CP Violation and Flavour

Lecture 3

Dottorato in Fisica – XXI Ciclo

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Recap

- B mixing and CPV: detailed pattern of SM (CKM) predictions, many channels
  - Typical expectations: O(10%) asymmetries in rare (10^{-4} and less) decays
  - need many reconstructed and tagged B mesons $\Rightarrow$ high luminosity!

- Measurements to be discussed in lectures 3 - 5:
  - Tevatron: B_s mixing ($\Delta\Gamma_s$, Δm_s)
  - B factories: CPV in B_d, $B^{\pm}$

    "direct" in decays,

    "indirect" in mixing, and

    "mixing-induced"

    $\Rightarrow$ CKM Unitarity Angles $\alpha(\phi_2)$, $\beta(\phi_1)$, $\gamma(\phi_3)$

Lecture 3 - Outline

- Experimental facilities
- B_s mixing at the Tevatron
  - $\Delta\Gamma_s$, Δm_s
- Detectors at the B-factories
  - design criteria and performance
- Direct CPV
  - $B \to K\pi$
- Limits on indirect CPV
  - $A_{SL} = (N(l^+l^+) - N(l^-l^-)) / (N(l^+l^+) + N(l^-l^-))$

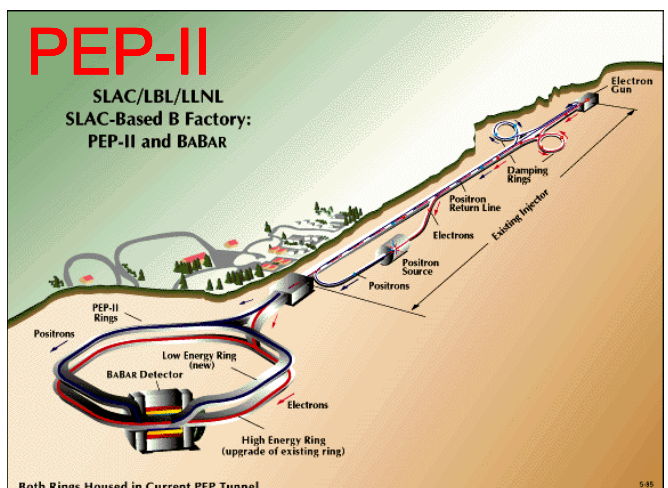
- Methods
- Results
- Statistics, systematics

Experimental facilities (B physics)

Past: LEP, CESR

Present: Tevatron, PEP-II, KEK-B

Future: LHC; Super B-Factory?



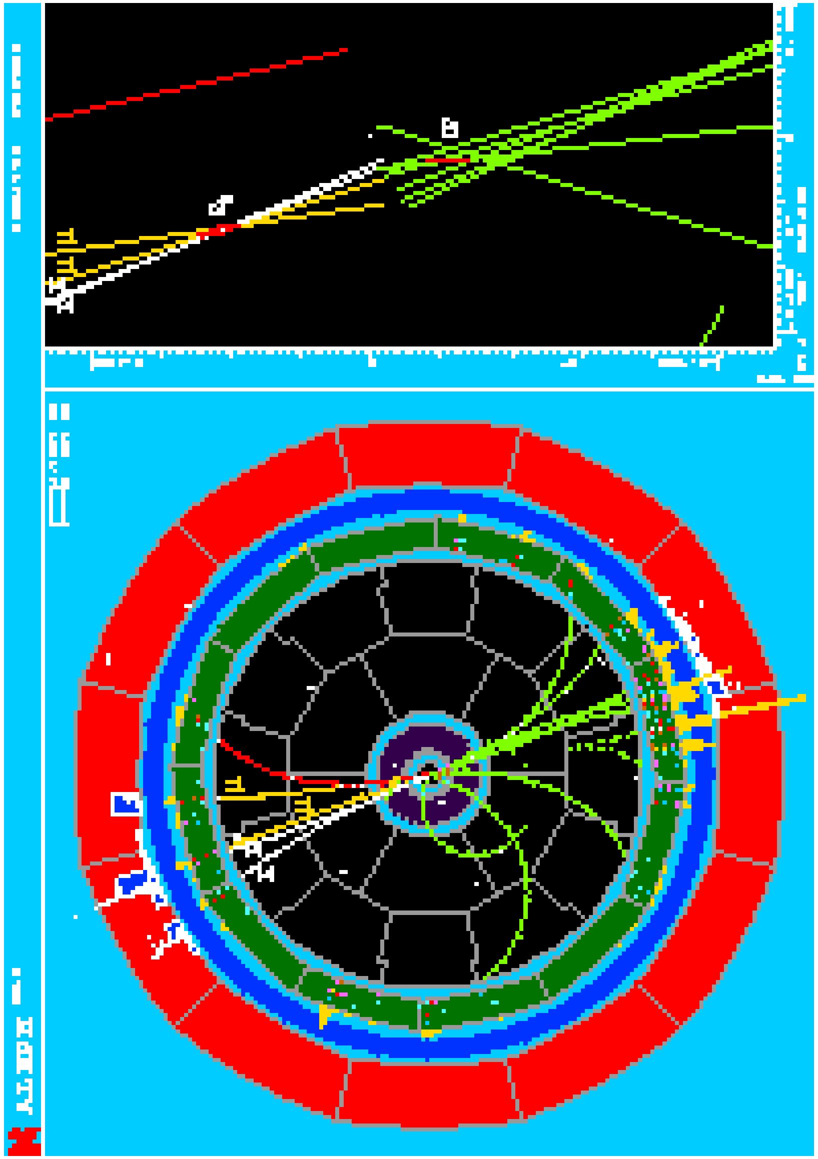
Recent past: LEP, SLC and CLEO

- $e^+e^- \to Z^0 \to b\bar{b}$
  - LEP (Aleph, Delphi, L3, OPAL)
    - 4 M $Z^0 \Rightarrow$ 1.4 M $B_{u,d}$; B_s, b-baryons, …; $\sigma_{bb} / \sigma_{had} \cong 0.2$
    - $p_{lab} \cong 30$GeV $\Rightarrow$ boost $\gamma\beta c\tau \cong 3$ mm
    - Silicon vertex detectors, particle identification
    - Lifetimes, mixing, b-tags
  - SLC (linear collider: SLD)
    - 400K $Z^0 \Rightarrow$ 140K $B_{u,,d}$; Polarized beam (A_{FB} measurement!)
    - Smaller diameter vacuum pipe, pixel vertex detector
- $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0, B^+B^-$
  - CESR (CLEO, several upgrades) until 2001
    - 17 M events, $B_{u,d}$ only; $\sigma_{bb} / \sigma_{had} \cong 0.25$
    - Monochromatic B mesons, small boost: $\gamma\beta \cong 0.06$
    - Vertex detector, particle identification; many important results!

Decay vertex technology

An $e^+e^- \to Z^0 \to b\bar{b}$ event recorded by ALEPH

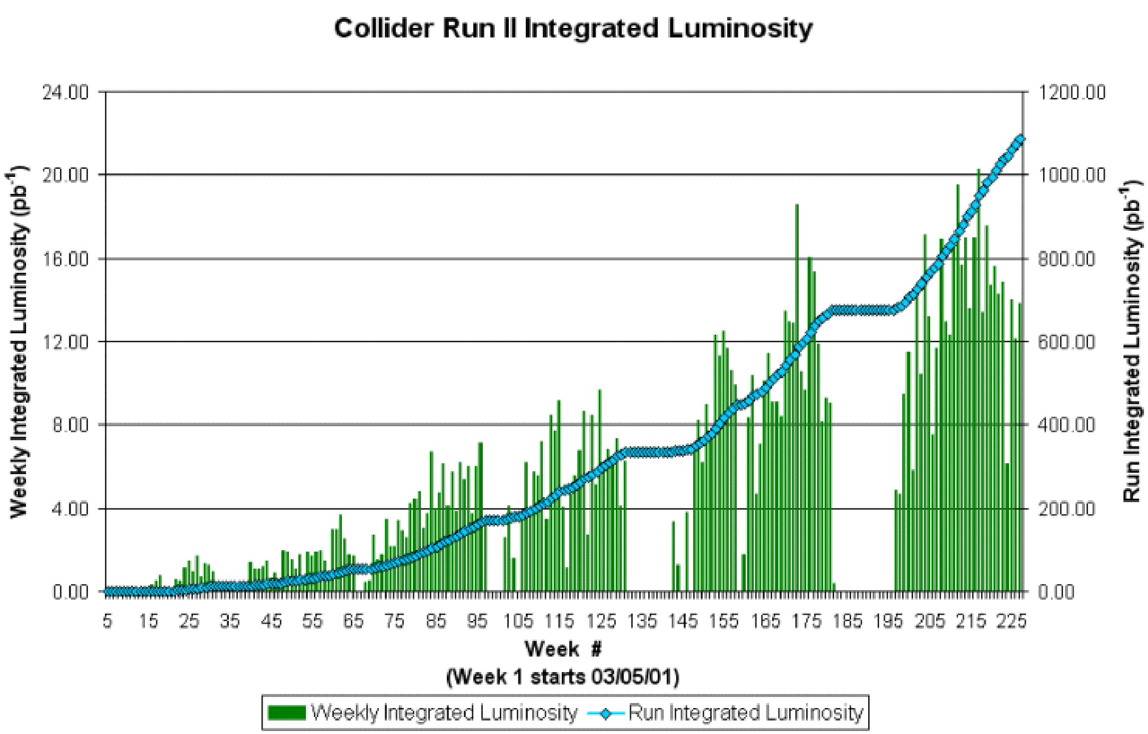
One b hadronizes to B_s fully reconstructed with detached decay vertex



Present (1): Tevatron, Run II

- Tevatron @ FNAL: $p\bar{p}$ collider (CDF, D0)
  - Large cross section *and* backgrounds, at E_{cm} = 1.96 TeV:

    $\sigma_{bb} \cong 10^5$ nb , $\sigma_{bb} / \sigma_{had} \cong 0.001$
  - All species of b-hadrons: $B^{\pm}$, B^0, B_S, B_C, Λ_b, Ξ_b ; $\gamma\beta c\tau \cong 3$ mm
  - Present *peak* luminosity: $\cong 10^{32}$ cm^{-2} s^{-1} ; *integrated* about 1 fb^{-1}



Max. recordable rate, *all processes* ≈ 50 Hz

B rate ≈ 300 Hz !

⇒ a selective trigger is essential !
also on hadrons, not only on leptons

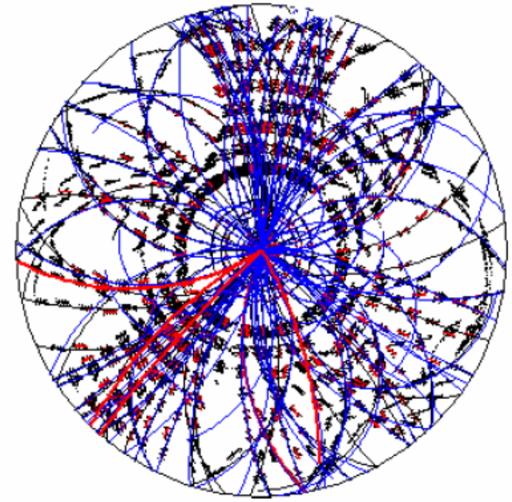
Tevatron, Run II

Ambitious program:

- luminosity up to 4-8 fb^{-1} by 2009
- upgraded CDF and D0 detectors

Physics reach:

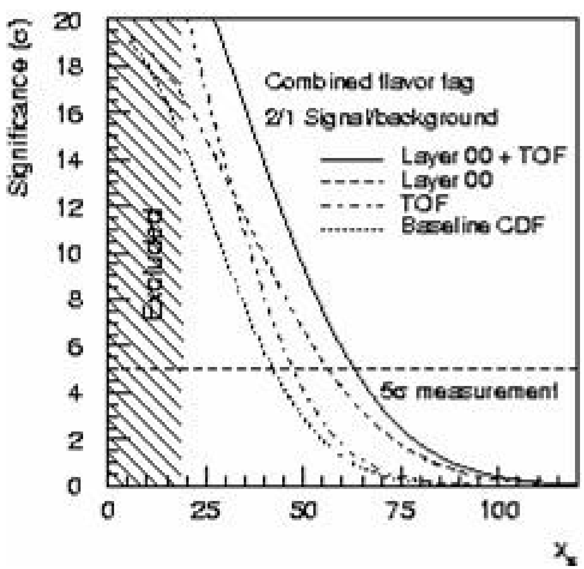
- top, W, searches, QCD
- B-physics, including:
  - Rare decays, CPV, CKM, B_c
  - *B_s mixing: $(\Delta\Gamma/\Gamma)_s$, $(\Delta m/\Gamma)_s$*
  - unique opportunity!



Pretty tough … !

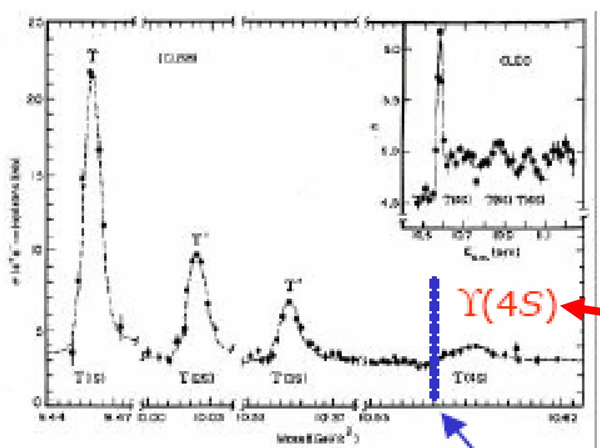
B_s mixing (old upgrade proposal, 2fb^{-1}) →

- 20000 $B_s \rightarrow D_s^+\pi^-$, $D_s^+\pi^-\pi^+\pi^-$
- Tag efficiency: $\varepsilon D^2 = 5.7 \div 11.3\%$



Present (2): the B-factory approach

- CM energy = 10.580 GeV



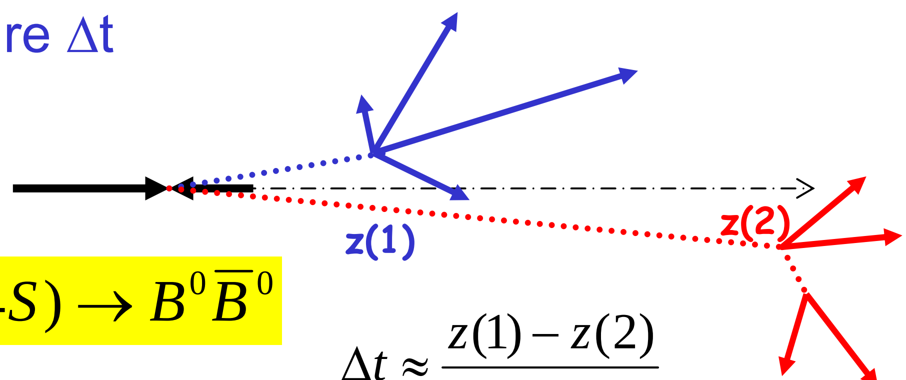
Favorable
Signal / Background:

$$\frac{\sigma_{b\bar{b}}}{\sigma_{had}} \cong 0.28$$

Effective cross sections:

$e^+e^- \to$	σ (nb)
bb	1.05
cc	1.30
ss	0.35
uu	1.39
dd	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	≈ 40

- Asymmetric energy beams: boost the B pair to measure Δt



$$e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0$$

$$\Delta t \approx \frac{z(1) - z(2)}{c\gamma\beta}$$

boost :

$\gamma\beta \approx 0.56$

for :

$E(e^-) \approx 9\,\text{GeV},$

$E(e^+) \approx 3\,\text{GeV},$

$\Upsilon(4S) \to B\bar{B}$ events are simpler…

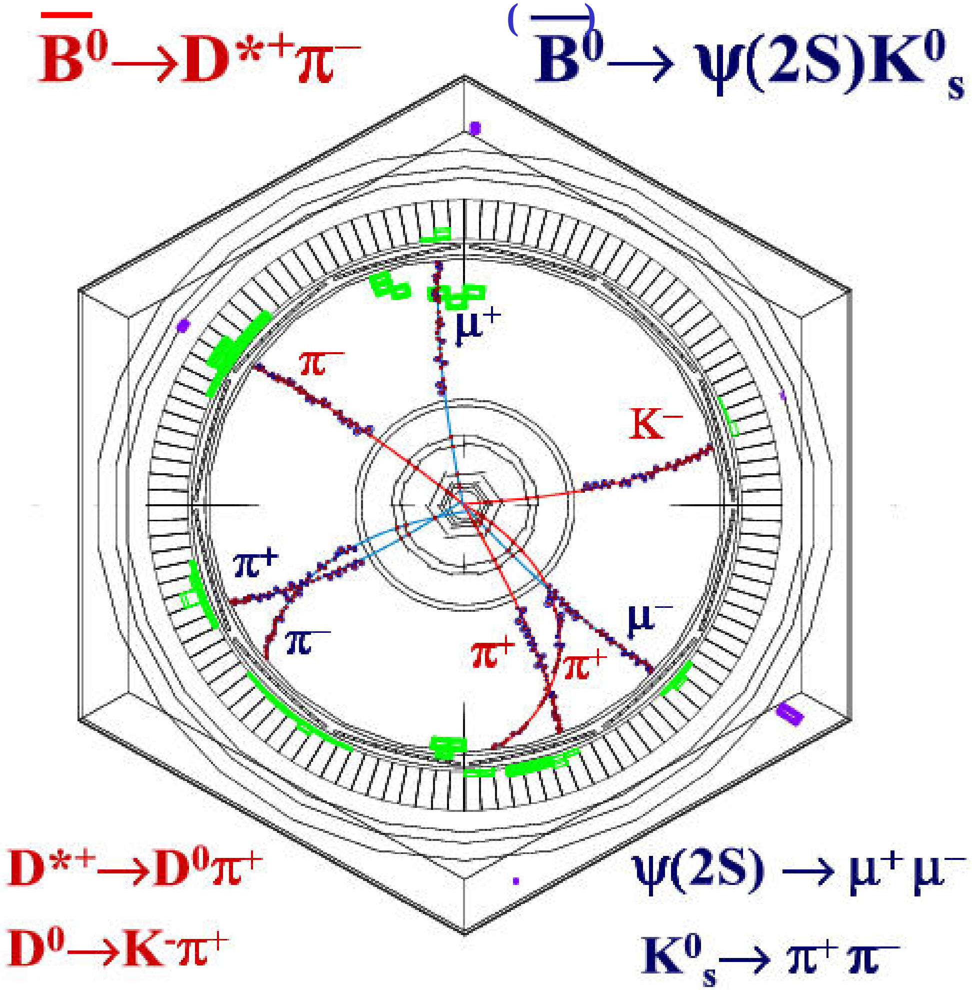
CP eigenstate

$$B^0\left(\overline{B}^0\right) \to \psi(2S) K_S^0$$

Flavour eigenstate

$$\overline{B}^0 \to D^{*+}\pi^-$$

Fish-eye view:

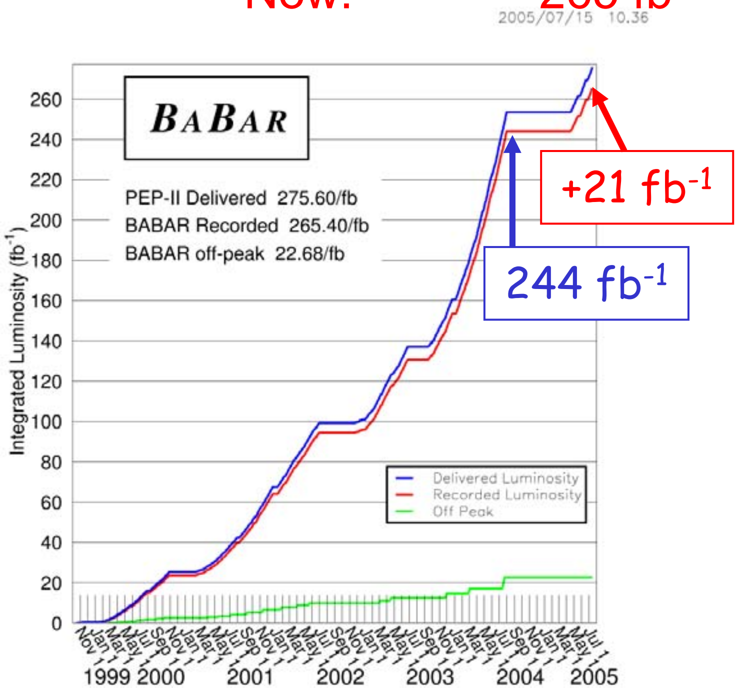


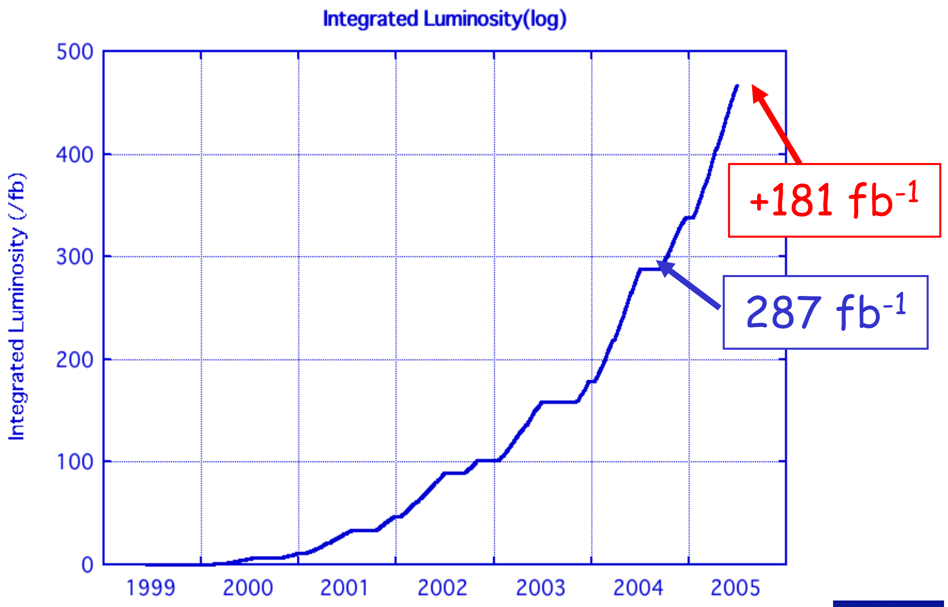
B-Factories: PEP-II and KEK-B

- $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0_d \overline{B}^0_d$ with asymmetric energy to boost the B mesons: PEP-II at SLAC and KEK-B at KEK
- clean environment, low backgrounds, high efficiency; small cross section (≈ 1nb): luminosity is the key factor. KEK-B record: 15.8 events/(nb s)
- *> 700 M B-meson pairs* recorded in total by Belle and BaBar !

PEP-II Last summer: 244 fb^{-1}
Now: 265 fb^{-1}

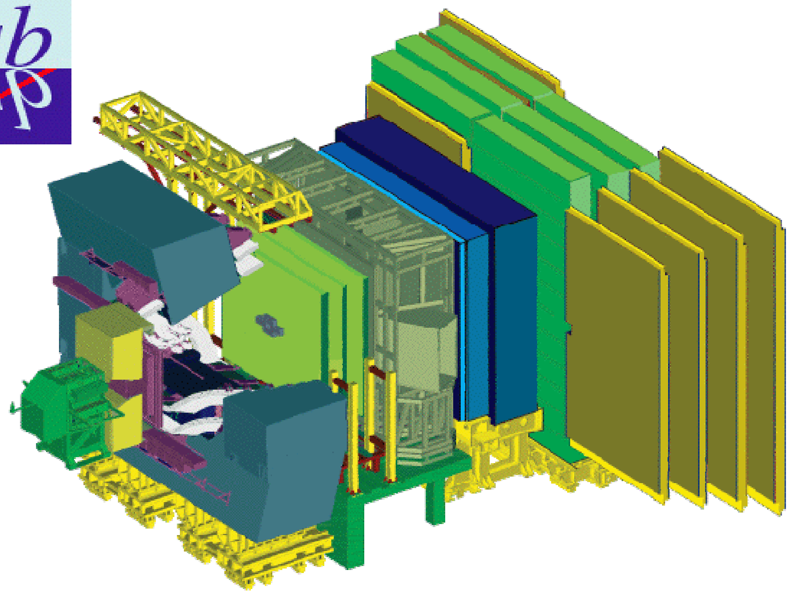
KEK-B Last summer: 287 fb^{-1}
Now: 468 fb^{-1}





Future: LHC & Super B-Factories?

- Dedicated seminars:
  - *J.N.Butler,* “Future experiments on CP violation in the B system at hadron machines”
  - *M.Giorgi,* “Possibilities for future experiments on CP violation in the B system at super B-factories”
  - *D.Hitlin,* “The asymmetric B factories”

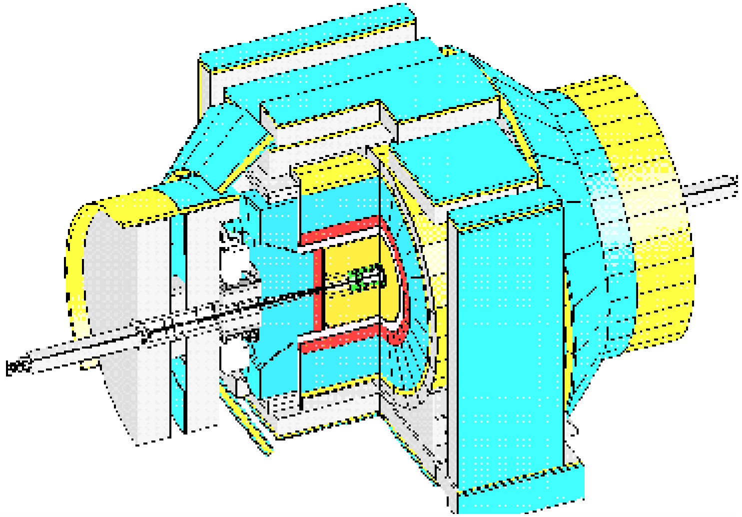


Detectors

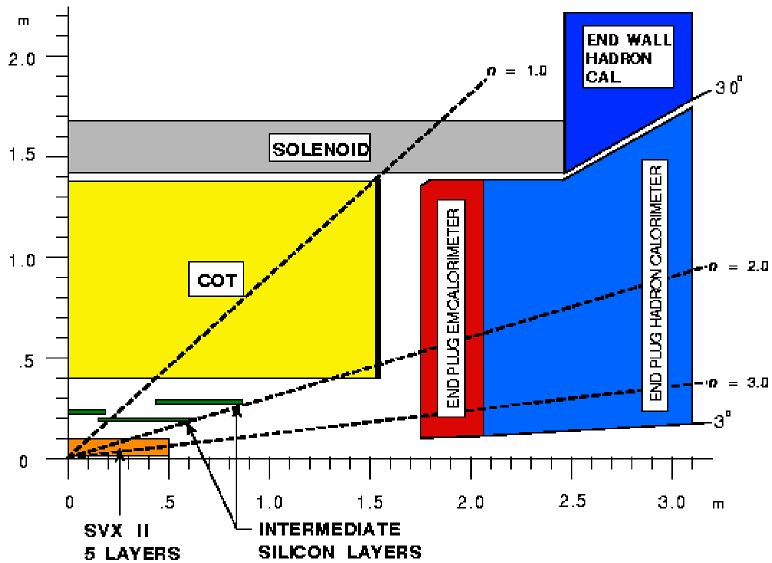
CDF and D0

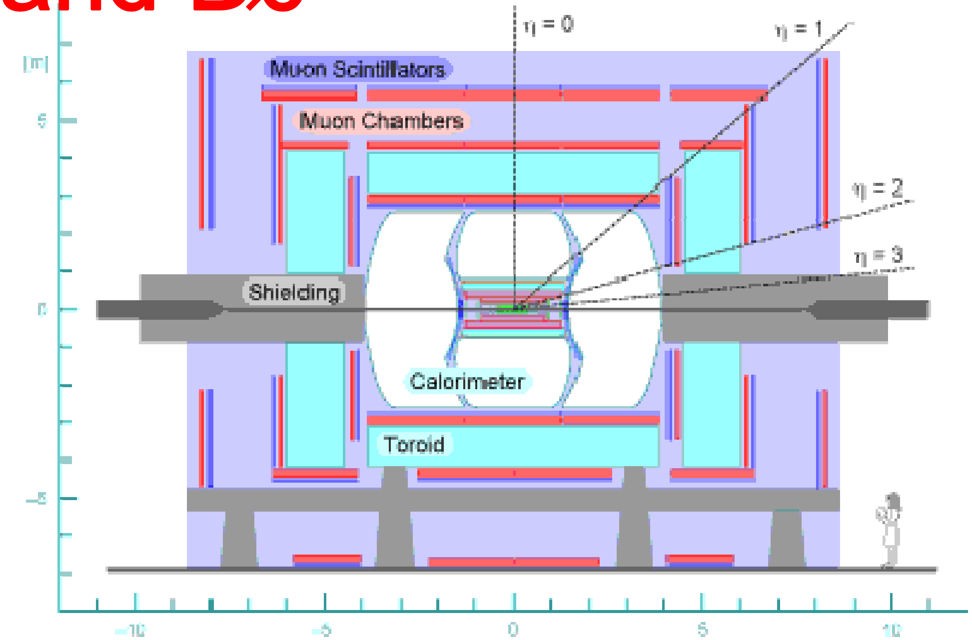
(*BABAR* and *BELLE* : next lecture)

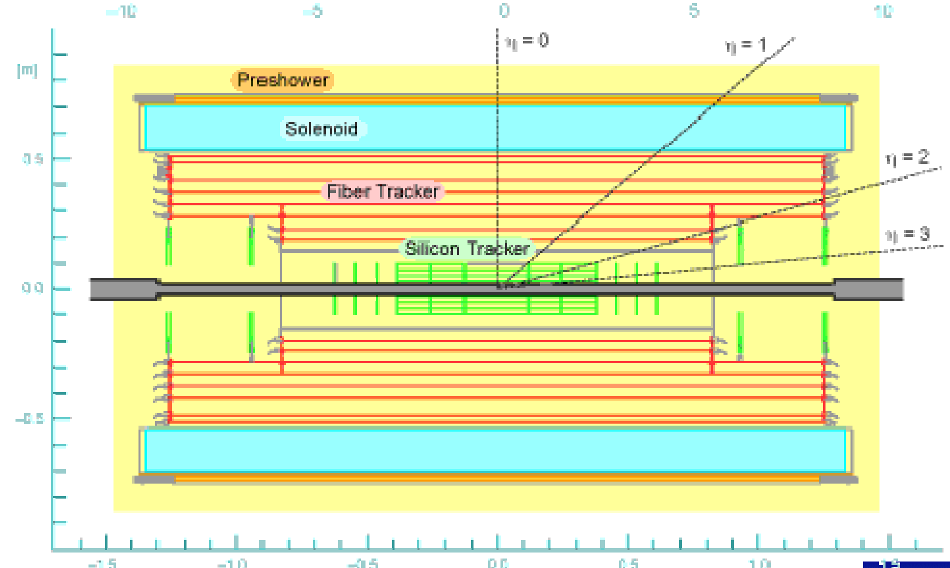
CDF and DØ



CDF Tracking Volume

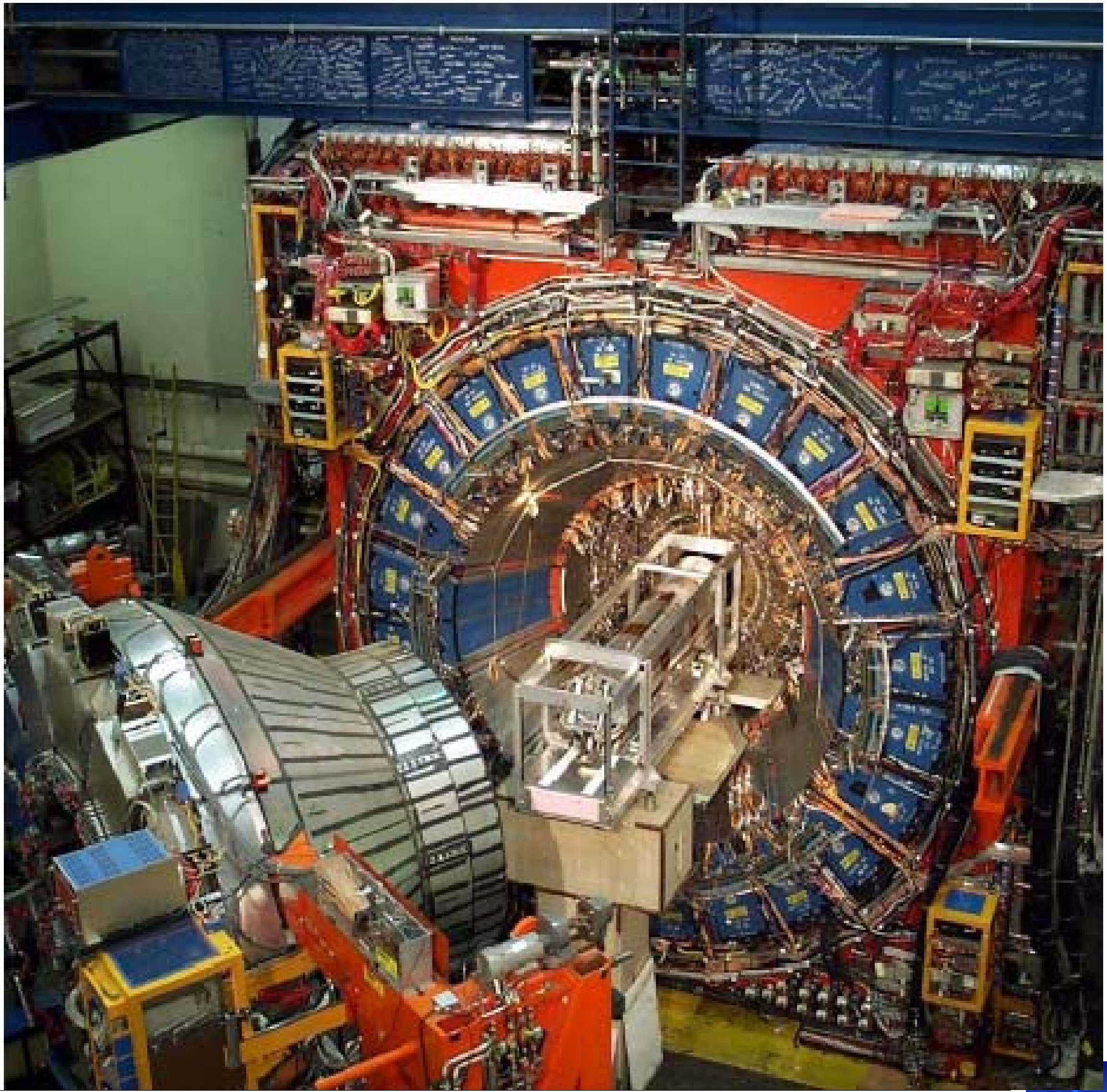






The CDF Run II Detector

- New silicon vertex detector
  - inner layer at 1.35 cm
- New central tracker
  - Excellent mass resolution
- Extended μ coverage
- TOF and dE/dx particle ID
- Second level impact parameter trigger
  - Allows all hadronic B decay triggers



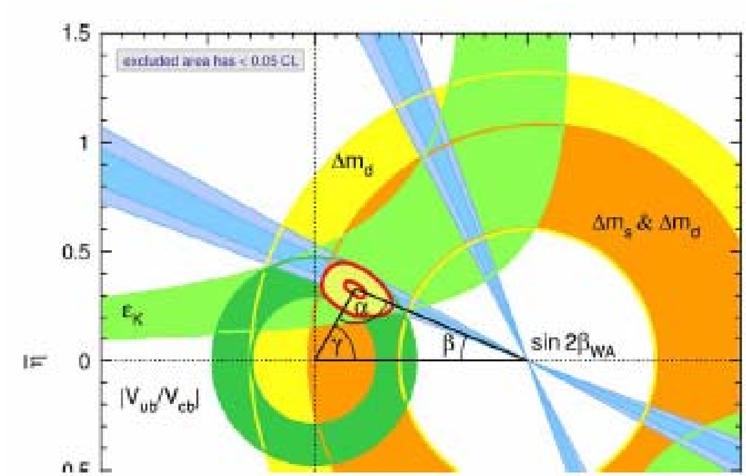
(Rick Jesik, LP2005)

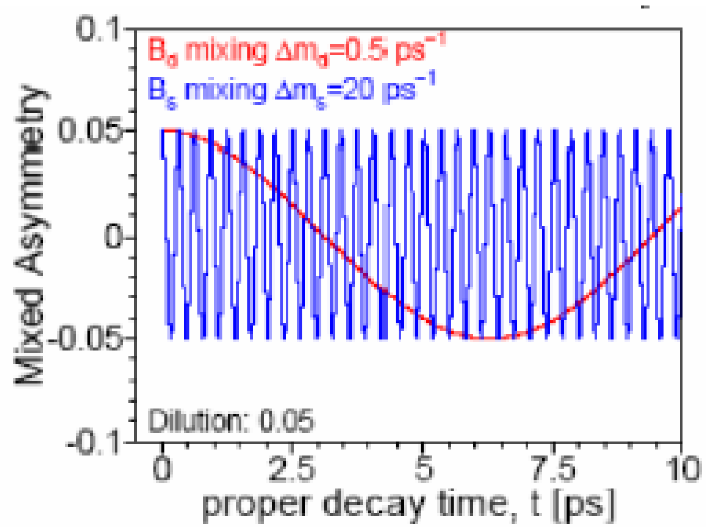
The DØ Run II Detector

- Silicon vertex detector
  - $|\eta| < 3.0$
- Central fiber tracker and pre-shower detectors
  - $|\eta| < 1.5$
- 2 T solenoid magnet
- New low pT central muon trigger scintillators
- New forward μ system
  - Excellent muon purity and coverage: $|\eta| < 1.5$
- Second level silicon track trigger being commissioned, B tagging at 3rd level now

(Rick Jesik, LP2005)

B_s mixing at the Tevatron





B_s mixing: an open issue

- B_s mixing: $$P(B_s \rightarrow \overline{B}_s) \propto e^{-t/\tau_s}(1-\cos x_s t/\tau_s)$$

$$x_s = \frac{\Delta m_s}{\Gamma_s} \quad \Gamma_s = \frac{\hbar}{\tau_s}$$

LEP, SLD, CDF-I $\Delta m_s > 14.5 ps^{-1}$ $x_s > 21.1$

$$\frac{x_s}{x_d} = \frac{m_{B_s}\eta_{B_s} \; B_{B_s} \; f_{B_s}}{m_{B_d}\eta_{B_d} \; B_{B_d} \; f_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

- $\Delta\Gamma_s$ and Δm_s: expectations

$$\left(\frac{\Delta\Gamma_s}{\Gamma_s}\right)_{theor} = \left(\frac{f_{B_s}}{210 \mathrm{MeV}}\right)^2 \left(0.054^{+0.016}_{-0.032} \pm \ldots\right)$$

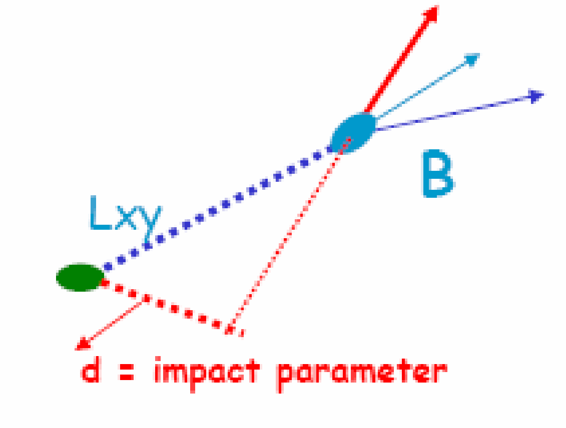
$12 \pm 6\%$ (quoted by CDF)

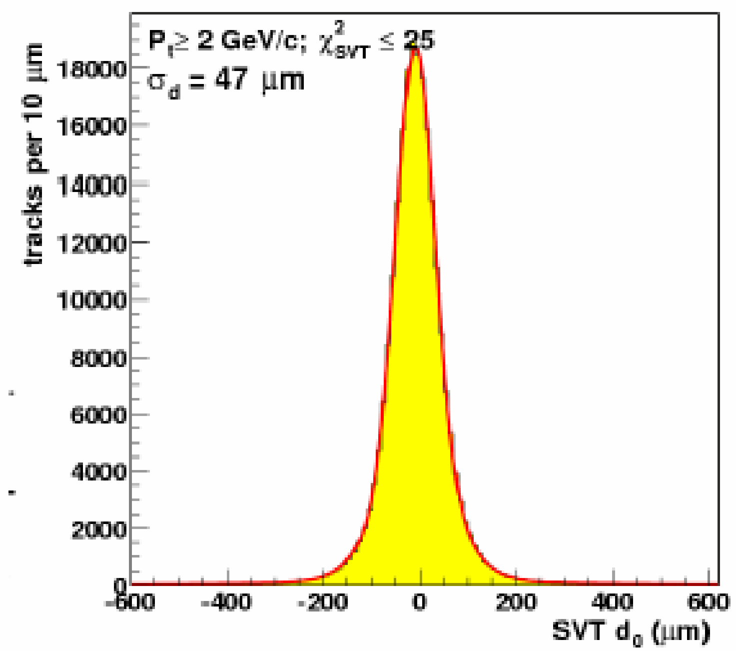
$$\left(\frac{\Delta\Gamma_s}{\Delta m_s}\right)_{theor} = \left(2.63^{+0.67}_{-1.36} \pm \ldots\right) \times 10^{-3}$$

Dunietz et al, PRD 63, 114015 (2001)
Beneke et al, PLB 459, 631 (1999)

Triggering at the Tevatron

- Dimuons: J/ψ modes
  - p_T > 1.5 – 3.0 GeV
  - CDF central, D0 out to $|\eta| < 3.0$
- Single muons: semileptonic & tag
  - D0: track-matched, p_T > 4 GeV
  - CDF: also p_T > 2 GeV, with
    - 120 μm < d < 1 mm (*)
- CDF only: two displaced vertex tracks: hadronic samples!
  - p_T > 2GeV, 120 μm < d < 1 mm (*)
  - Σp_T > 5.5 GeV

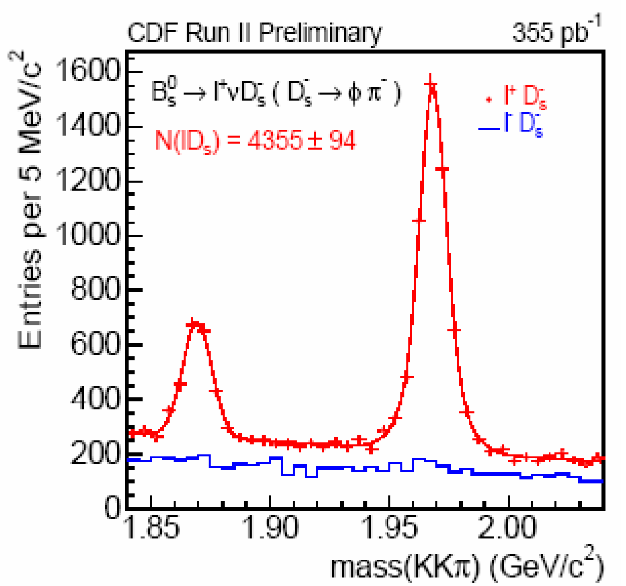




(*) CDF Silicon Vertex Trigger (lev.2)

- Beamspot reconstruction, updated every 30 s; d resolution ≈ 50μm
- Trigger on displaced tracks

b-hadron samples at the Tevatron

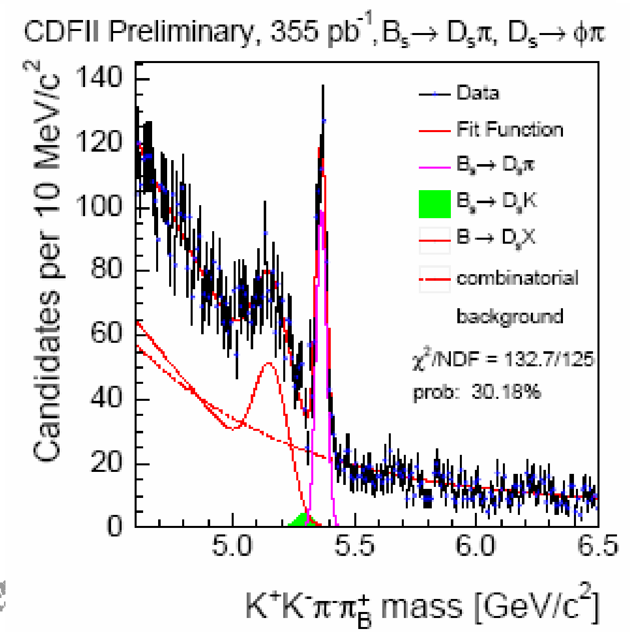


CDF

$B_s \to D_s l \nu$

N = 4355 ± 94

Lumi = 355 pb^{-1}



CDF

$B_s \to D_s \pi$

N = 526 ± 33

Lumi = 355 pb^{-1}

DØ *b-hadron* samples

Mode	evts / 100pb^{-1}
$J/\psi \to \mu^+ \mu^-$	1.14 M
$B^+ \to J/\psi K^+$	1700
$B_d \to J/\psi K^{*0}$	740
$B_d \to J/\psi K^0_S$	40
$B_s \to J/\psi \phi$	100
$\Lambda_b \to J/\psi \Lambda$	25
$B_c \to J/\psi \mu X$	65
$X(3872) \to J/\psi \pi^+ \pi^-$	230
$B \to D^{**} \mu \nu$	210
$B^{**} \to B \pi$	150
$B_s \to D_{s1} \mu X$	4
$B^+ \to D^0 \mu^+ X$	46.2 K
$B_d \to D^{*-} \mu^+ X$	10 K
$B_s \to D_s(\phi\pi) \mu X$	2900
$B_s \to D_s(K^*K) \mu X$	2500

$\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

$\Delta\Gamma_s$ from $B_s \to J/\psi\phi$: method

- Relation of matrix elements to decay and oscillation parameters:

$$\Delta m = M_H - M_L \approx 2|M_{12}|$$

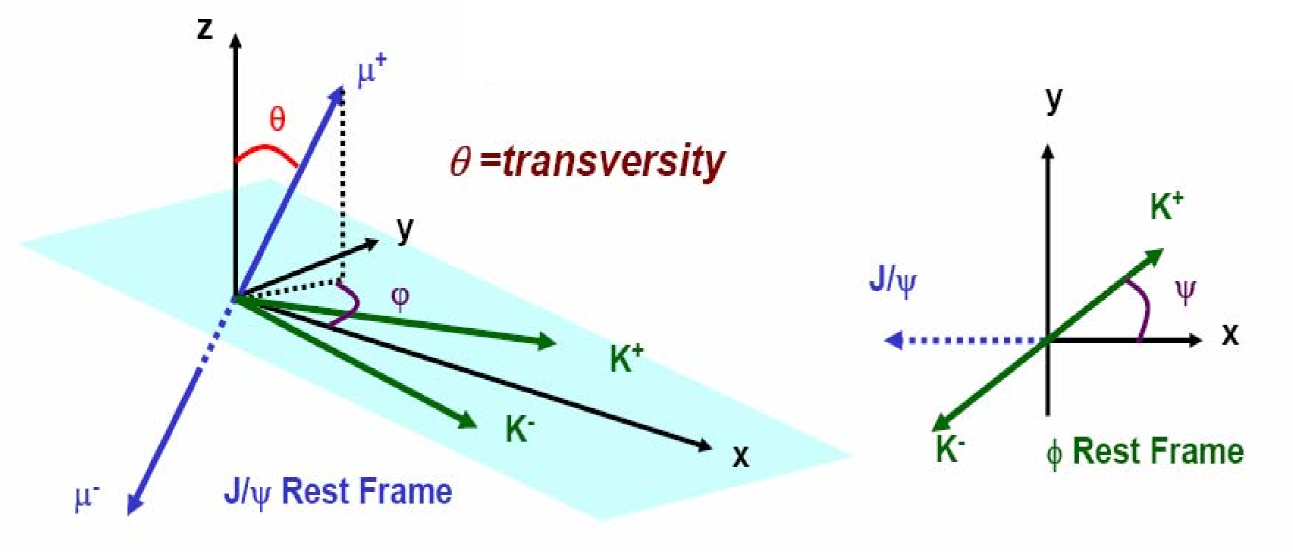
$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$$

$$\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

- In the Standard Model:
  - The CP violating phase, ϕ is expected to be small
  - Mass eigenstates are ~ CP eigenstates with definite lifetimes
- The $J/\psi\ \phi$ final state is a mixture of CP states
  - L=0, 2; CP even; (A_0, $A_{\parallel}$)
  - L=1; CP odd; ($A_{\perp}$)
- Assuming no CP violation in the $\mathbf{B_s}$ system, measure two $\mathbf{B_s}$ lifetimes, τ_L and τ_H, (or $\Delta\Gamma/\Gamma$ and τ) by simultaneously fitting time evolution and angular distribution in untagged $B_s \to J/\psi\ \phi$ decays
- CDF result last summer: $\Delta\Gamma/\Gamma = 0.65^{+0.25}_{-0.33} \pm 0.01$

Phys.Rev.Lett. 94 (2005) 101803

$B_s \to J/\psi\phi$: transversity analysis



Angles and proper decay time:

$$\vec{\rho} \equiv \{\cos\theta, \varphi, \cos\psi\}$$

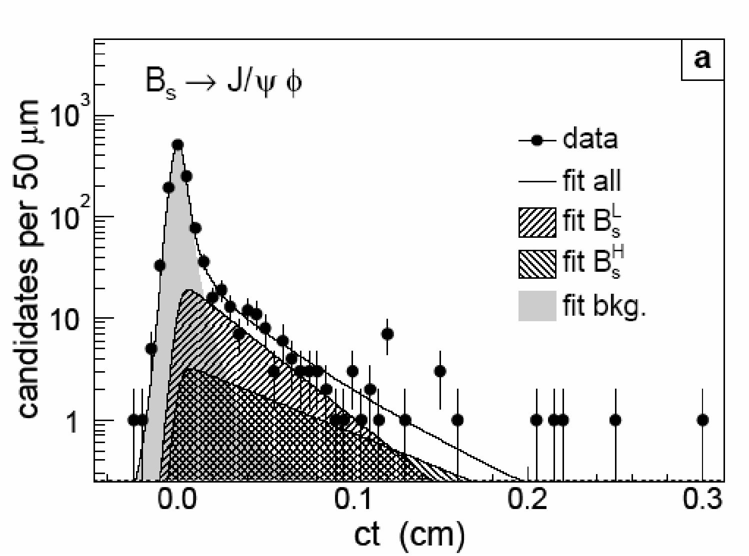
$$ct = c(\vec{l}_T \cdot \vec{p}_T)M_B/p_T^2$$

From an unbinned Max. Likelihood fit to decay time-and-angles distribution:

$$A_0\,,\, A_{\parallel}\,,\, A_{\perp}\,,\, c\tau_L\,,\, c\tau_H\,,\, \Delta\Gamma_s$$

$$\frac{d^4\mathcal{P}(\vec{\rho},t)}{d\vec{\rho}\,dt} \propto |A_0|^2 e^{-\Gamma_L t} \cdot f_1(\vec{\rho}) + |A_{\parallel}|^2 e^{-\Gamma_L t} \cdot f_2(\vec{\rho}) + |A_{\perp}|^2 e^{-\Gamma_H t} \cdot f_3(\vec{\rho}) + \mathrm{Re}(A_0^* A_{\parallel}) \cdot f_5(\vec{\rho}) e^{-\Gamma_L t}.$$

$\Delta\Gamma_s$ from $B_s \to J/\psi\phi$: recent results



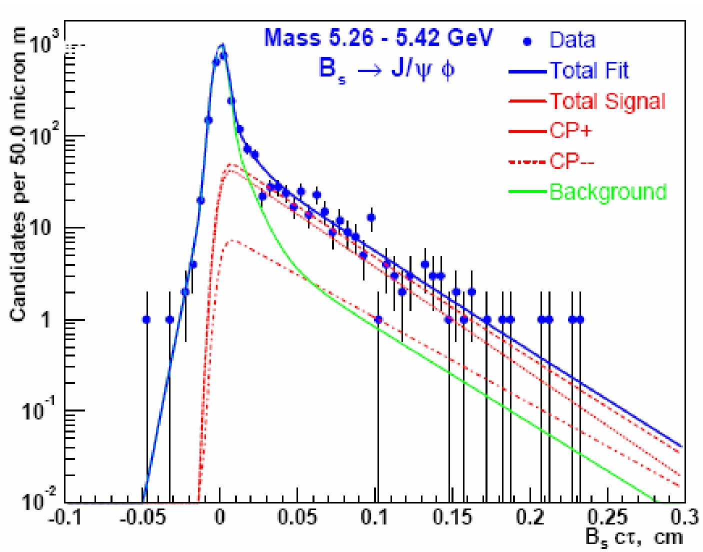
CDF published: L = 260 pb^{-1}, N = 203±15

$$\tau_L = (1.05\ ^{+0.16}_{-0.13} \pm 0.02)\ \mathrm{ps}$$

$$\tau_H = (2.07\ ^{+0.58}_{-0.46} \pm 0.03)\ \mathrm{ps}$$

$$\Delta\Gamma_s = (0.47\ ^{+0.19}_{-0.24} \pm 0.01)\ \mathrm{ps}^{-1}$$

$$\Delta\Gamma_s/\Gamma_s = (65\ ^{+25}_{-33} \pm 1)\%$$



D0 preliminary: Lumi = 450 pb^{-1}, N = 483±32

$$\bar{\tau}(B_s^0) = 1.39^{+0.13}_{-0.14} \pm 0.08\,ps$$

$$\frac{\Delta\Gamma}{\bar{\Gamma}} = 0.21^{+0.27}_{-0.40} \pm 0.20$$

0.02 ?

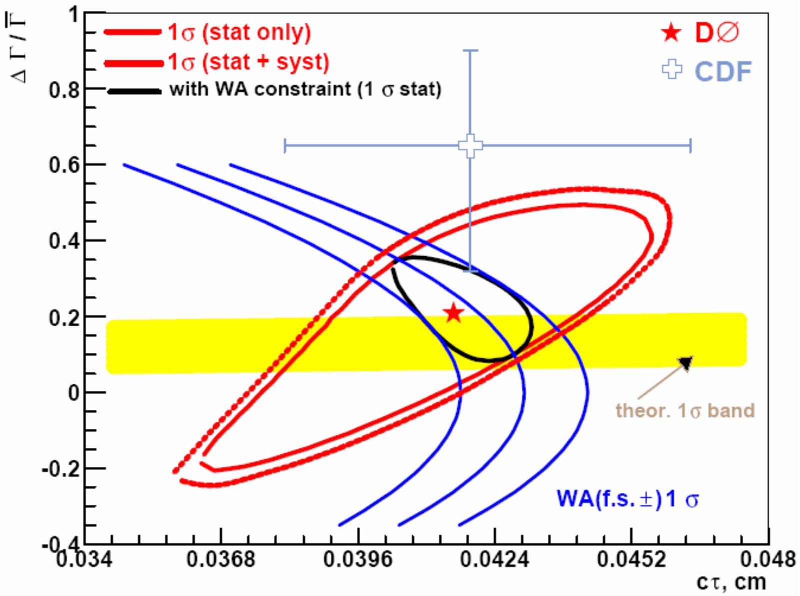
$$R_\perp = 0.17 \pm 0.10 \pm 0.02$$

$$\frac{|A_\perp|^2}{|A_0|^2 + |A_\parallel|^2}$$

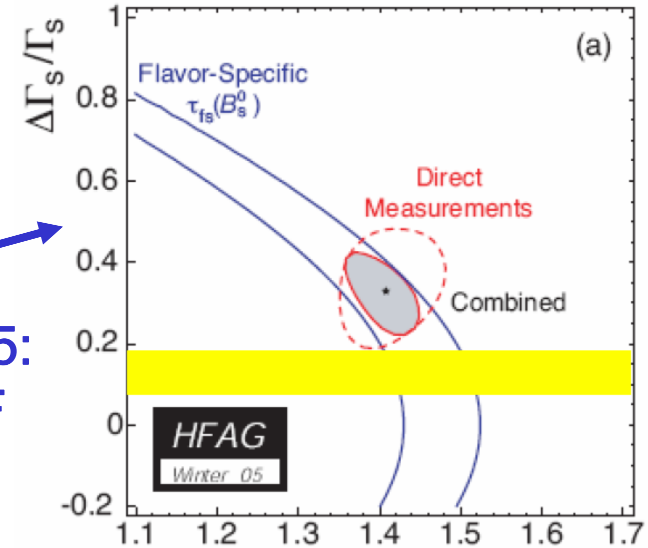
$$\frac{d\Gamma(t)}{d\cos\theta} \propto \left(|A_0(t)|^2 + |A_\parallel(t)|^2\right)\frac{3}{8}\left(1+\cos^2\theta\right) + |A_\perp(t)|^2 \frac{3}{4}\sin^2\theta$$

$\Delta\Gamma_s$: status and outlook

D0 vs CDF and $(\Delta\Gamma/\Gamma)_{theor}$ = (12±6)%



HFAG Winter 2005: LEP & CDF



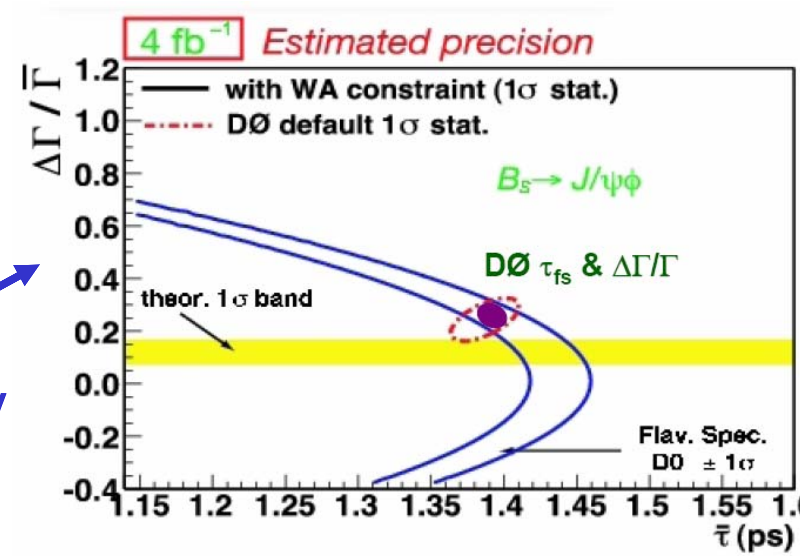
D0, with lifetime constraint:

$$\Gamma_{fs} = \bar{\Gamma}\left(\frac{1-(\Delta\Gamma/2\bar{\Gamma})^2}{1+(\Delta\Gamma/2\bar{\Gamma})^2}\right)$$

$$\bar{\tau}_{fs} = 1.43 \pm 0.05\,ps$$

$$\Rightarrow \frac{\Delta\Gamma}{\Gamma} = 0.23^{+0.16}_{-0.17}$$

D0 sensitivity for 4 fb^{-1}



Δm_s from $B_s \to D_s l \nu$, $D_s \pi$

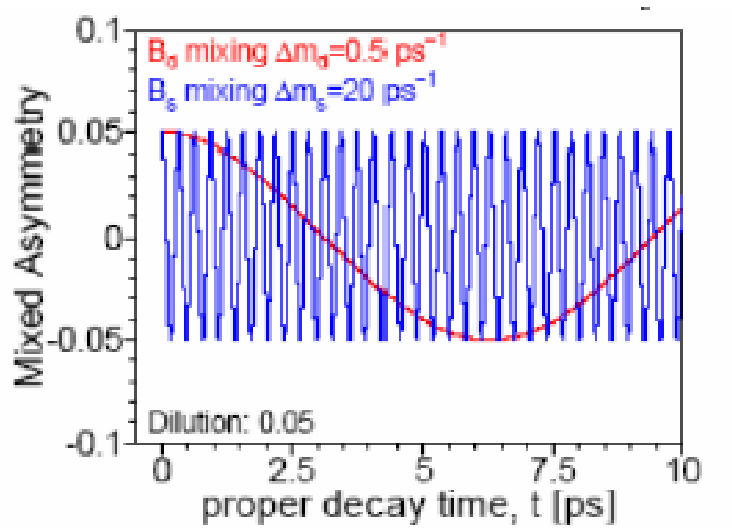
Tevatron

Collider, experiments

B_s mixing measurement

$$P(B_s \rightarrow \overline{B}_s) \propto e^{-t/\tau_s}(1-\cos x_s\, t/\tau_s)$$

$$x_s = \frac{\Delta m_s}{\Gamma_s} \qquad \Gamma_s = \frac{\hbar}{\tau_s}$$



LEP, SLD, CDF-I

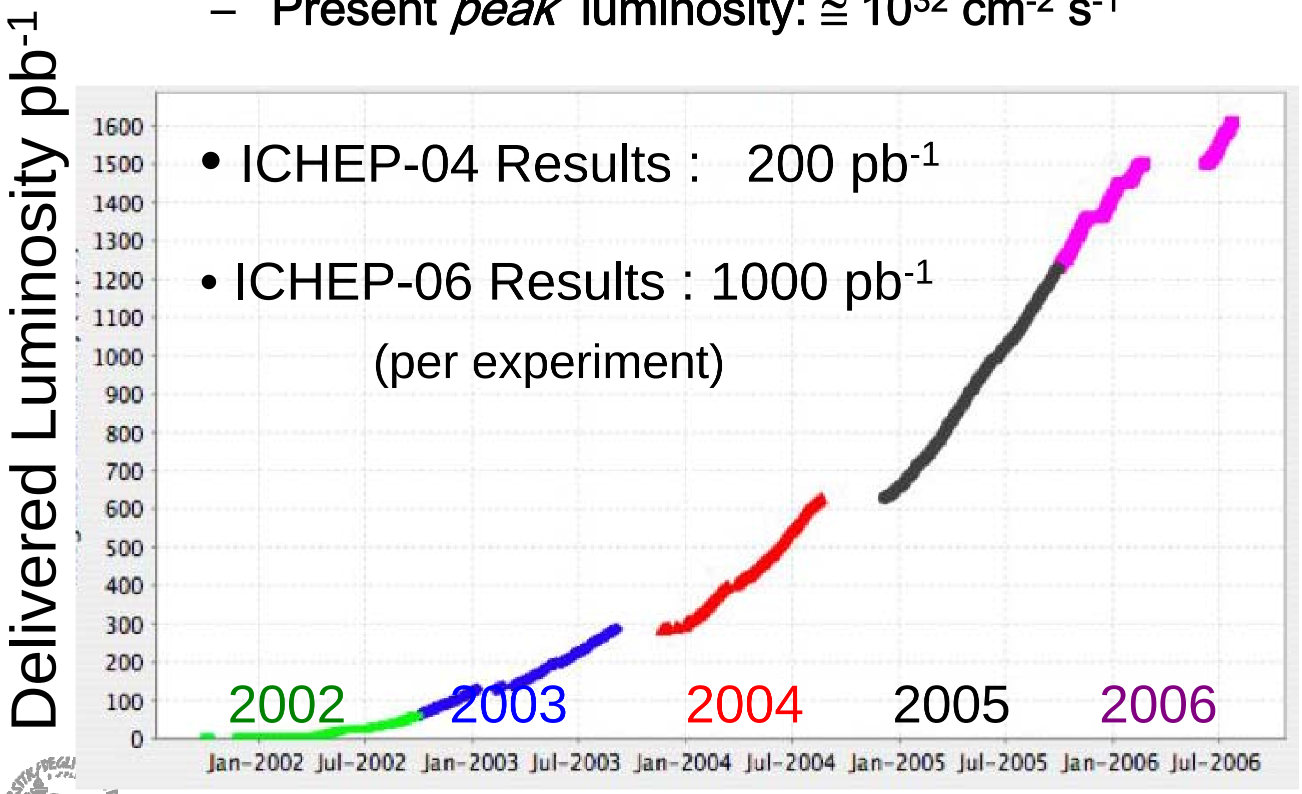
$\Delta m_s > 14.5\, ps^{-1}$ $\qquad x_s > 21.1$

$$\frac{x_s}{x_d} = \frac{m_{B_s}\eta_{B_s}\; B_{B_s}\, f_{B_s}}{m_{B_d}\eta_{B_d}\; B_{B_d}\, f_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

Present (1): Tevatron, Run II

- Tevatron @ FNAL: $p\bar{p}$ collider (CDF, D0)
  - Large cross section *and* backgrounds, at E_{cm} = 1.96 TeV:

    $\sigma_{bb} \cong 10^5$ nb , $\sigma_{bb} / \sigma_{had} \cong 0.001$
  - All species of b-hadrons: $B^\pm$, B^0, B_S, B_C, Λ_b, Ξ_b ; $\gamma\beta c\tau \cong 3$ mm
  - Present *peak* luminosity: $\cong 10^{32}$ cm^{-2} s^{-1}

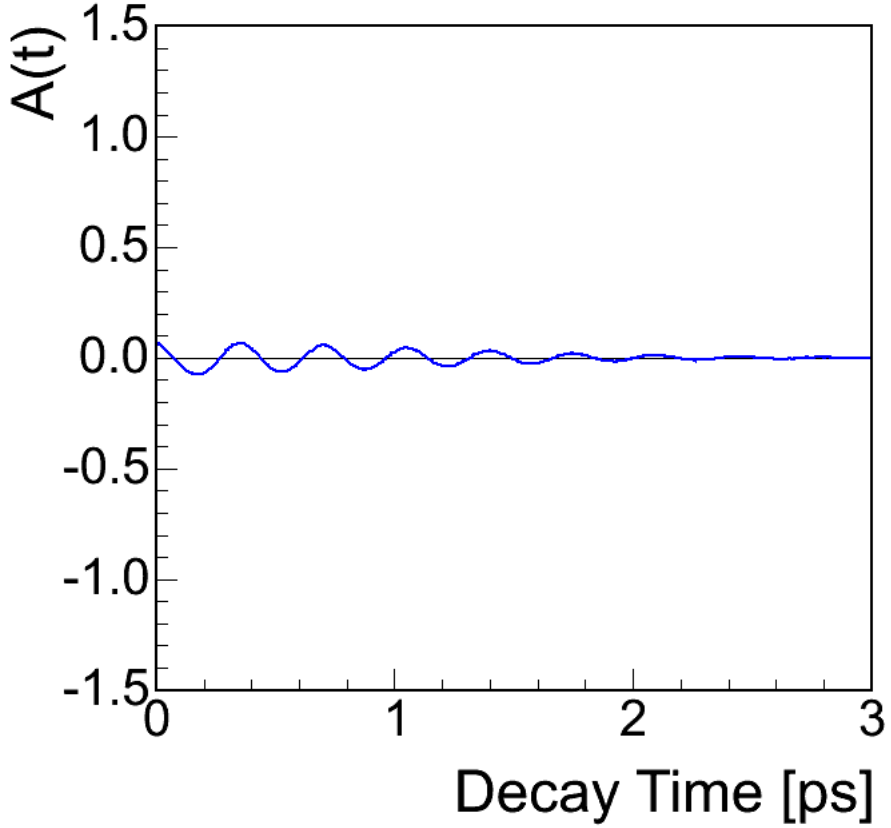


Max. recordable rate, *all processes* ≈ 50 Hz

B rate ≈ 300 Hz

⇒ a selective trigger is essential also on hadrons, not only on leptons

B_s Mixing: Basics



Actual Detector

B_s Mixing: Ingredients

- For each event they need to determine

1) B_s or $\overline{B}_s$ at production?
   determined using "Flavor Taggers" → εD^2

2) B_s or $\overline{B}_s$ at decay?
   determined by reconstruction of B_s at decay → N_B

} mixed or unmixed?

3) Proper decay time

   determined by reconstruction of B_s at decay → δ_t

$$\mathrm{Signif} = \sqrt{\frac{N_B \varepsilon D^2}{2}}\, e^{\frac{-(\Delta m_s \delta_t)^2}{2}} \sqrt{\frac{\mathrm{N_B}}{\mathrm{N_{total}}}}$$

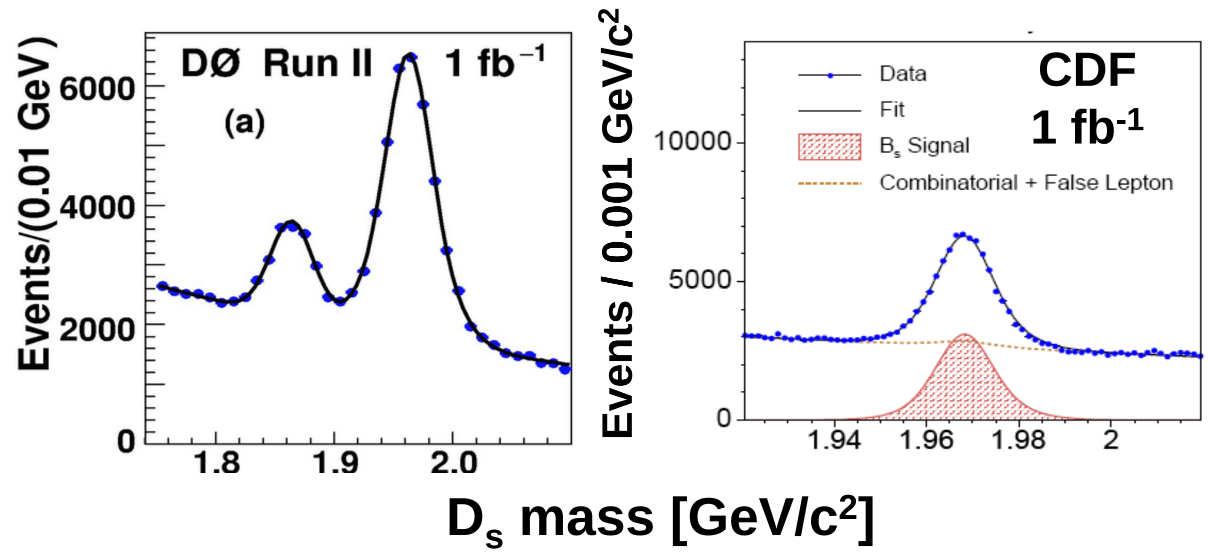
B_s Mixing: 1) Identify Sample

semi-leptonic decays

$$B_s \to D_s^- e^+ \nu_s$$

D0: N_B = 36500

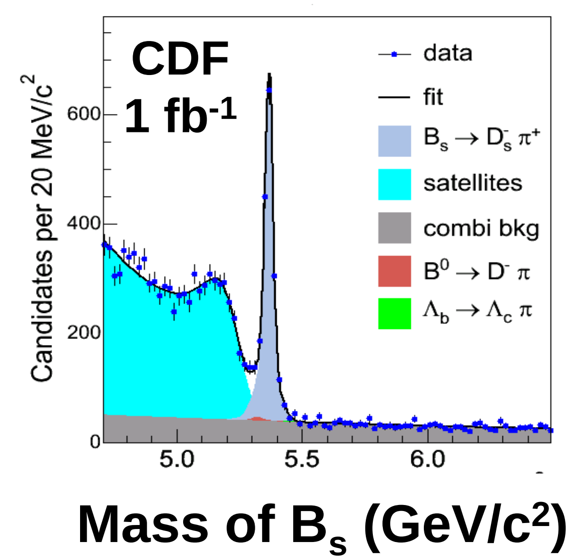
CDF: N_B = 37000



hadronic decays:

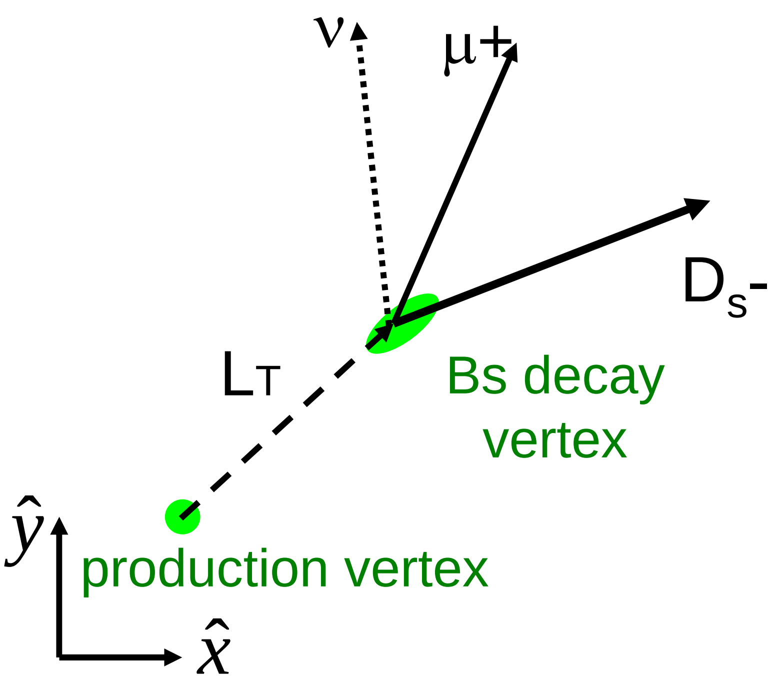
$$B_s \to D_s^- \pi^+,\ D_s^- \pi^+ \pi^- \pi^+$$

CDF: N_B = 3600



B_s Mixing: 2) Proper Decay Time

- Determine proper decay time from final state:



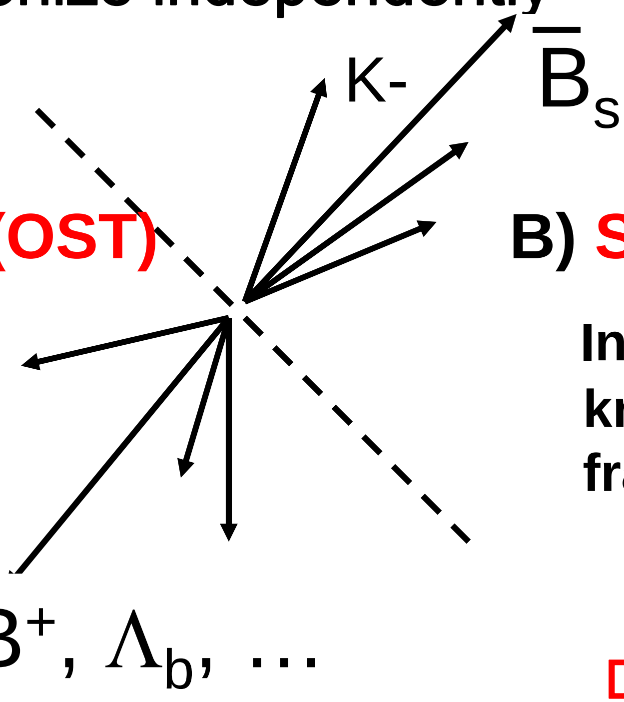
$$\tau = \frac{L_T M_{B_s}}{P_T^{vtx}} \kappa$$

κ determined from Monte Carlo (MC) simulation

Semileptonic Decays	Hadronic Decays
$<\delta> \sim 45\ \mu m$	$<\delta> \sim 25\ \mu m$

B_s Mixing: 3) Flavor Tagging

- B-Hadron Production at the Tevatron
  - Predominantly produced in $b\bar{b}$ pairs
  - b and $\bar{b}$ hadronize independently



A) Opposite Side Tag (OST)

Infer production flavor knowing flavor of the other b in the event

D0: $\varepsilon D^2 = 2.5\%$
CDF: $\varepsilon D^2 = 1.5\%$

B) Same Side Tag (SST)

Infer production flavor knowing flavor of fragmentation tracks

D0: -
CDF: $\varepsilon D^2 = 3.5\%$

Δm_s : Likelihood and “amplitude scan”

Signal PDF

$$P'_{mix}(t') = N\left[1/2\,\Gamma e^{-\Gamma t}\left(1 - A\,D\,S_D\cos(\Delta m_s t)\right)\right] \otimes G(t'|t,\sigma) \times \mathrm{E}(t')$$

- “Amplitude” (A)
- Tag dilution (D)
- Proper time resolution (G)
- Proper time efficiency (E)

The complete likelihood function includes terms for four different types of backgrounds; their parameters are determined by control samples (sidebands) and simulations. Perform an “amplitude A scan” vs Δm_s values

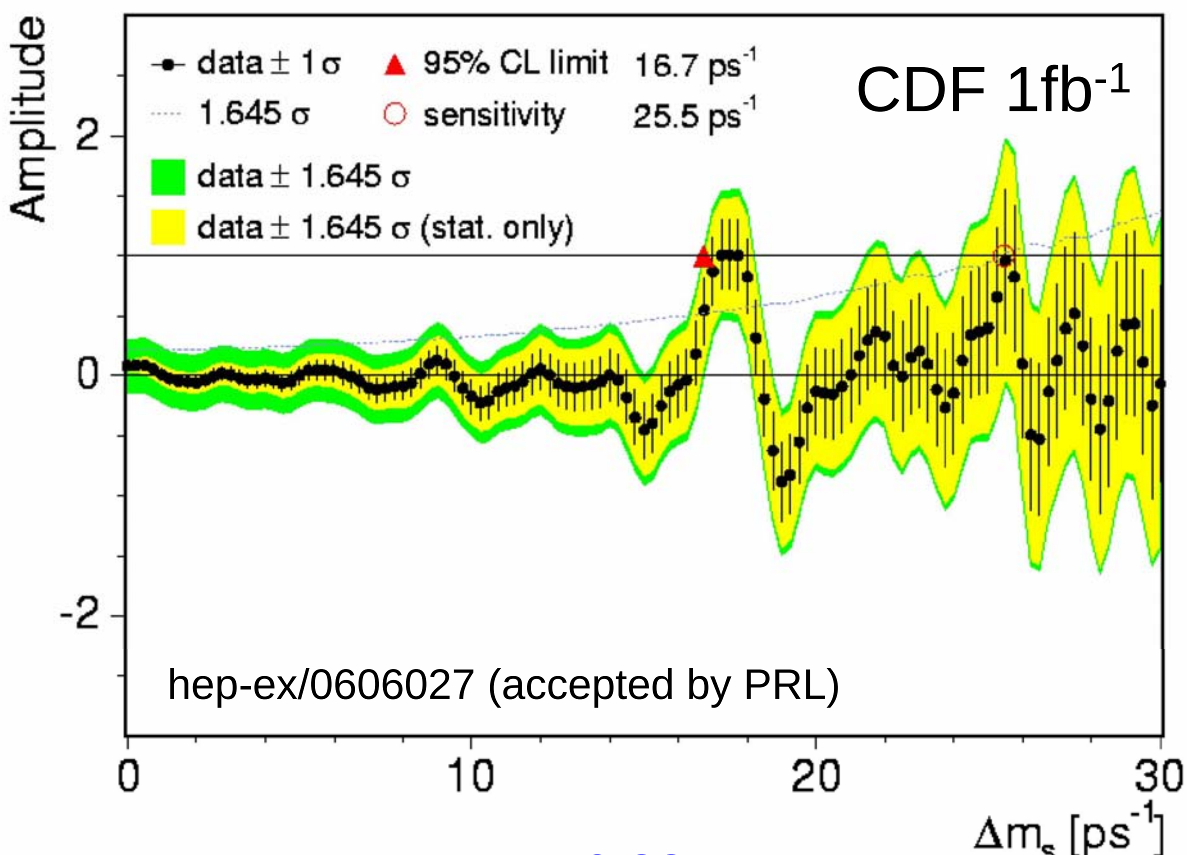
“Amplitude scan”

If $\Delta m_s \approx$ true value, A=1 is expected within its uncertainty σ_A

If Δm_s far from the true value, A = 0 is expected

The Δm_s value can be excluded at 95% CL if $(A + 1.645\,\sigma_A) < 1$

B_s Mixing: CDF Results (Apr-06)

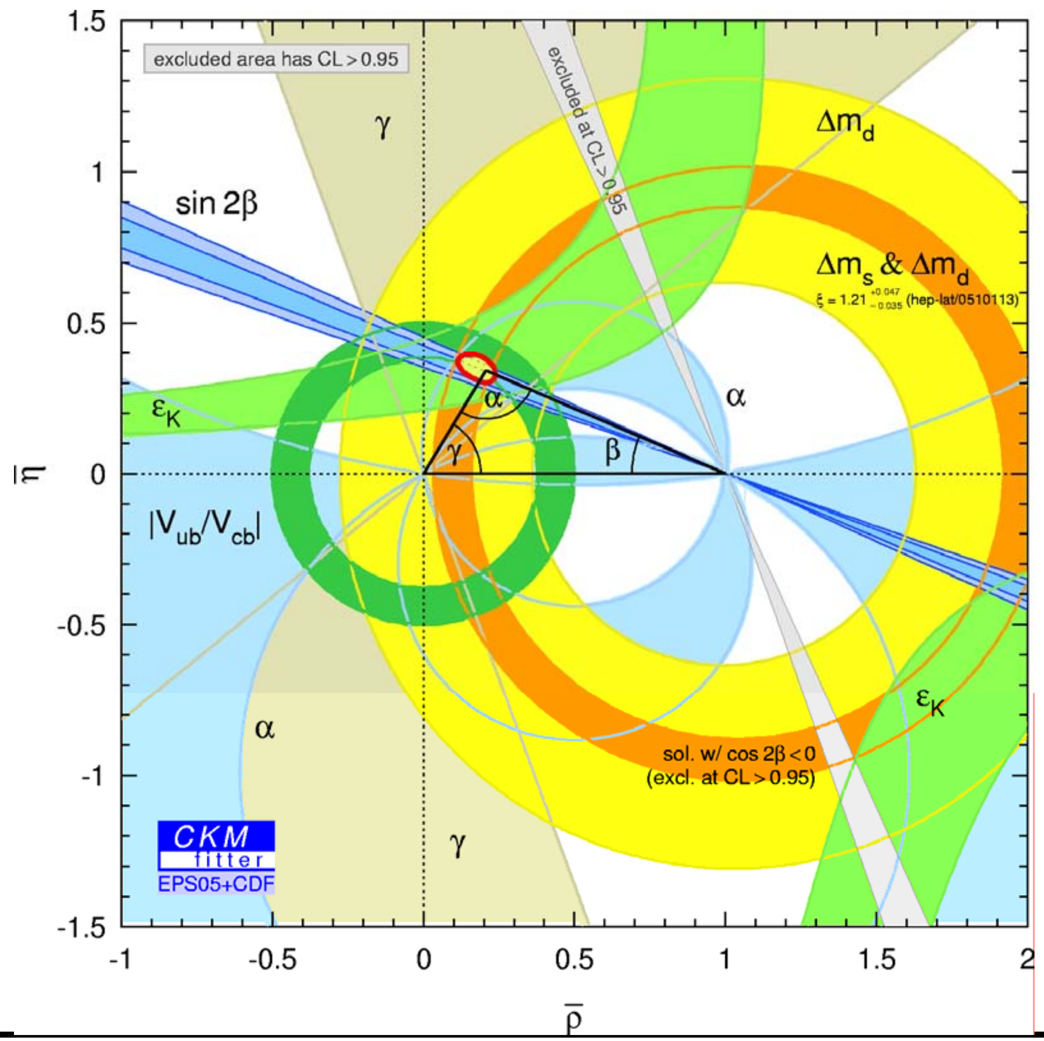


$$\Delta m_s = 17.31^{+0.33}_{-0.18}(\text{sta}) \pm 0.07\ (\text{sys})$$

0.2% probability Random tags would look as significant

For more details see the talk by S.Giagu.

B_s Mixing: UT constraints

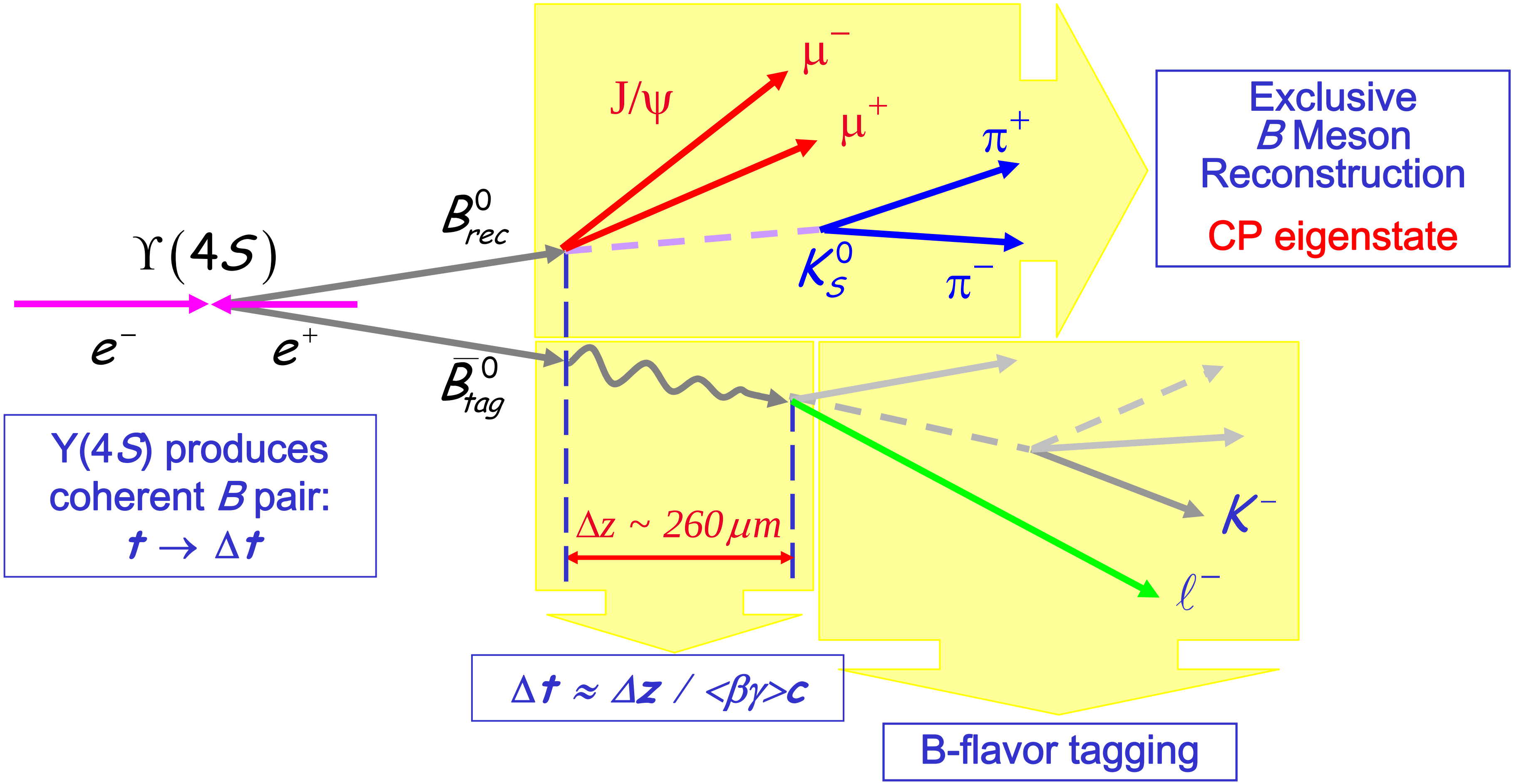


B-factory detectors

BABAR and *BELLE:*

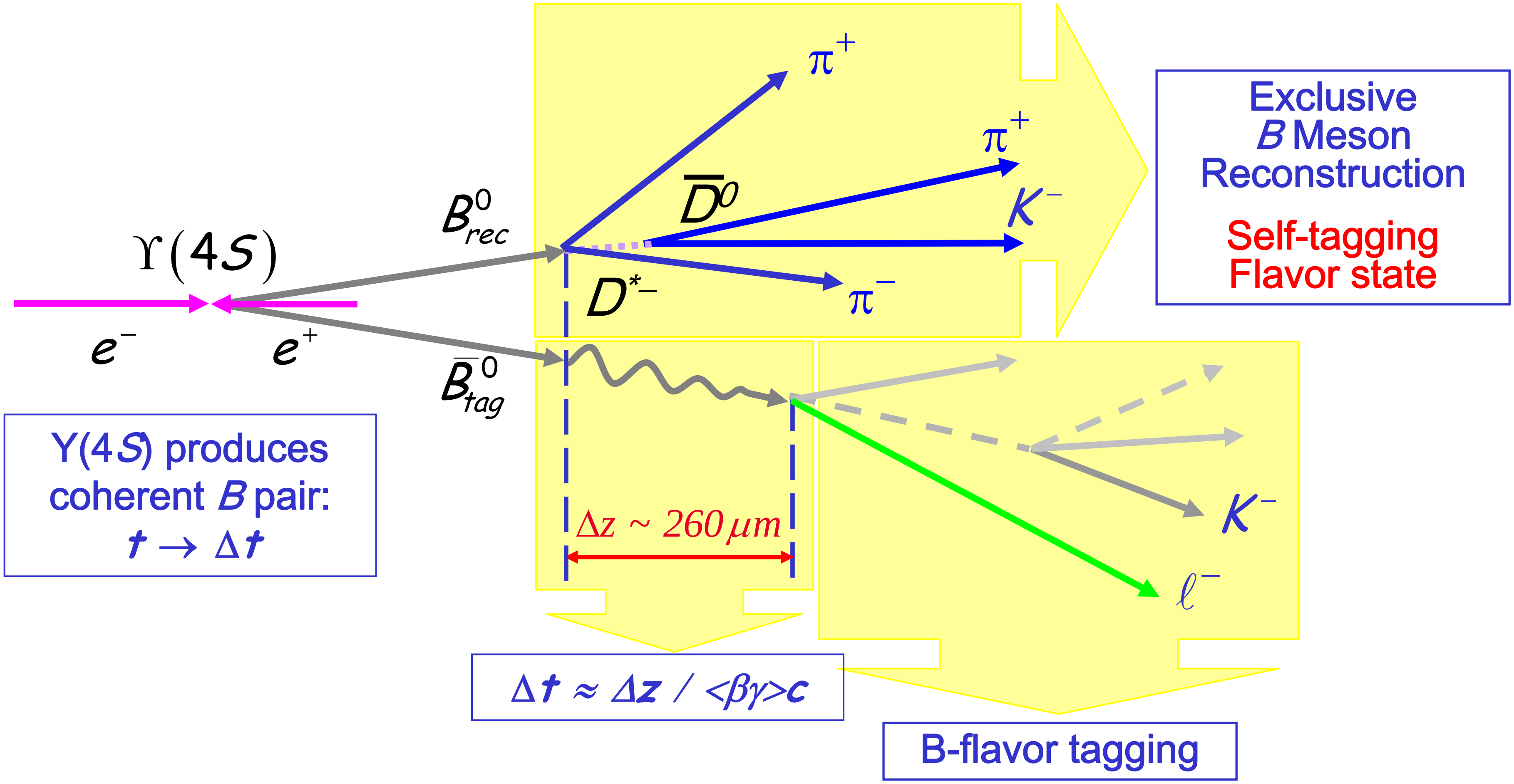
Optimized for time-dependent CP asymmetries

Time-Dependent CP Asymmetry Measurement



B-flavor tagging efficiency and Δt resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging flavor states)

Time-Dependent Mixing Measurement



B-flavor tagging efficiency and Δt resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging flavor states)

"Back-of-the-envelope" sensitivity

- CP asymmetry: sensitivity
  - Observed asymmetry: diluted! $A_{obs} = D\, A_{CP}$
  - Uncertainty on $A_{CP} = A_{obs} / D$:

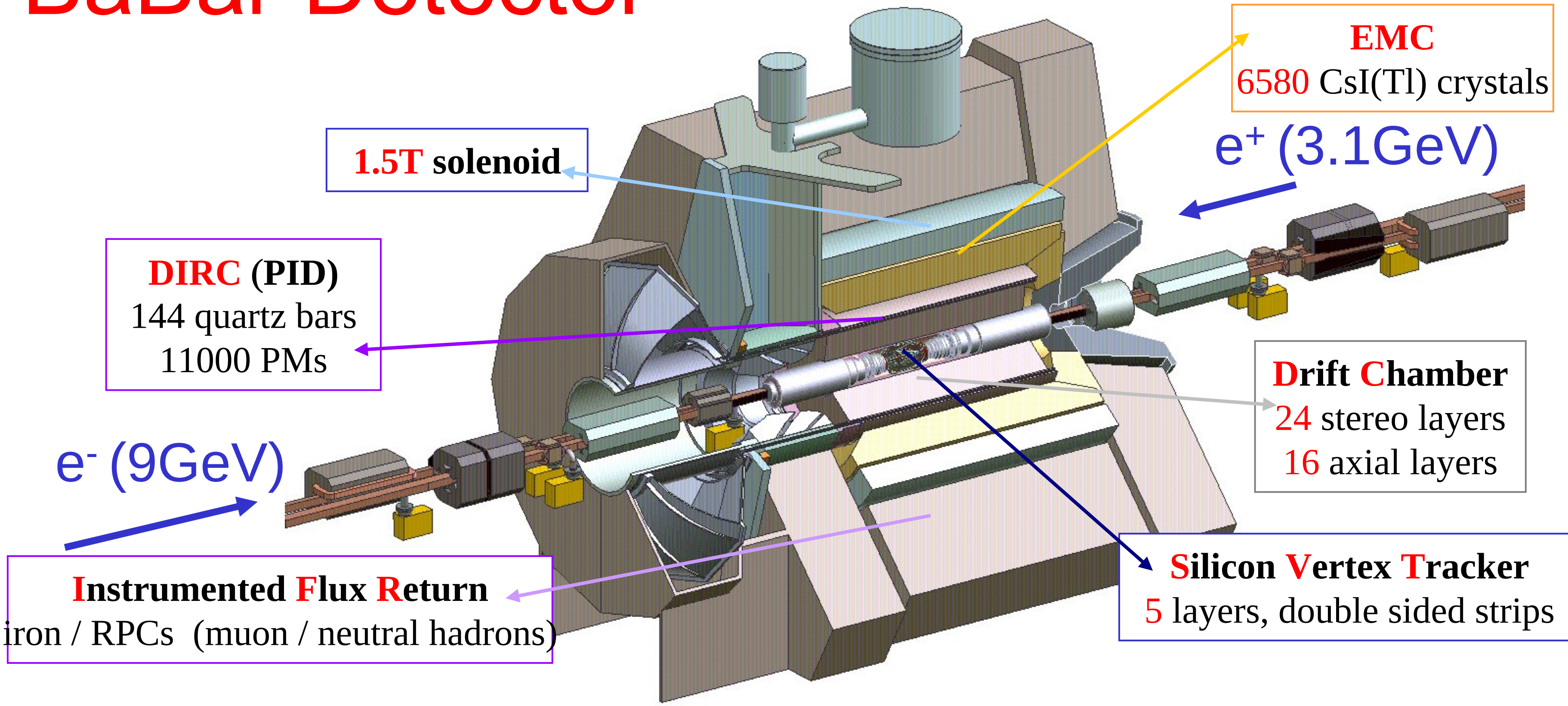
$$\delta A_{CP} \simeq \frac{1}{D\sqrt{N_{obs}}} = \frac{1}{D\sqrt{\epsilon \times Br \times N_{prod}}}$$

examples and numbers: see for instance BaBar Physics Book

- Figures of merit
  - Number of produced events $N_{prod} = \int L dt \times \sigma_{b\bar{b}} \times 2 f_0$
  - Efficiencies $\varepsilon = \varepsilon_{det} \times \varepsilon_{CP} \times \varepsilon_{tag}$
  - Dilution factors $D = d_{mix} \times d_{tag} \times d_{bkg}$

$d_{mix} = x/(1+x)^2 \approx 0.47$, for time-integrated

BaBar Detector



SVT: vertexing and tracking: crucial for Δt and low p_T tracks

DCH: main tracking device, also dE/dx for particle ID

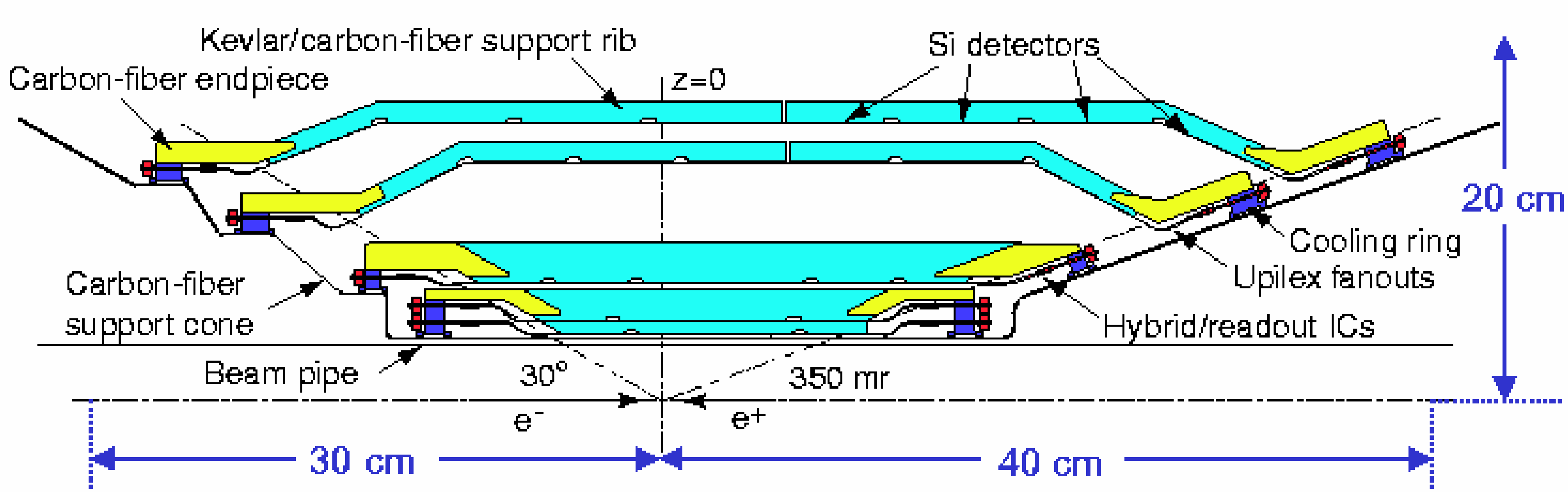
DIRC: K-π separation > 3.4σ for P < 3.5GeV/c

EMC: very good energy resolution; electron ID, π^0 and γ reco.

IFR: Muon and neutral hadrons (K^0_L) ID

BaBar: the Silicon Vertex Tracker

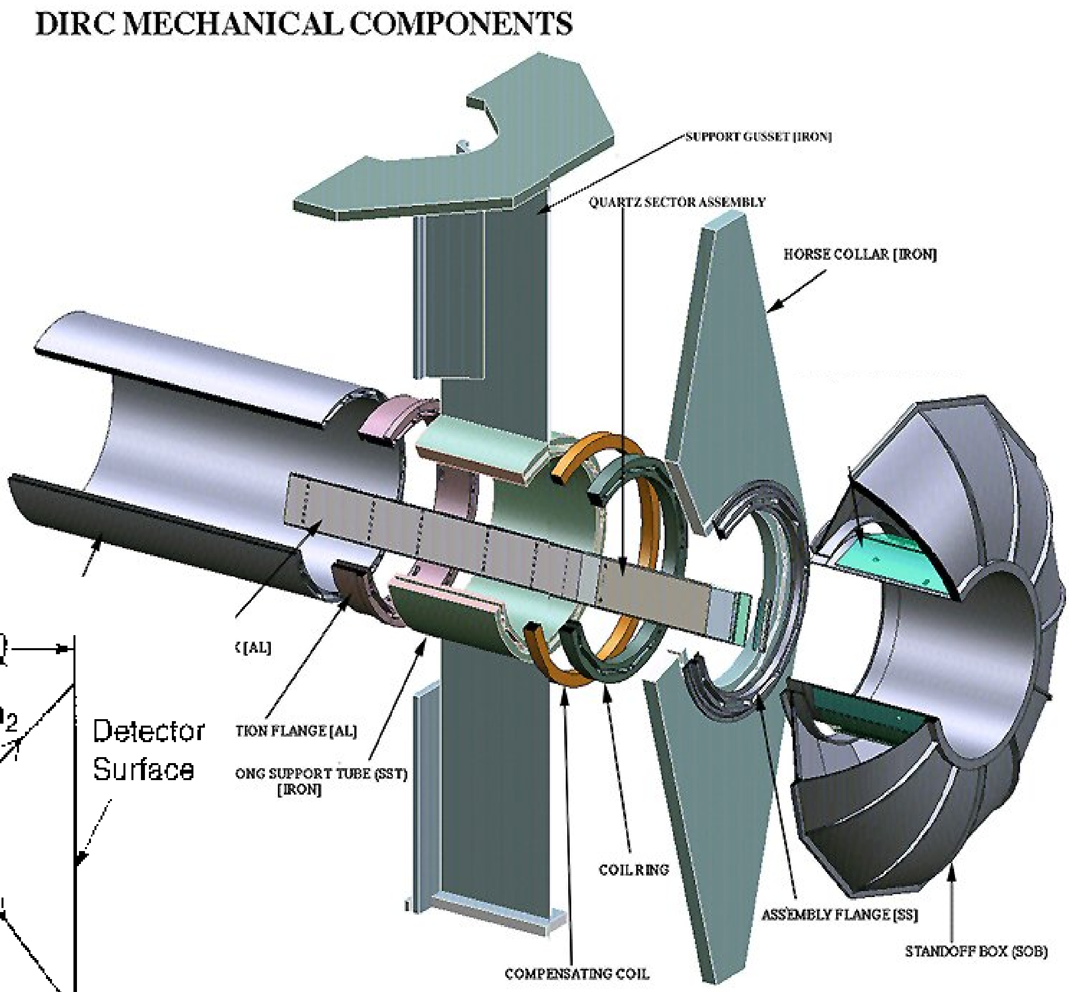
- double-sided Si microstrip detectors
- 5 layers: 340 wafers, 150000 readout channels
- $20^o < \theta < 150^o$
- $\sigma_{point} \approx$ 10-15 μm for the inner layers

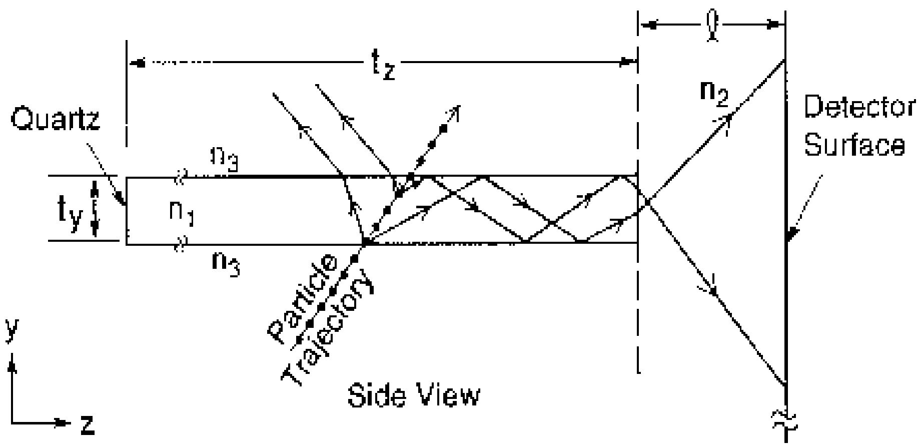


Particle identification: the DIRC

- Detector of Internally Reflected Cherenkov light

144 quartz bars (1.5 cm thick)
11000 PMTs, 25-50 p.e./particle,
9mrad single photon resolution





K identification performance

Charged K identified by

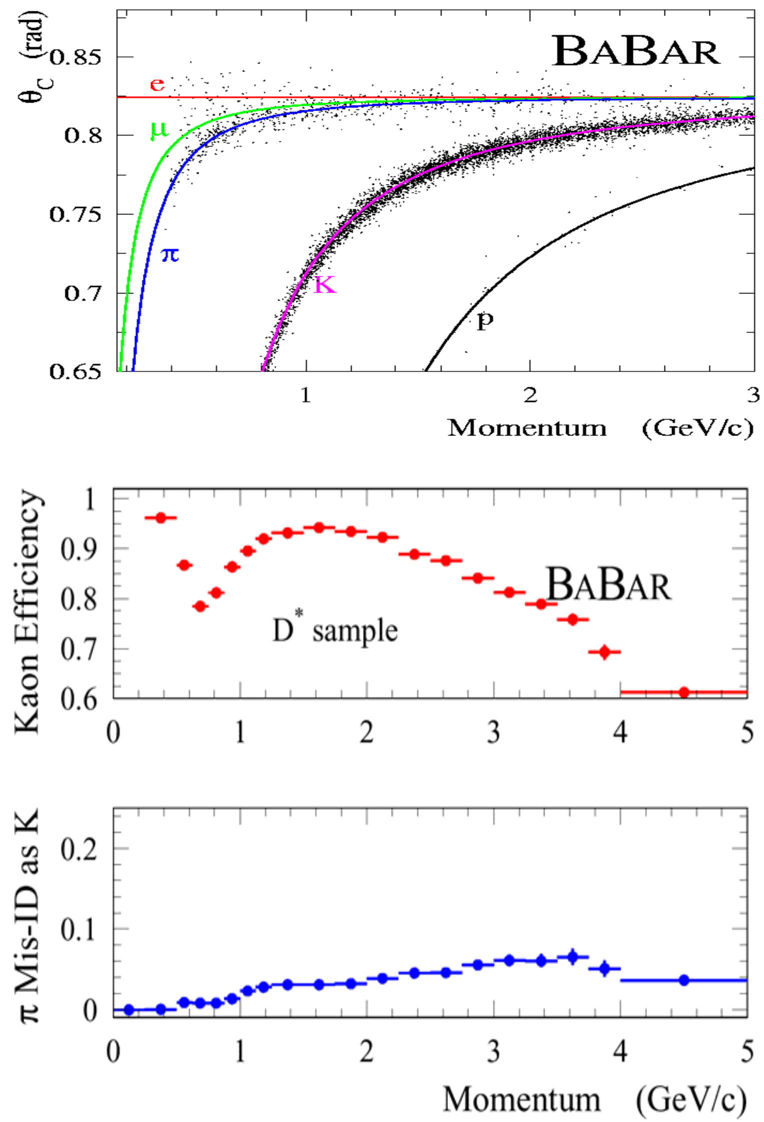
DIRC: Cerenkov angle

DCH: dE/dx (p < 0.7 GeV/c)

Efficiency and purity measured on control samples (soft pion tag)

$D^{*+} \rightarrow D^0\pi^+, \quad D^0 \rightarrow K^-\pi^+$

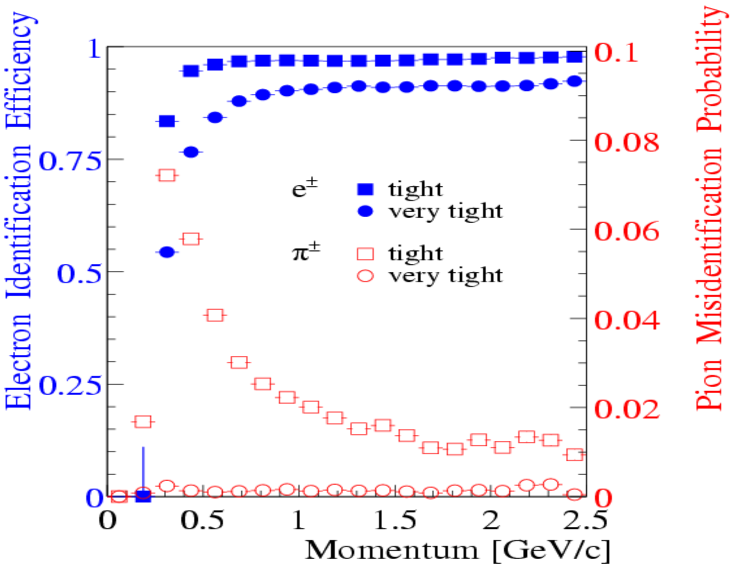
> 3.4σ π/K separation up to ≈ 3.5 GeV/c



Lepton identification performance

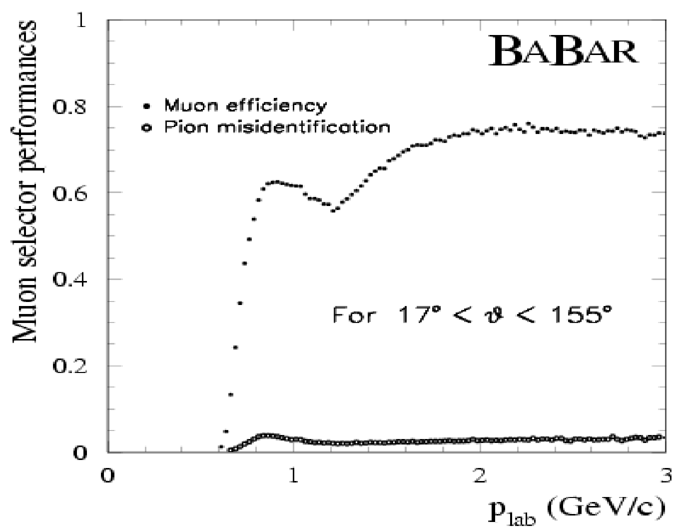
electrons

- Ingredients: track matching, E/p,
  - EMC cluster shape, dE/dx consistency
- Typical tight selection efficiency (E>0.5GeV):
  - ε ≈ 92%, 0.1% π misID
- Measured on control samples

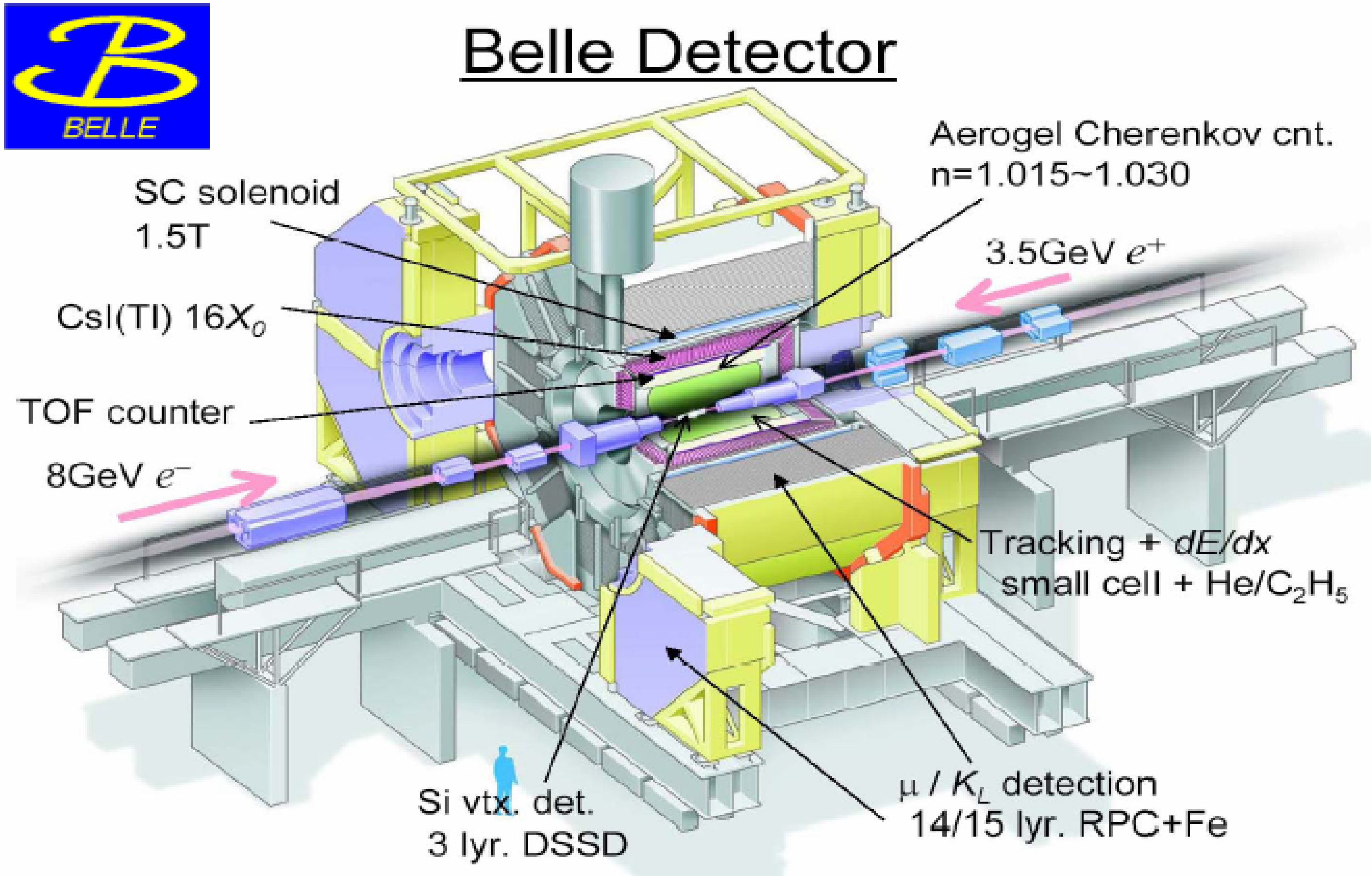


muons

- IFR penetration and hit pattern, MIP consistency in EMC
- Typical tight selection efficiency (E>1.5GeV):
  - ε ≈ 75%, 3% π misID



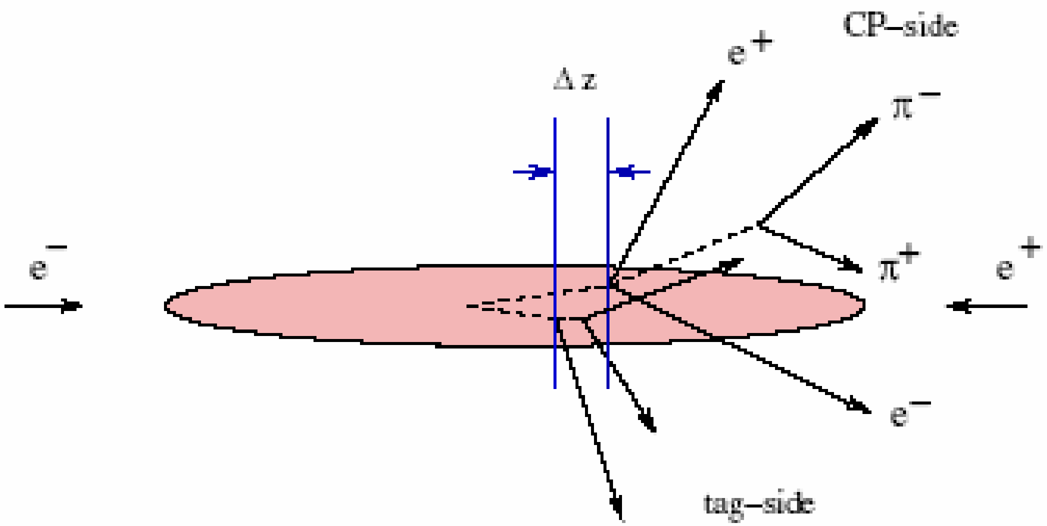
Belle detector at KEK



Both BaBar and Belle: optimized for CP asymmetries

Δt from $(\Delta z)_{LAB}$

K.Abe
LP 2005



- $\Delta z = z_{cp} - z_{tag}$

  $\Delta t \simeq \Delta z / (\gamma\beta c)$
- Interaction Point $\gg \Delta z$

  B flight-length in x-y: only $\sim 30\mu$
- C conservation in $\Upsilon(4S) \to BB$

  $\psi(t) = |B_1^0> |B_2^0> - |B_1^0> |B_2^0>$

  (one is B^0 and other is B^0 at any time)

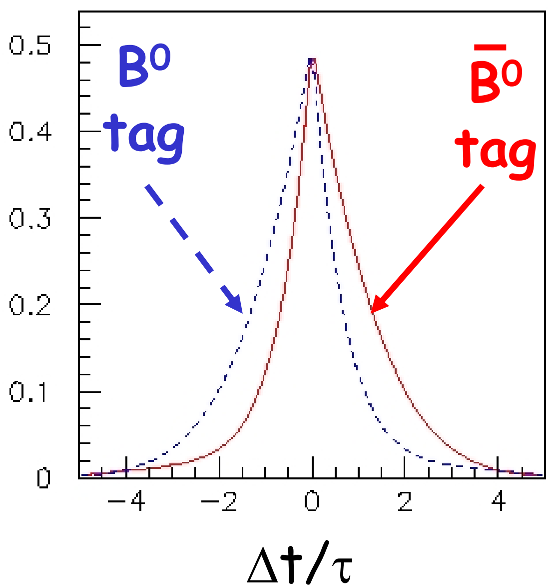
The other B provides time reference and flavor tagging at $\Delta t = 0$

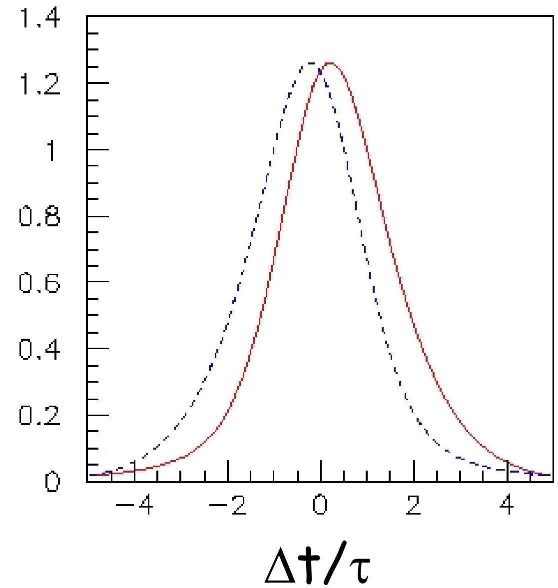
Parameters	BaBar	Belle
e^+e^- energy	$3.1 \times 9\,\mathrm{GeV}$	$3.5 \times 8.5\,\mathrm{GeV}$
$\gamma\beta$	0.56	0.425
Interaction point ($h \times v \times l$)	$120\,\mu\mathrm{m} \times 5\,\mu\mathrm{m} \times 8.5\,\mathrm{mm}$	$80\,\mu\mathrm{m} \times 2\,\mu\mathrm{m} \times 3.4\,\mathrm{mm}$
Typical Δz	$260\mu\mathrm{m}$	$200\mu\mathrm{m}$
σ_z (CP-side)	$50\,\mu\mathrm{m}$	$75\,\mu\mathrm{m}$
σ_z (tag-side)	$100 \sim 150\,\mu\mathrm{m}$	$140\,\mu\mathrm{m}$

Δt resolution effect

CP time-dependent asymmetry (C=0, S≠0)

Tag from "other B"





perfect resolution

smeared resolution

Time-integrated asymmetry = 0
⇒ Need both Δt and tag !

$$B^0\left(\overline{B}^0\right) \rightarrow f_{CP}$$

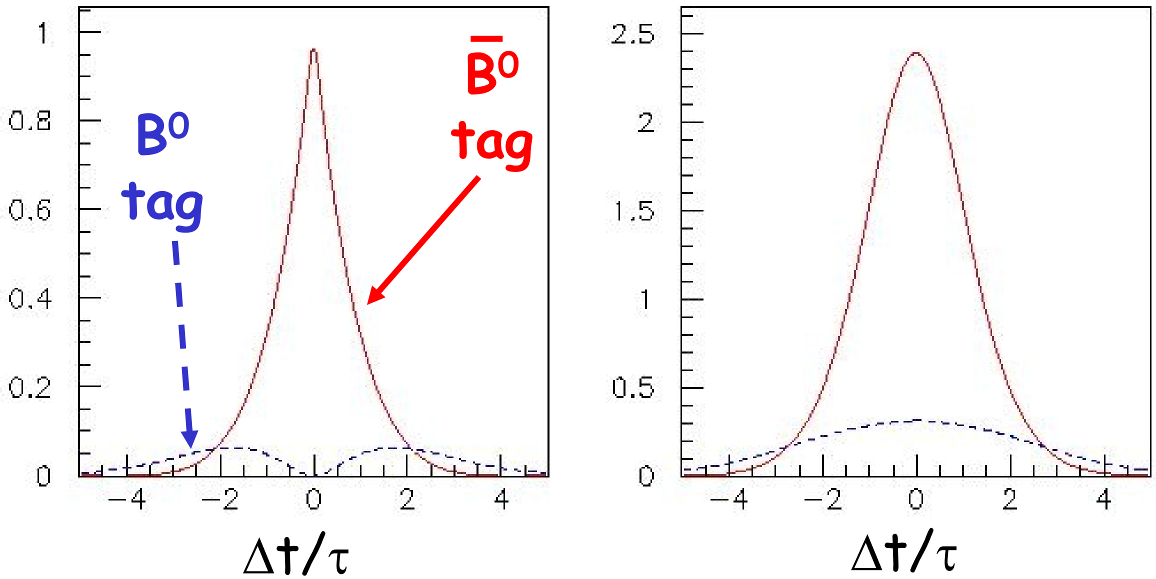
Δt resolution dominated by tag side:
~1 ps ⇔ 170 μm

$\tau_B \sim 1.6$ ps ⇔ 250 μm

Δt resolution effect

time-dependent mixing

Tag from "other B"



perfect resolution | **smeared resolution**

Measure mixing
and tag efficiency
using self-tagging decays

$$\overline{B}^0 \rightarrow \bar{f}_{self-tag}$$

Δt resolution dominated by tag side:
$\sim$1 ps $\Leftrightarrow$ 170 μm

$\tau_B \sim 1.6$ ps $\Leftrightarrow$ 250 μm

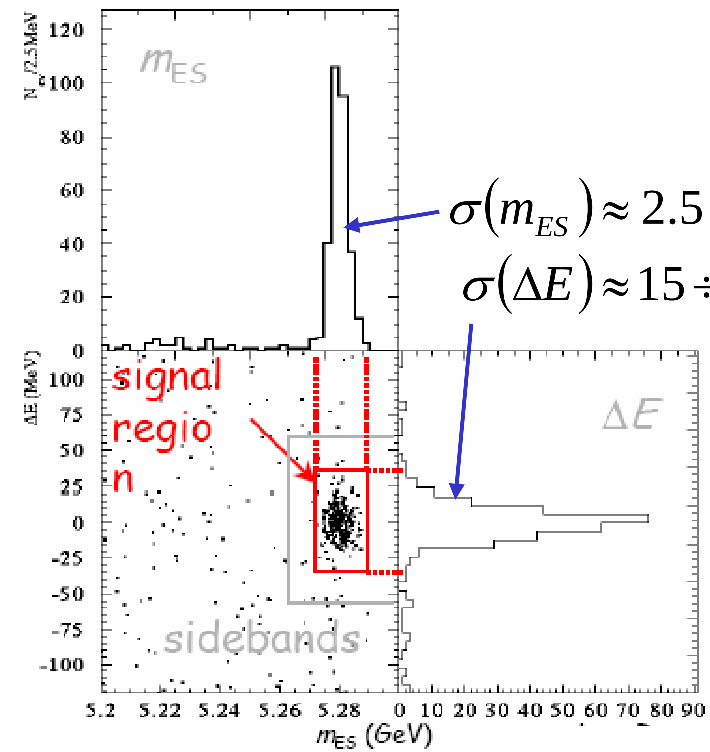
Exclusive B decay reconstruction

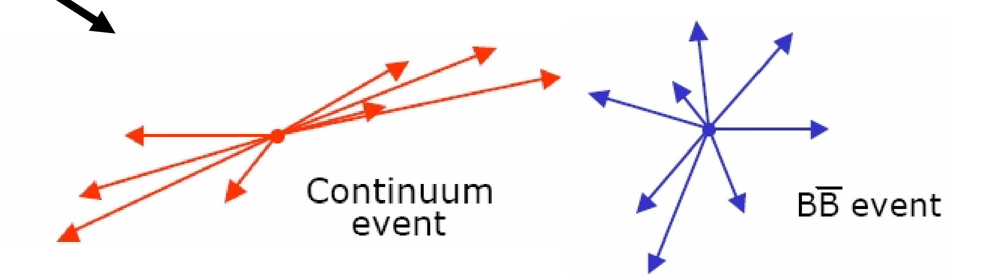
- Likelihood fits with discriminating variables:
  - Kinematics:

$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

$$\Delta E = E_B^* - E_{beam}^*$$

  - Particle ID: π, K, e, μ, …
  - Event shape variables, to separate the continuum bkgd (use “off-resonance” data as control sample!!!)
- Efficiency
  - Typically $\varepsilon \approx 15 \div 40\%$
- Purity
  - Up to 97% (for $J/\psi K_S$)





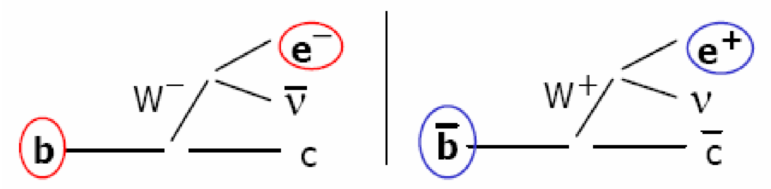
B Flavour Tagging

CP asymmetry is between $B^0 \to f$ and $\overline{B^0} \to f$

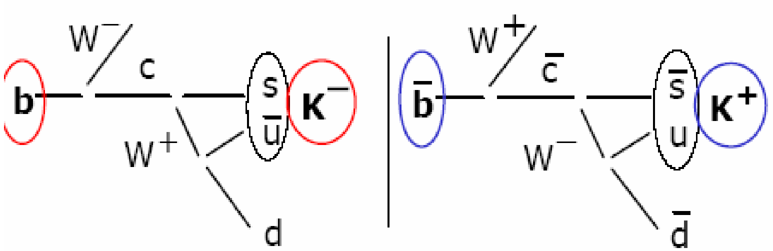
Must tag flavor at $\Delta t=0$ (when we know flavor of two Bs is opposite).

Use decay products of *other* (tag) B.

Leptons : Cleanest tag. Correct >95%



Kaons : Second best. Correct 80-90%



Soft and hard pion tagging

$$\bar{B}^0 \to D^{*+}\pi^-$$

$$\hookrightarrow D^0\pi^+$$

$\bar{B}^0$: fast π^-, soft π^+

B^0: fast π^+, soft π^-

Overall tagging performance

$$\sum_i \varepsilon_i (1-2\omega_i)^2 \approx 28\%$$

recently improved to 30.5%

BaBar

ε_i tag efficiency

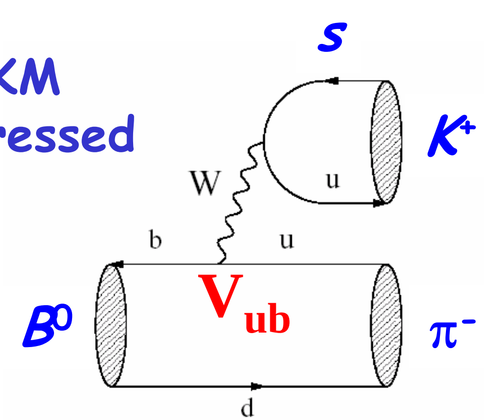
ω_i wrong tag probability

Direct CP Violation in B decays

$B^0 \to h^+h^-$: direct CPV ?

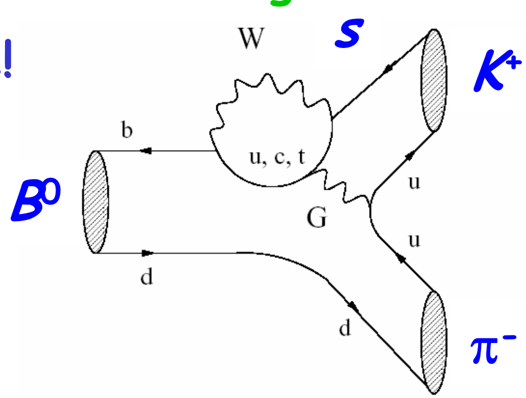
Tree-level $b \to u$ = T

CKM suppressed



Internal Penguin = P

Large!



$$BF(B^0 \to K^+\pi^-) = (18.5 \pm 1.0) \times 10^{-6}$$

Penguin dominated:

$$A_{K\pi} = \lambda^2 e^{i\gamma} T + P$$

Expect direct *CPV* asymmetry and constraints on γ (theoretically difficult!)

$$A = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = \frac{2|T||P|\sin\delta\sin\gamma}{|T|^2 + |P|^2 + 2|T||P|\cos\delta\cos\gamma}$$

(where δ = CP-conserving strong phase complicated by long-distance & re-scattering)

Look for direct CPV!

Direct CP asymmetry in $B^0 \to K^+\pi^-$!

- BaBar analysis (2004)
  - 227 M $B\overline{B}$ events
  - 68030 selected events
- Extended ML fit:
  - discriminating variables:

$$\vec{x}_j = \{m_{ES}, \Delta E, \mathcal{F}, \theta_c^+, \theta_c^-\}$$

  - Fisher, Cherenkov angles
- Fitted parameters
  - Yields for $K\pi$, $\pi\pi$, KK

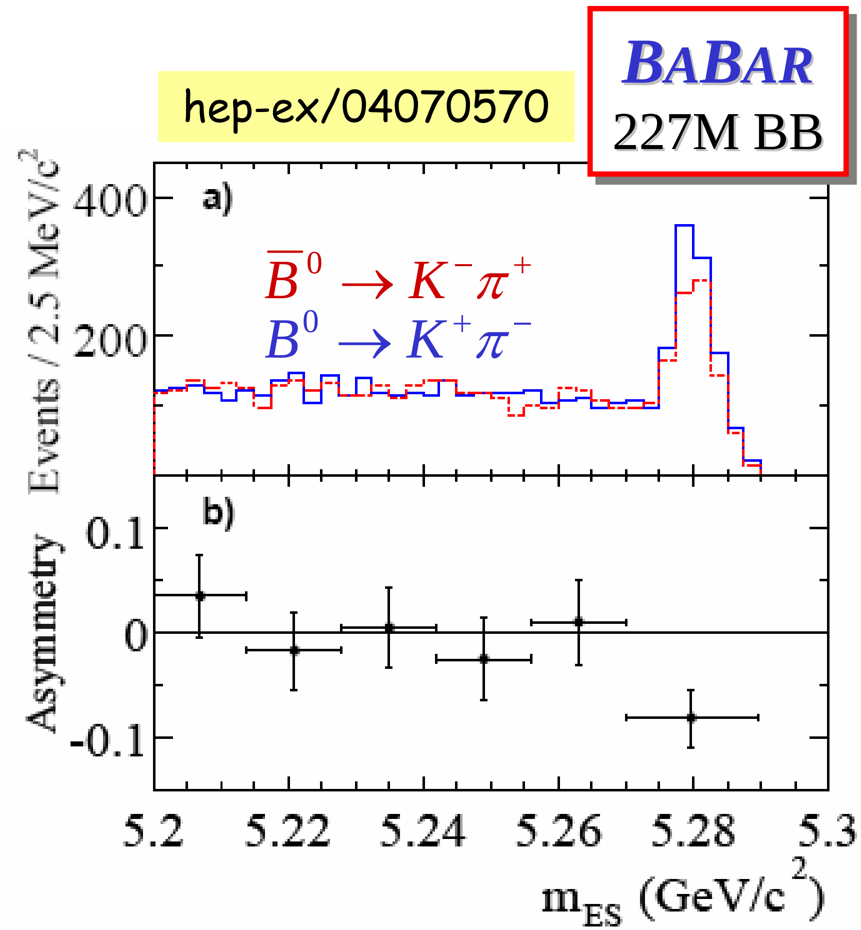
$$n_{K\pi} = 1606 \pm 51$$

$$n_{\pi\pi} = 467 \pm 33$$

$$n_{KK} = 3 \pm 12$$

  - asymmetries for signal and background $A_{K\pi}$, $A_{K\pi}{}^b$

(Likelihood Projection !)



Observation in 2004

- BaBar result (significance: 4.3σ), soon confirmed by Belle

$$A_{K\pi} = \frac{n(K^-\pi^+) - n(K^+\pi^-)}{n(K^-\pi^+) + n(K^+\pi^-)} = -0.133 \pm 0.030\,(\text{stat}) \pm 0.009\,(\text{syst})$$

- Systematic uncertainty
  - Dominated by the asymmetry of identified charged tracks
  - Controlled by the background asymmetry, compatible with zero; the bkgd is from real K and π with the correct kinematics, from opposite jets of continuum cc events

$$A^b_{K\pi} = -0.001 \pm 0.008$$

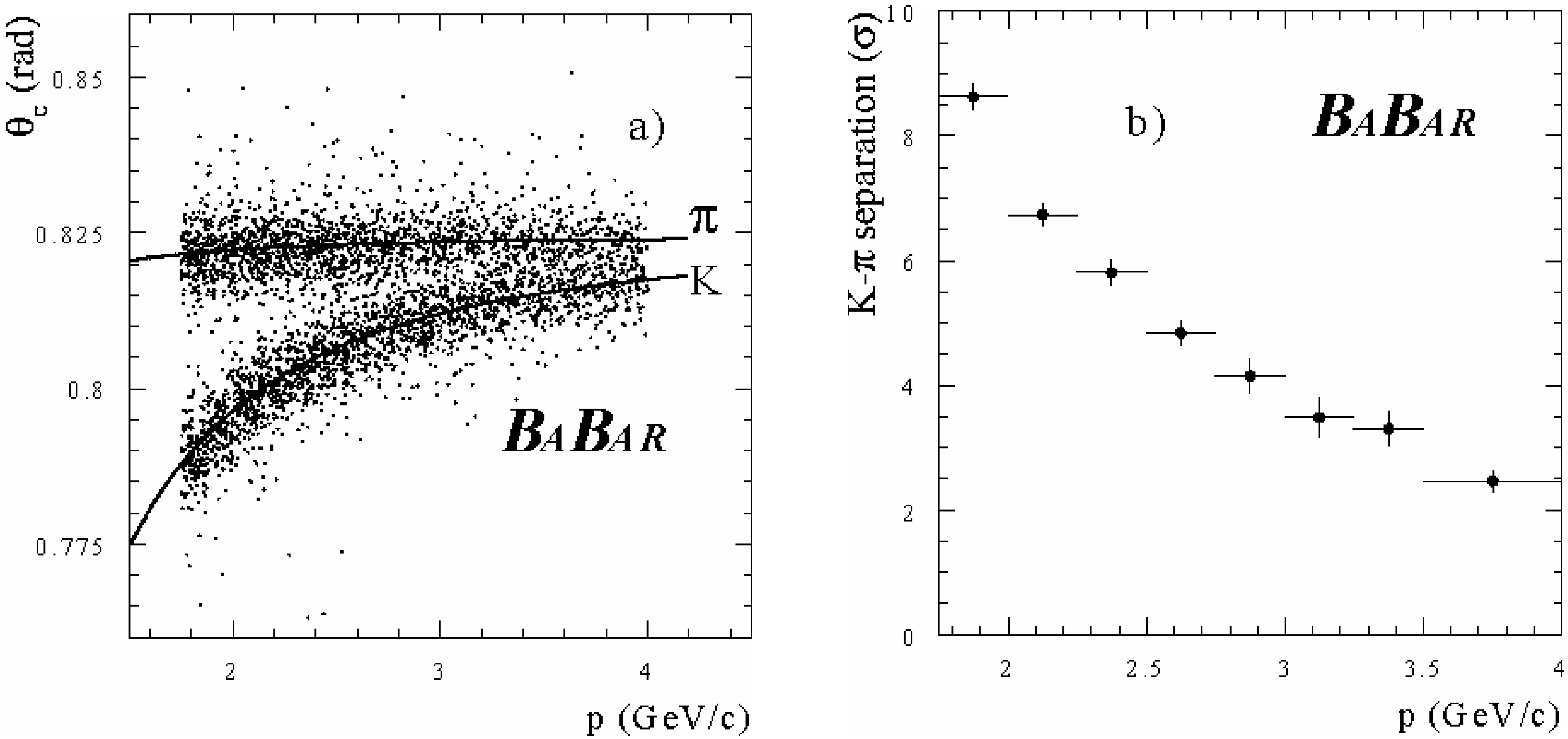
- Coherent results in all subsamples

Sample	$N_{B\overline{B}}$	$n_{K\pi}$	$A_{K\pi}$	$A^b_{K\pi}$
1999–2001	21.1	142 ± 15	-0.240 ± 0.102	0.006 ± 0.026
2002	66.4	479 ± 27	-0.102 ± 0.055	-0.008 ± 0.015
2003	34.1	241 ± 19	-0.109 ± 0.079	0.007 ± 0.021
2004	104.9	743 ± 33	-0.142 ± 0.044	0.004 ± 0.012

K-π separation

Crucial ingredient to distinguish B → Kπ from B→ ππ

particle identification: K/π separation > 3σ up to 3.5 GeV

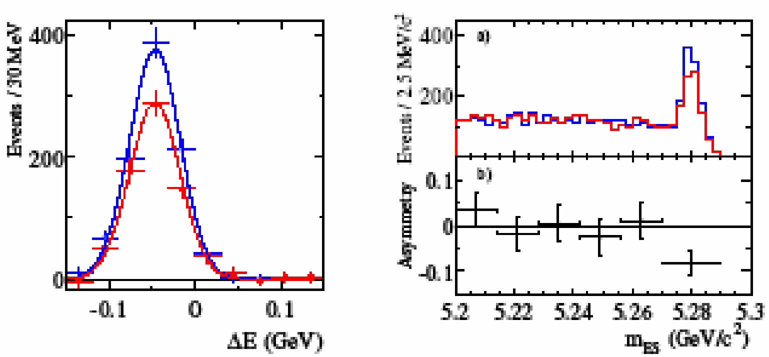


Update at LP 2005

K.Abe
LP 2005

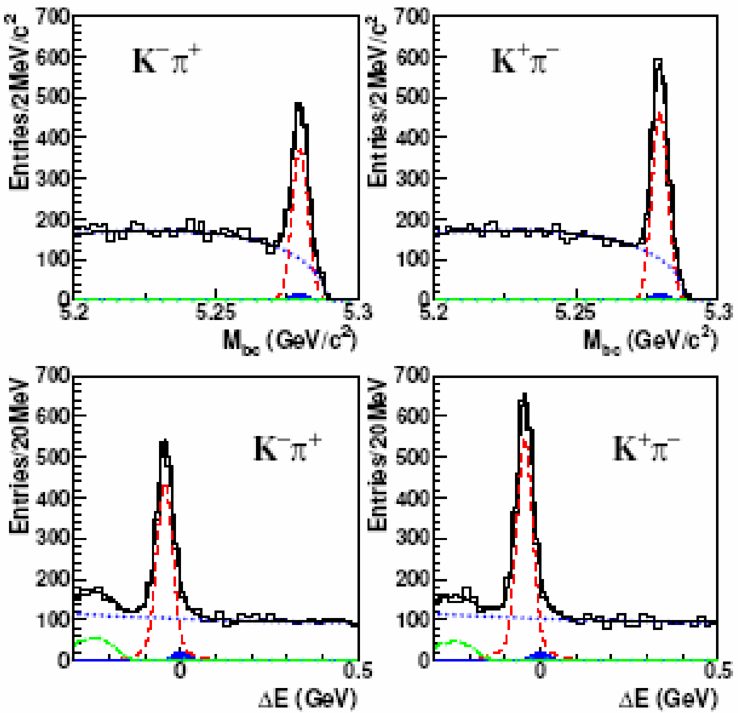
$\bar{B}^0 \to K^-\pi^+$ is Different from $B^0 \to K^+\pi^-$

Babar $(227 \times 10^6 B\bar{B})$



solid lines are for $K^+\pi^-$

Belle $(386 \times 10^6 B\bar{B})$



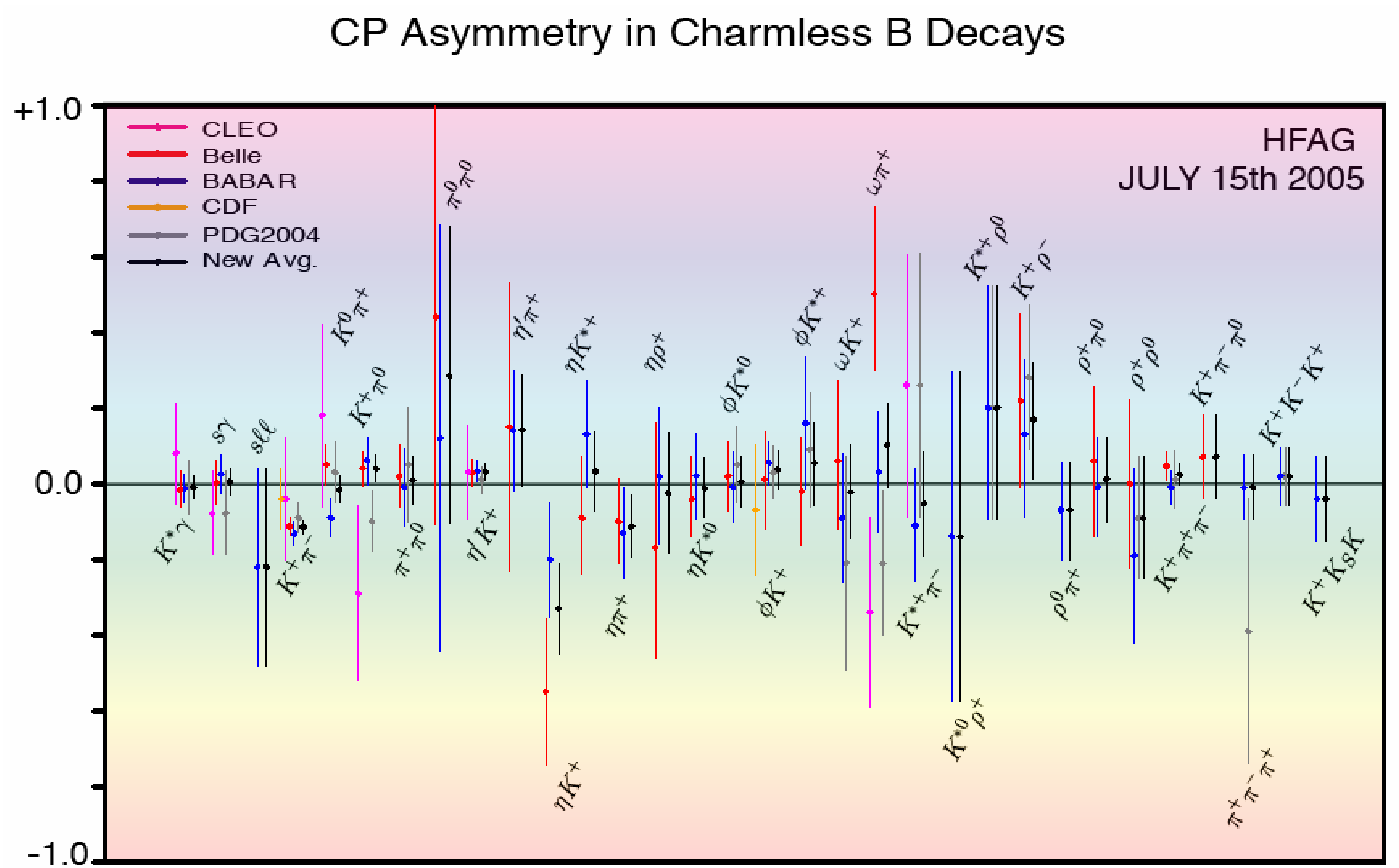
$$A_{CP}(K^+\pi^-) = -0.133 \pm 0.030 \pm 0.009$$

$$A_{CP}(K^+\pi^-) = -0.113 \pm 0.022 \pm 0.008$$

(was $-0.101 \pm 0.025 \pm 0.005$ with $275 \times 10^6 B\bar{B}$)

Definitively rules out Superweak models

“direct” A_{CP}: experimental status

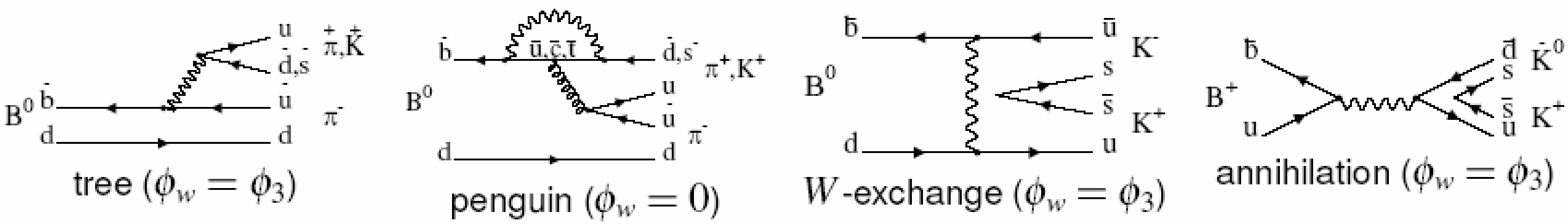


No other evidence up to now

A_{CP} in charmless $B \to PP$

K.Abe, LP05

Decay Mode	BaBar	Belle	SM diagrams
$K^+\pi^-$	$-0.133 \pm 0.030 \pm 0.009$	$-0.113 \pm 0.021 \pm 0.008$	tree, penguin
$K^+\pi^0$	$+0.06 \pm 0.06 \pm 0.01$	$+0.04 \pm 0.04 \pm 0.02$	tree, penguin
$K_S^0\pi^+$	$-0.09 \pm 0.05 \pm 0.01$	$+0.05 \pm 0.05 \pm 0.01$	penguin
$K_S^0\pi^0$	$-0.06 \pm 0.18 \pm 0.03$	$+0.16 \pm 0.29 \pm 0.05$	penguin
$\pi^+\pi^-$	$+0.09 \pm 0.15 \pm 0.04$	$+0.52 \pm 0.14$	tree, penguin
$\pi^+\pi^0$	$-0.01 \pm 0.10 \pm 0.02$	$+0.02 \pm 0.08 \pm 0.01$	tree
$\pi^0\pi^0$	$+0.12 \pm 0.56 \pm 0.06$	$0.44^{+0.53}_{-0.52} \pm 0.17$	tree, penguin
K^+K^-	signal not seen	signal not seen	W-exchange
K^+K^0	seen	seen	penguin, annihilation
$K^0\bar{K}^0$	seen	seen	penguin



Extraction of ϕ_3 may be difficult due to hadronic effects. Hope to learn about them from measurements.
(e.g. Why $A_{CP}(K^+\pi^0) \neq A_{CP}(K^+\pi^-)$? Expect the same based on naive factorization)

B_d : limits on CPV in mixing

B_d lifetime and mixing: status

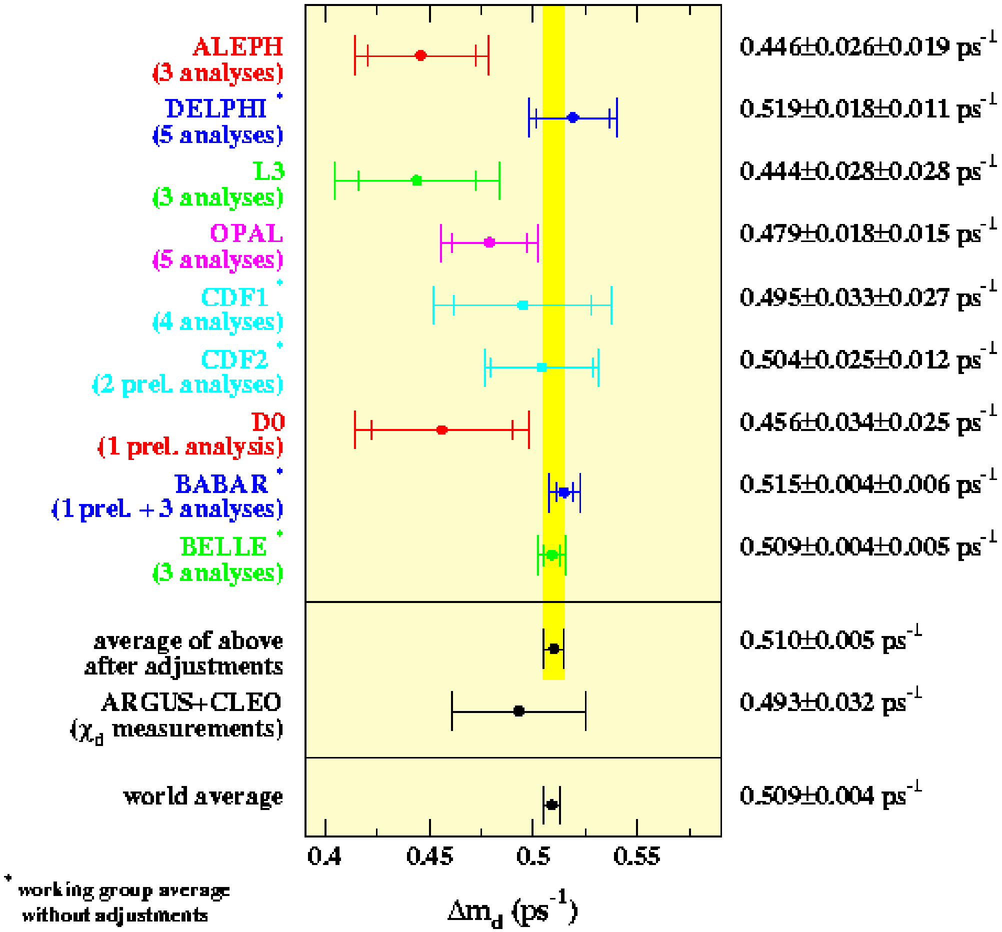
HFAG, Winter 2005

(from all ALEPH, DELPHI, L3, OPAL, CDF, D0, BABAR, BELLE, ARGUS and CLEO measurements)

assuming

$$\tau_{Bd} = 1.528 \pm 0.009 \text{ ps}$$

$$\Delta m_d = 0.509 \pm 0.004 \text{ ps}^{-1}$$
$$x_d = 0.778 \pm 0.008$$
$$\chi_d = 0.189 \pm 0.002$$



A_{SL} and CPV in mixing

CPV in $B\bar{B}$ Mixing (Analogous to ε_K in K^0 System)

CPV in mixing $\rightarrow |q/p| \neq 1$

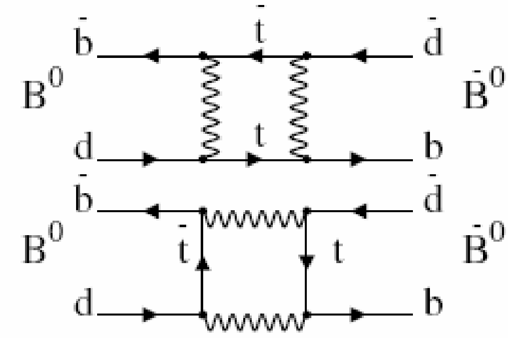
This can occur if M_{12} and Γ_{12} have different phases

- $\left|\frac{\Gamma_{12}}{M_{12}}\right| \simeq \frac{3\pi}{2}\frac{m_b^2}{m_W^2}\frac{1}{S_0(m_t^2/m_W^2)} \sim \mathcal{O}(\frac{m_b^2}{m_t^2})$
- $\phi_{M_{12}} - \phi_{\Gamma_{12}} = \pi + \mathcal{O}(\frac{M_c^2}{m_b^2})$ ($\phi_{M_{12}} = \phi_1$ in SM)
- $1 - |\frac{q}{p}|^2 \simeq Im\left(\frac{\Gamma_{12}}{M_{12}}\right) \sim \mathcal{O}(10^{-3})$

Mass and flavor eigenstates:

$|B_1> = p|B^0> + q|\bar{B}^0>$

$|B_2> = p|B^0> - q|\bar{B}^0>$



Charge asymmetry in same-sign dilepton events $A_{SL} = (1 - |q/p|^4)/(1 + |q/p|^4)$

at the B-factories:

$$A_{SL} \equiv \frac{P(\bar{B}^0 \rightarrow B^0) - P(B^0 \rightarrow \bar{B}^0)}{P(\bar{B}^0 \rightarrow B^0) + P(B^0 \rightarrow \bar{B}^0)} = \frac{\Gamma_{\Upsilon(4S) \rightarrow l^+ l^+} - \Gamma_{\Upsilon(4S) \rightarrow l^- l^-}}{\Gamma_{\Upsilon(4S) \rightarrow l^+ l^+} + \Gamma_{\Upsilon(4S) \rightarrow l^- l^-}}$$

A_{SL} , |q/p| , ε_B are related

A_{SL} observable and CP parameters:

$$A_{SL} \equiv \frac{P\left(\overline{B}^0 \to B^0\right) - P\left(B^0 \to \overline{B}^0\right)}{P\left(\overline{B}^0 \to B^0\right) + P\left(B^0 \to \overline{B}^0\right)}$$

$$A_{SL} = \frac{\Gamma_{\Upsilon(4S)\to l^+l^+} - \Gamma_{\Upsilon(4S)\to l^-l^-}}{\Gamma_{\Upsilon(4S)\to l^+l^+} + \Gamma_{\Upsilon(4S)\to l^-l^-}} =$$

← at the B-factories

$$= \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \cong \frac{4\,\mathrm{Re}\,\varepsilon_B}{1 + |\varepsilon_B|^2}$$

← equivalent to ε_K in the K system

$$\varepsilon_B = \frac{p - q}{p + q} \quad \Rightarrow \quad \frac{q}{p} = \frac{1 - \varepsilon_B}{1 + \varepsilon_B}$$

$$\left|\frac{q}{p}\right| = \sqrt[4]{\frac{1 - A_{SL}}{1 + A_{SL}}}$$

CPV in B_d mixing: A_{SL}

Experimental status:
from measurements at LEP, CLEO, BaBar and Belle:

$$|q/p| = 1.0013 \pm 0.0067$$
$$A_{SL} = -0.0026 \pm 0.0034$$
$$\frac{\mathrm{Re}\,\varepsilon_B}{1+|\varepsilon_B|} = -0.0007 \pm 0.0017$$

HFAG, Winter'05 average

Not easy to improve: systematics!

For example, the most recent paper: *BELLE,* hep-ex/0505017:

$$A_{\rm sl} = (-1.1 \pm 7.9(\mathrm{stat}) \pm 7.0(\mathrm{sys})) \times 10^{-3},$$
$$|q/p| = 1.0005 \pm 0.0040(\mathrm{stat}) \pm 0.0035(\mathrm{sys}).$$
$$\frac{\mathrm{Re}(\epsilon_B)}{1+|\epsilon_B|^2} = (-0.3 \pm 2.0(\mathrm{stat}) \pm 1.7(\mathrm{sys})) \times 10^{-3}$$

BELLE 2005
(78 + 9) fb^{-1}

< 1/5 of the available data !

A_{SL} : what does it take?

To measure the charge asymmetry in dilepton events,

Quoting from *BELLE,* hep-ex/0505017:

careful charge-dependent corrections, in several steps.

Subtraction of the background from continuum $e^+e^- \rightarrow q\bar{q}$ (where q = u, d, s or c), using off-resonance data.

From control samples: corrections of all detected lepton tracks:

- charge asymmetries in the efficiencies for track finding (< 1%) and for lepton identification (< 1%)
- charge-dependent probabilities of mis-identifying hadrons as leptons (main effect: 2% “fake” $\mu^\pm$ are $K^\pm$, with $0.02\times0.5 \approx 1\%$ charge asymmetry)

Separation of the remaining backgrounds from $B^0\bar{B}^0$ and B^+B^- using their different behavior in the Δt (Δz) distributions.

A_{SL} : typical systematic uncertainties

TABLE II: Source of systematic errors for the measurement of A_{sl}.

Category	Source	ΔA_{sl} ($\times 10^{-3}$)
Event selection	Track selection	± 2.61
	$\cos\theta^*_{\ell\ell}$ cut	± 0.63
	Lepton pair veto	± 2.33
Continuum subtraction		± 4.88
Track corrections	Track finding efficiency	± 1.56
	Electron identification efficiency	± 0.56
	Muon identification efficiency	± 1.98
	Fake electrons	± 0.45
	Fake muons	± 0.81
	Relative multiplicity	± 0.56
Δz fit for dileptons	Detector response function	± 0.07
	Δm_d	± 0.08
	τ_{B^0}	± 0.07
	69 μm smearing of background Δz	± 0.13
	Statistics of signal MC	± 0.01
	Statistics of background MC	± 0.19
	Fitting range	± 0.04
	Assuming $N_b^{++} = N_b^{--}$	± 1.59
Δz fit for A_{sl}	Fitting range	± 1.30
Total		± 6.97

Control samples:

$e^+e^- \to (e^+e^-)e^+e^-$, $e^+e^-\gamma$

simulation embedded in data

$K^0_S \to \pi^+\pi^-$, $\phi \to K^+K^-$,

$\Lambda \to p\pi$,

$(D^{*-} \to \overline{D}^0\pi^-$, $\overline{D}^0 \to K^-\pi^+)$

A_{SL}:
systematic uncertainty
BELLE, hep-ex/0505017
$0.007 = 7\times 10^{-3}$

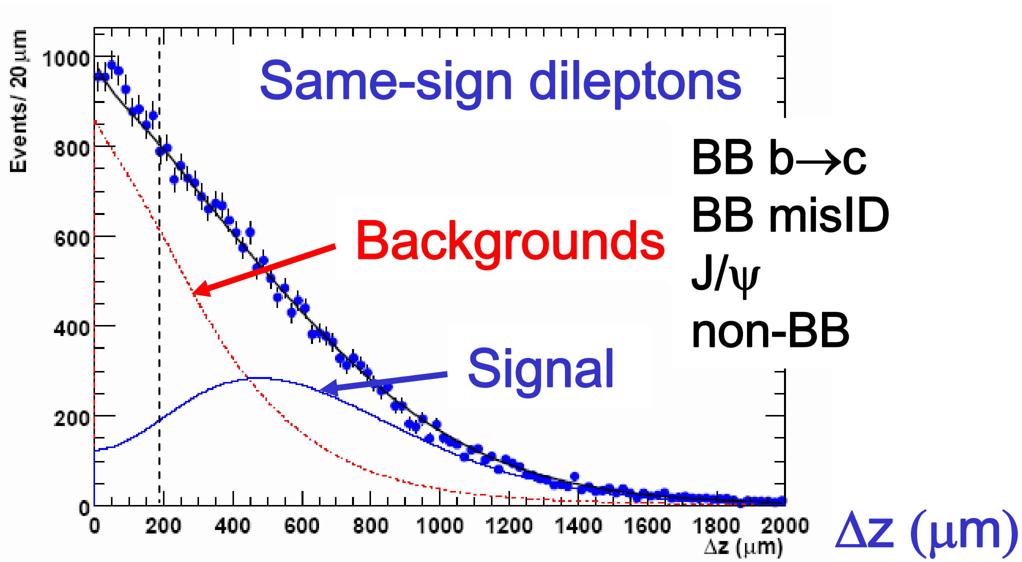
Older BaBar result (23 M B-pairs)

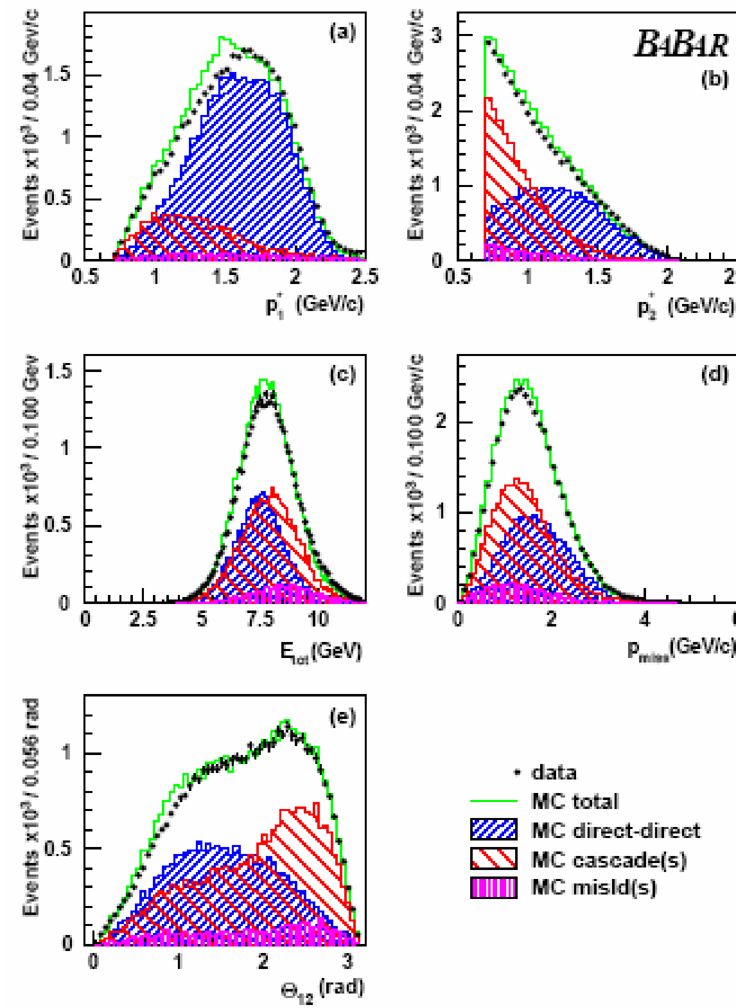
$$A_{T/CP} = (0.5 \pm 1.2(\text{stat}) \pm 1.4(\text{syst}))\ \%$$

PRL 88, 231801 (2002)

$$|q/p| = 0.998 \pm 0.006(\text{stat}) \pm 0.007(\text{syst}).$$

Type of systematic error	$\sigma(A_{T/CP})(\%)$
Electron charge asymmetry in the detection	0.5
Muon charge asymmetry in the detection	0.6
Non-$B\overline{B}$ background charge asymmetry	0.7
$B\overline{B}$ background charge asymmetry	0.9
Correction of the background dilution	0.01
Total	1.4





Lecture 3: Summary

- Bs mixing from CDF and D0:

  Still $x_s > 21$, significant work needed to improve (…LHCb ?)

- "Direct" CPV seen in $B_d \to K\pi$!

  $$A_{CP}\left(K^+\pi^-\right) = -0.133 \pm 0.030 \pm 0.009$$ BaBar 2004

  $$A_{CP}\left(K^+\pi^-\right) = -0.113 \pm 0.022 \pm 0.008$$ Belle update 2005

- "Indirect" CPV in mixing (ASL) not seen yet

  $$A_{SL} = -0.0026 \pm 0.0034$$ HFAG world average, winter 2005

Next: … Unitarity Angles!