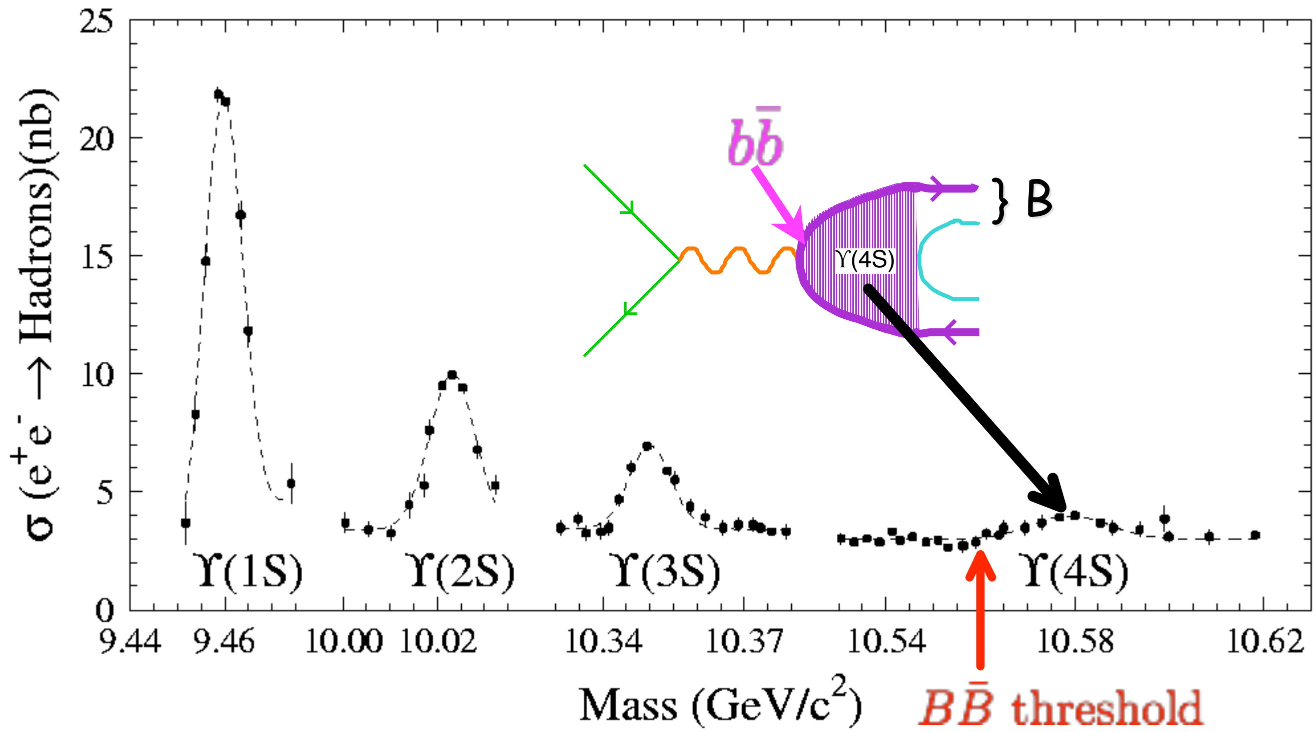
Iowa State University, April 25, 2007

Belle and the Beast: Strange Beauty at the $\Upsilon(5S)$ Resonance

- B-factory and $\Upsilon(4S)$ Resonance
- $\Upsilon(5S)$ Resonance and B_s
  - motivation
  - Belle data
  - prospects

Kay Kinoshita
University of Cincinnati
Belle Collaboration

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



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

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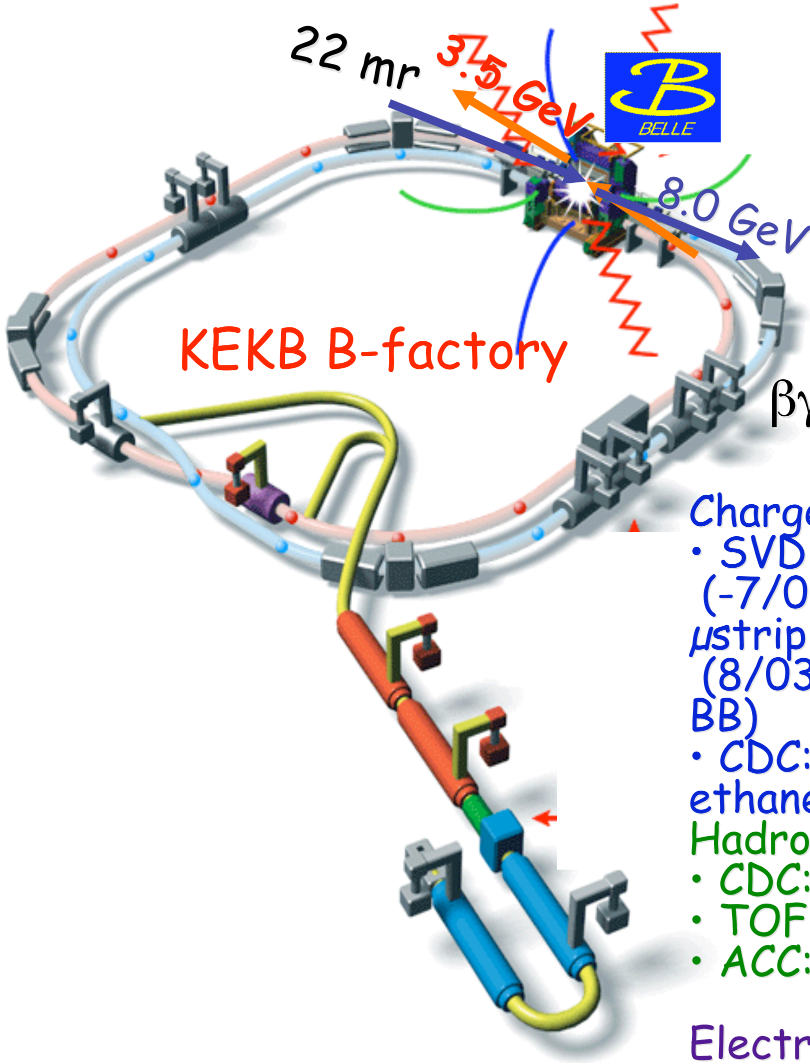
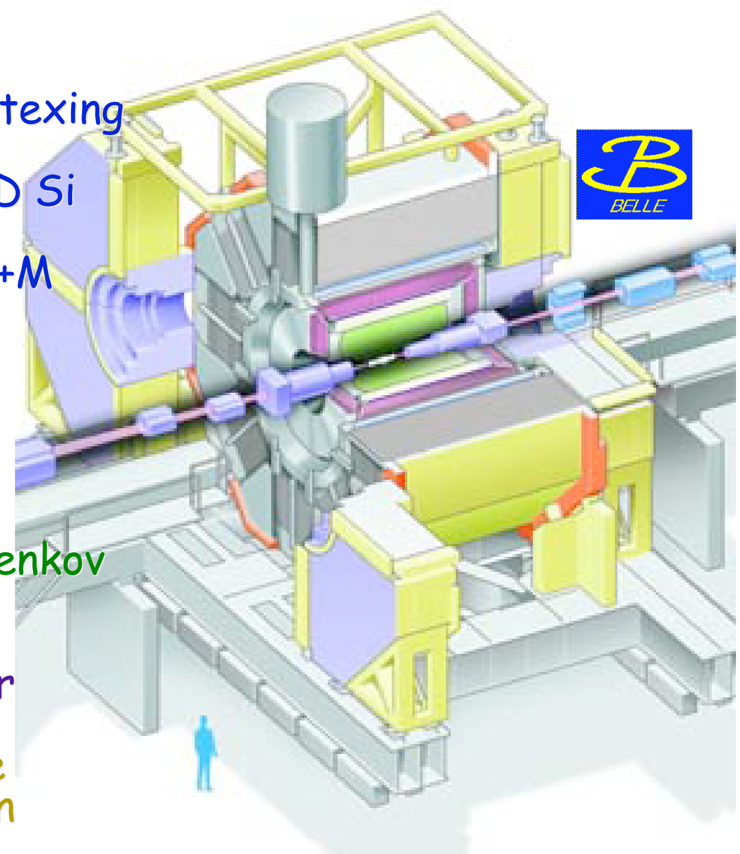
the hardware



- L_{max} = 1.71 X 10^{34} $cm^{-2}s^{-1}$ (world record)
- Data (6/1999–3/2007)
- $\int Ldt$ = 710 fb^{-1}@{$\Upsilon(4S)$+off(~10%)}
- (>7.1x10^8 B events)
- $\int Ldt$ = 24.6 fb^{-1}@$\Upsilon(5S)$

$\beta\gamma = 0.425$

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 Čerenkov (aerogel)
Electron/photon
• ECL: CsI calorimeter
Muon/K_L
• KLM: Resistive plate counter/iron



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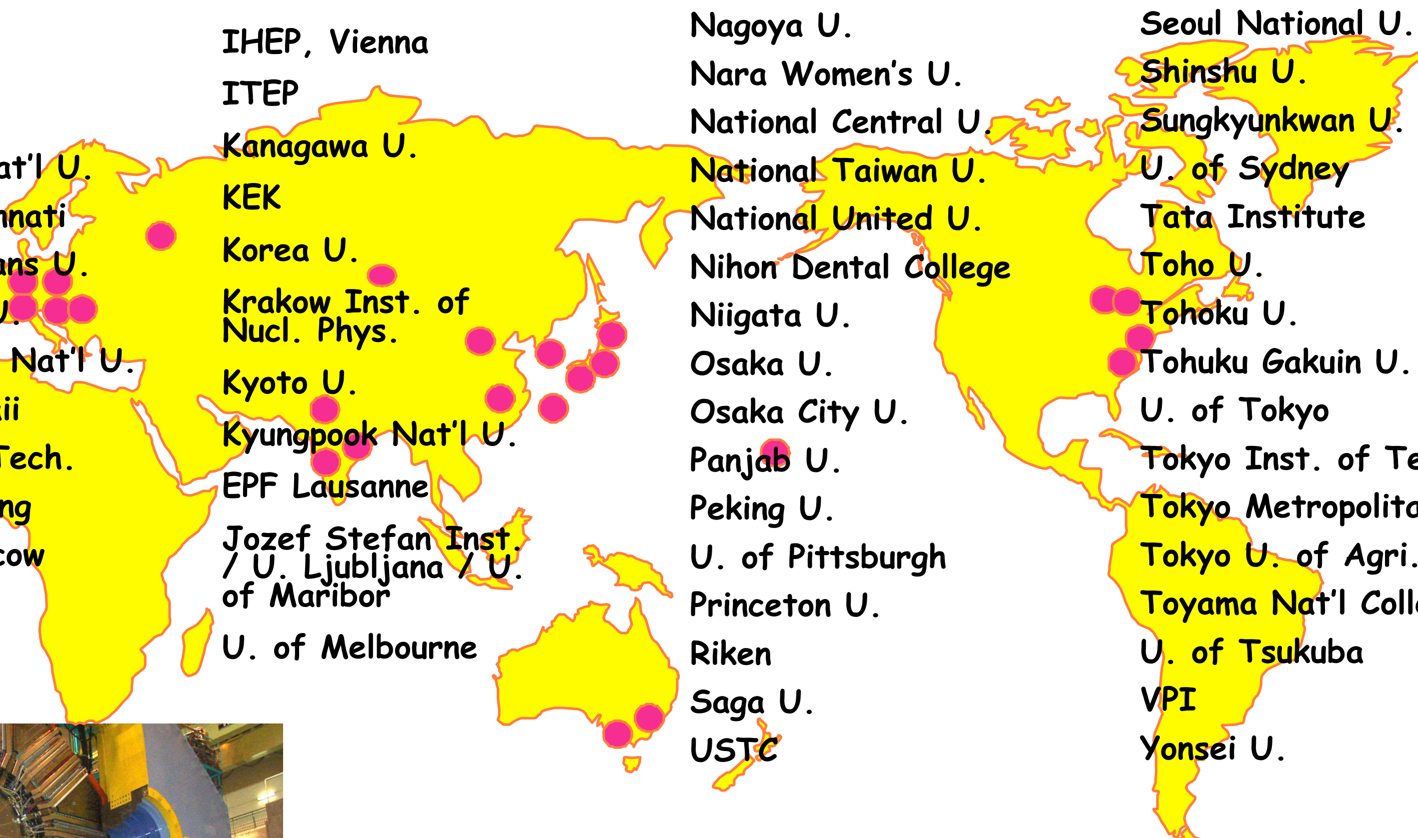
… the people



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Chiba U.
Chonnam Nat'l U.
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Ewha Womans U.
Frankfurt U.
Gyeongsang Nat'l U.
U. of Hawaii
Hiroshima Tech.
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Tokyo U. of Agri. and Tech.
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U. of Tsukuba
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Yonsei U.

~13 countries, 55 institutes, ~400 collaborators

(authors vary, each paper)

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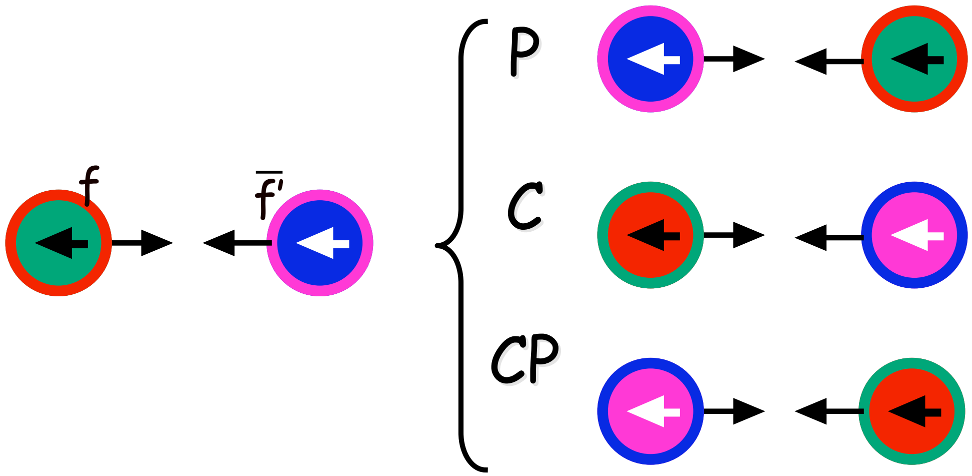
CP Violation & weak force

Weak force: under symmetry operations



violated maximally

" "

conserved (mostly)

How can an interaction violate CP?

Complex coupling constant

$$CP\{\, f \xrightarrow{\;g\;} f' \,\} = \bar{f}' \xleftarrow{\;g\;} \bar{f} \neq \bar{f}' \xleftarrow{\;g^*\;} \bar{f}$$ (hermitian conjugate)

Why is CP violation of interest?

- matter-antimatter asymmetry requires CP-violating interactions (Sakharov 1967)

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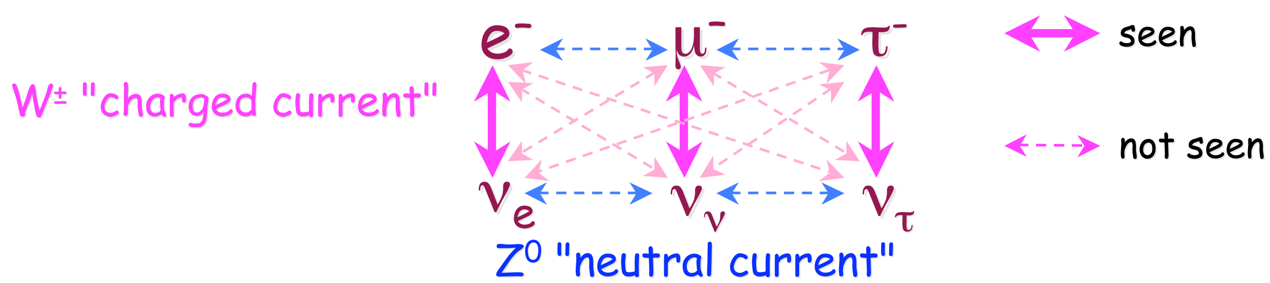
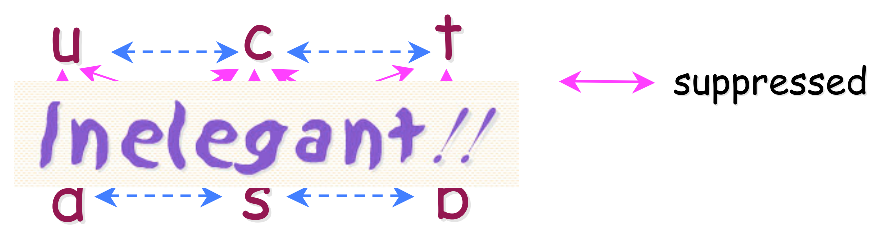
Flavor & the weak force

Standard Model = 12 fermion flavors (+antifermion)

- 3 generations(distinguished only by mass)x2 typesx2 ea(strong & EM couplings) (stable, but for weak interaction)
- leptons: ~universal coupling, no generation x-ing



- quarks: neutral current – ~universal, no generation x-ing
- quarks: charged current – all different, approx. generation-conserving



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Elegance Restored

Picture {matrix of couplings} is universal & generation-conserving

$$g_F \times \begin{array}{c|ccc} & d & s & b \\ \hline u & & & \\ c & & & \\ t & & & \end{array}$$

$$g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{matrix} d & s & b \end{matrix} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array} \qquad g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{matrix} d' & s' & b' \end{matrix} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

- d', s', b' are eigenstates resulting from perturbation by weak interaction, ≠ 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

$$\left.\begin{array}{r} \text{complex} \\ \text{preserves metric} \\ \text{" orthogonality} \end{array}\right\} \equiv \text{unitary}$$

GIM (Glashow-Iliopoulos-Maiani) mechanism *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:

Unitarity conditions $V_{ji}^{*}V_{jk}=\delta_{ik}$ -> 3 real + 1 imaginary free parameters

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! -> *CP violating*

(Kobayashi-Maskawa 1973)

First 3rd-generation particle (τ) observed 1975

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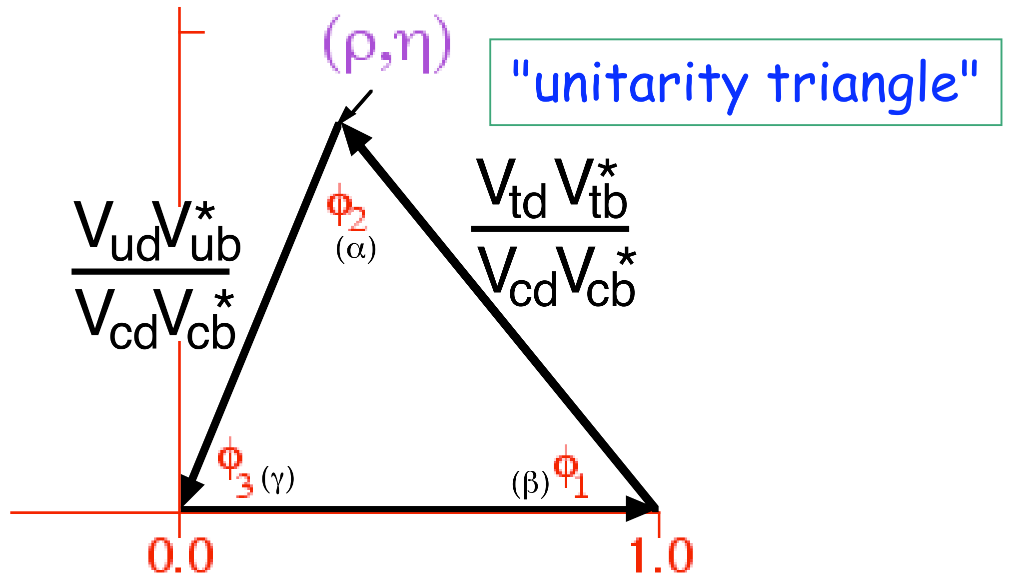
Unitarity

Unitarity condition for {i=1,k=3} $V_{ub}{}^*V_{ud}+V_{cb}{}^*V_{cd}+V_{tb}{}^*V_{td}=0$

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

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



B-factories test self-consistency of UT

- fully constrained by 3 of {3 angles, 3 sides} **==> overconstrain**

Inconsistency -> New Physics

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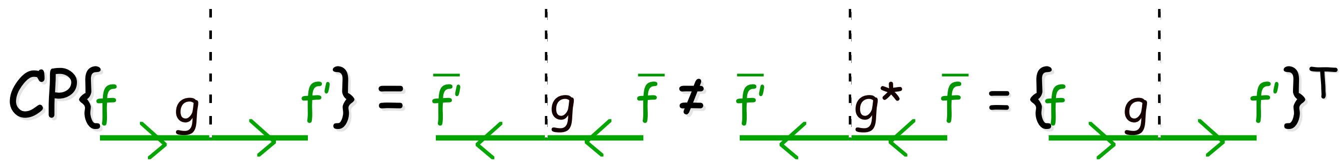
Observing CP asymmetry

Complex coupling constant is CP-violating



BUT to observe CP asym, need 2+ interfering amplitudes {T,P}:

$T=gA, P=g'A' \rightarrow |gA+g'A'| \xrightarrow{CP} |gA^*+g'A'^*|$

Equal only if relative phase of g,g'=0

AND for irreducibly complex weak coupling in CKM, need process w. all 3 generations

===>>> B Decays ===>>>

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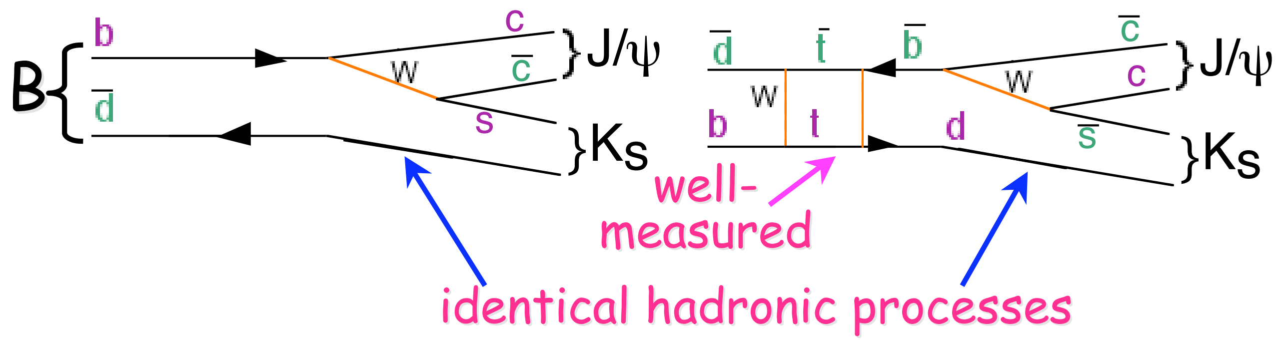
CP asymmetry in B decay: example

B -> $J/\psi\ K_s$ (Sanda/Bigi/Carter)

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

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

$\propto V_{tb}^{*2}V_{td}^{2}V_{cb}V_{cs}^{*}$



Bottom line: CP-dependent oscillation in time from x-term(s)

- no theoretical uncertainty: $\arg(V_{td}^2) = 2\varphi_1$ ← β

$$\frac{dN}{dt}(B \to f_{CP}) = \frac{1}{2}\Gamma e^{-\Gamma\Delta t}(1 + \eta_b\eta_{CP}\sin 2\phi_1 \sin(\Delta m\Delta t));$$

$$\eta_b = \begin{pmatrix} +1 \text{ if } B_{t=0} = B^0 \\ -1 \text{ if } B_{t=0} = \bar{B}^0 \end{pmatrix} \quad \eta_{CP} = \begin{pmatrix} -1 \text{ if } CP\ odd \\ +1 \text{ if } CP\ even \end{pmatrix}$$

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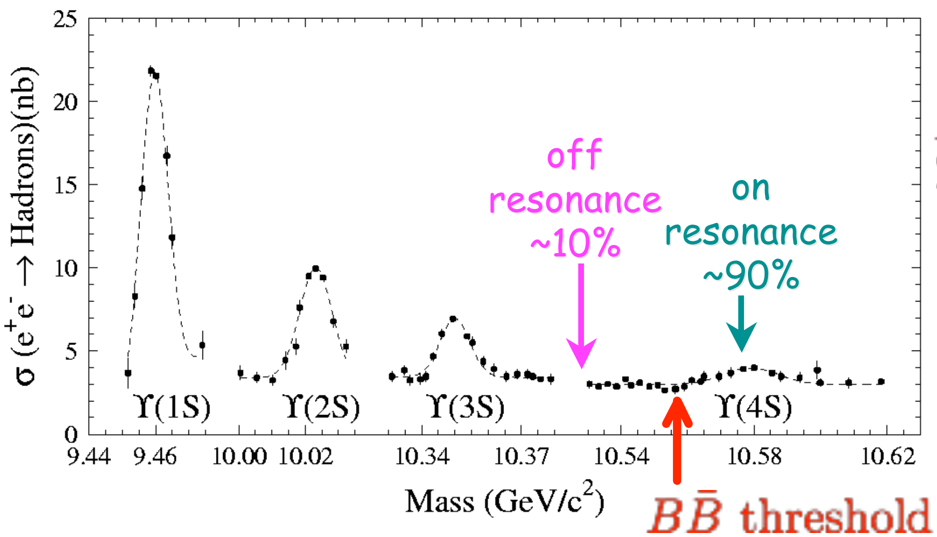
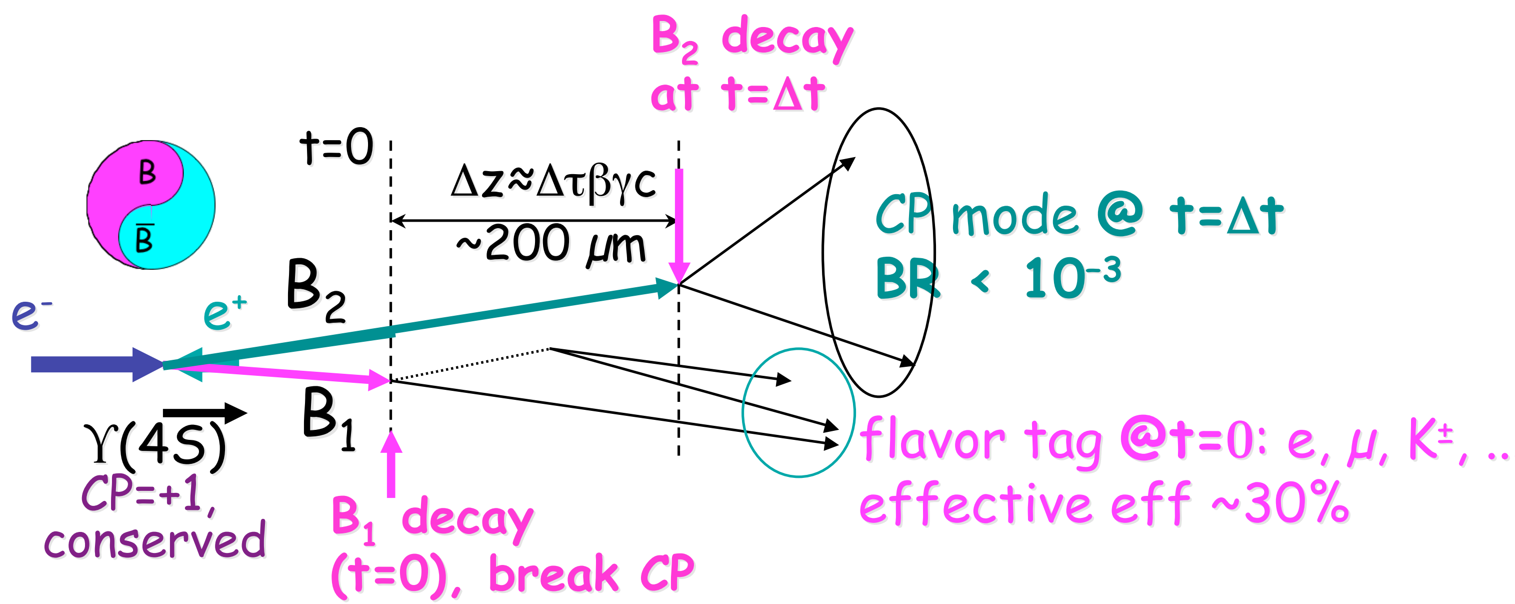
B factory: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



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

Δt by asymmetric energy $e^+e^- \to \Upsilon(4S)$

(symmetric $\Upsilon(4S)$: CLEO 1979-2001)



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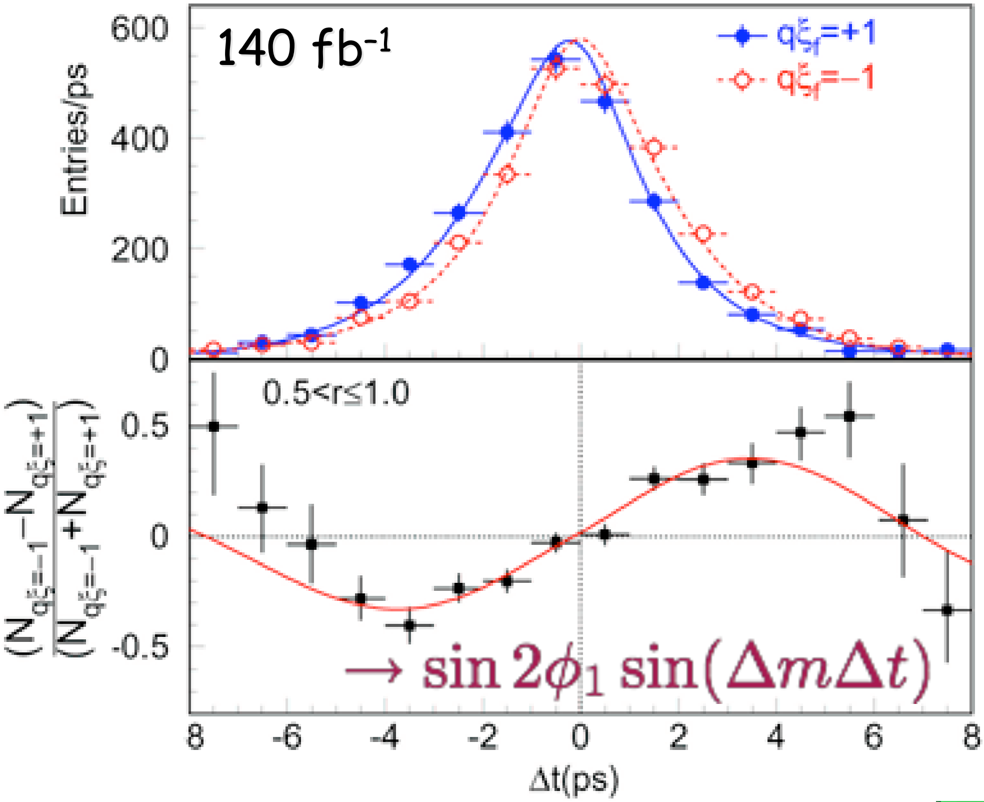
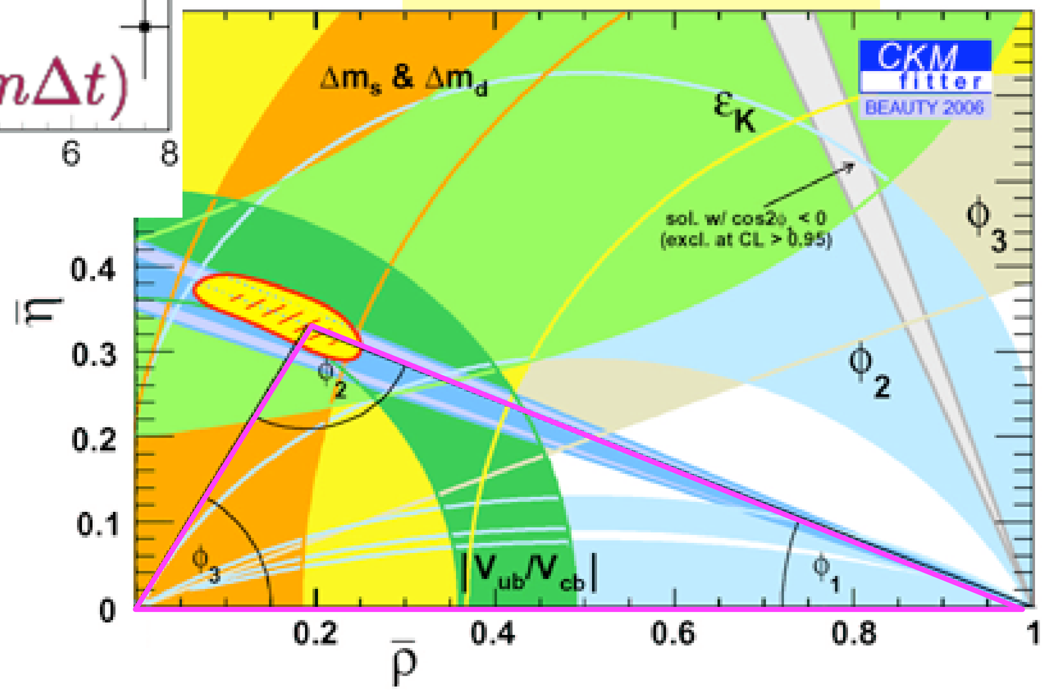
CP asymmetry



$\sin2\phi_1 = 0.728 \pm 0.056 \pm 0.023$

PRD 71, 072003 (2005)

world average:
$\sin2\phi_1 = 0.726 \pm 0.037$



Belle physics

208±5 papers published or in press (#1 in 3/2001)

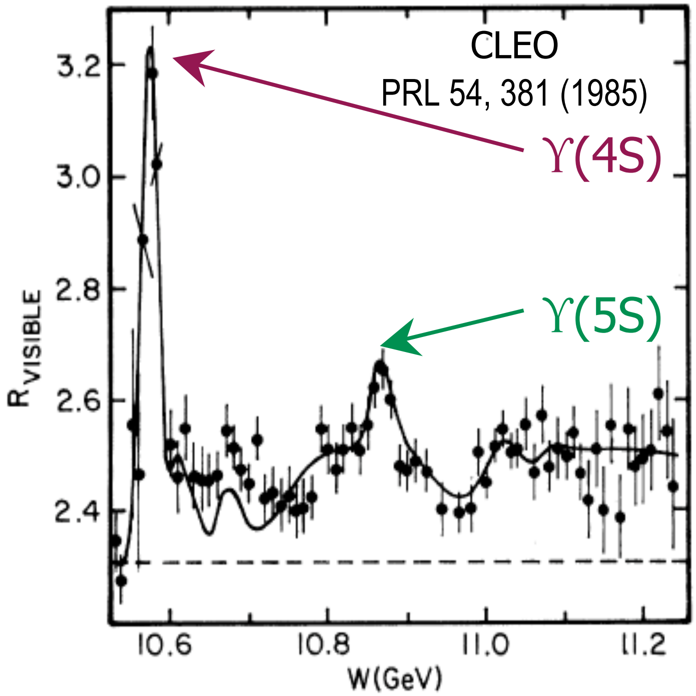
(CP asymmetry in B decay, other B decay, charm, tau, 2-photon)

Recent highlights

- evidence for D^0 mixing
- quantum entanglement (EPR)
- new charmonium-like states Y(3940), X(3872)

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

Looking to the future: $\Upsilon(5S)$ Resonance



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

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

M=10580±1 MeV/c^2, 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/c^2, Γ=110±13 MeV

Can we (competitively) study B_s at the $\Upsilon(5S)$? (FNAL, LHC)

Maybe...

- exclusive B pair events (quantum coherence), high trigger eff, clean γ's
- B-factory: high luminosity, established detector

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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
- Similarity/difference w (non-strange) B

  -> quark-hadron duality,

  fine-tune hadronic models
- Υ(5S) spectroscopy:

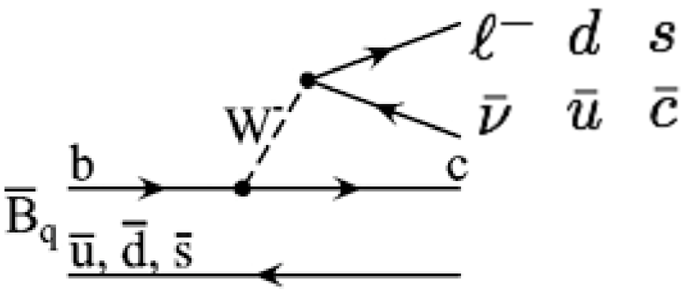
  $B_{(s)}$ event fractions (needed to evaluate prospects for B_s)

  $B_s^{(*)}$ mass

B_s decays: outline

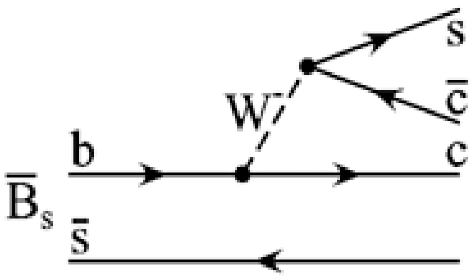
Similarity w $B_{u,d}$

- 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



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

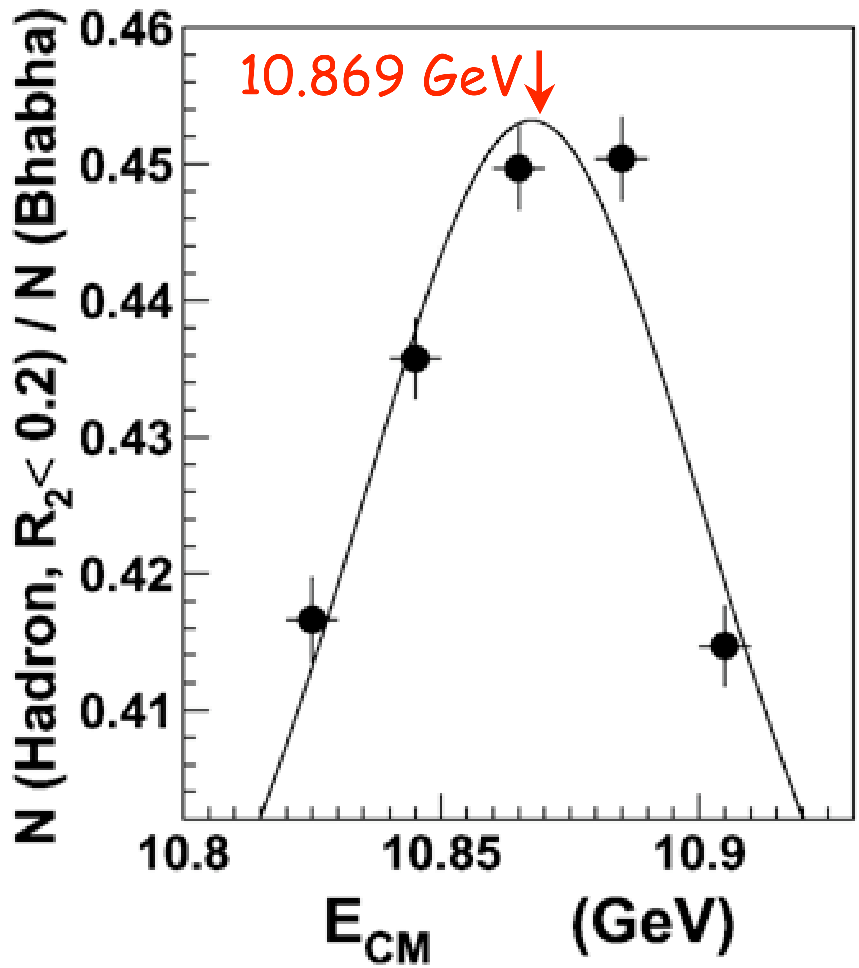
Aleksan, Dunietz, Kayser Z. Phys., C54, 653 (1992)

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)

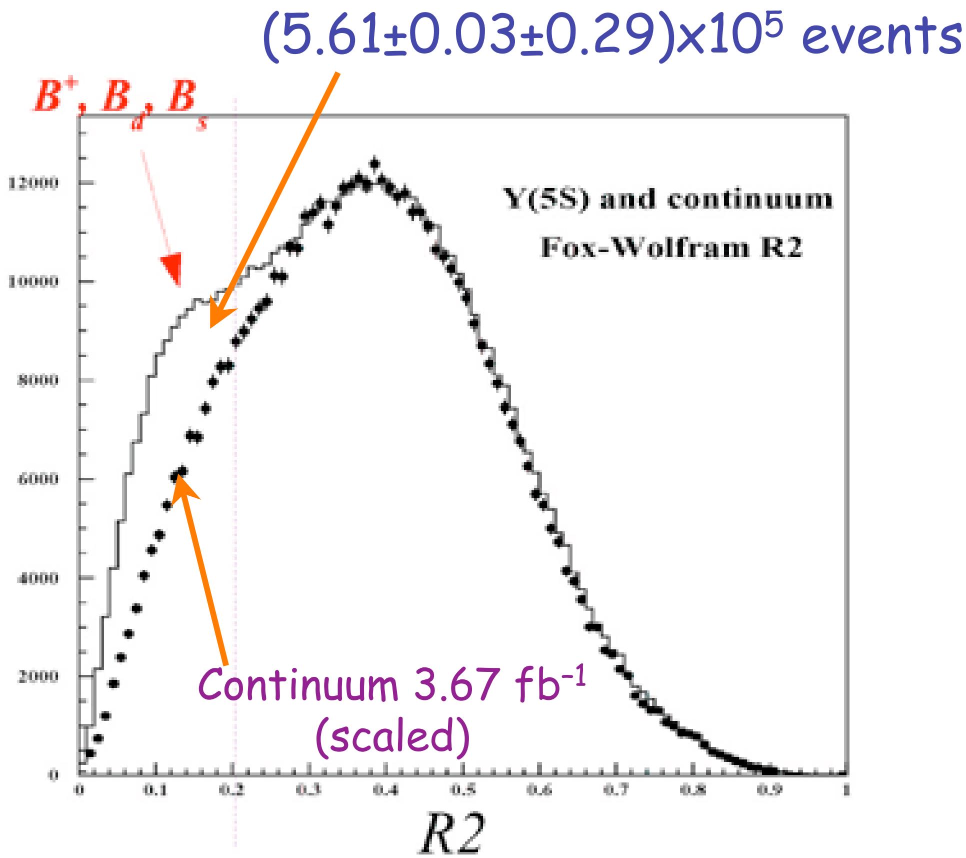
A. Drutskoy et al., PRL 98, 052001 (2007)
A. Drutskoy et al., hep-ex/0610003 submitted to PRD



June 2006: 20-day run

- 21.7 fb^{-1} on resonance
- data analysis starting

Event count in 1.86 fb^{-1}



Event shape parameter
(Fox-Wolfram moments)

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

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

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

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

inclusive D_s production

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

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

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

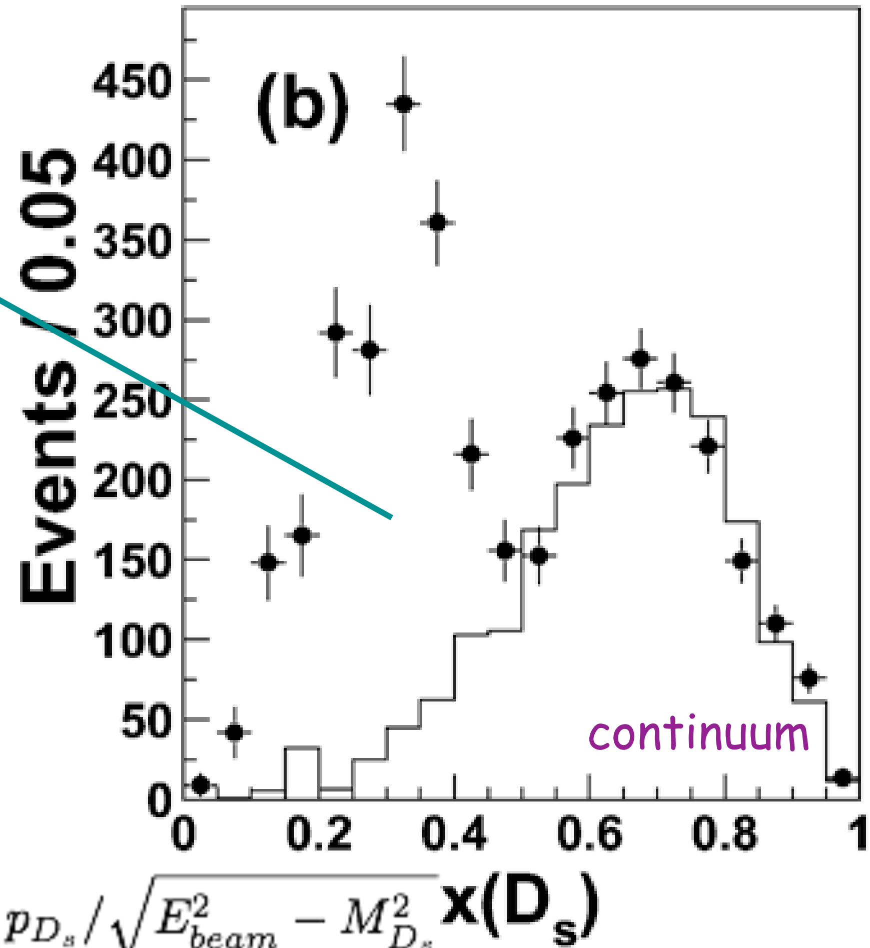
$(23.6 \pm 1.2 \pm 3.6)\%$

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

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

combined:

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



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

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

Readily reconstructed CKM-favored modes

$$D_s^-\pi^+,\ D_s^-\rho^+,\ D_s^{*-}\pi^+,\ D_s^{*-}\rho^+,\ J/\psi\phi,\ J/\psi\eta$$

Full reconstruction of B_s:

$$D_s^{*-} \to D_s^-\gamma \qquad D_s^- \to \phi\pi^-,\ K^{*0}K^-,\ K_S^0K^-$$

$$\phi \to K^+K^-,\ K^{*0} \to K^+K^-,\ K_S^0 \to \pi^+\pi^-$$

$$J/\psi \to \mu^+\mu^-,\ e^+e^-$$

$$\rho^+ \to \pi^+\pi^0,\ \pi^0 \to \gamma\gamma,\ \eta \to \gamma\gamma$$

Not reconstructed: $B_s^* \to B_s\gamma$

-> B_s candidate E_{cand}, p_{cand} in cms of e^+e^-

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

Candidate reconstruction: energy, momentum of B_s at $\Upsilon(5S)$

$B_s\bar{B}_s$

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

-> Reconstruct candidates with

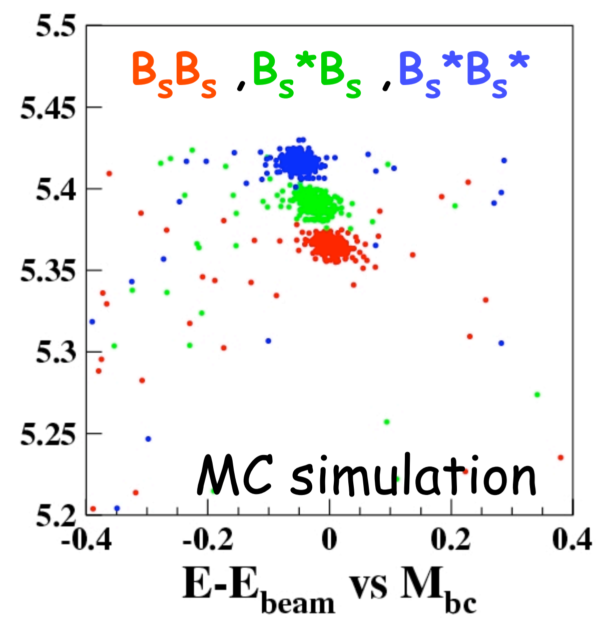
$$\Delta E \equiv E_{cand} - E_{beam} \qquad M_{\rm bc} \equiv \sqrt{E_{beam}^2 - p_{cand}^2}$$

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

B_s energy is lower by $E_\gamma/2$ (~25, ~50) MeV

-> ΔE lower, M_{bc} higher

Resolution does not change much



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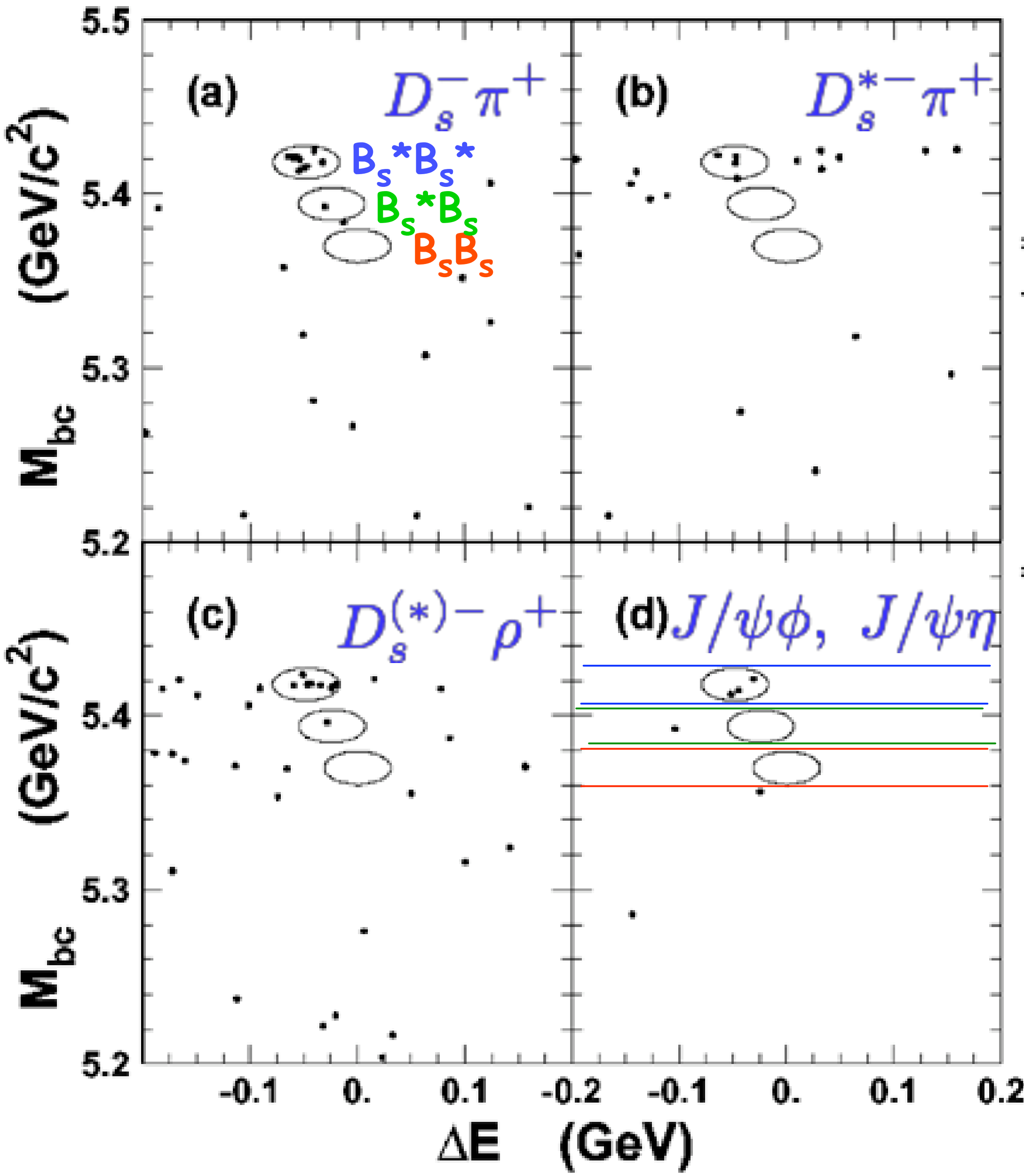
B_s candidates in 1.86 fb^{-1}



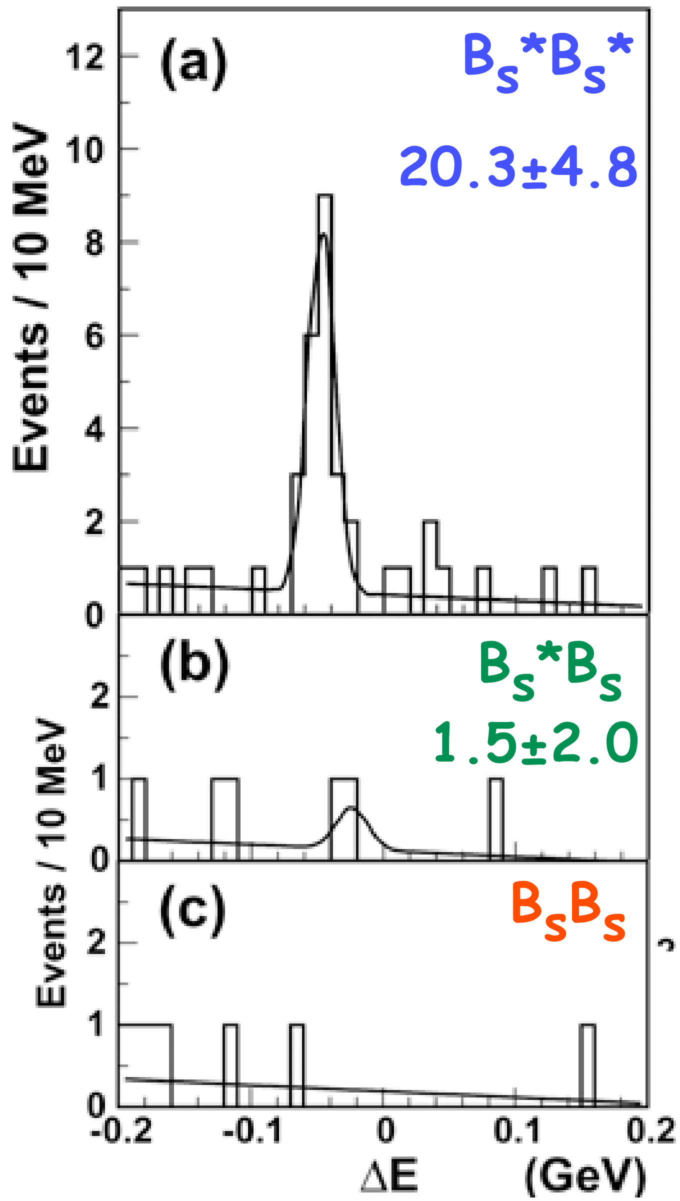
$B_s{}^*B_s{}^*$ dominates

$B_s{}^*B_s{}^*$ signal region

Decay mode $D_s^- \to$	$\phi\pi^-$	$K^{*0}K^-$	$K_S^0 K^-$	Sum
$B_s^0 \to D_s^- \pi^+$	4	2	3	9
$B_s^0 \to D_s^{*-} \pi^+$	2	1	1	4
$B_s^0 \to D_s^- \rho^+$	2	1	0	3
$B_s^0 \to D_s^{*-} \rho^+$	2	2	0	4
$B_s^0 \to J/\psi\phi$				2
$B_s^0 \to J/\psi\eta$				1

Fit ΔE in M_{bc} signal bands

B_s candidates in 1.86 fb^{-1}



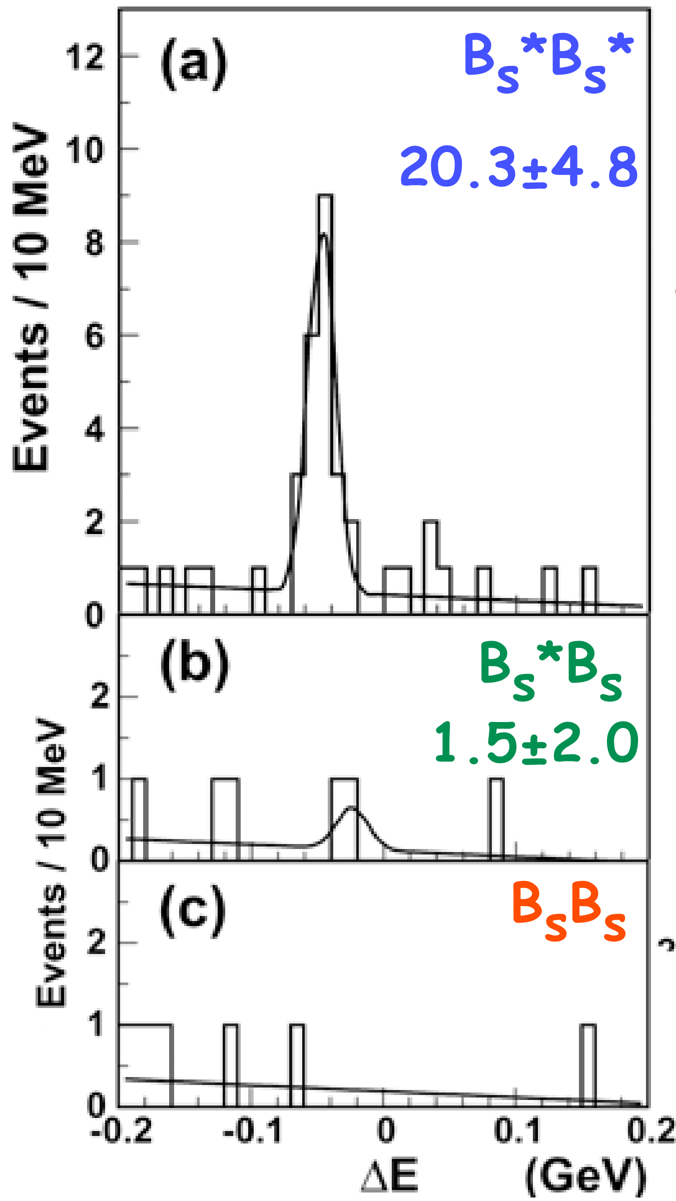
Combine 6 modes

$B_s^*B_s^*$ signal region

Decay mode $D_s^- \to$	$\phi\pi^-$	$K^{*0}K^-$	$K_S^0K^-$	Sum
$B_s^0 \to D_s^-\pi^+$	4	2	3	9
$B_s^0 \to D_s^{*-}\pi^+$	2	1	1	4
$B_s^0 \to D_s^-\rho^+$	2	1	0	3
$B_s^0 \to D_s^{*-}\rho^+$	2	2	0	4
$B_s^0 \to J/\psi\phi$				2
$B_s^0 \to J/\psi\eta$				1

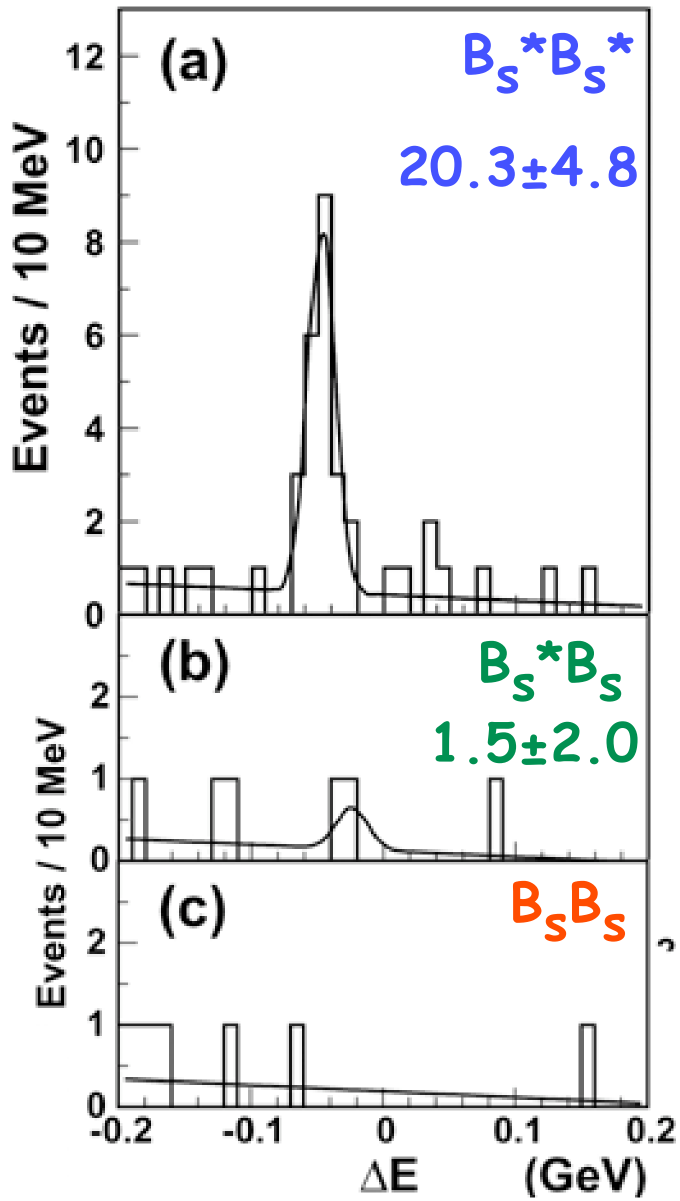
Fit ΔE in M_{bc} signal bands

B_s candidates in 1.86 fb^{-1}



$$\frac{\sigma(e^+e^- \to B_s^* \bar{B}_s^*)}{\sigma(e^+e^- \to B_s^{(*)} \bar{B}_s^{(*)})} = (93^{+7}_{-9} \pm 1)\%$$

$B_s^{(*)}$ mass



Reconstructing B_s candidates:

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

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

in $B_s^*B_s^*$ event, $\langle p_{Bs} \rangle = p_{B^*}$

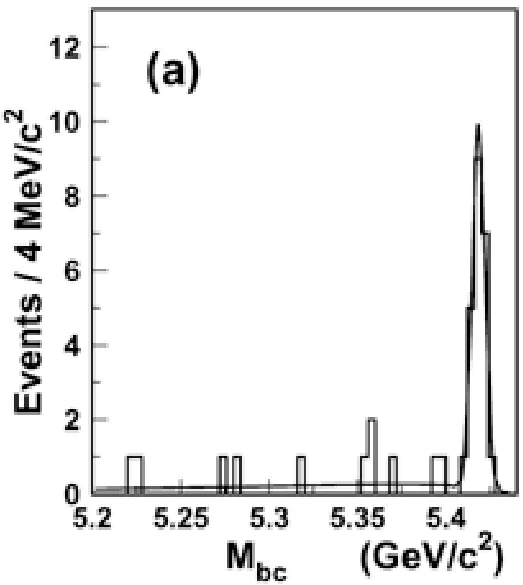
$$\Rightarrow M_{B_s^*} = \langle M_{\rm bc} \rangle$$

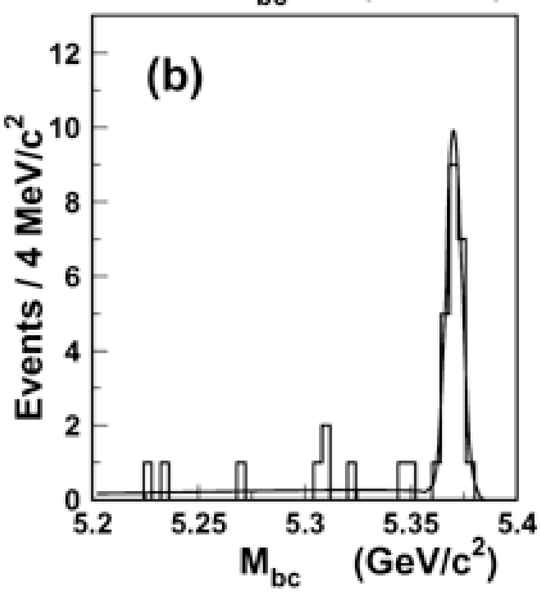
in $B_s^*B_s^*$ event, $\langle E_{Bs} \rangle = E_{beam} - \langle \Delta E \rangle$

$$\Rightarrow M_{B_s}$$

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

$B_s^{(*)}$ mass





Reconstructing B_s candidates:

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

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

in $B_s^*B_s^*$ event, $\langle p_{Bs}\rangle = p_{B*}$

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

$=(5411.7\pm1.6\pm0.6)$ Mev/c^2

in $B_s^*B_s^*$ event, $\langle E_{Bs}\rangle = E_{beam} - \langle\Delta E\rangle$

$$\Rightarrow M_{B_s}$$

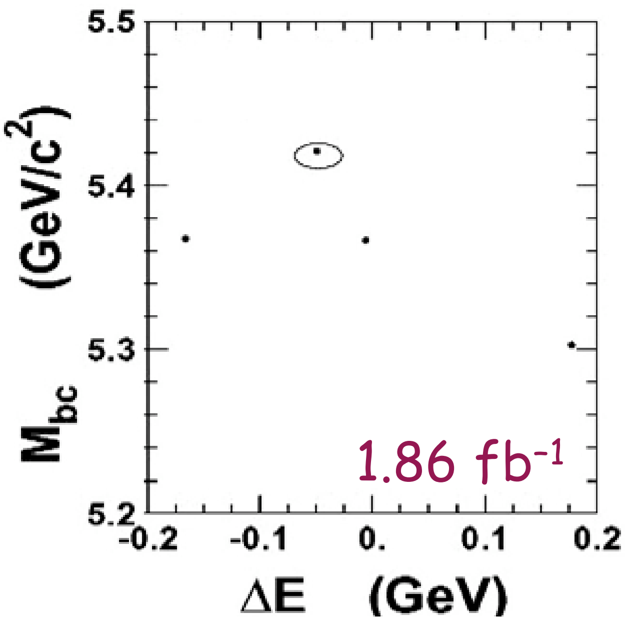
$$= \left\langle \sqrt{(E_{beam} - \langle\Delta E\rangle)^2 - p_{cand}^2} \right\rangle$$

$=(5370\pm1\pm3)$ Mev/c^2

Searches for new modes

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

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



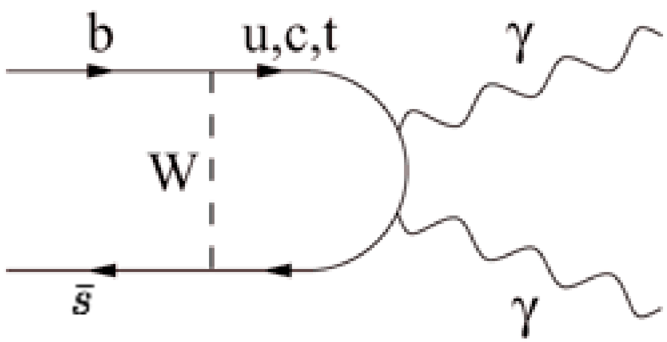
Analyze 3 modes together; little background
-> 2006 data: ±30%(stat), (small sys. err.)

CDF 2007:

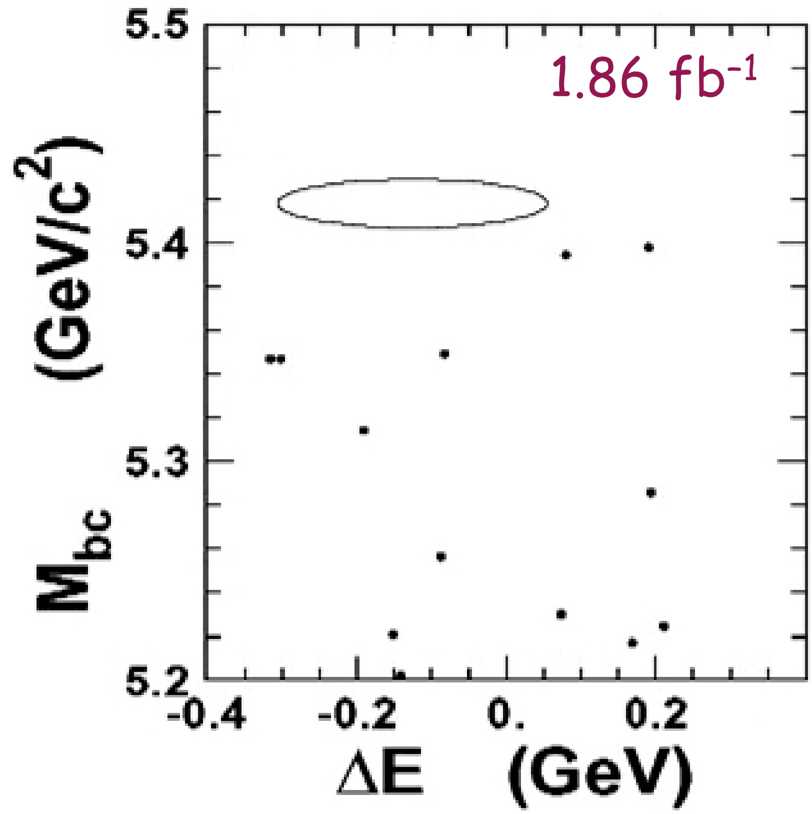
$\mathcal{B}(B_s \to D_s^+ D_s^-) = (1.09 \pm 0.27 \pm 0.47)\%$

	$\mathcal{B}$(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

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



beyond SM: up to 5×10^{-6}



$$\mathcal{B} < 0.53 \times 10^{-4} \ (90\% \ CL)$$

[previous limit: 1.48×10^{-4}]

2006 data will probe ~ 5×10^{-6}

Summary

Belle 1999-

- $\Upsilon(4S)$: 7×10^8 $B\bar{B}$

  CP asymmetries, other B decay studies
  -> overconstraining Unitarity Triangle
  charm, tau, 2-photon, ...

- $\Upsilon(5S)$: 1×10^5 $B_s\bar{B}_s$ results, 1×10^6 in process

  inclusive D_s rate -> fraction of B_s
  reconstruction of B_s decays ->
    dominance of $B_s^*B_s^*$
    masses B_s^*, B_s
    hints of $D_s^{(*)}$, best limit on $\gamma\gamma$
  clean data, high-luminosity machine ->
    Belle *will* contribute to B_s

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