The TORCH Detector

Physics case

Tom Hadavizadeh,
on behalf of the TORCH collaboration
9th April 2019
4th Workshop on LHCb Upgrade II
- The aim of our physics studies are to quantify the improvement in physics performance from the proposed TORCH detector

- The current RICH system provides no positive kaon or proton identification below 10 GeV/c

- The TORCH detector is designed to complement the existing RICH detector discrimination
A number of recommendations were made during the review of the TORCH proposal. This talk has been updated with respect to the one given in the review session.

**Recommendations**

- **Today**
  - Continue physics studies with full simulation of TORCH integrated into LHCb

- **Future studies**
  - Extend TORCH physics studies to Upgrade II conditions
  - Perform physics studies with degraded performance, e.g. time resolution and photon yield
  - Perform realistic studies to determine if there is any degradation in other channels from TORCH
    - We intend to produce samples of $B \rightarrow K^* \gamma$ and $B \rightarrow K^* ee$ to check for degradation in ECAL performance
Outline

- PID performance
- Flavour tagging studies
  - Improved low-momentum PID
  - Impact of timing information
- Improvements for specific channels
  - Key modes with protons/kaons
  - Other modes
- Further studies of interest
- The TORCH PID performance is determined using full simulations of TORCH in LHCb

- This PID performance is incorporated into existing Upgrade I LHCb MC samples on an analysis-by-analysis basis

- The simulated TORCH and RICH PID efficiencies are combined for the relevant set of PID requirements
Some clarifications

- The candidates in the LHCb MC are constructed using reconstructed tracks

- The RICH PID performance is taken from the MC samples themselves
Flavour tagging

- Two aspects of flavour tagging have been investigated:
  - The effect of improved low-momentum PID performance on tagging power
  - The effect of correct track-PV association on tagging power as a function of the number of PVs

- To achieve this, simple cut-based tagging algorithms have been constructed

- This method has been used to isolate the effect of TORCH
Tagging Part I: PID

- Simple tagging algorithms are developed: **OSKaon** and **SSKaon**

- Three tag track selection methods are used:

<table>
<thead>
<tr>
<th>Selection</th>
<th>Tracks with p&lt;10 GeV/c</th>
<th>Tracks with p&gt;10 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>Nominal (i.e. p/p_T and RICH PID cuts)</td>
<td>Nominal</td>
</tr>
<tr>
<td>TORCH PID</td>
<td>Use TORCH efficiencies/mis-id rates</td>
<td>Nominal</td>
</tr>
<tr>
<td>Perfect PID</td>
<td>Only truth matched kaons</td>
<td>Nominal</td>
</tr>
</tbody>
</table>

- **Nominal**: the requirements on (RICH) PID and momentum are applied (selections in backup)

- **TORCH PID**: the TORCH efficiency and mis-id rates from the stand-alone simulations are used with the truth information to select the right fraction of each species for the corresponding RICH PID requirements

- **Perfect PID**: the performance using just the correct particle type (e.g. kaon) is compared as an upper limit of the possible PID-related improvement
- The tagging power is compared for the different configurations

\[ \varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} \times (1 - 2\omega)^2 \]

<table>
<thead>
<tr>
<th>Tagger</th>
<th>( B_s^0 \rightarrow D_s^+\pi^- ) Nominal</th>
<th>TORCH</th>
<th>Perfect</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSKaon</td>
<td>1.20 ± 0.05%</td>
<td>1.52 ± 0.05%</td>
<td>1.61 ± 0.05%</td>
</tr>
<tr>
<td>OSKaon</td>
<td>1.29 ± 0.05%</td>
<td>1.73 ± 0.06%</td>
<td>1.80 ± 0.06%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tagger</th>
<th>( B^+ \rightarrow J/\psi K^+ ) Nominal</th>
<th>TORCH</th>
<th>Perfect</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSKaon</td>
<td>1.06 ± 0.04%</td>
<td>1.51 ± 0.05%</td>
<td>1.61 ± 0.05%</td>
</tr>
</tbody>
</table>

- TORCH increases the tagging power for both algorithms
- Improvements consistent between the two samples
- Performance approaches upper limit with perfect PID below 10 GeV/c
- The TORCH detector could provide information about the timing of tracks to help correctly associate tracks to primary interactions
- Presently, the simulation doesn’t model the per-track timing
- The flavour tagging group has already shown that the tagging performance decreases with higher levels of pile up
- This TORCH study aims to determine the upper limit of the improvement if tracks could be correctly associated to their PV
Two opposite side tagging algorithms, OSKaon and OSMuon, are constructed.

The performance is compared between the nominal configuration (filled) and the situation in which all tracks originating from a different PV are removed (dashed).

The tagging power improves, but the dependence on the number of PVs and tracks is not removed entirely.
Specific decays

- The second part of the physics studies quantitatively assess the impact of TORCH on specific decay modes:

  - **Signal efficiency**: How much more signal would TORCH select?

  - **Background rejection**: Would TORCH improve the misidentification rate of backgrounds?

  - **Flatness**: Would the dependence of efficiency on phase-space be reduced?

- The RICH and TORCH PID performances are combined by selecting whichever is larger below 20GeV/c (above 20GeV/c just RICH PID is used)

- This PID performance is combined with samples of Upgrade I MC for each mode
\[ \Lambda_b^0 \rightarrow J/\psi pK^- \]

- This decay uses PID cuts to reduce misidentification backgrounds
- Including the TORCH performance for the same PID cuts increases the signal yield by 23%
- The variation in PID efficiency across the Dalitz plot significantly reduces

- Run II data is used to qualitatively investigate the level of combinatorial background
- Assuming the background is composed entirely of pions, TORCH improves the low momentum background rejection
Baryon asymmetry

\[ \Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^- \]

- Similarly, this mode requires PID requirements to select the proton (using a ProbNNp cut)
- Using a corresponding DLL cut, there is \( \sim 10\% \) more signal using the TORCH PID performance

- Run II data has been used to qualitatively investigate the background level
- The TORCH performance shows an improved background rejection, assuming all background are pions
- Semi-leptonic decay modes used to measure $V_{ub}$ will gain from TORCH

- Theoretically predicted form factors are most precise at high $q^2$, where the experimental efficiency is lowest

- These analyses require tight PID requirements to suppress misidentification backgrounds

- Incorporating the TORCH performance at low momentum leads to substantial improvements in signal yields:

$$\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu \quad \text{both } q^2 > 15 \text{ GeV}^2/c^2 \rightarrow \quad 130\% \text{ increase}$$

$$B_s^0 \rightarrow K^- \mu^+\nu_\mu \quad \text{all } q^2 \quad q^2 > 10 \text{ GeV}^2/c^2 \rightarrow \quad 35\% \text{ increase}$$

$$\rightarrow \quad 54\% \text{ increase}$$
A range of other modes have been investigated:

- Generally, the improvements depend on how tight the requirement on kaon-proton separation is.

\[ B^+ \rightarrow p\bar{p}\mu^+\nu_\mu \]

Tight momentum and PID requirements
- Gains around 121% extra signal yield

\[ \Lambda_b^0 \rightarrow pK^-\mu^+\mu^- \]

Medium PID requirements
- Gains around 24% extra signal yield
Other modes

- A range of other modes have been investigated:
  - Lots of modes could benefit from TORCH less directly, e.g.

\[ B^0 \rightarrow DK^{*0} \]

- Used to measure CKM angle gamma
- The K^{*0} mass window is fairly narrow to control K^{*0} double mis-id background
- Improvements from TORCH would mean the mass window could be widened for the same mis-id rate
- Leads to 8% increase in signal yield
Summary

- This selection of analyses discussed here is intended to be a cross-section of some interesting modes.
- The tagging studies suggest TORCH could improve the tagging power by 25–35% for algorithms that require kaon identification.
- Timing information from TORCH could help reduce the degradation of tagging performance with increased pile up.
- A range of decay mode would have signal yields 10–130% larger, depending on the existing tightness of selections.
Future outlook

Today

✓ Continue physics studies with full simulation of TORCH integrated into LHCb

- The internal note has been updated with these latest studies
  - A new version will be available shortly
- We intend to further these studies to address the other recommendations of the TORCH review:

Future studies

➡ Extend TORCH physics studies to Upgrade II conditions
➡ Perform physics studies with degraded performance, e.g. time resolution and photon yield
➡ Perform realistic studies to determine if there is any degradation in other channels from TORCH
  - We intend to produce samples of $B \rightarrow K^* \gamma$ and $B \rightarrow K^* \, e^+ e^-$ to check for degradation in ECAL performance
Back up
The charge of the chosen tag is compared to the MC truth information of the b-hadron initial flavour to determine whether the tagging decision is correct. The perfect PID category is used to set an upper limit of the possible improvement in the tagging performance. This method has been constructed to simplify the comparison of the different tagging configurations. Therefore the performance of these algorithms are suboptimal compared to the state-of-the-art methods. Additionally, these algorithms provide no prediction of the mistag rate which further limits their performance. The selection requirements implemented in these simple tagging algorithms are detailed in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Nominal</th>
<th>SSKaon TORCH</th>
<th>Nominal</th>
<th>OSKaon TORCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$&gt;5250 \text{ MeV/c}$</td>
<td>$&gt;2000 \text{ MeV/c}$</td>
<td>$&gt;2000 \text{ MeV/c}$</td>
<td>$&gt;2000 \text{ MeV/c}$</td>
</tr>
<tr>
<td>$p_T$</td>
<td>$&gt;850 \text{ MeV/c}$</td>
<td>$&gt;200 \text{ MeV/c}$</td>
<td>$&gt;200 \text{ MeV/c}$</td>
<td>$&gt;700 \text{ MeV/c}$</td>
</tr>
<tr>
<td>PIDK</td>
<td>$&gt;3.5$</td>
<td>$&gt;15.0$</td>
<td>$&gt;3.5$</td>
<td>$&gt;30.0$</td>
</tr>
<tr>
<td>PIDp−PIDK</td>
<td>$&lt;8.5$</td>
<td>$&lt;-5.0$</td>
<td>$&lt;8.5$</td>
<td>$&lt;10.0$</td>
</tr>
<tr>
<td>$\chi^2_{\text{IP}}$</td>
<td>$&lt;4.125$</td>
<td></td>
<td>$&gt;31.0$</td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td></td>
<td></td>
<td>$&lt;1.6$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>$&lt;0.825$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \eta$</td>
<td>$&lt;0.6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>$&lt;10$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m(BK) - m(B)$</td>
<td>$&lt;1850 \text{ MeV/c}^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PU $\chi^2_{\text{IP}}$</td>
<td>$&gt;3.0$</td>
<td></td>
<td>$&gt;31.0$</td>
<td></td>
</tr>
<tr>
<td>Dist phi</td>
<td>$&gt;0.005$</td>
<td></td>
<td>$&gt;0.005$</td>
<td></td>
</tr>
<tr>
<td>$\chi^2_{\text{Trk}}$</td>
<td>$&lt;3.0$</td>
<td></td>
<td>$&lt;3.0$</td>
<td></td>
</tr>
<tr>
<td>Ghost Prob.</td>
<td>$&lt;0.35$</td>
<td></td>
<td>$&lt;0.35$</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Selection requirements used for each of the simple tagging algorithms. The variables PIDK and PIDp refer to the difference in the log-likelihood of the kaon and pion, or proton and pion hypotheses in either the simulation of the Upgrade Ib RICH detectors (nominal), or from the TORCH stand-alone performance (TORCH). The variables IP and $\chi^2_{\text{IP}}$ are the impact parameter and difference in the best primary vertex fit $\chi^2$ with and without the tag track included. The best primary vertex is the one to which the candidate has the smallest $\chi^2_{\text{IP}}$. The variables $\Delta \phi$, $\Delta \eta$ and $\Delta R$ describe the difference in direction of the candidate and tag track in the azimuthal angle, pseudo-rapidity, and in their combination $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$. The quantity $m(BK) - m(B)$ is the difference between the invariant mass of the candidate and tagging track and the invariant mass of just the candidate. PU $\chi^2_{\text{IP}}$ is the value of $\chi^2_{\text{IP}}$ for the second best primary interaction vertex, i.e. a pile up (PU) vertex. Dist phi helps remove cloned tracks by comparing the angle between all candidate tracks and the tag. The quantity $\chi^2_{\text{Trk}}$ describes the quality of the track fit, and Ghost Prob helps discriminate against ghost tracks.
### Tagging selections

<table>
<thead>
<tr>
<th>Variable</th>
<th>OSMuon</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T^2 )</td>
<td>&gt;1100 MeV/c</td>
</tr>
<tr>
<td>( \chi^2_{IP} )</td>
<td>&gt; 0.0</td>
</tr>
<tr>
<td>( \text{PU } \chi^2_{IP} )</td>
<td>&gt; 3.0</td>
</tr>
<tr>
<td>Dist phi</td>
<td>&gt; 0.005</td>
</tr>
<tr>
<td>( \chi^2_{Trk} )</td>
<td>&lt; 3.0</td>
</tr>
<tr>
<td>Ghost Prob.</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>PIDmu</td>
<td>&gt; 3.0</td>
</tr>
<tr>
<td>ProbNNmu</td>
<td>&gt; 0.35</td>
</tr>
<tr>
<td>ProbNNk</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td>ProbNNe</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td>ProbNNpi</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td>ProbNNp</td>
<td>&lt; 0.8</td>
</tr>
</tbody>
</table>

Table 3: Selection requirements used for the simple OSMuon tagging algorithm. The \( \text{ProbNN} \) variables are neural-network based PID variables.