\( \phi_1 \) and \( \phi_2 \) at Belle (II)

Yosuke Yusa
Niigata University
$$\phi_1 / \phi_2 \quad \text{— angles of unitary triangle}$$

Quark transition: Cabibbo-Kobayashi-Maskawa (CKM) Matrix

CP violation is induced by complex phase and parameterized as angles of the unitary triangle.

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

Decay rate is described as difference of decay time between $B^0$ mesons.

$$A_{CP} = \frac{\mathcal{P}(B^0(\Delta t) \to f_{CP}) - \mathcal{P}(B^0(\Delta t) \to \bar{f}_{CP})}{\mathcal{P}(B^0(\Delta t) \to f_{CP}) + \mathcal{P}(B^0(\Delta t) \to \bar{f}_{CP})}
= S \sin \Delta m \Delta t + A \cos \Delta m \Delta t
$$

mixing induced CPV direct CPV

$\Delta m$: mass difference of eigenstates
$\Delta t$: decay time difference of eigenstates
**$\phi_1$ measurement**

Time-dependent CP violation:
Quantum interference between two diagrams.

\[ \phi_1(=\beta) = \text{arg}(V_{cd} V_{cb}^*/V_{td} V_{tb}^*) \]

→ Accessible using CP-eigenstates induced by $b\to c\bar{c}s$ tree diagram.

\[ S = -\xi_f \sin 2\phi_1 \]

\[ \xi_f: \text{CP eigenvalue:} \]

-1 for $(c\bar{c})K^0_S$, +1 for $(c\bar{c})K^0_L$

Since contribution from other diagrams are tiny, $\phi_1$ measured from these CP-eigenstates are theoretically clean.

→ Good reference point of the Standard Model.

\[ \sin 2\phi_1 = 0.668\pm0.023\pm0.013, \]

\[ A = 0.007\pm0.016\pm0.013 \]
$\phi_1$ measurement

$\phi_1$ is also measured using CP-eigenstates induced by $b \rightarrow c\bar{c}d$ tree diagram.
Pollution from penguin diagram can be considered but effect is expected to be low in SM.
→ If large deviation from $b \rightarrow c\bar{c}s$ is seen,
it indicates contribution of new physics.

In $B^0 \rightarrow D^+D^-$, large direct CP violation was seen in Belle (4.0 $\sigma$).
Tension is relaxed after update but we need further study using more statistics.

$B^0 \rightarrow J/\psi\pi^0$ can be used for estimation of possible penguin polution in $B^0 \rightarrow J/\psi K^0$
(PRL 95, 221804 (2005)) → Necessary information for large statistic measurement.
\( \phi_2(=\alpha) = \arg(V_{ud} V_{ub}^*/V_{td} V_{tb}^*) \)

→ Accessible via \(b\rightarrow u\) tree diagram but contribution from \(b\rightarrow d\) penguin diagram is not negligible.

\[ S = -\xi f \sqrt{1-A^2} \sin 2 \phi_2^{\text{eff}} \]

\( \phi_2^{\text{eff}} = \phi_2 - \Delta \phi_2 \) ("effective" \( \phi_2 \))

**Strategies to determine \( \phi_2 \) without CP phase from penguin contamination**

- Isospin relations between \( B \rightarrow \pi^i \pi^j / \rho^i \rho^j \) decay amplitudes

Gronau and London, PRL65 3381 (1990)

\[ A^{+0} = \frac{1}{\sqrt{2}} A^{+-} + A^{00} \]  
\[ A^{-0} = \frac{1}{\sqrt{2}} \overline{A}^{+-} + \overline{A}^{00} \]  

\( A^{ij} \) : Decay amplitudes of \( B \rightarrow \pi^i \pi^j / \rho^i \rho^j \)

⇒ Using branching fractions and CP violation parameters, \( \Delta \phi_2 \) is determined with four-fold ambiguity.

- Dalitz analysis for \( \pi \pi \pi^0 \) 3-body system

A. Snyder and H. Quinn, PRD 48 2139 (1993)

Interference between three \( B \rightarrow \rho \pi \) states  
\( \Delta t \) fit with coefficients of Dalitz plot functions

⇒ Constrain \( \phi_2 \) with a small ambiguity in theoretical point of view.
sin2 φ \text{_{1\,\text{eff}}} measurement in \(b \to sqq\)

Same weak phase as \(b \to c\bar{c}s\)

if only SM penguin contributes.

\[ S = -\xi_f \sin2 \phi \text{_{1\,\text{eff}}} = -\xi_f \sin2 \phi \text{_{1}} \]

Penguin loop is sensitive to the new physics contribution.

\[ S = -\xi_f \sin2 \phi \text{_{1\oplus}} \text{ extra CP phase from non-SM?} \]

<table>
<thead>
<tr>
<th>(B^0 \to \eta , 'K^0)</th>
<th>(\Delta S)</th>
<th>BF (x10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^0 \to \phi , K^0)</td>
<td>0.02±0.01</td>
<td>0.86</td>
</tr>
<tr>
<td>(B^0 \to \omega , K^0 S)</td>
<td>0.13±0.08</td>
<td>0.5</td>
</tr>
<tr>
<td>(B^0 \to \rho^0 K^0 S)</td>
<td>-0.08+0.08</td>
<td>-0.12</td>
</tr>
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<td>(B^0 \to K^0 S \pi^0)</td>
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Hai-Yang Cheng, hep-ph/0702252

\(\Delta S\): \(S\) shift from theoretically predicted from other SM diagrams (mainly from \(b \to u\) tree)

J. Zupan, hep-ph/0707.1323

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6th KEK Flavor Factory Workshop (KEK-FF 2019), February 15 2019, KEK
$\sin 2\phi_1^{\text{eff}}$ measurement in $b \to sqq$

Same weak phase as $b \to c\bar{c}s$

if only SM penguin contributes.

$S \equiv -\xi_f \sin 2\phi_1^{\text{eff}} = -\xi_f \sin 2\phi_1$

Penguin loop is sensitive to the new physics contribution.

$S = -\xi_f \sin 2\phi_1 \oplus \text{extra CP phase from non-SM?}$

Naïve $b \to s$ penguin average

$\sin 2\phi_1^{\text{eff}} = 0.655 \pm 0.032$

$b \to c$ tree average

$\sin 2\phi_1 = 0.699 \pm 0.017$

Theoretical shifts below are not considered for “naïve” average.

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Hai-Yang Cheng, hep-ph/0702252

$\Delta S$: $S$ shift from theoretically predicted from other SM diagrams (mainly from $b \to u$ tree)
sin2 \phi_1^{\text{eff}} \text{ measurement in } b \to ssq

Same weak phase as \( b \to cc \bar{s} \)
if only SM penguin contributes.

\[ S = -\xi_f \sin 2 \phi_1^{\text{eff}} = -\xi_f \sin 2 \phi_1 \]

Penguin loop is sensitive to the new physics contribution.

\[ S = -\xi_f \sin 2 \phi_1^{\text{eff}} \text{ or } \text{extra CP phase from non-SM?} \]

Naiive \( b \to s \) penguin average

\[ \sin 2 \phi_1^{\text{eff}} = 0.655 \pm 0.032 \]

\( b \to c \) tree average

\[ \sin 2 \phi_1 = 0.699 \pm 0.017 \]

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J. Zupan, hep-ph/0707.1323

Δ\( S \): \( S \) shift from theoretically predicted from other SM diagrams (mainly from \( b \to u \) tree)

\( \sin (2\beta^{\text{eff}}) = \sin (2\phi_1^{\text{eff}}) \)

Also, \( b \to u \) tree

Hai-Yang Cheng, hep-ph/0702252

Recently published using Belle full data

\( \Delta S \) shift from theoretically predicted from other SM diagrams (mainly from \( b \to u \) tree)
Vertex reconstruction and Charged particle tracking
- Silicon vertex detector: 3/4 layers DSSD
- Central Drift Chamber: small cell +He/C₂H₆
- Superconducting solenoid: 1.5T magnetic field

Particle identification
- 3.5 GeV e⁺
- Aerogel Cherenkov counter: Aerogel radiator + PMT
- Time-of-Flight counter
- γ/electron measurement
  - CsI(Tl) Electromagnetic calorimeter
- μ identification/K⁻ detection
  - 14/15 layers Resistive Plate Counter+Fe

8 GeV e⁻ → 3.5 GeV e⁺ → γ → 8 GeV e⁻
Photon detection in Belle

Photon detection efficiency degradation (-10%) due to materials between $e^+e^-$ interaction point and calorimeter.

Photon convert vertex position studied in $B^0 \rightarrow \pi^0 \pi^0 K^0_S$ (MC)

(Calorimeter is located outside region of these plots)

Efficiency to detect 2 $\pi^0$ decays into 4 photons is $< (1-0.1)^4 = 64\%$.

$\Rightarrow$ We need large statistics to analyze $B$ decays including multi-$\pi^0$.

To solve this issue, Cherenkov counter is replaced to low material devices in Belle II.
How to obtain $\phi_1/\phi_2$ — reconstruction of CP side

Reconstruct CP-side using momentum, energy and particle identification information from detector.

Suppression of continuum background is done using shape variable parameter of all observables in an event.

**Reconstructed variables in $B^0 \rightarrow \pi^0 \pi^0 K^0_S$ analysis**

Fraction of signal and background used to extract CP violation parameters is obtained from the fit to kinematic variables together with that used for continuum suppression.

Signal yield with vertex information $= 146.7 \pm 23.6$ events
How to obtain $\phi_1 / \phi_2$ — Fit to $\Delta t$ and $q$

- $\Delta t$ is measured by vertex positions of $B$ and $\bar{B}$.
- Tag side

Remaining observables in an event is used for flavor determination $\bar{B}^0 \to D^{*+} l^- \nu$, $B^0 \to D^{*\pm} D^0 \pi^+$, $D^0 \to K^- l^+ \nu$.

To determine flavor based on integrated information, multi-dimensional likelihood is used in Belle. New technologies are introduced in Belle II (Boosted Desision Tree, Artificial Neural Network, Deep Neural Network).

$\Delta t$ distribution (lifetime fit)

$B^0 \to J/\psi K^0_S$ from 772M BB

$q$-integrated

$10^3$

$10^2$

$10^1$

$10^0$

$10^{-1}$

$10^{-2}$

$10^{-3}$

events / $0.5 \text{ ps}$

$\Delta t$ (ps)

CP violation parameters ($S, A$) are obtained by the fit to $\Delta t$.

Signal PDF: $P(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} q( A \cos m\Delta t + S \sin m\Delta t )$.
**Vertex reconstruction with Ks**

Vertex reconstruction using non-primary tracks is available with constraint on interaction point (IP).

**Standard vertex reconstruction**

- IP constraint calculated by every 10000 events average

This technique enables time-dependent CP violation measurements in CP-eigenstates in which no primary tracks from IP.

“Measurement of CP asymmetries in $B^0 \rightarrow K^0 \pi^0$ decays”


In Belle II, constraint from IP is expected to be better due to nano-beam scheme (demonstrated later). $\rightarrow$ Vertex quality should be improved.
**\( \phi_1^{\text{eff}} \) measurement in \( B^0 \rightarrow \pi^0 \pi^0 K^0_S \)**

![Graph showing the measurement of \( \phi_1^{\text{eff}} \) in the decay \( B^0 \rightarrow \pi^0 \pi^0 K^0_S \). The graph includes histograms for the signal and background, as well as a plot of the raw asymmetry against the decay time difference. The result is given by \( \sin 2\phi_1^{\text{eff}} = 0.92^{+0.27}_{-0.31} \) (stat.) \( +0.10^{-0.11} \) (syst.), and the asymmetry \( A = 0.28 \pm 0.21 \) (stat.) \( \pm 0.04 \) (syst.).](image)

First published result from Belle. Third measurement of \( \sin 2\phi_1^{\text{eff}} \) using CP-even eigenstate induced by \( b \rightarrow s q\bar{q} \) followed by \( B^0 \rightarrow \eta \ ' K^0_L \) and \( B^0 \rightarrow \phi K^0_L \).

Consistent with SM expectation.
### Belle II — Where we are now?

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Feb. Phase 1 (w/o Belle, w/o final focusing) starts</td>
</tr>
<tr>
<td></td>
<td>Jun. Phase 1 ends</td>
</tr>
<tr>
<td>2017</td>
<td>Apr. Belle II detector roll in</td>
</tr>
<tr>
<td>2018</td>
<td>Mar. Phase 2 (partial VXD, w/ final focusing) starts</td>
</tr>
<tr>
<td></td>
<td>Apr. First collision</td>
</tr>
<tr>
<td></td>
<td>Jul. Phase 2 ends</td>
</tr>
<tr>
<td></td>
<td>Integrated luminosity ~500 pb⁻¹</td>
</tr>
<tr>
<td>2019</td>
<td>Mar. Phase 3 (almost full VXD) starts</td>
</tr>
</tbody>
</table>

- Onwards to Phase 3 and the Physics Run
- The VXD will be installed in Phase 3.
- Restart Belle II data taking in February 2019.

**SVD** +x half-shell, Jan 2018
- SVD -x half-shell, July 2018

**PXD layer 1 ladders**
- First PXD half-shell being tested at DESY

The scene at the experimental control room in Tsukuba Hall B3

This is scientific history in the making:
- SuperKEKB / Belle II joins DORIS/ARGUS, CESR/CLEO, and PEP-II/BaBar and KEKB/Belle

Some Belle II jargon

**PHASE 1**: Simple background commissioning detector (diodes, diamonds TPCs, crystals…). No final focus.
- Only single beam background studies possible [started in Feb 2016 and completed in June 2016.]

**PHASE 2**: More elaborate inner background commissioning detector (VXD samples).
- Full Belle II outer detector.
- Full superconducting final focus.
- No vertex detectors.

[Phase 2 collisions: April 26 - July 17, 2018]

6th KEK Flavor Factory Workshop (KEK-FF 2019), February 15 2019, KEK
Belle II detector

PXD and SVD has been installed after phase 2 and ready now. Problems of subsystem found in phase 2 operation are fixed.
Benefits of upgrade for $\phi_1/\phi_2$ measurements

Smaller radius of inner layers of PXD contributes to improve vertex resolution.

$\rightarrow$ Resolution of tracking improves 40%

More $K^0_S$ decay inside of larger radius of outer SVD layer.

$\rightarrow$ $K^0_S$ finding efficiency increases.

Efficiency of vertex reconstruction using $K^0_S$ daughter improves.

Improvement of particle identification performance contributes to flavor tagging quality.

Photon detection efficiency increases due to less material of inner part.
Phase 2 data analysis

Spread of IP estimated using closest approach of tracks in $z$-coordinate is consistent with small beam crossing spot size calculated from phase 2 beam optics.

Using 500 pb$^{-1}$ of the data collected during phase 2 operation, we confirm many of particles that are included in CP-eigenstates are reconstructed.
Phase2 data analysis

Using 500 pb\(^{-1}\) of the data collected during phase 2 operation, we confirm many of particles that are included in CP eigenstates can be reconstructed.

\[ B^{0,+} \rightarrow J/\psi \, K^{0(*)/+} \]

\( B^{0,\rightarrow J/\psi \, K^{0,s} \) sign is indicated in reconstructed distributions (orange and magenta).
Re-discovery of CP-violation within our reach
Re-discovery of CP-violation within our reach

Integrated Luminosity [fb⁻¹]

5.1 fb⁻¹

\( B^0 \bar{B}^0 \rightarrow \text{Dilepton (mixing)} \)

29.1 fb⁻¹

\( B^0 \rightarrow (cc)K^0 (\phi_1) \)

264 events (KLR > 0.86) \( \chi^2 = 12.5/12 \)

219 events (KLR > 0.86) \( \chi^2 = 14.7/16 \)

140 fb⁻¹

\( B^0 \rightarrow \pi^+ \pi^- (\phi_2) \)

600

400

200

0

1998

2000

2002

2004

2006

2008

2010

2012

5.9 fb⁻¹

\( B^0 \rightarrow \eta'K^0_S (\phi_{1eff}) \)

6th KEK Flavor Factory Workshop (KEK-FF 2019), February 15 2019, KEK
Re-discovery of CP-violation within our reach

Integrated Luminosity [fb⁻¹]

- $A(\Delta z) = \text{Nos} - \text{Nss}
  \quad \text{Nos + Nss}$
- $B^0 \bar{B}^0 \rightarrow \text{Dilepton (mixing)}$
- $5.1 \text{ fb}^{-1}$
- $B^0 \rightarrow (cc)K^0 \ (\phi \ 1)$
- $29.1 \text{ fb}^{-1}$
- $B^0 \rightarrow \eta'K_S$ (high statistics modes)
- $\eta' \rightarrow \pi\pi\pi\pi$
- $\chi^2 = 1.03 \pm 0.15 \pm 0.05$
- $N_{\text{sig}} = 512 \pm 27$
  purity 0.61
- $K^*K^-K^0$ (\phi excluded)
- $N_{\text{sig}} = 399 \pm 28$
  purity 0.56
- $513 \text{ fb}^{-1}$
- $B^0 \rightarrow \eta'K^0_S \ (\phi \ 1_{\text{eff}})$
- $253 \text{ fb}^{-1}$
- $\sin 2\phi_1$ is large:
  - $0.99 \pm 0.14 \pm 0.06$
- We are here (0.5 / fb)
- Phase 3 until 2019 summer

$A_{\pi\pi} = 0.58^{+0.15}_{-0.16}$ (MINOS)
$S_{\pi\pi} = -1.00^{+0.22}_{-0.20}$ (MINOS)

- $264 \text{ events} \ (KLR > 0.86)$
  $\chi^2 = 12.5/12$
- $219 \text{ events} \ (KLR > 0.86)$
  $\chi^2 = 14.7/16$

6th KEK Flavor Factory Workshop (KEK-FF 2019), February 15 2019, KEK
Far milestone — beyond Belle/BABAR results

Decay modes in which first observation of $\phi_1$ is expected using a few ab$^{-1}$ data.

**$b \rightarrow c$**

<table>
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<tr>
<th>Mode</th>
<th>Experiment (# of $BB$)</th>
<th>$S$</th>
<th>significance</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow J/\psi \pi^0$</td>
<td>BABAR (466M)</td>
<td>$-1.23 \pm 0.21 \pm 0.04$</td>
<td>$4.0 \sigma$</td>
<td>$0.20 \pm 0.19 \pm 0.03$</td>
</tr>
<tr>
<td></td>
<td>Belle (772M)</td>
<td>$-0.59 \pm 0.19 \pm 0.03$</td>
<td>$3.0 \sigma$</td>
<td>$0.08 \pm 0.16 \pm 0.05$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^+D^-$</td>
<td>BABAR (467M)</td>
<td>$-0.63 \pm 0.36 \pm 0.05$</td>
<td>—</td>
<td>$0.07 \pm 0.23 \pm 0.03$</td>
</tr>
<tr>
<td></td>
<td>Belle (772M)</td>
<td>$-1.06_{-0.14}^{+0.21} \pm 0.08$</td>
<td>$4.2 \sigma$</td>
<td>$0.43 \pm 0.16 \pm 0.05$</td>
</tr>
<tr>
<td></td>
<td>LHCb (3 fb$^{-1}$)</td>
<td>$-0.54_{-0.16}^{+0.17} \pm 0.05$</td>
<td>$4.0 \sigma$</td>
<td>$-0.26_{-0.17}^{+0.18} \pm 0.05$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^{<em>+}D^{</em>-}$</td>
<td>BABAR (467M)</td>
<td>$-0.70 \pm 0.16 \pm 0.03$</td>
<td>—</td>
<td>$-0.05 \pm 0.09 \pm 0.0$</td>
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<tr>
<td></td>
<td>Belle (772M)</td>
<td>$-0.79 \pm 0.13 \pm 0.03$</td>
<td>$5.4 \sigma$</td>
<td>$0.15 \pm 0.08 \pm 0.02$</td>
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<tr>
<td>$B^0 \rightarrow D^{*+}D^-$</td>
<td>BABAR (467M)</td>
<td>$-0.68 \pm 0.15 \pm 0.04$</td>
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<td>$-0.78 \pm 0.15 \pm 0.05$</td>
<td>$4.0 \sigma$</td>
<td>$0.01 \pm 0.11 \pm 0.04$</td>
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**$b \rightarrow s$**

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<td>$0.94_{-0.24}^{+0.21} \pm 0.06$</td>
<td>$3.8 \sigma$</td>
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<td>Belle (535M)</td>
<td>$0.30 \pm 0.32 \pm 0.08$</td>
<td>—</td>
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<td>$B^0 \rightarrow \pi^0K^0_s$</td>
<td>BABAR (467M)</td>
<td>$0.55 \pm 0.20 \pm 0.03$</td>
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<td>Belle (657M)</td>
<td>$0.67 \pm 0.31 \pm 0.08$</td>
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<tr>
<td>$B^0 \rightarrow \rho^0K^0_s$</td>
<td>BABAR (383M)</td>
<td>$0.35_{-0.31}^{+0.26} \pm 0.06 \pm 0.03$</td>
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<tr>
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<td>$0.91 \pm 0.32 \pm 0.05$</td>
<td>$3.1 \sigma$</td>
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Recently published. PRD98, 112008 (2018)

This will be revised soon using full data set.
milestone — beyond Belle/BABAR results

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$b \to s$

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<tr>
<th>Mode</th>
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<th>$S$</th>
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<td>$B^0 \to K^0_sK^0_sK^0_s$</td>
<td>BABAR (468M)</td>
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<tr>
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Recently published. PRD98, 112008 (2018)

This will be revised soon using full data set.
milestone — beyond Belle/BABAR results

Decay modes in which first observation of $\phi_1$ is expected using a few ab$^{-1}$ data.

### $b \rightarrow c$

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<tr>
<th>Mode $\rightarrow$</th>
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<th>$S$</th>
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<tr>
<td>$B^0 \rightarrow J/\psi \pi^0$</td>
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6th KEK Flavor Factory Workshop (KEK-FF 2019), February 15 2019, KEK

Recently published. PRD98, 112008 (2018)

Anomaly among experiments should be solved in future.

This will be revised soon using full data set.
milestone — beyond Belle/BABAR results

For $\phi_2$, new input for iso-spin relation analysis:

$B^0 \rightarrow \pi^0 \pi^0$ time-dependent analysis.

Electromagnetic calorimeter detects hit position of photons.

$\rightarrow$ In usual analysis, no $B^0$ decay vertex information from $\pi^0$.

If we use a large data sample in Belle II, we can approach “$\pi^0$ vertexing” using Dalitz decay ($\pi^0 \rightarrow e^+e^-\gamma$) or $\pi^0$ direction from photon conversion.

Although statistic error is large, (= ±0.28), we can reduce ambiguity for $\phi_2$. 

(Plots from Belle II Physics Book)
Systematic error in large statistic analysis

We have already been close to systematic limit.
In Belle II, we have to consider this issue in many studies.

<table>
<thead>
<tr>
<th>Categories</th>
<th>dS</th>
<th>dA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertexing</td>
<td>0.012</td>
<td>0.009</td>
</tr>
<tr>
<td>Possible fit bias</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>$\Delta t$ Resolution function</td>
<td>0.009</td>
<td>0.001</td>
</tr>
<tr>
<td>BG fractions ($J/\psi K_L$)</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>Wrong tag probability</td>
<td>0.004</td>
<td>0.003</td>
</tr>
<tr>
<td>BG fractions ($J/\psi K_S$)</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Fixed Physics parameters</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>BG $\Delta t$</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Tag-Side interference</td>
<td>0.001</td>
<td>0.009</td>
</tr>
<tr>
<td>Total</td>
<td><strong>0.019</strong></td>
<td><strong>0.014</strong></td>
</tr>
</tbody>
</table>

One reference point is systematic error in 2006:
dS = 0.019, dA = 0.014

At worst, same level with statistical error expected from toy study
dS = 0.024, dA = 0.016

Measured dS
0.019 ←?→ 0.024

We discussed whether we can set systematic uncertainty enough small comparing to previous analysis and also to expected of statistical error.

My slide in Belle general meeting for $\phi^1$ measurement in $B^0 \rightarrow (c\bar{c})K^0$ using full data.
Systematic error in large statistic analysis

Systematic is expected to be dominant in $\phi_1$ measurement using 50 ab$^{-1}$

Vertex improvement contributes to reduce systematic error of $S$.

If we use only high momentum leptons (mainly come from semi-leptonic decay) for flavor tagging, uncertainty from tag-side interference on $A$ is largely suppressed. Total error becomes small although statistic is sacrificed.

$\rightarrow$ We have to try further idea to suppress systematic error.
In some case, approach from theoretical side is needed.

<table>
<thead>
<tr>
<th>Error expectation considering luminosity scale (Belle II Physics Book)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{J/\psi K^0_S}$ (50 ab$^{-1}$)</td>
</tr>
<tr>
<td>stat.</td>
</tr>
<tr>
<td>syst. reducible</td>
</tr>
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</tbody>
</table>

| $A_{J/\psi K^0_S}$ (50 ab$^{-1}$)                  | No improvement | Vertex improvement | Leptonic categories |
| stat.                        | 0.0025         | 0.0025             | 0.0043             |
| syst. reducible             | 0.0007         | 0.0007             | 0.0007             |
| syst. irreducible           | +0.043         | +0.042             | 0.011              |

Interference between non-zero two diagram $\rightarrow$ CP violation in tag side: $2r' \sin(2\phi_1 + \phi_3 \pm \delta')$
Summary

$\phi_1$ and $\phi_2$ angles have been measured in Belle through time-dependent analysis of $B^0$ decays.

More sensitivity is expected in Belle II not only increasing of data but also from detector upgrade.

Decay products of CP-eigenstates have been already observed in phase 2 data.

From phase 3 operation with vertex detectors, measurements of $\phi_1$ and $\phi_2$ in Belle II are within our reach now.

We expect first observation in many decay modes but have to make effort for systematic estimation for high precision study.
Backup
How to obtain $\phi_1/\phi_2$ — signal reconstruction
Reconstruct CP-side using momentum, energy and particle
identification information from detector.

ex. $B^0 \to (c\bar{c})K^0_S$: Very clean signal, selected by loose criteria.

$B^0 \to J/\psi K^0_L$: Only $K^0_L$ flight direction is detected as hadron cluster
in KLM (Cluster energy can not obtained)

<table>
<thead>
<tr>
<th>$B^0 \to (c\bar{c})K^0_S$ (CP-odd: $\xi_f = -1$)</th>
<th>$B^0 \to J/\psi K^0_L$ (CP-even: $\xi_f = +1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Signal region of reconstructed energy" /></td>
<td><img src="image" alt="Data" /></td>
</tr>
<tr>
<td><img src="image" alt="Beam constraint mass: $M_{bc} = \sqrt{E_{beam}^2 - p_{B\text{CM}}^2}$" /></td>
<td><img src="image" alt="Fit" /></td>
</tr>
<tr>
<td><img src="image" alt="Events / 1 MeV/c²" /></td>
<td><img src="image" alt="BG w/ $K^0_L$" /></td>
</tr>
<tr>
<td><img src="image" alt="Events / 50 MeV/c" /></td>
<td><img src="image" alt="BG w/o $K^0_L$" /></td>
</tr>
<tr>
<td><img src="image" alt="J/ψ combinatorial BG" /></td>
<td><img src="image" alt="J/ψ" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$J/\psi K^0_S$</th>
<th>$\Psi (2S)K^0_S$</th>
<th>$\chi_{c1}K^0_S$</th>
<th>$J/\psi K^0_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal yield</td>
<td>12727±115</td>
<td>1981±46</td>
<td>949±33</td>
</tr>
<tr>
<td>Purity (%)</td>
<td>97</td>
<td>93</td>
<td>89</td>
</tr>
</tbody>
</table>

10th KEK Flavor Factory Workshop (KEK-FF 2019), February 15 2019, KEK
How to obtain $\phi_1/\phi_2$ — correction on $\Delta t$ and $q$

$q$ and $\Delta t$ change due to imperfectness of the measurement.

$\Delta t$:
- Detector resolution
- Non-primary track effect
  - $D$ lifetime $\neq 0$
- Kinematic approximation
  $$\Delta t \equiv \Delta z/c\beta\gamma \approx \Delta t_{\text{true}}$$

$q$:
- PID failure
- Ambiguity of flavor determination algorithm

Those effects is estimated using a large number of control sample of $B^0 \rightarrow D^*-\ell^+\nu$, $B^{0/+} \rightarrow D^{(*)}\pi/\rho$ and $B^+ \rightarrow J/\psi K^+$

$\Rightarrow$ Observed time-dependent decay rate

$$P_{\text{sig}}(\Delta t, q) = \frac{1}{4\tau} e^{t_{\text{TB}}} (1-2w)q(A \cos \Delta m \Delta t + S \sin \Delta m \Delta t) \otimes R(\Delta t)$$

- Dilution factor
- Resolution function
$B^0 \to J/\psi \pi^0$

N_{signal} = 332.0 \pm 22.1 \\
N_{qq} = 16.3 \pm 3.5 \\
\
S = -0.59 \pm 0.19 \pm 0.03 \\
A = -0.15 \pm 0.14^{+0.04}_{-0.03}$
Flavor tagging analysis stream in Belle

Information on charged tracks

- Slow pion
  - Select track with largest "r"
- Lambda
  - Calculate combined "q.r"
- Kaon
- Lepton
  - Select track with largest "r"

Track-level look-up tables

Event-level look-up table

q.r

(q.r)K/Λ

q.r

Flavor information "q" and "r"
**φ₂ measurement using isospin relation**

\[ B^0 \rightarrow \pi^+ \pi^- \]

**772M BB PRD 88 092003 (2013)**

\[ A_{CP}(B^0 \rightarrow \pi^+ \pi^-) = +0.33 \pm 0.06(\text{stat}) \pm 0.03(\text{syst}) \]

\[ S_{CP}(B^0 \rightarrow \pi^+ \pi^-) = -0.64 \pm 0.08(\text{stat}) \pm 0.03(\text{syst}) \]

\[ B(B^0 \rightarrow \pi^+ \pi^-) = (5.04 \pm 0.21 \pm 0.18) \times 10^{-6} \]

\[ B^+ \rightarrow \pi^+ \pi^0 \]

**772M BB PRD 87 031103(R) (2013)**

\[ A_{CP}(B^+ \rightarrow \pi^+ \pi^0) = 0.025 \pm 0.043 \pm 0.007 \]

\[ B(B^+ \rightarrow \pi^+ \pi^0) = (5.86 \pm 0.26 \pm 0.38) \times 10^{-6} \]

Large uncertainty of φ₂ is due to measurements in \( B^0 \rightarrow \pi^0 \pi^0 \) decay

- Low branching fraction
- Photon detection efficiency
- (No \( S_{CP} \) due to lack of vertex in signal side \( \rightarrow \) eight-fold ambiguity)

\[ B^0 \rightarrow \pi^0 \pi^0 \]

**275M BB PRL 94 181803 (2005)**

\[ A_{CP} = 0.44^{+0.53}_{-0.52} \pm 0.17 \]

\[ B(B^0 \rightarrow \pi^0 \pi^0) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}, \]
$B^0 \rightarrow \pi^0 \pi^0$ measurement

Update using full data set PRD 96 032007 (2017)

Many photons are lost by conversion with material in front of calorimeter.

→ Converted photon reconstructed by $\gamma \rightarrow e^+e^-$ that is apart from IP is also used for $\pi^0$ reconstruction.

Photon interaction points (MC) sideview

Signal yield = 217±32 events

6th KEK Flavor Factory Workshop (KEK-FF 2019), February 15 2019, KEK
$B^0 \rightarrow \pi^0 \pi^0$ measurement

\[
A_{CP} = +0.14 \pm 0.36 \pm 0.10
\]
\[
B(B^0 \rightarrow \pi^0\pi^0) = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}
\]
(6.4 $\sigma$ significance)

$\phi_2$ confidence level scan including new observables from $B^0 \rightarrow \pi^0 \pi^0$

Excluded region: $9.5^\circ < \phi_2 < 81.6^\circ$ (68% C.L.) , $15.5^\circ < \phi_2 < 75.0^\circ$ (95% C.L.)

(Based on Belle $\pi\pi$ measurements only)