Flavour Tagging at LHCb

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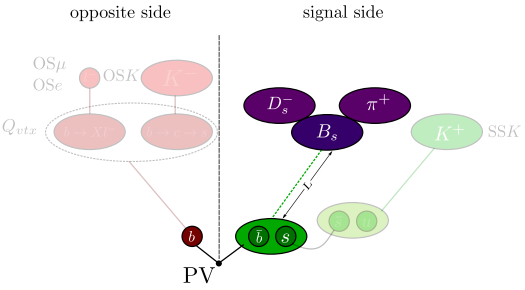
B_s^0-$\overline{B}_s^0$ oscillation frequency Δm_s
CP violating phase ϕ_s

How do we measure mixing?

- B_s^0 reconstruction and selection
- B_s^0 decay time and decay time resolution: $t = \frac{Lm_B}{p}$
- B_s^0 production flavour: Flavour Tagging (main challenge at hadron colliders)

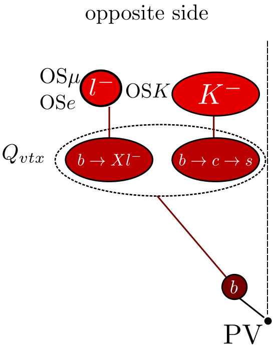


Time dependent asymmetry measurement:

$$\mathcal{A}_{\text{meas}}(t) = \frac{N(t)_{\text{unmixed}} - N(t)_{\text{mixed}}}{N(t)_{\text{unmixed}} + N(t)_{\text{mixed}}} = \mathcal{D}\mathcal{A}_{\text{theo}}(t)$$

Opposite side taggers

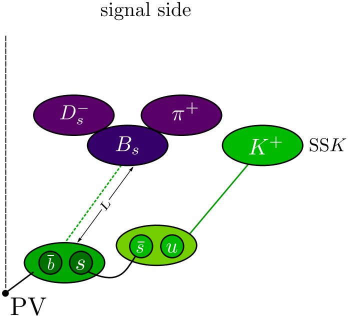
- exploit the decay of the associated b hadron
- Advantages:
  - OS taggers are independent of the signal B decay
  - $\Rightarrow$ developed on high statistics flavour specific decay channels



- Challenges:
  - high track multiplicity
  - b and $\overline{b}$ are not entangled: the opposite B^0/ B_s^0 can also oscillate
  - $\Rightarrow$ high mistag probability ($\sim 30 - 40\%$)

Signal side taggers

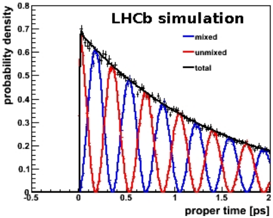
- exploit the fragmentation tracks of the signal b hadronization
- Advantages:
  - possible at hadron colliders
  - uncorrelated to OS taggers



- Challenges:
  - high track multiplicity
  - depends strongly on signal B^0/ B_s^0 decay
  - need to resolve oscillation of signal decay

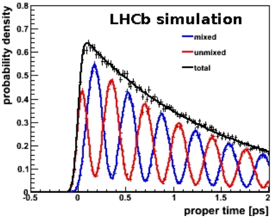
  $\Rightarrow$ high mistag probability ($\sim 35\%$)

How to quantify tagging performance



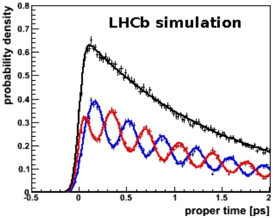
ideal case:

- no *ct* resolution
- no tagging dilution



more realistic case:

- *ct* resolution
- no tagging dilution



realistic case:

- *ct* resolution
- tagging dilution

- mixing amplitude is heavily damped by tagging dilution $\mathcal{D} = (1 - 2\omega)$
- figure of merit: $\varepsilon_{\text{tag}}\mathcal{D}^2$

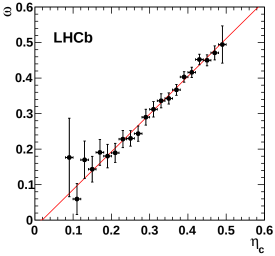
$\Rightarrow$ represents the statistical power of the data sample

mistag probability: $\omega = \frac{\text{wrong tagged events}}{\text{all tagged events}}$, tagging efficiency: $\varepsilon_{\text{tag}} = \frac{\text{all tagged events}}{\text{all events}}$

Tagger Development

- For each individual tagger:
  - cut based selection: charge of highest p_T track
  - Neural Net predicts mistag probability η
  - calibrate measured mistag probability $\omega(\eta)$
  - $\Rightarrow$ calibration universal for all channels
  - $\Rightarrow$ use event-by-event ω to increase $\varepsilon_{\text{tag}} D^2$
- combination of taggers (decisions and mistag probabilities)
- for *CP* asymmetries: crucial to calibrate ω as well separately for B and $\overline{B}$
- further developments ongoing

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



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

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

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

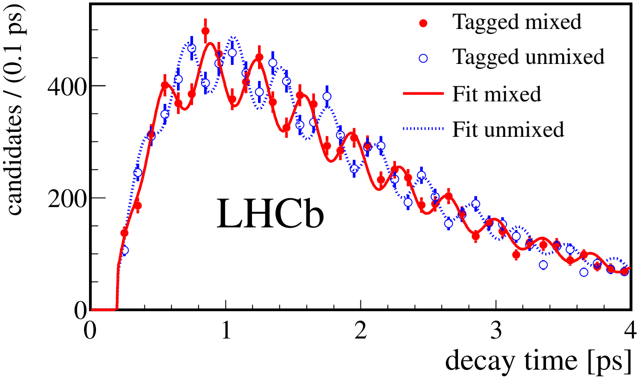
Flavour Tagging Performance

- 1.0 fb^{-1} of data, collected in 2011
- OS measured in 250k $B^+ \to J/\psi K^+$ decays
- SS measured in 26k $B_s^0 \to D_s^- \pi^+$ decays

tagger	$\varepsilon_{\rm tag}(\%)$	$\omega(\%)$	$\varepsilon_{\rm tag} D^2(\%)$
OSμ	5.20 ± 0.04	30.8 ± 0.4	0.77 ± 0.04
OSe	2.46 ± 0.03	30.9 ± 0.6	0.36 ± 0.03
OSK	17.67 ± 0.08	39.33 ± 0.24	0.81 ± 0.04
Q_{vtx}	18.46 ± 0.08	40.31 ± 0.24	0.70 ± 0.04
SSK	16.3 ± 0.4	35.3 ± 2.1	1.4 ± 0.4

Eur. Phys. J. C (2012) 72:2022, LHCb-CONF-2012-026, LHCb-CONF-2012-033

Δm_s Result: most precise measurement to date



- data: 1 fb^{-1} @ 7 TeV (2011)
- 34k $B_s^0 \to D_s^- \pi^+$ signal deacys
- OST: $\varepsilon_{\mathrm{tag}} D^2 = (2.6 \pm 0.4)\%$
- SST: $\varepsilon_{\mathrm{tag}} D^2 = (1.2 \pm 0.3)\%$
- $\sigma_\tau = 44\,\mathrm{fs}$
- main syst.: longitudinal scale, momentum scale

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

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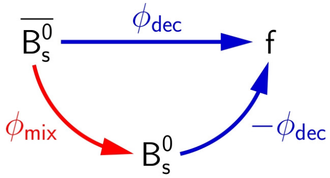
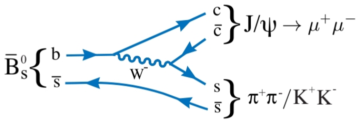
CP violating phase ϕ_s

- *CP* violation: interference between mixing and decay

$$\phi_s = \phi_{mix} - 2\phi_{dec}$$



- $b \to c\bar{c}s$: dominated by tree-level amplitude



⇝ all *CP* violation induced by mixing

- ϕ_s small in SM [1]

$$\phi_s^{SM} = -2\beta_s = -0.0363^{+0.0016}_{-0.0015}\,\text{rad}$$

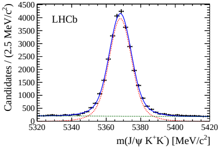
⇒ enhancement ≙ sign for New Physics

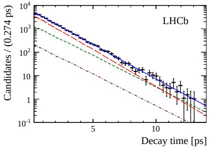
[1] J. Charles et al., Phys. Rev. D84 (2011) 033005, http://ckmfitter.in2p3.fr

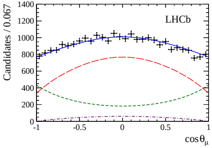
Measure ϕ_s

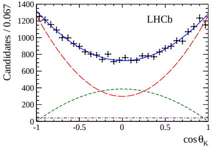
- $B_s^0 \to J/\psi K^+ K^-$ polarizations:
  - P-wave ($\phi(1020)$): *CP*-even and *CP*-odd
  - S-wave: *CP*-odd
- $B_s^0 \to J/\psi \pi^+ \pi^-$ polarizations:
  - S-wave: *CP*-odd fraction > 0.977 @ 95%
- opposite oscillations for *CP* even and *CP* odd

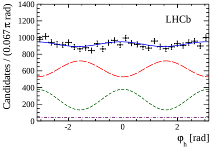
$\Rightarrow$ 4 dim maximum likelihood fit: decay time, 3 angles











all: solid, *CP*-even: long-dashed, *CP*-odd: short-dashed, S-wave: dotted-dashed

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ϕ_s Ingredients

- 1 fb^{-1} data, 2011, @ 7 TeV
- $B_s^0 \to J/\psi K^+K^-$: 28k decays
- $B_s^0 \to J/\psi \pi^+\pi^-$: 8k decays
- decay time resolution $\approx$ 45 fs

tagger	$\varepsilon_{\text{tag}}(\%)$	$\omega(\%)$	$\varepsilon_{\text{tag}}D^2(\%)$
OS	33.00 ± 0.06	36.83 ± 0.15	2.29 ± 0.06
SSK	10.26 ± 0.18	45.66 ± 0.77	0.89 ± 0.17

- overall tagging power: $\varepsilon_{\text{tag}}D^2 = (3.13 \pm 0.12 \pm 0.20)\%$

$\Rightarrow$ $\varepsilon_{\text{tag}}D^2$ slightly different wrt control channel, but calibration is valid

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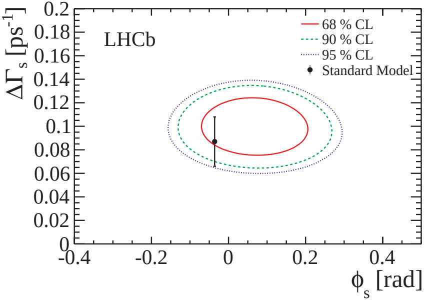
Results

$B_s^0 \to J/\psi K^+ K^-$ only:



$B_s^0 \to J/\psi K^+ K^-$ & $B_s^0 \to J/\psi \pi^+\pi^-$ combined:

Parameter	Value
Γ_s [ps^{-1}]	$0.661 \pm 0.004 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.106 \pm 0.011 \pm 0.007$
ϕ_s [rad]	$0.01 \pm 0.07 \pm 0.01$

SM expectation: $\Delta\Gamma_s = 0.082 \pm 0.021\,\mathrm{ps}^{-1}$, $\phi_s = -0.036 \pm 0.002\,\mathrm{rad}$

J. Charles et al., Phys. Rev. D84 (2011) 033005, `http://ckmfitter.in2p3.fr`

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Summary

- Flavour Tagging is:
  - a crucial ingredient for time dependent *CP* measurements
  - a challenging task at hadron colliders

  ⇒ ongoing improvement in tagger development
- Most precise measurement for Δm_s performed by LHCb:

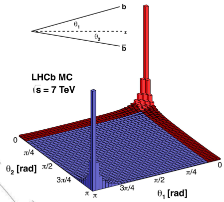
$$\Delta m_s = 17.768 \pm 0.023(\mathrm{stat}) \pm 0.006(\mathrm{syst})\,\mathrm{ps}^{-1}$$

- First direct observation of a non-zero value of $\Delta\Gamma_s$ by LHCb:

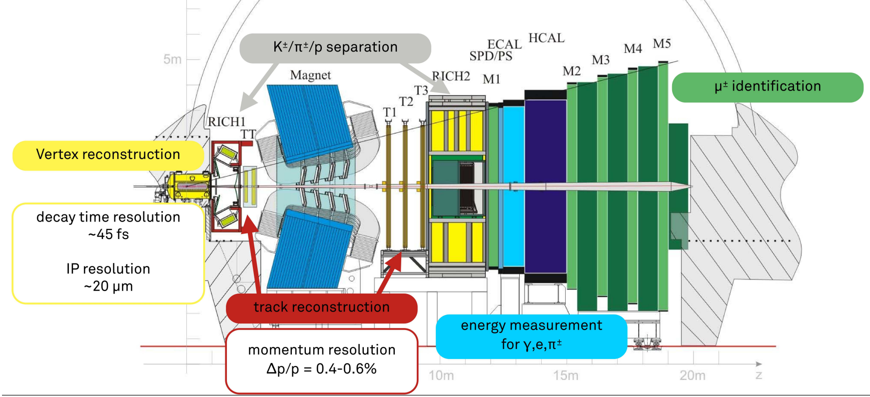
$$\Delta\Gamma_s = (0.106 \pm 0.011 \pm 0.007)\,\mathrm{ps}^{-1}$$

$$\phi_s = (0.01 \pm 0.07 \pm 0.01)\,\mathrm{rad}$$

The LHCb Detector

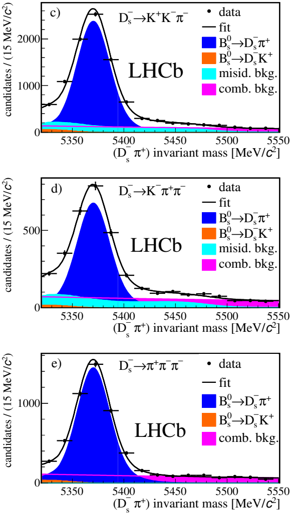


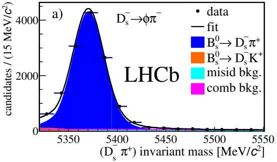
- single arm spectrometer (2 < η < 5)
- correlated (incoherent) production of *b* quark pairs in *pp*-collisions
  - harsh hadronic environment requires efficient triggers
  - dedicated for the study of *b* and *c* hadrons

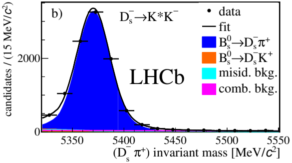


Mass Fits for Δm_s

- 34k $B_s^0 \to D_s^- \pi^+$ decays in 1.0 fb^{-1} data (2011)
- with 5 D_s^- decay modes (flavour specific):
  - $D_s^- \to \phi(K^+K^-)\pi^-$
  - $D_s^- \to K^{*0}(K^+\pi^-)K^-$
  - $D_s^- \to K^+K^-\pi^-$ nonresonant
  - $D_s^- \to K^-\pi^+\pi^-$
  - $D_s^- \to \pi^-\pi^+\pi^-$
- mass fit: double CB (signal) + exp. (bkg)
- misid. bkg. from B^0 and Λ_b^0 decays







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Δm_s systematics

dominant: absolute value of the decay time

- longitudinal scale $\rightarrow$ 0.02% on decay time scale $\rightarrow \pm 0.004\,\mathrm{ps}^{-1}$ on Δm_s
- overall momentum scale, semi cancellation by taking inv mass and momentum, simulation: 0.02% on decay time scale $\rightarrow \pm 0.004\,\mathrm{ps}^{-1}$ on Δm_s
- possible bias of the measured decay time (track reconstruction, selection procedure) $\leq 2\,\mathrm{fs} \rightarrow \pm 0.001\,\mathrm{ps}^{-1}$ on Δm_s

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ϕ_s result $B_s^0 \to J/\psi K^+ K^-$

Table: Results of the maximum likelihood fit for the principal physics parameters. The first uncertainty is statistical and the second is systematic.

Parameter	Value
Γ_s [ps^{-1}]	$0.663 \pm 0.005 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.100 \pm 0.016 \pm 0.003$
$\|A_\perp\|^2$	$0.249 \pm 0.009 \pm 0.006$
$\|A_0\|^2$	$0.521 \pm 0.006 \pm 0.010$
$\delta_\parallel$ [rad]	$3.30\,^{+0.13}_{-0.21} \pm 0.08$
$\delta_\perp$ [rad]	$3.07 \pm 0.22 \pm 0.07$
ϕ_s [rad]	$0.07 \pm 0.09 \pm 0.01$
$\|\lambda\|$	$0.94 \pm 0.03 \pm 0.02$

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ϕ_s result $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ combined

Table: Results of combined fit to the $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ datasets. The first uncertainty is statistical and the second is systematic.

Parameter	Value
Γ_s [ps^{-1}]	$0.661 \pm 0.004 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.106 \pm 0.011 \pm 0.007$
$\lvert A_\perp\rvert^2$	$0.246 \pm 0.007 \pm 0.006$
$\lvert A_0\rvert^2$	$0.523 \pm 0.005 \pm 0.010$
$\delta_\parallel$ [rad]	$3.32\,^{+0.13}_{-0.21} \pm 0.08$
$\delta_\perp$ [rad]	$3.04 \pm 0.20 \pm 0.07$
ϕ_s [rad]	$0.01 \pm 0.07 \pm 0.01$
$\lvert\lambda\rvert$	$0.93 \pm 0.03 \pm 0.02$

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ϕ_s systematics

Table: Statistical and systematic uncertainties.

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp \rvert^2$	$\lvert A_0 \rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	–	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	–	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Ang. acc. reweighting	0.0007	–	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	–	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	–	–	–	–	–	–
Upper decay time acc. model	0.0040	–	–	–	–	–	–	–
Length and mom. scales	0.0002	–	–	–	–	–	–	–
Fit bias	–	–	0.0010	–	–	–	–	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.07	0.009	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.091	0.038

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