Physics at **BABAR**

Christos Touramanis

**THE UNIVERSITY of LIVERPOOL**

for the BABAR Collaboration

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The **BABAR** collaboration

**9 Countries**
**72 Institutions**
**554 Physicists**

### 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, Bari
- INFN, Ferrara
- Lab. Nazionali di Frascati dell' INFN
- INFN, Genova
- INFN, Milano
- INFN, Napoli
- INFN, Padova
- INFN, Pavia
- INF, Pisa
- INFNN, Roma and U "La Sapienza"
- INFN, Torino
- INFN, Trieste

### Norway [1/3]
- U of Bergen

### Russia [1/13]
- Budker Institute, Novosibirsk

### 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

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Overview

• Physics programme
• PEP-II and BABAR
• Event reconstruction
• Selected preliminary measurements
• First CP results
• Conclusion-outlook
CKM matrix, Unitarity Triangle, CP violation

In the SM CP violation arises from the non-vanishing phase of the unitary CKM matrix:

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

Experimentaly CP violation can be observed as time dependent decay rate asymmetry of CP conjugate processes, i.e. for a CP eigenstate \( f \):

\[ a_f (t) = \frac{R(B^0(t) \rightarrow f) - R(B^0(t) \rightarrow \bar{f})}{R(B^0(t) \rightarrow f) + R(B^0(t) \rightarrow \bar{f})} \]

Independent measurements of \( \sin(2\beta) \) with different theoretical and experimental systematics:

\[ B^0 \rightarrow J/\psi K^0 \ (K_S \rightarrow \pi^+\pi^- \ ;; \pi^0\pi^0 \ ;; K_L) \ ; \ B^0 \rightarrow D^+D^- \ ; D^*D^- \ ; \phi K_S \]

for \( f = J/\psi K_S(K_L) \):

\[ a_f (t) = (\pm 1) \sin (2\alpha) \sin (\bar{\Delta}m t) \]
The **BABAR** physics programme

- **Main focus is B physics and in particular CP violation:**
  - CP measurements: angles $\beta$, $\alpha$ and $\gamma$
- Determination of unitarity triangle sides through:
  - $V_{ub}$ and $V_{cb}$: semileptonic B decays
  - $V_{td}$: B mixing ($\Delta m$)
- Above measurements allow to overconstrain the unitarity triangle and check for consistency between related observables $\Rightarrow$ Stringent tests of the SM
- High statistics and broad access to the rich phenomenology of B sector allows BABAR to **probe new physics** at energy scales higher than the current reach of “direct search” experiments
- Furthermore, a rich non-B physics programme is accessible and ongoing in BABAR, covering charm, tau, two photon and QCD.
9GeV $e^-$ on 3.1GeV $e^+$:

$$e^+e^- \rightarrow Y(4S) \rightarrow B^0\overline{B}^0$$

- **coherent** neutral B pair production and decay (p-wave)

- **boost** of $Y(4S)$ in lab fame : $\beta\gamma=0.56$
SLAC B factory performance

- PEP-II top lumi: $2.4 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ (design $3.0 \times 10^{33}$)
- Top 24h L: 150/pb (design 135)
- BABAR logging efficiency: $>95$

1 June 1999 31 August 2000

PEP-II delivered: 18.8/fb
BABAR recorded: 17.5/fb (1.8/fb off peak)
The BABAR detector

• Tracking: \( \sigma(p_T)/p_T = 0.15\% \times p_T \oplus 0.45\% \)
• DIRC: K-\(\pi\) separation >3.4\(\sigma\) for \(P<3.5\)GeV/c
Reconstruction quality(I)

\[ J/\psi \quad \sigma = 13 \text{MeV/c}^2 \]

\[ K_S \rightarrow \pi^+\pi^- \]

\[ \sigma_1 = 2.8 \text{MeV/c}^2 \quad (69\%) \]

\[ \sigma_2 = 11 \text{MeV/c}^2 \quad (31\%) \]
Reconstruction quality (II)

Photon pair mass (hadronic events)

\[ \pi^0 \quad \sigma = 6.9 \text{MeV}/c^2 \]

\[ \eta \quad \sigma = 16 \text{MeV}/c^2 \]

\[ \mathbf{K_S} \rightarrow \pi^0\pi^0 \quad \sigma = 10 \text{MeV}/c^2 \]
Y(4S) event reconstruction

Reco -> physics measurement & CP analysis input

- $B_1$ (incl, excl): $B$ decay fractions, kinematics; signal purity (exclusive)
- $B_1$ (incl, semiexcl, excl), $B_2$ flav. tag, $\Delta z$: $B$ lifetime, mixing; tagging quality, $\Delta z$ resolution
- $B_1$ (excl CP state), $B_2$ flav. tag, $\Delta z$: CP

B Flavor Tagging:
- Primary Lepton
- Charged Kaon
- Neural Net (NT1, NT2)

Kinematic variables in exclusive reconstruction:

- $\Delta E = E^*_B - \sqrt{s}/2$
- $m_{ES} = \sqrt{(s/4 - p^*_B)^2}$
Fully reconstructed $Y(4S)$ event

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

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

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

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

$\psi(2S) \rightarrow \mu^+\mu^-$

$K^0_s \rightarrow \pi^+\pi^-$
Exclusive hadronic B sample

Sample: 8.9 fb⁻¹ on-resonance, 0.9 fb⁻¹ off-resonance

From these samples we measure:

- \( B^0, B^\pm \) lifetimes
- \( \Delta m \) (mixing) of neutral B
- \( \Delta z \) resolution and tagging performance for the \( \sin(2\beta) \) measurement

\[
B^0 \rightarrow D^*\pi^+, D^*\rho^+, D^*a_1^+
\]

\[
B^0 \rightarrow D\pi^+, D\rho^+, Da_1^+
\]

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

\[
B^- \rightarrow D^0\pi^-, D^{*0}\pi^-
\]

\[
B^- \rightarrow J/\Psi K^-, \gamma(2S)K^-
\]
**B lifetimes**

- Determine $z_{\text{RECO}}$ and $z_{\text{TAG}}$ (the other B)
- Boost approximation: $\Delta t = \Delta z / c<\beta\gamma>$
- Fit:
  - Maximum likelihood: $\Gamma e^{-|\Delta t|} \otimes R(\Delta t;a)$
  - event-by-event error
- Resolution:
  - dominated by TAG side
  - Slight bias (0.2 psec) from sec. decays
  - 3 gaussians

**Preliminary** result from 7.4 fb$^{-1}$ on-resonance data:

$$\tau_{B^0} = 1.51 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ ps}$$

$$\tau_{B^+} = 1.60 \pm 0.05 \text{ (stat)} \pm 0.04 \text{ (syst)} \text{ ps}$$

$$\tau_{B^+} / \tau_{B^0} = 1.065 \pm 0.044 \text{ (stat)} \pm 0.021 \text{ (syst)}$$
B mixing

Tagging efficiency
\[ Q = \varepsilon D^2 \quad , \quad D = 1 - 2w \]
\( D \) = Dilution
\( w \) : wrong tag fraction
\( \varepsilon \) : fraction of tagged events

Hadronic sample:
\[ \Delta m_d = 0.516 \pm 0.031 \text{(stat)} \pm 0.018 \text{ (syst)} \quad \text{\( \text{hr} \text{ps}^{-1} \)} \]

Semipleptonic sample (\( D^* \)lv, 7517 events):
\[ \Delta m_d = 0.508 \pm 0.020 \text{(stat)} \pm 0.022 \text{ (syst)} \quad \text{\( \text{hr} \text{ps}^{-1} \)} \]

Combined preliminary result:
\[ \Delta m_d = 0.512 \pm 0.017 \text{(stat)} \pm 0.022 \text{ (syst)} \quad \text{\( \text{hr} \text{ps}^{-1} \)} \]
B mixing using dileptons

\[ A(\Delta t) = \frac{N(^{+}_{-})(\Delta t) - N(^{\pm}_{\pm})(\Delta t)}{N(^{+}_{-})(\Delta t) + N(^{\pm}_{\pm})(\Delta t)} \]

- **B Flavor**
  ⇒ sign of the direct lepton

- **Inclusive approach**
  ⇒ large BR (~4%)

- **Mixture of B^0 and B^±**
  ⇒ Fraction R fitted

- **Cascade leptons**
  ⇒ Mistag fraction fitted

Preliminary result from 7.7 fb\(^{-1}\) on-resonance and 1.1 fb\(^{-1}\) off-resonance data:

\[ \Delta m_d = 0.507 \pm 0.015 \text{(stat)} \pm 0.022 \text{ (syst)} \, \text{\(\hat{\alpha}\) ps}^{-1} \]
Charmless 2-body decays

Cut based analysis, no PID
N(h⁺h⁻) = 67 ± 11
(consistent with CLEO)

Kaon/pion content after sideband (m_{ES}) substraction:

θ_C: Cerenkov angle in DIRC
θ_C(π): expected angle, pion
θ_C(K): expected angle, Kaon

Preliminary result from likelihood fit (m_{ES}, ΔE, Fisher discriminant and K/π PID):

<table>
<thead>
<tr>
<th>Mode</th>
<th>N_S</th>
<th>Stat. Sig. (σ)</th>
<th>B(10^{-6})</th>
<th>CLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺π⁻</td>
<td>29^{+8+3}_{-7-4}</td>
<td>5.7</td>
<td>9.3^{+2.6+1.2}_{-2.3-1.4}</td>
<td>4.3^{+1.6}_{-1.4} ± 0.5</td>
</tr>
<tr>
<td>K⁺π⁻</td>
<td>38^{+9+3}_{-8-5}</td>
<td>6.7</td>
<td>12.5^{+3.0+1.3}_{-2.6-1.7}</td>
<td>17.2^{+2.5}_{-2.4} ± 1.2</td>
</tr>
<tr>
<td>K⁺K⁻</td>
<td>7^{+5}_{-4} (&lt; 15)</td>
<td>2.1</td>
<td>&lt; 6.6</td>
<td>&lt; 1.9</td>
</tr>
</tbody>
</table>
Measuring $\sin(2\beta)$

\[ F_\pm(\Delta t) \ exp(-\Gamma \Delta t) \ (1 \pm \sin(2\beta) \sin(\Delta m \Delta t)) \]

Decay rates $(F_+, F_-)$ to CP eigenstate for $(B^0, \bar{B}^0)$ tags

$[\sin(2\beta) = 0.7$, no detector effects$]\]

- Select exclusive $B^0 \rightarrow CP$ eigenstate events
  - Background fraction, type $\Rightarrow$ exclusive studies
- Tag the flavor of the other $B$ at decay time
  - Dilution $\Rightarrow$ mixing analysis
- Reconstruct the two $B$ decay vertices and determine $\Delta t = \Delta z / \langle \beta \gamma \rangle$
  - Resolution $\Rightarrow$ lifetime analysis
- Unbinned max likelihood fit
  - event by event $\Delta t$ error and outlier cut
  - Dilution dependent on tag type (lepton, kaon, NN)

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The CP sample

\[ B^0 \rightarrow J/\Psi \, K_S \, (K_S \rightarrow \pi^+\pi^-) \]
121 events
purity 96% 

\[ B^0 \rightarrow J/\Psi \, K_S \, (K_S \rightarrow \pi^0\pi^0) \]
19 events
purity 91% 

\[ B^0 \rightarrow \Psi(2S) \, K_S \, (K_S \rightarrow \pi^+\pi^-) \]
28 events
purity 93% 

Total: 168 fully reconstructed candidates
Flavor tagging of the other B

Tagging categories (ranked):
1. Lepton: Primary electron OR muon charge
2. Kaon (total) charge
3. NT1 Neural Net (slow pion charge, “Jet Charge”)
4. NT2 same Neural Net, lower separation region

In presence of dilution factor $D$ the CP and mixed/unmixed B decay rates become:

$$F_\pm(\Delta t) \exp(-\Gamma \Delta t) (1 \pm D \sin(2\beta) \sin(\Delta m \Delta t))$$
$$F_{U,M}(\Delta t) \exp(-\Gamma \Delta t) (1 \pm D \cos(\Delta m \Delta t))$$

We extract the tagging performance form the mixing analysis:

<table>
<thead>
<tr>
<th>Tagging Category</th>
<th>$\varepsilon$ (%)</th>
<th>$w$ (%)</th>
<th>$Q$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>11.2 ± 0.5</td>
<td>9.6 ± 1.7 ± 1.3</td>
<td>7.3 ± 0.3</td>
</tr>
<tr>
<td>Kaon</td>
<td>36.7 ± 0.9</td>
<td>19.7 ± 1.3 ± 1.1</td>
<td>13.5 ± 0.3</td>
</tr>
<tr>
<td>NT1</td>
<td>11.7 ± 0.5</td>
<td>16.7 ± 2.2 ± 2.0</td>
<td>5.2 ± 0.2</td>
</tr>
<tr>
<td>NT2</td>
<td>16.6 ± 0.6</td>
<td>33.1 ± 2.1 ± 2.1</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td>all</td>
<td>76.7 ± 0.5</td>
<td></td>
<td>27.9 ± 0.5</td>
</tr>
</tbody>
</table>
Δt measurement

• CP side (fully reco’d) : $\sigma_z \sim 45-65\mu m$ (mode dependent)
• Tag side :
  - $\sigma_z \sim 125\mu m$
  - bias $\delta_z \sim 25\mu m$ (charm)

• Resolution extracted from lifetime measurement and verified on mixing :
  - Core : $\sigma = 0.6ps$ ; 75%
  - Tail : $\sigma = 1.8ps$
  - Outliers : $\sigma = 8ps$ ; 1%
sin(2\beta) : precautions and checks

Blind Analysis

- sin(2\beta) fitted value and CP asymmetry in \Delta t distribution hidden to eliminate analyst’s bias
- Event selection, tagging, vertexing fixed and studied blind
- Will revert to blind analysis for new data

Null CP asymmetry tests

<table>
<thead>
<tr>
<th>Sample</th>
<th>Apparent CP-asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic charged B decays</td>
<td>0.03 ± 0.07</td>
</tr>
<tr>
<td>Hadronic neutral B decays</td>
<td>-0.01 ± 0.08</td>
</tr>
<tr>
<td>(J/\psi K^+)</td>
<td>0.13 ± 0.14</td>
</tr>
<tr>
<td>(J/\psi K^{*0} (K^{*0} \rightarrow K^+\pi^-))</td>
<td>0.49 ± 0.26</td>
</tr>
</tbody>
</table>
The sin(2β) fit

120 of 168 events tagged

$\sin(2\beta) = 0.12 \pm 0.37\text{(stat)} \pm 0.09 \text{ (syst)}$

<table>
<thead>
<tr>
<th>sample</th>
<th>$\sin2\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CP$ sample</td>
<td>0.12 ± 0.37</td>
</tr>
<tr>
<td>$J/\psi K_S^0 \to \pi^+\pi^-$</td>
<td>0.10 ± 0.42</td>
</tr>
<tr>
<td>other $CP$ events</td>
<td>0.87 ± 0.81</td>
</tr>
<tr>
<td>Lepton</td>
<td>1.6 ± 1.0</td>
</tr>
<tr>
<td>Kaon</td>
<td>0.14 ± 0.47</td>
</tr>
<tr>
<td>NT1</td>
<td>−0.59 ± 0.87</td>
</tr>
<tr>
<td>NT2</td>
<td>−0.96 ± 1.30</td>
</tr>
</tbody>
</table>
Fit quality and systematic errors

- Log likelihood function

- $\chi^2$ for binned asymmetry and likelihood fit is 9.2 / 7

<table>
<thead>
<tr>
<th>source of uncertainty</th>
<th>effect on $\sin2\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$ lifetime</td>
<td>0.012</td>
</tr>
<tr>
<td>$\Delta m_d$</td>
<td>0.015</td>
</tr>
<tr>
<td>$\Delta z$ resolution, CP sample</td>
<td>0.019</td>
</tr>
<tr>
<td>Time resolution bias, CP sample</td>
<td>0.047</td>
</tr>
<tr>
<td>Mistag fraction measurement</td>
<td>0.059</td>
</tr>
<tr>
<td>Mistag difference in CP - nonCP samples</td>
<td>0.050</td>
</tr>
<tr>
<td>Different mistag fractions for $B^0$, anti-$B^0$</td>
<td>0.005</td>
</tr>
<tr>
<td>Background, CP sample</td>
<td>0.015</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.091</td>
</tr>
</tbody>
</table>
Conclusions and Outlook

ivism start for PEP-II and BABAR:
- 18.8fb$^{-1}$ delivered
- 17.5fb$^{-1}$ recorded
- 9fb$^{-1}$ analysed by July

✓ $\sin(2\beta) = 0.12 \pm 0.37_{\text{stat}} \pm 0.09_{\text{syst}}$

✓ many other interesting physics measurements already presented

⃣ Run until End October :: collect 25fb$^{-1}$
  😊 interesting $\sin(2\beta)$ measurement
  😊 and much more
  ...... in a few months