Selection and study of the $B_s^0 \rightarrow D_s^- \pi^+$ decay at LHCb

Louis Nicolas

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Master thesis directed by Prof. Olivier Schneider, assisted by Luis Fernández and Dr Jeroen van Hunen.

- Introduction
- Event selection
- Efficiencies, annual yield and B/S ratio
- Resolutions and proper time analysis
- Conclusion
- LHC = Large Hadron Collider at CERN, collisions of proton bunches with a center of mass energy of $\sqrt{s} = 14$ TeV
- LHCb = LHC beauty experiment, study of the $b$ decays, study of CP violation and search for new physics
- Single-arm spectrometer, forward angular coverage from 10 mrad to 300 (250) mrad in the bending (non-bending) plane
- Only long tracks will be used in the offline selection (tracks with clusters in VeLo and T stations)
The LHCb trigger

- **40 MHz**
  - **Level-0**
    - Identification of $l$, $h$ and $\gamma$ with high $p_T$ + pile-up veto

- **1 MHz**
  - **Level-1**
    - Partial reconstruction, using VeLo – TT and L0 objects
    - Enhancement of $b$ content and identification of $\mu$, dimuons and $J/\Psi$

- **40 kHz**
  - **HLT**
    - ~2 kHz: inclusive events
    - ~200 Hz: specific
    - Generic HLT: partial reconstruction using all available detector's information
    - Identification of $\mu$, $J/\Psi$ and $D^*$ and selection of $b$ decays
Flavour tagging at LHCb

Several algorithms used to determine the flavour of the signal $B$ meson at production:

- opposite side $e$, $\mu$, $K$
- opposite side vertex charge
- same side $K$ ($B_s$) and $\pi$ ($B_d$)

\[ \epsilon_{\text{tag}} = \frac{R + W}{R + W + U} \]

Tagging efficiency

\[ \omega = \frac{W}{R + W} \]

Wrong tag fraction

The statistical uncertainty on the measured CP asymmetry is directly related to the effective combined tagging efficiency $\epsilon_{\text{eff}}$:

\[ \sigma_A^2 = \frac{1 - A_{\text{obs}}^2}{N_{\text{phys}} \epsilon_{\text{tag}} (1 - 2 \omega)^2} = \frac{1 - A_{\text{obs}}^2}{N_{\text{phys}} \epsilon_{\text{eff}}} \]

where

\[ \epsilon_{\text{eff}} = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}} (1 - 2 \omega)^2 \]
The $B_s^0 \rightarrow D_s^- \pi^+$ decay

- Flavour specific decay, no CP violation expected
- $D_s^\pm \Rightarrow K^+ K^- \pi^\pm$ chosen for its significant BR (4.4% in total, 36% through $\phi$ resonance, 45% through $K^*$ and 19% non-resonant)
- Decay used for the extraction of $\Delta M_s$, $\Delta \Gamma_s$ and $\omega$
- Control channel for $B_s^0 \rightarrow D_s^\pm K^\pm$
- $B_s^0 \rightarrow D_s^- \pi^+$ branching ratio: $\text{BR} = 2760 \cdot 10^{-6}$ $\Rightarrow$ visible BR: $\text{BR}_{\text{vis}} = 120 \cdot 10^{-6}$

The observed flavour asymmetry (case of perfect resolution) is:

$$A_f^{\text{obs}}(t) = (1 - 2\omega) \left( -\frac{\cos(\Delta M_s t)}{\cosh\left(\frac{\Delta \Gamma_s}{2} t\right)} \right)$$

where

$$\Delta M_s \equiv M_H - M_L \sim \mathcal{O}(20 \text{ ps}^{-1})$$

and

$$\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H, \quad \frac{\Delta \Gamma_s}{\Gamma_s} \sim \mathcal{O}(10\%)$$
Selection strategy

Three steps selection (on $B_s^0 \rightarrow D_s^- \pi^+$ and charge conjugate):

1. Tracks selection, cuts on:
   i. Impact Parameter Significance ($IPS$, w.r.t. all PVs)
   ii. momentum ($P$) and transverse momentum ($p_T$)
   iii. particle identification (PID, using $DLL$, inclusive selection)

2. $D_s$ and $\pi$ selection, $D_s$ is formed using a $K^+$, a $K^-$ and a $\pi$:
   i. tighter cuts on $IPS$, $P$ and $p_T$
   ii. cut on flight distance ($z$ coordinate) of $D_s$ (should be downstream of $B_s$)
   iii. vertex fit ($\chi^2_{D_s\text{Vtx}}$) cut
   iv. cut on reconstructed $D_s$ mass

3. $B_s$ selection, $B_s$ is reconstructed by combining a $D_s$ and a $\pi$:
   i. cut on $IPS$ ($B_s$ should point back to PV, chosen as that w.r.t. which smallest $IPS$)
   ii. cut on Flight distance Significance ($FS$)
   iii. cut on flight direction ($\cos(\theta_P) = \frac{\vec{p} \cdot \vec{r}}{||\vec{p}|| ||\vec{r}||}$)
   iv. vertex fit ($\chi^2_{B_s\text{Vtx}}$) cut
   v. cut on reconstructed $B_s$ mass
Three significant cuts to reject $b\bar{b}$ background (bkg)

**IPS of the bachelor:**
- Red: Preselected signal
- Blue: Preselected bkg
- Dotted: Cut on lower value

The bachelor ($H$) should not point back to the primary vertex

$\rightarrow IPS_H > 4$

**$p_T$ of the $D_s$:**
- Red: Preselected signal
- Blue: Preselected bkg
- Dotted: Cut on lower value

Large mass difference between $B_s$ and its daughters, $D_s$ and $\pi$ are expected to have a large $p_T$

$\rightarrow p_{T,D_s} > 2000$ MeV/c

**FS of the $B_s$:**
- Red: Preselected signal
- Blue: Preselected bkg
- Dotted: Cut on lower value

Presence of detached secondary vertices due to long $B_s$ lifetime

$\rightarrow FS_{PV-B_s} > 12$

The $B_s^0 \rightarrow D_s^- \pi^+$ decay

March 7th, 2005
Mass distributions

$D_s$ mass distribution:

- Preselected signal
- Preselected bkg

The cut for the $D_s$ mass is chosen at
$$\pm 15 \text{ MeV}/c^2 = \pm 3 \sigma$$

$B_s$ mass distribution:

- Preselected signal
- Loose mass window cut
- Preselected bkg
- Tight mass window cut

Two different cuts for the reconstructed $B_s$ mass:
- tight window ($\pm 50 \text{ MeV}/c^2 = \pm 3 \sigma$)
- loose window ($\pm 500 \text{ MeV}/c^2$) to artificially increase statistics
Summary of the selection cuts

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Min cut</th>
<th>Max cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{H}$</td>
<td>[MeV/c]</td>
<td>2000</td>
<td>---</td>
</tr>
<tr>
<td>$P_{DsProd}$</td>
<td>[MeV/c]</td>
<td>2000</td>
<td>---</td>
</tr>
<tr>
<td>$P_{T,Ds}$</td>
<td>[MeV/c]</td>
<td>2000</td>
<td>---</td>
</tr>
<tr>
<td>$P_{T,H}$</td>
<td>[MeV/c]</td>
<td>600</td>
<td>---</td>
</tr>
<tr>
<td>$P_{T,DsProd}$</td>
<td>[MeV/c]</td>
<td>300</td>
<td>---</td>
</tr>
<tr>
<td>$M_{Bs}$ (l)</td>
<td>[MeV/c$^2$]</td>
<td>4869.6</td>
<td>5869.6</td>
</tr>
<tr>
<td>$M_{Bs}$ (t)</td>
<td>[MeV/c$^2$]</td>
<td>5319.6</td>
<td>5419.6</td>
</tr>
<tr>
<td>$M_{Ds}$</td>
<td>[MeV/c$^2$]</td>
<td>1953.5</td>
<td>1983.5</td>
</tr>
<tr>
<td>$IPS_{Bs}$</td>
<td>---</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>$IPS_{Ds}$</td>
<td>4</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$IPS_{H}$</td>
<td>4</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$IPS_{DsProd}$</td>
<td>3</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$\chi^2_{Bs,Vtx}$</td>
<td>---</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>$\chi^2_{Ds,Vtx}$</td>
<td>---</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>$FS_{Bs-PV}$</td>
<td>12</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$z_{Ds} - z_{Bs}$</td>
<td>[mm]</td>
<td>0</td>
<td>---</td>
</tr>
<tr>
<td>$\cos (\theta_p)$</td>
<td>0.99997</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$DLL_{H}(\pi - K)$</td>
<td>-10</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$DLL_{n}(\pi - K)$</td>
<td>-10</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$DLL_{k}(K - \pi)$</td>
<td>-5</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$DLL_{k}(K - p)$</td>
<td>-10</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

Loose (l) mass window : ±500 MeV/c$^2$
Tight (t) mass window : ±50 MeV/c$^2$ (= ±3 $\sigma$)
Mass window : ±15 MeV/c$^2$ (= ±3 $\sigma$)
Statistics and efficiencies

$$\epsilon_{\text{det}} : \text{detection} \quad \epsilon_{\text{rec/det}} : \text{reconstruction}$$

$$\epsilon_{\text{sel/rec}} : \text{selection} \quad \epsilon_{\text{trg/sel}} : \text{trigger}$$

$$\epsilon_{\text{tot}} : \text{total}$$

<table>
<thead>
<tr>
<th>Data</th>
<th>Factors (in %) forming $\epsilon_{\text{tot}}$ (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\epsilon_{\text{det}}$</td>
</tr>
<tr>
<td>TDR</td>
<td>5.36 ± 0.05</td>
</tr>
<tr>
<td>DC04</td>
<td>6.255 ± 0.011</td>
</tr>
</tbody>
</table>

$B_s \to D_s \pi$ visible branching ratio :

$$\text{BR}_{\text{vis},B_s \to D_s \pi} = \text{BR}_{B_s \to D_s \pi} \times \text{BR}_{D_s \to KK\pi} = (2.76 \cdot 10^{-3}) \times (4.4 \cdot 10^{-2}) \approx 120 \cdot 10^{-6}$$

Annual signal yield ($N_{\text{phys}}$), untagged, no HLT :

$$N_{\text{phys}} = \mathcal{L}_{\text{int}} \times \sigma_{bb} \times (2 \times f_{B_s}) \times \text{BR}_{\text{vis}} \times \epsilon_{\text{tot}}$$

$N_{\text{phys}} = 111.4k$ reconstructed, selected and triggered events per year

⇒ Improvement of 36% (relative) between TDR study ($N_{\text{phys},TDR} = 81.7k$) and now

Great Achievement!!!
Categories of $b\bar{b}$ background events

Four categories of selected inclusive-$b\bar{b}$ events:

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Examples</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>True signal events:</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>- should not be counted as background</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Incompletely reconstructed $b$ decays ($\gamma$, $\pi^0$ or $\nu$ missing)</td>
<td></td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>- always reconstructed outside the tight mass window</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- should not be counted as background</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Real $b$ events and misidentification:</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>- $B_d \rightarrow (D \Rightarrow K\pi\pi) \pi$ and $\Lambda_b \rightarrow (\Lambda_c \Rightarrow pK\pi) \pi$ events</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(other decays if more statistics?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- misidentification of a $\pi$ from $D$ or the $p$ from $\Lambda_c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- events in the tight mass window counted as real background</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Combinatorial background:</td>
<td></td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>- events in the loose mass window counted as real background</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- downscaled to the tight mass window ($\pm 50/\pm 500 = 1/10$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mass distributions of background events

Mass distribution of the selected inclusive-$b\bar{b}$ events:

Peak of true signal events and specific background reconstructed inside the tight mass window
(e.g. $B_d \rightarrow D \pi$, $\Lambda_b \rightarrow \Lambda_c \pi$)

Peaks of specific background incompletely reconstructed outside the tight mass window
(e.g. $B_s \rightarrow D_s^* \pi$, $B_s \rightarrow D_s l \nu$, $B_s \rightarrow D_s \rho$)

Large fraction of the peak falls inside the tight mass window
⇒ Must be counted as background
⇒ Contribution to the B/S ratio

Mass distribution of the selected $B_d \rightarrow D \pi$ events:
Three contributions to the background-to-signal ratio:

1. Contribution from the combinatorial background (11.8M events):

\[
\frac{B}{S} = \frac{N_{\text{phys}}(b\bar{b})}{N_{\text{phys}}(\text{signal})} = \frac{L_{\text{int}} \times \sigma_{b\bar{b}} \times \epsilon_{\theta/b\bar{b}} \times \epsilon_{\text{sel}/b\bar{b}} \times \frac{1}{10}}{\frac{N_{\text{phys}}(\text{signal})}{\epsilon_{\text{trg/sel}}}}
\]

2. Contribution from the \(B_d \to D \pi\) decay (110k events):

\[
\left( \frac{B}{S} \right)_{B_s \to D_s \pi}^{B_d \to D \pi} = \left( \frac{f_{B_d}}{f_{B_s}} \right) \left( \frac{\text{BR}_{\text{vis}, B_d \to D \pi}}{\text{BR}_{\text{vis}, B_s \to D_s \pi}} \right) \left( \frac{\epsilon_{\text{tot}, B_d \to D \pi}}{\epsilon_{\text{tot}, B_s \to D_s \pi}} \right)
\]

3. Contribution from the \(\Lambda_b \to \Lambda_c \pi\) decay:

\[
\left( \frac{B}{S} \right)_{B_s \to D_s \pi}^{\Lambda_b \to \Lambda_c \pi} = \left( \frac{f_{\Lambda_b}}{f_{B_d}} \right) \left( \frac{\text{BR}_{\Lambda_c^+ \to pK^-\pi^+}}{\text{BR}_{D^- \to K^-\pi^+\pi^+}} \right) \left( \frac{B}{S} \right)_{B_s \to D_s \pi}^{B_d \to D \pi}
\]
B/S ratio (2/2)

Total background-to-signal ratio = sum of the three contributions (+ other contributions?) :

$$\left( \frac{B}{S} \right)_{\text{tot}} = \left( \frac{B}{S} \right)_{b\bar{b}} + \left( \frac{B}{S} \right)_{B_d \to D \pi} + \left( \frac{B}{S} \right)_{\Lambda_b \to \Lambda_c \pi}$$

$$= (0.47 \pm 0.08) + (0.31 \pm 0.03) + (0.05 \pm 0.01)$$

$$= 0.83 \pm 0.09$$

The result looks worse than at the time of the TDR (0.32 ± 0.10) BUT :

- more realistic calculation of the B/S ratio (no downscale of the number of specific background events that fall inside the tight mass window and more contributions taken into account)

- the same calculation than for the TDR gives : $$\left( \frac{B}{S} \right)_{\text{tot}} = 0.34 \pm 0.05$$

<table>
<thead>
<tr>
<th>Data</th>
<th>Assumed BR&lt;sub&gt;vis&lt;/sub&gt; (in 10&lt;sup&gt;-6&lt;/sup&gt;)</th>
<th>Annual signal yield</th>
<th>B/S ratio from incl. $b\bar{b}$ back.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDR</td>
<td>120 ± 30</td>
<td>(81.7 ± 1.9)k</td>
<td>0.32 ± 0.10</td>
</tr>
<tr>
<td>DC04</td>
<td>120 ± 30</td>
<td>(111.4 ± 0.5)k</td>
<td>0.83 ± 0.09</td>
</tr>
</tbody>
</table>
Tagging performances and sensitivity to $\Delta M_s$

Tagging efficiency : $\epsilon_{\text{tag}} = (56.17 \pm 0.18)\%$
Wrong tag fraction : $\omega = (33.53 \pm 0.15)\%$

\[ \Rightarrow \epsilon_{\text{eff}} = (6.10 \pm 0.19)\% \]

Average statistical significance on the $B_s^0 - \overline{B_s^0}$ oscillations amplitude:

\[ S \approx \sqrt{\frac{N_{\text{tag}}}{2} \cdot f_{\text{sig}} \cdot (1 - 2\omega_{\text{tag}}) \cdot e^{-\frac{(\Delta M_s \sigma_T)^2}{2}}} = \sqrt{\frac{N_{\text{phys}}}{2} \cdot \epsilon_{\text{eff}} \cdot f_{\text{sig}} \cdot e^{-\frac{(\Delta M_s \sigma_T)^2}{2}}} \]

Plotting $S$ vs $\Delta M_s$:

5$\sigma$ measurement possible up to:
$\Delta M_s = 46$ ps$^{-1}$

Values smaller than $\Delta M_s = 58$ ps$^{-1}$ can be excluded with a CL of 95%

$\Rightarrow$ Approximation, toy MC needed
Resolutions analysis (1/3)

Resolution on the $B_s$ mass:

- Single Gaussian: $\sigma_{M_{B_s}} \approx 14.3$ MeV/$c^2$
- $\sigma_1 = 12.1$ MeV/$c^2$ ($f_1 = 71\%$)
- $\sigma_2 = 20.3$ MeV/$c^2$ ($f_2 = 29\%$)
- $B_s$ tight mass window cut: $\sim \pm 3\sigma$

Resolution on the $D_s$ mass:

- Single Gaussian: $\sigma_{M_{D_s}} \approx 5.30$ MeV/$c^2$
- $\sigma_1 = 3.72$ MeV/$c^2$ ($f_1 = 40\%$)
- $\sigma_2 = 6.47$ MeV/$c^2$ ($f_2 = 60\%$)
- $D_s$ mass window cut: $\sim \pm 3\sigma$
Resolutions analysis (2/3)

Resolution on the $B_s$ momentum:

- $x$ coordinate: double Gaussian:
  \[
  \sigma_1 = 11.9 \text{ MeV/c} \quad (f_1 = 74\%)
  \]
  \[
  \sigma_2 = 35.8 \text{ MeV/c} \quad (f_2 = 26\%)
  \]

- $y$ coordinate: double Gaussian:
  \[
  \sigma_1 = 11.6 \text{ MeV/c} \quad (f_1 = 73\%)
  \]
  \[
  \sigma_2 = 36.2 \text{ MeV/c} \quad (f_2 = 27\%)
  \]

- $z$ coordinate: triple Gaussian:
  \[
  \sigma_1 = 118 \text{ MeV/c} \quad (f_1 = 31\%)
  \]
  \[
  \sigma_2 = 318 \text{ MeV/c} \quad (f_2 = 46\%)
  \]
  \[
  \sigma_3 = 867 \text{ MeV/c} \quad (f_3 = 23\%)
  \]

\[\Rightarrow \quad \sigma_{P_{zB_s}} \simeq \sqrt{\sum_i f_i \sigma_i^2} = 473 \text{ MeV/c}\]
Resolutions analysis (3/3)

Resolution on the primary vertex position:
- $x$ coordinate: double Gaussian:
  - $\sigma_1 = 6.47 \, \mu m$ ($f_1 = 73\%$)
  - $\sigma_2 = 13.0 \, \mu m$ ($f_2 = 27\%$)
- $y$ coordinate: double Gaussian:
  - $\sigma_1 = 6.35 \, \mu m$ ($f_1 = 76\%$)
  - $\sigma_2 = 12.8 \, \mu m$ ($f_2 = 24\%$)
- $z$ coordinate: triple Gaussian:
  - $\sigma_1 = 27.7 \, \mu m$ ($f_1 = 36\%$)
  - $\sigma_2 = 48.2 \, \mu m$ ($f_2 = 51\%$)
  - $\sigma_3 = 104 \, \mu m$ ($f_3 = 13\%$)
  \[ \Rightarrow \sigma_{z,PV} \approx 53.6 \, \mu m \]

Resolution on the $B_s$ decay vertex position:
- $x$ coordinate: double Gaussian:
  - $\sigma_1 = 11.5 \, \mu m$ ($f_1 = 72\%$)
  - $\sigma_2 = 24.7 \, \mu m$ ($f_2 = 28\%$)
- $y$ coordinate: double Gaussian:
  - $\sigma_1 = 10.1 \, \mu m$ ($f_1 = 71\%$)
  - $\sigma_2 = 24.4 \, \mu m$ ($f_2 = 29\%$)
- $z$ coordinate: triple Gaussian:
  - $\sigma_1 = 105 \, \mu m$ ($f_1 = 41\%$)
  - $\sigma_2 = 280 \, \mu m$ ($f_2 = 41\%$)
  - $\sigma_3 = 780 \, \mu m$ ($f_3 = 18\%$)
  \[ \Rightarrow \sigma_{z,Bs} \approx 382 \, \mu m \]
The $B_s$ proper time

Proper time calculation: constrained fit and $\chi^2$ minimisation with

$$\tau = \frac{M}{c} \frac{\vec{L} \cdot \vec{p}}{p^2}$$

where

- $M$ : $B_s$ mass
- $\vec{L}$ : $B_s$ flight distance ($\overrightarrow{\text{Sec} - \overrightarrow{\text{PV}}}$)
- $\vec{p}$ : $B_s$ momentum

Fitting an exponential curve:

$B_s$ lifetime : $\tau_{B_s} = (1.455 \pm 0.006)$ ps,
consistent (1\,$\sigma$) with the value used in the generation : $\tau_{B_s} = 1.461$ ps

Solid black curve : acceptance + exponential (see later)
Proper time resolution:

$\sigma$ of the distribution of $\tau_{B_s,\text{reco}} - \tau_{B_s,\text{true}}$

Proper time pull:

$\sigma$ of the distribution of $\frac{\tau_{B_s,\text{reco}} - \tau_{B_s,\text{true}}}{\sigma_{\tau_{B_s}}}$

Proper time resolution:

$\sigma_1 = 29.7$ fs ($f_1 = 63\%$)
$\sigma_2 = 56.7$ fs ($f_2 = 37\%$)

$\Rightarrow \sigma_\tau \approx \sqrt{f_1 \sigma_1^2 + f_2 \sigma_2^2} = 41.8$ fs

Bias : -2.43 fs $\Rightarrow$ Proper time is under-estimated

Pull : 1.2 ± 0.0 $\Rightarrow$ Errors are under-estimated

Bias : -0.074 ± 0.003 $\Rightarrow$ Proper time is under-estimated
Decomposition of the $B_s$ proper time resolution

Using all MC values in: $\tau = \frac{M \vec{L} \cdot \vec{p}}{c \sqrt{\vec{p}^2}}$ except for one parameter (“All true but...”), one gets the contribution to the proper time resolution of each parameter

- All true but $M_{B_s}$:
  \[ \sigma_{\tau / M_{B_s}} = 3.08 \text{ fs (71%)} + 9.84 \text{ fs (29%) } \]

- All true but $P_{B_s}$:
  \[ \sigma_{\tau / P_{B_s}} = 3.11 \text{ fs (71%)} + 10.5 \text{ fs (29%) } \]

- All true but PV position:
  \[ \sigma_{\tau / PV} = 4.64 \text{ fs (64%)} + 15.5 \text{ fs (36%) } \]

- All true but $B_s$ decay vertex position:
  \[ \text{Largest contribution to the proper time resolution (no suprise): } \]
  \[ \sigma_{\tau / B_s\text{Vtx}} = 26.7 \text{ fs (63%)} + 55.8 \text{ fs (37%) } \]
  \[ \Rightarrow \sigma_{\tau} \approx 40.1 \text{ fs} \]
  \[ \text{Bias : -2.26 fs} \]

with $\sigma_{\tau}^{\text{tot}} \approx 41.8 \text{ fs and total bias : -2.43 fs}$
Dependences of the $B_s$ proper time pull

Projection of proper time pull in bins of other parameters
Most significant: projections in bins of $P_{B_s}$ and of opening angle $\phi$ between $D_s$ and $\pi$

The larger the momentum, the larger the pull on the proper time

Large momentum $\Rightarrow$ worse secondary vertex resolution $\Rightarrow$ worse proper time resolution
$(?) \Rightarrow (?)$ errors not well estimated

The larger the opening angle, the smaller the pull on the proper time

Small opening angle $\Rightarrow$ worse secondary vertex resolution $\Rightarrow$ worse proper time resolution
$(?) \Rightarrow (?)$ errors not well estimated
Acceptance analysis

Events with small proper time implicitly rejected ⇒ Probability described by acceptance function:

Important parameters:
- $c$ (slope at large proper times)
- $b$ and $n$ (shape)

$$
\frac{a\left(b\tau_{MC}\right)^n}{\left(1 + \left(b\tau_{MC}\right)^n\right)^2}\left(1 + c\tau_{MC}\right)
$$

where $\tau_{MC} =$ true proper time

Before trigger:

- $b = 2.84$ ps$^{-1}$
- $c = (-0.011 \pm 0.003)$ ps$^{-1}$
- $n = 1.52$

Acceptance drops for small proper time, due to cuts on $FS$, on $IPS$ and on $\cos(\theta_p)$. Would be more shifted if selection/all data.

Not significant drop of the acceptance for large proper times

After L0 and L1:

- $b = 1.90$ ps$^{-1}$
- $c = (-0.039 \pm 0.004)$ ps$^{-1}$
- $n = 1.52$

Acceptance drops for small proper time, even more after L1, due to cuts requiring large $IP$ tracks

Significant drop for large proper times after L1 (?)
Summary and conclusion

- Annual signal yield: improvement of 36% (relative) since TDR: 111.4 k untagged, reconstructed, selected and triggered (no HLT) events per year
- B/S ratio: increased from 0.32 to 0.83 BUT more realistic estimate
- Wrong tag fraction: $\omega = 33.53\%$, tagging efficiency: $\epsilon_{\text{tag}} = 56.17\%$
- Sensitivity to $\Delta M_s$: $5\sigma$ measurement possible up to $46 \text{ ps}^{-1}$ (using approximation formula)
- Proper time resolution: $\sigma_T = 41.8 \text{ fs}$, highly dominated by resolution on position of $B_s$ decay vertex, bias: -2.43 fs $\Rightarrow$ proper time is under-estimated
- Proper time pull: 1.2 $\Rightarrow$ errors are under-estimated. Pull dependent on $B_s$ momentum and on opening angle between momentum of $D_s$ and bachelor
- Acceptance: small for small proper time and biased by L1 for both small and large proper times
BKP1 : statistics and efficiencies

- 3.55M \(B_s^0 \rightarrow D_s^{-} \pi^+ \) (+cc) events analysed

- Several efficiencies can be calculated:

  - Reconstruction efficiency :
    \[ \epsilon_{\text{rec/det}} = \frac{N_{\text{rec''ible}}}{N_{\text{rec'ble}}} \]

  - Selection efficiency :
    \[ \epsilon_{\text{sel/rec}} = \frac{N_{\text{sel}}}{N_{\text{rec'ed}}} \]

  - Geometric acceptance :
    \[ \epsilon_{\theta} = (34.71 \pm 0.03)\% \]

  - Offline efficiency :
    \[ \epsilon_{\text{off}} = \epsilon_{\text{det}} \times \epsilon_{\text{rec/det}} \times \epsilon_{\text{sel/rec}} = \frac{N_{\text{sel}}}{N_{\text{tot}}} \times \epsilon_{\theta} \]

  - Detection efficiency :
    \[ \epsilon_{\text{det}} = \frac{\epsilon_{\text{off}}}{\epsilon_{\text{rec/det}} \times \epsilon_{\text{sel/rec}}} \]

  - Trigger efficiency :
    \[ \epsilon_{\text{trg/sel}} = \frac{N_{\text{trg}}}{N_{\text{sel}}} \]

Total efficiency :
\[ \epsilon_{\text{tot}} = \epsilon_{\text{det}} \times \epsilon_{\text{rec/det}} \times \epsilon_{\text{sel/rec}} \times \epsilon_{\text{trg/sel}} = \epsilon_{\text{off}} \times \epsilon_{\text{trg/sel}} \]
BKP2 : background data analysed

☆ Minimum Bias :
- ~12.8M events in initial sample (~1 sec of LHCb)
- ~32k L0-L1 accepted events analysed
- 0 selected events in loose mass window (lucky me!!!)

☆ Inclusive-bb⁻ :
- ~11.8M events in initial sample
- 106 selected events in loose mass window
- 39 combinatorial background events in loose mass window

☆ Specific background : \( B_d \to D \pi \) decay :
- ~110k events in initial sample
- 150 selected events in tight mass window
- 93 L0-L1 accepted and selected events in tight mass window
Tagging performances after L0-L1 triggers:

\[
\begin{align*}
\epsilon_{\text{tag}} &= (56.17 \pm 0.18)\% \\
\omega &= (33.53 \pm 0.15)\% \\
\end{align*}
\]

\[\Rightarrow \epsilon_{\text{eff}} = \epsilon_{\text{tag}} (1 - 2\omega)^2 = (6.10 \pm 0.19)\%\]

At time of TDR:

\[
\begin{align*}
\epsilon_{\text{tag}} &= (54.6 \pm 1.2)\% \\
\omega &= (30.0 \pm 1.6)\% \\
\end{align*}
\]

\[\Rightarrow \epsilon_{\text{eff}} = \epsilon_{\text{tag}} (1 - 2\omega)^2 = (8.7 \pm 1.2)\%\]

\[\Rightarrow \text{Both } \epsilon_{\text{tag}} \text{ and } \omega \text{ increased, but } \epsilon_{\text{eff}} \text{ decreased. However, much smaller statistical uncertainty}\]

New tagging algorithms being implemented \[\Rightarrow \epsilon_{\text{eff}} \text{ could increase again}\]