SLAC, October 21, 2008

Strange Beauty and Other Beasts: At and Above the Υ(5S) with Belle

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

Kay Kinoshita
University of Cincinnati
Belle Collaboration

The people

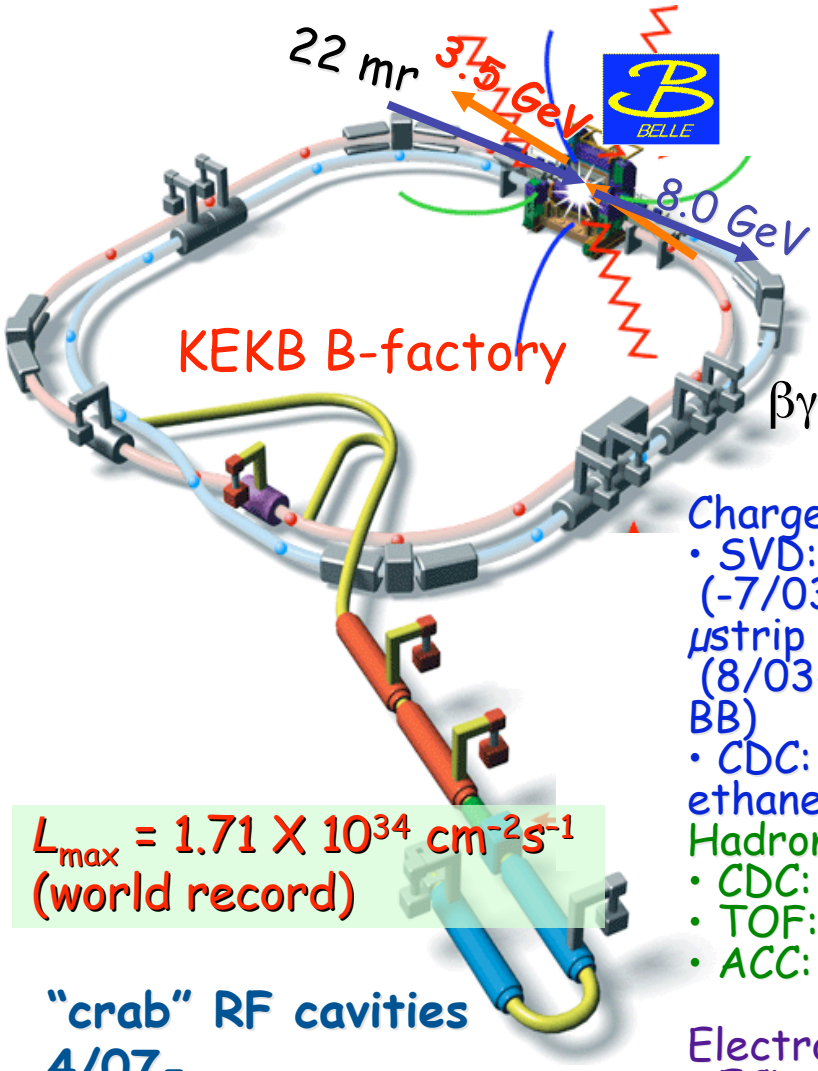
Belle collaboration

Aomori U.
BINP
Chiba U.
Chonnam Nat'l U.
U. of Cincinnati
Ewha Womans U.
Frankfurt U.
Gyeongsang Nat'l U.
U. of Hawaii
Hiroshima Tech.
IHEP, Beijing
IHEP, Moscow
IHEP, Vienna
ITEP
Kanagawa U.
KEK
Korea U.
Krakow Inst. of Nucl. Phys.
Kyoto U.
Kyungpook Nat'l U.
EPF Lausanne
Jozef Stefan Inst. / U. Ljubljana / U. of Maribor
U. of Melbourne
Nagoya U.
Nara Women's U.
National Central U.
National Taiwan U.
National United U.
Nihon Dental College
Niigata U.
Osaka U.
Osaka City U.
Panjab U.
Peking U.
U. of Pittsburgh
Princeton U.
Riken
Saga U.
USTC
Seoul National U.
Shinshu U.
Sungkyunkwan U.
U. of Sydney
Tata Institute
Toho U.
Tohoku U.
Tohuku Gakuin U.
U. of Tokyo
Tokyo Inst. of Tech.
Tokyo Metropolitan U.
Tokyo U. of Agri. and Tech.
Toyama Nat'l College
U. of Tsukuba
VPI
Yonsei U.

~14 nations, 55 institutes, ~400 collaborators

(authors vary, each paper)

... the hardware



$\beta\gamma = 0.425$

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

"crab" RF cavities
4/07-
$L = 1.6 \times 10^{34}\ cm^{-2}s^{-1}$

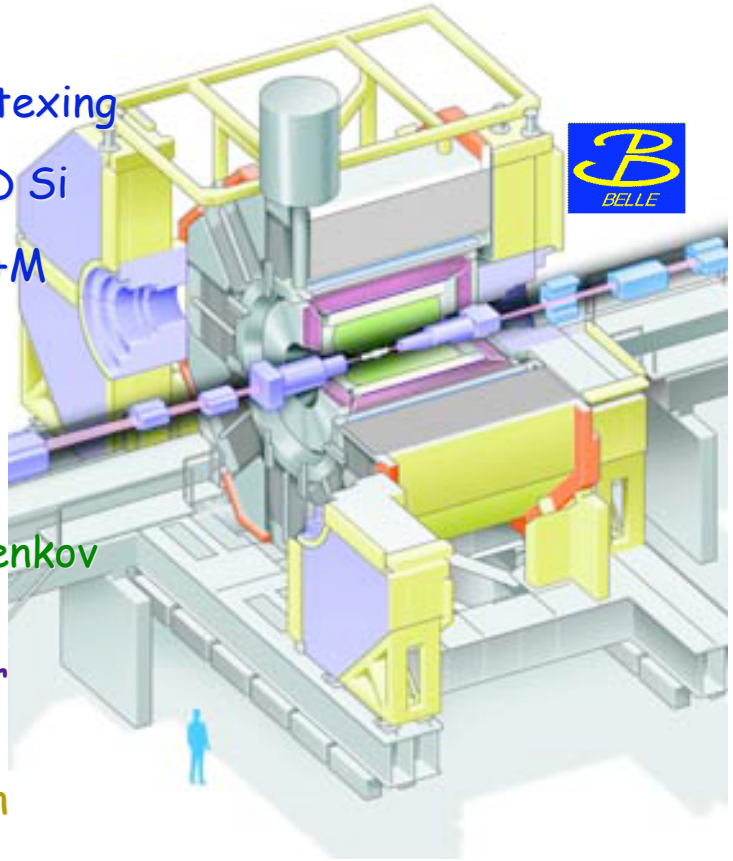
4/07- COPPER pipelined DAQ system

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)

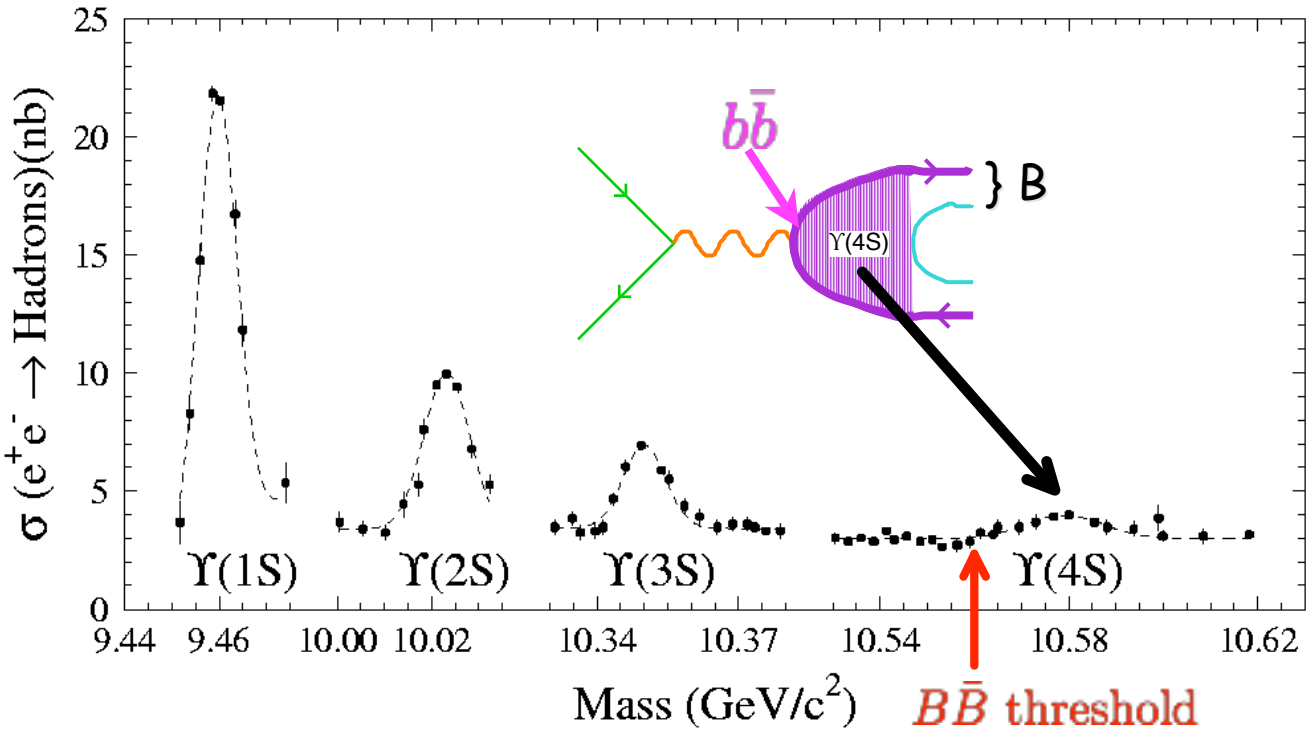
Hadron identification
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon
- ECL: CsI calorimeter

Muon/K_L
- KLM: Resistive plate counter/iron



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



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

Data (6/1999-9/2008)
- $\int L dt$ = ~820 fb^{-1}@{Υ(4S)+off(~10%)}
- (>8x10^8 B events)

... but there's MUCH more!

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

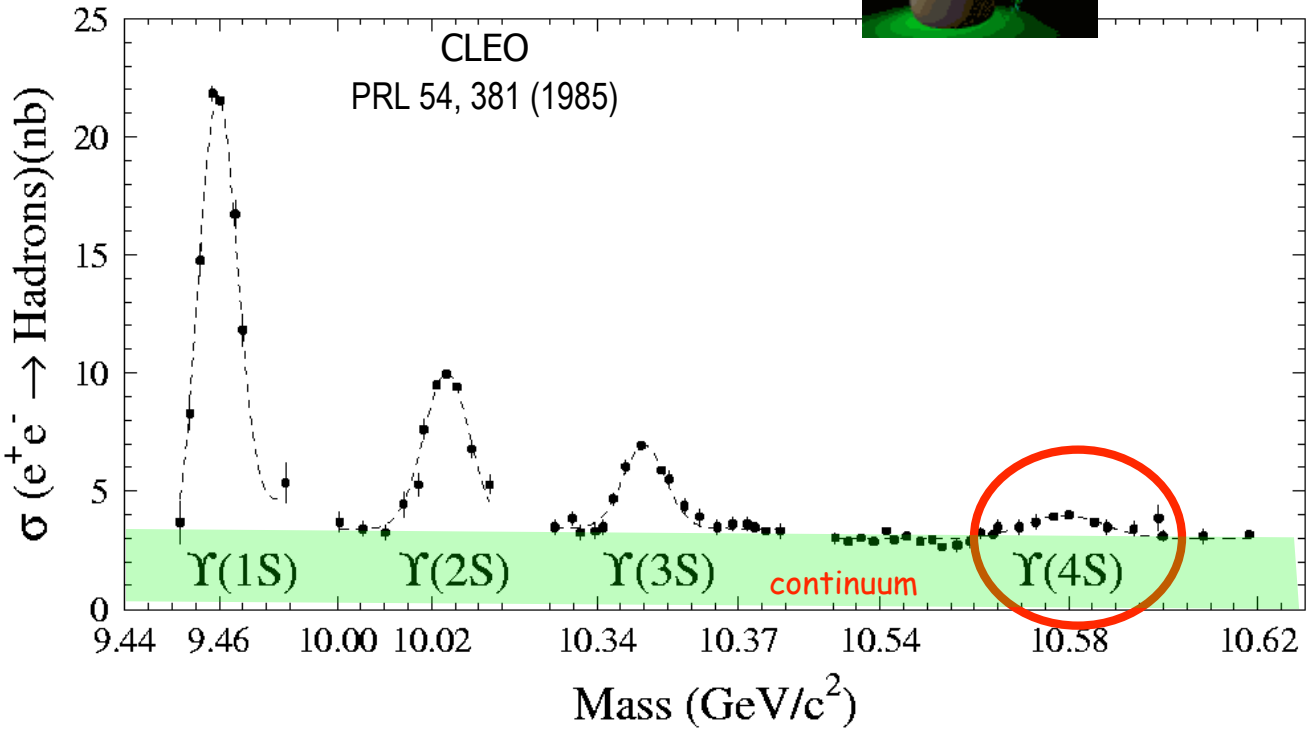
- CP asymmetry in B decay
- B decays
- charm
- tau
- 2-photon
- addressing CP, CKM, QCD, HQ spectroscopy, ...

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

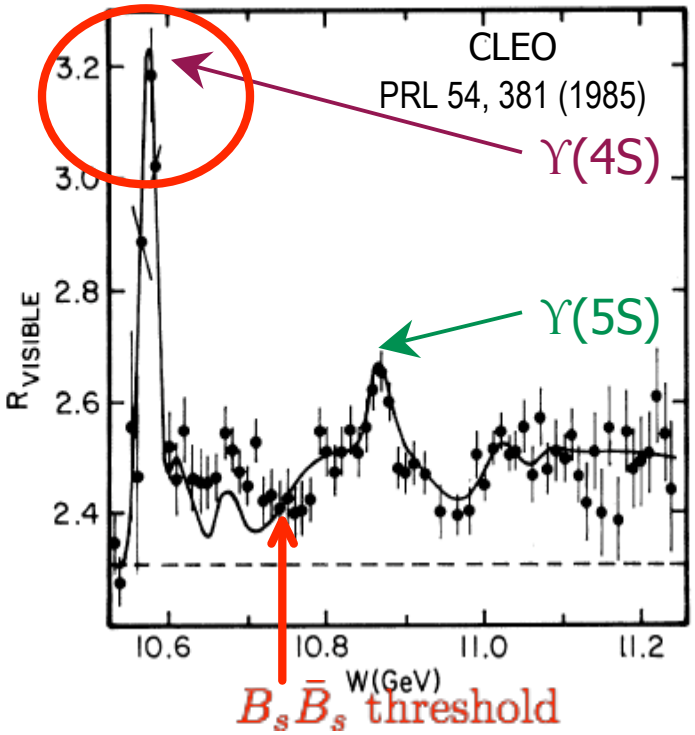
Non-4S Data (-9/2008)
- $\int L dt$ = 24.6 fb^{-1}@Υ(5S)
- (1.3 x 10^6 B_s events)
- $\int L dt$ = ~8 fb^{-1}@Υ(5S)+ scan
- + Υ(3S), Υ(2S)

- ... 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
Υ(1S)
Υ(2S)
Υ(3S)
continuum
Υ(4S)
9.44
9.46
10.00
10.02
10.34
10.37
10.54
10.58
10.62
Mass (GeV/c2)

... more: Υ(5S)



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

$\rightarrow B^+B^-,\ B^0\bar{B}^0$

M=10580±1 MeV/c², Γ=20.5±2.5MeV

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

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 Υ(5S)?

pro's (A. Drutskoy)

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

Υ(5S) physics

B_s studies

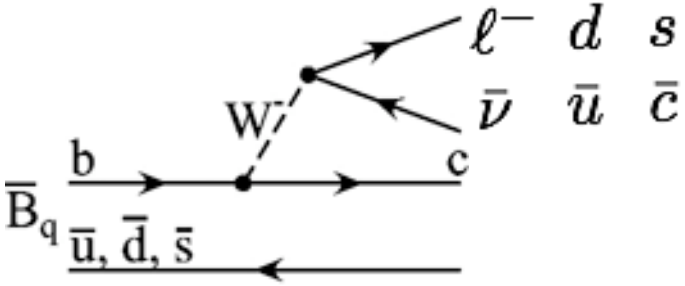
- Low CP-asymmetry in SM
  -> sensitivity to New Physics

  "SM CP violation is insufficient to explain baryon asymmetry"

  Mod. Phys. Lett A9, 75 (1994); PRD 51, 379 (1995); Nucl.Phys. B287, 757 (1987)
- $\Delta\Gamma/\Gamma_{CP}/\Gamma$=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

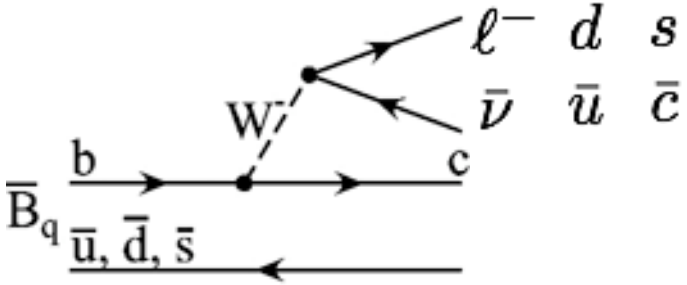
- $B_{(s)}^{(*)}(\pi)$ event fractions
- Other bottomonium-like states?



B_s decays: outline

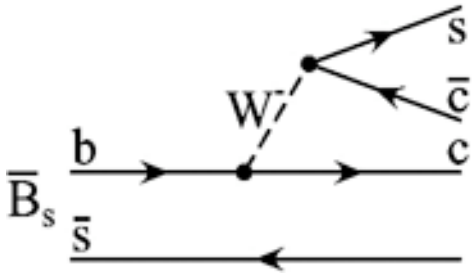
Similarity w $B_{u,d}$

- 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->∞
  ~ saturated by 2-body $D_s^{(*)+}D_s^{(*)-}$
  -> difference in widths of CP=±1



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

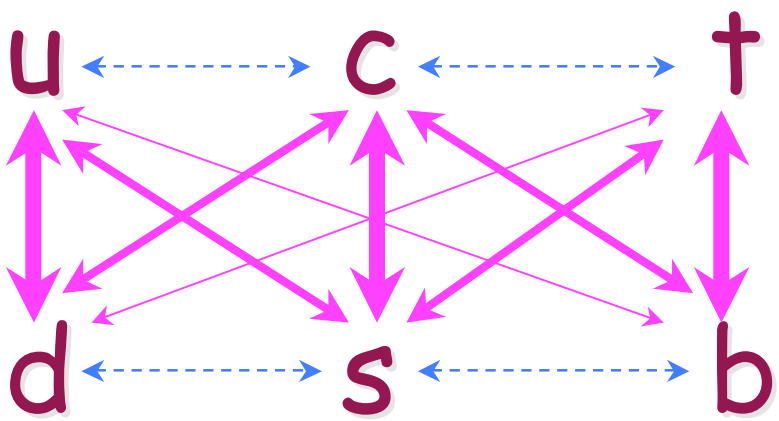
Aleksan, Dunietz, Kayser Z. Phys., C54, 653 (1992)

What about CP violation?

Unlike leptons, which exhibit no generation-xing couplings

Weak couplings of quarks:

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



Z^0 "neutral current"

not seen

$W^{\pm}$ charged current"

favored

suppressed

Weak charged-coupling matrix for quarks

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

9 complex couplings
-> 18 free parameters

Inelegant !!

GIM (Glashow-Iliopoulos-Maiani) mechanism

universal & generation-conserving

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

"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

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

pre "*Elegance Restored*"

Explains

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

… for >2 generations, e.g. **3**, {9$\mathcal{R}$+9$\mathcal{I}$} 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

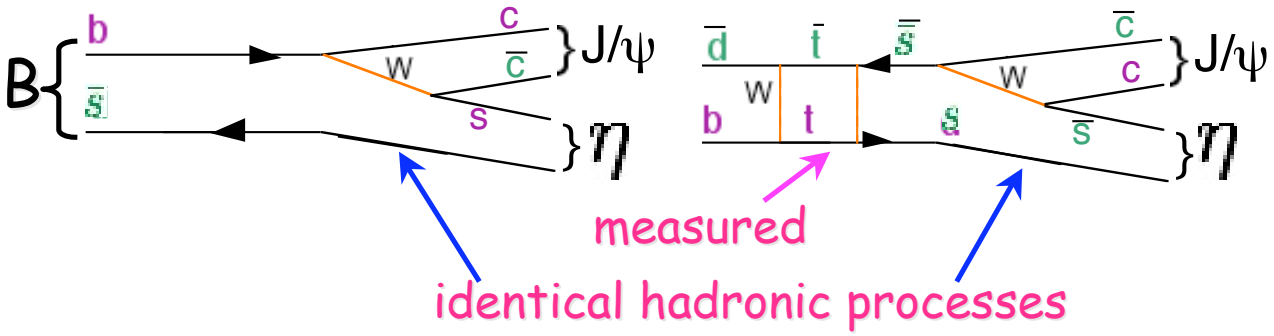
- matter-antimatter asymmetry requires CP-violating interactions (Sakharov 1967)
- CKM explains observed CP, appears insufficient for universe

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

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

mixing+tree ($\propto V_{td}^{*2}$)

tree (real V_{ij}) $\propto V_{cb}^{*}V_{cs}$ $\propto V_{tb}^{*2}V_{ts}^{2}V_{cb}V_{cs}^{*}$



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

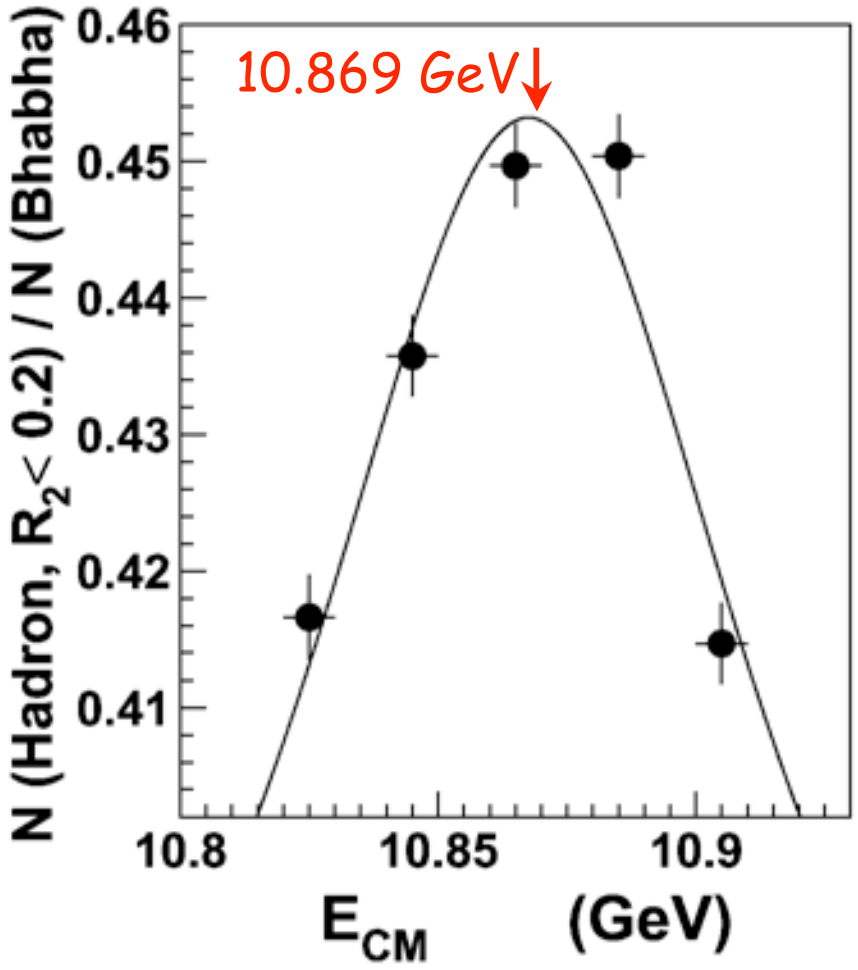
June 2005: 3-day "engineering" run

- 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

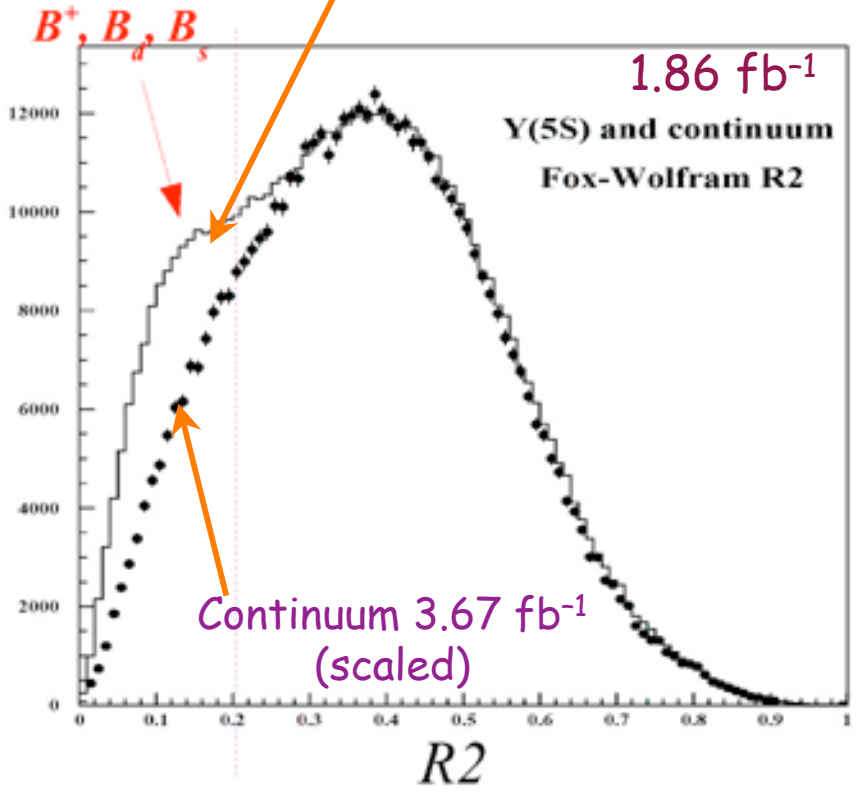
- 21.7 fb^{-1} on peak
- total = 23.6 fb^{-1}



Fundamentals

Event count

(3.01±0.02±0.16)x10^5 events/fb^{-1}



Event shape parameter
(Fox-Wolfram moments)

$$R_2 = \frac{\sum_{i,j} |p_i||p_j| P_2(\cos\theta)}{\sum_{i,j} |p_i||p_j| P_0(\cos\theta)}$$

$3x^2-1$ over P_2; 1 over P_0

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

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

Fundamentals

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

inclusive D_s production

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

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

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

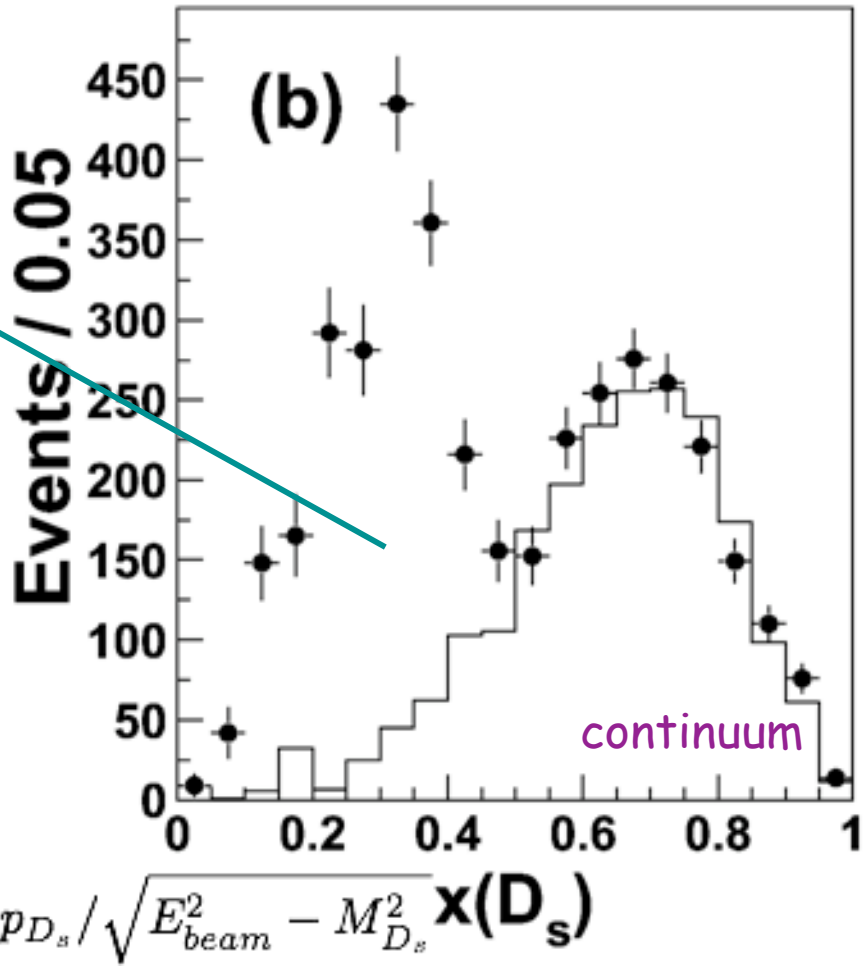
$$(23.6 \pm 1.2 \pm 3.6)\%$$

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

similar analysis using inclusive D^0:
f_s=(18.1±3.6±7.5)%

combined:

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



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

R. Louvot, J. Wicht, O. Schneider, et al.
arXiv:0809.2526[hep-ex], submitted to PRL

B_s at $\Upsilon(5S)$: 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}

$$B_s\bar{B}_s$$

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

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

$$B_s^* \to B_s\gamma$$

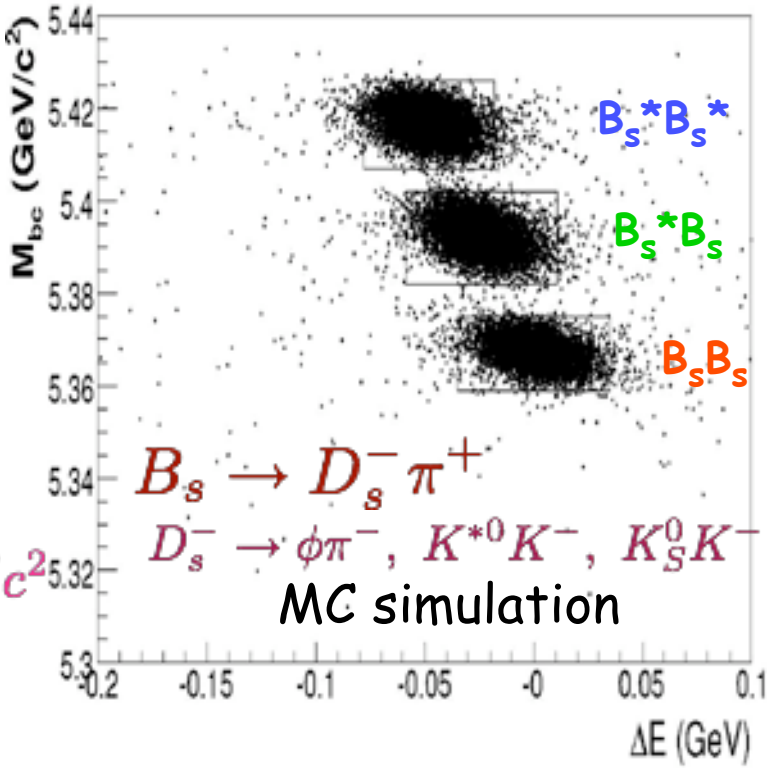
$$\Delta M \equiv M_{B_s^*} - M_{B_s} \approx 50\ \mathrm{MeV}/c^2$$

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

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

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

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



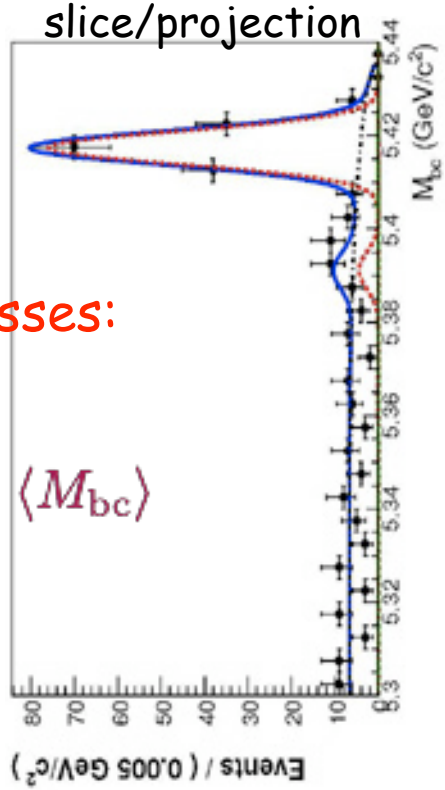
$$M_{\mathrm{bc}} \equiv \sqrt{E_{beam}^2 - p_{cand}^2}$$

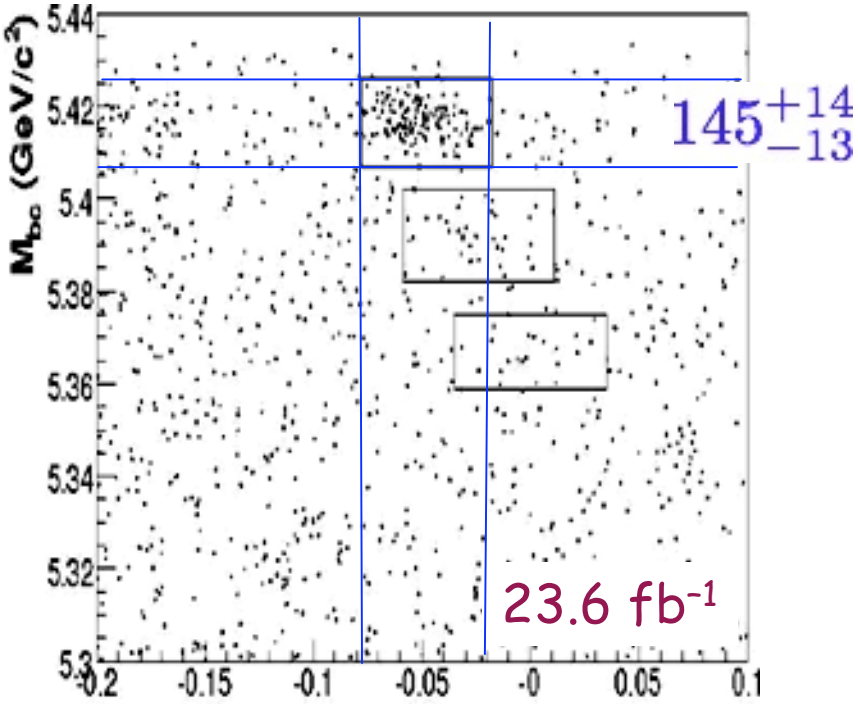
$$\Delta E \equiv E_{cand} - E_{beam}$$

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

$B_s^* B_s^*$

slice/projection





measure masses:

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

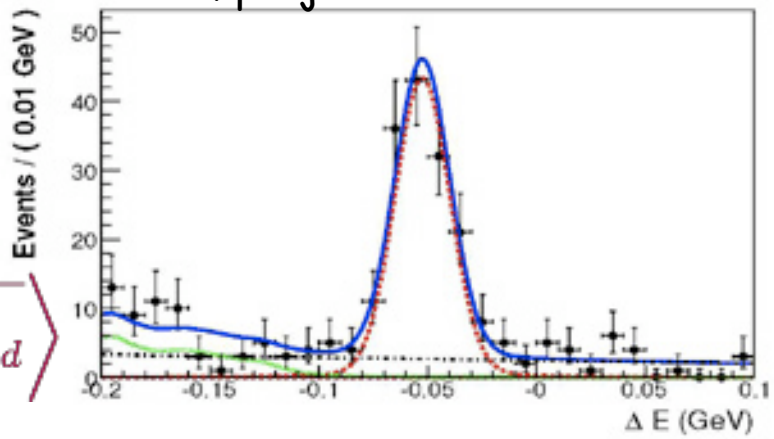
$$\Rightarrow M_{B_s^*} = \langle M_{\rm bc} \rangle$$

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

$$\Rightarrow M_{B_s}$$

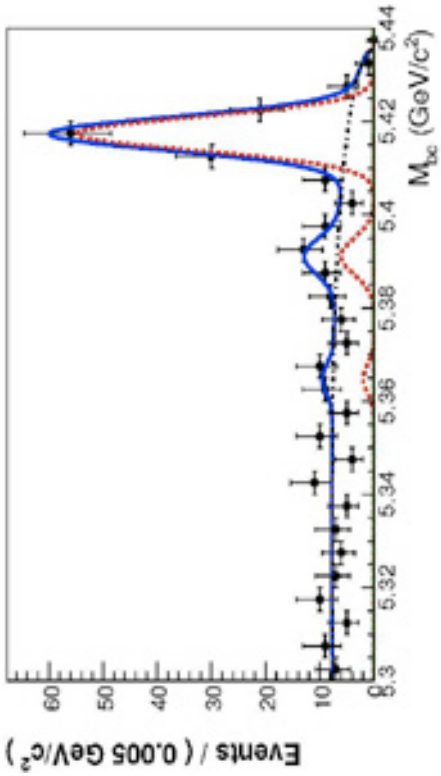
$$= \left\langle \sqrt{(E_{beam} - \langle \Delta E \rangle)^2 - p_{cand}^2} \right\rangle$$

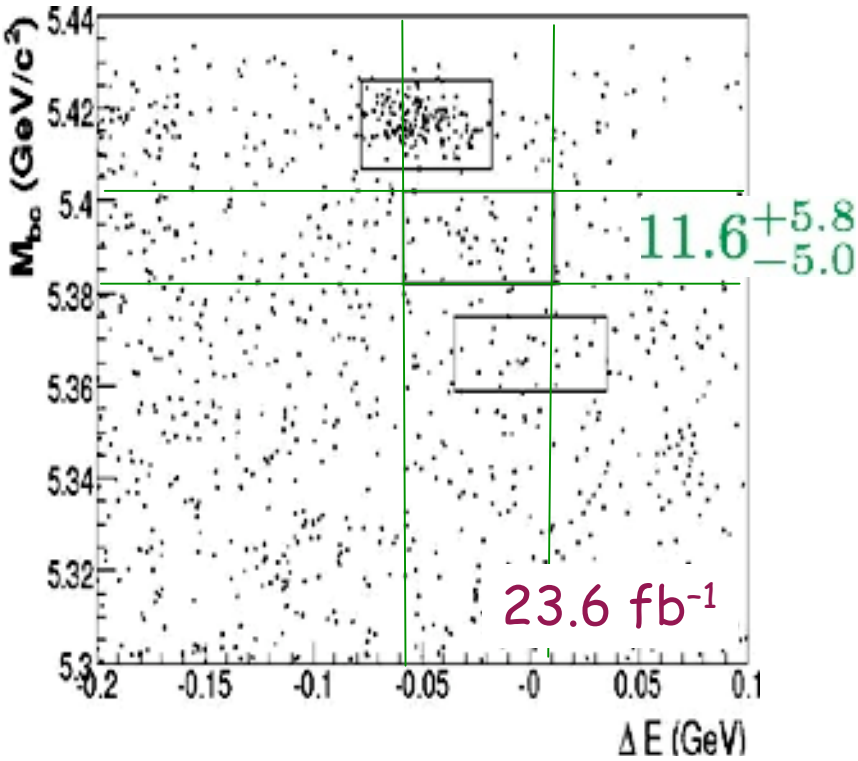
slice/projection



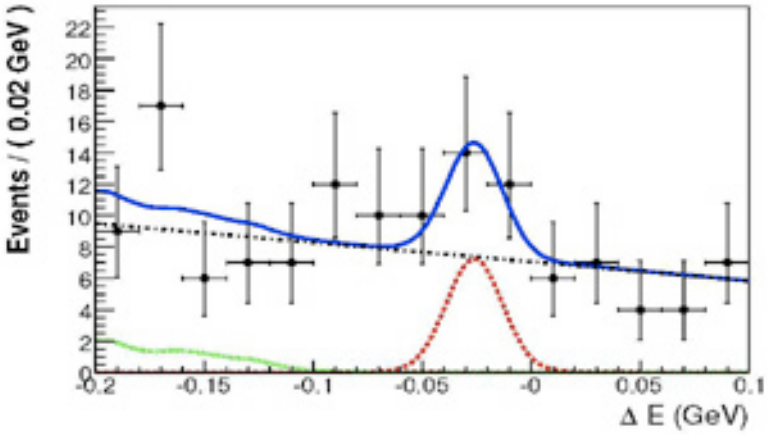
data $B_s \to D_s^- \pi^+$

$B_s^* B_s$



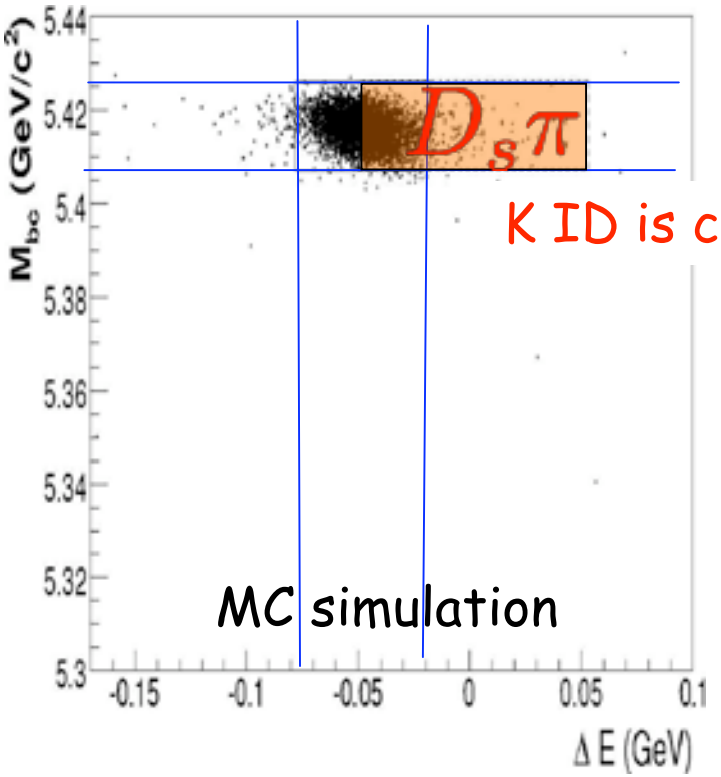


significance = 2.7σ



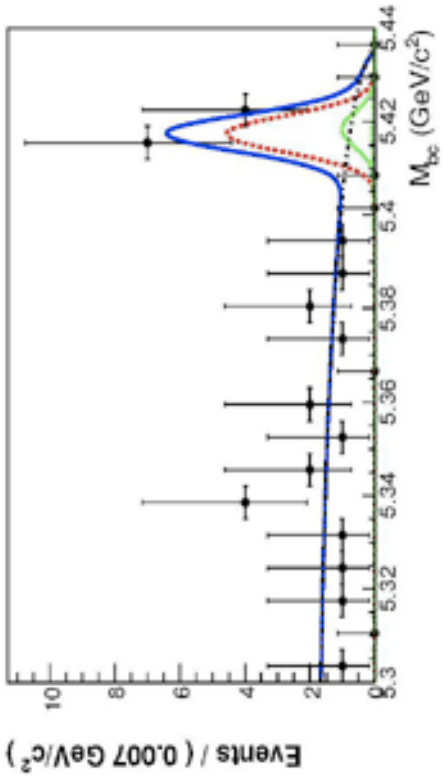
$B_s \to D_s^- K^+$

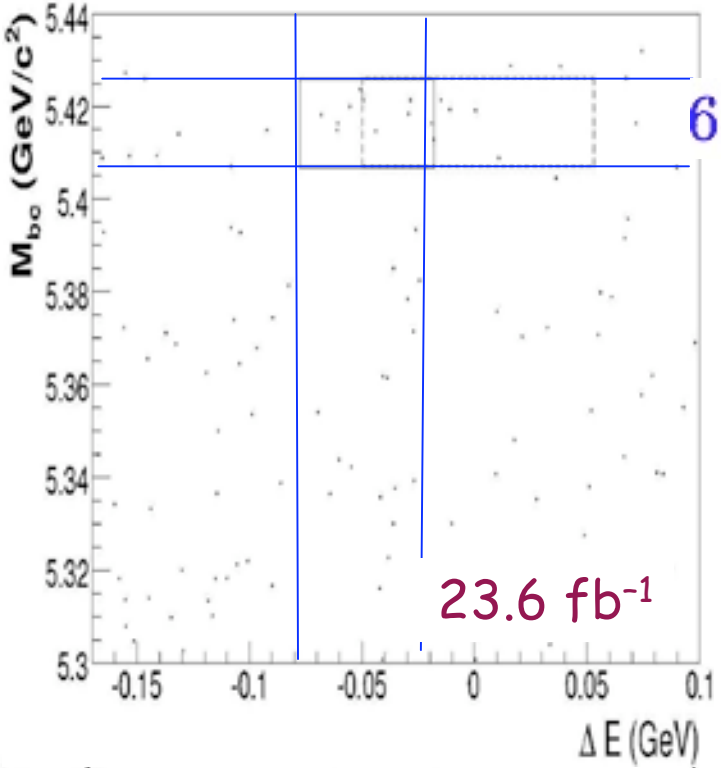
$B_s^* B_s^*$ only (statistics)



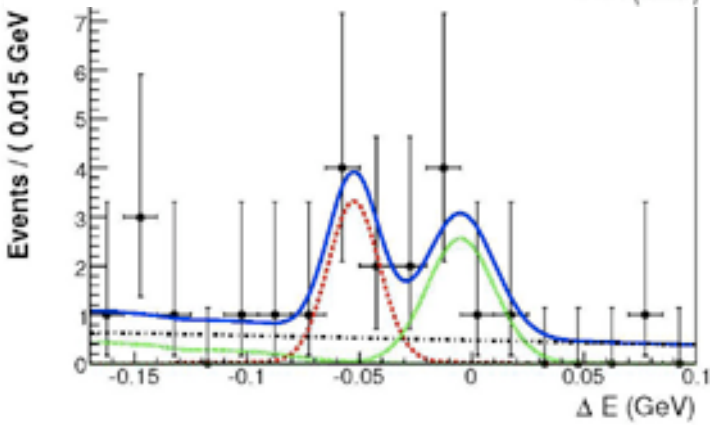
data $B_s \to D_s^- K^+$

$B_s^* B_s^*$





significance = 3.5σ



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

	Belle, 23.6 fb^{-1}	PDG
$\mathcal{B}(B_s \to D_s\pi)$	$(3.67^{+0.35+0.43}_{-0.33-0.42}) \times 10^{-3}$	$(3.0 \pm 0.7) \times 10^{-3}$
$f_{B_s^* B_s^*}$	$(90.3^{+3.8}_{-4.0} \pm 0.2)\%$	–
$f_{B_s^* B_s}$	$(7.2^{+3.3}_{-3.0} \pm 0.1)\%$	–
$f_{B_s B_s}$	$(2.5^{+2.6}_{-2.5})\%$	–
m_{B_s}	$(5364.6 \pm 1.3 \pm 0.7)$ MeV/c^2	(5366.1 ± 0.6) MeV/c^2
$m_{B_s^*}$	$(5417.6 \pm 0.4 \pm 0.5)$ MeV/c^2	(5412.0 ± 1.2) MeV/c^2
$\mathcal{B}(B_s \to D_s K)$	$[2.4^{+1.2}_{-1.0} \pm 0.3(\text{sys}) \pm 0.3(f_s)] \times 10^{-4}$	–
$\frac{\mathcal{B}(B_s \to D_s K)}{\mathcal{B}(B_s \to D_s \pi)}$	$[6.5^{+3.5}_{-2.9}]\%$	$(10.7 \pm 2.1)\%$

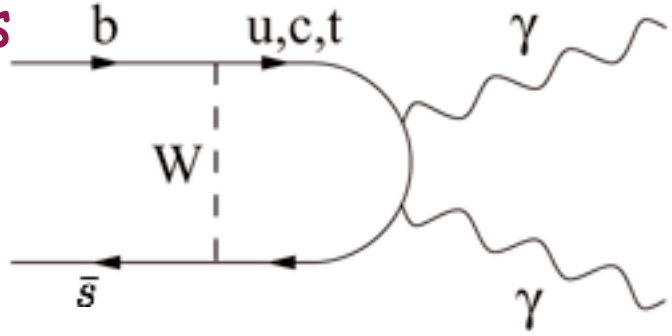
$$f_{B_s^* B_s^*} \equiv \frac{\sigma(e^+e^- \to B_s^* \bar{B}_s^*)}{\sigma(e^+e^- \to B_s^{(*)} \bar{B}_s^{(*)})} \qquad f_{B_s^* B_s} \equiv \frac{\sigma(e^+e^- \to B_s^* \bar{B}_s + B_s \bar{B}_s^*))}{\sigma(e^+e^- \to B_s^{(*)} \bar{B}_s^{(*)})}$$

Searches for radiative modes of B_s

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

Searches for new modes of B_s

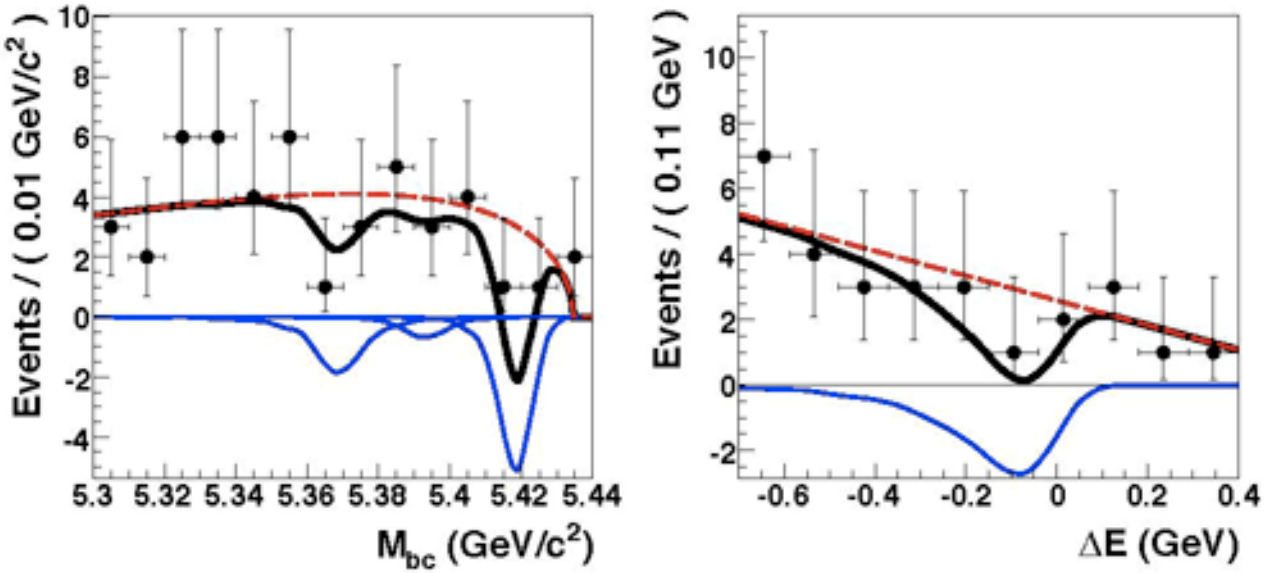
$\gamma\gamma$: difficult for hadron machines



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

beyond SM: up to 5×10^{-6}

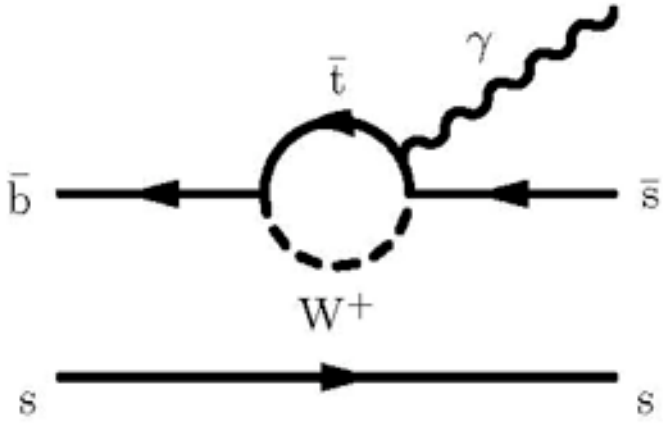
23.6 fb^{-1}



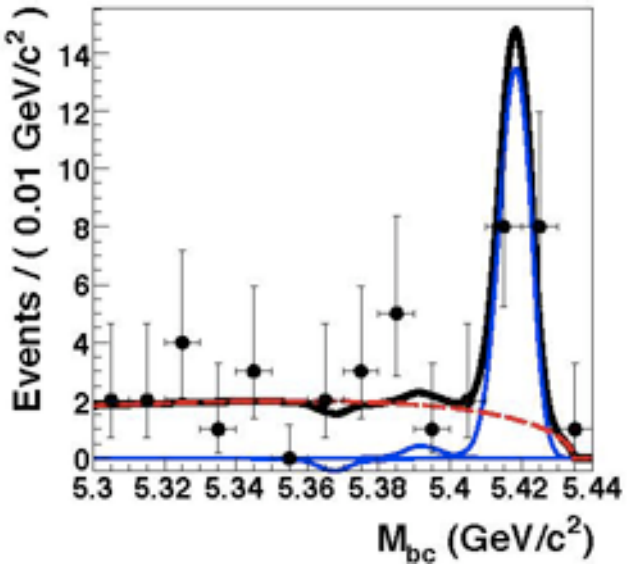
$\mathcal{B} < 8.7 \times 10^{-6}$ (90% CL) (prev. Belle: <5.3 x 10^{-5})

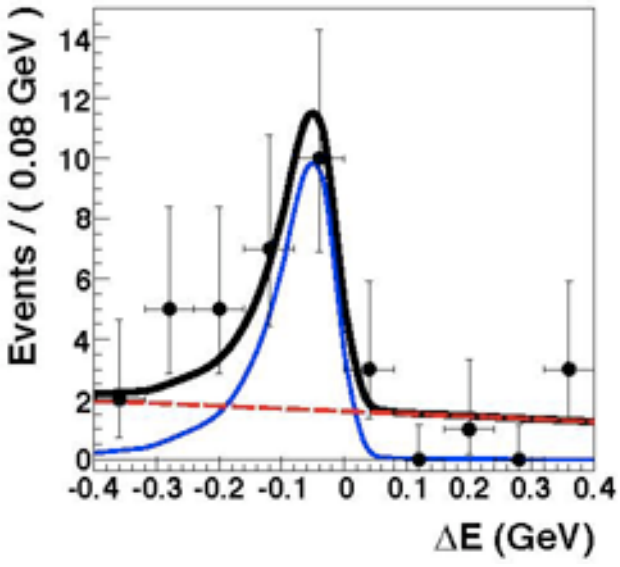
Searches for new modes of B_s

φγ



23.6 fb^{-1}





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

First observation

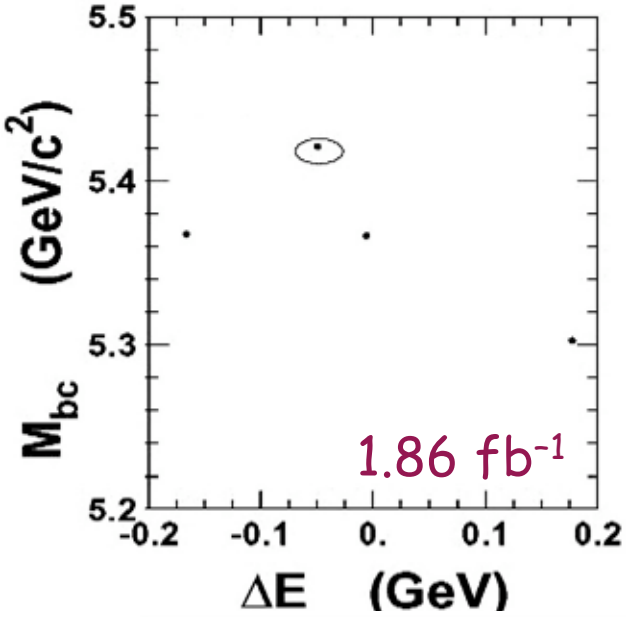
$$\frac{\Delta\Gamma_{CP}}{\Gamma} \; via \; \mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-})$$

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	6.7×10^{-2}	4
$D_s^{*+} D_s^-$	2.0×10^{-2}	1	12.1×10^{-2}	4
$D_s^{*+} D_s^{*-}$	1.9×10^{-2}	0	25.7×10^{-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!

Is the Y(10860) purely Y(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 MeV

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

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

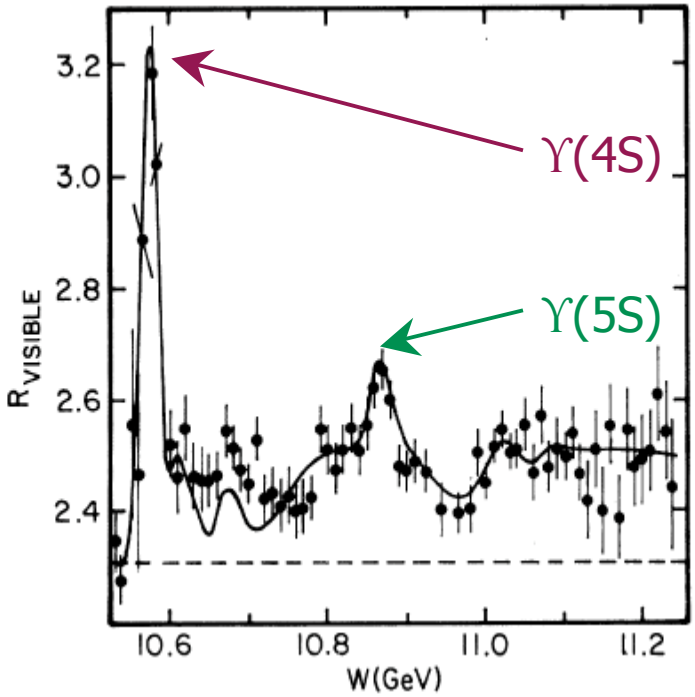
Others

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

+more - than predicted!

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)?



Does(do) analogous state(s) Y_b exist in Upsilon region?

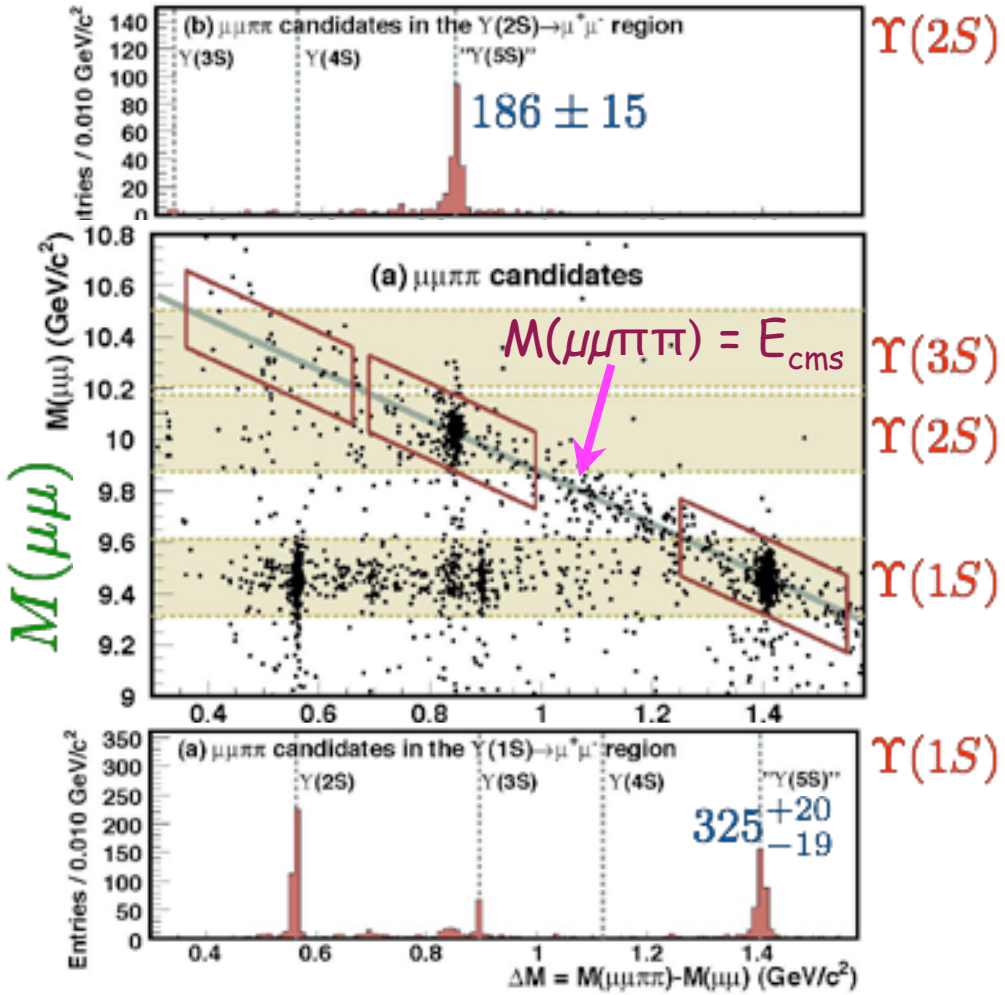
[W.S. Hou, PRD 74, 017504 (2006)]

Is the Υ(10860) purely Υ(5S)?

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

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

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



Is the Υ(10860) purely Υ(5S)?

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, search for anomalous $e^+e^- \to \Upsilon(nS)h^+h^-$

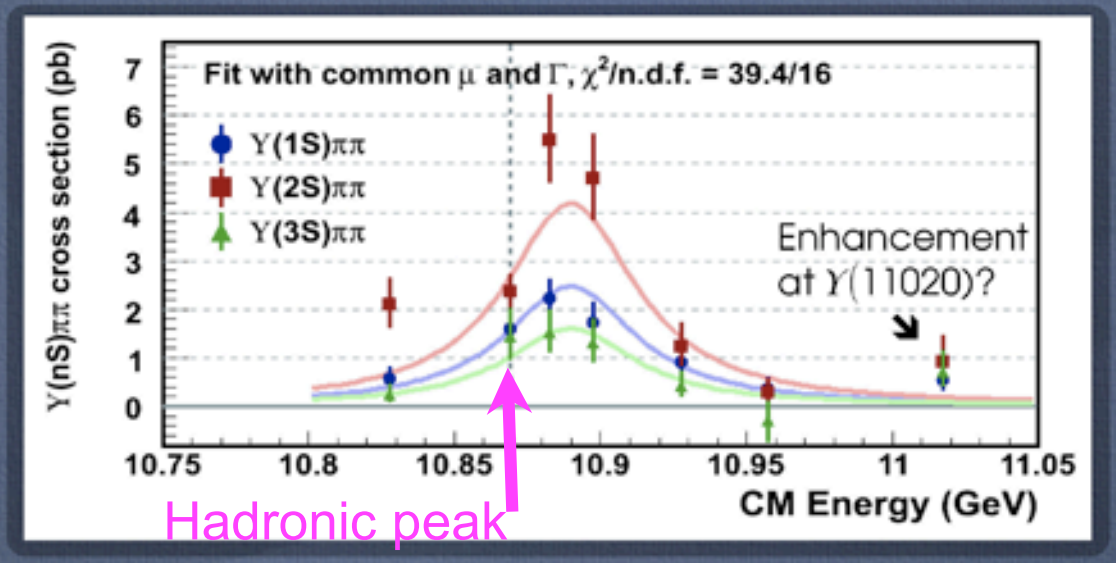
Followup: scan above $\Upsilon(5S)$

$\sqrt{s}(\mathrm{GeV})$	$\mathcal{L}(\mathrm{fb}^{-1})$
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 -> $D_s\pi$, evidence D_sK

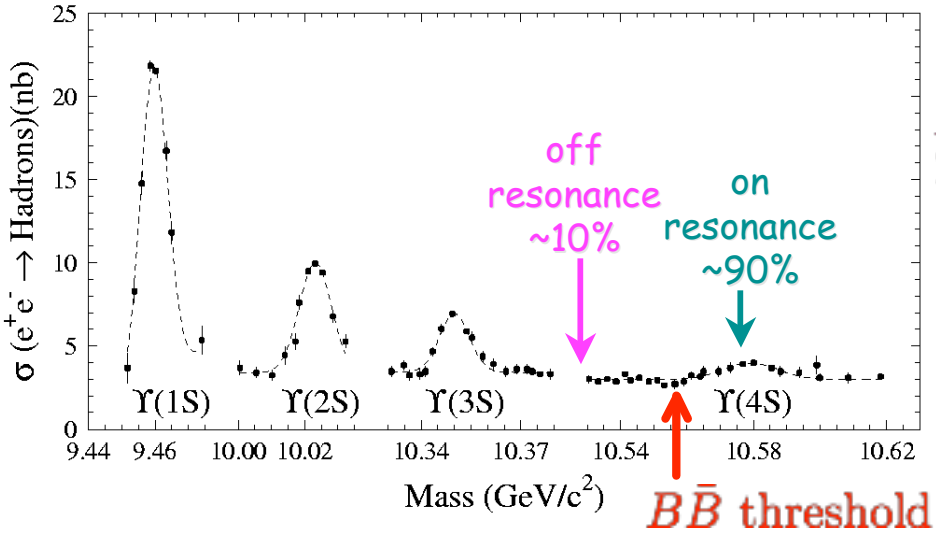
  $B_s^*B_s^*$ rate, masses of B_s^*, B_s

  best limit on B_s -> $\gamma\gamma$

  first observation of B_s -> $\phi\gamma$
- more to come ...

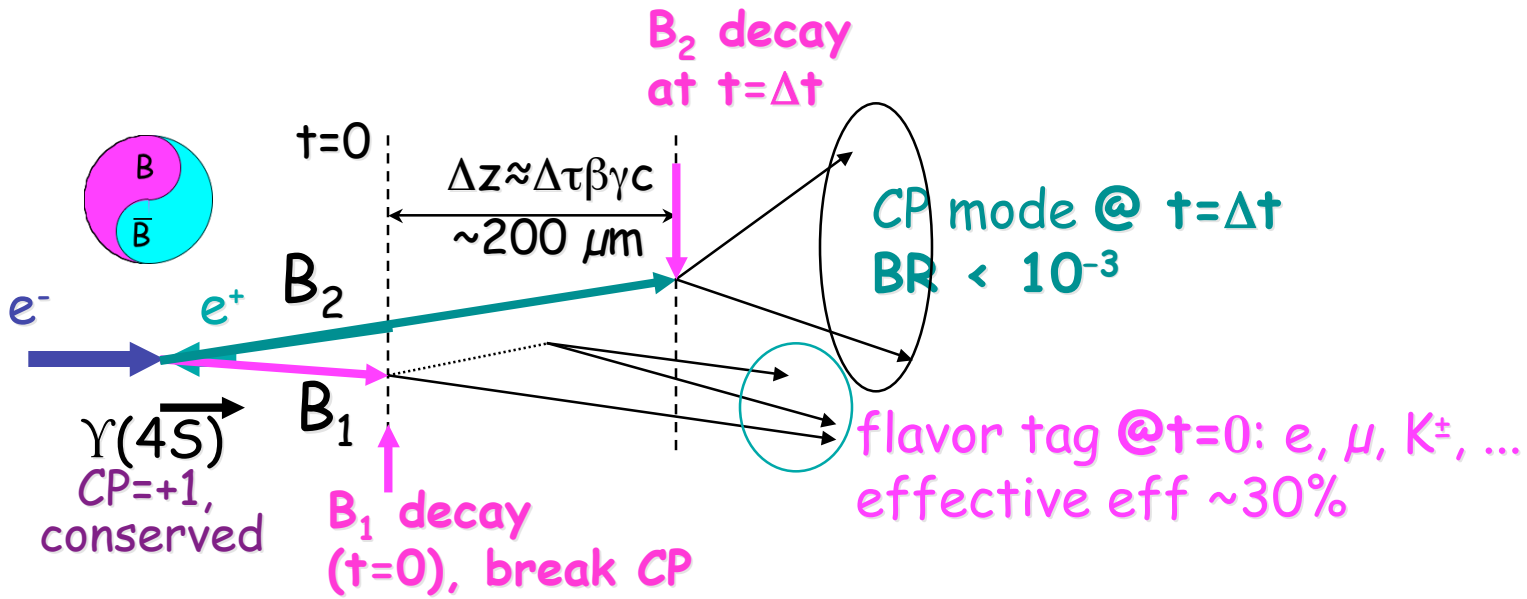
  October 2008, extended run -> ?? fb^{-1}

B factory: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



$$\frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1+\eta_b\eta_{CP}\sin 2\phi_1 \sin(\Delta m\Delta t))$$

Δt by asymmetric energy e^+e^- ->Υ(4S)
(symmetric Υ(4S): CLEO 1979-2001)



… 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 $V_{ji}^* V_{jk} = \delta_{ik}$

for {i=1,k=3}

$$\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} = 0$$

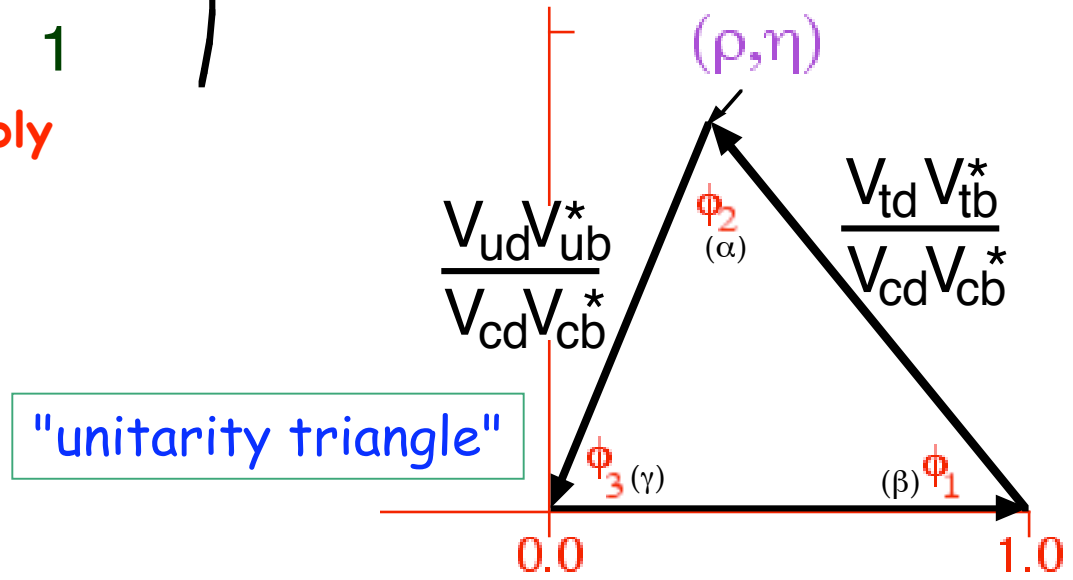
$$\downarrow \qquad\qquad \downarrow$$

$$-(\rho+i\eta) \qquad -(1-\rho-i\eta)$$

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



"unitarity triangle"