Physics Motivation

Direct CP violation is perhaps the simplest case. Consider the CP mirror processes:

\[ B \rightarrow f \] and \[ \bar{B} \rightarrow \bar{f} \]

The CP asymmetry is defined as

\[ A_{CP} \equiv \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow \bar{f})} \]

The decay amplitudes are

\[ A_f = |A_f| e^{i\phi_w} e^{i\phi_s} \text{ and } A_{\bar{f}} = |A_f| e^{-i\phi_w} e^{i\phi_s} \]

Note that the weak phase changes sign.
Direct CP Violation

Note that

\[ |A_f|^2 = |A_{\bar{f}}|^2 \Rightarrow \Gamma_f = \Gamma_{\bar{f}} \]

We need some sort of interference, two amplitudes, for example

\[ A_f = |A_1| e^{i\phi_{w_1}} e^{i\phi_{s_1}} + |A_2| e^{i\phi_{w_2}} e^{i\phi_{s_2}} \]

\[ A_{\bar{f}} = |A_1| e^{-i\phi_{w_1}} e^{i\phi_{s_1}} + |A_2| e^{-i\phi_{w_2}} e^{i\phi_{s_2}} \]

Yielding

\[ \Gamma_f = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\Delta\phi_w + \Delta\phi_s) \]

\[ \Gamma_{\bar{f}} = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\Delta\phi_w - \Delta\phi_s) \]
Direct CP Violation

Despite its conceptual and experimental simplicity, there are two problems with direct CP violation:

• Cases where there are two comparable amplitudes that are large are (probably) rare.

• The strong phases are poorly understood, making it difficult to extract the weak (KM) phases that are of greatest interest.

This leads one in the direction of asymmetric B factories aimed at the study of indirect CP violation.
Indirect CP Violation

In this approach we provide the interference using \( B^0 \bar{B}^0 \) state mixing, i.e.,

\[
\left| B^0(t) \right> = e^{-i(m-i\Gamma)/2} \times \left[ \cos\left(\frac{\Delta m t}{2}\right) \left| B^0 \right> + i \sin\left(\frac{\Delta m t}{2}\right)e^{-2i\phi_m} \left| \bar{B}^0 \right> \right]
\]
Indirect CP Violation

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

Working through the algebra, yields a time-dependent CP asymmetry

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

$$= -2\eta_f \sin(\Delta m \Delta t) \sin 2(\phi_M + \phi_D)$$

Where $\phi_M$ and $\phi_D$ are the weak phases for the mixing and decay diagrams, respectively and

$$CP |f\rangle = \eta_f |f\rangle$$

$$\eta_f = \pm 1$$
Quark mixing is described via

\[
M = \begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix} \approx \begin{pmatrix}
1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\
-\lambda & -\lambda^2/2 & A\lambda^2 \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

Where the second matrix is the Wolfenstein parameterization.

The “d b” unitarity relation yields

\[
V_{ud}^*V_{td} + V_{us}^*V_{ts} + V_{ub}^*V_{tb} = 0
\]

\[
V_{td} + V_{ub}^* \approx A\lambda^3
\]
The Kobayashi-Maskawa Mixing Scheme

Quark mixing is described via

\[ M = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \cong \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} \]

Where the second matrix is the Wolfenstein parameterization.

The “d b” unitarity relation yields

\[ V_{ud}V_{td} + V_{us}V_{ts} + V_{ub}V_{tb} = 0 \]

\[ V_{td} + V_{ub}^* \approx A\lambda^3 \]
CP Phases in the Gold-Plated Mode

Decay

\[ B^0 \rightarrow J/\Psi \ K_S \]

\[ \phi_D \approx 0 \]

Mixing

\[ \phi_M \approx \text{arg}(V_{td}) \]

The KM phase comes from the mixing.
The gold-plated mode determines the angle $\phi_1$ which is also called $\beta$.
Existing measurements of $B^0 \bar{B}^0$ mixing and $V_{ub}$ limit the allowed region in the $(\rho, \eta)$ plane.
The Measurement

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

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

KEK-B is similar to PEP-II in many ways, although there is a (potentially) important difference in the way in which the beams are brought into collision.
Beam Crossing Schemes

By colliding the beams at an angle, the KEK-B design achieves a simplified interaction region.

Moreover, every RF bucket (2 ns spacing) can be filled to achieve maximum luminosity. However, this approach risks destabilizing couplings between transverse and longitudinal modes of the machines.

A crab-crossing cavity is under development in case this proves to be a problem.
## Linac Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HER e- Design</th>
<th>HER e- Achieved</th>
<th>LER e+ Design</th>
<th>LER e+ Achieved</th>
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<tbody>
<tr>
<td>Beam Energy</td>
<td>8 GeV</td>
<td>8.5 GeV</td>
<td>3.5 GeV</td>
<td>4.0 GeV</td>
</tr>
<tr>
<td>Charge/bunch</td>
<td>1.2 nC</td>
<td>1.2 nC</td>
<td>.64 nC</td>
<td>.60 nC</td>
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<tr>
<td>Transmission</td>
<td>100%</td>
<td>80-100%</td>
<td>100%</td>
<td>70%</td>
</tr>
<tr>
<td>Rep. Rate</td>
<td>50 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Emittance</td>
<td>&lt;0.1 um</td>
<td>.06 um</td>
<td>&lt;.25 um</td>
<td>.4 um</td>
</tr>
</tbody>
</table>
## Ring Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HER e-</th>
<th>LER e+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Current</td>
<td>1100 mA</td>
<td>514 mA</td>
</tr>
<tr>
<td>Single Bunch Current</td>
<td>.22 mA</td>
<td>4 mA</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>5000</td>
<td>800</td>
</tr>
<tr>
<td>$\beta_x / \beta_y$ @ IP</td>
<td>33/1 cm</td>
<td>100/1.1 cm</td>
</tr>
<tr>
<td>Injection Efficiency</td>
<td>100%</td>
<td>80%</td>
</tr>
</tbody>
</table>

October 1999

The First Events from BELLE
The luminosity is a factor of ~30 below design, but steady progress was made before the summer shutdown.
October 1999

The First Events from BELLE
The BELLE Collaboration

About 10 Countries, 50 Institutes, & 200 People
Key Belle Milestones

- Early 1990’s - Japanese groups begin working.
- April 1995 - TDR Submitted.
  …lots of work by lots of people in lots of places...
- Dec 18, 1998 - Belle detector completed (including SVD)
- Jan 26, 1999 - First cosmic ray with full detector.
- May 1, 1999 - Belle rolled into place.
- June 1, 1999 - First hadronic event!!!!!
- June 1999 About 1200 hadron events obtained before vacuum pipe mishap.
- July 1999 More data (30K events) and lots learned.
June 1, 1999: Our First Hadronic Event
More Fun: SVD Included

October 1999

The First Events from BELLE
First $J/\psi$ Candidate

- $J/\psi \rightarrow ee$
  - $M(\text{ee}) = 3.1 \text{ GeV}$
SVD Performance

$B^+ \rightarrow J/\psi K^+$ candidate
SVD Performance

$e^{-}$

$\Delta \phi$

$e^{+}$

Bhabha miss
distance
SVD Performance

SVD impact parameter resolution (rphi)

**Vertical tracks**

- **Distance between bhabha tracks at vertex (good SVD track)**
  - ID: 27
  - Entries: 842
  - Mean: 0.138E-02
  - RMS: 0.653E-02
  - \( \chi^2/\text{ndf} \): 49.48 / 34
  - \( \text{ndf} \): 108.1
  - Mean: 0.1299E-02
  - Sigma: 0.4625E-02

**Horizontal tracks**

- **Distance between bhabha tracks at vertex (good SVD track)**
  - ID: 27
  - Entries: 714
  - Mean: 0.2789E-03
  - RMS: 0.7729E-02
  - \( \chi^2/\text{ndf} \): 46.68 / 35
  - \( \text{ndf} \): 69.68
  - Mean: 0.3759E-03
  - Sigma: 0.6063E-02

October 1999 The First Events from BELLE
SVD Tomography

X-Z distribution of primary vertices for all triggers, including beam gas.

The IP, the beam crossing angle, and various flanges etc in the IR are clearly evident.
CDC Performance

$P_T$ resolution measured by $\mu^+\mu^-$ events.

Spatial resolution
per point = 160 $\mu$m

$K_S$ reconstruction

$\Lambda$ reconstruction

October 1999  The First Events from BELLE
CDC Performance (Cosmic Rays)

Bellev Central Drift Chamber

Fit
$(0.198 \pm 0.004)\%Pt \oplus (0.251 \pm 0.01)\%$

Design
$0.175\%Pt \oplus 0.198\%$

October 1999

The First Events from BELLE
Particle ID (dE/dx, ToF, & Aerogel)

\[ \text{dE/dx measured by CDC} \]

- 80% truncated mean of 50 layers
- \( 0.3 < P < 0.7 \) GeV
- \( \sigma(dE/dx) = 6.8\% \)

Aerogel Cherenkov counter

- \( n = 1.010 - 1.03 \) depending on \( \theta \)
- \( N_{\text{p.e.}} = 20.0 \) for \( \beta = 1 \) part.
  - (with \( n = 1.015 \))

Time-of-flight measurement

- \( \sigma_{\text{TOF}} = 120 \) psec

Track matching eff.

\( \approx 90\% \)

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The First Events from BELLE
Particle ID (dE/dx, ToF, & Aerogel)

$D^{*+} \rightarrow D^0\pi^+$

$\rightarrow K^-\pi^+$

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CsI EM Calorimeter Performance

\[ \pi^0 \text{ Reconstruction} \]

\[ E_\gamma > 50 \text{ MeV} \]

\[ \eta \rightarrow \gamma\gamma \text{ Reconstruction} \]

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The First Events from BELLE
More CsI

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Electron ID

Electron ID

- Track-cluster match
- $dE/dx = \text{electron}$
- Shower shape cut
- $E/p$ cut

Before e ID

After e ID

$P^* > 1.0 \text{ GeV}/c$

Reconstruction of

$\pi^0 \rightarrow e^+ e^- \gamma$

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The First Events from BELLE
Muon ID

$\mu^\pm$ ID by KLM

Number of hit layers associated with a charged track

$p > 1.5 \text{ GeV}$

$|\cos \theta| < 0.4$

Number of hit layers
Muon ID

Cosmics (solid) and MC muons (dashed) (0.5–4.0 GeV/c) 99/06/15 22.47

(Cosmics scaled up to equal area)

MC Muon into → Entries: 9098
Mean: 0.8770
RMS: 0.7511

(Cosmics scaled down to equal area)

Muon likelihood (MC muons)

No KLM hits (3.6%)

Entries: 9098

Reduced $\chi^2$ (MC muons)

Reduced $\chi^2$ (Cosmics)

Entries: 5803

Muon likelihood (cosmics)

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The First Events from BELLE
October 1999

The First Events from BELLE

First $\sim$1000 hadronic events.

\[ P_{\text{miss}} = P_{4S} - \sum_{i=\gamma, h^\pm} P_i \]

\[ P_{KL} \]

\[ P_{\text{miss}} \]
Physics from the First Runs: Energy Scan

$R_2$ distribution

Fox-Wolfram moment ratio

$R_2 \equiv \frac{H_2}{H_0}$

No. of events with $R_2 \leq 0.2$

/ No. of Bhabha events

$B\bar{B}$ event rate

from lepton spectrum

Peak at $10.584\pm0.0005$ GeV

(In "KEKB scale")

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The First Events from BELLE
$J/\psi \rightarrow \mu^+\mu^-$
and $e^+e^-$

One tight lepton cut
+ one loose cut

Lepton-pair Spectrum

$12e^+e^- + 10\mu^+\mu^-$
A “Typical” Dimuon event

- $J/\psi \rightarrow \mu\mu$
- $M(\mu\mu) = 3.1 \text{ GeV}$
- both muons tracks clearly evident in magnet return yoke

This event is consistent with

$B \rightarrow J/\psi \ K_L$

although there were no hits in the RPCs
$B^+ \rightarrow J/\Psi K^+$ candidate

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The First Events from BELLE
$B^+ \rightarrow J/\Psi K^+$ candidate
Charm Mass Plots

\[ D^0 \rightarrow K^- \pi^+ \]

\[ D^+ \rightarrow K^- \pi^+ \pi^- \]

On 4S

Off 4S
Charmed Baryon

\[ \Lambda_c \rightarrow pK^-\pi^- \]
Unstable Particles

$\rho^0 \rightarrow \pi^+ \pi^-$

$m = 728 \pm 8 \text{MeV}
\Gamma = 130 \pm 29 \text{MeV}$

$\eta \rightarrow \gamma \gamma$

$m = 544 \pm 1 \text{MeV}
\sigma = 12 \pm 1 \text{MeV}$

$K^{* \pm} \rightarrow K_S \pi^\pm$

$m = 899 \pm 4 \text{MeV}
\Gamma = 37 \pm 14 \text{MeV}$

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

$m = 897 \pm 2 \text{MeV}
\Gamma = 32 \pm 7 \text{MeV}$

October 1999

The First Events from BELLE
Unstable Particles

\( \phi \rightarrow K^+K^- \)

\( \omega \rightarrow \pi^+\pi^-\pi^0 \)

Impossible without PID

\( \rho^\pm \rightarrow \pi^\pm\pi^0 \quad p > 2.5 \text{GeV} \)

\( m(\pi^+\pi^-\pi^0) \quad p > 1.5 \text{GeV} \)

October 1999

The First Events from BELLE
D Lifetimes

$D^0$ selection

Decay-time distribution.

$\tau_{D^0} = (0.38 \pm 0.05) \text{ ps}$

c.f. $\tau_{D^0} = (0.415 \pm 0.004) \text{ ps}$

(PDG)
D Lifetimes

\[ \tau_{D^+} = (1.0 \pm 0.2) \text{ ps} \]

c.f. \[ \tau_{D^+} = (1.057 \pm 0.015) \text{ ps} \]

(PDG)
Truth in Advertising

- CDC backgrounds higher than expected
  - Wire currents somewhat high
  - Crosstalk raises effective occupancy
  - Problem under study, one option is to reduce Q/T converter ramp-down time

- SVD inner layer destroyed by synchrotron radiation.
  - 20 um gold added to inside of beampipe
  - new SVD installed during shutdown
  - SVD #3 and #4 in the works!
Conclusions & Outlook

• The KEK-B accelerator is working with luminosity of $3 \times 10^{32}$ cm$^{-2}$s$^{-1}$ before shutdown.
• The entire Belle detector, including the DAQ and offline reconstruction software, is working.
• We face daunting challenges in terms of increasing the luminosity while keeping the backgrounds under control.
• If steady rate of improvement continues, we should be competitive.
• The months ahead will be interesting!