A Study of Stops Decaying Into Final States with Large Jet Multiplicities for $\sqrt{s} = 13$ TeV

Adrian Patrick S. Labtic,[*1] and (Supervisor) Dr. Marvin M. Flores[*2]

University of the Philippines - Diliman
[*1]Corresponding author: aslabtic@up.edu.ph
[*2]Corresponding author: marvin.flores@cern.ch

Abstract

After almost a decade, no supersymmetric particles and SUSY signals have been detected so far. The proponents then aimed to analyze a SUSY signal, the pair production of the top squark, decaying into a chargino, $\tilde{\chi}_1^{\pm}$, and a bottom quark against the most prominent background which is the multijet. The proponents generated the background and signal events using PYTHIA 8.301. The proponents first observed the jet multiplicities of the background and signal events, and found out that they peaked at different values. We then wrote a custom Rivet analysis to analyze the different distributions of the signal and background events. The jet and b-jet multiplicity plots of the signal and background events show that these two are different. We also introduced jet multiplicity cuts to distinguish the signal from the background, which was later on found out to be effective. Lastly, the proponents attempted to reconstruct the $\tilde{\chi}_1^{\pm}$ mass, $m_{\tilde{\chi}_1^{\pm}} = 750$ GeV, but unfortunately failed to do so.

1 Introduction

The Standard Model (SM) of particle physics is the theory used to describe how fundamental particles (or fermions) interact with fundamental forces (which are mediated by bosons). It describes the behavior of 12 fermions (six quarks and six leptons, arranged into three 'generations') under the electromagnetic, weak, and strong forces. Each fermion has an antimatter counterpart, which is treated in the same way as its matter counterpart in the Standard Model. The theory has a remarkable and successful track record of accurately predicting experiment outcomes. It is, however, an imperfect and incomplete theory. It has yet to be fully validated, and many aspects of the universe remain unexplained by the SM. [1]

There are flaws to the SM that lead to thirty years of research focused on the pursuit for the theory that will extend the SM as the proper description of nature at the energies beyond the TeV scale. First of which is that it does not include gravity. It says literally nothing regarding one of the four fundamental forces of nature. Second is the popular "mass hierarchy" problem. SM also does not explain why the charge of elementary particles are quantized. In addition, SM does not describe the dark matter or the dark energy of the universe. It does not explain the observed neutrino masses and the oscillations, nor does it predict any gauge coupling unification suggested by experiments. [2] This is where Supersymmetry (SUSY) comes in as it attempts to give solution of the arguments mentioned above since it provides dark matter candidates and readily solves the hierarchy problem.

SUSY introduces partners of the known bosons and fermions. It predicts the existence of superpartner states (with different statistics) associated to each of the SM fields and particles. [3] With the Run 1 and Run 2 of the Large Hadron Collider (LHC) attempting to give evidence for new physics Beyond the Standard Model (BSM), for almost a decade of searches, no supersymmetric particles and SUSY signals have been detected so far.

Searches for new physics require some distinct feature or signature to discern a signal from the SM backgrounds. And among the many existing LHC searches, the requirement of one or more b-tagged jets can be very useful in eliminating certain SM backgrounds. [3] Events with large number of jets with high-transverse momentum (p_{T}) coming from the fragmentation of b-quarks are rarely produced by SM processes in proton-proton collisions at the LHC. This implies that the mentioned signature can provide sensitivity to some

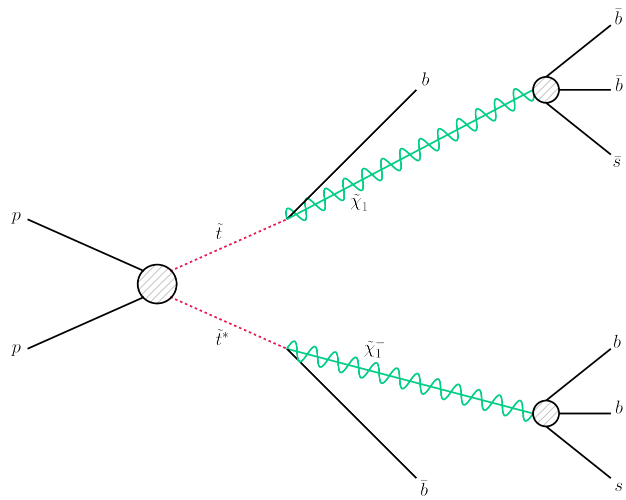


Figure 1: Diagram of the signal process involving pair production of top squarks $\tilde{t}$. The stop, $\tilde{t}$, decays via the top yukawa into a b-quark and the intermediate, on-shell chargino, $\tilde{\chi}_1^+$. The chargino then decays back through the off-shell $\tilde{t}$. This in result produces an eight-jet final state with six b-quarks, counting together the anti-stop decay.

phenomena BSM. Many models of new physics can produce a high b-jet multiplicity signature, e.g. SUSY models with violated R-parity or hidden valley extensions. [4]

The purpose of this project is to analyze the pair production of the top squark, decaying into a chargino, $\tilde{\chi}_1^\pm$, and a bottom quark against the most prominent background which is the multijet. In short, which cuts can we introduce to both signal and background which preserves the former and at the same time eliminating the latter. The chargino then decays into bbs quark triplets, as shown in Figure 1.

2 Tools Used

An overview of the tools used in this project will be discussed briefly.

2.1 PYTHIA

PYTHIA is a program for the generation of high-energy physics collision events, i.e. for the description of collisions at high energies between electrons, protons, photons and heavy nuclei. It contains theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial- and final-state parton showers, multiparton interactions, fragmentation and decay. It is largely based on original research, but also borrows many formulae and other knowledge from the literature. As such it is categorized as a general purpose Monte Carlo event generator. [5]

2.2 Rivet

The Rivet toolkit (Robust Independent Validation of Experiment and Theory) is a system for validation of Monte Carlo event generators. It provides a large (and ever growing) set of experimental analyses useful for MC generator development, validation, and tuning, as well as a convenient infrastructure for adding your own analyses. Rivet is the most widespread way by which analysis code from the LHC and other high-energy collider experiments is preserved for comparison to and development of future theory models. It is used by phenomenologists, MC generator developers, and experimentalists on the LHC and other facilities. [6, 7]

2.3 CheckMATE

CheckMATE (Check Models At Terascale Energies) is a program package which accepts simulated event files in many formats for any given model. The program then determines whether the model is excluded or not at 95% C.L. by comparing to many recent experimental analyses. Furthermore, the program can calculate confidence limits and provide detailed information about signal regions of interest. It is simple to use and the program structure allows for easy extensions to upcoming LHC results in the future. [8, 9]

2.4 MadGraph5_aMC@NLO

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, an the NLO accuracy in the case of models that support this kind of calculations – prominent among these are QCD and EW corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained. [10, 11]

3 Event Generation

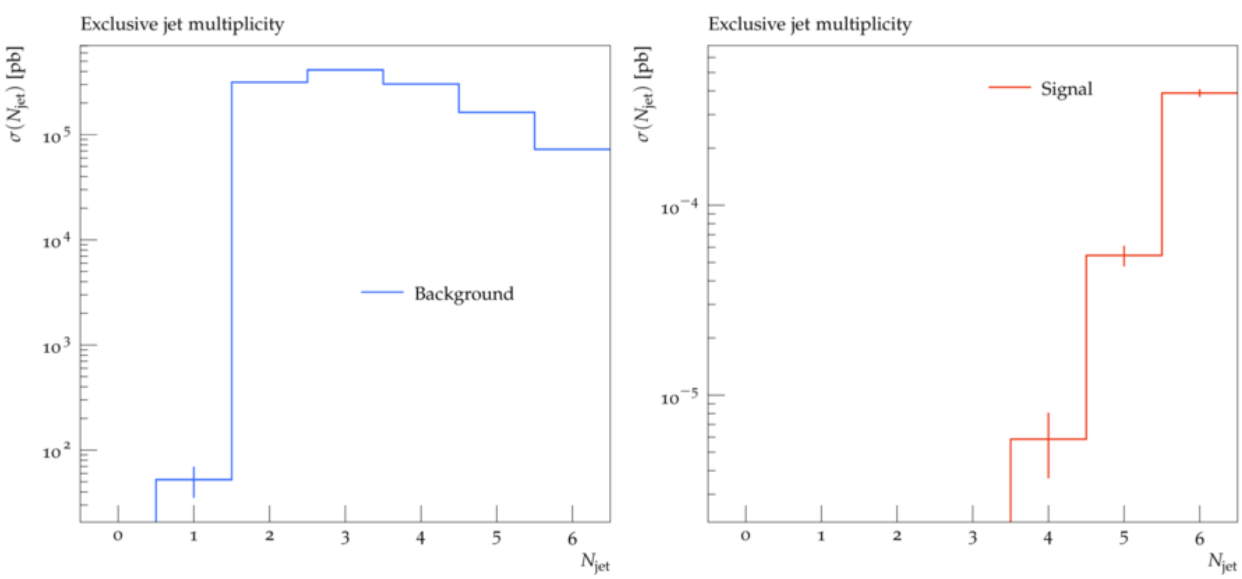
Monte Carlo (MC) simulations were used to model the SUSY signals, as well as to aid in the description of the multijet background processes. The simulated SUSY signals, as well as the background events, were generated using PYTHIA 8.301.

For the generation of signal events, the proponents edited the main42 example by creating a spectrum file that would indicate the required signal process. The stop-quark mass is assumed to be $m_{\tilde{t}} = 800$ GeV and the chargino mass is taken to be $m_{\tilde{\chi}_1^{\pm}} = 750$ GeV, and the branching ratio for the decay given by Figure 1 was made 100%. The number of events generated were 20,000 and the CM energy of collision is 13 TeV.

For the background events generation, the main93 example was edited to generate 1 million hard QCD events with 13 TeV CM collision energy. Since 1 million events is quite many, main93 was used so that its "no hepmc file produced" feature can be utilized.

The signal events were also crossed-checked via MadGraph5_aMC@NLO 2.9.2. Signal events were also generated using the MSSM_SLHA2 model. The run_card and param_card were edited to produce events with the same parameters as the signal produced by PYTHIA.

The benchmark point was also checked against CheckMATE 2.0.26. This was done because the future goal of the proponents is to incorporate a specific ATLAS search targeting large bjet multiplicities into CheckMATE.



(a) (b)

Figure 2: Number of events as a function of jet multiplicity, $N_{\rm jet}$, for (a) SM background and (b) top-squark pair production in the $\tilde{t} \to \bar{b}\tilde{\chi}_1^+(\tilde{\chi}_1^+ \to \bar{b}\bar{b}\bar{s})$ channel, for $m_{\tilde{t}} = 800$ GeV and $m_{\tilde{\chi}_1^{\pm}} = 750$ GeV

4 Analysis

Distributions of the signal and background events were studied by using the existing Rivet 2.6.0 analyses MC_JETS and MC_JETTAGS. The main difference between background and signal is their jet multiplicity as can be seen in Figure 2 where we plotted the exclusive jet multiplicity of the background and signal events. We can observe that the jet multiplicity of the background peaks at around $N_{\text{jet}} \sim 3$ while the jet multiplicity of the signal is $N_{\text{jet}} > 6$. The proponents then wrote a customized Rivet analyses in order to extend the range of jet multiplicity plot since signal jet multiplicity peaks at $N_{\text{jet}} > 6$ while background peaks at $N_{\text{jet}} \sim 3$.

Jets are reconstructed usingthe anti-k_t jet algorithm [12] with radii parameter of 0.4 and 1.0. Jets used in the custom analysis are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. The b-jets are identified using the technique used by an already published Rivet analysis of a study [13] of the same nature. The resulting plots from the customized Rivet analysis shows that the signal and background are different. This is exhibited by their jet multiplicity plots shown by Figure 3, and b-jet multiplicity plots shown by Figure 4.

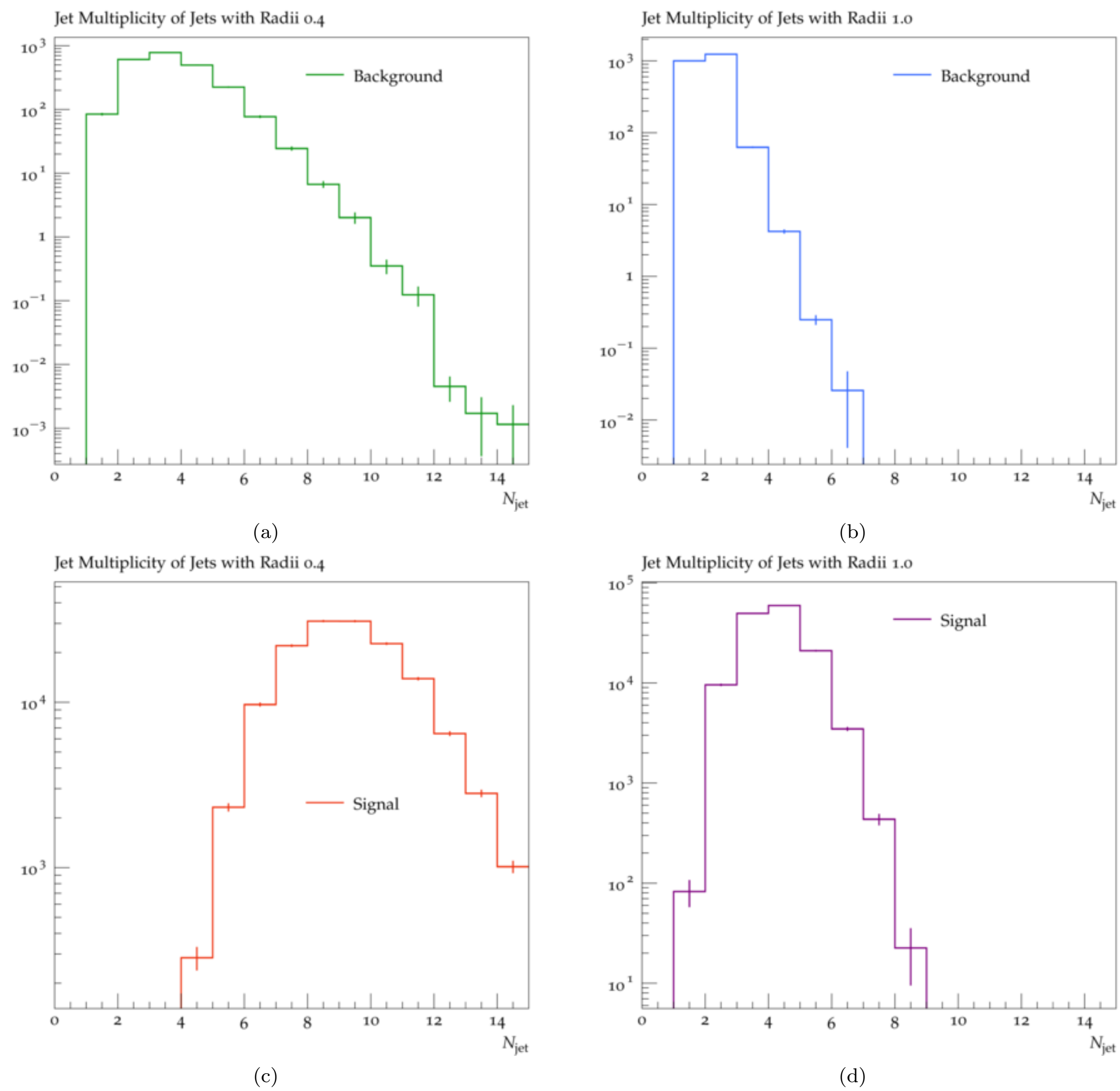


Figure 3: Number of events as a function of jet multiplicity, N_{jet}, for the SM background with (a) radius 0.4 and (b) radius 1.0; and for the SUSY signal with (c) radius 0.4 and (d) radius 1.0

The proponents introduced jet multiplicity cuts ($N_{\text{jet}} > 5$) to distinguish the signal events from the background, and we can say that the cuts are effective as it is evident from the plots for the total mass of all jets (Figure 5) and b-jets (Figure 6). A lot of signal survived while the background events are almost gone.

The signal process considered in this project produces an eight-jet final state with six b-quarks as shown in Figure 1. The proponents hoped to reconstruct the $\tilde{\chi}_1^{\pm}$ mass by imposing a jet multiplicity condition $N_{\text{jet}} > 7$ so that the events will be filtered. The proponents then obtained the sum of 3 leading jets out of the first 8 leading jets of the events and created different combinations to determine which of these combinations can reconstruct the $\tilde{\chi}_1^{\pm}$ mass. Unfortunately, after determining the result of all 56 combinations (56 combinations can be created from the selection of 3 items in an 8-item collection), the proponents did not find any combination that may reconstruct the $\tilde{\chi}_1^{\pm}$ mass with the jet radii that we chose. Example plots for one combination is given by Figure 7. Almost no background events survived the condition set above, as seen in Figure 7.

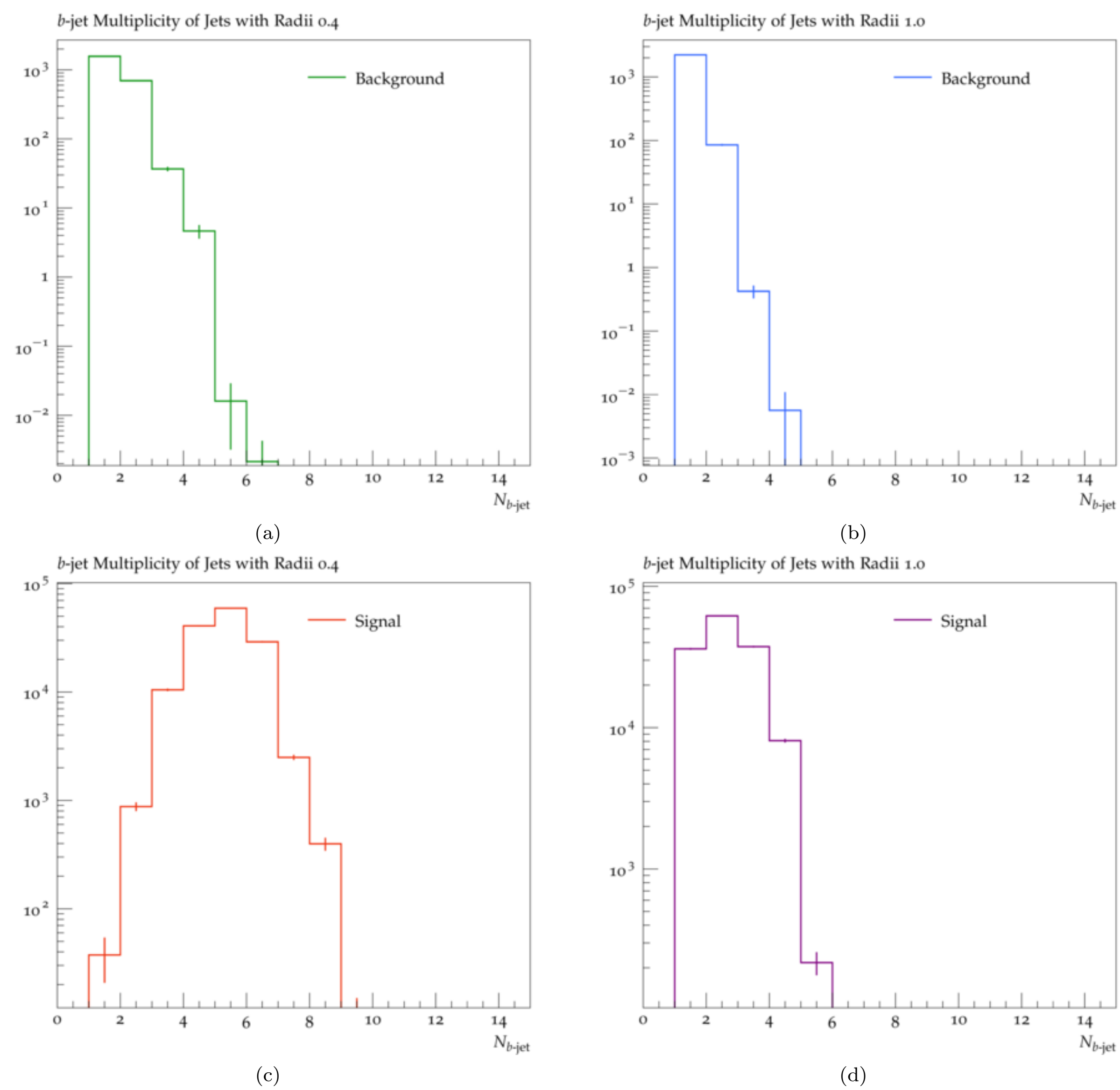


Figure 4: Number of events as a function of b-jet multiplicity, $N_{b\text{-jet}}$, for the SM background with (a) radius 0.4 and (b) radius 1.0; and for the SUSY signal with (c) radius 0.4 and (d) radius 1.0

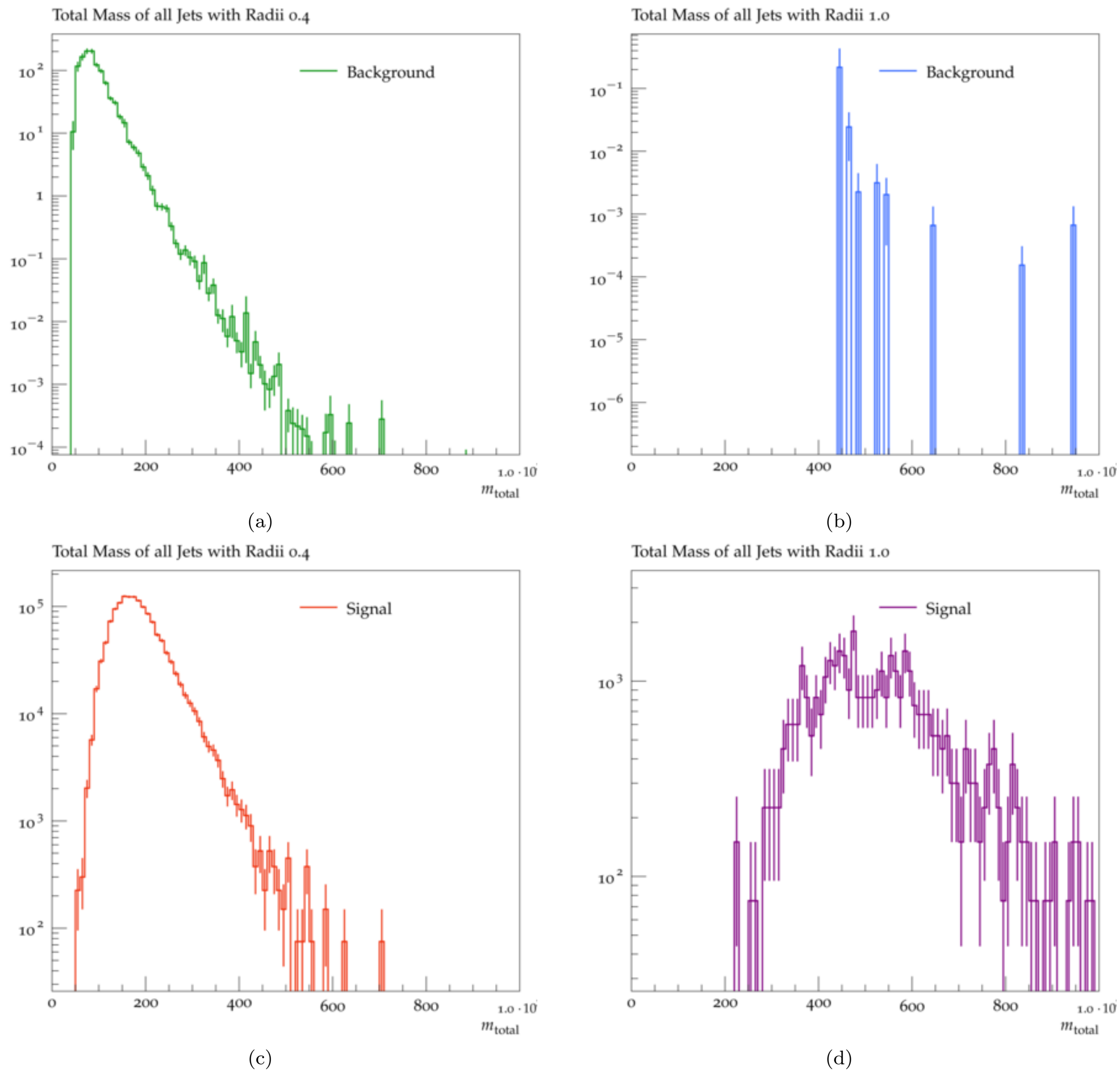


Figure 5: Number of events as a function of the total jet mass for the SM background with (a) radius 0.4 and (b) radius 1.0; and for the SUSY signal with (c) radius 0.4 and (d) radius 1.0

5 Conclusions and Future Work

The proponents aimed to analyze the pair production of the top squark, decaying into a chargino, $\tilde{\chi}_1^{\pm}$, and a bottom quark against the most prominent background which is the multijet. It was observed that jet and b-jet multiplicities for the background and signal events peaked at different values, implying that the background and signal events were different. We also introduced jet multiplicity cuts ($N_{\text{jet}} > 5$) to distinguish the signal events from the background. The total mass distribution of the jets and b-jets for the background and signal events have shown that the cuts imposed was effective as observed from the low number of events for the background. The proponents also attempted to reconstruct the $\tilde{\chi}_1^{\pm}$ mass, $m_{\tilde{\chi}_1^{\pm}} = 750$ GeV, and unfortunately failed to do so.

During my time in the program, I learned a lot of stuff from watching different lectures, which gave me additional knowledge about the field. I also learned how to use different programs used in particle phenomenology such as Rivet, CheckMATE, Pythia, and MadGraph. I also learned a little bit about coding.

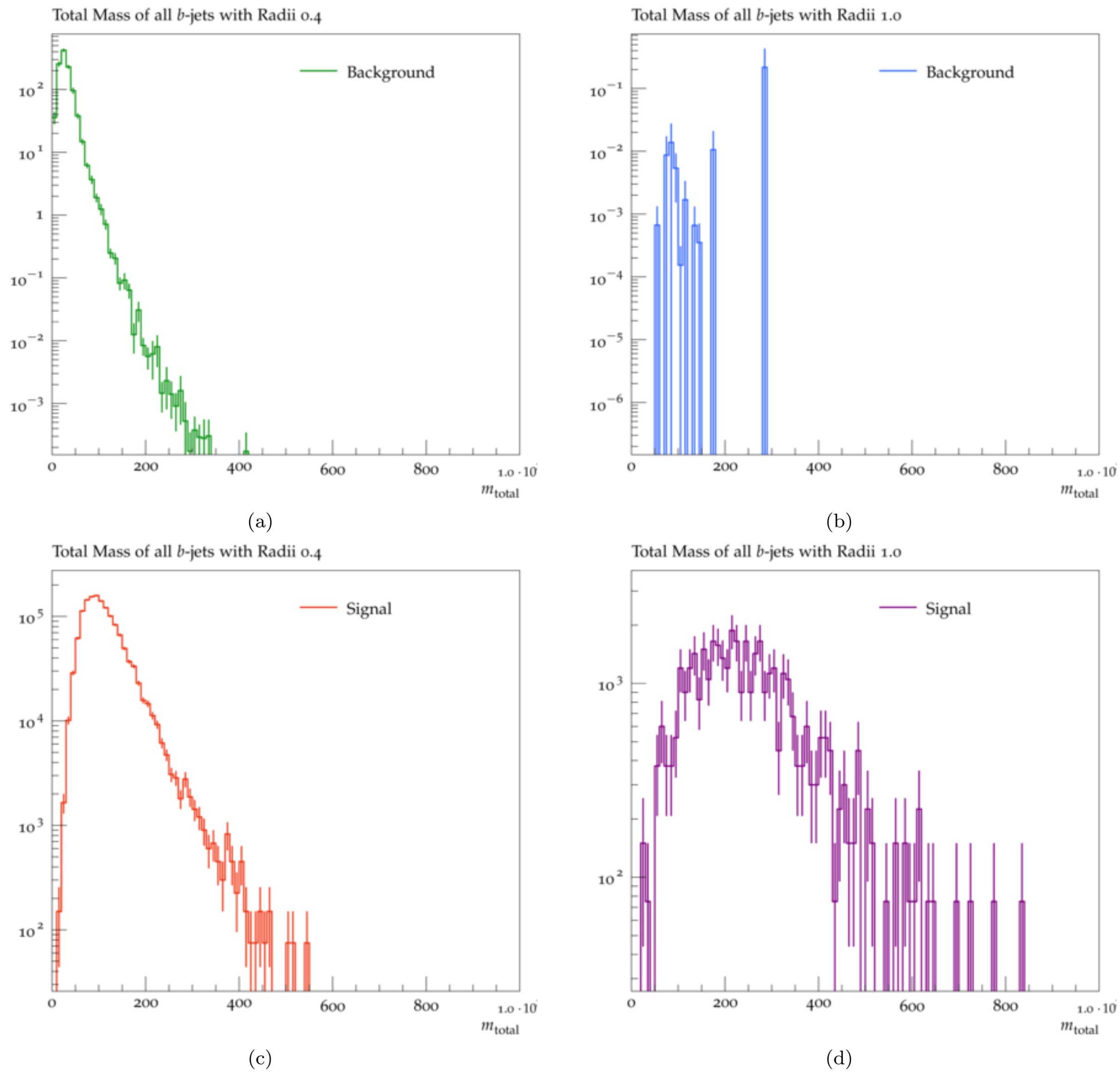


Figure 6: Number of events as a function of the total b-jet mass for the SM background with (a) radius 0.4 and (b) radius 1.0; and for the SUSY signal with (c) radius 0.4 and (d) radius 1.0

In the future, we hope to find other observables that we can impose cuts on, in addition to the most apparent ones which are the jet and b-jet multiplicities, in order to further improve the signal over background plots.

Acknowledgments

First of all, I am grateful to the CERN summer school committee for accepting me as a student to their program and providing a wonderful environment for learning. I also would like to take this opportunity to express my deep sense of gratitude to my supervisor, Dr. Marvin Flores, for his guidance, expertise, and patience. The completion of this project would not be possible without him. A special thanks to Dr. Ian Vega and Dr. Marvin Flores for the recommendation and opportunity that they have given me. Lastly, I would like to thank Katherine Ednacot for the help and encouragement in making this report.

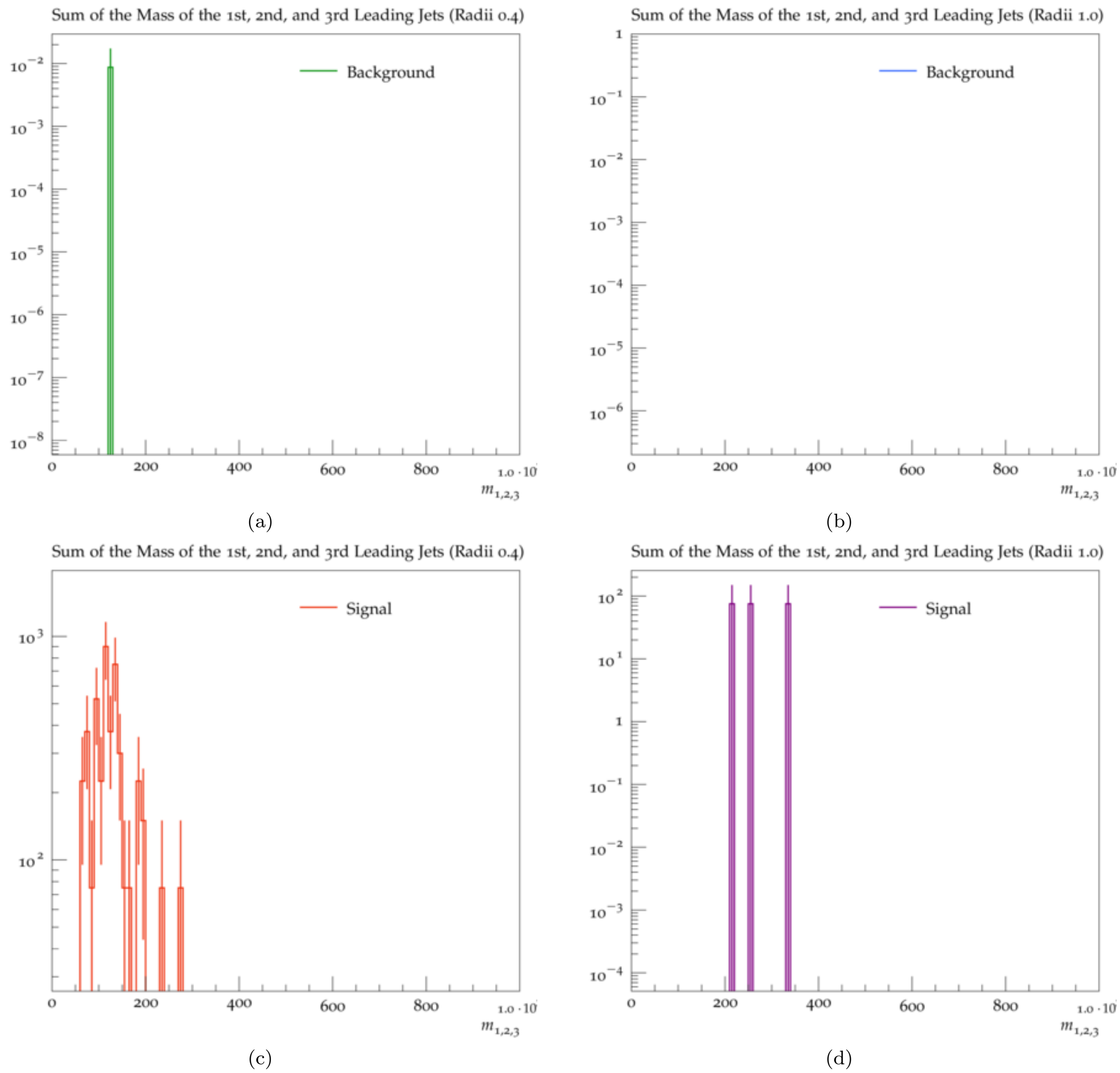


Figure 7: Number of events as a function of the sum of the mass of the 1st, 2nd, and 3rd leading jets for the SM background with (a) radius 0.4 and (b) radius 1.0; and for the SUSY signal with (c) radius 0.4 and (d) radius 1.0

References

[1] T. Shears, The standard model, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **370**, 805 (2012).

[2] I. Antoniadis and P. Tziveloglou, Beyond the standard model: supersymmetry (2009).

[3] G. Aad, B. Abbott, D. C. Abbott, A. A. Abud, K. Abeling, D. K. Abhayasinghe, S. H. Abidi, O. AbouZeid, N. Abraham, H. Abramowicz, et al., Search for phenomena beyond the standard model in events with large b-jet multiplicity using the atlas detector at the lhc, *The European Physical Journal C* **81**, 1 (2021).

[4] J. A. Evans, A swarm of b s, *Journal of High Energy Physics* **2014**, 1 (2014).

[5] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to pythia 8.2, *Computer physics communications* **191**, 159 (2015).

[6] A. Buckley, J. Butterworth, D. Grellscheid, H. Hoeth, L. Lönnblad, J. Monk, H. Schulz, and F. Siegert,

Rivet user manual, *Computer Physics Communications* **184**, 2803 (2013).

[7] C. Bierlich, A. Buckley, J. Butterworth, C. H. Christensen, L. Corpe, D. Grellscheid, J. F. Grosse-Oetringhaus, C. Gutschow, P. Karczmarczyk, J. Klein, et al., Robust independent validation of experiment and theory: Rivet version 3., *SciPost physics.* **8**, 026 (2020).

[8] M. Drees, H. K. Dreiner, J. S. Kim, D. Schmeier, and J. Tattersall, Checkmate: confronting your favourite new physics model with lhc data, *Computer Physics Communications* **187**, 227 (2015).

[9] D. Dercks, N. Desai, J. S. Kim, K. Rolbiecki, J. Tattersall, and T. Weber, Checkmate 2: From the model to the limit, *Computer Physics Communications* **221**, 383 (2017).

[10] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Sletzer, Madgraph 5 (2011).

[11] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, Madgraph 5: going beyond, *Journal of High Energy Physics* **2011**, 1 (2011).

[12] M. Cacciari, G. P. Salam, and G. Soyez, The anti-kt jet clustering algorithm, *Journal of High Energy Physics* **2008**, 063 (2008).

[13] G. Aad, B. Abbott, J. Abdallah, S. A. Khalek, R. Aben, B. Abi, M. Abolins, O. AbouZeid, H. Abramowicz, H. Abreu, et al., Measurement of differential production cross-sections for a z boson in association with b-jets in 7 tev proton-proton collisions with the atlas detector, *Journal of High Energy Physics* **2014**, 1 (2014).