Mixing and Time-Dependent CP Asymmetries in $e^+e^-$ Annihilation

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Outline

➢ Lecture 1
  o Requirements for time-dependent $CP$ violation measurements and implementation at the asymmetric energy $e^+e^-$ B Factories
  o $\Upsilon(4S)$ as a source and design of BABAR and Belle detectors

➢ Lecture 2
  o Reconstruction of $B$ mesons
  o Determination of proper decay time differences and measurement of $B$ lifetimes
  o Methods for tagging the state of the recoil $B$ meson at time of its decay and measurement of the $B^0$ oscillation frequency

➢ Lecture 3
  o $CP$ asymmetries in the golden charmonium modes
  o Measuring $\sin2\beta$ in other channels
  o Asymmetries in 2-body neutral modes
  o Brief word on future prospects and plans
Lecture 1: Asymmetric Energy B Factories and Their Detectors

- Requirements for time-dependent asymmetry measurements at the $\Upsilon(4S)$
- Brief review of PEP-II and KEKB colliders
- Review of design and performance of BABAR and Belle detectors, with emphasis on vertexing and PID
Seeds of an Idea: B Lifetimes

- **Isolate samples of high-$p_T$ leptons (155 muons, 113 electrons) wrt thrust axis**
  - Measure impact parameter $\delta$ wrt interaction point
  - Signed by taking thrust axis of $b$-jet as the $B$ hadron direction

- **Lifetime implies $V_{cb}$ small**
  - MAC: $(1.8\pm0.6 \pm0.4)$ ps
  - Mark II: $(1.2\pm0.4 \pm0.3)$ ps

- **Integrated luminosity at 29 GeV:**
  - $109 (92)$ pb$^{-1} \sim 3,500 \, bb$ pairs

MAC, PRL 51, 1022 (1983)
MARK II, PRL 51, 1316 (1983)
Seeds of an Idea: $B^0\bar{B}^0$ Oscillations

- **Reconstructed $\Upsilon(4S)$ event**
  \[ \Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow B_1^0B_2^0 \]
  \[ B_1^0 \rightarrow D_1^{*-}\mu^+\nu_1, \quad D_1^{*-} \rightarrow D^0\pi_1^- \]
  \[ B_2^0 \rightarrow D_2^{*-}\mu^+\nu_2, \quad D_1^{*-} \rightarrow D^-\pi^0 \]

- **Time-integrated 21% mixing rate**
  - 25 (270) like (opposite) sign dilepton events
  - 4.1 lepton-tagged semileptonic $B$ decays

- **Integrated $\Upsilon(4S)$ luminosity 1983–87:**
  - 103 pb$^{-1}$ $\sim$ 110,000 $B$ pairs

\[ \chi_d = 0.17 \pm 0.05 \]

ARGUS, PL B 192, 245 (1987)
Expect CP Violation in the B System

- CPV through interference of decay amplitudes
- CPV through interference of mixing diagram
- CPV through interference between mixing and decay amplitudes

Directly related to CKM angles for single decay amplitude
Golden Channel: $B^0 \rightarrow J/\psi K^0_{S,L}$

$B^0$  
\[ \begin{array}{c} \bar{b} \\ \Phi \\ c \\ \bar{s} \\ d \end{array} \]

$J/\psi$  
\[ \begin{array}{c} \bar{c} \\ \Phi \\ c \\ \bar{s} \\ d \end{array} \]

$K^0 \rightarrow K^0_S$

$CP$ Eigenstate: \[ \eta_{CP} = -1 \]

$CP$ parameter
\[
\text{Im } \lambda_{b \rightarrow ccs} = \eta_{f_{CP}} \left\{ \text{Im} \left[ \frac{V_{cb} V_{cs}^*}{V_{cb} V_{cs}} \times \frac{V_{tb} V_{td}^*}{V_{tb} V_{td}} \times \frac{V_{cd} V_{cs}^*}{V_{cd} V_{cs}} \right] \right\} = \eta_{f_{CP}} \text{Im } \frac{V_{td}^*}{V_{td}} = \eta_{f_{CP}} \sin 2\beta
\]

Quark subprocess  $B^0$ mixing  $K^0$ mixing

$A_{f_{CP}}(t) = \frac{\Gamma(B^0_{phys}(t) \rightarrow f_{CP}) - \Gamma(B^0_{phys}(t) \rightarrow f_{CP})}{\Gamma(B^0_{phys}(t) \rightarrow f_{CP}) + \Gamma(B^0_{phys}(t) \rightarrow f_{CP})} = -\text{Im } \lambda_{f_{CP}} \sin \Delta m_d t$
CPV and Unitarity Constraints for CKM

\[ \Gamma(b \rightarrow u \ell \nu) \]

\[ (0,0) \]

\[ \tau_B \text{ and } \Gamma(b \rightarrow c \ell \nu) \]

\[ (1,0) \]

\[ \rho, \bar{\rho}, \eta, \bar{\eta}, \alpha, \beta, \gamma \]

\[ B^0 - \bar{B^0} \text{ mixing} \]

\[ CPV \text{ in } B^0 \rightarrow J/\psi K^0_s \]

\[ b \rightarrow c\bar{c}s \text{ channels} \]

- Theoretically clean way to measure $\sin 2\beta$
- Clear experimental signatures
- Relatively large branching fractions
**Sample Requirements: Snowmass Study 1988**

<table>
<thead>
<tr>
<th></th>
<th>Asymmetric γ(4S) collider</th>
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<tr>
<td>σ(bb) [nb]</td>
<td>1.2</td>
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<tr>
<td>B⁰ fraction</td>
<td>0.43</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>0.61</td>
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<tr>
<td>Tagging efficiency</td>
<td>0.48 (l, K)</td>
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<tr>
<td>Wrong-tag fraction</td>
<td>0.08</td>
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<tr>
<td>Dilution</td>
<td>0.61</td>
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<tr>
<td>Integrated Luminosity for 3σ measurement [x10⁴⁰ cm⁻²] *</td>
<td>0.45-16</td>
</tr>
</tbody>
</table>

* Assumes:
- sin2β in range from 0.05 to 0.3,
- BF(B → J/ψKₜ)=5x10⁻⁴
- BF(J/ψ → l⁺l⁻)=0.14,
- Luminosity in units of \( L_{\text{peak}} \) at full efficiency for 10⁷ s

**Conclude:** Asymmetric energy e⁺e⁻ collider has discovery capability at \( L_{\text{peak}} \sim 3-10x10^{33} \text{ cm}^{-2}\text{s}^{-1} \) in 2-5 years of running
Genesis of Worldwide Effort

Primary Goal

Precision measurements of charged weak interactions as a test of the CKM sector of the Standard Model and a probe of the origin of the CP violation
Producing B Mesons

\( \Upsilon \) States = (bb) resonances

Cross Sections at \( \Upsilon(4S) \):
- bb ~ 1.1 nb
- cc ~ 1.3 nb
- dd, ss ~ 0.3 nb
- uu ~ 1.4 nb

\( e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \)
\( L = 1 \) state
Time Evolution for Coherent Source

- \( L=1 \) \( B^0 \bar{B}^0 \) system requires antisymmetric initial-state wave function in \( \Upsilon(4S) \) frame:

\[
S(t_f, t_b) = \frac{1}{\sqrt{2}} \left[ B^0_{\text{phys}}(t_f, \theta, \varphi) \bar{B}^0_{\text{phys}}(t_b, \pi - \theta, \varphi + \pi) - \bar{B}^0_{\text{phys}}(t_f, \theta, \varphi) B^0_{\text{phys}}(t_b, \pi - \theta, \varphi + \pi) \right] \sin \theta
\]

\((\theta, \varphi)\) are wrt \( e^- \) beam direction;

\((f, b)\) are the forward (backward) going \( B \) meson,

with \((\theta_f < \pi / 2)\) and \( t_f = t_b \) until one \( B \) meson decays

- Consequently \( B^0 \bar{B}^0 \) evolves coherently until one \( B \) mesons decays
  - At any given time, until one of the \( B \) mesons decays, there is exactly one \( B^0 \) and one \( \bar{B}^0 \) including at time \( \Delta t = t_{CP} - t_{tag} = 0 \)
  - \( CP/Mixing \) oscillation clock only starts ticking at the time of the first decay, relevant time parameter is \( \Delta t \)
  - Half of the time the \( CP \) eigenstate \( B \) decays first \((\Delta t < 0)\)
Golden Channel Asymmetry on $\Upsilon(4S)$

$\Upsilon(4S)$ state

$L = 1$ state

$B^0(t_{CP})$

Inclusively tagged with decay product(s): $e^-$, $\mu^-$, or $K^-$ signal

$A_{f_{CP}}(\Delta t) = \frac{\Gamma(B^0_{phys}(\Delta t) \to f_{CP}) - \Gamma(B^0_{phys}(\Delta t) \to f_{CP})}{\Gamma(B^0_{phys}(\Delta t) \to f_{CP}) + \Gamma(B^0_{phys}(\Delta t) \to f_{CP})} = \sin 2\beta \sin \Delta m_d \Delta t$

$\Delta t = t_{CP} - t_{tag}$
Neutral B Time Evolution

Evolution for $B^0(\bar{B}^0)$ state at $t_{CP} = 0$

Incoherent

Coherent

For coherent source, integrated asymmetry is zero: must do a time-dependent analysis

$$\int F(\Delta t) d\Delta t = \int \bar{F}(\Delta t) d\Delta t$$
Experimental Technique for B Factories

$B_{\text{tag}} = \bar{B}^0(t)$
$\implies B_{\text{rec}} = B^0(t)$

$\Upsilon(4S)$ produces coherent $B$ pair:
$t \rightarrow \Delta t$

$\Delta z \sim 260 \mu m$

Time-integrated asymmetries are zero
$B_{\text{rec}}^0 = B_{\text{flav}}^0$ (flavor eigenstates) $\rightarrow$ lifetime, mixing analyses
$B_{\text{rec}}^0 = B_{CP}^0$ ($CP$ eigenstates) $\rightarrow$ $CP$ analysis

$B$-Flavor Tagging

Exclusive $B$ Meson
Reconstruction

Experimental Technique for B Factories
PEP-II Asymmetric B Factory

Located in the 2.2 km PEP tunnel at the Stanford Linear Accelerator Center

9 GeV $e^{-} \times$ 3.1 GeV $e^{+}$
$\Upsilon(4S)$ boost: $\beta_{\Upsilon} = 0.55$
Head-on collisions

Located in the 2.2 km PEP tunnel at the Stanford Linear Accelerator Center
PEP-II Arc Section
PEP-II HER RF Cavities
# PEP-II Parameters

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<tr>
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<th>Design</th>
<th>Achieved</th>
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<tbody>
<tr>
<td></td>
<td>e⁻</td>
<td>e⁺</td>
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<td><strong>Beam energies [GeV]</strong></td>
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<td>3.1</td>
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<td><strong>Currents [A]</strong></td>
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<td></td>
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<td><strong>Bunch spacing [m]</strong></td>
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<tr>
<td><strong>Bunch currents [mA]</strong></td>
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<td><strong>Beam stored energy [kJ]</strong></td>
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<td>49</td>
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<td><strong>Beam power [GW]</strong></td>
<td>6.7</td>
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<tr>
<td><strong>Beam rf power [MW]</strong></td>
<td>1.8</td>
<td>1.7</td>
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</table>
PEP-II Interaction Region
KEKB Storage Ring Layout

8 GeV $e^-$ $\times$ 3.5 GeV $e^+$
\[ \Upsilon(4S) \text{ boost: } \beta\gamma = 0.425 \]
\[ \pm 11 \text{ mrad crossing angle} \]

Located in the 3 km Tristan tunnel at KEK
KEKB Arc Section
## KEKB Parameters

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<td>$e^+$</td>
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<td>$e^-$</td>
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<td>3.5</td>
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<tr>
<td>$e^+$</td>
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<tr>
<td><strong>Currents [A]</strong></td>
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<tr>
<td>$e^-$</td>
<td>1.1</td>
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<tr>
<td>$e^+$</td>
<td>2.6</td>
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<td><strong>Number of bunches</strong></td>
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<tr>
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<td>5000</td>
<td>1223</td>
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<td><strong>Luminosity [$\times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$]</strong></td>
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<td><strong>Bunch spacing [m]</strong></td>
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<td><strong>Bunch currents [mA]</strong></td>
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<td>$e^-$</td>
<td>0.22</td>
<td>0.52</td>
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<tr>
<td>$e^+$</td>
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<tr>
<td><strong>Beam stored energy [kJ]</strong></td>
<td>90</td>
<td>92</td>
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<td><strong>Beam power [GW]</strong></td>
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<tr>
<td>$e^-$</td>
<td>9</td>
<td>9</td>
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<tr>
<td>$e^+$</td>
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<td><strong>Beam rf power [MW]</strong></td>
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<td>$e^-$</td>
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<td>4.5</td>
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<tr>
<td>$e^+$</td>
<td>4.5</td>
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KEKB Interaction Region

KEKB Interaction Region

Centimeters

Meters

8 GeV

3.5 GeV

QC1EL

QC2EL

QC1ER

QC2ER

LEB

QC2PL

QCSL

CSL

CSR

QCSR

Detector
BABAR Collaboration

Gathering at SLAC, July 2002

9 Countries
76 Institutions
550 Physicists

July 2002
BABAR Detector

- Cerenkov Detector (DIRC)
- 1.5 T solenoid
- Electromagnetic Calorimeter
- Instrumented Flux Return
- Drift Chamber
- Silicon Vertex Tracker
- $e^+ (3.1 \text{ GeV})$
- $e^- (9 \text{ GeV})$
Belle Collaboration

12 Countries
54 Institutions
285 Physicists
July 2002
Belle Detector

SC solenoid
1.5T

CsI(TI) 16\(X_0\)

TOF counter

8GeV \(e^-\)

3.5GeV \(e^+\)

Aerogel Cherenkov cnt.
n=1.015~1.030

Tracking + \(dE/dx\)
small cell + He/C\(_2\)H\(_5\)

Si vtx. det.
3 lyr. DSSD

\(\mu / K_L\) detection
14/15 lyr. RPC+Fe
Requirements: Geometric Acceptance

Most difficult

Angular coverage

Momentum coverage

![Graphs showing efficiency vs. momentum and angular coverage for different particle pairs.](image)
Requirements: Tracking and PID

Kaon spectra from $\Upsilon(4S)$ decays

Tagging Kaons

Relatively soft, $\ms$ dominated for tracking

$B \rightarrow \pi\pi$

Requires dedicated PID

$B \rightarrow DK$

Requires dedicated PID
Requirements: Photons

Generic $B^0$ decay

$B^0 \rightarrow \pi^0 \pi^0$

Photon energy [GeV]

Reconstruction efficiency

Minimum photon energy [MeV]
BABAR Detector
Impact of Boost

Detector Protractor - γ's

BACKWARD POLAR ANGLES

FORWARD POLAR ANGLES

35°

9 GeV on 3.109 GeV

Y(4S) \( \beta \gamma = 0.56 \)

\( \theta_{cc} \)

350 mrad

Aug 5-7, 2002

D. MacFarlane at SSI 2002
Vertex Detector Design

- **Requirements**
  - Transverse and longitudinal vertex resolution
    - Resolution on $\Delta z$ must be small compared to oscillation distance
  - Polar and azimuthal angles at IP
  - [Stand-alone tracking and $D^*$ detection]
  - High background tolerance and hence segmentation
  - Tolerance and longevity in high radiation environment

- **Constraints**
  - IP geometry sets acceptance (magnets occlude below 350mrad)
  - Shielding of SR backgrounds sets minimum radius
  - Cost sets outside radius

- **Implementation**
  - Double-sided AC-coupled silicon microstrip detectors
  - Custom radiation-hard readout chip
Vertex Resolution

\[ \sigma_{xy,z}^2 = \sigma_{ms}^2 + \sigma_{det}^2 \]

\[ \sigma_{det} \sim 15 \mu m \text{ at } 90^\circ \]

\[ \sigma_{ms} = \frac{0.014 r \sqrt{X}}{\beta cp \sin^{5/2} \theta} \quad [p \text{ in GeV/c}] \]

\[ \sim 50 \mu m \text{ at } 1 \text{ GeV/c} \]

Typical single point resolution for silicon microstrip detectors

\[ r_{BP} = 2.5 cm \]

1.13% \( X_0 \) in Be+H\(_2\)O
Vertex Resolution

\[ \sigma^2_{xy,z} = \sigma^2_{ms} + \sigma^2_{det} \]

\[ \sigma_{det} \sim 15 \mu m \text{ at } 90^\circ \]

\[ \sigma_{ms} = \frac{0.014 r \sqrt{X}}{\beta c p \sin^{5/2} \theta} \quad [p \text{ in GeV/c}] \]

\[ \sim 50 \mu m \text{ at } 1 \text{ GeV/c} \]
PEP-II IR SR fans: LER Beam

Interaction Region

Incoming & Outgoing Dipole SR

Outgoing Quadrupole SR

 Incoming Quadrupole SR

Meters
**PEP-II IR SR fans: HER Beam**

**Interaction Region**

- **Incoming Quadrupole SR**
- **Incoming & Outgoing Dipole SR**

![Diagram showing the interaction region with labels for incoming and outgoing quadrupole and dipole SR.]
SR Fans in KEKB Design

Incoming beams on axis: No SR

Smaller $r_{BP}$ possible: smaller boost as well
Silicon Vertex Detector at BABAR

- 5 Layer AC-coupled double-sided silicon detector
- Located in high radiation area
  - Radiation hard readout electronics (4-5 Mrad)
- 97% hit reconstruction efficiency
- Hit resolution ~15 µm at 90°
Completed SVT Detector

B1 bending magnet

Readout chips

Beam pipe

Layer 1,2

Layer 3

Layer 4

Layer 5

$r_{BP,IR} = 25 \text{ mm}
2 \times \text{Be walls} = 0.83 + 0.53 \text{ mm T}
1.5 \text{ mm H}_2\text{O}
cooling gap
Resolutions and Efficiencies

![Graphs showing z Resolution (μm) vs. angle (degrees) for Layers 1 to 5.](image)

![Graphs showing Efficiency vs. Half-module number for a) and b).](image)
Requirements: Low $p_\perp$ Tracking

Common to reconstruct $D^{*+} \rightarrow D^0\pi^+$ with very soft $\pi^+$

**Advantage:** Excellent resolution for mass difference

**Disadvantage:** Small bending radius, difficult to track

![Graph showing efficiency vs. momentum](image)

- Efficiency ~ 85% at 100 MeV/c
**Silicon Vertex Detector at Belle**

$r_{BP, IR} = 20$ mm

2xBe walls = 2x0.5 mm T

2.5 mm Helium cooling gap

**SVD endview**

**SVD sideview**

- IP
- Be beam pipe
- 139°
- 23°
- Heat pipe
- Heat sink
- Hybrid
- VA1
- p-side
- DSSD
Drift Chamber Design

**Requirements**
- \( p_t \) measurement over maximum possible solid angle
- 5 track parameters for secondary tracks
- Track projections onto DIRC (angle) and EMC
- \( dE/dx \) measurements for tagging (low momentum)
- Fast L1 input to tracking trigger

**Constraints**
- Machine elements define angular acceptance
- Outside radius balances cost (EMC) and \( p_t \) resolution \( \sigma(p_t) \sim BR^2 \)
- Minimize material in front of EMC, DIRC

**Implementation**
- Small-cell design for large number of tracks, low momentum
- Aluminum field wires, helium-based gas to minimize multiple scattering contribution to resolution
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
Belle 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)

\[
\sigma(p_T) = 0.19\% \times p_T \oplus \frac{0.30\%}{\beta}
\]

15 layers: 8.8-22.4 cm radius
Hadron PID Detector Design

- **PID Requirements**
  - In range 0.6-2 GeV/c for kaon tagging
  - Up to 4.4 GeV/c in forward direction for 2-body B decay modes
- **Constraints**
  - Inside radius set by need to maximize tracking volume; outside by cost of calorimeter
  - Magnetic field limits photon detector choices in active volume
  - Minimal material degradation of calorimeter performance
- **Implementation**
  - dE/dx covers part of kaon tag spectrum
  - For BABAR, novel ring-imaging Cherenkov detector (DIRC) based on quartz radiators and phototube imaging of rings
  - For Belle, time-of-flight (TOF) and threshold Cherenkov counters based on low-density materials and fine-mesh phototubes in active volume (ACC)
**Principle of the DIRC**

- UV Cherenkov light generated in quartz with characteristic $1/\beta$ opening angle
- Light transmitted length of bar by internal reflection, preserving angle information due to precision surfaces
- Rings projected in water-filled standoff box (best match to quartz index), where photons are detected with an array of 10K PMTs
Elements of DIRC System

- 17.25 mm Thickness (35.00 mm Width)
- Synthentic Fused Silica, Bars glued end-to-end
- 4 x 1.225 m
- PMT + Base ~11,000 PMTs
- Light Catcher
- Standoff Box
- PMT Surface
- Window
Comparing Hits with Cherenkov Signature

<table>
<thead>
<tr>
<th>Main</th>
<th>Dip</th>
<th>FG</th>
<th>FR</th>
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<tr>
<td>0.34</td>
<td>-15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.37</td>
<td>18.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.31</td>
<td>54.8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Run No = 5933
ETime = 25300
EDate = 6170000
Event = 10

- Reco Hits (in time)
- Reco Hits (back)
- Best solutions (FG)

Simulation:
- Electron
- Pion
- K and
- Proton
Control samples for $\pi$ and $K$

From $D_{s}^{+} \rightarrow D^{0} (\rightarrow K^{-}\pi^{+})\pi^{+}$

Projection for $2.5 < p < 3 \text{ GeV/c}$
Kaon ID at BABAR

- NN based on likelihood ratios in DCH and SVT (dE/dx), and in DIRC (compare single hits with expected pattern of cherenkov light)
- > 3σ K/p separation for 0.25 < p < 3.4 GeV/c

$K_{eff} = 85\%, \pi_{misid} = 5\%$
Kaon Spectra from $\Upsilon(4S)$ Decays

**Tagging Kaons**

- $B \rightarrow \pi \pi$
- $B \rightarrow DK$

---

**Aug 5-7, 2002**

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PID System at Belle

Barrel ACC
- n=1.028
- 60mod.
- n=1.020
- 240mod.
- n=1.015
- 240mod.
- n=1.010
- 360mod.

CDC

Endcap ACC
- n=1.030
- 228mod.

3" FM-PMT
2.5" FM-PMT
2" FM-PMT

B (1.5 Tesla)

854 (BACC)
1165R (BACC/outer)
1622 (BACC)
1670 (EACC/inside)
1950 (EACC/outside)

885 R (BACC/inner)

Aug 5-7, 2002 D.MacFarlane at SSI 2002
**TOF and TSC Modules**

- BC408 (4 x 6 x 255 cm T x W x L)
- TOF: Fine-mesh PMT's (both ends)
- TSC = Trigger Scintillator Counter (0.5 cm T): one FM-PMT
- 64 modules (128 TOF and 64 TSC)

**Achieves 80 ps timing resolution**

![Diagram showing TOF and TSC modules with specifications and measurements.](image)
Aerogel Cherenkov Counters (ACC)

- Hydrophobic silica-aerogels
- $n = 1.01\sim1.028$ (barrel), 1.03 (endcap)
- 960 modules (barrel) -> 1560 PMT's
- 228 modules (endcap) -> 228 PMT's

Cherenkov light thresholds

Fractal structure
Separation Capability of ACC

No field
Test beam response to 3.5 GeV/c protons and pions

3σ separation for n = 1.015

Observed photoelectron yield across ACC modules
Measuring Kaon ID Performance

Use a kinematics selection to tag clean $K, \pi$ sample

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

Compute kaon probability from $K$ and $\pi$ likelihoods obtained from dE/dx, TOF, and ACC

$$\text{Prob}(K) = \frac{L(K)}{L(K) + L(\pi)}$$

~0 for $\pi$

~1 for $K$

Momentum [GeV/c]
Components of Kaon ID Performance

- **dE/dx**
- **TOF**
- **ACC**

Momentum (GeV/c) vs. K efficiency & π fake rate
Combined Performance

Kaon efficiency [87%]

π misidentification [8%]

PID(K) > 0.6
Kaon Spectra from $\Upsilon(4S)$ Decays

Tagging Kaons

$B \rightarrow \pi\pi$

$B \rightarrow DK$
Calorimetry Design

➢ **Requirements**
  o Best possible energy and position resolution
    • 11 photons per (4S) event; 50% below 200 MeV in energy
  o Acceptance down to lowest possible energies and over large solid angle
  o Electron identification down to low momentum

➢ **Constraints**
  o Cost of raw materials and growth of crystals
  o Operation inside magnetic field
  o Background sensitivity

➢ **Implementation**
  o Thallium-doped Cesium-Iodide crystals with 2 PID photodiodes per crystal for readout
  o Thin structural cage to minimize material between and in front of crystals
Electromagnetic Calorimeter at BABAR

- 6580 CsI(Tl) crystals with photodiode readout
- About 18 X0, inside solenoid

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

\[\pi^0\] - mass = 135.0 MeV
\[\pi^0\] - width = 6.8 MeV

\[\sigma = 5.0\%\]
Electromagnetic Calorimeter at Belle

- 8736 CsI(Tl) crystals with photodiode readout
- About 16.2 X0, inside solenoid
- Coverage from 12 to 155°

\[ \pi^0 \rightarrow \gamma \gamma \] in hadronic events

\[ \sigma_m = 4.75 \pm 0.08 \text{ (MeV/c}^2\text{)} \]
Instrumented Flux Return/KLM

- **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 EMC/ECL

- **Bakelite RPCs at BABAR**
  - Problems with QC, dark current, and stability
  - Forward endcap replacement this summer; barrel in 2005

- **Glass RPCs at Belle**
  - Possible problems with neutrons in forward endcap
  - Probably problems at higher background rates
Completed Detectors

Completed Feb 1999
First collisions May, 1999

First collisions May, 1999
# PEP-II Integrated Luminosity

<table>
<thead>
<tr>
<th>PEP-II Records</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak luminosity</strong></td>
<td>4.60x10^{33} cm^{-2} s^{-1}</td>
</tr>
<tr>
<td><strong>Best shift</strong></td>
<td>108.3 pb^{-1}</td>
</tr>
<tr>
<td><strong>Best 24 hours</strong></td>
<td>308.8 pb^{-1}</td>
</tr>
<tr>
<td><strong>Best day</strong></td>
<td>288.7 pb^{-1}</td>
</tr>
<tr>
<td><strong>Best 7 days</strong></td>
<td>1.865 fb^{-1}</td>
</tr>
<tr>
<td><strong>Best week</strong></td>
<td>1.836 fb^{-1}</td>
</tr>
<tr>
<td><strong>Best month</strong></td>
<td>6.66 fb^{-1}</td>
</tr>
<tr>
<td><strong>BABAR logged</strong></td>
<td>93.8 fb^{-1}</td>
</tr>
</tbody>
</table>

50% above design

**PEP-II Records**
- PEP-II Delivered 98.58/fb
- BABAR Recorded 93.80/fb
- BABAR off-peak 9.93/fb

(As of Jun 30, 2002)
Typical “Very Good” Day at PEP-II

<table>
<thead>
<tr>
<th>I HER</th>
<th>I LER</th>
<th>Luminosity</th>
<th>Spec Lum</th>
<th>E HER</th>
<th>E LER</th>
<th>E CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>955.33</td>
<td>1563.52</td>
<td>4023</td>
<td>2.14</td>
<td>8992</td>
<td>3120</td>
<td>10594</td>
</tr>
<tr>
<td>mA</td>
<td>mA</td>
<td>10^30</td>
<td>N*10^30/</td>
<td>MeV</td>
<td>MeV</td>
<td>MeV</td>
</tr>
<tr>
<td>mA**2</td>
<td></td>
<td></td>
<td>mA**2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N Buckets/HER Pattern: 796 by4_trains_of_23_off_by_2_her

N Buckets/LER Pattern: 796 by4_trains_of_23_off_by_2

Last Owl/Day/Swing/24 Hr: 105.0 97.6 106.2 308.8 Shift: 40.39 /pb

Peak Luminosities: 4339 4353 4395 4353

PEP-II Luminosity and Currents

Current record for 24 hr integration
KEKB Integrated Luminosity

<table>
<thead>
<tr>
<th>KEKB Records</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak luminosity</td>
<td>$7.25 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Best shift</td>
<td>129.5 fb$^{-1}$</td>
</tr>
<tr>
<td>Best 24 hours</td>
<td>377.2 fb$^{-1}$</td>
</tr>
<tr>
<td>Best day</td>
<td>371.2 fb$^{-1}$</td>
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<tr>
<td>Best 7 days</td>
<td>2.207 fb$^{-1}$</td>
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<tr>
<td>Best month</td>
<td>7.25 fb$^{-1}$</td>
</tr>
<tr>
<td>Belle logged</td>
<td>89.6 fb$^{-1}$</td>
</tr>
</tbody>
</table>
Typical “Good Day” at KEKB

Nearly a new record for integration in a 24 hr period
Summary

Dream of exploring CP violation has now been realized

- PEP-II/BABAR and KEKB/Belle operating with high efficiency and record luminosities
- Detectors have been optimized for CP studies, with demonstrated capability for vertex separation measurement, tagging, and B meson reconstruction
- Data samples are in hand: about 88 million $B\bar{B}$ pairs at BABAR, 85 million at Belle

Luminosity at PEP-II and KEK-B is the key factor in reaching samples that are capable of decisive CP asymmetry measurements

Tomorrow:

- How to extract lifetimes, the $B^0$ oscillation frequency, and mixing-induced CP asymmetries from the time-dependent development of $B$ mesons in these samples
Bibliography: Lecture 1

2. PEP-II: An asymmetric B Factory, Conceptual Design Report, SLAC-418, 1993