CPV in $B$ decays: results at Belle and prospects at Belle 2

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on behalf of the Belle and Belle II Collaborations

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Outline

• Introduction of CP violation
• Overview of Belle experiment
• Recent Belle results
  • $B^0 \rightarrow J/\psi\pi^0$
  • $B^0 \rightarrow D^0\pi^0$ and $B^+ \rightarrow D^0\pi^+$
• Overview of Belle2 experiment
• Latest results from Belle2
• Some prospects of CPV at Belle2
• Summary
CP Violation

- **Direct CP violation**
  - CP violation in the decay
  \[ A_{CP} \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = \frac{N_{\bar{B}} - N_B}{N_{\bar{B}} + N_B} \]

- **CP violation in mixing**
  - difference in the probabilities between
  \[ P(B^0 \rightarrow \bar{B}^0) \neq P(\bar{B}^0 \rightarrow B^0) \]

- **CP violation from interference between mixing/decay**
  \[ A_{fCP}(\Delta t) \equiv \frac{\Gamma[\bar{B}(\Delta t)] - \Gamma[B(\Delta t)]}{\Gamma[\bar{B}(\Delta t)] + \Gamma[B(\Delta t)]} \]
  \[ = A \cos(\Delta m \Delta t) + S \sin(\Delta m \Delta t) \]
  - Direct CPV
  - Mixing-induced CPV
CPV in the SM

- CKM matrix describes the couplings between quarks of different generations via weak interaction

**CKM Matrix**

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

**Wolfenbstein representation**

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

CPV is due to a complex phase in the quark mixing matrix

Unitary requires

\[V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\]
Asymmetric energy $e^+e^-$ collider at KEK

LER($e^+$): 3.5 GeV
HER($e^-$): 8.0 GeV
with crossing angle $\pm 11$ mrad

The CM energy was set to be $Y(4S)$ resonance to produce $B$ meson pairs.

$711 \text{ fb}^{-1} Y(4S)$ were collected at Belle

All results presented here are based on the full Belle data set.

Belle Detector

Integrated luminosity of $B$ factories

> 1 ab$^{-1}$
On resonance:
$Y(5S): 121 \text{ fb}^{-1}$
$Y(4S): 711 \text{ fb}^{-1}$
$Y(3S): 3 \text{ fb}^{-1}$
$Y(2S): 25 \text{ fb}^{-1}$
$Y(1S): 6 \text{ fb}^{-1}$
Off reson./scan:
$\sim 100 \text{ fb}^{-1}$

$\sim 550 \text{ fb}^{-1}$
On resonance:
$Y(4S): 433 \text{ fb}^{-1}$
$Y(3S): 30 \text{ fb}^{-1}$
$Y(2S): 14 \text{ fb}^{-1}$
Off resonance:
$\sim 54 \text{ fb}^{-1}$
Belle Experiment

- Asymmetric energy $e^+e^-$ collider at KEK
- LER($e^+$): 3.5 GeV
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  with crossing angle $\pm 11$ mrad
- The CM energy was set to be Y(4S) resonance to produce B meson pairs.
- $711 \text{ fb}^{-1}$ Y(4S) were collected at Belle

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Belle Detector

- SC solenoid 1.5T
- CsI(Tl) 16Y
- TOF counter
- $8 \text{ GeV} \quad e^-$
- Aerogel Cherenkov cnt.
- $n=1.015\text{~}1.030$
- $3.5 \text{ GeV} \quad e^+$
- Central Drift Chamber
  - small cell +He/C$_2$H$_6$
- Si vtx. det.
  - 3/4 lyr. DSSD
- $\mu / K_L$ detection
  - 14/15 lyr. RPC+Fe

Integrated luminosity of B factories

- $>1 \text{ ab}^{-1}$
  - On resonance: $Y(5S): 121 \text{ fb}^{-1}$
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  - Y(2S): 25 fb$^{-1}$
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  - Y(3S): 30 fb$^{-1}$
  - Y(2S): 14 fb$^{-1}$
  - Off resonance: $\sim 54 \text{ fb}^{-1}$
Analysis technique

- Kinematic variables are used to identify B decays:
  \[ M_{bc} = \sqrt{E_{beam}^* - p_B^*} \]
  \[ \Delta E = E_B^* - E_{beam}^* \]

- Continuum suppression:
  Variables describing the event topology are combined in a multivariate analysis (Fisher Discriminant or Neural Network).

- The information can be used to extract signals.
TCPV in $B^0 \rightarrow J/\psi\pi^0$

PRD98 112008 (2018)

- CP violation appears as a decay time difference.
- Tag-side determines its flavour, and is used to reconstruct the $B_{\text{tag}}$ vertex. ($\varepsilon_{\text{eff}} \sim 30\%$)
- Sensitive to the CP violating angle $\phi_1$
- In the absence of the penguin amplitude, the direct CP asymmetry $A = 0$ and the mixing-induced CP asymmetry $S = -\sin(2\phi_1)$
- $\sin(2\phi_1) = 0.699 \pm 0.017$ from $b \rightarrow ccq$ (HFLAV)
- Compare the results with one in $B^0 \rightarrow J/\psi K_S$ to understand the contribution from penguin diagram.

Measure decay position instead of time
Measurement of $B^0 \rightarrow J/\psi \pi^0$

PRD98 112008 (2018)

$$Br(B^0 \rightarrow J/\psi \pi^0) = \frac{N_{\text{Sig}}}{\epsilon_{\text{sig}} \times N_{BB} \times Br(J/\psi) \times Br(\pi^0)}$$

$$= (1.62 \pm 0.11 \pm 0.06) \times 10^{-5}$$

- Consistent with the world average $(1.76 \pm 0.16) \times 10^{-5}$
  most precise measurement to-date

- Extract from a fit to $(\Delta t)$
  $$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$
  $$\mathcal{A} = -0.15 \pm 0.14^{+0.04}_{-0.03}$$

- Consistent with results from
  $B^0 \rightarrow J/\psi K_S$

- $3.2\sigma(\ast)$ away from
  BaBar measurement
$B^0 \to D^0\pi^0$ And $B^+ \to D^0\pi^+$

Preliminary

- $b \to c\bar{u}d$ decay, no penguin contribution $\Rightarrow$ large $A_{CP}$ could hint at BSM physics
  - Time-dependent measurement $C(B^0 \to D^*(h^0)) = (-2 \pm 8)\%$
    - Time independent measurement allows higher precision.
- $B^0 \to D^0\pi^0$ with notable large non-factorizable components
  - Branching fraction $\gg$ “naive” factorisation predictions
  - Constraints for models of final state interactions
- Both commonly used control mode in experiments, allow for high-precision validations of techniques.
  - **Important for Belle II precision frontier.**
- Previous experimental results:

<table>
<thead>
<tr>
<th>Decay</th>
<th>Dataset</th>
<th>$B$</th>
<th>$A_{CP}$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to D^0\pi^0$ (Belle)</td>
<td>$152 \times 10^6$</td>
<td>$(2.25 \pm 0.14 \pm 0.35) \times 10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>$B^0 \to D^0\pi^0$ (BaBar)</td>
<td>$454 \times 10^6$</td>
<td>$(2.69 \pm 0.09 \pm 0.13) \times 10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>$B^+ \to D^0\pi^+$ (Belle)</td>
<td>$772 \times 10^6/275 \times 10^6$</td>
<td>$(4.34 \pm 0.10 \pm 0.23) \times 10^{-3}$</td>
<td>$-0.8 \pm 0.8$</td>
</tr>
<tr>
<td>$B^+ \to D^0\pi^+$ (BaBar)</td>
<td>$454 \times 10^6$</td>
<td>$(4.90 \pm 0.07 \pm 0.22) \times 10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td>$B^+ \to D^0\pi^+$ (LHCb)</td>
<td>$1 fb^{-1}$</td>
<td>-</td>
<td>$-0.6 \pm 0.5 \pm 1.0$</td>
</tr>
</tbody>
</table>
\[ B^+ \rightarrow \overline{D}^0 \pi^+ \] Result

- 3D unbinned ML fit to \( M_{bc}, \Delta E, \) and \( C'_{NN} \).
  Simultaneous fit to four datasets divided by Kaon charge

\[
C'_{NN} = \log \frac{C^N_{NN}}{C^\text{max}_{NN} - C^\text{min}_{NN}}
\]

all signal
BB continuum
Rare B

\[ Br(B^+ \rightarrow \overline{D}^0 \pi^+) = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3} \]

\[ A_{CP} = (0.19 \pm 0.36 \pm 0.57) \% \]

Highest precision measurement for this decay
$B^0 \rightarrow \bar{D}^0\pi^0$ Result

- 3D unbinned ML fit to $M_{bc}$, $\Delta E$, and $C'_\text{NN}$.
- Simultaneous fit to four datasets divided by Kaon charge

$Br(B^0 \rightarrow \bar{D}^0\pi^0) = (2.68 \pm 0.06 \pm 0.09) \times 10^{-4}$

$A_{CP} = (0.10 \pm 2.05 \pm 1.22)\%$

First measurement in this channel
SuperKEKB and Belle II

- 40 times larger peak luminosity than at KEKB
- Data taking started.
- Achieved luminosity of $1.2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- Accumulated 6.5 fb$^{-1}$ data by this summer. (results shown today are from a subset of the data)

The final goal is an integrated luminosity of 50 ab$^{-1}$ at Y(4S)

- Use frame of the Belle detector and ECL
- New vertex detector VXD (PXD + SVD)
- Improved particle identification for K/$\rho$/\pi separation
- Improved CDC tracking - smaller cells and larger coverage
- Improved KLM for $\mu$ and K-long detection
- New electronics for ECL
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Flavour tagging method improved with
- improved vertex resolution
- algorithm includes more modes
- better particle identification reduced wrongly tagged rate
- Effective efficiency of flavour tagging is **37.2%**. (~30% at Belle)
- More precise measurement for time-dep. analyses.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Targets for $\overline{B}^0$</th>
<th>Underlying decay modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^-$</td>
<td>$\overline{B}^0 \to D^{*+} \nu_{\ell} \ell^-$</td>
</tr>
<tr>
<td>Intermediate Electron</td>
<td>$e^+$</td>
<td>$\downarrow D^0 \pi^+$</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu^-$</td>
<td>$\downarrow X K^-$</td>
</tr>
<tr>
<td>Intermediate Muon</td>
<td>$\mu^+$</td>
<td>$\overline{B}^0 \to D^+ \pi^- (K^-)$</td>
</tr>
<tr>
<td>Kinetic Lepton</td>
<td>$l^-$</td>
<td>$\downarrow K^0 \nu_{\ell} \ell^+$</td>
</tr>
<tr>
<td>Intermediate Kinetic Lepton</td>
<td>$l^+$</td>
<td>$\overline{B}^0 \to \Lambda_c^+ X^-$</td>
</tr>
<tr>
<td>Kaon</td>
<td>$K^-$</td>
<td>$\downarrow \Lambda \pi^+$</td>
</tr>
<tr>
<td>Kaon-Pion</td>
<td>$K^{-}, \pi^+$</td>
<td>$\overline{B}^0 \to A^+_c X^-$</td>
</tr>
<tr>
<td>Slow Pion</td>
<td>$\pi^+$</td>
<td>$\downarrow p \pi^-$</td>
</tr>
<tr>
<td>Maximum P*</td>
<td>$l^-, \pi^-$</td>
<td></td>
</tr>
<tr>
<td>Fast-Slow-Correlated (FSC)</td>
<td>$l^-, \pi^+$</td>
<td></td>
</tr>
<tr>
<td>Fast Hadron</td>
<td>$\pi^-, K^-$</td>
<td></td>
</tr>
<tr>
<td>Lambda</td>
<td>$\Lambda$</td>
<td></td>
</tr>
</tbody>
</table>
**B mixing in Belle II**

- Mixed-unmixed yield asymmetry as a function of $\Delta t$ using semileptonic B decays $B^0 \to D^{*+}\ell\nu$, $\ell = e, \mu$
- Dilepton tagging, only reconstruct a lepton ($l_{\text{tag}}$) on the tag side.
- Vertex from $l_{\text{tag}}$
- Unmixed: opposite sign leptons  Mixed: same-sign leptons
- Good agreement between data and expectations.
- Sufficient to observe the pattern of BB oscillations.

**Evidence of mixing**

![Graph showing evidence of mixing](image)

**A($|\Delta t|$)**

- $A(|\Delta t|)$ - off-res data

![Graph showing $A(|\Delta t|)$ - off-res data](image)

Flat behavior with statistical uncer.
Prospects for $\phi_1$

- Golden mode for $\sin(2\phi_1)$ measurement
- Theoretically and exp. precise
- $A = 0, S = \sin(2\phi_1)$
- Expected total uncertainty $\delta \phi_1 \leq 0.1^\circ @50 \text{ab}^{-1}$
- Re-discovery of $B^0 \rightarrow J/\psi K_S$
  $N = 26.9 \pm 5.2$ at Belle II

- Projection of CPV @50ab$^{-1}$
Prospects for $\phi_2$

- $\sin(2\phi_2)$ can be measured from $B \to \pi\pi/\rho\rho$ decays.
- $S_{\pi\pi\pi\pi}$ has never been measured.
  - Decay vertex only from $\pi^0$ Dalitz decay ($\pi^0 \to \gamma\gamma\gamma$) or photon conversion ($\pi^0 \to \gamma\gamma(e^+e^-)$).
- $B^0 \to \pi\pi/\rho\rho$ should reach $\sigma(\phi_2) \approx 0.6^\circ \pm 50 \text{ ab}^{-1}$.
- Reduce ambiguity for $\phi_2$, breaking the degeneracy with $B^0 \to \pi\pi$.

<table>
<thead>
<tr>
<th>$B$</th>
<th>Value</th>
<th>Belle @ 0.8 ab$^{-1}$</th>
<th>Belle2 @ 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\frac{\pi^+}{\pi^-}}$</td>
<td>$[10^{-6}]$</td>
<td>5.04</td>
<td>$\pm 0.21 \pm 0.18$ [2]</td>
</tr>
<tr>
<td>$B_{\frac{\pi^0}{\pi^0}}$</td>
<td>$[10^{-6}]$</td>
<td>1.31</td>
<td>$\pm 0.19 \pm 0.18$ [1]</td>
</tr>
<tr>
<td>$B_{\frac{\pi^0}{\pi^0}}$</td>
<td>$[10^{-6}]$</td>
<td>5.86</td>
<td>$\pm 0.26 \pm 0.38$ [2]</td>
</tr>
<tr>
<td>$C_{\frac{\pi^+}{\pi^-}}$</td>
<td>$[10^{-6}]$</td>
<td>$-0.33$</td>
<td>$\pm 0.06 \pm 0.03$ [3]</td>
</tr>
<tr>
<td>$S_{\frac{\pi^+}{\pi^-}}$</td>
<td>$[10^{-6}]$</td>
<td>$-0.64$</td>
<td>$\pm 0.08 \pm 0.03$ [3]</td>
</tr>
<tr>
<td>$C_{\frac{\pi^0}{\pi^0}}$</td>
<td>$[10^{-6}]$</td>
<td>$-0.14$</td>
<td>$\pm 0.36 \pm 0.12$ [1]</td>
</tr>
</tbody>
</table>

$S_{\pi^0\pi^0}$ | — | — | $\pm 0.29 \pm 0.03$ |


[1]: PRD 96(3) 032007
[2]: PRD 87(3) 031103
[3]: PRD 88(9) 092003
Summary

- Flavour physics at high luminosity B-factory offers good probe for testing SM and looking for NP
- Branching fractions and $A_{CP}$ of $B \rightarrow D^0 \pi$ is measured. $A_{CP}$ is consistent with the SM prediction.

- Belle II physics run started
- More precise measurements will be provided by Belle II in the coming years!
Backup
Continuum Suppression

- Continuum background
- Dominant background
- Different event topology from signal

\[ e^+e^- \rightarrow q\bar{q}(u, d, s, c) \]

- Using modified Fox-Wolfram moments expand events in terms of Legendre polynomials

\[ H_l = \sum_{i,j=1}^{N} \frac{\vec{p}_i \cdot \vec{p}_j}{s} P_l(\cos \Omega_{ij}) \]

\[ i, j = \text{particles} \]

- Information combining with other shape variables are used to suppress the continuum background.
Measurements of DCPV in $B^+ \rightarrow K^+\pi^0$ found to be different than the same quantity in $B^0 \rightarrow K^+\pi^-$

\[ \mathcal{A}_{K^+\pi^0} - \mathcal{A}_{K^+\pi^-} = 0.112 \pm 0.027 \pm 0.007 \ (4\sigma) \]

• Combine with other measurements and with the larger Belle II dataset, strong interaction effects can be controlled and the validity of the SM can be tested in a model-independent way.

• Isospin sum rule can be presented as a band in the $\mathcal{A}_{K^0\pi^0}$ vs. $\mathcal{A}_{K^+\pi^0}$ plane.

Most demanding measurement is $K^0\pi^0$ final state. With Belle II, the uncertainty on $A_{\text{CP}}$ from time-dep. analyses is expected to reach $\sim 4\% \Rightarrow \text{sufficient for NP studies}$
\( B \rightarrow K \pi \) at Belle II

- A 2D\([A_{K\pi}, I_{K\pi}]\) scan for different Belle II scenarios.
  - Asymmetry of \( K^0/\bar{K}^0 \) interactions in material (\( \sigma_{\text{ired}} \approx 0.2\% \))
    \textit{Phys. Rev. D 84, 111501 (2011)}
    - Assume that the errors are not correlated.
  - Additionally the systematic uncertainties are conservatively provided and they are still smaller than the statistical errors.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Value</th>
<th>( A_{K^0\pi^0} )</th>
<th>( I_{K\pi} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>0.14</td>
<td>0.13</td>
<td>((0.06, 0.02))</td>
</tr>
<tr>
<td>Belle + ( B \rightarrow K^0\pi^0 ) at Belle II 5 ab(^{-1})</td>
<td>0.05</td>
<td>((0.02, 0.02))</td>
<td>(-0.27 \pm 0.07)</td>
</tr>
<tr>
<td>Belle II 50 ab(^{-1})</td>
<td>0.01</td>
<td>((0.01, 0.02))</td>
<td>(-0.27 \pm 0.03)</td>
</tr>
</tbody>
</table>