Upsilon(5S) Physics at Belle:

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

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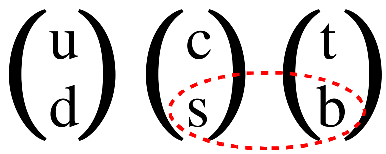
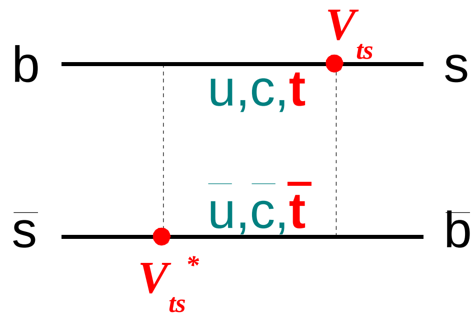
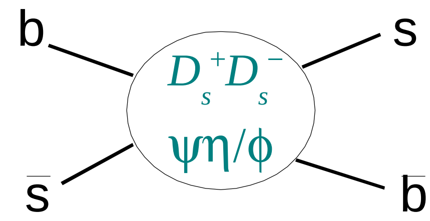
- introduction
- the Belle $\Upsilon(5S)$ dataset
- inclusive B_s production at the $\Upsilon(5S)$
- exclusive B_s decays: $D_s^{+(*)}\rho^-$, $D_s^{+(*)}\pi^-$, $J/\psi\,\phi$, $J/\psi\,\eta$
- rarer B_s decays: K^+K^-, $D_s^{+(*)}D_s^{+(*)}$, $\phi\gamma$, $\gamma\gamma$

Why study the B_s ?







short distance: Δm **long distance: $\Delta\Gamma$**

Meson	flavors	$\Delta m/\Gamma$	$\Delta\Gamma/\Gamma$	mixing observed?
D^0	$c\bar{u}$	< 2.9%	1.6 %	not yet, decays too fast
K^0	$\bar{s}d$	0.5	2	yes
B^0	$\bar{b}d$	0.77	<1%	yes
→ B_s	$\bar{b}s$	> 21	0.20?	not yet, mixes too fast

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

There are fundamental advantages over hadronic machines (CDF/D0/LHCb):

much lower background
measure absolute branching fractions, inclusive branching fractions
excellent π^0 identification, and thus ρ^+, ω, η, η', K^{*+}, a_1, etc.

$\Rightarrow$ many more final states reconstructed

B_sB_s produced in a correlated state; gives sensitivity to mixing parameters x, y

Belle is now evaluating physics potential of $e^+e^-\to\Upsilon(5S)\to B_sB_s$ running.

Some initial B_s studies (using 50 fb^{-1} dataset):

- **comparing $\mathcal{B}(B_s\to D_s^-\pi^+)$ to $\mathcal{B}(B_d\to D^-\pi^+)$x (τ_s/τ_d) tests *SU(3)* symmetry (250 events expected)**
- **measurement of $\mathcal{B}(B_s\to D_s^{(*)-}\pi^+)$, $\mathcal{B}(B_s\to D_s^{(*)-}\rho^+)$, $\mathcal{B}(B_s\to D_s^{(*)-}a_1^+)$ (120 events each)**
- **$\mathcal{B}(B_s\to J/\psi\,\phi)$ (60 events), $\mathcal{B}(B_s\to J/\psi\,\eta)$, $\mathcal{B}(B_s\to J/\psi\,\eta')$**
- **comparing $\mathcal{B}(B_s\to D_s^+ l^-\nu)$ to $\mathcal{B}(B_d\to D^- l^+\nu)$x (τ_s/τ_d) tests *SU(3)* (1000 events)**
- **inclusive $\mathcal{B}(B_s\to X_s^+ l^-\nu)$ (using 800 fully-reconstructed $B_s\to D_s^-\pi^+/\rho^+$) tests quark-hadron duality**
- **Measurement of $\Delta\Gamma_s$ using $B_s\to D_s^{(*)+}D_s^{(*)-}$ $CP = +1$ decays**

Expected rate of B_s production

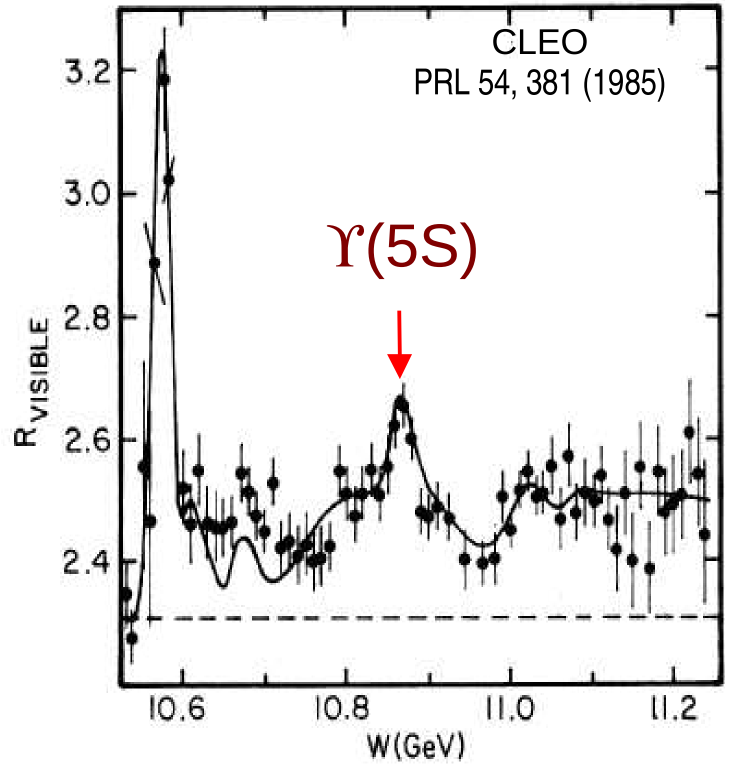
$e^+e^- \to \Upsilon(5S)$: $\sigma[\Upsilon(5S)] \sim 0.35$ nb
$\Rightarrow$ 3.5×10^5 $\Upsilon(5S)$ per fb^{-1}

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

CLEO in 2003 took 0.42 pb^{-1} of data at the $\Upsilon(5S)$. From the D_s yield + assuming $B(B_s \to D_s X) = 0.92$ they deduce (hep-ex/0508047):

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

$\Rightarrow$ 1.1×10^5 B_s per fb^{-1}



To test feasibility of $\Upsilon(5S)$ running at KEKB, Belle took short engineering run in June, 2005 (1.9 fb^{-1}, about 4x CLEO sample)

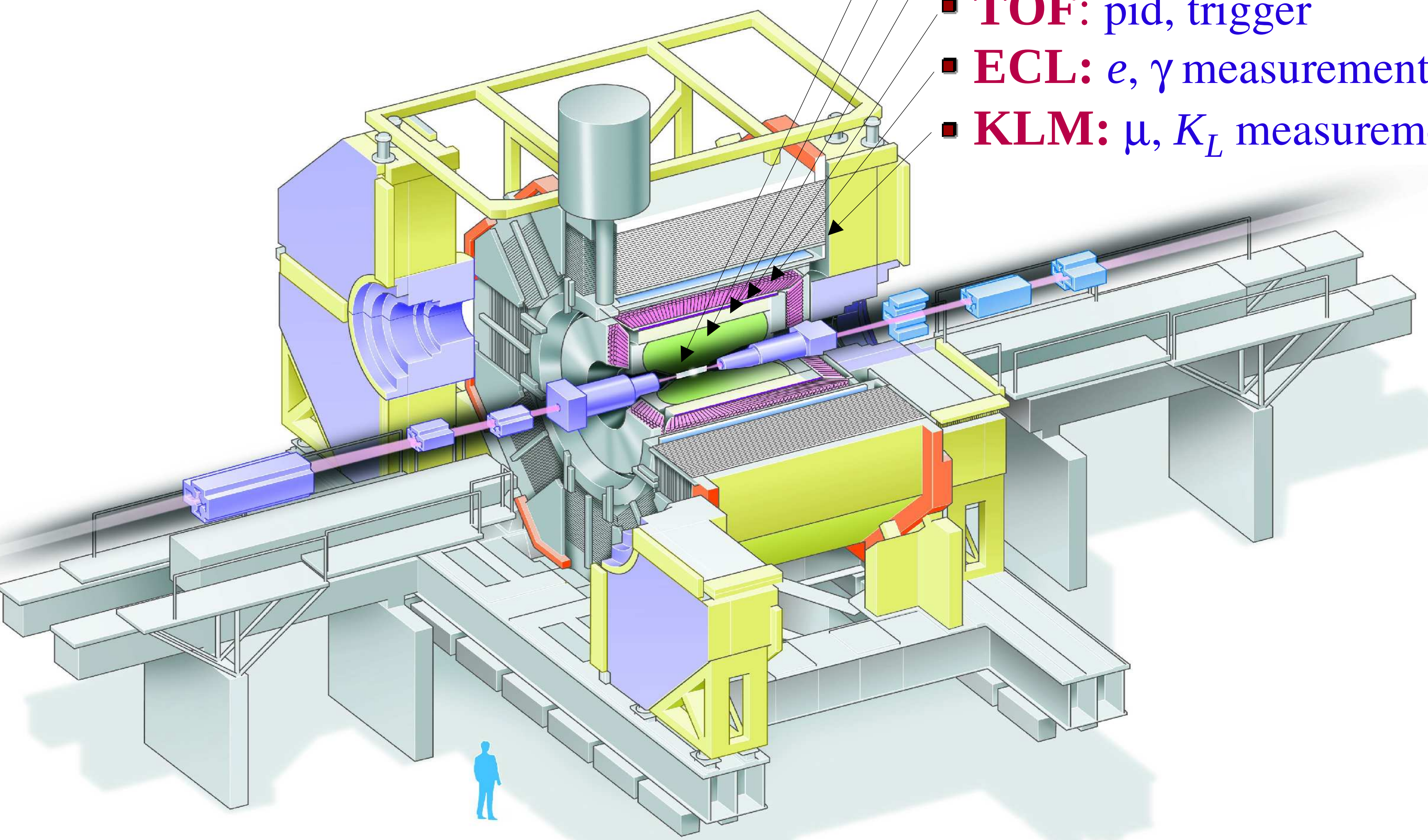
Spectrum

Particle	Mass, MeV/c^2	Width, MeV/c^2	ΔM, MeV/c^2	$c\tau$, μm	P_{cm}(BB), MeV/c
Υ(5*S*)	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

Belle detector

Moving Υ(4*S*) → Υ(5*S*): increase E_{beam} by 2.7% (same Lorentz boost of βγ = 0.425)
No modification of detector/trigger needed

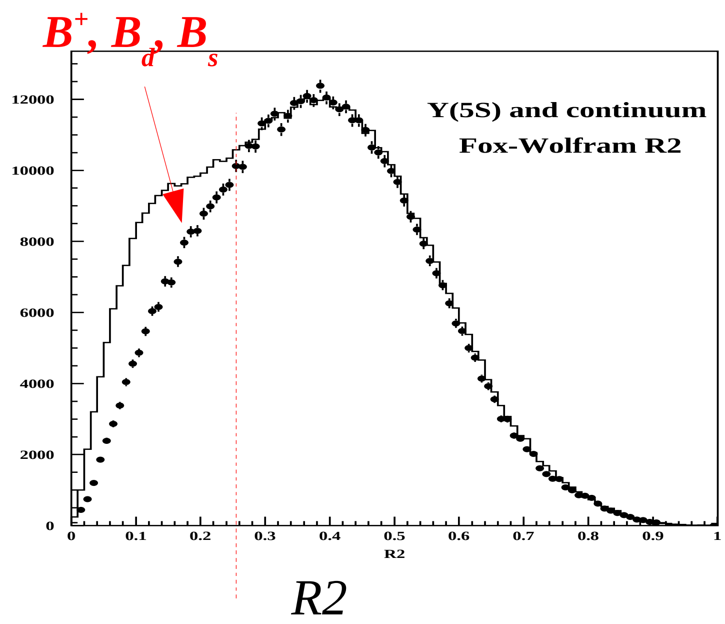
- **SVD:** vertexing (lifetime)
- **CDC:** tracking, *dE/dx* for pid
- **ACC:** aerogel Cerenk. Counter
- **TOF**: pid, trigger
- **ECL:** *e*, γ measurement
- **KLM:** μ, K_L measurement



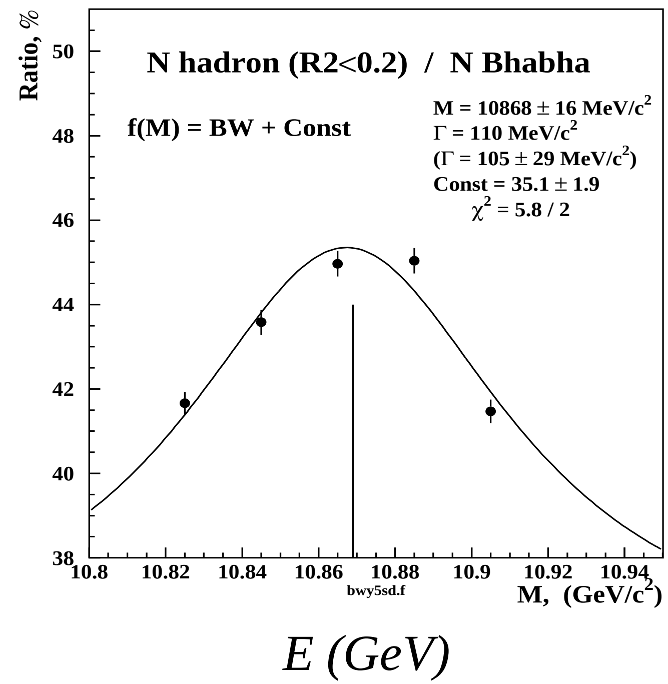
Y(5S) Engineering run in June 2005

Data set:
- first did energy scan at five points: E = 10.825, 10.845, 10.865, 10.885, 10.905 GeV, about 0.030 fb^{-1} each point
- shifted to E=10.869 GeV (nominal peak), took 1.86 fb^{-1} of data
- by end of run, inst. Lum. = 1.4 x 10^{34} $cm^{-2}s^{-1}$ (like Y(4*S*) running)

Fox-Wolfram moment R2:



Energy scan:



$m_{Y(5S)}$ = 10867 ± 17 MeV/c^2 Γ = 105 ±29 MeV

PDG: $m_{Y(5S)}$ = 10865 ± 8 Γ = 110 ±13

Y(5S)/cont = 1/3.5

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

Inclusive analysis: $\Upsilon(5S) \rightarrow D_s X$

fraction of $B_s B_s$ events:

1) count # of hadronic events
2) subtract continuum ($u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}$) contribution by scaling from continuum data:

$$N_{cont}(5S) = N_{cont}(E{=}10.519)\ \mathcal{L}(5S)\,/\,\mathcal{L}(E{=}10.519)\ \ (E_{cont}/E_{5S})^2\ (\varepsilon_{5S}/\varepsilon_{cont})$$
$$= 561{,}000 \pm 3{,}000 \pm 29{,}000$$

3) reconstruct $D_s \rightarrow \phi\pi$ decays to determine (after cont. subtraction):

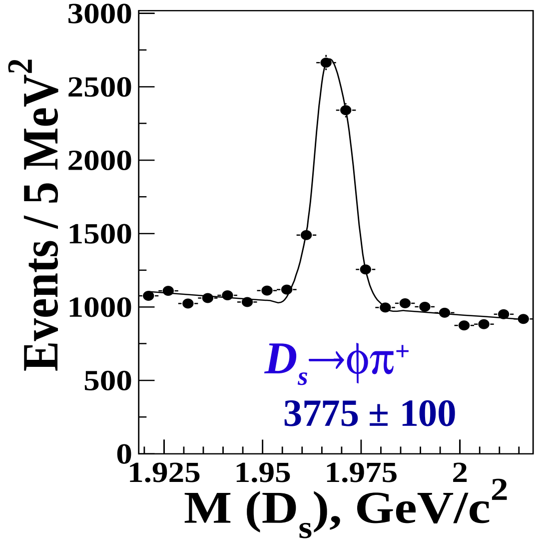
$$\mathcal{B}(\Upsilon(5S) \rightarrow D_s X)\,/2 = (22.6 \pm 1.2 \pm 2.8)\ \%$$

4) calculate $f_s = (B_s \bar{B}_s)/b\bar{b}$ ratio via:

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

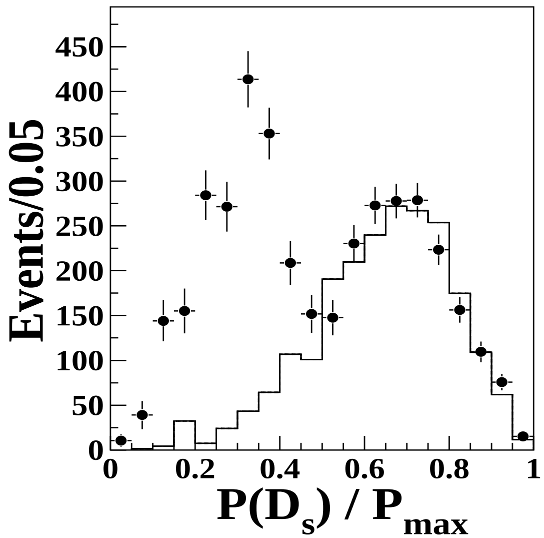
$$\Rightarrow \quad f_s = (16.4 \pm 1.4 \pm 4.1\ )\%$$

CLEO: (16.0 ± 2.6 ± 5.8)%



must estimate:

$\mathcal{B}(B_s \rightarrow D_s X) = (92 \pm 11)\%$ (hep- ex/0508047 CLEO)



other inputs:

$\mathcal{B}(B \rightarrow D_s X) = (8.94 \pm 0.16 \pm 1.12)\%$ (BaBar)

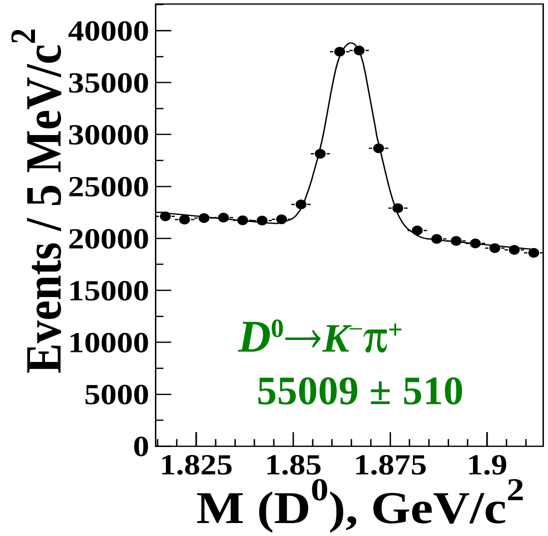
$\mathcal{B}(D_s \rightarrow \phi\pi^+) = (4.4 \pm 0.5)\%$ (dominant systematic)

Inclusive analysis: $\Upsilon(5S)\to D^0X$

fraction of B_sB_s events:

1) reconstruct $D^0\to K^-\pi^+$ decays to determine (after cont. subtraction):

$$\mathcal{B}(\Upsilon(5S)\to D^0 X)/2 = (53.3 \pm 2.0 \pm 2.9)\ \%$$



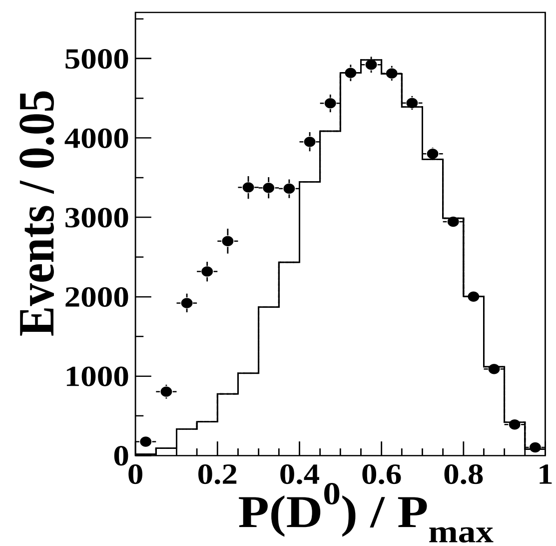
2) calculate $f_s = (B_sB_s)/bb$ ratio via:

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

$$\Rightarrow \quad f_s = (18.7 \pm 3.6 \pm 6.7)\%$$

must estimate:

$\mathcal{B}(B_s\to D^0 X) = (8 \pm 7)\%$ (hep- ex/0508047 CLEO)



other inputs:

$\mathcal{B}(B\to D^0 X) = (63.7 \pm 3.0)\%$ (PDG)

$\mathcal{B}(D^0\to K^-\pi^+) = (3.81 \pm 0.09)\%$

Inclusive analysis: $\Upsilon(5S)\to J/\psi\, X$

fraction of $B_s B_s$ events:

1) reconstruct $J/\psi\to\mu^-\mu^+$ decays to determine (after cont. subtraction):

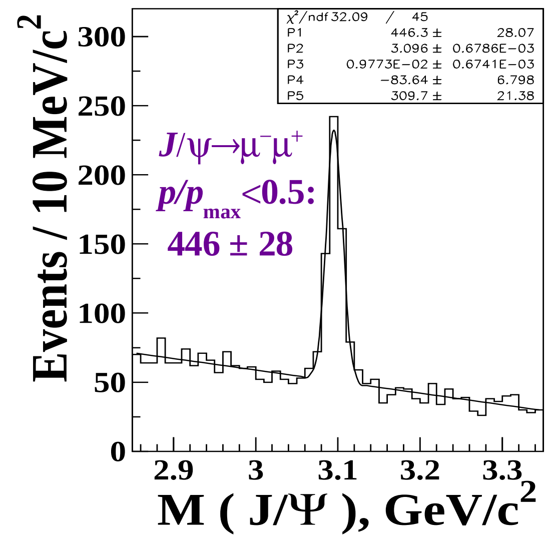
$$\mathcal{B}(\Upsilon(5S)\to J/\psi\, X)\,/2 = (1.068 \pm 0.086 \pm 0.057)\ \%$$

2) assuming $f_s = (B_s B_s)/bb = 17\%$, calculate $\mathcal{B}(B_s\to J/\psi\, X)$:

$$\mathcal{B}(\Upsilon(5S)\to J/\psi\, X) =$$

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

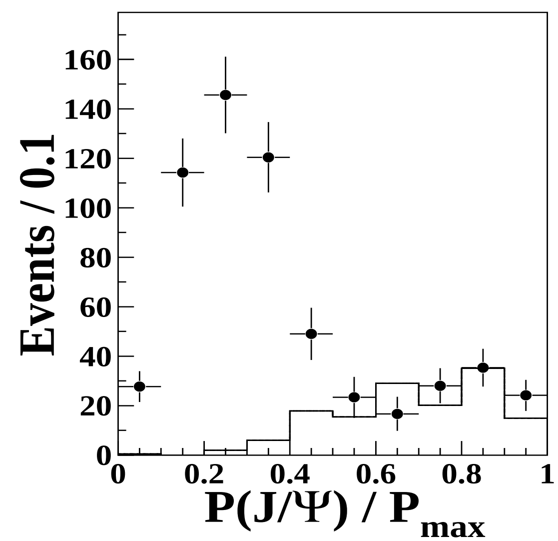
$$\Rightarrow \quad \mathcal{B}(B_s\to J/\psi\, X) = (0.94 \pm 0.51 \pm 0.37)\%$$



other inputs:

$\mathcal{B}(B\to J/\psi\, X) = (1.094 \pm 0.032)\%$ (PDG)

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



Exclusive analysis: B_s reconstruction

12 Search modes:

Cabibbo favored

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

$b \to s$ rare

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

hadronic events at $\Upsilon(5S)$

↓ $\mathcal{L} = 1.857\ \text{fb}^{-1}$

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

↓ **16.4%**

$B_s^{(*)}\bar{B}_s^{(*)}$ events **92,000**

Selection:

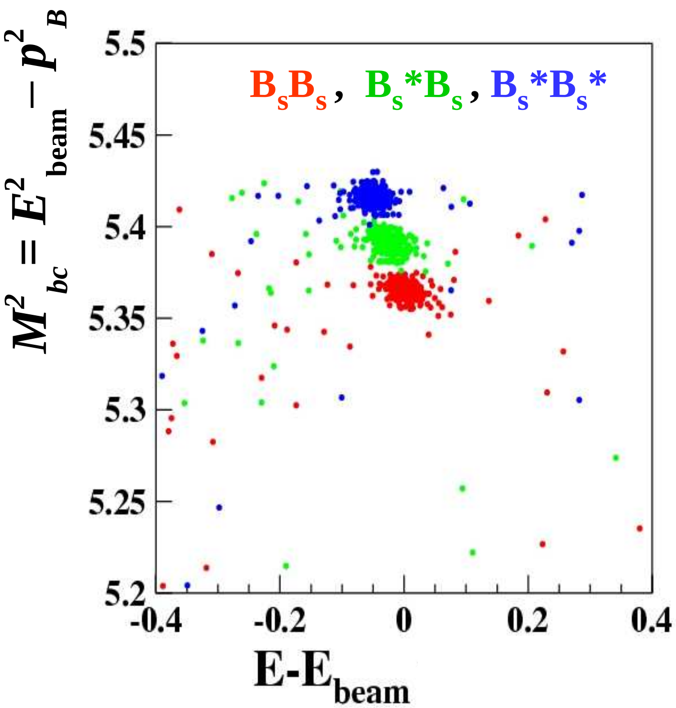
- ***K*** **identification using time-of-flight, aerogel Cerenkov counter, *dE/dx* in central tracker**
- **mass windows are 2σ, 2.5σ, 3σ**
- **continuum events rejected via Fox-Wolfram $R_2 < 0.3, 0.4$**
- **B_s : $|\cos\theta| < 0.6 - 0.9$**
- **D_s^+: $|\cos\theta_{helicity}| > 0.25$**
- **$p_\gamma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

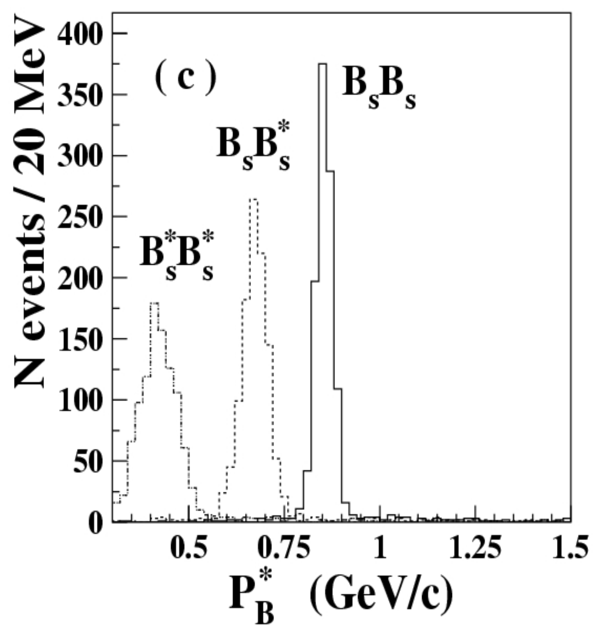
Exclusive analysis: ΔE-m_{bc}

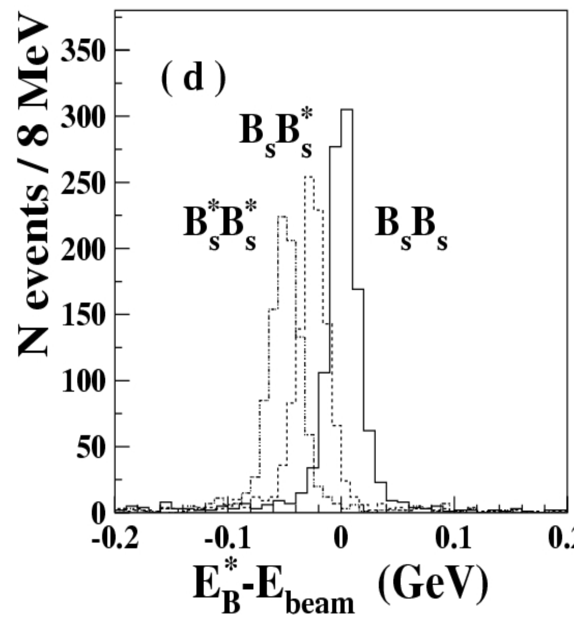
$$m_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

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

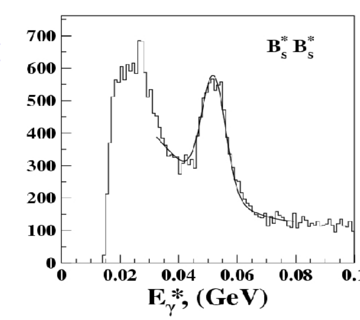
$B_s \rightarrow D_s^- \pi^+$, $D_s^- \rightarrow \phi\, \pi^-$ Monte Carlo:







γ spectrum:

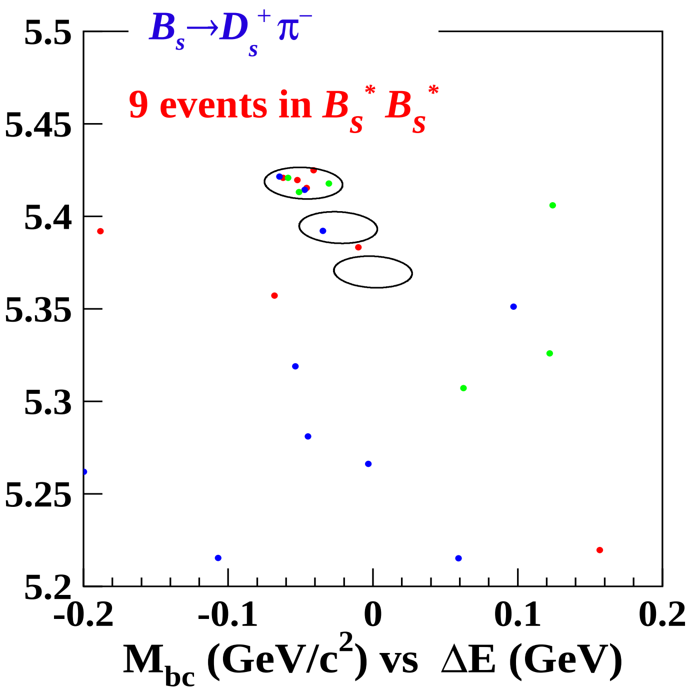


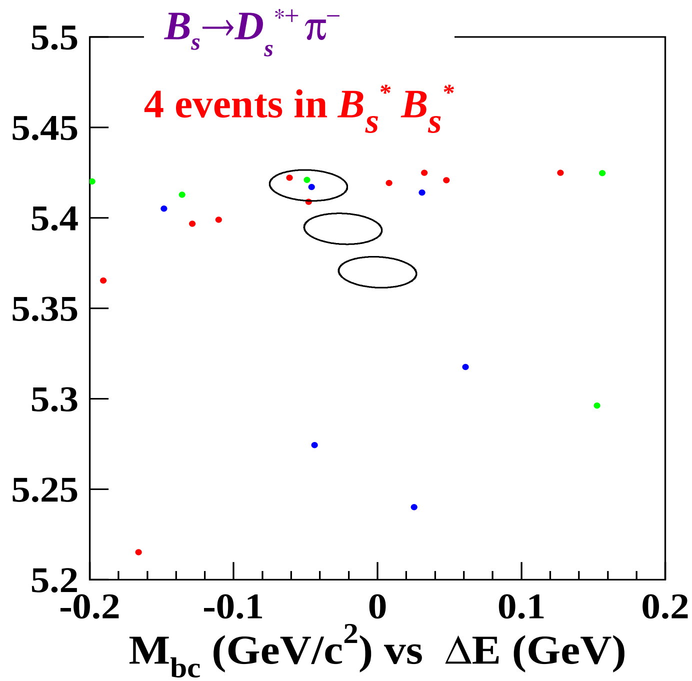
B_s* signals are well-separated for *B_sB_s*, *$B_s^*B_s$*, *$B_s^*B_s^*$

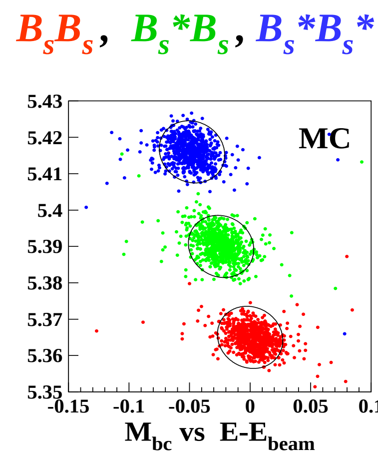
Signals are 20-30% wider than *B_d* at the Y(4*S*)

***p_γ* has only small effect**

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







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

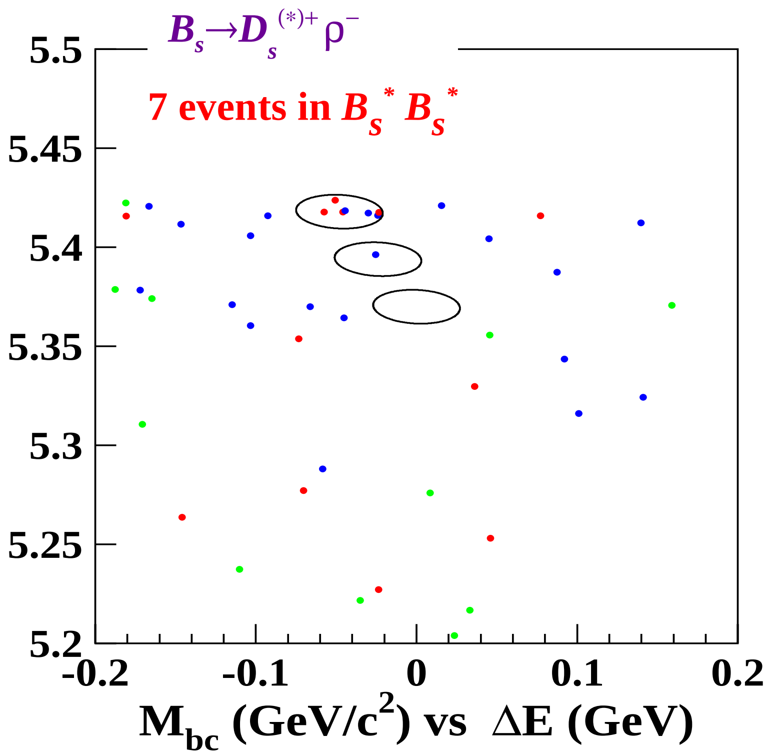
Clear signal in $B_s^* B_s^*$ channel; one event in $B_s^* B_s$, no signal in B_sB_s channels

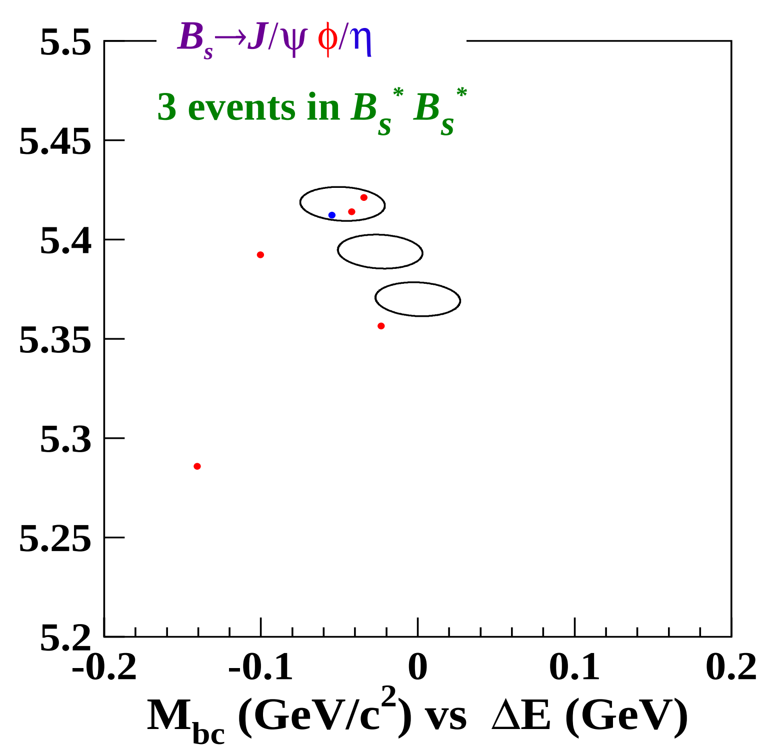
Taking number of B_s^* mesons from the inclusive analysis (92000 ± 7900 ± 23500) :

$$\mathcal{B}(B_s \to D_s^+ \pi^-) = (0.65 \pm 0.21 \pm 0.19)\%$$

consistent with CDF: (0.40 ± 0.06 ± 0.13)%

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





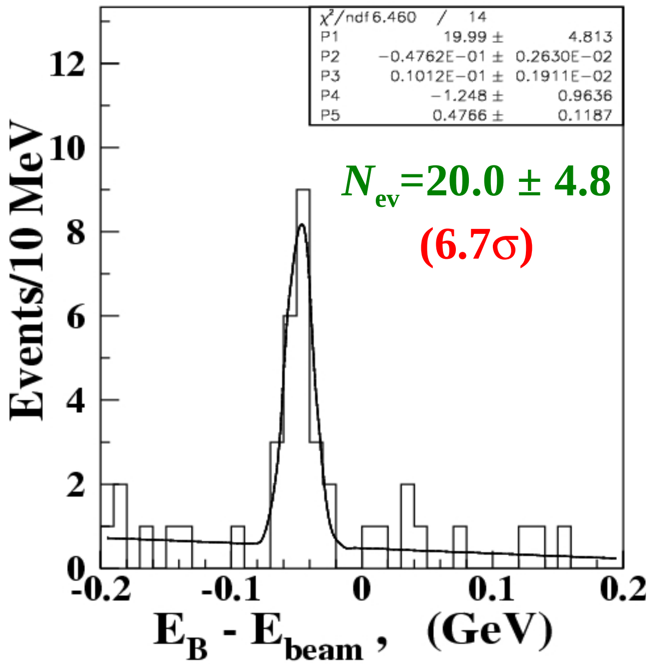
Clear signal in $B_s^* B_s^*$ channel; no obvious signal in $B_s^* B_s$ or $B_s B_s$ channels

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

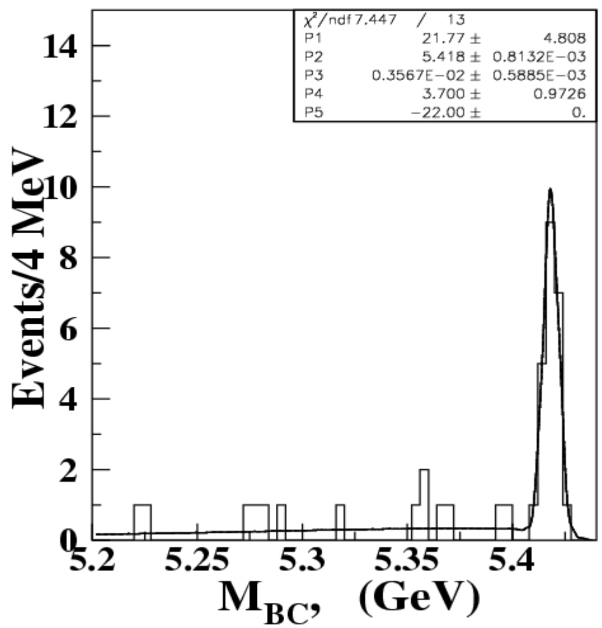
somewhat smaller than CLEO observation (hep-ex/0510034)

Exclusive analysis: sum together CF modes

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



−0.08 < Δ*E* < −0.02 MeV



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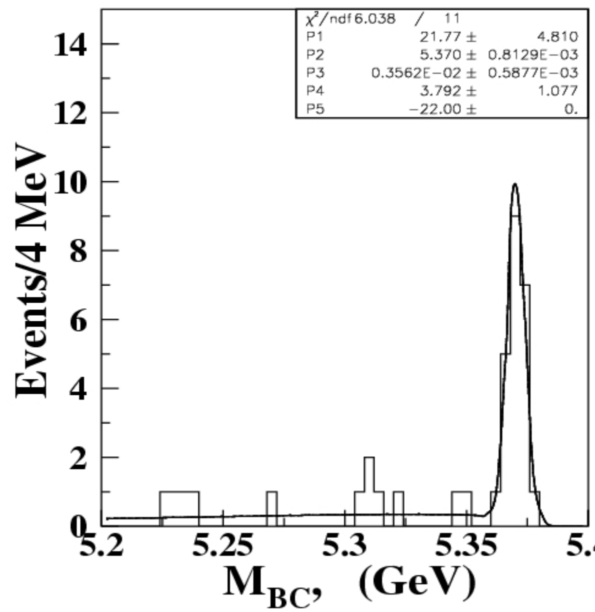


$\Upsilon(5S) \rightarrow B_s^* B_s^*$ $(B_s^* \rightarrow B_s \gamma)$

$\Delta E^{\text{peak}} = \langle E(\gamma) \rangle$
$= -47.6 \pm 2.6$ MeV

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

= 5418 ± 1 ± (acc. err) MeV/c²

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

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

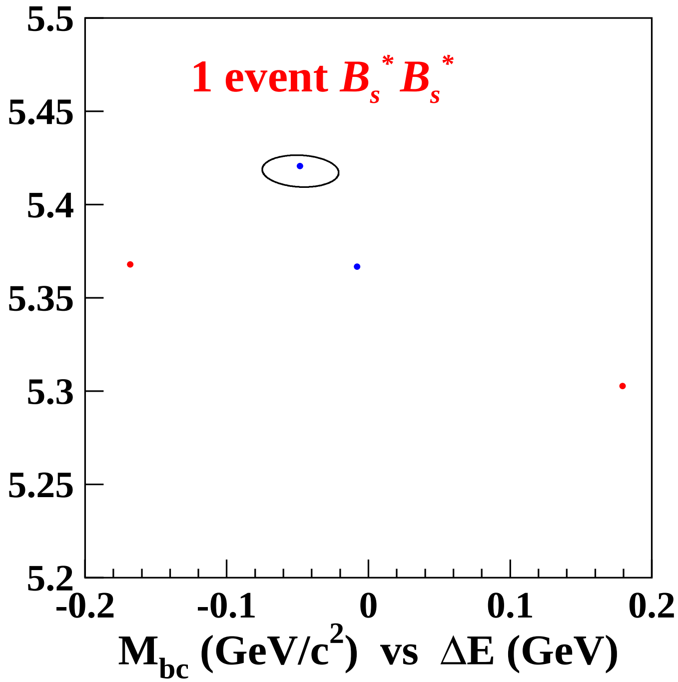
= 5370 ± 1 ± 3 MeV/c²

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

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



Expected: ~0.5 event in each mode

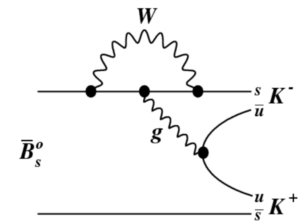
$\mathcal{B}(B_s \to D_s^{*+} D_s^{*-}) < 0.27$ **(90% CL)**

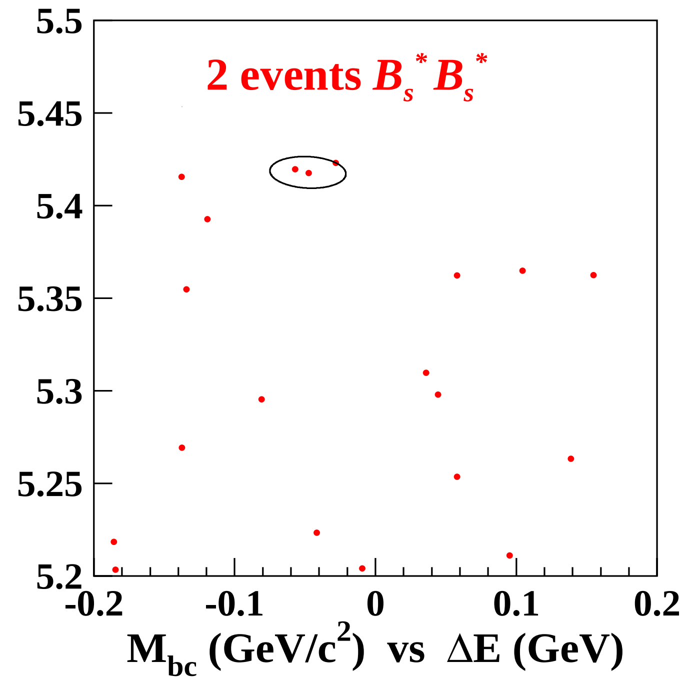
$\mathcal{B}(B_s \to D_s^{*+} D_s^{-}) < 0.13$

$\mathcal{B}(B_s \to D_s^{+} D_s^{-}) < 0.071$

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

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

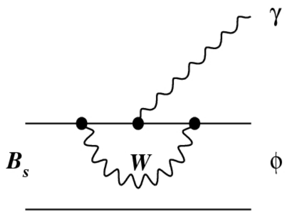


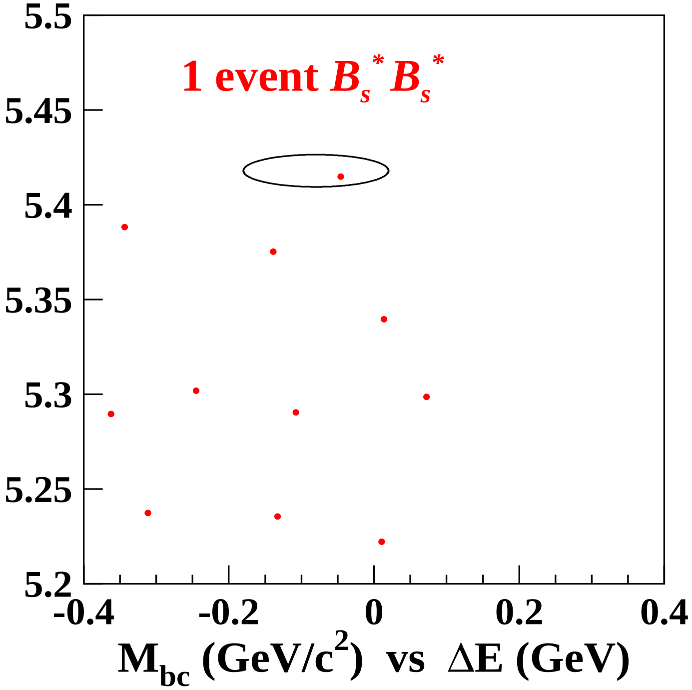


background ~ 0.14 event
expected signal ~ 0.7 event

Radiative decays: $B_s \to \phi\gamma$, $B_s \to \gamma\gamma$

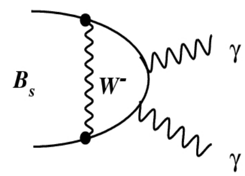
$B_s \to \phi\gamma$:

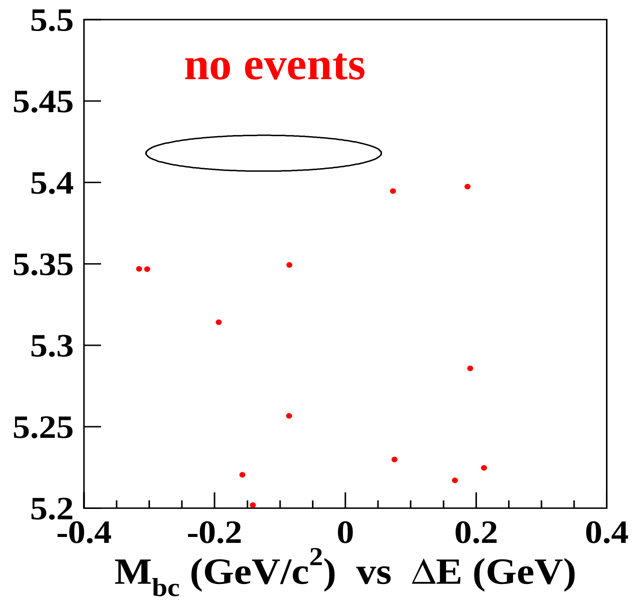




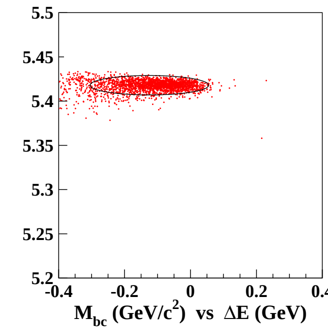
background ~ 0.15 event
expected signal ~ 0.4 event

$B_s \to \gamma\gamma$:





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: $\mathcal{B}(B_s \to \gamma\gamma) < 0.56 \times 10^{-4}$ **(90% CL)**

Summary of Υ(5S) at KEKB

- KEKB ran smoothly, luminosity was similar to Υ(4S) running (high), integr. $\mathcal{L}$ = 1.86 fb^{-1} (4x CLEO). Belle detector ran problem-free.
- We have observed a significant excess of D_s^+ production at the Υ(5S). The ratio of B_s meson production over all bb events is measured: $f_s = (16.4 \pm 1.4 \pm 4.1)\%$ This value is consistent with that obtained from measuring incl. D^0 production.
- 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 $\mathcal{B}(B_s \to D_s^+ \pi^-) = (0.65 \pm 0.21 \pm 0.19)\%$.
- We combine CF modes together to determine $m(B_s^*) = 5418 \pm 1 \pm$ (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 $B_s \to D_s^{(*)+} D_s^{(*)-}$, $B_s \to K^+ K^-$, $B_s \to \phi\gamma$, $B_s \to \gamma\gamma$ (all very difficult at a hadron machine). We obtain the limit

  $\mathcal{B}(B_s \to \gamma\gamma) < 0.56 \times 10^{-4}$ (90% CL) (3x lower than PDG value).

A new physics area (B_s decays) can be opened up by Belle for a modest amount of running. We are now studying the physics potential of a longer Υ(5S) run.