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Searches for new phenomena in hadronic final states using the ATLAS detector

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Many theories beyond the Standard Model predict new phenomena giving rise to multijet final states. These jets could originate from the decay of a heavy resonance into SM quarks or gluons, or from more complicated decay chains involving additional resonances. Also of interest are resonant and non-resonant hadronic final states with jets originating from a dark sector, giving rise to a diverse phenomenology depending on the interactions between the dark sector and SM particles. This talk presented the latest 13 TeV ATLAS results.

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1. Introduction

Dijet and multijet final states may stem from the decay of beyond the Standard Model (BSM) heavy resonances into SM quarks or gluons. In this context, simplified resonance models have historically been examined, and during ATLAS [1] Run-2, numerous standard candle searches were published [2], some of which involved additional objects, such transverse missing energy components [3].
In the following sections, recent results obtained using hadronic final state events recorded by the ATLAS detector in the context of 13 TeV Run-2 collisions will be presented.

2. New directions for probing hadronic final states

Run-2 data continue to provide a fertile ground for exploring hadronic final states from multiple angles, introducing new approaches and techniques. One can think to intricate decay chains involving additional resonances, leading to high jet multiplicities. Furthermore, resonant and non-resonant hadronic final states featuring jets originating from a new dark sector became appealing and accessible. In the context of hadronic final states, novel approaches employing fully unsupervised Machine Learning (ML) based models for tagging and identifying anomalous events are emerging as potent tools for the quest to discover New Physics.

2.1 Increasing jet multiplicities

The quest for dijet resonances has been a cornerstone of collider physics, both at the LHC and previous colliders. However, the evolving landscape of particle physics demands the exploration of more complex final states. When decay chains become intricate, and the number of jets in the final state grows, the challenges of combinatorics and the associated difficulties in jet pairing can often afflict the effective interpretation of the decay history. The problem becomes even more difficult in practice due to the possible existence of additional high-momentum jets from initial state radiation (ISR) and overlapping particle interactions (pileup).
Traditionally, heuristic methods have been employed in final states with a low object multiplicity, such as dijet pairs, where it's feasible to test all possible combinations. In a recent result from ATLAS [4], a search was conducted for a generic massive resonance, denoted as Y, that decays into pairs of intermediate resonances X with identical masses. Each of these intermediate resonances X, in turn, decays into two partons, typically giving rise to a pair of dijet systems. Such a model represents one of the simplest extensions of s-channel resonances decaying into two jets.
In the analysis, both the tetrajet mass m_{4j} and the average dijet mass m_{2j} are explored, in regions of $\alpha = m_{2j}/m_{4j}$ (a proxy for m_X/m_Y)[1], with the idea to perform independent data-driven fits with a functional form for each obserbable and check for significant deviations with the BumpHunter algorithm.
Fully calibrated anti-k_t $R = 0.4$ jets are used and are required to have $p_T > 60$ GeV and $|\eta| < 2.4$. The topology is clear: events are require to have a least four of these jets, later to be paired. The pairing is implemented by minimizing the angular distance

$$\Delta R = |\Delta R_{AB} - 0.8| + |\Delta R_{CD} - 0.8| \tag{1}$$

where A, B, C, D are the indices of the highest-p_T jets in the event and 0.8 is so to have collimated jets, but not so boosted to have them resulting in a large-R jet. After the pairing, in order to suppress

[1]The two masses are correlated; a parameterization of the kinematic space in terms of the Lorentz boost of the decay products is needed to avoid undesired background sculpting.

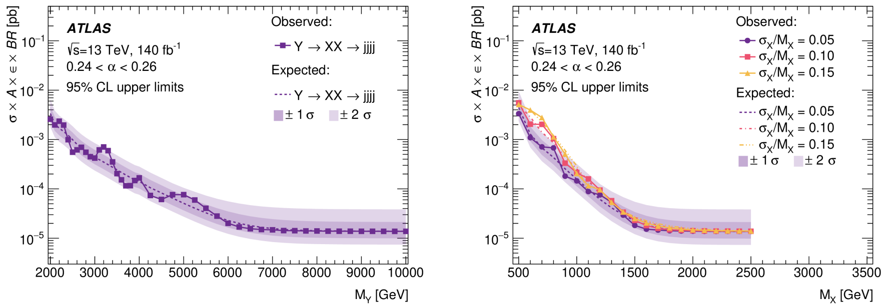

Figure 1: Expected and observed model dependent (left) and independent (right) limits on cross-section times acceptance, efficiency, and branching ratio as a function of m_Y (left) and m_X (right) in the region $0.24 < \alpha < 0.26$. This is just a subset of the obtained results [4].

QCD background processes, dijet pairs are additionally supposed to have $\Delta R_{AB,CD} < 2.0$, they are required to be central $|\eta_{AB} - \eta_{CD}| < 1.1$ since Y decays in s-channel, and they are required to be balanced in mass $|(m_{AB} - m_{CD})/(m_{AB} + m_{CD})| < 0.1$ since they are expected to be originated from the same X mediator. Given the non-resonant nature of QCD background processes, both the mass variables are expected to follow a smoothly falling distributions, thus they are modeled with a traditional "dijet" function of the form

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln(x) + p_5 \ln(x)^2} \tag{2}$$

No significant deviation has been identified, using the BumpHunter p-value, generally in all the regions probed, so 95% confidence level (CL) limits are placed on a large range of possible production cross-sections for the hypothetical X and Y bosons. Some examples of the constraints set in the work are reported in Figure 1, for both model dependent and independent scenarios.
As just seen, minimizations over the set of combinations in invariant mass or angle are particularly popular for solving the jet combinatorial problem for simple signatures, as the one just described. ML based approaches can be used to overcome the many limitations of the classical strategies. In a recent work by ATLAS [5], in the context of R-parity-violating (RPV) supersymmetry (SUSY) models that feature prompt gluino-pair production decaying directly to three jets each, a Neural Network (NN) based on the attention mechanism and taking inspiration from the modern transformer model has been built. The input to the network is the jet four-momenta, connected to an embedding block where each jet is mapped to a latent space. The embedded jets are passed to an encoder step consisting of self-attention and cross-attention blocks. The outputs of the model encodes the optimal jet pairing, also considering possible non-signal sources such as ISR of pileup. The performance of the NN is summarized in Figure 2.

The work is part of a larger effort [6, 7] aiming at solving combinatorial assignment problems without the need to introduce prior knowledge or assumptions about the particles' decay. These tools, developed in the context of several ATLAS searches, can serve as general tool for the larger HEP audience.

2.2 Anomaly detection

ML-based techniques are rapidly expanding their scope in the realm of New Physics searches. These methods are not limited to creating clustering tools, as discussed in the previous section, but are also employed in designing novel search regions. These regions identify events solely based on their

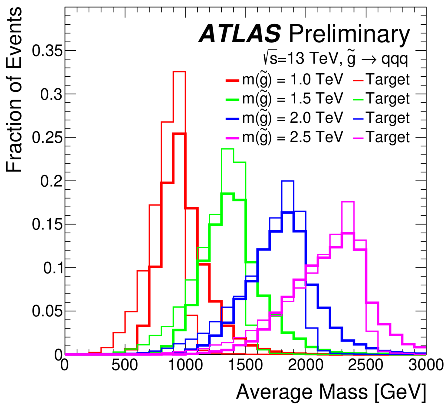

Figure 2: Normalised average mass spectrum comparing the shapes of the reconstructed by the NN pairing model (solid) and target (light) Monte Carlo truth-level distributions, for different masses [5].

deviation from a learned background-only model. In the pursuit of heavy resonances Y decaying into a Standard Model Higgs boson H and a new particle X within a fully hadronic final state, ATLAS has recently introduced a jet-level anomaly detection tagger [8]. This tagger allows for the selection of boosted X particles without relying on a specific signal model, marking a significant milestone as the first application of fully unsupervised machine learning in an ATLAS analysis.
The regions for analysis in this search primarily focus on selecting two large-R jets. These jets are constructed using the anti-k_t algorithm with a radius parameter of $R = 1.0$. They are required to have transverse momentum (p_T) greater than 200 GeV and pseudorapidity within the range $|\eta| < 2.0$. The anomaly detection and the definition of the associated search region are implemented through a jet-level Anomaly Score (S_A) generated by a variational recurrent neural network (VRNN). The VRNN is trained on large-R jets from the ATLAS Run 2 dataset, selected to deal with highly boosted topologies. The input representation of jets is designed as a sequence of up to 20 constituent four-vectors per jet. This input modeling is crafted to unveil correlations among constituents and substructures, enabling the VRNN to discern jets with anomalous energy-deposition patterns from the background of homogeneous jets originating from QCD processes. The loss function of the VRNN consists of a reconstruction error term and the Kullback–Leibler (KL) divergence of the encoded approximate posterior distribution from the Gaussian prior. Consequently, the Anomaly Score is defined in terms of the overall KL divergence itself. Given the target decay chain of $Y \to HX \to JJ$, a second network is also deployed to address the H/X ambiguity.
To augment the anomaly detection region, a comprehensive analysis selection strategy is implemented, which includes two regions with merged and resolved small-R jets. This approach aims to maximize the sensitivity phase space of the search. Traditional bump-hunting techniques are applied in the anomaly region to quantify a p-value, while striving to minimize dependence on specific signal models. The most significant excess is detected in the anomaly region, with a global significance of 1.43 σ when considering all possible values of m_Y and m_X. The results are further interpreted as 95% CL upper limits on the cross section $\sigma(pp \to Y \to HX \to qqbb)$ within a two-dimensional parameter space, where m_Y ranges from 1.5 to 6 TeV and m_X spans from 65 to 3000 GeV.

2.3 New jets from new portals

In recent years, there has been a growing interest in exploring scenarios beyond the Standard Model (BSM) that involve additional hidden sectors. These sectors, thought to contain dark quarks and dark gluons, could potentially serve as candidates for dark matter, resulting in stable dark hadrons with unique signatures at colliders. At the Large Hadron Collider (LHC), the production of dark quarks can occur through the decay of a heavy mediator, serving as a portal between the Standard Model (SM) and the new hidden sector. Subsequently, these dark quarks undergo hadronization, leading to the formation of dark hadrons, which can produce jet-like objects, depending on the underlying theory's parameters. To categorize these potential signatures, it is often beneficial to parameterize these jet-like objects based on the fraction of invisible particles they contain and the lifetime of the dark mesons. These signatures include semi-visible jets and emerging jets final states, leading to various analysis efforts [9]. Additionally, it's important to consider how these scenarios interact with other searches for Long-Lived Particles (LLPs).

If we assume that the dark hadrons decay promptly into SM particles and that the fraction of invisible components (i.e. stable dark hadrons) produced is negligible, we observe a dijet-like signature. ATLAS recently conducted an investigation into these dark jets [10], which are typically broader and more complex than their SM QCD counterparts due to the dual hadronization process—first within the dark sector and then in the SM. The substructure of these jets plays an important role in distinguishing the signal. The analysis focuses on searching for a resonant excess above a smoothly varying background in the dijet invariant mass (m_{JJ}) distribution, obtained through the use of high-momentum, high-track-multiplicity, large-R jets. To determine the invariant mass spectrum of the dominant SM QCD background, a data-driven method, similar to the one described earlier, is employed.

As anticipated, the characteristics of the signal jets are closely linked to the parameters of the hypothetical dark QCD model. However, the number of tracks (n_{tracks}) within a jet emerges as a universal feature to exploit, as depicted in Figure 3. To enhance the signal-to-background ratio, it is advantageous to impose a minimum value of n_{tracks} on the jets. Yet, this requirement has the potential to shape the background distribution in m_{JJ} since the number of tracks associated with a jet correlates with its momentum. In order to avoid this undesirable effect, which would impact the identification of a clear resonance over the background spectrum, the analysis introduces a decorrelation between the two variables. It entails applying a cut on n_{tracks} (separately for the two jets), which evolves as a function of m_{JJ} to maintain a fixed level of background rejection. This method, along with the determination of the thresholds, relies entirely on Monte Carlo (MC) simulations, requiring dedicated data validation and control regions. Any remaining discrepancies in shape between the data signal region and control region are adjusted using double ratios of systematic uncertainties.

No significant hints of New Physics have been observed, so the analysis search sets the first ATLAS limits on QCD-like dark-jet production, opening the portal for more results to come.

3. Conclusion

In summary, ATLAS Run-2 data has opened up exciting avenues for exploring hadronic final states from a variety of angles. It has prompted the development of innovative methods and model-independent search strategies, including the examination of more complex decay chains with additional resonances, resulting in higher jet multiplicities. The enigmatic world of resonant and non-resonant hadronic final states, featuring jets originating from a concealed dark sector,

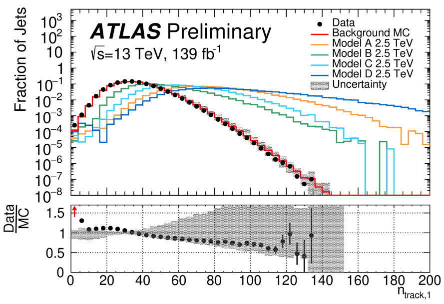

Figure 3: Distributions of the number of tracks associated to the leading jet in the event for the data, the simulated multi-jet background and of some representative signals. All distributions are normalised to unity [10].

offers a new rich phenomenology to explore. In the realm of hadronic final states, novel techniques utilizing fully unsupervised ML models for event classification and anomaly detection have also injected fresh enthusiasm into the quest for uncovering New Physics. This dynamic landscape continues to drive the exploration of the fundamental building blocks of the universe and the quest for New Physics, also with an eye to the on-going Run-3 data-taking.

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