"Flavour tagging at LHCb and measurements of B meson oscillations"

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on behalf of the LHCb collaboration

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Outline

The LHCb experiment and physics motivations

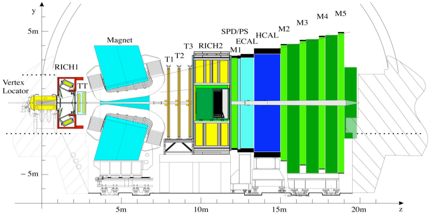
The LHCb experiment: precision studies of b and c-hadron decays (CP violation, rare decays) $\rightarrow$ test SM/indirect evidence of NP

Requirements:

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

For time dependent CP asymmetries in the B sector:

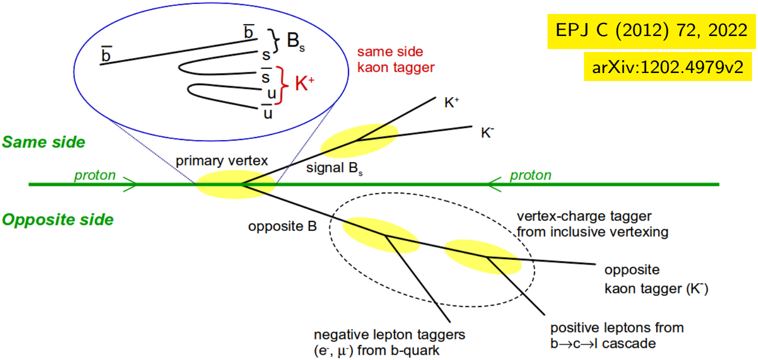
- tag the initial flavour $\rightarrow$ tagging power: particle identification, impact parameter resolution.
- Measure the B decay time $\rightarrow$ resolution (B_s^0).



LHCb detector: 2008 JINST 3 S08005

- 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)

Tag the initial B flavour



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

- μ, e ($b \rightarrow c l^- \bar{\nu}_l$), K ($b \rightarrow c \rightarrow s$), 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). Trained on MC.
  - η_i calibrated using data.

Combination of taggers based on $(q_i,\ \eta_i)$ if more than one tagger is available ($\rightarrow q,\ \eta$)

Tagging performance:

- $\varepsilon_{tag} = \frac{R+W}{R+W+U}$, $\rightarrow$ can be measured in any channel
- $\omega = \frac{W}{R+W}$ $\rightarrow$ can only be measured in flavour-specific channel and used to measure CP violation asymmetries. If η is calibrated ($=\omega$) use it ev-by-event.
- Tagging power: $\varepsilon_{eff} = \varepsilon_{tag}(1-2\omega)^2 = \varepsilon_{tag}\mathcal{D}^2$

Flavour Tagging optimization ...

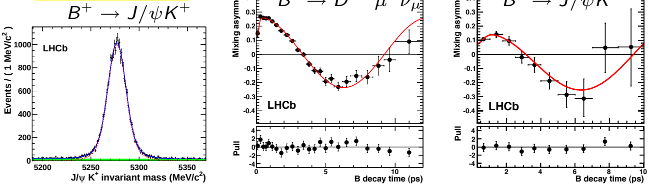
Tagging performance optimized using data and several flavour-specific channels.
AIM: to find the set of cuts that maximize the ε_{eff} of each tagger and of the combination of taggers.

Channel	Tagger	Yield ($1fb^{-1}$)	B/S	
$B^0 \to D^{*-}\mu^+\nu_\mu$	OS & SSπ	1.3M	~0.14	largest control channel
$B^+ \to J/\psi K^+$	OS & SSπ	250k	~0.034	reference for $B_s^0 \to J/\psi\phi$
$B^0 \to J/\psi K^{*0}$	OS & SSπ	107k	~0.40	useful for $B_s^0 \to J/\psi\phi$
$B^0 \to K^+\pi^-$	OS & SSπ	20k	~0.5	reference for $B^0 \to H^+H^-$
$B^0 \to D^-\pi^+$	OS & SSπ	170k	~0.04	reference for $B_s^0 \to D_s^-\pi^+$
$B^+ \to \bar{D}^0\pi^+$	OS & SSπ	130k	~0.02	useful for $B_s^0 \to D_s^-\pi^+$
$B_s^0 \to D_s^-\pi^+$	OS & SSK	26k	~0.1–0.4	the only c.c. for SSK

Determine the mistag:

- For B^+ just compare the tag decision with the observed flavour: $\omega = W/(R+W)$
- For B^0 fit the time-dependent mixing asymmetry: $\mathcal{A}(t) \propto (1 - 2\,\omega)\cos(\Delta m t)$

EPJ C (2012) 72, 2022



... and calibration

2011 data sample $1fb^{-1}$

LHCb-CONF-2012-026

Use the $B^+ \to J/\psi K^+$ channel to perform the calibration of the predicted mistag, η

- first to the single taggers
- then to the combination (OS), to account for the correlation among taggers.

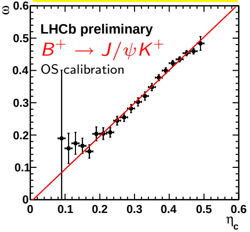
Linear parametrization:

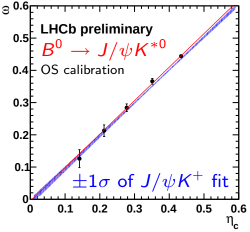
- $\omega = p_0 + p_1(\eta - \langle\eta\rangle) \qquad \to \eta_c$

p_0=0.392±0.002±0.009 p_1=1.035±0.021±0.012 $\langle\eta_c\rangle = 0.391$

- systematic uncertainties account for differences related to signal B flavour, tag decision, running conditions.

The calibration is validated using other control channels ($B^0 \to J/\psi K^{*0}$, $B^0 \to D^{*-}\mu^+\nu_\mu$, ...).





Flavour Tagging optimized performance

- Single tagger performances:

$B^+ \to J/\psi K^+$, 2011 data, $1 fb^{-1}$, LHCb-CONF-2012-026

	ε_{tag} (%)	ω (%)	$\varepsilon_{tag}\mathcal{D}^2$ (%)
μ	5.20±0.04	30.8±0.4	0.77±0.04
e	2.46±0.03	30.9±0.6	0.36±0.03
K	17.67±0.08	39.33±0.24	0.81±0.04
$Q_{\rm vtx}$	18.46±0.08	40.31±0.24	0.70±0.04

- OS combination (using per-event mistag):

2011 data, $0.37 fb^{-1}$, EPJ C (2012) 72, 2022

	ε_{tag} (%)	ω (%)	$\varepsilon_{tag}\mathcal{D}^2$ (%)
$B^+ \to J/\psi K^+$	27.3±0.1	36.1±0.3±0.8	2.10±0.08±0.24
$B^0 \to J/\psi K^{*0}$	27.3±0.3	36.2±0.3±0.8	2.09±0.09±0.24
$B^0 \to D^{*-}\mu^+\nu_\mu$	30.1±0.1	35.5±0.3±0.8	2.53±0.10±0.27

- differences among channels are due to different trigger

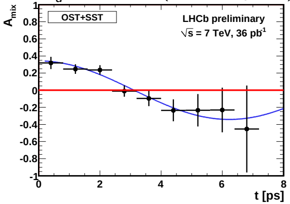
$B^0_{d/s} - \bar{B}^0_{d/s}$ oscillations: mixing frequencies

Measurement of the $B^0_d - \bar{B}^0_d$ mixing frequency LHCb-CONF-2011-010

Preliminary:
$\Delta m_d = 0.499 \pm 0.032(\text{stat}) \pm 0.003(\text{sys})\ ps^{-1}$
($\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$ world average, PDG)

	$\varepsilon_{tag}\mathcal{D}^2$
OS	3.4±0.9%
SSπ+OS	4.3±1.0%

$B^0_d \to D^- \pi^+$ (6k in 36 pb^{-1})



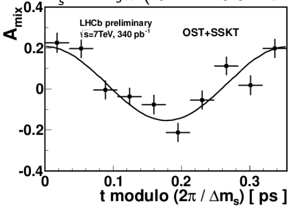
Measurement of the $B^0_s - \bar{B}^0_s$ mixing frequency Phys.Lett.B 709 (2012) 177, LHCb-CONF-2011-50

Preliminary (most precise):
$\Delta m_s = 17.725 \pm 0.041(\text{stat}) \pm 0.026(\text{sys})\ ps^{-1}$

	$\varepsilon_{tag}\mathcal{D}^2$
OS	3.2±0.8%
SSK	1.3±0.4%

SSK preliminary optimization using prompt $D_s^{\pm} \to \phi\pi^{\pm}$

$B^0_s \to D_s\pi$ (9.2k in 0.34 fb^{-1})



$B^0_{d/s} - \bar{B}^0_{d/s}$ oscillations: mixing phases

Measurement of $\sin(2\beta)$ in $B^0 \to J/\psi K^0_s$

LHCb-CONF-2011-004

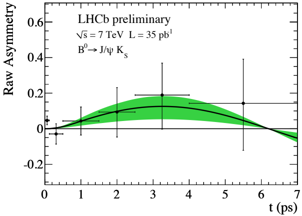
Preliminary:

$S_{J/\psi K^0_s} = 0.53^{+0.28}_{-0.29}(\text{stat.}) \pm 0.05(\text{sys})$

($\sin(2\beta) = 0.673 \pm 0.023$ World average, PDG)

	$\varepsilon_{tag}\mathcal{D}^2$
SSπ+OS	2.82±0.87%

$B^0_d \to J/\psi K^0_s$ (1.3k in 35 pb^{-1})



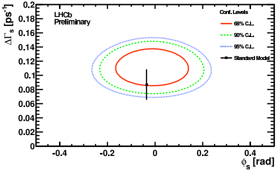
Most precise measurement of the $B^0_s - \bar{B}^0_s$ mixing phase ϕ_s and $\Delta\Gamma_s$ (→ see G.Cowan's presentation)

LHCb-CONF-2012-002, Phys.Rev.Lett. 198 (2012) 101803,

Phys.Lett.B 707 (2012) 497, arXiv:1204.5675

OS	$\varepsilon_{tag}\mathcal{D}^2$	
$B^0_s \to J/\psi\phi$	2.29±0.07±0.26%	(*)
$B^0_s \to J/\psi f_0(980)$	2.12±0.26%	
$B^0_s \to J/\psi\pi\pi$	2.43±0.08±0.26%	(*)

$B^0_s \to J/\psi\phi$ (21.2k in 1 fb^{-1})



(*) OS reoptimized on the full 1.0 fb^{-1} 2011 data

Summary

Flavour tagging is a fundamental ingredient for measurements of B^0 oscillations and time-dependent CP asymmetries.

Using flavour-specific decays it is possible to measure, optimize and calibrate the performance of flavour tagging on data.

- several channels used as reference or validation:
  - OS&SSπ: $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to D^{*-}\mu^+\nu_\mu$, $B_d^0 \to D^-\pi^+$
  - SSK: preliminary optimization using prompt $D_s^\pm \to \phi\pi^\pm$

Flavour tagging was already used in several physics measurements:

- best measurement of $\Delta m_s = 17.725 \pm 0.041(\text{stat}) \pm 0.026(\text{sys})\ ps^{-1}$
- best measurement of ϕ_s ($\to$ see G.Cowan's presentation)

Prospects:

- SSK improved tagging power that requires the whole 2011 data sample of 1 fb^{-1} of $B_s^0 \to D_s^-\pi^+$ for optimization and calibration

Backup

Flavour Tagging: combination of taggers

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

- In case multiple taggers give a response use (q_i,η_i) to achieve the best combination and to determine the combined probability:

$$p(b) = \prod_i \left(\frac{1+q_i}{2} - q_i(1-\eta_i) \right), \quad p(\bar{b}) = \prod_i \left(\frac{1-q_i}{2} + q_i(1-\eta_i) \right)$$

$$P(b) = \frac{p(b)}{p(b)+p(\bar{b})}, \quad P(\bar{b}) = 1 - P(b)$$

  - the combined tagging decision is d=–1 and $\eta=1-P(b)$ if $P(b) > P(\bar{b})$ (d=+1 and $\eta=1-P(\bar{b})$ otherwise)

- Use η event-by-event in CP analyses to re-weight the events $\rightarrow$ increase the overall tagging power:

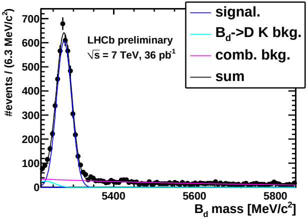
$$\varepsilon_{eff}^{ev-by-ev} = \frac{1}{N}\sum_i^{R+W} \mathcal{D}_i^2 \; > \; \varepsilon_{tag}\langle\mathcal{D}\rangle^2 = \varepsilon_{eff}$$

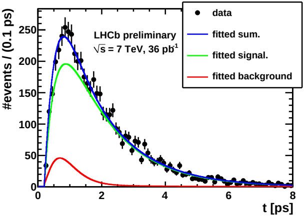
- Use η to separate the events in **categories** of events with similar mistag & gain in tagging performances (statistical independent samples)

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

LHCb-CONF-2011-010 [?]

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





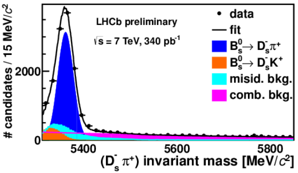
- Use a double Gaussian *time resolution model* from Monte Carlo ($<\sigma_t>$=49fs)
- proper time acceptance from Monte Carlo
- Use *per-event* mistag probability with free calibration parameters (different trigger&selection with respect to the $B^+ \to J/\psi K^+$ channel.)

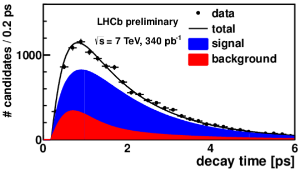
Systematic uncertainties on Δm_d

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**

$B_s^0 - \bar{B}_s^0$ oscillations   LHCb-CONF-2011-050 [?]

Analysis of $B_s^0 \to D_s^- \pi^+$ channel: 9.2k signal events from $D_s^- \to \phi\pi^-$, $K^* K^-$ and non res. $K^+ K^- \pi^-$





- Use *per-event* time resolution $\rightarrow$ calibration on data using prompt $D_s\&\pi$: $\mathcal{S}_{\sigma_t} = 1.37 \pm 0.01$
  - $<\sigma_t>=$ 45 fs ($D_s\pi$)
- Tagging:
  - OS: Use *per-event* mistag probability
  - SSK: use the decision fit for an average value
  - OS&SSK: choose one with the best predicted mistag

  $\epsilon_{eff}^{OS+SSK} = 4.3 \pm 0.9$ %
- Proper time acceptance from Monte Carlo.

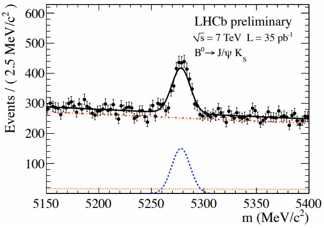
Systematic uncertainties on Δm_s

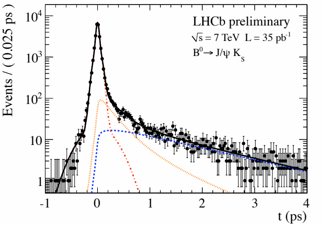
source	$\Delta_{\Delta m_s}$[ps^{-1}]
decay time resolution $\mathcal{S}_{\sigma_t}$ =[1.25-1.45]	0.001
decay time resolution model	0.001
decay time acceptance	0.000
diff. signal shape in mass fit	0.003
variation of η and σ_t PDFs	0.001
z-scale (0.1%)	0.018
momentum scale (0.1%)	0.018
$\Delta\Gamma_s = [0 - 0.2] \times \Gamma_s$	0.002
total systematic uncertainties	**0.026**

Measurement of $\sin(2\beta)$ in $B^0 \to J/\psi K_s^0$

LHCb-CONF-2011-004

- 280 signal tagged events (trigger "unbiased" & "biased")
- use event-by-event mistag (calibrated on $B^0 \to J/\psi K^{*0}$)





$$S_{J/\psi K_s^0} = 0.53^{+0.28}_{-0.29} \pm 0.05$$

$\sin(2\beta) = 0.673 \pm 0.023$ World average

Systematic uncertainties to S in absolute terms.

Source	uncertainty
tagger calibration	0.044
per-event mistags p.d.f.	0.016
Δm_d uncertainty, z scale	0.0017
proper time resolution	0.0085
high propertime acceptance	0.00018
biased events acceptance	0.0039
biased TIS events acceptance	0.0063
production asymmetry	0.024
total (sum in squares)	0.054

Flavour tagging: comparison with other experiments

	experiment	$\varepsilon_{tag}\mathcal{D}^2$ %	notes
OS	LHCb	2.1±0.1	$B \rightarrow J/\psi X$ channels
		2.5±0.1	$B^0 \rightarrow D^{*-}\mu^+\nu_\mu$
		3.4±0.9	$B_{(s)} \rightarrow D_{(s)}\pi$ channels
	CDF	1.54±0.05	$B \rightarrow D\mu X$
		1.2±0.2	$B^+ \rightarrow J/\psi K^+$
	D0	2.48±0.21	$B \rightarrow D\mu X$
	B-factories	∼30	coherent $B - \bar{B}$ production
SSK	LHCb	1.3±0.4	preliminary optimization using prompt D_s
	CDF	3.5±1.4	$B_s^0 \rightarrow D_s(3)\pi$
OS&SSK	D0	4.68±0.54	for $B_s^0 \rightarrow J/\psi\phi$