Combined Measurement of the $CP$ Violating Angle $\beta$
by the BaBar and Belle Experiments

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**CP Violation in the Standard Model**

- Within the Standard Model (SM), *CP* violation is accounted for by a single weak phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix:

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

- CKM matrix describes weak coupling constants between quarks

- Under the Wolfenstein parameterization, we approximate the CKM matrix as:

\[
V_{\text{CKM}} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda \\
-\lambda & 1 - \lambda^2/2 \\
A\lambda^3(1 - \rho - i\eta) & A\lambda^2
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

where \(\lambda \approx 0.22\) and \(A \approx 0.83\)

- We have *CP* violation if \(\eta \neq 0\)
Unitarity of the CKM matrix \((V^\dagger V = I)\) leads to 6 independent constraints on sums of cross-terms \((V_{q_1 q_2} V_{q_3 q_4}^*)\).

These constraints can be represented as triangles in the complex plane.

All but two are severely elongated:

\[
V_{td} V_{ud}^* + V_{ts} V_{us}^* + V_{tb} V_{ub}^* = 0
\]

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

The second of these relates to quark transitions involved in \(B_d\) mixing.

The Unitarity Triangle

Neutral \(B\) Meson Mixing Diagram
Dividing each side of the triangle by the best-known one ($V_{cd}V_{cb}^*$), we get:

\[
\begin{align*}
\alpha &= \phi_2 = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \\
\beta &= \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \\
\gamma &= \phi_3 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)
\end{align*}
\]

By measuring 3 angles and 2 sides, one can overconstrain the apex of the unitarity triangle.

The Unitarity triangle
Unitarity Triangle Constraints

Constraints on the Unitarity Triangle

Global Fit Result
Traditionally, time-dependent CP violation measurements in the “golden mode” \(B^0 \rightarrow J/\psi K_S^0\) and other decays mediated by \(b \rightarrow \bar{c}c\bar{s}\) transitions have been used to extract \(\sin 2\beta\) and thus \(\beta\).

However, measurements of \(\sin 2\beta\) suffer from a trigonometric 2-fold ambiguity between \(2\beta\) and \(\pi - 2\beta\):

This ambiguity can be resolved by measuring \(\cos 2\beta\).

So far, there has been no conclusive determination of the sign of \(\cos 2\beta\) (Previous measurements had large uncertainties)
The $B$ Factories

- This analysis was performed using data collected by both the BaBar and Belle experiments.

- Designed as “$B$ factories” operating primarily at the $Y(4S)$ resonance ($\sqrt{s} \approx 10.58$ GeV/c$^2$)

- 1.24 billion $B\bar{B}$ pairs recorded
The $B$ Factories - Luminosity

- Integrated Luminosity of the $B$ Factories:

\begin{itemize}
  \item Also operated at other $\Upsilon$ resonances as well as “Off resonance” ($\approx 40$ MeV/$c^2$ below the $\Upsilon(4S)$)
\end{itemize}

- > 1 $ab^{-1}$
  - On resonance:
    \begin{itemize}
      \item $\Upsilon(5S)$: 121 $fb^{-1}$
      \item $\Upsilon(4S)$: 711 $fb^{-1}$
      \item $\Upsilon(3S)$: 3 $fb^{-1}$
      \item $\Upsilon(2S)$: 25 $fb^{-1}$
      \item $\Upsilon(1S)$: 6 $fb^{-1}$
    \end{itemize}
  - Off reson./scan:
    \begin{itemize}
      \item $\approx 100$ $fb^{-1}$
    \end{itemize}

- $\sim 550$ $fb^{-1}$
  - On resonance:
    \begin{itemize}
      \item $\Upsilon(4S)$: 433 $fb^{-1}$
      \item $\Upsilon(3S)$: 30 $fb^{-1}$
      \item $\Upsilon(2S)$: 14 $fb^{-1}$
    \end{itemize}
  - Off resonance:
    \begin{itemize}
      \item $\sim 54$ $fb^{-1}$
    \end{itemize}
A key feature of the B factories is that they used asymmetric energy electron and positron beams

- 9 GeV electrons and 3.1 GeV positrons at BaBar
- 8 GeV electrons and 3.5 GeV positrons at Belle

The asymmetric energy beams caused the $e^+e^-$ CM to be boosted in the lab frame

- $\beta\gamma \approx 0.56$ at BaBar and $\beta\gamma \approx 0.43$ at Belle
The $B$ Factories – Measuring $\Delta t$

- Due to the boost, the distance between the $B$ decay vertices can be used to calculate the time between $B$ and $\bar{B}$ decays.

- Fully reconstruct the decay of one $B$ meson ($B_{\text{rec}}^0$) and use the decay of the other $B$ meson ($B_{\text{tag}}^0$) to determine its flavor.

- The $B$ mesons are produced as entangled pairs and evolve coherently, so at the moment the first $B$ decays, the other $B$ is the opposite flavor.

- Define $\Delta t \equiv t_{\text{rec}} - t_{\text{tag}}$ as the time between the decays of the two mesons (based on their separation $\Delta z$ along the boost direction).

\[ \Delta z = \gamma \beta c \Delta t \]
Time-Dependent DP Analysis

- We use a time-dependent Dalitz Plot analysis to extract both $\sin 2\beta$ and $\cos 2\beta$

- Signal mode is $B^0 \to D^{(*)} h^0$ where $D^0 \to K^0_S \pi^+ \pi^-$

- Our signal decay rate is proportional to:

$$
\frac{e^{-|\Delta t|}}{2} \left\{ \left| \mathcal{A}_{D^0} \right|^2 + \left| \mathcal{A}_{D^0}^* \right|^2 \\
- q \left( \left| \mathcal{A}_{D^0} \right|^2 - \left| \mathcal{A}_{D^0}^* \right|^2 \right) \cos(\Delta m_d \Delta t) \\
+ 2q\eta_{h^0} (-1)^L \text{Im} \left( e^{-2i\beta} \mathcal{A}_{D^0} \mathcal{A}_{D^0}^* \right) \sin(\Delta m_d \Delta t) \right\}
$$

where the $\beta$-dependence in the last term can be rewritten as:

$$
\text{Im} \left( e^{-2i\beta} \mathcal{A}_{D^0} \mathcal{A}_{D^0}^* \right) = \text{Im} \left( \mathcal{A}_{D^0} \mathcal{A}_{D^0}^* \right) \cos(2\beta) - \text{Re} \left( \mathcal{A}_{D^0} \mathcal{A}_{D^0}^* \right) \sin(2\beta)
$$

- The interference between $D^0$ and $\bar{D}^0$ and the variations across the DP allow the extraction of the $CP$-violating weak phase $2\beta$

$$
|M_{B^0}(\Delta t)|^2 = \left| \cos(\Delta m \Delta t/2) - ie^{+2i\beta} \times \sin(\Delta m \Delta t/2) \right|^2
$$

$$
|M_{\bar{B}^0}(\Delta t)|^2 = \left| \cos(\Delta m \Delta t/2) - ie^{-2i\beta} \times \sin(\Delta m \Delta t/2) \right|^2
$$
The kinematics of a spin-0 particle decaying into three spin-0 particles are fully described by two parameters.

Typically, we use the squared invariant masses of two pairs of final state particles.

This allows easy determination of intermediate state masses, and phase space decays are uniform in these variables.

Parameterization referred to as “Dalitz Plot” (DP).

Example $D^0/\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ DP.
Analysis Steps

• (1) Perform a 2D fit to Belle $c\bar{c}$ data to obtain yields for the signal and background categories

• (2) Extract the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz model from the high-statistics Belle $c\bar{c}$ data

• (3) Perform a 3D fit to $B^0 \rightarrow D^{(*)} h^0$ events to extract yields for the signal and background categories

• (4) Perform the final time-dependent Dalitz plot fit to $B^0 \rightarrow D^{(*)} h^0$ events, using the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz plot model obtained earlier
We perform time-integrated analysis of the Belle $c\bar{c}$ data to extract sig+bkg yields for the DP model fit.

Signal (CAT 1) is correctly reconstructed $D^{*+} \rightarrow D^0 \pi^+_S$ with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays.

Background is divided into 4 categories:

- **CAT 2**: True $D$, random soft pion
- **CAT 3**: $D^0 \rightarrow K_S^0 K_S^0$ and $4\pi$
- **CAT 4**: True $\pi^+_S$ mesons, but incorrect $D$
- **CAT 5**: Remaining combinatorial bkg.

We extract the yields in a 2D unbinned maximum likelihood fit to the $M_{D^0}$ vs. $\Delta M$ (the $D^{*+} - D^0$ mass difference).

<table>
<thead>
<tr>
<th>Component</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1: Signal</td>
<td>1217329 ± 2015</td>
</tr>
<tr>
<td>Category 2: True $D$, random soft pion</td>
<td>61330 ± 1282</td>
</tr>
<tr>
<td>Category 3: $D^0 \rightarrow K_S^0 K_S^0$ and $4\pi$</td>
<td>3438 (fixed to MC expectation)</td>
</tr>
<tr>
<td>Category 4: True $\pi^+_S$ mesons, but incorrect $D$</td>
<td>249701 ± 10017</td>
</tr>
<tr>
<td>Category 5: Remaining combinatorial bkg.</td>
<td>270990 ± 9077</td>
</tr>
</tbody>
</table>
In order to measure $\cos 2\beta$ using $B^0 \rightarrow D^{(*)} h^0$ decays, the Dalitz model of the $D$ decay needs to be known.

Extract the $D^0 \rightarrow K^0_S \pi^+ \pi^-$ Dalitz model from Belle $c\bar{c}$ data.

With 924 fb$^{-1}$ of Belle data collected at or near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, we do not need to include BaBar data for this part of the analysis.

Decay Amplitude Parameterization:

$$\mathcal{A}(M_{K^0_S \pi^-}, M_{K^0_S \pi^+}) = \sum a_r e^{i\phi_r} \mathcal{A}_r(M^2_{K^0_S \pi^-}, M^2_{K^0_S \pi^+}) + F_1(M^2_{\pi^+ \pi^-}) + \mathcal{A}_{\pi^- L=0}(M^2_{K^0_S \pi^-}) + \mathcal{A}_{\pi^+ L=0}(M^2_{K^0_S \pi^+})$$

Quasi 2-Body Resonances (Relativistic Breit – Wigner)

$\pi\pi$ S-Wave (K Matrix)

$K\pi$ S-Wave + $K^*_0(1430)$ (LASS Parameterization)

Intermediate resonances:

- Cabibbo-favored: $K^*(892)^-, K^*_2(1430)^-, K^*(1680)^-, K^*(1410)^-$
- Cabibbo-suppressed: $K^*(892)^+, K^*_2(1430)^+, K^*(1410)^+$
- CP eigenstates: $\rho(770)^0, \omega(782), f_2(1270), \rho(1450)^0$
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz Plot Fit Projections

Preliminary

Belle data
Fit projection
Background
Before performing the final time-dependent \( CP \) analysis using \( B^0 \rightarrow D^{(*)0} h^0 \) decays, we must also extract signal and background yields for these modes.

- The specific modes we reconstruct are: \( D^0 \pi^0, D^0 \eta, D^0 \omega, D^{*0} \pi^0, D^{*0} \eta \)

- Similar selection criteria are used for the BaBar and Belle data

- We use a neural network (NN) combining event-shape variables to reject continuum \( e^+ e^- \rightarrow q \bar{q} \)

- Yields are extracted in 3-dimensional maximum likelihood fits to:
  - Modified beam-energy constrained mass (\( M'_{bc} \)):
    \[
    M'_{bc} = \sqrt{E_{beam}^* - \left[ \hat{p}_{D^{(*)}}^* + \hat{p}_{h^0}^* \sqrt{(E_{beam}^* - E_{D^{(*)}}^*)^2 - M_{h^0}^2} \right]^2}
    \]
  - \( \Delta E \)
    \[
    \Delta E = E_B^* - E_{beam}^*
    \]
  - Neural Network Output (NN\(_{out}\))
$B^0 \rightarrow D^{(*)0} h^0$ Yield Fit Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield BABar</th>
<th>Yield Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \bar{D}^0\pi^0$</td>
<td>$469 \pm 31$</td>
<td>$768 \pm 37$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^0\eta$</td>
<td>$220 \pm 22$</td>
<td>$238 \pm 23$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^0\omega$</td>
<td>$219 \pm 21$</td>
<td>$285 \pm 26$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^{*0}\pi^0$</td>
<td>$147 \pm 18$</td>
<td>$182 \pm 19$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^{*0}\eta$</td>
<td>$74 \pm 11$</td>
<td>$94 \pm 13$</td>
</tr>
</tbody>
</table>

All above $B^0 \rightarrow \bar{D}^{(*)0} h^0$ modes $1129 \pm 48$ $1567 \pm 56$

BaBar and Belle Event Signal Yields
\[ B^0 \rightarrow D^{(*)0} h^0 \] Time-Dependent Fit

- Finally, we perform a time-dependent fit to \( B^0 \rightarrow D^{(*)0} h^0 \) events where \( D^0 \rightarrow K_S^0 \pi^+ \pi^- \) in order to simultaneously extract \( \sin 2\beta \) and \( \cos 2\beta \)

- Our final likelihood is a combination of BaBar and Belle likelihoods:

\[
\ln P = \sum_i \ln P_i^{\text{BaBar}} + \sum_j \ln P_j^{\text{Belle}}
\]

- We use a common Dalitz plot model for BaBar and Belle data and fit to the \( \Delta t \) distributions

- The signal decay rate is proportional to:

\[
\frac{-|\Delta t|}{2e^{\tau_{B^0}}} \left\{ \left| A_{D^0} \right|^2 + \left| A_{D^0}^* \right|^2 \right\} - q \left( \left| A_{D^0} \right|^2 - \left| A_{D^0}^* \right|^2 \right) \cos(\Delta m_d \Delta t) + 2q\eta_{h^0} (-1)^L \text{Im} (e^{-2i\beta} A_{D^0} A_{D^0}^*) \sin(\Delta m_d \Delta t) \right\}
\]

where \( \text{Im} (e^{-2i\beta} A_{D^0} A_{D^0}^*) = \text{Im} (A_{D^0} A_{D^0}^*) \cos(2\beta) - \text{Re} (A_{D^0} A_{D^0}^*) \sin(2\beta) \)

- We use separate resolution models and flavor-tagging algorithms for BaBar and Belle
Final Fit Results I

• **Region A:**
  - Predominantly populated by CP eigenstates
  - Interference between direct decays of neutral B mesons, and mixing followed by decays
  - Sinusoidal oscillation in CP asymmetry reflects mixing-induced CP violation governed by weak phase $\beta$

• **Region B:**
  - Predominantly populated by quasi-flavor-specific decays
  - Time evolution exhibits $B_0 - \bar{B}_0$ oscillations governed by the oscillation frequency, $\Delta m_d$

The time-dependent asymmetry exhibits an oscillation pattern proportional to $\cos(\Delta m_d \Delta t)$
Final Fit Results

- Final Fit Results
  
  \[ \sin 2\beta = 0.80 \pm 0.14 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \pm 0.03 \text{ (model)} \]
  
  \[ \cos 2\beta = 0.91 \pm 0.22 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.07 \text{ (model)} \]
  
  \[ \beta = (22.5 \pm 4.4 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.6 \text{ (model)})^\circ \]
  
- Most precise measurement of \(\cos 2\beta\)
  
- First evidence for \(\cos 2\beta > 0\) (3.7\(\sigma\))
  
  - We exclude the second solution \((\pi/2 - \beta = (68.1 \pm 0.7)^\circ)\) at 7.3\(\sigma\) significance, resolving the ambiguity in the apex of the CKM Unitarity Triangle
  
  - We exclude \(\beta = 0\) at 5.1\(\sigma\), and thus observe \(CP\) violation in \(B^0 \rightarrow D^{(*)} h^0\)
Result Comparison

Preliminary
Summary

• We have combined the final BaBar and Belle data samples (an integrated luminosity of more than 1 ab$^{-1}$ collected at the $\Upsilon(4S)$ resonance) and performed a time-dependent Dalitz plot analysis of $B^0 \rightarrow D^{(*)}h^0$ with $D \rightarrow K_S^0\pi^+\pi^-$ decays

• We report the world’s most precise measurement of $\cos 2\beta$

• We obtain the first evidence for $\cos 2\beta > 0$ and exclude the trigonometric multifold solution at 7.3$\sigma$ significance

• Papers have been submitted to PRL and PRD