Time-dependent measurement of CP violation in $B^0 \to D^- \pi^+$ decays at LHCb

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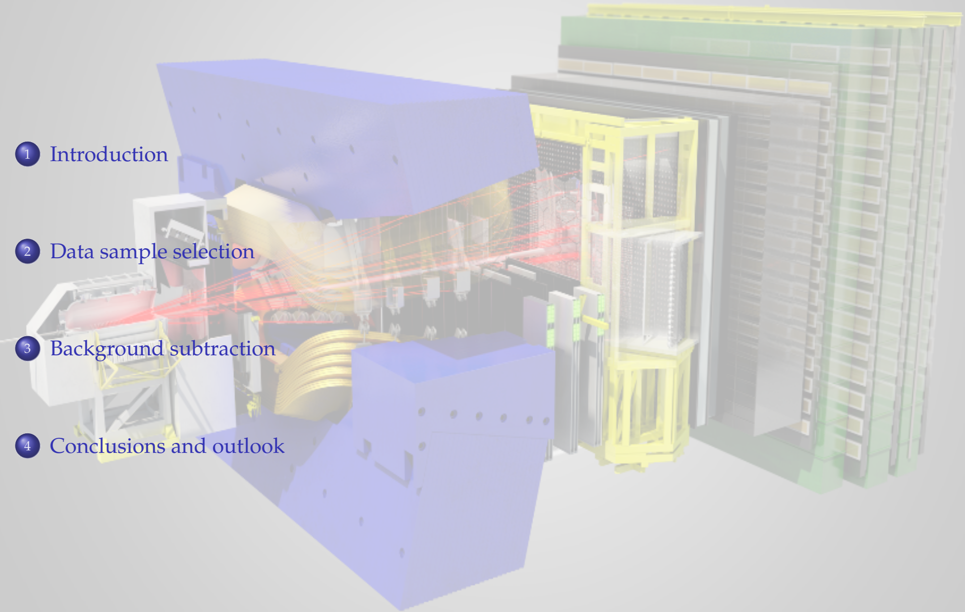
Outline



1. Introduction
2. Data sample selection
3. Background subtraction
4. Conclusions and outlook

Introduction

CP violation: *complex phase* in the *Cabibbo-Kobayashi-Maskawa* (CKM) matrix (*charged-current* weak interactions).

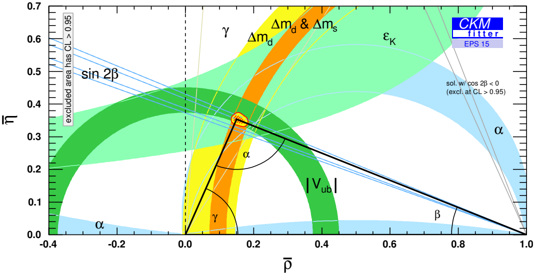
$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \begin{pmatrix}\bar{u} & \bar{c} & \bar{t}\end{pmatrix} V_{\text{CKM}} \gamma^{\mu} \frac{(1-\gamma^5)}{2} \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_{\mu}^{+} + h.c..$$

Why do we measure CPV?

- SM alone can't explain observed *matter-antimatter* asymmetry → new physics must be there.

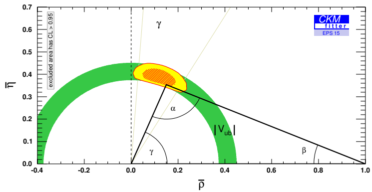
V_{CKM} unitarity conditions: *Unitarity Triangle* (UT).

CP-violation enhanced in *b*-physics (sides of UT of same order of magnitude).

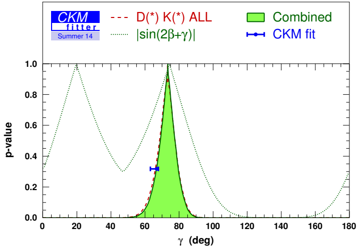


$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

Direct measurements of CKM angle γ



Constraints from $B \to DK$ measurements.



Constraint from $B \to D^{(*)}\pi/\rho$ time-dependent measurements using β as external input.

Least known CKM angle.

Central value:

- Global CKM fit: $(67.01^{+0.88}_{-1.99})^\circ$
- Direct measurement: $(73.2^{+6.3}_{-7.0})^\circ$

Direct measurements driven by $B \to DK$ decays (*higher sensitivity*).

Crucial to improve γ precision from time-dependent measurements.

- Today: $\sin(2\beta + \gamma)$ at LHCb from $B^0 \to D^-\pi^+$.
- Previous measurements of $\sin(2\beta + \gamma)$ at *B factories* from $B \to D^{(*)}\pi/\rho$.

No single γ measurement has enough sensitivity $\to$ need to combine results from complementary approaches.

CPV: interference between amplitudes *with* and *without* oscillation.
Clean measurement, free from hadronic uncertainties.
CP coefficients from fit to B^0 decay rate distribution:

$$S_{D^-\pi^+} = \frac{2r\sin[\delta-(\gamma+2\beta)]}{1+r^2},$$

$$S_{D^+\pi^-} = \frac{2r\sin[\delta+(\gamma+2\beta)]}{1+r^2}.$$

r parameter:

- ratio of *Cabibbo suppressed* and *favoured* amplitudes;

$$r = \left|A(\bar{B}^0 \to D^-\pi^+)/A(B^0 \to D^-\pi^+)\right|.$$

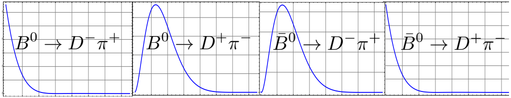
- BaBar [arXiv:0803.4296], Belle [arXiv:1007.4619]: $r \approx 1.7\%$.

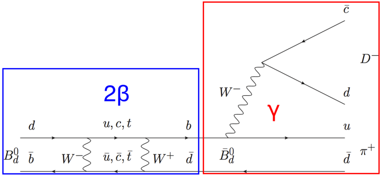
Sensitivity:

- *reduced* by low r;
- *increased* by high LHCb statistics ($\sim$ 500 k signal events in 3 fb^{-1}).

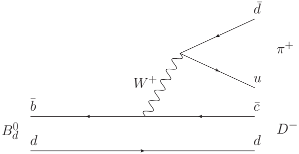
$$\frac{d\Gamma(B^0 \to D^\mp\pi^\pm)}{dt} \propto e^{-t/\tau}\,[\mp S_{D^\mp\pi^\pm}\sin(\Delta m t) + \ldots$$

$$\frac{d\Gamma(\bar{B}^0 \to D^\mp\pi^\pm)}{dt} \propto e^{-t/\tau}\,[\pm S_{D^\mp\pi^\pm}\sin(\Delta m t) + \ldots$$





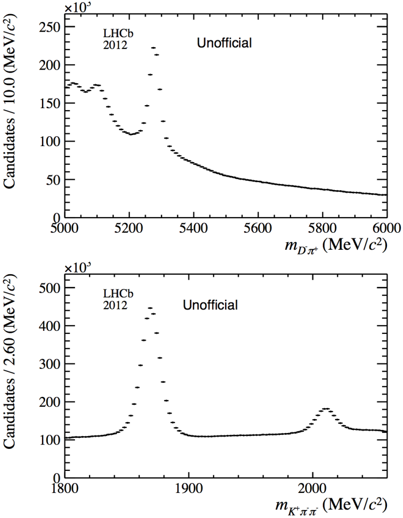
Oscillation + $b \to u$ amplitude.



$b \to c$ amplitude.

Data sample selection

Preselection



B^0 and D^- invariant mass after preliminary selection.

Data: 3 fb^{-1} collected in 2011-2012.

Preliminary selection:

- three charged particles forming a common vertex (D^- meson).
- B^0 candidate formed by adding additional charged tracks ("bachelor").
- *topological* and *kinematical* criteria on all charged tracks.

Pion-kaon discrimination ($\text{PID}_{K\pi}$ observable) from Cherenkov detectors (RICH) data.

Requirements for D daughters:

- $\text{PID}_{K\pi} < 8$ for pions.
- $\text{PID}_{K\pi} > -2$ for kaons.

Essential to control **physical backgrounds** to have clean *CP* measurements.

$\boldsymbol{\Lambda_b^0 \rightarrow \Lambda_c^- (\rightarrow K^+ \pi^- \bar{p}) \pi^+}$
$\boldsymbol{B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+}$
Proton misidentified as pion.
Exclude candidates in 20 MeV around Λ_c mass.

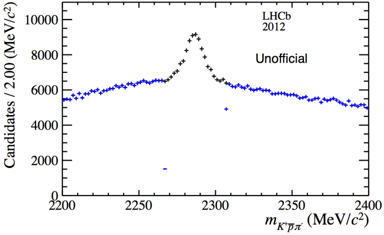
$\boldsymbol{B_s^0 \rightarrow D_s^- (\rightarrow K^+ K^- \pi^-) \pi^+}$
$\boldsymbol{B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+}$
Check $K^+ K^- \pi^-$ mass in:

- B_s^0 signal range: $5300 < m_{B^0} < 5400$ MeV
- B_s^0 sideband: $5400 < m_{B^0} < 5500$ MeV

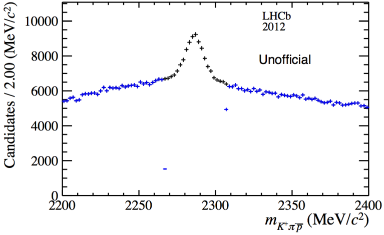
$\rightarrow$ no veto needed.

$\boldsymbol{B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \mu^- \bar{\nu}}$
$\boldsymbol{B^0 \rightarrow D^- (\rightarrow K^+ \pi^- \pi^-) \pi^+}$
Bachelors need to fail μ identification criteria.

$\boldsymbol{B^0 \rightarrow D^- K^{(*)+}}$
$\boldsymbol{B^0 \rightarrow D^- \rho^+}$
$\boldsymbol{B^0 \rightarrow D^{*-} \pi^+}$
Parameterised directly in the fit to B^0 invariant mass.



Λ_c^- invariant mass (first π misid as proton).



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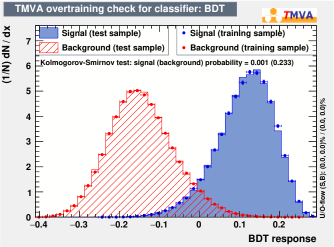
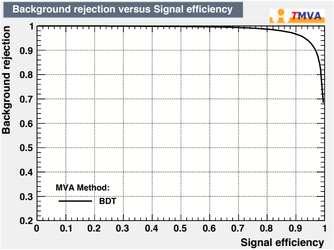


BDT output.



Background rejection vs signal efficiency.

BDT trained to discriminate signal against combinatorial background.

- Signal: simulation.
- Combinatorial: upper B^0 mass "sideband" in 2012 data ($m_{B^0} > 5500$ MeV).

16 input features containing vertices/tracks quality, topology and kinematics.

Cut point BDT > 0 from pseudo-experiments:

- Minimise statistical uncertainty on *CP* coefficients.
- Maximise background rejection.

Background subtraction

Fit to B^0 invariant mass distribution (1)

Two samples defined (PID cut on bachelor):

- $\mathrm{PID}_{K\pi} \leqslant 5$ (pion sample).
- $\mathrm{PID}_{K\pi} > 5$ (kaon sample).

Simultaneous maximum likelihood fit to B^0 invariant mass distribution in both samples:

- Select signal over background.
- Compute *sWeights* for *sPlot* technique [arXiv:physics/0402803].

Control amount of "peaking" $B^0 \to D^- K^+$ background:

$$N^K_{B^0 \to D\pi} = \frac{1 - \epsilon_{\mathrm{PID}}(B^0 \to D\pi)_\pi}{\epsilon_{\mathrm{PID}}(B^0 \to D\pi)_\pi} \times N^\pi_{B^0 \to D\pi}$$

$$N^\pi_{B^0 \to DK} = \frac{1 - \epsilon_{\mathrm{PID}}(B^0 \to DK)_K}{\epsilon_{\mathrm{PID}}(B^0 \to DK)_K} \times N^K_{B^0 \to DK}$$

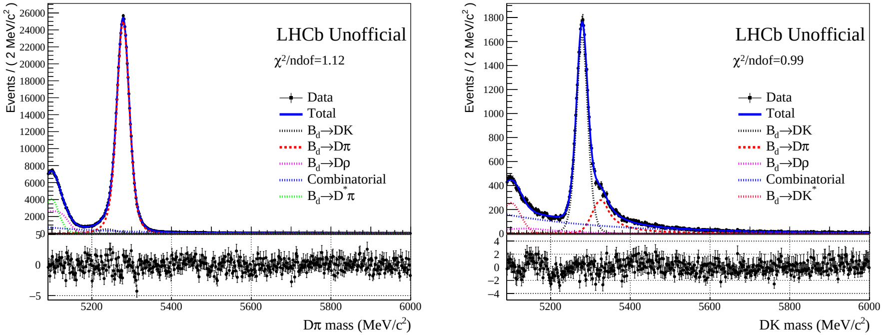
Efficiency after preselection + BDT (from simulation).

Sample	Efficiency [%]
$B^0 \to D^-\pi^+$	2.329 ± 0.007
$B^0 \to D^-K^+$	2.169 ± 0.015
$B^0 \to D^-\rho^+$	0.1429 ± 0.0026
$B^0 \to D^{*-}\pi^+$	0.867 ± 0.007
$B^0_s \to D_s^-\pi^+$	0.2230 ± 0.0021
$\Lambda_b^0 \to \Lambda_c^-\pi^+$	0.0139 ± 0.0008
$B^0 \to D^-K^{*+}$	0.0419 ± 0.0020

PID efficiencies (from simulation calibrated on data).

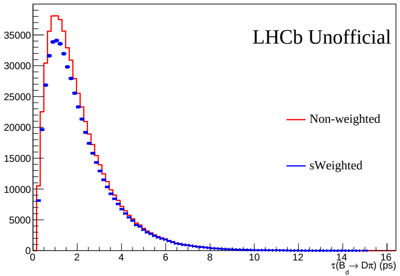
Sample	PIDK cut	ϵ_{PID}
$B^0 \to D\pi$	< 5.0 (π sample)	0.979 ± 0.004
$B^0 \to DK$	> 5.0 (K sample)	0.636 ± 0.007

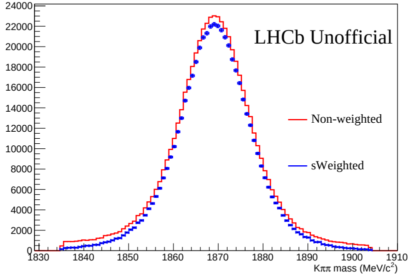
Fit to B^0 invariant mass distribution (2)



Found $\sim$ **570 *k*** signal events in the pion sample (left plot).

Non-weighted and *sWeighted* B^0 decay time and D^- invariant mass distributions on data.





Dominant background from true D^- + "random" track → D^- mass distribution very clean even before *sWeighting*.

Preliminary sensitivity studies on *CP* coefficients

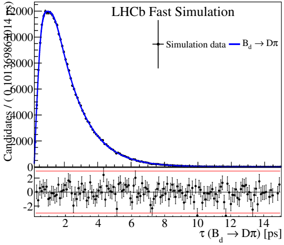
Pseudo-experiments simulated to estimate sensitivity on $S_{D^-\pi^+}$, $S_{D^+\pi^-}$.

$$\frac{d\Gamma(B^0 \to D^\mp \pi^\pm)}{dt} \propto e^{-t/\tau}[\mp S_{D^\mp\pi^\pm} \sin(\Delta m t) + \dots$$
$$\frac{d\Gamma(\bar{B}^0 \to D^\mp \pi^\pm)}{dt} \propto e^{-t/\tau}[\pm S_{D^\mp\pi^\pm} \sin(\Delta m t) + \dots$$

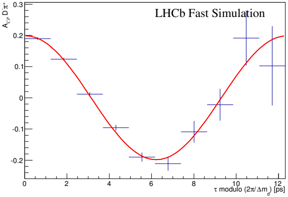
All experimental effects taken into account:

- Time-dependent efficiency (*acceptance*).
- Finite *time resolution*.
- *Production* and *detection* asymmetries.
- *Flavour Tagging* algorithms to identify initial B flavour.
  - See my poster on Flavour Tagging for more details!

Generation values (from expectations):
$S_{D^-\pi^+} = 0.031$, $S_{D^+\pi^-} = -0.028$.
Average statistical uncertainty:
$\sigma(S_{D^-\pi^+}) = \sigma(S_{D^+\pi^-}) = 0.013$.



Decay time distribution.



$B^0 - \bar{B}^0$ asymmetry for $D^-\pi^+$ final state.

Conclusions and outlook

(Over)constraining the CKM triangle is crucial to look for new physics.

Time-dependent measurements of poorly known γ angle ongoing at LHCb:

- $B^0 \to D^- \pi^+$ presented here.
- $B_s^0 \to D_s^- K^+$ "in parallel":
  - similar approach as $B^0 \to D^- \pi^+$, but less statistics and more sensitivity due to higher r parameter.

Signal selection and strategy streamlined.

- Fit to B^0 decay time for CP coefficient measurement will come soon!

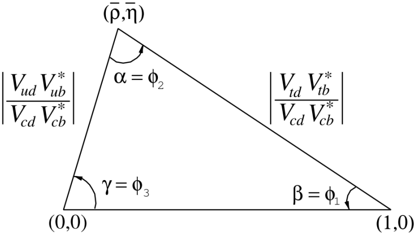
Sensitivity on γ will come from combination with other time-dependent measurements of $\sin(2\beta + \gamma)$:

- Now (Run I data): establish the analysis.
- Then (RunI+Run II data): exploit full dataset to improve measurement.

Thank you

Backup

The CKM triangle



$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Previous measurements of S coefficients at B factories

Main references:

B. Aubert *et al.*, BaBar Collaboration, "Measurement of time-dependent CP-asymmetries in $B^0 \to D^{(*)\pm}\pi^{\mp}$ and $B^0 \to D^{\pm}\pi^{\mp}$ decays", PRD 73, (2006), 111101 [arXiv:hep-ex/0602049].

F. J. Ronga *et al.*, Belle Collaboration, "Measurement of CP violation in $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^-\pi^+$ decays", PRD 73, (2006), 092003 [arXiv:hep-ex/0604013].

PDG averages: $S_{D^-\pi^+} = -0.068 \pm 0.031$, $S_{D^+\pi^-} = -0.024 \pm 0.031$.

From the average, an estimate of the *strong phase* δ can be made: $\delta = 2.28^{+0.91}_{-0.43}$.

A theoretical estimate (from [arXiv:0705.1575]) exists: $\delta = 0.07$.
This value has been used in $B^0 \to D^-\pi^+$ LHCb simulation. The *sensitivity* of $S_{D^-\pi^+}$ and $S_{D^+\pi^-}$ is a *weak function* of δ.

Theoretical estimate of the r ratio

- The $B^0 \to D^{\pm}\pi^{\mp}$ and $B^0 \to D_s^{\pm}\pi^{\mp}$ are related by SU(3) symmetry.
- Up to SU(3) breaking effects, the following equality holds:

$$r = \tan\theta_c \frac{f_D}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)}}.$$

- Using inputs from branching ratio measurements and lattice QCD calculations, an estimation is:

$$r = 0.021 \pm 0.004 \pm 0.006, \qquad (1)$$

where the last uncertainty accounts for SU(3) breaking effects.

Quantum mechanics of $B^0 \to D^{\pm}\pi^{\mp}$ decays (1)

- The time evolution of $|\psi(t)\rangle$, initially built as $|\psi(0)\rangle = a(0)\,|B^0\rangle + b(0)\,|\bar{B}^0\rangle$, can be described by a 2×2 complex Hamiltonian H:

$$H = M - \frac{i}{2}\Gamma,$$

where the two Hermitian matrices M and Γ are the *mass* and the *decay* matrix respectively.

- If CPT invariance holds, the *eigenstates* $|B_L\rangle$ (*low mass*) and $|B_H\rangle$ (*high mass*) of H can be written as:

$$|B_L\rangle = p\,|B^0\rangle + q\,|\bar{B}^0\rangle, \qquad |B_H\rangle = p\,|B^0\rangle - q\,|\bar{B}^0\rangle, \qquad |p|^2 + |q|^2 = 1.$$

- For B^0 ($\bar{B}^0$) mesons, $\left|\frac{p}{q}\right| = 1$ is a good approximation (no CP violation *in mixing*).
- The following quantities can be also defined:

$$\Delta m_d = m_H - m_L \qquad \Delta\Gamma_d = \Gamma_L - \Gamma_H, \qquad \tau = \left(\frac{\Gamma_L + \Gamma_H}{2}\right)^{-1}.$$

- Current measurements: $\Delta m_d = 0.510 \pm 0.003\ \mathrm{ps}^{-1}$, $\tau = 1.519 \pm 0.005$ ps , $\Delta\Gamma_d$ compatible with zero.

Quantum mechanics of $B^0 \to D^\pm\pi^\mp$ decays (2)

- Amplitudes:

$$A_f = \langle f|T|B^0\rangle, \qquad \bar{A}_f = \langle f|T|\bar{B}^0\rangle,$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = re^{i(\Delta-2\beta-\gamma)}, \qquad \bar{\lambda}_{\bar{f}} = \frac{p}{q}\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}} = re^{i(\Delta+2\beta+\gamma)},$$

- CP coefficients:

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad S_f = \frac{2Im(\lambda_f)}{1+|\lambda_f|^2}, \qquad D_f = \frac{2Re(\lambda_f)}{1+|\lambda_f|^2},$$

$$C_{\bar{f}} = \frac{1-|\bar{\lambda}_{\bar{f}}|^2}{1+|\bar{\lambda}_{\bar{f}}|^2}, \qquad S_{\bar{f}} = \frac{2Im(\bar{\lambda}_{\bar{f}})}{1+|\bar{\lambda}_{\bar{f}}|^2}, \qquad D_{\bar{f}} = \frac{2Re(\bar{\lambda}_{\bar{f}})}{1+|\bar{\lambda}_{\bar{f}}|^2}.$$

- In the B^0 meson system, $|q/p| = 1$.
- CPT invariance: $|\bar{A}_f| = |A_{\bar{f}}|$, $|\bar{A}_{\bar{f}}| = |A_f|$, thus $|\lambda_f| = |\bar{\lambda}_{\bar{f}}| = r$.

$B_d \to D\pi$ decay time distribution

Decay rates:

$$\frac{d\Gamma(B^0 \to f)}{dt}(t) \propto e^{-t/\tau}\left[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) + C\cos(\Delta m_d t) - S_f \sin(\Delta m_d t)\right],$$

$$\frac{d\Gamma(\bar{B}^0 \to f)}{dt}(t) \propto e^{-t/\tau}\left[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) - C\cos(\Delta m_d t) + S_f \sin(\Delta m_d t)\right],$$

$$\frac{d\Gamma(B^0 \to \bar{f})}{dt}(t) \propto e^{-t/\tau}\left[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) - C\cos(\Delta m_d t) + S_{\bar{f}} \sin(\Delta m_d t)\right],$$

$$\frac{d\Gamma(\bar{B}^0 \to \bar{f})}{dt}(t) \propto e^{-t/\tau}\left[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) + C\cos(\Delta m_d t) - S_{\bar{f}} \sin(\Delta m_d t)\right].$$

CP coefficiencts:

$$S_f = \frac{2r\sin[\Delta - (\gamma + 2\beta)]}{1 + r^2} \approx -0.031, \qquad S_{\bar{f}} = \frac{2r\sin[\Delta + (\gamma + 2\beta)]}{1 + r^2} \approx 0.029,$$

$$D_f = \frac{2r\cos[\Delta - (\gamma + 2\beta)]}{1 + r^2} \approx -0.01, \qquad D_{\bar{f}} = \frac{2r\cos[\Delta + (\gamma + 2\beta)]}{1 + r^2} \approx -0.015,$$

$$C = \frac{1 - r^2}{1 + r^2} \approx 1,$$

Slow oscillations ($\Delta m_d = 0.51\ \mathrm{ps}^{-1}$), low sensitivity to CP even terms ($\Delta\Gamma_d \approx 0$).