Measurements of the CKM Angle $\gamma$ in Tree-Dominated $B$ Decays at LHCb

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Discrete 2012, Lisbon


\( \gamma \) in Tree-Level \( B \) Decays

- \( \gamma \) is the least well-constrained angle of the CKM triangle:
  \[ \gamma = 66 \pm 12^\circ \ (CKMFitter), \quad \gamma = 76 \pm 10^\circ \ (UTFit) \]
- Measurements of \( \gamma \) from \( B \) decays mediated only by tree-level transitions provide an "standard candle" for the SM.
- This can be compared with \( \gamma \) values from \( B \) decays involving loop-level transitions
  - For example \( B^0(s) \rightarrow hh' \) decays\(^(*)\)
- Significant difference between these would indicate New Physics contribution to the loop process.

\(^(*)\) See talk of D. Derkach
Menu of Results

• **Time-independent** measurements:
  – $B^+ \to D^0 K^+$ with $D^0 \to K\pi, KK, \pi\pi$ (Phys. Lett. **B 712** (2012) 203)
  – $B^+ \to D^0 K^+$ with $D^0 \to K\pi\pi\pi$ (LHCb-CONF-2012-030)
  – $B^+ \to D^0 K^+$ with $D^0 \to K_S\pi\pi, K_S KK$ (Phys. Lett. **B 718** (2012) 43)

• **Gamma combination** from time-independent:
  – Using $B^+ \to D^0 K^+$ and $B^+ \to D^0 \pi^+$ (LHCb-CONF-2012-032)

• **Time-independent** with neutral $B$ decays:
  – $B^0 \to D^0 K^{*0}$ with $D^0 \to KK$ (LHCb-CONF-2012-024)

• **Time-dependent** measurements:
  – $B_s \to D_s K$ decays (first!) (LHCb-CONF-2012-029)

All using 1.0/fb of 2011 data ($\sqrt{s} = 7$TeV)
The LHCb Experiment

- Situated on LHC ring; $pp$ collisions at $E_{CM} = 7$ TeV. (8 TeV in 2012)
- Forward arm spectrometer, optimised for study of $B$ and $D$ decays.

**Hardware trigger** reduces event rate to 1MHz, followed by software trigger reducing to several kHz. This allows high trigger efficiency, even on purely hadronic final states.
Experimental Aspects

- Impact parameter (IP) and momentum resolution of tracking system allows to separate $B$ decay products from prompt tracks, and gives narrow mass resolution.
- Hadronic particle identification (from RICH) separates suppressed $DK$ modes from favoured $D\pi$ modes.

- e.g. Branching fraction measurement of $B_s \rightarrow J/\psi K^{*0}$ (Phys. Rev. D 86 (2012) 071102)
Time-Integrated Methods

- Sensitivity to $\gamma$ from interference between $b \to c$ and $b \to u$ transitions at tree level, when $D$ final state is accessible to both $D^0$ and $\bar{D}^0$
- Aside from $\gamma$, have hadronic unknowns $r_{B(D)}$, $\delta_{B(D)}$, where ratio of favoured to suppressed $B(D)$ decay amplitudes is $r_B e^{i(\delta_B - \gamma)} (r_D e^{i\delta_D})$
- Method to extract these hadronic unknowns (and $\gamma$) depends on the $D$ final state

- Discussed today:
  - **ADS**: $D \to$ quasi-flavour-specific state, e.g. $K\pi$, $K\pi\pi\pi$ (Phys. Rev. Lett. 78 (1997) 257, Phys. Rev. D 63 (2001) 036005)
GLW, ADS Observables

- The two main GLW observables for $B \to DK$ are the average partial rate $R_{CP+}$ and the asymmetry $A_{CP+}$, where the CP+ state can be $KK$ or $\pi\pi$:

$$R_{CP+} \equiv 2 \frac{\Gamma(B^- \to D_{CP+}K^-) + \Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to D^0K^+)} = 1 + r_B^2 + 2\kappa r_B \cos \delta_B \cos \gamma$$

$$A_{CP+} \equiv \frac{\Gamma(B^- \to D_{CP+}K^-) - \Gamma(B^+ \to D_{CP+}K^+)}{\Gamma(B^- \to D_{CP+}K^-) + \Gamma(B^+ \to D_{CP+}K^+)} = \frac{2\kappa r_B \sin \delta_B \sin \gamma}{R_{CP+}}$$

- The equivalents also exist for $B \to D\pi$, but the asymmetry is expected to be negligible.

- The main ADS observables for $B \to DK$ relate to the Doubly-Cabibbo-suppressed $D$ final state:

$$R_{ADS} = \frac{\Gamma(B^- \to (K^+\pi^-)_D K^-) + \Gamma(B^+ \to (K^-\pi^+)_D K^+)}{\Gamma(B^- \to (K^-\pi^+)_D K^-) + \Gamma(B^+ \to (K^+\pi^-)_D K^+)} = r_B^2 + r_D^2 + 2r_D r_B C_f \cos \gamma \cos(\delta_B + \delta_D)$$

$$A_{ADS} = \frac{\Gamma(B^- \to (K^+\pi^-)_D K^-) - \Gamma(B^+ \to (K^-\pi^+)_D K^+)}{\Gamma(B^- \to (K^-\pi^+)_D K^-) + \Gamma(B^+ \to (K^-\pi^+)_D K^+)} = \frac{2r_D r_B C_f \sin \gamma \sin(\delta_B + \delta_D)}{R_{ADS}}$$

N.B. $C_f$ (or $\kappa$) is the coherence factor, with $C_f = 1$ for two-body decay, and $0 < C_f < 1$ for multi-body decay.
GLW Results for $\mathbf{B \rightarrow DK}$

- Raw asymmetries are visible in the suppressed $\mathbf{DK}$ modes.

After correcting for (small) detector and production asymmetries, obtain:

$$A_K^{\mathcal{K}\mathcal{K}} = 0.148 \pm 0.037 \pm 0.010,$$

$$A_{\mathcal{K}}^{\pi\pi} = 0.135 \pm 0.066 \pm 0.010,$$

with average:

$$A_{\mathcal{CP}^+} = 0.145 \pm 0.032 \pm 0.010$$

Also:

$$R_{\mathcal{CP}^+} = 1.007 \pm 0.038 \pm 0.012$$
ADS Results for $B\rightarrow DK$

- Raw asymmetries visible in the suppressed $D$ mode (both $D\pi$ and $DK$)

\[
R_{\text{ADS}(\pi)} = 0.00410 \pm 0.00025 \pm 0.00005
\]

\[
A_{\text{ADS}(\pi)} = 0.143 \pm 0.062 \pm 0.011
\]

\[
R_{\text{ADS}(K)} = 0.0152 \pm 0.0020 \pm 0.0004
\]

First observation!

\[
A_{\text{ADS}(K)} = -0.52 \pm 0.15 \pm 0.02
\]

Considering KK, $K\pi$ and $\pi\pi$ together, CPV is observed (5.8σ) in $B\rightarrow DK$ decays for the first time.
ADS and GLW Averages

- LHCb results **significantly improve** on the precision of previous B-Factory and TeVatron measurements.
**ADS for $B \rightarrow D(K\pi\pi\pi)K$**

- Compared to $B \rightarrow D(K\pi)K$, $r_B$ and $\delta_B$ are unchanged, but the $D$ decay parameters differ.
- So we gain **complementary information** to $B \rightarrow D(K\pi)K$, beyond simply adding further events.

First observations of the 4-body ADS modes in both $B \rightarrow D\pi (>10\sigma)$ and $B \rightarrow DK (5.1\sigma)$:

$$R_{K^3\pi}^{ADS(K)} = 0.0124 \pm 0.0027$$

$$R_{K^3\pi}^{ADS(\pi)} = 0.00369 \pm 0.00036$$

Some hint of asymmetry in both $B \rightarrow D\pi$ and $B \rightarrow DK$:

$$A_{ADS(K)}^{K3\pi} = -0.42 \pm 0.22$$

$$A_{ADS(\pi)}^{K3\pi} = +0.13 \pm 0.10$$
GGSZ Analysis of $B \rightarrow DK$

- Can measure $\gamma$ by comparing Dalitz plots of $D \rightarrow K_S \pi \pi$ (or $K_S KK$) decay for $B^+ \rightarrow DK^+$ and $B^- \rightarrow DK^-$
- Need information on how $D$ decay amplitude varies over Dalitz plot
- Current LHCb analysis uses CLEO-c measurements of the strong phase variation as input (Phys. Rev. D 82 (2010) 112006)
- Dalitz plots are binned in regions of similar strong phase, numbered from $-n$ to $n$:

  - Number of events in $i^{th}$ bin is given by:
    - For $B^+$: $N_{\pm i}^+ = h_{B^+} \left[ K_{\mp i} + (x_+^2 + y_+^2)K_{\pm i} + 2\sqrt{K_iK_{-i}}(x_+ c_{\pm i} \mp y_+ s_{\pm i}) \right]$ 
    - For $B^-$: $N_{\pm i}^- = h_{B^-} \left[ K_{\pm i} + (x_-^2 + y_-^2)K_{\mp i} + 2\sqrt{K_iK_{-i}}(x_- c_{\pm i} \pm y_- s_{\pm i}) \right]$ 

  We then measure:
  
  $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$
  $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$

  $K_i$ represents (known) Dalitz distribution in flavour-tagged $D$ decays.
GGSZ Analysis of $B \rightarrow DK$

- Events divided according to $K_S$ reconstruction: decays within VeLo ("long $K_S$") or after leaving VeLo ("downstream $K_S$.")

- Use $B \rightarrow D\pi$ as control mode (assume no CPV there)
GGSZ Results

- Dominant experimental systematic is assumption of no CPV in \( B \rightarrow D \pi \) (used to determine efficiencies).
- Third uncertainty is that from the CLEO-c inputs.

\[
\begin{align*}
\chi_- &= (0.0 \pm 4.3 \pm 1.5 \pm 0.6) \times 10^{-2}, \\
y_- &= (2.7 \pm 5.2 \pm 0.8 \pm 2.3) \times 10^{-2} \\
\chi_+ &= (-10.3 \pm 4.5 \pm 1.8 \pm 1.4) \times 10^{-2}, \\
y_+ &= (-0.9 \pm 3.7 \pm 0.8 \pm 3.0) \times 10^{-2}
\end{align*}
\]

- From these, extract:

\[
\begin{align*}
\mathcal{r}_B &= 0.07 \pm 0.04, \\
\gamma &= (44^{+43}_{-38})^\circ
\end{align*}
\]

- Despite the precision on \( x \) and \( y \) being similar to the B-Factories, the low measured value of \( r_B \) hurts the precision on \( \gamma \).
Gamma Combination

- Uses LHCb analyses of $B \to Dh$ with $D \to \{hh, hhhh, K_{S}hh\}$ ($h = \{K, \pi\}$), plus CLEO data on $D \to K\pi\pi\pi$ strong phase (Phys. Rev. D 80 (2009) 031105)
- The experimental likelihoods are combined as $\mathcal{L}(\alpha) = \prod f_i(A_i^{\text{obs}}|A_i(\alpha_i))$, where $A$ are the experimental observables ($R_{CP}$, $x_+$, etc) and $\alpha$ are the physics parameters ($\gamma$, $r_B$, etc).
- Confidence intervals are obtained from this in a frequentist way.

\[ \gamma = (71.1^{+16.6}_{-15.7})^\circ \]

$B \to DK$ only: $\gamma \in [61.8, 67.8]^\circ \text{ or } [77.9, 92.4]^\circ$ @ 68% CL

$B \to D\pi$:

\[ \gamma \in [43.8, 101.5]^\circ \text{ @ 95% CL} \]
GLW with $B_d \rightarrow D(KK)K^{*0}$

- Similar diagram to internal tree of $B^+ \rightarrow DK^+$, but with spectator $u \rightarrow d$ quark giving $K^+ \rightarrow K^{*0}$ (sign of Kaon from $K^{*0}$ tags flavour of $B$ at decay)
- Both diagrams are colour-suppressed, leading to larger interference but also smaller yields.

The first observation of $B_d \rightarrow D(KK)K^{*0}$ is made, with a significance (summing $K^{*0}$ and $\bar{K}^{*0}$) of $5.1\sigma$

- Hint of asymmetry in $B_d \rightarrow D(KK)K^{*0}$: $A_{d,KK}^{KK} = -0.47 \pm 0.24 \text{ (stat)} \pm 0.02 \text{ (syst)}$
- No hint of asymmetry in $B_s \rightarrow D(KK)K^{*0}$: $A_{s,KK}^{KK} = 0.04 \pm 0.17 \text{ (stat)} \pm 0.01 \text{ (syst)}$
- Ratio to favoured $B_d \rightarrow D(K\pi)K^{*0}$: $\mathcal{R}_{d,KK}^{KK} = 1.42 \pm 0.41 \text{ (stat)} \pm 0.07 \text{ (syst)}$
Measuring $\gamma$ with $B_s \rightarrow D_s K$

- Tree diagrams of similar magnitude exist for both $B_s$ and $\bar{B}_s$ decaying to $D_s^-K^+$, hence large interference between them is possible.

- Using a flavour-tagged, time-dependent analysis, we can measure four decay rates ($B_s$ or $\bar{B}_s$ to $D_s^+K^-$ or $D_s^-K^+$) and extract $\gamma$ in an unambiguous and theoretically clean way.

\[
\frac{dN_{B_s \rightarrow f(t)}}{dt} = \frac{1}{2} |A_f|^2 \left( 1 + |\lambda_f|^2 \right) e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - D_f \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right] + C_f \cos (\Delta m_s t) - S_f \sin (\Delta m_s t)
\]

\[
\frac{dN_{\bar{B}_s \rightarrow f(t)}}{dt} = \frac{1}{2} |A_f|^2 \left( \frac{p}{q} \right)^2 \left( 1 + |\lambda_f|^2 \right) e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - D_f \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right] - C_f \cos (\Delta m_s t) + S_f \sin (\Delta m_s t)
\]

\[
C_f = C_{\bar{f}} = C = \frac{1 - r_{D_s K}^2}{1 + r_{D_s K}^2}, \quad D_f = \frac{2r_{D_s K} \cos(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_s K}^2}, \quad S_f = \frac{2r_{D_s K} \sin(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_s K}^2}
\]

\[
( r_{D_s K} = |A(\bar{B}_s^0 \rightarrow D_s^- K^+)/A(B_s^0 \rightarrow D_s^- K^+)|, \Delta \text{ is strong phase difference})
\]
Ingredients for $B_s \rightarrow D_s K$

Mass fits (sum of three $D_s$ final states: $KK\pi$, $K\pi\pi$ and $\pi\pi\pi$):

$$N_{B_s^0 \rightarrow D_s^- \pi^+} = 27,965 \pm 395$$

$$N_{B_s^0 \rightarrow D_s^+ K^\pm} = 1390 \pm 98$$

Flavour tagging:

Decay time resolution:

Only Opposite-side (OS) tagging in this analysis, with $\varepsilon D^2 = (1.9\pm0.3)\%$. Same-side (SS) tagging to be added in future.
**$B_s \rightarrow D_s K$ Results**

- The CPV parameters in $B_s \rightarrow D_s K$ are measured for the first time:

  \[
  C = 1.01 \pm 0.50 \pm 0.23 \\
  S_f = -1.25 \pm 0.56 \pm 0.24 \\
  D_f = -1.33 \pm 0.60 \pm 0.26 \\
  S_{\bar{f}} = 0.08 \pm 0.68 \pm 0.28 \\
  D_{\bar{f}} = -0.81 \pm 0.56 \pm 0.26
  \]

Dominant systematic uncertainties arise from fixed parameters ($\Delta m_s$, $\Gamma_s$, $\Delta \Gamma_s$, acceptance) and (for $C$ and $S$) flavour tagging calibration.

No attempt yet to determine $\gamma$ (need to understand covariance matrix for systematics).
LHCb has made its first measurements of $\gamma$ with $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow D^0 \pi^+$ decays, using various methods (ADS, GLW, GGSZ) depending on the $D^0$ decay mode.

At the moment, no one method dominates the sensitivity.

Combination of $B^+ \rightarrow D^0 K^+$ results gives $\gamma = (71.1^{+16.6}_{-15.7})^\circ$, which has similar precision to the Belle and Babar results.

LHCb also has first results on CP parameters in other modes: $B_d \rightarrow D^0(KK)K^*$ and $B_s \rightarrow D_s K$.

Work on new channels in the pipeline, e.g. $D_s K \pi \pi$, $D^0 K \pi \pi$.

Stay tuned for more results in the future!

- LHCb has already collected $\approx 2.0/fb$ at 8 TeV in 2012
Backup
Gamma Combination

- **CLEO-c result on** $D \rightarrow K\pi\pi\pi$:

- **From** $B \rightarrow DK$ **decays only:**

![Graphs showing $\delta_B$ and $r_B$ distributions with CLEO and LHCb results.](image)
GLW with $B \rightarrow D(KK)K^{*0}$

- Check with favoured $B \rightarrow D(K\pi)K^{*0}$ mode: no significant asymmetry seen.

\[ A^{\text{fav}}_{d} = -0.08 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)} \]
Measuring $\gamma$ with $B_s \rightarrow D_s K$

\[ \Gamma_{B_s^{\pm} \rightarrow f}(t) = |A_f|^2 (1 + |\lambda_f|^2) \frac{e^{-\Gamma_{st}}}{2} \left( \cosh \frac{\Delta \Gamma_{st}}{2} + D_f \sinh \frac{\Delta \Gamma_{st}}{2} + C_f \cos \Delta m_{st} - S_f \sin \Delta m_{st} \right), \]

\[ \Gamma_{B_s^{0} \rightarrow f}(t) = |A_f|^2 \left| \frac{p}{q} \right|^2 (1 + |\lambda_f|^2) \frac{e^{-\Gamma_{st}}}{2} \left( \cosh \frac{\Delta \Gamma_{st}}{2} + D_f \sinh \frac{\Delta \Gamma_{st}}{2} - C_f \cos \Delta m_{st} + S_f \sin \Delta m_{st} \right), \]

\[ \Gamma_{B_s^{0} \rightarrow f}(t) = |\tilde{A}_f|^2 (1 + |\tilde{\lambda}_f|^2) \frac{e^{-\Gamma_{st}}}{2} \left( \cosh \frac{\Delta \Gamma_{st}}{2} + D_f \sinh \frac{\Delta \Gamma_{st}}{2} + C_f \cos \Delta m_{st} - S_f \sin \Delta m_{st} \right), \]

\[ \Gamma_{B_s^{0} \rightarrow f}(t) = |\tilde{A}_f|^2 \left| \frac{q}{p} \right|^2 (1 + |\tilde{\lambda}_f|^2) \frac{e^{-\Gamma_{st}}}{2} \left( \cosh \frac{\Delta \Gamma_{st}}{2} + D_f \sinh \frac{\Delta \Gamma_{st}}{2} - C_f \cos \Delta m_{st} + S_f \sin \Delta m_{st} \right), \]

For $D_s K$, $|\lambda_f| = |\tilde{\lambda}_f|$, so:

\[ C_f = C_{\tilde{f}} = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \]

\[ S_f = \frac{2 \text{Im}(\lambda_f)}{1 + |\lambda_f|^2}, \quad D_f = \frac{2 \text{Re}(\lambda_f)}{1 + |\lambda_f|^2}, \]

\[ S_{\tilde{f}} = \frac{2 \text{Im}(\tilde{\lambda}_f)}{1 + |\tilde{\lambda}_f|^2}, \quad D_{\tilde{f}} = \frac{2 \text{Re}(\tilde{\lambda}_f)}{1 + |\tilde{\lambda}_f|^2}. \]
GLW with $B^+ \rightarrow D^0 K \pi \pi$

- First observation of $B^+ \rightarrow D^0(\rightarrow KK)K \pi \pi$, and measurement of CP observables
- With larger dataset, aim to also perform ADS analysis and obtain constraints on $\gamma$
Observation of $B_s \rightarrow D_s K \pi \pi$

- Time-dependent analysis can be done in a similar way to $B_s \rightarrow D_s K$
- First, need to observe it!
- Using only $\phi \pi$ and $K^*K$ submodes of $D_s \rightarrow KK \pi$, to improve S/B

N($B^0$) = 402±33
N($B_s$) = 216±21

$$\frac{B(\overline{B}_s^0 \rightarrow D_s^+ K^- \pi^+ \pi^-)}{B(\overline{B}_s^0 \rightarrow D_s^+ \pi^- \pi^+ \pi^-)} = (5.2 \pm 0.5 \pm 0.3) \times 10^{-2}$$

$$\frac{B(\overline{B}_s^0 \rightarrow D_s^+ K^- \pi^+ \pi^-)}{B(\overline{B}_s^0 \rightarrow D_s^+ K^- \pi^+ \pi^-)} = 0.54 \pm 0.07 \pm 0.07,$$

hep-ex/1211.1541
(submitted to Phys. Rev. D)