The BaBar sin22β Measurement

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HF+CP Violation Workshop,
Durham, 19/9/00
Outline

- The BaBar detector
- CP Violation and the UT
- Measuring CP Violation
- Selection of CP events
- Accounting for $\Delta z$ resolution
- B-Tagging and mistag rates
- Measurement of CP-violating asymmetries
- Conclusion
PEP-II and BaBar

- First $e^+e^-$ collisions in Summer 1998
- Detector in place Spring 1999 with first events May 26, 1999
- Luminosity as high as $2.28 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (design = 3.0)
- Result based on $\sim 10$ fb$^{-1}$ of data
- $\sim 9$ fb$^{-1}$ at the $\Upsilon(4S)$ ($19 \times 10^6$ B’s)
The BABAR Detector

- Superconducting Coil (1.5T)
- Silicon Vertex Tracker (SVT)
- Drift Chamber (DCH)
- CsI Calorimeter (EMC)
- Instrumented Flux Return (IFR)
- Cherenkov Detector (DIRC)

e⁻ (9 GeV)
e⁺ (3 GeV)
The Wolfenstein parametrization of the CKM matrix

\[
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

where \( \lambda \) and \( A \) are better determined than \( \rho \) and \( \eta \)

The unitarity of the CKM matrix provides six constraints, the most useful of which

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

is called the unitarity triangle:

![Diagram of the unitarity triangle]

The area of the unitarity triangle, the “Jarlskog Invariant”, is proportional to the strength of CP violation in the Standard Model:

\[ J = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin \delta \]
The Y(4S) resonance decays to $B \bar{B}$ pairs in a coherent $L=1$ state. At PEP-II, $E(e^-) = 9$ GeV and $E(e^+) = 3.1$ GeV yielding a boosted $\Upsilon(4S)$ with $\beta \gamma = 0.56$.

The mean decay distance $\Delta z$ between the B decay vertices is $\sim 250$ $\mu$m, allowing determination of the time order of the decays (since $\sigma(\Delta z) \sim 90$ $\mu$m).

Measure the flavour of a $B^0 (\bar{B}^0)$ decay ($B_{\text{tag}}$) at time $t$, then at that time, the flavour of the other $\bar{B}^0 (B^0)$ is known.

Reconstruct second $B^0$ into a $CP$ eigenstate:

$$f_{\pm}(\Delta t; \Gamma, \Delta m_d, D \sin 2\beta) =$$

$$\frac{1}{4} \Gamma e^{-\Gamma |\Delta t|} \left[ 1 \pm D \sin 2\beta \times \sin \Delta m_d \Delta t \right]$$

Where the dilution $D = (1-2w)$ is derived from the measured mistag fraction $w$. 

Measuring CP Violation at the Y(4S)
Overview of the analysis

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

$D_z$

$B_{tag}$ $B_{CP}$

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

Select $B_{CP}$ events ($B^0 \rightarrow J/\psi \ K_S$ ,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 $\Delta z$

$$R(\Delta t; \hat{a}) = \sum_{i=1}^{i=2} \frac{f_i}{\sigma_i \sqrt{2\pi}} \exp\left(-(\Delta t - \delta_i)^2\right) / 2\sigma_i^2$$

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

$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{F}_+(\Delta t) - \mathcal{F}_-(\Delta t)}{\mathcal{F}_+(\Delta t) + \mathcal{F}_-(\Delta t)} \propto \mathcal{D} \sin 2\beta \times \sin \Delta m_d \Delta t$$
The $B_{CP}$ sample

$J/\psi K_S (K_S \rightarrow \pi^+ \pi^-)$
124±12 events
purity 96%

$J/\psi K_S (K_S \rightarrow \pi^0 \pi^0)$
18±4 events
purity 91%

$\Psi(2S) K_S$
27±6 events
purity 93%
The resolution function for $\Delta t$

The time resolution is dominated by the $z$ resolution of the tagging vertex.

The vertex resolution function is well-described by a five-parameter sum of two gaussians:

$$
\mathcal{R}(\Delta t; \hat{\alpha}) = \sum_{i=1}^{i=2} \frac{f_i}{\sigma_i \sqrt{2\pi}} \exp\left(-\frac{(\Delta t - \delta_i)^2}{2\sigma_i^2}\right)
$$

In the likelihood fits, we use event-by-event time resolution errors. We introduce two scale factors $S_1$ and $S_2$:

$$
\sigma_i = S_i \sigma_{\Delta t}
$$

To account for $\sim 1\%$ of events with very large $\Delta z$, a third gaussian with a fixed width of 8ps, is included.

The parameters extracted from the fit are:

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_1$ (ps)</td>
<td>$-0.20 \pm 0.06$</td>
<td>from fit</td>
</tr>
<tr>
<td>$S_1$</td>
<td>$1.33 \pm 0.14$</td>
<td>from fit</td>
</tr>
<tr>
<td>$f_w$ (%)</td>
<td>$1.6 \pm 0.6$</td>
<td>from fit</td>
</tr>
<tr>
<td>$f_1$ (%)</td>
<td>$75$</td>
<td>fixed</td>
</tr>
<tr>
<td>$\delta_2$ (ps)</td>
<td>$0$</td>
<td>fixed</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$2.1$</td>
<td>fixed</td>
</tr>
</tbody>
</table>
**B^0 Decay Sample for w_i, Δm_d and Cross-checks**

**Hadronic sample**

\[ B^{-} \to D^{(*)0} \pi^{-}, J/\Psi K^{-}, \Psi(2S) K^{-} \]

2577\pm59

Purity \sim 86\%

**Semileptonic sample**

\[ B^0 \to D^{(*)} \pi^+, D^{(*)} \rho^+, D^{(*)} a_1^+, J/\Psi K^*0 \]

**B^0 -> D^* - l^+ \nu_l**

7517\pm104

Purity \sim 84\%
Measurement of mistag fractions & $\Delta m_d$

- Fully reconstruct one $B^0$, $B_{\text{rec}}$ in a flavour eigenstate mode
- Apply flavor-tagging algorithms to the rest of the event, which constitutes the potential $B_{\text{tag}}$
- Tagging categories:
  - Electron
  - Muon
  - Kaon
  - NT1
  - NT2
  } Lepton

  } Neural network

- Classify events as mixed or unmixed, depending on whether the $B_{\text{tag}}$ has the same or opposite flavour as the $B_{\text{rec}}$
Particle ID and mis-ID

**Electrons**

- $20^\circ < \theta < 140^\circ$
- $0.5 \text{ GeV/c} < p_{\text{lab}} < 4.5 \text{ GeV/c}$

**Muons**

- For $17^\circ < \varphi < 155^\circ$

**Kaons**

- $1 < p_{\text{lab}} (\text{GeV/c}) < 3$
Neural Net Tagging

For events not selected in lepton or kaon categories
Time-dependent measurement of $w_i$ & $\Delta m_d$

$W_i$ from small $\Delta t$

$\Delta m$ from oscillation frequency

Hadronic sample

Check: single-bin (time-integrated)

$$\chi_i = \chi_d + (1 - 2\chi_d)w_i$$

where

$$\chi_d = \frac{x_d^2}{2(1 + x_d^2)}$$,
$$x_d = \frac{\Delta m_d}{\Gamma}$$
$\Delta m_d$ from the tag/mix likelihood fit

**Hadronic decays**

$\Delta m_d = 0.516 \pm 0.031$ (stat) 
$\pm 0.018$ (syst) $\bar{\nu}$ ps$^{-1}$

**Semileptonic decays**

$\Delta m_d = 0.508 \pm 0.020$ (stat) 
$\pm 0.022$ (syst) $\bar{\nu}$ ps$^{-1}$

**Combined result**

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

[PDG: $\Delta m_d = 0.472 \pm 0.017$ $\bar{\nu}$ ps$^{-1}$]
Results of the tag/mix likelihood fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>hadronic</th>
<th>semileptonic</th>
<th>hadronic</th>
<th>semileptonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_d$ [h ps$^{-1}$]</td>
<td>0.516 ± 0.031</td>
<td>0.508 ± 0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w$(Lepton)</td>
<td>0.116 ± 0.032</td>
<td>0.084 ± 0.020</td>
<td>0.136</td>
<td>0.133</td>
</tr>
<tr>
<td>$w$(Kaon)</td>
<td>0.196 ± 0.021</td>
<td>0.199 ± 0.016</td>
<td>0.064</td>
<td>0.210 ± 0.028</td>
</tr>
<tr>
<td>$w$(NT1)</td>
<td>0.135 ± 0.035</td>
<td>0.210 ± 0.028</td>
<td>0.023</td>
<td>0.066</td>
</tr>
<tr>
<td>$w$(NT2)</td>
<td>0.314 ± 0.037</td>
<td>0.361 ± 0.025</td>
<td>0.023</td>
<td>0.013</td>
</tr>
<tr>
<td>scale$_{\text{core, sig}}$</td>
<td>1.33 ± 0.13</td>
<td>1.32 ± 0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta_{\text{core, sig [ps]}}$</td>
<td>−0.20 ± 0.07</td>
<td>−0.25 ± 0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{\text{outlier}}$</td>
<td>0.016 ± 0.006</td>
<td>0.000 ± 0.002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\sum Q_i = 0.285$ \hspace{2cm} $\sum Q_i = 0.283$
**Dilepton Mixing: Results**

7.7 fb\(^{-1}\) on-resonance  
1.1 fb\(^{-1}\) off-resonance

Dilepton sub-sample enriched in \(B^0\) with partial reconstruction of \(B^0 \rightarrow D^* \ell \nu\)

\[
\Delta m_d = (0.507 \pm 0.015\,\text{stat} \pm 0.022\,\text{syst}) \, \text{h ps}^{-1}
\]

[PDG: \(\Delta m_d = (0.472 \pm 0.017) \, \text{h ps}^{-1}\)]

Very Preliminary
The sin$2\beta$ analysis was done blind to eliminate experimenters’ bias

- The amplitude in the asymmetry $A_{CP}(\Delta t)$ was hidden by arbitrarily flipping its sign and by adding an arbitrary offset
- The $CP$ asymmetry in the $\Delta t$ distribution was hidden by multiplying $\Delta t$ by the sign of the tag and by adding an arbitrary offset

Allows systematic studies of tagging, vertex resolution and their correlations to be done while keeping the value of sin$2\beta$ hidden
Extracting $\sin 2\beta$

- The $\Delta t$ distribution of the tagged $CP$ eigenstate decays, which is analyzed using maximum likelihood to extract the asymmetry $A_{CP}(\Delta t)$

$B^0$ and $\bar{B}^0$ tags

![Graph showing $B^0$ and $\bar{B}^0$ distributions vs $\Delta t$ (ps)]
Extracting $\sin 2\beta$

Log likelihood function

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

$\chi^2$ for likelihood fit to binned data = 9.2 for 7 dof

$P (L < L_{\text{meas}}) = 20\%$

<table>
<thead>
<tr>
<th>sample</th>
<th>$\sin 2\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CP$ sample</td>
<td>$0.12 \pm 0.37$</td>
</tr>
<tr>
<td>$J/\psi K_S^0 (K_S^0 \rightarrow \pi^+\pi^-)$ events</td>
<td>$-0.10 \pm 0.42$</td>
</tr>
<tr>
<td>other $CP$ events</td>
<td>$0.87 \pm 0.81$</td>
</tr>
<tr>
<td>Lepton</td>
<td>$1.6 \pm 1.0$</td>
</tr>
<tr>
<td>Kaon</td>
<td>$0.14 \pm 0.47$</td>
</tr>
<tr>
<td>MT1</td>
<td>$-0.59 \pm 0.87$</td>
</tr>
<tr>
<td>MT2</td>
<td>$-0.96 \pm 1.30$</td>
</tr>
</tbody>
</table>
Study of Statistical Error

Toy Monte Carlo of 120 event experiments:

\[ \mu = 0.32 \]
\[ \sigma = 0.03 \]

\[ P(\text{Err} > \text{Err}_{\text{meas}}) = 5\% \]

CP asymmetry of channels that should have none

<table>
<thead>
<tr>
<th>Sample</th>
<th>Apparent CP asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadronic charged</td>
<td>0.03 ± 0.07</td>
</tr>
<tr>
<td>hadronic neutral</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>
Fit including direct $CP$ violation

\[ A_{CP} = \frac{2D \sin 2\beta \sin \Delta m_d \Delta t + (1 - |\lambda_{CP}|^2) \cos \Delta m_d \Delta t}{(1 + |\lambda_{CP}|^2)} \]

\[ \frac{2}{1 + |\lambda_{CP}|^2} \sin 2\beta = 0.12 \pm 0.37 \quad \frac{1 - |\lambda_{CP}|^2}{1 + |\lambda_{CP}|^2} = 0.26 \pm 0.19 \]
Systematic uncertainties

Compute fractional systematic errors using the measured value of the asymmetry increased by $1\sigma$. Different contributions are added in quadrature.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty on $\sin 2\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{B^0}$</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>
Constraints on the Unitarity Triangle

The set of ellipses represents the allowed range of \((\bar{\rho}, \bar{\eta})\) based on our knowledge of the magnitudes of CKM matrix elements, for a set of typical values of model-dependent theoretical parameters:

### Experimental inputs

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

### Theoretical inputs

<table>
<thead>
<tr>
<th>Theoretical est.</th>
<th>lower bound</th>
<th>higher bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{\Lambda_{\text{QCD}}}{\Lambda})</td>
<td>0.070</td>
<td>0.300</td>
</tr>
<tr>
<td>(f_{B_d}/B_{B_d})</td>
<td>0.185</td>
<td>0.255</td>
</tr>
<tr>
<td>(\epsilon^\prime_\mu)</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>

\(\sin 2\beta = 0.12 \pm 0.37 \pm 0.09\) is NOT included in the fits
Summary and Conclusions

- We have reconstructed and tagged 120 $B^0$ decays to CP eigenstates from 10 fb$^{-1}$ of data (~9 fb$^{-1}$ on-peak and ~1 fb$^{-1}$ off-peak):

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

- The current PEP-II run will continue until the end of October producing ~25 fb$^{-1}$ in total.

- The next value of $\sin 2\beta$ will be even more interesting!

- We expect $\sigma(\sin 2\beta) \sim 0.2$ by the winter conferences.
Current $\sin^2 \beta$ World Values

- **BaBar** (
  \[0.45^{+0.43 + 0.07}_{-0.44 - 0.09}\])
- **Belle** (*PRELIMINARY*),
  \[0.86^{+0.83}_{-1.05} \pm 0.20\]
- **CDF**, \[0.79 \pm 0.39 \pm 0.1\]
- **ALEPH** (*PRELIMINARY*),
  \[0.12^{+0.37 + 0.0}_{-0.0}\]
- **OPAL**, \[3.20^{+1.8}_{-2.0} \pm 0.5\]