Hadronic B Decays at LHCb

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The article outlines three new or updated LHCb results presented at Moriond QCD 2012, using 1.0 fb⁻¹ of data collected in 2011.

1 B₀ to double-charm final states

Double charm decays of B mesons provide an interesting avenue to search for signs of new physics beyond the Standard Model (SM). For example, the decays \( B^0 \rightarrow D^+D^- \) and \( B^0_s \rightarrow D^+_sD^- \) can be used to measure the weak phase \( \gamma \), assuming \( U \)-spin symmetry and the decay \( B^0 \rightarrow D^+D^- \) provides an alternate way to measure \( \sin(2\beta) \), which can in principle differ from the values determined in \( B^0 \rightarrow (c\bar{c})K^0 \) because of penguin contributions.

1.1 Event Selection and Analysis

Signal candidates are formed using reconstructed \( D^0 \rightarrow K^-\pi^+ \), \( D^+ \rightarrow K^-\pi^+\pi^+ \) and \( D^+_s \rightarrow K^+K^-\pi^+ \) decays. The B candidates are then reconstructed from the appropriate pair of charm mesons, applying both mass and vertex constraints to the assumed decay chain and loose particle identification requirements on the \( D \) children. To further improve the signal purity, a multivariate selection is then applied, trained on data using clean signals of \( D \) mesons obtained from background subtracted \( B^0 \rightarrow D^+s\pi^- \) and \( B^- \rightarrow D^0\pi^- \) decays. Background for the training is taken from the \( D \) mass sideband regions. In addition to including kinematical quantities of the \( D \) and the \( D \) children, a number of track-quality and particle-identification variables are also used to maximize the discriminating power.

The mass spectra are fitted using a single Crystal Ball function which is used for all \( \bar{B} \rightarrow D\bar{D}' \) modes. Simulated events are used to derive Gaussian parametrizations for the backgrounds due to mis-reconstructed decays. An exponential combinatoric background term is also included. Examples of the fitted mass spectra are shown in Figures 1 and 2.

The results for the branching ratios, computed from the fitted signal yields, are

\[
\begin{align*}
\frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D^+D^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+D^-)} = 1.00 \pm 0.18 \pm 0.09, & \quad \frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D^+_sD^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+_sD^-)} = 0.048 \pm 0.008 \pm 0.004, \\
\frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D^+_sD^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+_sD^-)} = 0.508 \pm 0.026 \pm 0.043, & \quad \frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D^0\bar{B}^0)}{\mathcal{B}(\bar{B}^- \rightarrow D^0\bar{B}^0)} = 0.015 \pm 0.004 \pm 0.002, \\
\end{align*}
\]

where the errors are statistical and systematic respectively. See² for details on the determination of the systematic uncertainties.
Testing the unitary of the CKM quark mixing matrix, by verifying the condition $|V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^*| = 0$, is a powerful check of the SM. This condition describes a triangle in the complex plane, whose area is proportional to the amount of CP violation in the model, and the unitary of which can be tested by making over-constraining measurements of its sides and angles.

Measurements of the partial widths of $B^\pm \rightarrow D K^\pm$ decays, with $D$ either a $D^0$ or $\bar{D}^0$ meson, provide one of the most powerful methods for determining the currently least-well determined observable, the CKM phase $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$. If the same $D$ final state is accessible for both $D^0$ and $\bar{D}^0$ mesons, the interference of these two processes gives sensitivity to $\gamma$ and may exhibit direct CP violation. This feature of open-charm $B^-$ decays was first recognised in its application to CP eigenstates, such as $D \rightarrow K^+K^-$, $\pi^+\pi^-\eta$, but can be extended to other decays, e.g. $D \rightarrow \pi^-K^+$, labelled “ADS” modes in reference to the authors.

1.2 Summary

First observations and relative branching fractions measurements of the decays $\bar{B}_s^0 \rightarrow D^+D^-$, $\bar{B}_s^0 \rightarrow D^+_sD^-$ and $\bar{B}_s^0 \rightarrow D^0\bar{D}^0$ have been made. A new result on the branching fraction of $\bar{B}_s^0 \rightarrow D^+_sD^-$ relative to $\bar{B}_s^0 \rightarrow D^+_sD^-$, which has a precision about 5 times better than the current world average value, has also been presented.

2 Observation of CP violation in $B^\pm \rightarrow D K^\pm$ decays

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2.1 Event Selection and Analysis

All sixteen combinations of $B^\pm \rightarrow Dh^\pm$, $D \rightarrow h^+h^-$ with $h = K, \pi$ are formed with the candidate $D$ mass within $1765 - 1965$ MeV/$c^2$. $P$ and $Pt$ cuts are applied to the $D$ daughter tracks, in order to ensure best pion versus kaon discrimination.

A multi-variate selection is then trained using a simulated sample of $B^\pm \rightarrow [K^+\pi^\mp]DK^\pm$ and background events from the $D$ sideband ($35 < |m(hh) - m_{PDG}| < 100$ MeV/$c^2$) of an independent sample collected in 2010. The selection uses a combination of track and vertex...
quality variables, $B^\pm$ and $D$ flight distance and the angle between the $B^\pm$ momentum vector and the line joining its decay vertex to the primary interaction vertex. For further details see\(^3\).

The observables of interest are determined from a fit to the invariant mass distributions of selected $B$ candidates, as shown in Figure 3.

![Figure 3: Invariant mass distributions of $B^\pm \to [K^\pm \pi^\mp] D_h^\pm$ (left) and $B^\pm \to [\pi^\pm K^\mp] D_h^\pm$ (right) candidates.](image)

In total, thirteen observables are measured in the fit:

\[
\begin{align*}
R_{K/\pi}^{f} & = \frac{\Gamma(B^- \to [f]_{D} K^-) + \Gamma(B^+ \to [f]_{D} K^+)}{\Gamma(B^- \to [f]_{D} \pi^-) + \Gamma(B^+ \to [f]_{D} \pi^+)} , \quad R_{K}^{f} = \frac{\Gamma(B^\pm \to [\pi^\pm K^\mp] D_h^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp] D_h^\pm)} , \\
A_{f} & = \frac{\Gamma(B^- \to [f]_{D} h^-) - \Gamma(B^+ \to [f]_{D} h^+)}{\Gamma(B^- \to [f]_{D} h^-) + \Gamma(B^+ \to [f]_{D} h^+)} \\
\end{align*}
\]

where $f$ represents $KK$, $\pi\pi$ and the favoured $K\pi$ mode. The following quantities are deduced:

- $R_{CP^+} \approx <R_{K/\pi}^{KK}, R_{K/\pi}^{\pi\pi}> / R_{K/\pi}^{K} = 1.007 \pm 0.038(\text{stat}) \pm 0.012(\text{syst})$
- $A_{CP+} = <A_{KK}^{K}, A_{KK}^{\pi\pi}> = 0.145 \pm 0.032(\text{stat}) \pm 0.010(\text{syst})$
- $R_{ADS(K)} = (R_{K}^{+} - R_{K}^{-})/(R_{K}^{+} + R_{K}^{-}) = 0.0152 \pm 0.0020(\text{stat}) \pm 0.0004(\text{syst})$
- $A_{ADS(K)} = (R_{K}^{-} - R_{K}^{+})/(R_{K}^{-} + R_{K}^{+}) = -0.52 \pm 0.15(\text{stat}) \pm 0.02(\text{syst})$
- $R_{ADS(\pi)} = (R_{\pi}^{+} - R_{\pi}^{-})/(R_{\pi}^{+} + R_{\pi}^{-}) = 0.00410 \pm 0.00025(\text{stat}) \pm 0.00005(\text{syst})$
- $A_{ADS(\pi)} = (R_{\pi}^{-} - R_{\pi}^{+})/(R_{\pi}^{-} + R_{\pi}^{+}) = 0.143 \pm 0.062(\text{stat}) \pm 0.011(\text{syst})$.

2.2 Summary

The $B^\pm \to DK^\pm$ ADS mode has been observed with a statistical significance of $\sim 10\sigma$ and displays evidence $(4.0\sigma)$ of a large negative asymmetry. The $B^\pm \to D\pi^\pm$ ADS mode shows a hint of a positive asymmetry with $2.4\sigma$ significance. The $KK$ and $\pi\pi$ modes both show positive asymmetries. The statistical significance of the combined asymmetry, $A_{CP^+}$, is $4.5\sigma$. With a total significance of $5.8\sigma$, direct CP violation in $B^\pm \to DK^\pm$ decays is observed.

3 Polarization amplitudes and triple product asymmetries in the decay $B_s^0 \to \phi\phi$

In the SM, the flavour-changing neutral current decay $B_s^0 \to \phi\phi$ proceeds via a $b \to s\bar{s}s$ penguin process. These decays can be used to investigate new sources of CP violation in the comparison of their time-dependent CP asymmetry with the charmonia modes (e.g $B_s \to J/\Psi\phi$).

As the decay is a pseudoscalar to vector-vector transition, three possible spin configurations of the vector meson pair are allowed by angular momentum conservation, namely $H_{+1}, H_{-1}$ and $H_0$. From these states, three linear polarization amplitudes can be defined

\[
\begin{align*}
A_0 &= H_0 , \quad A_\perp = \frac{H_{+1} - H_{-1}}{\sqrt{2}} , \quad A_{\parallel} = \frac{H_{+1} + H_{-1}}{\sqrt{2}} .
\end{align*}
\]

The $\phi\phi$ final state can be a mixture of CP-even and CP-odd eigenstates. The longitudinal ($A_0$) and parallel ($A_{\parallel}$) components are CP-even and the perpendicular component ($A_\perp$) is
$CP$-odd. From the V–A structure of the weak interaction, the longitudinal component, $f_L = \frac{|A_0|^2}{(|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2)}$, is expected to be dominant. The relevant decay angles are defined in Figure 4.

Figure 4: Decay angles for the $B_s^0 \to \phi\phi$ decay.

A search for physics beyond the SM can also be performed by studying the triple products $U = \frac{\sin(2\Phi)}{2}$ and $V = \pm \sin(\Phi)$. Non zero values of the asymmetries in these variables (0 in the SM), $A_U$ and $A_V$, can be either due to $T$-violation or final-state interactions.

3.1 Event Selection and Analysis

$B_s^0 \to \phi\phi$ candidates are reconstructed using events where both $\phi$ mesons decay into a $K^+K^-$ pair. Excellent signal purity (Figure 5) is achieved using cuts on the minimum impact parameter of the tracks to all reconstructed $pp$ interaction vertices, and by requiring the tracks also are identified as kaons.

3.2 Summary

The polarization amplitudes ($|A_0|^2$, $|A_\perp|^2$, $|A_\parallel|^2$) and triple product asymmetries $A_U$ and $A_V$ are determined by performing an unbinned maximum likelihood fits to data. The results are:

\[
\begin{align*}
|A_0|^2 & = 0.365 \pm 0.022 \text{ (stat) } \pm 0.012 \text{ (syst)}, \\
|A_\perp|^2 & = 0.291 \pm 0.024 \text{ (stat) } \pm 0.010 \text{ (syst)}, \\
|A_\parallel|^2 & = 0.344 \pm 0.024 \text{ (stat) } \pm 0.014 \text{ (syst)}, \\
\cos(\delta_\parallel) & = -0.844 \pm 0.068 \text{ (stat) } \pm 0.029 \text{ (syst)}. \\
\end{align*}
\]

and are consistent previous measurements and do not exhibit any $T$-odd violation effects.

2. First observations and branching fraction measurements of $B_s^0 \to D^0 K_S^0$ and $B_s^0 \to D \phi$. Phys. Lett., B253:483, 1991.
4. Improved methods for observing CP violation in $B^\pm \to K D^0(D^0)$ modes and extraction of the CKM angle $\gamma$. *Phys.Rev.Lett.*, 78:3257, 1997.
5. David Atwood, Isard Dunietz, and Amarjit Soni. Enhanced CP violation with $B \to K D^0(D^0)$ modes and extraction of the CKM angle $\gamma$. *Phys.Rev.*, D63:036005, 2001.