Measurements of B^0 and B_s^0 mixing frequencies at LHCb

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on behalf of the LHCb collaboration

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Outline

1. Introduction to the LHCb detector

2. Measurements of B_d^0 and B_s^0 mixing in LHCb

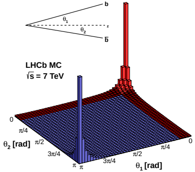
3. Measurements of B^0 and B_s^0 Production Asymmetry in LHCb

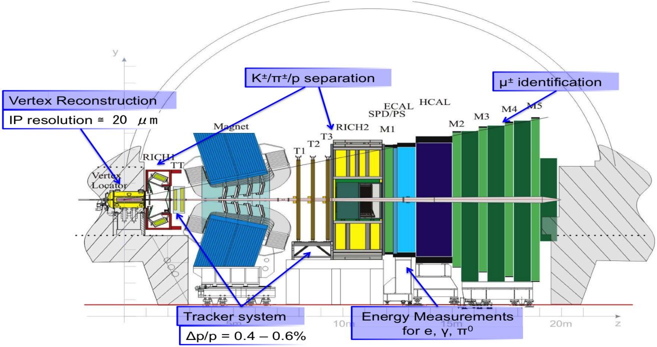
$\Rightarrow$ Performed using 1 fb^{-1} at 7 TeV in 2011 dataset

4. Summary

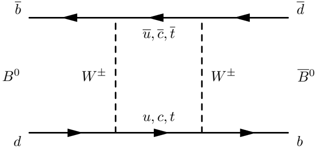
The LHCb detector

- Single-arm spectrometer ($2 < \eta < 5$)
- Large production of $b\bar{b}$ pairs in pp collisions in the forward region
- Beauty and charm hadrons study: Rare decays, CP violation
- Exploit excellent vertex (time) and mass resolution, and particle-ID
- Crucial role of the trigger (hardware + software): from 20MHz collisions to 4kHz output

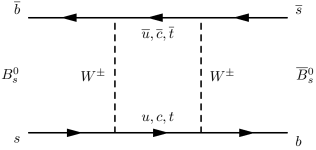




B_d^0 - $\bar{B}^0{}_d$ mixing $\rightarrow \Delta m_d$



B_s^0 - $\bar{B}_s^0$ mixing $\rightarrow \Delta m_s$



- Oscillations of neutral B_q^0 (q=d,s) mesons through box diagrams
- The oscillation frequency corresponds to $\Delta m_q = m_H$ - m_L
- It represents an important ingredient for the time-dependent CP asymmetry measurements

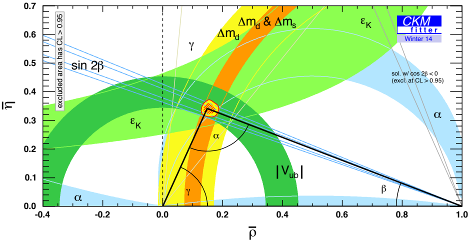
Relevance - the CKM triangle

In the Standard Model the B_q^0 mixing through box diagram:

$$\Delta m_q \propto m_{B_q} \ \hat{B}_{B_q} f_{B_q}^2 | \ V_{tb} V_{tq}^* \ |^2 \ \text{(q=d,s)}$$

In the ratio $\frac{\Delta m_s}{\Delta m_d}$ most of theoretical uncertainties cancel:

$$\Rightarrow \frac{\Delta m_s}{\Delta m_d} \propto \frac{m_{B_s}}{m_{B_d}} \ \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$



from CKMfitter group - for Moriond 2014

- **Δm_d** and **Δm_s** provide useful constraints
- in particular for the **apex** of the unitarity triangle

With current world averages of Δm_s and Δm_d, the determination of the apex is dominated by theoretical uncertainty on ξ^2 and $\frac{m_{B_s}}{m_{B_d}}$

Introduction - Δm_q measurements

Mixing frequency measurements using flavour-specific decays:

- Exclusive reconstructed hadronic decay modes:
  - $\Rightarrow \Delta m_s$ in $B_s^0 \to D_s^- \pi^+$
  - $\Rightarrow \Delta m_d$ in $B^0 \to D^- \pi^+$ and $B^0 \to J/\psi K^{*0}$
- Δm_s and Δm_d in Semi-Leptonic decays

Measurements

- *Time-dependent analysis*
- *Mixing asymmetry (q=d,s):*

$$A_q^{th}(t) = \frac{N_{unmixed}(t) - N_{mixed}(t)}{N_{unmixed}(t) + N_{mixed}(t)} \approx \cos(\Delta m_q t)$$

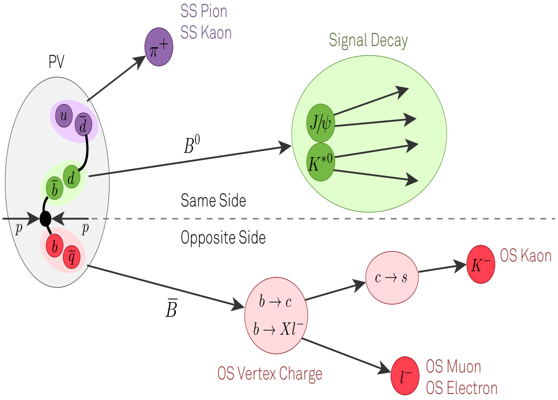
- *Knowledge of the initial flavour of the* $B_q^0 \Rightarrow$ *Flavour Tagging Tool*
- *Measurement of the* B_q^0 *decay time* $\Rightarrow$ *Time Resolution Model*
- *Experimental mixing asymmetry (q=d,s):*

$$A_q^{exp}(t) \approx (1 - 2\omega)\ exp^{-\frac{(\Delta m_q \sigma_t)^2}{2}} \cos(\Delta m_q t)$$

Flavour Tagging

Eur. Phys. J. C 72 (2012) 2022, LHCb-CONF-2012-026

- **Same Side taggers**: exploit the charge of the fragmentation tracks accompanying the B signal meson (SSK for B_s^0, SSπ for B^0)
- **Opposite Side taggers**: inclusive reconstruction of the non signal B hadron (OSe, OSμ, OSK, OS VtxCharge)



Other types of taggers have been recently developed:

- *SSp, SSKnnet*
- *OScharm, OSKnnet*

Flavour Tagging

Tagging Algorithms

- *The Flavour is determined by the charge of the particle used to tag (K,e,μ,π)*
- *Each Tagging algorithm, depending on the charge of the selected tagging particle, provides:*
  1) *a tagging decision d_i (with a given Tagging Efficiency ε_{tag})*
  2) *probability of mistag η_i: used to re-weight the events and gain in Tagging Power*
- *Combinations of taggers give a combined tagging decision d_i^c and a combined η_i^c:*
  - $\Rightarrow$ *(OS, SSπ) $\rightarrow$ for B^+ and B_d^0 mesons*
  - $\Rightarrow$ *(OS, SSK) $\rightarrow$ for B_s^0 mesons*

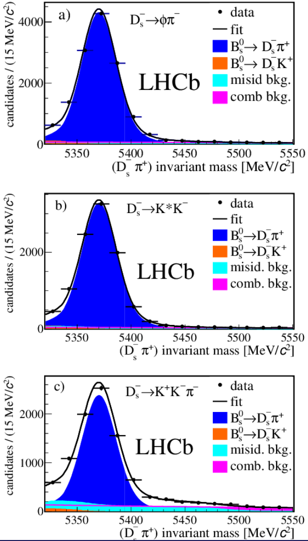
Tagging Performances:

- Tagging Efficiency $\varepsilon_{tag} = \frac{N_{tag}}{N_{untag}+N_{tag}}$
- Mistag fraction $\omega = \frac{N_{wrong}}{N_{tag}}$ $\Rightarrow$ η is ω if the tagger is calibrated (details in backup)
- Tagging Power $\varepsilon_{tag}\mathcal{D}^2 = \varepsilon_{tag} \cdot (1-2\omega)$

Measurement of Δm_s in $B_s^0 \to D_s^- \pi^+$

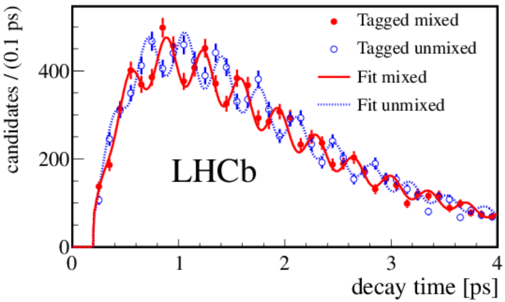
New J. Phys. 15 (2013) 053021, LHCb-PAPER-2013-006

- Simultaneous fit to the B_s^0 invariant mass, decay time and tagging decision in the 5 D_s decay modes
- $D_s \to \Phi\pi$, $D_s \to K^*K$, $D_s \to K\pi\pi$ (non-res), $D_s \to KK\pi$, $D_s \to \pi\pi\pi$ $PDF_{tot} = PDF(m) \cdot PDF(t, q \mid \sigma_t, \eta) P(\sigma_t) P(\eta)$
- Signal yield of 34 000 evts
- per-event Time Resolution $\Rightarrow$ calibration on data *promptD*$_s$+π: $S_{\sigma_t} = 1.37$
  $\Rightarrow S_{\sigma_t} \cdot < \sigma_t > = 44$ fs
- Decay Time Acceptance function $\Rightarrow$ parametrization from simulated data
- (OS, SSK) combination
  - $\varepsilon_{tag}\mathcal{D}^2\,(\text{OS}) = (2.6 \pm 0.4)\%$
  - $\varepsilon_{tag}\mathcal{D}^2\,(\text{SSK}) = (1.2 \pm 0.3)\%$



Measurement of Δm_s in $B_s^0 \to D_s^- \pi^+$

New J. Phys. 15 (2013) 053021, LHCb-PAPER-2013-006



In the mass range around the B_s^0 mass peak
$5320 < m_{B_s^0} < 5550$ *MeV:*

$$A(t)^{meas} = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)}$$

$$\Rightarrow \Delta m_s = 17.768 \pm 0.023^{(stat)} \pm 0.006^{(syst)} \; ps^{-1}$$

- Systematic dominated by the knowledge of the decay time:
  - length scale $\Rightarrow$ 0.004 ps^{-1}
  - momentum scale $\Rightarrow$ 0.004 ps^{-1}
- World Average $\Delta m_s = 17.761 \pm 0.022 \; ps^{-1}$ by CDF and LHCb (from HFAG)
- LHCb most precise measurement to date

Measurement of Δm_d in $B^0 \to D^- \pi^+$

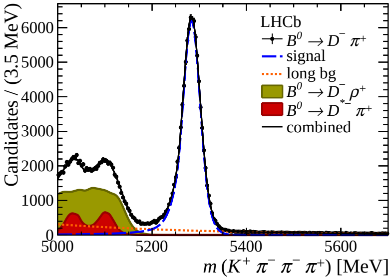
Phys. Lett. B 719 (2013) 318-325, LHCb-PAPER-2012-032

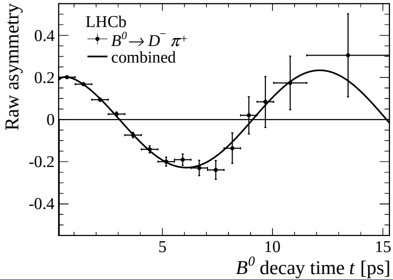
- $PDF_{tot} = PDF(m) \cdot PDF(t, q \mid \eta) P(\eta)$ (for signal and combinatorial)
- Signal yield 87 724 $\pm$ 321 ($D \to K^+ \pi^- \pi^-$) in $5200 < m_{B^0} < 5450$ MeV
- Single Gaussian to model Time Resolution effects ($\sigma_t = 0.05$ ps)
- Decay Time Acceptance $\Rightarrow$ parametrization from simulation
- (OS, SSπ) taggers combination

tagger	ε_{tag} [%]	$\varepsilon_{tag} \mathcal{D}^2$ [%]
OS	38.56	2.98 $\pm$ 0.16
SSπ	23.3	1.32 $\pm$ 0.11

$$\Delta m_d = 0.5178 \pm 0.0061^{(stat)} \pm 0.0037^{(syst)} ps^{-1}$$

(largest syst. from background modeling in PDF_t)





Measurement of Δm_d in $B^0 \to J/\psi K^{*0}$

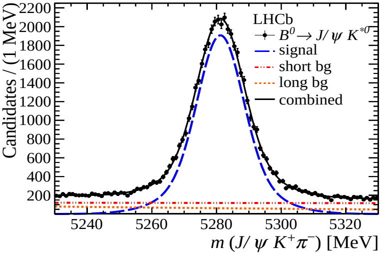
Phys. Lett. B 719 (2013) 318-325, LHCb-PAPER-2012-032

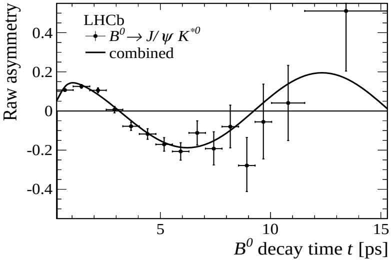
- Very similar to previous analysis
- Signal yield 39 148 $\pm$ 316 ($J/\psi \to \mu^+\mu^-$, $K^{*0} \to K^+\pi^-$) in [5230; 5330] MeV

tagger	ε_{tag} [%]	$\varepsilon_{tag}\mathcal{D}^2$ [%]
OS	33.18	2.04 $\pm$ 0.14
SSπ	16.3	0.63 $\pm$ 0.07

$$\Delta m_d = 0.5096 \pm 0.0114^{(stat)} \pm 0.0022^{(syst)} ps^{-1}$$

(largest syst. from background modeling PDF_t)





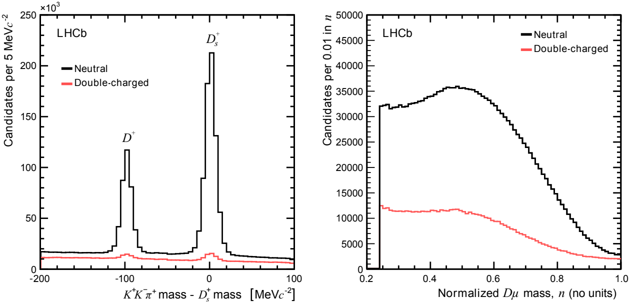
Combined* results: $\Delta m_d = 0.5156 \pm 0.0051^{(stat)} \pm 0.0033^{(syst)}\ ps^{-1}$

* weighted average including correlated systematic uncertainties

Measurement of Δm_d and Δm_s in Semi-Leptonic decays

Eur. Phys. J. C 73 (2013) 2655, LHCb-PAPER-2013-036

- First observation of B_s^0 mixing using only Semi-Leptonic decays
- Selected $B_{(s)}^0 \to D_{(s)}^- \mu^+ \nu_\mu X$ with $D_{(s)}^- \to KK\pi$
- Perform two closely related analysis for Δm_d and Δm_s
- Simultaneous fit to m(KKπ), decay time t' and tagging decision q



- OS tagger for $B^0 \to D^- \mu^+ \nu_\mu$
- (OS, SSK) taggers combination for $B_s^0 \to D_s^- \mu^+ \nu_\mu$

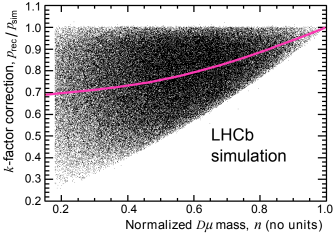
Measurement of Δm_d and Δm_s in Semi-Leptonic decays

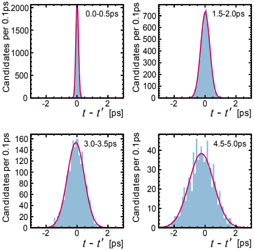
Eur. Phys. J. C 73 (2013) 2655, LHCb-PAPER-2013-036

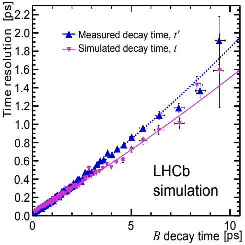
decay time measurement:

$$t_{meas} = \frac{\vec{d} \cdot m}{p_{meas}} \Rightarrow t' = t_{meas} \cdot k$$

- p_{meas} loses the missing particle momentum
- corrected by a simulation-based function that fits $< \frac{p_{rec}}{p_{sim}} >$ as a function of the normalized mass n
- $k(n) = \frac{p_{rec}}{p_{sim}}$
- $\sigma(t')$ dominated by the $\sigma_{p_{corr}}$
- $\sigma(t')$ parametrized in terms of measured decay time t' in simulation



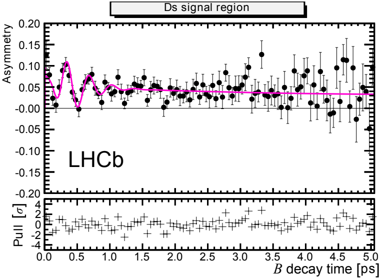




Measurement of Δm_d and Δm_s in Semi-Leptonic decays

Eur. Phys. J. C 73 (2013) 2655, LHCb-PAPER-2013-036

$D_s^- \mu^+ X$ Yield: 201 210 events

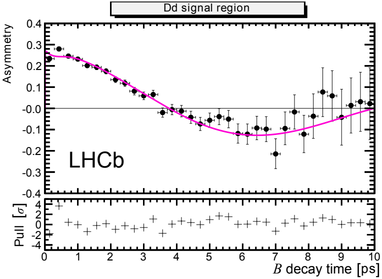


$\Delta m_s = 17.93 \pm 0.22^{(stat)} \pm 0.15^{(syst)} ps^{-1}$

largest systematics [ps^{-1}]

- time resolution model: 0.09
- k-factor model: 0.09
- k-factor (simulation input): 0.06

$D^- \mu^+ X$ Yield: 50 681 events



$\Delta m_d = 0.503 \pm 0.011^{(stat)} \pm 0.014^{(syst)} ps^{-1}$

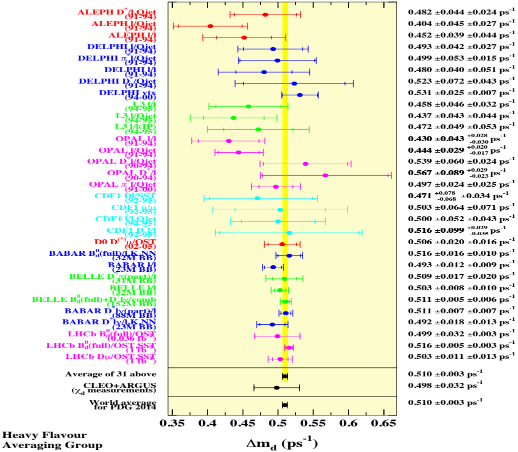
largest systematics [ps^{-1}]

- B^+ bkg parametrization: 0.008
- time resolution model: 0.007
- k-factor model: 0.0055

Δm_d World Average

World Average (from HFAG): $\Delta m_d = 0.510 \pm 0.003\ ps^{-1}$

- LHCb
  $B^0 \to D^- \pi^+$ and
  $B^0 \to J/\psi K^{*0}$
  combined
  measurement is
  the best Δm_d
  single
  measurement



Measurement of the B^0-$\bar{B}^0$ and B_s^0-$\bar{B}_s^0$ production asymmetries at LHCb

LHCb-PAPER-2014-042

- The Production Asymmetry $A_P(B^0_{(s)})$ in pp collision is an ingredient to perform CP asymmetry measurements
- It depends on the type of collision ($\Rightarrow$ pp) and on the energy ($\Rightarrow$ 7 TeV)
- Only LHCb itself can provide this asymmetry $\Rightarrow$ using flavour-specific decays:
  - $A_P(B^0)$ in $B^0 \to J/\psi K^{*0}$ and $B^0 \to D^-\pi^+$ decays
  - $A_P(B_s^0)$ in $B_s^0 \to D_s^-\pi^+$ decay
- Simultaneous fit to the invariant mass and decay time distributions

$$\Gamma(B^0_{(s)}) \approx (1 - f(A_{CP} + A_{det})) \cdot e^{-\Gamma_{(s)}t} \cdot [\cosh(\frac{\Delta\Gamma_{(s)}t}{2}) - f \cdot A_P \cos(\Delta m_{(s)} t)] \quad (A_{CP}=0,\ A_{det} \text{ free, f} = \pm 1)$$

Untagged time-dependent measurements:

1) performed as functions of p_T and η

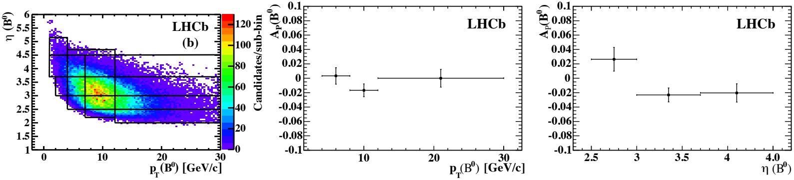
2) integrated in ranges: $4 < p_T < 30$ Gev/c and $2.5 < \eta < 4.5$
   $\Rightarrow$ ingredient required by CP asymmetry measurements

INPUTS $\Rightarrow$ $\Delta m_d = 0.510 \pm 0.004$ ps^{-1} (HFAG) $\Rightarrow$ $\Delta m_s = 17.768 \pm 0.024$ ps^{-1} (LHCb)

Measurement of the B^0-$\bar{B}^0$ and B_s^0-$\bar{B}_s^0$ production asymmetries

LHCb-PAPER-2014-042

1) $A_P(B^0)$ functions of p_T and $\eta \Rightarrow$ 2D bins



$\Rightarrow$ no striking dependences on the values of p_T and η

2) $A_P(B^0_{(s)})$ integrated in ranges: $4 < p_T < 30$ Gev/c and $2.5 < \eta < 4.5$

for the integrated $A_P(B^0_{(s)})$ efficiency correction are applied $A_P = \frac{\sum_i \frac{N_i}{\epsilon_i} A_{P,i}}{\sum_i \frac{N_i}{\epsilon_i}}$

$$\Rightarrow A_P(B^0) = -0.35 \pm 0.76^{(stat)} \pm 0.28^{(syst)} \ \%$$

$$\Rightarrow A_P(B_s^0) = 1.09 \pm 2.61^{(stat)} \pm 0.61^{(syst)} \ \%$$

Summary

- LHCb features
  - clean signals with relevant statistics
  - excellent decay time resolution $\rightarrow$ fast oscillation well solved
  - flavour tagging well-suited
- Best measurements of $B^0_{(d,s)}$ mixing frequencies
  - $\Delta m_d = 0.5156 \pm 0.0051^{(stat)} \pm 0.0033^{(syst)}\ ps^{-1}$
  - $\Delta m_s = 17.768 \pm 0.023^{(stat)} \pm 0.006^{(syst)}\ ps^{-1}$
  - SL: $\Delta m_d = 0.503 \pm 0.011^{(stat)} \pm 0.0137^{(syst)}\ ps^{-1}$
  - SL: $\Delta m_s = 17.93 \pm 0.22^{(stat)} \pm 0.15^{(syst)}\ ps^{-1}$

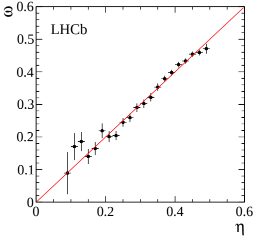
$\Rightarrow$ The CKM apex constraint dominated by theoretical limitation

- Used in TD analysis and to determine other parameters:
  - Production Asymmetry:
    - $A_P(B^0) = -0.35 \pm 0.76^{(stat)} \pm 0.28^{(syst)}$ %
    - $A_P(B^0_s) = 1.09 \pm 2.61^{(stat)} \pm 0.61^{(syst)}$ %
  - Several on going TD analysis using Δm_d and Δm_s

backup - Flavour Tagging Calibration

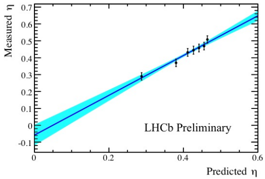
Tagging Calibration

- $\omega = p0 + p1\ (\eta - <\eta>)$
- *perfect calibration if:* $p_0 = \langle \eta \rangle$ *and* $p_1 = 1$
- *calibration done on charge and neutral B flavour-specific decays*
  - *for OS on* $B^+ \to J/\psi K^+$
  - *for* $SS\pi$ *on* $B^0 \to D^- \pi^+$ *and* $B^0 \to J/\psi K^{*0}$
  - *for SSK on* $B_s^0 \to D_s^- \pi^+$
- *calibration validation on additional control channels*



$B^+ \to J/\psi K^+ \Rightarrow$ OS calibration

PRD 87 (2013) 112010



$B_s^0 \to D_s^- \pi^+ \Rightarrow$ SSKnnet calibration

LHCB-PAPER-2014-038

backup - $B_s^0 \to D_s^- \pi^+$

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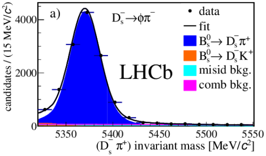

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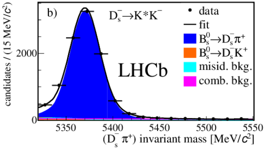

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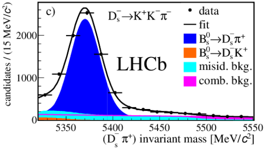

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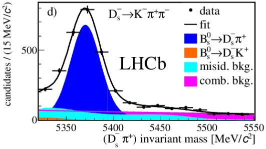

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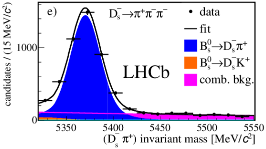


SYSTEMATICS	uncertainty (ps^{-1})	note
z-scale	0.004	
Momentum scale	0.004	
Decay time bias	0.001	from simulation
Total	0.006	

NEGLIGIBLE SOURCES: decay time acceptance, decay time resolution, variations of $\Delta\Gamma_s$, variations of the signal models, variation of the $B_s^0 \to D_s^{\pm} K^{\mp}$ fraction.

backup - $B^0 \to D^-\pi^+$ and $B^0 \to J/\psi K^{*0}$ Systematic Uncertainties

Systematic Uncertainties:

Source	$B^0 \to D^-\pi^+$	$B^0 \to J/\psi K^{*0}$	note
Decay Time Acceptance	0.0004	0.0001	
Decay Time Resolution	0.0002	0.0002	
Fit Model	0.0037	0.0022	PDF_t parametrization using sWeights
Total uncorrelated	0.0037	0.0022	
z-scale	0.0005	0.0005	
Total including correlated	**0.0037**	**0.0023**	used for the combination

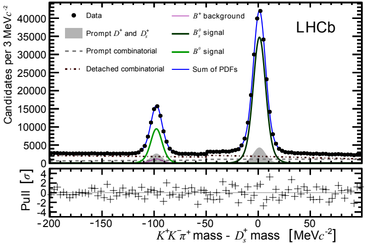
backup - Δm_s and Δm_d in Semi-Leptonic decays

To quantify the measured mass $M(D\mu)$ within its possible range a Normalized Mass is defined:

$$n = \frac{M(D\mu) - M_{PDG}(D) - M_{PDG}(\mu)}{M_{PDG}(B) - M_{PDG}(D) - M_{PDG}(\mu)}$$

$\Rightarrow$ accepted events if n $\in$ $0.24 < n < 1$

$\Rightarrow$ $n > 0.56$ to improve the resolution on Δm_s measurement



Systematic Uncertainties:

Source	$\mathbf{\Delta m_s}$	$\mathbf{\Delta m_d}$	note
k-factor (Sim. Inputs)	**0.06**	0.0052	
Detector Alignment	0.03	0.0008	z-scale, momentum scale, track position uncer.
Values of $\Delta\Gamma_{(s)}$	-	0.0004	
k-factor Model bias	**0.09**	**0.0055**	from simulation
time resolution model	**0.09**	-	parametrized as a function of t_{sim}
variations in resolution and acceptances	-	**0.007**	
models and binning	0.05	0.001	
B^+ parametrization	-	**0.008**	(fraction, lifetime, tagging)
Total	**0.15**	**0.013**	

1) $A_P(B_s^0)$ in bins of p_T and η