CP violation and related issues

Part 3+4: Experiments

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Contents

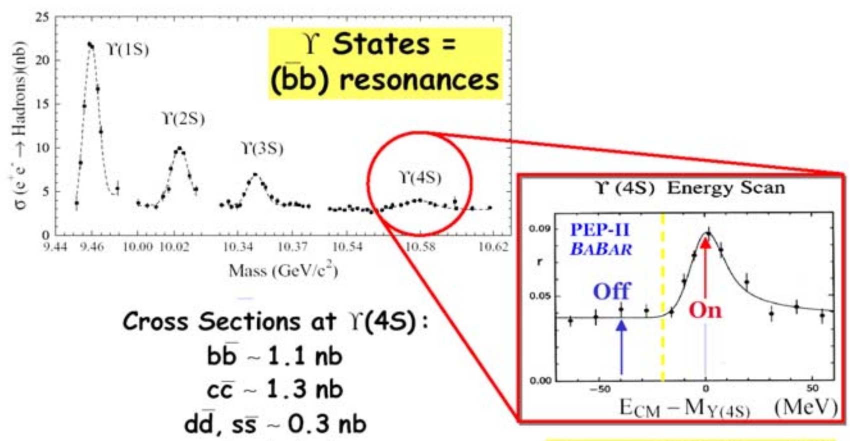
Principle of measurement

Principle of measurement:

- Produce pairs of B mesons, moving in the lab system
- Find events with B meson decay of a certain type (usually B -> f_{CP} - CP eigenstate)
- Measure time difference between this decay and the decay of the associated B (f_{tag}) (from the flight path difference)
- Determine the flavour of the associated B (B or anti-B)
- Measure the asymmetry in time evolution for B and anti-B

Restrict for the time being to B meson production at Y(4s)

B meson production at Y(4s)



Cross Sections at $\Upsilon(4S)$:

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

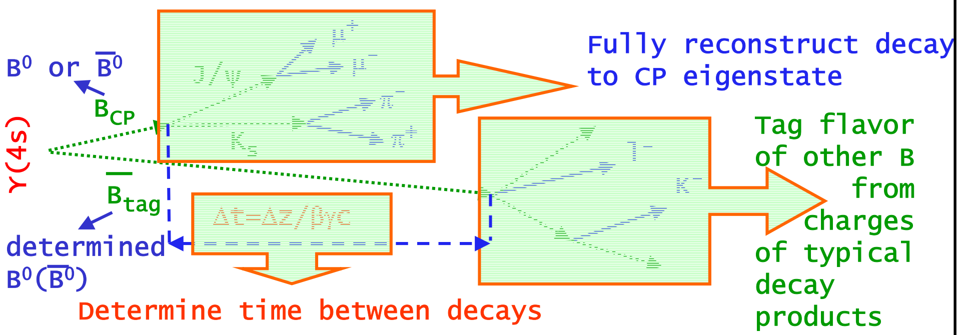
$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

$u\bar{u} \sim 1.4$ nb

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

$L = 1$ state

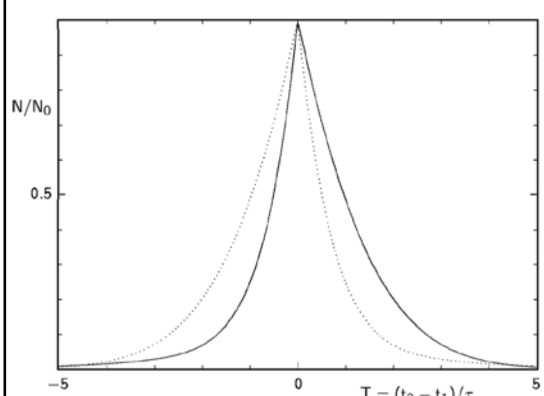
Principle of measurement



Experimental considerations

What kind of vertex resolution do we need to measure the asymmetry?

$$P(B^0(\overline{B}^0) \to f_{CP}, t) = e^{-\Gamma t}\left(1 \mp \sin(2\phi_1)\sin(\Delta m t)\right)$$



Want to distiguish the decay rate of B (dotted) from the decay rate of anti-B (full).

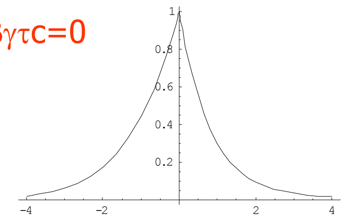
-> the two curves should not be smeared too much

Integrals are equal, time information mandatory! (at Y(4s), but not for incoherent production)

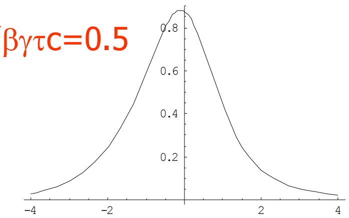
Experimental considerations

B decay rate vs t for different as vertex resolutions in units of typical B flight length σ(z)/βγτc

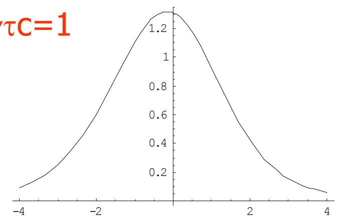
σ(z)/βγτc=0



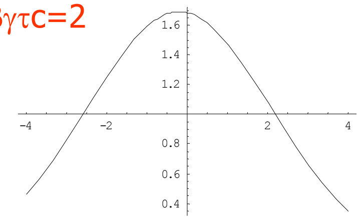
σ(z)/βγτc=0.5



σ(z)/βγτc=1



σ(z)/βγτc=2



Experimental considerations

Since there are no pure samples of B and B tags, what is really measured is the probability that the tagging B is a B or a anti-B.

Denote with x: variable between –1 (tag=anti-B) and +1 (tag=B) and the probability that the tag is wrong with w(x)

Probability density function for an event with t and x is

$$f\left(t,x,A\right)dxdt = e^{-\Gamma t}\left[1+q\left(x\right)A\sin\Delta mt\right]n(x)dxdt$$

with A=CP asymmetry (e.g. sin2ϕ_1), q(x)=1-2w

Taking into account the finite vertex resolution, we arrive at

$$f\left(t,x,A,\sigma_t\right)dxdt = \left[\int \frac{1}{\sqrt{2\pi}\sigma_t} e^{-\frac{1}{2}\left(\frac{t-t'}{\sigma_t}\right)^2} e^{-\Gamma|t'|}\left[1+q\left(x\right)A\sin\Delta mt'\right]n(x)dt'\right]dxdt$$

Experimental considerations

This can be rewritten as

$$f(t,x,A,\sigma)\,dxdt = \left[E(t) + Aq(x)\,S(t)\right] n(x)dxdt$$

$$E(t) = \int \frac{1}{\sqrt{2\pi}\sigma_t} e^{-\frac{1}{2}\left(\frac{t-t'}{\sigma_t}\right)^2} e^{-\Gamma|t'|}dt',$$

$$S(t) = \int \frac{1}{\sqrt{2\pi}\sigma_t} e^{-\frac{1}{2}\left(\frac{t-t'}{\sigma_t}\right)^2} e^{-\Gamma|t'|}\sin\Delta m t' dt'.$$

Experimental considerations

The log-likelihood function is a sum over all reconstructed and tagged events

$$\ln\mathcal{L} = \ln\prod_{i=1}^{N} f(t_i,x_i,A,\sigma_t) = \sum_{i=1}^{N}\ln f(t_i,x_i,A,\sigma_t)$$

$$\begin{aligned}\ln\prod_{i=1}^{N} f(t_i,x_i,A,\sigma_t) &= \sum_{i=1}^{N}\ln\left[(1+Aq(x)\,S(t)\,/E(t))\,E(t)\,n(x)\right]\\ &= \sum_{i=1}^{N}\ln\left(1+Aq(x)\,S(t)\,/E(t)\right) + C\,.\end{aligned}$$

$$\Rightarrow\quad \ln\mathcal{L}' = \sum_{i=1}^{N}\ln\left(1 + A\frac{qS}{E}\right)$$

Experimental considerations

Error on the asymmetry parameter A can be evaluated in the standard way:

$$\frac{1}{\sigma_A^2} = N \int_{-1}^{1} \int_{-\infty}^{\infty} \frac{1}{f} \left(\frac{\partial f}{\partial A} \right)^2 n(x) dt dx$$

$$\sigma_A \approx \frac{\sigma_0}{\sqrt{N}\sqrt{\langle q^2 \rangle}} ,$$

Use $f(t,x,A,\sigma_t)$ to get σ_A

$$\langle q^2 \rangle \equiv \int_{-1}^{1} q^2(x)\, n(x) dx$$

$$\sigma_0 \equiv \frac{1}{\sqrt{\int_{-\infty}^{\infty} \frac{\left(\frac{S(t)}{E(t)}\right)^2}{\left[1+A\frac{S(t)}{E(t)}\right]} E(t)\, dt}} .$$

Experimental considerations

Final expression for the asymmetry error (error on $\sin 2\phi_1$) as a function of vertex resolution and wrong tag probability

$$\sigma_A(A, \Delta m/\Gamma, \sigma_t, N, w) = \frac{\sigma_0(A, \Delta m/\Gamma, \sigma_t)}{\sqrt{N}\sqrt{\epsilon}(1-2w)}.$$

N: number of reconstructed events,

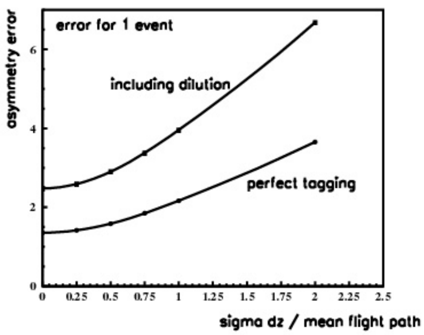
ε: tagging efficiency

w: wrong tag probability

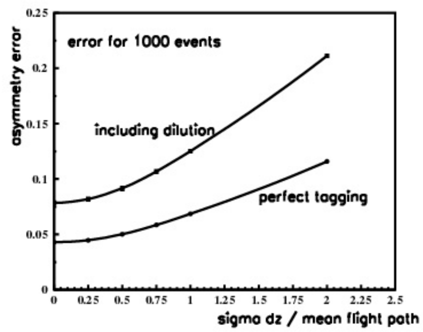
Experimental considerations

Error on $\sin 2\phi_1 = \sin 2\beta$ as function of vertex resolution in units of typical B flight length $\sigma(z)/\beta\gamma\tau c$

For 1 event



for 1000 events



Experimental considerations

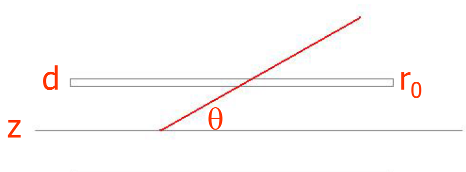
Choice of boost $\beta\gamma$:

Vertex resolution vs. path length

Typical B flight length: $z_B = \beta\gamma\tau c$

Typical two-body topology: decay products at 90^o in cms; at $\theta = \mathrm{atan}(1/\beta\gamma)$ in the lab

Assume: vertex resolution determined by multiple scattering in the first detector layer and beam pipe wall at r_0



$\sigma_\theta = 15\ \mathrm{MeV}/p\ \sqrt{(d/\sin\theta X_0)}$

$\sigma(z) = r_0\, \sigma_\theta / \sin^2\theta$

$\Rightarrow$ $\sigma(z) \propto r_0/\sin^{5/2}\theta$

Experimental considerations

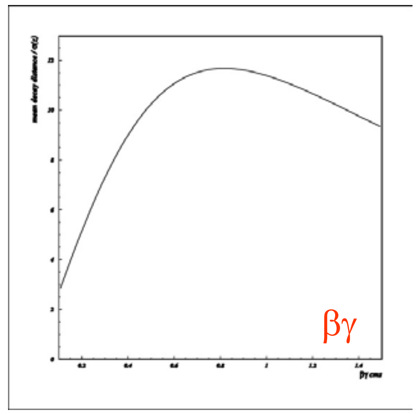
Choice of boost $\beta\gamma$:

Vertex resolution in units of typical B flight length

Boost around $\beta\gamma$=0.8 seems optimal

However....

$\beta\gamma\tau c/\sigma(z)$



Experimental considerations

Which boost...

Arguments for a smaller boost:

- Larger boost -> smaller acceptance ->
- Larger boost -> it becomes hard to damp the betatron oscillations of the low energy beam: less synchrotron radiation at fixed ring radius (same as the high energy beam)

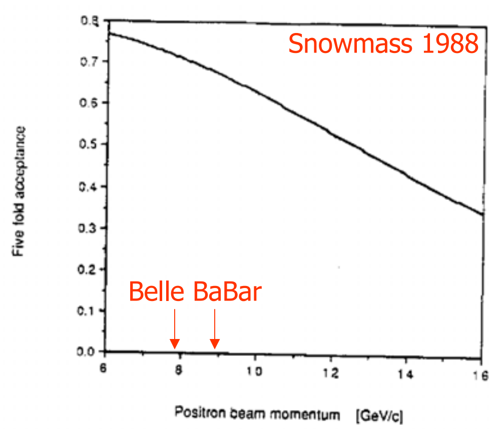
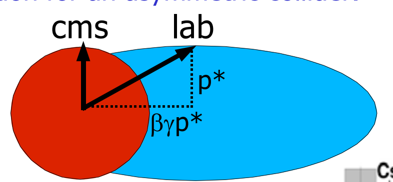


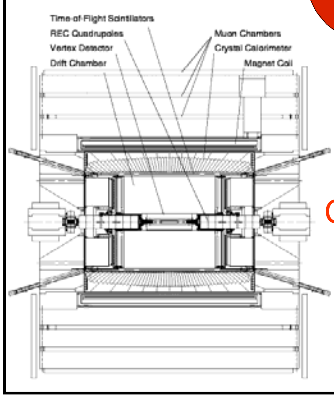
Figure 4. The acceptance of a detector covering $|\cos\theta_{lab}| < 0.95$ for five uncorrelated particles as a function of the energy of the more energetic beam in an asymmetric collider at the $\Upsilon(4S)$.

Experimental considerations

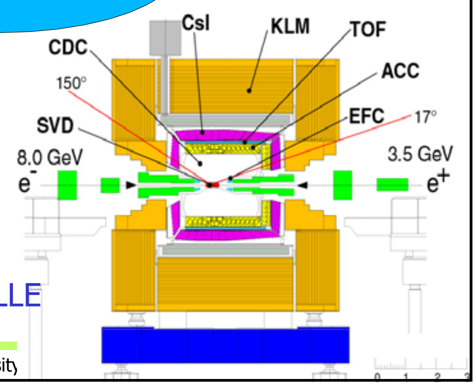
Detector form: symmetric for symmetric energy beams; extended in the boost direction for an asymmetric collider.



Exaggerated plot: $\beta\gamma=0.5$



CLEO



BELLE

How many events?

Rough estimate:

Need ~1000 reconstructed B-> J/ψ K_S decays with J/ψ -> ee or $\mu\mu$, and K_S-> $\pi^+ \pi^-$

½ of Υ(4s) decays are B^0 anti-B^0 (but 2 per decay)

BR(B-> J/ψ K^0)=8.4 10^{-4}

BR(J/ψ -> ee or $\mu\mu$)=11.8%

½ of K^0 are K_S, BR(K_S-> $\pi^+ \pi^-$)=69%

Reconstruction effiency ~ 0.2 (signal side: 4 tracks, vertex, tag side pid and vertex)

N(Υ(4s)) = 1000 / (½ * ½ * 2 * 8.4 10^{-4} * 0.118 * 0.69 * 0.2) =
= 140 M

How to produce 140 M BB pairs?

Want to produce 140 M pairs in two years
Assume effective time available for running is 10^7 s per year.
-> need a rate of $140\ 10^6 / (2\ 10^7\ \mathrm{s}) = 7$ Hz

Observed rate of events = Cross section x Luminosity

$$\frac{dN}{dt} = L\sigma$$

Cross section for Υ(4s) production: 1.1 nb = $1.1\ 10^{-33}\ \mathrm{cm}^2$

-> Accelerator figure of merit luminosity has to be

$$L = 6.5\ /\mathrm{nb/s} = 6.5\ 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

This is much more than any other any other accelerator achieved before!

Colliders: asymmetric B factories

$\sqrt{s}=10.58$ GeV

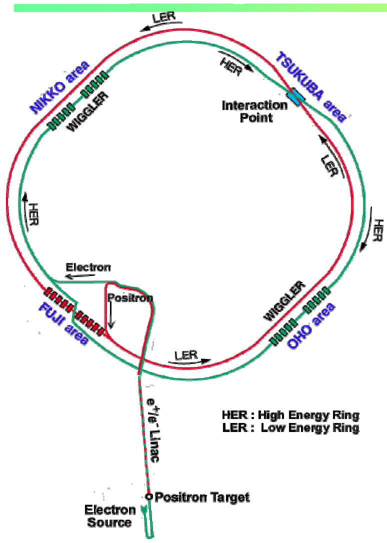
$e^+ \rightarrow \Upsilon(4s) \leftarrow e^-$

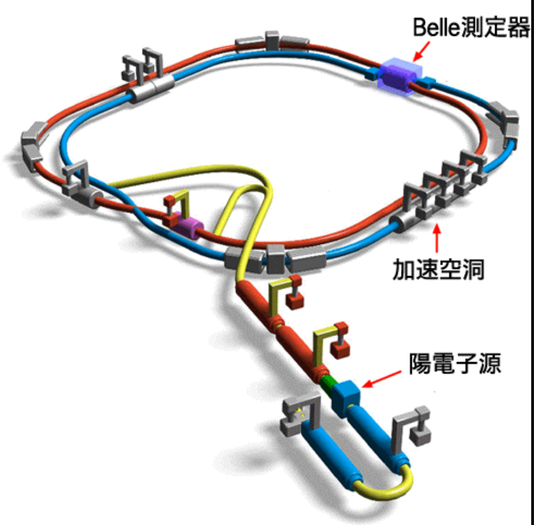
$\Upsilon(4s) \rightarrow B\,\bar{B}$ $\Delta z \sim c\beta\gamma\tau_B \sim 200\,\mu\mathrm{m}$

BaBar $p(e^-)=9$ GeV $p(e^+)=3.1$ GeV $\beta\gamma=0.56$

Belle $p(e^-)=8$ GeV $p(e^+)=3.5$ GeV $\beta\gamma=0.42$

Accelerator complex: KEK-B





Accelerator performace

Observed rate of events = Cross section x Luminosity

$$\frac{dN}{dt} = L\sigma$$

Accelerator figures of merit: luminosity ***L***

and integrated luminosity $L_{\text{int}} = \int L(t)dt$

Records:

L_{peak} = **15.81 /nb/sec (May 18, 2005)** ($=1.58\times10^{34}\ s^{-1}cm^{-2}$)

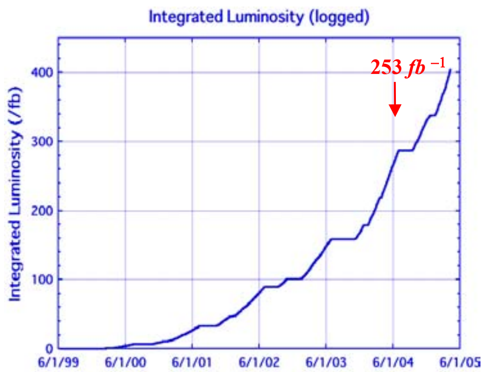
L_{int}= **434.355 /fb (May. 18, 2005)**

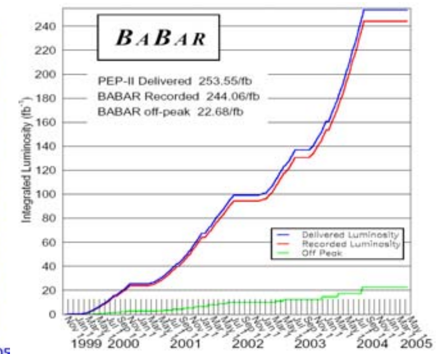
~470 M BB pairs

Accelerator performance

3.5 GeV on 8.0 GeV
$\gamma\beta = 0.425$

3.1 GeV on 9.0 GeV
$\gamma\beta = 0.56$



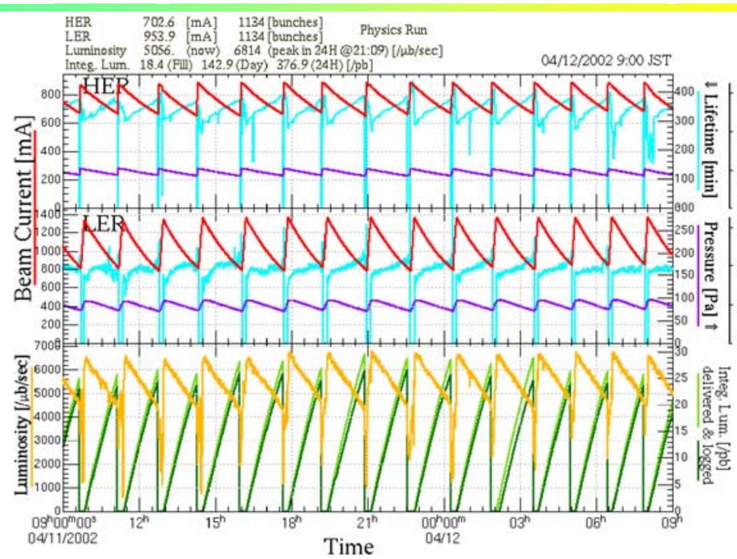


$\int L(t)dt =$ 434 fb^{-1} on May 18

L_{peak} (max) = 1.58 x 10^{34} cm^{-2} s^{-1}

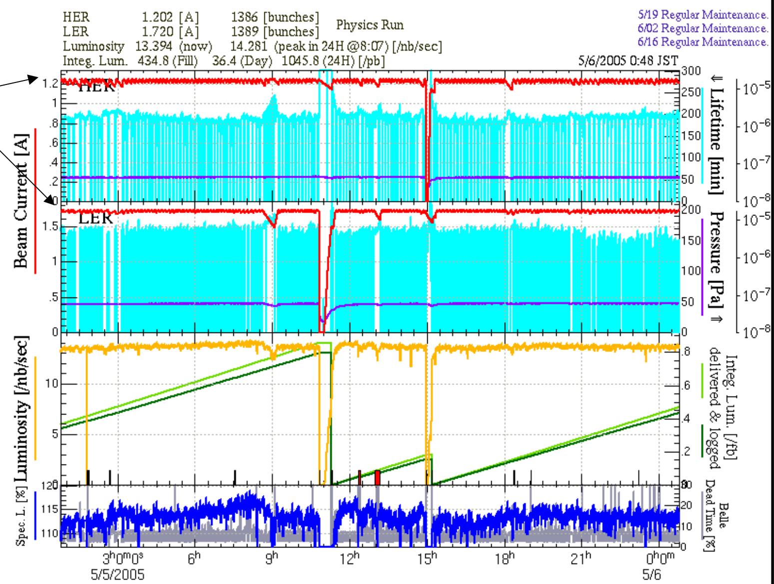
electrical accident halted machine on Oct. 11th (254 fb^{-1}) – restarted in April after SLAC/DOE safety review

Accelerator performance: Typical "Good Day" at KEKB in 2002

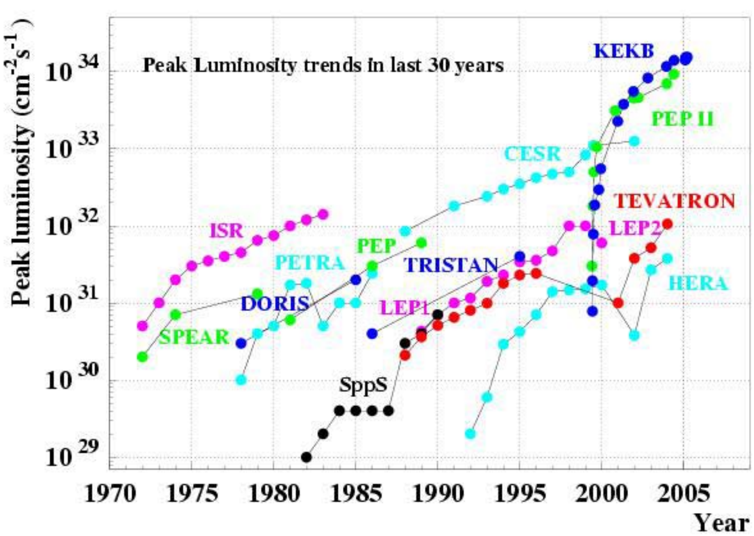


Accelerator performance: just a day at KEKB in 2005 (two weeks ago)

Continuous injection

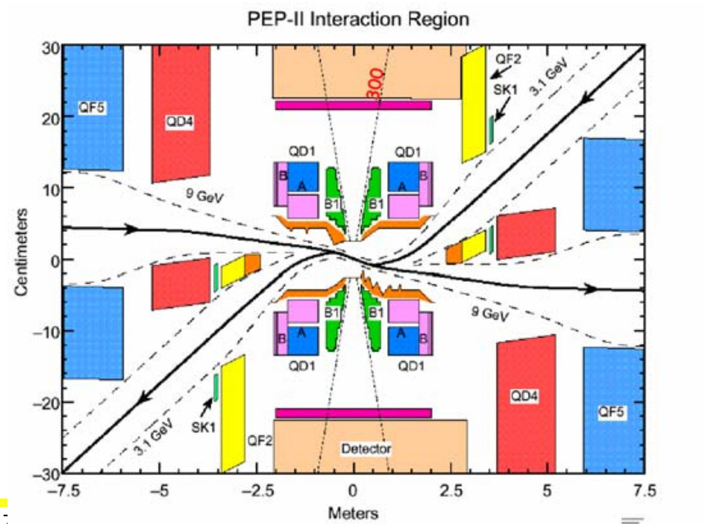


Accelerator performance



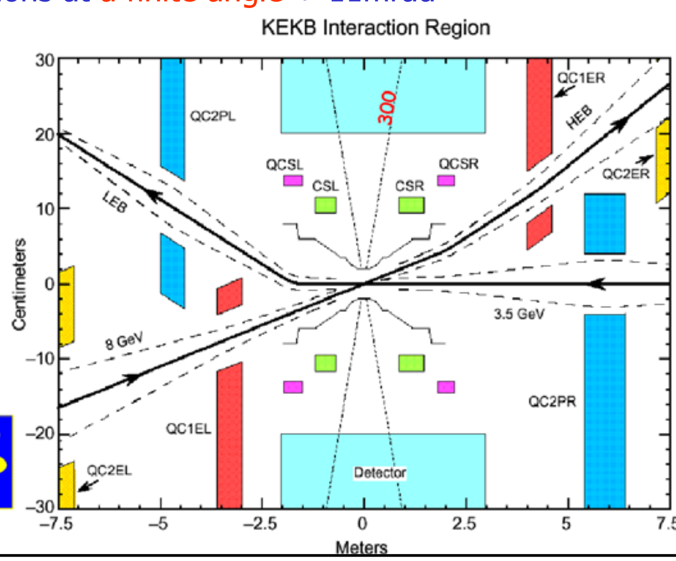
Interaction region: BaBar

Head-on collisions

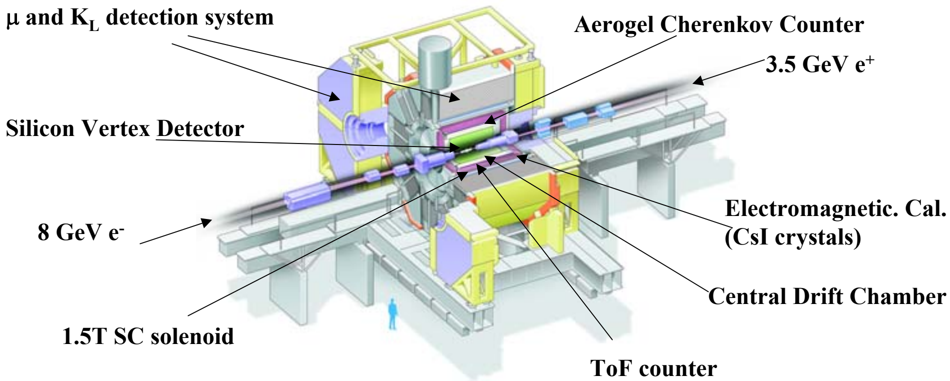


Interaction region: Belle

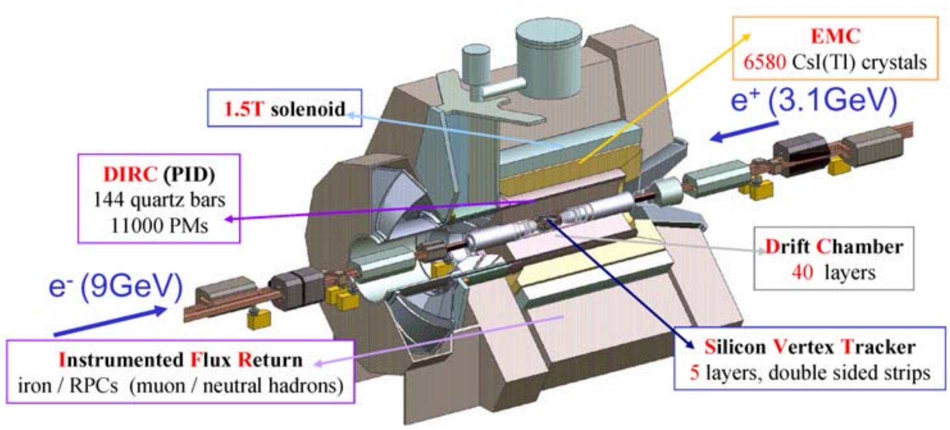
Collisions at a finite angle +-11mrad



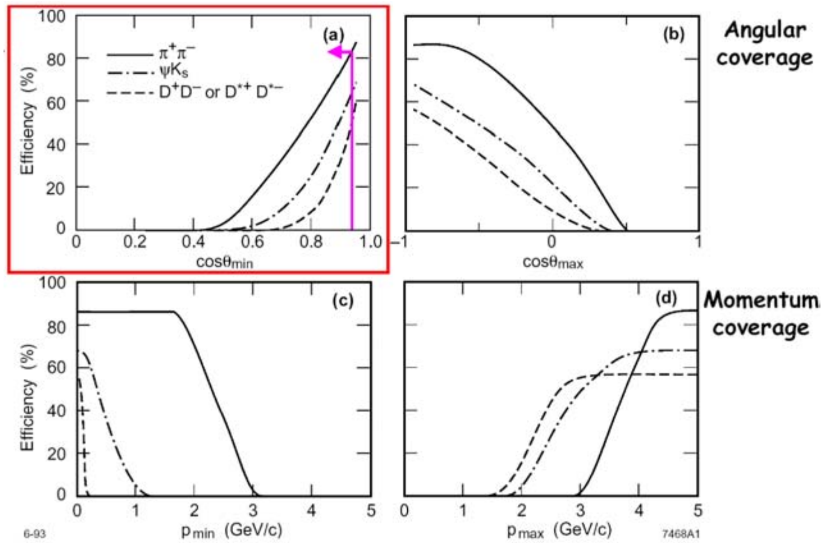
Belle spectrometer at KEK-B



BaBar spectrometer at PEP-II



Requirements: Geometric Acceptance

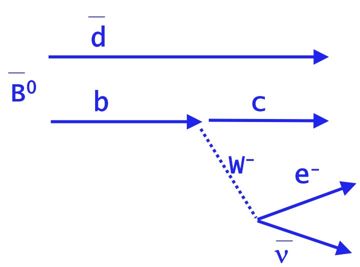


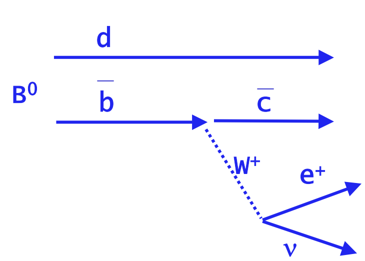
Flavour tagging

Was it a B or anti-B that decayed to the CP eigenstate?

Look at the decay products of the associated B

- Charge of high momentum lepton





Flavour tagging

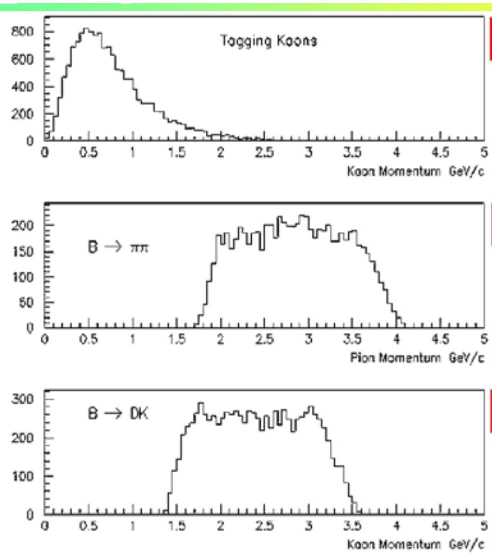
Was it a B or anti-B that decayed to the CP eigenstate?

Look at the decay products of the associated B

- Charge of high momentum lepton
- Charge of kaon
- Charge of ‘slow pion’ (from D^*->$D\pi$ decay)
- .....

Charge measured from curvature in magnetic field, need reliable particle identification

Requirements: Particle Identification



Tagging Kaons

Relatively soft, ms dominated for tracking

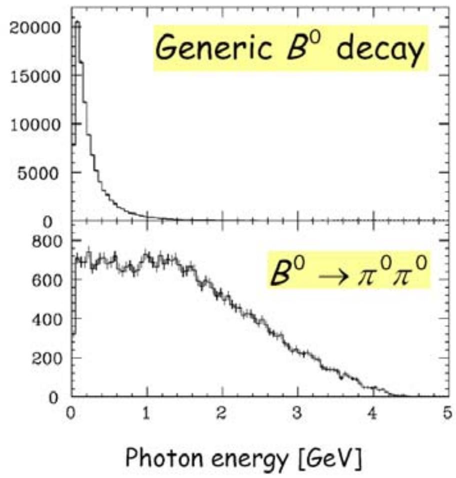
$B \to \pi\pi$

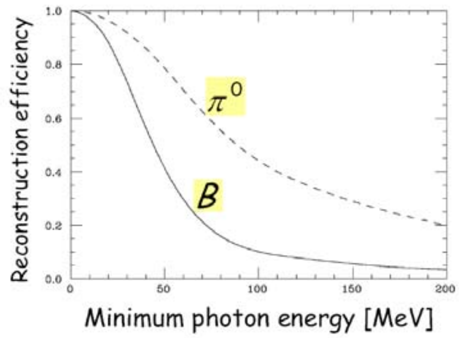
Requires dedicated PID

$B \to DK$

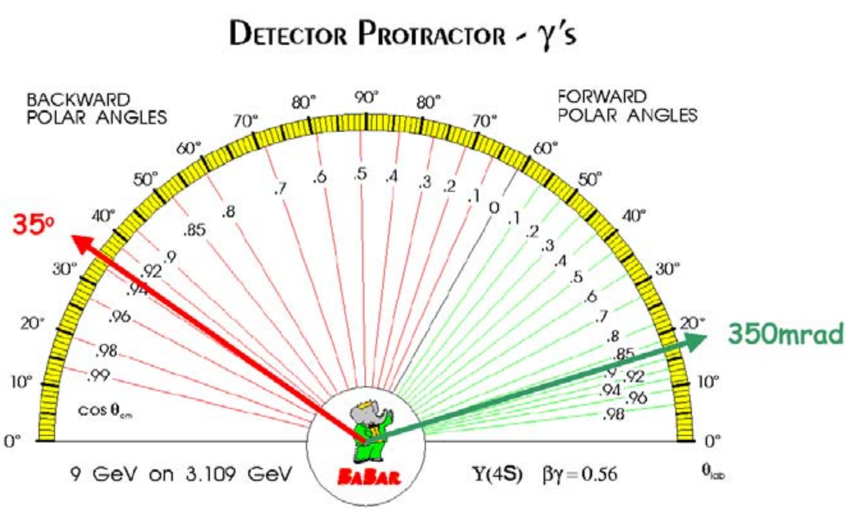
Requires dedicated PID

Requirements: Photons





Photons in the lab system



Requirement: measure both b-> c anti-c s CP=+1 and CP=-1 eigenstates

$$a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)$$

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

Asymmetry sign depends on the CP parity of the final state f_{CP}, η_{fcp}=+-1

$J/\psi\, K_S\, (\pi^+ \pi^-)$: CP=-1

- J/ψ: P=-1, C=-1 (vector particle $J^{PC}=1^{--}$): CP=+1
- $K_S\, (\to \pi^+ \pi^-)$: CP=+1, orbital ang. momentum of pions=0 -> $P(\pi^+ \pi^-)=(\pi^- \pi^+)$, $C(\pi^- \pi^+)=(\pi^+ \pi^-)$
- orbital ang. momentum between J/ψ and K_S l=1, $P=(-1)^1=-1$

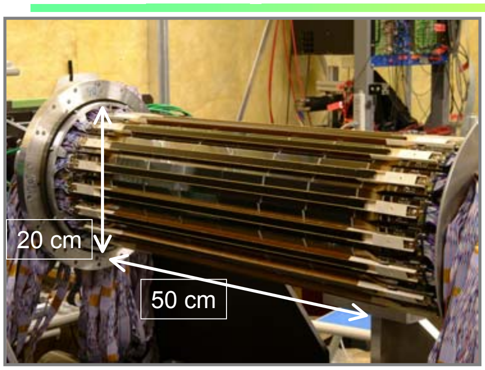
$J/\psi\, K_L(3\pi)$: CP=+1

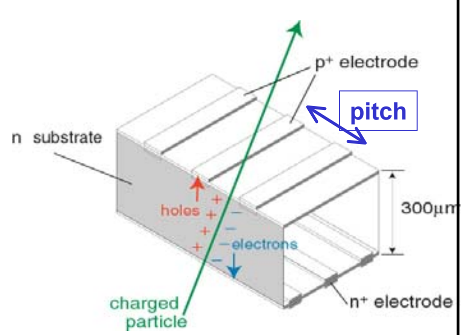
Opposite parity to $J/\psi\, K_S\, (\pi^+ \pi^-)$, because $K_L(3\pi)$ has CP=-1

-> need K_L detection

Silicon vertex detector (SVD)

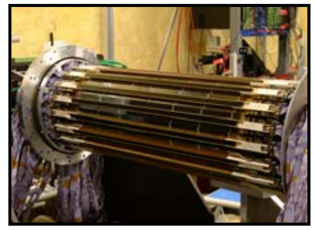
BELLE

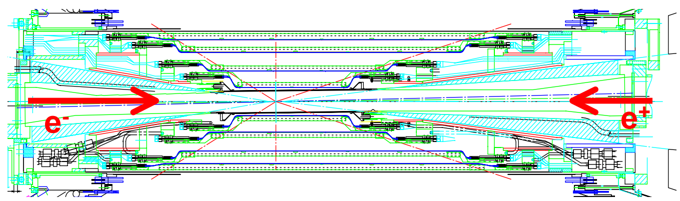




Two coordinates measured at the same time; strip pitch: 50 µm (75 µm); resolution about 15 µm (20 µm).

Silicon vertex detector (SVD)

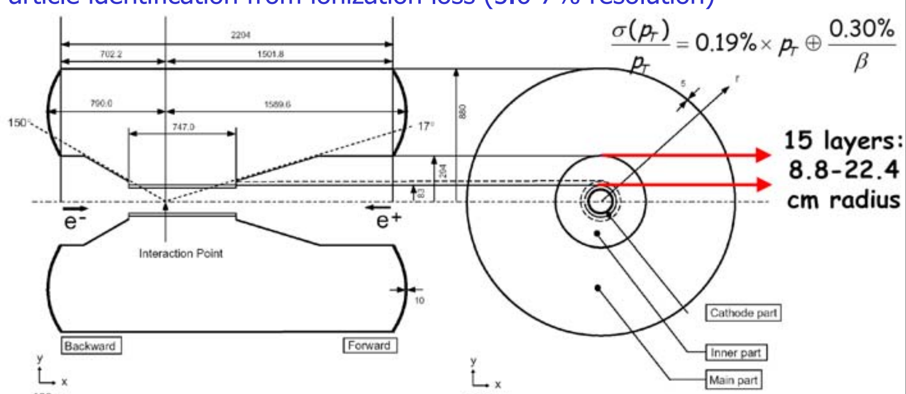




4 layers covering polar angle from 17 to 150 degrees

Tracking: Belle central drift chamber

- 50 layers of wires (8400 cells) in 1.5 Tesla magnetic field
- Helium:Ethane 50:50 gas, Al field wires, CF inner wall with cathodes, and preamp only on endplates
- Particle identification from ionization loss (5.6-7% resolution)

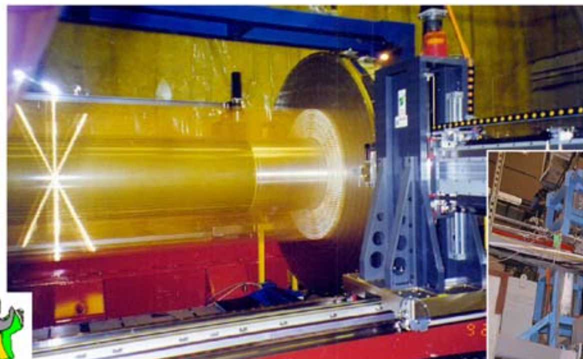


Tracking: BaBar drift chamber

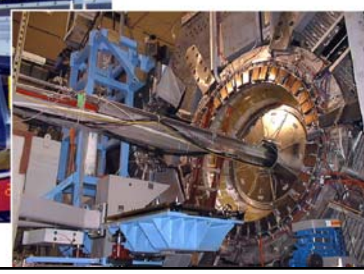
40 layers of wires (7104 cells) in 1.5 Tesla magnetic field

Helium:Isobutane 80:20 gas, Al field wires, Beryllium inner wall, and all readout electronics mounted on rear endplate

Particle identification from ionization loss (7% resolution)



$$\frac{\sigma(p_T)}{p_T} = 0.13\% \times p_T + 0.45\%$$



16 axial, 24 stereo layers

Identification

Hadrons (π, K, p):

- Time-of-flight (TOF)
- dE/dx in a large drift chamber
- Cherenkov counters

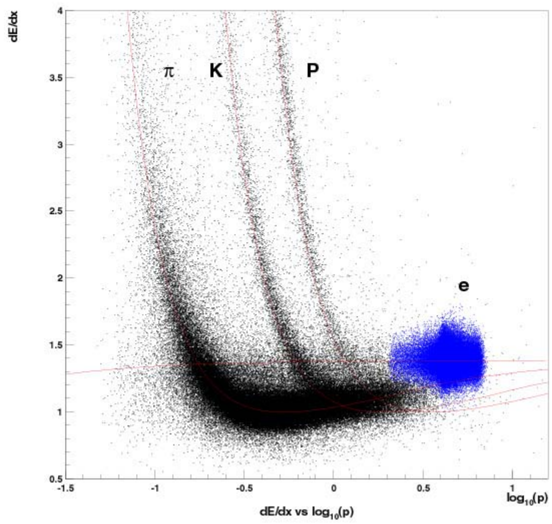
Electrons: electromagnetic calorimeter

Muon: muon chambers in the instrumented magnet yoke

Identification with dE/dx measurement

dE/dx performance in a large drift chamber.

Essential for hadron identification at low momenta.



Cherenkov counters

Essential part of particle identification systems.

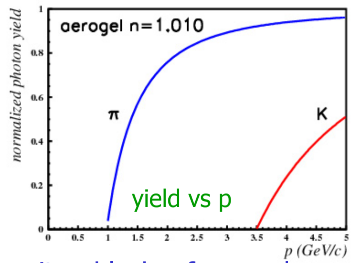
Cherenkov relation: **cos**θ **= c/nv = 1**/β**n**

Threshold counters --> count photons to separate particles below and above threshold; for $\beta < \beta_t = 1/n$ (below threshold) no Čerenkov light is emitted

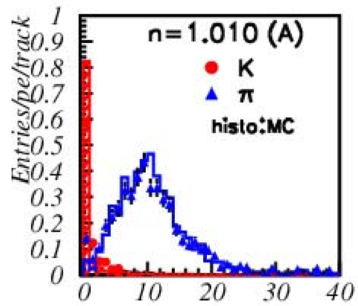
Ring Imaging (RICH) --> measure Čerenkov angle and count photons

Belle ACC (aerogel Cherenkov counter): threshold Čerenkov counter

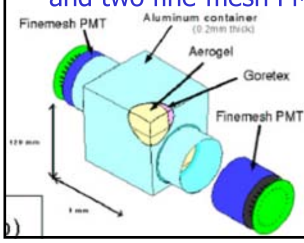
K (below thr.) vs. π (above thr.): adjust n



measured for 2 GeV < p < 3.5 GeV
expected, measured ph. yield

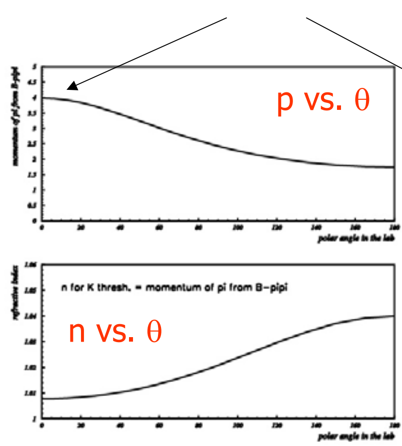


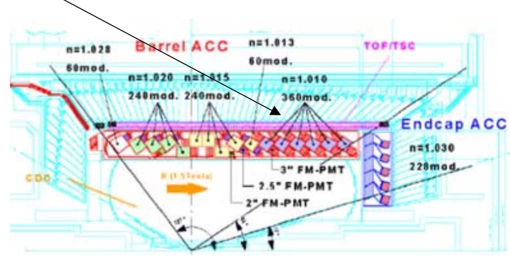
Detector unit: a block of aerogel and two fine-mesh PMTs



Belle ACC (aerogel Cherenkov counter): threshold Cherenkov counter

K (below thr.) vs. π (above thr.): adjust n for a given angle kinematic region (more energetic particles fly in the 'forward region')

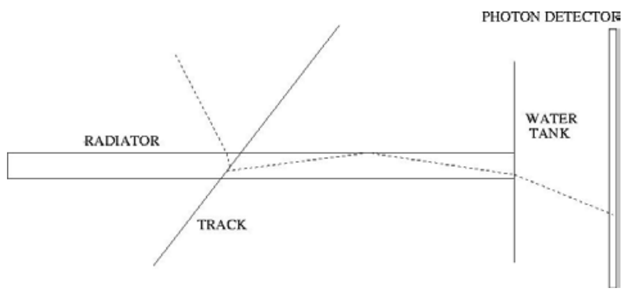




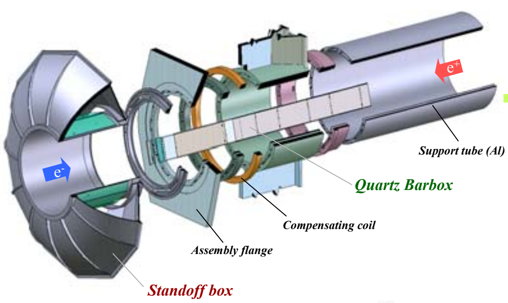
DIRC: Detector of Internally Reflected Cherekov photons

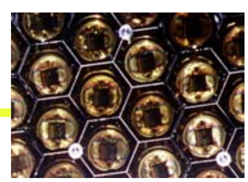
Use Cherenkov relation $\cos\theta = c/nv = 1/\beta n$ to determine velocity from angle of emission

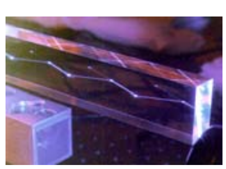
DIRC: a special kind of RICH (Ring Imaging Cherenkov counter) where Čerenkov photons trapped in a solid radiator (e.q. quartz) are propagated along the radiator bar to the side, and detected as they exit and traverse a gap.

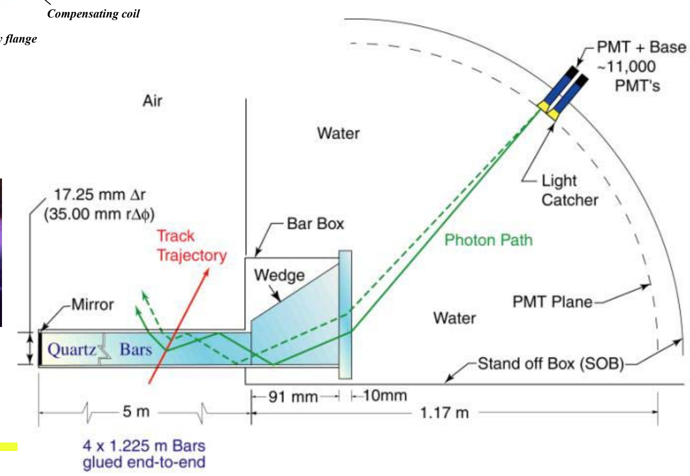


DIRC



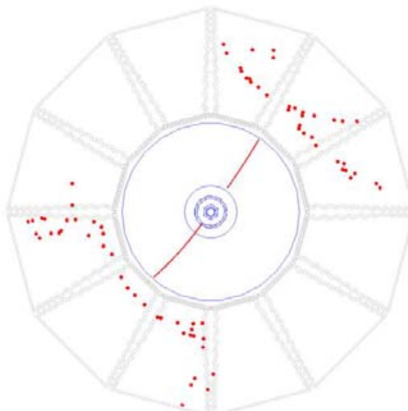




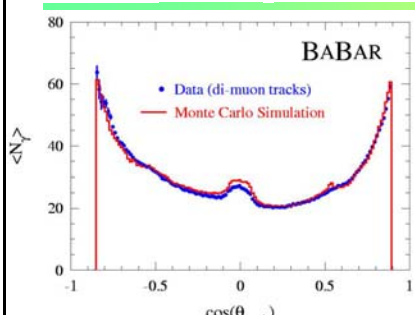


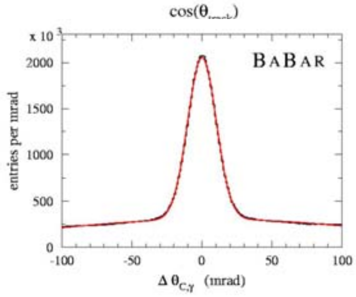
DIRC event

Babar DIRC: a Bhabha event $e^+ e^- \to e^+ e^-$

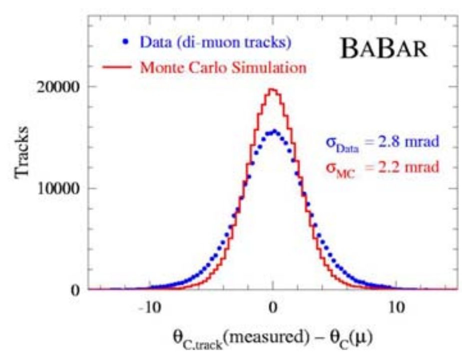


DIRC performance

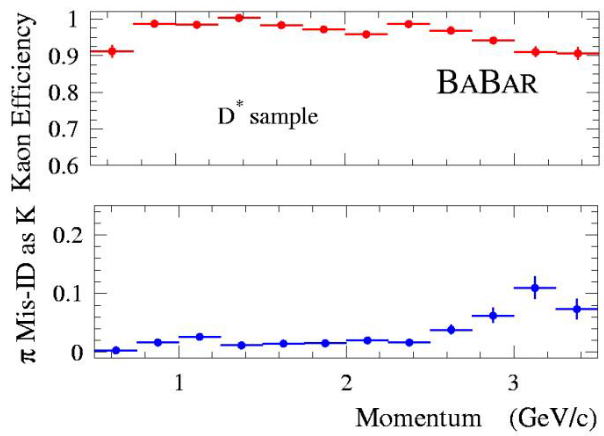




Performance

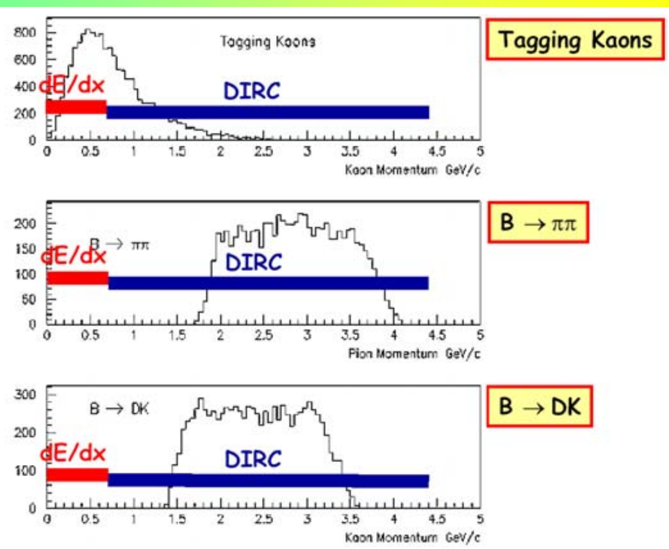


DIRC performance

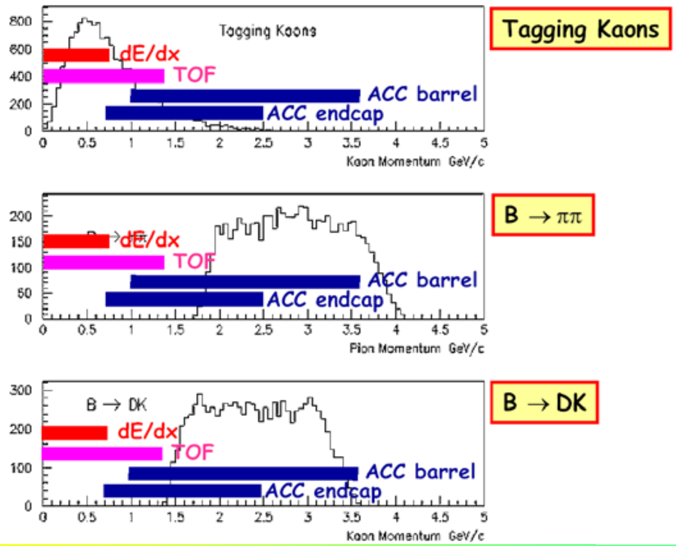


To check the performance, use kinematically selected decays:
$D^{*+} \to \pi^+ D^0$, $D^0 \to K^- \pi^+$

PID coverage of kaon/pion spectra



PID coverage of kaon/pion spectra



Calorimetry Design

Requirements

•Best possible energy and position resolution: 11 photons per Y(4S) event; 50% below 200 MeV in energy

•Acceptance down to lowest possible energies and over large solid angle

•Electron identification down to low momentum

Constraints

•Cost of raw materials and growth of crystals

•Operation inside magnetic field

•Background sensitivity

Implementation

Thallium-doped Cesium-Iodide crystals with 2 photodiodes per crystal

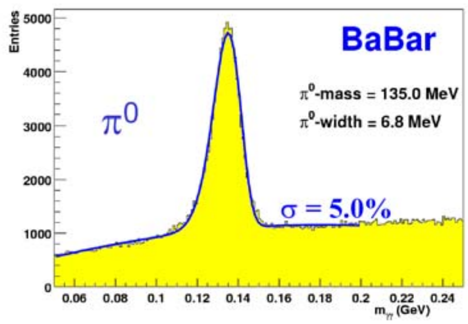
Thin structural cage to minimize material between and in front of crystals

Calorimetry: BaBar

6580 CsI(Tl) crystals with photodiode readout

About 18 X_0, inside solenoid

$$\frac{\sigma(E)}{E} = \frac{(2.32 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E}} \oplus (1.85 \pm 0.07 \pm 0.1)\%$$



Muon and K_L detector

Up to 21 layers of resistive-plate chambers (RPCs) between iron plates of flux return

Muon identification >800 MeV/c

Neutral hadrons (K_L) detection - also with electromagnetic calorimeter

Bakelite RPCs at BABAR

Glass RPCs at Belle