Measurements of $B^0 \rightarrow J/\psi \pi^0$ and other CPV modes at Belle

Bilas Pal (Brookhaven National Laboratory) on behalf of the Belle and Belle II Collaborations

Contents
- Branching fraction & CP asymmetries in $B^0 \rightarrow J/\psi \pi^0$
- CP asymmetries in $B^0 \rightarrow K_S \pi^0 \pi^0$
- Measurements of $\cos (2\Phi_1)$ (BaBar + Belle combined)

CKM 2018
10TH INTERNATIONAL WORKSHOP ON THE CKM UNITARITY TRIANGLE
SEPTEMBER 17 – 21, 2018 | UNIVERSITÄT HEIDELBERG

BROOKHAVEN NATIONAL LABORATORY
Introduction

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

CKM matrix

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

Unitarity requires

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

Wolfenstein representation

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

- **CPV in decays**
- **CPV in mixing**
- **CPV in interference**

Between a decay with and without mixing:

Time-dependent CP violation

Mixing-induced CPV

Direct CPV

Directly related to CKM angles

\[ A_{CP} \equiv \frac{\Gamma(B^0 \rightarrow f_{CP} ; \Delta t) - \Gamma(B^0 \rightarrow f_{CP} ; -\Delta t)}{\Gamma(B^0 \rightarrow f_{CP} ; \Delta t) + \Gamma(B^0 \rightarrow f_{CP} ; -\Delta t)} \]

\[ = S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t) \]


$B^0 \rightarrow J/\psi \pi^0$: analysis motivation

- These decays are sensitive to the $CP$ violating angle $\Phi_1(\beta)$ of the unitarity triangle.
- In the absence of the penguin amplitude, the direct $CP$ asymmetry $A = 0$ and the mixing-induced $CP$ asymmetry $S = -\sin(2\Phi_1)$
- Penguin and/or any new physics (NP) process will shift $A$ and $S$ from these values. Thus, experimental measurement of these parameters provide a way to search for NP.
- The values of $A$ and $S$ in this decay are useful to constrain the penguin pollution in the golden mode $B^0 \rightarrow J/\psi K_S$ decays [1,2,3,4,5]

1) M. Ciuchini et al, PRL 95, 221804 (2005)
2) S. Faller et al, PRD 79, 014030 (2009)
3) M. Jung, PRD 86, 053008 (2012)
4) Z. Ligeti and D. Robinson, PRL 115, 251801 (2015)
$B^0 \rightarrow J/\Psi \pi^0$: analysis motivation

- Previous measurements of mixing induced CP asymmetries from BaBar and Belle experiments are not in good agreement and BaBar result lies outside the physically allowed region (although the error is large).
- A more precise measurement can clarify this unsatisfactory situation.
- Previous Belle measurement is based on 535M BB pairs.
- We expect improvement with final Belle data set, which corresponds to 772M BB pairs.
Previous Belle measurement of the branching fraction was only with 30/fb. With the final data set, we expect huge improvement.

Reconstruction: $J/\psi \rightarrow \mu^+\mu^-$, $e^+e^-$ and $\pi^0 \rightarrow 2$ gamma
Background components are $B \rightarrow J/\psi K_S$, $B \rightarrow J/\psi K_L$, other $B \rightarrow J/\psi X$ and continuum.
Vertex reconstruction & Flavor tagging

We fully reconstruct one $B$ meson which decays to $CP$ eigenstate $J/\Psi \pi^0$ for this case.

Since there are no other particles in the event beside the two $B$ mesons, all tracks that are not associated to $B_{CP}$ are used to reconstruct the $B_{tag}$ vertex. [H. Tajima et al, NIM A 533, 370 (2004)]

Proper time ($\Delta t$) is measured from decay-vertex difference $\Delta z$:

$$\Delta t \approx \Delta z/\beta \gamma c, \beta \gamma = 0.425$$ is the boost factor

Tag side determines the initial flavor. The effective tagging efficiency $\sim 30\%$. [H. Kakuno et al, NIM A 533, 516 (2004)]

Event with poorly reconstructed vertices are rejected by applying cut on the vertex $\chi^2$ and error on the vertex z-coordinate.
Branching fraction measurement

\[ \mathcal{B}(B^0 \rightarrow J/\psi \pi^0) = \frac{Y_{\text{sig}}}{\varepsilon \times N_{B\bar{B}} \times \mathcal{B}_{J/\psi} \times \mathcal{B}_{\pi^0}} \]

\[ \mathcal{B}(B^0 \rightarrow J/\psi \pi^0) = (1.55 \pm 0.10^{+0.06}_{-0.07}) \times 10^{-5} \]

**TABLE I.** Fractional systematic uncertainties for \( \mathcal{B}(B^0 \rightarrow J/\psi \pi^0) \).

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF parametrization</td>
<td>0.1</td>
</tr>
<tr>
<td>( \pi^0 ) reconstruction</td>
<td>1.5</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.7</td>
</tr>
<tr>
<td>Lepton-ID selection</td>
<td>2.1</td>
</tr>
<tr>
<td>Incorrectly reconstructed signal events</td>
<td>1.8</td>
</tr>
<tr>
<td>( B \rightarrow J/\psi (K_S^0, K_L^0, X) ) background</td>
<td>±1.8, ±2.0</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.4</td>
</tr>
<tr>
<td>Secondary branching fractions</td>
<td>0.8</td>
</tr>
<tr>
<td>Number of ( B\bar{B} ) pairs</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>±4.0, ±4.2</td>
</tr>
</tbody>
</table>

Our measurement is consistent with the WA and more precise than any previous measurement!

Signal = 330 ± 22
Continuum bkg = 16 ± 4
Measurements of $S$ and $A$

\[
P_i(\Delta t) = (1 - f_{o1}) \int d(\Delta t') \left[ R_{\text{sig}}(\Delta t_i - \Delta t') \times \right. \\
\left. \left( f_{\text{sig}} P_{\text{sig}}(\Delta t') + f_{J/\psi K_S^0} P_{J/\psi K_S^0}(\Delta t') + f_{J/\psi K_L^0} P_{J/\psi K_L^0}(\Delta t') + f_{J/\psi X} P_{J/\psi X}(\Delta t') \right) \right] \\
+ f_{q\bar{q}} P_{q\bar{q}}(\Delta t_i) + f_{o1} P_{o1}(\Delta t_i),
\]

(3)

- For $B^0 \to J/\Psi K_S^0$ and $B^0 \to J/\Psi K_L^0$, the PDF is similar to signal PDF, but $S$ and $A$ are fixed to the results from [PRL 108, 171802 (2012)]
- For $B^0 \to J/\Psi X$ we also use the same PDF but with $A = 0$, $S = 0$ and $B$ lifetime is replaced with effective lifetime. Effective lifetime is measured from MC (100x the data) and fixed in the fit to data.
- Sideband data is used to study $qq$ background.
- Outlier component described by a board Gaussian with small fraction.
- The resolution function [H. Tajima et al, NIM A 533, 370 (2004)] is a convolution of four components: $B_{\text{CP}}$ vertex resolution, $B_{\text{tag}}$ vertex resolution, Shift of the $B_{\text{tag}}$ vertex position due to secondary tracks from charmed particle decay, the kinematic approximation that the $B$ mesons are at rest in the CM frame.

\[
S = -0.59 \pm 0.19 \pm 0.03 \\
A = -0.15 \pm 0.14 \pm 0.04,
\]

Manuscript to be submitted soon
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$s$ (%)</th>
<th>$A$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex reconstruction</td>
<td>+2.36</td>
<td>+1.40</td>
</tr>
<tr>
<td></td>
<td>−1.75</td>
<td>−2.22</td>
</tr>
<tr>
<td>Resolution function</td>
<td>+1.43</td>
<td>+1.00</td>
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<tr>
<td></td>
<td>−2.37</td>
<td>−0.91</td>
</tr>
<tr>
<td>Physics parameters</td>
<td>+0.04</td>
<td>±0.04</td>
</tr>
<tr>
<td>Fit bias</td>
<td>±0.68</td>
<td>±0.27</td>
</tr>
<tr>
<td>Wrong tag fraction</td>
<td>+0.41</td>
<td>+0.43</td>
</tr>
<tr>
<td></td>
<td>−0.20</td>
<td>−0.17</td>
</tr>
<tr>
<td>$M_{bc} - \Delta E$ Shape</td>
<td>+0.52</td>
<td>+0.50</td>
</tr>
<tr>
<td></td>
<td>−0.45</td>
<td>−0.48</td>
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<tr>
<td>Signal and background fraction</td>
<td>+0.71</td>
<td>+0.49</td>
</tr>
<tr>
<td></td>
<td>−0.62</td>
<td>−0.72</td>
</tr>
<tr>
<td>Background $\Delta t$ shape</td>
<td>+0.20</td>
<td>±0.10</td>
</tr>
<tr>
<td></td>
<td>−0.12</td>
<td>±0.00</td>
</tr>
<tr>
<td>Tag side interference</td>
<td>±0.20</td>
<td>+3.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−0.00</td>
</tr>
<tr>
<td>Total</td>
<td>+3.02</td>
<td>+4.26</td>
</tr>
<tr>
<td></td>
<td>−3.14</td>
<td>−2.57</td>
</tr>
</tbody>
</table>
Measurements of $S$ and $A$: discussions

- Our measured CP asymmetries are consistent with and supersede our previous measurements.
- $S$ differs from zero by 3.0 standard deviations.
- We also differ from BaBar by 3.2 standard deviations.
- Our measured value is consistent with the measurements from $b \to c\bar{c}s$ channels.

\[
S = -0.59 \pm 0.19 \pm 0.03
\]

\[
A = -0.15 \pm 0.14 \pm 0.03
\]
\[ \sin(2\phi_1) \] in \( b \to sqq \) transition

\( (B^0 \to K_s \pi^0\pi^0) \)

\[ \sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}}) \]

- Penguin loop is sensitive to the new physics contribution.
- Only few CP-even \( b \to sqq \) modes are studied: \( \phi K_L, \eta K_L, K_s \pi^0\pi^0 \)

- Reconstruction: \( K_S \to \pi^+\pi^- \), \( \pi^0 \to 2 \) gamma
- Background: continuum and BB
- Veto: \( M_{\pi^0\pi^0} < 0.6 \text{ GeV} \), \( 2.8 \text{ GeV} < M_{\pi^0\pi^0} < 3.6 \text{ GeV} \), \( 1.77 \text{ GeV} < M_{K_s\pi^0} < 1.94 \text{ GeV} \) and \( M_{K_s\pi^0} > 4.8 \text{ GeV} \)
- Reconstruction of signal side vertex with flight direction of \( K_S \) with the constraint of interaction point

2.2 \( \sigma \) deviation from the \( \sin(2\phi_1) \) measured in \( b \to css \) decays.

BaBar 227M BB PRD 76, 071101 (2007)
**Sin \( (2\Phi_1) \) in \( b \to \text{sqq} \) transition**

- Signal yield with vertex reconstruction
  
  \[ 146.7 \pm 23.6 \text{ (purity 11.4\%)} \]

\[ \sin 2\Phi_1^{\text{eff}} = 0.92^{+0.27}_{-0.31} \text{ (stat.)} \pm 0.10 \text{ (syst.)} \]

\[ A = 0.28 \pm 0.21 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \]

- The result of \( \sin (2\Phi_1) \) is consistent with the value measured in \( b \to \text{ccs} \) decays
- Statistical uncertainties are large

<table>
<thead>
<tr>
<th>TABLE I. Systematic uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>Vertexing</td>
</tr>
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<td>Flavor tagging</td>
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<tr>
<td>Resolution function</td>
</tr>
<tr>
<td>Physics parameters</td>
</tr>
<tr>
<td>Fit bias</td>
</tr>
<tr>
<td>Background fraction</td>
</tr>
<tr>
<td>Background ( \Delta t )</td>
</tr>
<tr>
<td>Tag-side interference</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Manuscript to be submitted soon
Ambiguity in $\Phi_1$ measurements

- The determination of the angle $\Phi_1$ of the unitarity Triangle from $\sin(2\Phi_1)$ measurements lead to a trigonometric ambiguity.

This ambiguity can be resolved by measuring the $\cos(2\Phi_1)$ from time-dependent analysis of:

- $B^0 \to J/\Psi K_S \pi^0$
- $B^0 \to D^{*+}D^{*-}K_S$
- $B^0 \to K_SK^+K^-$, $B^0 \to K_S \pi^+\pi^-$
- $B^0 \to D^{(*)}h^0$, $D \to K_S \pi^+\pi^-$

Uncertainties are large to solve the trigonometric ambiguity.
**Φ₁ measurement in B⁰ → D(*)h⁰**

- BaBar and Belle shared their data in a single analysis to resolve this ambiguity using the decay B⁰ → D(*)h⁰, D → Kₜπ⁺π⁻ and h⁰ = π⁰, η, ω
  - D → Kₛπ⁺π⁻ is not a CP eigenstate, rather mixture of CP eigenstate Kₛρ, flavor specific K*⁺π⁻ and K*⁻π⁺
- Standard time-dependent CPV measurement does not work
- The approach is similar to the GGSZ method originally proposed for Φ₃ (γ) measurements, adapted by A. Bondar, T. Gershon and P. Krokovny for Φ₁. [PLB 624, 1 (2005)]

\[ B⁰ → D(*)h⁰ \text{ (} D → K₀π⁺π⁻ \text{)} \text{ decay rate:} \]

\[ e^{-|\Delta t|/\tau_B^0} \left[ (|A_{D^0}|^2 + |A_{D^0*}|^2) - q(|A_{D^0*}|^2 - |A_{D^0}|^2) \cos(\Delta m_d \Delta t) + 2q\eta h₀ (-1)^L \text{Im}(e^{-2i\phi_1} A_{D^0} A_{D^0*}) \sin(\Delta m_d \Delta t) \right] \]

\[ \text{Im}(A_{D^0} A_{D^0*}) \cos 2\phi_1 - \text{Re}(A_{D^0} A_{D^0*}) \sin 2\phi_1 \]

Interference between D⁰ and D⁰̅, and the strong phase variations over the Dalitz plot give us the access to cos (2Φ₁).

924/fb Belle data is used for D⁰ Dalitz model.
$\Phi_1$ measurement in $B^0 \rightarrow D^{(*)}h^0$

- $D^0 h^0$, with $h^0$ in
  - $\pi^0 \rightarrow \gamma\gamma$
  - $\eta \rightarrow \gamma\gamma, \pi^+\pi^-\pi^0$
  - $\omega \rightarrow \pi^+\pi^-\pi^0$
- $D^{*0}h^0$ with
  - $D^{*0} \rightarrow D^0\pi^0$
  - $h^0 \in \{\pi^0, \eta\}$

1129 ± 48 events for BaBar
1567 ± 56 events for Belle

$CP$ eigenstate final states

Interference between $B^0$ and $\bar{B}^0$
→ time-dependent CPV with characteristic pattern as in sin(2$\beta$) measurements
\[ \Phi_1 \text{ measurement in } B^0 \to D(\ast)h^0 \]

\[
\begin{align*}
\sin (2\Phi_1) &= 0.80 \pm 0.14 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \pm 0.03 \text{ (model)} \\
\cos (2\Phi_1) &= 0.91 \pm 0.22 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.07 \text{ (model)} \\
\Phi_1 &= 22.5 \pm 4.4 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.6 \text{ (model)}
\end{align*}
\]

- Single most precise measurement of \( \cos (2\Phi_1) \)
- First evidence for \( \cos (2\Phi_1) > 0 \) @ 3.7\( \sigma \)
- Direct exclusion of the 2\textsuperscript{nd} solution \([ \pi/2 - \Phi_1 = (68.1 \pm 0.7)^{\circ} ]\) of the CKM unitarity triangle @ 7.3\( \sigma \)
- Observation of CP violation in \( B^0 \to D(\ast)h^0 \) @ 5.1\( \sigma \)

Submitted to PRL and PRD: 
arXiv:1804.06152[hep-ex]
arXiv:1804.06153[hep-ex]
Summary

- Using final set of Belle data, we have measured
  - the branching fraction and CP asymmetries of $B^0 \rightarrow J/\psi \pi^0$ decays
    \[ B = (1.55 \pm 0.10^{+0.06}_{-0.07}) \times 10^{-5} \quad \text{[most precise to date]} \]
    \[ S = -0.59 \pm 0.19 \pm 0.03 \]
    \[ A = -0.15 \pm 0.14^{+0.04}_{-0.03} \]
  - CP asymmetries of charmless $B^0 \rightarrow K_S \pi^0 \pi^0$ decays
    \[ \sin 2\Phi_1^{\text{eff}} = 0.92^{+0.27}_{-0.31} \text{ (stat.)} \pm 0.10 \text{ (syst.)} \quad \text{[consistent with measurement from } b \rightarrow ccs \text{]} \]
    \[ A = 0.28 \pm 0.21 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \]

- From a joint BaBar + Belle analysis of $B^0 \rightarrow D(\ast) h^0$, we have measured
  \[ \sin (2\Phi_1) = 0.80 \pm 0.14 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \pm 0.03 \text{ (model)} \quad \text{[Observation of CPV @5.1}\sigma\text{]} \]
  \[ \cos (2\Phi_1) = 0.91 \pm 0.22 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.07 \text{ (model)} \quad \text{[Evidence of } \cos (2\Phi_1) > 0 \text{ @3.7}\sigma\text{]} \]
  \[ \Phi_1 = 22.5 \pm 4.4 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.6 \text{ (model)} \quad \text{[Exclusion of the second solution @7.3}\sigma\text{]} \]