Caltech, March 3, 2009

Strange Beauty and Other Beasts: At and Above the $\Upsilon(5S)$ with Belle

- Belle/KEKB, $\Upsilon(4S)$ Resonance, B meson
- $\Upsilon(5S)$ Resonance and B_s
    - motivation
    - Belle data & results
    - prospects

Kay Kinoshita
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Belle Collaboration

The people

Belle collaboration

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Tokyo Inst. of Tech.
Tokyo Metropolitan U.
Tokyo U. of Agri. and Tech.
Toyama Nat'l College
U. of Tsukuba
VPI
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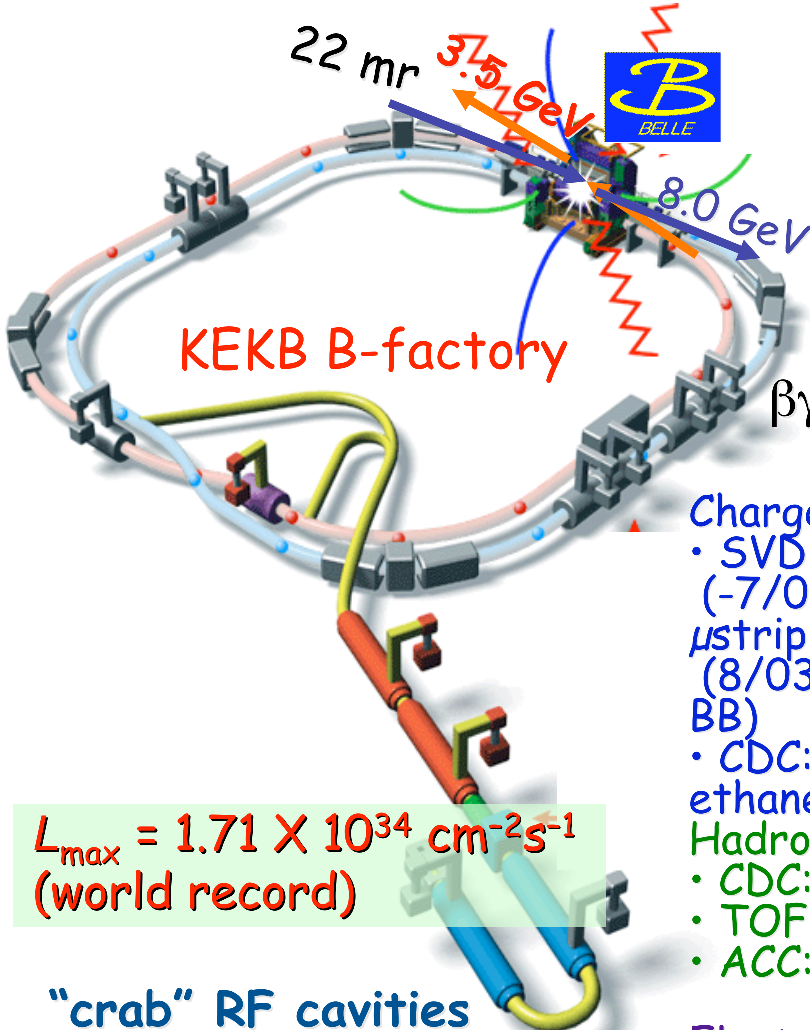
~14 nations, 55 institutes, ~400 collaborators

(authors vary, each paper)

... the hardware



$\beta\gamma$ = 0.425

L_{max} = 1.71 X 10^{34} $cm^{-2}s^{-1}$
(world record)

"crab" RF cavities
4/07-
L = 1.64 X 10^{34} $cm^{-2}s^{-1}$

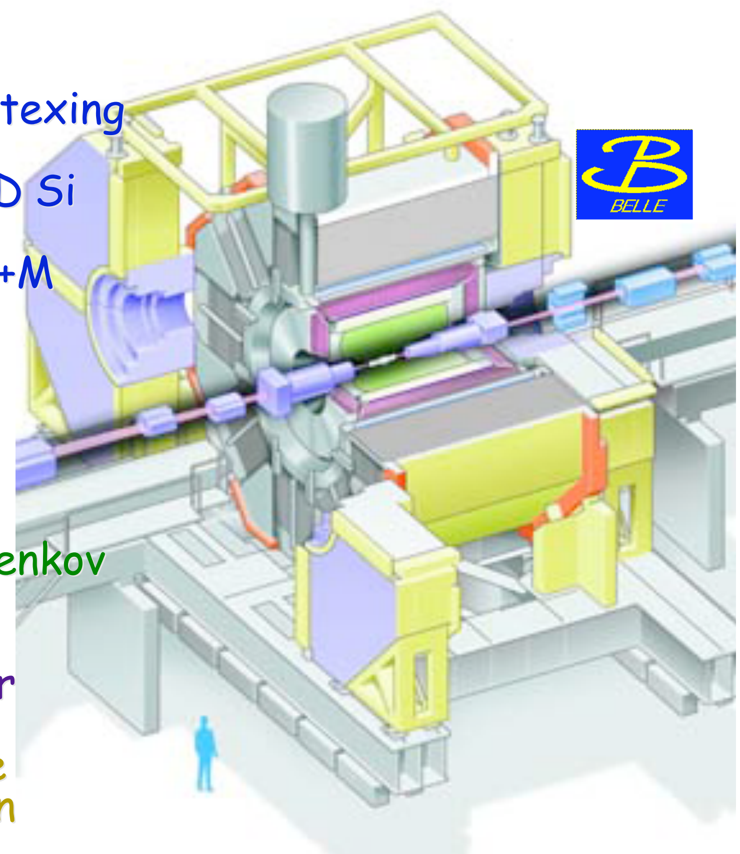
4/07- COPPER pipelined DAQ system

Charged tracking/vertexing
- SVD:
  (-7/03) 3-layer DSSD Si μstrip (152M B pairs)
  (8/03-) 4-layer (550+M BB)
- CDC: 50 layers (He-ethane)

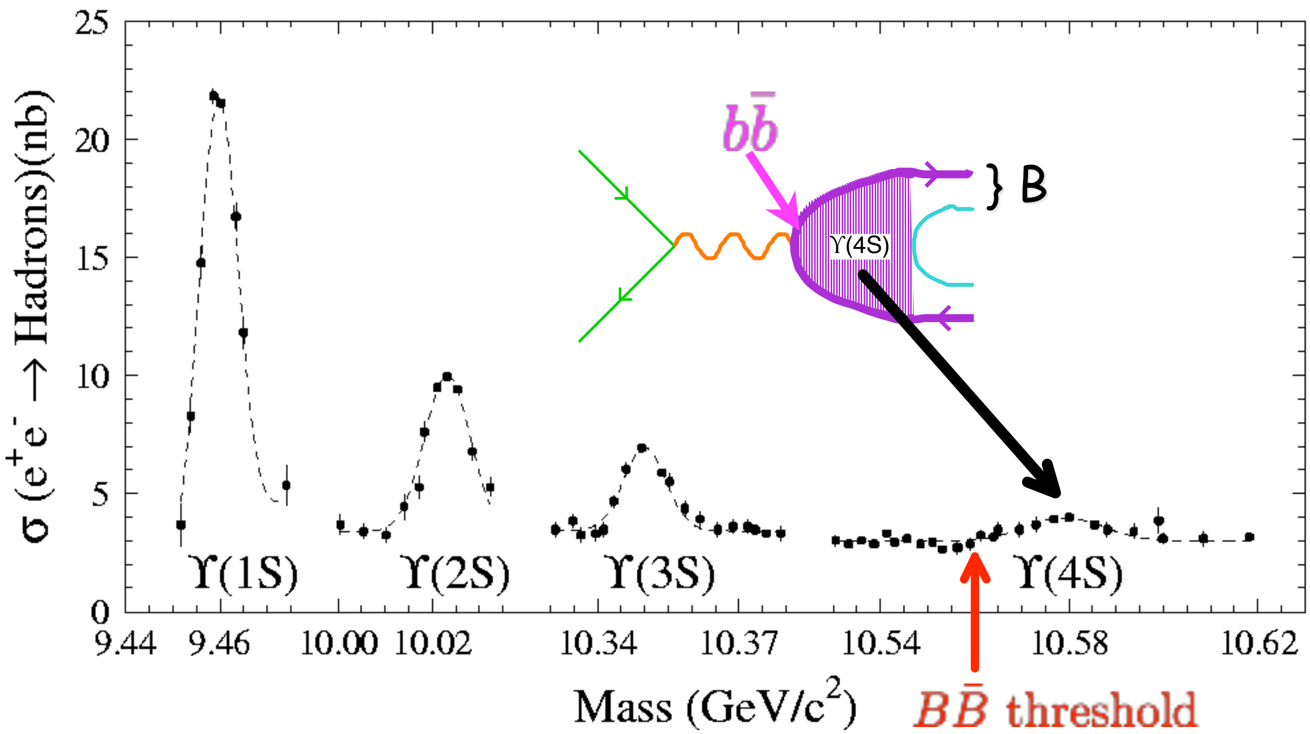
Hadron identification
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon
- ECL: CsI calorimeter

Muon/K_L
- KLM: Resistive plate counter/iron



... the Physics $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ (mostly)



Primary goal: study CP violation in weak decays of B meson

Data (6/1999-12/2008)
- $\int Ldt$ = ~820 fb^{-1}@{Υ(4S)+off(~10%)}
- (>8x10^8 B events)

... but there's MUCH more!

283 papers published/in press/submitted (3/2001-)

- CP asymmetry in B decay
- B decays
- charm
- tau
- 2-photon

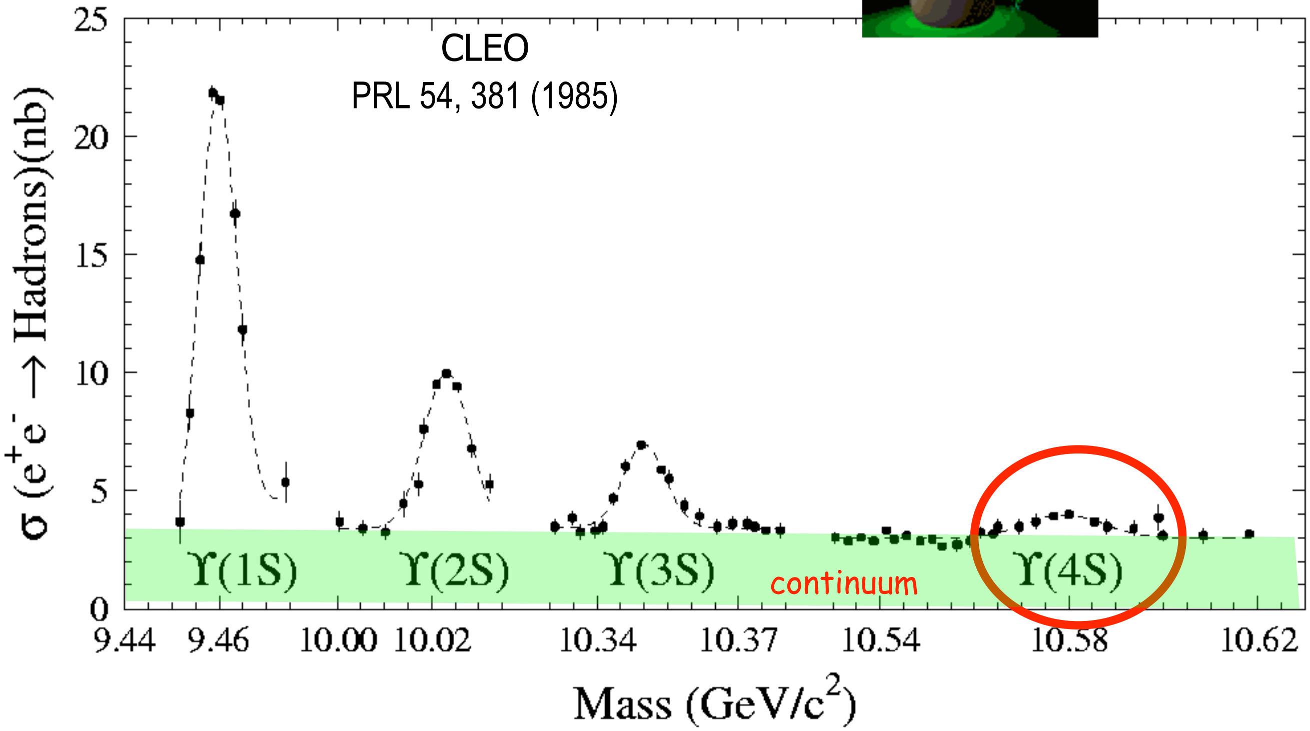
Non-4S Data (-12/2008)
- $\int Ldt$ = 24.6 fb^{-1}@Υ(5S)
  (1.3 x 10^6 B_s events)
  +30 fb^{-1} in 2008
- $\int Ldt$ = ~8 fb^{-1}@Υ(5S)+ scan
- \+ Υ(3S), Υ(2S) , Υ(1S)

- addressing CP, CKM, QCD, HQ spectroscopy, ...

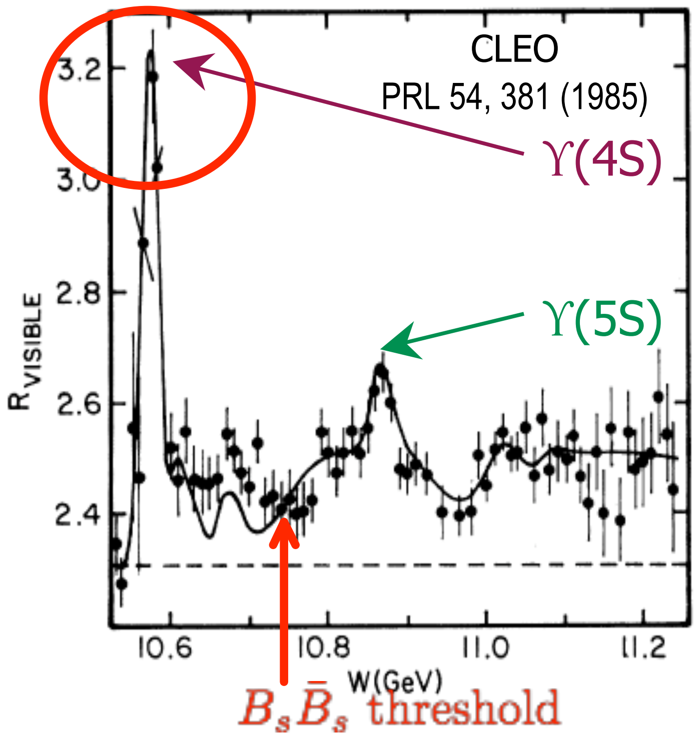
occasional overlap of topics
e.g., new charmonium(-like) states in B decay.

- ... and now, Υ(10860), "5S"
  - B_s decays & CP, search for New Physics
  - Upsilon, B_s spectroscopy

... more: Υ(5S)


CLEO
PRL 54, 381 (1985)
σ (e+e- → Hadrons)(nb)
25
20
15
10
5
0
9.44
9.46
10.00
10.02
10.34
10.37
10.54
10.58
10.62
Mass (GeV/c2)
ϒ(1S)
ϒ(2S)
ϒ(3S)
continuum
ϒ(4S)

... more: $\Upsilon(5S)$



$$B_q = \{B_d^0, B_u^+\}$$

$\Upsilon(4S) \rightarrow B^+B^-,\ B^0\bar{B}^0$

M=10580±1 MeV/c², Γ=20.5±2.5MeV

$\Upsilon(5S) \rightarrow B_s^{(*)}\bar{B}_s^{(*)},\ B_q^{(*)}\bar{B}_q^{(*)},\ B_q\bar{B}_q^{(*)}\pi,\ B_q\bar{B}_q\pi\pi$

M=10865±8 MeV/c², Γ=110±13 MeV

B_s produced copiously in pp(bar) collisions (FNAL, LHC) –
could B-factories (competitively) study B_s at the $\Upsilon(5S)$?

pro's (A. Drutskoy)

- MUCH cleaner, better energy definition, event efficiency, clean γ's
- B-factory: high luminosity, established detector, compare w $\Upsilon(4S)$

Υ(5S) physics

B_s studies

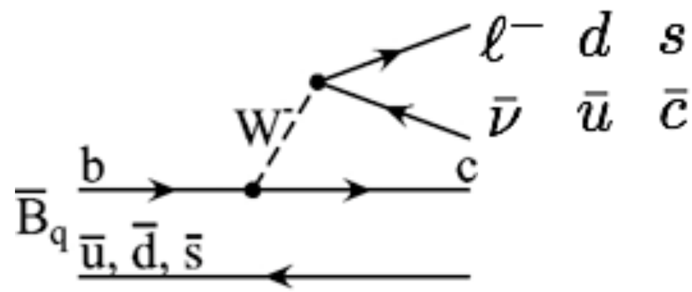
- Low CP-asymmetry in SM
  - -> sensitivity to New Physics (NP)

  "SM CP violation is insufficient to explain baryon asymmetry"

  Mod. Phys. Lett A9, 75 (1994); PRD 51, 379 (1995); Nucl.Phys. B287, 757 (1987)
- $\Delta\Gamma_{CP}/\Gamma$=O(10%) in SM
  - -> differences in CP, flavor eigenstates
- Absolute B_s branching fractions
- Similarity/difference w (non-strange) B
  - -> quark-hadron duality,
  - fine-tune hadronic models
- $B_s^{(*)}$ mass

Υ(5S) spectroscopy

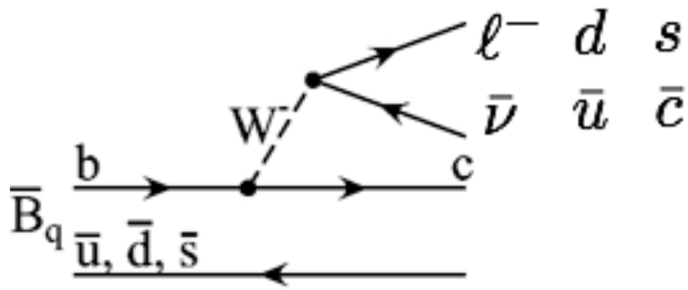
- $B_{(s)}^{(*)}(\pi)$ event fractions
- Other bottomonium-like states?



B_s decays: outline

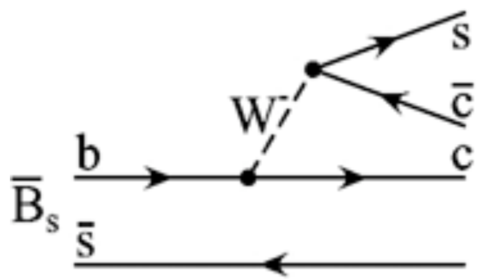
Similarity to $B_{u,d}$

- dominated by spectator process
  - similar semileptonic widths
  - D->D_s for many modes



difference

- CKM-favored AND flavor-neutral
  CP=+1 in heavy quark limit, $m_c \to \infty$
  ~ saturated by 2-body $D_s^{(*)+} D_s^{(*)-}$
  -> difference in widths of CP=±1



$$\frac{\Delta\Gamma_{CP}}{\Gamma} \approx \frac{2\Gamma(B_s \to D_s^{(*)+} D_s^{(*)-})}{\Gamma} \approx 0.1 - 0.2$$

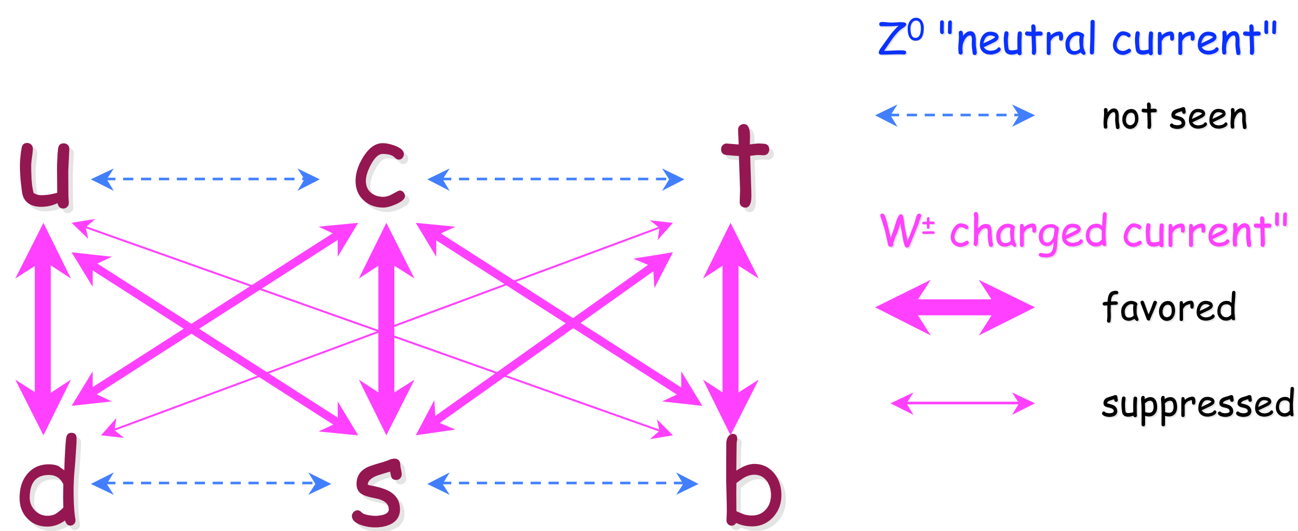
Aleksan, Dunietz, Kayser Z. Phys., C54, 653 (1992)

What about CP violation?

Unlike leptons, which exhibit no generation-xing couplings

Weak couplings of quarks look anomalous:

- neutral current – universal, generation-conserving
- charged current – approx. generation-conserving, but different



Weak charged-coupling matrix for quarks

$$g_F \times \begin{array}{c c} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

9 complex couplings

→ 18 free parameters

Inelegant!!

GIM (Glashow-Iliopoulos-Maiani) mechanism

universal & generation-conserving

$$g_F \times \begin{array}{c c} & \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

"weak eigenstates,"
≠ mass eigenstates d, s, b

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix

Weak couplings of quarks: CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

preserves metric "complex orthogonality" = unitary

Elegance Restored

Explains

- suppression of flavor-changing neutral currents
- multiplicity of charged current couplings
- AND …….

… for >2 generations, e.g. **3**, $\{9\Re+9\Im\}$ dof constrained by unitarity:
4 free parameters, incl. 1 irreducible **imaginary** part

> > *CP Violation* > > (Kobayashi-Maskawa 1973)

Makoto Kobayashi

First 3rd-generation particle (τ) seen 1975

Toshihide Maskawa

… for >2 generations, e.g. **3**, $\{9\mathcal{R}+9\mathcal{I}\}$ dof constrained by unitarity:
4 free parameters, incl. 1 irreducible **imaginary** part

Unitarity conditions $V_{ji}^{*}V_{jk}=\delta_{ik}$

explicit parametrization(Wolfenstein):

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

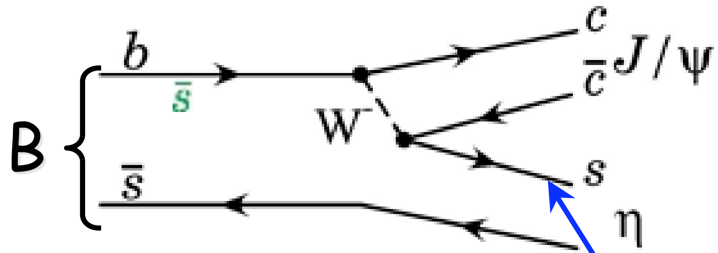
irreducibly complex

- matter-antimatter asymmetry requires CP-violating interactions (Sakharov 1967)
- CKM explains observed CP, appears insufficient for universe

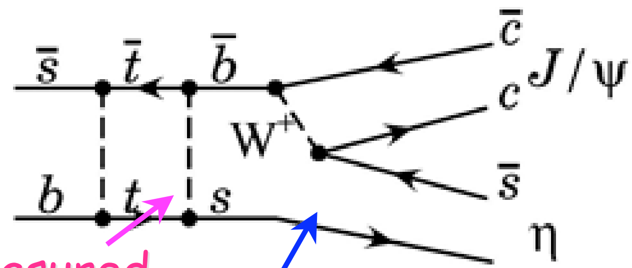
CP asymmetry in B_s -> $J/\psi\ \eta$

Analogous to B -> J/ψ K_s(Sanda/Bigi/Carter)

tree (real V_{ij}) $\propto V_{cb}^{*}V_{cs}$



mixing+tree ($\propto V_{td}^{*2}$)
$\propto V_{tb}^{*2}V_{ts}^{2}V_{cb}V_{cs}^{*}$



measured

identical hadronic processes

CP-dependent oscillation in time from x-term(s)
- no theoretical uncertainty: $\arg(V_{tb}^{*2}V_{ts}^{2}) = 0$

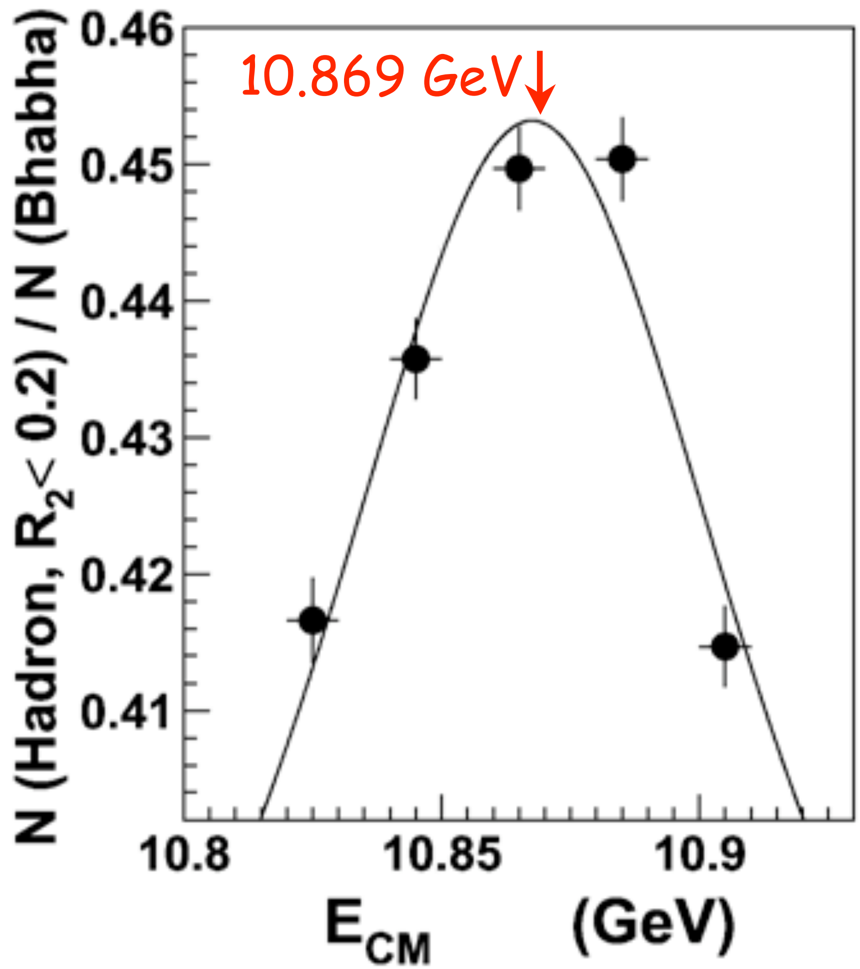
⇒No mixing-mediated CP violation in SM -> any CP asymmetry is NP
... something for the future...

Data at $\Upsilon(5S)$

June 2005: 3-day "engineering" run

- to study $\Upsilon(5S)$ properties, B_s prospects
- test KEKB - L_{max}~$1.39 \times 10^{34} cm^{-2}s^{-1}$
- energy scan, 5 points, 30 pb^{-1} each
- 1.86 fb^{-1} at peak
- 4 x largest previous sample (CLEO)

A. Drutskoy et al., PRL 98, 052001 (2007)
A. Drutskoy et al., PRD 76, 012002 (2007)



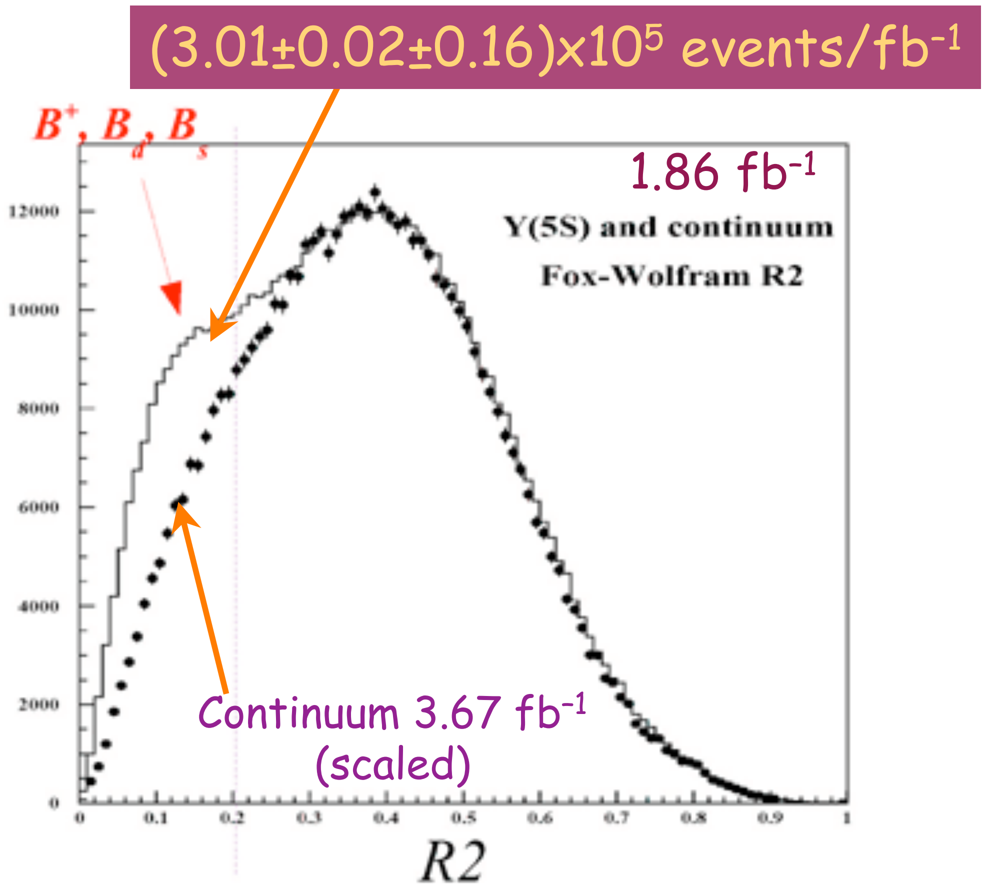
June 2006: 20-day run

- 21.7 fb^{-1} on peak
- total = 23.6 fb^{-1}

October 2008: extended run

- ~30 fb^{-1} on peak so far
- more in 2009

Event count



Event shape parameter
(Fox-Wolfram moments)

$$R_2 = \frac{\sum_{i,j} |p_i||p_j| \underbrace{P_2}_{3x^2-1}(\cos\theta)}{\sum_{i,j} |p_i||p_j| \underbrace{P_0}_{1}(\cos\theta)}$$

2-jet $e^+e^- \rightarrow q\bar{q}$ R_2->1

$e^+e^- \rightarrow B\bar{B}$ R_2->0

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Fundamentals

B_s fraction in $\Upsilon(5S)$ events

inclusive D_s production

(model estimate)
$(92 \pm 11)\%$

(measured)
$(8.7 \pm 1.2)\%$

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

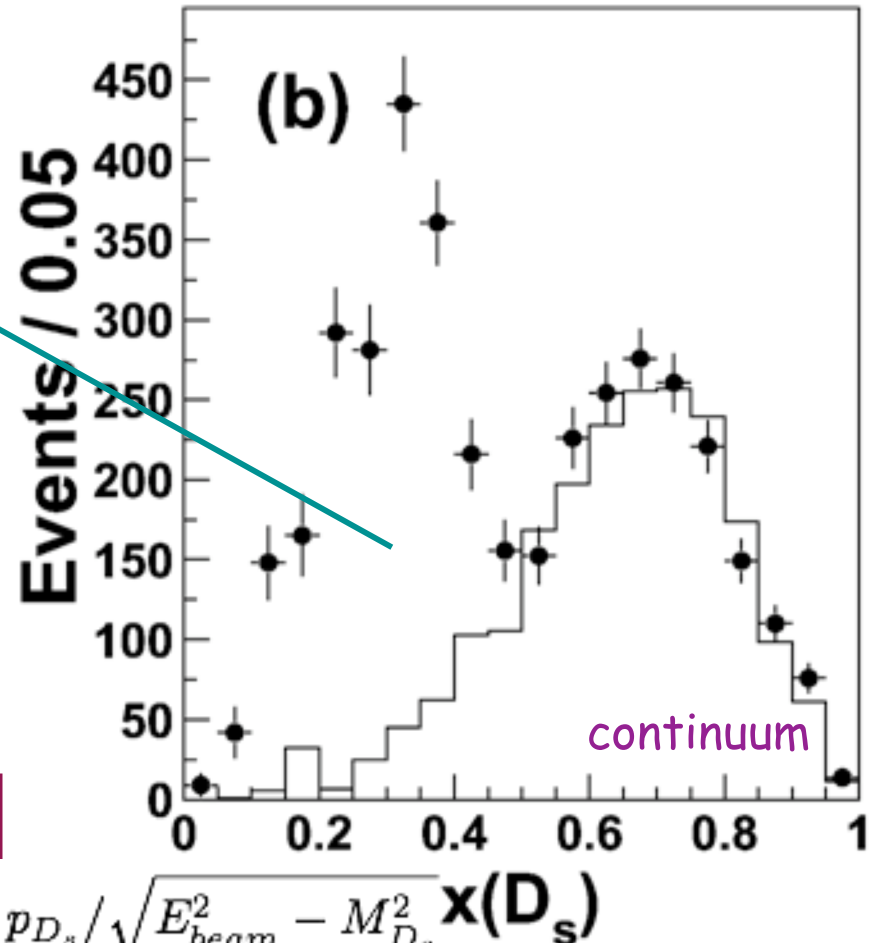
$$(23.6 \pm 1.2 \pm 3.6)\%$$

$$f_s = (17.9 \pm 1.4 \pm 4.1)\%$$

similar analysis using inclusive D^0:
$f_s=(18.1\pm3.6\pm7.5)\%$

combined:

$$f_s = (18.0 \pm 1.3 \pm 3.2)\%$$



$x = p_{D_s} / \sqrt{E_{beam}^2 - M_{D_s}^2}$

$$B_s \rightarrow D_s^- \pi^+,\ D_s^- K^+$$

R. Louvot, J. Wicht, O. Schneider, et al.
PRL 102, 021801 (2009)

B_s at Υ(5S): mix of $B_s\bar{B}_s : B_s^*\bar{B}_s / B_s\bar{B}_s^* : B_s^*\bar{B}_s^*$

Candidate reconstruction:
energy, momentum -> ΔE, M_{bc}

$B_s\bar{B}_s$

$$E_{B_s} = E_{beam}$$

$$p_{B_s} = \sqrt{E_{B_s}^2 - M_{B_s}^2}$$

$B_s^* \to B_s\gamma$

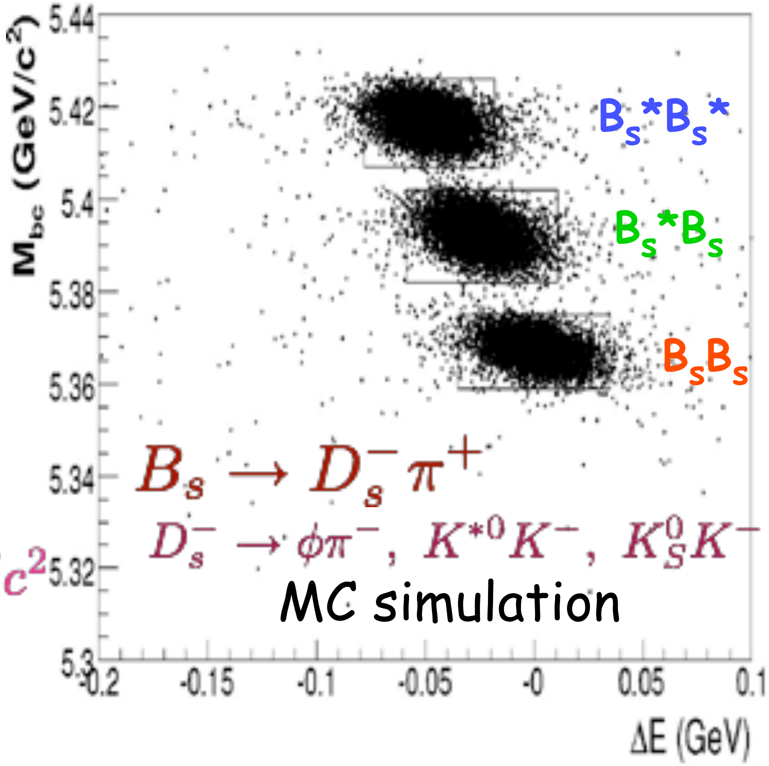
$$\Delta M \equiv M_{B_s^*} - M_{B_s} \approx 50 \text{ MeV}/c^2$$

$B_s^*\bar{B}_s$

$$E_{B_s} \approx E_{beam} - \Delta M/2$$

$B_s^*\bar{B}_s^*$

$$E_{B_s} \approx E_{beam} - \Delta M$$

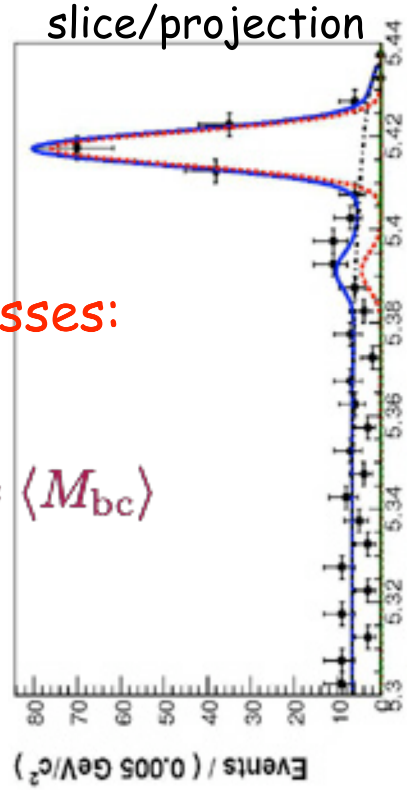


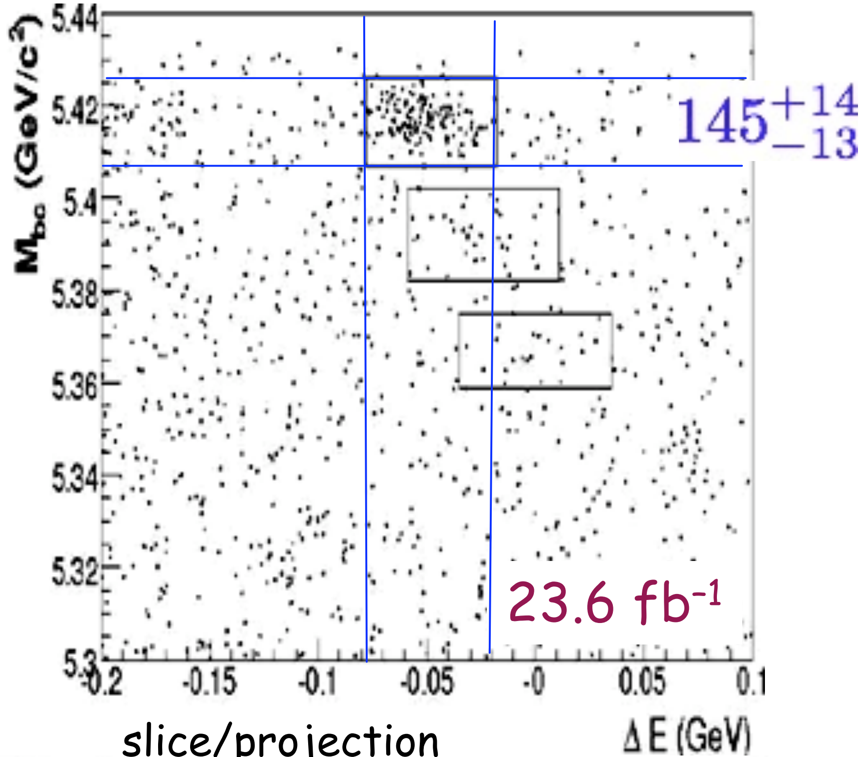
$$\Delta E \equiv E_{cand} - E_{beam}$$

$$M_{bc} \equiv \sqrt{E_{beam}^2 - p_{cand}^2}$$

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

$B_s^* B_s^*$





measure masses:

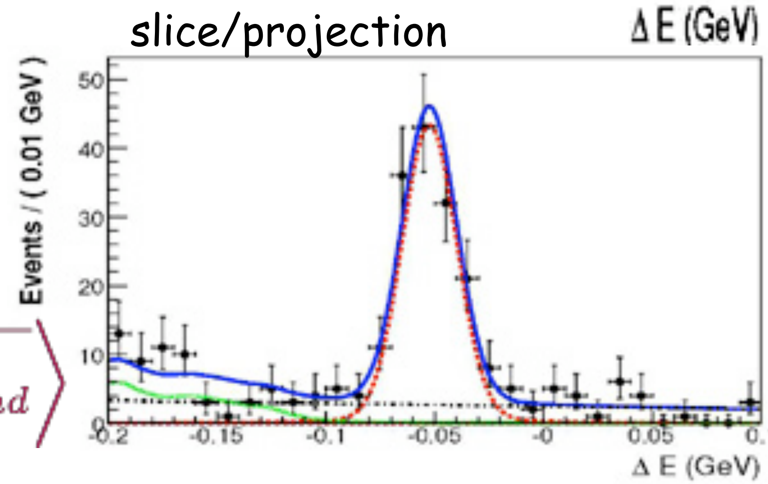
$\langle p_{B_s} \rangle = p_{B^*}$

$$\Rightarrow M_{B_s^*} = \langle M_{bc} \rangle$$

$\langle E_{B_s} \rangle = E_{beam} - \langle \Delta E \rangle$

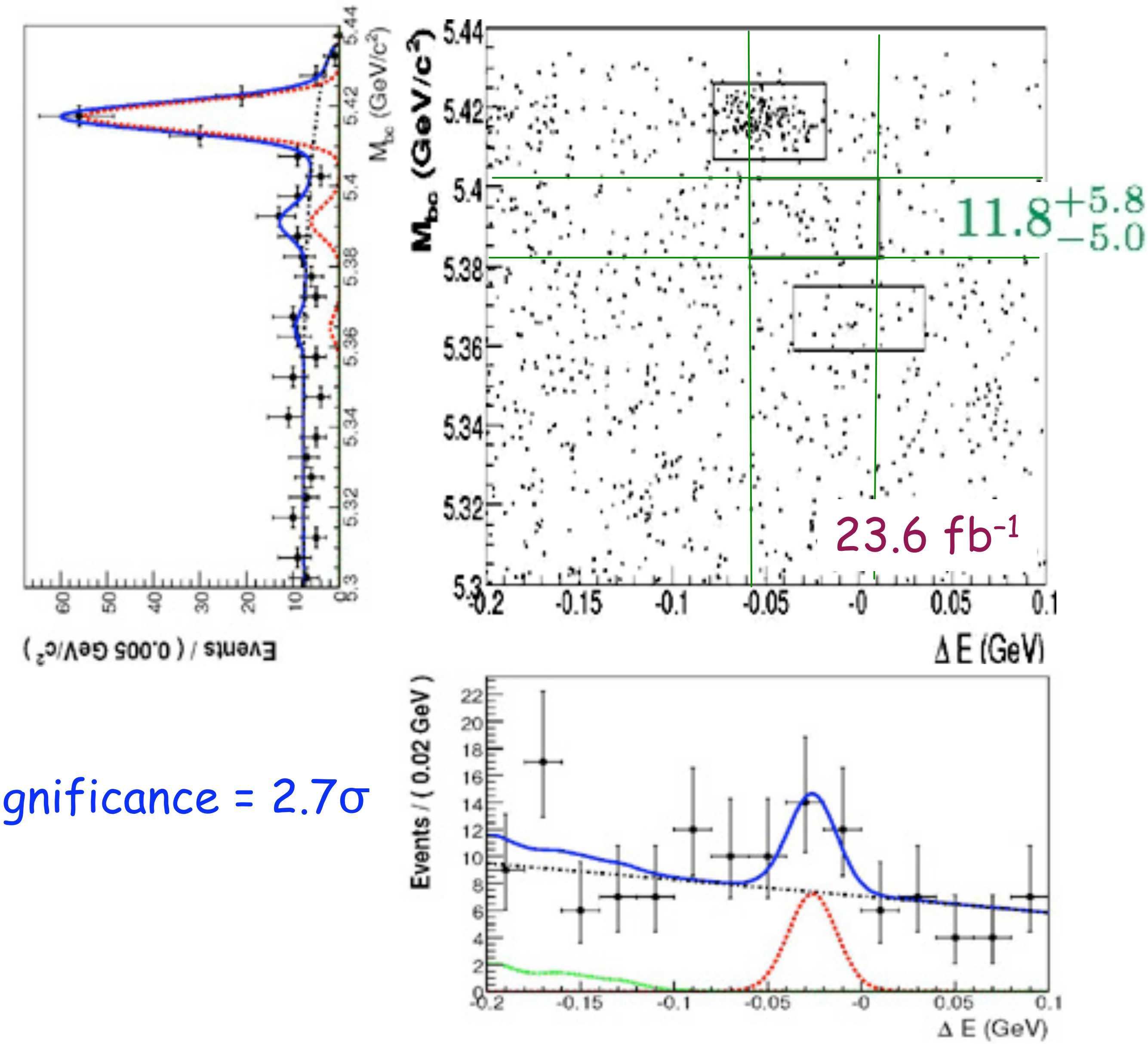
$$\Rightarrow M_{B_s}$$

$$= \left\langle \sqrt{(E_{beam} - \langle \Delta E \rangle)^2 - p_{cand}^2} \right\rangle$$



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

$B_s{}^*B_s$



significance = 2.7σ

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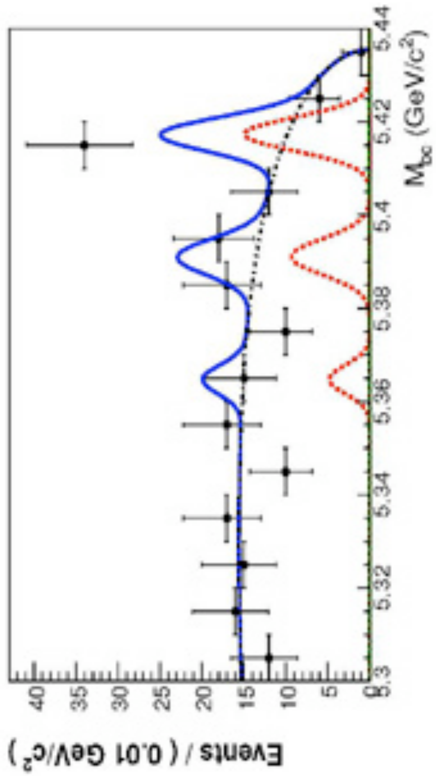
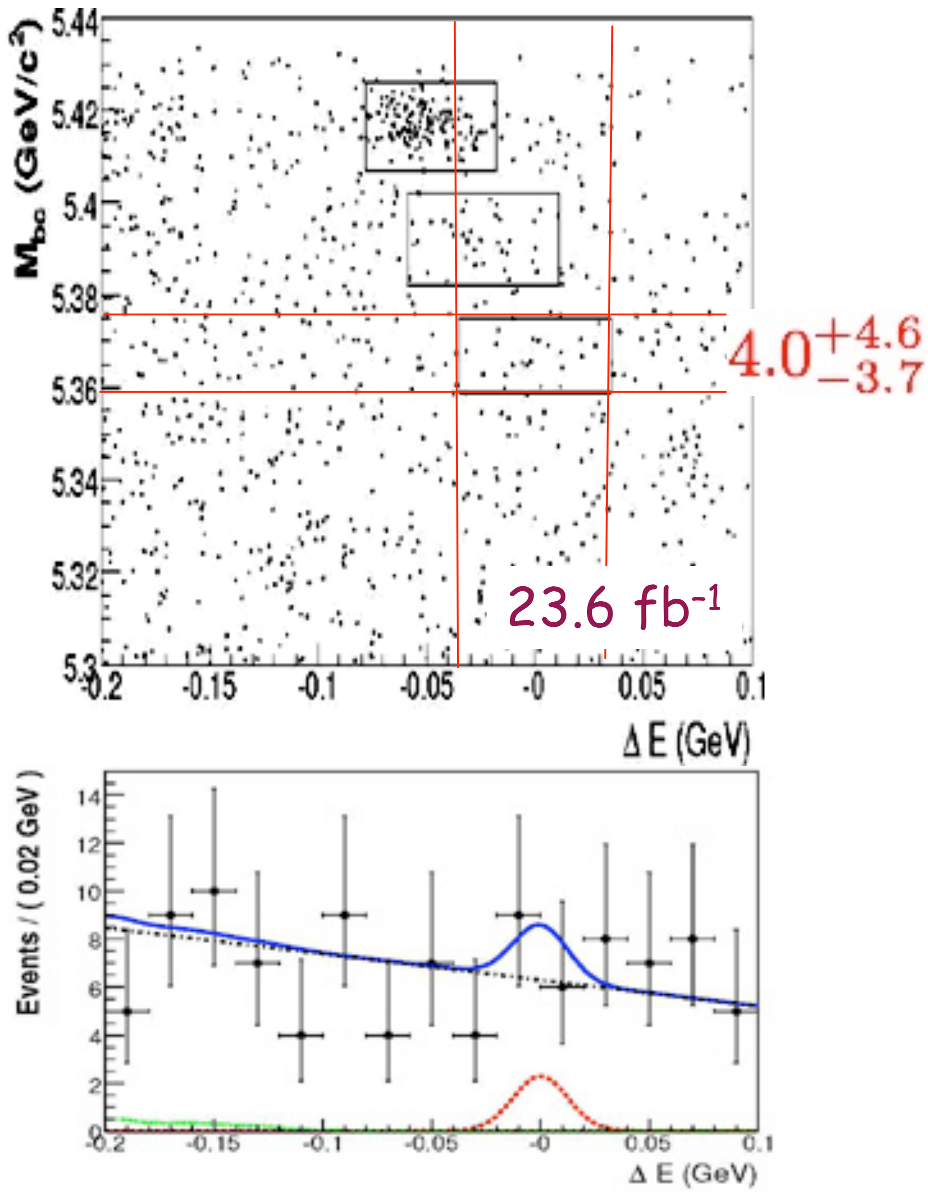
data $B_s \to D_s^- \pi^+$

B_sB_s

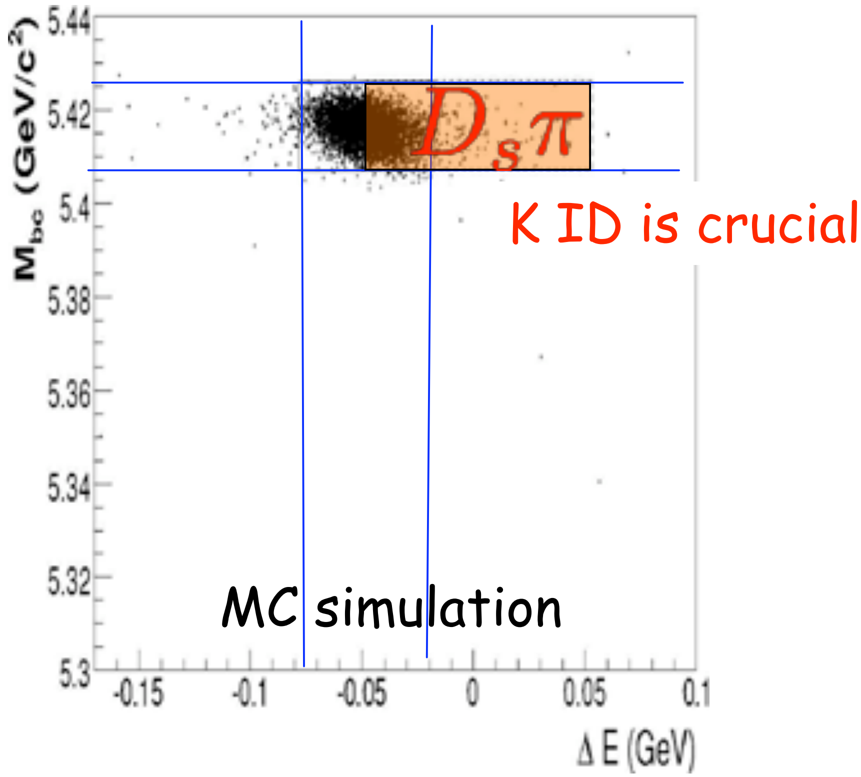




significance 1.1σ

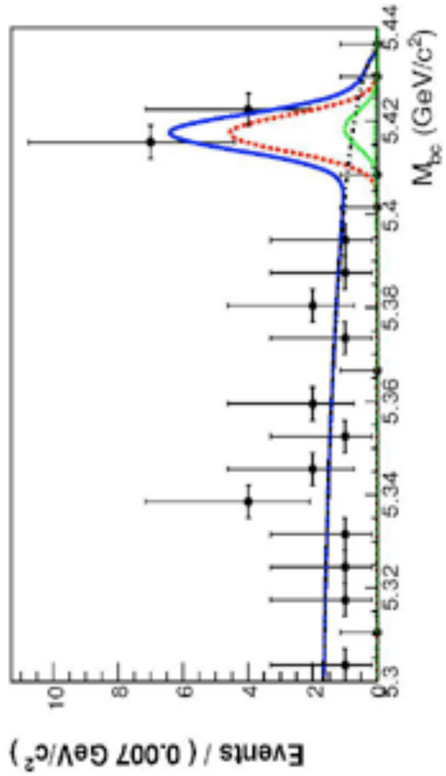
$B_s \to D_s^- K^+$

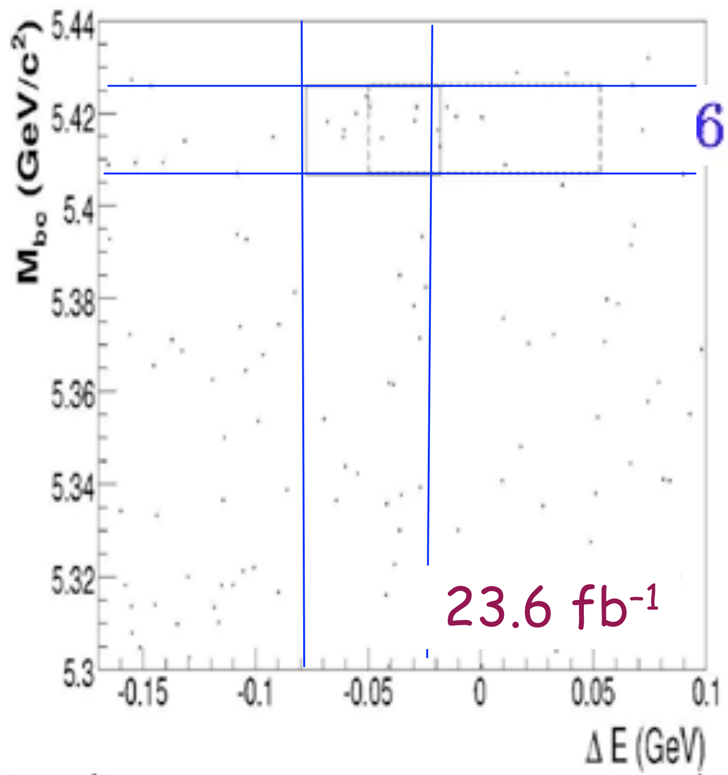
B_s*B_s* only
(statistics)



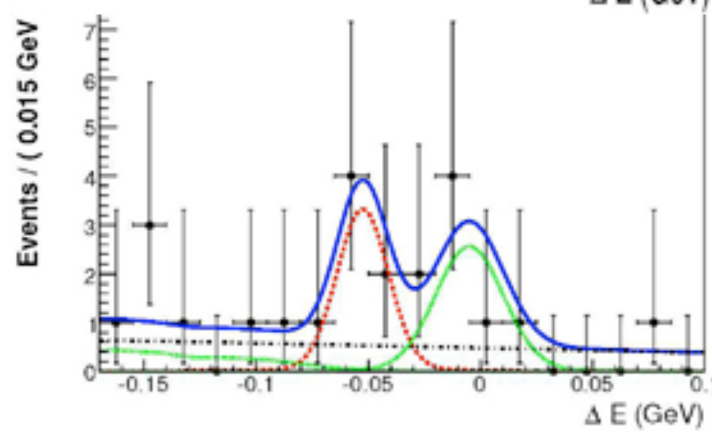
data $B_s \rightarrow D_s^- K^+$

$B_s^* B_s^*$





$6.7^{+3.4}_{-2.7}$



significance = 3.5σ

results $D_s^-\pi^+$, $D_s^-K^+$

	Belle, 23.6 fb^{-1}	PDG
$\mathcal{B}(B_s \to D_s\pi)$	$(3.67^{+0.35+0.43}_{-0.33-0.42}) \times 10^{-3}$	$(3.0 \pm 0.7) \times 10^{-3}$
$f_{B_s^*B_s^*}$	$(90.1^{+3.8}_{-4.0} \pm 0.2)\%$	–
$f_{B_s^*B_s}$	$(7.3^{+3.3}_{-3.0} \pm 0.1)\%$	–
$f_{B_sB_s}$	$(2.6^{+2.6}_{-2.5})\%$	–
m_{B_s}	$(5364.4 \pm 1.3 \pm 0.7)$ MeV$/c^2$	(5366.1 ± 0.6) MeV$/c^2$
$m_{B_s^*}$	$(5416.4 \pm 0.4 \pm 0.5)$ MeV$/c^2$	(5412.0 ± 1.2) MeV$/c^2$
$\mathcal{B}(B_s \to D_sK)$	$[2.4^{+1.2}_{-1.0} \pm 0.3(\mathrm{sys}) \pm 0.3(f_s)] \times 10^{-4}$	–
$\frac{\mathcal{B}(B_s\to D_sK)}{\mathcal{B}(B_s\to D_s\pi)}$	$[6.5^{+3.5}_{-2.9}]\%$	$(10.7 \pm 2.1)\%$

$$f_{B_s^*B_s^*} \equiv \frac{\sigma(e^+e^- \to B_s^*\bar{B}_s^*)}{\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})} \qquad f_{B_s^*B_s} \equiv \frac{\sigma(e^+e^- \to B_s^*\bar{B}_s + B_s\bar{B}_s^*))}{\sigma(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)})}$$

Searches for radiative modes of B_s

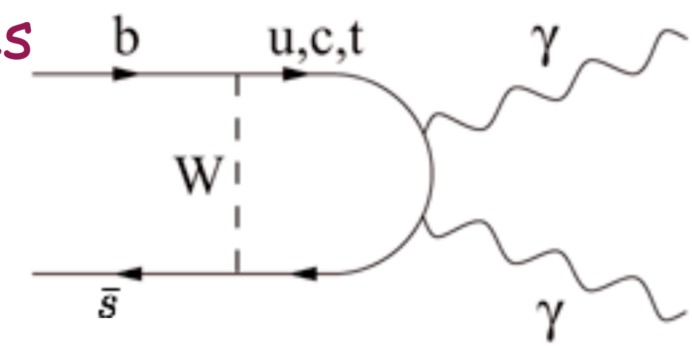
J. Wicht, et al.
PRL 100, 121801 (2008)

Searches for new modes of B_s

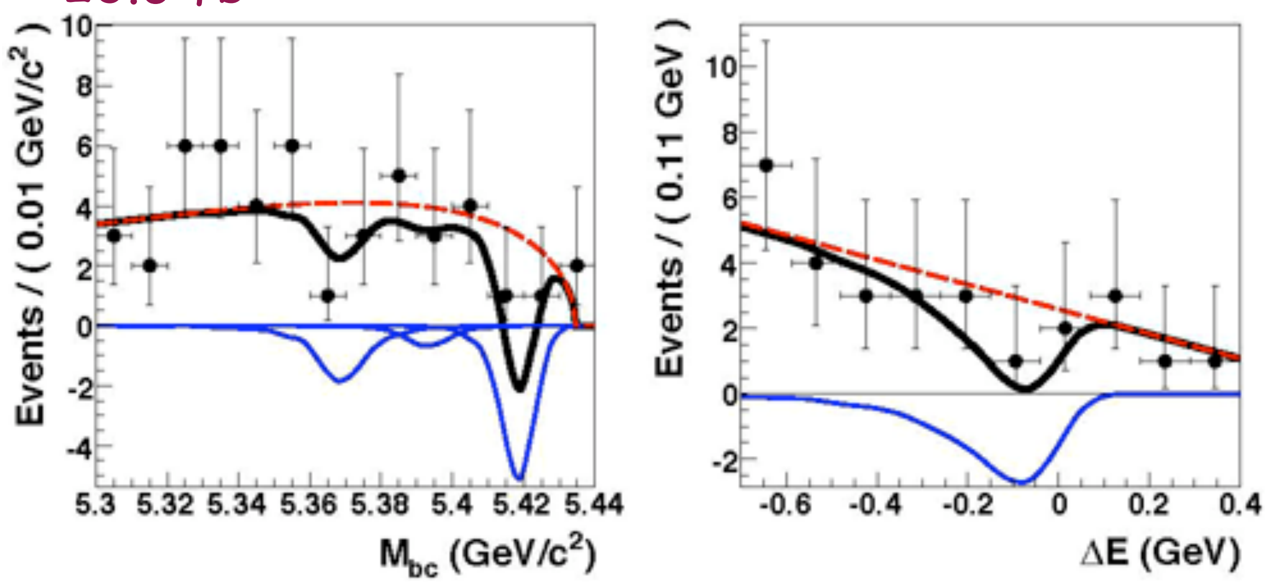
γγ: difficult for hadron machines

$$\mathcal{B}_{SM} \sim (0.4 - 1.0) \times 10^{-6}$$

beyond SM: up to 5×10^{-6}



23.6 fb^{-1}



$$\mathcal{B} < 8.7 \times 10^{-6} \; (90\% \; CL)$$ (prev. Belle: <5.3×10^{-5})

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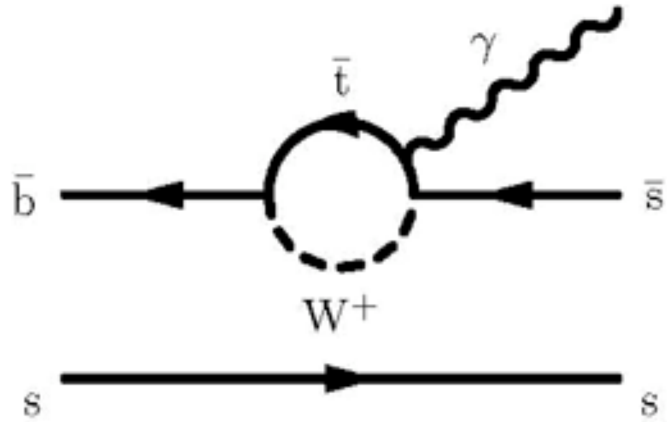
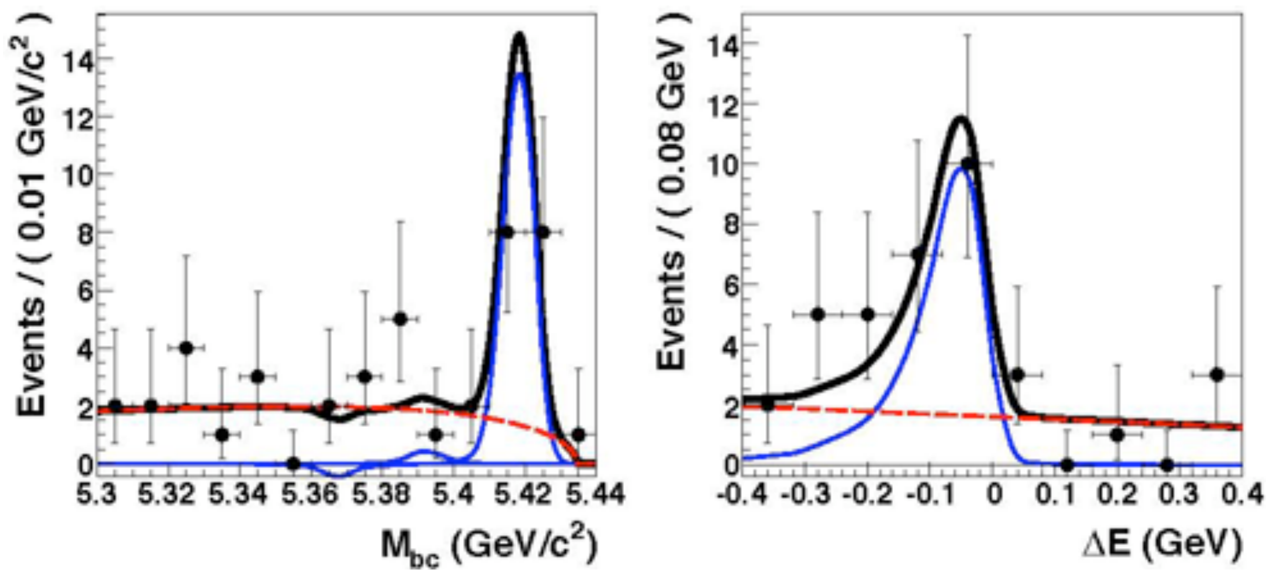
φγ



23.6 fb^{-1}



$$\mathcal{B} = (57^{+18}_{-15}(stat)^{+12}_{-11}(sys)) \times 10^{-6}$$

First observation

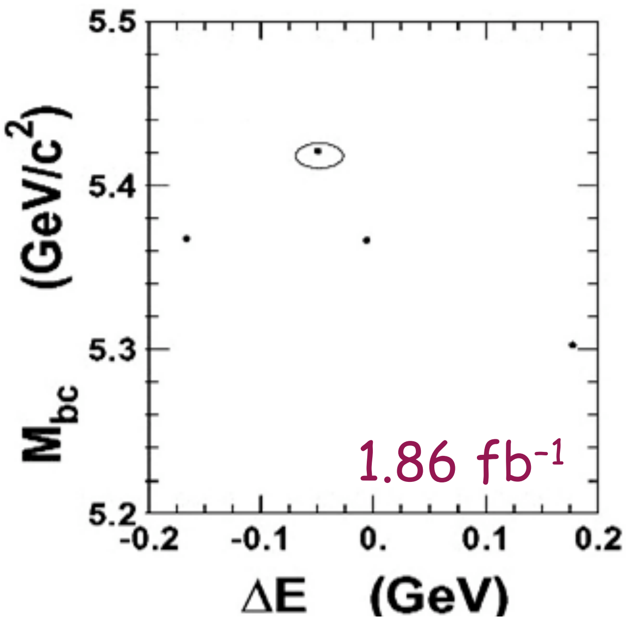
$$\frac{\Delta\Gamma_{CP}}{\Gamma} \; via \; \mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-})$$

A. Drutskoy, et al.
PRD 76, 012002 (2007)

Searches for new modes

$D_s^{(*)+}D_s^{(*)-}$: CKM favored, first sensitivity to

$$\frac{\Delta\Gamma_{CP}}{\Gamma} \approx 2\mathcal{B}(B_s \to D_s^{(*)+}D_s^{(*)-}) \approx 0.1 - 0.2$$



Analyze 3 modes together; little background
-> 23.6 fb^{-1}: in progress

CDF 2007:
$\mathcal{B}(B_s \to D_s^+ D_s^-) = (1.09 \pm 0.27 \pm 0.47)\%$

	$\mathcal{B}$(th.)	# cands	UL (90% CL)	Est#/20 fb^{-1}
$D_s^+D_s^-$	8.0×10^{-3}	0	$6.7{\times}10^{-2}$	4
$D_s^{*+}D_s^-$	2.0×10^{-2}	1	$12.1{\times}10^{-2}$	4
$D_s^{*+}D_s^{*-}$	1.9×10^{-2}	0	$25.7{\times}10^{-2}$	3

$$\Upsilon(10860) = \Upsilon(5S)?$$

K.-F. Chen, W.-S. Hou, M. Shapkin, A. Sokolov, et al.
PRL 100, 112001 (2008)

Is the Υ(10860) purely Υ(5S)?

- recently found in e⁺e⁻ collisions:

$$e^+e^- \to \gamma_{ISR}\,\pi^+\pi^- J/\psi \qquad e^+e^- \to \pi^+\pi^- J/\psi$$

New charmonium-like particle at 4260 GeV

Babar PRL 95, 142001 (2005)
Belle PRD 77, 011105 (R) (2008)
CLEO PRD 74, 091104(R) (2006)

$$Y(4260) \to \pi^+\pi^- J/\psi$$

Others

$$Y \to \pi^+\pi^- \psi(2S)$$

+more - than predicted!

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Does(do) analogous state(s) Y_b exist in Upsilon region?
[W.S. Hou, PRD 74, 017504 (2006)]

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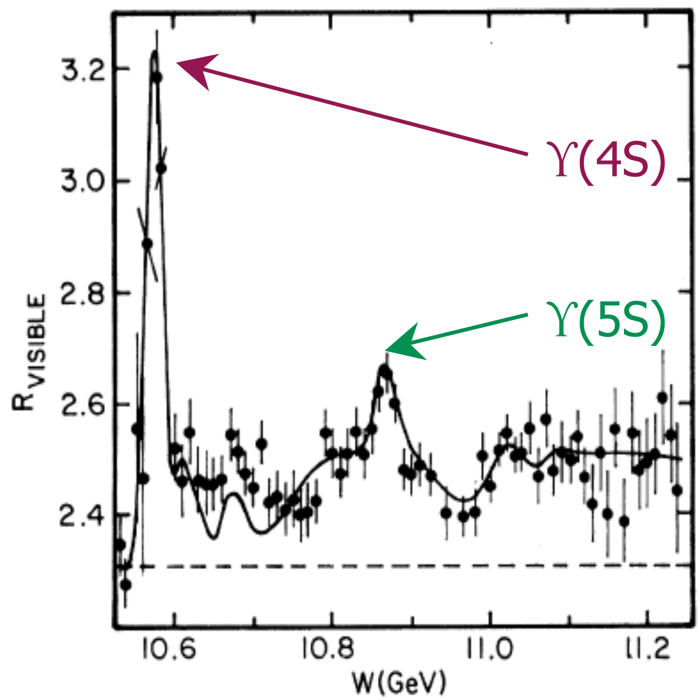


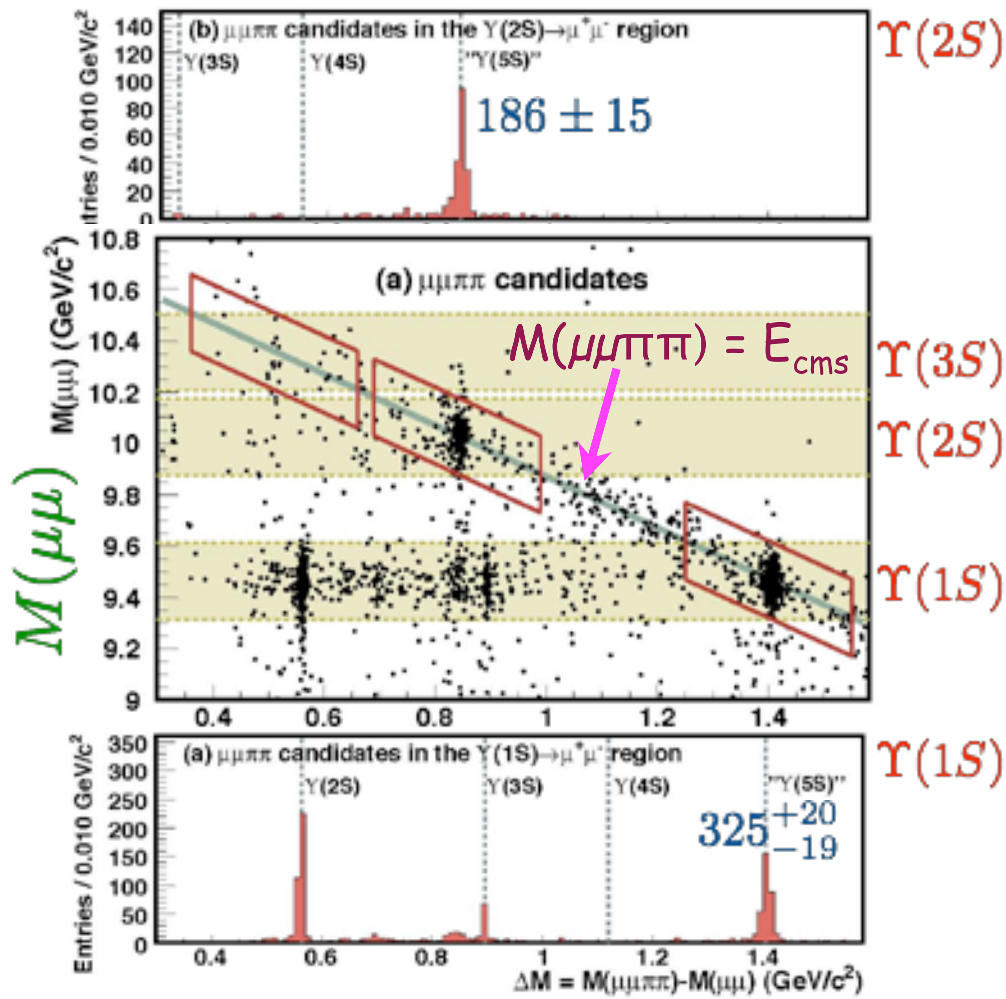
Does(do) analogous state(s) Y_b exist in Upsilon region?
[W.S. Hou, PRD 74, 017504 (2006)]

Is the Υ(10860) purely Υ(5S)?

-> look for: $\mu^+\mu^-h^+h^-$

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

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



$$\Delta M = M(\mu\mu\pi\pi) - M(\mu\mu)$$

4 modes seen $\Upsilon(10860) \to \Upsilon(nS)h^+h^-$

Process	σ(pb)	$\mathcal{B}$(%)	Γ(MeV)
$\Upsilon(1S)\pi^+\pi^-$	$1.61 \pm 0.10 \pm 0.12$	$0.53 \pm 0.03 \pm 0.05$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	$2.35 \pm 0.19 \pm 0.32$	$0.78 \pm 0.06 \pm 0.11$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$1.44^{+0.55}_{-0.45} \pm 0.19$	$0.48^{+0.18}_{-0.15} \pm 0.07$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$0.185^{+0.048}_{-0.041} \pm 0.028$	$0.061^{+0.016}_{-0.014} \pm 0.010$	$0.067^{+0.017}_{-0.015} \pm 0.013$

Expectation: Υ(5S) width comparable to Υ(2S/3S/4S)

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

larger by > 10^2

Conclusion: <u>not</u> pure Υ(5S)?

12/07: energy scan, measure $e^+e^- \to \Upsilon(nS)h^+h^-$

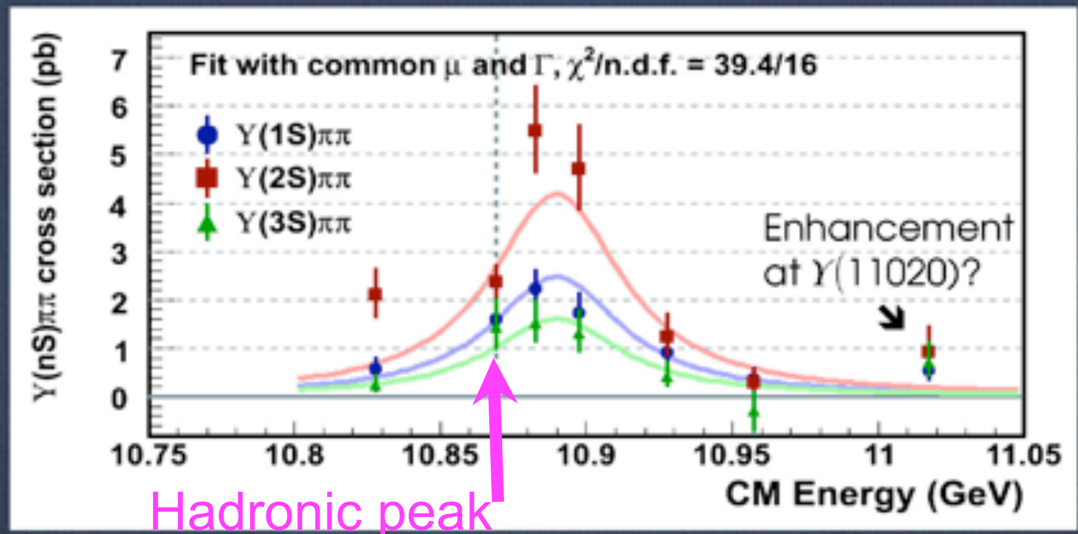
Followup: scan above $\Upsilon(5S)$

$\sqrt{s}(\mathrm{GeV})$	$\mathcal{L}(\mathrm{fb}^{-1})$
10.8275	1.68
10.8825	1.83
10.8975	1.41
10.9275	1.14
10.9575	1.01
11.0175	0.86

K-F Chen
BELLE-CONF-0861
ArXiv: 0808.2445

$\Upsilon(nS)\pi\pi$ Resonant Shapes

- A χ^2 fit to the measured cross sections:
  (7 energies x 3 states = 21 points)



A common Breit-Wigner (floated mean & width) with floated 3 normalizations (for 1S, 2S, and 3S).

The mean value is ~20 MeV higher than the Υ(10860), and the width is around half (110 MeV → 55 MeV)!

	$\Upsilon(1S)\pi\pi$	$\Upsilon(2S)\pi\pi$	$\Upsilon(3S)\pi\pi$
Peak	$2.46\ ^{+0.27}_{-0.25} \pm 0.18$ pb	$4.18\ ^{+0.49}_{-0.46} \pm 0.55$ pb	$1.61\ ^{+0.31}_{-0.28} \pm 0.21$ pb
Mean		10889.6 ±1.8 ±1.5 MeV	
Width		$54.7^{+8.5}_{-7.2} \pm 2.5$ MeV	

(Peak cross section for Υ(5S) is around 300 pb)

Summary

KEB and Belle at $\Upsilon(10860)$

- 23 days, 23.6 fb^{-1}, 1.3M B_s events
- 8 fb^{-1} near and above $\Upsilon(10860)$
- Beast(s)

  anomalous $\Upsilon(ns)\pi\pi$, ~10^2X expectation at $\Upsilon(10860)$
  $\Upsilon(ns)\pi\pi$ rate peaks ~ 20 MeV above hadronic peak
  -> $\Upsilon(10860)$: not pure $\Upsilon(5S)$?
- Strange beauty

  large sample of $B_s \to D_s\pi$, evidence D_sK
  $B_s^*B_s^*$ rate, masses of B_s^*, B_s
  best limit on $B_s \to \gamma\gamma$
  first observation of $B_s \to \varphi\gamma$
- more to come ...

  October 2008, extended run -> ~100 fb^{-1}