Recent Results on Flavor Physics from Belle

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on behalf of the Belle Collaboration
(Tohoku University)
**Belle and KEKB**

- **KEKB**
  - The World Highest Luminosity Collider
    - \( L = 2.1 \times 10^{34} \text{ /cm}^2\text{/sec} \)
  - Asymmetric energy to boost B mesons
    - 8.0GeV e\(^-\) × 3.5GeV e\(^+\)

- **Belle**
  - designed to measure time dependent CPV
    - also multi-purpose 4\(\pi\) detector for other physics
Integrated Luminosity

• Belle has accumulated the world largest integrated luminosity of > 1ab⁻¹!
  – ~0.77 Billion B meson pairs on Y(4S)
  – ~1.3 Billion charm pairs
  – ~0.9 Billion τ pairs

• → very good playground for heavy flavor physics!
Disclaimer

• Only recent results are shown so there are many important/your favorite analyses I cannot cover.
B Physics
KM unitarity triangle and CPV parameter convention

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

by Wolfenstein parameterization

Irreducible complex phase cause CP Violation!

Comprehensive test; measure all the angles and sides.

B system: very good place, all the angle are O(0.1)!
Time Dependent CPV

- Time dependent CPV arises from interference of mixing and decay.
  - Final states should be accessible from both $B^0$ and $B^{0}\overline{b}$

\[
A_{\text{CP}}(f_{\text{CP}}; t) = \frac{N(B^0(t) \rightarrow f_{\text{CP}}) - N(B^{0}\overline{t}(t) \rightarrow f_{\text{CP}})}{N(B^0(t) \rightarrow f_{\text{CP}}) + N(B^{0}\overline{t}(t) \rightarrow f_{\text{CP}})} \\
= S \sin \Delta m_d t + A \cos \Delta m_d t
\]

\[
S = \frac{2\text{Im}\lambda}{|\lambda|^2 + 1} \quad A = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \quad \lambda = \frac{q A(B^0 \rightarrow f_{\text{CP}})}{p A(B^{0}\overline{t} \rightarrow f_{\text{CP}})}
\]

- In the SM
  - $B^0 \rightarrow (cc)K^0 : S = -\frac{\xi_{\text{CP}}}{2} \sin 2\phi_1$ , $A = 0$
  - $B^0 \rightarrow \pi^+ \pi^- : S = \sin 2\phi_2$ (if tree only)
B→(cc)K⁰ samples for Final sin2ϕ₁

### CP-odd

<table>
<thead>
<tr>
<th></th>
<th>J/ψ K_s</th>
<th>J/ψ K_L</th>
<th>ψ(2S) K_s</th>
<th>χ_{c1} K_s</th>
<th>N_{BB}</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{sig.}</td>
<td>12727 ± 115</td>
<td>10087 ± 154</td>
<td>1981 ± 46</td>
<td>943 ± 33</td>
<td>772 M</td>
</tr>
<tr>
<td>Purity(%)</td>
<td>97</td>
<td>63</td>
<td>93</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>N_{sig.} (prev.)</td>
<td>7484 ± 87</td>
<td>6512 ± 123</td>
<td>Not used.</td>
<td>Not used.</td>
<td>535 M</td>
</tr>
<tr>
<td>Purity(%) (prev.)</td>
<td>97</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ M_{bc} \text{ (GeV/c}^2 \text{)} \]

\[ \text{events / 1 MeV/c}^2 \]

### CP-even

- Data
- J/ψK_L
- J/ψK_s X BG, K_L detected
- J/ψX BG, other
- Combinatorial BG

\[ p_{\text{miss}} \text{ (GeV/c)} \]
**Final sin $2\phi_1$ in $B \to (cc)K^0$**

\[ \sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012 \]
\[ A = 0.006 \pm 0.016 \pm 0.012 \]

Still statistically dominated $\to$ Belle II
Most precise measurement!

previous analysis  \[
\begin{align*}
\sin 2\phi_1 &= 0.642 \pm 0.031 \pm 0.017 \\
A &= 0.018 \pm 0.021 \pm 0.014
\end{align*}
\]

\[\sin(2\beta) \equiv \sin(2\phi_1)\]
\[ \sin 2\phi_1 \text{ in } B \rightarrow D^+D^- \]

- SM predicts \( S = \sin 2\phi_1 \) and \( A=0 \)
- But penguin contribution is larger than \( B \rightarrow (cc)K^0 \)
  - If new physics enhances the penguin amplitudes, \( S \) and \( A \) can be deviated from the SM values.

- Reconstruction
  - \( B^0 \rightarrow D^+D^- \rightarrow (K^-\pi^+\pi^+)(K^+\pi^-\pi^-) \)
    \( \rightarrow (K^-\pi^+\pi^+)(K_S^0\pi^-) \)
  
  \[
  S_{D^+D^-} = -1.06 \pm 0.21 \pm 0.08 \\
  C_{D^+D^-} = -0.43 \pm 0.16 \pm 0.05 
  \]

4.2\sigma from no CPV

PRD 85, 091106(R) (2012)
\( \sin 2\phi_1 \) in \( B \to D^{*+}D^{*-} \)

- Similar to \( B \to D^+D^- \) but needs angular analysis to decompose CP even/odd fraction

\[
R_0 = 0.624 \pm 0.029 \pm 0.007 \\
R_\perp = 0.138 \pm 0.024 \pm 0.005 \quad \text{(CP-odd)}
\]

- First observation of Time Dependent CP violation in \( B \) to open charm decays

\[
S = -0.79 \pm 0.13 \pm 0.05 \\
A = 0.15 \pm 0.08 \pm 0.06
\]
$\sin 2\phi_1$ in $B^0 \rightarrow D^* \pm D^\mp$

- $B^0$ can decay into both non-CP eigenstates $D^{*+}D^-$ and $D^{*-}D^+$.
  - 5 TDCPV parameters
  - If relative hadronic phase can be neglected

$$f_{D^* \pm D^\mp}(\Delta t) = (1 \pm A_{D^*D}) \frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}} \times \{1 + q[(S_{D^*D} \pm \Delta S_{D^*D}) \sin(\Delta m_d \Delta t) - (C_{D^*D} \pm \Delta C_{D^*D}) \cos(\Delta m_d \Delta t)]\}$$

$A_{D^*D} = +0.06 \pm 0.05 \pm 0.02$
$S_{D^*D} = -0.78 \pm 0.15 \pm 0.05$
$C_{D^*D} = -0.01 \pm 0.11 \pm 0.04$
$\Delta S_{D^*D} = -0.13 \pm 0.15 \pm 0.04$
$\Delta C_{D^*D} = +0.12 \pm 0.11 \pm 0.03$

4.0$\sigma$ from no CPV

PRD 85, 091106(R) (2012)
\[ B \rightarrow a_1^{\pm} \pi^{\mp} \]

- \( B \rightarrow a_1^{\pm} \pi \) can be used to extract \( \phi_2 \).
- Signal extracted from a 4D(\( \Delta E, F, m_{3\pi}, H_{3\pi} \)) fit

\[ N_{\text{sig.}} = 1445 \pm 101 \]

\[ \text{Br}(B^0 \rightarrow a_1^{\pm}(1260)\pi^-) \times \text{Br}(a_1^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}) = (11.1 \pm 1.0 \pm 1.4) \times 10^{-6} \]
The document discusses the measurement of the mixing-induced CP violation parameter $\phi_2^{\text{eff}}$ in the decay $B \rightarrow a_1^{\pm} \pi^\mp$. The measurement is significant because it provides the first evidence of such CP violation in this decay channel with a statistical significance of $3.1\sigma$.

$\phi_2^{\text{eff}}$ is determined with a four-fold ambiguity, which can be resolved using isospin analysis as described in the references:


The measured values are:

- $A_{\text{CP}} = -0.06 \pm 0.05 \pm 0.07$
- $C_{\text{CP}} = -0.01 \pm 0.11 \pm 0.09$
- $S_{\text{CP}} = -0.51 \pm 0.14 \pm 0.08$
- $\Delta C = +0.54 \pm 0.11 \pm 0.07$
- $\Delta S = -0.09 \pm 0.14 \pm 0.06$

The angle $\phi_2^{\text{eff}}$ is further constrained by\the following intervals:

- $[-25.5^\circ, -9.1^\circ]$ with $A_{\text{CP}}$
- $[34.7^\circ, 55.3^\circ]$ with $S_{\text{CP}}$
- $[99.1^\circ, 115.5^\circ]$ with $C_{\text{CP}}$

The parameter $\phi_2$ can be extracted using isospin analysis and SU(3) flavour symmetry, as mentioned in the references.

References:

\( \phi_3 \) measurements from \( B \to DK \)

- Access \( \phi_3 \) via interference between \( B \to DK \) and \( B \to \overline{D}K \)

\[
\begin{align*}
\text{color allowed} & \quad \begin{array}{c}
B^- \to D^0 K^- \\
& \sim V_{cb} V_{us}^* \\
& \sim A \lambda^3
\end{array} \\
\text{color suppressed} & \quad \begin{array}{c}
B^- \to D^0 K^- \\
& \sim V_{ub} V_{cs}^* \\
& \sim A \lambda^3 (\rho + i \eta)
\end{array}
\end{align*}
\]

\[
\frac{r_B}{|A_{\text{allowed}}|} = \frac{|A_{\text{suppressed}}|}{|A_{\text{allowed}}|} \sim \frac{V_{ub} V_{cs}^*}{V_{cb} V_{us}^*} \times \text{[color supp.]} = 0.1 - 0.2
\]

Relative weak phase is \( \phi_3 \),
Relative strong phase is \( \delta_B \).
\( \phi_3 \) measurements from \( B \rightarrow DK \)

- Reconstruct \( D \) in final states accessible to both \( D^0 \) and \( \overline{D^0} \)
  - Tree-body decay as \( D \rightarrow K_S \pi^+ \pi^-, K_S K^+ K^- \)
  - \( D = D_{sup} \), Doubly-Cabbibo-suppressed decay as \( K\pi \)
  - \( D = D_{CP} \), CP eigenstates as \( K^+ K^-, \pi^+ \pi^-, K_S \pi^0 \)

- Charm mixing and CPV are negligible.

  Y.Grossman, A.Soffer, J.Zupan
  [PRD 72, 031501 (2005)]
Binned Dalitz ($B^- \to [K_S\pi\pi]_D K^-$)

- Avoid the modeling error by optimal binning of the Dalitz($K_S\pi\pi$) plot

\[ \phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ \]
\[ r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011 \]
\[ \delta_B = (129.9 \pm 15.0 \pm 3.8 \pm 4.7)^\circ \]

The 3rd errors come from binning in Dalitz plane provided by CLEO-c.

$\phi_3 = (80.8^{+13.1}_{-14.8} \pm 5.0 \pm 8.9)^\circ$

Previous result
\[ r_B = 0.161^{+0.040}_{-0.038} \pm 0.011^{+0.050}_{-0.010} \]
\[ \delta_B = (137.4^{+13.0}_{-15.7} \pm 4.0 \pm 22.9)^\circ \]
ADS in neutral B

- ADS in charged B
  - Suppressed B decay $\times$ Favored D decay $\times$ color suppression
  - Favored B decay $\times$ Doubly Suppressed D decay
  - amplitude ratio $(r_B)$ for the two paths is $0.1 \sim 0.2$

$$r_B \sim \frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*} \times \text{[color supp.]} \sim 0.1-0.2$$

- ADS in neutral B
  - Both paths are color suppressed.
  - The amplitude ratio $(r_s)$ can be $\sim 0.4 \rightarrow$ larger CPV and higher sensitivity to $\phi_3$ are expected!!
ADS in $B^0 \rightarrow [K\pi]_D K^{*0}$

B flavor is tagged by the charge of K from $K^*$. ($K^*$ is reconstructed with charged K and $\pi$.)

$$R_{DK^{*0}} = \frac{\Gamma(B^0 \rightarrow [K^{-}\pi^+]_D K^{+}\pi^-)}{\Gamma(B^0 \rightarrow [K^{+}\pi^-]_D K^{-}\pi^+)} = r_S^2 + r_D^2 + 2k r_S r_D \cos(\delta_S + \delta_D) \cos \phi_3$$

$$R_{DK^{*0}} < 0.16 \text{ @95 \% C.L}$$
$$r_S < 0.4 \text{ @ 95 \% C.L.}$$

Most stringent limit on $R_{DK^{*0}}$ to date
Charm Physics
Large $D^0$ mixing observed by Belle, Babar and CDF is one of the interesting results in charm physics.

Since $D^0$ mixing ($x$ and $y$) is small, decay rate can be expressed by

$$\frac{dN_{D^0\rightarrow f}}{dt} \propto |\langle f|\mathcal{H}|D^0(t)\rangle|^2 = e^{-\Gamma t} |\langle f|\mathcal{H}|D^0\rangle|^2 + \frac{q}{p} \left( \frac{y + ix}{2}\Gamma t \right) |\langle f|\mathcal{H}|D^0\rangle|^2$$

- Exponential decay modulates with $x$ and $y$ very slowly

Measurement of life time difference btw flavor specific $K^+K^-$ and $\pi^+\pi^-$ and CP eigenstate $K^+\pi^-$ can probe $y_{CP}$

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$$

If CP conserved, $y_{CP} = y$

If CP is violated, lifetime asymmetry seen

$$A_{\Gamma} = \frac{\tau(D^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^+K^-)}{\tau(D^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^+K^-)}$$

$$y_{CP} = y \cos \phi - \frac{1}{2} A_M x \sin \phi$$

$$A_{\Gamma} = \frac{1}{2} A_M y \cos \phi - x \sin \phi$$

Evidence for difference of CPV was observed by LHCb and CDF.
Proper Time Distributions

- Simultaneous binned fit to KK, $K\pi$ and $\pi\pi$.

3-layer SVD
153 fb$^{-1}$

4-layer SVD
823 fb$^{-1}$
Fit Result

• Measurement of $\gamma_{CP}$ with a significance of $4.5\sigma$
  – $5.1\sigma$ if only stat error considered

• $A_{\Gamma}$ is consistent with null.

\[ \gamma_{CP} = (+1.11 \pm 0.22 \pm 0.11)\% \]
\[ A_{\Gamma} = (-0.03 \pm 0.20 \pm 0.08)\% \]
$D_s$ Decay Constant $f_{Ds}$

- Decay constant $f_{Ds}$ can be extracted from measurements of branching fraction of pure leptonic decays.
  - Test of Lattice QCD.
  - SU(3) flavor breaking by taking ratio $f_{Ds}/f_D$
    - To check $B$ meson decay constant, since $f_{Ds}/f_D = f_{Bs}/f_B$ is good approximation

\[
\mathcal{B}(D_s^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} f_{D_s}^2 |V_{cs}|^2 \tau_{D_s} M_{D_s} m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right)^2
\]
Reconstruction of Unbiased $D_s$

- Using a recoil mass technique, unbiased $D_s$ is reconstructed.

$$e^+ e^- \rightarrow c\bar{c} \rightarrow D_{\text{tag}} K X_{\text{frag}} D_s^{\ast +}$$

$$X_{\text{frag}} = \text{nothing, } \pi^\pm, \pi^0, \pi^\pm \pi^\pm, \pi^\pm \pi^0, \pi^\pm \pi^\pm \pi^\pm, \pi^\pm \pi^\pm \pi^0$$

$$M_{\text{miss}}^2(D_{\text{tag}} K X_{\text{frag}} \gamma) = |p_{e^+ e^-} - p_{D_{\text{tag}}} - p_K - p_{X_{\text{frag}}} - p_\gamma|^2$$
$D_s \to l\nu$

- Leptonic decays are reconstructed by
  - $D_s \to \mu\nu$ : $\mu$ and $m_{\nu}^2 = 0$ in $M^2_{miss}(D_{tag}KX_{frag}\gamma\mu)$
  - $D_s \to \tau\nu$, $\tau \to e\nu\nu, \mu\nu\nu, \pi\nu$:
    - Single charged particle
    - Extra Energy in ECL $E_{ECL} = 0$

- Branching Fraction and Decay constant

\[
\begin{align*}
B(D_s^+ \to \mu^+\nu_\mu) &= (0.528 \pm 0.028(\text{stat.}) \pm 0.019(\text{syst.}))% \\
B(D_s^+ \to \tau^+\nu_\tau) &= (5.70 \pm 0.21(\text{stat.}) \pm 0.31(\text{syst.}))% 
\end{align*}
\]

Belle Preliminary (913 fb⁻¹)

<table>
<thead>
<tr>
<th>$D_s \to l\nu$</th>
<th>$f_{D_s}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\nu$</td>
<td>$249.0 \pm 6.6(\text{stat.}) \pm 4.6(\text{syst.}) \pm 1.7(\tau_{D_s})$</td>
</tr>
<tr>
<td>$\tau\nu$</td>
<td>$261.9 \pm 4.9(\text{stat.}) \pm 7.0(\text{syst.}) \pm 1.8(\tau_{D_s})$</td>
</tr>
<tr>
<td>Combination</td>
<td>$255.0 \pm 4.2(\text{stat.}) \pm 4.7(\text{syst.}) \pm 1.8(\tau_{D_s})$</td>
</tr>
</tbody>
</table>
**f_{D_s} Comparison**

- **Belle result** is the most precise to date.
- **Experimental average** is consistent with (and 1.8\(\sigma\) away from) the most precise Lattice QCD result.

### Table: f_{D_s} [MeV]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mode</th>
<th>B</th>
<th>(f_{D_s}^{(5)}) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO-c</td>
<td>(\mu^+\nu)</td>
<td>((5.65 \pm 0.45 \pm 0.17) \times 10^{-3})</td>
<td>257.6 (\pm 10.3 \pm 4.3)</td>
</tr>
<tr>
<td>BaBar</td>
<td>(\mu^+\nu)</td>
<td>((6.02 \pm 0.38 \pm 0.34) \times 10^{-3})</td>
<td>265.9 (\pm 8.4 \pm 7.7)</td>
</tr>
<tr>
<td>Belle</td>
<td>(\mu^+\nu)</td>
<td>((5.28 \pm 0.28 \pm 0.19) \times 10^{-3})</td>
<td>249.0 (\pm 6.6 \pm 4.9)</td>
</tr>
<tr>
<td>Average</td>
<td>(\mu^+\nu)</td>
<td>((5.54 \pm 0.24) \times 10^{-3})</td>
<td>255.1 (\pm 5.5)</td>
</tr>
<tr>
<td>CLEO-c</td>
<td>(\tau^+\nu)</td>
<td>((5.58 \pm 0.33 \pm 0.13) \times 10^{-2})</td>
<td>259.1 (\pm 7.7 \pm 3.5)</td>
</tr>
<tr>
<td>BaBar</td>
<td>(\tau^+\nu)</td>
<td>((5.00 \pm 0.35 \pm 0.49) \times 10^{-2})</td>
<td>245.3 (\pm 8.6 \pm 12.2)</td>
</tr>
<tr>
<td>Belle</td>
<td>(\tau^+\nu)</td>
<td>((5.70 \pm 0.21 \pm 0.31) \times 10^{-2})</td>
<td>261.9 (\pm 4.9 \pm 7.2)</td>
</tr>
<tr>
<td>Average</td>
<td>(\tau^+\nu)</td>
<td>((5.54 \pm 0.24) \times 10^{-2})</td>
<td>258.2 (\pm 5.6)</td>
</tr>
<tr>
<td>Experimental Average</td>
<td>(\mu^+\nu + \tau^+\nu)</td>
<td></td>
<td>257.2 (\pm 4.5)</td>
</tr>
<tr>
<td>Lattice HPQCD</td>
<td></td>
<td></td>
<td>248.0 (\pm 2.5)</td>
</tr>
</tbody>
</table>

**Experimental W.A.: 257.2 \pm 4.5 MeV**
Lattice (HPQCD): 248.0 \pm 2.5 MeV
Summary

• Belle has accumulated the world largest integrated luminosity of more than 1ab$^{-1}$.

• With the data, recent results on B and charm are shown
  – $\phi_1 : B \rightarrow (cc)K^0, DD, D^*D, D^*D^*$
  – $\phi_2 : B \rightarrow a_1\pi$
  – $\phi_3 : B \rightarrow DK$
  – $D^0$ mixing
  – Decay constant of Ds meson

• Still many analyses for final results are in pipeline. Stay tuned!

• Belle II at Super-KEKB which is under construction will probe new physics with 50 times larger data.
  – $\rightarrow$ Thomas Kuhr’s talk
backup
Previous $\sin 2\phi_1$ in $B \to (cc)K^0$

\[
\sin 2\phi_1 = 0.642 \pm 0.031 \pm 0.017 \\
A = 0.018 \pm 0.021 \pm 0.014
\]