Measurements of $B \rightarrow DK^{(*)}$ decays to constrain the CKM unitarity triangle angle $\gamma$ at LHCb

Andrew Powell (University of Oxford)

On behalf of the LHCb Collaboration
Hadronic B Decays for Accessing $\gamma$

- $\gamma$ is unique: only CPV parameter accessible via
  - Tree Process: $\gamma_{SM}$
  - Loop Process: $\gamma_{SM} + \gamma_{NP}$

- Comparison of measurements sensitive to NP
Hadronic B Decays for Accessing $\gamma$

- $\gamma$ is unique: only CPV parameter accessible via
  - Tree Process: $\gamma_{\text{SM}}$
  - Loop Process: $\gamma_{\text{SM}} + \gamma_{\text{NP}}$

- Comparison of measurements sensitive to NP

- Tree-level $b \rightarrow c$ and $b \rightarrow u$ transitions
  - For $q = u$:
    - $B^\pm \rightarrow D_X$ where $X = \{K^\pm, K^\pm\pi\pi, K^{*\pm}, \ldots\}$
    - Colour favoured diagrams possible
  - For $q = d$:
    - $B^0 \rightarrow D_X$ where $X = K^{*0}$
    - $D\overline{D}$ decay to common final state
Hadronic B Decays for Accessing $\gamma$

- $\gamma$ is unique: only CPV parameter accessible via
  - Tree Process: $\gamma_{SM}$
  - Loop Process: $\gamma_{SM} + \gamma_{NP}$
- Comparison of measurements sensitive to NP

- Tree-level $b \to c$ and $b \to u$ transitions
  - For $q = s$ (colour favoured decays)
    - $B_s^0 \to D_s^+ K^\pm$
    - Interference from $B_s^0 \leftrightarrow \overline{B_s^0}$ mixing
Hadronic B Decays for Accessing $\gamma$

- $\gamma$ is unique: only CPV parameter accessible via
  - Tree Process: $\gamma_{SM}$
  - Loop Process: $\gamma_{SM} + \gamma_{NP}$
- Comparison of measurements sensitive to NP

- Loop-level via $B \to h \cdot h^{+'}$ family
  - Sensitive to:
    - $\gamma$, $\phi_d$, $\phi_s$
  - See talk by Paul Soler in this session
LHCb – Optimised for B & D Physics

- All γ analyses at LHCb benefit greatly from dedicated PID

- Data acquired to date:
  - 2010: 37 pb⁻¹
  - 2011: 1 fb⁻¹
  - 2012: 0.6 fb⁻¹ so far
    - Aiming for 1.5 fb⁻¹

Andrew Powell, University of Oxford       B → DK(*) Decays at LHCb

ICHEP 2012
• $B^{\pm} \rightarrow D^0 X_s^{\pm} (1 \text{ fb}^{-1} \text{ 2011 data})$
  – ’GLW’ parameters $A_{CP^+}$ & $R_{CP^+}$ using $D^0 \rightarrow \{\pi\pi, KK\}$
    – $X_s = K$ [Phys. Lett. B 712 (203)]
    – $X_s = K\pi\pi$ [LHCb-CONF-2012-021] \text{ New!}
  – ’ADS’ parameters $A_{ADS}$ & $R_{ADS}$ using $D^0 \rightarrow K\pi$
    – $X_s = K$ [Phys. Lett. B 712 (203)]

• $B^0 \rightarrow D^0 K^{*0} (1 \text{ fb}^{-1} \text{ 2011 data})$ \text{ New!}
  – ’GLW’ parameters $A_{CP^+}$ & $R_{CP^+}$ using $D^0 \rightarrow KK$
    – [LHCb-CONF-2012-024]

• $B_s^0 \rightarrow D_s^{\mp} K^\pm (0.37 \text{ fb}^{-1} \text{ 2011 data})$
  – Branching ratio measurements
    – $\mathcal{B}(B_s \rightarrow D_s K)$ [JHEP 06 (2012) 115]
    – $\mathcal{B}(B_s \rightarrow D_s \pi)$ [JHEP 06 (2012) 115]
$B^{\pm} \rightarrow D^0 X_s^{\pm} : GLW$
• $X_s$: final state with same quantum numbers as $K^\pm$
  – Two LHCb analyses: $X_s^\pm = \{K^\pm, K^\pm\pi^\mp\pi^\pm\}$ with $X_d^\pm = \{\pi^\pm, \pi^\pm\pi^\mp\pi^\pm\}$

• Exploit interference of $D^0/\bar{D}^0$ decaying to CP-eigenstate

\[
\begin{align*}
B^- & \xrightarrow{A_B(p)e^{-i\gamma}} D^-X_s^- \\
\bar{D}^- & \xrightarrow{\bar{A}_B(p)e^{-i\gamma}} \bar{D}^-X_s^- \\
B^+ & \xrightarrow{A_B(p)} D_{CP}X_s^- \\
\end{align*}
\]

• $A(p) = A_B(p) + \bar{A}_B(p)e^{-i\gamma}$

• $p$: position in multi-body $B$ phase space

• Total rate $\rightarrow \int A(p) dp$
\[ B^\pm \to D^0 X_s^\pm \] ‘GLW’ Analyses

- \( X_s \) : final state with same quantum numbers as \( K^\pm \)
  - Two LHCb analyses: \( X_s^\pm = \{K^\pm, K^\pm\pi^\mp\pi^\pm\} \) with \( X_d^\pm = \{\pi^\pm, \pi^\pm\pi^\mp\pi^\pm\} \)

- Exploit interference of \( D^0/\bar{D}^0 \) decaying to CP-eigenstate

\[
\begin{align*}
&\begin{array}{c}
\Delta X^-(p)
\end{array} \\
&\begin{array}{c}
B^-
\end{array} \quad \begin{array}{c}
A_B(p)\ e^{-i\gamma}
\end{array} \quad \begin{array}{c}
\bar{D}X^-(p)
\end{array} \\
&\begin{array}{c}
D_{CP}X^-(p)
\end{array}
\end{align*}
\]

- \( A(p) = A_B(p) + \bar{A}_B(p)e^{-i\gamma} \)
- \( p \) : position in multi-body B phase space
- Total rate \( \to \int A(p)\ dp \)

- Two CP observables:

\[
\begin{align*}
R_{CP^+} &\equiv 2 \frac{\Gamma(B^- \to D_{CP}K^-) + \Gamma(B^+ \to D_{CP}K^+)}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to \bar{D}^0K^+)} & \text{Av. Partial Rate} \\
A_{CP^+} &\equiv \frac{\Gamma(B^- \to D_{CP}K^-) - \Gamma(B^+ \to D_{CP}K^+)}{\Gamma(B^- \to D_{CP}K^-) + \Gamma(B^+ \to D_{CP}K^+)} & \text{CP Asymmetry}
\end{align*}
\]

Andrew Powell, University of Oxford       B \to DK(\star) Decays at LHCb                 ICHEP 2012
• $X_s$ : final state with same quantum numbers as $K^\pm$
  – Two LHCb analyses: $X_s^\pm = \{K^\pm, K^\pm \pi^\mp \pi^\pm\}$ with $X_d^\pm = \{\pi^\pm, \pi^\mp \pi^\mp \}$

• Exploit interference of $D^0/\overline{D}^0$ decaying to CP-eigenstate

\[
\begin{align*}
A(p) &= A_B(p) + \overline{A}_B(p) e^{-i\gamma} \\
p & : \text{position in multi-body B phase space} \\
\text{Total rate} & \rightarrow \int A(p) \, dp
\end{align*}
\]

• Two CP observables:

\[
R_{CP^+} = 1 + r_B^2 + 2\kappa r_B \cos \delta_B \cos \gamma
\]

\[
A_{CP^+} = \frac{2\kappa r_B \sin \delta_B \sin \gamma}{R_{CP^+}}
\]

• $r_B$ : ratio decay amplitudes $A$ and $\overline{A}$
• $\delta_B$ : strong phase difference within $B$ decays
• $\kappa$ : coherence factor $\{0 \leq \kappa \leq 1\}$
B → D⁰X, D⁰ → \{ππ, KK\}, X=3h

\[ X_d^\pm = \pi^\pm ππ \]

\[ X_s^\pm = K^\pm ππ \]

LHCb Preliminary

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B → DK(\bar{K}) Decays at LHCb

ICHEP 2012
$B \rightarrow D^0 X$, $D^0 \rightarrow \{\pi\pi, KK\}$, $X=3\ h$

$\pi\pi D X_{(d,s)}^-$

$\pi\pi D X_{(d,s)}^+$

$KK D X_{(d,s)}^-$

$KK D X_{(d,s)}^+$

$X^+_d = \pi^+ \pi^\pi$

$X^+_s = K^+ \pi^\pi$

- Raw asymmetries visible in Cabibbo Suppressed ($X_s$) final states
- Require corrections for production & detection asymmetries (from data)

Andrew Powell, University of Oxford       B → DK(\*\*) Decays at LHCb       ICHEP 2012
$B \to D^0 X, D^0 \to \{\pi\pi,KK\}, X=3h$

$A_{CP}^{CP+} = -0.018 \pm 0.018 \pm 0.010$

$A_{s}^{CP+} = -0.14 \pm 0.10 \pm 0.01$

$R_{CP+} = 0.95 \pm 0.11 \pm 0.02$

- Raw asymmetry
- Require corrections for production & detection asymmetries

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B $\to$ DK($^{(*)}$) Decays at LHCb  
ICHEP 2012
$B \rightarrow D^0 X$, $D^0 \rightarrow \{\pi\pi, KK\}$, $X=h$

$\pi^+ = \pi^+_{(d,s)}$

$K^+ = K^+_{(d,s)}$

$X^+_{(d,s)}$ and $X^-_{(d,s)}$ distributions for $B \rightarrow D^0 X$, $D^0 \rightarrow \{\pi\pi, KK\}$, $X=h$. The distributions are shown for different decay modes, with the $m(B)$ distribution plotted against the number of events per 5 MeV/c$^2$. The data are from the LHCb experiment with 1 fb$^{-1}$ of integrated luminosity.
\[ B \rightarrow D^0 X, \quad D^0 \rightarrow \{\pi\pi, KK\}, \quad X=h \]

- Again, raw asymmetries visible in the Cabibbo Suppressed mode
B → D⁰X, D⁰ → {ππ,KK}, X=h

\[ \frac{[\pi\pi]_{D^0 X^-}^{(d,s)}}{[\pi\pi]_{D^0 X^+}^{(d,s)}} = \frac{[KK]_{D^0 X^-}^{(d,s)}}{[KK]_{D^0 X^+}^{(d,s)}} \]

\[ A_d^{CP+} = -0.02 \pm 0.02 \pm 0.01 \]

\[ A_s^{CP+} = 0.145 \pm 0.022 \pm 0.010 \]

- Again, raw asymmetries visible in the Cabibbo Suppressed mode

\[ R_{CP^+} = 1.007 \pm 0.038 \pm 0.012 \]
World $1^{st}$ $A_{CP}$ measurements in $B^0 \to D K^{*0}$

- See talk by Alexandra Martín Sánchez earlier today

$[KK]_D \bar{KK}^{*0}$

$[KK]_D K^{*0}$

$[K^- \pi^+]_D \bar{KK}^{*0}$

$[K^+ \pi^-]_D K^{*0}$
**B^0 \rightarrow D^0 K^{*0}, D^0 \rightarrow KK**

- World 1^{st} A_{CP} measurements in $B^0 \rightarrow DK^{*0}$
  - See talk by Alexandra Martín Sánchez earlier today

\[
\begin{align*}
A_{KK}(B_d) &= -0.47^{+0.24}_{-0.25} \pm 0.02 \\
A_{KK}(B_s) &= 0.04 \pm 0.17 \pm 0.01 \\
R_{KK}(B_d) &= 1.42^{+0.41}_{-0.35} \pm 0.07 \\
A_{K\pi}(B_d) &= -0.08 \pm 0.08 \pm 0.01
\end{align*}
\]

Andrew Powell, University of Oxford       B $\rightarrow$ DK($^{(*)}$) Decays at LHCb       ICHEP 2012
$B^\pm \rightarrow D^0 X_s^\pm : ADS$
\[ B^\pm \rightarrow DX_s^\mp : \text{‘ADS’ Analysis} \]

- Particular sensitivity to $\gamma$ from suppressed ADS modes where interference is large:

\[ R_s^\pm \equiv \frac{\Gamma([K^\mp \pi^\pm]D X_s^\pm)}{\Gamma([K^\pm \pi^\mp]D X_s^\pm)} \]

- \( R_s^{ADS} \equiv \frac{1}{2}(R_s^+ + R_s^-) \)

- \( A_s^{ADS} \equiv \frac{R_s^- - R_s^+}{R_s^- + R_s^+} \)

- ‘Rare’ (\( B \sim 2 \times 10^{-7} \))
- + 2 favoured modes (SS kaons)
- \( B \rightarrow DX_d \) control modes

Andrew Powell, University of Oxford       B \rightarrow DK(\kappa) Decays at LHCb       ICHEP 2012
• Particular sensitivity to $\gamma$ from suppressed ADS modes where interference is large:

$$\mathcal{R}^\pm_s = \frac{\Gamma([K^\mp \pi^\pm]_D X_s^\pm)}{\Gamma([K^\pm \pi^\mp]_D X_s^\pm)}$$

$$\mathcal{R}^{ADS}_s = r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D) \cos \gamma$$

$$\mathcal{A}^{ADS}_s = 2\kappa r_B r \sin(\delta_B + \delta_D) \sin \gamma / \mathcal{R}^{ADS}_s$$

• ‘Rare’ ($\mathcal{B} \sim 2 \times 10^{-7}$)
• + 2 favoured modes (SS kaons)
• $B \to D X_d$ control modes

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B $\to$ DK($^*$) Decays at LHCb  
ICHEP 2012
$B \rightarrow D^0 X$, $D^0 \rightarrow K\pi$, $X=h$

$[K\pi]_{D\pi^-}$, $[K\pi]_{D\pi^+}$, $[K\pi]_{DK^-}$, $[K\pi]_{DK^+}$
B → D⁰X, D⁰ → Kπ, X=h

[Kπ]_Dπ−  [Kπ]_Dπ⁺  [Kπ]_DK−  [Kπ]_DK⁺
B \rightarrow D^0X, D^0 \rightarrow K\pi, X=h

\begin{align*}
\pi^+ K^- &\quad \text{Fav.} \\
[\pi^- K^+] &\quad \text{Sup.} \\
\end{align*}

\begin{align*}
R_d^{ADS} &= (0.410 \pm 0.025 \pm 0.005)\% \\
R_s^{ADS} &= (1.52 \pm 0.20 \pm 0.04)\% \\
\end{align*}

Andrew Powell, University of Oxford    B \rightarrow DK(\pi) \text{ Decays at LHCb    ICHEP 2012}
$B \rightarrow D^0X, D^0 \rightarrow K\pi, X=h$

\[ [K\pi]_{D\pi^-} \quad [K\pi]_{D\pi^+} \quad [K\pi]_{DK^-} \quad [K\pi]_{DK^+} \]

$A^{ADS}_d = (14.3 \pm 6.2 \pm 1.1)\%$

$A^{ADS}_s = (-52 \pm 15 \pm 2)\%$

- First ‘hint’ of CPV in this decay
- Combining with KK/$\pi\pi$ this is the $1^{st}$ single analysis to observe (5.8 $\sigma$) CPV in $B^\pm \rightarrow DK^\pm$

Andrew Powell, University of Oxford       B $\rightarrow$ DK($^*$) Decays at LHCb       IHEP 2012
γ from $B_s \rightarrow D_s^{\mp} K^{\pm}$
Large interference effects expected
  – Two interfering tree-level processes of similar strength

Time dependent analysis sensitive to $(\gamma + \phi_s)$
  – Requires excellent proper time resolution + statistics
  – Analysis method unique to LHCb!

Measurement of $\mathcal{B}(B_s \to D_s^{\mp}K^{\pm})$ an important stepping stone to accessing $\gamma$ with this mode:
  – Determine $\frac{\mathcal{B}(B_s^0 \to D_s^{+}K^{\pm})}{\mathcal{B}(B_s^0 \to D_s^{-}\pi^{+})}$ and $\frac{\mathcal{B}(B_s^0 \to D_s^{-}\pi^{+})}{\mathcal{B}(B_s^0 \to D_s^{-}\pi^{+})}$
  – Use LHCb’s measurement of $f_s/f_d$ @ $\sqrt{s} = 7$ TeV

\[
\begin{align*}
\mathcal{B}(B_s^0 \to D_s^{+}K^{\pm}) &= (1.90 \pm 0.12 \pm 0.13^{+0.12}_{-0.14}) \times 10^{-4} \\
\mathcal{B}(B_s^0 \to D_s^{-}\pi^{+}) &= (2.95 \pm 0.05 \pm 0.17^{+0.12}_{-0.14}) \times 10^{-3}
\end{align*}
\]
\[ \mathbf{B}_s \rightarrow \mathbf{D}_s^\mp \mathbf{K}^\pm : \text{Towards } \gamma \]

- **Proper time studied**
  - 45 fs resolution (\( \mathbf{D}_s \pi \))

- **Tagging understood**
  - \( \varepsilon \mathbf{D}^2 = (3.2 \pm 0.8)\% \) OS
  - Additional power from SS
  - See talk by S. Vecchi earlier today

- **Milestone measurements:**
  - \( \Delta m_s = (17.725 \pm 0.041 \pm 0.026) \text{ ps}^{-1} \)
    - LHCb-CONF-2011-050
  - \( \mathcal{B}(\mathbf{B}_s^0 \rightarrow \mathbf{D}_s^\mp \mathbf{K}^\pm) \)

- **All necessary ingredients are there**
  - Just awaiting the statistics
Summary

• B → DK decays provide an extensive set of channels in order to measure the CKM angle $\gamma$

• Results are now coming in from several of them:
  – $B^\pm \rightarrow D^0 X_s^\pm :$ GWL + ADS
  – $B^0 \rightarrow D^0 K^*$ (see talk by A. Martín Sánchez earlier today)
  – $B_{s}^0 \rightarrow D_{s}^{+} K^\pm$

• ...and many are on their way:
  – $B^\pm \rightarrow D^0 X_s^\pm, D^0 \rightarrow K_s \pi \pi :$ GGSZ + Dalitz
  – $B^\pm \rightarrow D^0 X_s^\pm, D^0 \rightarrow \{K_3 \pi, K \pi \pi^0\}$

• Lots of exciting results in the pipeline – stay tuned!
Backup
B^− → D^0 X_s^- : ‘GLW’ Analyses

• X_s : final state with same quantum no.’s as K^±
  – Two LHCb analyses: X_s = \{K^±, K^±\pi^\mp\pi^\±\}

• Exploit interference of D^0/\bar{D}^0 decaying to CP-eigenstate

\[
A(p) = A_B(p) + \bar{A}_B(p)e^{-i\gamma}
\]

• p : position in multi-body B phase space

• Total rate \( \rightarrow \int A(p) dp \)

• For \( R_{CP^+} \), experimentally we actually measure:

\[
R_+ \equiv \frac{R^{CP^+}_{s/d}}{R^{K^\mp\pi}_{s/d}} \quad \text{where} \quad R^{f}_{s/d} = \frac{\Gamma(B^\pm \rightarrow D_f X_s^\pm)}{\Gamma(B^\pm \rightarrow D_f X_d^\pm)}
\]

• Equivalent to within a theoretical uncertainty of \( \mathcal{O}(1\%) \)
Analysis Strategy

- $B^\pm \rightarrow DX^\pm$ selected using MVA algorithm
  - $X = h$: TMVA BDT
  - $X = 3h$: NeuroBayes Neural Network

- Compose 8 mutually exclusive sub-samples:
  - Use PID to:
    - isolate $DX_s/DX_d$ enhanced samples
    - Distinguish KK and $\pi\pi$
  - Employ data-driven method to determine PID cut efficiency
Analysis Strategy

• \( B^\pm \rightarrow DX^\pm \) selected using MVA algorithm
  – \( X = h \) : TMVA BDT
  – \( X = 3h \) : NeuroBayes Neural Network

• Compose 8 mutually exclusive sub-samples:
  - \( DX_s \)
  - \( DX_d \)
  - \( X^+ \)
  - \( X^- \)
  - \( KK \)
  - \( \pi\pi \)

• Peaking Backgrounds
  - Charmless backgrounds
    • Suppressed with D\(^0\) flight significance cut and PID cuts on D\(^0\) daughter tracks
  - Non-prompt \( X = 3h \) backgrounds (e.g. \( B \rightarrow D^0D_s^* \))
    • Apply a mass veto about the D\(_s^*\) mass
  - Fully reconstructed \( B \rightarrow DX \) decays (e.g. \( B \rightarrow D(K\pi)a_1(KK\pi) \))
    • Assess in D\(^0\) mass sidebands

• Simultaneous, maximum-likelihood fits to all \( B^\pm \) mass distributions
  - Fit for Cabibbo Favoured yields + physics asymmetries
  - Detection and production asymmetries accounted for

Andrew Powell, University of Oxford          B \( \rightarrow DK^{(*)} \) Decays at LHCb          ICHEP 2012
**B^0 → D K^*0 analysis**

- Based on 2011 LHCb data sample: 1.0 fb^{-1}.
- **Cut-based** selection: kinematics, vertex quality, PID (DLL_{K,π}).
- Background from charmless decays (such as B^0 → K^- π^+ K^*0, etc.) removed by D meson flight distance significance cut.
- D_{(s)} h^+ contributions vetoed.
- D^{*0} K^0 partially reconstructed background (D^{*0} → D^{0} π^0/γ) and D^{0} ρ^0 cross-feed (π misidentified as K) modeled in the fit to the invariant mass.
- Unbinned maximum likelihood fit to the invariant mass distribution.
  - Signal and background shapes modeled from simulation.
  - Dominant systematic uncertainty comes from the fit model.
$B^0 \to D K^{*0}, \ D^0 \to K^- \pi^+$

Favoured, control mode
No CP asymmetry expected

$$A_{d}^{\text{fav}} = -0.08 \pm 0.08 \ (\text{stat}) \pm 0.01 \ (\text{syst})$$

$N(B^0) = 94 \pm 11$

$N(B^0) = 108 ^{+12}_{-11}$
$B^0 \rightarrow D K^{*0}$, $D^0 \rightarrow K^- K^+$

\[
\mathcal{A}^{KK}_d = -0.47^{+0.24}_{-0.25} \text{ (stat)} \pm 0.02 \text{ (syst)}
\]

\[
\mathcal{A}^{KK}_s = 0.04 \pm 0.17 \text{ (stat)} \pm 0.01 \text{ (syst)}
\]

\[
\mathcal{R}^{KK}_d = 1.42^{+0.41}_{-0.35} \text{ (stat)} \pm 0.07 \text{ (syst)}
\]

---

5.1 $\sigma$ $B^0$ signal ($B^0 + \bar{B}^0$)

- $N(B^0) = 7 \pm 4$
- $N(B^0) = 20 \pm 6$
- $N(B^s) = 22 \pm 6$
- $N(B_s^0) = 24 \pm 6$

1st measurement in the $B^0 \rightarrow D(K^+K^-)K^{*0}$ system