b-flavour tagging in *pp* collisions at LHCb

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Forward spectrometer ($2 < \eta < 5$) optimized for b- and c- hadron physics.

High-precision measurements in flavour physics (CKM, beyond SM...).

Collected data:

- 2010-2012 (RunI, $\approx 3\text{fb}^{-1}$) + 2015 ($\approx 320\text{pb}^{-1}$).
- More than 26×10^{10} $b\bar{b}$ pairs, all b- and c- hadron species (B, Λ_b, Ω_b...).

Excellent performances [Int. J. Mod. Phys. A 30, 1530022 (2015)]:

- Momentum resolution: $\frac{\sigma_p}{p} \approx 0.5\text{-}0.8\ \%$ ($p < 100$ GeV/c).
- Impact Parameter (IP) resolution: $\sigma_{IP} \approx 20\ \mu\text{m}$ (at high p_T).
- Decay time resolution: $\sigma_t \approx 50$ fs.
- Particle Identification (PID): $\epsilon(K) \approx 95\%$, π mis-ID$\approx 5\%$ ($p < 100$ GeV/c).

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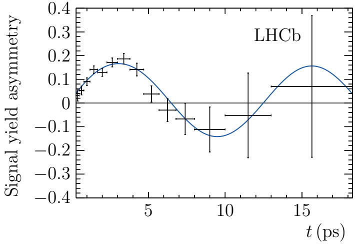
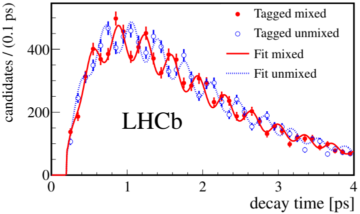
Why Flavour Tagging?



$B^0 \to J/\psi K^0_S$ [PRL 115, 031601 (2015)]



$B^0_s \to D_s^- \pi^+$ [New J. Phys. 15 (2013) 053021]

Measurements of time-dependent asymmetries and decay rates require knowledge of **B flavour at the production time:**

$$\frac{\Gamma(\bar{B} \to f) - \Gamma(B \to f)}{\Gamma(\bar{B} \to f) + \Gamma(B \to f)} \propto$$

$$S \sin(\Delta m t) - C \cos(\Delta m t)$$

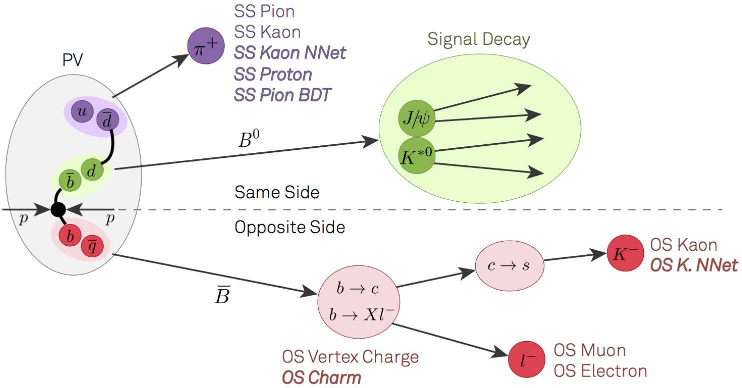
$$\Gamma(B \to f) \propto e^{-t/\tau} [\ldots \pm \cos(\Delta m t) + \ldots$$

Flavour tagging algorithms tag the candidate as B or $\bar{B}$ (*tag decision*) with some efficiency and mistag probability.

See Mirco Dorigo's talk on CP violation and mixing (08/03/2016).

Flavour Tagging Algorithms

Same Side (SS): correlation between flavour of the b-hadron and charge of the particle (pion, kaon, proton) produced next to the signal b-hadron in the hadronisation process.



Opposite Side (OS): correlation between flavour of the b-hadron and charge of a particle (pion, kaon, lepton, charmed hadron) or the reconstructed secondary vertex produced from the other b-hadron in the event.

Relevant Quantities

Efficiency: fraction of tagged events.

$$\epsilon_{\text{tag}} = \frac{N_{\text{tag}}}{N_{\text{tag}} + N_{\text{untag}}}$$

$\Rightarrow$ Depends of p_T spectrum of signal B.

Mistag fraction: fraction of events with wrong tag decision.

$$\omega = \frac{N_{\text{wrong}}}{N_{\text{wrong}} + N_{\text{right}}}$$

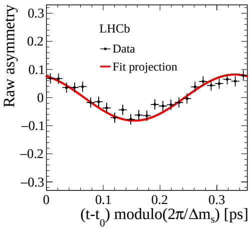
$\Rightarrow$ *Dilution* of asymmetries and decay rates.
$\Rightarrow$ Mistag probability η computed by taggers needs calibration $\omega(\eta)$ to provide unbiased estimate of ω.

Tagging power:

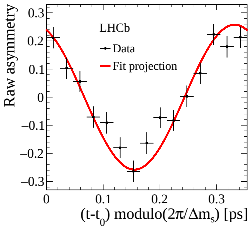
$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}} \langle (1 - 2\omega(\eta))^2 \rangle$$

$\Rightarrow$ Effect on the expected statistical uncertainty on a time-dependent asymmetry:
$\sigma \propto 1/\sqrt{\epsilon_{\text{eff}} N}$

[LHCB-PAPER-2015-056]

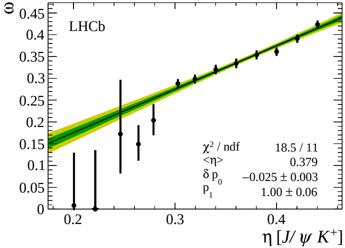


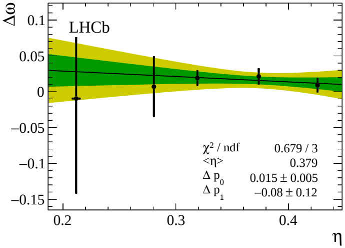
$B_s^0 \to D_s^- \pi^+$



$B_s^0 \to D_s^- \pi^+, \omega < 0.35$

Mistag Calibration





OSCharm [JINST 10 (2015) P10005]

Calibrate predicted mistag on data:

$$\omega = p_0 + p_1(\eta - \langle\eta\rangle)$$
$$\omega(B) - \omega(\bar{B}) = \Delta\omega = \Delta p_0 + \Delta p_1(\eta - \langle\eta\rangle)$$

Charged *B* decays: $B^+ \to J/\psi K^+$, $B^+ \to D^0\pi^+$
Self-tagged decays. Large statistics/small systematics.

Neutral *B* decays: $B^0 \to J/\psi K^*$, $B^0 \to D^{*-}\mu^+\nu_\mu$
Mistag ω obtained from $B - \bar{B}$ oscillation amplitude (*dilution*).
Large statistics, but more systematics.

B_s^0 decay: $B_s^0 \to D_s^-\pi^+$, $B_s^{**} \to B^+K^-$
Only data-driven modes for B_s^0. Low statistics.

Opposite Side (OS) taggers [EPJC 72:2022 (2012)]

Selection of OS leptons and kaons:
large IP and p_T, PID requirements applied.
Selection of OS secondary vertices:
two tracks with high IP and p_T, good vertex *quality*

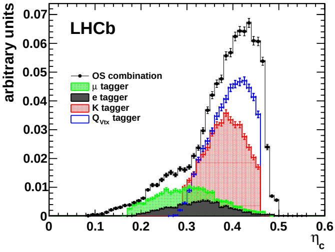
Mistag estimation from Neural Networks (NN).
Calibration on $B^+ \to J/\psi K^+$ data.
Both global information (number of tagging particles, pile-up vertices...) and tagging particle properties (kinematics...) used for training.

Tagging decision and **mistag** for each tagger (e, μ, ...) combined in a single response.

Relative increase of ϵ_{eff} by $\approx$ **15%** w.r.t 2011 analyses due to selection improvement.

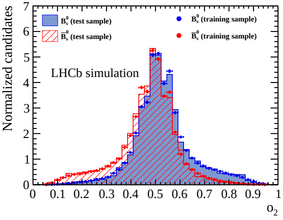
Taggers	$\varepsilon_{\rm tag}$ [%]	ω [%]	$\varepsilon_{\rm tag}(1-2\omega)^2$ [%]
μ	4.8±0.1	29.9±0.7	0.77±0.07
e	2.2±0.1	33.2±1.1	0.25±0.04
K	11.6±0.1	38.3±0.5	0.63±0.06
$Q_{\rm vtx}$	15.1±0.1	40.0±0.4	0.60±0.06
OS average (η_c <0.42)	17.8±0.1	34.6±0.4	1.69±0.10
OS sum of η_c bins	27.3±0.2	36.2±0.5	2.07±0.11

OS taggers performance

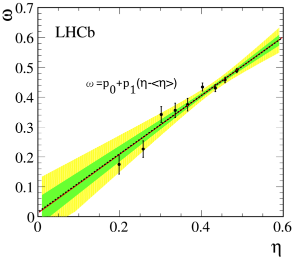


$B^+ \to J/\psi K^+$ calibrated mistag

Improving SSKaon: SSKaonNNet [LHCB-PAPER-2015-056]



NN2 output



Calibration on $B_s^0 \to D_s^- \pi^+$

SS Kaons related to the fragmentation process of the signal B_s^0.

Two NN, both trained on simulated $B_s^0 \to D_s^- \pi^+$ samples:

- NN1: discriminate fragmentation kaons from background tracks.
- NN2: determine tagging decision and mistag probability.

Calibration on $B_s^0 \to D_s^- \pi^+$ from fit to decay time distribution:

- simultaneous fit to *untagged*, *mixed* and *unmixed* samples, with η treated as observable;
- Decay rate for untagged sample:

  $$\propto (1 - \epsilon_{tag}) e^{-t/\tau_s} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right)$$

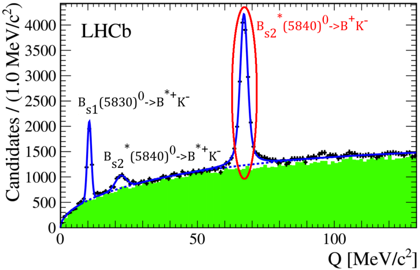
- Decay rate for mixed/unmixed samples:

  $$\propto \epsilon_{tag} e^{-t/\tau_s} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm (1 - 2\omega(\eta)) \cos(\Delta m_s t)\right]$$

  p_0 and p_1 fitted, $\langle\eta\rangle$ fixed.

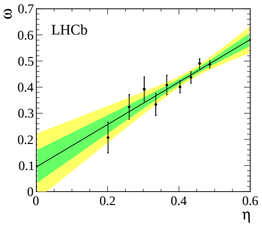
Calibration on $B_s^0 \to D_s^- \pi^+$ combined with the calibration from *self-tagged, hadronic* $B_{s2}^*(5840)^0 \to B^+ K^-$ decay:

- Assume that B_s^0 and $B_{s2}^*(5840)^0$ have the same hadronization process.
- Charge of B^+ determines flavour of $B_{s2}^*(5840)^0$. It is compared with tagger decision to calibrate η.



$Q = m_{B^+K^-} - M_{B^+} - M_{K^-}$ distribution

Calibration portability checked on $B_s^0 \to J/\psi\phi$, $B_s^0 \to D_s^+ D_s^-$ and $B_s^0 \to \phi\phi$.
Largest systematic due to different distribution of $p_T(B)$ in these decays w.r.t $B_s^0 \to D_s^- \pi^+$.



Performances (on $B_s^0 \to D_s^- \pi^+$):

$\epsilon_{tag} = (60.38 \pm 0.16)\%$

$\epsilon_{eff} = (1.80 \pm 0.19(\text{stat}) \pm 0.18(\text{syst}))\%$

Improvement $\mathcal{O}(50\%)$ w.r.t. previous SSKaon implementation.

$B_s^0 \to J/\psi K^+ K^-$ [PRL 114, 041801 (2015)]

Weak phase (combined with $B_s^0 \to J/\psi\pi^+\pi^-$):

$\phi_s = -0.010 \pm 0.039$

Most precise measurement to date.

OS Combination + SSNNetKaon:

$\epsilon_{eff} = (3.73 \pm 0.15)\%$

$+0.60\%$ **w.r.t [PRD 87, 112110 (2013)]**

Tagger	$\epsilon_{\rm eff}$
OS (Incl.)	$(2.55 \pm 0.14)\%$
SS (Incl.)	$(1.26 \pm 0.17)\%$

$B_s^0 \to D_s^+ D_s^-$ [PRL 113, 211801 (2014)]

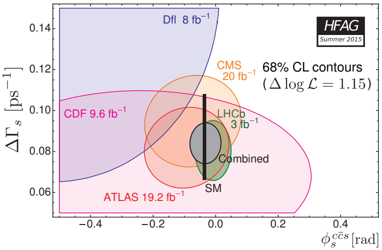
First ϕ_s measurement in this mode:

$\phi_s = 0.02 \pm 0.17(\text{stat}) \pm 0.02(\text{syst})$

OS Combination + SSNNetKaon:

$\epsilon_{eff} = (5.33 \pm 0.18(\text{stat}) \pm 0.17(\text{syst}))\%$

Tagger	$\epsilon_{\rm eff}$
OS (Incl.)	$(3.49 \pm 0.10 \pm 0.17)\%$
SS (Incl.)	$(2.37 \pm 0.23 \pm 0.18)\%$



[HFAG 2015]

Other analyses using SSKaonNNet:

$B_s^0 \to J/\psi\pi^+\pi^-$ [PLB 736, 186 (2014)]

$B_s^0 \to \phi\phi$ [PRD 90, 052011 (2014)]

$B_s^0 \to D_s^- K^+$ [JHEP 11 (2014) 060]

A new tagger: OSCharm [JINST 10 (2015) P10005]

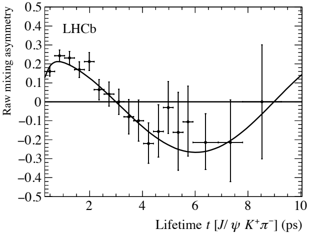
OS Charmed hadrons produced via $b \to c$ transitions:
$D^0 \to K^-\pi^+, D^+ \to K^-\pi^+\pi^+, ...$

Boosted Decision Tree (BDT) to suppress background and estimate mistag:

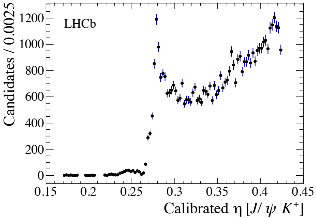
- Features: decay kinematics and vertex, c-hadron flight distance...
- Training on Monte Carlo sample.

Standalone performance on data
($B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{0*}$, $B^0 \to D^-\pi^+$, $B_s^0 \to D_s^-$):
$\epsilon_{tag} \approx 3.1 - 4.1\%$
$\epsilon_{eff} \approx 0.3 - 0.4\%$

Combination with other standard OS taggers:
Tagging power (on $B^+ \to J/\psi K^+$): absolute gain $\approx +0.11\%$ compared to standard OS only. ($\approx 2.5\%$)



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



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

Current developments (Preliminary)

- New BDT-based SSPion and SSProton taggers [CERN-THESIS-2015-040].

  BDT trained on $B^0 \to D^{\pm}\pi^{\mp}$ data with decay time $t < 2.2$ ps (to suppress oscillations).

  Mistag from time-dependent fit in bins of BDT.

  Tagging power on $B^0 \to D^{\pm}\pi^{\mp}$:
  $\epsilon_{eff} \approx$ **1.6%** for SSPion (**+20%** relative increase w.r.t standard SSPion tagger)
  $\epsilon_{eff} \approx$ **0.5%** for SSProton

- New Inclusive Tagger [ACAT 2016]

  BDT trained with features related to signal B, tracks and vertices from the entire event.

  No OS vs SS distinction.

Flavour Tagging in LHCb allows precision measurements in b-hadron physics, despite the difficult environment (*pp collider*):

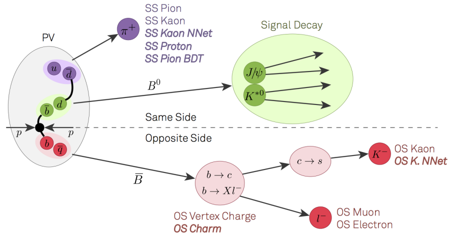
- Most precise measurement of ϕ_s.
- CP violation in $B^0 \to J/\psi K^0_S$ [PRL 115, 031601 (2015)]:
  $S = 0.731 \pm 0.035(\text{stat}) \pm 0.020(\text{syst})$
  $C = -0.038 \pm 0.032(\text{stat}) \pm 0.005(\text{syst})$
  Most precise result at hadron machines, same precision as BaBar and Belle.

OS taggers: standard algorithm for all analyses. Relative tagging power increase $\approx$ **15%** since 2011.

SSKaon: great improvement with new NN-based algorithm. Relative tagging power increase $\approx$ **50%** w.r.t previous implementation.

New results and developments:

- OSCharm: $\approx$ **4%** relative increase of tagging power for OS combination.
- BDT-based SS Pion and Proton.
- Inclusive Tagger.



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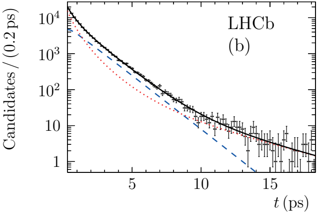
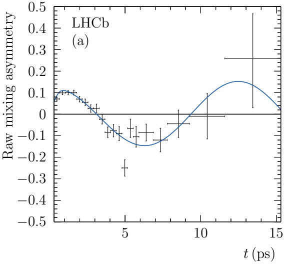
Thank you

Backup

The Golden Mode $B^0 \to J/\psi K^0_S$ [PRL 115, 031601 (2015)]



$B^0 \to J/\psi K^0_S$ decay time



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

Standard OS combination + SSPion.

Calibration on $B^+ \to J/\psi K^+$ (only OS) and $B^0 \to J/\psi K^{*0}$ (both).

Total tagging power:
$\boldsymbol{\epsilon_{eff} = (3.02 \pm 0.05)\%}$
$+0.64\%$ w.r.t [PLB 721 (2013) 24-31]
Increase due to introduction of SSPion.

Tagger	ϵ_{eff}
OSComb	$(2.63 \pm 0.04)\%$
SSPion	$(0.376 \pm 0.0024)\%$
Overlap	$(0.503 \pm 0.010)\%$

Measured CP violation:
$\boldsymbol{S = 0.731 \pm 0.035(\text{stat}) \pm 0.020(\text{syst})}$
$\boldsymbol{C = -0.038 \pm 0.032(\text{stat}) \pm 0.005(\text{syst})}$
Same precision as BaBar, Belle.
Most precise measurement at hadron machines.

More on OS taggers [EPJC 72:2022 (2012)]

Vertex Charge Tagger. Inclusive reconstruction of two tracks (under π hypothesys) compatible with a B decay vertex.
Other tracks compatible with same vertex added.
Charge of the tagging B:

$$Q_{\text{vtx}} = \frac{\sum_i Q_i p_{T_i}^k}{p_{T_i}^k}$$

Tagging power maximum for $k = 0.4$. Candidates $|Q_{\text{vtx}}| < 0.275$ rejected (*untagged*)

Tagging combination.

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

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

Mistag and tagging decision.

If $P(b) > P(\bar{b})$: $d = -1, \eta = 1 - P(b)$
If $P(\bar{b}) > P(b)$: $d = +1, \eta = 1 - P(\bar{b})$

Correlations among taggers neglected. Correction via calibration on data.

How to: mistag from NN (SSKaonNNet) [LHCB-PAPER-2015-056]

Output o_1 of NN1 used as input variable for NN2.

NN2 output:

$$P(B_s^0|o_2) = o_2 = \frac{N_{B_s^0}(o_2)}{N_{B_s^0}(o_2) + N_{\bar{B}_s^0}(o_2)}$$

But: o_2 distribution has to be symmetric around $o_2 = 0.5$.
CP and K detection asymmetries shift the o_2 output

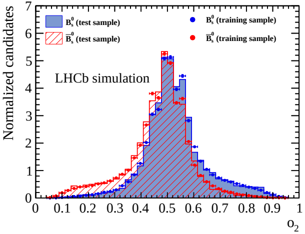
Take symmetrized NN2 output instead:

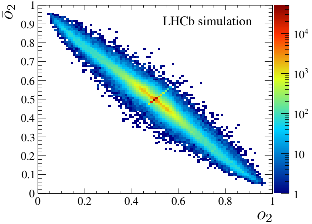
$$o_2^{'} = \frac{o_2 + (1 - \bar{o}_2)}{2}$$

where $\bar{o}$ is obtaining flipping the charge of input NN2 variables.

Tagging decision:
$\boldsymbol{B_s^0}$ if $\boldsymbol{o_2^{'} > 0.5}$
$\boldsymbol{\bar{B}_s^0}$ if $\boldsymbol{o_2^{'} < 0.5}$

Mistag probability:
$\boldsymbol{\eta = 1 - o_2^{'}}$ for $\boldsymbol{B_s^0}$
$\boldsymbol{\eta = o_2^{'}}$ for $\boldsymbol{\bar{B}_s^0}$





SSNNetKaon calibration systematics

Source	σ_{p_0}	σ_{p_1}
Decay time resolution	0.0033	0.060
Calibration method	0.0002	0.006
Signal mass model	0.0001	0.002
Background mass model	0.0015	0.025
$B_s^0 \to D_s^- K^+$ yield	0.0001	0.008
Sum in quadrature	0.0036	0.066

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

Source	σ_{p0}	σ_{p1}
Signal model	0.0063	0.012
Background model	0.0008	0.054
K from $B_{s2}^*(5840)^0$ p_{T} selection	0.0028	0.039
K from $B_{s2}^*(5840)^0$ particle identification	0.0025	0.015
Sum in quadrature	0.0074	0.069

$B_{s2}^*(5840)^0 \to B^+ K^-$

Source	σ_{p_0}	σ_{p_1}
Weighting in p_{T}	0.0011	0.030
Weighting in track multiplicity	0.0006	0.006
Sum in quadrature	0.0012	0.031

Calibration portability

SSNNetKaon calibration asymmetries

Calibrate mistag difference between B_s^0 and $\bar{B}_s^0$:

$$\omega(\eta) = p_0 + \frac{\Delta p_0}{2} + \left(p_1 + \frac{\Delta p_1}{2}\right)(\eta - \langle\eta\rangle)$$
$$\bar{\omega}(\eta) = p_0 - \frac{\Delta p_0}{2} + \left(p_1 - \frac{\Delta p_1}{2}\right)(\eta - \langle\eta\rangle)$$

Data-driven method: $D_s^- \rightarrow \phi(\rightarrow K^+K^-)\pi^-$.
SSKaonNNet tag D_s^- flavour (decision opposite to that for B_s^0).

Background subtracted using *sWeights* computed on D_s^- invariant mass distribution.

Results:

$$\Delta p_0 = -0.0163 \pm 0.0022(\text{stat}) \pm 0.0030(\text{syst})$$
$$\Delta p_1 = -0.031 \pm 0.025(\text{stat}) \pm 0.045(\text{syst})$$
$$\Delta\epsilon_{\text{tag}} = (0.17 \pm 0.11(\text{stat}) \pm 0.68(\text{syst}))\%$$

Non-zero shift of p_0 due to different interaction in matter of $K^\pm$.

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More on OSCharm [JINST 10 (2015) P10005]

Decay mode	Relative rate	Relative power
$D^0 \to K^-\pi^+$	10.0%	24.0%
$D^0 \to K^-\pi^+\pi^+\pi^-$	5.9%	8.4%
$D^+ \to K^-\pi^+\pi^+$	10.3%	2.6%
$H_c \to K^-\pi^+X$	69.7%	61.5%
$H_c \to K^-e^+X$	0.5%	0.2%
$H_c \to K^-\mu^+X$	3.4%	0.3%
$\Lambda_c^+ \to p^+K^-\pi^+$	0.2%	2.4%

Decay modes used

Sample	δp_0 (10^{-3})	p_1	Δp_0 (10^{-3})	Δp_1
$B^+ \to J/\psi^+$	$-25 \pm 3 \pm 3$	$1.00 \pm 0.06 \pm 0.02$	$15 \pm 5 \pm 4$	$-0.08 \pm 0.12 \pm 0.04$
$B^0 \to J/\psi^{*0}$	$-18 \pm 8 \pm 3$	$1.16 \pm 0.17 \pm 0.02$	$23 \pm 11 \pm 4$	$0.21 \pm 0.25 \pm 0.04$

Calibration

Sample	$\varepsilon_{\rm tag}$	ω	$\varepsilon_{\rm eff}$
Simulation	4.88%	37.0%	0.33%
$B^+ \to J/\psi^+$	$(3.11 \pm 0.02)\%$	$(34.6 \pm 0.3 \pm 0.3)\%$	$(0.30 \pm 0.01 \pm 0.01)\%$
$B^0 \to J/\psi^{*0}$	$(3.32 \pm 0.04)\%$	$(35.0 \pm 0.8 \pm 0.3)\%$	$(0.30 \pm 0.03 \pm 0.01)\%$
$B^0 \to D^-\pi^+$	$(4.11 \pm 0.03)\%$	$(34.4 \pm 0.4 \pm 0.3)\%$	$(0.40 \pm 0.02 \pm 0.01)\%$
$B_s^0 \to D_s^-\pi^+$	$(3.99 \pm 0.07)\%$	$(34.4 \pm 0.6 \pm 0.3)\%$	$(0.39 \pm 0.03 \pm 0.01)\%$

Performance

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Expected sensitivity assuming same Flavour Tagging performances of Run I

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–