New CP Violation Results from Combined $\textit{BABAR}+\textit{Belle}$ Measurements

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On behalf of the $\textit{BABAR}$ and Belle Collaborations

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CKM Quark Mixing Matrix

- The quark masses and mixing arise from Yukawa couplings of the fermion fields to the Higgs condensate:

\[ \mathcal{L}_Y = -Y^d_{ij} \bar{Q}_L i \phi d_{Rj} - Y^u_{ij} \bar{Q}_L \epsilon \phi^* u_{Rj} + h.c. \]

- Kobayashi + Maskawa: cannot simultaneously align up- and down-type quarks,

CKM matrix: 3 real parameters + 1 CP violating phase

\[ V_{\text{CKM}} = V^u_L V^{d\dagger}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} e^{-i\beta} & \cdot & \cdot \\ \cdot & 1 & \cdot \\ \cdot & \cdot & e^{-i\gamma} \end{pmatrix} \]

B factoriesBABAR(US) and Belle (Japan):
- Discovery CP violation in the B meson system
- Exploring and constraining the quark flavor structure of the Standard Model
- Experimental confirmation of the Kobayashi-Maskawa theory

The Nobel Prize in Physics 2008
The Unitarity Triangle

- Unitarity requires $V_{td} V_{tb}^* + V_{cd} V_{cb}^* + V_{ud} V_{ub}^* = 0 \rightarrow$ Triangle in the complex plane

$\beta \equiv \phi_1$

- The determination of the angle $\beta$ of the Unitarity Triangle from $\sin(2\beta) \equiv \sin(2\phi_1)$ measurements, for example, using $B^0 \rightarrow J/\psi K_S^0$, leads to a trigonometric ambiguity:

$\beta = 21.9^\circ$ or $\beta = (\pi/2 - 21.9^\circ) = 68.1^\circ$

$\rho$, $\eta$ plane

$B^0 \rightarrow J/\psi K_S^0$

- The ambiguity can be resolved by measuring also $\cos(2\beta)$ in addition to $\sin(2\beta)$.

- $\cos(2\beta)$ is not well known. The current best single experimental uncertainty is $\approx \pm 0.36$. 

[PRD 94 (2016) 052004]
Combined $\text{BaBar} + \text{Belle}$ Analysis of $B^0 \rightarrow D^{(*)} h^0$ decays

- $B^0 \rightarrow D^{(*)} h^0$ with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays enable to extract both $\sin(2\beta)$ and $\cos(2\beta)$.

- The approach is similar to the GGSZ method to extract $\gamma$ from multi-body $B^\pm \rightarrow D K^\pm$.

- Interference between $D^0$ and $\bar{D}^0$, and variations over the Dalitz plot provide access to the CP-violating weak phase $2\beta$.

- Illustration of the B meson decay rate as function of the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz plot:

  \[
  |M_{B^0}(\Delta t)|^2 = \left| \begin{array}{c}
  \times \cos(\Delta m_2 \Delta t/2) - i e^{+2i\beta} \\
  \times \sin(\Delta m_2 \Delta t/2)
  \end{array} \right|^2
  \]

  \[
  |M_{\bar{B}^0}(\Delta t)|^2 = \left| \begin{array}{c}
  \times \cos(\Delta m_2 \Delta t/2) - i e^{-2i\beta} \\
  \times \sin(\Delta m_2 \Delta t/2)
  \end{array} \right|^2
  \]

- If the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz plot amplitude model is known, then both $\sin(2\beta)$ and $\cos(2\beta)$ can be extracted from the time evolution of the B decay.

  [A. Bondar, P. Krokovny, T. Gershon PLB 624 1 (2005)]

→ Perform time-dependent Dalitz analysis combining $\text{BaBar} + \text{Belle}$ data to improve the sensitivity on $\cos(2\beta)$.
Combined $\textit{BABAR}$+Belle analyses to make full use of the about 1.1 $\text{ab}^{-1}$ or $\approx1240 \times 10^6$ $\text{BB}$ collected on the $Y(4S)$.

In a first $\textit{BABAR}$+Belle analysis, we previously demonstrated the feasibility and the advantage of the joint approach [PRL 115, 121604 (2015), presented at La Thuile 2016].
The $\textbf{BaBar}$ and Belle Experiments

**Cherenkov Detector (DIRC)**
- Particle identification
- $\pi K$ separation $> 3.4 \sigma$
- at $p < 3.5$ GeV

**Solenoid 1.5 T**
- Instrumented Flux Return
- Identification of muons and neutral hadrons
- $\mu$ efficiency $> 85%$
- $n$ misid $\sim 4\%$ at $p > 1.5$ GeV

**Electromagnetic Calorimeter**
- 6580 CsI(Tl) crystals
- Electron and photon energy measurement
- $\sigma(E)/E = 1.4\% E^{1/3} \oplus 2.2\%$

**Silicon Vertex Tracker**
- 5 layers of double-sided Si-strip detectors
- Vertex reconstruction, tracking + dE/dx
- Efficiency $\sim 97\%$

**Drift chamber**
- 40 layers, momentum measurement for charged particles and dE/dx
- $\sigma(p)/p_r = 0.13\% \oplus 0.45\%$

**KEKB B-Factory**
- Superconducting magnets

**AERES copper cans (LCSR)**

**TRISTAN tunnel**
- 8 GeV $e^-$

**ToF-Counter**
- Central-Drift-Chamber
  - (small cell + He/C$_2$H$_6$)

**Si-Vertex-Detector**
- (3/4 layers DSSD)

**μ/KL-Detector**
- (14/15 layers RPC+Fe)

**3.5 GeV $e^+$**

**Secondary Solenoid**
- (1.5 T)

**SC-Vertebra (16 X$_0$)**

**NEG-CHerenkov-Counter**
- (n=1.015~1.030)
Principle of Time-dependent Measurements at \textit{BABAR} and Belle

Threshold $B\bar{B}$ production on the $\Upsilon(4S)$:

- Coherent $B^0\bar{B}^0$ mixing
- $B_{\text{rec}}$
- $B_{\text{tag}}$
- Experimental effects due to finite vertex resolution and imperfect tagging are important.
Combined $\mathcal{B}_{\mathcal{B} \Lambda \mathcal{B}}$+Belle Analysis of $B^0 \rightarrow D^{(*)} h^0$ decays

- The $D^0 \rightarrow K^0_S \pi^+ \pi^-$ Dalitz model is directly obtained from flavor-tagged $e^+e^- \rightarrow c\bar{c}$ data.

- Reconstruct $D^{*+} \rightarrow D^0 \pi^+_S$ with $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays.

- The charge of the low-momentum pion $\pi^+_S$ tags the neutral D meson flavor.

- The yield is $(1,217,300 \pm 2,000)$ $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays.

- The purity is 94% in the signal region.
Combined $\text{BaBar} + \text{Belle}$ Analysis of $B^0 \rightarrow D^{(*)} h^0$ decays

- The $D^0 \rightarrow K_{S}^0 \pi^+ \pi^-$ Dalitz plot data distributions from the flavor-tagged $e^+e^- \rightarrow c\bar{c}$ data:

- The $D^0 \rightarrow K_{S}^0 \pi^+ \pi^-$ Dalitz plot is parameterized by the following model:

\[
A_{D^0}(m_+^2, m_-^2) = \sum_{r \neq (K\pi/\pi\pi)_{L=0}} a_r e^{i\phi_r} A_r(m_+^2, m_-^2) + A_{K\pi_{L=0}}(s) + F_1(s)
\]

- The model parameters are estimated by a fit to the Dalitz plot distributions above.
Combined $\textbf{B}_{\text{ABAR}}+\text{Belle}$ Analysis of $\mathbf{B}^{0} \rightarrow \mathbf{D}^{(*)} h^{0}$ decays

Projections of the $\mathbf{D}^{0} \rightarrow \mathbf{K}^{0}_{S} \pi^{+} \pi^{-}$ Dalitz plot fit:

- The Dalitz plot model accounts for 14 intermediate two-body resonances.
- The $\mathbf{K}$-matrix and LASS parameterizations are used to model the $\pi\pi$ and $\mathbf{K}\pi$ S-waves.
- The $\mathbf{D}^{0} \rightarrow \mathbf{K}^{0}_{S} \pi^{+} \pi^{-}$-decay amplitude model extracted from $e^{+}e^{-} \rightarrow c\bar{c}$ data is used to extract $\sin(2\beta)$ and $\cos(2\beta)$ from the $\mathbf{B}^{0}$ decay combining $\textbf{B}_{\text{ABAR}}+\text{Belle}$ data.
Combined $\mathbf{B}_{\mathbf{A}B_{\mathbf{A}R}}$+Belle Analysis of $B^0 \rightarrow D^{(*)} h^0$ decays

- Reconstruct $B^0 \rightarrow D^{(*)} h^0$ with $h^0$ in $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\pi^+\pi^-\pi^0$ and $\omega \rightarrow \pi^+\pi^-\pi^0$

\[D \rightarrow K_S^0 \pi^+\pi^- \text{ and } D^*^0 \rightarrow D\pi^0.\]

- In total, 5 $B^0$ decay modes are reconstructed.
- $e^+e^- \rightarrow q\bar{q}$ ($q \in \{u, d, s, c\}$) continuum background is identified by neural networks.
- Coherent analysis strategy, apply almost same selection on $\mathbf{B}_{\mathbf{A}B_{\mathbf{A}R}}$ and Belle data.
- Extract signal by 3D fit of beam-constr. mass $M'_{bc}$, energy-difference $\Delta E$ and $NN'_{out}$.

$\mathbf{B}_{\mathbf{A}B_{\mathbf{A}R}}$: 1129 ± 48 signal events
Belle: 1567 ± 56 signal events
Combined $\textbf{B}_{\text{BABAR}}+\text{Belle}$ Analysis of $B^0 \to D^{(*)} h^0$ decays

- Perform measurement by maximizing the combined log-likelihood function:

\[
\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\text{BABAR}} + \sum_j \ln \mathcal{P}_j^{\text{Belle}}
\]

- Physics PDFs are convoluted with specific resolution functions:

\[
\mathcal{P}^{\text{Exp.}} = \sum_k f_k \int [P_k(\Delta t') R_k(\Delta t - \Delta t')] d(\Delta t')
\]

- Apply $\text{BABAR}$ and Belle specific resolution models and flavor tagging algorithms.

- Apply common signal model:

\[
P_{\text{sig}}(\Delta t) \propto \left[ |A_{D^0}|^2 + |A_{\bar{D}^0}|^2 \right]
\]

\[
\pm \left( |A_{D^0}|^2 - |A_{\bar{D}^0}|^2 \right) \cos(\Delta m \Delta t)
\]

\[
\pm 2\eta_{h^0} (-1)^L \left[ \text{Im}(A_{D^0}A_{\bar{D}^0}^*) \cos(2\beta) - \text{Re}(A_{D^0}A_{\bar{D}^0}^*) \sin(2\beta) \right] \sin(\Delta m \Delta t)
\]
Combined $B_{\text{BABAR+Bel}} \rightarrow D^{(*)} h^0$ decays

$B^0 \rightarrow [K_\pi^+ \pi^-]^{(le)}_{D^0} h^0$ with $|M_{D^{*0}} - M_{D^+ \pi^-}| < 150 \text{ MeV}/c^2$

$B^0 \rightarrow [K_\pi^+ \pi^-]^{(le)}_{D^0} h^0$ with $|M_{D^{(*)} \pi^0} - M_{D^{(*)} \pi^0}| < 75 \text{ MeV}/c^2$

$B^0_{\text{BABAR+Bel}}$ with 1.1 ab$^{-1}$:

$\sin(2\beta) = 0.80 \pm 0.14 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \pm 0.03 \text{ (model)}$

$\cos(2\beta) = 0.91 \pm 0.22 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.07 \text{ (model)}$

$\beta = (22.5 \pm 4.4 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.6 \text{ (model)})^\circ$
Combined $^{\text{BaBar+BELLE}}$ Analysis of $B^0 \to D^{(*)}h^0$ decays

- First evidence for $\cos(2\beta) > 0$ (3.7$\sigma$)

- Direct exclusion of the 2$^{\text{nd}}$ solution
  \[ \pi/2 - \beta = (68.1 \pm 0.7)^\circ \]
  of the CKM Unitarity Triangle (7.3$\sigma$)
  → Reduction of the trigonometric ambiguity of the CKM Unitarity Triangle

- Exclusion of $\beta = 0^\circ$ (5.1$\sigma$)
  → Observation of CP violation in $B^0 \to D^{(*)}h^0$ decays
Summary

• The $\text{BABAR}$ and Belle experiments recently started performing measurements combining the about 1.1 ab$^{-1}$ collected on the Y(4S), which allows for an unprecedented sensitivity in time-dependent CP violation measurements.

• Results of the new analysis presented:
  - First evidence for $\cos(2\beta) > 0$ at the level of 3.7$\sigma$
  - Exclusion of the 2$^{\text{nd}}$ solution of the CKM Unitarity Triangle
    \[ \pi/2 - \beta = (68.1 \pm 0.7)\degree \text{ at } 7.3\sigma \]
  - Good agreement with $\sin(2\beta)$ from $b \to c\bar{c}s$ and an observation of CP violation at 5.1$\sigma$