Recent results on CPV and hadronic decays of B mesons at Belle

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B-factory concept

asymmetric energy

\( e^- \) (8 GeV) \( e^+ \) (3.5 GeV)

Time-dependent CPV of Golden mode:

✓ \( B^0 \rightarrow J/\psi K_S \)

✓ flavor tag

\( \epsilon_{\text{effective}} \sim 30\% \)

✓ \( \sigma(\Delta z) \sim 100 \mu m \)

\( \Leftrightarrow \langle \Delta z \rangle \sim 200 \mu m \)

\( S_{c\bar{c}s} = \sin 2\phi_1 = +0.667 \pm 0.023 \pm 0.013 \) PRL 108, 171802 (2012)

\( S_{c\bar{c}s} = \sin 2\beta = +0.687 \pm 0.028 \pm 0.012 \) PRD 79, 072009 (2009)

(\( C_{c\bar{c}s} \sim 0 \), consistent with SM)
\[ 2\phi_1 = \phi \left( \begin{array}{c} V_{td} \\ V_{td} \end{array} \right) \]

\[ 2\phi_2 = \phi \left( \begin{array}{c} V_{td} \\ V_{td} \end{array} \right) + \phi \left( \begin{array}{c} V_{ub} \\ V_{ub}^* \end{array} \right) \]

\[ \phi_3 = \phi \left( \begin{array}{c} V_{ub} \\ V_{ub}^* \end{array} \right) \]

**Golden Mode \((B \to J/\psi K_S)\): phase in \(B^0 - \overline{B^0}\) mixing**

- Very clean, only tiny SM penguin pollution so far neglected
- NP phase in mixing if any cannot be distinguished
- Small SM pollution should eventually be problem \((O(1\text{--}2\%))\)

**Overconstraint of UT triangle**

- All angles and sides can be measured
- CPV parameters from other means: \(V_{ub}, \phi_3\) (tree, SM)
Success of SM:

- overconstrained unitarity triangle

However...

- Still problem in $V_{ub}$
- It's only $\phi_1$ and $\Delta m_d/\Delta m_s$ giving high precision
- Second $\phi_1$ solution is not yet excluded with high CL
- Nothing precludes O(10%) beyond the SM physics(!)
Outline

- **3 topics today**
  - \( \sin 2\phi_1 \) in \( B^0 \rightarrow D^{(*)}_CP h^0 \) with Belle+BaBar data
    
    ![Belle][Belle] ![BaBar][BaBar] [PRL 115, 121604 (2015)]

  - \( \sin 2\phi_1 \) & \( \cos 2\phi_1 \) in \( B^0 \rightarrow D^{(*)} h^0, D \rightarrow K_S \pi \pi \)
    
    ![Belle][Belle] [preliminary, NEW!]

  - First observation of \( B^0 \rightarrow \psi(2S) \pi^0 \)
    
    ![Belle][Belle] [PRD 93, 031101(R) (2016)]

- **Overflow** (in backup slides)
  - \( \phi_2 \) from \( B^0 \rightarrow \rho^+ \rho^- \)
    
    ![Belle][Belle] [PRD 93, 032010 (2016)]
  - Evidence for \( B^0 \rightarrow \eta \pi^0 \)
    
    ![Belle][Belle] [PRD 92, 011101(R) (2015)]

All results based on full dataset of 772M \( B \bar{B} \) (+471M from BaBar)
\[(b \rightarrow c \text{ tree}) \Rightarrow b \rightarrow c\bar{c}s \quad B \rightarrow J/\psi K_S \quad (\phi_1 \text{ golden mode})\]

\[\Rightarrow b \rightarrow c\bar{c}d \quad B \rightarrow J/\psi \pi^0, \psi(2S)\pi^0 \quad (\phi_1)\]

\[b \rightarrow c\bar{u}s \quad B \rightarrow D\bar{K} \quad (\phi_3, \text{ tree only})\]

\[\Rightarrow b \rightarrow c\bar{u}d \quad B \rightarrow D\pi \quad (\phi_1, \phi_3)\]

\[(b \rightarrow u \text{ tree, suppressed}) \\quad b \rightarrow u\bar{c}s \quad B \rightarrow D\bar{K} \quad (\phi_3)\]

\[b \rightarrow u\bar{c}d \quad B \rightarrow D\pi \quad (\phi_1, \phi_3, \text{ suppressed})\]

\[b \rightarrow u\bar{u}s \quad B \rightarrow K\pi \text{ tree} \]

\[\Rightarrow b \rightarrow u\bar{u}d \quad B \rightarrow \pi\pi \quad (\phi_2)\]

\[(b \rightarrow s \text{ penguin}) \Rightarrow b \rightarrow s\bar{c}c \quad B \rightarrow J/\psi K_S \quad (\phi_1 \text{ pollution})\]

\[b \rightarrow s\bar{s}s \quad B \rightarrow \phi K \]

\[b \rightarrow s\bar{u}u \quad B \rightarrow K\pi \text{ penguin} \]

\[b \rightarrow s\bar{d}d \quad B \rightarrow K\pi \text{ penguin} \]

\[(b \rightarrow d \text{ penguin, suppressed}) \Rightarrow b \rightarrow d\bar{c}c \quad B \rightarrow J/\psi \pi^0, \psi(2S)\pi^0 \quad (\phi_1 \text{ pollution})\]

\[b \rightarrow d\bar{s}s \quad B \rightarrow KK \text{ penguin} \]

\[\Rightarrow b \rightarrow d\bar{u}u \quad B \rightarrow \pi\pi \text{ penguin} \quad (\phi_2 \text{ isospin analysis})\]

\[b \rightarrow d\bar{d}d \quad B \rightarrow \pi\pi \text{ penguin} \quad (\phi_2 \text{ isospin analysis})\]
$\phi_1 \rightarrow B^0 \rightarrow D^{(*)}_{cp} h^0$

(see also talk by Markus Röhrken at EPS-HEP 2015 conference)
$B \rightarrow D^{(*)}_{cp} h^0$

- **Decay modes**
  - $D_{cp} = D^0 / \bar{D}^0$ decaying into $K^+ K^-$ (CP$^+$); $K_S \pi^0$, $K_S \omega$ (CP$^-$)
  - $D^{*}_{cp} \rightarrow D_{cp} \pi^0$ (still CP eigenstate)
  - $h^0$ — neutral meson: $\pi^0$, $\eta$, $\omega$ (CP$^-$)
  - $D^{(*)}_{cp} h^0$ final states are also CP eigenstates (CP$^+$ or $^-$)

- **Time-dependent CPV analysis gives** $S = -(-1)^{CP} \sin 2\phi_1$
  - But not only “yet-another” CPV measurement for $\phi_1$
  - tree diagram only and hence **penguin pollution free**

(CPV in $D$ decay is much smaller and neglected)
Time-dependent Analysis for $B \rightarrow D^{(*)} h^0$

- **Average** $\Delta z \sim 200\mu m$ for Belle, $\sim 250\mu m$ for BaBar
- **Standard time-dependent CPV measurement**, but
  - Vertex extrapolated from $K_S \rightarrow \pi^+\pi^-$ for $h^0 \rightarrow \gamma\gamma$
  - Trajectory from **displaced** $D^0$ vertex with IP constraint
  - Resolution $\sim 100\mu m$, depending on final state
- **Standard flavor tagging algorithm**
First Belle-BaBar Joint Analysis

- **Motivation** — small branching fraction \(O(10^{-6})\)
- **Difficulty** — event vertex resolution and tagging efficiency
- **Analysis** — who joined BaBar from Belle and working on both
  - Continuum background — event shape variables (NN)
  - Beam-energy constrained mass — \(M_{bc} = \sqrt{(E_{beam}^*)^2 - (p_B^*)^2}\)

![Graphs showing signal and background events](image)

- **Signal:** 508 ± 31 events
- **Signal:** 757 ± 44 events
Principle of the Combined Analysis

- Combined by maximizing the **joint log-likelihood function**

\[
\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\text{BaBar}} + \sum_j \ln \mathcal{P}_j^{\text{Belle}}
\]

- PDFs with **experiment specific resolution functions**

\[
\mathcal{P}^{\text{exp}} = \sum_k f_k \int [P_k(\Delta t') R_k(\Delta t - \Delta t')] d\Delta t'
\]

[k: signal or background index, \(P_k\): signal or background model, \(R_k\): resolution function]

- Event/experiment dependent flavor tagging quality — \(q\)

- **Common signal model**

\[
P_{\text{sig}}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} [1 + q(S \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t))]\]

\[-(-1)^{CP} S = \sin 2\phi_1 \text{ and } C = 0 \text{ in the SM}\]

- Background determined from \(M_{bc}\) sidebands
$B \rightarrow D_{cp}^{(*)} h^0$ Results

$\left(-1\right)^{CP} S = +0.66 \pm 0.10 \pm 0.06$
$C = -0.02 \pm 0.07 \pm 0.03$

(5.4\sigma$ non-zero CPV)

First observation in agreement with CPV parameters from $b \rightarrow c\bar{c}s$

Full Belle II data will allow to address O(10%) NP effect
$B^0 \to D(^*)^0 h^0$, $D \to K_S \pi^+ \pi^-$

Belle Collaborations, preliminary (first shown today)
$B^0 \rightarrow D^{(*)0} h^0$, $D \rightarrow K_S \pi^+ \pi^-$

- Similar to $B \rightarrow D^{(*)0}_{cp} h^0$, but $D \rightarrow K_S \pi^+ \pi^-$ is not a CP eigenstate
- Mix of e.g. $K^{*-} \pi^+$ (favored), $K_S \rho^0$ (CP), $K^{*+} \pi^-$ (DCS)
- Many $K$ resonances: $K^*(892)$, $K^*_0(1430)$, $K_1(1270)$, $K^*_2(1430)$, ...
- Dalitz plot provides rich and **measureable** strong phase structure

**Dalitz model**

- Sum of known resonances, relative amplitude and phase from a fit to $D^{*-} \rightarrow D^0 \pi^+$
  (unbinned, model-dependent)
- $|\text{amplitude}|^2$ from $B^- \rightarrow D^0 \pi^-$, phase from coherent $\psi(3770) \rightarrow D^0 \bar{D}^0$ into $(D \rightarrow K_S \pi^+ \pi^-)^2$ and CP-tagged modes by CLEO
  (binned, model-independent)
Time-dependent Dalitz analysis

\[ P_{\text{sig}}(m_+^2, m_-^2, \Delta t) \propto e^{-|\Delta t|/\tau_B} \left[ 1 + q_B(A(m_+^2, m_-^2) \cos(\Delta m_B \Delta t) + S(m_+^2, m_-^2) \sin(\Delta m_B \Delta t)) \right] \]

\[ S(m_+^2, m_-^2) \propto \text{Im}[f(m_-^2, m_+^2)f^*(m_+^2, m_-^2)e^{2\phi_1}] \]

- **Sensitive directly to** \( \phi_1 \), **or both** \( \sin 2\phi_1 \) **and** \( \cos 2\phi_1 \)
  [Bondar, Gershon, Krokovny: PLB 624, 1(2005)]

- **Combination of widely used techniques**
  - \( D \) Dalitz plot analysis developed for \( \phi_3 \)
  - Time-dependent Dalitz to measure \( \phi_1^{\text{eff}} \) in \( b \to s \) penguin (\( B \to K_S \pi \pi \))

- **Previous model-dependent analysis**
  - Belle (386M \( B\bar{B} \)) [PRL 97, 081801 (2006)]
  - BaBar (383M \( B\bar{B} \)) [PRL 99, 231802 (2007)]
  - Exclusion of second \( \phi_1 \) solution only by 98% and 86% CL

- **New analysis with full Belle data** (772M \( B\bar{B} \))
Model-independent binned analysis

\[ N_i(\Delta t, \phi_1) = h_2 e^{-\frac{|\Delta t|}{\tau_B}} \left[ 1 + Q_B \frac{K_i - K_{-i}}{K_i + K_{-i}} \cos(\Delta m_B \Delta t) \right. \\
\left. + 2Q_B \xi_{h^0} (-1)^l \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}} \sin(\Delta m_B \Delta t) (S_i \cos 2\phi_1 + C_i \sin 2\phi_1) \right] \]

**Integrated |amplitude|^2**

\[ K_i = \int |A_D| (m_2^-, m_2^+) |^2 dD \]

from \( B^- \rightarrow D^0 \pi^- \) (flavor specific)

**Integrated strong phase**

\[ S_i = \frac{\int |A_D| \overline{|A_D|} \sin \Delta \delta_D dD}{\sqrt{K_i K_{-i}}} \]

\[ C_i = \frac{\int |A_D| \overline{|A_D|} \cos \Delta \delta_D dD}{\sqrt{K_i K_{-i}}} \]

from coherent \( D^0 \overline{D^0} \) by CLEO

**Measured in 8 \times 2 bins**

(binning based on a realisting resonant model)
Signal

- Standard $M_{bc}$-$\Delta E$ fit
- Total: $962 \pm 41$ signal events
- Signal fraction used in the $\Delta t$ Dalitz fit

**preliminary**

<table>
<thead>
<tr>
<th>mode</th>
<th>$N_{\text{sig}}$</th>
<th>$f_{\text{sig}}$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \pi^0$</td>
<td>$464 \pm 26$</td>
<td>$72 \pm 4$</td>
</tr>
<tr>
<td>$D^0 \eta \gamma \gamma$</td>
<td>$99 \pm 14$</td>
<td>$51 \pm 7$</td>
</tr>
<tr>
<td>$D^0 \eta_{\pi^+ \pi^- \pi^0}$</td>
<td>$51 \pm 9$</td>
<td>$66 \pm 11$</td>
</tr>
<tr>
<td>$D^0 \omega$</td>
<td>$182 \pm 18$</td>
<td>$58 \pm 6$</td>
</tr>
<tr>
<td>$D^0 \eta'$</td>
<td>$28 \pm 6$</td>
<td>$70 \pm 16$</td>
</tr>
<tr>
<td>$D^{*0} \pi^0$</td>
<td>$103 \pm 17$</td>
<td>$44 \pm 7$</td>
</tr>
<tr>
<td>$D^{*0} \eta$</td>
<td>$36 \pm 8$</td>
<td>$64 \pm 13$</td>
</tr>
</tbody>
</table>

$B^0 \rightarrow D \pi^0$

$B^0 \rightarrow D \pi^0$

$M_{bc}$ (GeV/c$^2$)

$\Delta E$ (GeV)
Flavor-tagged Dalitz plot

- Clear pattern visible for $B^0$ tagged and $\overline{B}^0$ tagged Dalitz plots (selected events with good tag probability)
## Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sin 2\phi_1$</th>
<th>$\cos 2\phi_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow D\pi^0$</td>
<td>$0.61 \pm 0.37$</td>
<td>$0.88^{+0.46}_{-0.52}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D\omega$</td>
<td>$-0.12 \pm 0.58$</td>
<td>$1.28^{+0.62}_{-0.69}$</td>
</tr>
<tr>
<td>Others</td>
<td>$0.44 \pm 0.51$</td>
<td>$0.89^{+0.49}_{-0.55}$</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>$0.43 \pm 0.27 \pm 0.08$</td>
<td>$1.06 \pm 0.33^{+0.21}_{-0.15}$</td>
</tr>
</tbody>
</table>

\[
\phi_1 = 11.7^\circ \pm 7.8^\circ \pm 2.1^\circ 
\]

(this analysis)

⇔ two solutions
from golden mode
\[
\phi_1 = 21.9^\circ \ (1.3\sigma \text{ away}) \\
\phi_1 = 68.1^\circ \ (5.1\sigma \text{ away})
\]

Definitely disfavors the second $\phi_1$ solution
$B^0 \rightarrow \psi(2S)\pi^0$ — for future $\phi_1$

(see also talk by Vipin Gaur at Moriond QCD 2016 conference)
To quantify the penguin pollution to $\phi_1$ in $b \rightarrow c\bar{c}s$, let's look at a different diagram: $b \rightarrow c\bar{c}d$

$B \rightarrow \psi(2S)\pi^0$ has been measured: [PRD77,071101R(2008), Belle 535M $B\bar{B}$]

$S_{\psi\pi^0} = -0.65 \pm 0.21 \pm 0.05$ (consistent with $\sin 2\phi_1$ from $b \rightarrow c\bar{c}s$)

but $B \rightarrow \psi(2S)\pi^0$ has not been previously observed

Analysis technique:
- Decay chain: $\psi(2S) \rightarrow \ell^+\ell^-$ or $J/\psi \rightarrow \ell^+\ell^-\pi^+\pi^- \ (\ell = e, \mu)$, $\pi^0 \rightarrow \gamma\gamma$
- Background: $b \rightarrow (c\bar{c})q$ feed-across, $R_2 < 0.5$ for continuum
- Signal: $M_{bc} = \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2} \Rightarrow m_B$, $\Delta E = E_B - E_{\text{beam}}^* \Rightarrow 0$
$B \rightarrow \psi(2S)\pi^0$ results

$\mathcal{B}(B \rightarrow \psi(2S)\pi^0) = (1.17 \pm 0.17 \pm 0.08) \times 10^{-5}$ (7.2σ)

$\Leftrightarrow \mathcal{B}(B \rightarrow J/\psi\pi^0) = (1.76 \pm 0.16) \times 10^{-5}$ (PDG)

85 ± 12 events

first observation, time dependent CP fit with future Belle II data
Summary
First observation of CPV in $B \rightarrow D_{cp}^{(*)} h^0$ from Belle + BaBar, not possible without combining, promising for Belle II NP search

New results on $\cos 2\phi_1$ from model-independent and time-dependent Dalitz analysis of $B \rightarrow D^{(*)} h^0, D \rightarrow K_S \pi \pi$

second $\phi_1$ solution is excluded by $5\sigma$

Observation of $B \rightarrow \psi(2S)\pi^0$ — a new $b \rightarrow c\bar{c}d$ mode

Modes with $h^0$ will be more interesting with Belle II statistics, and may not be so easy by LHCb

But that’s not all — Belle still has number of analyses in preparation for $\phi_1, \phi_2$ and other hadronic $B$ decays

Stay tuned (even before Belle II turns on)!
Overflow
$\phi_2 \rightarrow B^0 \rightarrow \rho^+ \rho^-$

(see also talk by Pit Vanhoefer at EPS-HEP 2015 conference)
\( \phi_2 \) and isospin analysis

- \( \sin 2\phi_2 \) can be extracted from \( B \to \pi^+\pi^- \) and \( B \to \rho^+\rho^- \), \( S = \sin 2\phi_2 \), if there is no "penguin pollution"

- Unfortunately this is not the case, \( S = \sqrt{1-A^2} \sin 2(\phi_2 + \Delta\phi_2) \), but fortunately size of penguin contribution can be resolved

- **Solution using isospin relations:**
  3 branching fractions and 2 direct CPV are needed

\[
\begin{align*}
A_{++}: B^0 &\to h^+ h^- \\
A_{--+}: B^0 &\to h^+ h^- \\
A_{00}: B^0 &\to h^0 h^0 \\
\bar{A}_{00}: \bar{B}^0 &\to h^0 h^0 \\
A_{+0}: B^+ &\to h^+ h^0 \\
(h = \pi, \; \rho)
\end{align*}
\]

Gronau, London PRL65, 3381 (1990)
$B^0 \rightarrow \rho^+ \rho^-$ analysis

- Polarization has to be resolved as vector-vector final state is mixture of CP-even and CP-odd
- Predicted to be almost fully longitudinally polarized, and hence almost CP-even
- Decomposed by helicity angle
- $\rho^+ \rightarrow \pi^+ \pi^0$ to be separated from other $\pi^+ \pi^0$ contributions
- Standard time-dependent fit
- 9-parameter ML fit

$\Delta E, M_{bc}, F, m_{+0}, m_{-0}, \cos \theta^+_H, \cos \theta^-_H, \Delta t, q$
**Fit results**

**Belle preliminary**

\[
\mathcal{B}(B^0 \rightarrow \rho^+ \rho^-) = (28.3 \pm 1.5 \pm 1.4) \times 10^{-6}
\]

\[
f_L = 0.988 \pm 0.012 \pm 0.023
\]

\[
S = -0.13 \pm 0.15 \pm 0.05, \quad A = 0.00 \pm 0.10 \pm 0.06
\]

Better precision than previous world average
**\( \phi_2 \) extraction**

From longitudinally polarized (LP) \( B \to \rho \rho \) Belle data only:

\[
\phi_2 = (93.7 \pm 10.6)^\circ \quad \Leftrightarrow \quad \text{WA, all modes: } \phi_2 = (87.6^{+3.5}_{-3.3})^\circ
\]

**Additional input:**

- \( \rho^0 \rho^0 \) (2014), PRD89, 072009
- \( \rho^+ \rho^0 \) (2003!), PRL91,221801 (only 10% data!)

Thanks to small \( B \to (\rho^0 \rho^0)^{LP} \), 4-fold ambiguity reduced to 2-fold

Belle’s final \( \phi_2 \) is yet to come, by updating \( \rho^+ \rho^0 \) and \( \rho \pi \) analyses
$\phi_2$ related — $B^0 \rightarrow \eta\pi^0$

(see also talk by Bilas Pal at CIPANP 2015 conference)
$B^0 \rightarrow \eta \pi^0$ motivations

- Color suppressed $b \rightarrow u$ and highly suppressed $b \rightarrow d$

- Useful to constrain isospin breaking in $\phi_2$ from $B \rightarrow \pi \pi$
  [Gronau et al, PRD71, 074017 (2005); Gardner, PRD72 034015 (2005)]

- Also useful to constrain $\Delta \phi_1 = \phi_{1}^{\text{eff}} - \phi_1$ from $B \rightarrow \eta' K^0$
  [Gronau et al, PLB596, 107 (2004); Gronau et al, PRD74, 093003 (2006)]

- Previous upper limits:
  $\mathcal{B} < 2.5 \times 10^{-6}$ (Belle, 152M $B \overline{B}$, PRD71, 091106R (2005))
  $\mathcal{B} < 1.5 \times 10^{-6}$ (BaBar, 459M $B \overline{B}$, PRD78, 011107R (2008))

- Update with Belle full dataset (753M $B \overline{B}$)
$B^0 \rightarrow \eta \pi^0$ results

- $\eta \rightarrow \gamma \gamma$ and $\eta \rightarrow \pi^+ \pi^- \pi^0$
- Fit to $M_{bc}$, $\Delta E$ and continuum suppression variable $C'_{NB}$
- $\mathcal{B}(B \rightarrow \eta \pi^0) = (4.1^{+1.7}_{-1.5} \pm 0.7) \times 10^{-7}$ ($3.0\sigma$), first evidence
- Limit on isospin breaking effect: $|(\Delta \alpha - \Delta \alpha_0)_{\pi^0-\eta-\text{eta}'}| < 0.97^\circ$ (90% CL) (previously $< 1.6^\circ$)

plots for $\eta \rightarrow \gamma \gamma$ mode

(similar plots for $\eta \rightarrow \pi^+ \pi^- \pi^0$ mode)