Precision measurement of $\Delta m_d$ using semi-leptonic decays at LHCb

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Outline

1. LHCb
2. $\Delta m_d$ measurement at LHCb
3. Conclusion
4. Backups
LHCb

- **LHCb experiment:**
  - Single-arm forward spectrometer
  - Unique $\eta$ coverage ($2 < \eta < 5$)
- **LHCb physics:**
  - Designed to search for New Physics in CP violation & Rare decays in Beauty & Charm
- **LHCb luminosity:**
  - Run I: $1 \text{ fb}^{-1}$ (2011 @ 7 TeV), $2 \text{ fb}^{-1}$ (2012 @ 8 TeV)
  - Run II: $\mathcal{O}(\text{ pb}^{-1})$

indico.cern.ch/event/356420/session/8/contribution/388
indico.cern.ch/event/356420/session/8/contribution/251
indico.cern.ch/event/356420/session/5/contribution/183
LHCb detector

- **VELO**: $20\,\mu m$ for high $p_T$ tracks
- **Tracking system**: $\delta(p)/p = (0.4 - 0.6)\%$, reversible magnet polarity
- **RICH system**: $\epsilon(K) \sim 95\%$, 5% $\pi \rightarrow K$ mis-id probability
- **Calorimeter**: Energy measurement, identify $\pi^0, \gamma$
- **Muon detector**: $\epsilon(\mu) \sim 97\%$, $(1 - 3)\%$, $\pi \rightarrow \mu$ mis-id probability
- **Trigger**: 40 MHz $\rightarrow$ 5 kHz, efficiency ($\mu$ trigger) $\sim 90\%$
A precise measurement of the $B^0$ meson oscillation frequency,

LHCB-CONF-2015-003

$^1$Paper is in preparation
Introduction

- **Flavour oscillation** through electroweak interaction in neutral B mesons

\[ N_{\pm}(t) \propto e^{-\frac{t}{\tau}} (1 + q_{\text{mixing}} \cos(\Delta m_d t)) \]

- **Tagged time-dependent analysis:**
  - \( N_- (t) \): mixed (\( B^0(\bar{B}^0) \rightarrow \bar{B}^0(B^0) \)), \( N_+ (t) \): unmixed
  - Mixing state \( (q_{\text{mixing}} = \pm 1) \) of \( B^0 \): flavour at decay \( \times \) flavour at production
  - Decay time of \( B^0 \) (\( t \))
Analysis strategy

- Analysis in two channels $B^0 \rightarrow D^{(*)-} \mu^+ \nu_\mu$ using Run I data (3 fb$^{-1}$)
  - $B^0 \rightarrow D^- \mu^+ \nu_\mu$ ($D^- \rightarrow K^+ \pi^- \pi^-$)
  - $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ ($D^{*-} \rightarrow \bar{D}^0 (\rightarrow K^+ \pi^-) \pi^-$)

- Flavour Tagging ($q_{\text{mixing}}$)

- Decay time estimation ($t$)

- Background rejection

- Extraction of $\Delta m_d$ from tagged time-dependent fit

- Evaluation of systematic uncertainties
Flavour tagging: \( q_{\text{mixing}} \)

- Mixing state \( q_{\text{mixing}} \): flavour at decay \( \times \) flavour at production = ±1

- Determine the flavour of \( B^0 \) at production in LHCb


  indico.cern.ch/event/356420/session/3/contribution/167

  - Use Opposite B and Fragmentation products
  - Flavour at production \((q_i : \pm 1, 0)\)
  - ... With Mistag probability

- Flavour at decay in \( B^0 \to D(\ast)^- \mu^+ \nu_\mu \) is determined by \( \mu \) charge

\[
N_{\pm}(t) \propto e^{-\frac{t}{\tau}} (1 + q_{\text{mixing}} (1 - 2\omega) \cos(\Delta m_d t))
\]

- Events are Grouped in 4 categories in increasing mistag probability
  - a ∈ [0, 0.25], b ∈ [0.25, 0.33], c ∈ [0.33, 0.41], d ∈ [0.41, 0.47]
Determination of B decay time

- Wrong B momentum due to missing neutrino → wrong $t$
- Use $k$-factor method to correct $t$
  - $k(m_{D\mu})$: $p_{D\mu}^{\text{rec}}/p_{D\mu}^{\text{true}}$ as a function of B mass (simulation)
  - Apply correction function on data
    $$t_{\text{corr}} = \frac{L_B}{p_{D\mu}^{\text{rec}}} \times k(m_{D\mu})$$

- $k(m_{D\mu})$: average correction → additional resolution function $F(k)$

$$N_{\pm}(t) \propto e^{\frac{-t}{\tau}} (1 + q_{\text{mixing}}(1 - 2\omega) \cos(\Delta m_d t)) \otimes R(t) \otimes F(k)$$
Background rejection I

• First type of backgrounds: Combinatorics, $D^0$ from B decays
  - Not sharing $D^{(*)-}$ with the signal in their final state
• Apply sPlot technique to subtract those backgrounds (Nucl. Instrum. Meth. A555 (2005) 356)
  - $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$: $m_{D^0}, \delta m(= m_{D^{*-}} - m_{D^0})$ distributions
  - $B^0 \rightarrow D^{-} \mu^+ \nu_\mu$: $m_{D^{-}}$ distribution
Background rejection II

- Second type of backgrounds: \( B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X \) decays
  - Sharing \( D^{(*)-} \) with signal in their final state
  - Exploit topological differences between signal and \( B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X \)
    - Additional \( \pi \) in \( B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X \) decays w.r.t signal
  - Kinematic & geometric variables combined in a MVA classifier (BDT)
Background rejection II

• Use the BDT classifier to estimate the contribution of \( B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X \) in data
  
  • Fit to BDT distributions in data

\[ \begin{array}{c}
\text{Events} \times 10^3 / 0.05 \\
\hline
\text{(a)} & \text{(b)} \\
\text{(c)} & \text{(d)} \\
\end{array} \]

• Apply a cut on the BDT classifier \( \rightarrow \) retain 90% of signal & reduce \( B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X \) by 70%
  
  • Determine the fraction of remaining \( B^+ \rightarrow D^{(*)-} \mu^+ \pi^+ \nu_\mu X \) by extrapolation

\[ \frac{2}{2} \text{Weights from sPlot technique are applied} \]
Asymmetry fit

- Use binned likelihood sFit (arXiv:0905.0724) to extract $\Delta m_d$

$$\mathcal{P}(t, q^{\text{mixing}}) = (1 - f_{B^+}) S(t, q^{\text{mixing}}) + f_{B^+} B^+(t, q^{\text{mixing}})$$

- $S(t, q), B^+(t, q)$: decay rates of signal & background
- $f_{B^+}$: fraction of the $B^+ \to D^{(*)-} \mu^+ \pi^+ \nu_\mu X$ in the sample

- Time-dependent asymmetry

![Graphs](Images)
Results

- Several sources of systematic uncertainties
  - k-factor method, $B^+$ and other background sources & Other sources (time acceptance, detector resolution, momentum and length scale)
  - Large number of parameterized simulation to evaluate systematic uncertainties
  - Results per decay channel:

<table>
<thead>
<tr>
<th>Mode</th>
<th>2011 sample</th>
<th>2012 sample</th>
<th>Total sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow D^- \mu^+ \nu_\mu$</td>
<td>$\Delta m_d [\text{ns}^{-1}]$</td>
<td>$504.7 \pm 4.9_{\text{stat}}$</td>
<td>$503.2 \pm 2.9_{\text{stat}}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$</td>
<td>$\Delta m_d [\text{ns}^{-1}]$</td>
<td>$496.2 \pm 5.9_{\text{stat}}$</td>
<td>$506.9 \pm 3.9_{\text{stat}}$</td>
</tr>
</tbody>
</table>

- Combination of $\Delta m_d$ measurement across the two channels using Run I data:

$$\Delta m_d = 503.6 \pm 2.0 \ (\text{stat}) \pm 1.3 \ (\text{syst}) \ \text{ns}^{-1}$$
- LHCb measure $\Delta m_d$ in $B^0 \to D^{(*)-} \mu^+ \nu_\mu$ channels using 3 fb$^{-1}$

$$\Delta m_d = 503.6 \pm 2.0 \,(\text{stat}) \pm 1.3 \,(\text{syst}) \,\text{ns}^{-1}$$

- LHCb provides the most precise measurement of $\Delta m_d$
- Systematic uncertainties are under control
- New world average form HFAG including this measurement:

$$\Delta m_d(\text{world average 2015}) = 505.5 \pm 2.0 \,\text{ns}^{-1}$$
Backups
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$B^0 \to D^- \mu^+ \nu_\mu$ [ns$^{-1}$]</th>
<th>$B^0 \to D^{*-} \mu^+ \nu_\mu$ [ns$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncorrelated  Correlated</td>
<td>Uncorrelated  Correlated</td>
</tr>
<tr>
<td>$B^+$ background</td>
<td>0.4  0.1</td>
<td>0.8  –</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>–  0.5</td>
<td>–  –</td>
</tr>
<tr>
<td>$k$-factor distribution</td>
<td>0.4  0.5</td>
<td>0.3  0.6</td>
</tr>
<tr>
<td>Other fit-related</td>
<td>0.6  0.9</td>
<td>0.2  0.9</td>
</tr>
<tr>
<td>Total</td>
<td>0.9  1.1</td>
<td>0.9  1.1</td>
</tr>
</tbody>
</table>
Time projections in 2012 data
D⁰ mass distributions for 2012

- D⁰ mass fits in B⁰ → D*⁻ µ⁺ νµ decay
- Components with D*⁻ D⁰π can be only distinguished using δm(= m_{D^*} – m_{D⁰})
Asymmetries in 2011

LHCb preliminary

Asymmetry vs. decay time [ps]

(a) (b) (c) (d)
k-factor versus B mass in $B^0 \rightarrow D^- \mu^+ \nu_\mu$ (simulation)
BDT classifier

\[ B^0 \rightarrow D^- \mu^+ \nu_\mu \]

\[ B^0 \rightarrow D^{*-} \mu^+ \nu_\mu \]
\[ \Delta m_d (\text{world average 2015}) = 505.5 \pm 2.0 \, \text{ns}^{-1} \]