LHCb performance for
\( B_s \to D_s \pi \) (\( B_s \) mixing)
and \( B_s \to D_s K \) decays (\( \gamma \))
Outline

- The Physics
  - CKM matrix and Unitarity Triangles
  - Mixing in $B_s^0$ system
- Event selection at LHCb
- Annual event yields and backgrounds
- Sensitivity to $\Delta m_s$ and $\gamma$
  - Extraction method
  - Results
- Current B-physics experiments can’t explore the $B_s$ sector
  - Need LHCb for this
By exploiting the Unitarity of the CKM matrix, one can form triangles in the complex plane. For the B-system:

\[ V_{cd} V_{cb}^* + V_{td} V_{tb}^* + V_{ud} V_{ub}^* = 0 \]

\[ V_{ts} V_{us}^* + V_{td} V_{ud}^* + V_{tb} V_{ub}^* = 0 \]
The two mass eigenstates $|B_i\rangle$ and $|B_h\rangle$ are given by:

$$|B_{i(h)}\rangle = \frac{1}{\sqrt{p^2 + q^2}} \left[ p |B_s\rangle \pm q |\bar{B}_s\rangle \right]$$

Time-dependent rates for initial flavour eigenstates $B_s$ and $\bar{B}_s$ decaying into final states $f$ or $\bar{f}$ are:

$$R_f(t) \propto \left| \frac{A_f}{2} \right|^2 e^{-\Gamma t} \left[ I_+(t) + I_-(t) \right]$$

$$\bar{R}_{\bar{f}}(t) \propto \left| \frac{A_{\bar{f}}}{2} \right|^2 \left| \frac{p}{q} \right|^2 e^{-\Gamma t} \left[ I_+(t) - I_-(t) \right]$$

$$I_+(t) = (1 + |\eta|^2) \cosh \frac{\Delta \Gamma}{2} t - 2 \mathcal{R}(\eta) \sinh \frac{\Delta \Gamma}{2} t$$

$$I_-(t) = (1 - |\eta|^2) \cos \Delta m t - 2 \mathcal{I}(\eta) \sin \Delta m t$$

Where $A_f$ is the instantaneous decay amplitude for $B_s \rightarrow f$

In the Standard Model: $q / p = e^{2i\delta \gamma}$
This channel has a flavour specific final state hence:

\[ A_f = \bar{A}_f = 0 \]

\[ \eta = \bar{\eta} = 0 \]

Can be used to measure \( \Gamma_s, \Delta \Gamma_s \) and \( \Delta m_s \)

Branching ratio assumed same as \( B_d \rightarrow D^- \pi^+ : 3 \times 10^{-3} \)
From the two time-dependent rates, $R_{D_s^- K^+}$ and $R_{D_s^+ K^-}$ measure $\gamma - 2\delta \gamma$ and strong-phase difference $\Delta_{T_1/T_2}$.

Branching ratio assumed same as $B_d \rightarrow D^- K^+$ and $B_d \rightarrow D_s^+ \pi^- : 2 \times 10^{-4}$ and $4.8 \times 10^{-5}$.

Rapid oscillations make time-dependent analysis essential.
\( \text{Bs} \rightarrow \text{Ds} \, h \) Kinematics at LHCb

• The Bs is heavily boosted in the beam direction (Z)

• Vertex resolution in Z dominated

\[
\begin{align*}
\text{Choose Ds} \rightarrow \text{KK}\pi & \text{ since fully reconstructible and high branching ratio} \\
\text{Ds} \, \pi & \text{ acts as a background to Ds} \, \text{K (12 – 15 times x-section)} \\
\text{Very small kinematic difference between Ds} \, \pi & \text{ and Ds} \, \text{K – the K/} \, \pi \text{ separation provided by the two RICH systems is critical.}
\end{align*}
\]
Proper Time Resolution

Define proper time as: \( \tau = \frac{m x \cdot p}{c p^2} \)

- Double Gaussian fits to reconstructed – MC truth values
- \( D_s \) core resolution of 57 fs with 78% in core
- \( B_s \) core resolution of 42 fs with 77% in core

\( \Delta m_s = 30 \text{ ps}^{-1} \) gives period of 209 fs – sufficient resolution
Event selection

Common selection for $B_s \rightarrow D_s \pi$ and $B_s \rightarrow D_s K$

- Track impact parameter, quality and momentum
- Vertex fits
- Mass windows
- Lifetimes
- Exploit $D_s$ resonance decays
- Mass and angular cuts

RICH PID critical for separating the two channels

$K/\pi$ separation of ‘bachelor’ particle

$B_s \rightarrow D_s \pi$
$B_s \rightarrow D_s K$
Separation of $B_s \rightarrow D_s K$ from $B_s \rightarrow D_s \pi$

Without RICH you are dead in the water
With it, can handle main background
Yields and Backgrounds

Annual number for untagged events

Signals

current selections yield:

\[ 87K \, B_s \rightarrow D_s \pi \quad 6.1K \, B_s \rightarrow D_s K \]

Specific backgrounds

\( D_s K \) pollution of \( D_s \pi \) signal negligible
\( D_s \pi \) pollution of \( D_s K \) signal B/S = [0.06,0.21] 90% CL

\textbf{bb background}

\( D_s K \) B/S = [0.0,4.2] 90% CL \quad \text{zero selected in 10.2M sample}
\( D_s \pi \) B/S = [0.01,0.53] 90% CL
Acceptance Functions

$B_s \rightarrow D_s \pi$

$\chi^2 / ndf = 18.73 / 25$

- $a = 0.1015 \pm 0.009133$
- $b = -0.75 \pm 0.0623$
- $c = 0.01263 \pm 0.005538$
- $d = -0.1107 \pm 0.009678$

$B_s \rightarrow D_s K$

$\chi^2 / ndf = 27.29 / 26$

- $a = 0.06357 \pm 0.005875$
- $b = -1.015 \pm 0.09219$
- $c = 0.008215 \pm 0.008499$
- $d = -0.06706 \pm 0.01693$

- Short lifetimes suppressed because visible secondary vertex needed
- Large lifetimes can give large $B_s$ impact parameter
Evaluation of Sensitivities

- Decay at some proper time $t$ reconstructed at time $t_{rec}$
- Error in proper time, $\Delta t_{rec}$, from momentum and vertex resolution, determined event by event
- $R_+(t)$ is rate for specific initial state to required final state e.g. $B_s \rightarrow D_s^- \pi^+$
- $R_-(t)$ is rate for CC of specific initial state to required final state e.g. $\bar{B}_s \rightarrow D_s^- \pi^+$
- So: $R_{sig}(t) = (1-\omega_{tag}) R_+(t) + \omega_{tag} R_-(t)$
- Background rate $R_{bkg}(t) = \Gamma e^{-\Gamma t}$

Then $P_i(t_{rec}) = \int_0^\infty [(1-f)R_{sig}(t) + fR_{bkg}(t)]a(t) s(t_{rec} - t) dt$

Where $s(t_{rec} - t) = \frac{1}{\sqrt{2\pi\Delta t_{rec}}} e^{-(t_{rec} - t)^2 / 2(\Delta t_{rec})^2}$

Likelihood $L = \prod_{i=1}^{N_{evt}} P_i$ (Can extract $\Gamma_s$, $\Delta \Gamma_s$, $\Delta m_s$, $\eta$, $\bar{\eta}$, arg($\eta$) and arg($\bar{\eta}$))
Examples

Initial pure $B_s$ decaying to $D_s^-K^+$ at time $t$.

No smear and perfect acceptance

Realistic picture with $\omega_{\text{tag}} = 0.3$
Examples

$B_s \rightarrow D_s \pi$ with two different $\Delta m_s$
Sensitivity to $\Delta m_s$
From $B_s \rightarrow D_s\pi$

- Standard Model predicts: $\Delta m_s = 14.3 - 26$ ps$^{-1}$ and $\Delta \Gamma_s / \Delta m_s = (4 \pm 2) \times 10^{-3}$

- Error on $\Delta m_s$ irrelevant: Sensitive up to $\Delta m_s = 60$ ps$^{-1}$
Nominal $\omega = 30\%$ and $f = 20\%$
Linear dependence, but $\sigma(\Delta m_s)$ largely irrelevant anyway
Sensitivity to $\gamma - 2\delta\gamma$
From $B_s \rightarrow D_s K$

Different values of strong phase difference:
\[ \Delta_{T_1/T_2} = 0 \quad \Delta_{T_1/T_2} = 0.5 \quad \Delta_{T_1/T_2} = 1.0 \]

$x_s = \Delta m_s / \Gamma = 15$

Sensitivity only weakly dependent on $\Delta_{T_1/T_2}$

$x_s = \Delta m_s / \Gamma = 30$
Summary

- $\delta(\Delta m_s)/\Delta m_s < 1\%$ for $\Delta m_s < 60$ ps$^{-1}$: Good sensitivity up to this point
- $\gamma - 2\delta\gamma$ only weakly dependent on strong phase difference

<table>
<thead>
<tr>
<th>$\Delta T_1/T_2$</th>
<th>$\gamma - 2\delta\gamma$ (rad)</th>
<th>$\Delta m_s = 20$</th>
<th>$\Delta m_s = 30$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.26</td>
<td>0.36</td>
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<tr>
<td>0.6</td>
<td>0.23</td>
<td>0.48</td>
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<tr>
<td>1.2</td>
<td>0.31</td>
<td>0.26</td>
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- LHCb capable of measuring $B_s$ mixing and $\gamma$ to high precision
- $B_s \rightarrow D_s K$ gives very clean extraction of $\gamma$