Review of measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency Δm_s in $B_S^0 \to D_s^-(3)\pi$ decays with the LHCb detector

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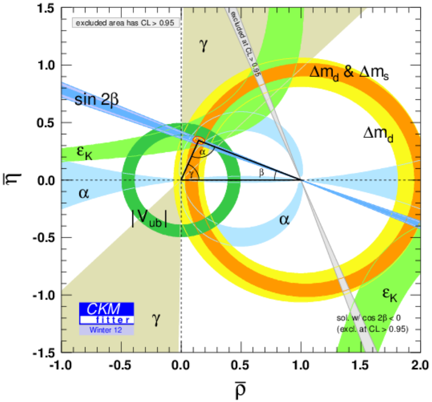
Introduction

1. The first observation of the $B^0 - \overline{B}^0$ mixing - 1987.
2. $\boldsymbol{\Delta m(B_s^0 - \overline{B}_s^0) = 35\Delta m(B^0 - \overline{B}^0)}$
   Present experimental accuracy (time resolution of the detectors) allows to measure the $\boldsymbol{B_s^0 - \overline{B}_s^0}$ oscillation frequency.
3. Measurement of $B_s^0 - \bar{B}_s^0$ oscillation frequency (Δm_s) is a prerequiste for many physics analyses (study of the time-dependent CP asymmetry of $B_s^0 \to J/\psi\phi$)
4. $\frac{\Delta m_{B_d}}{\Delta m_{B_s}} = \frac{|V_{td}|^2}{|V_{ts}|^2} \times \frac{<\bar{B}_s|(\bar{b}_L\gamma^\mu s_L)^2|B_s>}{<\bar{B}_d|(\bar{b}_L\gamma^\mu d_L)^2|B_d>}$



hep-ex/1112.4311 - LHCb-PAPER-2011-010

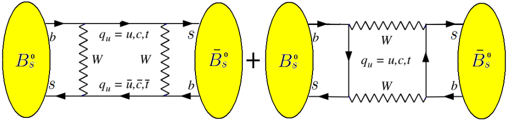
Time evolution of $B_s^0 - \overline{B}_s^0$ states

$$i\frac{d}{dt}\begin{pmatrix} |\, B_s^0 \,\rangle \\ |\, \overline{B}_s^0 \,\rangle \end{pmatrix} = \left[M - i\frac{\Gamma}{2}\right]\begin{pmatrix} |\, B_s^0 \,\rangle \\ |\, \overline{B}_s^0 \,\rangle \end{pmatrix} \Rightarrow \text{mass eigenstates} : \begin{array}{c} |\, B_L \,\rangle = p\,|\, B_s^0 \,\rangle + q\,|\, \overline{B}_s^0 \,\rangle \\ |\, B_H \,\rangle = p\,|\, B_s^0 \,\rangle - q\,|\, \overline{B}_s^0 \,\rangle \\ p^2 + q^2 = 1 \end{array}$$

One-loop contributions:

CPT symmetry $\Rightarrow$ $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$

$L^{eff}_{\Delta B=2} \Rightarrow$ M_{12} and M_{21}, Γ_{12} and Γ_{21}



$$|\, B_{L,H}(t) \,\rangle = e^{-(iM_{L,H} + \frac{\Gamma_{L,H}}{2})t}\,|\, B_{L,H}(0) \,\rangle \Rightarrow \begin{array}{c} m_s = \frac{M_H + M_L}{2},\ \Delta m_s = \frac{M_H - M_L}{2} \\ \Gamma_s = \frac{\Gamma_H + \Gamma_L}{2},\ \Delta\Gamma_s = \Gamma_H - \Gamma_L \end{array}$$

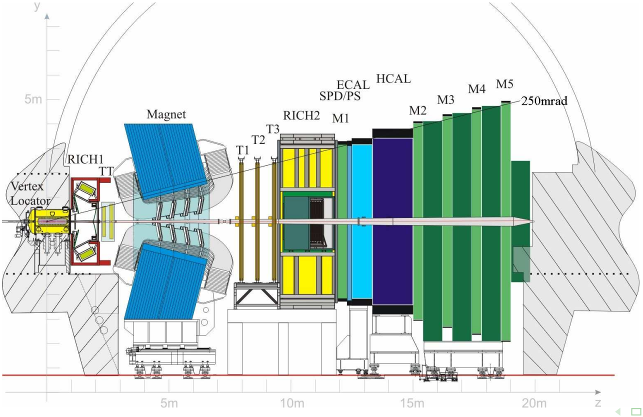
In this notation:

$$|\, B_s^0(t) \,\rangle = e^{-(im_s + \frac{\Gamma_s}{2})t}\left[f_+(t)\,|\, B_s^0(0)\rangle + \frac{q}{p} f_-(t)\,|\, \overline{B}_s^0(0) \,\rangle\right]$$
$$|\, \overline{B}_s^0(t) \,\rangle = e^{-(im_s + \frac{\Gamma_s}{2})t}\left[\frac{q}{p} f_-(t)\,|\, B_s^0(0)\rangle + f_+(t)\,|\, \overline{B}_s^0(0) \,\rangle\right]$$

$$f_+(t) = \cosh\left(\frac{\Delta\Gamma_s t}{2}\right)\cos(\Delta m_s t) - i\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\sin(\Delta m_s t)$$
$$f_-(t) = -\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\cos(\Delta m_s t) + i\cosh\left(\frac{\Delta_s\Gamma t}{2}\right)\sin(\Delta m_s t)$$

The LHCb detector

- One of the four big experiments on the LHC ring
- Dedicated flavour-physics experiment to search for new physics
- Specialties: Precision measurement of *B*-hadrons decays and CP violation



Description

- Forward pseudo rapidities (from 2 to 5)
- Vertex detector (VELO)
- tracking stations
- RICH:s for particle ID
- ECAL (with SPD and PS)
- HCAL
- Muon detector
- Dipole magnet

Analysis strategy

- Selection
- Flavour tagging
- 3 steps fitting procedure:
  1. Invariant mass distribution
  2. Decay time distribution
  3. Δm_S
- For each step an unbinned maximum likelihood fit is performed simultaneously across all decay modes.

$$\mathcal{L} = \prod_{i\ \text{event}} \left[f^{sig} \mathcal{P}_i^{sig} + (1 - f^{sig}) \mathcal{P}_i^{bkg} \right] \quad (1)$$

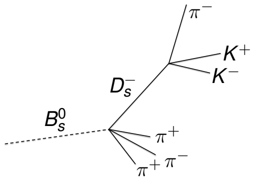
$$\text{where} \ \ \mathcal{P} = \mathcal{P}_m(m) \mathcal{P}_t^{\epsilon}(t, q | \sigma_t, \eta) \mathcal{P}_{\sigma_t}(\sigma_t) \mathcal{P}_\eta(\eta) \quad (2)$$

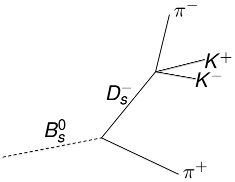
LHCb-CONF-2011-005

Event selection and background

Four decay modes

- $B_s^0 \to D_s^- \pi^+$
- $B_s^0 \to D_s^- \pi^+ \pi^- \pi^+$
  - $D_s^- \to K^+ K^- \pi^-$ (include K^{*0} ; ϕ)





Pre-selection

1. Hardware Trigger (hadronic calorimeter cluster, lower threshold)
2. Software Trigger (displaced vertex, two tracks with p_T threshold, inv. mass)

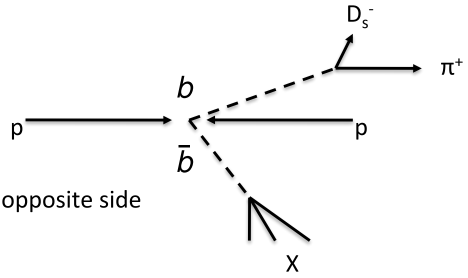
Event selection

1. Kinematic variable (impact parameter, momentum, distance between primary and secondary vertex)

Backgrounds

1. partial : partially reconstructed B_s^0
2. mis-id : B^0 and Λ_b mis-identified
3. comb : combinatorial

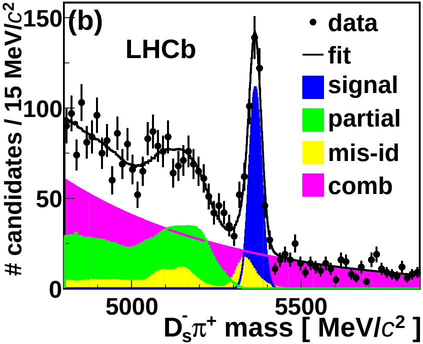
Opposite side flavour tagging



- Flavour of the B_s^0 candidate at production from opposite side b-hadron semileptonic decay (LHCb-CONF-2011-003 - LHCb-PAPER-2011-027)
- Fraction of events selected and correctly tagged:
  - $\epsilon_{eff} = \epsilon_s \times \frac{1}{\sum_i W_i} \sum_i (1 - 2\omega(\eta_i))^2 \times W_i = 3.8 \pm 2.1\%$
- ϵ_s: tagging efficiency
- W_i: signal efficiency for the i-th B_s^0 candidate
- ω: calibrated mistag probability
- η_i: mistag probability from neural network output

Fit to invariant mass distribution

$$\mathcal{P} = \mathcal{P}_m(m)\mathcal{P}_t^\epsilon(t, q|\sigma_t, \eta)\mathcal{P}_{\sigma_t}(\sigma_t)\mathcal{P}_\eta(\eta) \quad (3)$$



$\mathcal{P}_m^{sig}$: Gaussian(m, σ_m^α)
$\mathcal{P}_m^{comb}$: exponential
$\mathcal{P}_m^{b-decay}$: MC mass templates

Fit results

$m(B_s^0) = 5364.7 \pm 0.7$ MeV$/c^2$
$\sigma_m(D_s\pi) = 18.1$ MeV$/c^2$
$\sigma_m(D_s 3\pi) = 12.7$ MeV$/c^2$

Keep $m(B_s^0)$ and σ_m fixed, only use events in:

- $[m(B_s^0)] - 3\sigma_m, 5.85$ GeV$/c^2]$ for $D_s\pi$
- $[m(B_s^0)] - 3\sigma_m, 5.60$ GeV$/c^2]$ for $D_s 3\pi$

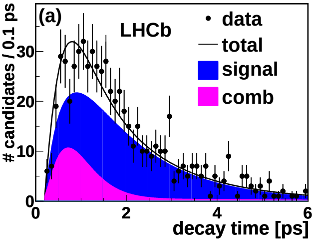
Decay mode	Signal yield
$B_s^0 \to D_s^- (\phi\pi^-)\pi^+$	515 ± 25
$B_s^0 \to D_s^- (K^{*0}K^-)\pi^+$	338 ± 27
$B_s^0 \to D_s^- (K^+K^-\pi^-)\pi^+$	283 ± 27
$B_s^0 \to D_s^- \pi^+\pi^-\pi^+$	245 ± 46
Total	1381 ± 65

Fit to decay time distribution

$$\mathcal{P} = \mathcal{P}_m(m)\mathcal{P}_t^{\epsilon}(t, q|\sigma_t, \eta)\mathcal{P}_{\sigma_t}(\sigma_t)\mathcal{P}_\eta(\eta) \quad (4)$$

$$\mathcal{P}_t^{sig}(t|\sigma_t) \propto \left[\Gamma_s e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s}{2} t\right) \theta(t)\right] \otimes G(t, S_{\sigma_t}\sigma_t)\epsilon(t) \quad (5)$$

$$\mathcal{P}_t^{comb}(t) \propto (t-a)^2 \left(fe^{-c_1 t} + (1-f)e^{-c_2 t}\right) \quad (6)$$



- For signal: Γ_s free parameter, $\Delta\Gamma_s = 0.09\Gamma_s$
- For b-decay background: Γ_s from PDG, $\Delta\Gamma_s = 0$
- $G(t, S_{\sigma_t}\sigma_t)$: decay time res. function (Gaussian)
  - σ_t: time resolution
  - S_{σ_t}: correction factor (detector misalignment)
- $\sigma_t = 44$ fs ($D_s\pi$) $\quad \sigma_t = 36$ fs ($D_s3\pi$)
- $\epsilon(t)$: acceptance function (trigger, offline selection)

$\Rightarrow$ Keep fixed Γ_s, a, f, c_1, c_2 from now on

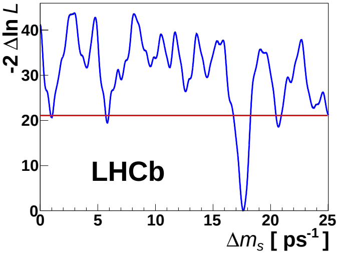
Δm_s - measurement

$$\mathcal{P}_t\left(t, q|\sigma_t, \eta\right) \propto \left(\Gamma_s e^{-\Gamma_s t}\frac{1}{2}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + q\left[1 - 2\omega(\eta)\right]\cos(\Delta m_s t)\right]\Theta(t)\right)$$
$$\otimes \quad G\left(t, S_{\sigma_t}, \sigma_t\right)\epsilon(t)\epsilon_s$$

- q = tag of the offsite charge: *(-1,1) = mixing ; 0 = integration of both initial states*

Fit yields

- $\mathbf{\Delta m_s = 17.63 \pm 0.11\ (stat) \pm 0.02\ (sys)\ ps^{-1}}$
- Significance 4.6 σ w.r.t. no oscillation scenario ($\Delta m_s = \infty$)
- Note: good agreement with CDF: $\Delta m_s = 17.77 \pm 0.10$ (stat) $\pm\, 0.07$ (sys) ps^{-1}



Source	Uncertainty [ps^{-1}]
Momentum scale	0.004
z scale	0.018
Comb. background mass shape	0.010
Decay time resolution	0.006
Total systematic uncertainty	0.022

Criticism

- Ambiguous phrasing of the word simultaneously
- What is fixed / what is floating for each of the 3 fits
- Likelihood definition not given
- Invariant mass fit unclear
- Fit result for Γ_s omitted
- Calculation of significance σ unclear
- Extraction of the fit value for the tagging efficiency unclear
- Effect $q \neq 0$ on the $\mathcal{P}_t$ not explained
- Assumptions for background pdf unclear

Acknowledgments

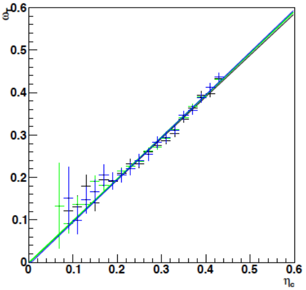
- Harrison
- Gino
- Olga
- LHCb
- WIFIJDA

BACKUP

Object definition

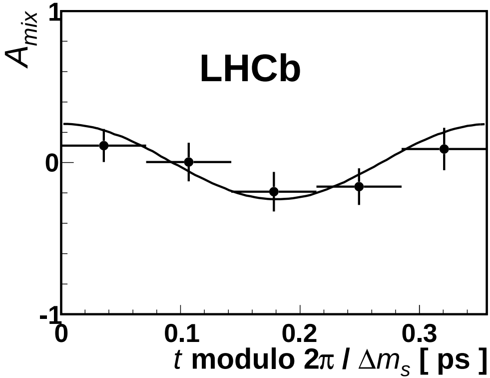
- Candidates passing selection criteria for one mode are not further counted (prevent double counting).
- Hardware trigger
  - 1 cluster in hadronic calorimeter with minimum energy of 2.5 to 3.6 GeV .
  - Cut placed on number of hits in SPD – reject high occupancy events.
- Software Trigger
  - First 2.4 pb^{-1} of data: one level – one good quality displaced vertex required (two tracks, each with $p_T > 0.5\,\mathrm{GeV/c}$)
  - Remaining data: Two – level software trigger
    - Level 1: Good quality track with high impact parameter relative to primary vertex and $p_T > 1.85\,\mathrm{GeV/c}$, P > 13.3 GeV/c
    - Level 2: Good quality displaced vertex required (two tracks, each with pT > 0.5 GeV/c and p > 5 GeV/c with mass between 2 and 7 GeV/c2).
- Cuts on impact parameters and significance, p and pT of daughter tracks made to optimize study of decay modes.
- Reconstructed Ds - mass required to be consistent with PDG value.

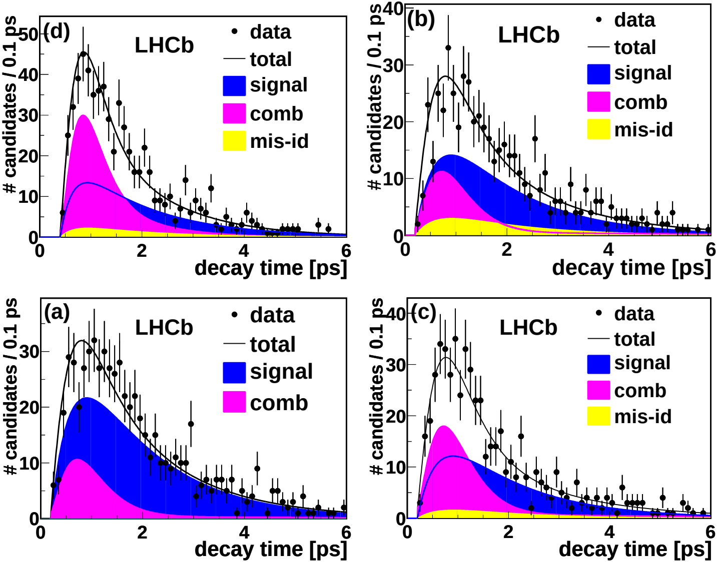
- Tagger calibrated in independent samples with similar signature
- Calibration: $B_0 \to D^- \pi^+$
  - $\omega = a + b \times (\eta - <\eta>)$
  - $a = 0.311 \pm 0.022$
  - $b = 0.61 \pm 0.25$
  - $<\eta> = 0.3276$

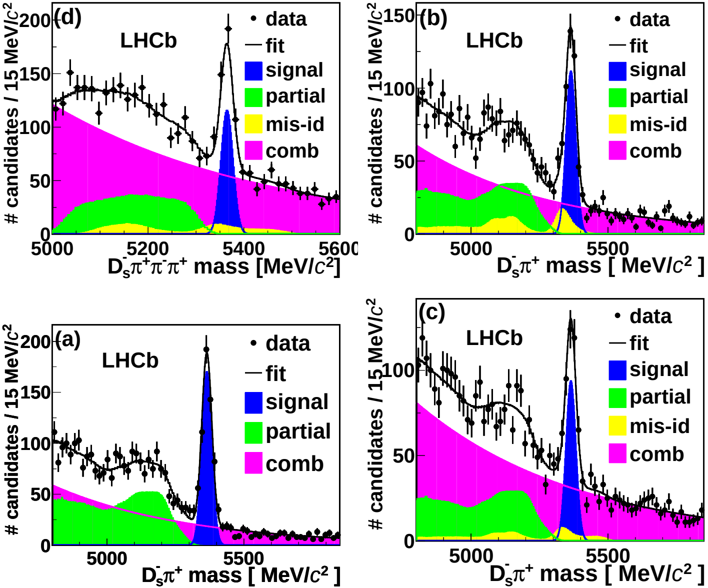


$B^+ \to J/\psi K^+$

$$A_{mix}(t) = \frac{N^+(t) - N^-(t)}{N^+(t) + N^-(t)}$$




(d)
LHCb
data
total
signal
comb
mis-id
candidates / 0.1 ps
decay time [ps]
(b)
LHCb
data
total
signal
comb
mis-id
candidates / 0.1 ps
decay time [ps]
(a)
LHCb
data
total
signal
comb
candidates / 0.1 ps
decay time [ps]
(c)
LHCb
data
total
signal
comb
mis-id
candidates / 0.1 ps
decay time [ps]


(d)
LHCb
data
fit
signal
partial
mis-id
comb
candidates / 15 MeV/c^2
$D_s^-\pi^+\pi^-\pi^+$ mass [MeV/c^2]
(b)
LHCb
data
fit
signal
partial
mis-id
comb
candidates / 15 MeV/c^2
$D_s^-\pi^+$ mass [MeV/c^2]
(a)
LHCb
data
fit
signal
partial
comb
candidates / 15 MeV/c^2
$D_s^-\pi^+$ mass [MeV/c^2]
(c)
LHCb
data
fit
signal
partial
mis-id
comb
candidates / 15 MeV/c^2
$D_s^-\pi^+$ mass [MeV/c^2]