First Data from BELLE

HEP Seminar
TRIUMF

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Physics Motivation

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

\[ B \rightarrow f \text{ and } \overline{B} \rightarrow \overline{f} \]

The CP asymmetry is defined as

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

The decay amplitudes are

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

Note that the weak phase changes sign.
**Direct CP Violation**

Note that
\[ |A_f|^2 = |A_f|^2 \implies \Gamma_f = \Gamma_f \]

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
\[ \Gamma_f = |A_1|^2 + |A_2|^2 + 2 |A_1||A_2| \cos(\Delta \phi_w \bigoplus \Delta \phi_s) \]
\[ \Gamma_{\bar{f}} = |A_1|^2 + |A_2|^2 + 2 |A_1||A_2| \cos(\Delta \phi_w \bigominus \Delta \phi_s) \]
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.,

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

\[\begin{array}{cccc}
\bar{b} & \bar{V}_{tb}^* & \bar{t} & \bar{V}_{td}
\end{array}\]

\[\begin{array}{cccc}
\bar{V}_{tb} & W & W & \bar{b}
\end{array}\]

\[\begin{array}{cccc}
\bar{V}_{td} & \bar{t} & \bar{V}_{tb}^* & d
\end{array}\]

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The First Data from BELLE
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

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

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

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

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

$\eta_f = \pm 1$
The Kobayashi-Maskawa Mixing Scheme

Quark mixing is described via

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

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

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

The KM phase comes from the mixing.
The gold-plated mode determines the angle $\phi_1$ which is also called $\beta$.
Existing measurements of $B^0\overline{B}^0$ 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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</thead>
<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>
</tr>
<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- Design</th>
<th>Achieved</th>
<th>LER e+ Design</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Current</td>
<td>1100 mA</td>
<td>514 mA</td>
<td>2600 mA</td>
<td>532 mA</td>
</tr>
<tr>
<td>Single Bunch Current</td>
<td>.22 mA</td>
<td>4 mA</td>
<td>.52 mA</td>
<td>2.3 mA</td>
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<tr>
<td>Number of Bunches</td>
<td>5000</td>
<td>800</td>
<td>5000</td>
<td>1024</td>
</tr>
<tr>
<td>$\beta_x / \beta_y @ IP$</td>
<td>33/1 cm</td>
<td>100/1.1 cm</td>
<td>33/1 cm</td>
<td>100/1 cm</td>
</tr>
<tr>
<td>Injection Efficiency</td>
<td>100%</td>
<td>80%</td>
<td>100%</td>
<td>80%</td>
</tr>
</tbody>
</table>
Luminosity
January 2000

The First Data 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/July 1999 first serious running
June 1, 1999: Our First Hadronic Event
More Fun: SVD Included
First J/\psi Candidate

- J/\psi \rightarrow ee
  - M(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

Horizontal tracks

The distance between two tracks in r/phi good svd

The distance between two tracks in r/phi good svd
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

$\sigma = 2.5$ MeV

$\sigma = 1.4$ MeV
CDC Performance (Cosmic Rays)

BELLE Central Drift Chamber

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

Design
$0.175\%Pt \oplus 0.198\%$
Particle ID (dE/dx, ToF, & Aerogel)

\[ \text{dE/dx measured by CDC} \]
80% truncated mean of 50 layers
0.3 < P < 0.7 GeV
\( \sigma(\text{dE/dx}) = 6.8\% \)

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.
\( \approx 90\% \)
Particle ID (dE/dx, ToF, & Aerogel)

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

$M(D^*) - M(D)$ (GeV/$c^2$)

![Graph showing the mass difference between D* and D particles, with peaks indicating the decay $D^{*+} \rightarrow D^0 \pi^+$ and $D^0 \rightarrow K^- \pi^+$.)
CsI EM Calorimeter Performance

$\pi^0$ Reconstruction

$E_\gamma > 50$ MeV

$\eta \rightarrow \gamma\gamma$ Reconstruction

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

$m = 133.4 \pm 0.1$ MeV
$\sigma = 5.64 \pm 0.10$ MeV
More CsI
Electron ID

Electron ID

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

Before e ID

After e ID

$p^\gamma > 1.0 \text{ GeV/c}$

Reconstruction of $\pi^0 \rightarrow e^+ e^- \gamma$
Muon ID

Replace with Abe san plot.
First ~1000 hadronic events.
Physics from the First Runs: Energy Scan

$R_2$ distribution

Fox-Wolfram moment ratio

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

No. of events with $R_2 < 0.2$

/ No. of Bhabha events

$B\bar{B}$ event rate

from lepton spectrum

Peak at $10.5841 \pm 0.0005$ GeV

(In "KEKB scale")
Lepton-pair Spectrum

Replace with new plots.
A “Typical” Dimuon event

- $J/\psi \rightarrow \mu\mu$
  - $M(\mu\mu) = 3.1$ 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
$B^+ \rightarrow J/\Psi K^+$ 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}

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

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

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

\[ \omega \rightarrow \pi^+\pi^-\pi^0 \]

\[ \rho^\pm \rightarrow \pi^\pm\pi^0 \quad p > 2.5 \text{GeV} \]

\[ m = 752 \pm 11 \text{MeV} \quad \Gamma = 183 \pm 40 \text{MeV} \]

\[ m = 780 \pm 3 \text{MeV} \quad \sigma = 6 \pm 2 \text{MeV} \]

\[ m = 781 \pm 2 \text{MeV} \quad \sigma = 15 \pm 5 \text{MeV} \]

Impossible without PID
D Lifetimes

$D^0$ selection

Decay-time distribution.

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

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

• Backgrounds are a major problem.
  – High occupancy
  – High trigger rates
  – Radiation damage

• In general, the BELLE design did not address these issues (simplicity in design received greater emphasis).

• We have fairly consistently been at the limit (and in some cases beyond) of what the detector can handle.
Backgrounds

• Steps to mitigate the solution have thus far allowed us to keep our heads above water.
  – 20 um gold added to inside of beampipe
  – changes to CDC electronics
  – changes in beam pipe
  – implementation of a rad-tolerant SVD
Conclusions & Outlook

- We have acquired about 250/pb of data, a tiny fraction of the 100/fb that is our Phase-I goal, but a good start nonetheless.
- The KEK-B accelerator is working with luminosity of $6 \times 10^{32}$ cm$^{-2}$s$^{-1}$ before shutdown.
- The entire Belle detector, including the DAQ and offline reconstruction software, is working.
- We continue in a constant struggle to increase the luminosity while fighting background.
Conclusions & Outlook

• A new “high emittance” tune implemented just prior to the most recent disaster showed some promise.
• We’ll see what happens in mid-January when we come back on.