Recent EW results from Belle

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On behalf of Belle collaboration
Unitarity triangle:

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

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

Unitarity triangle:

\[
\frac{V_{ub}^* V_{ud}}{V_{cd}^* V_{cb}} + 1 + \frac{V_{tb}^* V_{td}}{V_{cd}^* V_{cb}} = 0
\]

\[\phi_1 \equiv \beta = \arg \left( \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)\]

\[\phi_3 \equiv \gamma = \arg \left( \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)\]

Search for NP via measurement of sides and angles of UT.

Tension in the CKM fit: \(\sim 3\sigma\) between direct and indirect \(\sin 2\phi_1\)

This talk: two new results from Belle

- Updated \(\sin 2\phi_1\) measurement with \(B \to (c\bar{c})K^0\)
- Measurement of \(\phi_3\) with model-independent Dalitz plot analysis of \(B \to DK, D \to K_S^0\pi\pi\)
Belle detector, KEKB collider at KEK laboratory, Tsukuba, Japan

- World record luminosity: $L \simeq 2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (at $\Upsilon(5S)$).
- Stopped data taking in 2010 ⇒ upgrade to Belle II [M. Danilov’s talk]
- Final data sample: more than 1 ab$^{-1}$
  - 711 fb$^{-1}$ at $\Upsilon(4S)$ ($772 \times 10^{6} B\bar{B}$ decays)
  - 121 fb$^{-1}$ at $\Upsilon(5S)$
  - $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, energy scans
Time-dependent CP asymmetry in $B \to (c\bar{c})K^0$

Golden mode for CP violation measurement: $B^0 \to J/\psi K^0_S$. Measure mixing-induced CP violation, $b \to c\bar{c}s$ transition

Penguin diagram is suppressed, has the same weak phase $\Rightarrow$ negligible theoretical uncertainty.

Measure CP asymmetric decay time distribution separately for $B^0$ and $\bar{B}^0$:

$$p(\Delta t) = \frac{e^{|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 \pm \left[ S_{f_{CP}} \sin(\Delta m_d \Delta t) + A_{f_{CP}} \cos(\Delta m_d \Delta t) \right] \right\}$$

In the Standard Model, $S_{f_{CP}} = -\xi_{f_{CP}} \sin 2\phi_1$ — indirect CPV

$A_{f_{CP}} \simeq 0$ — direct CPV.

Last published Belle result: $\sin 2\phi_1 = 0.642 \pm 0.031 \pm 0.017$ (535M $B\bar{B}$)

Anton Poluektov

Recent EW results from Belle

Moriond EW, 16 March 2011
Flavor tagging and $\Delta t$ measurement

Machine with asymmetric beam energy. $\Delta t$ is measured by $z$ coordinates of vertices of signal $B$ and tagging $B$. $B^0$ and $\bar{B}^0$ are in entangled state: the flavor of one $B$ is fixed by another $B$ at the moment of its decay.

In practice, need to account for the wrong tag probability and vertexing resolution — calibrated with data.
Signal selection

In $\Upsilon(4S)$ decays, pairs of $B$ mesons are produced near threshold. $E_B = E_{CM}/2$, small CM momentum (300 MeV/c).

Selection variables:

- CM energy difference
  \[ \Delta E = \sum E_i - E_{CM}/2 \]

- Beam-constrained mass of the $B$ meson:
  \[ M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum p_i)^2} \]
sin 2\(\phi_1\): Selection of \(B \rightarrow (c\bar{c})K^0\) events

Use 711 fb\(^{-1}\) sample (772M \(B\bar{B}\) pairs).

More data, improved tracking \(\Rightarrow \sim 50\%\) more statistics than prev. analysis

**Belle preliminary**

**CP = −1 modes:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B \rightarrow J/\psi K^0) (S), (J/\psi \rightarrow l^+l^-)</td>
<td>12681 ± 114</td>
</tr>
<tr>
<td>(B \rightarrow \psi(2S)K^0) (S), (\psi(2S) \rightarrow l^+l^-)</td>
<td>908 ± 31</td>
</tr>
<tr>
<td>(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)</td>
<td>1072 ± 33</td>
</tr>
<tr>
<td>(B \rightarrow \chi_{c1}K^0) (S), (\chi_{c1} \rightarrow J/\psi\gamma)</td>
<td>943 ± 33</td>
</tr>
</tbody>
</table>

**CP = +1 mode:**

\(B \rightarrow J/\psi K_L\)

Signal yield: 10041 ± 154

Missing information about \(K_L^0\) momentum:
\(K_L^0\) cluster reconstructed in ECL or KLM, match it with the \(K_L^0\) direction from kinematical constraints.
Good tag only, background subtracted.

\[ B \rightarrow J/\psi K^0_S \]
\[ B \rightarrow J/\psi K^0_L \]
\[ B \rightarrow \psi(2S)K^0_S \]
\[ B \rightarrow \chi_{c1}K^0_S \]

Asymmetry

\[ S = 0.671 \pm 0.029 \quad S = 0.641 \pm 0.047 \quad S = 0.739 \pm 0.079 \quad S = 0.636 \pm 0.117 \]
\[ A = -0.014 \pm 0.021 \quad A = 0.019 \pm 0.026 \quad A = 0.103 \pm 0.055 \quad A = -0.023 \pm 0.083 \]

CP violation is observed in all modes
**sin 2\(\phi_1\): Combined sin 2\(\phi_1\) measurement**

**Belle preliminary**

**Systematic errors:**

<table>
<thead>
<tr>
<th>Source</th>
<th>(\Delta S)</th>
<th>(\Delta A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertexing</td>
<td>+0.008</td>
<td>±0.008</td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>+0.004</td>
<td>±0.003</td>
</tr>
<tr>
<td>Resolution function</td>
<td>±0.007</td>
<td>±0.001</td>
</tr>
<tr>
<td>Physics parameters</td>
<td>±0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Fit bias</td>
<td>±0.004</td>
<td>±0.005</td>
</tr>
<tr>
<td>(J/\psi K^0_S) signal fraction</td>
<td>±0.002</td>
<td>±0.001</td>
</tr>
<tr>
<td>(J/\psi K^0_L) signal fraction</td>
<td>±0.004</td>
<td>+0.000</td>
</tr>
<tr>
<td>(\psi(2S)K^0_S) signal fraction</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>(\chi_{c1} K^0_S) signal fraction</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Background (\Delta t)</td>
<td>±0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Tag-side interference</td>
<td>±0.001</td>
<td>±0.008</td>
</tr>
<tr>
<td>Total</td>
<td>±0.013</td>
<td>±0.013</td>
</tr>
</tbody>
</table>

**Combination of four modes:**

\[
S = 0.668 \pm 0.023 \pm 0.013 \text{ (syst)} \\
A = 0.007 \pm 0.016 \pm 0.013 \text{ (syst)}
\]

Expect tension in CKM fit to be loosened

Significant improvement in sys. error (vertexing, resolution function)
Measurement of $\phi_3$ in $B \rightarrow DK$ decays

$B^- \rightarrow D^0 K^-$:

\[ A \sim V_{cb} V^*_{us} \sim A \lambda^3 \]

$B^- \rightarrow \bar{D}^0 K^-$:

\[ A \sim V_{ub} V^*_{cs} \sim A \lambda^3 (\rho - i \eta) \]

If $D^0$ and $\bar{D}^0$ decay into the same final state: $|\tilde{D}\rangle = |D^0\rangle + re^{i\theta} |\bar{D}^0\rangle$

Relative phase in $B^+ \rightarrow DK^+$: $\theta = +\phi_3 + \delta$,

$B^- \rightarrow DK^-$: $\theta = -\phi_3 + \delta$.

Ratio of the two amplitudes:

\[ r = \left| \frac{A(B^- \rightarrow \bar{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)} \right| = \left| \frac{V_{ub} V^*_{cs}}{V_{cb} V^*_{us}} \right| \times [\text{Color supp}] \sim 0.1 \]
Dalitz analysis of $D$ decay from $B^{\pm} \rightarrow DK^{\pm}$


[A. Bondar, Belle Dalitz analysis meeting, 24-26 Sep. 2002]

Use $B^{\pm} \rightarrow DK^{\pm}$ modes with 3-body decay $D \rightarrow K_{S}^{0}\pi^{+}\pi^{-}$. Dalitz plot density: $d\sigma_{\pm}(m^{2}_{+}, m^{2}_{-}) \sim |M_{\pm}|^{2}dm^{2}_{+}dm^{2}_{-}$

$$|M_{\pm}(m^{2}_{+}, m^{2}_{-})|^{2} = |f_{D}(m^{2}_{+}, m^{2}_{-}) + re^{i\delta_{B}^{\pm}i\phi_{3}} f_{D}(m^{2}_{-}, m^{2}_{+})|^{2}$$

$$= \begin{vmatrix} \text{Dalitz Plot Density} \end{vmatrix}^{2} + re^{i\delta_{B}^{\pm}i\phi_{3}}$$

$D^{0} \rightarrow K_{S}^{0}\pi^{+}\pi^{-}$ amplitude $f_{D}$ is extracted from continuum ($D^{*\pm} \rightarrow D\pi^{\pm}$), parametrized as a set of two-body amplitudes.

Only $|f_{D}|^{2}$ is observable $\Rightarrow$ Model dependence as a result.

Latest Belle result: $\phi_{3} = [78^{+11}_{-12} \pm 4(\text{syst}) \pm 9(\text{model})]^{\circ} (605 \text{ fb}^{-1})$

$$r_{B} = 0.16 \pm 0.04 \pm 0.01(\text{syst})^{+0.05}_{-0.01}(\text{model})$$

Model error would dominate precise measurements at Super B factories.
Solution: use binned Dalitz plot and deal with numbers of events in bins.

[A. Bondar, A. P. EPJ C 47, 347 (2006); EPJ C 55, 51 (2008)]

\[ M_i^\pm = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i + y_\pm s_i)\} \]

\[ x_\pm = r_B \cos(\delta_B \pm \phi_3) \quad y_\pm = r_B \sin(\delta_B \pm \phi_3) \]

\( M_i^\pm \): numbers of events in \( D \to K_S^0 \pi^+ \pi^- \) bins from \( B^\pm \to D K^\pm \)

\( K_i \): numbers of events in bins of flavor \( \bar{D}^0 \to K_S^0 \pi^+ \pi^- \) from \( D^* \to D \pi \).

\( c_i, s_i \) contain information about strong phase difference between symmetric Dalitz plot points \( (m_{K_S^0 \pi^+}^2, m_{K_S^0 \pi^-}^2) \) and \( (m_{K_S^0 \pi^-}^2, m_{K_S^0 \pi^+}^2) \):

\[ c_i = \langle \cos \Delta \delta_D \rangle, \quad s_i = \langle \sin \Delta \delta_D \rangle \]
\( \phi_3: \text{Obtaining } c_i, s_i \)

Coefficients \( c_i, s_i \) can be obtained in \( \psi(3770) \rightarrow D^0\overline{D}^0 \) decays. Use quantum correlations between \( D^0 \) and \( \overline{D}^0 \).

- If both \( D \) decay to \( K^0_S\pi^+\pi^- \), the number of events in \( i \)-th bin of \( D_1 \rightarrow K^0_S\pi^+\pi^- \) and \( j \)-th bin of \( D_2 \rightarrow K^0_S\pi^+\pi^- \) is

\[
M_{ij} = K_i K_{-j} + K_{-i} K_j - 2 \sqrt{K_i K_{-i} K_j K_{-j}} (c_i c_j + s_i s_j).
\]

\( \Rightarrow \) constrain \( c_i \) and \( s_i \).

- If one \( D \) decays to a CP eigenstate, the number of events in \( i \)-th bin of another \( D \rightarrow K^0_S\pi^+\pi^- \) is

\[
M_i = K_i + K_{-i} \pm 2 \sqrt{K_i K_{-i}} c_i.
\]

\( \Rightarrow \) constrain \( c_i \).

c_i, s_i \) measurement has been done by CLEO and can be done in future at BES-III.
Binned analysis reduces stat. precision.
Can improve this by choosing a binning inspired by $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ model.

[CLEO collaboration, PRD 82, 112006 (2010)]

Optimized $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$ binning using BaBar 2008 measurement.

Optimal binning depends on model, but $\phi_3$ does not.
Bad model ⇒ worse precision, but no bias!
Use 711 fb$^{-1}$ sample (772M $B \bar{B}$ pairs).

Data reprocessed with new tracking ⇒ improved efficiency (12% → 16%)

Signal selection variables: $M_{bc}$, $\Delta E$, event shape ($\cos \theta_{\text{thr}}$, "virtual calorimeter" Fisher discriminant). 4D unbinned fit to get signal yield.

Signal yield: $1176 \pm 43$ events ($\sim 55\%$ more data than in prev. analysis)
Dalitz plots of $D \rightarrow K^0_S \pi^+ \pi^-$ decay from $B^\pm \rightarrow DK^\pm$

$B^- \rightarrow D^0 K^-$:

$B^+ \rightarrow D^0 K^+$:

Dalitz plots for signal-enriched region:

$(M_{bc} > 5.27 \text{ GeV}/c^2, |\Delta E| < 30 \text{ MeV}, \cos \theta_{\text{thr}} < 0.8)$. 
$$\phi_3: \text{CP asymmetry in } B^\pm \to DK^\pm$$

Fit signal selection distribution separately in bins

Belle preliminary

$$B^\pm \to DK^\pm \text{ sample}$$

$$B^\pm \to D\pi^\pm \text{ control sample}$$

Significant direct CP asymmetry in $$B^\pm \to DK^\pm$$ sample: probability of stat. fluctuation $$p = 0.4\%.$$
$$\phi_3 : B^\pm \rightarrow DK^\pm$$ fit results

Simultaneous fit to signal selection variables in all bins.  
Belle preliminary

Free parameters: \((x, y)\), normalization, background fractions in bins.

$$x_- = +0.095 \pm 0.045 \pm 0.014 \pm 0.017$$

$$y_- = +0.137^{+0.053}_{-0.057} \pm 0.019 \pm 0.029$$

$$\text{corr}(x_-, y_-) = -0.315$$

$$x_+ = -0.110 \pm 0.043 \pm 0.014 \pm 0.016$$

$$y_+ = -0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.021$$

$$\text{corr}(x_+, y_+) = +0.059$$

1st error is statistical, 2nd — systematic, 3rd — \(c_i, s_i\) precision.
This analysis was done in close communication with CLEO.

I think, this is the beginning of a beautiful friendship.
Two new preliminary Belle results on UT angles with full statistics (711 fb$^{-1}$)

- sin $2\phi_1$ measurement in “golden modes”
  \[ B \rightarrow J/\psi K_S^0, \quad B \rightarrow J/\psi K_L^0, \quad B \rightarrow \psi(2S)K_S^0, \quad B \rightarrow \chi_{c1}K_S^0 \]
  \[ \sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013 \]
  Now the most precise measurement of this quantity.

- First $\phi_3$ measurement with binned Dalitz plot analysis of
  \[ B^\pm \rightarrow DK^\pm, \quad D \rightarrow K_S^0\pi^+\pi^- \]
  \[ \phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2(syst) \pm 4.3(c, s))^\circ \]
  Precision comparable to model-dependent analysis
  First try of novel procedure to be used at LHCb and Super B factories.

More Belle results with full sample to come soon.
(When life in KEK is back to normal)
Signal selection

In $\Upsilon(4S)$ decays, pairs of $B$ mesons are produced near threshold. $E_B = E_{\text{CM}}/2$, small CM momentum (300 MeV/c).

Selection variables:

- **CM energy difference**
  \[
  \Delta E = \sum E_i - E_{\text{CM}}/2
  \]

- **$B$-meson beam-constrained mass**
  \[
  M_{bc} = \sqrt{(E_{\text{CM}}/2)^2 - (\sum p_i)^2}
  \]

- **Event shape variables**:

  $$e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}: \quad e^+e^- \rightarrow b\bar{b}:$$
Use momentum range $1.8 < p_D < 2.8$ GeV/c to cancel efficiency shape difference with $B^\pm \rightarrow DK^\pm$ (with $p_D \approx 2.3$ GeV/c)

2D fit in $(M_D, \Delta M)$ in each bin.

$426900 \pm 800$ events

$10.1 \pm 0.5\%$ background

$\Delta M$ projections in bins
$\phi_3: \ B^\pm \rightarrow DK^\pm$ fit in bins

$\Delta E$ distributions in bins:

$B^- \rightarrow DK^-$  \hspace{5cm} $B^+ \rightarrow DK^+$
Systematic errors in units $10^{-3}$.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta x_-$</th>
<th>$\Delta y_-$</th>
<th>$\Delta x_+$</th>
<th>$\Delta y_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalitz plot efficiency</td>
<td>4.8</td>
<td>2.0</td>
<td>5.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Crossfeed between bins</td>
<td>0.4</td>
<td>9.0</td>
<td>0.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Signal shape</td>
<td>7.3</td>
<td>7.4</td>
<td>7.3</td>
<td>5.1</td>
</tr>
<tr>
<td>$u, d, s, c$ continuum background</td>
<td>6.7</td>
<td>5.6</td>
<td>6.6</td>
<td>3.2</td>
</tr>
<tr>
<td>$B\bar{B}$ background</td>
<td>7.8</td>
<td>12.2</td>
<td>7.2</td>
<td>6.1</td>
</tr>
<tr>
<td>$B^{\pm} \rightarrow D\pi^{\pm}$ background</td>
<td>1.2</td>
<td>4.2</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Flavor-tagged statistics</td>
<td>1.5</td>
<td>2.7</td>
<td>1.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Fit bias</td>
<td>3.2</td>
<td>5.8</td>
<td>3.2</td>
<td>5.8</td>
</tr>
<tr>
<td>$c_i, s_i$ precision</td>
<td>10.1</td>
<td>22.5</td>
<td>7.2</td>
<td>17.4</td>
</tr>
<tr>
<td>Total without $c_i, s_i$ precision</td>
<td>±14.0</td>
<td>±19.4</td>
<td>±14.0</td>
<td>±11.3</td>
</tr>
<tr>
<td>Total</td>
<td>±17.3</td>
<td>±29.7</td>
<td>±15.7</td>
<td>±20.7</td>
</tr>
</tbody>
</table>