# Selection Optimization in the Search for Universal Extra Dimensions in the Multilepton Final State at the ATLAS Experiment

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**Abstract:**

Models of physics beyond the Standard Model (SM) with at least one compactified universal extra spatial dimension (mUED) are being investigated at the ATLAS experiment at CERN by studying events with a final state consisting of at least three leptons with jets and missing transverse energy. An important preliminary step in this analysis is understanding the SM backgrounds that exist in this channel and developing a selection that reduces these backgrounds without affecting the potential mUED signal. In this report, development of a selection for these trilepton events using Monte Carlo simulated SM processes is described, and several methods to suppress SM backgrounds while maximizing mUED signal are examined.

**Introduction:**

Models of compactified extra spatial dimensions have been proposed to reconcile the observation of three spatial dimensions at macroscopic scales with the numerous extra spatial dimensions proposed by string theory. The existence of extra spatial dimensions can help to resolve several outstanding issues not addressed by the Standard Model of particles and fields, including the fermion mass hierarchy problem and unification of gauge coupling constants, as well as providing a dark matter candidate. The Universal Extra Dimensions (UED) model proposes that the Standard Model (SM) fields exist in 4 + $\delta$ spacetime dimensions. These $\delta$ extra dimensions are compactified with a given radius $R$ and a corresponding compactification scale ($R^{-1}$) so that the effects of their presence are insignificant above a given cutoff scale ($\Lambda > R^{-1}$). Below this scale, however, the effective field theory must account for these extra dimensions. The minimal UED model (mUED) proposes a single extra dimension ($\delta = 1$) that is compactified on a $S^1/Z_2$ orbifold[1]. As a result, mUED has only three parameters: $R$, $\Lambda$, and the mass of the SM Higgs boson $m_H$. Theory predicts new physics to be at the TeV scale, and thus the compactification scale ($R^{-1}$) of this extra dimension to be on the order of a few TeV, within the range that can be probed by the Large Hadron Collider at CERN. All SM particles in the mUED model can be excited into the extra dimension, producing an infinite tower of excited Kaluza Klein (KK) partners for each particle[2]. Momentum of the particle in the compactified extra dimension is quantized, so each KK excited state can be indexed by an integer $n$ corresponding to its momentum in the extra dimension. Conservation of momentum in the extra dimension, therefore, manifests as conservation of this integer $n$, called the KK number of the particle. Collisions involving

SM particles in their KK ground-state ($n = 0$) will never produce a single particle $n > 0$, as the total momentum in the extra dimension of all KK excited particles produced from processes involving KK ground-state particles must equal zero. KK particles can decay into lighter KK particles with the same KK number by emitting SM leptons with energy related to the mass difference between the KK particles. The masses of the KK modes are given by the formula:

$$m_n^2 = m_{SM}^2 + \frac{n^2}{R^2}$$

This produces a mass spectrum that is highly degenerate, as the $\frac{n^2}{R^2}$ term dominates the SM mass of the particles. Inclusion of radiative corrections reduces the degeneracy, allowing cascade decays of KK particles with the emission of soft SM particles that terminate at the stable lightest KK particle (LKP), which in mUED is the KK excited photon.

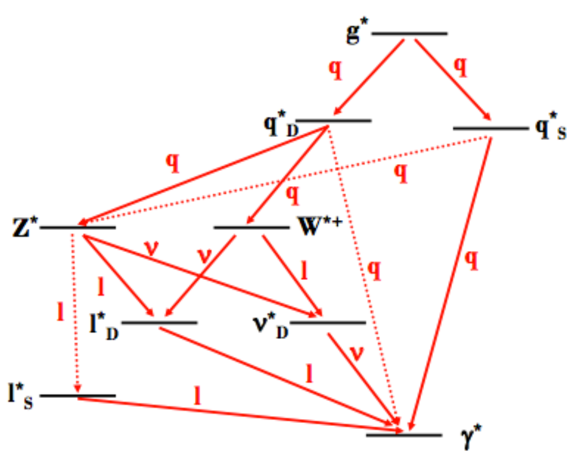


Fig. 1: Mass hierarchy of $n = 1$ KK excited states (denoted by an asterisk) of SM particles with cascade decays from KK excited gluon to LKP. The trilepton final state arises when the KK excited gluons produced in a proton-proton collision decay via excited Z* or W* bosons. The three final leptons are accompanied by jets from quarks produced in the decay from KK excited gluons to KK excited W* or Z* as well as missing transverse energy due to the KK excited photon, which escapes the detectors.

The search for mUED at the ATLAS experiment at the LHC is focused on the trilepton plus jets and missing transverse energy channel (Fig 1). My work at UBC and at CERN focused on developing the selection to isolate events with this signature and refining the selection to exclude SM background processes without affecting the potential mUED signal.

**Analysis:**

The criteria used to select baseline leptons and jets for further analysis were primarily based on those employed in the search for supersymmetry (SUSY) in multilepton final states[3]. Electrons were selected if they were reconstructed from clusters in the electromagnetic calorimeter alone or in combination with a track in the inner detector, if they were of medium quality, as defined in [4]. Electrons were also required to have transverse momentum ($p_T$) greater than 10 GeV and pseudorapidity between -2.47 and 2.47 for their associated deposit in the electromagnetic calorimeter. Muons were selected if they were reconstructed with the STACO algorithm, which uses statistical methods to combine tracks in the inner-detector with tracks in the muon-spectrometer. Muons reconstructed by matching tracks extrapolated from the inner-detector with segments in the muon-spectrometer (segment-tagged muons) were also selected. Only muons of loose quality or higher with pseudorapidity between -2.40 and 2.40 and $p_T$ greater than 10 GeV were selected. Isolation of leptons is characterized by the scalar sum of the transverse momentum of tracks with $p_T > 1$ GeV in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.2$ around the lepton. For electrons, the isolation in the $\Delta R$ cone was required to be less than 10% of the transverse energy of the electron, while for muons the transverse energy in the cone was required to be less than 1.8 GeV. Jets were reconstructed with the anti-$k_t$ jet clustering algorithm and were selected if they had $p_T >$ 20 GeV and pseudorapidity between -2.8 and 2.8. Leptons were required to be separated from jets by discarding jets when they were found within $\Delta R < 0.2$ of an electron. Electrons and muons found within $\Delta R < 0.4$ of the nearest remaining jet were also discarded. Finally, electrons and muons found within $\Delta R < 0.1$ of each other were both discarded. Events were rejected if the leading vertex had fewer than 5 tracks originating from it, if the required single or dilepton triggers were not activated, if any jet failed the quality criteria designed to remove the effects of calorimeter noise and signals from non-collision events, or if a jet was found in the hole region of the liquid argon calorimeter. Events were also checked against a good run list containing the list of luminosity blocks meeting data quality requirements prepared for the SUSY multilepton analysis group. The missing transverse energy was calculated from the modulus of the vector sum in the transverse plane of the energies of all reconstructed objects (leptons and jets) along with calorimeter clusters not associated with objects. The baseline selection of events with three well-isolated leptons was verified against the selections of other groups working on multi-lepton analysis by comparing the numbers of events and of baseline objects passing each stage of the selection for a given Monte Carlo (MC) simulated sample file. This information was also used to determine the correct scale factors to be applied to the MC simulated data to account for the effects of pileup as well as the efficiency of the triggers and the reconstruction and identification algorithms. A selector was designed to process the events in D3PD format and output trees containing only the trilepton events along with all information necessary (MET, object $p_T$, etc.) to modify the cuts made in the selection.

From the baseline SUSY selection, it was necessary to tailor the selection to maximize acceptance of the mUED signal while suppressing the SM background processes that pass the trilepton selection. For this purpose, MC simulated mUED signal events were generated using Herwig++ for several points in the mUED parameter space of $R$ and $\Lambda$. The SM background passing the trilepton selection was investigated by applying the selection to samples of MC simulated SM events for several processes. The processes investigated were: top quark pair production (simulated by MC@NLO), diboson events (Herwig), electroweak guage bosons and jets (ALPGEN), and Drell-Yan processes and jets (ALPGEN). The distribution of missing transverse energy (MET) for events with three leptons selected from these background processes shows that requiring MET greater than 100 GeV suppresses the vast majority of SM background events (Fig. 2).

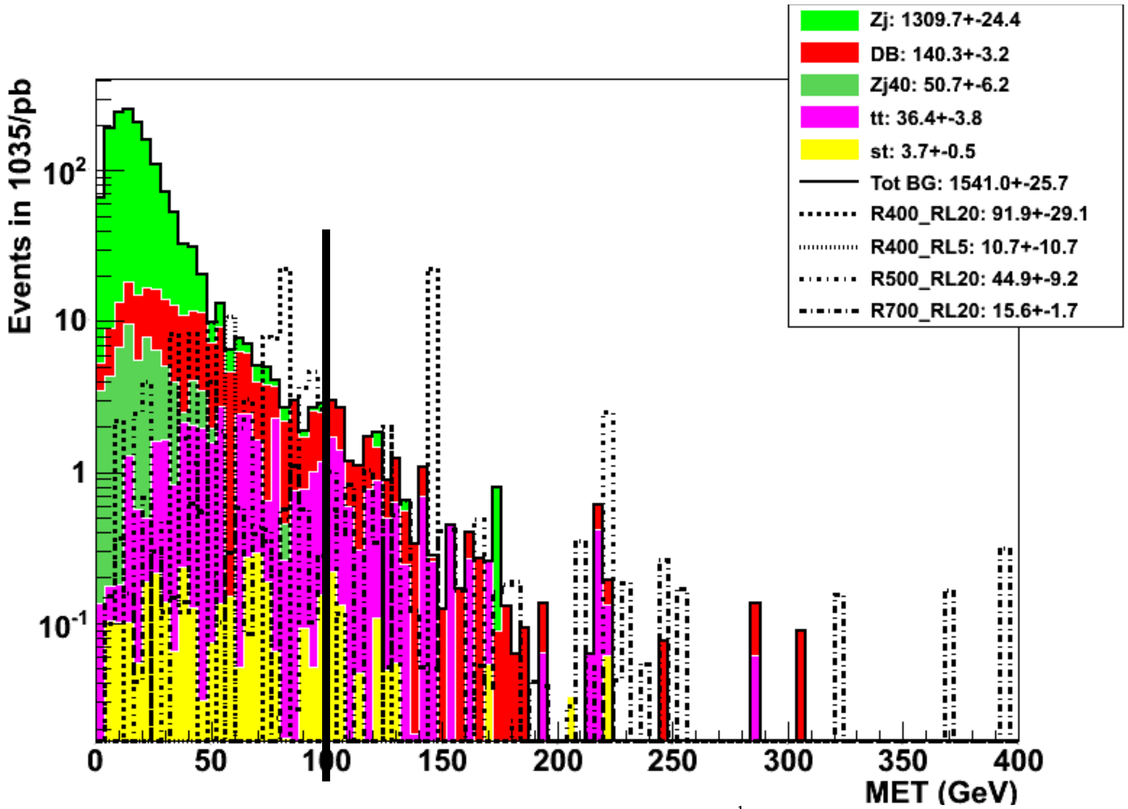


Fig. 2: Missing transverse energy distribution scaled to 1035 $pb^{-1}$ for MC simulated trilepton events selected using baseline SUSY criteria with Drell-Yan processes suppressed by veto on events with $m_{l+l-} < 12$ GeV. The four superimposed dashed lines represent MC simulated mUED signal events for four chosen points in the mUED parameter space, which are represented by their values of $R$ in $GeV^{-1}$ and $R\Lambda$ (RL), which is a dimensionless quantity. The black line marks a potential cut on MET > 100 GeV. Abbreviations used in all figures are as follows: Zj = Z boson plus jets, DB = diboson, Zj40 = Drell-Yan processes plus jets, tt = top pair, st = single top. The numbers given in the upper right indicate the total number of events for each process with the statistical error.

However, this selection also rejects most of the mUED signal. Rather than make this crude cut on MET, the various SM backgrounds were targeted with specific cuts to remove their contributions. A significant portion of the background events passing the trilepton selection come from SM processes involving an on-shell Z boson. This background was suppressed by rejecting events where two of the three leptons were produced by the decay of an on-shell Z. The invariant mass of all same flavor and opposite charge (SFOC) lepton pairs in an event ($m_{l+l-}$) was calculated, and events were rejected if they contained SFOC pairs with invariant mass within 5GeV of the mass of the Z boson and quarkonia (J/psi, Upsilon) (86.2 GeV < $m_{l+l-}$ < 96.2 GeV)[5]. Drell-Yan processes were suppressed by removing all SFOC lepton pairs with invariant mass less than 12 GeV. These cuts reduced the backgrounds from events with electroweak guage bosons (diboson, Z plus jets), but they did not completely suppress these backgrounds (Fig. 3).

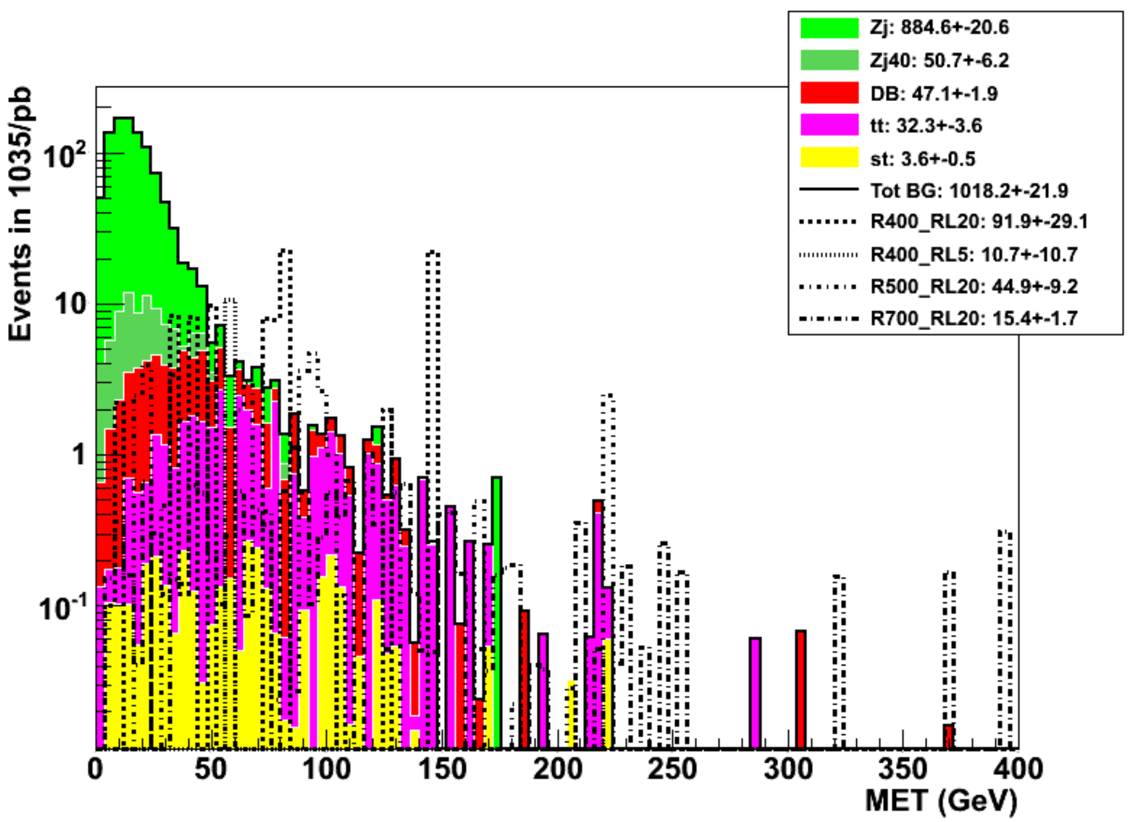


Fig. 3: Missing transverse energy distribution scaled to 1035 $pb^{-1}$ for MC simulated trilepton events selected using baseline SUSY criteria with Drell-Yan processes suppressed by veto on events with $m_{l+l-}$ < 12 GeV and leptons from Z boson decays excluded by vetoing events with 86.2 GeV < $m_{l+l-}$ < 96.2 GeV.

With these cuts applied, the optimal cut on the MET to maximize the signal while minimizing background was investigated by producing a plot of the significance of the signal with respect to the MET with various MET cuts applied. The plot was produced by integrating the total signal and background events with MET above a given value and calculating the significance for the cut on the MET, defined as the ratio of the integrated signal over the square root of the square root of the sum of the integrated signal and background:

$$Significance = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bg}}}$$

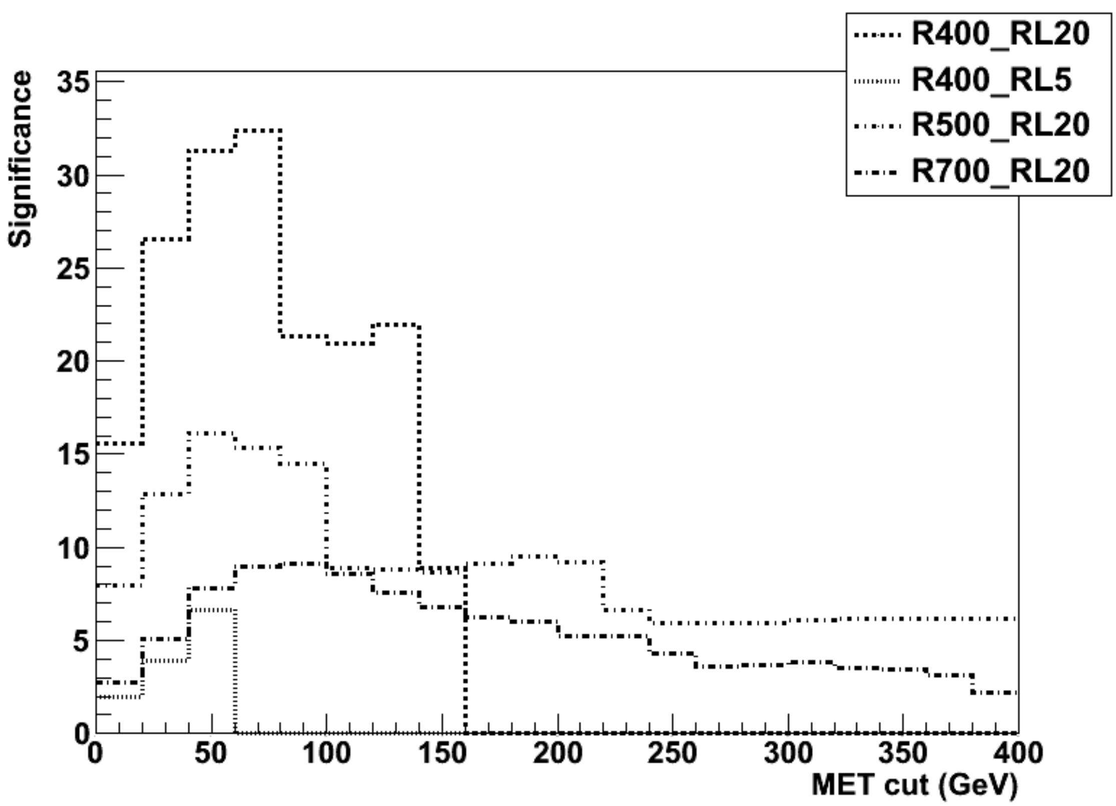


Fig. 4: Plot of significance of cuts made on the MET of trilepton events passing selection with Drell-Yan processes suppressed and Z mass window excluded. For the four points in the mUED parameter space chosen, the highest signal significance is obtained with a cut on the MET excluding events with MET less than about 50 GeV.

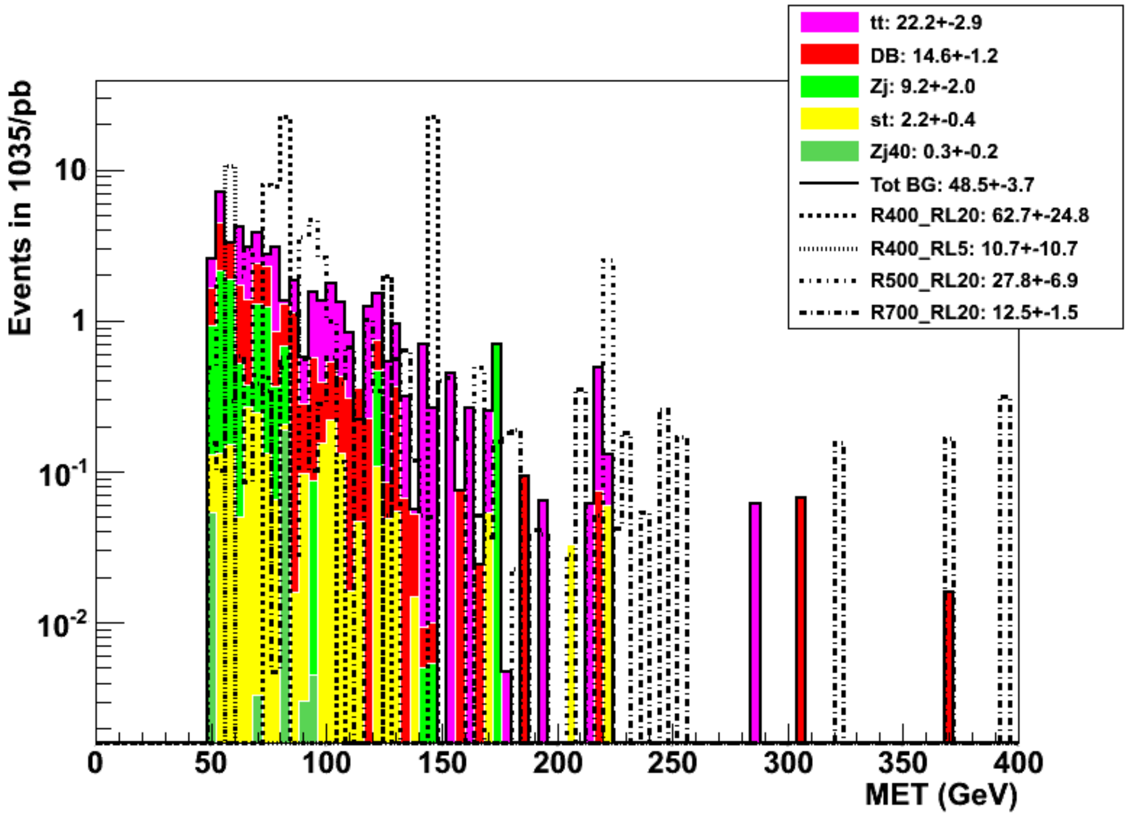


Fig. 5: Missing transverse energy distribution scaled to 1035 pb$^{-1}$ for MC simulated trilepton events selected using baseline SUSY criteria with Drell-Yan processes suppressed by veto on events with $m_{l+l-}$ < 12 GeV, leptons from Z boson decays excluded by vetoing events with 86.2 GeV < $m_{l+l-}$ < 96.2 GeV, and MET greater than 50 GeV.

The significance plot indicates that a cut rejecting events with MET lower than 50 GeV results in the highest signal significance for several points in the mUED parameter space (Fig. 4). With this cut applied, the background is significantly reduced, with the major contribution coming from top pair events (Fig. 5). A potential method to suppress the background from top events that exploited the flavor correlation of the leptons produced from decay of the Z* boson was explored. Two of the three leptons in the trilepton final state of the mUED model are produced by decay of a Z boson excited in the extra dimension in the mUED model. These leptons will always be produced as a pair with the same flavor and opposite charge as a result of conservation of charge and of lepton number. Leptons produced in top pair events, however, have uncorrelated flavors. The signal and background events were divided into four separate categories, based on whether the flavors and charges of the leptons in the pair with the lowest invariant mass were the same or opposite. The category of events with the lowest mass lepton pair having the same flavor and opposite charge was enriched with signal events, while the background was roughly evenly divided between the four categories (Fig. 6).

a) Same Flavor Opposite Charge

| Process | Nev (1035 $pb^{-1}$) |
|---|---|
| Z+jet | 215.4 ± 11.7 |
| Drell-Yan+jet | 26.0 ± 4.5 |
| Diboson | 20.2 ± 1.2 |
| Top pair | 8.7 ± 1.8 |
| Single top | 0.9 ± 0.2 |
| Total Background | 271.1 ± 12.7 |
| R 400 RL 20 | 73.0 ± 26.6 |
| R 400 RL 5 | 10.7 ± 10.7 |
| R 500 RL 20 | 29.9 ± 7.9 |
| R 700 RL 20 | 6.4 ± 1.1 |

b) Same Flavor Same Charge

| Process | Nev (1035 $pb^{-1}$) |
|---|---|
| Z+jet | 182.0 ± 8.6 |
| Drell-Yan+jet | 4.3 ± 1.9 |
| Diboson | 8.1 ± 0.7 |
| Top pair | 5.3 ± 1.7 |
| Single top | 0.9 ± 0.2 |
| Total Background | 200.5 ± 8.9 |
| R 400 RL 20 | 8.7 ± 8.3 |
| R 400 RL 5 | 0.0 ± 0.0 |
| R 500 RL 20 | 2.5 ± 2.5 |
| R 700 RL 20 | 4.6 ± 1.0 |

c) Opposite Flavor Opposite Charge

| Process | Nev (1035 $pb^{-1}$) |
|---|---|
| Z+jet | 249.0 ± 10.5 |
| Drell-Yan+jet | 10.2 ± 2.6 |
| Diboson | 9.4 ± 0.9 |
| Top pair | 9.7 ± 1.9 |
| Single top | 0.9 ± 0.2 |
| Total Background | 279.1 ± 11.0 |
| R 400 RL 20 | 8.2 ± 8.1 |
| R 400 RL 5 | 0.0 ± 0.0 |
| R 500 RL 20 | 7.5 ± 3.1 |
| R 700 RL 20 | 1.7 ± 0.6 |

d) Opposite Flavor Same Charge

| Process | Nev (1035 $pb^{-1}$) |
|---|---|
| Z+jet | 238.3 ± 10.2 |
| Drell-Yan+jet | 10.1 ± 2.9 |
| Diboson | 9.4 ± 0.9 |
| Top pair | 8.6 ± 1.8 |
| Single top | 0.9 ± 0.3 |
| Total Background | 267.4 ± 10.8 |
| R 400 RL 20 | 2.0 ± 2.0 |
| R 400 RL 5 | 0.0 ± 0.0 |
| R 500 RL 20 | 5.0 ± 2.6 |
| R 700 RL 20 | 2.7 ± 0.7 |

Fig. 6: Total signal and background events where the lowest invariant mass pair of leptons has the same (a, b) or opposite (c, d) flavor and the same (b, d) or opposite (a, c) charge. Background events are divided roughly evenly between the four categories, while signal events are enriched in the same flavor opposite charge category.

This difference could be exploited to reduce the SM background by a quarter, with only a much smaller reduction in the signal.

The MC simulated background was compared to the 2011 data from all periods while maintaining the signal region blind by examining the dilepton invariant mass spectrum for events with MET less than 50 GeV. This revealed a significant discrepancy between the MC simulated background and the data. To investigate the source of this discrepancy, truth information from the event generator used to produce the MC simulations was included in the trees produced by the selector. The identity of true particles produced by the event generator and the GEANT4 simulation of the detector with transverse momentum greater than 1 GeV and with $\Delta R$ less than 0.15 between the truth particle and each reconstructed lepton was included in the trees produced by the selector. This information will be used to verify the classification of the truth particles done during production of the D3PDs and then to examine the rate at which leptons are produced from sources other than electroweak gauge bosons in the MC simulation. If this rate of fake lepton production is low, it could explain the observed discrepancy between the MC simulated background and the data.

**Conclusions:**

My work focused on implementing and verifying the selection developed by the SUSY trilepton analysis group, as well as modifying this selection to apply it to investigation of the mUED model. The selector offers flexibility to modify the selection without returning to the D3PDs by creating trees that contain the trilepton events along with all associated data required to adjust the cuts made in the selection. I also investigated methods to suppress SM backgrounds without affecting the mUED signal, focusing on the Z boson and top pair events. Finally, I began to investigate the fake rate in MC simulated events by verifying the classification of truth particles in D3PD production. Once the discrepancy between data and MC simulations has been resolved and the SM background is correctly modeled, the selection developed with MC simulations can be applied to data in the signal region for the mUED model.

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