CP-Violation in B-Decays: Status and Prospects of BaBar

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LAL Orsay
for the BaBar Collaboration
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Orbis Scientiae
Fort Lauderdale

BaBar
- SVT
- DCH
- DIRC
- EMC
- IFR

Physics
- CP-Violation
- Perspective

PEP II
- Performance
- Perspective
Introduction

Universe is made out of matter

Where is the antimatter?

Maybe it decayed?

Idea:

Lock for differences in the decay rate of
matter and antimatter

Standard Model:

Large CP-Violation in B-System expected *

* Even if the SM is confirmed it can not account for the seen asymmetry
The CKM Matrix

CKM Matrix (Wolfenstein Parameterization):

\[ V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \]

Complex phase in \( V_{ub} \), \( V_{td} \)

\( \lambda = V_{us} = 0.2205 \pm 0.0018 \quad A = V_{cb}/\lambda^2 = 0.83 \pm 0.06 \)

Unitarity: \[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \]
Unitary Triangle

Today measurement of $\sin^2\beta$

But over the long run: Overconstrain this triangle to verify or falsify the standard model
Non B-CP violating $\rho$ and $\eta$ constraints

$|\varepsilon_K|$ from CP violation in the neutral Kaon system

$|V_{ub}/V_{cb}|$ from $B \rightarrow u\ell\nu$

$\Delta m_{B_d}$ from $B_d$ mixing

$\Delta m_{B_s}$ from $B_s$ mixing
CP Violation in $B^0 \rightarrow J/\psi K^0_S$

Unmixed Decay

Mixed Decay $B^0$

- Count number of $B^0/B^0 \rightarrow J/\psi K^0_S$ Decays
- Tag the flavor ($B^0$ or $B^0$ decay)
The Golden Decay: $B^0 \to J/\psi K^0_s$

The charge of the tagging particles determines the flavor of the $B$ Mesons.
SLAC/LBL/LLNL
SLAC-Based B Factory:
PEP-II and BaBAR

Both Rings Housed in Current PEP Tunnel
PEP II Status and Perspective

• PEP II had first collisions May 26 1999
• Since then all major design goals were achieved
  • Peak luminosity $3.1 \times 10^{33}$
  • Daily delivered luminosity $> 150 \text{ pb}^{-1}$
  • Weekly luminosity $> 800 \text{ pb}^{-1}$
• PEP II delivered 25 fb$^{-1}$ in 1999 and 2000
• BaBar recorded nearly 24 fb$^{-1}$
• Now in Winter shutdown until end of January 2001
• 40 fb$^{-1}$ in 2001, 80 fb$^{-1}$ in 2002, 110 fb$^{-1}$ in 2003
BaBar Daily Recorded Luminosity

Date

Luminosity (pb⁻¹)

BaBar Recorded luminosity - 1999 + 2000

PEP II Delivered Luminosity
Total Recorded Luminosity
Off-peak Recorded Luminosity

9+1 fb⁻¹ used for this analysis

PEP dev=25.3/fb, BaBar log=23.6/fb
The BaBar Detector

IFR
Magnet 1.5T
DIRC
DCH
ECAL
SVT

DIRC PhotoTubes
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]
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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

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, 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
Silicon Vertex Tracker (SVT)

- 5 Layer double sided AC-coupled silicon detector
- Radiation hard readout electronics
- Up to 98% hit reconstruction efficiency
- Hit resolution better than 20 micron
- Capable of stand alone tracking (needed for low momentum tracks)
Drift Chamber (DCH)

40 Layers

Hit Res. 100-200 μm

Average of 125 μm better than design (140 μm)
dE/dx in DCH and SVT

DCH

SVT

σ = 15%

Nearly at Design
DIRC
Detection of Internally Reflected Cherenkov Light
- On average more than 30 photons per track
- Greater than $3\sigma$ K-$\pi$ separation up to 3.3 GeV
- $\Theta_C$-Resolution $\sim$ 2.55 mrad

Right: Cherenkov angle for pions and kaons from $D \rightarrow K\pi$
Electromagnetic Calorimeter (EMC)

- ~6500 CsI(Tl) crystals
- ~18 $X_0$
- Readout by PIN diodes inside of magnet

Typical electron identification efficiency $> 90\%$ (p $> 1$ GeV)

Pion fake rate $< 0.15\%$

BaBar

- $\pi^0$-mass = 135.1 MeV
- $\pi^0$-width = 6.9 MeV
Muon Chambers
(Instrumented Flux Return IFR)

Iron Plates 2-10 cm (= 65 cm)

Up to 21 Layers of RPCs
(Resistive Plate Chambers)

2300 m² of Detectors operated at 8keV
Measuring Space Points

RPC efficiency is (only) around 80%
tendency down (1% per month)
Overview of the Analysis

Reconstruct the $B$ decays to $CP$ eigenstates and tag the flavor of the other $B$ decay

Select $B_{tag}$ events using, primarily, leptons and $K$'s from $B$ hadronic decays & determine $B$ flavor

Select $B_{CP}$ events ($B^0 \rightarrow J/\Psi K_{s}^0$, etc.)

Measure the mistag fractions $w_i$ and determine the dilutions $D_i = 1 - 2w_i$
Measure $\Delta z$ between $B_{CP}$ and $B_{tag}$ to determine the signed time difference $\Delta t$ between the decays.

Determine the resolution function for $\Delta z$

$$R(D t; \hat{a}) = \sum_{i=1}^{i=2} f_i \exp(- (D t - d_i)^2/2 s_i^2)$$

$$F_{\pm}(\Delta t; \Gamma, \Delta m_d, D \sin 2\beta, \hat{a}) = f_{\pm}(\Delta t; \Gamma, \Delta m_d, D \sin 2\beta) \otimes R(\Delta t; \hat{a})$$

$$A_{CP}(\Delta t) = \frac{F_+(\Delta t) - F_-(\Delta t)}{F_+(\Delta t) + F_-(\Delta t)} \propto D \sin 2\beta \times \sin \Delta m_d \Delta t$$
**J/Ψ (and K⁰_s) Reconstruction**

\[ \text{J/Ψ → e}^+\text{e}^- \quad \text{BABAR} \]

Events / 0.01 GeV/c²

\[ M(\text{e}^+\text{e}^-) \text{ (GeV/c}^2\text{)} \]

\[ 2.6 \quad 2.7 \quad 2.8 \quad 2.9 \quad 3.0 \quad 3.1 \quad 3.2 \quad 3.3 \quad 3.4 \quad 3.5 \]

\[ 0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \]

\[ \text{J/Ψ → μ}^+\text{μ}^- \quad \text{BABAR} \]

Events / 0.01 GeV/c²

\[ M(\text{μ}^+\text{μ}^-) \text{ (GeV/c}^2\text{)} \]

\[ 2.6 \quad 2.7 \quad 2.8 \quad 2.9 \quad 3.0 \quad 3.1 \quad 3.2 \quad 3.3 \quad 3.4 \quad 3.5 \]

\[ 0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \]

\[ \pi^+\pi^- \quad \text{K}^0_s \quad \pi^0\pi^0 \]
The B -- CP Sample

J/ψ K_s (K_s → π^+ π^-)
124±12 events
purity 96%

J/ψ K_s (K_s → π^0 π^0)
18±4 events
purity 91%

Ψ(2S) K_s
27±6 events
purity 93%
A fully reconstructed Event

\[
\begin{align*}
\bar{B}^0 & \rightarrow D^{*+}\pi^- \\
B^0 & \rightarrow \psi(2S)K_s^0 \\
D^{*+} & \rightarrow D^0\pi^+ \\
D^0 & \rightarrow K^-\pi^+ \\
\psi(2S) & \rightarrow \mu^+\mu^- \\
K_s^0 & \rightarrow \pi^+\pi^- 
\end{align*}
\]
**Exclusive B Reconstruction**

Samples of exclusively reconstructed $B_0$ mesons are used to measure mistag fraction $B_{TAG}$ vertex resolution and $\Delta_{md}$

<table>
<thead>
<tr>
<th>Final State</th>
<th>Yield</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{*-}\pi^+$</td>
<td>622 ± 27</td>
<td>90</td>
</tr>
<tr>
<td>$D^{*-}\rho^+$</td>
<td>419 ± 25</td>
<td>84</td>
</tr>
<tr>
<td>$D^{*-}a_1^+$</td>
<td>239 ± 19</td>
<td>79</td>
</tr>
<tr>
<td>$D^-\pi^+$</td>
<td>630 ± 26</td>
<td>90</td>
</tr>
<tr>
<td>$D^-\rho^+$</td>
<td>315 ± 20</td>
<td>84</td>
</tr>
<tr>
<td>$D^-a_1^+$</td>
<td>225 ± 20</td>
<td>74</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2438 ± 57</td>
<td>85</td>
</tr>
<tr>
<td>$\bar{D}^0\pi^+$</td>
<td>1755 ± 47</td>
<td>88</td>
</tr>
<tr>
<td>$\bar{D}^{*0}\pi^+$</td>
<td>543 ± 27</td>
<td>89</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2293 ± 54</td>
<td>88</td>
</tr>
<tr>
<td>$D^{*-}\ell^+\nu$</td>
<td>7517 ± 104</td>
<td>84</td>
</tr>
</tbody>
</table>
Particle Id and Fake Rate

Electrons

Muons

Kaons

\[ p_{\text{lab}} \text{ [GeV/c]} \]

efficiency

mis-identification

For \( 17^\circ < \theta < 155^\circ \)

December 15th 2000

Carsten Hast, LAL Orsay

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Flavor Tagging

All tracks which are not used for the reconstruction of $B_{CP}$ are used for tagging.

The flavor of $B_{TAG}$ is determined in 5 categories:

1./2. Lepton tag: Electron or Muon with $p^* > 1.1$ GeV

3. Kaon tag if $\Sigma Q_K$ not equals 0

4./5. Two neural network categories, NT1 and NT2 combining information from lepton-, kaon-, pion-, identification, fastest particle in the event, and slow pions from $D^*$
Fully Reconstructed and Tagged Hadronic B Mesons

**B**a**B**a**R**

*Lepton Tag*

**B**a**B**a**R**

*Kaon Tag*

**B**a**B**a**R**

*NT1 Tag*

**B**a**B**a**R**

*NT2 Tag*
Mistag fraction and $\Delta m_d$ are measured simultaneously in a fit to the $\Delta t$ distribution of the hadronic events
Results of Combined Tagging and Mixing Analysis

$\Delta m_d = 0.512 \pm 0.017\text{(stat)} \pm 0.022\text{(syst)} \text{ ps}^{-1}$

<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 ± 0.3</td>
<td>16.7 ± 2.2 ± 2.0</td>
<td>5.2 ± 0.2</td>
</tr>
<tr>
<td>NT2</td>
<td>16.6 ± 0.3</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>

$Q = e_{\text{tag}}(1-2\omega)^2 = e_{\text{tag}} D^2$
\[
\sin 2\beta = 0.12 \pm 0.37 \text{ (stat)} \pm 0.09 \text{ (syst)}
\]
## Systematic Uncertainties for $\sin 2\beta$

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty on $\sin 2\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{\mu}^{0}$</td>
<td>0.012</td>
</tr>
<tr>
<td>$\Delta m_d$</td>
<td>0.015</td>
</tr>
<tr>
<td>$\Delta z$ resolution for $CP$ sample</td>
<td>0.019</td>
</tr>
<tr>
<td>Time resolution bias for $CP$ sample</td>
<td>0.047</td>
</tr>
<tr>
<td>Measurement of mistag fraction</td>
<td>0.059</td>
</tr>
<tr>
<td>Different mistag fraction for $CP$ and non $CP$ samples</td>
<td>0.050</td>
</tr>
<tr>
<td>Different mistag fractions for $B^0$ and $\bar{B}^0$</td>
<td>0.005</td>
</tr>
<tr>
<td>Background in $CP$ sample</td>
<td>0.015</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.091</td>
</tr>
</tbody>
</table>

### Sample | Apparent $CP$ asymmetry
---|-----------------|
Hadronic $B^+$ decays | $0.03 \pm 0.07$ |
Hadronic $B^0$ decays | $-0.01 \pm 0.08$ |
$J/\psi K^+$ | $0.13 \pm 0.14$ |
$J/\psi K^{*0}$ ($K^{*0} \rightarrow K^+\pi^-$) | $0.49 \pm 0.26$ |
Constraints on the Unitary Triangle

Experimental Input

<table>
<thead>
<tr>
<th>measurement</th>
<th>central value</th>
<th>exp. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}/V_{cd}</td>
<td>$</td>
</tr>
<tr>
<td>$\Delta m_{B_d}$ (ps$^{-1}$)</td>
<td>.472</td>
<td>.017</td>
</tr>
<tr>
<td>$\Delta m_{B_s}$ from $A$ (Moriond 2000)</td>
<td>$\sigma_A$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\epsilon_K</td>
<td>(10^{-3})$</td>
</tr>
</tbody>
</table>

Theoretical Input

<table>
<thead>
<tr>
<th>Theoretical est.</th>
<th>lower bound</th>
<th>higher bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; V_{ub}/V_{cb} &gt;$</td>
<td>0.070</td>
<td>0.100</td>
</tr>
<tr>
<td>$f_{B_d} \sqrt{B_{B_d}}$</td>
<td>0.185</td>
<td>0.255</td>
</tr>
<tr>
<td>$\xi_s^2$</td>
<td>1.14</td>
<td>1.46</td>
</tr>
<tr>
<td>$B_K$</td>
<td>0.72</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Conclusions and Future Plans

- We have measured with 9 fb$^{-1}$ of data
  \[ \sin 2\beta = 0.12 \pm 0.37 \text{ (stat)} \pm 0.09 \text{ (syst)} \]
- Currently we are analyzing our 24 fb$^{-1}$ of recorded data
- More CP violating decays $B^0 \rightarrow J/\Psi K_L$ and $B^0 \rightarrow J/\Psi K^{*0}$ will be added
- We expect a statistical error of 0.25 ready to report in March 2001
- In 2001 we hope to record another 40 fb$^{-1}$

BaBar and PEP II had an incredible good start
Now we have to keep up for the long run to precisely measure the parameters of the CKM Matrix