Search for a wrong-flavour contribution to $B_s \rightarrow D_s \pi$ at LHCb

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Wrong-flavour $B_s \rightarrow D_s \pi$
Background

- It’s assumed that in the Standard Model, $B_s \rightarrow D_s \pi$ is flavour-specific
  - so $B_s \rightarrow D_s^- \pi^+$ ‘all’ the time
  - and $B_s \rightarrow D_s^+ \pi^-$ none of the time
  - conversely for the $\bar{B}_s$

- Many results indirectly rely on this assumption
- This has never been explicitly checked by any experiment
- There are very small higher-order SM contributions as well as possible BSM contributions
  - for example, an exotic quark with charge $-\frac{4}{3}$
- The aim of the analysis was to measure any contribution from the wrong-flavour decay
- Run as a side project to measurement of $B_s^0 \rightarrow D_s K$
Wrong-flavour decay in $B_s^0 \rightarrow D_s K$
Wrong-flavour decay

$$B_s^0 \rightarrow D_s \pi$$

Diagram:

- Initial state: $b \bar{c}$
- Final state: $s\bar{s}$
- Mediator: $W^+$

Diagram:

- Initial state: $b \bar{c}$
- Final state: $u,c,t\bar{u}$
- Mediator: $D_s^+$
Decay description

- Two initial states ($B_s^0$, $\bar{B}_s^0$), two final states ($D_s^-\pi^+$, $D_s^+\pi^-$)
- Initial state is unknown due to mixing
  - need flavour tagging
- Need a full description of propagation and decay of $B_s^0$ mesons to fit against data
Decay description

\[ \Gamma(B^0_s(t) \rightarrow f) = \frac{1}{2} \mathcal{N}_f |A_f|^2 (1 + |\lambda_f|^2) e^{-\Gamma_s t} \]
\[ \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) + D_f \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right. \]
\[ \left. + C_f \cos (\Delta m_s t) - S_f \sin (\Delta m_s t) \right], \]

\[ \Gamma(\bar{B}^0_s(t) \rightarrow f) = \frac{1}{2} \mathcal{N}_f |A_f|^2 (1 - a) (1 + |\lambda_f|^2) e^{-\Gamma_s t} \]
\[ \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) + D_f \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right. \]
\[ \left. - C_f \cos (\Delta m_s t) + S_f \sin (\Delta m_s t) \right], \]
\[ \Gamma(B_s^0(t) \to f) = \frac{1}{2} \mathcal{N}_f |\bar{A}_f|^2 (1 + |\bar{\lambda}_f|^2) e^{-\Gamma t} \]
\[ \left[ \cosh \left( \frac{\Delta \Gamma t}{2} \right) + D_{\bar{f}} \sinh \left( \frac{\Delta \Gamma t}{2} \right) \right. \]
\[ + C_{\bar{f}} \cos (\Delta mt) - S_{\bar{f}} \sin (\Delta mt) \left. \right] , \]

\[ \Gamma(B_s^0(t) \to f) = \frac{1}{2} \mathcal{N}_f |\bar{A}_f|^2 \frac{1}{1 - a} (1 + |\bar{\lambda}_f|^2) e^{-\Gamma t} \]
\[ \left[ \cosh \left( \frac{\Delta \Gamma t}{2} \right) + D_{\bar{f}} \sinh \left( \frac{\Delta \Gamma t}{2} \right) \right. \]
\[ - C_{\bar{f}} \cos (\Delta mt) + S_{\bar{f}} \sin (\Delta mt) \left. \right] . \]
Parameterisation

- The wrong flavour-contribution is parameterised with $D_f$, $D_{\bar{f}}$, $S_f$ and $S_{\bar{f}}$.
- Standard Model prediction is that they will be zero – flavour-specific.
- They are highly correlated, so reparameterise to:

\[
\bar{S} = \frac{S_f + S_{\bar{f}}}{2} \quad \Delta S = \frac{S_f - S_{\bar{f}}}{2}
\]
\[
\bar{D} = \frac{D_f + D_{\bar{f}}}{2} \quad \Delta D = \frac{D_f - D_{\bar{f}}}{2}
\]

- Which should also all be zero.
- These are our parameters of interest.
Event selection

- The event selection was originally tuned for $B_s^0 \to D_s K$
  - It doesn’t know about the $K$ so is safe to use
- Uses a BDT trained on background-subtracted data
- Optimised to maximise

$$S = \frac{N_{sig}}{\sqrt{N_{sig} + N_B}}$$

![Graph showing the BDTG Response vs Signal Significance]
Analysis plan

- Fit mass distribution
- Fix yields
- Fit time distribution
- CP parameters
Mass fit

Distribution of $m(B_s)$

Events / 6 MeV/c$^2$

$B_s \rightarrow D_s \pi$

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Backgrounds

- Fully reconstructed
  - $B^0 \rightarrow D\pi$, $B^0 \rightarrow D_s\pi$, $\Lambda_b \rightarrow \Lambda_c\pi$
- Low-mass $B_s^0$
  - $B_s^0 \rightarrow D_s\rho$, $B_s^0 \rightarrow D_s^*\pi$, $B_s^0 \rightarrow D_s^*\rho$
- Low-mass $B^0$
  - $B^0 \rightarrow D\rho$, $B^0 \rightarrow D_s^*\pi$, $B^0 \rightarrow D^*\pi$
- Combinatorial
Mass fit

- Most backgrounds are modelled on simulated data
- Combinatorial is an exponential fitted to sidebands in data
- Signal is a double Crystal Ball function
- Yields of some backgrounds are fixed based on relative expected yields
- The $B^0 \rightarrow D\pi$ yield is fixed based on a fit to a set of real $B^0 \rightarrow D\pi$ events
Signal template
Mass fit

LHCb Preliminary $L_{int} = 1.0 \text{ fb}^{-1}$
- Data
- Signal $B \to D_s \pi$
- $B_s \to D_{s}^{(*)} (\pi, \rho)$
- $B_d \to D \pi$
- $\Lambda_b \to \Lambda \pi$
- $B_d \to D_{(s)} (\pi, \rho)$
- Combinatorial

$27,965 \pm 187 B^0_s \to D_s \pi$ events
Analysis plan

- Fit mass distribution
- Fix yields
- Fit time distribution
- CP parameters
### Oscillating with wrong-flavour

<table>
<thead>
<tr>
<th>Oscillating with wrong-flavour</th>
<th>Flavour specific</th>
<th>Non-oscillating</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow D\pi$</td>
<td>$B^0 \rightarrow D_s\pi$</td>
<td>$\Lambda_b \rightarrow \Lambda_c\pi$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D \rho$</td>
<td>$B^0 \rightarrow D_s^*\pi$</td>
<td>Combinatorial</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^*\pi$</td>
<td>$B_s^0 \rightarrow D_s\rho$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B_s^0 \rightarrow D_s^*\pi$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B_s^0 \rightarrow D_s^*\rho$</td>
<td></td>
</tr>
</tbody>
</table>
Time fit fixed parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_d$</td>
<td>0.656 ps$^{-1}$</td>
</tr>
<tr>
<td>$\Delta \Gamma_d$</td>
<td>0 ps$^{-1}$</td>
</tr>
<tr>
<td>$\Delta m_d$</td>
<td>0.507 ps$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma_s$</td>
<td>0.658 ps$^{-1}$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$</td>
<td>-0.116 ps$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma_{\Lambda_b}$</td>
<td>0.719 ps$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma_{comb}$</td>
<td>0.800 ps$^{-1}$</td>
</tr>
</tbody>
</table>

- $\bar{S}$, $\bar{D}$, $\Delta S$, $\Delta D$ are floated, as are the tagging efficiencies and $\Delta m_s$
Time fit

- Decay-time acceptance and decay-time resolution are modelled on simulated data

\[
\begin{align*}
0 & \quad \text{when } (at)^n - b < 0 \text{ or } t < 0.2 \text{ ps}, \\
\left(1 - \frac{1}{1+(at)^n-b}\right) \times (1 - \beta t) & \quad \text{otherwise},
\end{align*}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$1.42 \pm 0.204$ ps$^{-1}$</td>
</tr>
<tr>
<td>$b$</td>
<td>$0.0230 \pm 0.0364$</td>
</tr>
<tr>
<td>$n$</td>
<td>$1.81 \pm 0.066$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$0.0363 \pm 0.0118$ ps$^{-1}$</td>
</tr>
</tbody>
</table>
Sources of systematic uncertainty

**Decay-time resolution**  This is fitted on simulated data and its width is varied by 20%

**Decay time acceptance**  This is fitted on simulated data and each parameter is varied within its measured uncertainty

**Background yields**  These are varied within their measured uncertainties from the mass fit

**Background parametrisation**  The time fit is performed as an sFit which does not model the backgrounds

**Physics parameters**  Various fixed physics parameters ($\Gamma_s$, $\Delta\Gamma_s$ etc.) from PDG or LHCb are varied within their published uncertainties

**Flavour tagging calibration**  Measured on $B^+ \rightarrow J/\psi K^+$ data and varied within measured uncertainties

**Asymmetries**  Production, detection and flavour tagging asymmetries are varied consistent with what is observed in data
## Sources of systematic uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>$\bar{S}$</th>
<th>$\bar{D}$</th>
<th>$\Delta S$</th>
<th>$\Delta D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay-time resolution</td>
<td>0.022</td>
<td>0.020</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>Flavour tagging calibration</td>
<td>0.004</td>
<td>0.008</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>Background yields</td>
<td>0.007</td>
<td>0.010</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>Background parametrisation</td>
<td>0.005</td>
<td>0.008</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Physics parameters</td>
<td>0.003</td>
<td>0.117</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Asymmetries</td>
<td>0.006</td>
<td>0.009</td>
<td>0.001</td>
<td>0.169</td>
</tr>
<tr>
<td>Decay time acceptance</td>
<td>0.003</td>
<td>0.528</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.025</td>
<td>0.541</td>
<td>0.004</td>
<td>0.169</td>
</tr>
</tbody>
</table>
Results

\( \bar{S} = 0.197 \pm 0.150 \pm 0.025 \)
\( \bar{D} = -0.888 \pm 0.098 \pm 0.541 \)
\( \Delta S = 0.066 \pm 0.083 \pm 0.004 \)
\( \Delta D = -0.062 \pm 0.050 \pm 0.169 \)

- All the parameters are within 2\( \sigma \) of zero and \( \Delta S \) and \( \Delta D \) are less than 1\( \sigma \)
- At this level of uncertainty, no evidence of non-flavour-specific decays of \( B_s^0 \rightarrow D_s \pi \)
△D is related to the difference in the effective lifetimes of $D_s^-\pi^+$ and $D_s^+\pi^-$

The above result effectively states that $|\Delta D| < 0.1$

- it is possible to put a constraint on the difference in effective lifetimes between these two final states

The effective lifetime is given by $\tau_{\text{eff}} = \tau_{B_s^0} \left(1 + D_f \times \frac{\Delta \Gamma_s}{2 \Gamma_s}\right)$, and using the measured value of $\Delta D$ we find

$$\left|\frac{\Delta \tau_{\text{eff}}}{\tau_{B_s^0}}\right| \lesssim 0.02.$$  

This shows that the $D_s^-\pi^+$ and the $D_s^+\pi^-$ have the same lifetime to better than 2%

In the case that the $B_s^0 \rightarrow D_s\pi$ decay is assumed to be flavour-specific, this provides a test of CPT invariance which predicts that particles and anti-particles have equal lifetimes
Thank you