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Optimizing Higgs Boson Signal Efficiency with Small-R (R = 0.4) and Large-R (R = 1.0) Jets

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Abstract

Many Beyond the Standard Model searches at ATLAS employ jets to simplify event reconstruction. These jets cluster particle shower products into calculable objects, which are then used to obtain information about parent particles. Large-R (R = 1.0) jets combine these products into one jet that spans 2 radians, while small-R (R = 0.4) jets are used to further refine individual b-quark trajectories. Optimizing the use of jets is crucial for making precision measurements of Higgs bosons with high transverse momenta, and this project uses b quarks produced in the Wino chargino LSP decay to identify parameters that best do so. It found that parameters such as the span between paired b-quarks were relevant in selecting the most accurate reconstructions. In future work, a neural network would prove useful for further identifying relevant jet type parameters. Likewise, because a combination of the most accurate jet types increased signal efficiency, it would be useful to explore the effect of this method on background information for future search sensitivity.

Beyond the Standard Model

The Standard Model (SM) of particle physics describes all known particles and their interactions. This model predicts matter to be fundamentally composed of generations of quarks and leptons, characterized by mass, electric charge, and spin. SM particles interact via the exchange of gauge bosons, which act as force carriers [1, 2]. Specifically, the strong, weak, and electromagnetic forces arise from these elementary gauge bosons—encompassing much of physics as we know it [2].

While SM predicted particles have all been experimentally confirmed, necessary corrections to this model must be implemented at a scale where new physics is relevant. To reconcile SM issues, many Beyond the Standard Model (BSM) theories have thus been developed. One such theory is Supersymmetry (SUSY), which introduces a "superpartner" for each currently known particle [4-6]. SUSY is attractive because it creates viable dark matter candidates: when R-parity is violated, these are observed as SM products of the lightest supersymmetric particle [9].

The ATLAS Detector

The ATLAS detector identifies BSM interactions by accelerating protons, whose head-on collisions form beams of new particles [17]. To measure different properties of these particles, it uses an inner tracking system, electromagnetic and hadronic calorimeters, and a muon spectrometer.

The Inner Detector reconstructs charged particle tracks in the pseudorapidity region $|\eta| < 2.5$. Its location within a 2 T axial magnetic field allows it to measure charged-particle momenta, which must initially be zero in the transverse plane [10].

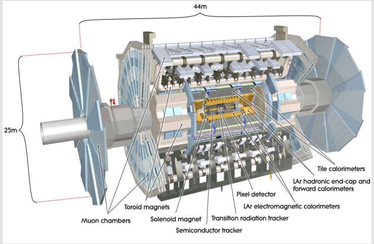

Figure 1: Side view of ATLAS detector and its components

Located above the inner detector are the electromagnetic and hadronic calorimeters, which measure particle energy in the region covering $|\eta| < 4.9$ [10]. To collect energy, high density "absorbing" layers within the calorimeters induce particle showers, halting incoming particles.

Because muons are too massive to deposit significant energy in the calorimeters, the muon spectrometer (MS) is used to measure muon momenta in the region $|\eta| < 2.7$. [10]. The MS's trigger and tracking chambers surround the calorimeters, measuring muon deflection in a toroidal magnetic field [15].

Finally, the ATLAS trigger system is used in reconstructing real and simulated data events. It is made up of hardware- and software-based triggers, which detect the locations and identities of particles [17].

Recent BSM Searches at the Large Hadron Collider

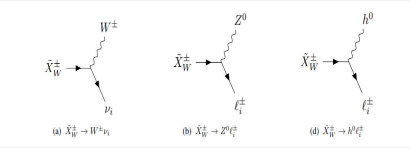

Figure 2: Possible decay channels of the Wino chargino LSP.

The ATLAS Collaboration searches for signatures of physics beyond the Standard Model via the Large Hadron Collider (LHC). ATLAS employs theoretical methods to predict the contents and locations of targets in its searches. Recent searches have focused on the decay of the Wino chargino LSP. Shown in Figure 1, the general massive chargino state decays into three potential R-parity-violating channels—each with final products that contain different levels of abundance and visibility in the detector. For example, the decay in Figure 1a can only be observed in the detector as missing energy, while the decay in Figure 1c yields quark and lepton traces that are difficult to interpret [9]. Most easily detected is the decay in Figure 1b, which produces many leptons from a single resonance. Recent pair production analyses have therefore focused on this decay [10].

Using Jets to Improve Future Search Sensitivity

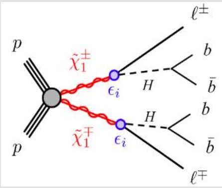

Figure 3: Feynman diagram of the favored Wino chargino decay channel

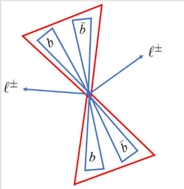

Figure 4: Large-R clustering method

Searching for the above channel complements previous searches in its hunt for chargino pair production, whose favored final state consists of two leptons and two Higgs bosons. These Higgs bosons decay 56.9% of the time to two pairs of b quarks, whose high-momenta trajectories are captured with the use of jets. By clustering showers of particles into calculable objects, jets reduce combinatorics in decays with difficult-to-pair products: large R (R = 1.0) jets combine their decay products into one jet that spans 2 radians, while small-R (R = 0.4) jets are used to further refine individual b-quark trajectories [14]. Large-R jets are particularly useful for simplifying the Higgs to b-quark decay, whose reconstruction would otherwise have 6 possible b-quark pairings.

Reconstruction techniques with collimated jets are crucial for improving the search's sensitivity. Optimizing the use of jets is thus important in making precision measurements of Higgs boson production at different pTs [14]. This project identifies parameters that improve jet performance by optimizing simulated signal efficiency for different jet types.

Simulated Samples

Monte Carlo (MC) techniques were required to simulate interactions of decay products inside the detector. These techniques ultimately evaluate a search's expected sensitivity, tuning event selection and estimating expected event yields and kinematic shapes [18].

Small- and large-R jets were externally constructed by ATLAS using the anti-kt algorithm, meeting its requirements for MC simulations. Using electron, muon, and jet data, this project was then able to reconstruct chargino information with ROOT software.

Object Reconstruction

Lepton Selection: Events were tagged as EE, EM, ME, or MM, corresponding to events where both leptons are electrons, one lepton is an electron and the other is a muon, and both leptons are muons. The leptons with the highest momenta were chosen for each event type.

Higgs Reconstruction (Small-R): The four-momenta were calculated for all jets, and the two correct reconstructions were selected from 6 possible pairings of small-R b-jets. This is done by finding the two pairs that have the smallest combined mass asymmetry between themselves and the 125 GeV Higgs bosons.

Higgs Reconstruction (Large-R): The four-momenta were calculated for both jets.. Because large-R jets envelop 2 b-quarks, Higgs boson information is already reconstructed.

Higgs Reconstruction (Combined-R): The jet type with the lowest combined mass asymmetry between its pairs and the Higgs masses was chosen. This information was kept if both reconstructed Higgs masses were within 20 GeV of the true Higgs mass.

Chargino Reconstruction: To reconstruct the two chargino masses, the lepton and Higgs four-momenta were added. Because there are four possible pairings of the two jets and two leptons, the momenta of each combination were calculated. These vectors were then manipulated to determine the invariant masses of each potential pairing. To select which two combinations were correct, mass asymmetry was used. Resulting chargino information was further kept if the mass asymmetry was less than 0.2.

Results

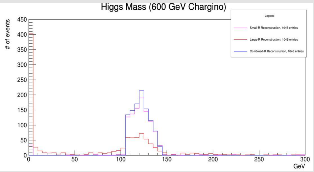

Figure 5a: Reconstructed Higgs boson mass from 600 GeV chargino data using different jet types

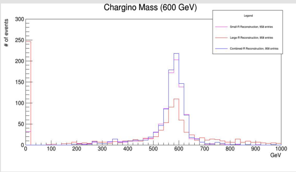

Figure 5b: Reconstructed 600 GeV chargino mass using different jet types

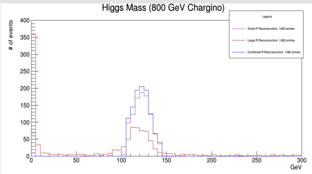

Figure 6a: Reconstructed chargino mass from 800 GeV chargino data using different jet types

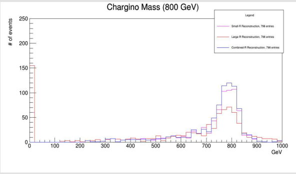

Figure 6b: Reconstructed chargino mass from 800 GeV chargino data using different jet types

Figures 5a and 6a depict Higgs boson reconstruction for 600 and 800 GeV chargino masses, respectively. Both small-R and large-R reconstructions are shown, and the combined-R data plots the jet-type reconstruction with the more accurate Higgs masses. For events that capture less than two large-R jets, both Higgs masses were set to zero, indicating that the full reconstruction was unachievable. The same procedure is used for events with fewer than four small-R jets.

The combined jet type method best rebuilt both Higgs bosons to an accuracy within 20 GeV of the true Higgs mass. This method not only optimized the use of jets near the Higgs mass but introduced data when one jet type could not capture an event. Because of this, both chargino masses were reconstructed more accurately with the combined-R method, shown in Figures 5b and 6b.

Small-R jets were most successful at reconstructing Higgs data from lower mass charginos. Some discrepancies were seen between accepted jet types and their rejected counterparts. It was found that jet span is highly relevant in selecting accurate small-R jets and largely insignificant in selecting accurate large-R jets: small-R jets were thus chosen because of their ability to capture events whose Higgs bosons are both within the range of the large-R span, which large-R jets incorrectly cluster.

Conclusion

Optimizing jet performance proved valuable in improving future BSM search sensitivity. By reconstructing the Higgs bosons more accurately, the use of both types of jets reveals the importance of determining conditions that best optimize jet performance. For small-R jets, this proved to be jet span.

Because certain event conditions correlated highly with the use of a certain jet type, algorithms that take these conditions into account in determining which jet to use would prove to be very useful. In fact, the combined consideration of pT, lepton-jet distance, and jet span would be useful for a neural network to determine which jet type should be used to analyze the decay.

Finally, it should be noted that, while the combined-R method was used to determine which jet types were chosen and the parameters that influenced this decision, the combined-R procedure proved to be successful. This method increased signal efficiency for both reconstructions. Resorting to one jet type when the other did not give sufficient information, this method also increased the overall number of usable events. While the impact that the combined-R method has on background events must be further studied, potential use of this method in capturing future decays proves to be promising.

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