

Searching for SUSY in events with Jets and Missing Transverse Energy using α_T with the CMS Detector at the LHC

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Abstract

A search for new physics resulting in missing energy in events with high $p_{T\text{jets}}$ is presented. The analysis is performed with 1.1fb^{-1} of 7TeV data taken using the Compact Muon Solenoid detector at the Large Hadron Collider in 2011. The kinematic variable α_T is used to control the background from fake missing energy originating from mis-measurement. The remaining electroweak backgrounds are estimated using data-driven techniques through the use of control samples. The background from boosted W decays is estimated with the use of a dedicated $\mu + \text{jets}$ control sample, while the irreducible background from $Z \rightarrow \nu\bar{\nu}$ is estimated using a $\gamma + \text{jets}$ control sample. A shape analysis is performed across 8 bins in H_T , with the signal selection alongside the two control samples are treated simultaneously in a likelihood fit. The data was found to agree very well with the Standard Model only hypothesis with a p-value of 0.56, indicating no evidence of new physics. The results are interpreted in the scope of a popular new physics model, the Constrained Minimal Supersymmetric Standard Model. Exclusion limits are set at the 95% confidence level on the parameters m_0 and $m_{1/2}$ that set the mass hierarchies of the sparticles. An extension is also presented allowing additional signal into the μ control sample. The effect on the limit is negligible, although adopting a leptonic variable of the α_T variable increases the ratio between signal and background events significantly. We recommend this approach in searches with higher statistics in 2012.

Declaration

Except where otherwise stated, the research undertaken in this thesis was the unaided work of the author. Where the work was done in collaboration with others, a significant contribution was made by the author.

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Contents

Abstract	2
Declaration	3
Acknowledgements	4
Contents	4
1 Introduction	7
2 Theoretical Overview	9
2.1 The Standard Model	9
2.1.1 Gauge Theory of Interactions	11
2.1.2 EWSB and the Higgs Mechanism	19
2.2 Motivation for Physics Beyond the Standard Model	20
2.2.1 The Hierarchy Problem	21
2.2.2 Cold Dark Matter	22
2.2.3 Unification of Coupling Constants	23
2.3 Supersymmetry	23
2.3.1 R-Parity	25
2.3.2 MSSM	26
2.3.3 Supersymmetry Breaking	27
2.3.4 Minimal Supergravity and the Constrained MSSM	28
2.3.5 Production Mechanisms in pp collisions	30
3 The Compact Muon Solenoid Experiment at the LHC	33
3.1 The Large Hadron Collider	33
3.2 The Compact Muon Solenoid	36
3.2.1 Coordinate System	39
3.2.2 Superconducting Magnet	39
3.2.3 Tracker	40
3.2.4 ECAL	41
3.2.5 HCAL	43
3.2.6 Muon System	45

3.2.7	Trigger	47
4	Event Reconstruction	50
4.1	Beamspot	51
4.2	Tracks	51
4.3	Vertex	53
4.4	Jets	53
4.4.1	The anti- k_T jet clustering method	54
4.4.2	Jet Energy Scale Corrections	56
4.5	Missing Energy	58
4.5.1	\cancel{E}_T Corrections	59
4.5.2	Using Jets for Missing Energy - \cancel{H}_T	60
4.6	Muon	61
4.7	Photons	62
4.8	Electrons	63
5	Searching for SUSY with α_T	65
5.1	Inclusive SUSY Search	65
5.2	α_T in a di-jet system	67
5.3	α_T in a n-jet system	68
5.4	Defining the ratio R_{α_T}	70
5.5	Extending α_T for single-lepton searches	71
5.6	Reliance of α_T on jet object definition	71
6	All-Hadronic Analysis	74
6.1	Samples	74
6.1.1	Monte Carlo Simulation	75
6.1.2	Data Sample	76
6.2	Analysis Framework	77
6.3	Trigger	77
6.4	Object Definitions	80
6.4.1	Good Event Definition	80
6.4.2	Jets	80
6.4.3	H_T and \cancel{H}_T	81
6.4.4	Muons	81
6.4.5	Electrons	82
6.4.6	Photons	82
6.5	Pre-Selection	84
6.6	Final Signal Selection	84
6.7	An H_T Shape Analysis	85
6.8	Hadronic Signal Region Results	86
6.8.1	Data to Monte-Carlo Comparisons	86
6.8.2	R_{α_T} on H_T	89

6.8.3	Composition of Selected $t\bar{t}$ + jets and W + jets Background Events	91
6.9	Estimation of $t\bar{t}$ and W + Jets Backgrounds with a high p_T control sample using $W \rightarrow \mu\nu$ events.	93
6.9.1	μ Control Sample Selection	93
6.9.2	Prediction Calculation	94
6.9.3	μ Control Sample Systematic Uncertainty	97
6.9.4	Signal Contamination in μ Control Sample	101
6.10	Estimation of $Z \rightarrow \nu\bar{\nu}$ + jets background using photon + jets events	101
6.10.1	Z Background Prediction Calculation	103
6.10.2	γ Control Sample Systematic Uncertainty	104
6.10.3	Cross-Prediction between Control Samples	105
6.11	Signal Region Systematic Uncertainties	106
6.12	Statistical Interpretation	107
6.12.1	Hadronic Signal Selection Likelihood	108
6.12.2	Expression of b^i using R_{α_T} evolution in H_T	108
6.12.3	Electroweak Control Sample Likelihoods	109
6.12.4	Presence of Signal	110
6.12.5	Total Likelihood	111
6.13	Testing the SM-only hypothesis	111
6.14	Excluding Signal Models	114
6.14.1	Constructing a Test Statistic	114
6.14.2	The CL_S Method	115
6.14.3	Setting an Exclusion Limit in the CMSSM Plane	115
7	Extending the μ Control Sample to a Signal Sample	117
7.0.4	Relaxing the Cuts	117
7.0.5	Event Yields	118
7.0.6	Fit Results	119
7.1	Interpretation	123
8	Conclusion	124
A	Data Samples	126
	Bibliography	128

Chapter 1

Introduction

At the heart of science is the quest to further mankind’s knowledge of the universe we live in. The Standard Model of particle physics is one of the greatest achievements in this effort, forming the basis of a description of the most fundamental building blocks of nature. However, despite its many successes verified in experimental physics, there are many indications it is not a complete theory.

As particle physicists look inwards to smaller scales with higher energies, cosmologists look outwards into space. Cosmological experiments confirm that the matter of the observable universe accounts for only 4% of the mass in the universe. Another type of matter, known as “Dark Matter”, accounts for 23% and yet there is no particle in the existing Standard Model to account for this, indicating new physics. Supersymmetry, one popular extension of the Standard Model predicts a new symmetry in which each known particle has an as-yet undiscovered partner. The lightest of these is stable and weakly interacting, and therefore could account for dark matter.

Experimental particle physics pushes the frontier of energy ever upwards in order to probe the heart of matter to better resolution. The Large Hadron Collider is the first collider that can access physics on the TeV scale, where many hope the first indications of physics behind the Standard Model will lie. The Compact Muon Solenoid detector will collect data during these proton collisions for analysis in many areas of possible new physics.

Motivated by Supersymmetry, this thesis details the search for signs of new physics consistent with a dark matter candidate particle. Events are required to

have jets and missing energy where the candidate particle escapes the detector. The Standard Model theory is presented in Chapter 2 along with motivations for physics beyond, and a description of Supersymmetry. The data used is taken using the Compact Muon Solenoid Detector at the Large Hadron Collider, experimental descriptions of which are found in Chapter 3, and the reconstruction performed prior to data release for the analysis users is described in Chapter 4.

Chapter 5 documents the design and verification of the novel background rejection variable α_T , using work undertaken by the author's analysis group in previous iterations of the analysis, and work on the leptonic definition undertaken by the author described in Section 5.5. The work presented in Chapter 6 is documented in a public CMS Physics Analysis Summary [1] and published in Physical Review Letters [2] in 2011. The work was undertaken by a small analysis group of which the author was a key active member singularly responsible for the μ control sample used for background prediction and in addition providing plots and yields for the signal selection. The work in Chapter 7 represents an extension to the published analysis that is the sole work of the author, using the aforementioned leptonic definition of the α_T variable.

Chapter 2

Extending the μ Control Sample to a Signal Sample

In Chapter 6, the μ control sample was used effectively to predict the background contribution from W and $t\bar{t}$ events. The μ likelihood’s incorporation into the overall likelihood in order to interpret the hadronic results allowed for some small signal contamination. However it was in general viewed as a constraint on the “signal” region of the hadronic selection.

The cuts outlined in Section 6.9 are designed to select events from Standard Model W decays, hence minimising the contamination from signal. However, as the simultaneous fit includes the signal efficiency in the μ control sample it is possible to relax the cuts and allow more potential signal into the μ yield. Instead of viewing it as a control sample it may then be considered as a second signal sample in the simultaneous fit. The electroweak background behaviour is still constrained by the flat behaviour in R_{α_T} whereas the presence of signal would exhibit an exponentially increasing behaviour. Thus it is possible to construct a dual-sample search in order to extend the reach of the analysis. The following work represents the author’s personal investigation into the effect of increasing the chance for signal contamination in the μ selection on the eventual limit with the current dataset.

2.0.1 Relaxing the Cuts

The primary cut in the μ control sample responsible for restricting the signal is the M_T requirement, as it puts a restriction on boosted W decays. The first step

is to remove this cut, allowing more potential signal into the sample. Having done so there are three possible scenarios with respect to the α_T cut. Using the α_T cut as defined in the hadronic analysis is a natural choice. However the use of an α_T cut limits the statistics, so removing this cut would increase the μ sample statistics. Conversely, using the hadronic definition of the α_T cut without concerning the μ leads to the false appearance of missing energy, hence allowing more background into the sample. The use of the leptonic version of α_T , α_T^{lep} cut as defined in Section 5.5 does not suffer from this issue, but as this is a tighter cut will reduce the available statistics.

The four μ selection criteria considered are therefore:

- 2011 Selection (unchanged)
- a) No M_T Cut and use the $\alpha_T > 0.55$ cut from the hadronic analysis where the muon is ignored (as previously in the 2011 selection)
- b) No M_T Cut and take out the α_T cut (the MHT/HT cut ensures the elimination of QCD background is maintained)
- c) No M_T Cut and make a cut with the leptonic α_T , $\alpha_T^{lep} > 0.55$

The one muon requirement cut and the other cuts mentioned in Section 6.9 remain as they do not pertain to the rejection of signal but rather the selection of a good isolated muon not overlapping with a jet, in the case where the decay is not from a Z where a second μ is not identified by the quality criteria. The \cancel{H}_T/H_T cut is generally superseded by the α_T cut therefore removing it has little effect, however it is left in so that in the case where the α_T cut is removed we remain in the kinematic phase space of the hadronic signal region.

2.0.2 Event Yields

The bin-by-bin yields in Monte Carlo normalised to 1.1fb^{-1} for the Standard Model backgrounds (B) and potential signal (S) from LM6 are shown in Table 7.1. The values of the ratio S/\sqrt{B} are also shown as a measure of the potential significance of LM6 signal in each bin. As in the hadronic selection, where signal is present it shows the greatest significance with regards to background in the highest H_T bins. Removing the M_T cut raises the ratio S/\sqrt{B} in the highest three

bins whilst in the lower bins S/\sqrt{B} has fallen due to the increase of background. As expected removing the α_T cut lowers the S/\sqrt{B} as more background enters the selection, but the available statistics are much higher. In the case where the muon is used in the α_T definition the ratio is improved in all bins. The values in the highest two bins are large but currently suffer from low available Monte Carlo statistics in the SM backgrounds.

The ratio S/\sqrt{B} can be further explored in the $m_0 - m_{1/2}$ plane of the CMSSM using the SUSY Signal Scan used previously to set exclusion limits. Figure 7.1 shows the values of S/\sqrt{B} for 1.1fb^{-1} across the region relevant to the exclusion limit, using the four highest bins only ($H_T > 575$). These bins are chosen as an illustration of the effect of the different criteria on the sensitivity of the muon signal sample, although the eventual fit is an H_T shape analysis and therefore is affected by the shape of S/\sqrt{B} across all bins. Across the full range of SUSY points the conclusions fit those identified in the table for LM6, although the criteria a) and b) with the M_T cut removed show little difference from the previous 2011 selection, in terms of increasing the number of signal points that reach a certain S/\sqrt{B} at this luminosity. On the other hand, the use of the leptonic cut $\alpha_T^{lep} > 0.55$ shows a noticeable increase in the number of points achieving a certain S/\sqrt{B} .

2.0.3 Fit Results

The event yields from the previous section are then entered into the simultaneous likelihood fit described previously in Section 6.12. The presence of signal in both the hadronic selection and the muon selection is allowed and the hadronic and photon sample results are unchanged from the 2011 analysis. The CL_s value is again calculated in the $m_0 - m_{1/2}$ plane for each of the four selection definitions. The results of the test ($\text{CL}_s > 0.05$) are shown in Figure 7.2, where those points for which this is true are shown red, corresponding to a 95% confidence in excluding that point. Points for which the test is false are shown blue, and points missing due to Monte-Carlo statistics are not plotted.

The results of the fit show no marked difference in the eventual result between the four categories. In the extreme low m_0 region where the reach in $m_{1/2}$ is greatest, the criteria which extends the limit slightly with respect to the 2011 analysis is the removal of the α_T cut, indicating the additional statistics slightly improve the limit, although the difference is slight. The lowered statistics

	H_T Bin (GeV)	275–325	325–375	375–475	475–575
2011 Selection	B (SM)	407.5	179.1	131.6	48.7
	S (LM6)	0.15	0.15	0.53	0.82
	S/\sqrt{B}	0.000	0.001	0.004	0.017
a) No M_T Cut & $\alpha_T > 0.55$	B (SM)	549.93	243.33	179.51	63.80
	S (LM6)	0.19	0.20	0.59	0.92
	S/\sqrt{B}	0.000	0.001	0.003	0.0014
b) No M_T Cut & No α_T	B (SM)	1335.81	603.61	485.62	192.61
	S (LM6)	0.26	0.32	0.89	1.43
	S/\sqrt{B}	0.000	0.001	0.002	0.007
c) No M_T Cut & $\alpha_{T \text{ lep}} > 0.55$	B (SM)	163.95	70.64	39.87	16.38
	S (LM6)	0.13	0.17	0.51	0.79
	S/\sqrt{B}	0.001	0.002	0.013	0.048

	H_T Bin (GeV)	575–675	675–775	775–875	875– ∞
2011 Selection	B (SM)	13.32	7.95	3.20	0.97
	S (LM6)	1.09	1.17	0.95	1.21
	S/\sqrt{B}	0.082	0.147	0.297	1.343
a) No M_T Cut & $\alpha_T > 0.55$	B (SM)	18.53	8.59	3.34	0.97
	S (LM6)	1.23	1.35	1.08	1.42
	S/\sqrt{B}	0.066	0.157	0.324	1.5747
b) No M_T Cut & No α_T	B (SM)	67.64	30.04	12.77	3.26
	S (LM6)	1.87	2.04	1.77	3.07
	S/\sqrt{B}	0.028	0.068	0.139	0.940
c) No M_T Cut & $\alpha_{T \text{ lep}} > 0.55$	B (SM)	7.85	1.76	0.05	0.05
	S (LM6)	1.05	1.13	0.89	1.06
	S/\sqrt{B}	0.134	0.641	19.282	22.982

Table 2.1: Monte Carlo yields for μ control sample for Standard Model Monte Carlo (B) and potential SUSY signal from test point LM6. Four separate selection criteria are considered: 2011 Selection as detailed in Chapter 6 alongside three selections with the M_T cut removed and different approaches to the α_T cut: a) $\alpha_T > 0.55$, b) α_T cut removed and c) $\alpha_{T \text{ lep}} > 0.55$ as detailed in Section 5.5

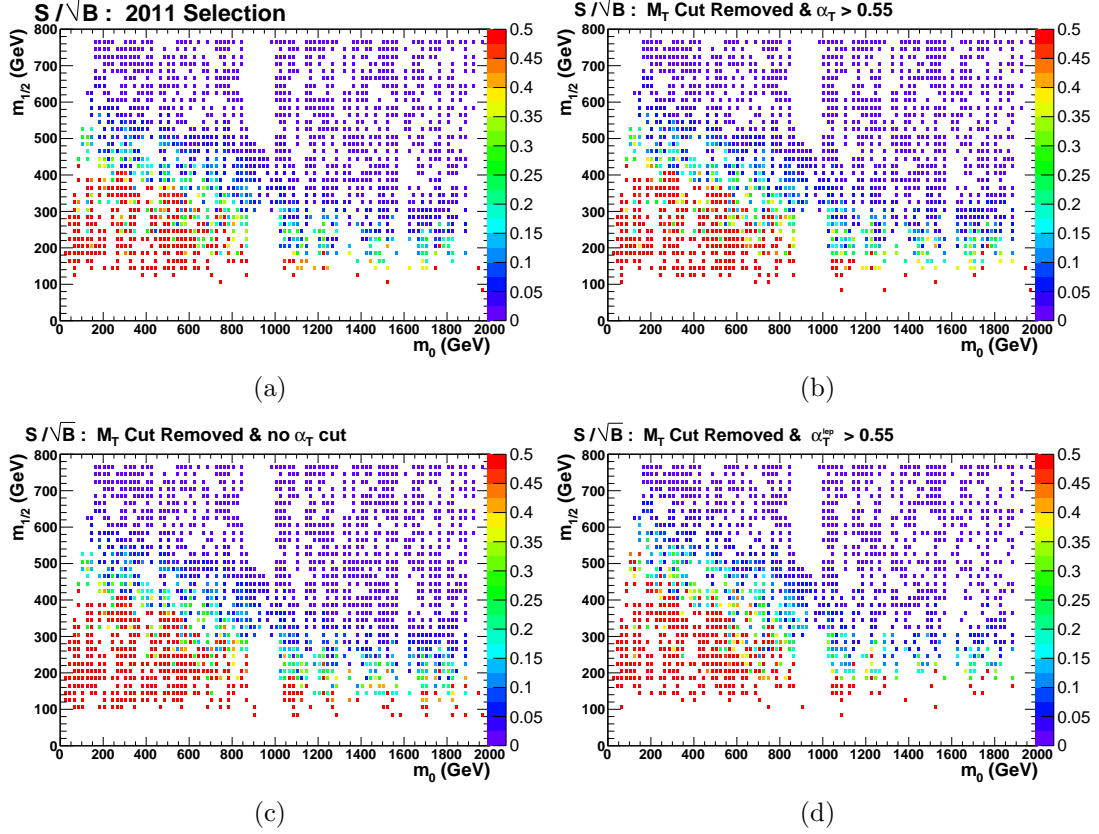


Figure 2.1: The signal to background ratio S/\sqrt{B} for each point in the CMSSM $(m_0, m_{1/2})$ plane for the four different μ selection criteria at NLO cross sections for events $H_T > 575$ (the four highest bins). The 2011 Selection (a) is unchanged from Chapter 6. The M_T cut is removed for (a) with $\alpha_T > 0.55$, (b) with no α_T cut and (c) with $\alpha_T^{lep} > 0.55$.

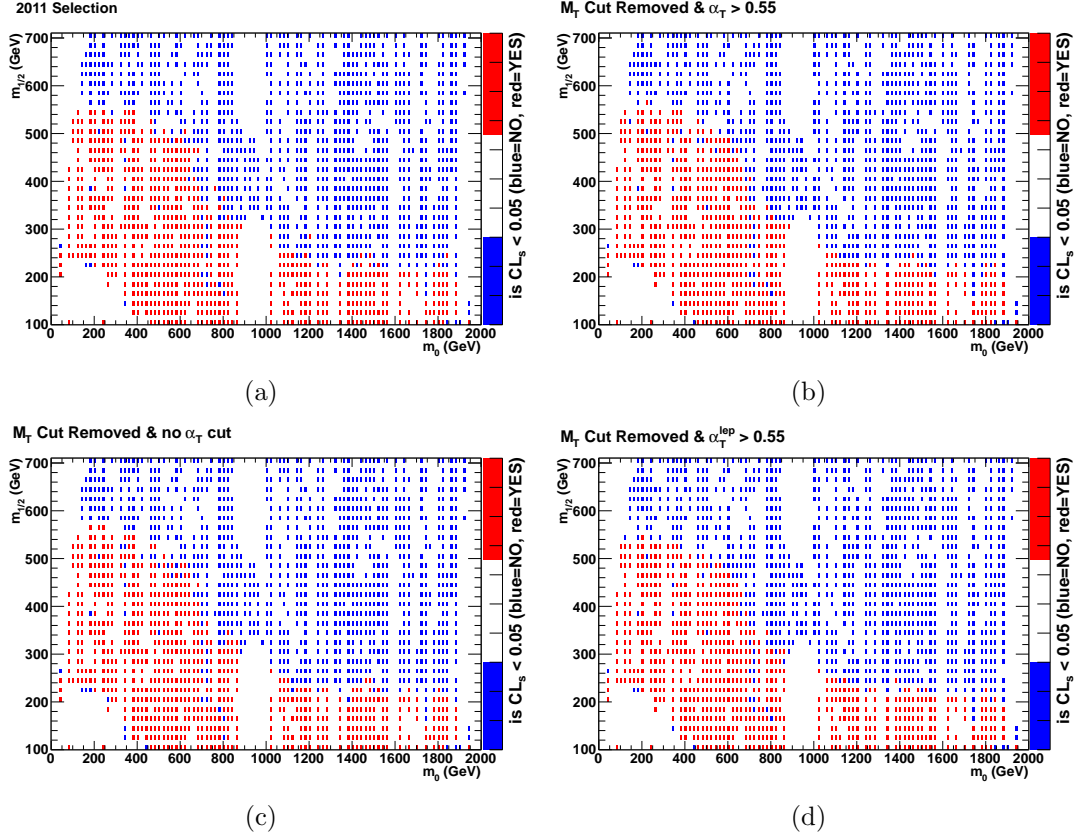


Figure 2.2: The CL_s exclusion limit for the four different μ selection criteria, with $CL_s < 0.05$ shown in red (excluded at 95% confidence) and $CL_s > 0.05$ shown in blue. Missing points are due to holes in Monte Carlo statistics. The 2011 Selection (a) is unchanged from Chapter 6 and corresponds to the final limit plot there. The M_T cut is removed for (a) with $\alpha_T > 0.55$, (b) with no α_T cut and (c) with $\alpha_T^{lep} > 0.55$.

of the leptonic α_T^{lep} cut does not affect the exclusion power.

2.1 Interpretation

At this luminosity the CL_s exclusion power of the likelihood fit shows no significant change of power with the removal of the M_T . Therefore it is safe to remove the M_T cut in future iterations of this analysis and allow more signal into the μ sample. The limited statistics found by the selection requiring the leptonic α_T cut does not affect the exclusion power over the hadronic cut, or removal entirely. In addition the use of this cut significantly increases the significance, S/\sqrt{B} , in the higher bins of H_T indicating a large impact in the shape analysis. As moving to higher luminosities will increase both the statistics available using this definition and the potential S/\sqrt{B} , this definition is suitable for defining a μ signal sample for used in a dual-signal search strategy alongside the hadronic signal selection. Although this provides no greater limit at the present luminosity it is recommended to investigate further in the next luminosity update.

Chapter 3

Conclusion

A comprehensive search for a final state with missing energy and jets motivated by R-Parity conserving supersymmetry is presented in this analysis. The analysis considers the first 1.1fb^{-1} of 7TeV data taken by the CMS detector at the LHC in 2011. Using an inclusive strategy which requires a final state with jets, no leptons or photons and significant missing energy targets new physics models in which a dark matter candidate is present.

Due to the large background from QCD processes at the LHC there is a considerable background from fake missing energy due to mis-measurment. The use of a novel variable α_T is employed to effectively remove this component of the background. The additional backgrounds are estimated with the help of two dedicated control samples, of $\mu + \text{jets}$ and $\gamma + \text{jets}$ to estimate the $t\bar{t}/W$ and Z backgrounds respectively.

A shape analysis across eight bins of H_T simultaneously in the signal region and two control regions is performed using a likelihood fit. The data agree very well with simulation and are found by the goodness-of fit test to be consistent with the hypothesis of the Standard Model only.

Having established that there is no distinction from the Standard Model hypothesis with this luminosity, the results are interpreted in the scope of the Constrained Minimal Supersymmetric Standard Model, in order to exclude regions of its parameter space. Using values of $A_0 = 0$, $\tan \beta = 10$ and $\text{sign}(\mu) = +$, the $m_0 - m_{1/2}$ plane is probed using the CL_s statistical method and an exclusion limit is set at a 95% confidence level.

The exclusion corresponds to a lower limit on equal gluino masses and the

mean of the squark masses at 1.1 TeV for the range $m_0 < 500$ GeV, where the exclusion power is at its greatest. For higher values of m_0 , where the gluino mass is much lower than that of the mean squark mass, the exclusion limit corresponds to a gluino mass of 0.5 TeV.

At the time of publishing of these results, the exclusion limits far exceeded those set previously by collider experiments, expanding considerably the region of the CMSSM that is incompatible with experimental results.

At the end of this thesis, in Chapter 7 the effects of allowing more signal into the μ control sample is studied. At the present luminosity the limit remains unchanged by the removal of the transverse mass cut. The move to the leptonic definition of α_T also leaves the current limit unchanged, although with the inclusion of potential signal this would significantly increase the significance of signal events in the higher regions of H_T . The recommendation for the next iteration of the analysis is to proceed with the dual-signal scenario using the leptonic α_T cut to increase the significance in this bin, while retaining the previous control definition for cross-checks.

Appendix A

Data Samples

HT 1.1fb^{-1} Data

/HT/Run2011A-May10ReReco-v1/AOD
/HT/Run2011A-PromptReco-v4/AOD

Photon 1.1fb^{-1} Data

/Photon/Run2011A-May10ReReco-v1/AOD
/Photon/Run2011A-PromptReco-v4/AOD

Standard Model Background Monte Carlo

/QCD_Pt_*_TuneZ2_7TeV_pythia6/Summer11-PU_S1_START42_V11-v1/AODSIM
/QCD_TuneD6T_HT-*_7TeV-madgraph/Summer11-PU_S1_START42_V11-v1/AODSIM
/TTJets_TuneZ2_7TeV-madgraph-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/WJetsToLNu_TuneZ2_7TeV-madgraph-tauola/Summer11-PU_S4_START42_V11-v1/AODSIM
/ZinvisibleJets_7TeV-madgraph/Spring11-PU_S1_START311_V1G1-v1/GEN-SIM-RECO
/GJets_TuneD6T_HT-*_7TeV-madgraph/Spring11-PU_S1_START311_V1G1-v1/AODSIM

SUSY Signal Reference Monte Carlo

/LM4_SUSY_sftsht_7TeV-pythia6/Spring11-PU_S1_START311_V1G1-v1/AODSIM
/LM6_SUSY_sftsht_7TeV-pythia6/Spring11-PU_S1_START311_V1G1-v1/AODSIM

Table A.1: Details of the Monte Carlo simulation samples used in this thesis, with cross-sections and relevant same sizes available. Produced in the Spring11/Summer11 CMS Official Production Campaigns. The MadGraph Z, γ and QCD samples have a k -factor of 1.27 applied to σ , from differences in Z+Jets production at NO and NNLO.

Process	Notes	σ / pb	# events
QCD (PYTHIA6) [Tune Z2]	$15 < \hat{p}_T < 30$ GeV	8.159×10^8	9,720,000
	$30 < \hat{p}_T < 50$ GeV	5.312×10^7	4,060,424
	$50 < H_T < 80$ GeV	6.359×10^6	5,605,000
	$80 < H_T < 120$ GeV	7.843×10^5	6,589,956
	$120 < H_T < 170$ GeV	1.151×10^5	5,073,528
	$170 < H_T < 300$ GeV	2.426×10^4	5,473,920
	$300 < H_T < 470$ GeV	1.168×10^3	4,452,669
	$470 < H_T < 600$ GeV	7.022×10^1	3,210,085
	$600 < H_T < 800$ GeV	1.555×10^1	4,105,695
	$800 < H_T < 1000$ GeV	1.844×10^0	3,833,888
	$1000 < H_T < 1400$ GeV	3.321×10^{-1}	2,053,222
	$1400 < H_T < 1800$ GeV	1.087×10^{-2}	2,156,200
	$H_T > 1800$ GeV	3.575×10^{-4}	273,139
QCD (MadGraph) [Tune Z2]	$100 < \hat{p}_T < 250$ GeV	8.891×10^6	21,066,112
	$250 < \hat{p}_T < 500$ GeV	2.174×10^5	20,594,219
	$500 < \hat{p}_T < 1000$ GeV	6.607×10^3	14,397,469
	$\hat{p}_T > 1000$ GeV	$\times 10^2$	6,294,851
γ + jets (MadGraph) [Tune Z2]	$40 < H_T < 100$ GeV	3.000×10^4	2,217,101
	$100 < H_T < 100$ GeV	4.415×10^3	1,065,691
	$H_T > 200$ GeV	1.054×10^2	1,142,171
W + Jets (MadGraph)	NNLO	3.131×10^4	46,608,773
$t\bar{t}$ + jets (MadGraph)	NLO	1.575×10^2	3,701,947
$Z \rightarrow \nu\bar{\nu}$ (MadGraph)	NNLO	5.715×10^3	2,165,002
LM4	-	1.879	218,380
LM6	-	3.104×10^{-1}	220,000

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