A search for sparticles in zero lepton final states

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ABSTRACT

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Acknowledgements

Dedication

Chapter 1

Introduction

Particle physics is a remarkably successful field of scientific inquiry. The ability to precisely predict the properties of a exceedingly wide range of physical phenomena, such as the description of the cosmic microwave background [1, 2], the understanding of the anomalous magnetic dipole moment of the electron [3, 4], and the measurement of the number of weakly-interacting neutrino flavors [5] is truly amazing.

The theory that has allowed this range of predictions is the *Standard Model* of particle physics (SM). The Standard Model combines the electroweak theory of Glashow, Weinberg, and Salam [6–8] with the theory of the strong interactions, as first envisioned by Gell-Mann and Zweig [9, 10]. This quantum field theory (QFT) contains a tiny number of particles, whose interactions describe phenomena up to at least the TeV scale. These particles are manifestations of the fields of the Standard Model, after application of the Higgs Mechanism. The particle content of the SM consists only of the six quarks, the six leptons, the four gauge bosons, and the scalar Higgs boson.

Despite its impressive range of described phenomena, the Standard Model has some theoretical and experimental deficiencies. The SM contains 26 free parameters [1]. It would be more theoretically pleasing to understand these free parameters in terms of a more fundamental theory. The major theoretical concern of the Standard Model, as it pertains to this thesis, is the *hierachy problem*[11–15]. The light mass

[1] This is the Standard Model corrected to include neutrino masses. These parameters are the fermion masses (6 leptons, 6 quarks), CKM and PMNS mixing angles (8 angles, 2 CP-violating phases), W/Z/Higgs masses (3), the Higgs field expectation value, and the couplings of the strong, weak, and electromagnetic forces (3 α_{force}) .

of the Higgs boson (125 GeV) should be quadratically dependent on the scale of UV physics, due to the quantum corrections from high-energy physics processes. The most perplexing experimental issue is the existence of *dark matter*, as demonstrated by galactic rotation curves [16–22]. This data has shown that there exists additional matter which has not yet been seen interacting with the particles of the Standard Model. There is no particle in the SM which can act as a candidate for dark matter.

Both of these major issues, as well as numerous others, can be solved by the introduction of *supersymmetry* (SUSY) [15, 23–33]. In supersymmetric theories, each SM particles has a so-called *superpartner*, or sparticle partner, differing from given SM particle by 1/2 in spin. These theories solve the hierachy problem, since the quantum corrections induced from the superpartners exactly cancel those induced by the SM particles. In addition, these theories are usually constructed assuming $R-$parity, which can be thought of as the "charge" of supersymmetry, with SM particles having $R = 1$ and sparticles having $R = -1$. In collider experiments, since the incoming SM particles have total $R = 1$, the resulting sparticles are produced in pairs. This produces a rich phenomenology, which is characterized by significant hadronic activity and large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$), which provide significant discrimination against SM backgrounds [34].

Despite the power of searches for supersymmetry where $E_{\mathrm{T}}^{\mathrm{miss}}$ is a primary discriminating variable, there has been significant interest in the use of other variables to discriminate against SM backgrounds. These include searches employing variables such as αT, $M_{T,2}$, and the razor variables (M_R, R^2) [35–45]. In this thesis, we will present the first search for supersymmetry using the novel Recursive Jigsaw Reconstruction (RJR) technique. RJR can be considered the conceptual successor of the razor variables. We impose a particular final state "decay tree" on an events, which roughly corresponds to a simplified Feynmann diagram in decays containing weakly-interacting particles. We account for the missing degrees of freedom associated to the weakly-interacting particles by a series of simplifying assumptions, which allow us to calculate our variables of interest at each step in the decay tree. This allows an unprecedented understanding of the internal structure of the decay and the ability to construct additional variables to reject Standard Model backgrounds.

This thesis details a search for the superpartners of the gluon and quarks, the gluino and squarks, in final states with zero leptons, with 13.3 $\text{fb}^{-1}$of data using the ATLAS detector. We organzie the thesis as follows. The theoretical foundations of the Standard Model and supersymmetry are described in Chapters 2 and 3. The Large Hadron Collider and the ATLAS detector are presented in Chapters 4 and 5. Chapter 5 provides a detailed description of Recursive Jigsaw Reconstruction and a description of the variables used for the particular search presented in this thesis. Chapter 6 presents the details of the analysis, including details of the dataset, object reconstruction, and selections used. In Chapter 7, the final results are presented; since there is no evidence of a supersymmetric signal in the analysis, we present the final exclusion curves in simplified supersymmetric models.

Chapter 2

The Standard Model

Here you can write some introductory remarks about your chapter. I like to give each sentence its own line.

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2.1 Quantum Field Theory

2.2 Symmetries

2.3 The Standard Model

Overview

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Fermions

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Bosons

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2.4 Electroweak Symmetry breaking

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2.5 Deficiencies of the Standard Model

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Chapter 3

Supersymmetry

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3.1 Motivation

Only Additional allowed Lorentz invariant symmetry

Dark Matter

Cancellation of quadratic divergences in corrections to the Higgs Mass

3.2 Supersymmetry

3.3 Additional particle content

3.4 Phenomenology

R parity Consequences for sq/gl decays

Chapter 4

The Large Hadron Collider

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4.1 Magnets

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Chapter 5

The ATLAS detector

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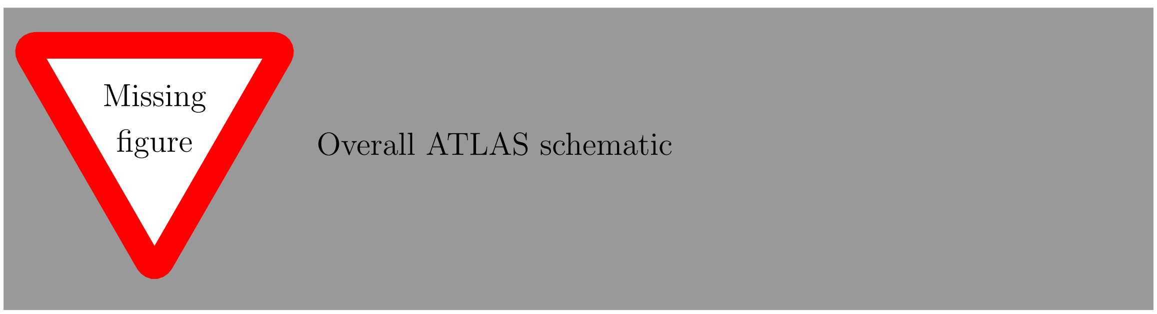

5.1 Inner Detector

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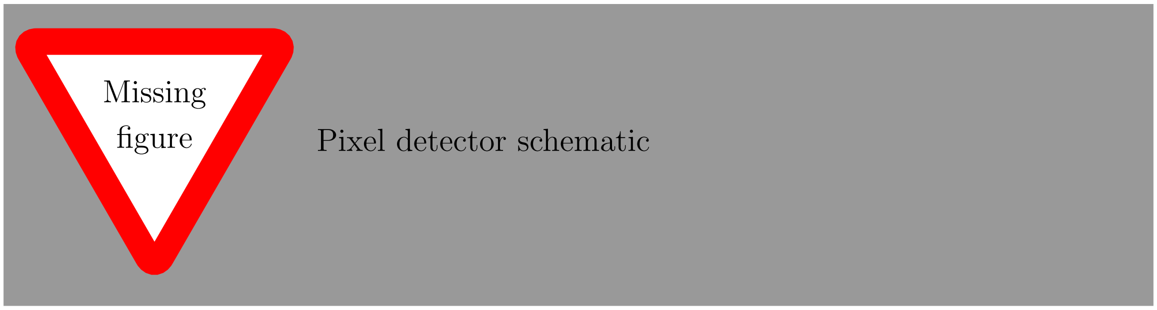
Pixel Detector



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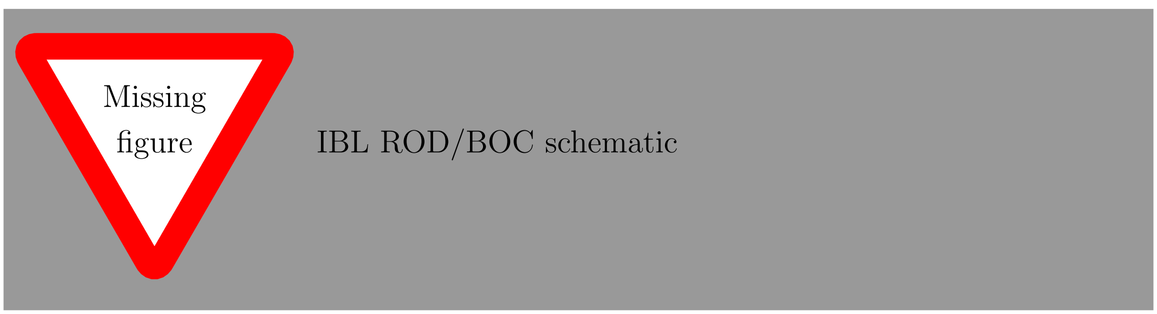
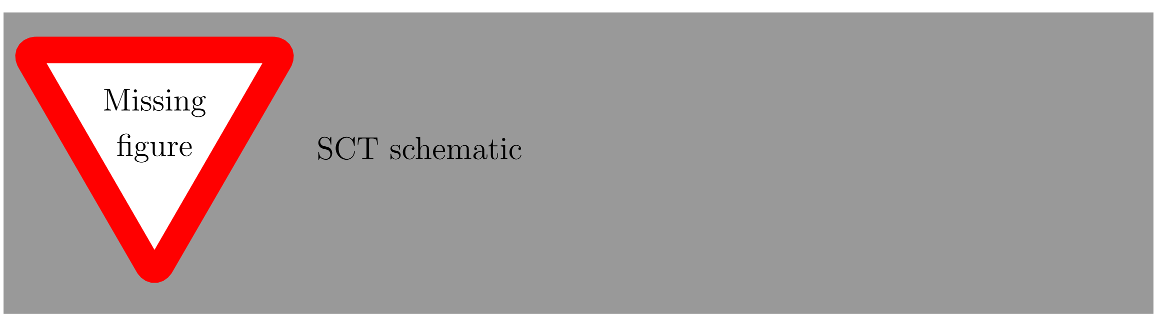
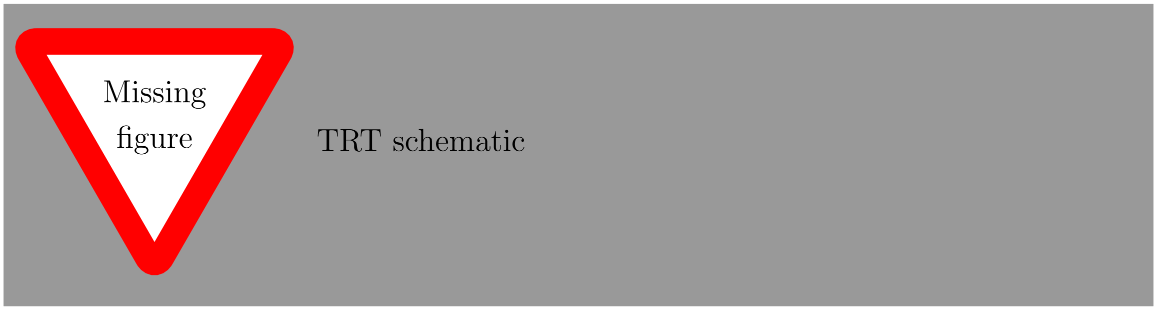
Qualification task, so add a bit more.



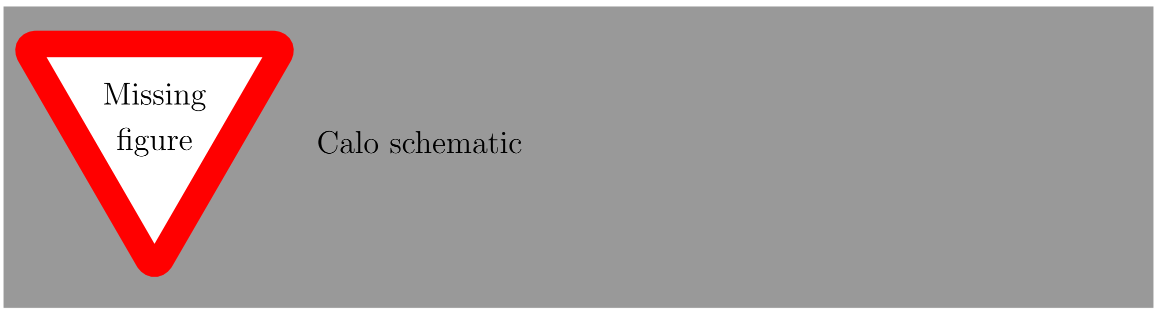
Semiconductor Tracker



Transition Radiation Tracker



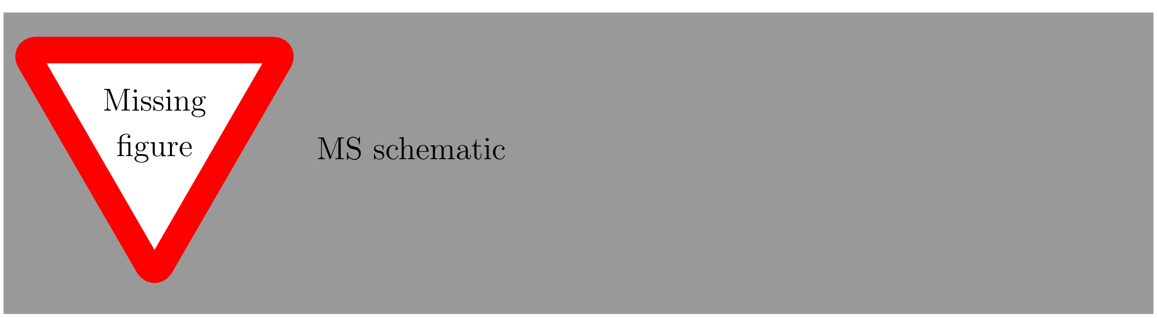
5.2 Calorimeter



Electromagnetic Calorimeter

Hadronic Calorimeter

5.3 Muon Spectrometer



Chapter 6

The Recursive Jigsaw Technique

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6.1 Razor variables

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6.2 SuperRazor variables

6.3 The Recursive Jigsaw Technique

6.4 Variables used in the search for zero lepton SUSY

Chapter 7

Title of Chapter 1

Chapter 8

Title of Chapter 1

Here you can write some introductory remarks about your chapter. I like to give each sentence its own line.

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8.1 Object reconstruction

Photons, Muons, and Electrons

Jets

Missing transverse momentum

Probably longer, show some plots from the PUB note that we worked on

8.2 Signal regions

Gluino signal regions

Squark signal regions

Compressed signal regions

8.3 Background estimation

Z vv

W ev

ttbar

Chapter 9

Title of Chapter 1

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9.1 Statistical Analysis

maybe to be moved to an appendix

9.2 Signal Region distributions

9.3 Pull Plots

9.4 Systematic Uncertainties

9.5 Exclusion plots

Conclusion

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9.6 New Section

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Bibliography

[1] O. Perdereau, *Planck 2015 cosmological results*, AIP Conf. Proc. **1743** (2016) p. 050014.

[2] N. Aghanim et al., *Planck 2016 intermediate results. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters* (2016), arXiv: `1608.02487 [astro-ph.CO]`.

[3] J. S. Schwinger, *On Quantum electrodynamics and the magnetic moment of the electron*, Phys. Rev. **73** (1948) p. 416.

[4] S. Laporta and E. Remiddi, *The Analytical value of the electron (g-2) at order alpha**3 in QED*, Phys. Lett. **B379** (1996) p. 283, arXiv: `hep-ph/9602417 [hep-ph]`.

[5] S. Schael et al., *Precision electroweak measurements on the Z resonance*, Phys. Rept. **427** (2006) p. 257, arXiv: `hep-ex/0509008 [hep-ex]`.

[6] S. L. Glashow, *Partial Symmetries of Weak Interactions*, Nucl. Phys. **22** (1961) p. 579.

[7] S. Weinberg, *A Model of Leptons*, Phys. Rev. Lett. **19** (1967) p. 1264.

[8] A. Salam, *Weak and Electromagnetic Interactions*, Conf. Proc. **C680519** (1968) p. 367.

[9] M. Gell-Mann, *A Schematic Model of Baryons and Mesons*, Phys. Lett. **8** (1964) p. 214.

[10] G. Zweig, "An SU(3) model for strong interaction symmetry and its breaking. Version 2," *DEVELOPMENTS IN THE QUARK THEORY OF HADRONS. VOL. 1. 1964 - 1978*, ed. by D. Lichtenberg and S. P. Rosen, 1964 p. 22, URL: `http://inspirehep.net/record/4674/files/cern-th-412.pdf`.

[11] S. Weinberg, *Implications of Dynamical Symmetry Breaking*, Phys. Rev. **D13** (1976) p. 974.

[12] S. Weinberg, *Implications of Dynamical Symmetry Breaking: An Addendum*, Phys. Rev. **D19** (1979) p. 1277.

[13] E. Gildener, *Gauge Symmetry Hierarchies*, Phys. Rev. **D14** (1976) p. 1667.

[14] L. Susskind, *Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory*, Phys. Rev. **D20** (1979) p. 2619.

[15] S. P. Martin, "A Supersymmetry Primer," 1997, eprint: `arXiv:hep-ph/9709356`.

[16] V. C. Rubin and W. K. Ford Jr., *Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions*, Astrophys. J. **159** (1970) p. 379.

[17] M. S. Roberts and R. N. Whitehurst, *"The rotation curve and geometry of M31 at large galactocentric distances*, Astrophys. J. **201** (1970) p. 327.

[18] V. C. Rubin, N. Thonnard, and W. K. Ford Jr., *Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 /R = 4kpc/ to UGC 2885 /R = 122 kpc/*, Astrophys. J. **238** (1980) p. 471.

[19] V. C. Rubin et al., *Rotation velocities of 16 SA galaxies and a comparison of Sa, Sb, and SC rotation properties*, Astrophys. J. **289** (1985) p. 81.

[20] A. Bosma, *21-cm line studies of spiral galaxies. 2. The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types.*, Astron. J. **86** (1981) p. 1825.

[21] M. Persic, P. Salucci, and F. Stel, *The Universal rotation curve of spiral galaxies: 1. The Dark matter connection*, Mon. Not. Roy. Astron. Soc. **281** (1996) p. 27, arXiv: `astro-ph/9506004 [astro-ph]`.

[22] M. Lisanti, "Lectures on Dark Matter Physics," 2016, eprint: `arXiv:1603.03797`.

[23] H. Miyazawa, *Baryon Number Changing Currents*, Prog. Theor. Phys. **36** (1966) p. 1266.

[24] J.-L. Gervais and B. Sakita, *Generalizations of dual models*, Nucl. Phys. **B34** (1971) p. 477.

[25] J.-L. Gervais and B. Sakita, *Field Theory Interpretation of Supergauges in Dual Models*, Nucl. Phys. **B34** (1971) p. 632.

[26] Yu. A. Golfand and E. P. Likhtman, *Extension of the Algebra of Poincare Group Generators and Violation of p Invariance*, JETP Lett. **13** (1971) p. 323, [Pisma Zh. Eksp. Teor. Fiz.13,452(1971)].

[27] A. Neveu and J. H. Schwarz, *Factorizable dual model of pions*, Nucl. Phys. **B31** (1971) p. 86.

[28] A. Neveu and J. H. Schwarz, *Quark Model of Dual Pions*, Phys. Rev. **D4** (1971) p. 1109.

[29] D. V. Volkov and V. P. Akulov, *Is the Neutrino a Goldstone Particle?* Phys. Lett. **B46** (1973) p. 109.

[30] J. Wess and B. Zumino, *A Lagrangian Model Invariant Under Supergauge Transformations*, Phys. Lett. **B49** (1974) p. 52.

[31] A. Salam and J. A. Strathdee, *Supersymmetry and Nonabelian Gauges*, Phys. Lett. **B51** (1974) p. 353.

[32] S. Ferrara, J. Wess, and B. Zumino, *Supergauge Multiplets and Superfields*, Phys. Lett. **B51** (1974) p. 239.

[33] J. Wess and B. Zumino, *Supergauge Transformations in Four-Dimensions*, Nucl. Phys. **B70** (1974) p. 39.

[34] G. R. Farrar and P. Fayet, *Phenomenology of the Production, Decay, and Detection of New Hadronic States Associated with Supersymmetry*, Phys. Lett. **B76** (1978) p. 575.

[35] ATLAS Collaboration, *Search for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **93** (2016) p. 052002, arXiv: `1509.07152 [hep-ex]`.

[36] ATLAS Collaboration, *Summary of the searches for squarks and gluinos using $\sqrt{s} = 8$ TeV pp collisions with the ATLAS experiment at the LHC*, JHEP **10** (2015) p. 054, arXiv: `1507.05525 [hep-ex]`.

[37] ATLAS Collaboration, *ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider*, Eur. Phys. J. C **75** (2015) p. 510, arXiv: 1506.08616 [hep-ex].

[38] CMS Collaboration, *Search for supersymmetry with razor variables in pp collisions at* $\sqrt{s} = 7$ *TeV*, Phys. Rev. D **90** (2014) p. 112001, arXiv: 1405.3961 [hep-ex].

[39] CMS Collaboration, *Inclusive search for supersymmetry using razor variables in pp collisions at* $\sqrt{s} = 7$ *TeV*, Phys. Rev. Lett. **111** (2013) p. 081802, arXiv: 1212.6961 [hep-ex].

[40] CMS Collaboration, *Search for Supersymmetry in pp Collisions at* 7 *TeV in Events with Jets and Missing Transverse Energy*, Phys. Lett. B **698** (2011) p. 196, arXiv: 1101.1628 [hep-ex].

[41] CMS Collaboration, *Search for Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy*, Phys. Rev. Lett. **107** (2011) p. 221804, arXiv: 1109.2352 [hep-ex].

[42] CMS Collaboration, *Search for supersymmetry in hadronic final states using* M_{T2} *in pp collisions at* $\sqrt{s} = 7$ *TeV*, JHEP **10** (2012) p. 018, arXiv: 1207.1798 [hep-ex].

[43] CMS Collaboration, *Searches for supersymmetry using the* M_{T2} *variable in hadronic events produced in pp collisions at* 8 *TeV*, JHEP **05** (2015) p. 078, arXiv: 1502.04358 [hep-ex].

[44] CMS Collaboration, *Search for new physics with the* M_{T2} *variable in all-jets final states produced in pp collisions at* $\sqrt{s} = 13$ *TeV* (2016), arXiv: 1603.04053 [hep-ex].

[45] ATLAS Collaboration, *Multi-channel search for squarks and gluinos in* $\sqrt{s} = 7$ *TeV pp collisions with the ATLAS detector at the LHC*, Eur. Phys. J. C **73** (2013) p. 2362, arXiv: 1212.6149 [hep-ex].