 Suppressing Beam Background and Fake Photons at Belle II using BDTs

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1. Introduction

The residual energy in the electromagnetic calorimeter (ECL), called $E_{\text{ECL}}$, is a key background-suppression tool for decays with missing energy (neutrinos). The power of $E_{\text{ECL}}$ degrades when beam background clusters and fake photons are included in the residual energy calculation. To remove these photon contributions from $E_{\text{ECL}}$, and improve its signal-background separation, two separate classifiers have been built to identify beam background and fake photons. The framework used is FastBDT [1] - a stochastic gradient boosted decision tree (BDT). The two BDTs presented are useful for experiments using crystal calorimeters with near-4$\pi$ coverage such as BES-III and KLOE. The BDTs are used in the Belle II analyses of $B \rightarrow D^{(*)}\ell\nu$, $B \rightarrow K\nu\ell\nu$, $B \rightarrow \mu\nu$, $B \rightarrow \tau\ell$, $B \rightarrow \tau\nu$, $\Upsilon(4S) \rightarrow \eta_{b}(1P)$ and inclusive $R(D)$. 

2. Belle II Detector

Belle II is located at the SuperKEKB asymmetric $e^+e^-$ collider in Tsukuba, Japan. The collider operates at the CMS energy of $\sqrt{s} = 10.58$ GeV. This corresponds to the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ meson decays almost exclusively to a pair of $B$ mesons i.e. $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$. Since operation began in 2018, Belle II has recorded an integrated luminosity of $\int L dt = 428 fb^{-1}$. Belle II has a near-4$\pi$ coverage of the interaction point, so full reconstruction of the event can be achieved.

3. Background Photons

Beam background clusters originate from beam interactions like Touschek scattering, Bhabha scattering and beam-gas scattering. Fake photons are calorimeter energy deposits that are split into multiple clusters during the reconstruction process, for example due to hadronic split-offs. Photon samples for the BDT training were sourced from Monte-Carlo simulated data. True photons from the $\Upsilon(4S)$ decay are labelled class 1 while beam background and fake photons are class 0.

4. BDT Features

Important features were determined using the total information gain of each feature in BDT.

Beam Background BDT Features
- Energy, timing and polar angle of the cluster
- Output of a separate MVA that characterizes cluster shapes
- Output of a separate MVA that uses pulse-shape information from activated ECL crystals, where class 0 = hadronic showers and class 1 = electromagnetic showers [2]

Fake Photon BDT Features - all the beam background BDT features plus
- Distance between the cluster and its nearest track

5. Classifier Performance

The optimal hyperparameters were chosen using holdout with results below:

<table>
<thead>
<tr>
<th></th>
<th># Trees</th>
<th>Max Depth</th>
<th>Shrinkage</th>
<th>Test AUC Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Background BDT</td>
<td>100</td>
<td>3</td>
<td>0.1</td>
<td>0.998</td>
</tr>
<tr>
<td>Fake Photon BDT</td>
<td>300</td>
<td>0.1</td>
<td></td>
<td>0.944</td>
</tr>
</tbody>
</table>

Output of beam background/fake photon BDT gives probability of being class 1 (signal photon)

6. Testing On $B^0 \rightarrow D^*(\ell\nu)$

Cuts used on the BDT outputs: beam background BDT > 0.6 and fake photon BDT > 0.7. A two-template fit (signal and combined background) to $E_{\text{ECL}} < 0.8$ GeV can be used to get the signal yield $S$, with fit uncertainty $\sigma(S)$.

7. References
