Time-Dependent CP violation in B decays at Belle

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On behalf of the Belle collaboration
Outlook

- Introduction
  - Time-Dependent CP violation in B meson system
  - how to measure CPV at B factories
  - The Belle experiment

- Time-dependent CP violation in:
  \[ B^0 \rightarrow \eta' K^0 \]
  \[ B^0 \rightarrow \omega K_S^0 \]
  \[ B^0 \rightarrow K_S^0 \eta \gamma \]

- Measurement of \( B^0 \rightarrow \pi^0 \pi^0 \) branching fraction.
**Time-dependent CP violation**

- Neutral B mesons mix + presence of CPV phase.

Measure the phase by observing the inference pattern of the direct and mixed decay into a common final state.

- Denoting by $B^0(\Delta t)$ a state that was pure $B^0$ at $\Delta t = 0$ (and equiv. for $\bar{B}^0(\Delta t)$) we get:

$$A_{CP}(\Delta t) = \frac{\Gamma(B^0(\Delta t) \to f) - \Gamma(\bar{B}^0(\Delta t) \to f)}{\Gamma(B^0(\Delta t) \to f) + \Gamma(\bar{B}^0(\Delta t) \to f)}$$

$$= A_f \cos \Delta M \Delta t + S_f \sin \Delta M \Delta t$$

**Direct CPV**

$$A_f = \frac{|\lambda_f|^2 - 1}{|\lambda_f|^2 + 1} \quad S_f = \frac{2\text{Im}\lambda_f}{1 + |\lambda_f|^2} \quad \lambda_f \equiv \left(\frac{q A_f}{p A_f}\right)$$

**In principle we need:**

- a B meson in a pure flavor eigenstate.
- to know its which eigenstate it was ($B^0$ or $\bar{B}^0$).
- to measure $\Delta t$.

**Many such B's**
How to measure T-D CP violation

- It is hard, but some luck + brilliant idea make it possible.

\( \Upsilon(4S) \) decays \(~\) exclusively into \( B\bar{B} \)

\( B\bar{B} \) \textbf{from} \( \Upsilon(4S) \) \textbf{is entangled}

\( B_{tag} \rightarrow \bar{B}^{0}(\bar{B}^{0}) \) flavor specific f.s. at \( t \)

\( B_{sig} \) was pure \( \bar{B}^{0}(\bar{B}^{0}) \) at \( t \)

Mass of \( \Upsilon(4S) \) is just above \( 2M_{B} \) \iff \( \text{B pair} \) \text{~at rest in CMS} \n
Collider with asymmetric beam energy: \( \Delta t = \Delta z/\beta\gamma c \)

- 2 B-factories were built. i.e. a high luminosity, asymmetric beam energy, \( e^+ e^- \) collider, that operates at \( \Upsilon(4S) \) energy and produces a lot of B meson pairs

  + a dedicated detector with good vertexing & particle ID!

Experimentally we need to:

1. Determine the flavor of \( B_{tag} \).
2. Reconstruct \( B_{sig} \) into final state \( f \).
3. Measure the distance between the decay vertices.
The Belle experiment

- Operating at the KEKB collider (1999-2010).
- Asymmetric beam energy: 8.0 GeV $e^-$ on 3.5 GeV $e^+$
- Boosted B meson pair produced in $e^- \xrightarrow{} e^+ \Rightarrow \Upsilon(4S) \Rightarrow B\bar{B}$
- Collected about 772M BB pairs.
Motivation

- FCNC process $\rightarrow$ penguin diagram
- The asymmetry parameters within the SM:
  $$A_{s\bar{q}q} \simeq 0 \quad S_{s\bar{q}q} \simeq -\xi_f \sin 2\phi_1$$
- Loop dominated $\rightarrow$ sensitive to new physics (NP).
- $\sin 2\phi_1$ can be very precisely measured in tree dominated (NP non-sensitve) $b \rightarrow c\bar{c}s$ decays.
  $$S_{J/\psi K^0_S} = \sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$$
- Observing $|S_{s\bar{q}q} - S_{J/\psi K^0_S}| > \text{few } \%$
  $\rightarrow$ sign of new physics.
**Time-dependent CPV in \( B^0 \to \eta'K^0 \)**

\( B(B^0 \to \eta'K^0) \sim 7 \times 10^{-5} \)

- **Reconstructed modes:** \( K_S \to \pi^+\pi^+ / \pi^0\pi^0, K_L, \eta' \to \rho^0\gamma / \eta\pi^+\pi^-, \eta \to 2\gamma/3\pi \)

- **Main background from** \( e^+e^- \to q\bar{q} \ (q = u, d, s, c) \)

- **To obtain signal yield we perform 3D fit to data distribution in**

\[ \eta'K^0, M_{bc}, \Delta E, R_{s/b} \]

\[ \Delta E = E_{B}^{\text{cms}} - E_{\text{beam}}^{\text{cms}} \quad M_{bc} = \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2} \]

\[ R_{s/b} - \text{ event shape variable} \]

- **For each decay mode, in 7 flavor tagging quality bins.**

- **\( \Delta t \) resolution function (event-by-event)**

- **Finally we fit \( \Delta t \) distributions of \( B^0 \) and \( \bar{B}^0 \) tagged candidates.**
Fit result: \[ S_{\eta'K^0} = +0.68 \pm 0.07(stat) \pm 0.03(syst) \]
\[ A_{\eta'K^0} = +0.03 \pm 0.05(stat) \pm 0.04(syst) \]

World's most precise measurement of CPV in \( B^0 \rightarrow \eta'K^0 \) and \( b \rightarrow s\bar{q}q \)

Well consistent with \( \sin 2\phi_1 \)
Time-dependent CPV in $B^0 \rightarrow \omega K_S^0$

- 7D fit to $\cos \theta_{Hel}$, $\Delta E$, $M_{bc}$, $R_{s/b}$, $m_{3\pi}$, $H_{3\pi}$, $\Delta t$, $q$

  to obtain branching fraction and CPV parameters simultaneously.

**Fit result**

**Branching fractions:**

$B(B^0 \rightarrow \omega K_S^0) = (4.5 \pm 0.4(stat) \pm 0.3(syst)) \times 10^{-6}$

$B(B^+ \rightarrow \omega K^+) = (6.8 \pm 0.4(stat) \pm 0.4(syst)) \times 10^{-6}$

**CPV parameters:**

$S_{\omega K_S^0} = +0.91 \pm 0.31(stat) \pm 0.05(syst)$

$A_{\omega K_S^0} = -0.36 \pm 0.19(stat) \pm 0.05(syst)$

First evidence of CPV in this mode
- Right-handed photon emission in $b \to s\gamma$ is strongly suppressed in the SM.
  → mixing induced CPV is also suppressed in the SM:\n  \[ S_{CP} \approx 2 \frac{m_s}{m_b} \sin 2\phi_1 \]

- Several NP models allow for RH photon emission → large indirect CPV

- Sister mode of $B^0 \to K_S^0 \pi^0 \gamma$

- Reconstructed modes: $K_S^0 \to \pi^+\pi^-, \eta \to \pi^+\pi^-\pi^0, \eta \to \gamma\gamma$

- Main background from continuum → neural network (event shape)

**Fit result**

- $A_{cp} = -0.48 \pm 0.41\text{(stat)} \pm 0.07\text{(syst)}$
- $S_{cp} = -1.32 \pm 0.77\text{(stat)} \pm 0.36\text{(syst)}$

No significant deviation from the SM
$B^0 \rightarrow \pi^0\pi^0$ branching fraction

- $\phi_2$ can be measured by T-D CPV in $B \rightarrow \pi^+\pi^-$, but large penguin pollution!
  
  $\rightarrow$ use isospin related decays to unveil $\phi_2$, one of them $B^0 \rightarrow \pi^0\pi^0$

- Main background comes from continuum events $\rightarrow$ event shape variable ($T_C$)

- 3D fit in $\Delta E$, $M_{bc}$, $T_C$ to extract $\mathcal{B}$. Theory: $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0) < 1 \times 10^{-6}$

Fit result: $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0) = (0.90 \pm 0.12 \pm 0.10) \times 10^{-6}$

BaBar PR D87 052009 (1.83 ±0.21 ±0.13 )x10-6

Belle PRL 94, 181803 (2005) (2.32 ± 0.5 ± 0.3 )x10-6
Summary

- Three recent measurements of time dependent CPV in B decays were presented. They provide:
  - most precise parameters of CPV in $B^0 \to \eta' K^0$ to date,
    $$S_{\eta'K^0} = +0.68 \pm 0.07\text{(stat)} \pm 0.03\text{(syst)}$$  
    \textit{JHEP 10, 165 (2014)}
  - first evidence of CPV in $B^0 \to \omega K^0$
    $$S_{\omega K^0_S} = +0.91 \pm 0.32\text{(stat)} \pm 0.05\text{(syst)}$$  
    \textit{PRD 90, 012002 (2014)}
  - most precise parameters of CPV in $B^0 \to K^0_S \eta \gamma$
    $$S_{cp} = -1.32 \pm 0.77\text{(stat)} \pm 0.36\text{(syst)}$$

- Measurement of $B^0 \to \pi^0 \pi^0$ branching fraction:
  $$\mathcal{B}(B^0 \to \pi^0 \pi^0) = (0.90 \pm 0.12 \pm 0.10) \times 10^{-6}$$

- + 2 recent measurements of direct CPV (not shown today)
  $B \to X_{s+d}\gamma$
  $$B^0 \to \eta' K^*(892)^0 \ A_{cp} = 0.22 \pm 0.29 \pm 0.07$$  
  \textit{PRD 90, 072009}
  $$A_{cp} = (2.2 \pm 4.0 \pm 0.8) \times 10^{-2}$$

- All measurements are statistically limited → many opportunities for Belle II.
Backup slides
$B^0 \rightarrow \pi^0 \pi^0$ out-of-time ECL background

- substantial background comes from out-of-time showers in the ECL (pileup).

- BB event + $e^+e^-$ scattering within a few $\mu$s.

- Timing cut on ECL trigger removes 99% of this background, while retains 99% of signal events.

- This is cut was not used in our previous analysis in 2006.

From previous Belle analysis
## Belle II prospects

<table>
<thead>
<tr>
<th>Observable</th>
<th>SM theory</th>
<th>Current measurement (early 2013)</th>
<th>Belle II * (50 ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S(B \to \phi K^0))</td>
<td>0.68</td>
<td>0.56 ± 0.17</td>
<td>±0.018</td>
</tr>
<tr>
<td>(S(B \to \eta' K^0))</td>
<td>0.68</td>
<td>0.59 ± 0.07</td>
<td>±0.011</td>
</tr>
<tr>
<td>(\alpha ) from (B \to \pi \pi, \rho \rho)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\gamma ) from (B \to DK)</td>
<td></td>
<td>±5.4(^\circ)</td>
<td>±1(^\circ)</td>
</tr>
<tr>
<td>(S(B \to K_S \pi^0 \gamma))</td>
<td>&lt; 0.05</td>
<td>−0.15 ± 0.20</td>
<td>±0.035</td>
</tr>
<tr>
<td>(S(B \to \rho \gamma))</td>
<td>&lt; 0.05</td>
<td>−0.83 ± 0.65</td>
<td>±0.07</td>
</tr>
<tr>
<td>(A_{CP}(B \to X_{s+d} \gamma))</td>
<td>&lt; 0.005</td>
<td>0.06 ± 0.06</td>
<td>±0.005</td>
</tr>
<tr>
<td>(A^d_{SL})</td>
<td>−5 × 10(^{-4})</td>
<td>−0.0049 ± 0.0038</td>
<td>±0.001</td>
</tr>
<tr>
<td>(B(B \to \tau \nu))</td>
<td>1.1 × 10(^{-4})</td>
<td>(1.64 ± 0.34) × 10(^{-4})</td>
<td>±3%</td>
</tr>
<tr>
<td>(B(B \to \mu \nu))</td>
<td>4.7 × 10(^{-7})</td>
<td>&lt; 1.0 × 10(^{-6})</td>
<td>≫ 5(\sigma)</td>
</tr>
<tr>
<td>(B(B \to X_s \gamma))</td>
<td>3.15 × 10(^{-4})</td>
<td>(3.55 ± 0.26) × 10(^{-4})</td>
<td>±6%</td>
</tr>
<tr>
<td>(B(B \to K^{(*)} \nu \bar{\nu}))</td>
<td>3.6 × 10(^{-6})</td>
<td>&lt; 1.3 × 10(^{-5})</td>
<td>±30%</td>
</tr>
<tr>
<td>(B(B \to X_s \ell^+ \ell^-)) (1 &lt; q^2 &lt; 6 GeV(^2))</td>
<td>1.6 × 10(^{-6})</td>
<td>(4.5 ± 1.0) × 10(^{-6})</td>
<td>±0.10 × 10(^{-6})</td>
</tr>
<tr>
<td>(A_{FB}(B^0 \to K^{*0} \ell^+ \ell^-)) zero crossing</td>
<td>7%</td>
<td>18%</td>
<td>5%</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>) from (B \to \pi \ell^+ \nu) (q^2 &gt; 16 GeV(^2))</td>
<td>9% → 2%</td>
</tr>
</tbody>
</table>

*Note: The Belle II prospects are based on projected measurements with 50 ab\(^{-1}\) of data. The current measurements are from early 2013.*