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

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On behalf of the LHCb collaboration

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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 \(^1\)

\(^1\)Paper is in preparation
Introduction

- Flavour oscillation through electroweak interaction in neutral B mesons

\[ \Delta m_d \]

\[ \Delta m_d \text{ measurement at LHCb} \]

- 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 $B^0 \rightarrow D(\ast)^- \mu^+ \nu_\mu$ using Run I data (3 $\text{fb}^{-1}$)
  - $B^0 \rightarrow D^- \mu^+ \nu_\mu$ ($D^- \rightarrow K^+ \pi^- \pi^-$)
  - $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ ($D^{*-} \rightarrow \bar{D}^0 (\rightarrow K^+ \pi^-) \pi^-$)
- 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 $= \pm 1$

- 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 $B^0 \to D^{(*)-} \mu^+ \nu_\mu$ 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
  - $a \in [0, 0.25]$, $b \in [0.25, 0.33]$, $c \in [0.33, 0.41]$, $d \in [0.41, 0.47]$
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
    \[
    t_{\text{corr}} = \frac{L_B M_{B^0_{PDG}}}{p_{D\mu}^{\text{rec}}} \times k(m_{D\mu})
    \]
- $k(m_{D\mu})$: 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)

\[ \text{Entries (arb. units)} \]

- \( \Delta m_d \) in semi-leptons at LHCb
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 $^2$

- Apply a cut on the BDT classifier → 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

$^2$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 showing asymmetry against decay time for $B^0 \to D^- \mu^+ \nu_\mu$ and $B^0 \to D^{*-} \mu^+ \nu_\mu$.]
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 $\Delta m_d$ [ns$^{-1}$]</th>
<th>2012 sample $\Delta m_d$ [ns$^{-1}$]</th>
<th>Total sample $\Delta m_d$ [ns$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow D^- \mu^+ \nu_\mu$</td>
<td>$504.7 \pm 4.9_{\text{stat}}$</td>
<td>$503.2 \pm 2.9_{\text{stat}}$</td>
<td>$503.6 \pm 2.5_{\text{stat}} \pm 1.4_{\text{syst}}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$</td>
<td>$496.2 \pm 5.9_{\text{stat}}$</td>
<td>$506.9 \pm 3.9_{\text{stat}}$</td>
<td>$503.6 \pm 3.2_{\text{stat}} \pm 1.4_{\text{syst}}$</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 $B^0 \rightarrow D^{(*)} - \mu^+ \nu_\mu$ channels using $3 \text{ fb}^{-1}$

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

• 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</td>
<td>Correlated</td>
</tr>
<tr>
<td>$B^+$ background</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>–</td>
<td>0.5</td>
</tr>
<tr>
<td>$k$-factor distribution</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Other fit-related</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>0.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Time projections in 2012 data

LHCb preliminary
- data
- Total fit
- signal $B^0$ component
- background $B^+$ component

Pull
-4
-2
0
2
4

decay time [ps]

LHCb preliminary
- data
- Total fit
- signal $B^0$ component
- background $B^+$ component

Pull
-4
-2
0
2
4

decay time [ps]
**D⁰ mass distributions for 2012**

- **D⁰ mass fits in** $B^0 \to D^{*-} \mu^+ \nu_\mu$ decay
- **Components with** $D^{*-}D^0\pi$ can be only distinguished using $\delta m(= m_{D^{*-}} - m_{D^0})$
Asymmetries in 2011

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$\Delta m_d$ in semi-leptonics at LHCb
k-factor versus B mass in $B^0 \rightarrow D^- \mu^+ \nu_\mu$ (simulation)
BDT classifier

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

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

LHCb preliminary

(a) Data
(b) Total fit
(c) Signal
(d) Background
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO+ARGUS (χ_d measurements)</td>
<td>0.498 ± 0.032 ps⁻¹</td>
</tr>
<tr>
<td>LHCb D (µ/OST(3 fb⁻¹), prel)</td>
<td>0.5036 ± 0.0020 ± 0.0013 ps⁻¹</td>
</tr>
<tr>
<td>LHCb B (µ/OST,SST(1 fb⁻¹))</td>
<td>0.511 ± 0.005 ± 0.003 ps⁻¹</td>
</tr>
<tr>
<td>LHCb D (µ/OST(0.036 fb⁻¹))</td>
<td>0.492 ± 0.018 ± 0.013 ps⁻¹</td>
</tr>
<tr>
<td>CDF1 l/l(92-95)</td>
<td>0.500 ± 0.016 ± 0.010 ps⁻¹</td>
</tr>
<tr>
<td>OPAL l/l(91-94)</td>
<td>0.493 ± 0.012 ± 0.009 ps⁻¹</td>
</tr>
<tr>
<td>CDF1 (92-95)</td>
<td>0.506 ± 0.0020 ± 0.016 ps⁻¹</td>
</tr>
<tr>
<td>L3 l/Qjet(94-95)</td>
<td>0.437 ± 0.043 ± 0.044 ps⁻¹</td>
</tr>
<tr>
<td>DELPHI l/l(91-94)</td>
<td>0.458 ± 0.046 ± 0.032 ps⁻¹</td>
</tr>
<tr>
<td>ALEPH l/Qjet(91-94)</td>
<td>0.499 ± 0.053 ± 0.015 ps⁻¹</td>
</tr>
<tr>
<td>OPAL l/Qjet(90-94)</td>
<td>0.516 ± 0.009 ± 0.035 ps⁻¹</td>
</tr>
<tr>
<td>DELPHI vtx(94-00)</td>
<td>0.471 ± 0.078 ± 0.020 ps⁻¹</td>
</tr>
<tr>
<td>BABAR l/Qjet(91-94)</td>
<td>0.497 ± 0.016 ± 0.010 ps⁻¹</td>
</tr>
<tr>
<td>L3 l/l(IP)(94-95)</td>
<td>0.458 ± 0.046 ± 0.032 ps⁻¹</td>
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<td>D0 D*(02-05)</td>
<td>0.471 ± 0.078 ± 0.020 ps⁻¹</td>
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<tr>
<td>OPAL D* /l(91-94)</td>
<td>0.507 ± 0.022 ± 0.006 ps⁻¹</td>
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<td>BABAR D*(full)/µK,NN(32M BB)</td>
<td>0.508 ± 0.0020 ± 0.016 ps⁻¹</td>
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<tr>
<td>LHCb B (µ/OST(0.036 fb⁻¹))</td>
<td>0.482 ± 0.044 ± 0.024 ps⁻¹</td>
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<td>LHCb D (µ/OST,SST(1 fb⁻¹))</td>
<td>0.5036 ± 0.0020 ± 0.0013 ps⁻¹</td>
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<td>LHCb D (µ/OST(0.036 fb⁻¹), prel)</td>
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**Heavy Flavour Averaging Group**

\[
\Delta m_d(\text{world average 2015}) = 505.5 \pm 2.0 \text{ ns}^{-1}
\]