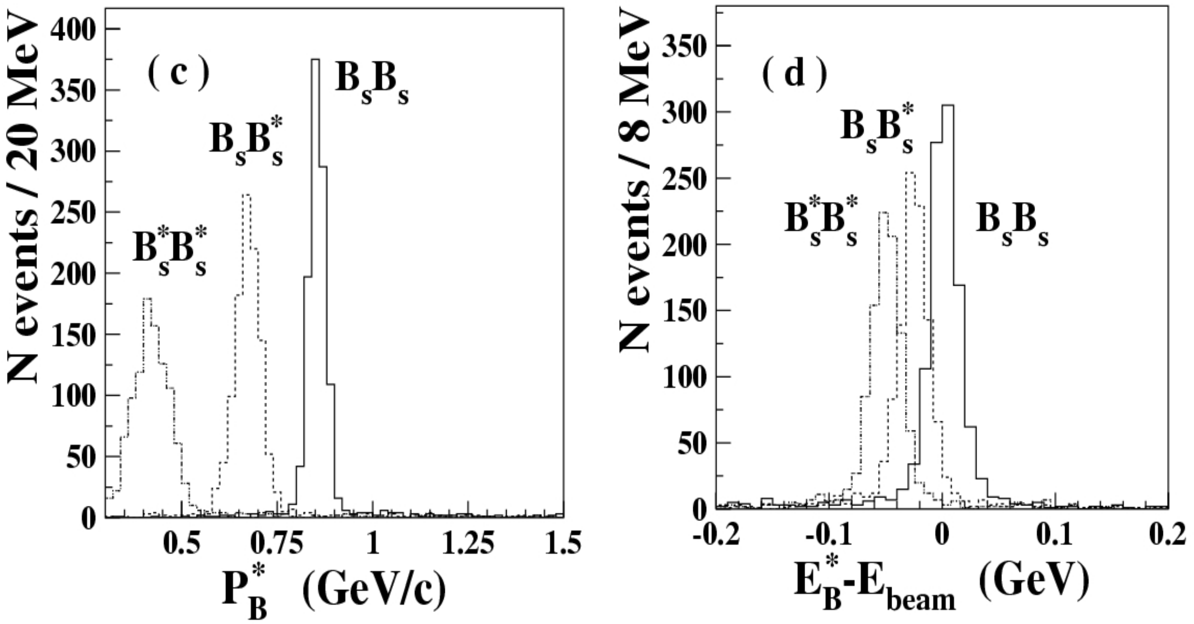
Exclusive analysis: ΔE-m_{bc}

$$m_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

$$\Delta E = E^*_B - E^*_{beam}$$

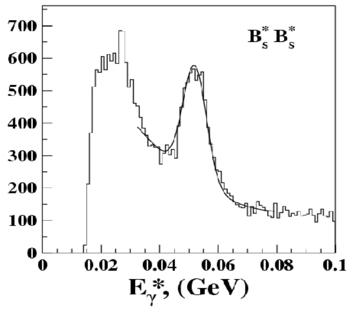
$B_s \to D_s^- \pi^+$, $D_s^- \to \phi\, \pi^-$ ***Monte Carlo:***





B_s signals are well-separated for B_sB_s, $B_s^*B_s$, $B_s^*B_s^*$

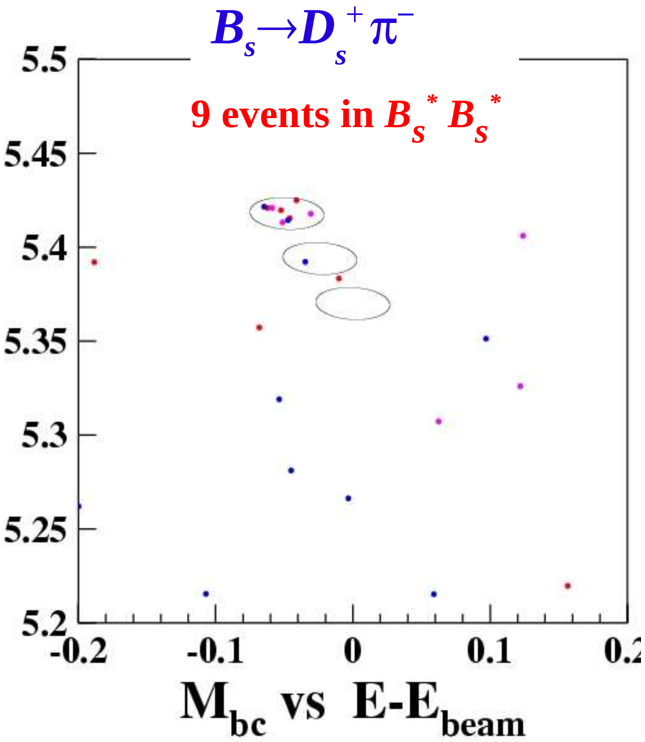
γ spectrum:



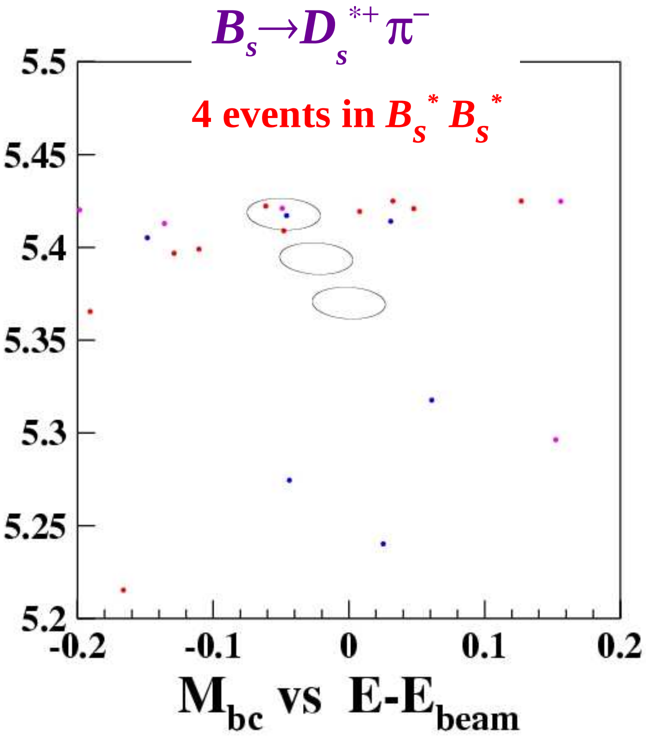
Signals are 20-30% wider than B_d at the $\Upsilon(4S)$

p_γ has only small effect

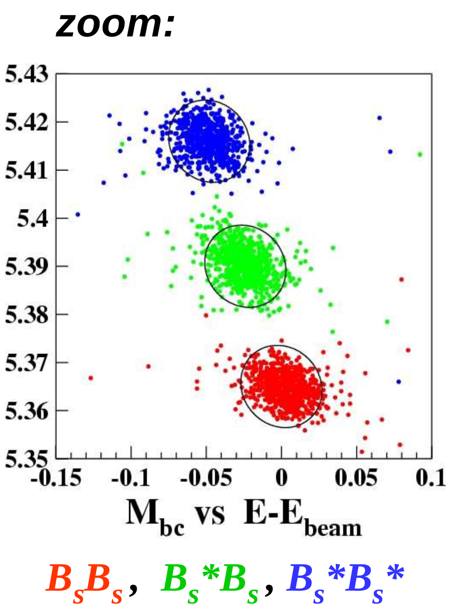
Exclusive analysis: $B_s \to D_s^{(*)+} \pi^-$ (hep-ex/0610003)


$B_s \to D_s^+ \pi^-$

9 events in $B_s^* B_s^*$


$B_s \to D_s^{*+} \pi^-$

4 events in $B_s^* B_s^*$



$D_s^+ \to$ $\phi\pi^+$, $K^{*0}K^+$, K_SK^+

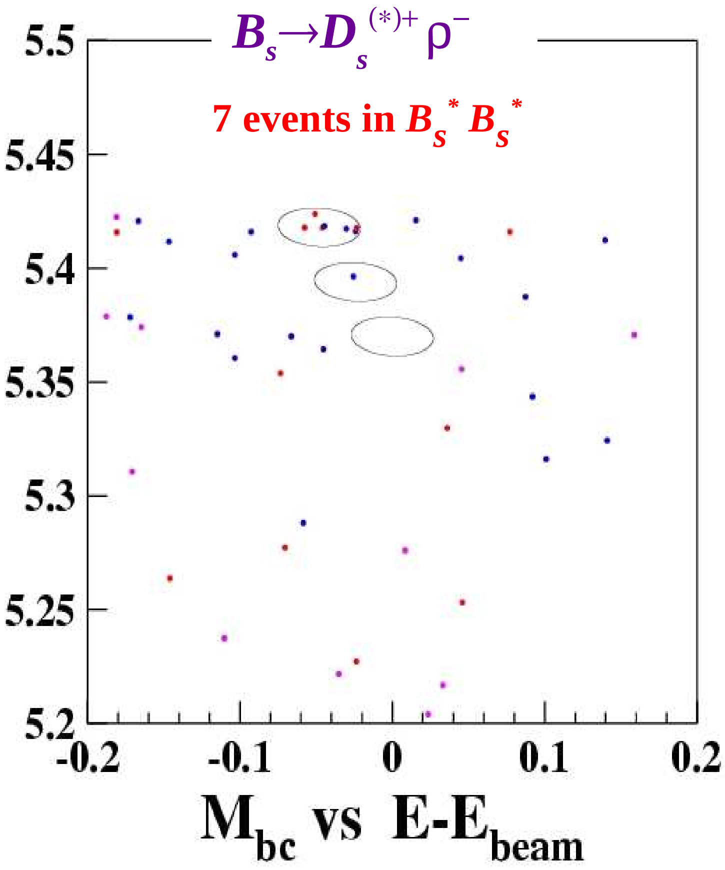
Clear signal in $B_s^* B_s^*$ channel; one event in $B_s^* B_s$, no signal in B_sB_s channels

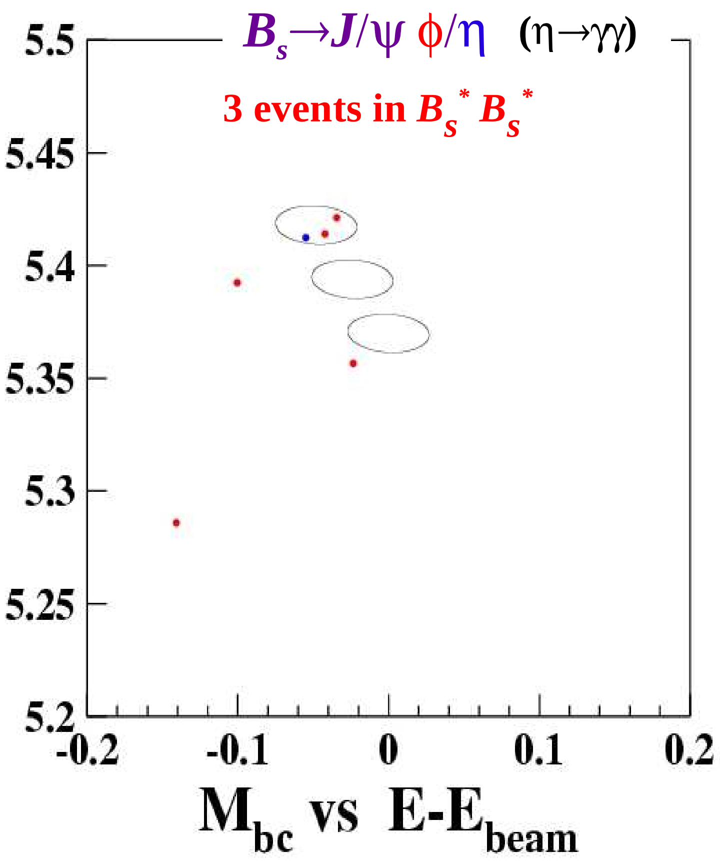
Taking number of $B_s^{(*)}$ mesons from the inclusive analysis:

$\mathcal{B}(B_s \to D_s^+ \pi^-) = (0.68 \pm 0.22 \pm 0.16)\%$

consistent with CDF (recalculated using PDG06): $(0.38 \pm 0.05 \pm 0.14)\%$

Exclusive: $B_s \to D_s^{(*)+} \rho^-$, $B_s \to J/\psi\ \phi/\eta$



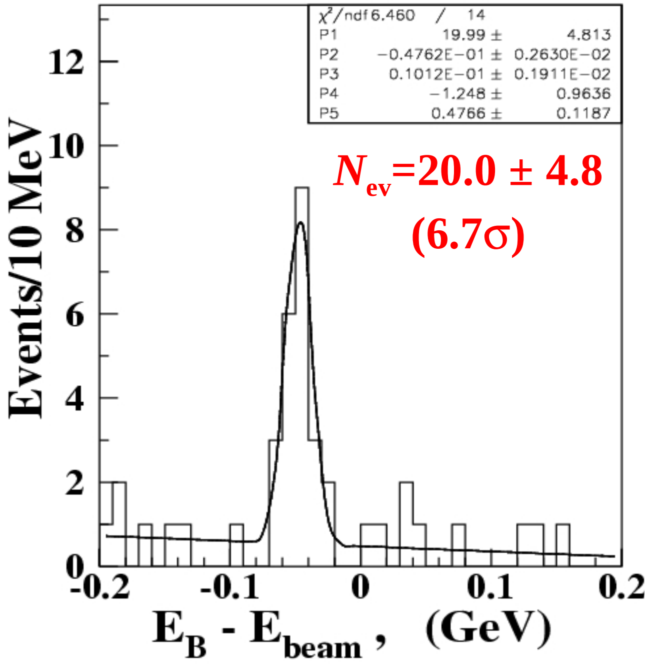


Clear signal in $B_s^* B_s^*$ channel; no obvious signal in $B_s^* B_s$ or $B_s B_s$ channels

Taking number of B_s mesons from the inclusive analysis: $\mathcal{B}(B_s \to J/\psi\ \phi) = 1 \times 10^{-3}$

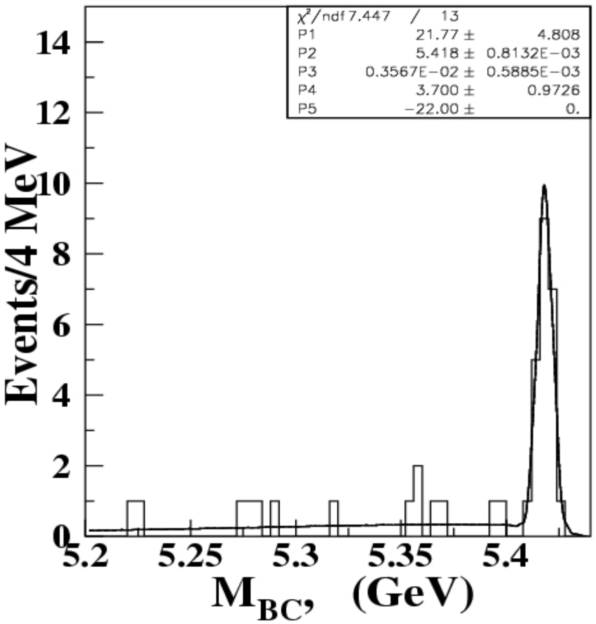
Exclusive: sum together CF modes *(hep-ex/0610003)*

$B_s^* B_s^*$ window: $5.41 < M_{bc} < 5.43$ GeV/c^2

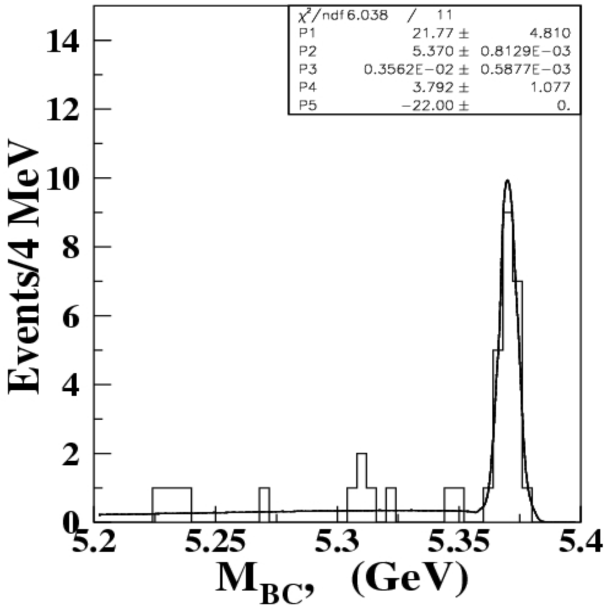


N_{ev}=20.0 ± 4.8 (6.7σ)

$-0.08 < \Delta E < -0.02$ MeV



$-0.08 < \Delta E < -0.02$ MeV



$\Upsilon(5S) \rightarrow B_s^* B_s^* \quad (B_s^* \rightarrow B_s \gamma)$

$\Delta E^{\text{ peak}} = \langle E(\gamma) \rangle = -47.8 \pm 2.6$ MeV

$N(B_s^* B_s^*)/N(B_s^* B_s^*) = (94\,^{+6}_{-9})\%$

(this dominance predicted by theory)

$$M_{bc}{}^2 = E_{\text{beam}}{}^2 - p_B{}^2 = M(B_s^*)^2$$

= 5418 ± 1 ± 3(acc. err) MeV/c^2

(neglected p_γ direction does not change $M(B_s)$ position)

$$\tilde{M}_{bc}{}^2 = (E_{\text{beam}} - \langle \Delta E_\gamma \rangle)^2 - p_B{}^2 = M(B_s)^2$$

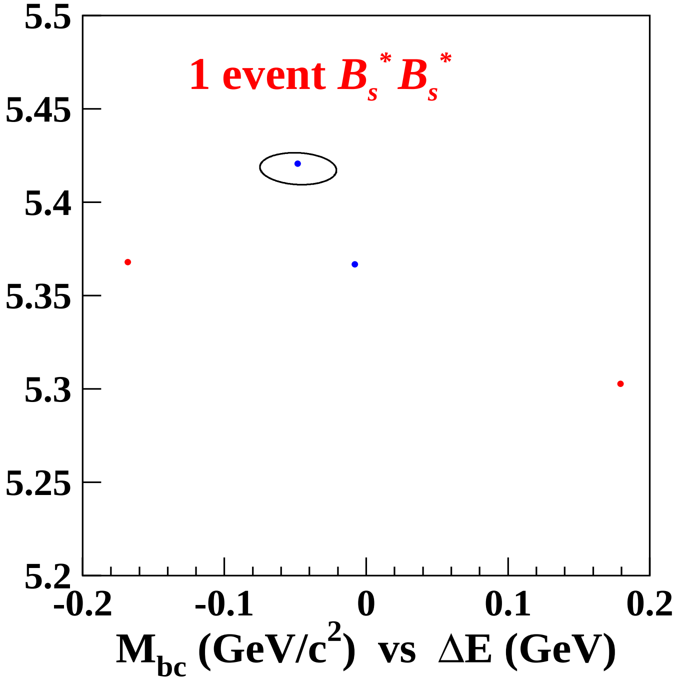
= 5370 ± 1 ± 3 MeV/c^2

PDG: $M = 5369.6 \pm 2.4$
CDF: $M = 5366.0 \pm 0.8$

(E_γ smearing does not change $M(B_s)$ position)

CP eigenstates: $B_s \to D_s^{(*)+} D_s^{(*)-}$, K^+K^- (hep-ex/0610003)

$B_s \to D_s^{(*)+} D_s^{(*)-}$: $(D_s^+ \to \phi\pi^+, K^{*0}K^+, K_S K^+)$



Expected: ~0.5 event in each mode

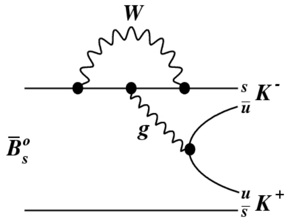
$\mathcal{B}(B_s \to D_s^{*+} D_s^{*-}) < 0.257$ (90% CL)

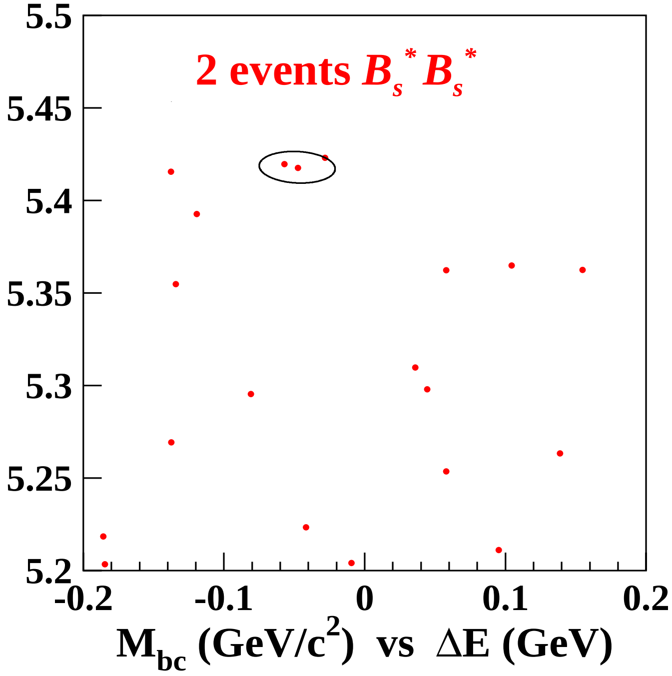
$\mathcal{B}(B_s \to D_s^{*+} D_s^{-}) < 0.121$

$\mathcal{B}(B_s \to D_s^{+} D_s^{-}) < 0.067$

$B_s \to K^+ K^-$:

Partner of $B \to K^+\pi^-$ penguin decay

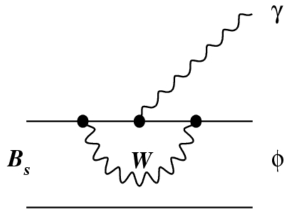


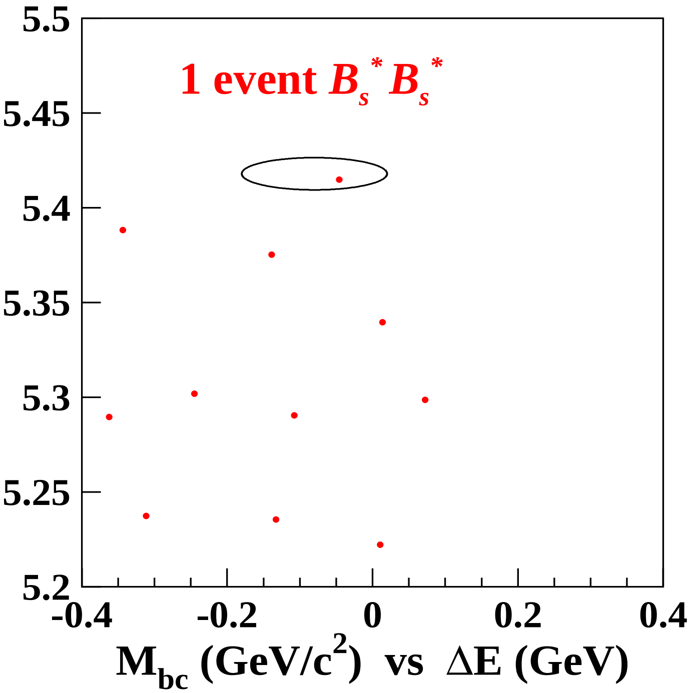


background ~ 0.14 event
expected signal ~ 0.7 event

Radiative decays: $B_s \to \phi\gamma$, $B_s \to \gamma\gamma$ *(hep-ex/0610003)*

$B_s \to \phi\gamma$:

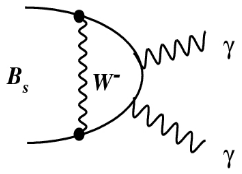


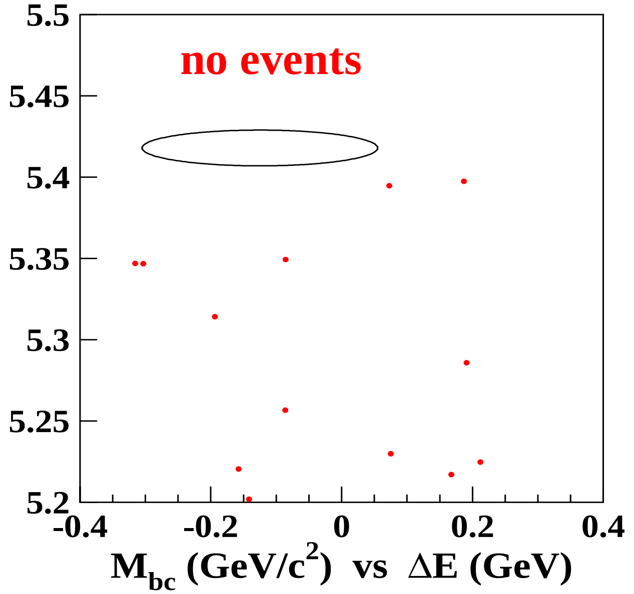


1 event $B_s^* B_s^*$

background ~ 0.15 event
expected signal ~ 0.4 event

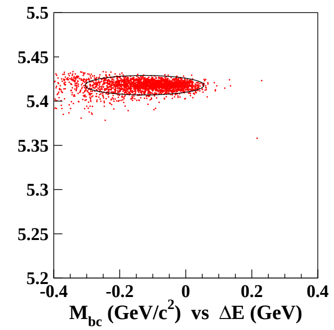
$B_s \to \gamma\gamma$:





no events

Monte Carlo:



SM: $\mathcal{B}(B_s \to \gamma\gamma) = (0.5 - 1.0) \times 10^{-6}$

new physics can increase by 1-2 orders of magnitude

PDG: $\mathcal{B}(B_s \to \gamma\gamma) < 1.5 \times 10^{-4}$

this analysis: $\boxed{\mathcal{B}(B_s \to \gamma\gamma) < 0.53 \times 10^{-4} \text{ (90\% CL)}}$

Summary of Υ(5S) at KEKB

- KEKB + Belle detector ran smoothly, luminosity similar to Υ(4S) running ($\mathcal{L} = 1.86\ \mathrm{fb}^{-1}$)
- We have observed a significant excess of D_s^+ production at the Υ(5*S*). The ratio of B_s meson production over all $b\bar{b}$ events is measured: $f_s = (18.0 \pm 1.3 \pm 3.2\ )\%$
- We have reconstructed Cabibbo-favored (CF) "spectator" decays $B_s \to D_s^{(*)+}\pi^-$, $B_s \to D_s^{(*)+}\rho^-$, and $B_s \to J/\psi\ \phi/\eta$. Using the $B_s^{(*)}B_s^{(*)}$ yield from inclusive analysis we determine $\mathcal{B}(B_s \to D_s^+\pi^-) = (0.68 \pm 0.22 \pm 0.16)\%$.
- We combine CF modes together to determine $m(B_s^*) = 5418 \pm 1 \pm 3$(acc. err) MeV/$c^2$ and $m(B_s) = 5370 \pm 1 \pm 3$ MeV/c^2 . The latter agrees with CDF: 5366.0 ± 0.8 MeV/c^2
- We have made the first search for rare decays $B_s \to D_s^{(*)+}D_s^{(*)-}$, $B_s \to \phi\gamma$, $B_s \to \gamma\gamma$ (all challenging at a hadron machine) and $B_s \to K^+K^-$, . We obtain the limit

  $\mathcal{B}(B_s \to \gamma\gamma) < 0.53 \times 10^{-4}$ (90% CL) (3x lower than the PDG value).

We have taken an order of magnitude larger sample (21 fb^{-1}) and are now reconstructing this data. Hope to see substantial signals in many of these modes, and several new branching fractions should result ($B_s \to D_s^{(*)-}\pi^+$, $J/\psi\ \phi$, $D_s^{(*)-}\rho^+$, $D_s^{(*)-}a_1^+$, $J/\psi\ \eta$, $J/\psi\ \eta'$, $D_s^{(*)+}D_s^{(*)-}$, K^+K^-, others). Now studying the physics potential of a long Υ(5*S*) run.

Spectrum

Particle	Mass, MeV/c^2	Width, MeV/c^2	ΔM, MeV/c^2	$c\tau$, μm	$P_{cm}(BB)$, MeV/c
Y(5S)	10865 ± 8	110 ± 13			
$B+$	5279.0 ± 0.5			502	1282
B^0	5279.4 ± 0.5			462	1281
$B*$	5325.0 ± 0.6		45.8 ± 0.4		1075
B_s	5365.5 ± 1.3			438	851
B_s*	5416.6 ± 3.5		51 ± 4		415

Estimated Yields for 100 fb^{-1}

Final state	Process	$\mathcal{B}_{\rm est}$	$\epsilon_{\rm recon}$ (%)	Events/100 fb^{-1}
$D_s^-\pi^+$	spectator	2.9×10^{-3}	0.81	220
$D_s^{*-}\pi^+$	spectator	2.8×10^{-3}	0.45	120
$D_s^-\rho^+$	spectator	7.7×10^{-3}	0.15	110
$D_s^{*-}\rho^+$	spectator	6.8×10^{-3}	0.081	52
$D_{sJ}^-(2317)\pi^+$	spectator	7.3×10^{-4}	0.28	19
$J/\psi\phi$	color-suppressed spectator	1.3×10^{-3}	1.3	180
$J/\psi\eta$	color-suppressed spectator	8.5×10^{-4}	0.56	45
$J/\psi\eta'$	color-suppressed spectator	$xx\times10^{-3}$	xx	xx
$D_s^+D_s^-$	spectator	8.0×10^{-3}	0.020	19
$D_s^{*+}D_s^-$	spectator	2.0×10^{-2}	0.0099	19
$D_s^{*+}D_s^{*-}$	spectator	1.9×10^{-2}	0.0052	15
$\phi\gamma$	$b\to s$ penguin	4.0×10^{-5}	5.9	22
$\bar{D}^0K_S$	color-suppressed spectator	3.0×10^{-4}	1.2	34
$D_s^-K^+$	spectator; ϕ_3	2.0×10^{-4}	0.64	12
K^-K^+	$b\to s$ penguin, $b\to u$ spectator	4.0×10^{-5}	9.5	36
$K^+\pi^-$	$b\to s$ penguin, $b\to d$ penguin	5.0×10^{-6}	8.7	4.1
$\gamma\gamma$	intrinsic penguin	1.0×10^{-6}	20.0	1.9

MC reconstruction:

$D_s^+\to\phi\pi^+$
$K^{*0}K^+$
K_sK^+
$D^0\to K^-\pi^+$
$K^-\pi^-\pi^+\pi^+$
$K^-\pi^+\pi^0$

Determining $\Delta\Gamma/\Gamma$ *via* $\mathcal{B}(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})$

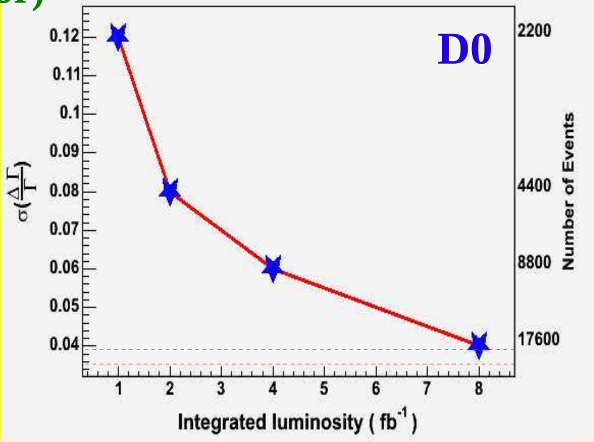
Barate *et al.*, (ALEPH), PLB 486, 286 (2000)
Dunietz,Fleischer, Nierste, PRD 63, 114015 (2001)
Aleksan *et al.*, PLB 316, 567 (1993)
Shifman, Voloshin, SJNP 47, 511 (1988)

Assume mixing phase is tiny ⇒ mass eigenstates are *CP* eigenstates
⇒ $\Delta\Gamma$ arises from *CP* channels

CDF:
$0.65^{+0.25}_{-0.33}$ $(\psi\phi)$
-0.08 ± 0.23 (K^+K^-)
D0:
$0.24^{+0.28}_{-0.38}$ $(\psi\phi)$

Heavy quark limit (M_c →infinity) and neglecting some terms of O(1/N_c),
$B_s \rightarrow D_s^* D_s^*$ is *CP* even ($D_s^* D_s^*$ only *S*-wave)

Shifman-Voloshin limit $2M_c \rightarrow M_b$ ⇒ duality ⇒
$\Delta\Gamma$ is saturated by $b \rightarrow ccs$ or $B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$ (Cabibbo-favored spectator)



⇒ $\Delta\Gamma = 2\Gamma(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})$ or $\Delta\Gamma/\Gamma = 2\mathcal{B}(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})$

⇒ 20% precision on $\mathcal{B}$ gives 20% precision on $\Delta\Gamma/\Gamma$; this corresponds to 50 fb^{-1} (14% prec. for 100 fb^{-1}). Theoretical assumptions expected to hold to 10% (and can be tested w/data)