Recent constraints on CKM and New Physics by Belle

Martin Ritter
on behalf of the Belle Collaboration

Moriond 2014 – Electroweak Session
March 16, 2014

The Belle Experiment
\[ B^0 \to \omega K_S^0 \]
\[ B^0 \to \eta' K^*(892) \]
\[ B^0 \to K_S^0 \eta \gamma \]
\[ D^0 \to \pi^0 \pi^0 \]

Conclusions
Quark Mixing and CP Violation

CP Violation (CPV) is established in the Standard Model (SM) in the weak interaction

- Cabibbo-Kobayashi-Maskawa-Matrix: Complex, unitary mixing Matrix between flavor/mass eigenstates

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

\[V_{\text{CKM}}\]

- CPV due to irreducible complex phase
- unitary constraints: \(\sum_k V_{ik} V_{jk}^* = 0\); \(V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0\)

\[
\bar{\rho} = \left(1 - \frac{\lambda^2}{2}\right) \rho \quad \bar{\eta} = \left(1 - \frac{\lambda^2}{2}\right) \eta
\]

\[
\phi_1 \{ = \arg \left(-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right) \quad \phi_2 \} = \arg \left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right)
\]

\[
\phi_3 \gamma \{ = \arg \left(-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*}\right)
\]

Martin Ritter on behalf of the Belle Collaboration

Recent constraints on CKM and New Physics by Belle
The Belle Experiment

- multi purpose detector designed for CPV measurement
- was located at the asymmetric $e^+e^-$ collider KEKB in Japan
- was running mainly at the $\Upsilon(4S)$ resonance (10.58 GeV)

Recent constraints on CKM and New Physics by Belle
The Belle Experiment

$B^0 \rightarrow \omega \bar{K}_S^0$

$B^0 \rightarrow \eta' K^*(892)$

$B^0 \rightarrow K_S^0 \eta \gamma$

$D^0 \rightarrow \pi^0 \pi^0$

Conclusions

**CPV Measurement at Belle**

Time dependent CP Asymmetry

$$a_{CP}(t) = \frac{\Gamma (\overline{B}^0 \rightarrow f_{CP}; t) - \Gamma (B^0 \rightarrow f_{CP}; t)}{\Gamma (\overline{B}^0 \rightarrow f_{CP}; t) + \Gamma (B^0 \rightarrow f_{CP}; t)} = A_{CP} \cos(\Delta m_d \Delta t) + S_{CP} \sin(\Delta m_d \Delta t)$$

- $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B}$ produced in quantum entangled state
- $B_{CP} =$ reconstruct CP eigenstate, $B_{tag} =$ determine flavour
- boost: $t \rightarrow \Delta t = \Delta z/\beta \gamma c$

Main Backgrounds:

- Continuum: Events from $u, d, s, c$ production
- $B \bar{B}$: Background from other $B \bar{B}$ decays

Useful variables:

$$M_{BC} = \sqrt{(E_{beam}^{CMS})^2 - (p_B^{CMS})^2} \quad \Delta E = E_B^{CMS} - E_{beam}^{CMS}$$

Martin Ritter on behalf of the Belle Collaboration

Recent constraints on CKM and New Physics by Belle
CP Violation in $b \to s\bar{s}q\bar{q}$ transitions

- $b \to c\bar{c}s$ ($B^0 \to J/\psi K_S^0$) is tree dominated
- $b \to s\bar{u}u$ and $b \to s\bar{d}d$ ($B^0 \to \omega K_S^0$) is penguin dominated,
  tree is color and Cabibbo suppressed.
- $b \to s\bar{s}s$ is penguin only

$b \to s\bar{u}u$, $b \to s\bar{d}d$, $b \to s\bar{s}s$ transitions:
- sensitive to New Physics
- same weak phase as $b \to c\bar{c}s$
- SM predictions:
  \[
  \mathcal{A}_{CP} \simeq 0 \quad S_{CP} \equiv \sin(2\phi_1^{\text{eff}})
  \]
  \[\sin(2\phi_1) \sim \sin(2\phi_1^{\text{eff}})\]

$\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$

<table>
<thead>
<tr>
<th>$b \to c\bar{c}s$</th>
<th>World Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{K^0}$</td>
<td>BaBar $0.66 \pm 0.07$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.90 \pm 0.09$</td>
</tr>
<tr>
<td>$\eta K^0$</td>
<td>BaBar $0.57 \pm 0.02$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.64 \pm 0.04$</td>
</tr>
<tr>
<td>$\phi K_S^0$</td>
<td>BaBar $0.35 \pm 0.03$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.30 \pm 0.03$</td>
</tr>
<tr>
<td>$\pi K^0$</td>
<td>BaBar $0.64 \pm 0.10$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.55 \pm 0.03$</td>
</tr>
<tr>
<td>$\omega K_S^0$</td>
<td>BaBar $0.48 \pm 0.04$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.11 \pm 0.04$</td>
</tr>
<tr>
<td>$f_0 K_S^0$</td>
<td>BaBar $0.40 \pm 0.04$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.74 \pm 0.15$</td>
</tr>
<tr>
<td>$f_0 K_{S'}^0$</td>
<td>BaBar $0.52 \pm 0.04$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.63 \pm 0.19$</td>
</tr>
<tr>
<td>$\pi^0 K_{S'}^0$</td>
<td>BaBar $0.52 \pm 0.07$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.72 \pm 0.08$</td>
</tr>
<tr>
<td>$\phi K_{S'}^0$</td>
<td>BaBar $0.20 \pm 0.03$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.97 \pm 0.02$</td>
</tr>
<tr>
<td>$\pi^+ K_{S'}^0$</td>
<td>BaBar $0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$Belle$</td>
<td>$0.65 \pm 0.02$</td>
</tr>
<tr>
<td>$b \to q\bar{q}s$</td>
<td>Naive average $0.64 \pm 0.03$</td>
</tr>
</tbody>
</table>
The Belle Experiment

$B^0 \rightarrow \omega K_S^0$

$W^+$

$V_{xb}^*$

$\bar{u}, c, t$

$V_{xs}$

$\bar{s}$

$K_S^0$

$\bar{b}$

$d$

$d$

$\omega$

$B^0$

$d$

$d$

$\bar{b}$

$\bar{u}$

$\omega$

$B^0$

$d$

$d$

$B^0 \rightarrow \omega K_S^0$ penguin dominated

previous Belle result [Phys.Rev.D 76, 091103(R) (2009)]

$S_{CP}(B^0 \rightarrow \omega K_S^0) = 0.11 \pm 0.46\,(\text{stat}) \pm 0.07\,(\text{syst})$

BaBar result [Phys.Rev.D 79, 052003 (2009)]

$S_{CP}(B^0 \rightarrow \omega K_S^0) = 0.55^{+0.26}_{-0.29}\,(\text{stat}) \pm 0.02\,(\text{syst})$

updated result with final data set
B\(^0\) → \(\omega K_S^0\) Analysis

- B\(^0\) → \(\omega K_S^0\) reconstructed from \(\omega \rightarrow \pi^+\pi^-\pi^0\) and \(K_S^0 \rightarrow \pi^+\pi^-\)
- suppress continuum using fisher discriminant
- simultaneous fit of B\(^0\) → \(\omega K_S^0\) and B\(^\pm\) → \(\omega K^\pm\) to reduce systematic errors (MC ↔ data)
- 7D unbinned extended ML fit to \(M_{BC}, \Delta E, F_{BB/qq}, m_{3\pi}, \cos \theta_{3\pi}^{Hel}, \Delta t, q\)
Branching fraction:

\[ B(B^0 \to \omega K_S^0) = [4.5 \pm 0.4 \text{(stat)} \pm 0.3 \text{(syst)}] \times 10^{-6} \]

\[ B(B^{\pm} \to \omega K^{\pm}) = [6.8 \pm 0.4 \text{(stat)} \pm 0.4 \text{(syst)}] \times 10^{-6} \]

CP Violation:

\[ A_{CP}(B^0 \to \omega K_S^0) = -0.36 \pm 0.19 \text{(stat)} \pm 0.05 \text{(syst)} \]

\[ S_{CP}(B^0 \to \omega K_S^0) = +0.91 \pm 0.32 \text{(stat)} \pm 0.05 \text{(syst)} \]

\[ A_{CP}(B^{\pm} \to \omega K^{\pm}) = -0.03 \pm 0.04 \text{(stat)} \pm 0.01 \text{(syst)} \]

- first evidence (3.1\sigma) for CP Violation in \( B^0 \to \omega K_S^0 \)
- no sign of New Physics
B$^0 \to \eta'K^*(892)$

- Previous Belle analysis with significance of 1.9$\sigma$, upper limit with 90% CL
  
  \[ \mathcal{B}(B^0 \to \eta'K^*(892)) < 2.6 \times 10^{-6} \]

- BaBar found evidence for \( B^0 \to \eta'K^*(892) \) with 4$\sigma$ significance
  
  \[ \mathcal{B}(B^0 \to \eta'K^*(892)) = [3.1^{+0.9}_{-0.8}(\text{stat}) \pm 0.30(\text{syst})] \times 10^{-6} \]

- pQCD predicts \( \mathcal{B} = 3.4 \pm 0.3 \times 10^{-6} \) [Phys.Rev.D 75, 054003]

- \( B^0 \to \eta'K^*(892) \) is a penguin dominated \( b \to s \) transition

- High potential for NP contributions.
B\(^0\) \rightarrow \eta'K^*(892)\) Analysis

- B\(^0\) \rightarrow \eta'K^*(892)\) candidates reconstructed from \( \eta' \rightarrow \eta\pi^+\pi^-\), \( \eta \rightarrow \gamma\gamma \) and \( K^*(892) \rightarrow K^+\pi^- \)

- continuum suppression using Neural Network

- events with good candidates for \( B^+ \rightarrow \eta'K^+ \) and \( B^0 \rightarrow \eta'K^0 \) rejected.

- 4D extended maximum likelihood fit to extract signal yield from \( M_{BC}\), \( \Delta E\), \( NN' = \ln \frac{NN - NN_{min}}{NN_{max} - NN} \) and the helicity angle \( \cos \theta_H \)

\[
\mathcal{B}(B^0 \rightarrow \eta'K^*(892)) = \frac{Y_{\text{sig}}}{N_{B\overline{B}} \times \epsilon_{\text{rec}} \times \epsilon_{\text{PID}} \times \epsilon_{Rq\overline{q}}}
\]
Branching fraction:

\[ B(B^0 \to \eta'K^*(892)) = [2.6^{+0.7}_{-0.6}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6} \]

- scan of Likelihood including systematic effects: 5σ significance

- \( B^0 \to \eta'K^*(892) \) is self-tagging (flavour from \( K^*(892) \to K^+\pi^- \))

- estimate overall CP asymmetry

\[ A_{CP} = -0.22^{+0.18}_{-0.17}(\text{stat})^{+0.02}_{-0.03}(\text{syst}) \]
The Belle Experiment

**B^0 \rightarrow K^0_S \eta \gamma**

- right handed photon emission in $b \rightarrow s \gamma$ is strongly suppressed in SM
- several New Physics models allow right handed emission (LR symmetric, SUSY, 2HDM)
- interference of $B^0 \rightarrow X^{CP}_s \gamma_R$ and $\bar{B}^0 \rightarrow X^{CP}_s \gamma_L$ is strongly suppressed in SM

$$S_{CP} = 2 \frac{m_s}{m_b} \sin(2\phi_1)$$


- large indirect CP asymmetry would be strong evidence for New Physics
B$^0 \rightarrow K_S^0 \eta \gamma$ Analysis

- B$^0 \rightarrow K_S^0 \eta \gamma$ candidates reconstructed from $K_S^0 \rightarrow \pi^+ \pi^-$ and $\eta \rightarrow \pi^+ \pi^- \pi^0$ or $\eta \rightarrow \gamma \gamma$
- rejection of continuum using a neural network
- reduce backgrounds by cuts on $m(\gamma K)$, $m(\gamma \eta)$ and $m(K \eta)$. (e.g. $B^0 \rightarrow J/\psi K_S^0$: reject $2.9 \text{ GeV}/c^2 < m(\eta \gamma) < 3.2 \text{ GeV}/c$)
- reject events with good $B \rightarrow K \pi^0 \gamma$ candidate.
- determine event signal probability with 3D extended maximum likelihood fit to $M_{BC}$, $\Delta E$ and $NN' = \ln \frac{NN - NN_{\text{min}}}{NN_{\text{max}} - NN}$
- signal probability is then used in lifetime fit to $\Delta t$

red=signal, green=B\bar{B} bg, blue=q\bar{q} bg
B\(^0\) → K\(_S^0\)\(\eta\gamma\) Results, Preliminary

- B\(\bar{B}\) background as exponential decay, lifetime determined from MC
- determine continuum shape from sideband

\[ A_{CP} = -0.48 \pm 0.41(\text{stat}) \pm 0.07(\text{syst}) \]
\[ S_{CP} = -1.32 \pm 0.77(\text{stat}) \pm 0.36(\text{syst}) \]

- No significant deviation from zero
Previous results by LHCb and CDF have indicated a possibly large CP asymmetry difference between $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$.

- Isospin considerations can provide constraints and NP predictions on the CP asymmetry for $D^0 \rightarrow \pi^0\pi^0$


- So far only one published result $A_{CP}(D^0 \rightarrow \pi^0\pi^0) = (+0.1\pm4.8)\%$ by CLEO [Phys. Rev. D 63, 071101 (2001)]
\(\textbf{D}^0 \rightarrow \pi^0\pi^0\text{ Analysis} \)

- in the decay \(\text{D}^{*+} \rightarrow \text{D}^0\pi^+\), the charge of the low-momentum pion \(\pi^+_{\text{slow}}\) identifies the flavor of the neutral D meson

- Measure the asymmetry

\[
A_{\text{rec}} = \frac{N_{\text{rec}}^{\text{D}^{*+} \rightarrow \text{D}^0\pi^+_{\text{slow}}} - N_{\text{rec}}^{\text{D}^{*-} \rightarrow \overline{\text{D}}^0\pi^-_{\text{slow}}}}{N_{\text{rec}}^{\text{D}^{*+} \rightarrow \text{D}^0\pi^+_{\text{slow}}} + N_{\text{rec}}^{\text{D}^{*-} \rightarrow \overline{\text{D}}^0\pi^-_{\text{slow}}}}
\]

for \(\text{D}^0 \rightarrow \pi^0\pi^0\) and \(\text{D}^0 \rightarrow K^0\pi^0\)

- D mesons from B decays are rejected by requiring \(p(\text{D}^{*\pm}) > 2.5 \text{ GeV/c} \) (3.1 \text{ GeV/c}) for events near the \(\Upsilon(4S)\) (\(\Upsilon(5S)\)) resonance.

- \(A_{\text{rec}}\) includes \(A_{\text{CP}}\), the forward-backward asymmetry \(A_{\text{FB}}\) and the detection asymmetry \(A_{e}^{\pi^+_{\text{slow}}}\)

- \(A_{e}^{\pi^+_{\text{slow}}}\) is determined by subtracting the asymmetries in \(\text{D}^0 \rightarrow K^-\pi^+\) and \(\text{D}^{*-} \rightarrow \text{D}^0\pi^+_{\text{slow}} \rightarrow K^-\pi^+\pi^+_{\text{slow}} \) [\(O(0.1\%)\)]
\( A_{CP} \) is independent of kinematic variables.

\( A_{FB} \) is odd function of of \( \cos \theta^* \), \( \theta^* \) being the polar angle of the \( D^{*+} \) in the center mass system

\[
A_{CP} = \frac{[A_{rec}^\text{cor}(\cos \theta^*) + A_{rec}^\text{cor}(-\cos \theta^*)]}{2} \quad A_{FB} = \frac{[A_{rec}^\text{cor}(\cos \theta^*) - A_{rec}^\text{cor}(-\cos \theta^*)]}{2}
\]

- dashed blue line leading order prediction for \( A_{FB}(e^+e^- \rightarrow c\bar{c}) \) [Z.Phys.C 30, 125 (1986)]

\[
A_{CP}(D^0 \rightarrow \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%
A_{CP}(D^0 \rightarrow K_S^0\pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%
\]

- improves previous CLEO result by more than an order of magnitude
Conclusions

Branching ratio and CP Violation in $B^0 \rightarrow \omega K_S^0$
- first evidence ($3.1\sigma$) for CPV

Branching ratio and overall CP Asymmetry in $B^0 \rightarrow \eta'K^*(892)$
- first observation of $B^0 \rightarrow \eta'K^*(892)$ with $5\sigma$ significance

Time dependent CP Violation in $B^0 \rightarrow K_S^0\eta\gamma$
- lifetime fit to extract CPV parameters
- no significant CPV observed

Overall CP Asymmetry in $D^0 \rightarrow \pi^0\pi^0$
- improvement of precision by more than one order of magnitude
- no direct CP Violation observed

So far, everything is consistent with SM
- most analyses are statistically limited
Thank you for your attention
Belle II Luminosity

Goal of Belle II/SuperKEKB

Commissioning starts in early 2015.

Shutdown for upgrade

Calendar Year

Integrated luminosity (ab$^{-1}$)

Peak luminosity ($\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$)

9 months/year
20 days/month

Martin Ritter on behalf of the Belle Collaboration

Recent constraints on CKM and New Physics by Belle
The Belle Experiment

The Belle Experiment

**B**$^0 \rightarrow \omega K_S^0$  
**B**$^0 \rightarrow \eta' K^*(892)$  
**B**$^0 \rightarrow K_S^0 \eta \gamma$  
**D**$^0 \rightarrow \pi^0 \pi^0$

### Conclusions

**b → sγ C$_{CP}$**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.14 ± 0.16 ± 0.03</td>
<td>0.20 ± 0.24 ± 0.05</td>
<td>-0.04 ± 0.14</td>
</tr>
</tbody>
</table>

**b → sγ S$_{CP}$**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.19 ± 0.14 ± 0.03</td>
<td>0.20 ± 0.20 ± 0.06</td>
<td>-0.07 ± 0.12</td>
</tr>
</tbody>
</table>

**Recent constraints on CKM and New Physics by Belle**

Martin Ritter on behalf of the Belle Collaboration