Measurements of CP-violating B Decay Rate Asymmetries with the BABAR Detector

Thomas Schietinger

Stanford Linear Accelerator Center

Bern, 13 June 2001
Outline

• Introduction: B physics, CP violation, the CKM matrix, sin2\(\beta\), and all that…

• The SLAC B Factory and BABAR

• Measurement of sin2\(\beta\) with charmonium modes

• Charmless decay modes and their potential to measure CKM angles
  – sin2\(\alpha\) with B\(^0\) → \(\pi^+\pi^-\)
  – sin2\(\beta\) with B\(^0\) → \(\phi K_S\)

• Outlook
Why B Physics?

Main theme of early 21st century (particle) physics:
Find the theory underlying the effective theory we call the Standard Model!

We have to push on all fronts:

**Standard Model of Electroweak Interactions:**

- **Gauge sector** ($\gamma$, W, Z bosons): extremely well tested at LEP, SLD, etc.
- **Higgs sector** (H boson): still outstanding; need higher energies (LHC)
- **Lepton sector**: neutrino (oscillation) experiments, neutrino factory?
- **Quark sector**: flavor, CP violation

B decays are ideal laboratory to test and map out the quark sector:

- Heavy, yet accessible particles $\Rightarrow$ hadronic effects are under control
- Third generation quark: intimately connected to CP violation
- Can study decays to c, s, u, and d, and access the coupling to t via flavor oscillations!
- All decays are Cabibbo- or loop-suppressed $\Rightarrow$ long lifetime allows time-dependent studies
The CKM Matrix
(CKM = Cabibbo-Kobayashi-Maskawa)

Charged hadronic current in SM:

\[ J_{cc}^{\mu} = \bar{u}'_L \gamma^{\mu} d'_L \]

The weak eigenstate quarks \( q' \) are related to the mass eigenstate quarks \( q \) by unitary transformations:

\[ \bar{u}'_L = \bar{u}_L U_u^\dagger \quad d'_L = U_d d_L \]

This can be combined into another unitary matrix \( V \) called the Cabibbo-Kobayashi-Maskawa (CKM) Matrix:

\[
U_u^\dagger U_d = V = \begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix}
\]

This 3×3 unitary matrix can be parameterized by 3 real parameters and 1 complex phase, which gives rise to complex couplings and thus introduces CP violation!
We know empirically that:

\[ V_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \]

\[ \lambda = \sin \theta_{\text{Cabibbo}} \]

\[ \sim 1 \quad \sim \lambda \quad \sim \lambda^2 \quad \sim \lambda^3 \]

**⇒ Wolfenstein Parameterization:**

\[ V_{\text{CKM}} = \begin{bmatrix} 1 - \lambda^2 / 2 & \lambda & A\lambda^3 (\rho - i\eta) \\ -\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\ A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} \]

Only the smallest elements \( V_{td} \) and \( V_{ub} \) carry complex phases
Unitarity constraint: $V^\dagger V = 1$

with first and third column (where phases are!):

$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$

$\Rightarrow V_{ub}^* + V_{td} = \lambda V_{cb}^*$

$V_{ub}$

$V_{td}$

$V^*_{ub}$

$\alpha \approx \arg(-V_{td} / V_{ub}^*)$

$\beta \approx \pi - \arg(-V_{td})$

$\gamma \approx \arg(V_{ub}^*)$
Unitarity Triangle (2)

In Wolfenstein parameters (after normalizing to $A\lambda^3$):

$$(\rho + i\eta) + (1 - \rho - i\eta) = 1$$

$$\alpha \approx \arctan \left( \frac{\eta}{\eta^2 + \rho^2 - \rho} \right)$$

$$\beta \approx \arctan \left( \frac{\eta}{1 - \rho} \right)$$

$$\gamma \approx \arctan \left( \frac{\eta}{\rho} \right)$$
Current Experimental Status

- $|V_{ub}|$ from $b \rightarrow u \nu$ decays
- $|V_{td}|$ from $\Delta m_d$ B mixing (also limited by $\Delta m_s$)
- ($\varepsilon_K$ from K experiments)

$|$ from $b \rightarrow u \nu$ decays
$|$ from $\Delta m_d$ B mixing
(allow limited by $\Delta m_s$)
($\varepsilon_K$ from K experiments)
CP Violation in B Decays

…opens up a new window on the unitarity triangle:

Measurable CP phases directly access the angles of the triangle!

This is exciting because almost all new physics models generate a plethora of new CP-violating phases whereas all CP-violating effects in the Standard Model are governed by one parameter, the CKM phase!

Remainder: **B Mesons**

\[
\begin{align*}
B^+ &= (u\bar{b}) \\
B^- &= (\bar{u}b) \\
B^0 &= (d\bar{b}) \\
\bar{B}^0 &= (\bar{d}b)
\end{align*}
\]

\[m(B^0) \approx m(B^+) \approx 5280 \text{ MeV}/c^2\]

\[\tau(B^+) = 1.65 \text{ ps}, \tau(B^0) = 1.55 \text{ ps},\]

\[\Delta m(B_d) = 0.47 \, \hbar \text{ ps}^{-1} = 0.31 \text{ meV}\]
B → J/ψ K_S and sin 2β

(prime) example: interference between mixed and unmixed decay to CP eigenstate J/ψ K_S gives access to the phase of V_{td}, i.e. β!

unmixed decay: no phase!

mixed decay: phase of V_{td}!

Interference term proportional to \( \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{i2\beta} \)
**B → J/ψ K_S and sin 2β (2)**

Observable of interest is time-dependent decay rate asymmetry:

\[
A_{J/ψ K_S}(t) = \frac{R(\bar{B}^0 \rightarrow J/ψ K_S)(t) - R(B^0 \rightarrow J/ψ K_S)(t)}{R(\bar{B}^0 \rightarrow J/ψ K_S)(t) + R(B^0 \rightarrow J/ψ K_S)(t)} = \sin 2β \sin Δm t
\]

Other angle measurements:
- **B → π⁺π⁻**: completely analogous but additional phase from b → u transition
  \(V_{ub} \Rightarrow γ\)
  \(⇒ A_{ππ} = \sin 2(β+γ) = \sin 2α\)
  BUT: complications due to higher-order diagrams with different phases!
- **B → DK** to extract γ
  (Gronau-Wyler method)
- many other ingenious methods to extract various angles…
The B-Factory Approach

- Produce B mesons via the reaction
  \[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B}^0 \]
- clean environment
- well known initial state
- B pair is entangled (EPR):
  \[ \Rightarrow \text{measuring the flavor of one B determines the flavor of the other at the same time} \]

BUT:
- Relatively low cross section of 1 nb (compared to mb’s at hadron colliders)
  \[ \Rightarrow \text{high current machine!} \]
- B mesons are almost at rest in CMS
  \[ \Rightarrow \text{Asymmetric collider to increase path length of B mesons to 260 \text{ \textmu}m!} \]
The SLAC B-Factory
## PEP-II Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>achieved</th>
<th>typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER energy (GeV)</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>LER current (mA)</td>
<td>2140</td>
<td>2140</td>
<td>1350</td>
</tr>
<tr>
<td>LER lifetime (hours)</td>
<td>4</td>
<td>3.3</td>
<td>3</td>
</tr>
<tr>
<td>HER energy (GeV)</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>HER current (mA)</td>
<td>750</td>
<td>920</td>
<td>730</td>
</tr>
<tr>
<td>HER lifetime (hours)</td>
<td>4</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>1658</td>
<td>829</td>
<td>553–829</td>
</tr>
<tr>
<td>Beam size x (µm)</td>
<td>222</td>
<td>190</td>
<td>–</td>
</tr>
<tr>
<td>Beam size y (µm)</td>
<td>6.7</td>
<td>6.0</td>
<td>–</td>
</tr>
<tr>
<td>Luminosity (nb⁻¹/s)</td>
<td>3</td>
<td>3.3</td>
<td>2.5</td>
</tr>
</tbody>
</table>
1999/2000 Run

October 1999 – November 2000:
- $20.7 \text{ fb}^{-1}$ recorded on $\Upsilon(4S)$ peak $\approx 23$ million B pairs
- $2.6 \text{ fb}^{-1}$ off-peak
Daily recorded luminosity: (design: 135 pb$^{-1}$/day)

Some records:
- 184 pb$^{-1}$/day
- 1.03 fb$^{-1}$/week
- 3.8 fb$^{-1}$/month

A typical day in the life of BABAR:
BABAR Collaboration

554 physicists from 72 institutions from 9 countries

Canada [4/16]
- U of British Columbia
- McGill U
- U de Montréal
- U of Victoria

China [1/6]
- Inst. of High Energy Physics, Beijing

France [5/50]
- LAPP, Annecy
- LAL Orsay
- LPNHE des Universités Paris 6/7
- Ecole Polytechnique
- CEA, DAPNIA, CE-Saclay

Germany [3/21]
- U Rostock
- Ruhr U Bochum
- Technische U Dresden

Italy [12/89]
- INFN and U Bari
- INFN and U Ferrara
- Lab. Nazionali di Frascati dell' INFN
- INFN and U Genova
- INFN and U Milano
- INFN and U Napoli
- INFN and U Padova
- INFN and U Pavia
- INFN, SNS and U Pisa
- INFN, Roma and U "La Sapienza"
- INFN and U Torino

Norway [1/3]
- U of Bergen

Russia [1/13]
- Budker Institute, Novosibirsk

United Kingdom [10/80]
- U of Birmingham
- U of Bristol
- Brunel University
- U of Edinburgh
- U of Liverpool
- Imperial College
- Queen Mary & Westfield College
- Royal Holloway, University of London
- U of Manchester
- Rutherford Appleton Laboratory

USA [35/276]
- California Institute of Technology
- UC, Irvine
- UC, Los Angeles
- UC, San Diego
- UC, Santa Barbara
- UC, Santa Cruz
- U of Cincinnati
- U of Colorado
- Colorado State
- Florida A&M
- U of Iowa
- Iowa State U
- LBNL
- LLNL
- U of Louisville
- U of Maryland
- U of Massachusetts, Amherst
- MIT
- U of Mississippi
- Mount Holyoke College
- Northern Kentucky U
- U of Notre Dame
- ORNL/Y-12
- U of Oregon
- U of Pennsylvania
- Prairie View A&M
- Princeton
- SLAC
- U of South Carolina
- Stanford U
- U of Tennessee
- U of Texas at Dallas
- Vanderbilt
- U of Wisconsin
- Yale

Thomas Schietinger

CP Violation with BABAR

June 2001
The **BABAR Detector**

- **DIRC** (Cherenkov Detector)
  - 144 quartz bars
  - 11,000 PMTs

- **1.5 T Solenoid** (superconducting)

- **Silicon Vertex Tracker**
  - 5 layers, double sided strips

- **Electromagnetic Calorimeter**
  - 6580 CsI(Tl) crystals

- **Drift Chamber**
  - 40 layers (24 stereo)
  - 80:20 He-Isobutane

- **Instrumented Flux Return** (Muon Chambers)
  - Iron / RPCs

- 3.1 GeV $e^+$

- 9 GeV $e^-$
The Silicon Vertex Tracker (SVT)

- double-sided Si detector: z-strips on inside, φ-strips on outside
- angular acceptance $20^\circ < \theta < 150^\circ$
- total of 143k read-out channels
- radiation hard up to 2 Mrad
Charged Track and Photon Reconstruction

Silicon and Drift Chamber tracking combined:

Cosmic ray muons

Calorimeter: $e^\pm$, $\gamma$, $\pi^0$

$E_\gamma > 500$ MeV

\[
\frac{\sigma(E)}{E} = \frac{2.3\%}{\sqrt[4]{E}} \oplus 1.9\%
\]

\[
\sigma(p_T)/p_T = 0.13\% \times p_T \oplus 0.45\%
\]
The DIRC

DIRC = Detector of Internally Reflected Cherenkov (light)

6 m³ water tank, read out by 11’000 photomultipliers

Box containing 12 quartz bars

In total 12×12 = 144 quartz bars, guiding Cherenkov light via total internal reflection to water tank where it expands and is recorded by photomultipliers. The Cherenkov angle is preserved.
**DIRC Performance**

Time resolution: 1.8 ns  
Cherenkov angle res.: 3 mrad

Thomas Schietinger  
*CP Violation with BABAR*  
June 2001
Ingredients for a CP measurement in $B^0 \rightarrow J/\psi K_S$

Goal:

$$A_{J/\psi K_S}(t) = \frac{R(B^0 \rightarrow J/\psi K_S)(t) - R(B^0_{t=0} \rightarrow J/\psi K_S)(t)}{R(B^0_{t=0} \rightarrow J/\psi K_S)(t) + R(B^0_{t=0} \rightarrow J/\psi K_S)(t)}$$

1) Reconstruct the CP decay:
   - $J/\psi \rightarrow \mu^+\mu^-$ and $e^+e^-$
   - $K_S \rightarrow \pi^+\pi^-$ and $\pi^0\pi^0$
   - also: $\psi(2S) \rightarrow l^+l^-$ and $J/\psi l^+l^-$
   - $J/\psi K_L$: $K_L$ with EMC or IFR

2) Determine the flavor of the other $B$:
   - Look for charged leptons and kaons in the remaining tracks

3) Measure of $\Delta z = \gamma \beta t$:
   - Fit the two vertices
   - Determine the distance

0) Produce (very) many $B^0$s:
   - want time bins
   - only a fraction of the events can be tagged
   - branching fraction is a few $10^{-4}$
Kinematic Selection of B Candidates

e^+e^- \rightarrow B^0\bar{B}^0$: energy of B mesons given by beam energy!
⇒ compare to reconstructed energy
⇒ substitute in invariant mass

\[ E_B^{\text{beam}} = \frac{s + 2 \vec{p}_i \cdot \vec{p}_B^{\text{rec}}}{2E_i} \]

\[ \Delta E = E_B^{\text{rec}} - E_B^{\text{beam}} \]

\[ m_{\text{ES}} = \sqrt{(E_B^{\text{beam}})^2 - (p_B^{\text{rec}})^2} \]

“energy-substituted mass” — independent of particle assignments!

Example: \( B^0 \rightarrow J/\psi K_S^0 \)
## CP = −1 Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Events (with tag)</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K_S^0(K_S^0 \rightarrow \pi^+\pi^-)$</td>
<td>188</td>
<td>98 ± 1</td>
</tr>
<tr>
<td>$J/\psi K_S^0(K_S^0 \rightarrow \pi^0\pi^0)$</td>
<td>41</td>
<td>85 ± 6</td>
</tr>
<tr>
<td>$\psi(2S)K_S^0(K_S^0 \rightarrow \pi^+\pi^-)$</td>
<td>44</td>
<td>97 ± 3</td>
</tr>
</tbody>
</table>

Total $\eta_{CP} = -1$ 273 96 ± 2
$B^0 \rightarrow J/\psi K_L$ (CP = +1)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Events (with tag)</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K^0_L$</td>
<td>256</td>
<td>39 ± 6</td>
</tr>
<tr>
<td>Total CP sample</td>
<td>529</td>
<td>69 ± 2</td>
</tr>
</tbody>
</table>

- $K_L$ signaled by isolated clusters in RPCs and/or calorimeter
- only the $K_L$ direction is measured; the B mass constraint is imposed
In principle we could use only events with fully reconstructed decays to CP eigenstates on one side and fully reconstructed decays to flavor-identifying decays on the other side.

Here’s an example for such an event:

However, we would only get a handful of events, not enough for an asymmetry measurement!

⇒ Resort to inclusive flavor tagging! (i.e. only look for $K^-$, not full decay)
Inclusive Flavor Tagging

3 consecutive categories:

1) Leptons
   • Electrons with $p_{cm} > 1.0$ GeV/c
   • Muons with $p_{cm} > 1.1$ GeV/c

2) Kaons
   • $\Sigma$ kaon charge $\neq 0$

3) NT1, NT2 (neural net to clean up)
   • slow pions from $D^*$ decays
   • isolated unidentified leptons

The figure of merit is:

$$Q_{\text{tag}} = \varepsilon S^2 = \varepsilon \times \left( \frac{r - w}{r + w} \right)^2$$

- $\varepsilon$: tagging efficiency
- $S$: separation
- $r(w)$: fraction of right (wrong) tags

(i.e., look at all the other tracks and try to figure out whether the other $B$ decayed as a $B^0$ or a $\bar{B}^0$)
A Candidate Event:

- $J/\psi \rightarrow \mu^+\mu^-$
- $K_S \rightarrow \pi^+\pi^-$
- $K^-\text{ indicates recoiling } B^0$
**Measurement of $\Delta z = \gamma \beta c \Delta t$**

- B lifetime is $c\tau_B = 464$ $\mu$m $\Rightarrow \Delta z \approx 250$ $\mu$m
- $z$ vertex resolution of $J/\psi$ of $B_{CP}$ is $\approx 70$ $\mu$m (core $\approx 45$ $\mu$m)
- $z$ vertex resolution of $B_{tag}$ is $\approx 170$ $\mu$m
  - charm decays removed by excluding high-$\chi^2$ tracks from fit
  - identified $K_S$ and $\Lambda$ are used in fit in place of their daughters
- B direction is used to correct for transverse component in $\Delta t$ event by event
- final $\Delta z$ resolution is $\approx 190$ $\mu$m
- a resolution function is applied in the final fit, with parameters extracted from data
Two crucial ingredients for the sin2\( \beta \) measurement are still missing:

1) What is the fraction of events for which our flavor tagging fails?
2) What are the parameters to describe the \( \Delta t \) resolution function?

⇒ Calibration Sample:

Hadronic Decays to Flavor Eigenstates!

Here we know the true asymmetry:
(simply given by flavor oscillation)

\[
A_f(t) = \frac{R(\overline{B}^0 \rightarrow \overline{B}^0)(t) - R(B^0 \rightarrow \overline{B}^0)(t)}{R(\overline{B}^0 \rightarrow \overline{B}^0)(t) + R(B^0 \rightarrow \overline{B}^0)(t)} = \cos \Delta m t
\]

⇒ We can determine: wrong-tag fraction
\( \Delta t \) resolution function
Fully reconstructed hadronic B decays into flavor-identifying modes

\[ \text{B}^+ \pi^+, \text{D}^- \rho^+, \text{D}^- a_1^+ \]

\[ J/\psi K^{*0} (K^{*0} \rightarrow K^+ \pi^-) \]

\[ \approx 6700 \text{ events} \]

Instead of explicitly extracting wrong-tag fraction and resolution function parameters from this B flavor sample, we perform a simultaneous maximum-likelihood fit on the combined sample of CP and flavor decays.
Global Unbinned ML Fit

• Simultaneous fit to $B_{CP}$ and $B_{flavor}$ samples for $\sin 2\beta$, plus 34 parameters to characterize the detector and the data:
  – Signal $\Delta t$ resolution function (9 parameters)
  – Signal wrong-tag fractions (4), allowing for $B_0$-$B_0$ differences (another 4)
  – Background time dependence (6), $\Delta t$ resolution function (3), and wrong-tag fractions (8)

• Extract background parameters from $m_{ES}$ sidebands, except $J/\psi K_L$ where $J/\psi$ sidebands and inclusive $B \rightarrow J/\psi$ Monte Carlo are used.

• $\tau_{B_0}$ and $\Delta m_{B_0}$ are fixed to PDG values

• Largest correlation between any linear combination of parameters and $\sin 2\beta$ is less than 7.6%
$\Delta t$ Distributions

**$K_S$ modes**

$B^0 \rightarrow J/\psi K^0_S$

$B^0 \rightarrow \psi(2S)K^0_S$

141 $B^0$ tags

129 $\bar{B}^0$ tags

**$K_L$ mode**

$B^0 \rightarrow J/\psi K^0_L$

138 $B^0$ tags

118 $\bar{B}^0$ tags
Raw Asymmetries

- not corrected for wrong-tag fraction or background ⇒ diluted asymmetries
- binomial errors

\[ \sin 2\beta = 0.25 \pm 0.22 \text{(stat.)} \]

\[ \sin 2\beta = 0.87 \pm 0.51 \text{(stat.)} \]
The Final Result

Log likelihood versus $\sin^2 \beta$:

$\ln \left( \frac{L}{L_{\text{max}}} \right)$

$\sin^2 \beta = 0.34 \pm 0.20\text{(stat.)} \pm 0.05\text{(syst.)}$

“The number from hell!” (A.J.S. Smith)
Cross Checks

Modes:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sin^2\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K_S^{0}(\pi^+\pi^-)$</td>
<td>$0.25 \pm 0.26$</td>
</tr>
<tr>
<td>$J/\psi K_S^{0}(\pi^0\pi^0)$</td>
<td>$-0.05 \pm 0.66$</td>
</tr>
<tr>
<td>$\psi(2S)K_S^{0}(\pi^+\pi^-)$</td>
<td>$0.40 \pm 0.50$</td>
</tr>
<tr>
<td>$J/\psi K_L^{0}$</td>
<td>$0.87 \pm 0.51$</td>
</tr>
<tr>
<td>All CP Modes</td>
<td>$0.34 \pm 0.20$</td>
</tr>
<tr>
<td>$B^\pm$</td>
<td>$0.02 \pm 0.05$</td>
</tr>
<tr>
<td>$B^0$ (non-CP)</td>
<td>$0.03 \pm 0.05$</td>
</tr>
</tbody>
</table>

Tagging Categories:

- **Lepton:** $0.07 \pm 0.43$
- **Kaon:** $0.40 \pm 0.29$
- **NT1:** $-0.03 \pm 0.67$
- **NT2:** $0.09 \pm 0.76$
- **All categories:** $0.25 \pm 0.22$

no trends observed…
Other $\sin 2\beta$ Measurements:

- BABAR: $0.34 \pm 0.20 \pm 0.05$
- Belle: $0.58^{+0.32}_{-0.34} \pm 0.10$
- CDF: $0.79^{+0.41}_{-0.44}$
- ALEPH: $0.84^{+0.82}_{-1.04} \pm 0.16$
- OPAL: $3.20^{+1.8}_{-2.0} \pm 0.5$
- World average: $0.48 \pm 0.16$
Unitarity Triangle Revisited
\[ \Delta m_d \text{ Measurement from } B_{\text{flav}} \text{ Sample} \]

Perform the same fit on flavor sample only, with floating $\Delta m_d$:

\[ \Delta m_d = 0.519 \pm 0.020 \text{(stat.)} \pm 0.016 \text{(syst.)} \, \text{fs}^{-1} \]

(We can do better with dilepton events…)

\[ \Delta m_d = 0.499 \pm 0.010 \text{(stat.)} \pm 0.012 \text{(syst.)} \, \text{fs}^{-1} \]
What’s Next?

• Continuous update of sin2β with charmonium modes

• sin2α
  – B^0 \rightarrow \pi^+\pi^-: exp. straightforward, theor. problematic
  – Isospin analysis of all B \rightarrow \pi\pi channels: hard (\pi^0\pi^0!)
  – Dalitz plot analysis of B \rightarrow 3\pi to access B \rightarrow \rho\pi (lots of statistics!)

• sin2β in other modes:
  – B^0 \rightarrow \phi K_S
  – B^0 \rightarrow \eta^K_S

2 examples: where are we with B^0 \rightarrow \pi^+\pi^- and B^0 \rightarrow \phi K_S?
**sin2α with $B^0 \rightarrow \pi^+\pi^-(b \rightarrow u)$**

- Analogous to $B^0 \rightarrow J/\psi K_S$, with additional phase from $b \rightarrow u$ transition: measure $\sin2(\beta+\gamma) = \sin2\alpha$
- But: $|V_{ub}|$ small $\Rightarrow$ higher order diagrams with different phases come into play! ("penguin pollution")
- We will measure $\sin2\alpha_{\text{eff}}$, interpretation will depend on ratio of penguin/tree amplitude (P/T)
**sin2β with B⁰ → φKₛ (b → s)**

- **b → s transition** forbidden at tree level
- **pure penguin decay** (with gluonic and electroweak contributions)
- no phase from decay \(\Rightarrow\) measure \(\text{sin}2\beta\) just as in \(B^0 \rightarrow J/\psi K_S\)...
- ...but **new physics** is likely to show up in loop and give rise to additional phase!
- Could be combined with \(B^0 \rightarrow \eta'K_S\) for more statistics (London, Soni)
Background Suppression

For every BB event, we get 3–4 $e^+e^- \rightarrow q\bar{q}$ (q = udsc) events (continuum beneath $\Upsilon(4S)$) ⇒ dominant background!

main distinction: continuum events are jet-like, whereas B$\bar{B}$ events are isotropic

Sensitive quantities:

- $\cos\theta_T$: cosine of thrust angle = angle between thrust axes of B candidate and the rest of the event (thrust axis = axis which maximizes sum of longitudinal momenta)
- angular energy flow with respect to B thrust axis, parameterized by a Fisher discriminant $F$
- for decays to resonances: helicity, Dalitz plot
- other variables:
  - Fox-Wolfram momentum of event
  - B emission angle
  - B candidate thrust angle with respect to beam axis; sometimes also in $F$
Extraction of Signal Yield

1) Event counting
   - apply tight selection (that optimizes significance for expected signal / upper limit)
   - count events in signal region in $m_{ES} - \Delta E$ plane
   - estimate background contamination from sidebands

2) Extended Maximum Likelihood Fit
   - loose preselection
   - determine for every selected event $i$ a signal and background probability, $p_{\text{sig}}$ and $p_{\text{bgr}}$, according to probability density functions (pdf’s)
   - maximize the following likelihood (for the simplest case)

$$L = e^{-\left(N_{\text{sig}} + N_{\text{bgr}}\right)} \times \prod_{i=1}^{N} \left[ N_{\text{sig}} p_{\text{sig}}(i) + N_{\text{bgr}} p_{\text{bgr}}(i) \right]$$

Poisson probability for observing $N$ events

$N$: total of selected events (observed)
$N_{\text{sig}}$: signal events (from fit)
$N_{\text{bgr}}$: background events (from fit)

signal probability for event $i$: $p_{\text{sig}}(i) = p_{\text{sig}}(m_{ES}(i), \Delta E(i), F(i),...)$
Calibration Channels

Maximum likelihood analysis requires assumption for expected signal and background pdf’s for input variables \((m_{ES}, \Delta E, F, \text{PID variables etc.})\)

- for background pdf’s use sidebands
- for signal pdf’s use (less rare) calibration channels!

**Kinematics:** \(B^- \rightarrow D^0 \pi^-\) \(\rightarrow K^- \pi^+\)

**Particle ID:** \(D^{*+} \rightarrow D^0 \pi^+\) \(\rightarrow K^- \pi^+\)

\[
\Rightarrow \sigma(m_{ES}) \approx 2.7 \text{ MeV}, \quad \sigma(\Delta E) \approx 20 \text{ MeV}
\]

\[
\Rightarrow \text{kinematically selected sample of K and } \pi
\]
**B^0 \rightarrow \pi^+\pi^- Branching Fraction**

- simultaneous fit to $B^0 \rightarrow \pi^+\pi^-$, $K^+\pi^-$, and $K^+K^-$
- background suppression: $|\cos \theta_T| < 0.9$
- total efficiency: 43–45 %
- 8 parameter ML fit:
  - input: $m_{ES}$, $\Delta E$, $F$, and measured Cherenkov angles $\theta_c^+$, $\theta_c^-$ for each event
  - output: $N_{\pi\pi}^{\text{sig}}, N_{K\pi}^{\text{sig}}, N_{KK}^{\text{sig}}, N_{\pi\pi}^{\text{bgr}}, N_{K\pi}^{\text{bgr}}, N_{KK}^{\text{bgr}}, A_{K\pi}^{\text{sig}}, A_{K\pi}^{\text{bgr}}$
- result: $N_{\pi\pi}^{\text{sig}} = 41.5 \pm 10.6; \quad N_{K\pi}^{\text{sig}} = 169 \pm 17; \quad N_{KK}^{\text{sig}} = 8.2 \pm 8.0$
  $A_{K\pi}^{\text{sig}} = -0.19 \pm 0.10$  $K^-\pi^+ / K^+\pi^-$ asymmetry (direct CP violation)

\[
\begin{align*}
\text{Br}(B^0 \rightarrow \pi^+\pi^-) &= (4.1 \pm 1.0 \pm 0.7) \times 10^{-6} \\
\text{Br}(B^0 \rightarrow K^+\pi^-) &= (16.7 \pm 1.6^{+1.2}_{-1.7}) \times 10^{-6} \\
\text{Br}(B^0 \rightarrow K^+K^-) &< 2.5 \times 10^{-6} \quad (90\% \text{ CL})
\end{align*}
\]

\[\Rightarrow \Gamma(\pi^+\pi^-)/\Gamma(K^+\pi^-) \approx 0.25\]

- \(\approx\ 40 \ \pi\pi\) events: good branching fraction measurement, not enough yet for an asymmetry measurement…

---

*Thomas Schietinger*  
*CP Violation with BABAR*  
*June 2001*  
*Page 48*
Event counting analysis as cross-check:
(stronger background suppression, selector-based PID)

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

$B^0 \rightarrow K^+\pi^-$

$B^0 \rightarrow K^+K^-$
**B^0 \rightarrow \phi K_S Branching Fraction**

- **channels:** to $\phi \rightarrow K^+K^-$, $K_S \rightarrow \pi^+\pi^-$
- **background suppression:** $|\cos \theta_T| < 0.9$
- **total efficiency:** 36.1% (12.6% with sub-BFs)
- **4 parameter ML fit:**
  - input: $m_{ES}$, $\Delta E$, $m_{KK}$, $|\cos \theta_T|$, $\cos \theta_B$ (B emission angle)
  - output: $N_{\phi K}^{\text{sig}}$, $N_{\phi K}^{\text{bgr}}$
- **Result:** $N_{\phi K}^{\text{sig}} = 10.8^{+4.1}_{-3.3}$

$$\text{Br}(B^0 \rightarrow \phi K_S) = (4.0^{+1.5}_{-1.2} \pm 0.4) \times 10^{-6}$$

- First unambiguous observation of this channel!
- $\approx 10$ events: longer wait for asymmetry…
$B^0 \rightarrow \phi K_S$ cont.

Event counting cross-check:

$B^0 \rightarrow \phi K_S$

also measured:

$\text{Br}(B^+ \rightarrow \phi K^+) = (7.7^{+1.6}_{-1.4} \pm 0.8) \times 10^{-6}$
Run 2

So far, so good…

We aim for 75–80 fb\(^{-1}\) by summer 2002
But... do we have the power?

- SLAC as a federal lab gets its power from WAPA (Western Area Power Administration), and is therefore independent of the “rolling blackouts” that the Californian Power companies are forced to impose.
- However, WAPA asks us to voluntarily cut down on electricity use (which we do without significantly compromising the science program).
- In this very dynamic situation, we must be prepared for sudden losses of power nevertheless.
  - All BABAR subsystems have prepared detailed plans for worst-case scenario of two-day blackout…
- It is going to be an interesting summer!
Outlook
You ain’t seen nothin’ yet!

short-term goal: 100 fb\(^{-1}\) by summer 2002
long-term goal: 500 fb\(^{-1}\) by summer 2005

(remember: the machine was designed for 30 fb\(^{-1}\)/year!)

…semi-serious thinking about “SuperBABAR”: new machine that would produce 20 ab\(^{-1}\)/year!
Summary

**BABAR** is well on its way to measure the CP-violating angles of the CKM-matrix:

- First result for $\sin^2\beta$ from charmonium decays
- Accumulating data for a first peek at $\sin^2\alpha_{\text{eff}}$ with $B^0 \rightarrow \pi^+\pi^-$
- Observation of $B^0 \rightarrow \phi K_S \Rightarrow$ will give $\sin^2\beta$ with a loop decay, sensitive to new physics!
- Many, many other results I haven’t had time to talk about…
- PEP-II performance exceeds all expectations!
- Continuous flood of new exciting physics results in the coming 5 years!
Unitarity constraint: $V^\dagger V = 1$
with first and third column
(where phases are!):

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\implies V_{ub}^* + V_{td} = \lambda V_{cb}^*$$

Unitarity Triangle (more elaborate)

$$\alpha = \arg\left(\frac{V_{tb}^*V_{td}}{-V_{ub}^*V_{ud}}\right) \approx \arg(-V_{td} / V_{ub}^*)$$

$$\beta = \pi - \arg\left(\frac{-V_{tb}^*V_{td}}{-V_{cb}^*V_{cd}}\right) \approx \pi - \arg(-V_{td})$$

$$\gamma = \arg\left(\frac{V_{ub}^*V_{ud}}{-V_{cb}^*V_{cd}}\right) \approx \arg(V_{ub}^*)$$
**CP Notation**

**Mass eigenstates:**

\[ B_H = pB^0 + q\bar{B}^0 \]

\[ B_L = pB^0 - q\bar{B}^0 \]

**Decay amplitudes:**

\[ A_f = A(B^0 \to f) \]

\[ \bar{A}_f = A(\bar{B}^0 \to f) \]

**Interference parameter:**

\[ \lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} \]

(Neutral kaons: \( \eta_f = \frac{1 - \lambda_f}{1 + \lambda_f} \))

\[ \left| \frac{q}{p} \right| \neq 1 \quad \Leftrightarrow \quad \text{CP violation in the mixing} \]

\[ \left| \frac{A_f}{\bar{A}_f} \right| \neq 1 \quad \Leftrightarrow \quad \text{CP violation in the decay} \]

\[ \left| \lambda_f \right| = 1, \quad \text{Im}(\lambda_f) \neq 1 \quad \Leftrightarrow \quad \text{CP violation in the interference between decays with and without mixing} \]
A Comparison:

**CPLEAR**

Both measure time-dependent CP-violating decay rate asymmetries.

\[
\frac{R(\overline{K}^0 \to \pi^+\pi^-) - R(K^0 \to \pi^+\pi^-)}{R(\overline{K}^0 \to \pi^+\pi^-) + R(K^0 \to \pi^+\pi^-)}
\]

\[
\approx -2 |\eta_{+-}| \cos(\Delta m t - \varphi_{+-})
\]

\[
\eta_{+-} \approx \mathcal{E}_K \approx e^{i\pi/4} C_\varepsilon B_K \text{Im}(V_{ts}^*V_{td}) \{\text{Re}(V_{cs}^*V_{cd}) \times [\eta_1 S_0(x_c) - \eta_3 S_0(x_c, x_t)] - \text{Re}(V_{ts}^*V_{td}) \eta_2 S_0(x_i)\}
\]

for large hadronic uncertainties.

**Babar**

\[
\frac{R(B^0 \to J/\psi K_S) - R(\overline{B}^0 \to J/\psi K_S)}{R(B^0 \to J/\psi K_S) + R(\overline{B}^0 \to J/\psi K_S)}
\]

\[
\approx \text{Im} \lambda_{J/\psi K_S} \sin(\Delta m t)
\]

Different language!

\[
\text{Im} \lambda_{J/\psi K_S} \approx \sin(2\beta)
\]

\[
\beta = \arg \left(-\frac{V_{cd}^*V_{cb}}{V_{td}^*V_{tb}}\right)
\]

very clean!
**CPLEAR:**

\[ A_f \approx -2 |\eta_f| \cos(\Delta m t - \varphi_f) \]

\[ = -2 |\eta_f| \left[ \cos(\Delta m t) \cos \varphi_f + \sin(\Delta m t) \sin \varphi_f \right] \]

\[ = -2 \left[ \text{Re}\eta_f \cos(\Delta m t) + \text{Im}\eta_f \sin(\Delta m t) \right] \]

Negligible in \( B^0 \to J/\psi K_S \)!

**CP violation in the mixing**

...of decays with and without mixing

\[ \Rightarrow \textbf{BABAR:} \]

\[ A_f = -2 \text{Im}\eta_f \sin(\Delta m t) \]

\[ A_f = \text{Im}\lambda_f \sin(\Delta m t) \]

Recall that

\[ \lambda_f = \frac{1-\eta_f}{1+\eta_f} \approx 1 - 2 \eta_f \]

\[ \Rightarrow \text{Im}\lambda_f \approx -2 \text{Im}\eta_f \]
\( p\bar{p}_{\text{rest}} \rightarrow K^-\pi^+K^0 \) (incoherent)

Production of \( K^0 / B^0 \)

\[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0 \] (coherent)

Identification of accompanying charged \( K \)

(\(~100\%\) efficient)

Flavor tagging

Decay of accompanying neutral \( B \) to a non-CP final state

(\(~25\%\) efficient)

Decay length

\( c\tau_S = 2.68 \text{ cm}, \ c\tau_L = 15.5 \text{ m} \)

boost from \( p\bar{p} \): \( \gamma v \approx 1 \)

\[ \Rightarrow \text{prop. and drift chambers} \]

\( c\tau = 500 \mu m \)

boost from \( \Upsilon(4S) \): \( \gamma v \approx 0.06! \)

\[ \Rightarrow 1) \text{ additional boost from accelerator:} \quad \gamma v = 0.56 \Rightarrow 250 \mu m \]

\[ \Rightarrow 2) \text{ Silicon Vertex Tracker} \]

with \(~100 \mu m\) resolution
CP violation effects tiny
⇒ collected O(10^8) K mesons

Branching ratios tiny; tagging inefficiency
⇒ will collect O(10^8) B mesons
(100 fb^{-1})

~100 physicists from
17 institutes from
9 countries

~600 physicists from
~70 institutes from
9 countries

Just finished! Just started!
Resolution Function
Parameters:

Wrong Tag Fractions:

<table>
<thead>
<tr>
<th>Tag Category</th>
<th>$\varepsilon$ (%)</th>
<th>$w$ (%)</th>
<th>$Q$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>10.9 ± 0.4</td>
<td>11.6 ± 2.0</td>
<td>6.4 ± 0.7</td>
</tr>
<tr>
<td>Kaon</td>
<td>36.5 ± 0.7</td>
<td>17.1 ± 1.3</td>
<td>15.8 ± 1.3</td>
</tr>
<tr>
<td>NT1</td>
<td>7.7 ± 0.4</td>
<td>21.2 ± 2.9</td>
<td>2.6 ± 0.5</td>
</tr>
<tr>
<td>NT2</td>
<td>13.7 ± 0.5</td>
<td>31.7 ± 2.6</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>Total</td>
<td>68.9 ± 1.0</td>
<td>26.7 ± 1.6</td>
<td></td>
</tr>
</tbody>
</table>
\[ R_{\text{reso}}(\Delta t, \Delta t_{\text{true}}, \sigma_{\Delta t} | f_{\text{tail}}, f_{\text{outlier}}, S_{\text{core}}, \delta_{\text{core}}, S_{\text{tail}}, \delta_{\text{tail}}, \sigma_{\text{outlier}}) = \]

\[
(1 - f_{\text{tail}} - f_{\text{outlier}}) \frac{\exp - \frac{1}{2} \left( \frac{\Delta t - \delta_{\text{core}} - \Delta t_{\text{true}}}{S_{\text{core}} \sigma_{\Delta t}} \right)^2}{\sqrt{2\pi} S_{\text{core}} \sigma_{\Delta t}}
\]

\[
+ f_{\text{tail}} \frac{\exp - \frac{1}{2} \left( \frac{\Delta t - \delta_{\text{tail}} - \Delta t_{\text{true}}}{S_{\text{tail}} \sigma_{\Delta t}} \right)^2}{\sqrt{2\pi} S_{\text{tail}} \sigma_{\Delta t}}
\]

\[
+ f_{\text{outlier}} \frac{\exp - \frac{1}{2} \left( \frac{\Delta t - \delta_{\text{outlier}} - \Delta t_{\text{true}}}{\sigma_{\text{outlier}}} \right)^2}{\sqrt{2\pi} \sigma_{\text{outlier}}}
\]