b-Flavour Tagging in $pp$ Collisions

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for the LHCb Collaboration
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Forward spectrometer designed for $b$- and $c$-hadron physics.

Run I (2010-2012). 3 fb$^{-1}$ of data on tape, $26 \times 10^{10} b\bar{b}$ in acceptance
Unprecedented sample of $b$-hadrons, all species ($B$, $B_s$, $B_c$, $\Lambda_b$, ...).

High performances. Tracks $\sigma_p/p \approx 0.4\%-0.6\%$; $\sigma(IP) \approx 20 \mu m$;
decay time resolution 40-50 fs for fully reco’d decays;
high PID, $\varepsilon(K)>90\%$, $\pi$ mis-id: <5%.

Tests of the CKM paradigm. Data reaching the precision to probe
interesting regions of SM and BSM scenarios.
B^0(s) MIXING AND CPV

Broad class of SM extensions can easily alter the mixing dynamics.

Decay rates

\[ e^{-\Gamma t} \left( \cdots \pm \cos(\Delta m t) \cdots \right) \]

Time-dependent CP asymmetries

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

Flavour tagging. Essential the knowledge of the B flavour at the production. Need an algorithm to tag the candidate as B or \( \bar{B} \) (tagging decision)
**Key Tagging Parameters**

**Efficiency** Fraction of events for which a tagging decision can be made.

\[ \varepsilon = \frac{N_{\text{tag}}}{N_{\text{tag}} + N_{\text{untag}}} \]

**Mistag probability** Fraction of the events with a wrong tag decision

\[ \eta = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}} \]

Dilutes the oscillation amplitude (the asymmetry) by O(60-80%)

**Tagging power** \( \varepsilon_{\text{eff}} = \varepsilon(1 - 2\eta)^2 \)

Determines the sensitivity to mixing observables

\[ \sigma \propto 1/\sqrt{\varepsilon_{\text{eff}}N} \]

NB. for \( B_s^0 \) the time resolution gives additional O(30%) dump of the amplitude for \( \sigma \approx 50 \) fs
The Players

**Same Side (SS):** charge of fragmentation pion ($B^0$) or kaon ($B_s^0$)

**Opposite Side (OS):** charge of lepton/kaon/inclusively reco’d sec. vertex from the other b-hadron decays
The Opposite Side

Require good quality tracks, no duplication with B signal tracks. Reject track from PV; ask for large IP. Exploit PID to identify the tagging particles.

Mistag from Neural Networks.
Use kinematical & geometrical information of the tagging particles, general event properties (number of tracks, PV,...). Train on $B^+ \rightarrow J/\psi K^+$ data.

Combine tag decisions and mistags to provide a single response.

Selection of tagging candidates optimized for the analyses of the full Run I LHCb data set. Improves tagging powers by $O(15\%)$ w.r.t 2011 analyses.
SSK tagger. Cut-based selection of the fragmentation kaon, closest to the $B_s^0$ signal in phase space. If more candidates, select the particle with highest $p_T$ [LHCb-CONF-2012-033].

New algorithm. Improved selection of fragmentation tracks with a Neural Network. Combine multiple candidates (up to 3) in a second Neural Network which computes the mistag and tagging decision. Train the NN’s on $B_s^0\rightarrow D_s^-\pi^+$ MC.

Higher efficiency $O(60\%)$ - w.r.t. $O(15\%)$. Mean mistag $O(43\%)$. Improves tagging power by 40%.
**Mistag Calibrations**

Calibrate the algorithms mistag in data.

\[ \omega = p_0 + p_1 (\eta - \langle \eta \rangle) \]

**Charged modes** \( B^+ \rightarrow J/\psi \ K^+ , \ B^+ \rightarrow D^0 \ \pi^+ \).
No oscillation, conceptually simple.
O(1M) events. Small systematic.

**Neutral \( B^0 \) modes** \( B^0 \rightarrow J/\psi \ K^* , \ B^0 \rightarrow D^* - \mu^+ \nu. \)
Need a full time-dependent analysis.
Large statistic; systematic relevant.

**Neutral \( B_s^0 \) modes** \( B_s^0 \rightarrow D_s^- \ \pi^+ \)
Only control decay for data SSK, full time-dependent analysis. Statistically limited.
Initial flavour asymmetries.
Differences of $B$ and $\bar{B}$ calibrations (different $K^+/K^-$ efficiency). SSK: from $D_{s}^{\pm}$ prompt decays – reweighted to match $B_{s}^{0}\rightarrow D_{s}^{-}\pi^{+}$ kinematic.
OS: compare $B^+$ and $B^-$ calibrations.

Calibration systematics:
• Consider each calibration method. Driven by the model of the decay time resolution in the fit of $B_{(s)}^{0}$ oscillations
• Check taggers portability with data (OS) and/or MC (SSK & OS)
• Account for differences between calibration samples and physics samples - reweight to match relevant distributions ($p_{T}(B)$, number tracks, ...)

LHCb-PAPER-2014-038
## Performances

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

- **Event type** | $\epsilon_{\text{tag}}$ [%] | $\epsilon_{\text{eff}}$ [%]
- OS-only | 19.80 ± 0.23 | 1.61 ± 0.03 ± 0.08
- SSK-only | 28.85 ± 0.27 | 1.31 ± 0.22 ± 0.17
- OS-SSK | 18.88 ± 0.23 | 2.15 ± 0.05 ± 0.09
- **Total** | 67.53 | 5.07

*+170% w.r.t. LHCb-CONF-2012-029*

### $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$\epsilon$ [%]</th>
<th>$\epsilon_{\text{eff}}$ [%]</th>
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</thead>
<tbody>
<tr>
<td>OS-only</td>
<td>13.6 ± 0.3</td>
<td>1.15</td>
</tr>
<tr>
<td>SS-only</td>
<td>31.7 ± 0.3</td>
<td>0.88</td>
</tr>
<tr>
<td>OS-SSK</td>
<td>18.0 ± 0.3</td>
<td>1.86</td>
</tr>
<tr>
<td><strong>TOT</strong></td>
<td>68.68 ± 0.33</td>
<td>3.89 ± 0.25</td>
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</tbody>
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*+60% w.r.t. PLB 713 (2012) 378*

### $B_s^0 \rightarrow \phi \phi$

<table>
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<th>$\epsilon_{\text{eff}}$ [%]</th>
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<tbody>
<tr>
<td>OS-only</td>
<td>13.8 ± 0.6</td>
<td>1.42 ± 0.06</td>
</tr>
<tr>
<td>SS-only</td>
<td>35.2 ± 0.8</td>
<td>0.87 ± 0.14</td>
</tr>
<tr>
<td>OS-SSK</td>
<td>27.0 ± 0.7</td>
<td>3.09 ± 0.17</td>
</tr>
<tr>
<td><strong>TOT</strong></td>
<td>75.94 ± 1.2</td>
<td>5.38 ± 0.23</td>
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*+60% w.r.t. PRL 110 (2013) 241802*

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*See Agnieszka’s talk*

*See Roel’s talk*

*See Matthew’s talk*
Performances

$B_s^0 \rightarrow J/\psi \phi$

PRD 87 (2013) 112010

$\varepsilon_{\text{eff}} = (3.13 \pm 0.23)\% \text{ (OS+SSK)}$

effect a $+20\%$ more for 2011+2012 data, mainly due to new SSK

See Roel’s talk

$B^0 \rightarrow J/\psi K_S$

PLB 721 (2013) 24-31

$\varepsilon_{\text{eff}} = (2.38 \pm 0.27)\% \text{ (OS)}$

expect a $+25\%$ more for 2011+2012 data, mainly due to inclusion of SS$\pi$
Conclusions

Flavour tagging essential to study neutral B meson mixing and CP violation.

**pp** collisions harsh environment.

Good detector + new algorithms: improved tagging performances since beginning of LHC Run I

**OS:** \(O(15\%)\) improvement in tagging power w.r.t 2011

**SSK:** \(O(40\%)\) improvement in tagging power w.r.t. 2011

Developments of new algorithms ongoing:
- improved **OSK** based on **NNet**
- **OS Charm**, benefits from low mistag
- **SS Proton** and **SSπ** taggers based on **BDT**