Measurement of CP Observables in $B^0 \rightarrow DK^{*0}$ decays at LHCb

Edmund Smith

IOP HEPP and APP Group Meeting 2013, 8 – 10 May 2013, University of Liverpool.
\textbullet\, \( \gamma \) is the least well known of the angles in the UT, \( 66 \pm 12^\circ \).

\textbullet\, Accessed with \( b \to u \) transitions, which are rare.

\textbullet\, \( B^0 \to D^0 K^{*0} \) gives a tree-level/SM determination of \( \gamma \).
CP violation in interference

- Common final state $f_D$ of $D^0K^{*0}$ and $D^0K^{*0} \rightarrow$ interference.
- Weak phase difference $= \gamma$.
- CP invariant strong phase difference $= \delta_B$. 

April 9, 2013
CP violation in interference

\[ |A_B| \neq |A_{\bar{B}}| \Rightarrow \text{CP violation} \]

- Charge conjugate process has different amplitude.
- Measure \( \gamma \) from the different decay rates.

\[ N \propto |A_B|^2 \]
\[ N \propto |A_{\bar{B}}|^2 \]
We Measure

We measure the CP observables using the following expressions:

\[
R_{CP^+} = \frac{\Gamma(B^0 \rightarrow D(KK)K^*) + \Gamma(B^0 \rightarrow D(KK)K^*)}{\Gamma(B^0 \rightarrow D(K^-K^+K^*) + \Gamma(B^0 \rightarrow D(K^+K^-K^*)K^*)}
\]

\[
A_{CP^+} = \frac{\Gamma(B^0 \rightarrow D(KK)K^*) - \Gamma(B^0 \rightarrow D(KK)K^*)}{\Gamma(B^0 \rightarrow D(KK)K^*) + \Gamma(B^0 \rightarrow D(KK)K^*)}
\]

Relation to physics parameters:

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

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

- \(\delta_B\) = strong phase difference.
- \(r_B\) = amplitude ratio.
- \(\kappa\) = coherence factor.
- \(\gamma\) = CKM angle.

- Not sensitive to \(\gamma\) independently yet.
- Can provide input when combined with other LHCb analyses.
Analysis Summary:

- Rectangular cut based selection, optimised for the $B^0 \rightarrow D(KK)K^*$ signal.
- Simultaneous fit to the $B^0$ invariant mass.

Backgrounds:
- $B \rightarrow D_{(s)}h$
- $\Lambda_b \rightarrow D^0 ph$
- $B^0 \rightarrow KKK^*$
- $B_d^0 \rightarrow D\rho^0$
- $B^0_{(s)} \rightarrow D^*K^*$

Excluded with cuts

Charmless Background

Modelled

Reduced this yield to 0 with cut on $D^0$ flight distance.
2011 Dataset = 1 fb$^{-1}$

\begin{align*}
(a) + (b) &= 5.1\sigma \text{ observation of } B^0 \rightarrow D(KK)K^*0 \\
\text{Large CP asymmetry}
\end{align*}
Sources of systematic uncertainty:

- Production asymmetry.
- Trigger efficiency.
- Particle ID efficiency.
- Selection efficiency.
- Fit-related effects.
- Branching ratios.

External Input
Data-driven Calibration
Monte Carlo
Toy Experiments
Systematics and Results

Sources of systematic uncertainty:

- Production asymmetry.
- Trigger efficiency.
- Particle ID efficiency.
- Selection efficiency.
- Fit-related effects.
- Branching ratios.

\[
A_{CP^+} = -0.45 \pm 0.23 \text{ (stat)} \pm 0.02 \text{ (syst)}
\]

\[
R_{CP^+} = 1.36^{+0.37}_{-0.32} \text{ (stat)} \pm 0.07 \text{ (syst)}
\]

[JHEP 1303 (2013) 067]
Future plans

What’s missing? \( \rightarrow \text{ADS observables from } B^0 \rightarrow D^0(K^+\pi^-)K^{*0} \)

\[
\begin{align*}
R_{ADS} &= r_B^2 + r_f^2 + 2r_B r_f \cos(\delta_B + \delta_f) \cos \gamma \\
A_{ADS} &= \frac{2r_B r_f \kappa \sin(\delta_B + \delta_f) \sin \gamma}{R_{ADS}}
\end{align*}
\]

- Measured with non-CP eigenstate \( D^0 \) final states.
- \( r_f \) and \( \delta_f \) depend on the final state.
- Potentially larger interference effects.
- Requires suppressed \( D^0 \rightarrow K^+\pi^- \).

Future plans:
- ADS observables give sensitivity to \( \gamma \rightarrow \) search for the suppressed mode.
- Move to a multi-variate selection.
- Additional constraints on \( A_{CP^+} \) and \( R_{CP^+} \) from \( B^0 \rightarrow D(\pi\pi)K^{*0} \).
Sneak preview

**BDT Performance** (relative to rectangular cuts)

- **LHCb Unofficial**
  - $B^0$ peak $S/B$ vs $S/B$

- **Suppressed ADS mode**

**LHCb Unofficial**

1. $D \rightarrow KK$
2. $D \rightarrow \pi\pi$

$$B \rightarrow D(KK)K^*0$$

$$N_{2011+2012} = 3.1 \times N_{2011}$$

$$2fb^{-1} 8TeV + 0.9fb^{-1} 7TeV$$
Datasets:
• 2011: $1 fb^{-1}$ collected (published analysis).
• 2012: $2 fb^{-1}$ collected (analysis in progress).

Detector:
• Trigger is 30% efficient for multibody hadronic final states.
• Makes use of unique detector elements e.g. RICH and VELO.

Acceptance
• pseudorapidity: $2 < \eta < 5$

Resolutions
• momentum resolution: $\Delta p / p = 0.4 \%$ at 5 GeV/c to 0.6 $\%$ at 100 GeV/c
• ECAL resolution (nominal): $1 \% + 10 \% / \sqrt{E[GeV]}$
• impact parameter resolution: 20 $\mu$m for high-pT tracks
• invariant mass resolution: $\sim 8$ MeV/c$^2$ for $B \rightarrow J/\psi X$ decays with constraint on $J/\psi$ mass $\sim 22$ MeV/c$^2$ for two-body $B$ decays $\sim 100$ MeV/c$^2$ for $B_s \rightarrow \phi \gamma$, dominated by photon contribution
• decay time resolution: 45 fs for $B_s \rightarrow J/\psi \phi$ and for $B_s \rightarrow D_s \pi$

Efficiencies
• percentage of working detector channels: $\sim 99 \%$ for all sub-detectors
• data taking efficiency: $> 90 \%$
• data good for analyses: $> 99 \%$
• trigger efficiencies: $\sim 90 \%$ for dimuon channels $\sim 30 \%$ for multi-body hadronic final states
• track reconstruction efficiency: $> 96 \%$ for long tracks
• electron ID efficiency: $\sim 90 \%$ for $\sim 5 \% e \rightarrow h$ mis-id probability
• kaon ID efficiency: $\sim 95 \%$ for $\sim 5 \% \pi \rightarrow K$ mis-id probability
• muon ID efficiency: $\sim 97 \%$ for $1-3 \% \pi \rightarrow \mu$ mis-id probability
• Huge $b\bar{b}$ cross section at the LHC.

• **VELO** – displaced vertex reconstruction.

• **RICH** – final state hadron identification.
### Kinematic selection:

- $p_T(h_D) > 400\text{MeV}$
- $p_T(h_{K^{*0}}) > 300\text{MeV}$
- $\text{Vertex} \chi^2(B^0) < 4$
- $\text{Vertex} \chi^2(D^0) < 5$
- Flight distance significance > 2.5
- $\text{Min IP } \chi^2(K^{*0}) > 25$
- $\text{Min IP } \chi^2(D^0) > 4$
- $\text{Min IP } \chi^2(B^0) < 9$
- $\cos(\theta_{\text{dira}})(B^0) > 0.99995$
- $\Sigma_{\text{tracks}}\sqrt{\text{IP} \chi^2} > 32$
- $|M(D^0) - M_{\text{pdg}}(D^0)| < 20\text{MeV}$
- $|M(K^{*0}) - M_{\text{pdg}}(K^{*0})| < 50\text{MeV}$
- $|\cos(\theta^*)| > 0.4$
- $|M(K\pi\pi) - M_{\text{pdg}}(D^+) > 15\text{MeV}$
- $|M(KK\pi) - M_{\text{pdg}}(D_s^+) > 15\text{MeV}$

### Particle ID:

- $D \rightarrow K\pi$
- $DLL_{K\pi}(K_D) > 0$
- $DLL_{K\pi}(\pi_D) < 4$
- $D \rightarrow KK$
- $DLL_{K\pi}(K_D) > 0$
- ALL
- $DLL_{K\pi}(\pi_{K^{*0}}) < 3$
- $DLL_{K\pi}(K_{K^{*0}}) > 3$
- $DLL_{pK}(K_{K^{*0}}) < 10$

### Multiple Candidate Removal:
Keeping candidate with largest FDCHI2 of the B.
Particle ID calibration

Calibration sample:

- Can identify these from their charges.
- No PID required.
- Pure samples of real \( K \)'s and \( \pi \)'s.
- Apply PID cut.
- Bin efficiency in kinematic variables.

Signal sample:

- Calibration histogram for each track.
- Efficiency taken from the histograms according to decay kinematics.
- Takes into account correlations between tracks in multi-body final states.
Production asymmetry

Correction factor

\[ a_{\text{prod}}^{d} = \frac{1 - \kappa A_{\text{prod}}}{1 + \kappa A_{\text{prod}}} \]

\[ \kappa(B^0 \rightarrow \bar{D}^0 K^*) = \frac{\int_0^{+\infty} e^{-\Gamma d t} \cos(\Delta m_d t) e_{B^0 \rightarrow \bar{D}^0 K^*}(t) dt}{\int_0^{+\infty} e^{-\Gamma d t} \cosh\left(\frac{\Delta \Gamma d t}{2}\right) e_{B^0 \rightarrow \bar{D}^0 K^*}(t) dt} \]

\[ \kappa(B^0 \rightarrow \bar{D}^0 K^*) = \frac{1}{N_{\text{offline total}}} \int_0^{+\infty} \cos(\Delta m_d t) N_{\text{offline selected}}(t) dt \]

\[ A_{\text{prod}} = 0.010 \pm 0.013 \]

\[ \kappa = 0.456 \pm 0.011 \]

• Monte Carlo for kinematic acceptance.
• Data-driven calibration for PID acceptance.

Dilution due to mixing

Correction factor

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