Search for Axion-Like Particles in FCNC Decays of the Top Quark within the ATLAS Experiment

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Motivation

The top quark is the heaviest elementary particle in the Standard Model (SM) and decays almost exclusively via $t \to Wb$. Axion-like particles (ALPs), which appear in many extensions of the SM, can couple to top quarks and thereby give rise to exotic decay signatures. Here, we focus on the decay $t \to qa$ with $q = u, c$, which proceeds through a flavour-changing neutral current (FCNC) interaction involving the ALP. The analysis targets ALPs with lifetimes long enough to produce displaced signatures inside the ATLAS detector. Such signatures are sensitive probes of new physics, since FCNC top-quark decays are highly suppressed in the SM.

Long-lived ALP signature

For ALP masses in the 1-10 GeV range, the decay products are typically highly collimated and reconstructed within a single jet. If the ALP decays in the outer electromagnetic or hadronic calorimeter, the resulting jet has little or no associated tracking activity and deposits a large fraction of its energy in the hadronic calorimeter. A characteristic observable is therefore the calorimeter energy ratio

$$\mathrm{LogRatio} = \log_{10}\left(\frac{E_{\mathrm{had}}}{E_{\mathrm{EM}}}\right).$$

This displaced, trackless jet signature is used to identify long-lived particle candidates.

Event reconstruction

For the FCNC top-decay channel, we consider $t\bar{t}$ events in which one top quark decays exotically via $t \to qa$, while the other follows the SM decay $t \to Wb$. The event reconstruction identifies an ALP candidate based on its large LogRatio value and assigns the remaining jets to the two top-quark decay branches. For each possible jet combination, the reconstructed top-quark masses and b-tagging information are combined in a likelihood that quantifies the compatibility of each assignment with the expected top-quark mass distributions. The best combination is selected, and its likelihood value is also used as an additional cut to improve the expected significance.

Background estimation and multivariate selection

A major challenge is the estimation of backgrounds that are difficult to model reliably with simulation alone. The analysis therefore uses a data-driven ABCD method. Two approximately independent discriminating variables define four regions, with A as the signal region, D as the most background-like region, and B and C serving as control regions. If the variables are sufficiently uncorrelated in background events, the yield in region A can be predicted from the other regions as

$$N_A^{\mathrm{pred}} = \frac{N_B N_C}{N_D}.$$

The consistency of this prediction is tested on simulation with a closure test. The closure is defined as the ratio of the background yield directly obtained in region A to the corresponding ABCD prediction and should be close to unity.

To improve the separation between signal and background while preserving the independence required by the ABCD method, two boosted decision trees (BDTs) are trained on different sets of observables. Cuts on their scores define the four regions, and both classifiers use gradient boosting. The first is optimized primarily for signal-background discrimination, while the second uses a modified loss function to reduce correlations between the two BDT scores. The present optimization balances sensitivity, sufficient background statistics in the control regions, and closure of the ABCD prediction.

Outlook

The current strategy combines the characteristic displaced, trackless jet signature with likelihood-based event reconstruction, b-tagging, and multivariate classification in a data-driven background estimate. The next steps are to increase the available simulated samples, further optimize the event selection and ABCD working point, and apply the strategy to collision data. In addition, further signal topologies such as flavour-diagonal $t\bar{t}$ + ALP production will be included to extend the analysis to complementary top–ALP couplings. The final goal is to set limits on the relevant top–ALP couplings and, for the FCNC channel, on the corresponding branching ratio.