"Flavour tagging and mixing at LHCb"

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on behalf of the LHCb collaboration

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Outline

The LHCb experiment and physics motivations

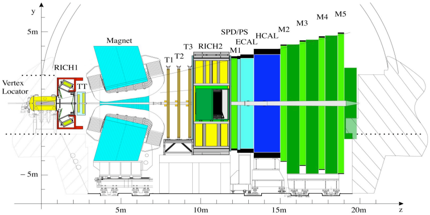
The LHCb experiment: precision studies of b-hadron decays (CP violation, rare B decays) $\rightarrow$ test SM/indirect evidence of NP

Requirements:

- High yield $\rightarrow$ efficient trigger and selection, large $\bar{b}b$ production cross section
- Low background $\rightarrow$ mass resolution, particle identification

For time dependent CP asymmetries:

- Measure the B proper time $\rightarrow$ resolution (B_s^0).
- tag the initial flavour $\rightarrow$ tagging power: particle identification, impact parameter resolution.

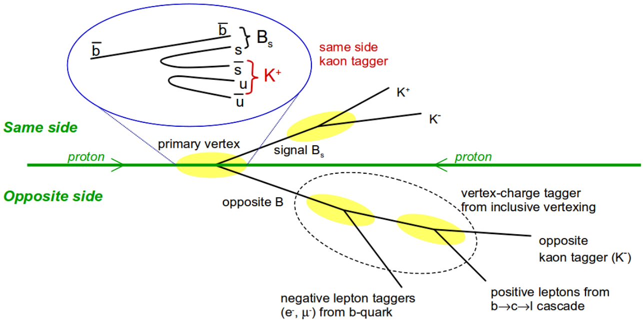


LHCb detector:

- Vertexing&Tracking: excellent resolutions
- Particle identification: $\pi/K/p$ (RICH), $\pi/e/\gamma$ (ECAL), μ (MUON)
- Trigger: L0 (hardware: highp_T e/γ/hadron/μ candidates), HLT1& HLT1 (software)

$\rightarrow$ **N.Harnew's presentation this morning**

Tag the initial B flavour



OS tagging: exploit the properties of the decays of the b-hadron opposite to the signal B

- μ, e ($b \to c l^- \bar{\nu}_l$), K ($b \to c \to s$), Q_{vtx} (inclusive secondary vertex reconstruction)

SS tagging: exploit the hadronization process of the signal B, or in the decays of excited states B^{**}

- SSπ (tag the B_d and B^+), SSK (tag the B_s)

Tag the initial B flavour

Each tagging algorithm determine:

- **tag decision**: $q_i = \pm 1, 0$ for the initial signal b-hadrons containing a $\bar{b}/b$ quark
  - charge of the lepton/kaon/inclusively reconstructed secondary vertex (OS)
  - charge of the pion/kaon (SS)
- estimate of the **mistag probability**: η_i
  - based on a *Neural Network* (inputs: kinematical & geometrical information on the tagger and the event properties).

Combination of taggers based on (q_i, η_i) if more than one tagger is available ($\rightarrow q, \eta$)
OS (all b-hadrons), **SS**π**+OS** (B_d^0, B_u), **SS**K**+OS** (B_s^0)

Tagging performance:

- $\epsilon_{tag} = \frac{R+W}{R+W+U}$, $\rightarrow$ can be measured in any channels
- $\omega = \frac{W}{R+W}$ needed to measure asymmetries due to CP violation $\rightarrow$ should be measured on flavour-specific channels. η can be a proxy of ω , if it is calibrated.
- Tagging power: $\epsilon_{eff} = \epsilon_{tag}(1-2\omega)^2 = \epsilon_{tag} D^2$

Flavour Tagging optimization

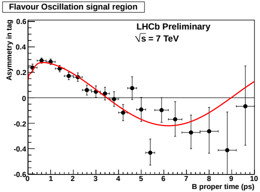
LHCb-CONF-2011-003 [3]

Tagging performance optimized on 2010 data ($\sqrt{s} = 7\,TeV$, $\int \mathcal{L} \cdot dt \sim 35 pb^{-1}$) with different flavour-specific channels.

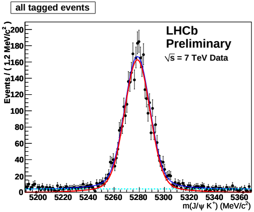
AIM: to find the set of cuts that maximize the ϵ_{eff} of **each tagger** and of the **combination of taggers**.
Each set split randomly into two to avoid over-tuning.

- $B^0 \to D^{*-}\mu^+\nu_\mu$ $\sim 48k$ signal events, B/S$\sim$0.3
  $\to$ fit to time dependent B_d oscillation to measure ω
- $B^+ \to J/\psi K^+$ $\sim 11k$ signal events, B/S$\sim$0.065 (t>0.3ps)
  $\to$ compare the tag decision with the $B^\pm$ charge, count W, R events $\to \omega$
- $B^0 \to J/\psi K^{*0}$ $\sim 3.3k$ signal evens, B/S$\sim$15
  $\to$ fit to time dependent B_d oscillation to measure ω (**cross-check**)
- $B_s^0 \to D_s^-(K^+K^-\pi^-)(3)\pi$: control channel for SSK tagger studies: too little statistics to optimize ($\sim$1 300).

$B^0 \to D^{*-}\mu^+\nu_\mu$



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



Flavour Tagging optimized performance

LHCb-CONF-2011-003 [3]

OS	ϵ_{tag} (%)	ω (%)	ϵ_{eff} (%)
$B^0 \to D^{*-}\mu^+\nu_\mu$	18.3±0.2	33.6±0.8	1.97±0.18
$B^+ \to J/\psi K^+$	15.4±0.3	32.2±1.2	1.97±0.31
$B^0 \to J/\psi K^{*0}$	15.8±0.7	30.0±6.6	2.52±0.82
SSπ+OS	ϵ_{tag} (%)	ω (%)	ϵ_{eff} (%)
$B^0 \to D^{*-}\mu^+\nu_\mu$	28.9±0.2	34.2±0.8	2.87±0.32
$B^+ \to J/\psi K^+$	23.0±0.5	33.9±1.1	2.38±0.33
$B^0 \to J/\psi K^{*0}$	26.1±0.9	33.6±5.1	2.82±0.87

- Measured ω agree within the channels $\to$ can be used in other channels for CP measurement (if trigger and selection are similar).
- Asymmetries of the tagging performance of $B/\bar{B}$ mesons due to the detector efficiency/acceptance or to particle interaction with matter are found negligible within the present statistical error.

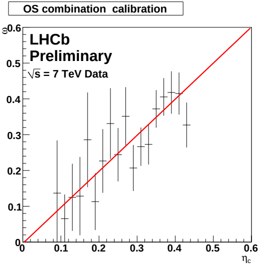
Calibration of the predicted mistag probability

LHCb-CONF-2011-003 [3]

The tagging optimization implies also that the predicted mistag η is calibrated.

- Use $B^+ \rightarrow J/\psi K^+$ channel to perform the calibration of the single taggers first, then of the combination.

signal: $\omega = p_0 + p_1 \cdot (\eta - <\eta>)$



	$p_0 - <\eta>$	p_1
	$B^+ \rightarrow J/\psi K^+$	
OS	-0.001±0.012±0.004	1.01±0.12±0.01
SSπ+OS	0.000±0.010±0.004	1.00±0.11±0.01

Use the calibrated mistag η per-event as a proxy of ω to exploit the tagging information at best.

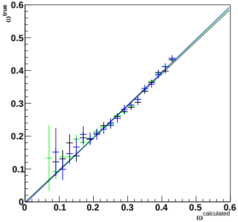
Validity of the calibration on different channels

LHCb-CONF-2011-003 [3]

Same trigger and similar selection for $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B_d^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi \phi$ channels to guarantee the same tagging performance.

$\to$ Use the calibrated mistag in $B^+ \to J/\psi K^+$ for the analysis of the other channels.

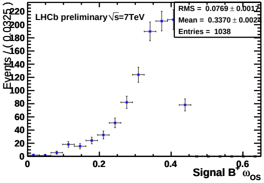
Monte Carlo



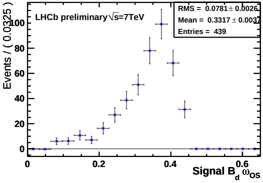
Validation on data, using $B^0 \to J/\psi K^{*0}$:

SSπ+OS tagging	$p_0 - <\eta>$	p_1
$B^0 \to J/\psi K^{*0}$	-0.017±0.025±0.003	0.71±0.26±0.24

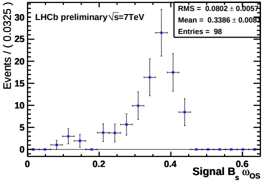
$B^+ \to J/\psi K^+$



$B^0 \to J/\psi K^{*0}$



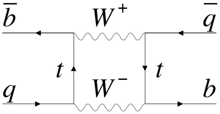
$B_s^0 \to J/\psi \phi$



$B^0 - \bar{B}^0$ oscillations

In the Standard Model $B^0_{d/s}$ mix through the box diagram:

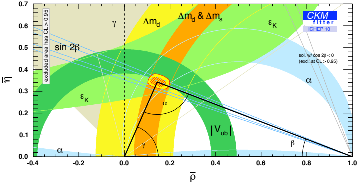
$$\Delta m_q \propto m_{B_q} \hat{\mathcal{B}}_{B_q} f^2_{B_q} |V_{tb} V^*_{tq}|^2 \qquad q = d, s$$



In the ratio $\Delta m_s \ / \Delta m_d$ most of theoretical uncertainties cancel:

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

$\xi^2 = 1.210^{+0.047}_{-0.035}$ Lattice QCD calculations.



$\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$ world average, PDG [1]
$\Delta m_s = 17.77 \pm 0.10(stat) \pm 0.07(sys)\ ps^{-1}$ CDF, 2006 [2]

$$\frac{|V_{ts}|^2}{|V_{td}|^2} = 0.2061 \pm 0.0012(exp)^{+0.0080}_{-0.0060}(lattice)$$

Measure the mixing in a flavour-specific decay:

$$\mathcal{A}^{th}(t) = \frac{\Gamma_{\bar{B}^0_d \to \bar{f}}(t) - \Gamma_{B^0_d \to f}(t)}{\Gamma_{\bar{B}^0_d \to \bar{f}}(t) + \Gamma_{B^0_d \to f}(t)} \sim cos(\Delta m_q\ t)$$

experimental asymmetry:

$$\mathcal{A}^{exp}(t) \propto (1 - 2\omega) \exp^{-(\Delta m_q\ \sigma_t)^2/2} cos(\Delta m_q\ t)$$

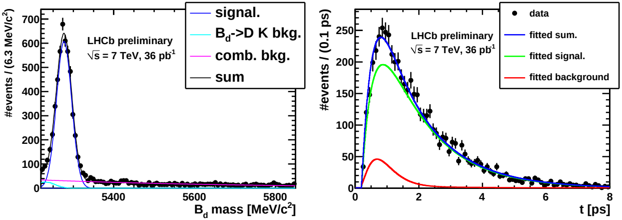
The average statistical significance is:

$$\mathcal{S} \sim \sqrt{N/2}\, f_{sig} \sqrt{\epsilon_{tag}(1 - 2\omega)^2} \exp^{-(\Delta m_q\ \sigma_t)^2/2}$$

$B_d^0 - \bar{B}_d^0$ oscillations

LHCb-CONF-2011-010 [4]

Analysis of $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ channel: $6k$ signal events



- Use a double Gaussian *time resolution model* from Monte Carlo ($<\sigma_t>$=49fs)
- proper time acceptance from Monte Carlo
- Use *per-event* mistag probability with free calibration parameters (different trigger&selection with respect to the $B^+ \to J/\psi K^+$ channel.)

	ϵ_{eff}	$p_0 - <\eta>$	p_1
OS	3.4±0.9%	-0.015±0.021±0.004	0.61±0.20±0.15
SSπ+OS	4.3±1.0%	-0.011±0.016±0.002	0.69±0.16±0.05

$B_d^0 - \bar{B}_d^0$ oscillations

LHCb-CONF-2011-010 [4]

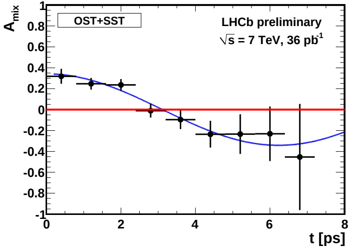
$\Delta m_d = 0.499 \pm 0.032(\text{stat}) \pm 0.003(\text{sys})\ ps^{-1}$

($\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$ world average, PDG [1])

Systematic uncertainties on Δm_d

source	$\Delta(\Delta m_d)$ [ps^{-1}]
proper time resolution [40-63] fs	0.000
proper time acceptance	0.002
variation of PDF(η)	0.000
floating fit parameters	0.001
double Gaussian mass signal PDF	0.001
z-scale ($\sim$0.1%)	0.0005
momentum scale ($\sim$0.1%)	0.0005
Sum	**0.003**

$B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ 6k (signal)

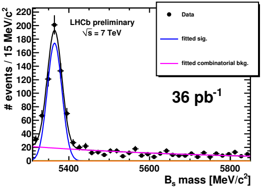


$B_s^0 - \bar{B}_s^0$ oscillations

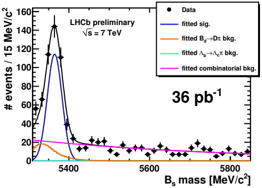
LHCb-CONF-2011-005 [5]

Combine several final states to add statistics:

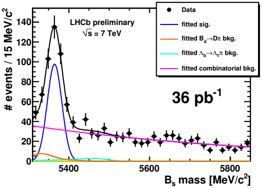
$B_s \rightarrow D_s^-(\phi\pi^-)\pi^+$: (515 ± 25 ev.)



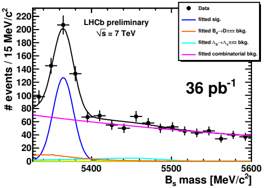
$B_s \rightarrow D_s^-(K^*K)\pi^+$: (338 ± 27 ev.)



$B_s \rightarrow D_s^-(K^+K^-\pi^-)\pi^+$: (283 ± 27 ev.)



$B_s \rightarrow D_s^-(K^+K^-\pi^-)3\pi$: (245 ± 46 ev.)

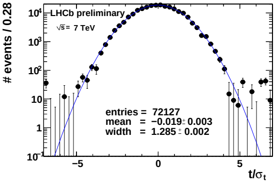


σ_m=18.1 MeV/c^2 $(D_s\pi)$, 12.7 MeV/c^2 $(D_s 3\pi)$

$B_s^0 - \bar{B}_s^0$ oscillations

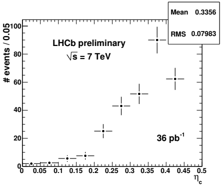
LHCb-CONF-2011-005 [5]

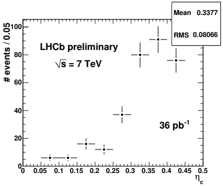
- Use *per-event* time resolution → calibration on data using prompt $D_s\&\pi$: $\mathcal{S}_{\sigma_t} = 1.3$
  - $<\sigma_t>=$ 44 fs ($D_s\pi$), 36 fs ($D_s 3\pi$)



- Use *per-event* mistag probability (OS only) re-calibrated in $B^0 \to D^-\pi^+$ channel
  Uncertainties on the calibration parameters propagated
  - $\epsilon_{eff}^{OS} = 3.8 \pm 2.1$ %

$PDF(\eta)$ (signal)





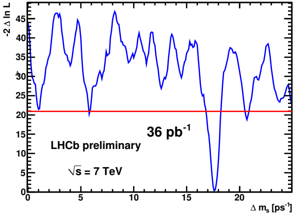
$PDF(\eta)$ (background)

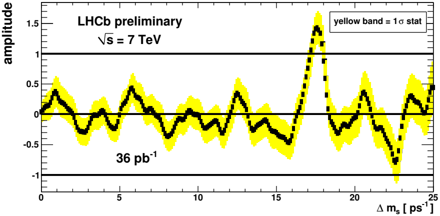
- Proper time acceptance from Monte Carlo.

$B_s^0 - \bar{B}_s^0$ oscillations

Clear dip at $\Delta m_s \sim 17.6 ps^{-1}$
the observed mixing signal
has 4.6σ significance.

Amplitude scan:
all parameters fixed except $\mathcal{A}$
$\mathcal{A}$=1.41±0.26 for Δm_s =17.6 (1.6σ from $\mathcal{A}$=1)





$B_s^0 - \bar{B}_s^0$ mixing frequency

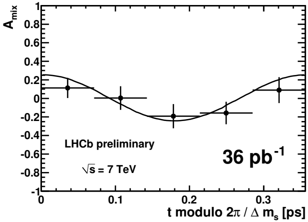
$\Delta m_s = {}^a\ 17.63 \pm 0.11(\text{stat}) \pm 0.04(\text{sys})\ ps^{-1}$

($\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{sys})\ ps^{-1}$ CDF, 2006 [2])

Systematic uncertainties on Δm_s

source	$\Delta_{\Delta m_s}$[ps^{-1}]
proper time resolution $\mathcal{S}_{\sigma_t} = [1.2 - 1.4]$	0.006
proper time resolution model	0.001
proper time acceptance function	0.000
fixed parameters floating	0.003
diff. background shape in mass fit	0.010
phys. bkg mass templates	0.002
variation of η and σ_t PDFs	0.026
z-scale (0.1%)	0.018
momentum scale (0.1%)	0.018
$\Delta\Gamma_s = [0 - 0.2] \times \Gamma_s$	0.002
total systematic uncertainties	**0.038**

asymmetry modulo $2\pi/\ \Delta m_s$



Nice prospects for an improvement of the Δm_s measurement in the (near) future

[a] Assumption: $\Delta\Gamma_s = 0.1 \times \Gamma_s$

Conclusions

With the statistics of $\int \mathcal{L} \cdot dt \sim 35 pb^{-1}$ collected by LHCb in 2010

- Optimization of **OS & SSπ+OS flavour tagging** performances using different control channels: $B^0 \to D^{*-}\mu^+\nu_\mu$, $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$
    - $B_s^0 \to D_s^- \pi^+$ sample too small to study SSK tagger ($\to$ not used)

  performance agree within errors:

    - Tagging power: $<\epsilon_{tag}^{\mathrm{OS}}>$=1.99±0.15% (~CDF); $<\epsilon_{tag}^{\mathrm{SS}\pi+\mathrm{OS}}>$=2.64±0.22%;
    - mistag: $<\omega^{\mathrm{OS}}>$=32.9±0.7%; $<\omega^{\mathrm{SS}\pi+\mathrm{OS}}>$=34.1±0.6%.

  Good margins of improvement with improved statistics (better optimization & calibration, SSK)

- The mistag probability was calibrated in $B^+ \to J/\psi K^+$ and cross-checked in $B^0 \to J/\psi K^{*0}$. It can be exported to the analysis of $B_s^0 \to J/\psi \phi$ channel.
- Validation of the tagging in a physics analysis:
    - measurement of the $B_d^0 - \bar{B}_d^0$ mixing frequency using $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$: Δm_d **= 0.499±0.032(stat)±0.003(sys)** ps^{-1}
    - measurement of the $B_s^0 - \bar{B}_s^0$ mixing frequency using $B_s^0 \to D_s^-(K^+K^-\pi^-)(3)\pi$: Δm_s **= 17.63±0.11(stat)±0.04(sys)** ps^{-1}
      Already reached the CDF precision. Prospects of improvements in the next future

- K.Nakamura, et al. (PDG coll.) Journal of Phys. G **37**, 7A, 075021 (2010)
- A.Abulencia, et al. (CDF coll.) Phys. Rev. Lett. **97**, 242003 (2006)
- (LHCb coll.) "Optimization and calibration of the LHCb avour tagging performance using 2010 data", LHCb-CONF-2011-003
- (LHCb coll.) "Measurement of Δm_d in $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ ", LHCb-CONF-2011-010
- (LHCb coll.) "Measurement of Δm_s in the decay $B_s^0 \to D_s^-(K^+K^-\pi^-)(3)\pi$", LHCb-CONF-2011-005.