Studies of the decay $B^0_s \rightarrow D_s^+ K^-$

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on behalf of the LHCb Collaboration
Motivation

Why is $B^0_s \rightarrow D_s^+ K^-$ interesting?

- Test SM through CKM-unitarity triangle
- $\gamma$ the least constraint parameters by direct measurements
- Clean time-dependent measurement with $B^0_s \rightarrow D_s^+ K^-$
- $\text{BR}(B^0_s \rightarrow D_s^+ K^-)$ still poorly known, $\pm 23\%$

$\rightarrow$ Today the World Best Measurement of its BR

[K. Nakamura et al. (Particle Data Group), Journal of Physics G37, 075021 (2010)]
Key ingredients:

• Large $b$ production rate $\sim 100 \text{ kHz } b\bar{b}$

• Excel. Prop. Time Res.

• Excel. PID $\epsilon_K \sim 95\%$, $O(<5\%)$

• $\pi^-$ misid

• Sensitivity to hadronic final states

• Specific hadronic trigger

• Final state $D_s^- K^+$ accessible by both $B_0^s$ and $\bar{B}_0^s$

• Large interference expected

\[ \gamma = \text{weak phase btw. } V^*_{cb} V_{ub} \]
Key ingredients:
• Large $b$ production rate

$\gamma =$ weak phase btw. $V^*_{cb} V_{ub}$

- Final state $D_s^- K^+$ accessible by both $B^0_s$ and $\bar{B}^0_s$
- Large interference expected
Key ingredients:

- Large $b$ production rate
- Excel. PID
  - $\varepsilon_{K} \approx 95\%$, $\pi < 5\%$
- Sensitive to hadronic final states
- Specific hadronic trigger
- $\gamma = \text{weak phase btw. } V^{*}_{cb} V_{ub}$
- Final state $D_s^{-} K^+$ accessible by both $B^0_s$ and $\overline{B}^0_s$
- Large interference expected

$\sim 60$ kHz $bb$
Time Dependent Measurement

Key ingredients:
• Large $b$ production rate  ~60 kHz $bb$
• Excellent Proper Time Resolution

$\gamma =$ weak phase btw. $V_{cb}^* V_{ub}$

• Final state $D_s^- K^+$ accessible by both $B^0_s$ and $\bar{B}^0_s$
• Large interference expected
Key ingredients:

- Large b production rate \( \sim 60 \text{ kHz } \overline{b}b \)
- Excellent Proper Time Resolution \( \sim 50 \text{ fs} \)
Key ingredients:

- Large $b$ production rate
  - $\sim 60$ kHz $bb$
- Excellent Proper Time Resolution
  - $\sim 50$ fs
- Excellent Particle Identification (PID)
Time Dependent Measurement

Key ingredients:

- Large $b$ production rate
  - $\sim 60$ kHz $bb$
- Excellent Proper Time Resolution
  - $\sim 50$ fs
- Excellent Particle Identification (PID)
  - $\varepsilon_K \sim 95\%$, $O(<5\%)$ $\pi$-$K$ misid

Final state $D_s^- K^+$ accessible by both $B^0_s$ and $\bar{B}^0_s$
Large interference expected
Key ingredients:

- Large b production rate
- Excellent Proper Time Resolution
- Excellent Particle Identification (PID)
- Sensitivity to hadronic final states

- Final state $D_s^- K^+$ accessible by both $B^0_s$ and $\bar{B}^0_s$
- Large interference expected

\[ \gamma = \text{weak phase btw. } V^*_{cb} V_{ub} \]
Key ingredients:

- Large b production rate \( \sim 60 \text{ kHz } bb \)
- Excellent Proper Time Resolution \( \sim 50 \text{ fs} \)
- Excellent Particle Identification (PID) \( \varepsilon_K \sim 95\% , O(<5\%) \pi-K \) misid
- Sensitivity to hadronic final states specific hadronic trigger
Time Dependent Measurement

First step is the Branching Fraction measurement!

\[ \gamma = \text{weak phase btw. } V^{*}_{cb} V_{ub} \]

- Final state \( D_s^- K^+ \) accessible by both \( B_s^0 \) and \( \overline{B}_s^0 \)
- Large interference expected
0.37 fb⁻¹ of LHCb data used (first part of 2011)

3 decays with the same topology

\[ B^0 \rightarrow D^- (K^+ 2\pi^-)\pi^+ \]
\[ B_s^0 \rightarrow D_s^- (K^+ K^- \pi^-)\pi^+ \]
\[ B_s^0 \rightarrow D_s^\pm (K^\mp K^\pm \pi^\pm)K^\mp \]

Meas. of BR( \( B_s^0 \rightarrow D_s^- \pi^+ \)) using fs/fd meas. In LHCb
Meas. of BR( \( B_s^0 \rightarrow D_s^\pm K^\mp \))

✓ Same trigger, stripping and offline selection (using BDT) to minimize efficiency corrections
✓ PID applied at the latest stage for distinguishing these decays channels

arXiv:1111.2357 [hep-ex]
Backgrounds

1. Combinatorial Background:
   - Random $\pi$ or K forming fake D or Ds
   - Real prompt D or Ds combined with random $\pi$ or K to form a fake $B^0$ or $B^0_s$

Our selection is efficiently cutting it!
1. Combinatorial Background:
   - Random $\pi$ or $K$ forming fake $D$ or $D_s$
   - Real prompt $D$ or $D_s$ combined with random $\pi$ or $K$ to form a fake $B^0$ or $B^{0_s}$

2. Partially Reconstructed Background:
   - Lost one particle in the reconstruction, ex: $B_s^0 \rightarrow D^-_s \rho^+$ where the $\pi^0$ from the $\rho^+$ is missed.

- Topology similar to the signal
- Sitting mostly on the left of the signal

\[ B_s^0 \rightarrow D^-_s \rho^+ \]
Backgrounds

1. Combinatorial Background:
   - Random $\pi$ or K forming fake D or Ds
   - Real prompt D or Ds combined with random $\pi$ or K to form a fake $B^0$ or $B^0_s$

2. Partially Reconstructed Background:
   - Lost one particle in the reconstruction, ex: $B^0_s \rightarrow D^- \rho^+$ where the $\pi^0$ from the $\rho^+$ is missed

3. Misidentified Background:
   - $B^0 \rightarrow (D^- \rightarrow D^-_s)\pi^+$ under $B^0_s \rightarrow D^-_s \pi^+$

Sitting under the signal
Backgrounds

1. Combinatorial Background:
   - Random $\pi$ or K forming fake D or Ds
   - Real prompt D or Ds combined with random $\pi$ or K to form a fake $B^0_s$ or $B^0$

2. Partially Reconstructed Background:
   - Lost one particle in the reconstruction, ex: $B^0_s \rightarrow D_s^- \rho^+$ where the $\pi^0$ from the $\rho^+$ is missed

3. Misidentified Background:
   - $B^0 \rightarrow (D^- \rightarrow D_s^-)\pi^+$
     under $B^0_s \rightarrow D_s^- \pi^+$
   - $B^0 \rightarrow (D^- \rightarrow D_s^-)K^+$
     under $B^0_s \rightarrow D_s^- K^+$
   - $B^0 \rightarrow D_s^- (\pi^+ \rightarrow K^+)$
     under $B^0_s \rightarrow D_s^- K^+$
   - $B^0 \rightarrow (D^- \rightarrow D_s^-) (\pi^+ \rightarrow K^+)$
     under $B^0_s \rightarrow D_s^- K^+$
Fit Strategy

Signal shape: double crystal ball function

Background shapes:
- **MisID**: from data using a reweighting procedure to correct for the momentum dependency of PID selection
- **Part. Reco**: template from MC
  - Gaussian constraint on the yields if the BR known or estimable
- **Comb**: exponential shape for $B_{(s)}^{0} \rightarrow D_{(s)}^{-} \pi^{+}$, flat for $B_{s}^{0} \rightarrow D_{s}^{\pm} K^{\mp}$
  - Checked with wrong-sign sample

- Sample divided according to the magnet polarities to achieve maximum sensitivity
- Simultaneous fit: same signal shape for both polarities
\[ \mathcal{B}( B^0_s \rightarrow D^-_s \pi^+) \]

Both polarities together for illustrative purpose

Using LHCb measurement:

\[
\frac{f_s}{f_d} = (0.268 \pm 0.008) + 0.022 \\
\frac{N_{B^0_s \rightarrow D^-_s \pi^+}}{N_{B^0 \rightarrow D^- \pi^+}} \mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+) + 0.020
\]

\[
\mathcal{B}( B^0_s \rightarrow D^-_s \pi^+) = (2.95 \pm 0.05 \pm 0.17^{+0.18}_{-0.22}) \times 10^{-3} \\
\text{Stat.} \quad \text{Syst.} \quad \text{From } f_s/f_d
\]

Previous Best Measurement: \((3.2 \pm 0.5) \times 10^{-3}\) [K. Nakamura et al. (Particle Data Group), Journal of Physics G37, 075021 (2010)]

[arXiv:1111.2357 [hep-ex]]
Both polarities together for illustrative purpose

\[ \text{Previous Best Measurement: } (3.0 \pm 0.7) \times 10^{-4} \]

\[ [K. \text{ Nakamura et al. (Particle Data Group)}, \text{Journal of Physics G37, 075021 (2010)}] \]
• World best measurement of the BR($B^0_s \rightarrow D_s^-\pi^+$) and BR($B^0_s \rightarrow D_s^+K^-$) with 0.37 fb$^{-1}$ collected in LHCb
  – $B^0_s \rightarrow D_s^+K^-$ measurement in agreement with prev. measurements, error reduced to $\sim$12%
  – $B^0_s \rightarrow D_s^-\pi^+$: best known $B^0_s$ mode now with an uncertainty of $\sim$10% (before was $\sim$16%)

• First step through the measurement of $\gamma$ with a $B^0_s \rightarrow D_s^+K^-$ time-dependent analysis
  – We already have 1.0 fb$^{-1}$ of data collected last year
Backup

Our Disaster Recovery Plan Goes Something Like This...

HELP! HELP!

DILBERT
By Scott Adams
Gaussian Const. $B^0_s \rightarrow D_s^- K^+$

Table 3: Gaussian constraints applied in the $B^0_s \rightarrow D_s^- K^+$ fit.

<table>
<thead>
<tr>
<th>Background type</th>
<th>Magn. Down</th>
<th>Magn. Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow D_s^* \pi^+$</td>
<td>70 ± 23</td>
<td>63 ± 21</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^* K^+$</td>
<td>80 ± 27</td>
<td>72 ± 34</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^- \rho^+$</td>
<td>150 ± 50</td>
<td>135 ± 45</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^- K^{*+}$</td>
<td>150 ± 50</td>
<td>135 ± 45</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^* \rho^+$</td>
<td>50 ± 17</td>
<td>45 ± 15</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^- K^{*+}$</td>
<td>50 ± 17</td>
<td>45 ± 15</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow D_s^- p + \Lambda_b \rightarrow D_s^* p$</td>
<td>80 ± 27</td>
<td>72 ± 34</td>
</tr>
</tbody>
</table>
### Systematic uncertainties

Table 4: The final systematic uncertainties for the measurement of the branching fractions of $B_s^0 \rightarrow D_s^- K^+$ and $B_s^0 \rightarrow D_s^- \pi^+$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>All non-PID selection ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>2%</td>
</tr>
<tr>
<td>All non-PID selection ($B^0 \rightarrow D^- \pi^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>2%</td>
</tr>
<tr>
<td>All non-PID selection ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B^0 \rightarrow D^- \pi^+$)</td>
<td>3%</td>
</tr>
<tr>
<td>Fit model $B^0 \rightarrow D^- \pi^+$</td>
<td>1.0%</td>
</tr>
<tr>
<td>Fit model $B_s^0 \rightarrow D_s^- \pi^+$</td>
<td>1.4%</td>
</tr>
<tr>
<td>Fit model $B_s^0 \rightarrow D_s^- K^+$</td>
<td>2.0%</td>
</tr>
<tr>
<td>PID selection ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>1.8%</td>
</tr>
<tr>
<td>PID selection ($B^0 \rightarrow D^- \pi^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>1.3%</td>
</tr>
<tr>
<td>PID selection ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B^0 \rightarrow D^- \pi^+$)</td>
<td>2.2%</td>
</tr>
<tr>
<td>Efficiency ratio ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>1.5%</td>
</tr>
<tr>
<td>Efficiency ratio ($B^0 \rightarrow D^- \pi^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>1.6%</td>
</tr>
<tr>
<td>Efficiency ratio ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B^0 \rightarrow D^- \pi^+$)</td>
<td>1.6%</td>
</tr>
<tr>
<td>Total ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>±3.9%</td>
</tr>
<tr>
<td>Total ($B^0 \rightarrow D^- \pi^+$ wrt. $B_s^0 \rightarrow D_s^- \pi^+$)</td>
<td>±3.4%</td>
</tr>
<tr>
<td>Total ($B_s^0 \rightarrow D_s^- K^+$ wrt. $B^0 \rightarrow D^- \pi^+$)</td>
<td>±4.6%</td>
</tr>
</tbody>
</table>
Table 1: PID efficiency and misidentification probabilities, split by magnet polarity. The first two lines refer to the bachelor track selection, the third line is the $D^-$ efficiency and the fourth the $D_s^-$ efficiency. Probabilities are obtained from the efficiencies in the $D^*$ calibration sample, binned in momentum and $p_T$. Only bachelor tracks with momentum below 100 GeV/$c^2$ are considered. The uncertainties shown are the statistical uncertainties due to the finite number of signal events used in the reweighting.

<table>
<thead>
<tr>
<th>PID Cut</th>
<th>Efficiency</th>
<th>MissID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$ DLL$_{K-\pi} &gt; 5$</td>
<td>(83.5 ± 0.2) %</td>
<td>(83.3 ± 0.2) %</td>
</tr>
<tr>
<td>$\pi$ DLL$_{K-\pi} &lt; 0$</td>
<td>(85.8 ± 0.2) %</td>
<td>(84.2 ± 0.2) %</td>
</tr>
<tr>
<td>$D^-$</td>
<td>85.7 ± 0.2</td>
<td>84.1 ± 0.2</td>
</tr>
<tr>
<td>$D_s^-$</td>
<td>78.4 ± 0.2</td>
<td>77.6 ± 0.2</td>
</tr>
</tbody>
</table>
PID performance performed on data from D* sample
• Evaluated eff. and midID rate on D* sample for the PID cuts applied in the analysis (in bins of p and pt)
• No dependence on track multiplicity since both signal and contr. channel are selected with the same trigger
• Different curve for magnet up and magnet down