Studies of hadronic B decays to open charm mesons at LHCb

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(on behalf of the LHCb collaboration)
• A number of “firsts” emerging in the study of hadronic B decays to open charm.
  – Going beyond the “Dh±” modes, we’re exploring 5, 6, and 7 particle final states.
  – Provide additional probes of CKM parameters
    • Ultimate precision on $\gamma/\phi_3$ must take advantage of many b-hadron decays
  – Study of strong interaction dynamics.
  – Made possible due to:
    • large $\sigma_{bb}$ @LHC, and
    • excellent capabilities of LHCb to trigger on and fully reconstruct high multiplicity final states.

• Here, we discuss some of the recent results from LHCb on $B \rightarrow DX$.

• All results based on 1 fb$^{-1}$, unless otherwise noted.
First observation of $B_s \to D^0\phi$

- Motivation: $\gamma$ determination using TI (ala $B^- \to D^0K^-$) or TD (as in $B_s \to D_sK$) analyses.
  - Both are theoretically clean.
  - Start with $D^0 \to K\pi$.
    More final states needed for TI $\gamma$ determination.

- First goal is to observe the decay and measure rates.
  - Normalize to $B_s \to D^0\bar{K}^*$

- Also improve measurement of $B(B_s \to D^0\bar{K}^*)$, normalized relative to $B(B^0 \to D^0\bar{K}^*)$.

- All results are preliminary, see LHCb-PAPER-2013-035
Signals in data

\[ N(B_s^0 \rightarrow \bar{D}^0 K^{*0}) = 535 \pm 30 \]
\[ N(B^0 \rightarrow \bar{D}^0 K^{*0}) = 260 \pm 24 \]

\[ N(B_s^0 \rightarrow \bar{D}^0 \phi) = 43 \pm 8 \]
\[ 7.1\sigma \text{ significance} \]
Results on branching fractions

\[
\frac{\mathcal{B}(B_s^0 \to \bar{D}^0 \bar{K}^{*0})}{\mathcal{B}(B^0 \to \bar{D}^0 K^{*0})} = 7.8 \pm 0.7_{\text{stat}} \pm 0.3_{\text{syst}} \pm 0.6_{\text{fs/fd}}
\]

Using \(B(B^0 \to \bar{D}^0 K^{*0})_{PDG} = (4.2 \pm 0.6) \times 10^{-5}\),

\[
\mathcal{B}(B_s^0 \to \bar{D}^0 \bar{K}^{*0}) = \left(3.3 \pm 0.3_{\text{stat}} \pm 0.1_{\text{syst}} \pm 0.3_{\text{fs/fd}} \pm 0.5_{\mathcal{B}(B_s^0 \to \bar{D}^0 \bar{K}^{*0})}\right) \times 10^{-4}
\]

(Consistent with & more precise than previous LHCb measurement)

Also \(B_s \to \bar{D}^0 \phi\) observed & measured for the 1\textsuperscript{st} time:

\[
\frac{\mathcal{B}(B_s^0 \to \bar{D}^0 \phi)}{\mathcal{B}(B_s^0 \to \bar{D}^0 \bar{K}^{*0})} = 0.069 \pm 0.013 \pm 0.007
\]

Leading to the absolute branching fraction:

\[
\mathcal{B}(B_s^0 \to \bar{D}^0 \phi) = \left(2.3 \pm 0.4_{\text{stat}} \pm 0.2_{\text{syst}} \pm 0.5_{\mathcal{B}(B_s^0 \to \bar{D}^0 \bar{K}^{*0})}\right) \times 10^{-5}
\]
Other interesting modes for $\gamma$

**Time-independent**

$B^- \rightarrow DK\pi\pi$, ADS, GLW  
(LHCb-CONF-2012-021)

$B^+: D^0 \rightarrow K\pi$

$B^-: D^0 \rightarrow K\pi$

$B^+: D^0 \rightarrow KK$

$B^-: D^0 \rightarrow KK$

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**Time-dependent**

$B_s \rightarrow D_sK\pi\pi$, $D_s \rightarrow KK\pi$  
(PRD86, 112005, 2013)

\[
\frac{\mathcal{B}(B_s^0 \rightarrow D_s^+ K^- \pi^+ \pi^-)}{\mathcal{B}(B_s^0 \rightarrow D_s^+ \pi^- \pi^+ \pi^-)} = (5.2 \pm 0.5 \pm 0.3) \times 10^{-2}
\]

\[
A_{s}^{CP+} = -0.14 \pm 0.10 \ (\text{stat}) \pm 0.01 \ (\text{syst})
\]

\[
A_{s}^{K^- \pi^+} = -0.009 \pm 0.028(\text{stat}) \pm 0.013(\text{syst})
\]

\[
A_{d}^{CP+} = -0.018 \pm 0.018(\text{stat}) \pm 0.007(\text{syst})
\]

\[
A_{d}^{K^- \pi^+} = -0.006 \pm 0.006(\text{stat}) \pm 0.010(\text{syst}),
\]
Searches for decays proceeding via W-exchange & penguin annihilation

- **Weak exchange** (O(λ²))
  \[ B \to D^{(*)} \bar{D}^{(*)} \]

- **Penguin annihilation** (O(λ²))
  \[ B \to D^{(*)} \bar{D}^{(*)} \]

- **Weak exchange** (O(λ³))
  \[ B_s^0 \to D^{(*)-} \pi^+ \]

- **Limited information available on the role of these decays in hadronic B decays.**
  - B⁰ → D_s^{(*)} K^{(*)} and B_s → π⁺π⁻ are the only other observed decays that proceed through these suppressed diagrams.

- **Double-charm final states also of interest for CKM angle determinations,** such as γ (combine several B → DD’), 2β (B⁰ → D⁺D⁻), and 2β_s (B_s → D_s D_s)
Search for $B_s \rightarrow D^{(*)-}\pi^+$

Bin in the angle between $D^*$ and $\pi$ in lab frame.

Exploits better mass resolution with larger opening angle.

No signal observed, limits set:

$$\mathcal{B}(B_s^0 \rightarrow D^{*-}\pi^+) < 6.1 \times 10^{-6} \ (90\% \ CL)$$

$$\mathcal{B}(B_s \rightarrow D^*\pi) \sim 1 \times 10^{-6} \text{ expected, from } \lambda^2 \times \mathcal{B}(B^0 \rightarrow D_s K).$$
Double charm final states
Observation of $B_{(s)} \rightarrow D^+D^-, D^0\bar{D}^0$

LHCb, PRD87 092007 (2013)

Relative BF$s$

$$\frac{\mathcal{B}(\bar{B}^0_s \rightarrow D^+D^-)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+D^-)} = 1.08 \pm 0.20\text{(stat)} \pm 0.10\text{(syst)}$$

$$\frac{\mathcal{B}(\bar{B}^0_s \rightarrow D^0\bar{D}^0)}{\mathcal{B}(B^- \rightarrow D^0D^-)} = 0.019 \pm 0.003\text{(stat)} \pm 0.003\text{(syst)}$$

Absolute BF$s$

$$\mathcal{B}(\bar{B}^0_s \rightarrow D^+D^-) = (2.2 \pm 0.4\text{(stat)} \pm 0.2\text{(syst)} \pm 0.3\text{(norm)}) \times 10^{-4}$$

$$\mathcal{B}(\bar{B}^0_s \rightarrow D^0\bar{D}^0) = (1.9 \pm 0.3\text{(stat)} \pm 0.3\text{(syst)} \pm 0.3\text{(norm)}) \times 10^{-4}$$

$B_s \rightarrow D^+D^-, D^0\bar{D}^0$ consistent, would expect so.

$\sim 10X$ larger than $B^0 \rightarrow D_sK$

Consistent with both PQCD predictions, and those based on rescattering, but large theory errors.

Look forward to more on these final states!
Other $B \to DD'$ signals / observations

First observation of Cabibbo-suppressed $B_s \to D^- D_s^+$

Why is this ratio only $\sim 0.5$?
→ If TREE only, expect ratio $\approx 1$?
Is this telling us something about PA and E contributions (which contribute to $B_s \to D_s D_s$, but not $B^0 \to D_s D$)?

$\frac{B(\bar{B}^0_s \to D^+_s D^-_s)}{B(B^0 \to D^- D^+_s)} = 0.56 \pm 0.03\text{(stat)} \pm 0.04\text{(syst)}$,

$\frac{B(\bar{B}^0_s \to D^- D^+_s)}{B(B^0 \to D^- D^+_s)} = 0.050 \pm 0.008\text{(stat)} \pm 0.004\text{(syst)}$

$\approx \tan^2 \theta_c$! as expected, tree dominant.

Note log scale, $S/B \sim 800:1$ at $B^0$ peak

Large and clean signals!
Moving up: $B_c \to J/\psi D_s(*)$

- Very little information yet available on $B_c$ decays due to their low production rate.
- Expect tree diagrams to dominate $D_s$ or $D_s^*$, $J/\psi$

From naïve factorization, would expect...

<table>
<thead>
<tr>
<th>$R_{D_s^+/\pi^+}$</th>
<th>$R_{D_s^{*+}/D_s^+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.90 \pm 0.42$</td>
<td>$2.20 \pm 0.35 \pm 0.62$</td>
</tr>
<tr>
<td>$1.58 \pm 0.34$</td>
<td>$2.07 \pm 0.52 \pm 0.52$</td>
</tr>
</tbody>
</table>

$R_{D_s^+/\pi^+} = \frac{\Gamma(B_c^+ \to J/\psi D_s^+)}{\Gamma(B_c^+ \to J/\psi \pi^+)} \approx \frac{\Gamma(B \to \bar{D}^* D_s^+)}{\Gamma(B \to \bar{D}^* \pi^+)}$

<table>
<thead>
<tr>
<th>$R_{D_s^{*+}/D_s^+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.3$</td>
</tr>
<tr>
<td>$2.6$</td>
</tr>
<tr>
<td>$2.0$</td>
</tr>
<tr>
<td>$2.2$</td>
</tr>
<tr>
<td>$1.2$</td>
</tr>
</tbody>
</table>

$V.$ Kiselev hep-ph/0308214
Colangelo et al PRD61 (2000)
Ivanov et al PRD73 (2006)
Dhir et al PRD79 (2009)
C.-H Chang et al PRD49 (1994)
Analysis

- Use $J/\psi \rightarrow \mu^+\mu^-$ triggered events;
  - $J/\psi$ displaced from PV by $> 3\sigma_{\text{disp}}$.
- Reconstruct $D_s \rightarrow \phi\pi$, $\phi \rightarrow KK$ candidates.
- Combine $J/\psi$ and $D_s$ candidates to form $B_c$ candidates
  - $J/\psi$ and $D_s$ mass & vertex constraints imposed in fitting the decay.
- Excellent mass resolution due to large $M(J/\psi+D_s)$
Results on $B_c \rightarrow J/\psi D_s$

Normalize with respect to $B_c \rightarrow J/\psi \pi$

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 2.90 \pm 0.57 \pm 0.24$$

Closer to $B^0$ ratio (see below)

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)} = 2.37 \pm 0.56 \pm 0.10$$

Consistent with factorization...

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated efficiencies</td>
<td>1.0</td>
</tr>
<tr>
<td>Trigger</td>
<td>1.1</td>
</tr>
<tr>
<td>Fit model</td>
<td>1.8</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>$2 \times 0.6$</td>
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<tr>
<td>Hadron interactions</td>
<td>$2 \times 2.0$</td>
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<tr>
<td>Track quality selection</td>
<td>$2 \times 0.4$</td>
</tr>
<tr>
<td>Kaon identification</td>
<td>3.0</td>
</tr>
<tr>
<td>$B^+_s$ lifetime</td>
<td>1.0</td>
</tr>
<tr>
<td>Stability for various data taking conditions</td>
<td>2.5</td>
</tr>
<tr>
<td>$B(D_s^+ \rightarrow (K^- K^+)\phi \pi^+)$</td>
<td>5.6</td>
</tr>
<tr>
<td>Total</td>
<td>8.4</td>
</tr>
</tbody>
</table>

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Colangelo et al PRD61 (2000)
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C.-H Chang et al PRD49 (1994)
This analysis reports the first observation of $B_c \rightarrow B_s \pi$.

Wide range of theoretical predictions for the branching fraction, from a few percent to $\sim 20\%$.

Strategy is to take fully reconstructed $B_s$ decays, add a $\pi^+$ and search for a peak at the $B_c$ mass.

Goal is to measure: 

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} B(B_c^+ \rightarrow B_s^0 \pi^+)$$
B_s candidates

B_s \rightarrow D_s \pi, \ D_s \rightarrow KK \pi

\approx 74,000 \text{ recon. } B_s \rightarrow D_s \pi

Form B_c^+ candidates

- B_s selection: mass windows [5335-5407] for D_s \pi, [5330-5410] for J/\psi \phi
- \pi^+: p_T > 100 \text{ MeV, IP } \chi^2 > 2 \& \text{ loose PID}
- BDT used to distinguish signal from background.
- \varepsilon(B_s)/\varepsilon(B_c) obtained from simulation, except PID (uses D^{*+} calib data)

B_s \rightarrow J/\psi \phi, \ \phi \rightarrow KK

\approx 104,000 \text{ recon. } B_s \rightarrow J/\psi \phi

Preliminary
$B_c^+ \rightarrow B_s \pi$ data

Using $B_s \rightarrow D_s \pi$, $D_s \rightarrow KK\pi$

Using $B_s \rightarrow J/\psi \phi$, $\phi \rightarrow KK$

\[
\sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = \left(2.51 \pm 0.40(stat)^{+0.23}_{-0.17}(syst)\right) \times 10^{-3}
\]

\[
\sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = \left(2.20 \pm 0.49(stat) \pm 0.23(syst)\right) \times 10^{-3}
\]

\[
\sigma(B_c^+) \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = \left(2.38 \pm 0.35(stat) \pm 0.11(stat)_{-0.12}^{+0.17}(\tau_{B_c})\right) \times 10^{-3}
\]

Assuming $B_c \rightarrow J/\psi \pi = 0.15\%$ from Ivanov et al, from theory, leads to $\mathcal{B}(B_c \rightarrow B_s \pi) \sim 10\%$ but large uncertainty. Well within the wide range of predictions.
Summary

• Many interesting measurements in $b \rightarrow cX$ decays performed with 1 fb$^{-1}$ data sample.

• Several aimed at measuring $\gamma$ or input to the combined $\gamma$ determination.

• Large samples being used to probe Weak exchange, Penguin annihilation decays.
  – New double-charm final states uncovered..
  – Promising for CPV and CKM angle m’ments..

• New $B_c$ decay discoveries, $B_c \rightarrow B_s \pi$, $B_c \rightarrow J/\psi D_s$
  – Excellent prospects for more $B_c$ decay mode discoveries

Stay tuned for full 2011+2012 3 fb$^{-1}$ results!