“Measurements of $\Delta m_{d,s}$ and $\Delta \Gamma_d$ at LHCb”

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on behalf of the LHCb collaboration

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Physics introduction on $B_d^0 - \bar{B}_d^0$ mixing: why measuring $\Delta m_d$, $\Delta m_s$ and $\Delta \Gamma_d$

How to measure $\Delta m_d/s$
- LHCb most precise measurement of $\Delta m_d$
- LHCb most precise measurement of $\Delta m_s$

How to measure $\Delta \Gamma_d$
- LHCb measurement of $\Delta \Gamma_d$ ($\Delta \Gamma_s$ covered by G.Cowan’s Talk)

Implications of the measurements to the Standard Model and to possible New Physics scenarios

Conclusions
In the Standard Model \( B^0_{d/s} - \bar{B}^0_{d/s} \) mix through the box diagrams.

The two mass eigenstates \( B_H \) and \( B_L \) have:

- \( \Delta m_q \propto m^2_w m_{B_q} B_{B_q} f_{B_q}^2 (V^*_t V_{tb})^2 \quad q = d, s \)
- \( \Delta \Gamma_q \propto m^2_b m_{B_q} B_{B_q} f_{B_q}^2 ((V^*_t V_{tb})^2 + V^*_t V_{tb} V^*_c V_{cb} \mathcal{O}(m^2_c/m^2_b) + (V^*_c V_{cb})^2 \mathcal{O}(m^4_c/m^4_b)) \)

Current WA: [HFAG Summer 2016]

- \( \Delta m_d = 0.5065 \pm 0.0016 \pm 0.0011 \) ps\(^{-1}\)
- \( \Delta m_s = 17.757 \pm 0.020 \pm 0.007 \) ps\(^{-1}\)
- \( \Delta \Gamma_d/\Gamma_d = (-0.2 \pm 1.0) \times 10^{-2} \)

constrain the apex \((\bar{\rho}, \bar{\eta})\) of the CKM unitarity triangle

\( \hat{B}_{B_q} f_{B_q}^2 \) uncertainties limit the precision of \( V_{CKM} \)

Some of the theoretical uncertainties cancel in the ratio:

- \( \frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \times \xi^2 \times \frac{|V_{ts}|^2}{|V_{td}|^2} \)
- \( \xi = 1.268 \pm 0.063 \) Lattice QCD, PDG2016 → [FNAL&MILC: arXiv:1205.7013]
  \( \Rightarrow 1.206 \pm 0.019 \) new calculation [FNAL&MILC: arXiv:1602.03560]
$B^0_{d/s} - \bar{B}^0_{d/s}$ oscillations: measurement of $\Delta m_{d/s}$

Best precision is achieved by measuring the time-dependent mixing asymmetry in \textit{flavour-specific} decays:

$$A_{\text{mix}}(t) = \frac{\Gamma_{\bar{B}^0_q \rightarrow \bar{f}(t)} - \Gamma_{B^0_q \rightarrow f(t)}}{\Gamma_{\bar{B}^0_q \rightarrow \bar{f}(t)} + \Gamma_{B^0_q \rightarrow f(t)}} \sim \cos(\Delta m_q t) \implies A_{\text{mix}}(t) \propto (1 - 2\omega) e^{-(\Delta m_q \sigma_t)^2/2} \cos(\Delta m_q t)$$

assuming no CPV in mixing and $\Delta \Gamma_q = 0$

The average statistical significance is:

$$S \sim \sqrt{\frac{N}{2}} f_{\text{sig}} \sqrt{\epsilon_{\text{tag}} (1 - 2\omega)^2} e^{-(\Delta m_q \sigma_t)^2/2}$$

Experimental key-factors fully addressed by LHCb:

- Signal yield and background suppression: $\sqrt{N/2} f_{\text{sig}}$
  - large $\sigma_{bb}$
  - $L^{\text{int}} = 3$ fb$^{-1}$ in Run1 (2 fb$^{-1}$ in Run2, so far)
  - efficient trigger and reconstruction
  - tracking: impact parameter, momentum, mass resolutions
  - particle identification: ($\mu/\pi/K/p$)

- Flavour tagging: $\sqrt{\epsilon_{\text{tag}} (1 - 2\omega)^2} = 3 - 6\%$
  - Opposite-side (OS $e, \mu, K$, Vertex, Charm)
  - Same-side (SS: $\pi$, $p$ and $K$)

- Decay time resolution: $e^{-(\Delta m_q \sigma_t)^2/2}$
  - excellent vertexing $\sigma_t \sim 45 - 55$ fs
$\Delta m_d$ was first measured at DESY by ARGUS [Phys.Lett. B192 (1987) 245-252] then at Cornell, LEP then at B-Factories.


Latest LHCb measurement exploits the full Run1 data sample (3 fb$^{-1}$) → most precise determination of $\Delta m_d$ [LHCb: Eur. Phys. J. C76 (2016) 412]

- Uses semileptonic $B_d^0 \rightarrow D(\ast)^- \mu^+ \nu_\mu X$ decays
  - large branching ratios ($B \sim 2-5\%$)
- Event reconstruction & selection:
  - reconstruct $D^{*-} \rightarrow \bar{D}^0 (\rightarrow K^+ \pi^-) \pi^-$ and $D^- \rightarrow K^+ \pi^- \pi^-$ decays
  - $D^{(\ast)^-} \mu^+$ from a common vertex (displaced from PV)
  - missing neutrino: cannot apply mass or kinematic cuts to the $B_d$, only to $D^0$, $D^{\ast^-}$ or $D^-$
  - vetoes on mis-ID $J/\psi$, $\Lambda_c$

Background:
- Combinatorial
- $D^0$ from $B$ decays
- $B^+ \rightarrow D^{(\ast)^-} \mu^+ \pi^+ \nu_\mu$

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$B^0_d - \bar{B}^0_d$ oscillations: Measurement of $\Delta m_d$ at LHCb

$B^+ \rightarrow D(*)^- \mu^+ \pi^+ \nu_\mu$ background:
- it is expected to be 10% and 13%, BUT its $B$ is known with a precision of 10% [PDG2016]
- its fraction is correlated with the fit value of $\Delta m_d$

→ need to suppress it to reduce the systematic uncertainty

MVA classifier was developed to discriminate such background from the signal:
- inputs:
  - geometrical and kinematical info on the $B$ candidate ($D(*)^- \mu^+$)
  - isolation info on additional tracks reconstructed in a cone around the $B$ candidate direction
- training:
  - on MC samples of signal $B^0 \rightarrow D^*- \mu^+ \nu_\mu$ and $B^+ \rightarrow D^*^- \mu^+ \pi^+ \nu_\mu$
- output (BDT):
  - used both as selection cut (suppression of 70%) and to evaluate on data the remaining fraction ($\rightarrow 3\%$ and $6\%$)
$B_d^0 - \bar{B}_d^0$ oscillations: Measurement of $\Delta m_d$ at LHCb

Event reconstruction suffers from the missing neutrino:

- $B_d$ momenta & decay time are corrected by a $k$-factor determined on MC:

\[
t = \frac{M_{B^0} \cdot L}{p_{D(*)\mu} \cdot c / k(m_B)} \quad \text{with} \quad k(m_B) = \langle p_{D(*)\mu} / p_{B^0}^{\text{true}} \rangle
\]

→ limited time resolution

Flavour Tagging:

- determine $q_{\text{mix}}$ from the tagging decision & the charge of the $\mu$ ($q_{\text{mix}} = \pm 1$)
- Split in four categories of increasing mistag $\omega$ to gain sensitivity
- Tagging power: $\varepsilon D^2 \sim 2.3$-2.6%
$B^0_d - \bar{B}^0_d$ oscillations: Measurement of $\Delta m_d$ at LHCb

Fit strategy:

- fit the $m_{D^-}/m_{D^0} & \delta m = m_{D^*} - m_{D^0}$ distributions: disentangle Signal + $B^+_s$ (sWeights) from other backgrounds (combinatorial + $B^0$ from $B$)
- perform an sFit to the weighted distribution of the decay time:
  \[ \mathcal{P}(t, q_{\text{mix}}) = (1 - f_{B^+}) S(t, q_{\text{mix}}) + f_{B^+} \beta^+(t, q_{\text{mix}}) \]
  \[ S(t, q_{\text{mix}}) \propto a(t) \left[ e^{-t/\tau} (1 + q_{\text{mix}})(1 - 2\omega) \cos(\Delta m_d t) \right] \otimes R(L) \otimes F(k) \]
- time acceptance $a(t)$, $f_{B^+}$ and $\omega$ extracted from fit to data
- convolution with resolution functions from MC $R(L), F(k)$

Assumptions: $\Delta \Gamma_d = 0$, $|q/p| = 1$

<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>$B_d^0 \to D^- \mu^+ \nu_\mu X$</td>
<td>506.2 ± 5.1</td>
<td>505.2 ± 3.1</td>
<td>505.5 ± 2.7 ± 1.1</td>
</tr>
<tr>
<td>$B_d^0 \to D^{*-} \mu^+ \nu_\mu X$</td>
<td>497.5 ± 6.1</td>
<td>508.3 ± 4.0</td>
<td>504.4 ± 3.4 ± 1.0</td>
</tr>
</tbody>
</table>


**Systematic uncertainties:**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$D^- \mu^+ \nu_\mu$ [ns$^{-1}$]</th>
<th>$D^{*-} \mu^+ \nu_\mu$ [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>0.4 –</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>0.5 0.4</td>
<td>0.3 0.5</td>
</tr>
<tr>
<td>Total</td>
<td>0.8 0.8</td>
<td>0.6 0.8</td>
</tr>
</tbody>
</table>

Most precise measurement, dominates the average.
$B_s^0 - \bar{B}_s^0$ oscillations: Measurement of $\Delta m_s$ at LHCb

$\Delta m_s$ was first measured by CDF in 2006: $\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}$ [CDF: Phys.Rev.Lett. 97 (2006) 242003]

Previous LHCb measurements used partial Run1 data samples of “flavour specific” $B_s^0 \rightarrow D_s^- (3) \pi^+$ decays [LHCb: Phys. Lett. B709 (2012) 177], and semileptonic $B_s^0$ decays [LHCb: Eur. Phys. J. C73 (2013) 2655]

The most precise LHCb measurement exploits 1 fb$^{-1}$ of Run1 data sample [LHCb: New J. Phys. 15 (2013) 053021]

- Uses $B_s^0 \rightarrow D_s^- \pi^+$ decays $\sim 34000$ signal events
  - hadronic flavour specific decay with the largest $B$ ($\sim 0.3\%$)
- Event selection: reconstruct $D_s^-$ in 5 fully reconstructed decay modes: $\phi \pi$, $K^* K$, $(KK\pi)_{nonres}$, $K\pi\pi$ and $3\pi$
  - MVA selection for an optimal discrimination of signal from background
Fit strategy:

- perform a simultaneous fit of the 5 data samples of all contributions
  \[ \mathcal{P}(m, t, \sigma_t, q, \eta) = \mathcal{P}_m(m) \mathcal{P}_{t,q}(t, q|\sigma_t, \eta) \mathcal{P}_{\sigma_t}(\sigma_t) \mathcal{P}_\eta(\eta) \]
  \[ \mathcal{P} = f_{\text{sig}} S + \sum_i f_{\text{bkg}}^i B_i \]
- \( \mathcal{P}_m(m) \) mainly discriminate signal from background contributions
- \( \mathcal{P}_{t,q}(t, q|\sigma_t, \eta) \):
  - Use per-event decay time resolution model \( \langle \sigma_t \rangle \sim 44 \text{ fs} \) \( (\mathcal{P}_{\sigma_t}(\sigma_t)) \), calibrated on data using prompt \( D_s \& \pi \)
  - Use per-event OS and SSK combined tagging decision and mistag: \( \varepsilon D^2 = 3.5\pm0.5\% \) \( (\mathcal{P}_\eta(\eta)) \)

Result: \[ \Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1} \]

Most precise measurement to date.

More recently LHCb determined \( \Delta m_s \) also in the analysis of \( B_s^0 \rightarrow J/\psi K^+ K^- \) for \( \phi_s \) and \( \Delta \Gamma_s \) measurements: \[ \Delta m_s = 17.711^{+0.055}_{-0.057} \pm 0.011 \text{ ps}^{-1} \]
(see also G.Cowan’s Talk)
$B^0_q - \bar{B}^0_q$ oscillations: Measurement of $\Delta \Gamma_q$

The decay rates of $B_L$ and $B_H$ to a given final state $f$ can be different, therefore:

$$\Gamma(B^0_q(t) \rightarrow f) \propto e^{-\Gamma_q t} \left[ \cosh(\Delta \Gamma_q t/2) + A^f_{\Delta \Gamma} \sinh(\Delta \Gamma_q t/2) + A^{dir,f}_{\text{CP}} \cos(\Delta m_q t) + A^{mix,f}_{\text{CP}} \sin(\Delta m_q t) \right]$$

$$\Gamma(\bar{B}^0_q(t) \rightarrow f) \propto e^{-\Gamma_q t} \left[ \cosh(\Delta \Gamma_q t/2) + A^f_{\Delta \Gamma} \sinh(\Delta \Gamma_q t/2) - A^{dir,f}_{\text{CP}} \cos(\Delta m_q t) - A^{mix,f}_{\text{CP}} \sin(\Delta m_q t) \right]$$

assuming $|q/p| = 1$

The untagged rate: $\Gamma(B^0_q(t) \rightarrow f) \propto e^{-\Gamma_q t} \left[ \cosh(\Delta \Gamma_q t/2) + A^f_{\Delta \Gamma} \sinh(\Delta \Gamma_q t/2) \right]$

assuming production asymmetry $A_P = 0$

The effective lifetime $\tau^{\text{eff}}_{B^0_q \rightarrow f}$ depends on $y_q = 2 \Delta \Gamma_q \cdot \Gamma_q$:

$$\tau^{\text{eff}}_{B^0_q \rightarrow f} = \frac{1}{\Gamma_q} \frac{1}{1 - y_q^2} \left[ \frac{1 + 2 A^f_{\Delta \Gamma} y_q + y_q^2}{1 + A^f_{\Delta \Gamma} y_q} \right]$$

$\Delta \Gamma_q$ can be measured by comparing $\tau^{\text{eff}}_{B^0_q \rightarrow f}$ in different decay channels (different $A^f_{\Delta \Gamma}$)


- $A^f_{\Delta \Gamma} = 0$ for flavour specific decays
- $A^f_{\Delta \Gamma} = \cos 2\beta$ for $B_d \rightarrow J/\psi K^0_S$
\(B_d^0 - \bar{B}_d^0\) oscillations: Measurement of \(\Delta \Gamma_d\) at LHCb

- **Strategy:** measure effective lifetime \(\tau_{B_d^0}^{\text{eff}}\) using
  - \(B_d^0 \to J/\psi K^0\) (flavour specific)
  - \(B_d^0 \to J/\psi K_s^0\) (CP eigenstate)

- **Selection:**
  - Run1 data sample (1 fb\(^{-1}\))
  - minimize any decay time biasing selection cuts

- **Fit strategy:**
  - fit the distributions of **time** and invariant mass:
    \[ \mathcal{P}(m, t) = f_{\text{sig}} S(m, t) + \sum_i f_{\text{bkg}}^i B_i(m, t) \]
  - time resolution \(\sigma_t \sim 45, 65\) fs

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Effective lifetime results:
\[ \tau_{\text{eff}}^{B_d^0 \rightarrow J/\psi K^0} = 1.524 \pm 0.006 \pm 0.004 \text{ ps} \]
\[ \tau_{\text{eff}}^{B_d^0 \rightarrow J/\psi K^0_s} = 1.499 \pm 0.013 \pm 0.005 \text{ ps} \]

\[ \tau_{\text{eff}}^{B_d^0 \rightarrow f} = \frac{1}{\Gamma_f} \frac{1}{1 - y_q^2} \left[ \frac{1 + 2A_{\Delta \Gamma}^f y_q + y_q^2}{1 + A_{\Delta \Gamma}^f y_q} \right] \]

- \( A_{\Delta \Gamma}^f = 0 \) for flavour specific decays
- \( A_{\Delta \Gamma}^f = \cos 2\beta \) for \( B_d \rightarrow J/\psi K^0_s \)

we measure:
\[ \Gamma_d = 0.656 \pm 0.003 \pm 0.002 \text{ ps}^{-1} \]
\[ \Delta \Gamma_d = -0.029 \pm 0.016 \pm 0.007 \text{ ps}^{-1} \]

\[ \Delta \Gamma_d / \Gamma_d = (-4.4 \pm 2.5 \pm 1.1) \times 10^{-2} \]
From the measurements to the SM-CKM picture

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_d$ [ps$^{-1}$]</td>
<td>$0.5050 \pm 0.0021 \pm 0.0010$</td>
<td>[LHCb: Eur. Phys. J. C76 (2016) 412]</td>
</tr>
<tr>
<td></td>
<td>$0.5064 \pm 0.0019$</td>
<td>[HFAG Summer 2016]</td>
</tr>
<tr>
<td>$\Delta m_s$ [ps$^{-1}$]</td>
<td>$17.768 \pm 0.023 \pm 0.000$</td>
<td>[LHCb: New J. Phys. 15 (2013) 053021]</td>
</tr>
<tr>
<td></td>
<td>$17.757 \pm 0.021$</td>
<td>[HFAG Summer 2016]</td>
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<td>$\Delta \Gamma_d/\Gamma_d$</td>
<td>$(-4.4 \pm 2.5 \pm 1.1) \times 10^{-2}$</td>
<td>[LHCb: JHEP 04 (2014) 114]</td>
</tr>
<tr>
<td></td>
<td>$(-0.1 \pm 1.1 \pm 0.9) \times 10^{-2}$</td>
<td>[ATLAS:JHEP06 (2016) 081]</td>
</tr>
<tr>
<td></td>
<td>$(-0.2 \pm 1.0) \times 10^{-2}$</td>
<td>[HFAG Summer 2016]</td>
</tr>
</tbody>
</table>

Within SM, such measurements constrain

$$\frac{|V_{ts}|^2}{|V_{td}|^2} = 0.2159 \pm 0.0004 (\text{exp}) \pm 0.0107 (\text{lattice}) \text{ [PDG2016]}$$

With the latest, improved LatticeQCD calculations

$$\frac{|V_{ts}|^2}{|V_{td}|^2} = 0.2052 \pm 0.0032 \text{ [FNAL&MILC: arXiv:1602.03560]}$$

a tension ($O(2\sigma)$) arises when comparing $|V_{ts}|, |V_{td}|$ results from mixing measurement with results from tree-processes
From the measurements to possible hints of NP?

Current measurements are compatible with SM in $1.5\sigma$.
From the measurements to possible hints of NP?

Future improvements can reveal NP.
LHCb measurements of $\Delta m_d$ and $\Delta m_s$ have reached a precision of $\%$, and dominate the current World Averages.

Together with the measurement of $\Delta \Gamma_d$ and $\Delta \Gamma_s$, they provide useful constraints to the CKM parameters $|V_{ts}|$ and $|V_{td}|$ and important tests of the SM.

The precision of $|V_{ts}|$ and $|V_{td}|$ is currently limited by theoretical uncertainties.

Latest Lattice QCD calculations allowed a factor $\sim 3$ of improvement in $|V_{ts}|^2/|V_{td}|^2$ with respect to previous calculations that renewed the interest on $B^0_q - \bar{B}^0_q$ mixing parameters.

Looking forward for further improvements on theoretical computations and on experimental measurements (for prospects at LHCb see talk by V. Chobanova)
Flavour Tagging: identifying the initial $B$ flavour

**OS tagging**: exploits the properties of the decays of the $b$-hadron opposite to the signal $B$  
  \[ \mu, \ e \ (b \to c l^- \bar{\nu}_l), \ K \ (b \to c \to s), \ Q_{vtx} \ \text{(inclusive secondary vertex reconstruction)} \]

**SS tagging**: exploits the hadronization process of the signal $B$, or in the decays of excited states $B^{**}$
  
  - $SS\pi, \ SSp$  \[ \text{[LHCb: LHCb-PAPER-2016-039, arXiv:1610.06019]} \ \text{(tag the } B_d \text{ ) (see also M.Calvi’s Talk)}, \]
  - $SSK$  \[ \text{[LHCb: JINST 11 (2016) P05010]} \ \text{(tag the } B_s \text{ )} \]

  tagging power: $\varepsilon(1 - 2\omega)^2 \sim 3 - 6\%$ depending on the $B$ decay channel