Studies of $\mathcal{CP}$ violation using semileptonic B decays

WIN 2013

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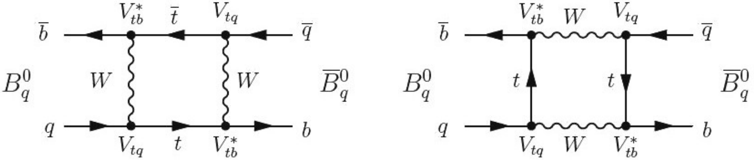
University of Manchester

September 17, 2013

Some theory...

- Two flavour eigenstates $|B^0\rangle$ and $|\overline{B^0}\rangle$, of a B^0 system (B_d^0 or B_s^0)



- Mixing described by off-diagonal elements M_{12} and Γ_{12} in $\hat{M}$ and $\hat{\Gamma}$

$$i\frac{d}{dt}\begin{pmatrix} |B^0\rangle \\ |\overline{B^0}\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B^0\rangle \\ |\overline{B^0}\rangle \end{pmatrix}$$

- Diagonalisation of $\hat{M}$ and $\hat{\Gamma}$ gives mass eigenstates, $|B_L\rangle$ and $|B_H\rangle$

$$|B_L\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$$

Flavour specific asymmetry

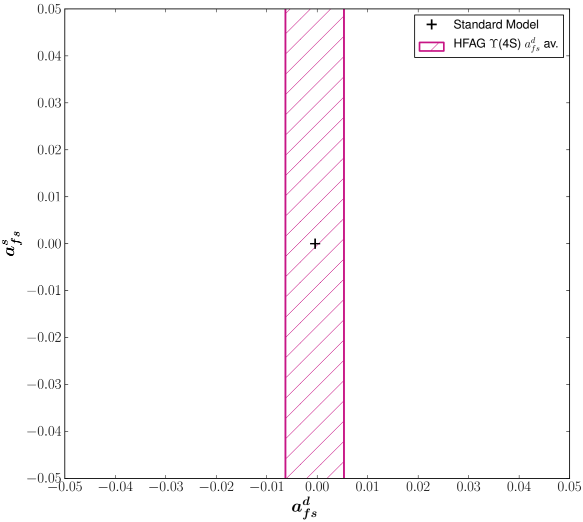
- Leading to three observables describing CPV in mixing. . .
  - Mass differences, $\Delta m = M_H - M_L \approx 2|M_{12}|$
  - Decay width differences, $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\phi)$
  - Flavour specific asymmetries, $a_{fs} = -2\left(\left|\frac{q}{p}\right| - 1\right) = \text{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)$
    - ★ Non-zero value leads to $\mathcal{CP}$-violation in B mixing
- Focus on the flavour specific asymmetries a^s_{fs} and a^d_{fs}
  - Along with a not-so-brief diversion on Δm_s and Δm_d

SM predictions [arXiv:1205.1444]

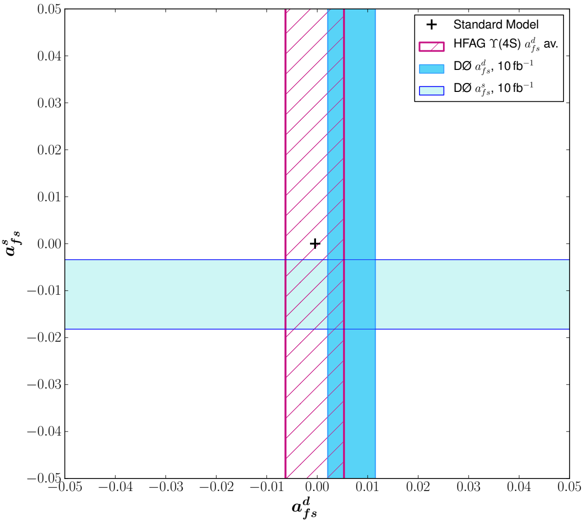
$$a^s_{fs} = (1.9 \pm 0.3) \times 10^{-5} \quad a^d_{fs} = -(4.1 \pm 0.6) \times 10^{-4}$$

$$\Delta m_s = (17.30 \pm 2.6)\,\mathrm{ps}^{-1} \quad \Delta m_d = (0.543 \pm 0.091)\,\mathrm{ps}^{-1}$$

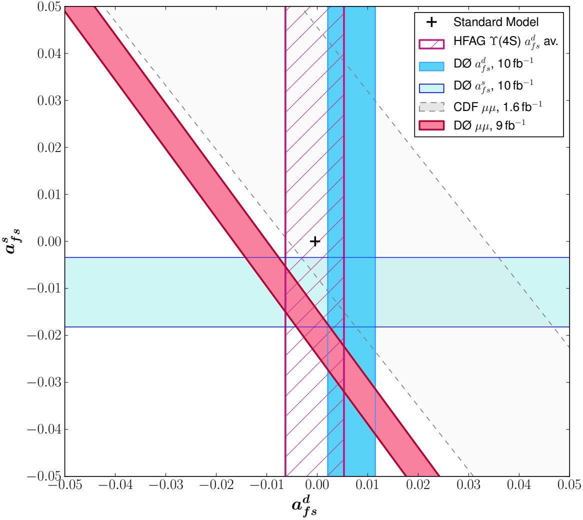
Previous measurement



Previous measurement



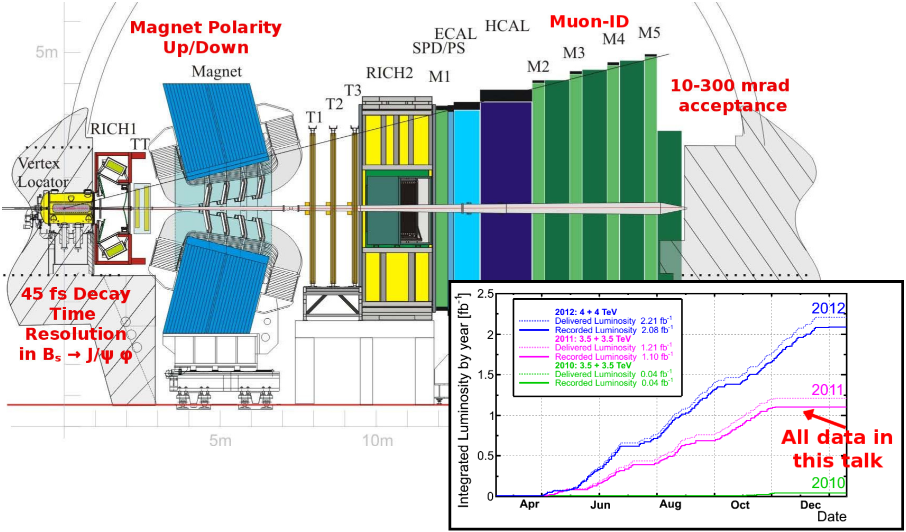
Previous measurement



- LHCb has two measurements of a_{fs}^{s} and a_{fs}^{d} in the pipeline

1. Completed time-integrated a_{fs}^{s} measurement [LHCB-PAPER-2013-033]
2. Ongoing time-dependent a_{fs}^{d} measurement

- Completed time-dependent mixing analysis [LHCB-PAPER-2013-036]


Magnet Polarity
Up/Down
Magnet
Muon-ID
10-300 mrad
acceptance
45 fs Decay
Time
Resolution
in $B_s \to J/\psi\ \phi$
5m
Vertex
Locator
RICH1
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
2012: 4 + 4 TeV
Delivered Luminosity 2.21 fb^{-1}
Recorded Luminosity 2.08 fb^{-1}
2011: 3.5 + 3.5 TeV
Delivered Luminosity 1.21 fb^{-1}
Recorded Luminosity 1.10 fb^{-1}
2010: 3.5 + 3.5 TeV
Delivered Luminosity 0.04 fb^{-1}
Recorded Luminosity 0.04 fb^{-1}
Integrated Luminosity by year [fb^{-1}]
2012
2011
2010
All data in
this talk
Apr
Jun
Aug
Oct
Dec
Date

Time-integrated a_{fs}^{s}

Time-integrated a^s_{fs}

- Look at decay of $B^0_s \to D^-_s \mu^+ \nu$, where $D^-_s \to \phi\pi^-$ and $\phi \to K^+K^-$
- Measure untagged final state charge asymmetry
- Aim for error on measurement to be of the order of 10^{-3}

$$\frac{N\left(D^-\mu^+\right) - N\left(D^+\mu^-\right)}{N\left(D^-\mu^+\right) + N\left(D^+\mu^-\right)}$$

$$= \frac{a^s_{fs}}{2} + \left(a_p + \frac{a^s_{fs}}{2}\right) \frac{\int_0^\infty e^{-\Gamma_s t} \cos\left(\Delta m_s t\right) \varepsilon(t) dt}{\int_0^\infty e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \varepsilon(t) dt}$$

- Integral ratio $\approx 0.2\%$ from MC
- $a_p(B^0_s) \approx 1\%$ [LHCB-PAPER-2011-029]

Time-integrated a_{fs}^s

- Look at decay of $B_s^0 \to D_s^- \mu^+ \nu$, where $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$
- Measure untagged final state charge asymmetry
- Aim for error on measurement to be of the order of 10^{-3}

$$\frac{N\left(D^-\mu^+\right) - N\left(D^+\mu^-\right)}{N\left(D^-\mu^+\right) + N\left(D^+\mu^-\right)}$$
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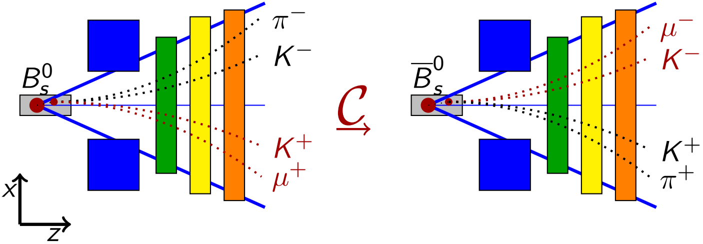
$$\frac{N(D^-\mu^+) - N(D^+\mu^-)}{N(D^-\mu^+) + N(D^+\mu^-)}$$

$$= \frac{a_{fs}^s}{2} + \left(a_p + \frac{a_{fs}^s}{2}\right) \frac{\int_0^\infty e^{-\Gamma_s t} \cos(\Delta m_s t)\, \varepsilon(t) dt}{\int_0^\infty e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \varepsilon(t) dt}$$

$$\approx \frac{a_{fs}^s}{2}$$

- $0.2\% \times 1\% \sim 10^{-5}$ can ignore this term

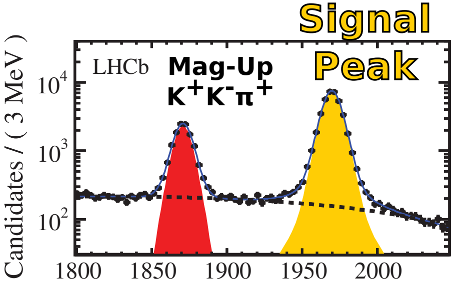
Detection asymmetries

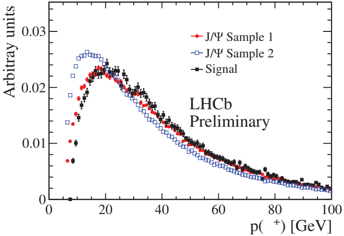


$$A_{meas} = \frac{N(D^-\mu^+)/\varepsilon(\mu^+) - N(D^+\mu^-)/\varepsilon(\mu^-)}{N(D^-\mu^+)/\varepsilon(\mu^+) + N(D^+\mu^-)/\varepsilon(\mu^-)} - A_{\mathrm{track}} - A_{\mathrm{bkg}} \approx \frac{a_{fs}^s}{2}$$

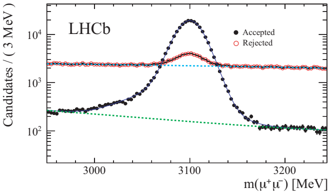
- First term is corrected asymmetry, A_c^μ
- Muon PID and trigger efficiency
- Charge asymmetry due to tracking
- Charge asymmetry due to backgrounds

Corrected signal yield





- Efficiency measured in two sets of momentum bins
- Using two $J/\psi \to \mu^+\mu^-$ samples



[LHCb-CONF-2012-022]

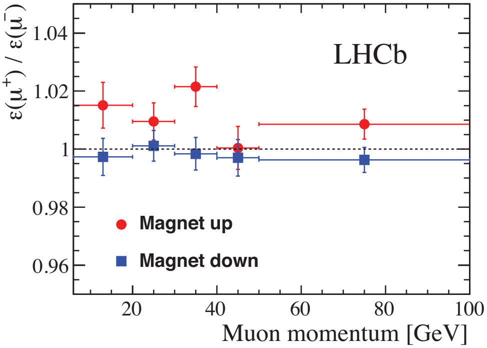
[LHCB-PAPER-2013-033]

Corrected signal yield

- Residual asymmetry due to alignment of muon stations
- Mostly affects hardware trigger

$$A_c^{\mu} = (+0.04 \pm 0.25)\%$$

[LHCB-PAPER-2013-033]

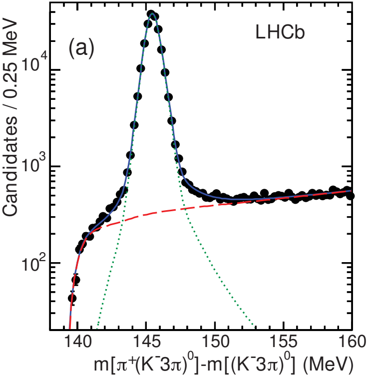


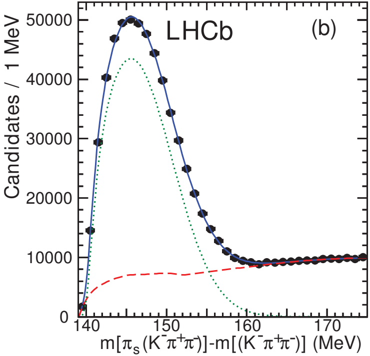
Muon sample 1 (KS)		
Binning	Mag-Up	Mag-Down
$pp_x p_y$	$+0.38 \pm 0.38$	-0.17 ± 0.32
$pp_t \phi$	$+0.30 \pm 0.38$	-0.25 ± 0.32
Avg.	$+0.34 \pm 0.27$	-0.21 ± 0.23

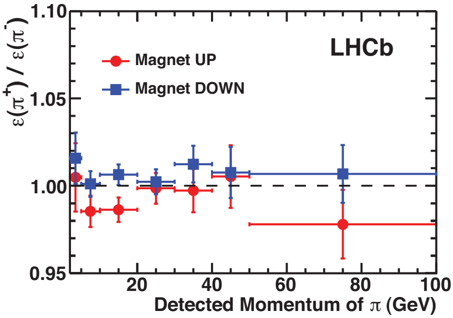
Muon sample 2 (MS)		
Binning	Mag-Up	Mag-Down
$pp_x p_y$	$+0.64 \pm 0.37$	-0.60 ± 0.32
$pp_t \phi$	$+0.63 \pm 0.37$	-0.62 ± 0.32
Avg.	$+0.64 \pm 0.26$	-0.61 ± 0.23

Tracking asymmetry

- Select $D^{*\pm} \to \pi^+ D^0(K^-\pi^+\pi^+\pi^-)$, with a pion missing
- Use kinematic constraints to find pion [PLB 713 (2012) 186]
- Count fully (a) and partially (b) reconstructed events, calculate asymmetry





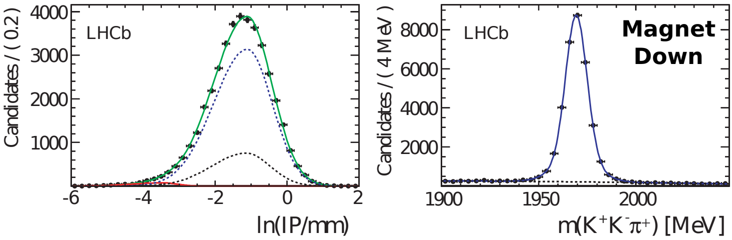


- After kinematic re-weighting, $A_{\mathrm{track}}(\pi^{\pm}\mu^{\mp}) = (0.01 \pm 0.13)\%$
- s-wave contribution causes differences in K^+ and K^- momentum

$$\frac{N\left(D^- \to K^+\pi^-\pi^-\right)}{N\left(D^+ \to K^-\pi^+\pi^+\right)} \times \frac{N\left(D^+ \to K_s^0\pi^+\right)}{N\left(D^- \to K_s^0\pi^-\right)} = \frac{\varepsilon\left(K^+\pi^-\right)}{\varepsilon\left(K^-\pi^+\right)}$$

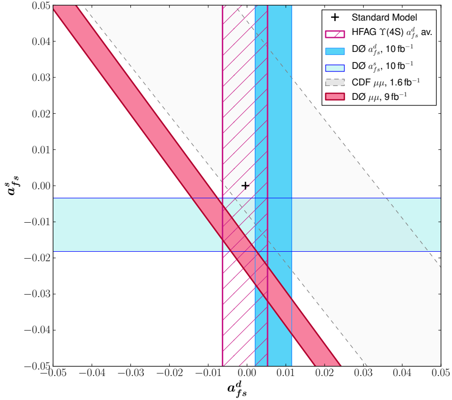
- $A_{\mathrm{track}}(K^+K^-) = (0.012 \pm 0.004)\%$ [LHCB-PAPER-2013-033]

- 2D fit used to estimate prompt D_s^+ background



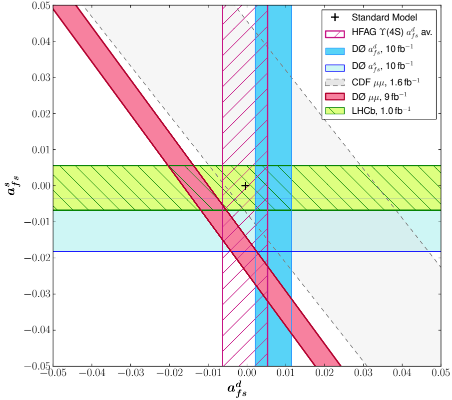
- Average over magnet polarities: $A_{\rm bkg}^{\rm prompt} = (+0.04 \pm 0.04)\%$
- μ and D_s^+ from other b-decays, $A_{\rm bkg}^{\rm other} = (0.01 \pm 0.04)\%$
- b-decays with fake muons, $A_{\rm bkg}^{\rm misid} < 0.01\%$ [LHCB-PAPER-2013-033]

Time-integrated results



Source	$\sigma\,(A_{\text{meas}})\,\%$
Tracking asymmetry	0.13
Muon efficiency	0.08
Fitting model	0.07
Background asymmetry	0.05
Software trigger bias	0.05
Run conditions	0.01
Total	0.18

Time-integrated results



$$A_{\text{meas}} = (-0.03 \pm 0.25 \pm 0.18)\%$$
$$\approx \frac{a^s_{fs}}{2}$$

$$\text{LHCb}: \; a^s_{fs} = (-0.06 \pm 0.50 \pm 0.36)\%$$
$$\text{SM}: \; a^s_{fs} = (0.0019 \pm 0.0003)\%$$

[LHCB-PAPER-2013-033]

Time-dependent a^d_{fs}

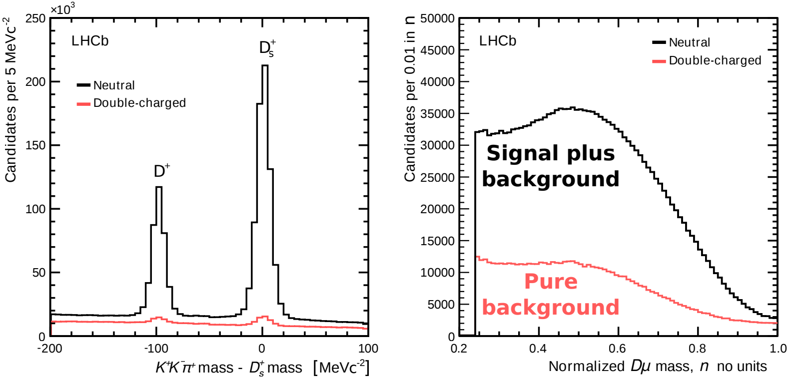
- More recent analysis, building on previous analysis
- Uses $B_d^0 \to D^- \mu^+ \nu$ decays, where $D^- \to K^+ \pi^- \pi^-$

$$= \frac{N(D^-\mu^+) - N(D^+\mu^-)}{N(D^-\mu^+) + N(D^+\mu^-)}$$

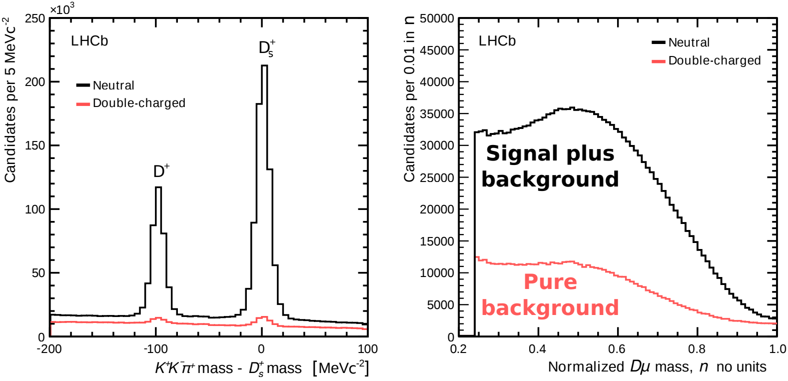
$$= \frac{a_{fs}^d}{2} + \left(a_p + \frac{a_{fs}^d}{2}\right) \frac{\int_0^\infty e^{-\Gamma_d t} \cos(\Delta m_d t)\, \varepsilon(t) dt}{\int_0^\infty e^{-\Gamma_d t} \cosh\left(\frac{\Delta\Gamma_d t}{2}\right) \varepsilon(t) dt}$$

- B_d system has slow oscillations, integral ratio is no longer small
- Must perform time-dependent analysis
- Use similar corrections to first analysis

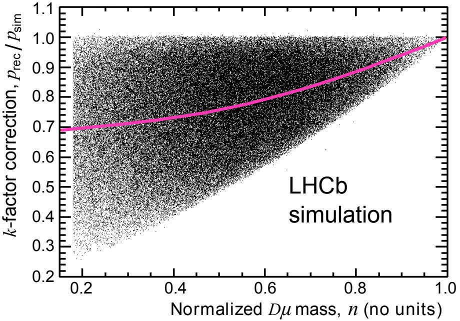
Mixing selection



- Measure Δm_s and Δm_d on the way to a^d_{fs} [LHCB-PAPER-2013-036]
- Using D_s^- cabibo favoured decay to $K^-K^+\pi^+$, need lots of events for Δm_s
- Also selects peaking background $B^+ \to D^-\mu^+(\nu, \pi^+, \gamma)$



$$\text{Normalised } B \text{ mass} : n = \frac{M_{rec}(B) - M_0(D) - M_0(\mu)}{M_0(B) - M_0(D) - M_0(\mu)}$$

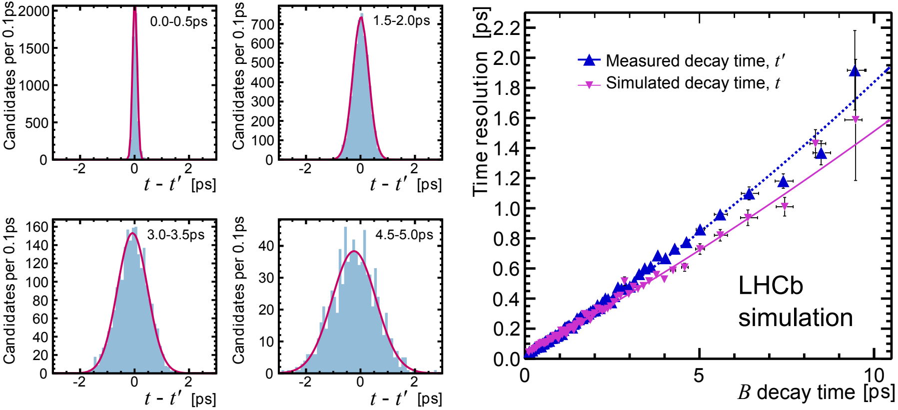


[LHCB-PAPER-2013-036]

- Missing particles in decay $\rightarrow$ missing momentum
- To measure decay time, need to know momentum
- Apply an average correction from MC, called k-factor
- $k = p^{rec}/p^{true}$ parametrised as function of B mass

Time dependent resolution

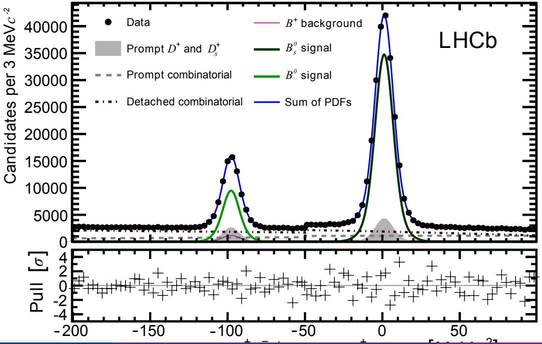
- $\tau \sim 0\,\text{ps}$ small vertex resolution dominates
- $\tau > 0\,\text{ps}$ resolution from missing momentum dominates

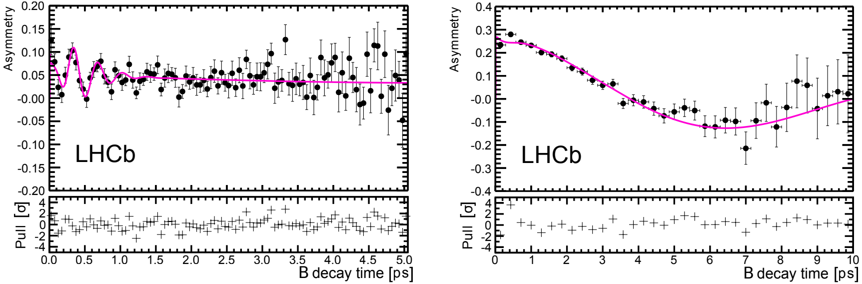


[LHCB-PAPER-2013-036]

Fitting

- RooFit binned log likelihood fit performed in three dimensions:
  - $KK\pi$-mass
  - corrected lifetime of the B
  - B flavour tag
    - Standard LHCb B flavour tagging is used [CERN-THESIS-2012-075]
- Simultaneously fit in two B mass categories $n < 0.56$ and $n > 0.56$
  - Improves resolution, to see B_s^0 oscillations [LHCB-PAPER-2013-036]





$$\Delta m_s = (17.93 \pm 0.22(\mathrm{stat}) \pm 0.15(\mathrm{syst}))\,\mathrm{ps}^{-1}$$

Reject null hypothesis of no mixing by 5.8σ

$$\Delta m_s^{\mathrm{PDG}} = (17.69 \pm 0.08)\,\mathrm{ps}^{-1}$$

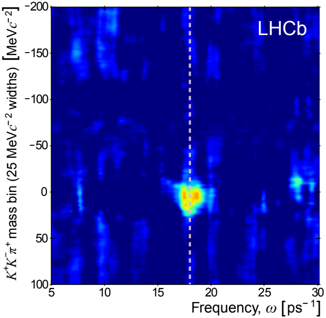
$$\Delta m_d = (0.503 \pm 0.011(\mathrm{stat}) \pm 0.013(\mathrm{syst}))\,\mathrm{ps}^{-1}$$

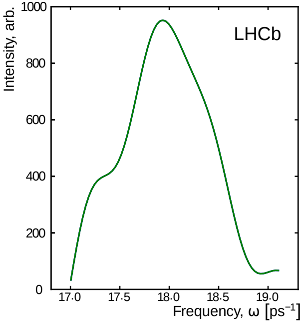
Reject null hypothesis of no mixing by 13.0σ

$$\Delta m_d^{\mathrm{PDG}} = (0.507 \pm 0.0040)\,\mathrm{ps}^{-1}$$

[LHCB-PAPER-2013-036]

- Subtract Fourier spectra of two flavour tags [LHCB-PAPER-2013-036]
  - Suppresses acceptance and lifetime effects





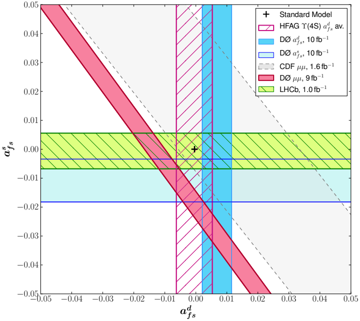
- $\Delta m_s = 17.95 \pm 0.40(\mathrm{rms}) \pm 0.11(\mathrm{syst})\ \mathrm{ps}^{-1}$
- Δm_d difficult to extract, heavily biased
- Methods demonstrate time-dependent a^d_{fs} analysis will be possible

- Measured a_{fs}^{s} consistent with SM

LHCb : $a_{fs}^{s} = (-0.06 \pm 0.50 \pm 0.36)\%$

SM : $a_{fs}^{s} = (0.0019 \pm 0.0003)\%$

- Measurement of a_{fs}^{d} possible and on its way

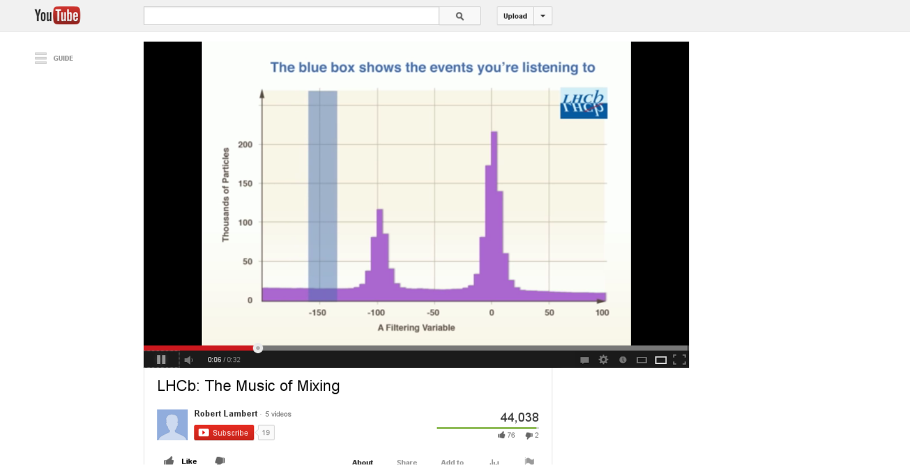


- First observation of B_s^0 mixing using only semileptonic decays

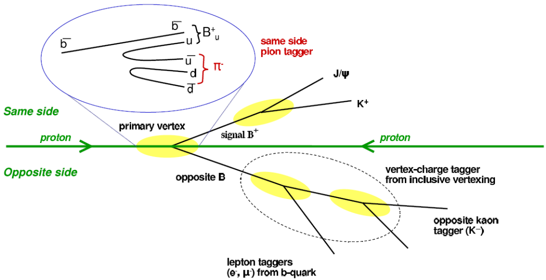
$$\Delta m_s = (17.93 \pm 0.22(\text{stat}) \pm 0.15(\text{syst}))\ \text{ps}^{-1}$$

$$\Delta m_d = (0.503 \pm 0.011(\text{stat}) \pm 0.013(\text{syst}))\ \text{ps}^{-1}$$

Click to listen to mixing on YouTube



Backup slides



- Standard LHCb B flavour tagging is used [CERN-THESIS-2012-075]
- For B_s^0 decays both opposite and same side taggers are applied
- While for B^0 decays only the opposite side taggers are used
  - Minimises the difference between the tagging of B^+ and B^0 decays
- Mistag fraction is allowed to float in the fit

Source of uncertainty	Systematic uncertainty Δm_s [ps^{-1}]	Δm_d [ps^{-1}]
$B^+ \to D^+$ (BR, efficiency, tagging)	n/a	0.008
signal proper-time model	0.09	0.007
k-factor	0.06	0.0052
model bias	0.09	0.0055
other models and binning	0.05	0.001
detector alignment	0.03	0.0008
values of $\Delta\Gamma$	n/a	0.0004
total systematic uncertainty	0.15	0.013
total statistical uncertainty	0.22	0.011

- $B^+ \to D^+$ (BR, efficiency, tagging)
  - B^+ background fixed from MC, vary its parameters: lifetime, fraction and relative tagging performance

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- Signal proper time model
  - Different implementation of signal decay time model
  - Resolution parametrised by true decay time or with no dependence

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- *k*-factor
  - Taken from MC, if MC not accurate correction will be baised
  - A large toy study determines possible bias if incorrect *k*-factor is used

Mixing systematic uncertainties

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total statistical uncertainty	0.22	0.011

- Model bias
  - A small residual bias of $\sim 1\%$ on Δm is seen in MC
  - This is corrected for and half of correction is applied as systematic