CP violation in hadronic B decays at LHCb

Dan Johnson, on behalf of the LHCb collaboration
Outline

- Standard Model CP violation and the CKM phase $\gamma$

- Towards a $\gamma$ measurement in tree-level processes
  $\Rightarrow$ First observation of suppressed $B^\pm \rightarrow D^0 (K\pi) K^\pm$

- Towards a $\gamma$ measurement in loop-level processes
  $\Rightarrow$ Time-integrated studies in $B_{(s)}^0 \rightarrow K\pi$
  $\Rightarrow$ Time-dependent studies in $B_{(s)}^0 \rightarrow hh, \ h=K,\pi$
Introducing $\gamma$

SM CP violation parameterised by complex phases in CKM matrix

Of the CKM phases, $\gamma$ is the least well known:

$$\gamma = (66 \pm 12)^\circ$$

(direct measurements)

At LHCb:

- Improved precision in theoretically clean tree-level decays to over-constrain the unitarity triangle $\Rightarrow \alpha + \beta + \gamma = 180^\circ$
- Measurement in tree- and loop-level processes $\Rightarrow$ possible NP sensitivity
Tree-level $B^\pm \rightarrow D^0 (\rightarrow hh) K^\pm$
\( B^\pm \rightarrow D^0 K^\pm \)

Sensitive to \( \gamma \) through interference between \( B^\pm \rightarrow F D_0 K^\pm \) and \( B^\pm \rightarrow F \bar{D}_0 K^\pm \)

Tree-level process \( \Rightarrow \) very low theoretical uncertainties

\[ \gamma = - \arg \left( \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right) \]

LHCB-TDR-012
\(B^\pm \rightarrow D^0 K^\pm\)

Sensitive to \(\gamma\) through interference between \(B^\pm \rightarrow F_{D^0} K^\pm\) and \(B^\pm \rightarrow F_{\bar{D}^0} K^\pm\)

Tree-level process

\(\Rightarrow\) very low theoretical uncertainties

\[\gamma = - \arg \left( \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)\]

\(r_B e^{i(\delta_B - \gamma)}\)

\(B^\pm \rightarrow D^0 K^\pm\)

Expected impact of LHCb \(B \rightarrow DK\) on UT

2018 LHCb \(\gamma: \pm 4^o\)
**ADS/GLW: \(B^\pm \rightarrow D^0(\rightarrow hh) K^\pm\)**

Sensitive to \(\gamma\) through interference between \(B^\pm \rightarrow F_{D0} K^\pm\) and \(B^\pm \rightarrow \overline{F}_{D0} K^\pm\)

Use abundant \(B^\pm \rightarrow F_D \pi^\pm\) to assist mass fit (smaller value of \(r_B\) so little CPV expected)

Decays of \(D^0\) to **two** daughters

**CF/DCS decays (‘ADS’)**

\[K^-\pi^+, K^+\pi^-\]

**Observables:**

1) \(R_{ADS} = \frac{\Gamma(B^\pm \rightarrow [\pi K]_D K^\pm)}{\Gamma(B^\pm \rightarrow [K\pi]_D K^\pm)}\)

**CP eigenstate (‘GLW’)**

\[K^+K^-, \pi^+\pi^-\]

**Observables:**

1) \(R_{CP+} = \frac{\Gamma(B^\pm \rightarrow [KK, \pi\pi]_D K^\pm)}{\Gamma(B^\pm \rightarrow [K\pi]_D K^\pm)}\)

2) \(A_{CP+} = \frac{\Gamma(B^- \rightarrow D_{CP} K^-) - \Gamma(B^+ \rightarrow D_{CP} K^-)}{\Gamma(B^- \rightarrow D_{CP} K^-) + \Gamma(B^+ \rightarrow D_{CP} K^+)}\)
Candidate selection

Use full 1fb\(^{-1}\) LHCb 2011 dataset
20-variable TMVA BDT trained on signal MC and 2010 data sidebands

Selection

- \(B^+, D^0\) and flight distance
- Transverse momenta
- RICH info
- \(D^0\) daughters impact parameters

Vertex Locator and tracking system:
Determination of \(B\) and \(D\) vertex position and track momenta

RICH detectors:
\(K/\pi\) separation

Magnet

D\(^0\) → \(\pi\pi, \pi K, KK\)
Favoured mode $K\pi\pi$ results

More abundant $B^\pm \to D\pi^\pm$ mode used to drive aspects of $B^\pm \to D K^\pm$ fit

- Partially reconstructed decays, modelled in MC
- $B^\pm \to D^0 K$ signal
- $B^+ \to [K^+ \pi^-]_D K^+$
- $B^- \to [K^- \pi^+]_D K^-$
- Very low combinatorics

Dan Johnson, University of Oxford
CPV in hadronic B decays
PLHC, Vancouver 4th-9th June '12
Direct CP violation observed in $B^- \rightarrow D^0 K^-$ with 5.8σ significance
2.4σ hint of CPV in $B^\pm \rightarrow D\pi^\pm$ mode

* dominant systematic due to $B_s^0 \rightarrow D^0 K^-\pi^+$ background shape
ADS mode results

Direct CP violation observed in $B^- \rightarrow D^0K^-$ with 5.8$\sigma$ significance

**Hint** of CP violation in $B^\pm \rightarrow D\pi\pm$ at 2.4$\sigma$

First observation of ADS mode $B^- \rightarrow [\pi^-K^+]_{D^0} K^-$ : $\sim 10\sigma$

Impact on global measurements of CP observables:

**$R_{ADS}$**

- Belle
- BaBar
- CDF
- HFAG average
- LHCb, 1 fb$^{-1}$

**$A_{ADS}$**

- Belle
- BaBar
- CDF
- HFAG average
- LHCb, 1 fb$^{-1}$
Combined non-zero $B \to DK$ CPV significance is $4.5\sigma$

No CPV observed in $B \to D\pi\pi$ decays
Combined non-zero B→DK CPV significance is **4.5σ**

Dominant systematic from production/detection asymmetries

Impact on global measurements of CP observables:

### $R_{CP+}$

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>1.03 ± 0.07 ± 0.03</td>
</tr>
<tr>
<td>BaBar</td>
<td>1.18 ± 0.09 ± 0.05</td>
</tr>
<tr>
<td>CDF</td>
<td>1.30 ± 0.24 ± 0.12</td>
</tr>
<tr>
<td>HFAG average</td>
<td>1.11 ± 0.06</td>
</tr>
<tr>
<td>Belle Dalitz</td>
<td>0.98 ± 0.06</td>
</tr>
<tr>
<td>BaBar Dalitz</td>
<td>0.974 ± 0.033</td>
</tr>
<tr>
<td>CKMFitter</td>
<td>0.981 ± 0.022</td>
</tr>
<tr>
<td>LHCb, 1 fb$^{-1}$</td>
<td>1.007 ± 0.038 ± 0.012</td>
</tr>
</tbody>
</table>

### $A_{CP+}$

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>0.29 ± 0.06 ± 0.02</td>
</tr>
<tr>
<td>BaBar</td>
<td>0.25 ± 0.06 ± 0.02</td>
</tr>
<tr>
<td>CDF</td>
<td>0.39 ± 0.17 ± 0.04</td>
</tr>
<tr>
<td>HFAG average</td>
<td>0.270 ± 0.040</td>
</tr>
<tr>
<td>Belle Dalitz</td>
<td>0.21 ± 0.14</td>
</tr>
<tr>
<td>BaBar Dalitz</td>
<td>0.16 ± 0.06</td>
</tr>
<tr>
<td>CKMFitter</td>
<td>0.187 ± 0.032</td>
</tr>
<tr>
<td>LHCb, 1 fb$^{-1}$</td>
<td>0.145 ± 0.032 ± 0.010</td>
</tr>
</tbody>
</table>

Dominant systematic from production/detection asymmetries
Future $B^\pm \rightarrow D^0 K^\pm$ final states

Sensitive to $\gamma$ through interference

$$B^- \rightarrow D^0 K^- f(D^0)K^-$$

$$r_B e^{i(\delta_B - \gamma)} D^0K^-$$

ADS/GLW method has trigonometric ambiguities for $\gamma$

Help ambiguity with another final state:

$$B^- \rightarrow D^0(\rightarrow K_S \pi^+ \pi^-)K^-$$

Belle (2011) arXiv:1106.4046

Analysis of $K_S \pi^+ \pi^-$ at LHCb: result soon

$$B_s \rightarrow D_s K$$

Plans for $\gamma$-analyses in:

$$B^0 \rightarrow D^0(\rightarrow h^+ h^-) K^{*0}$$

$$B^- \rightarrow D^0(\rightarrow K^+ \pi^-) K^- \pi \pi$$
Loop-level $B_{(S)}^0 \rightarrow hh$
**Charmless: $B_{(s)}^0 \rightarrow hh$**

Sensitive to $\gamma$ through interference in loop diagrams

Possible NP effects, compared to tree-level measurements
Test U-spin symmetry

---

**Time-integrated**

$B^0 \rightarrow K\pi$, $B_s^0 \rightarrow K\pi$

**Observables:**

$$A_{CP} = \frac{\Gamma(B_{(s)}^0 \rightarrow K^-\pi^+) - \Gamma(B_{(s)}^0 \rightarrow K^+\pi^-)}{\Gamma(B_{(s)}^0 \rightarrow K^-\pi^+) + \Gamma(B_{(s)}^0 \rightarrow K^+\pi^-)}$$

---

**Time-dependent**

$B^0, B_s^0 \rightarrow K^+K^-, \pi^+\pi^-$

**Observables:**

$$A(t) = \frac{\Gamma(t)(B_{(s)}^0 \rightarrow h^+h^-) - \Gamma(t)(B_{(s)}^0 \rightarrow h^+h^-)}{\Gamma(t)(B_{(s)}^0 \rightarrow h^+h^-) + \Gamma(t)(B_{(s)}^0 \rightarrow h^+h^-)}$$

$$\Rightarrow A(t) = A_{dir}\cos(\Delta mt) + A_{mix}\sin(\Delta mt)$$

$$\text{cosh} \left( \frac{\Delta \Gamma t}{2} \right) - A_{\Delta \Gamma}\sinh \left( \frac{\Delta \Gamma t}{2} \right)$$
Results $\int dt: B^0_{(s)} \rightarrow K\pi$

**Selection optimised for $B^0$:**

- **LHCb (a)**: $B^0$ signal
- **LHCb (b)**: $B^0$ signal

**Selection optimised for $B^s_0$:**

- **LHCb (c)**: $B^0$ cross-feed
- **LHCb (d)**: $B^0$ cross-feed

Dominant systematic from production and detection asymmetries

**Most precise** measurement of CP violation in $B^0 \rightarrow K\pi$: $>6\sigma$

**First** evidence of CP violation in $B^0_s \rightarrow K\pi$: $3.3\sigma$

$A_{CP} = -0.088 \pm 0.011 \pm 0.008$ (stat syst)

$A_{CP} = 0.27 \pm 0.08 \pm 0.02$ (stat syst)
Analysis (t): $B^0 \rightarrow \pi\pi\pi$

Time dependent asymmetry gives access to $A_{\text{dir}}$ and $A_{\text{mix}}$:

$$A(t) = \frac{A_{\text{dir}} \cos(\Delta m t) + A_{\text{mix}} \sin(\Delta m t)}{\cosh \left( \frac{\Delta \Gamma}{2} t \right) - A \Delta \Gamma \sinh \left( \frac{\Delta \Gamma}{2} t \right)}$$

direct CPV in decay

CPV in interference between decay and mixing

**Use abundant $B^0 \rightarrow K\pi\pi$ mode** to determine tag/mis-tag efficiency and production asymmetry.

2-d fit to invariant mass and decay time extracts tag performance.

$A_{\pi\pi\pi}^\text{dir}$: Currently significant tension between BaBar and Belle measurements

**BaBar**: $0.25 \pm 0.08 \pm 0.02$

**Belle**: $0.55 \pm 0.08 \pm 0.05$
Results (t): $B^0 \rightarrow \pi\pi\pi$

$A_{\pi\pi\pi}^{\text{dir}} = 0.11 \pm 0.21 \pm 0.03$

Shows preference for BaBar result

$A_{\pi\pi\pi}^{\text{mix}} = -0.56 \pm 0.17 \pm 0.03$

HFAG avg. $-0.65 \pm 0.07$

Dominant systematic from input $\Delta m_s$ and $\Delta m_d$ parameters

$A_{\pi\pi\pi} \Rightarrow \textbf{First} \text{ evidence of time-dep CPV at an hadronic collider : } 3.2\sigma$
Results (t): $B_s^0 \rightarrow KK$

$A_{KK}^{dir} = 0.02 \pm 0.18 \pm 0.04$
stat syst

U-spin sym. $\Rightarrow A_{KK}(B_s) = A_{K\pi}(B_0)$

$A_{KK}^{mix} = 0.17 \pm 0.18 \pm 0.05$
stat syst

Dominant systematic from input $\Delta m_s$ and $\Delta m_d$ parameters

First CPV investigation in $B_s^0 \rightarrow KK$
Conclusion
Summary

• CKM phase $\gamma$ known only to $\pm 12^\circ$ (direct measurements only)
• Progress towards a measurement of $\gamma$ in tree-level ($B \rightarrow DK$) and loop-level ($B_s \rightarrow hh$) processes
  • $B \rightarrow DK$: very small theoretical uncertainty $\Rightarrow$ consistency check of unitarity triangle
  • $B_s \rightarrow hh$: sensitivity to NP in loops ($<$full 2011 dataset)

Outlook

• $\gamma$ sensitivity to increase with study of further channels
• $\gamma$ ambiguities to resolve with addition of $B^\pm \rightarrow D(\rightarrow K^0_s hh)K^\pm$
• Update charmless analyses to full 2011 dataset.
• Dataset to more than double in 2012!