Flavour tagging in $pp$ collisions at LHCb

Vincenzo Battista$^1$, on behalf of the LHCb collaboration

$^1$École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

CHIPP & SPS Meeting, Geneva, 23/08/2017
Outline

1. Introduction

2. Examples of current algorithms

3. Recent physics results (Run 1)

4. New developments (very preliminary)

5. Conclusions and summary
Introduction
Time-dependent measurements for neutral $B$ mesons

CP violation in neutral $B$ meson system: measure differences between $B$ and $\bar{B}$.

$\rightarrow$ via time-dependent analyses.

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

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

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

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)**:

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

⇒ **Increase** of statistical uncertainty of time-dependent asymmetries: \( \sigma \propto 1/\sqrt{\epsilon_{\text{eff}} N} \)

[EPJC (2017) 77:238]

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

B0 \( \rightarrow D^- \pi^+ \) mixing asymmetry for SSPion tagged candidates
Examples of current algorithms
Two Neural Networks, both trained on simulated $B_s^0 \rightarrow D_s^- \pi^+$ samples.

**NN1**: discriminate fragmentation kaons from background tracks.

11 kinematic distributions as input features.

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

**NN2**: determine tagging decision and mistag probability (discriminate $B_s^0$ from $\bar{B}_s^0$).

9 input features (NN1 output + kinematics + particle ID).
Linear calibration model assumed:
\[ \omega(\eta) = p_0 + p_1(\eta - \langle \eta \rangle) \]

**Calibration** on \( B^0_s \rightarrow D^-_s \pi^+ \) 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 \( B^0_s \rightarrow D^-_s \pi^+ \) data):
- \( \epsilon_{tag} = (60.38 \pm 0.16)\% \)
- \( \epsilon_{eff} = (1.80 \pm 0.19\text{(stat)} \pm 0.18\text{(syst)})\% \)

Improvement \( \mathcal{O}(50\%) \) w.r.t. previous SSKaon implementation.
Exploiting correlation between pion/proton charge and signal B flavour.

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

<table>
<thead>
<tr>
<th>Target</th>
<th>Tagging particle</th>
<th>Signal decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right tag</td>
<td>$\pi^+$ or $p$</td>
<td>$B^0 \to D^- \pi^+$</td>
</tr>
<tr>
<td>Wrong tag</td>
<td>$\pi^-$ or $\bar{p}$</td>
<td>$B^0 \to D^- \pi^+$</td>
</tr>
</tbody>
</table>

Assumptions:

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

<table>
<thead>
<tr>
<th>Tagger</th>
<th>$\epsilon_{\text{tag}}$ (%)</th>
<th>$\epsilon_{\text{eff}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSPion</td>
<td>$71.96 \pm 0.23$</td>
<td>$1.69 \pm 0.10$</td>
</tr>
<tr>
<td>SSProton</td>
<td>$38.56 \pm 0.15$</td>
<td>$0.53 \pm 0.05$</td>
</tr>
</tbody>
</table>

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: $B^0 \rightarrow J/\psi K^0_S$

[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 $\phi_s^{\bar{c}c_s}$

$\Delta m_d$ 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 $\phi_s^{\bar{c}c_s} \approx -2\beta_s$

World’s leading result from LHCb.
All analyses use OSComb + SSKaonNNet.

$B^0_s \to J/\psi K^+ K^- [PRL 114 (2015) 041801]$
$B^0_s \to J/\psi \pi^+ \pi^- [PLB 736 (2014) 186]$
$B^0_s \to \psi(2S)\phi [PLB 762 (2016) 253-262]$

$\epsilon_{\text{eff}} \sim 3.8\%$

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

$\epsilon_{\text{eff}} = (5.33 \pm 0.18(\text{stat}) \pm 0.17(\text{syst}))\%$
Photon polarisation in $B_s^0 \to \phi \gamma$

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

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

Result from untagged analysis ($C$ and $S$ neglected):

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

Including tagging:

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

→ 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 ($B^+ \rightarrow J/\psi K^+$ data):

<table>
<thead>
<tr>
<th>Tagger</th>
<th>$\epsilon_{\text{eff}}$ (%) Run 1</th>
<th>$\epsilon_{\text{eff}}$ (%) Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSMuon</td>
<td>$1.018 \pm 0.034$</td>
<td>$0.7251 \pm 0.0228$</td>
</tr>
<tr>
<td>OSElectron</td>
<td>$0.365 \pm 0.021$</td>
<td>$0.1722 \pm 0.0108$</td>
</tr>
</tbody>
</table>

⇒ OS taggers affected by increased track multiplicity.

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

<table>
<thead>
<tr>
<th>Tagger</th>
<th>$\epsilon_{\text{eff}}$ (%) Run 1</th>
<th>$\epsilon_{\text{eff}}$ (%) Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSKaonNNet</td>
<td>$1.891 \pm 0.323$</td>
<td>$2.471 \pm 0.341$</td>
</tr>
</tbody>
</table>

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

SSKaonNNet and OS taggers reoptimization campaign ongoing for imminent CPV measurement in $B^0_s \rightarrow J/\psi \phi$. 
SSKaon reoptimisation (unofficial)

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

**NNets replaced by BDTs**
→ better speed and performance.

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

<table>
<thead>
<tr>
<th>Tagger</th>
<th>$\epsilon_{\text{eff}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>$2.471 \pm 0.341$</td>
</tr>
<tr>
<td><strong>New</strong></td>
<td>$\sim +24% \text{ rel. increase}$</td>
</tr>
</tbody>
</table>

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

(Current SSKaonNNet on Run 1 data: $\epsilon \sim 1.9\%$ !!!)
OSElectron reoptimisation (unofficial)

Replace simple cut-based selection with BDT:
- 8 features (kinematic, reconstruction quality, PID)
- training, testing and calibration on $B^+ \rightarrow J/\psi K^+$ data.
  → discriminate right tag from wrong tag.

Loss recovered!

<table>
<thead>
<tr>
<th>Tagger</th>
<th>$\epsilon_{eff}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current on Run 1</td>
<td>0.365 ± 0.021</td>
</tr>
<tr>
<td>Current on Run 2</td>
<td>0.1722 ± 0.0108</td>
</tr>
<tr>
<td>New</td>
<td>similar to Run 1</td>
</tr>
</tbody>
</table>

Similar studies ongoing for OSMuon:

<table>
<thead>
<tr>
<th>Tagger</th>
<th>$\epsilon_{eff}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current on Run 1</td>
<td>1.018 ± 0.034</td>
</tr>
<tr>
<td>Current on Run 2</td>
<td>0.7251 ± 0.0228</td>
</tr>
<tr>
<td>New</td>
<td>similar to Run 1</td>
</tr>
</tbody>
</table>
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

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:

<table>
<thead>
<tr>
<th>Control channel</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^\pm \rightarrow D^0 \pi^\pm )</td>
<td>( B^0 \rightarrow D^+ \pi^\pm )</td>
</tr>
<tr>
<td>( B^\pm \rightarrow J/\psi K^\pm )</td>
<td>( B^0 \rightarrow J/\psi K_S^0 )</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow D_s^{\mp} \pi^\pm )</td>
<td>( B_s^0 \rightarrow D_s^{\mp} K^\pm )</td>
</tr>
</tbody>
</table>

Charged \( B \) control channels:

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

Neutral \( B \) control channels:

- Full time-dependent analysis needed (examples later on).
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 $B^+ \rightarrow J/\psi K^+$ 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 $\epsilon_{\text{eff}}$ by $\approx 15\%$ w.r.t 2011 analyses due to selection improvement.
**Vertex Charge Tagger.** Inclusive reconstruction of two tracks (under $\pi$ hypothesis) compatible with a $B$ decay vertex. Other tracks compatible with same vertex added. Charge of the tagging $B$:

$$Q_{\text{vtx}} = \sum_i Q_i p^k_{T_i} / p^k_{T_i}$$

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

**Tagging combination.**

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

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

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

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

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

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Relative rate</th>
<th>Relative power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^−π^+$</td>
<td>10.0%</td>
<td>24.0%</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^−π^+π^+π^−$</td>
<td>5.9%</td>
<td>8.4%</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^−π^+π^+$</td>
<td>10.3%</td>
<td>2.6%</td>
</tr>
<tr>
<td>$H_c \rightarrow K^−π^+X$</td>
<td>69.7%</td>
<td>61.5%</td>
</tr>
<tr>
<td>$H_c \rightarrow K^−e^+X$</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$H_c \rightarrow K^−μ^+X$</td>
<td>3.4%</td>
<td>0.3%</td>
</tr>
<tr>
<td>$Λ^+_c \rightarrow p^+K^−π^+$</td>
<td>0.2%</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

Calibration

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta p_0 \ (10^{-3})$</th>
<th>$p_1$</th>
<th>$\Delta p_0 \ (10^{-3})$</th>
<th>$\Delta p_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow J/ψ^+$</td>
<td>$−25 \pm 3 \pm 3$</td>
<td>$1.00 \pm 0.06 \pm 0.02$</td>
<td>$15 \pm 5 \pm 4$</td>
<td>$−0.08 \pm 0.12 \pm 0.04$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/ψ^{*0}$</td>
<td>$−18 \pm 8 \pm 3$</td>
<td>$1.16 \pm 0.17 \pm 0.02$</td>
<td>$23 \pm 11 \pm 4$</td>
<td>$0.21 \pm 0.25 \pm 0.04$</td>
</tr>
</tbody>
</table>

Performance
Output $o_1$ of NN1 used as input variable for NN2.

NN2 output:

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

**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:**

$B^0_s$ if $o'_2 > 0.5$

$\bar{B}^0_s$ if $o'_2 < 0.5$

**Mistag probability:**

$$\eta = 1 - o'_2$$ for $B^0_s$

$$\eta = o'_2$$ for $\bar{B}^0_s$
Calibration on $B_s^0 \rightarrow D_s^- \pi^+$ 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 $B_s^0 \rightarrow D_s^- \pi^+$):

- $\epsilon_{tag} = (60.38 \pm 0.16)\%$
- $\epsilon_{eff} = (1.80 \pm 0.19(stat) \pm 0.18(syst))\%$

Improvement $\mathcal{O}(50\%)$ w.r.t. previous SSKaon implementation.
Calibration on $B_s^0 \to D_s^- \pi^+$ combined with the calibration from *self-tagged, hadronic* $B^*(5840)^0 \to B^+K^-$ 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.
## SSNNetKaon calibration systematics [LHCB-PAPER-2015-056]

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{p_0}$</th>
<th>$\sigma_{p_1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay time resolution</td>
<td>0.0033</td>
<td>0.060</td>
</tr>
<tr>
<td>Calibration method</td>
<td>0.0002</td>
<td>0.006</td>
</tr>
<tr>
<td>Signal mass model</td>
<td>0.0001</td>
<td>0.002</td>
</tr>
<tr>
<td>Background mass model</td>
<td>0.0015</td>
<td>0.025</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow D_s^- K^+$ yield</td>
<td>0.0001</td>
<td>0.008</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>0.0036</td>
<td>0.066</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{p_0}$</th>
<th>$\sigma_{p_1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal model</td>
<td>0.0063</td>
<td>0.012</td>
</tr>
<tr>
<td>Background model</td>
<td>0.0008</td>
<td>0.054</td>
</tr>
<tr>
<td>$K$ from $B_s^*(5840)^0$ $p_T$ selection</td>
<td>0.0028</td>
<td>0.039</td>
</tr>
<tr>
<td>$K$ from $B_s^*(5840)^0$ particle identification</td>
<td>0.0025</td>
<td>0.015</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>0.0074</td>
<td>0.069</td>
</tr>
</tbody>
</table>

### $B_s^0 \rightarrow D_s^- \pi^+$

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

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{p_0}$</th>
<th>$\sigma_{p_1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighting in $p_T$</td>
<td>0.0011</td>
<td>0.030</td>
</tr>
<tr>
<td>Weighting in track multiplicity</td>
<td>0.0006</td>
<td>0.006</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>0.0012</td>
<td>0.031</td>
</tr>
</tbody>
</table>

Calibration portability
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 $s$Weights 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 $K^\pm$. 
BDT output $\rightarrow$ 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)
Useful for $B_s^0$ tagging (in addition to SSKaon).

3 BDTs trained on simulated $B_s^0 \rightarrow D^- \pi^+$ (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:

$\epsilon_{\text{eff}} \sim 0.12\%$

$\rightarrow$ room for improvements!

---

**Algorithm**

**Events**

<table>
<thead>
<tr>
<th>Without using BDT_A and BDT_B</th>
<th>Using BDT_A and BDT_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$66204$</td>
<td>$66204$</td>
</tr>
<tr>
<td>$1151$</td>
<td>$1081$</td>
</tr>
<tr>
<td>$1368$</td>
<td>$1438$</td>
</tr>
<tr>
<td>$0.4569 \pm 0.0099$</td>
<td>$0.4291 \pm 0.0099$</td>
</tr>
<tr>
<td>$0.0380 \pm 0.0007$</td>
<td>$0.0380 \pm 0.0007$</td>
</tr>
<tr>
<td>$0.028 \pm 0.013%$</td>
<td>$0.076 \pm 0.021%$</td>
</tr>
</tbody>
</table>

---

**BDT_A**

**BDT_B**

**BDT_C**

**Vincenzo Battista (EPFL)**

23/08/2017
LHCb: RunII and upgrade

Expected sensitivity assuming same Flavour Tagging performances of Run I

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s$ mixing</td>
<td>$\phi_s(B^0_s \rightarrow J/\psi \phi)$ (rad)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B^0_s \rightarrow J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B^0_s)$ ($10^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$\phi^\text{eff}_{s}(B^0_s \rightarrow \phi \phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi^\text{eff}_{s}(B^0_s \rightarrow K^*0 K^0)$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$\phi^\text{eff}_{s}(B^0_s \rightarrow \phi K^0_s)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>$\phi^\text{eff}_{s}(B^0_s \rightarrow \phi \gamma)$ (rad)</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>currents</td>
<td>$\tau^\text{eff}<em>{s}(B^0_s \rightarrow \phi \gamma)/\tau</em>{B^0_s}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td>penguin</td>
<td>$q^2_0 A_{FB}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)$ ($10^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma(B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\gamma(B^0 \rightarrow D^+ K^0)$</td>
<td>17°</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B^0 \rightarrow J/\psi K^0_s)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm $CP$ violation</td>
<td>$A_T(D^0 \rightarrow K^+ K^-)$ ($10^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>$\dagger$</td>
</tr>
<tr>
<td></td>
<td>$\Delta A_{CP}$ ($10^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>$\dagger$</td>
</tr>
</tbody>
</table>