# Flavour tagging in $pp$ collisions at LHCb

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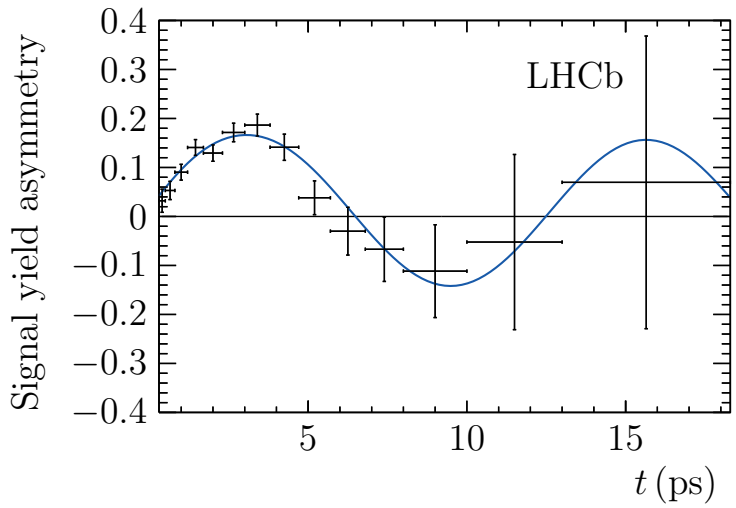
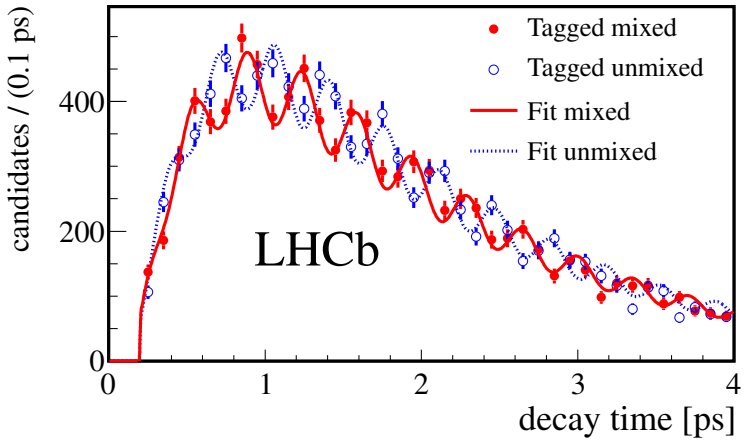
# Outline

# Introduction

# Time-dependent measurements for neutral $B$ mesons




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




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

CP violation in neutral $B$ meson system: measure differences between $B$ and $\bar{B}$.
$\to$ via **time-dependent analyses**.

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

$$\frac{\Gamma(\bar{B} \to f) - \Gamma(B \to f)}{\Gamma(\bar{B} \to f) + \Gamma(B \to f)} \propto S \sin(\Delta m t) - C \cos(\Delta m t)$$

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

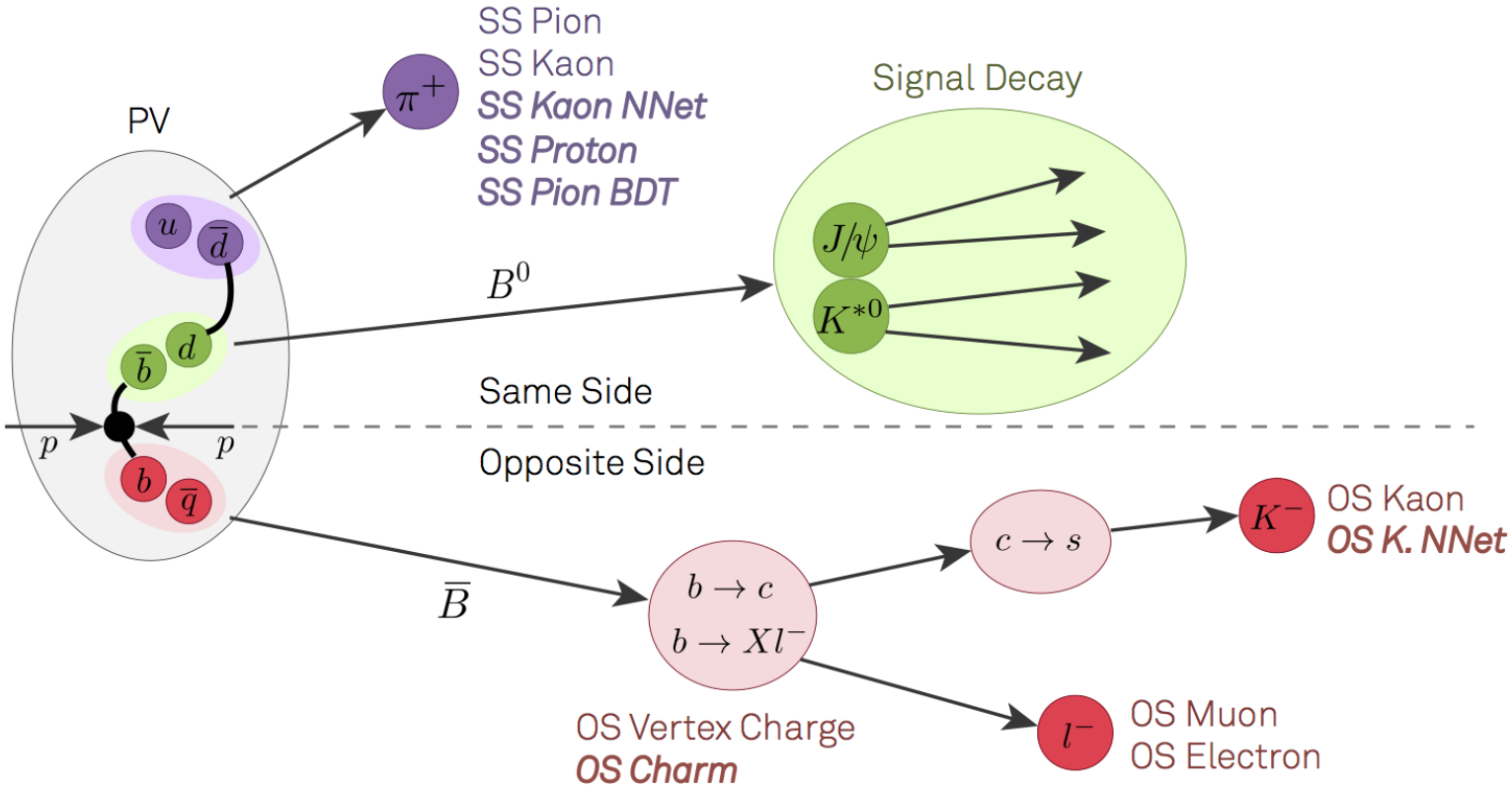
There are complications:

- Mixing of flavour (production $\neq$ decay).
- Sometimes non-flavour specific decays.

We need **Flavour Tagging** algorithms which tag the candidate as $B$ or $\bar{B}$ (*tag decision*)

# 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.

# Tagging performance

**Efficiency**: fraction of tagged events.

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

**Mistag fraction**: fraction of events with wrong tag decision.

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

Taggers give *mistag probability* $\eta$:

- ideally $\omega = \eta$.
- in fact, *calibration* is needed.

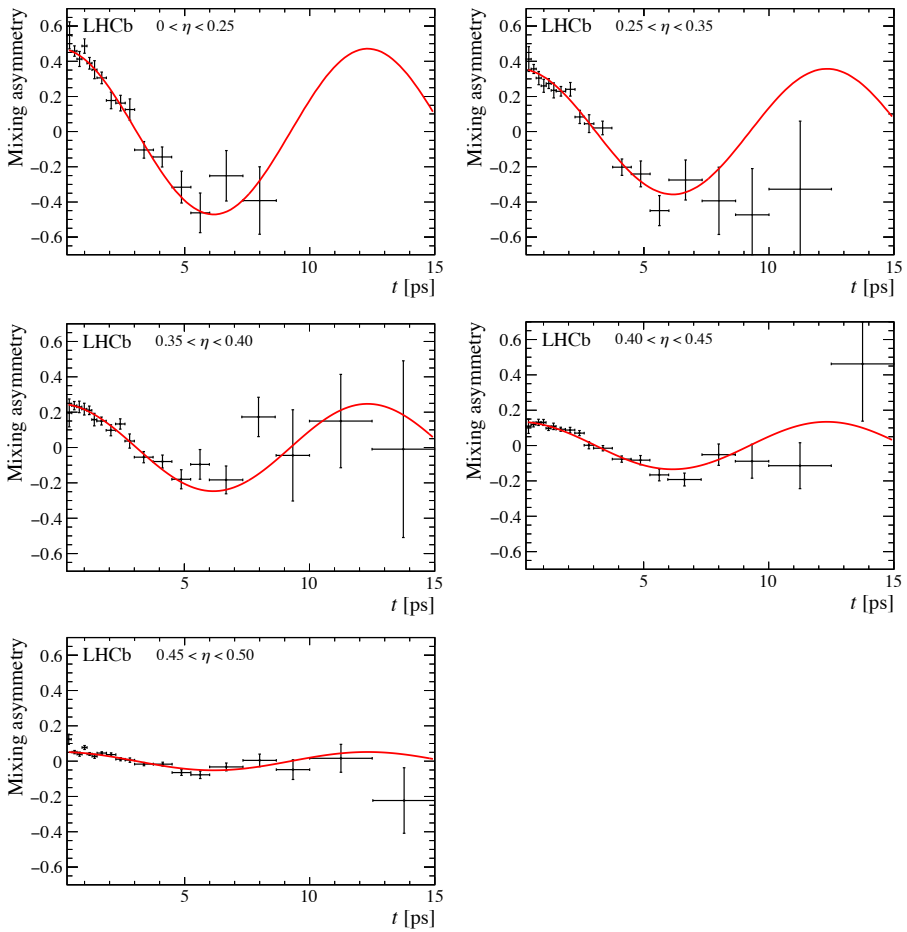
**Tagging power (*effective* tagging efficiency)**:

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

$\Rightarrow$ Increase of statistical uncertainty of time-dependent asymmetries: $\sigma \propto 1/\sqrt{\epsilon_{\text{eff}} N}$

[EPJC (2017) 77:238]

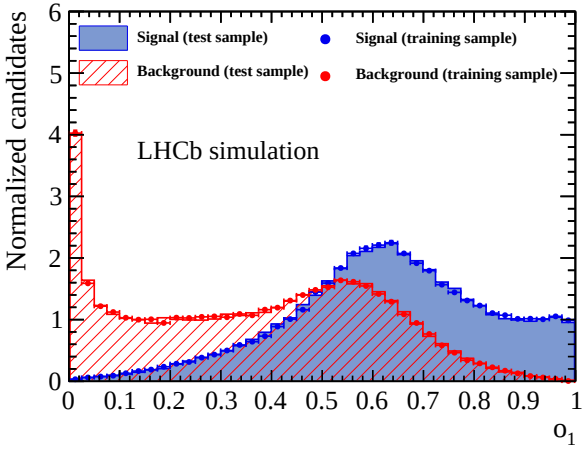
**Dilution: $A^{\text{meas}}(t) \sim (1 - 2\omega) A^{\text{phys}}(t)$**



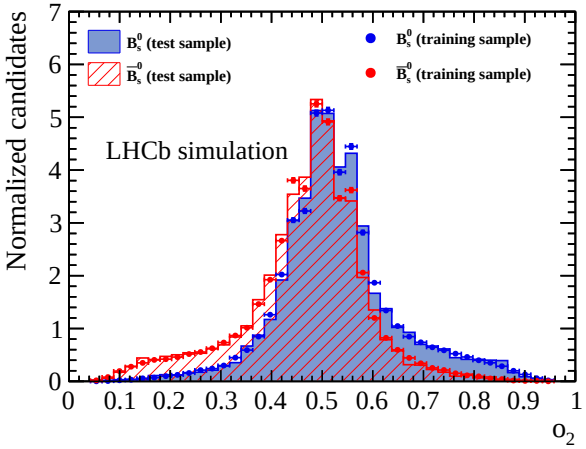

$B^0 \to D^- \pi^+$ mixing asymmetry for SSPion tagged candidates

# Examples of current algorithms

# SSKaonNNet training [JINST 11 (2016) P05010]




NN1 (Signal, Background)

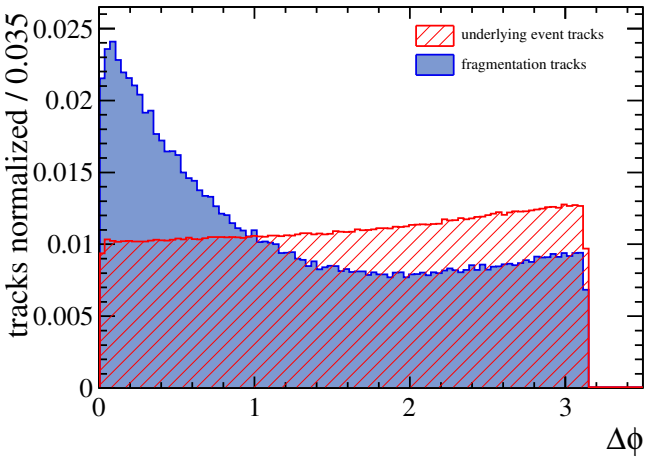



NN2 ($B_s^0$, $\bar{B}_s^0$)

Two Neural Networks, both trained on simulated $B_s^0 \to D_s^- \pi^+$ samples.

NN1: discriminate fragmentation kaons from background tracks.
11 kinematic distributions as input features.

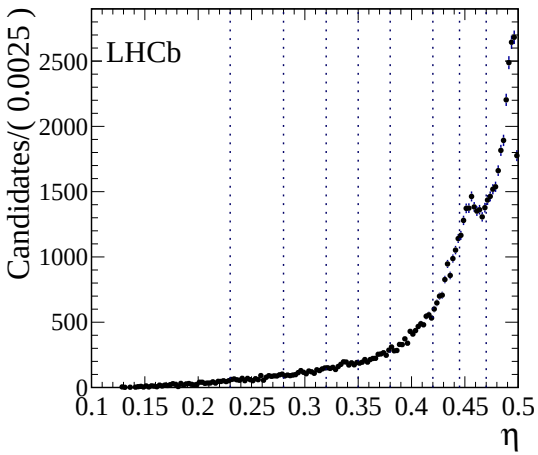
Example: $\Delta\phi$ between $B$ and tagging particle.



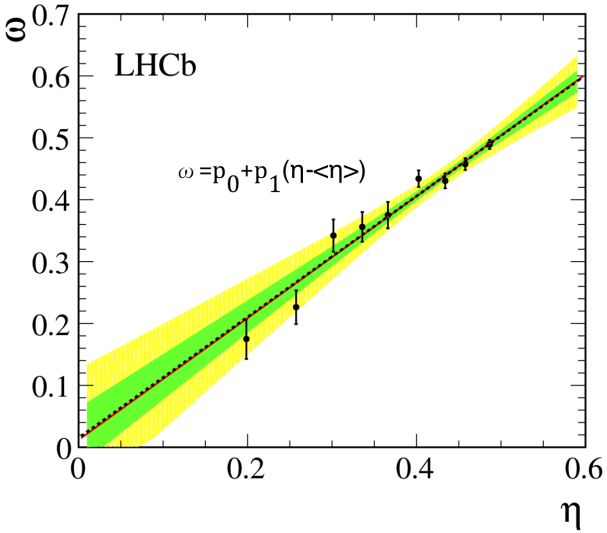

Signal, Background

NN2: determine tagging decision and mistag probability (discriminate $B_s^0$ from $\bar{B}_s^0$).
9 input features (NN1 output + kinematics + particle ID).

# SSKaonNNet calibration and performance [JINST 11 (2016) P05010]




Uncalibrated $\eta$ for $B_s^0 \to D_s^- \pi^+$




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

Linear calibration model assumed:
$\omega(\eta) = p_0 + p_1(\eta - \langle\eta\rangle)$

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

- Decay rate depends on $\omega$:
  $\propto \epsilon_{tag} e^{-t/\tau_s} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm (1 - 2\omega(\eta)) \cos(\Delta m_s t)\right]$
- $p_0$ and $p_1$ fitted, $\langle\eta\rangle$ fixed.

Performances (on Run 1 $B_s^0 \to D_s^- \pi^+$ data):

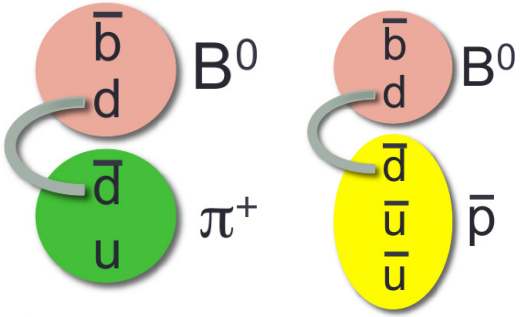
$\boldsymbol{\epsilon_{tag} = (60.38 \pm 0.16)\%}$

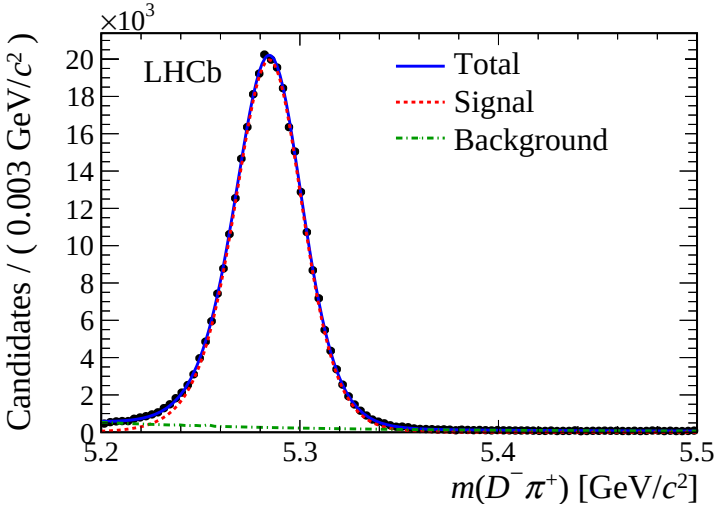
$\boldsymbol{\epsilon_{eff} = (1.80 \pm 0.19(\text{stat}) \pm 0.18(\text{syst}))\%}$

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

# SSPion and SSProton BDT training [EPJC (2017) 77:238]

Exploiting correlation between pion/proton charge and signal $B$ flavour.



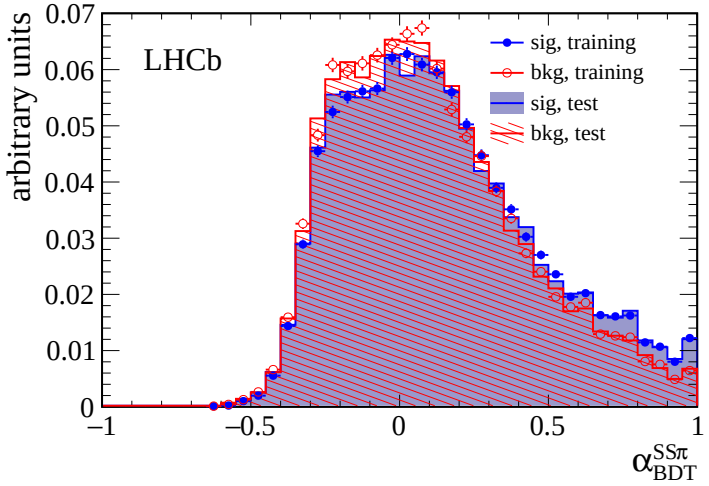

Signal candidates selection

Boosted Decision Tree (BDT) trained on of 2012 $B^0 \to D^-\pi^+$ data to separate **right** and **wrong** tag $B$ candidates:

| Target | Tagging particle | Signal decay |
|---|---|---|
| Right tag | $\pi^+$ or $p$ | $B^0 \to D^-\pi^+$ |
| Wrong tag | $\pi^-$ or $\bar{p}$ | $B^0 \to D^-\pi^+$ |

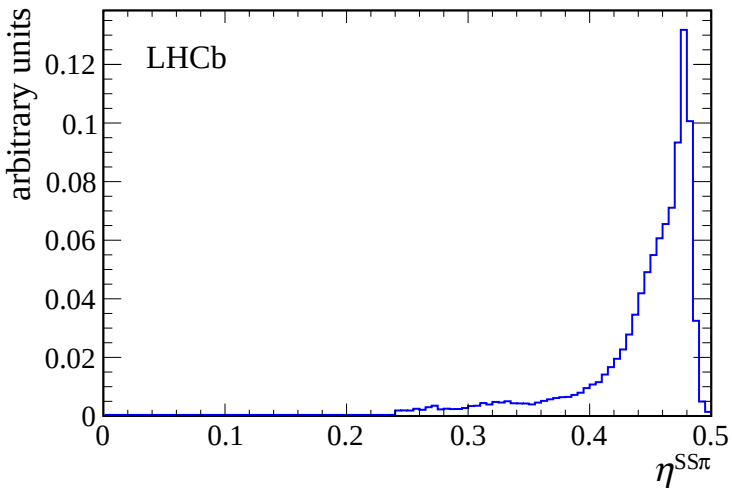
Assumptions:

- Doubly Cabibbo suppressed $B^0 \to D^+\pi^-$ decays neglected.
- Decay time $t < 2.2$ ps to suppress mixing.

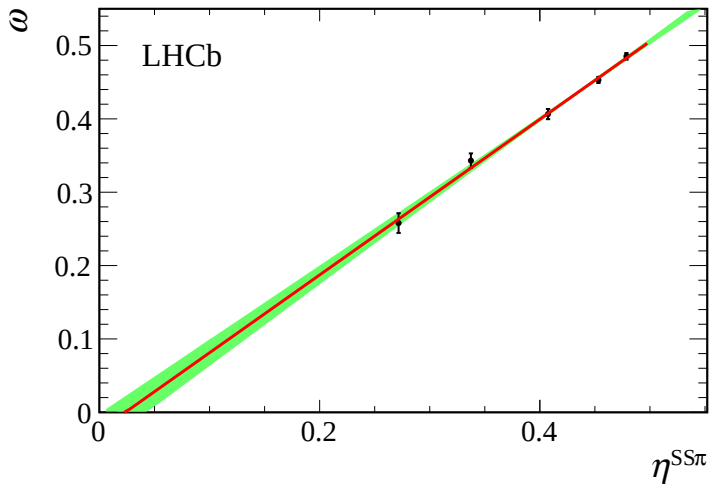



BDT output (SSPion)

# SSPion and SSProton BDT [EPJC (2017) 77:238]




SSPion predicted $\eta$




SSPion calibration

Mistag calibration from decay-time fit. Similar approach to SSKaonNNet calibration:

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

Performance (on Run 1 $B^0 \to D^-\pi^+$ data):

| Tagger | $\epsilon_{\text{tag}}(\%)$ | $\epsilon_{\text{eff}}(\%)$ |
|---|---|---|
| SSPion | $71.96 \pm 0.23$ | $1.69 \pm 0.10$ |
| SSProton | $38.56 \pm 0.15$ | $0.53 \pm 0.05$ |

**Improvement $\mathcal{O}(60\%)$ in $\epsilon_{\text{eff}}$ w.r.t. previous SSPion implementation.**

# Recent physics results (Run 1)

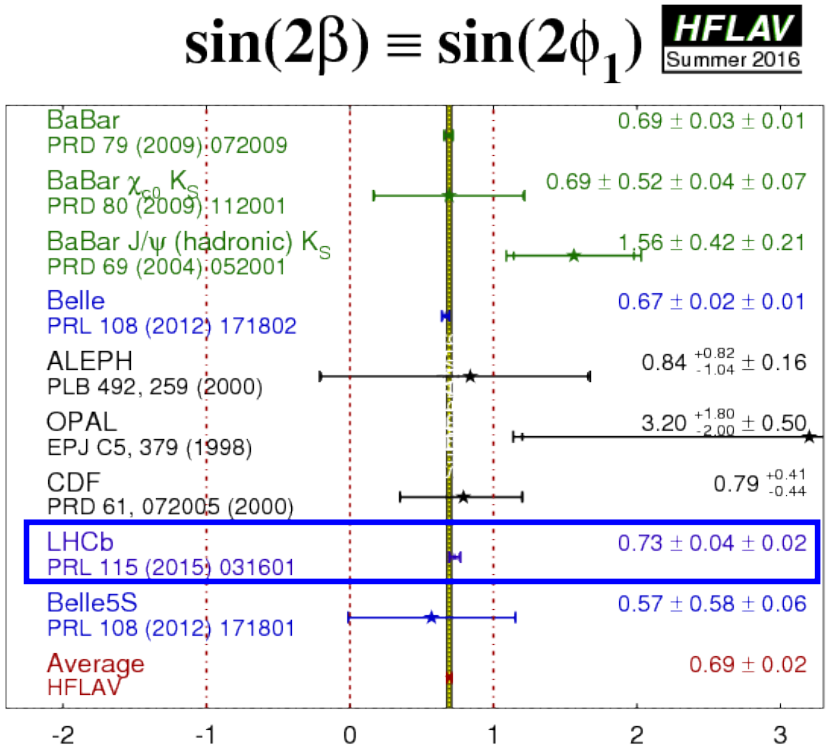
# The CKM angle $\beta$

**The Golden Mode: $B^0 \to J/\psi K_s^0$**
**[PRL 115 (2015) 031601]**

Best measurement at hadron machine.

OSComb + (old) SSPion:

$\epsilon_{\text{eff}} \sim 3.02\%$



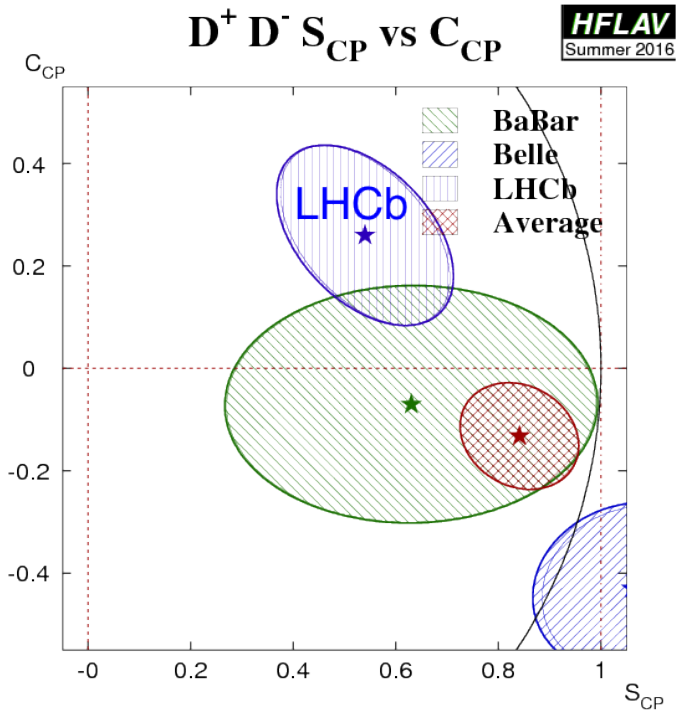

**High-order SM contributions**
**[PRL 117 (2016) 261801]**

First order SM: $\phi_d = 2\beta$
Higher order: phase shift $\Delta\phi$

World's best constraint on high-order SM:

$\Delta\phi = -0.16^{+0.19}_{-0.21}$

OSComb + (new) SSPion + SSProton:
$\epsilon_{\text{eff}} = (8.1 \pm 0.6)\%$ (highest at LHCb)



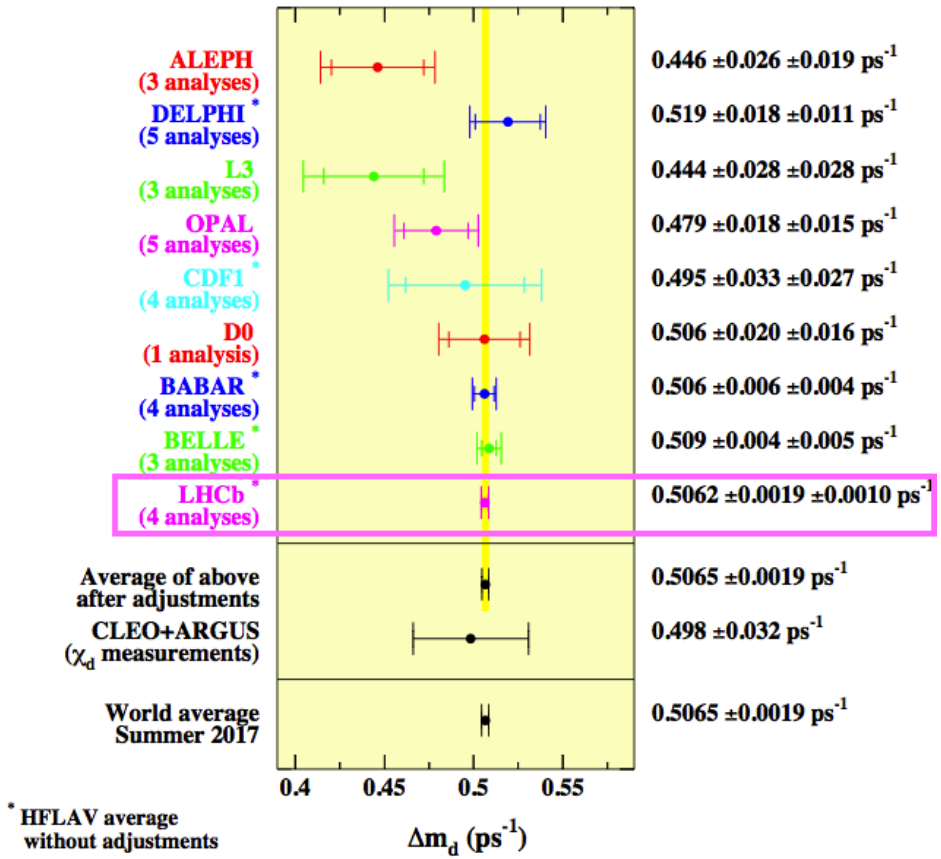
# $B^0$ oscillation frequency $\Delta m_d$ and weak phase $\phi_s^{c\bar{c}s}$

**$\Delta m_d$ from $B^0 \to D^{(*)-}\mu^+\nu X$**
**[EPJC (2016) 76:412]**

Most precise single measurement.

OSComb only: $\epsilon_{\text{eff}} \sim 2.4\%$

LHCb combo gives world leading result.



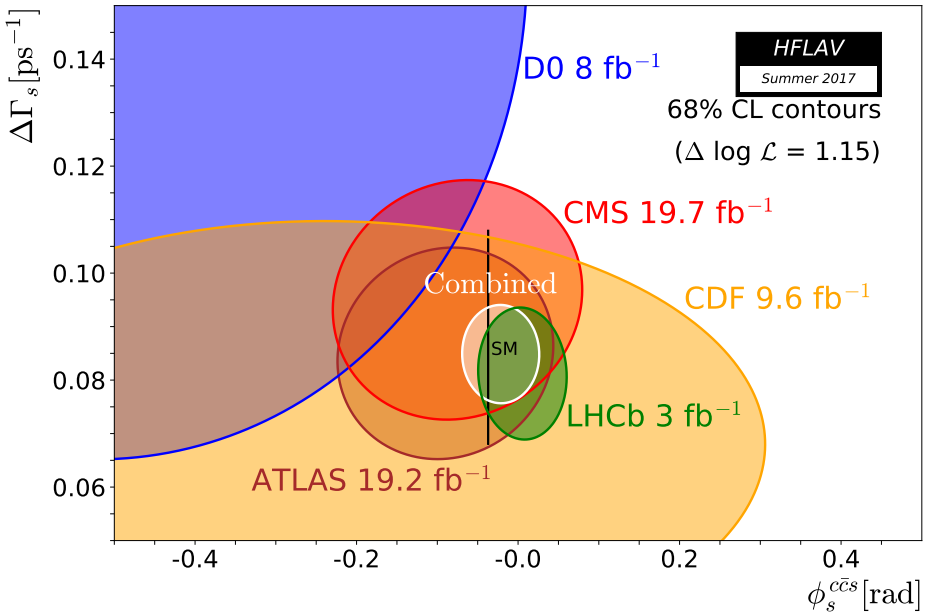

**Weak phase $\phi_s^{c\bar{c}s} \approx -2\beta_s$**

World's leading result from LHCb.

All analyses use OSComb + SSKaonNNet.

$B_s^0 \to J/\psi K^+K^-$ [PRL 114 (2015) 041801]
$B_s^0 \to J/\psi \pi^+\pi^-$ [PLB 736 (2014) 186]
$B_s^0 \to \psi(2S)\phi$ [PLB 762 (2016) 253-262]
$\epsilon_{\text{eff}} \sim 3.8\%$

$B_s^0 \to D_s^+ D_s^-$ [PRL 113 (2014) 211801]
$\epsilon_{\text{eff}} = (5.33 \pm 0.18(\text{stat}) \pm 0.17(\text{syst}))\%$



# Photon polarisation in $B_s^0 \to \phi\gamma$

Time-dependent analysis of $B_s^0 \to \phi\gamma$ is sensitive to **polarisation parameter** $\psi$:

$$\Gamma \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(2\psi)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \mathcal{C}\cos(\Delta m_s t) \mp \mathcal{S}\sin(\Delta m_s t)\right]$$

Result from untagged analysis ($\mathcal{C}$ and $\mathcal{S}$ neglected):

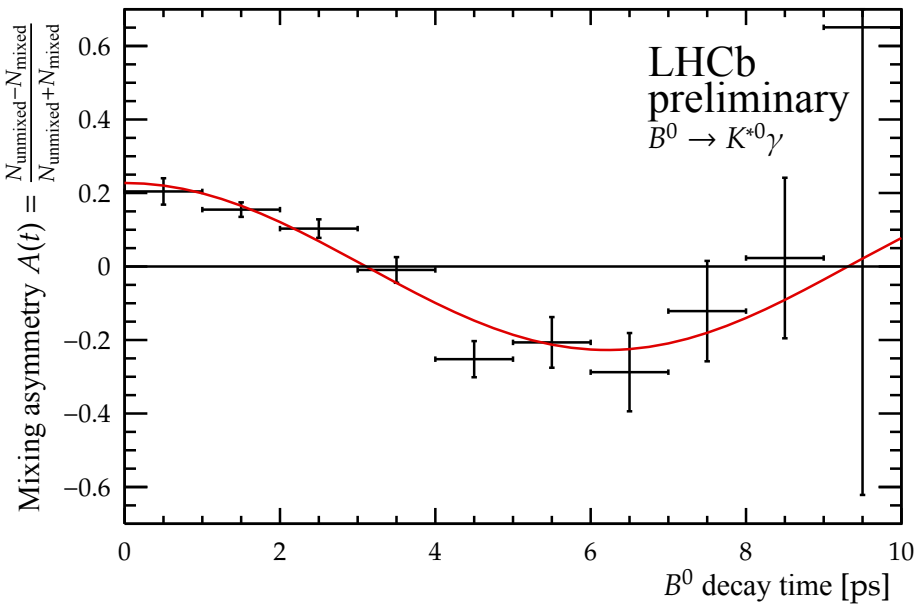
$\sin 2\psi = -0.98^{+0.46+0.23}_{-0.52-0.20}$ **[PRL 118, 021801]**

Including tagging:

- OSComb calibrated on $B^0 \to K^{*0}\gamma$
- SSKaonNNet calibrated on $B_s^0 \to D_s^- \pi^+$

$\to$ **performance** (Run 1) $\epsilon_{\text{eff}} \sim 4.58\%$

For $\epsilon_{\text{eff}} \sim 5\%$, factor $\sim 2$ reduction for statistical uncertainty compared to untagged analysis!!!



# New developments (very preliminary)

# From Run 1 to Run 2

Higher CM energy (from 8 TeV to 13 TeV):

Examples of OS performance ($B^+ \to J/\psi K^+$ data):

| Tagger | $\epsilon_{\text{eff}}(\%)$ Run 1 | $\epsilon_{\text{eff}}(\%)$ Run 2 |
|---|---|---|
| OSMuon | $1.018 \pm 0.034$ | $0.7251 \pm 0.0228$ |
| OSElectron | $0.365 \pm 0.021$ | $0.1722 \pm 0.0108$ |

$\Rightarrow$ OS taggers affected by increased track multiplicity.

Examples of SS performance ($B^0 \to D_s^- \pi^+$ data):

| Tagger | $\epsilon_{\text{eff}}(\%)$ Run 1 | $\epsilon_{\text{eff}}(\%)$ Run 2 |
|---|---|---|
| SSKaonNNet | $1.891 \pm 0.323$ | $2.471 \pm 0.341$ |

$\Rightarrow$ SS taggers profit from higher $B$ signal transverse momentum (higher efficiency).

SSKaonNNet and OS taggers reoptimization campaign ongoing for imminent CPV measurement in $B_s^0 \to J/\psi\phi$.

# SSKaon reoptimisation (unofficial)

Retraining ongoing on simulated $B_s^0 \to D_s^- \pi^+$ with 2016 conditions

**NNets replaced by BDTs**
$\to$ better speed and performance.

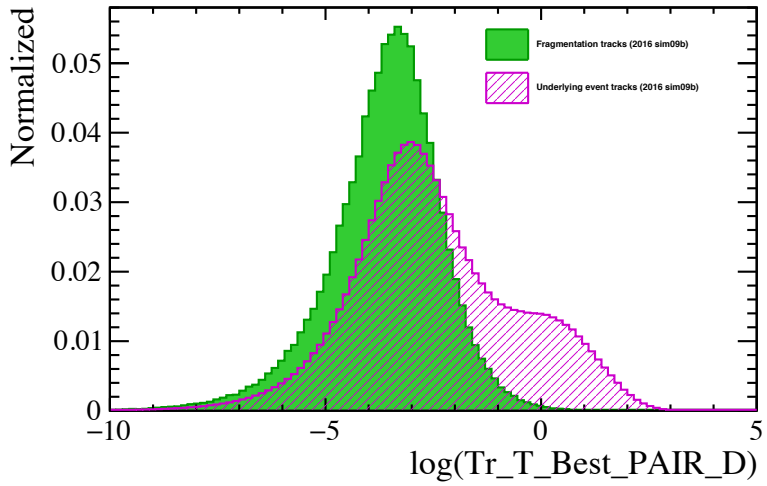
Performance on $B_s^0 \to D_s^- \pi^+$ 2016 data:

| Tagger | $\epsilon_{\text{eff}}(\%)$ |
|---|---|
| Current | $2.471 \pm 0.341$ |
| **New** | $\sim$ **+24% rel. increase** |

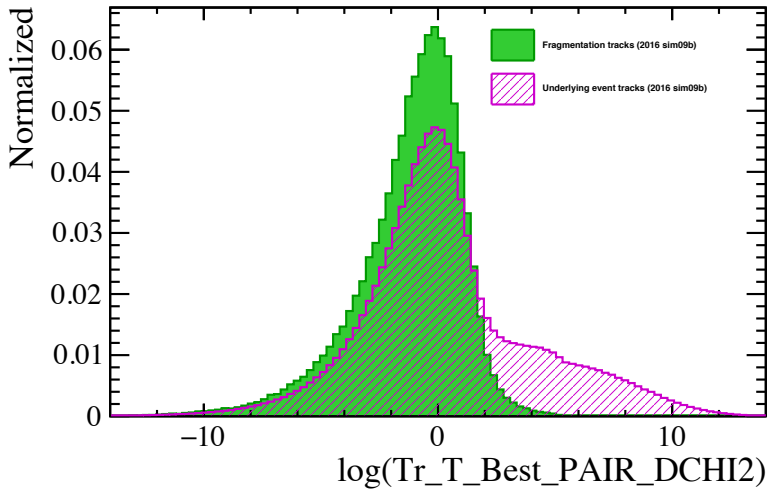
Isolation: distance between track and closest (*best*) one.
If included: $\sim$ **+36% rel. increase**

(Current SSKaonNNet on Run 1 data: $\boldsymbol{\epsilon} \sim$ **1.9%** !!!)

**Signal, Background**

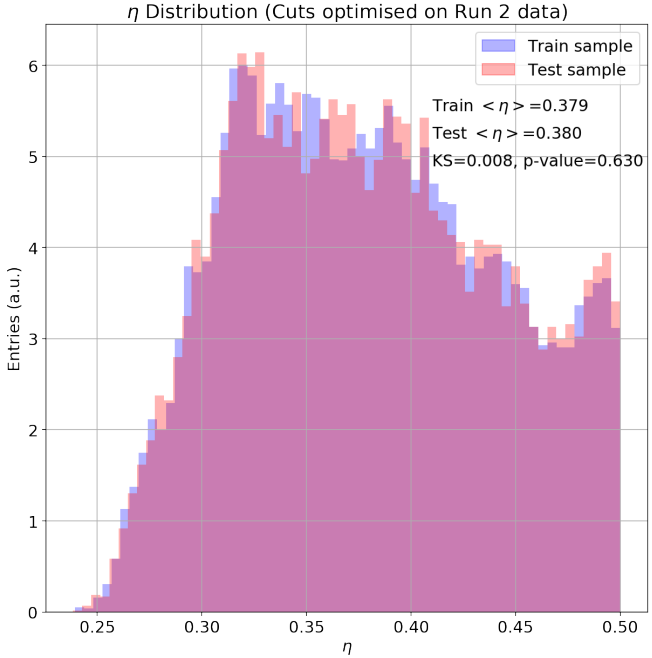


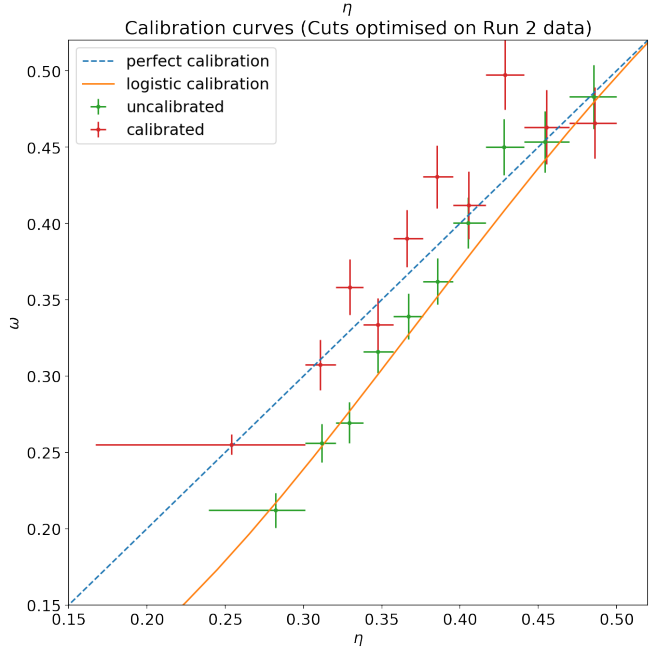

Isolation




Isolation $\chi^2$

# OSElectron reoptimisation (unofficial)




Replace simple cut-based selection with BDT:

- 8 features (kinematic, reconstruction quality, PID)
- training, testing and calibration on $B^+ \to J/\psi K^+$ data.

→ discriminate right tag from wrong tag.

**Loss recovered!**

| Tagger | $\epsilon_{\text{eff}}(\%)$ |
|---|---|
| Current on Run 1 | $0.365 \pm 0.021$ |
| Current on Run 2 | $0.1722 \pm 0.0108$ |
| **New** | **similar to Run 1** |

Similar studies ongoing for OSMuon:

| Tagger | $\epsilon_{\text{eff}}(\%)$ |
|---|---|
| Current on Run 1 | $1.018 \pm 0.034$ |
| Current on Run 2 | $0.7251 \pm 0.0228$ |
| **New** | **similar to Run 1** |

# Conclusions and summary

# Conclusions and summary

Flavour tagging algorithms in LHCb allow world leading results in time-dependent CPV measurement despite the harsh experimental conditions due to $pp$ collisions.

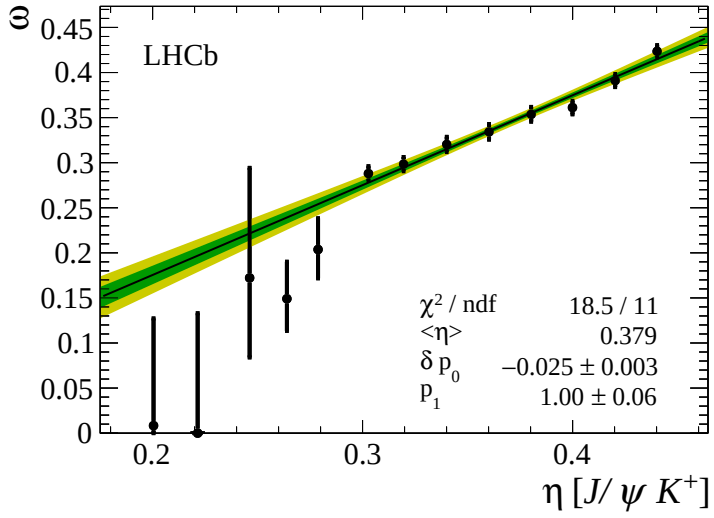
Recent developments are improving further our sensitivity to CP observables.

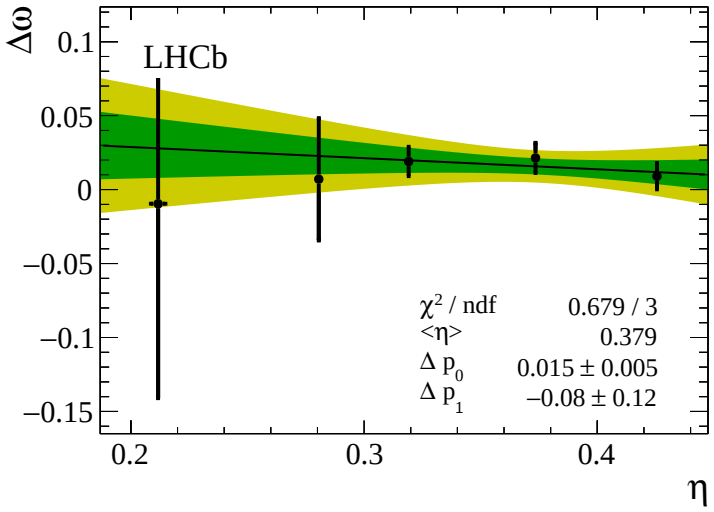
New decays (e.g. $B$ radiative decays) are entering into the game (in addition to the "traditional" ones).


*Thank you*

# Backup

# Mistag Calibration




OSCharm [JINST 10 (2015) P10005]

**Calibrate** predicted mistag on control channel on data:

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

Signal and control channel need **similar kinematics** to reduce systematics.
Examples:

| Control channel | Signal |
|---|---|
| $B^\pm \to D^0\pi^\pm$ | $B^0 \to D^\mp\pi^\pm$ |
| $B^\pm \to J/\psi K^\pm$ | $B^0 \to J/\psi K^0_S$ |
| $B^0_s \to D^\mp_s\pi^\pm$ | $B^0_s \to D^\mp_s K^\pm$ |

Charged $B$ control channels:

- Compare true tag ($B$ charge) with tagger decision.

Neutral $B$ control channels:

- Full *time-dependent* analysis needed (examples later on).

# 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*

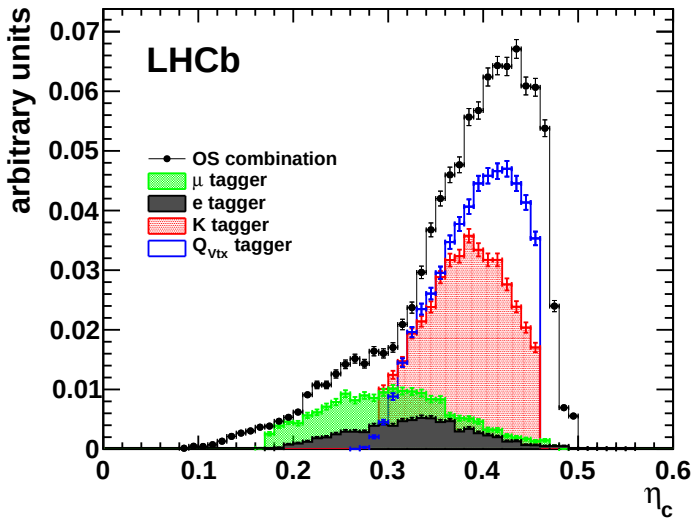
**Mistag** estimation from Neural Networks (NN).
Calibration on $B^+ \to J/\psi K^+$ data.
Both global information (number of tagging particles, pile-up vertices...) and tagging particle properties (kinematics...) used for training.

**Tagging decision** and **mistag** for each tagger ($e, \mu, \ldots$) combined in a single response.

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

| Taggers | $\varepsilon_{\rm tag}$ [%] | $\omega$ [%] | $\varepsilon_{\rm tag}(1-2\omega)^2$ [%] |
|---|---|---|---|
| $\mu$ | 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 ($\eta_c$ <0.42) | 17.8±0.1 | 34.6±0.4 | 1.69±0.10 |
| OS sum of $\eta_c$ bins | 27.3±0.2 | 36.2±0.5 | 2.07±0.11 |

OS taggers performance




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

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

**Vertex Charge Tagger.** Inclusive reconstruction of two tracks (under $\pi$ 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.

# OSCharm [JINST 10 (2015) P10005]

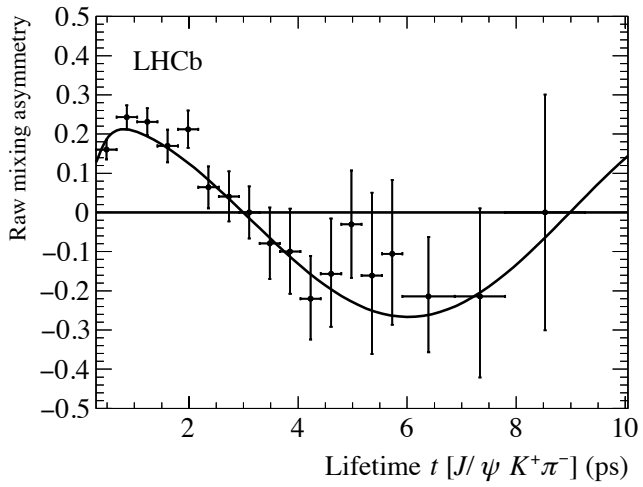
OS Charmed hadrons produced via $b \to c$ transitions:
$D^0 \to K^-\pi^+, D^+ \to K^-\pi^+\pi^+, ...$

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

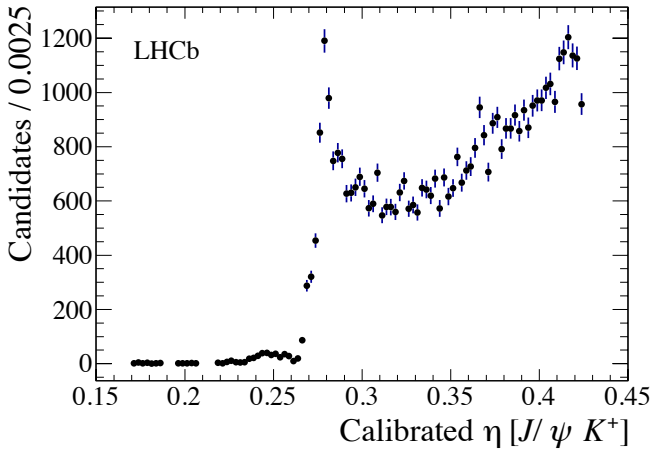
- Features: decay kinematics and vertex, $c$-hadron flight distance...
- Training on Monte Carlo sample.

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

# 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 | $\delta p_0$ $(10^{-3})$ | $p_1$ | $\Delta p_0$ $(10^{-3})$ | $\Delta p_1$ |
|---|---|---|---|---|
| $B^+ \to J/\psi^+$ | $-25 \pm 3 \pm 3$ | $1.00 \pm 0.06 \pm 0.02$ | $15 \pm 5 \pm 4$ | $-0.08 \pm 0.12 \pm 0.04$ |
| $B^0 \to J/\psi^{*0}$ | $-18 \pm 8 \pm 3$ | $1.16 \pm 0.17 \pm 0.02$ | $23 \pm 11 \pm 4$ | $0.21 \pm 0.25 \pm 0.04$ |

Calibration

| Sample | $\varepsilon_{\text{tag}}$ | $\omega$ | $\varepsilon_{\text{eff}}$ |
|---|---|---|---|
| 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

# 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

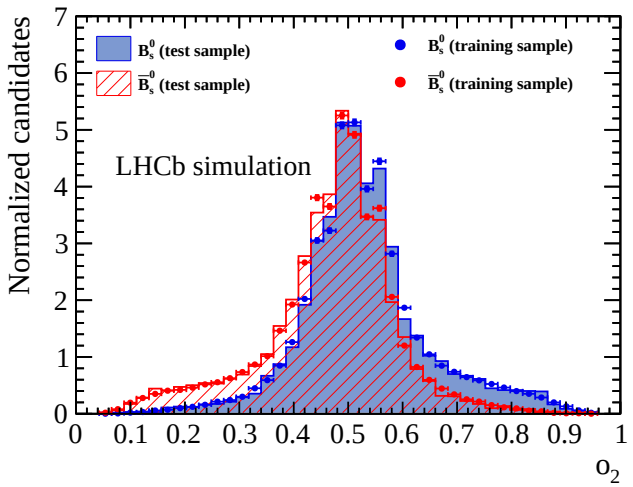
Take symmetrized NN2 output instead:

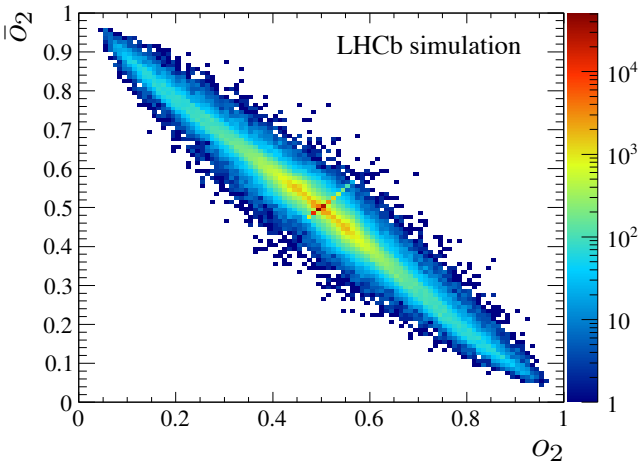
$$o_2^{'} = \frac{o_2 + (1 - \bar{o}_2)}{2}$$

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

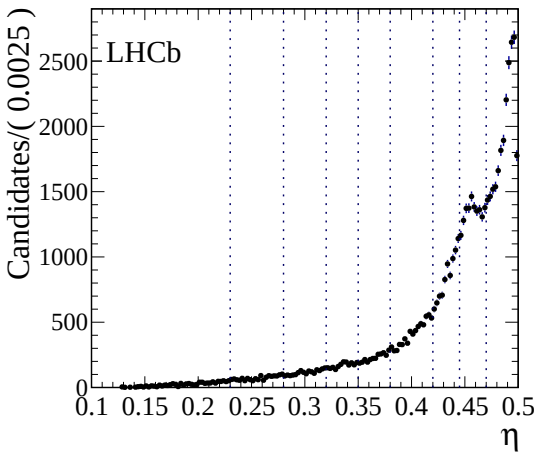
**Tagging decision**:
$B_s^0$ if $o_2^{'} > 0.5$
$\bar{B}_s^0$ if $o_2^{'} < 0.5$

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

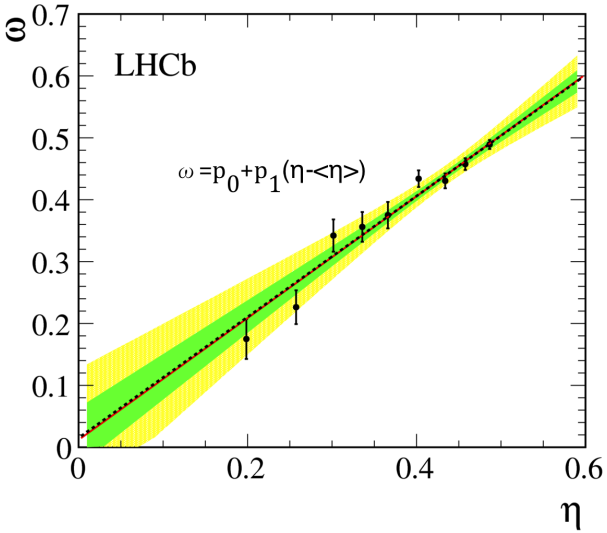


# SSKaonNNet calibration and performance [JINST 11 (2016) P05010]




Uncalibrated $\eta$ for $B_s^0 \to D_s^- \pi^+$




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

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

- simultaneous fit to *untagged*, *mixed* and *unmixed* samples, with $\eta$ 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.

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.**

# More on SSKaonNNet calibration [LHCB-PAPER-2015-056]

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 $\eta$.

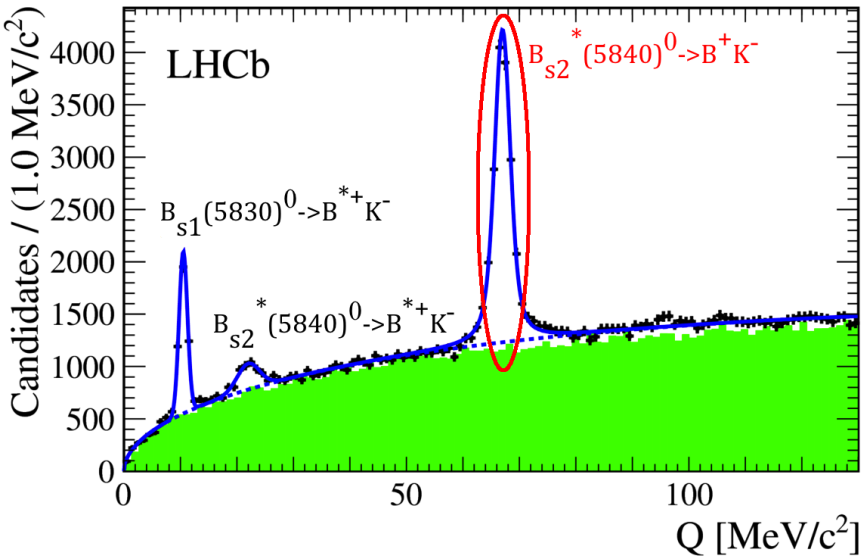
Calibration portability checked on $B_s^0 \to J/\psi\phi$, $B_s^0 \to D_s^+ D_s^-$ and $B_s^0 \to \phi\phi$.
Largest systematic due to different distribution of $p_T(B)$ in these decays w.r.t $B_s^0 \to D_s^- \pi^+$.

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

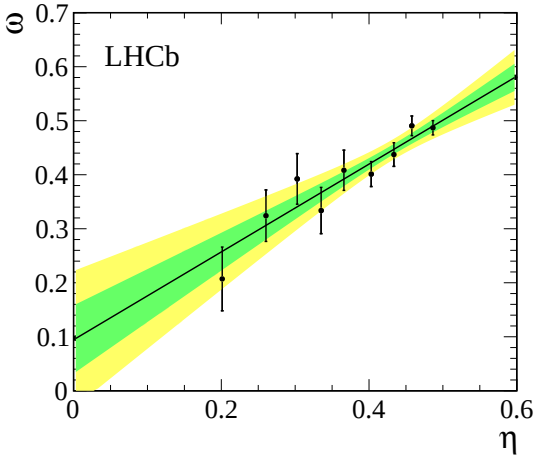
$\epsilon_{tag} = (60.38 \pm 0.16)\%$

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

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




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



# SSNNetKaon calibration systematics [LHCB-PAPER-2015-056]

| Source | $\sigma_{p_0}$ | $\sigma_{p_1}$ |
|---|---|---|
| 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 | $\sigma_{p0}$ | $\sigma_{p1}$ |
|---|---|---|
| Signal model | 0.0063 | 0.012 |
| Background model | 0.0008 | 0.054 |
| $K$ from $B_{s2}^*(5840)^0$ $p_{\mathrm{T}}$ 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 | $\sigma_{p_0}$ | $\sigma_{p_1}$ |
|---|---|---|
| Weighting in $p_{\mathrm{T}}$ | 0.0011 | 0.030 |
| Weighting in track multiplicity | 0.0006 | 0.006 |
| Sum in quadrature | 0.0012 | 0.031 |

Calibration portability

# SSNNetKaon calibration asymmetries [LHCB-PAPER-2015-056]

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: $D_s^- \to \phi(\to K^+K^-)\pi^-$.
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:

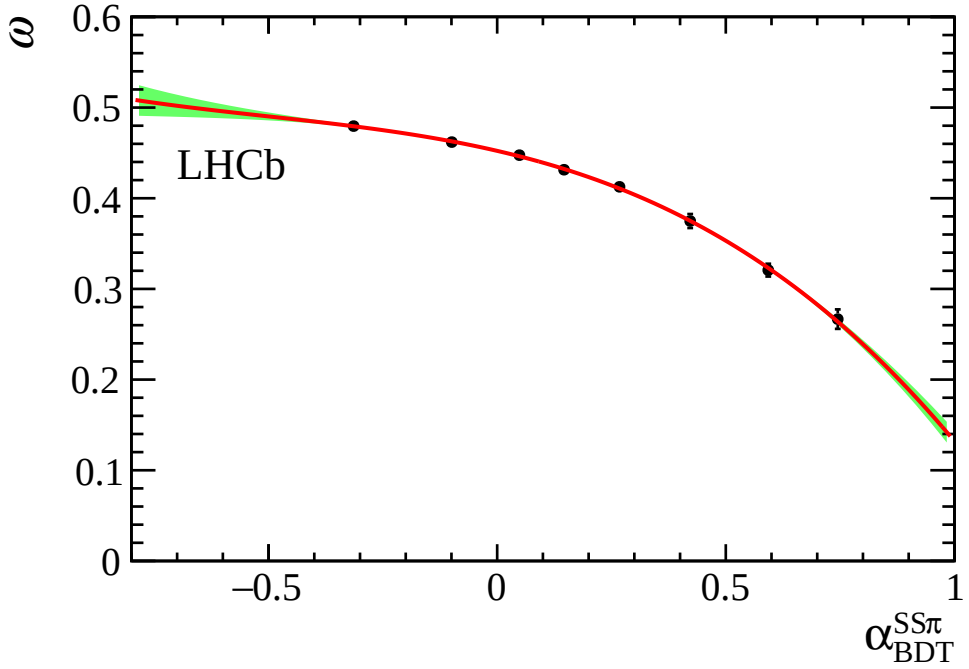
$$\Delta p_0 = -0.0163 \pm 0.0022(\text{stat}) \pm 0.0030(\text{syst})$$
$$\Delta p_1 = -0.031 \pm 0.025(\text{stat}) \pm 0.045(\text{syst})$$
$$\Delta\epsilon_{\text{tag}} = (0.17 \pm 0.11(\text{stat}) \pm 0.68(\text{syst}))\%$$

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

# SSPion and SSProton BDT [EPJC (2017) 77:238]

BDT output → mistag probability:

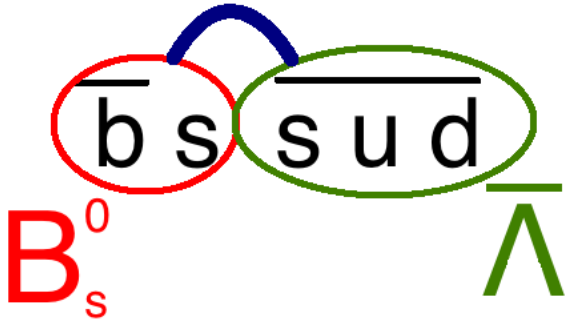
- Decay time fit in bins of BDT to get bin's mistag fraction $\omega$:
  $\propto e^{-t/\tau_d}[1 \pm (1-2\omega)\cos(\Delta m_d t)]$
- Predicted mistag $\eta = \eta(\text{BDT})$.




BDT transformation (SSPion)

# SSLambda (unofficial)

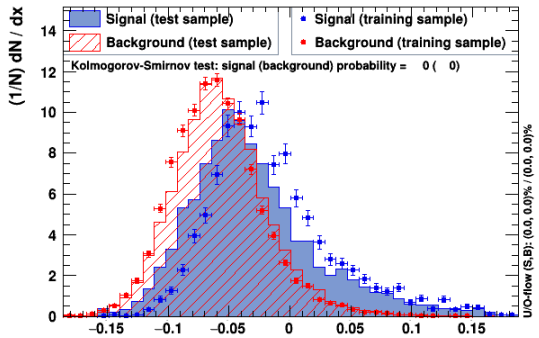
Useful for $B_s^0$ tagging (in addition to SSKaon).



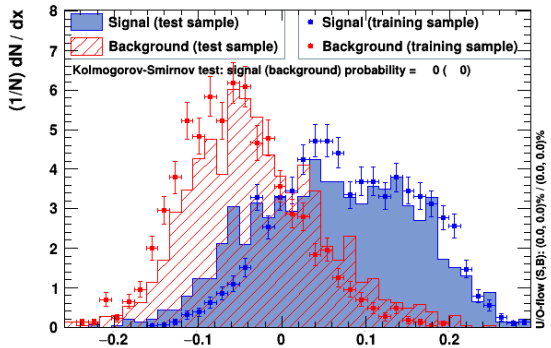

3 BDTs trained on simulated $B_s^0 \to D_s^- \pi^+$ (Run 1 conditions):

- **BDT A**: separate $\Lambda$'s from $b\bar{b}$ fragmentation and other processes.
- **BDT B**: separate SS and OS $\Lambda$'s.
- **BDT C**: separate right and wrong tagged $B_s^0$ **(and estimate $\eta$)**

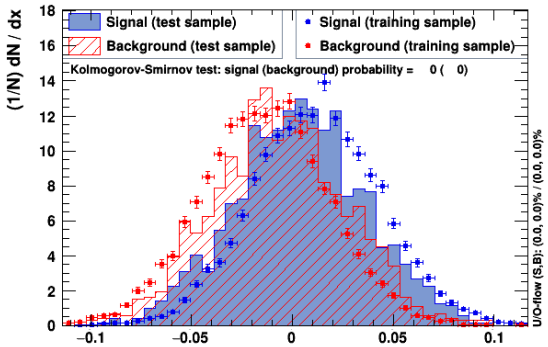
Tagging power:
$\epsilon_{\text{eff}} = (0.076 \pm 0.021)\%$
Maximum, theoretical power from simulation:
$\epsilon_{\text{eff}} \sim 0.12\%$
$\to$ **room for improvements!**




BDT A




BDT B




BDT C

# LHCb: RunII and upgrade

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** | $\sim 0.003$ |
| | $\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad) | 0.068 | 0.035 | **0.012** | $\sim 0.01$ |
| | $A_{\rm sl}(B_s^0)$ $(10^{-3})$ | 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** | $\sim 0.02$ |
| | $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ | 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** | – |
| | $\Delta A_{CP}$ $(10^{-3})$ | 0.8 | 0.5 | **0.1** | – |