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Are B Anomalies Breaking the Standard Model?

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1) Motivation

Leptons interact with the weak force independent of their flavour, this is known as lepton universality.

- The ratio of the branching fractions below (R_K) [1] is expected to be unity within the standard model (SM):

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}.$$

- Results from LHCb seem to hint towards avenues of new physics hiding within the underlying b quark decays, as the measured value of Rk = $0.84^{+0.044}_{-0.041}$ [1] disagrees with the SM prediction.
- Due to the large τ mass any new physics effect would be more pronounced in $b \to s\tau^+\tau^-$ decays.
- We aim to develop a method to detect notoriously hard to identify τ's in order to provide tools to probe this effect further.

2) Data Sample

- A Monte Carlo data sample of τ decay products (shown in Table I) and background π^0s was used.
- Successfully isolating the signal π^0s and their corresponding charged counterparts, would show the feasibility of reconstructing τ's.

Decay mode	$\mathcal{B}$ [%]
$\tau^- \to \pi^-\,\nu_\tau$	11.5
$\tau^- \to \pi^-\,\pi^0\,\nu_\tau$	26.0
$\tau^- \to \pi^-\,\pi^0\,\pi^0\,\nu_\tau$	9.5
$\tau^- \to \pi^-\,\pi^+\,\pi^-\,\nu_\tau$	9.8
$\tau^- \to \pi^-\,\pi^+\,\pi^-\,\pi^0\,\nu_\tau$	4.8
Other modes with hadrons	3.2
All modes containing hadrons	64.8

Table I: Adapted from reference [2]. The hadronic decay modes of the τ⁻ included in our data sample along with their branching fractions. Charge conjugation invariance is assumed to hold.

3a) Feature Engineering

Investigating typical event windows like in Fig. 1, gave us clues about what features may discriminate between background and signal π^0s.

For example, it illustrates how:

- Signal π^0s are much closer to $\pi^{+/-}$s when propagated to the calorimeter plane than background π^0s.
- We utilise multiple spatial features like this to identify signal π^0 candidates from a plethora of background.

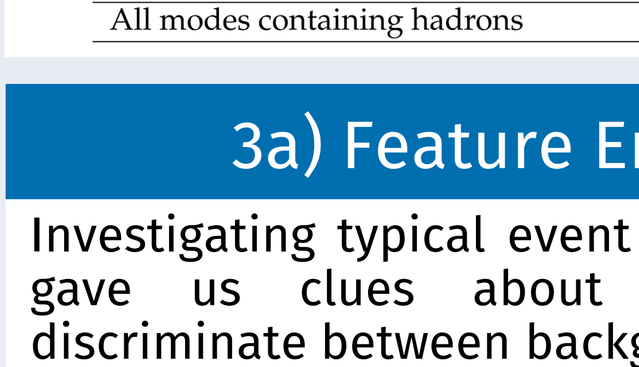

Figure 1: A typical event window created by assuming a vertex at the origin and propagating all particles (signal/background π^0s in red/blue and $\pi^{+/-}$s in green) to the calorimeter plane using their momenta.

[1] LHCb Collaboration, R. Aaij, Test of lepton universality in beauty-quark decays, (2021), [arXiv:2103.11769]
[2] CMS Collaboration, Reconstruction and Classification of τ lepton decays to hadrons and ν_τ at CMS, (2016), [arXiv:1510.07488v2]
[3] Band, H. and Camporesi, T., 1987. Measurements of tau decays to three pions. *Physics Letters B*, 198(2), pp.297-301.

3b) Feature Engineering

We also considered other avenues of reasoning such as:

- π^0 and $\pi^{+/-}$ systems with invariant mass greater than the τ mass cannot be physically produced.
- Signal π^0 cluster energy density tends to be greater than for background π^0s

By applying these features within a machine learning algorithm, we can create a model to predict which π^0s come from τ leptons.

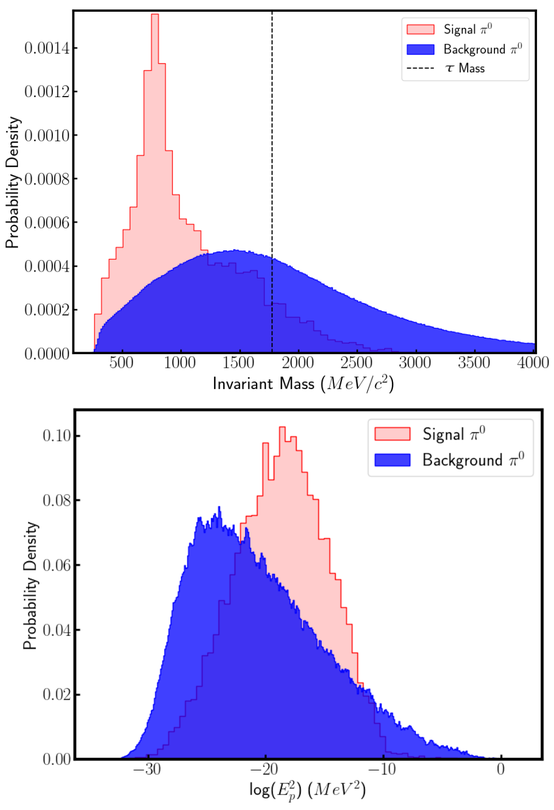

Figure 2: Histograms comparing signal (red) and background (blue) π^0 properties. Top displays invariant mass (with τ mass shown in black) while bottom shows cluster energy density.

4) Results

- The boosted decision tree model was trained on a sample containing roughly 6 million background π^0s and 12734 signal π^0s.
- The curve of true positive rate vs false positive rate in Fig 3 was produced and shows that a minimum of 14.1% of signal π^0s can be isolated with a zero false-positive rate.

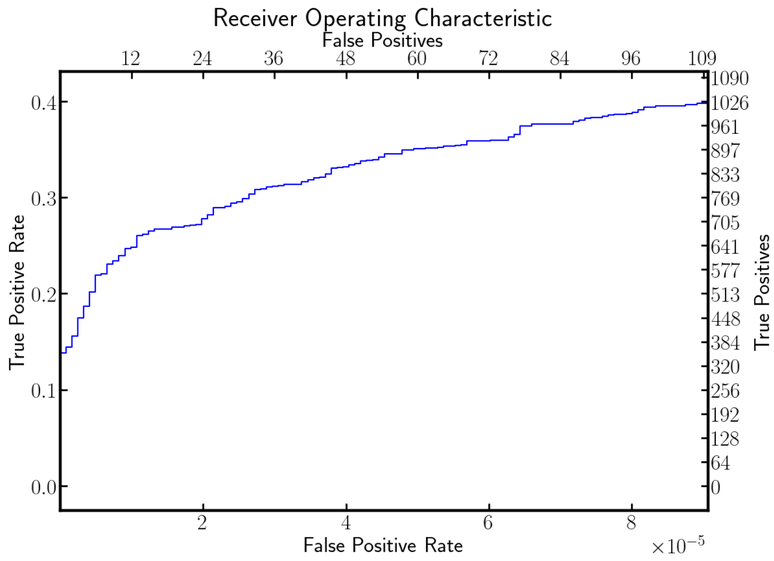

Figure 3: ROC Graph displaying the trade-off between number of signal π^0s detected and number of background π^0s included after using the resultant model.

5) Conclusions

- We see strong success in the ability to determine previously unknown π^0s, from background data.
- Combining this with the detection of $\pi^{+/-}$s, would enable the reconstruction of τs.
- Currently only τs that decay to more than 1 hadron can be reproduced accurately [3] – including the other decay modes (shown in Table I) would greatly increase our resolution.
- A better estimate of the $\mathcal{B}(B \to K\tau^+\tau^-)$ and similar decays can then be obtained thus further probing lepton-universality.