Machine Learning to Improve Electron Reconstruction at the LHCb

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1. Background and Theory

Lepton Flavour Universality

In the standard model, all leptons (e, μ, τ) couple equally to gauge bosons, only their mass varies [1]. We would then expect in the decay of b hadrons, electrons and muons to be produced equally, we expect then the **branching ratio**,

$$R_k = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

to be 1. Various experiments at the **LHCb** have demonstrated a branching ratio of less than 1 but have only reached a significance of 3 σ [2][3]. This **indicates deviations from the standard model**. One of the limiting factors is the **Bremsstrahlung radiation** emitted by electrons as they travel through the material of the detector [4].

Bremsstrahlung Radiation

Bremsstrahlung radiation, also referred to as 'braking radiation', is electromagnetic radiation emitted by charged particles as they slow down,

$$\sigma = \frac{Z^2}{137}\left(\frac{e^2}{mc^2}\right)^2$$

with the **cross section, σ,** inversely proportional to mass squared [4]. Electrons are most strongly affected by this process. If this missing energy isn't correctly accounted for then **accurate reconstructed mass plots of primary events aren't possible**. In the current method, Bremsstrahlung photons are naively added to electrons based on their position – introducing a lot of noise into the estimation of branching ratio [5].

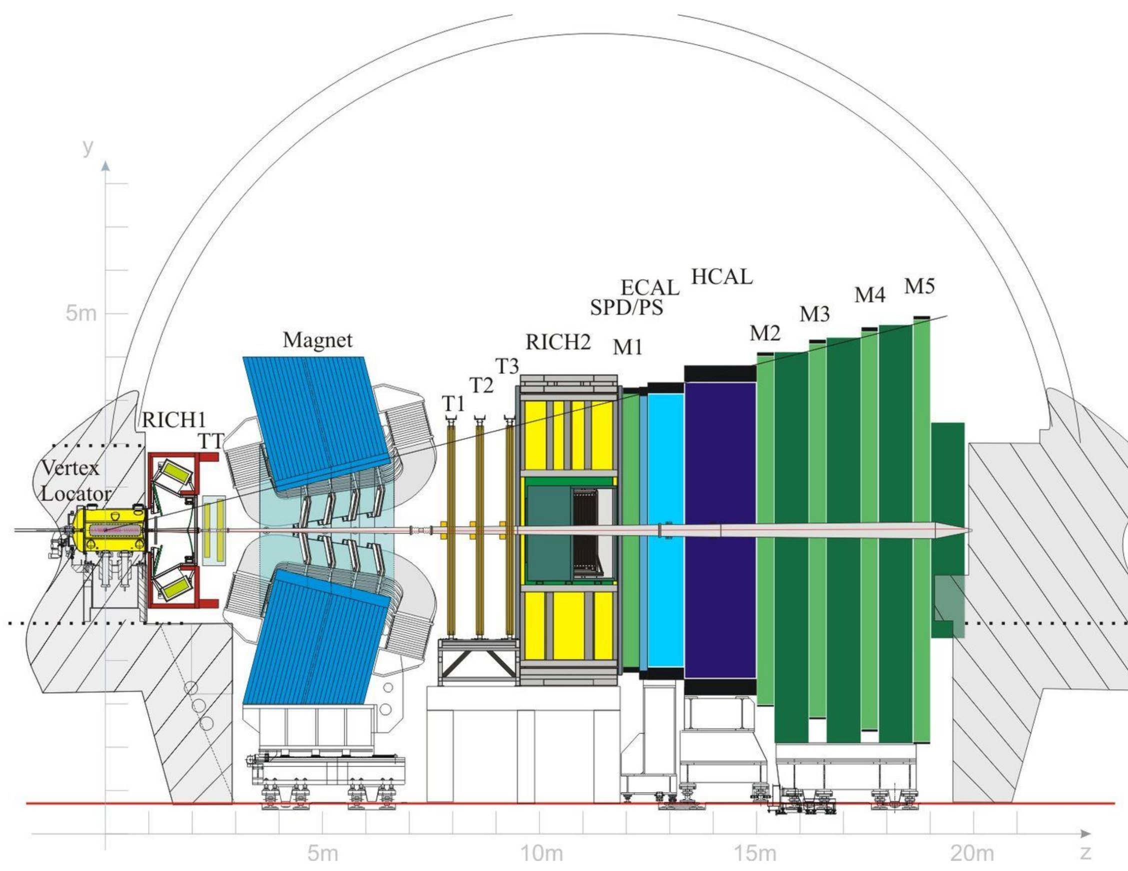

Fig 1. – Diagram of the LHCb detector at the LHC. It is a single arm forward spectrometer designed to measure the physics of b quarks. It has a number of key goals, including: Measuring the branching ratio of $B_s \to \mu^+ \mu^-$, measuring CP violating decays, measure flavour-changing current decays etc. [6]

2. Aims

Use ensemble machine learning methods to identify appropriate Bremsstrahlung photons associated with electrons

Reconstruct B, K and J/ϕ masses from the set of correctly identified Bremsstrahlung photons

Extend method to environment expected in the LHCb upgrade

3. Implementation

Simulation

LHCB simulation software **Gauss** is used to simulate the interactions of the particles with the detector. The interactions from **Gauss** with the active parts of the detector are then simulated by **Boole** to generate electronic readouts of the detectors. **Brunel** is then used to reconstruct the tracks and properties of the particles from the readout data. **Bender** is then used to convert the data into a more usable format for analysis.

Method

From the data generated by **Bender**, we take the Bremsstrahlung cluster positions and determine the momentum of the Bremsstrahlung photons, assuming they came from the VELO (as they do in [5]). We then take the pre-reconstruction electron and Bremsstrahlung photon 3-momenta and 3-positions and find $\boldsymbol{\delta\phi}$ and $\boldsymbol{\delta\theta}$. The angular information is then used as an input for the **XGBoost classifier** (a type of Boosted Decision Tree (BDT), with the correct subset of Bremsstrahlung photons for a particular electron labelled 1 and the incorrect labelled 0. This trained classifier then allows us to the reconstruct the B, K and J/ϕ masses from other datasets, including higher bunch crossing rates.

4. Analysis

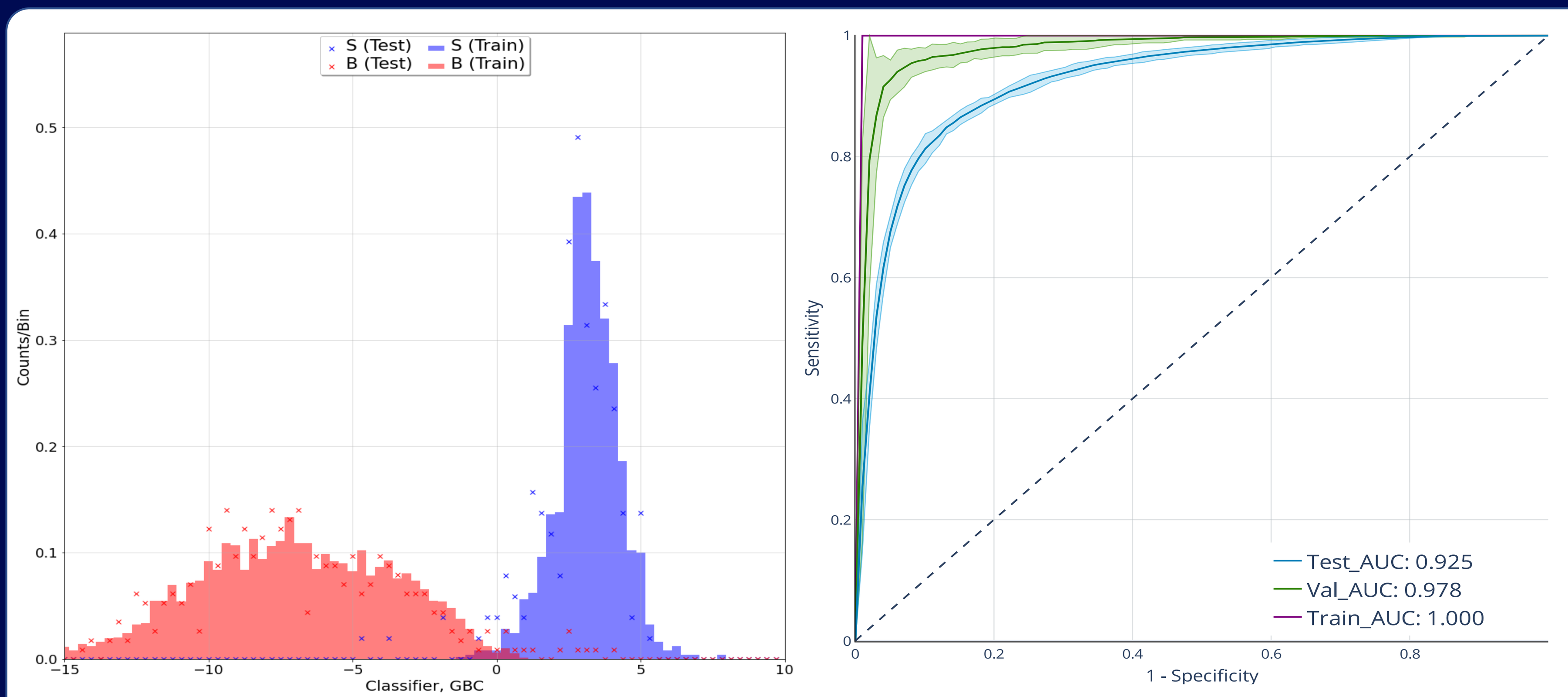

Fig 3. – Decision function (left) representing classifier's ability to separate signal and background in both training and testing data. ROC curve (right) represents the classifier's ability to correctly predict the positive class whilst minimizing the false positive rate.

XGBoost classifier performance

1) Classifier is able to correctly separate the signal and the background with a distinct threshold – much more effectively than other methods like MLP.
2) AUC score from the ROC curve for out-of-sample proton-proton collision with $\mu = 1.1$ is 0.925, and the average precision (AP) score is 0.924.
3) XGBoost classifier performs exceptionally well on $B^+ \to K^+ J/\psi(\to e^+ e^-)$ validation dataset with an AUC score of 0.978 and AP score of 0.975.
4) Classifier was trained only on 1000 $B^+ \to K^+ J/\psi(\to e^+ e^-)$ events, implying a much larger potential for this algorithm in identifying which photons came from which electron.

5. Future Work

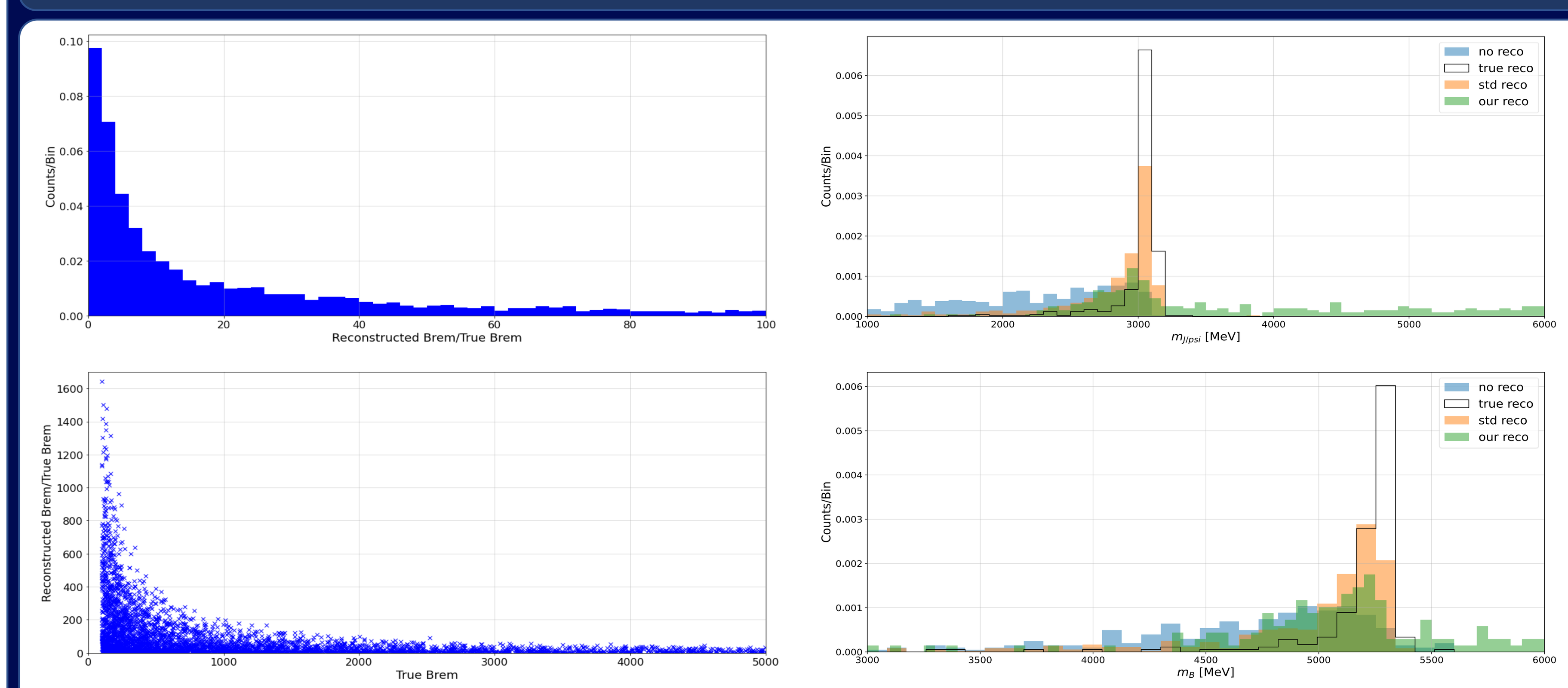

Fig 4. – Left plots represents True Bremsstrahlung vs reconstructed; we observe reconstructed photon energies are on average larger than true photons. Right plots represents the mass plot for J/ψ and B meson; we observe an overestimation on the mass even at a minimum energy threshold of 3000. Note the mass plots are only displaying the relevant domain for our reconstruction.

1. Develop a classifier to predict whether the true/reconstructed photon energy ratio is above a certain threshold to remove certain photons
2. Develop a regressor to predict the energy ratio, such that we can then adjust our photon momentum estimates
3. Develop a regressor to better determine the components of the electron 4-momentum from the photons

References

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