B-Factory Detectors

9th Vienna Conference on Instrumentation

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February 23, 2001
I am a member of Belle, but have been asked by the organizers to cover “B-Factory” detectors in general, which I took to mean the asymmetric $e^+e^-$ B-Factory detectors, BaBar and Belle. I have done my best to be even handed. Any inaccuracies with respect to BaBar are entirely of my own creation.
Theme

Both collaborations have *very* recently submitted their first meaningful measurements of indirect CP violation for publication. Keeping in mind the timeliness of those results and the purpose of this conference, I thought it might of interest to examine the CP violation measurement paying special attention to the detector techniques involved.
The principal physics goal of the B Factories is to test the KM picture of CP violation by measuring the angle $\phi_1$ (aka $\beta$) of the unitarity triangle.
Indirect CP Violation

Thus for a decay $B^0 \to f$ where $f$ is a CP eigenstate, we have two “indistinguishable” decay paths:

$$A_{CP}(\Delta t) = \frac{\Gamma(B^0 \to f) - \Gamma(\bar{B}^0 \to f)}{\Gamma(B^0 \to f) + \Gamma(\bar{B}^0 \to f)}$$

$$= \pm \sin(\Delta m_d \Delta t) \sin 2\phi_1$$

where

$$\phi_1 = \pi - \arg \left[ \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} \right] = \beta$$
The Measurement

Need to:
- Measure momenta
- ID leptons & K’s
- Measure vertices

\[ \Delta z = \beta \gamma c \Delta t \]

CP eigenstate
The Measurement

The time-dependent asymmetry appears mainly as a mean shift in the $\Delta t$ distribution between events tagged as $B^0$ decays and events tagged as $\bar{B}^0$ decays.

\[
\frac{dN}{dt}
\]

$\Delta t$ (ps)
A Specific Reaction (Case Study)

\[ e^+ e^- \rightarrow B^0 \bar{B}^0 \]

- Hadron Identification
- Lepton Identification
- Momentum Measurement

CP eigenstate

- \( J/\Psi \rightarrow K^- X^+ \)
- \( K_S \rightarrow l^+ l^- \)
- \( \pi^+ \pi^- \)
Asymmetric $e^+ e^-$ Colliders

KEK: KEK- 8.0 x 3.5 GeV/c
Lumi: Design $10^{34}$ cm$^{-2}$s$^{-1}$
Achieved $2.4 \times 10^{33}$ cm$^{-2}$s$^{-1}$

SLAC: PEP II 9.0 x 3.1 GeV/c
Lumi: Design $3 \times 10^{33}$ cm$^{-2}$s$^{-1}$
Achieved $3.1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
B=1.5 T

Detector Drawing

BABAR Coordinate System

Scale

0

y

X

Z

4 m

detector C

INSTRUMENTED FLUX RETURN (IFR) BARREL

SUPERCONDUCTING COIL

ELECTROMAGNETIC CALORIMETER (EMC)

DRIFT CHAMBER (DCH)

SILICON VERTEX TRACKER (SVT)

IFR ENDCAP

FORWARD END PLUG

e

e

Q4

Q2

Q1

B1

3045

1375

810

3500

1225

1749

4050

1149

1149

370

1015
Charged Particle Momentum Measurement

• The basis of essentially every signal we study.

• Uses drift-chamber technology, which has progressed from a “black art” to something approaching science over the past ~30 years.

• Basic concept is the same, but there are some refinements, e.g., the use of low-Z gas (He:C\textsubscript{2}H\textsubscript{6}), detector-mounted readout electronics, and shaped endplates.
Wire-Stringing Robot (BaBar)

Drift Chamber Mechanics

Curved Endplate (Belle)
The chambers are not huge by HEP standards.
Drift Chamber Performance

BELLE Central Drift Chamber

Cosmic Rays

Fit

$(0.198\pm0.004)\%Pt\oplus(0.251\pm0.01)\%$

Design

$0.175\%Pt\oplus0.198\%$

BaBar Position Resolution

February 2001

B Factory
dE/dx Particle Identification

A side benefit of the drift chambers is the ionization measurement, which is sensitive to velocity and therefore mass.

\[ \frac{dE}{dx} \propto \frac{1}{\beta^2} \left( \frac{dE}{dx} \right) \left[ 1 + \log p \right] \]
$K_S^0 \rightarrow \pi^+\pi^-$

$\sigma_{\text{eff}} = 4.6 \text{ MeV}/c^2$

Mass Reconstruction
Mass Reconstruction

\[ B^0 \rightarrow J/\psi \rightarrow l^+ l^- \rightarrow \pi^+ \pi^- \]

By reconstructing the invariant mass and the CM momentum of the decaying B meson, it is possible to eliminate almost all of the background for the gold-plated CP mode.
Photon Detection

Since roughly half of the energy in B decays comes in the form of neutrals, it is important to have precision photon detection.

\[ B^0 \rightarrow J/\Psi K^0 \rightarrow l^+l^- \pi^0 \pi^0 \]
Photon Detection

Photons are detected by using CsI(Tl) crystals read by silicon photodiodes. Nearly $4\pi$ coverage is attained with a “fly’s eye array comprising $\sim 10^4$ crystals.
CsI EM Calorimeter Performance

Belle

$\eta \rightarrow \gamma \gamma$ Reconstruction

$m = 544 \pm 1$ MeV
$\sigma = 12 \pm 1$ MeV

$E_\gamma > 50$ MeV

$\pi^0$ Reconstruction

$m = 133.4 \pm 0.1$ MeV
$\sigma = 5.64 \pm 0.10$ MeV
Electron Identification

The ability to discriminate between leptons and pions is crucial to the physics analysis, for example in identifying

\[ J / \Psi \rightarrow e^+ e^- \]

decays.

The most powerful separation techniques involve comparison between the measurements in the drift chamber and the calorimeter, for example E/p.
Electron Identification

A number of quantities in addition to $E/p$ are combined to form an electron-ID likelihood function.
Muon Identification

Muons are important for the same reason. They are identified by the way in which they penetrate the iron return yoke of the magnet.

\[ B^+ \rightarrow J/\Psi K^+ \]

\[ \rightarrow \mu^+ \mu^- K^+ \]

plus tag-side \( \mu \)

The gaps are instrumented with RPCs.
Instrumented Flux Return

342 RPC Modules

19 Layers

1250, 1940

3200

FW

920

18 Layers

432 RPC Modules

BW

BaBar
A passing charged particle induces an avalanche, which develops into a spark. The discharge is quenched when all of the locally available charge is consumed.

The discharged area recharges slowly through the high-resistivity glass plates (Belle) or linseed-oil coated bakelite (BaBar).
The RPC Experience Is Not All Positive

If high dark currents develop, RPCs can suffer a serious efficiency loss due to high IR voltage drops in the resistive plates. This problem developed in the early days of Belle (fortunately, we were able to solve it). BaBar also has serious problems along these lines.
The muon systems also are used to reconstruct

$$B^0 \rightarrow J/\Psi K_L$$

events by detecting the direction of the $K_L$. This mode complements the

$$B^0 \rightarrow J/\Psi K_S$$

mode, but has more background.
Thus far we have seen the tools needed to detect the $B^0$ that decays to a CP eigenstate. The analysis also requires that we know the flavor of the decaying $B^0$, which is done by observing the way in which the other $B^0$ decays. One way of doing this is to measure the sign of charged kaons. Measuring the sign is easy, but distinguishing kaons from the $\sim 10X$ more copious pions requires special detectors.
Particle Identification

It is in this area that Belle and BaBar differ the most. Belle chose to adopt and refine existing techniques, whereas BaBar employed a newly invented device called the DIRC. In both cases the idea is to measure the particle’s velocity.

- Belle uses time of flight (ToF) plus a system of aerogel Cerenkov counters (ACC).
- BaBar’s DIRC measures the emission angle of Cerenkov light in precisely machined and polished quartz bars.
- Both groups complement this information with dE/dx measurements mentioned earlier.
The ToF has a resolution of $\sigma=100$ ps, which provides $\pi/K$ separation up to about 1.2 GeV/$c$, at which point the ACC array kicks in. The index of refraction of the counters varies as a function of angle, reflecting the boosted CM.
Belle: Aerogel

Barrel Module

Kaons
(selected by ToF and dE/dx)

Bhabha e+/e−

Beam Data

Monte Carlo

Pulse Height (p.e.)
The DIRC

PMT + Base
10,752 PMT's

Standoff
Box

Light Catcher

Purified Water

Bar Box

PMT Surface

17.25 mm Thickness
(35.00 mm Width)

Mirror

Wedge

Track Trajectory

Window

4.9 m

4 x 1.225m Bars
glued end-to-end

1.17 m
The DIRC

- Support tube
- Quartz Barbox
- Compensating coil
- Assembly flange
- Standoff box
A DIRC Event

\[ e^+ e^- \rightarrow \mu^- \mu^+ \]

\[ |t| < 300 \text{ ns} \quad |t| < 8 \text{ ns} \]
PID Bake Off

BaBar

Belle

Looks like BaBar does better.
The characteristic decay times are \( \sim 1 \) ps, which is too short to measure by direct timing. Instead, we measure the decay distances (\( \Delta z \approx 200 \mu m \)) using a silicon vertex detector.

See also this morning’s talk by S. Stanic.
Silicon Vertex Detector

Belle
SVT Performance

Position resolution vs. angle.

BaBar
The Results