CP Violation Measurements in the $B\bar{B}$ System

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- CP violation in B decays
- Measurements of CP violation at Belle and BaBar
- Plans for Future
- Precision B Physics at Hadron Machines

CP Violation

Fundamental quantity: distinguishes matter from anti-matter.

A bit of history:

- First seen in K^0 decays in 1964
- Discovery of $B^0 - \bar{B}^0$ mixing at ARGUS in 1987 indicated that the effect could be large in B decays
- Many experiments were proposed to measure it, some general purpose experiments tried to do it
- Discovery in 2001 by the two dedicated spectrometers Belle and BaBar at asymmetric e^+e^- colliders - B factories

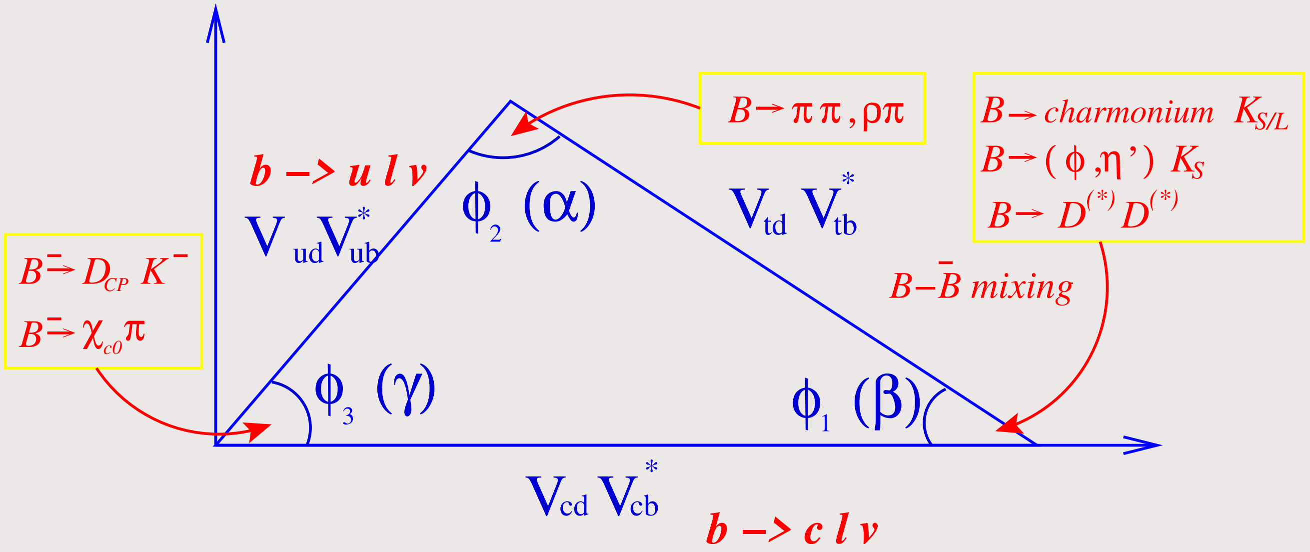
CP Violation in the Standard Model

CP violation is accommodated as an irreducible phase in the weak interaction mixing matrix (CKM)

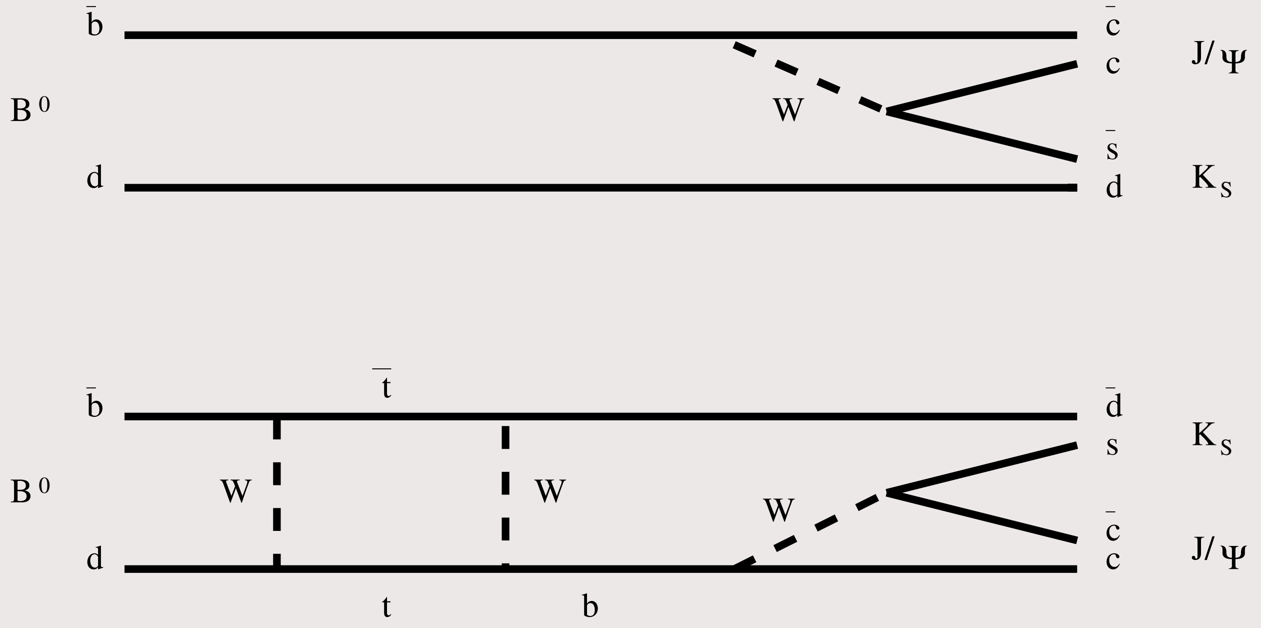
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity of V leads to conditions the matrix elements have to satisfy, e.g.
$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0.$

$\rightarrow$ unitarity triangle



CP violation effects in B decays are potentially large due to the interference of amplitudes for the direct decay to a CP final state f_{CP} (e.g. $J/\psi K_S$), $B^0 \to f_{CP}$, and the decay after mixing, $B^0 \to \bar{B}^0 \to f_{CP}$.

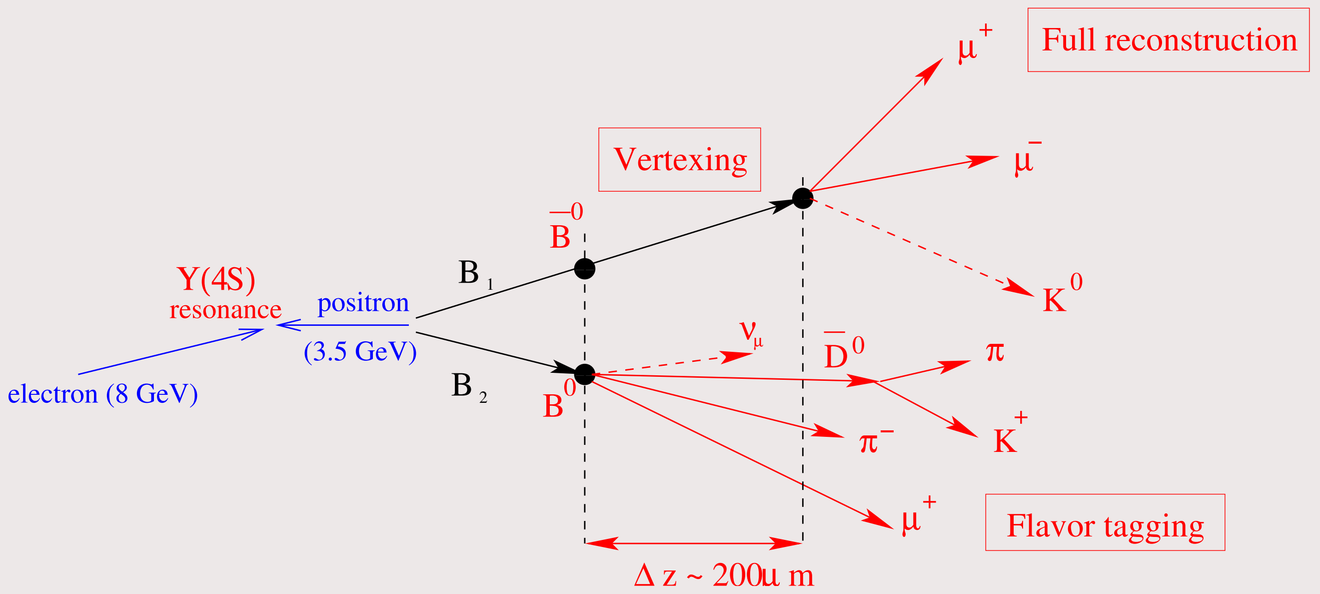


This results in a decay rate asymmetry:

$$A(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_d \Delta t$$

where ξ_f is the CP-eigenvalue of f_{CP} ($\xi_f = -1$ for $J/\psi K_S$, $\xi_f = +1$ for $J/\psi K_L$). Δm_d is the mass difference between the two B^0 mass eigenstates.

Measurement of CP violation - principle



Needed:

a large number of $B\bar{B}$ pairs (100 M)
$\rightarrow$ B-factory =
a high luminosity e^+e^- collider
with asymmetric beam energies

and a spectrometer with

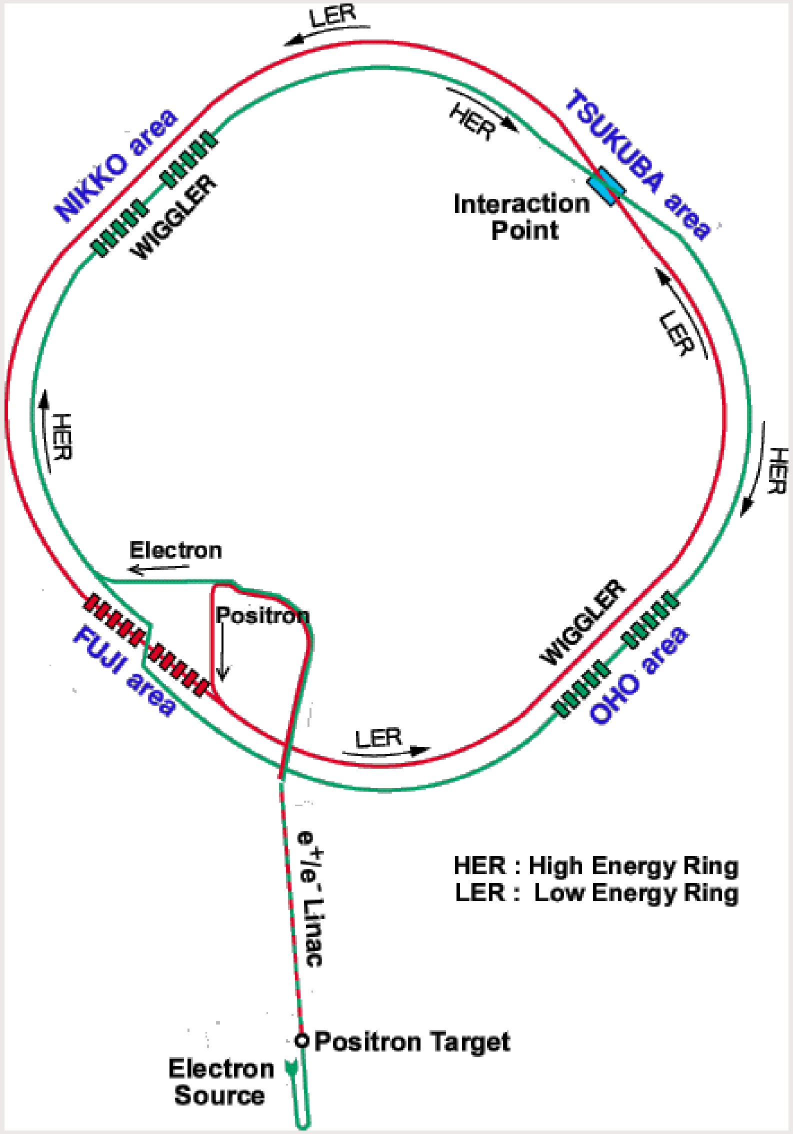
- precise vertexing (Δt)
- accurate tracking in magnetic field (momenta of decay products)
- efficient identification of e, μ, π, K (tagging of the B flavour)

$\rightarrow$ Belle at KEKB and BaBar at PEP-II

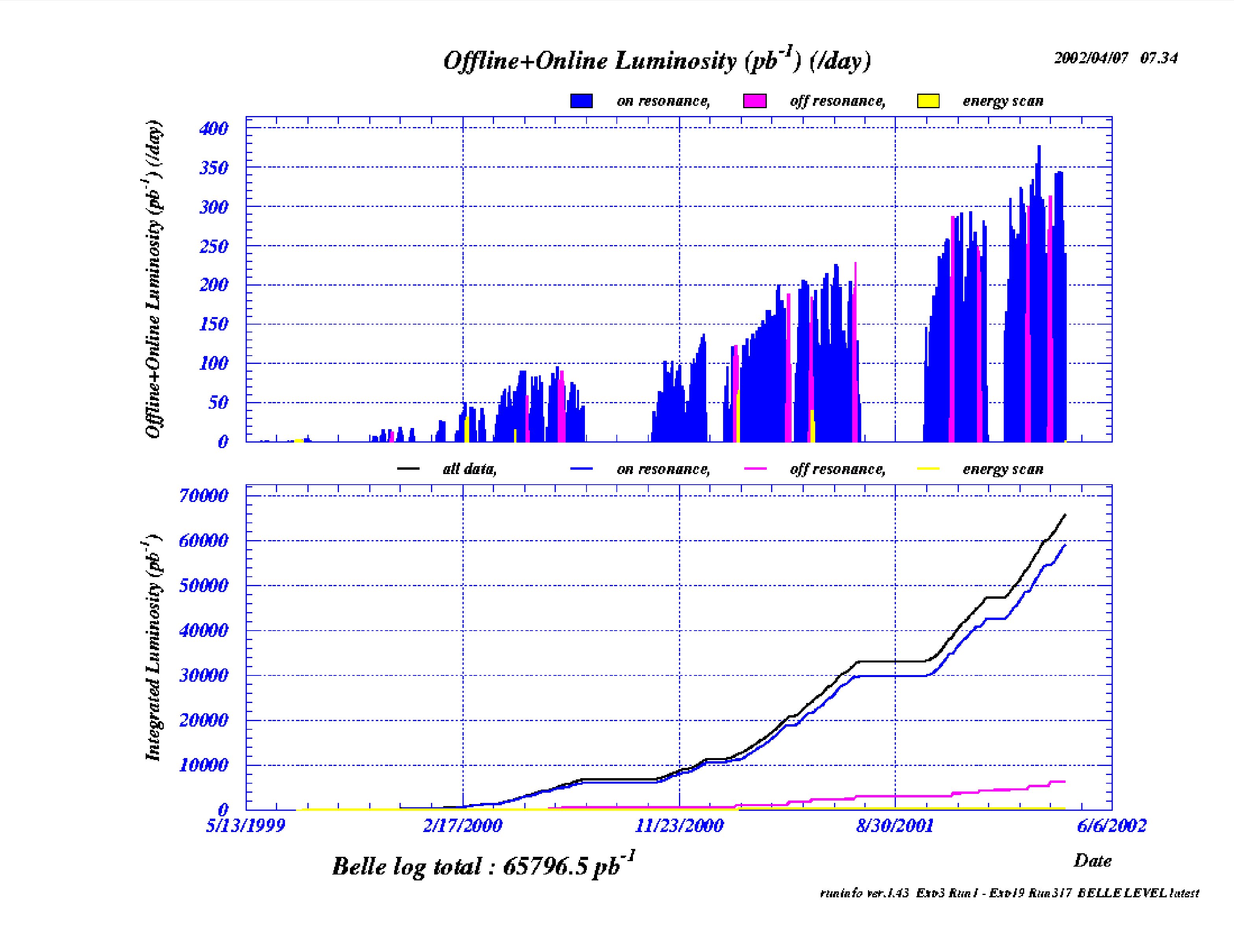
KEKB Accelerator performance 1

peak luminosity $= 7.249 \cdot 10^{33}$ cm^{-2}s^{-1}

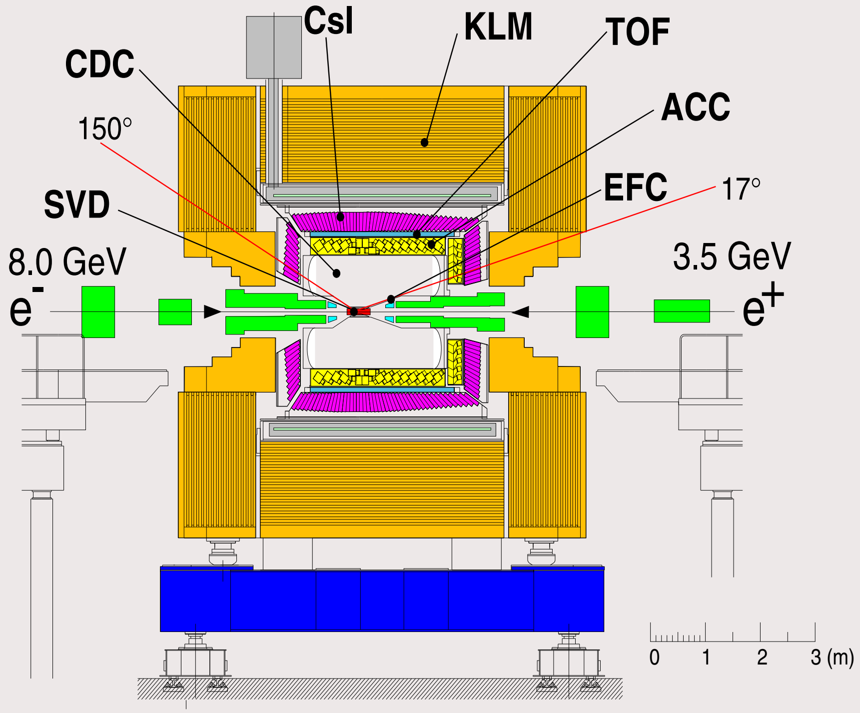
integrated luminosity :
shift = 128.8 /pb
day = 358.7 /pb
24h = 363.7 /pb
7days = 2207. /pb
month = 7241. /pb



KEKB accelerator performance 2



Belle Detector performance



Tracking and vertexing

- Central Drift Chamber (CDC)
  50 layers
  $\frac{\sigma_{p_T}}{p_T} \approx 0.35\%$ at 1 GeV/c
- Silicon Vertex Detector (SVD)
  3 double-sided silicon layers
  $\sigma = 55\ \mu$m for 1 GeV/c tracks (90^0)

Particle identification:

Identify $K^{\pm}$ up to 3.5 GeV/c

- Aerogel Cherenkov Counter (ACC): ref.index 1.01-1.03
- Time of Flight (TOF): $\sigma = 95$ ps
- dE/dx in CDC: $\sigma_{dE/dx} \approx 7\%$

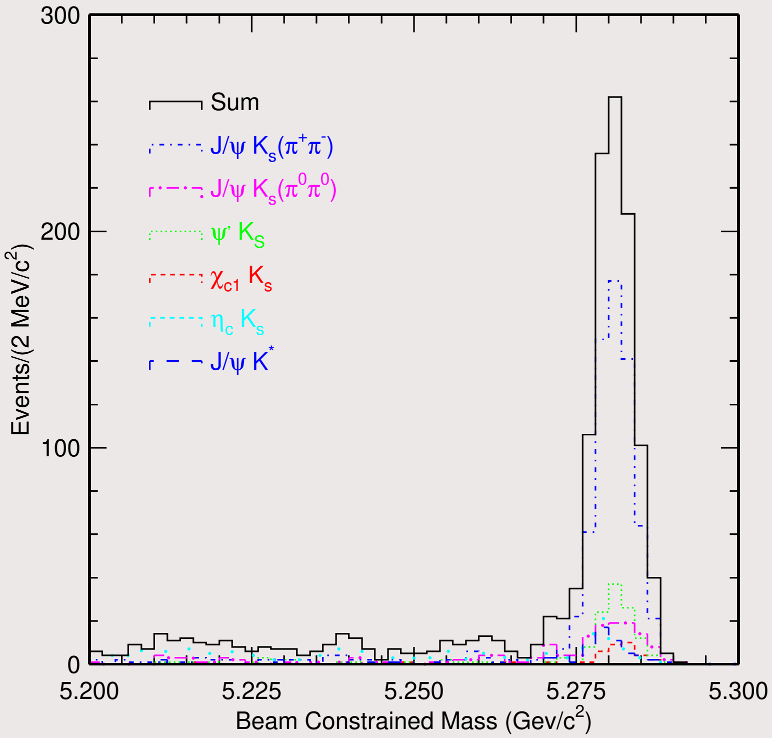
Electon id: Electromagnetic calorimeter (CsI) $\frac{\sigma_E}{E} \approx 1.8\%$ at 1 GeV

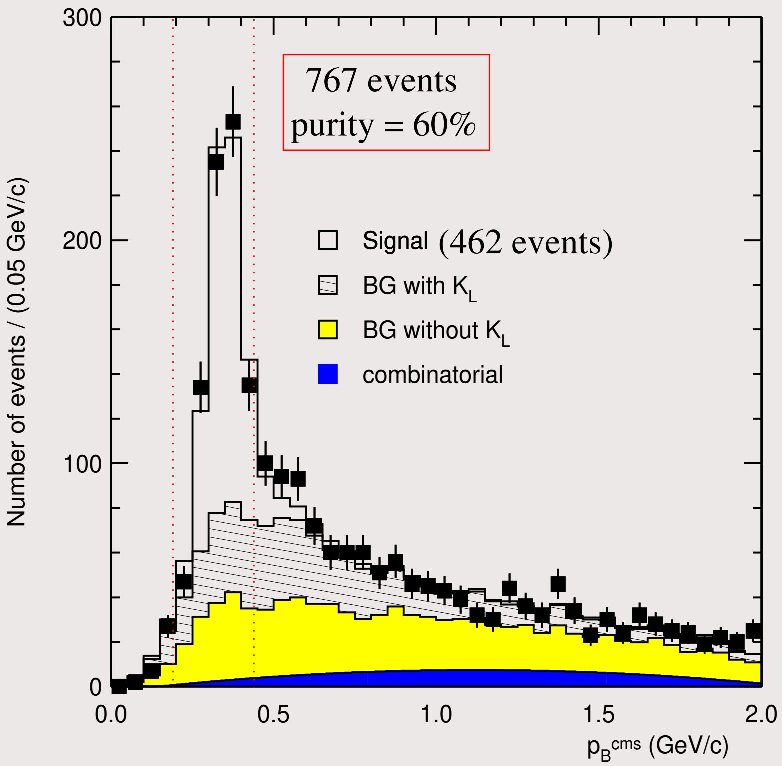
K_L and Muon detector (KLM): 14 layers, $\epsilon_\mu > 90\%$ at fake rate 2%

Reconstruction of f_{CP}

CP=-1: charmonium + K_S states:
$J/\psi K_S$, $\psi' K_S$, $\eta_c K_S$, ...

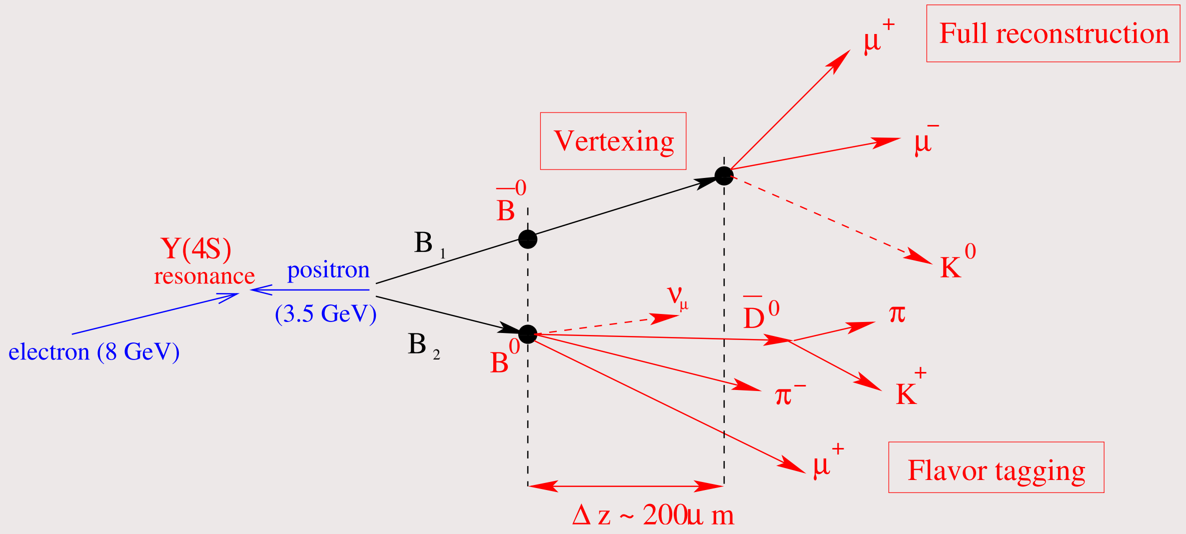
CP=+1: $J/\psi K_L$





636 $J/\psi K_S$ candidates, purity = 95%
369 other modes, purity = 84%

Measurement of CP violation - continued



Determine Δt from $\Delta z = \beta\gamma c \Delta t$:

- clock start: resolution on tag side 140 μm ($\epsilon = 91\%$) - charm decays
- clock stop: resolution on CP side 75 μm ($\epsilon = 92\%$)

N.B. typically $\Delta z = \beta\gamma c\tau_B = 200\ \mu$m

Flavour tagging:

- high momentum lepton charge: $B^0 \to \mu^+ X, e^+ X$ ($\bar{B}^0 \to \mu^- X, e^- X$)
- $B^0 \to K^+ X$ ($\bar{B}^0 \to K^- X$)
- slow pion charge (of $D^{*+} \to D^0 \pi^+$)
- Λ ($\bar{\Lambda}$)

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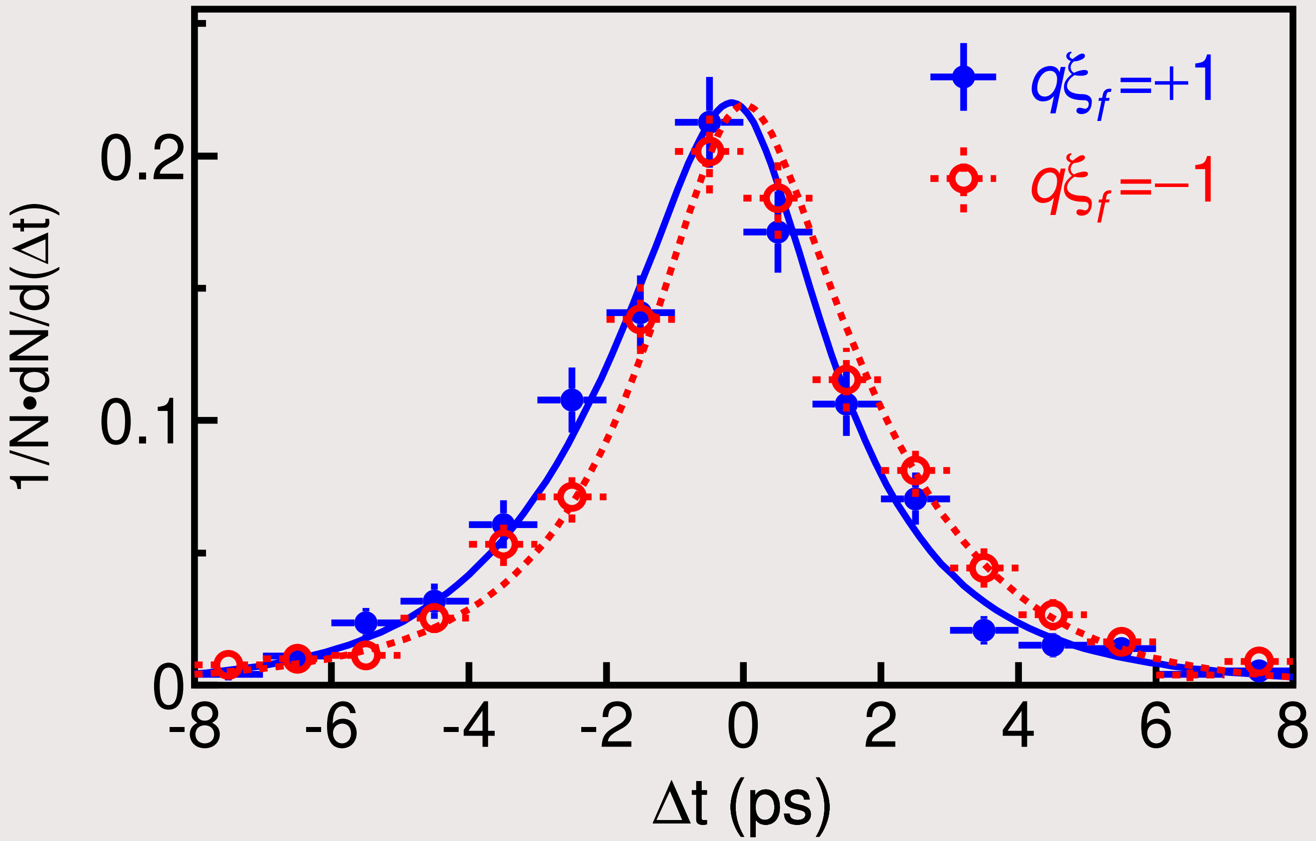
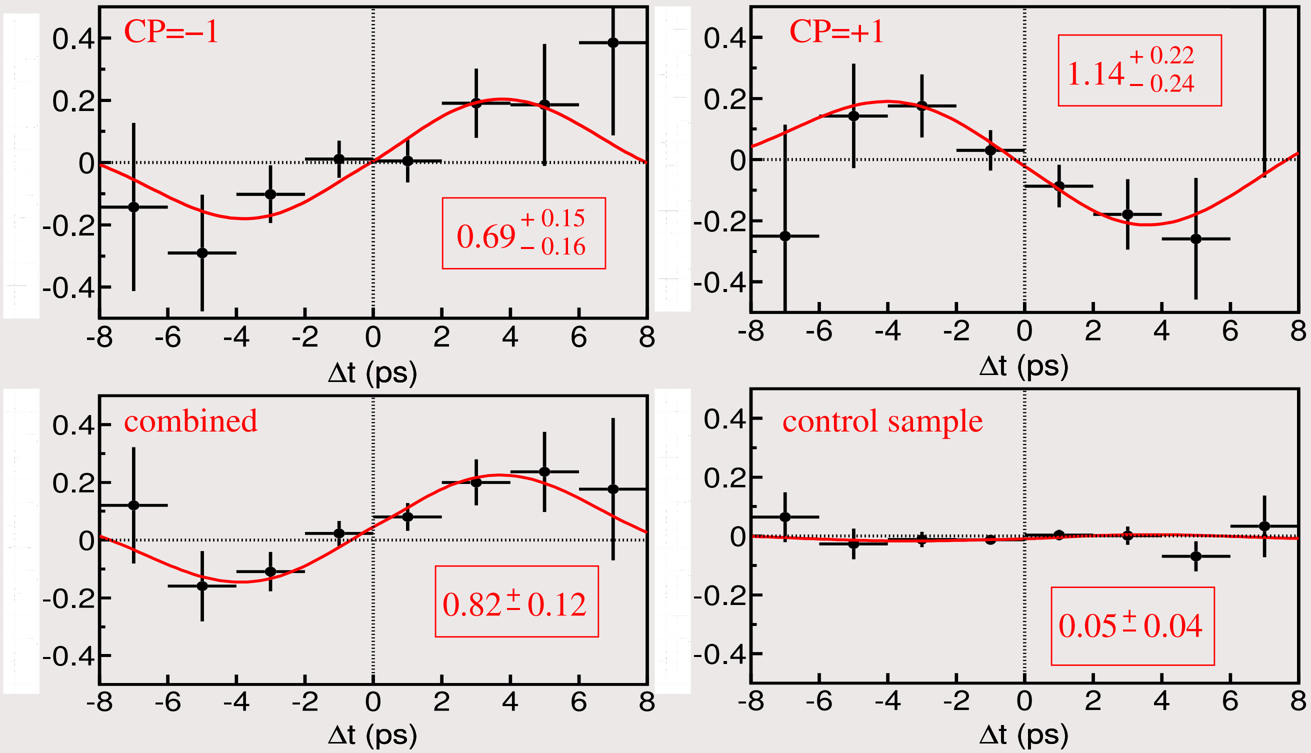
Result with full statistics (42 fb^{-1})

CP is violated! Red points differ from blue.



Red points: $\bar{B}^0 \to f_{CP=-1}$ (or $B^0 \to f_{CP=+1}$)
Blue points: $B^0 \to f_{CP=-1}$ (or $\bar{B}^0 \to f_{CP=+1}$)

Asymmetries, signals and control samples



Plotted: raw asymmetry. The amplitude of $-\xi_f \sin 2\phi_1 \sin \Delta m_d \Delta t$ is reduced due to wrong tagging by a factor $(1-2w)$.

Control samples: flavour specific, no CP asymmetry ($B^0 \to D^{*-}\pi^+$, $B^0 \to J/\psi K^{*0}, K^{*0} \to K^+\pi^-$, ...).

Systematic errors: dominated by systematic errors from vertexing (0.030), flavour tagging (0.025), resolution function (0.020).

Results on $\sin 2\phi_1$ - updates

Summer 2001: Belle and BaBar publish their statistically highly significant results on CP violation in B decays.

March 2002: both collaborations present at Moriond updated results with increased statistics and improved analysis tools:

Belle:

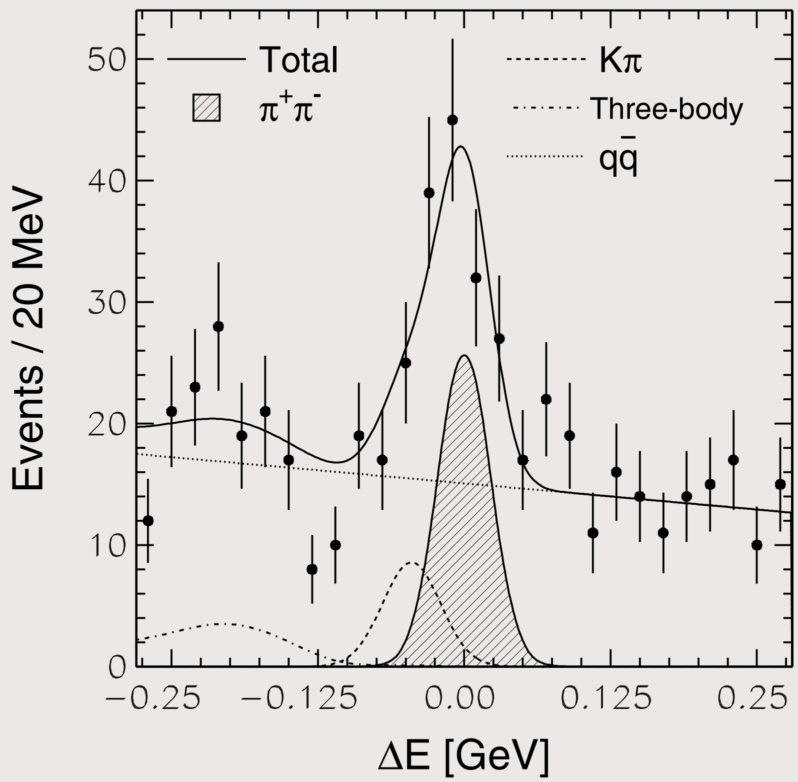
$$\sin 2\phi_1 = 0.82 \pm 0.12(stat) \pm 0.05(syst)$$

BaBar:

$$\sin 2\phi_1 = 0.75 \pm 0.09(stat) \pm 0.04(syst)$$

CP violation measurement in $B^0 \to \pi^+\pi^-$ at Belle

- Motivation: measure another angle in the unitary matrix, $\phi_2(\alpha)$.
- Good signal to noise, enough statistics to study the time evolution.
- N($\pi\pi$) $= 73.5 \pm 13.8$ events (28.4 ± 12.5 $K\pi$ feed-across)
- In addition to the sine term in Δt (with a coefficient S) (similar to the $J/\psi K_S$ case), a cosine term with coefficient C has to be considered (direct CP).



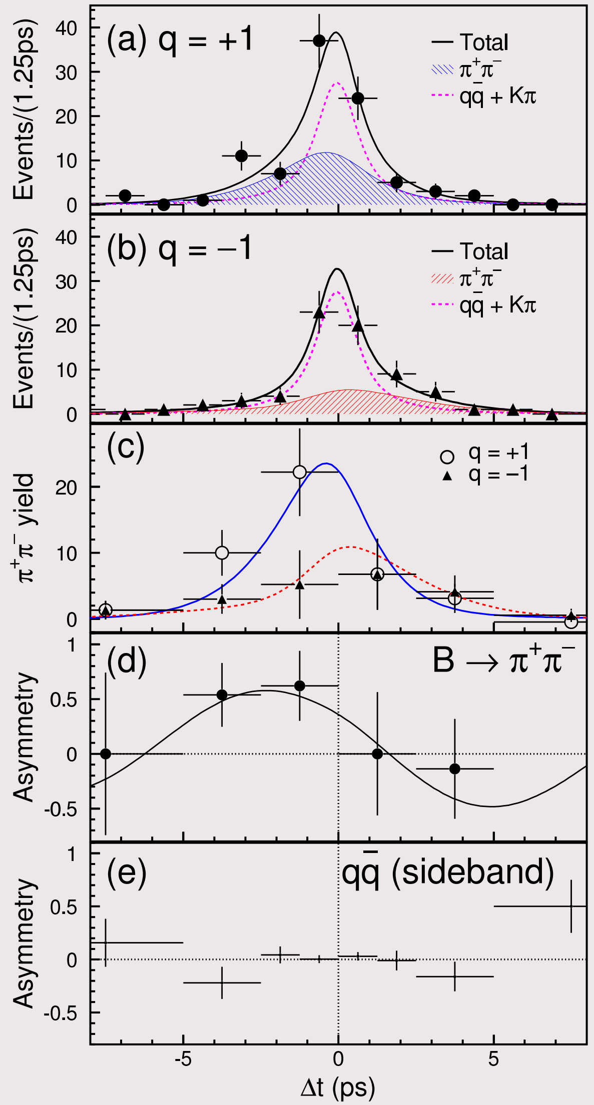
CP violation in $B^0 \to \pi^+\pi^-$

Preliminary result from Belle:

$$A(\Delta t) = S \sin \Delta m_d \Delta t + C \cos \Delta m_d \Delta t$$

$$S = -1.21^{+0.38+0.16}_{-0.27-0.13}$$

$$C = +0.94^{+0.25}_{-0.31} \pm 0.09$$



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e^+e^- B factories, outlook, possible scenarios

e^+e^- B factories, phases as discussed for KEKB

- Phase 1:
  Discovery of CP violation in the B system — 30 fb^{-1} with $L \approx 5 \cdot 10^{33}$ cm^{-2}s^{-1}
- Phase 2:
  Precise test of the KM scheme — 300 fb^{-1} with $L \approx 10^{34}$ cm^{-2}s^{-1}
- Phase 3:
  Supersymmetric flavour physics — 3000 fb^{-1} with $L > 10^{35}$ cm^{-2}s^{-1}

For the Phase 3, a major detector and machine upgrade would be necessary, with R+D that has already started, a construction which would begin in late 2003, and a 1 year shut-down in 2006/2007.

What can be done with 100x the data?

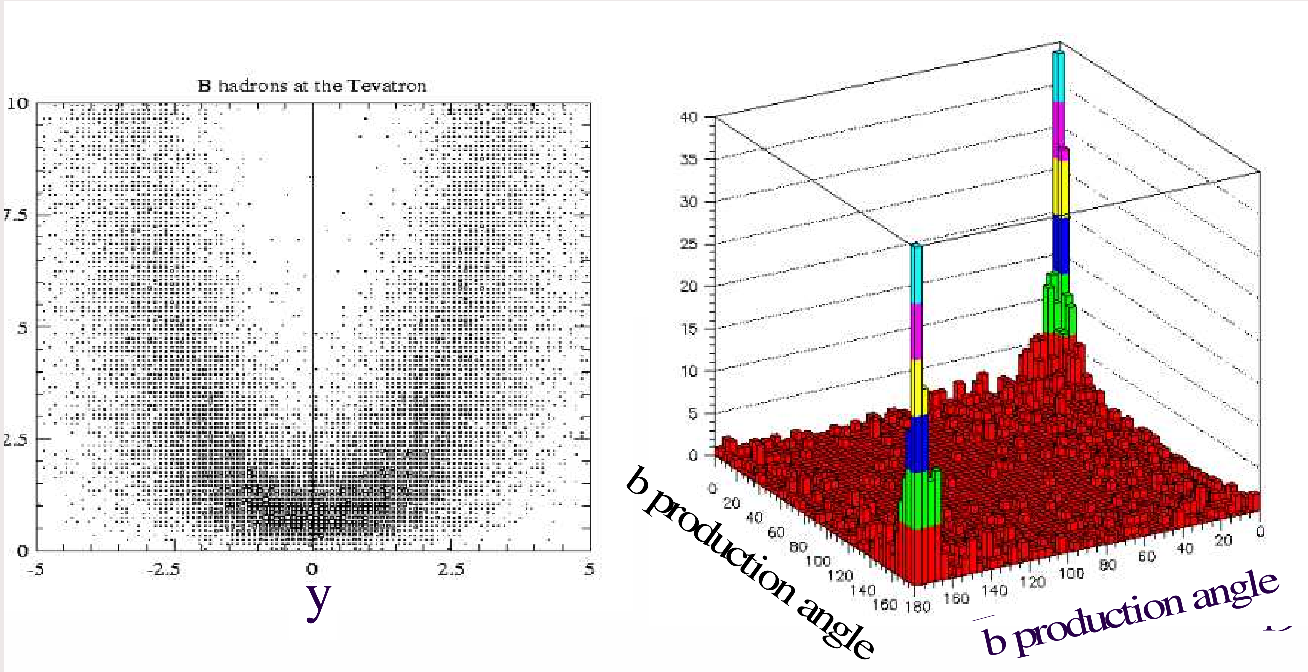
- $b \to s\mu^-\mu^+$: precise Br, $M_{\mu\mu}$, F/B charge asymmetry $\to$ search for H^+, supersymmetric particles
- $B \to D^{(*)}\mu\nu$ vs $B \to D^{(*)}\tau\nu$: search for H^+
- CP violation in $B \to \phi K_S$ vs $B \to J/\psi K_S$: search for supersymmetric contribution

Why hadron machines?

- B factories will firmly establish evidence for CP violation in B decays
- several questions will remain open due to lack of statistics, and restricted final states
- large $b\bar{b}$ production rates
- large boosts: $< L >=< \beta\gamma > 480\ \mu$m
- in addition to $B^0/B^{\pm}$ also B_s, B_c, Λ_b

Production	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$	$e^+e^- \to Z^0 \to b\bar{b}$	$pA \to b\bar{b}X$	$p\bar{p} \to b\bar{b}X$	$p\bar{p}(p) \to b\bar{b}X$ forward
Accelerator	CESR, DORIS PEPII, KEKB	LEP, SLD	HERA p	Tevatron	Tevatron, LHC
Spectrometer	CLEO, ARGUS BaBar, BELLE	ALEPH, DELPHI, L3, OPAL, SLD	HERA-B	CDF, D0	BTeV, LHCb
$\sigma(b\bar{b})$	≈ 1 nb	≈ 6 nb	≈ 12 nb	$\approx 50\ \mu$b	$\approx 100\ \mu$b ($\approx 500\ \mu$b)
$\sigma(b\bar{b})$:$\sigma(had)$	0.26	0.22	10^{-6}	10^{-3}	$2 \cdot 10^{-3}$ ($6 \cdot 10^{-3}$)
B^0, B^+ $B^0_s, B^+_c, \Lambda^0_b$	yes no	yes yes	yes yes	yes yes	yes yes
boost $< \beta\gamma >$	0.06 (0.5)	6	≈ 20	$\approx 2-4$	$\approx 4-20$
$b\bar{b}$ production	B's at rest (in c.m.s)	$b\bar{b}$ back-to-back	$b\bar{b}$ not back-to-back	$b\bar{b}$ not back-to-back	$b\bar{b}$ not back-to-back
multiple events	no	no	yes, 4	yes	yes, 2
trigger	inclusive	inclusive	lepton pairs (high p_t hadrons)	leptons only (high p_t hadrons)	displaced vertex

Hadron collider $b\bar{b}$ production



B detection in hadron collisions

What do we have to consider when designing a detector for B's at a hadron machine?

- High particle fluxes $\rightarrow$ radiation hard detectors
- Early selection of interesting events $\rightarrow$ selective triggers
  - high p_t decay products: $B \rightarrow \mu\nu X$, $B \rightarrow J/\psi K_s \rightarrow \mu\mu\pi\pi$, $B \rightarrow \pi^+\pi^-$
  - displaced vertex: $< L > = < \beta\gamma > 480\ \mu$m

Proof of principle: CDF

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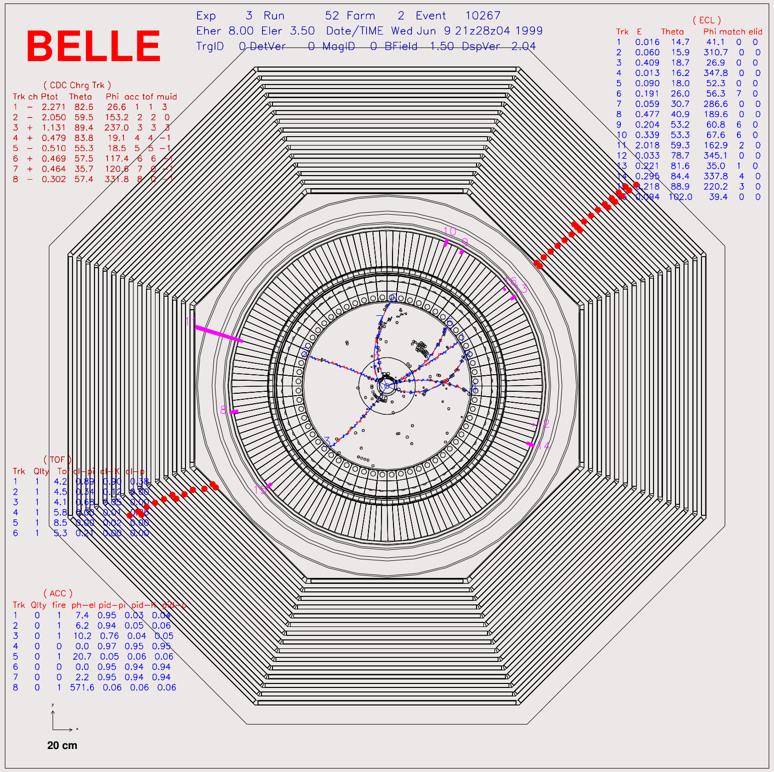
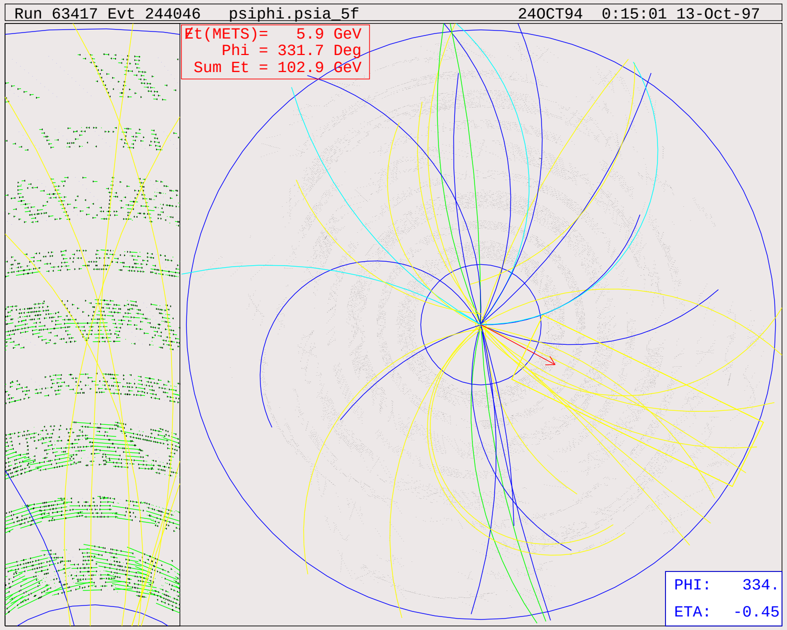
$b\bar{b}$ detection at hadron machines: complex events

$b\bar{b}$ event at an e^+e^- machine



$b\bar{b}$ event at CDF



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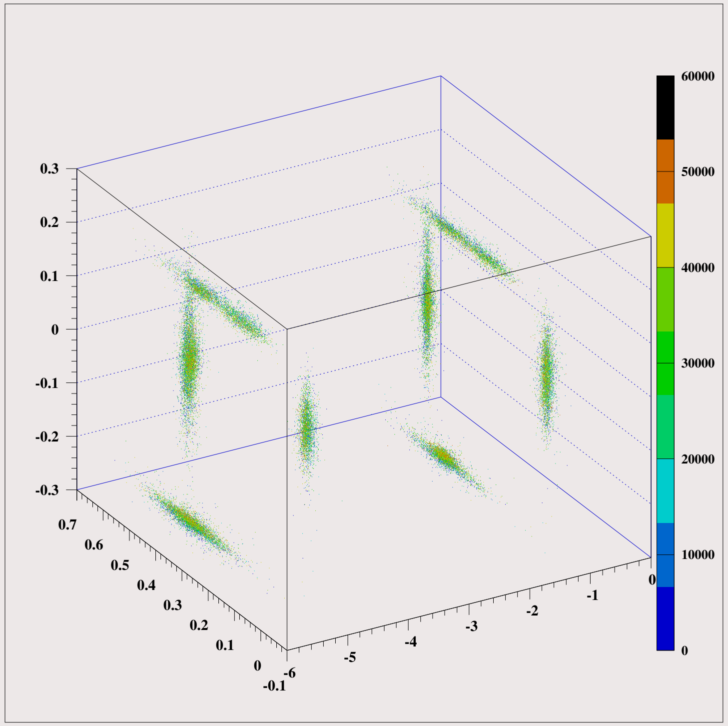
Operation of detectors at high particle fluxes

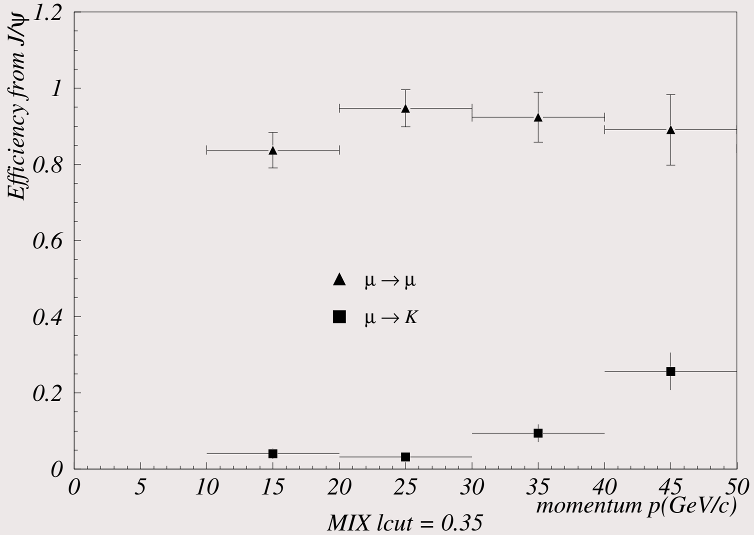
Difficult, but can be done: examples HERA-B vertex detector and RICH

VDS primary vertex resolution:
$\sigma_{x,y} = 50\ \mu$m, $\sigma_z = 500\ \mu$m



Reconstructed interaction vertices on 8 wires

RICH: in spite of the harsh environment very efficient single photon counting, no noise

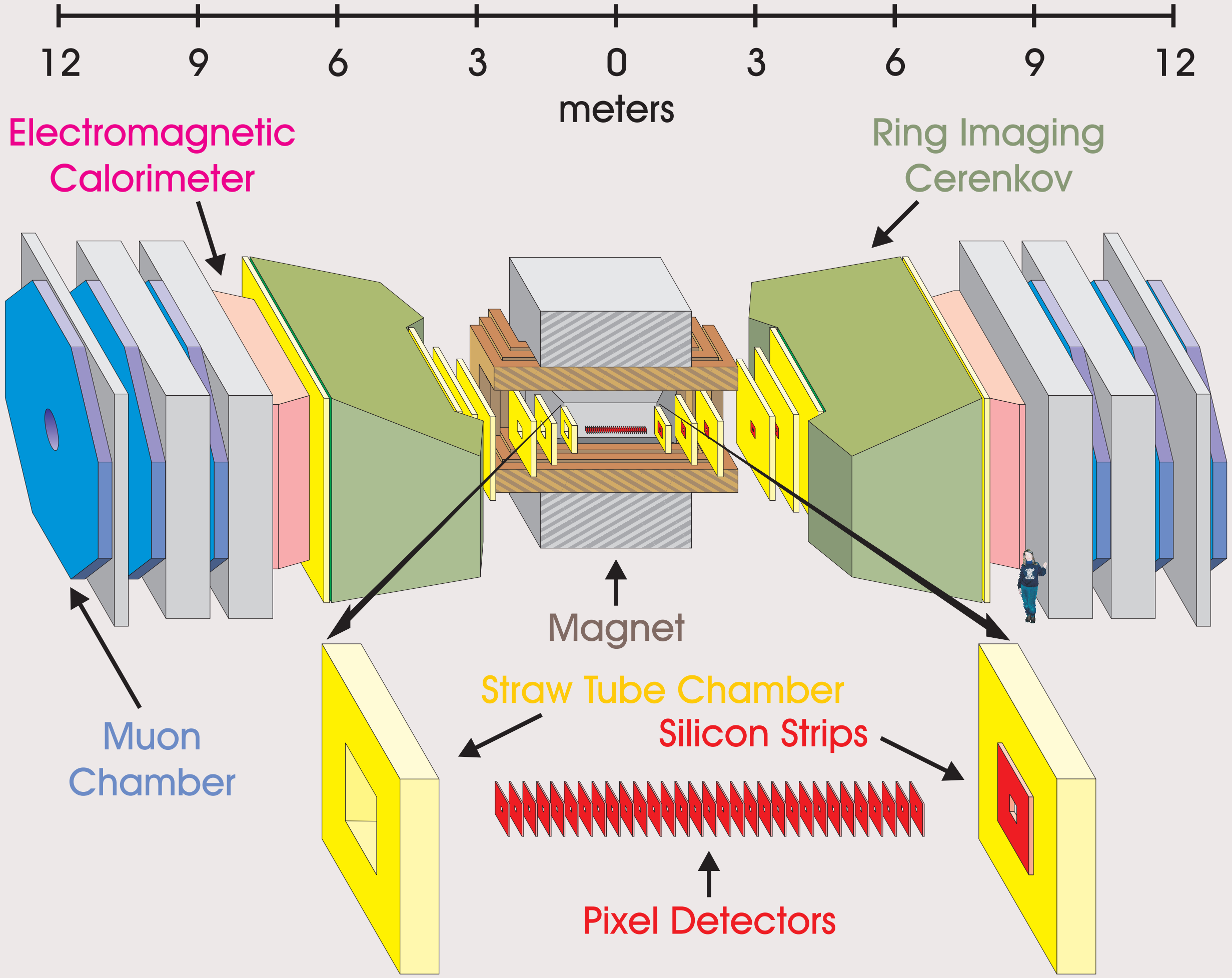


Particle identification efficiency as determined from $J/\psi \to \mu\mu$ decays

But: not all detectors are as successful, and triggering can be really difficult!

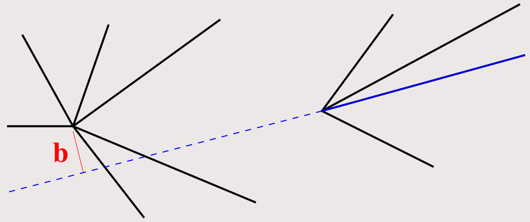
Example: BTeV spectrometer

Under construction at Fermilab

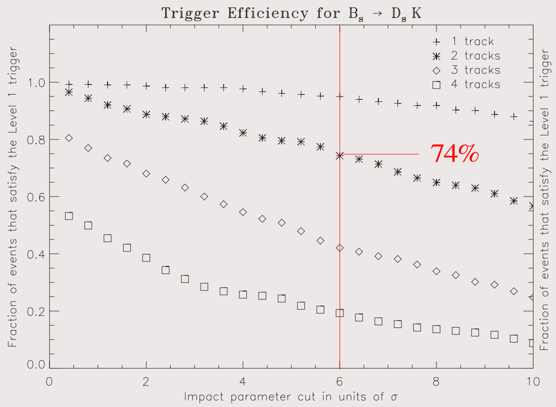


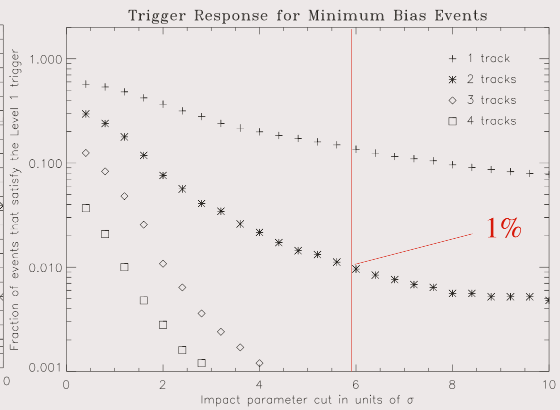
BTeV Detached Vertex Trigger at Level 1

Find segments in the entrance and exit of the pixel detector.
Find primary vertex, find tracks which miss it, and calculate the significance of detachment, $b/\sigma(b)$, for each track.
Goal: factor 100 or more rejection of crossings with no b events, and efficiency of $>$ 50% for good events with b's.



Signal example: Efficiency for $B_s \to D_s K$ and rejection power (efficiency for minimum bias events) as determined from MC





BTeV physics reach

Expected BTeV yield of reconstructed events in some interesting decay modes.

Mode	BTeV yield in 10^7 s	parameter	error (or value)
$B_d \to \pi^+\pi^-$	24000	asymmetry	0.024
$B_d \to J/\psi K_S$	80500	$\sin(2\beta)$	0.025
$B_s \to D_s K^-$	13000	γ	7^0
$B_s \to D_s \pi^-$	103000	x_s	75

Searches for new physics

Mode	BTeV yield in 10^7 s
$B^- \to \phi K^-$	11000
$B_d \to \phi K_S$	2000 (200 tagged)
$B_d \to K^* \mu\mu$	2200
$B_s \to J/\psi \eta^{(')}$	15000
$D^{*+} \to \pi^+ D^0, D^0 \to K^- \pi^+$	$\approx 10^8$

LHCb: similar values, see M. Schmeling's talk.

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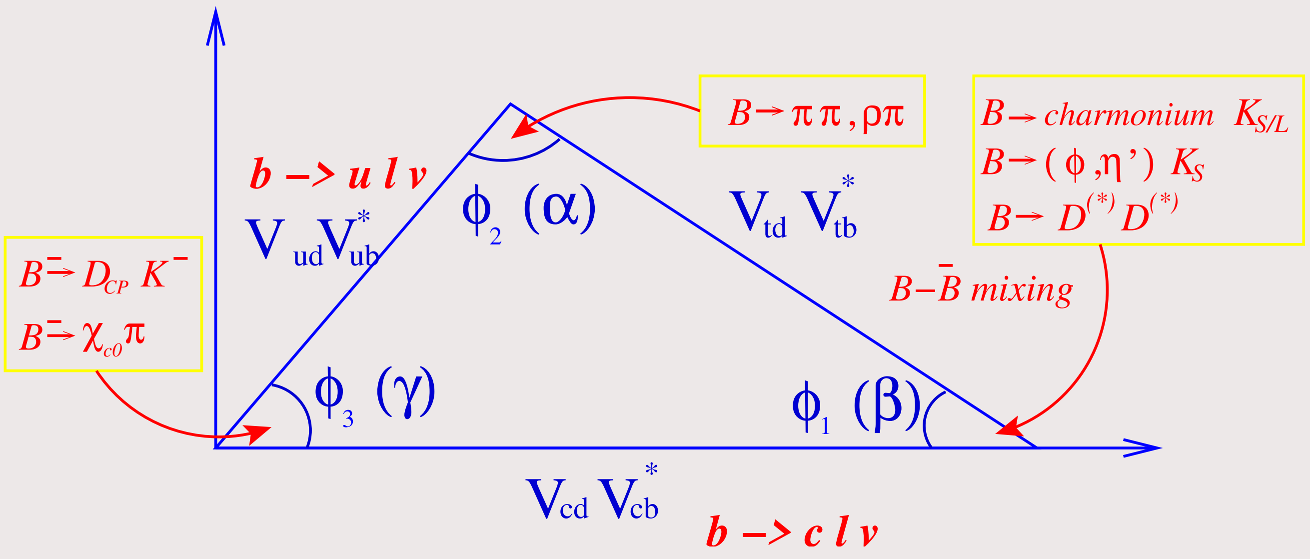
ATLAS/CMS CP reach

Expected ATLAS/CMS accuracy in measurements of CP violation parameters

parameter	error*
$\sin(2\beta)$	0.015
asymmetry in $B_d \to \pi^+\pi^-$, sine term	0.09-0.11
asymmetry in $B_d \to \pi^+\pi^-$, cosine term	0.07-0.08
asymmetry in $B_d \to K^+\pi^-$, sine term	0.02-0.03



* ... before cuts due to saving

Summary

- BaBar and Belle have measured CP violation in B decays
- Measurements of CP violation parameters in other decay modes is under way.
- The increased statistics will allow several very interesting measurements in the next three years, some studies will become precision measurements.

- Next generation: precision B physics with spectrometers at hadron machines currently under construction (CMS, ATLAS, LHCb, BTeV)
- and at the next generation of e^+e^- 'super' B factories