Search for supersymmetry in pp collisions with all-hadronic final states using the α_T variable with the CMS detector at the LHC

Bryn Mathias
Imperial College London

Supervisor: Dr Alex Tapper

DRAFT

Abstract

This is a thesis.

DRAFT

Declaration

There are many like it.

Author

DRAFT

Preface

Something witty.

DRAFT

Acknowledgements

Thanks.

DRAFT

Contents

1 Introduction **9**

2 Theory **10**

2.1 The Standard Model (SM) 10

2.1.1 Gauge Invariance 11

2.2 The Constrained Minimal Super Symmetric Model 13

3 The CMS detector **14**

3.1 The Silicon Tracker 15

3.2 The Electromagnetic Calorimeter (ECAL). 16

3.3 The Hadronic Calorimeter (HCAL). 17

3.4 The The Compact Muon Solenoid (C.M.S) Super-Conducting Solenoid . 19

3.5 The C.M.S Muon system. 19

3.6 The Level One Trigger System. 20

3.7 The High Level Trigger System. 21

4 Level One Calorimeter Trigger **22**

4.1 Level-1 Trigger Jet Algorithm [34] 23

4.2 Level-1 Trigger Performance 25

4.3 Level-1 Trigger Pile-up Mitigation 33

4.3.1 Effect on trigger efficiency 35

4.3.2 Summary 37

5 Motivating the α_T Analysis **39**

5.1 The Problem 39

6 Reconstruction and Event selection **41**

6.1 The α_T variable. 41

6.2 Event selection 43

6.2.1 Preselection of hadronic objects 43

DRAFT

6.2.2 Electrons . . . 45
6.2.3 Muons . . . 46
6.2.4 Photons . . . 47
6.3 Common Analysis cuts . . . 47
6.4 High Level triggers for the α_T analysis . . . 50
6.4.1 Trigger efficiency measurement . . . 51
6.5 Extension to higher analysis dimensions. B-tagging . . . 56

7 Background Prediction **64**
7.1 Electro-Weak Background Prediciton . . . 64
7.1.1 The μ + Jets control sample . . . 67
7.1.2 The $\mu\mu$ + Jets control sample . . . 68
7.1.3 The γ + Jets control sample . . . 68
7.1.4 Muon control samples with out an α_T cut. . . . 69
7.2 Systematic uncertainties on the electro-weak background model. . . . 72
7.3 Motivating the combined systematic on the translation factors . . . 74
7.4 Estimating the residual QCD background component.[6] . . . 75
7.5 Likelihood model . . . 77
7.6 Final Results . . . 81

8 Interpretation **87**
8.1 Signal Models . . . 87
8.2 Signal Efficiency . . . 88
8.2.1 Constrained Minimal SuperSymmetric Model (CMSSM) . . . 88
8.2.2 Simplified Models . . . 88
8.3 Uncertainty on Signal Efficiency . . . 89
8.4 Choice of Parton Density Function (PDF) set at generator level. . . . 90
8.5 Effects of Jet Energy Scale Variations on Signal Efficiency . . . 92
8.6 Systematic Uncertainty on Signal Yield from Cleaning Filters and Object Vetoes. . . . 92
8.7 Interpretation in terms of new physics models. . . . 93

9 Conclusion **98**

Bibliography **99**
1 Additional information on triggers . . . 103

DRAFT

2 Addition information on background estimation methods 107
2.1 Determination of k_{QCD} 107
3 Closure tests and systematic uncertainties 108
3.1 Defining muon samples without an α_T requirement 108
3.2 Closure tests for inclusive analysis 109
3.3 Closure tests for b-tag analysis 110
3.4 Closure tests concerning pile-up 112
4 Signal efficiency 113
4.1 CMSSM 113
4.2 `T1` 114
4.3 `T2` 115
4.4 `T2tt` 116
4.5 `T2bb` 117
4.6 `T1tttt` 118
4.7 `T1bbbb` 119
4.8 Signal contamination for `T1tttt` 120
5 Experimental systematic uncertainties on signal efficiency times acceptance 121
5.1 Systematics due to jet energy scale uncertainties 121
5.2 Systematics due to the MHT/MET cut 126
5.3 Systematics due to the dead ECAL cut 130
5.4 Systematics due to the lepton and photon vetoes 131

DRAFT

Chapter 1

Introduction

The accelerator and detectors The Large Hadron Collider (LHC) [14] is a proton-proton collider which is situated in the Large Electron Positron (LEP) tunnel approximately 100 m under the franco-swiss border. Design center of mass energy is 14 TeV with an instantaneous luminosity of $1 \times 10e^{34} cm^{-2}s^{-1}$. However during 2011 the center of mass energy was 7 TeV and the maximum luminosity was $5 \times 10e^{33}$ $cm^{-2}s^{-1}$. To achieve this high energy and high beam current the LHC uses superconducting niobium-titanium magnets, cooled to a temperature of 1.8 Kelvin, that produce a maximum field strength of 8.36 Tesla.

we might well need some more stuff about the LHC its self in here!

Situated around the LHC ring are four detectors, two general detectors ATLAS [10] and CMS (see Chapter 3 for a detailed discussion of the CMS detector) [27][44] which are designed to measure the Standard Model (S.M) to high precision and search for new physics. The LHC beauty experiment [37] is designed to study at previously unattainable precision the decays of heavy quark flavors, both to measure the S.M couplings and to search for beyond the S.M (BSM) physical processes. Finally the ALICE [11] experiment is designed to run when the LHC is running in it's secondary mode where rather than proton bunches, lead ions are collided, in an effort to study the quark-gluon plasma.

New physics Whilst the theory of the S.M and of new physics models will be discussed in chapter 2 it is prudent to discuss the observable features of these models with regard to design requirements for the general purpose detectors.

DRAFT

Chapter 2

Theory

2.1 The Standard Model (SM)

The S.M of particle physics seeks to describe all of the observed matter particles and their interactions. The theory is a quantum field theory which is both invariant under local gauge transform and renormilisable. The theory is constructed from the unitary product group $SU(3) \bigotimes SU(2)_L \bigotimes U(1)_Y$ where $SU(3)$ describes the colour charged strong nuclear force and $SU(2)_L \bigotimes U(1)_Y$ describes the electro-weak interactions. The electro-weak sector contains bosons which exhibit mass, which is contrary to what is inferred by the invariance under local gauge transform, that the gauge bosons should be massless. The $SU(2)_L \bigotimes U(1)_Y$ symmetry is thus seen to be broken, this is achieved by the addition of a scalar field with a non-zero vacuum expectation value, the extra degrees of freedom introducted by this scalar field allow the electro-weak bosons to gain mass with out breaking the local gauge invariance of the Lagrangian. The method was proposed by Englert, Brout, Higgs, Guralnik, Hagen and Kibble [] but is shortened to the "Higgs" mechanism and the resulting mediator is known as the Higgs boson (H).

The S.M matter particles have spin (1/2) and obey Fermi-Dirac statistics, they exist in three families of quark and lepton doublets. The force carrying particles have spin (1) except for the H which is predicted to have spin (0), the bosons obey Bose-Einstein statistics. Figure 2.1 shows the hierarchy of the standard model particles and the couplings between them.

DRAFT

Figure 2.1: caption

2.1.1 Gauge Invariance

The example of adding a local gauge term to the free Dirac Lagrangian is chosen to show the effects of requiring a system to be invariant under local gauge transform. It is to be noted that natural units are used throughout ($c = \hbar = 1$). The free Dirac Lagrangian is written as

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi, \tag{2.1}$$

under a simple global phase transform $\psi \to e^{i\theta}\psi$ and $\bar{\psi} \to e^{-i\theta}\bar{\psi}$ the exponents cancel and we are left with an invariant system. However if $\theta \to \theta(x)$ there is a θ dependant term introduced when evaluating the derivative which destroys the invariance of the system:

$$\partial_{\mu}\left(e^{i\theta}\psi\right) = i\left(\partial_{\mu}\theta\right)e^{i\theta}\psi + e^{i\theta}\partial_{\mu}\psi. \tag{2.2}$$

This infers that an extra term is added to the Lagrangian, i.e

$$\mathcal{L} \to \mathcal{L} - \left(\partial_{\mu}\theta\right)\bar{\psi}\gamma^{\mu}\psi \tag{2.3}$$

for convenience we set $\lambda(x) = -\frac{\theta(x)}{q}$ where q is the charge/coupling of the particle we can re-express the Lagrangian as

$$\mathcal{L} \to \mathcal{L} + \left(q\bar{\psi}\gamma^{\mu}\psi\right)\partial_{\mu}\lambda(x) \tag{2.4}$$

DRAFT

when demanding that the entire Lagrangian is invariant under local transform one must add a term to cancel the additional term in Equation (2.4), we take

$$L = i \quad @ \quad m \qquad q \qquad A \tag{2.5}$$

where A is some new field which transforms as

$$A \;!\; A + @ \;(x) \tag{2.6}$$

This property of A means that the Lagrangian is now invariant to the additions of a local phase or gauge. However L must include a term for the free field A

$$L = \frac{1}{16} F \quad F \quad + \frac{1}{8} m_A^2 A \quad A \tag{2.7}$$

for the Lagrangian to remain invariant m_A must equal zero. Hence requiring that the Dirac Lagrangian be invariant under local phase or gauge transform requires the addition of a massless vector field A giving the full Lagrangian as

$$L = i \quad @ \quad m \qquad \frac{1}{16} F \quad F \qquad q \qquad A \;: \tag{2.8}$$

Equation (2.6) shows the choice of gauge, in this case the electro-magnetic potential does not change the system. This additon of a local phase invariance to the free Dirac Lagrangian generates all electro dynamics.

The difference between the addition of a global phase and a local phase arrises from the calculation of the derivatives of the fields

$$@ \quad ! \quad e^{\,iq \;(x)} [@ \quad iq\,(@ \;(x))] \tag{2.9}$$

here rather than picking up a phase factor we pick up a term involving $@ \;(x)$, this can be removed by replacing $@$ in the full Lagrangian by the covariant derivative

$$D \quad @ + iqA \tag{2.10}$$

this replacement cancels the extra term in Equation (2.9). This substitution of D is an elegant method for promoting a globally invariant Lagrangian to a locally invariant one.

DRAFT

also serves to increase the precision of the measurement of the Level-1 missing energy trigger as the muons are not seen by the calorimeter system the $\not{E}_{\mathrm{T}}$ sample is enriched.

Figure 4.6: Comparison of the performance of L1_SingleJet16, L1_SingleJet36 and L1_SingleJet92, when using the piecewise cubic corrections and using the new correction scheme. The difference in performance of the two is negligible above 36GeV.

Figure 4.6 shows the performance of the piecewise cubic corrections (PWC) and the performance of the new corrections. The data was taken with the PWC enabled in the GCT hardware. The updated corrections were emulated in the bitwise reproduction of the GCT. The made an event by event comparison possible. At low E_{T} the new corrections turn on before the PWC corrections, if the new corrections were applied on with no change to the trigger menu, the Level-1 trigger rate would rise. At a threshold of 36 GeV and higher the performance of the two correction schemes is very similar. Due to the small change in observed performance and the ability to correct raw energies above 130 GeV, the new corrections were deployed online at the start of Run2011B and are still online at the end of data taking in 2012.

The performance of the updated corrections was then measured with data taken with the corrections applied in the GCT hardware. The reference sample was taken with the `HLT_IsoMu24_v*` high level muon trigger. The performance of three example triggers is show in Figure 4.7. The data collected and represented in Figure 4.7 has a peak mean pile up ($< PU >$) of 16 interactions, this is higher than the $< PU >$ of approximately 8-10

Figure 4.7: Performance measurements of L1_SingleJet16, L1_SingleJet36 and L1_SingleJet92, when using the new correction scheme deployed in the GCT hardware. The performance is slightly worse than that of the emulated triggers due to a change in pile up conditions between the two data taking periods.

present in Run2011A, on which the previous comparison was performed. The observed difference in the performance of the Level-1 single jet triggers as a function of pile up is a case of concern when data taking is underway at the LHC's design luminosity, where $< PU >$ is >36 at an instantaneous luminosity of $1{\times}10^{34} cm^{-27} s^{-1}$.

The instantaneous luminosity in 2012 was predicted to be $5{\times}10^{33} cm^{-27} s^{-1}$, with $< PU > \approx 32$. In order to study the effect on the trigger rate and efficiency a high pile up, low instantaneous luminosity, LHC fill was taken in 2011.

The Level-1 single jet performance was studied in this run in terms of two offline object definitions. The first was the standard anti-$k_t(0.5)$ calorimeter jet reconstruction, the second was a set of anti-$k_t(0.5)$ calorimeter jets which were corrected for pile up using the fastjet correction algorithm, which is further detailed in Section 6.2.1. The fast-jet corrections remove the energy deposited by the secondary interactions from the objects which are expected to come from the primary hard interaction, thus removing energy from the offline jets. The effect of these pile up corrections on the Level-1 trigger performance is first studied under conditions with $< PU >$ of 16, the performance of which has already been measured with respect to non pile up corrected offline objects, as a sanity check. The results are shown in Figure 4.8 , the performance is measured with respect

to `HLT_IsoMu24_v*`, in terms of both pile up corrected and standard offline objects. As expected the performance in the two cases is very similar. The same comparison is shown for H_{T} in Figure 4.9, where the effect of the fastjet corrections is more pronounced due to the sum over jets. The difference between the turn on points for the two offline quantities is on the order of 10 GeV under low pile up conditions.

Due to the high pile up fill being a specialised fill with low instantaneous luminosity, the high level trigger paths were disabled, instead Level-1 trigger pass though paths were utilised to take the data. The Level-1 single muon pass though trigger is used to collect the reference sample. Otherwise the same analysis method is common between the two data sets. Figure 4.10 shows the difference in turn on for three example Level-1 single jet triggers when using standard calorimeter jets and fastjet corrected calorimeter jets. In the high pile up conditions the switch to offline jets that are corrected for pile up shifts the turn on point to lower vales of E_{T}, the magnitude of this effect reduces as the Level-1 trigger trigger threshold raises. This implies that the same offline performance as seen in the low pile up conditions can be achieved by using the pile up corrected offline objects and raising the Level-1 single jet trigger thresholds.

Figure 4.11 shows the same high pile up comparison, but for the Level-1 H_{T} triggers. Due to the size of the sample the precision of this measurement is low. However the same trend of a shift to lower H_{T} values of the turn on point of the Level-1 triggers when using pile up corrected offline objects is observed. This again implies that the Level-1 H_{T} trigger thresholds can be raised whilst preserving the same offline performance as during the low pile up conditions.

DRAFT

Figure 4.8: Comparison of the performance of L1_SingleJet16, L1_SingleJet36 and L1_SingleJet92 triggers. Where $< PU > = 16$. For two offline reconstruction methods, standard anti-k$_t$(0.5) calorimeter jets and pile up corrected anti-k$_t$(0.5) calorimeter jets.

Figure 4.9: Comparison of the performance of L1_HTT75, L1_HTT100 and L1_HTT150 triggers. Where $< PU > = 16$. For two offline reconstruction methods, standard anti-k$_t$(0.5) calorimeter jets and pile up corrected anti-k$_t$(0.5) calorimeter jets.

Figure 4.10: Comparison of the performance of L1_SingleJet16, L1_SingleJet36 and L1_SingleJet92 triggers. Where $< PU > = 36$. For two offline reconstruction methods, standard anti-k$_t$(0.5) calorimeter jets and pile up corrected anti-k$_t$(0.5) calorimeter jets.

Figure 4.11: Comparison of the performance of L1_HTT75, L1_HTT100 and L1_HTT150 triggers. Where $< PU > = 36$. For two offline reconstruction methods, standard anti-k$_t$(0.5) calorimeter jets and pile up corrected anti-k$_t$(0.5) calorimeter jets.

4.3 Level-1 Trigger Pile-up Mitigation

Whilst we have seen that the offline performance of the Level-1 hadronic triggers can be maintained when raising the trigger thresholds to deal with increased rate, when switching to pile up corrected offline objects. Figure 4.14 shows the trigger cross section as a function of instantaneous luminosity for the `L1_HTT150` trigger, which requires $H_{\mathrm{T}} >$ 150 GeV. However beyond a certain point raising thresholds causes a loss of performance. In this section we look at a method to reduce the effects of pile up hadronic Level-1 triggers, by making an addition to the Level-1 jet finding algorithm.

In Section 4.1 the Level-1 jet clustering algorithm was described. The proposed change was to add a requirement that the seeding region has a direct energy threshold, in addition to the equality relations that are set up. The effects of applying a 2 GeV or a 5 GeV threshold are studied. This threshold is on the raw, uncorrected energy of the trigger towers and effects all Level-1 jets. The impact will be seen in the Level-1 jet triggers which use corrected energy and Level-1 H_{T} and $\not{H}_{\mathrm{T}}$ which are formed from uncorrected jets. The aim is to remove the events which are accepted due to pile up, but not to remove physics events.

The triggers most effected by this change are the energy sum triggers as they sum many jets of low threshold, where as the single object triggers are already cutting on high E_{T} objects.

Figure 4.12(a) shows the internal GCT uncorrected jet energy spectrum in high pile up conditions, taken with the `L1_SingleMu` pass though triggers. The three histograms are for; no application of jet seed threshold in black, where there are many low E_{T} jets; In red a 2 GeV seed requirement is made, the effect is to cut out all jets below 2 GeV and cut out jets with an energy up to approximately 35 GeV of uncorrected energy; The blue histogram shows the jet energy spectrum after applying a 5 GeV seed threshold, the effect is to remove all jets below 5 GeV and to cut out jets with energy up to 55 GeV. Figure 4.12(b) shows the efficiency with respect to the no seed sample for the two test seed thresholds. The removal of jets in the low energy region of the E_{T} spectrum is where the advantage of applying a seed threshold is seen over simply raising the trigger thresholds, or raising the threshold of jets to be included in the Level-1 H_{T} or $\not{H}_{\mathrm{T}}$ calculation.

To quantify the effects of the addition of the jet seed a low pile up sample, where the effects are expected to be small, is studied in terms of rate reduction and efficiency change. The dedicated high pile up fill is then studied in terms of rate reduction, due to

DRAFT

(a) GCT internal uncorrected jet E_T distributions for the same events with a 0, 2 or 5 GeV seed requirement.

(b) Efficiency of applying a requirement of 2 or 5 GeV with respect to no requirement.

Figure 4.12: Effect of requiring a jet seed threshold on GCT internal jets.

the limited sample size of the high pile up fill the change in efficiency on this sample is not studied. However due to the addition of energy from the secondary pile up interactions the change in efficiency in the low pile up sample is the worse case scenario.

Table 4.1 details the rate reduction with respect to the 0 GeV seed threshold for seed thresholds of 2 GeV and 5 GeV for three example triggers, these are:

- `L1_SingleJet50`, which requires at least one jet with $E_T > 50$ GeV with in $|\eta| < 3.0$;
- `L1_QuadJet38`, which requires 4 jets with $E_T > 38$ GeV with in $|\eta| < 3.0$;
- `L1_HTT100`, which requires that Level-1 $H_T > 100$ GeV.

The rate of `L1_SingleJet50` is not effected by the requirement of a 2 GeV seed threshold and is reduced by 15% when a 5 GeV seed requirement is made. The `L1_QuadJet38` trigger rate is reduced by the same amount as the single jet trigger, under low pile up conditions for both seed thresholds. `L1_HTT100` sees a 2% rate reduction when requiring a 2 GeV seed threshold and a 3% reduction in rate when requiring a 5 GeV seed.

Table 4.2 shows the rate reduction under high pile up conditions with respect to the 0 GeV seed threshold requirement, for the same three example triggers as in the low pile up case. The rate of `L1_SingleJet50` is not reduced when making a 2 GeV seed requirement, when making a 5 GeV seed requirement the single jet 50 GeV rate is reduced by 30%. The rate of `L1_QuadJet38` is reduced by 30% when requiring a 2 GeV

DRAFT

Table 4.1: Summary of rate reduction during low pile up conditions.

Trigger	% rate reduction with a 2GeVrequirement	% rate reduction with a 5GeVrequirement
L1_HTT100	$3 \pm 11\%$	$3 \pm 11\%$
L1_QuadJet38	$0 \pm 0\%$	$15 + 6 - 8\%$
L1_Jet50	$0 + 0 - 12\%$	$15 + 9 - 15\%$

Table 4.2: Summary of rate reduction during high pile up conditions.

Trigger	% rate reduction with a 2GeVrequirement	% rate reduction with a 5GeVrequirement
L1_HTT100	$40 \pm 5.7\%$	$99 + / - 50\%$
L1_QuadJet38	$30 \pm 20\%$	$40 + 22 - 24\%$
L1_Jet50	$0 + 7 - 0\%$	$30 + 10 - 12\%$

seed and by 40% when requiring a 5 GeV seed. The rate of `L1_HTT100` is reduced by 40% when requiring a 2 GeV seed threshold and when requiring a 5 GeV seed threshold the rate is reduced by $\approx 99\%$, however the statistical error on this prediction is large.

4.3.1 Effect on trigger efficiency

Section 4.3 shows that requiring a jet seed threshold substantially reduces the trigger acceptance rate at in high pile up conditions.

However the aim of requiring a jet seed is to reduce rate, but not at the cost of physics. In this section we look at the effects of requiring a seed threshold, whilst requiring some loose, generic offline selection on the hadronic objects.

The change in efficiency is measured under low pile up conditions where the least extra energy added to the event. This gives a worse case estimate of the effect of requiring a jet seed on the offline efficiency.

Each offline reconstructed calorimeter jet must adhere to the following quality criteria:

- Pass loose calorimeter ID;
- $p_{\mathrm{T}} \geq 30$ GeV;
- $|\eta| \leq 3.0$;

DRAFT

- Matched to a Level-1 jet with $\Delta R \leq 0.5$.

Where loose calorimeter ID is defined as; Electro-Magnetic fraction > 0.01, fraction of energy in the Hybrid Photo Diodes < 0.98 and the number of n90hits > 1.

Figure 4.13: Efficiency reductions for various Level-1 algorithms when applying a 2 or 5 GeV seed tower requirement, in low pile up conditions. Figure (a) shows the efficiency reduction for H_{T} triggers at low pile up in cut steps of 25 GeV. Figure (b) shows the efficiency reduction for jets with in $|\eta| < 3.$ and $p_{\mathrm{T}} > 50$GeV. Figure (c) show the efficiency reduction for a quad jet trigger, with jet $|\eta| < 3.$ and $p_{\mathrm{T}} > 38$GeV.

Efficiency of H_{T} Triggers Figure 4.13(a) shows the acceptance reduction after applying the two jet seed thresholds. The distribution is the cumulative number of events passing a cut of $L1HT^{cut}$ in bins of 25 GeV. Due to H_{T} being the scalar sum of the jet p_{T}'s in the event the value of Level-1 H_{T} is reduced as jets are removed from the calculation. To preserve efficiency the Level-1 trigger threshold will have to be reduced. When comparing to the high pile up rate reduction in table 4.2 it is shown that the trigger

DRAFT

rate can be reduced by $\approx 20\%$ when requiring a 2 GeV seed threshold and reduced by $\geq 99\%$ when requiring a 5 GeV seed threshold, for a trigger threshold of 100 100 GeV.

Efficiency of Jet Triggers Figure 4.13(b) shows the change in acceptance of jets in low pile up conditions when the two seed thresholds are required. The effect is on the order of a few percent for each of the thresholds. Requiring a 2 GeV seed reduces the efficiency for jets above 50 GeV by $\approx 2.5\%$, whilst requiring a 5GeVseed reduces the efficiency of the same jets by $\approx 4\%$.

Efficiency of MultiJet Triggers Figure 4.13(c) shows that the effect of requiring a seed threshold of 2 GeV has no effect on the efficiency of the quad jet 38 GeV trigger and requiring a seed threshold of 5 GeV reduces the efficiency of the quad jet 38 trigger by 8%. The change in rate is dramatic in high pile up conditions where for a 2 GeV seed threshold the rate is reduced by $\approx 30\%$ and by $\approx 40\%$ when requiring a 5 GeV seed. However it is to be noted that the sample where this measurement has been made is of limited size, inferring a reasonably large statistical uncertainty.

4.3.2 Summary

The effects of requiring a jet seed have been studied using the Level-1 trigger emulator on high and low pile-up samples. The studies show that requiring a jet seed of 5GeVgreatly reduces the rate of the H_{T} and Multi Jet triggers in high pile up conditions, whilst not adversely effecting the data taking efficiency of these triggers.

The cross section of L1_HTT150 has been measured with and with out the addition of a jet seed threshold of 5 GeV as shown in Figure 4.14. Ideally the trigger cross section would be independent of the instantaneous luminosity and pile up, Figure 4.14 shows that the addition of a 5 GeV seed threshold reduces the dependance on instantaneous luminosity of the trigger cross section.

DRAFT

Figure 4.14: Trigger cross section as a function of number of pile up interactions. Showing that applying a 5 GeV jet seed threshold dramatically reduces the dependance of cross section on the instantaneous luminosity.

DRAFT

Chapter 5

Motivating the α_T Analysis

5.1 The Problem

If Supersymmetry or some other beyond the S.M theory is to provide a yet undiscovered dark matter candidate the Lightest SUSY Particle (LSP), it is predicted that this candidate will interact via the weak nuclear force only. This gives a decay topology involving missing energy in the form of the dark matter particle escaping the detector. Due to the nature of interactions at the L.H.C, these particles would be produced at the end of a decay chain of heavy particles that interact strongly, giving a final topology involving hadronic objects which are classified as jets for the purpose of analysis and missing energy. There are several S.M processes that mimic this final state.

By far the largest of these backgrounds comes from QCD multi jet events where fake missing energy is introduced either from failures in reconstruction, or stochastic fluctuations in the calorimeter systems.

expand on this - E /sqrt E has non gaussian tails. Figures of jets falling below threshold, missed jets etc. probably from some jet-met paper.

However due to the theoretical errors on the QCD production cross section predicting the number QCD background events from Montecarlo simulation is not possible. A secondary QCD background also exists, where due to the requirement of a jet E_{T} threshold, multiple jets fall under threshold by a few GeV, this causes a balanced event to look unbalanced as the jets under threshold are no longer considered. It is these sources of QCD background that α_T is designed to remove.

DRAFT

The second major background comes from S.M electro-weak decays and is irreducible as the final states involve real missing energy, from neutrinos. The electro-weak decays that form the back ground are W $\rightarrow \tau\nu$ + Jets, where the τ is reconstructed as a jet, or the lepton fails the identification required for the dedicated lepton vetoes, Z $\rightarrow \nu\overline{\nu}$ + Jets is completely irreducible. These are generally di-jet topologies. At higher jet multiplicities top quark production followed by semi-leptonic top decay accounts of the largest background. These backgrounds are predicted using a well understood control sample this is fully explained in Section 7.1.

The final background source is that introduced by detector failure or electronic noise induced by the movement of the L.H.C proton beam. Approximately 1% of the ECAL read out is not available in offline event reconstruction, this provides a source of fake missing energy.

DRAFT

Chapter 6

Reconstruction and Event selection

In this chapter the event reconstruction and selection are defined, the search variable α_T is constructed both as an offline discriminator and as an analysis specific trigger, the performance of this trigger under different data taking conditions is measured with respect to the final event selection.

The first performance measurement is performed on the full 5 fb^{-1} of 7 TeV data collected in 2011, this data set is then used for the full analysis presented in this thesis. The performance of a suite of upgraded α_T triggers is then measured on 11 fb^{-1} of 8 TeV data which was collected during the 2012 L.H.C run. These performance measurements were used in the analysis presented in

ref latest paper.

6.1 The α_T variable.

α_T is inspired by Ref [38] and was expanded to transverse multi jet topologies by members of the CMS collaboration in Refs [22, 23]. The purpose is to provide a variable that can be cut on to eliminate QCD from the final selection. To do this the inherent balance of the QCD system is exploited.

For di-jet systems α_T is defined as:

$$\alpha_T = \frac{E_T^{j_2}}{M_T} \tag{6.1}$$

DRAFT

where $E_T^{j_2}$ is the transverse energy of least energetic of the two jets and M_T is defined as:

$$M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2} \tag{6.2}$$

For a perfectly measured di-jet system with $E_T^{j_1} = E_T^{j_2}$, where the jets are opposite in ϕ $\alpha_T = 0.5$, for events with back to back jets where one is miss-measured $\alpha_T < 0.5$. However the majority of signals predict many jets in the final state. α_T can be generalised to work with n-jets in the flowing way. The variables H_T, $\not{H}_\mathrm{T}$ and ΔH_T are constructed,

$$H_\mathrm{T} = \sum_{i=0}^{n\ jets} E_T^{jet_i}, \tag{6.3}$$

$$\not{H}_\mathrm{T} = \left|\sum_{i=0}^{n\ jets} \vec{p}_T^{jet_i}\right|, \tag{6.4}$$

for jets above some predefined threshold E_T which is common for all jet based quantities. The multi jet system is reduced to a pseudo di-jet system by forming two large jets. The individual jet E_T's are summed, with the final configuration being chosen to have the minimum difference in energy (ΔH_T) between the pseudo jets. This simple clustering criteria provides the best separation between miss-measured events and those with real $\not{E}_\mathrm{T}$.

α_T is then defined as:

$$\alpha_T = \frac{H_\mathrm{T} - \Delta H_\mathrm{T}}{2\sqrt{H_\mathrm{T}^2 - \not{H}_\mathrm{T}^2}} \tag{6.5}$$

Figure 6.1 shows the α_T distribution for both data and simulated background samples. The QCD multi jet background is negligible above an α_T value of 0.55, where as the standard model processes which involve real $\not{E}_\mathrm{T}$ exist at all possible values of α_T. Values of α_T in the range $0.5 < \alpha_T < 0.55$ arise in multi jet QCD due to jets falling below threshold or large stochastic fluctuations. It is to be noted that the discrepancy between data and simulation for $\alpha_T \leq 0.55$ is due to no trigger emulation being applied to the simulated background samples.

DRAFT

Figure 6.1: α_T distribution for background and data for the region $H_{\mathrm{T}} > 375$ GeV. Trigger emulation is not applied in the simulated background which leads to the discrepancy in the region $\alpha_T \leq 0.55$. The QCD multi-jet background is reduced to less than one event.

6.2 Event selection

In order to select events for the hadronic signal sample and the muon and photon control samples a common set of section cuts is defined. In this section the objects are defined as are the flow of the analysis cuts and filters.

6.2.1 Preselection of hadronic objects

Hadronic showers are clustered in to objects which from now on will be referred to as jets. These jets are formed from the energy deposits recored in the calorimeter towers. Individual jets are clustered using the anti-k$_t$(0.5) algorithm[17], for high p_{T} jets this produces cone like jets, for low p_{T} jets deviations from the circular geometry are allowed, as show in Figure 6.2. C.M.S uses two complimentary reconstruction methods for creating jets, the first uses only calorimeter information, these jets are referred to as anti-k$_t$(0.5)-Calorimeter jets, the second method adds information from the tracking system to improve the energy resolution and is not used in this analysis due to the

DRAFT

requirements of using the same objects at both trigger level and offline to preserve data taking efficiency.

Figure 6.2: Simulated hadronic objects clustered in to Jets using the anti-k$_t$(0.5) jet clustering algorithm, note the high p_{T} green object which causes the low p_{T} jet in close proximity to be cut off.

The jets have their raw energies corrected based on their position and momentum to establish a uniform relative response in η and a calibrated absolute response in transverse energy E_{T}, with an associated uncertainty of between 2% and 4% dependant on E_{T} and η[18]. Figure 6.3 shows the absolute jet energy scale uncertainty as a function of the jet's p_{T} for the jets considered in this analysis.

Figure 6.3: Absolute jet energy scale uncertainty as a function of jet p_{T} for anti-k$_t$(0.5)-Calorimeter jets[30].

DRAFT

It is also possible to correct the raw energies of the jets for pile up. Pile up causes energy from secondary interactions to be added to the event, for soft pile up interactions this energy is distributed uniformly though out the detector. Two forms of pile up corrections are used in C.M.S to correct the energies of calorimeter jets. The first is an offset correction, the raw energy has a constant energy removed though out the detector based on the number of primary vertices in the event. The second method is to calculate per event the average energy deposited in each calorimeter tower using the `FastJet`[2, 3] jet clustering package, this quantity is referred to as ρ and is also used to correct the isolation variables for elections, muons and photons.

The jets considered in the analysis are not corrected for pile up, each jet is required to have $E_{\mathrm{T}} > 50$ GeV, the highest E_{T} jet in the events is required to be within tracker acceptance ($|\eta| < 2.5$) and the sub leading jet is required to have $E_{\mathrm{T}} > 100$ GeV. In the lowest two offline H_{T} bins the jet thresholds are scaled to preserve the jet multiplicity, for the bin 275 GeV $< H_{\mathrm{T}} <$ 325 GeV, the jet threshold is $36.\dot{6}$ GeV and the sub leading jet threshold is $73.\dot{3}$ GeV. In the bin 325 GeV $< H_{\mathrm{T}} <$ 375 GeV, the jet threshold is $43.\dot{3}$ GeV and the sub leading jet threshold is $86.\dot{6}$ GeV.

The quantities H_{T} and $\not{H}_{\mathrm{T}}$ are then formed from these jets.

6.2.2 Electrons

Two complementary algorithms are used at the track seeding stage of the electron reconstruction. Tracker driven seeding which is more suitable for low p_{T} ($p_{\mathrm{T}} < 5$ GeV) electrons and ECAL driven seeding, which starts at the ECAL and works back towards the interaction point. The ECAL driven seeding starts by creating superclusters[28] which contain information on the lateral shower shape in the η direction of the electron or photon shower and the spread of energy deposits in the ϕ plane for elections, due to the radiation of photons by the election in the C.M.S magnetic field. Track seeds from inner tracking layers and electron track are then build from these track seeds. The trajectories are reconstructed using a dedicated modelling of the electron energy loss and fitted with a Gaussian Sum Filter[9]. For the purpose of the analysis an object is defined as an electron if it has $p_{\mathrm{T}} > 10$ GeV, $|\eta| < 2.5$ and passes "VBTF" working point 95 quality criteria[24]. Any event containing an identified electron is vetoed.

DRAFT

6.2.3 Muons

Muon reconstruction at C.M.S is designed to be regional meaning that the full reconstruction sequence can be run at both the HLT and offline. Regional reconstruction only performs the reconstruction in a small part of the detector meaning that the time taken is short. As an example the amount of information required to reconstruct a muon in the silicon tracker is less than one percent of the entire tracker read out. The regions which are reconstructed at the HLT are seeded by the muon candidates produced by the Level-1 trigger even if these muons did not cause the issue of the Level-1 accept. Global muon reconstruction uses information from both the stand alone muon system and from the silicon tracker and performs a fit to the individual detector hits. Figure 6.4 shows the muon p_{T} resolution for muons reconstructed using either the muon system only, the tracker only or the global muon reconstruction.

Figure 6.4: Resolution of (1/p) versus p for standalone, global and tracker-only reconstruction. a) Barrel, $\eta = 0.5$; b) Endcap, $\eta = 1.5$.[28]

Signal events are vetoed if they contain a muon with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.5$ that passes the "VBTF" working point 95 for muons [26]. Two separate muon control samples

are defined, one requiring exactly one muon with $p_{\mathrm{T}} > 10$ GeV, the second requiring two muons, who's invariant mass sums to the Z mass.

6.2.4 Photons

Photons are reconstructed in the ECAL using the same methods as used to reconstruct elections. However an anti selection is performed on the tracking requirements. For photons which do not convert in the tracker a supercluster energy deposit is required with no associated electron track, for photons which undergo pair production in the tracker material the tracks associated to the super clusters do not originate from the interaction vertex, instead they appear in a layer of the tracker. For unconverted photons the ratio of the energy deposited in the central ECAL crystal to the energy of the surrounding 3×3 group of ECAL crystals is used as an identification variable. Signal events are vetoed if they contain a photon with $E_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$ and that passes ID requirements[25]. A requirement of exactly one photon with $E_{\mathrm{T}} > 150$ GeV with in $|\eta| < 1.45$ is made for the photon control sample.

6.3 Common Analysis cuts

- **Good run selection**, All detector subsystems on, C.M.S in "Physics Declared" mode and all physics object groups have certified the runs and luminosity sections. This removes any events where the sub-detectors were in an error state or events from before the tracker was switched to high voltage mode.
- **P.K.A.M (Previously Known As Monsters) filter**, these events are caused by beam-gas interactions close to C.M.S, which cause a shower of particles to enter the pixel detector along the beam line, resulting in a large proportion of the pixel detector to record hits.
- **Vertex Selection** requires at least one non-fake vertex with at least four associated tracks, within a cylinder of radius 2 cm and length 48 cm, centred at Z = 0 of the C.M.S detector.
- **Hadronic barrel and end-cap noise filter**, this filter removes events where strips of towers in the hadronic calorimeters record energy from electrical noise, mimicking large, unbalanced energy deposits.

DRAFT

- **Vertex $\boldsymbol{p_{\mathrm{T}}/H_{\mathrm{T}} > 0.1}$**, removes events where the sum of the p_{T} of all tracks from all good vertices is less than 10% of the energy deposited by jets in the calorimeters. This cut is designed to remove events with tracking failure, which would otherwise pass the calorimeter only event quality requirements.

- **Masked ECAL channel filter:** Approximately 1% of the ECAL crystals are masked, or have read out failure. To avoid selecting events with large energy miss measurement, a topological cut was devised. The first step is to calculate $\Delta\phi^*$ for each jet ($\vec{j}$) in the event, where:

$$\Delta\phi^* = \Delta\phi\left(\vec{\not{E}}_T + \vec{j}, \vec{j}\right). \tag{6.6}$$

  Which gives a measure of the miss measurement of a jet, if $\Delta\phi^*$ is small, the missing energy points along the jet in the ϕ direction. By selecting the miss measured jet, full position information is preserved. If any jet has $\Delta\phi^* < 0.5$, the number of masked ECAL crystals with in ΔR <0.3 are summed, if there are more than 10 masked crystals adjacent to the jet, the event is vetoed.

- **$\boldsymbol{R_{miss} < 1.25}$:** The total hadronic energy in an event is required to be greater than 275 GeV which is well above the transverse energy threshold of 50 GeV for each jet. However several jets falling below this threshold can sum to a significant quantity of ignored energy. This is shown in Figure 6.5, here the missing energy calculated from jets in the range 10 GeV $< E_{\mathrm{T}} <$ 50 GeV is shown, whilst requiring that $\not{E}_{\mathrm{T}}$ $<$ 20 GeV. This shows that for a well balanced event the jets below threshold can carry greater than 100 GeV of ignored energy. R_{miss} is defined as $\not{H}_{\mathrm{T}}/\not{E}_{\mathrm{T}}$ and can be used to single out events where the inclusion of lower momentum jets does significantly improve the balance of the event. Figure 6.6 shows for two H_{T} regions the R_{miss} distribution after the application of the full cut flow, including α_T, QCD contamination is visible in the signal sample for $\mathrm{R}_{miss} > 1.25$.

This cut flow and set of object definitions define the common selection, on top of this an α_T cut is applied, the passing events are then binned in 8 H_{T} bins, these are 275 GeV - 325 GeV, 325 GeV - 375 GeV, 375 GeV - 475 GeV, 475 GeV - 575 GeV, 575 GeV - 675 GeV, 675 GeV - 775 GeV, 875 GeV - 7 TeV. However the raw number of events in the signal region is meaningless with out an accurate back ground prediction, as discussed earlier taking the background estimation from simulation is not viable due to the requirement of high order theory calculations on the cross sections of S.M processes involving jets, these have many divergencies due to the nature of QCD. Instead the

DRAFT

Figure 6.5: $\not{H}_{\mathrm{T}}$ from jets with 10 GeV $< E_{\mathrm{T}} <$ 50 GeV in events with $H_{\mathrm{T}} >$ 350 GeV and $\not{E}_{\mathrm{T}} <$ 20 GeV in 35 pb^{-1} of data.

(a) (b)

Figure 6.6: (a) R$_{miss}$ distribution for events in the 250 GeV $<H_{\mathrm{T}}<$350 GeV region, where due to the low H_{T} requirement QCD contamination is enriched.
(b) R$_{miss}$ distribution for events in the $H_{\mathrm{T}}>$350 GeV region, QCD contamination occurs at R$_{miss} >$ 1.25.

simulation is used to form a translation factor between two samples measured in data, a control sample which closely mimics the S.M processes producing missing energy, but has a visible muon or photon in the final state. The background estimation methods are described and the background predictions stated in Section 7.1. The next section describes the triggers used to collect the data samples

6.4 High Level triggers for the α_T analysis

The CMS trigger system has been discussed in detail in Section 3.7 and Chapter 4, however details of analysis specific trigger paths were not discussed. During 2011 the first α_T specific trigger was designed and deployed online. The trigger was then upgraded for the higher luminosity and energy conditions of the 2012 data taking period.

The trigger takes advantage of cutting on two variables, H_{T} and α_T at low H_{T} a high α_T value cuts the trigger rate, where as at high H_{T} where the trigger rate is lower the α_T requirement can be loosened.

Due to the scaling of jet thresholds in the lowest offline H_{T} bins as detailed in Section 6.2 using a fixed jet threshold would cause inefficiency in the lowest offline H_{T} bins. To over come this the trigger level α_T calculation is performed iteratively for all jets above a predefined threshold. This raises the total number of accepted events whilst adding the benefit of being efficient for any offline jet threshold above the minimum trigger jet threshold.

Due to concerns on the time taken to perform the ΔH_{T} minimisation at the trigger and time constraints enforced on trigger menu development, the first implementation calculates α_T for the first 3 jets. For higher jet multiplicities the variable β_T is calculated.

$$\beta_T = \frac{H_{\mathrm{T}}}{2\sqrt{H_{\mathrm{T}}^2 - \not{H}_{\mathrm{T}}^2}} \tag{6.7}$$

this gives us the relation:

$$\alpha_T \leq \beta_T. \tag{6.8}$$

The decision flow is shown in Figure 6.7 and explained in detail below.

DRAFT

When a level one accept is issued the trigger bits that fired are checked, if the event fires a L1 muon trigger it is passed to the HLT muon triggers where only muon reconstruction is performed, reducing the reconstruction time. The α_T triggers are seeded on the lowest threshold unprescaled L1 H_{T} trigger, during 2011 this was L1_HTT100. Any events issuing a L1 accept and passing L1_HTT100 undergo calorimeter jet reconstruction, the reconstruction algorithm is detailed in Section 6.2.1.

Once the jets have been formed the trigger filter is entered. Initially the first two jets ranked by E_{T}, are considered, H_{T} and α_T are calculated, if both pass the trigger thresholds the event is accepted and the full detector read out is performed. If either H_{T} or α_T is below threshold, the next jet in E_{T} order is added, if the jet collection contains more than 3 jets then the β_T approximation is used. All jets in the event are added until either the event is accepted, or there are no more jets to be added above 40 GeV.

The effect of switching to the β_T approximation is to accept events that have missing energy due to miss-measurement, when calculating α_T offline these events have values of $\alpha_T < 0.5$. This introduces an impurity to the trigger and costs rate for events that will not be considered in the offline analysis.

6.4.1 Trigger efficiency measurement

The performance of the α_T trigger suit is measured with respect to a sample collected using the muon system. This allows the measurement of efficiency of both the level one seed trigger and the higher level trigger at the same time as different sub-systems are used to collect the reference and the signal triggers. This is due to the exclusive use of calorimeter jets in the α_T trigger, if more complicated reconstruction methods which produce an event hypothesis were used, muons would at HLT level only be considered as jets. Where as during calorimeter only reconstruction, muons are not considered and the p_{T} of any muons in an event is viewed as missing energy.

The selection for the trigger efficiency measurement is the same as listed in Section 6.2 with the requirement of exactly one well identified muon with $p_{\mathrm{T}} > 45$ GeV, the sum of the $\not{E}_{\mathrm{T}}$ in the event and the muon must add to the W mass and finally the muon must be separated by at least 0.5 in ΔR to the closest jet, to avoid the muon energy changing the energy of the jet offline when the cross cleaning is applied.

Due to the increase in luminosity over the running period the trigger thresholds were increased, to ensure constant rate though out the year and the trigger version numbers

DRAFT

were increased each time the trigger menu was updated. The list of triggers considered and their reference triggers are listed in Tables 6.1 and 6.2.

The efficiency of each trigger version is measured in the required H_{T} bins, the total efficiency for each H_{T} bin is then calculated by combining the individual efficiencies using a weighted sum based on the fraction of the total luminosity of the sample that each version carries. This accounts for the change in running conditions during the data taking period and the criteria that the trigger suite takes constant rate. The higher trigger versions and thresholds generally represent more integrated luminosity due to the evolution of running conditions with time.

The efficiency is measured as a function of the cumulative number of events, ie the efficiency at each point on the x axis is the measured efficiency if a cut were applied offline at that cut value.

As an example, the efficiency of each trigger used in the 275 GeV $< H_{\mathrm{T}} <$ 325 GeV bin is measured and then combined to give the total efficiency. The cumulative efficiency curves for each trigger seeding the lowest bin is show in Figures 6.8, 6.9 & 6.10. Note that some of the triggers are repeated, due to the reference trigger version incrementing and the signal trigger not.

These are then combined to give Figure 6.11 the efficiency at a cut of $\alpha_T > 0.55$ is 83.3% + 0.5% - 0.6%. The loss in efficiency comes from the disparity between the minimum thresholds for jets to enter the H_{T} and α_T calculations at the HLT and those used in the analysis. The trigger jet E_{T} threshold is 40 GeV where as the analysis jet E_{T} threshold in this bin is 36.$\dot{6}$ GeV. The triggers used to take data at the end of this running period also have an α_T threshold above the analysis cut of $\alpha_T > 0.55$, which again causes an inefficiency. The list of efficiencies for each H_{T} bin are shown in Table 6.3. The trigger efficiencies are measured to better than one percent and this information is used in the final likelihood model, to correct the expected numbers from simulation when calculating the translation factors.

The α_T triggers were upgraded for the increased instantaneous luminosity and pile up conditions expected during the 2012 data taking period. The first stage was to implement the full α_T calculation for each addition of a new jet, this change increases the purity of the trigger, meaning that for the same threshold the rate taken is lower than that of the

DRAFT

Offline H_{T} bin	Signal Trigger	Reference Trigger
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p53_v2	HLT_Mu15_HT200_v2
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p53_v3	HLT_Mu15_HT200_v3
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p53_v4	HLT_Mu15_HT200_v4
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p53_v5	HLT_Mu30_HT200_v1
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p55_v1	HLT_Mu5_HT200_v4
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p55_v2	HLT_Mu40_HT200_v4
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p58_v3	HLT_DoubleMu8_Mass8_HT200_v4
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p58_v3	HLT_DoubleMu8_Mass8_HT200_v5
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p60_v3	HLT_DoubleMu8_Mass8_HT200_v4
275 GeV $< H_{\mathrm{T}} <$ 325 GeV	HLT_HT250_AlphaT0p60_v3	HLT_DoubleMu8_Mass8_HT200_v5
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p52_v1	HLT_Mu5_HT200_v4
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p52_v2	HLT_Mu8_HT200_v4
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p52_v3	HLT_Mu15_HT200_v2
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p53_v3	HLT_Mu15_HT200_v3
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p53_v4	HLT_Mu15_HT200_v4
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p53_v5	HLT_Mu30_HT200_v1
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p53_v6	HLT_Mu40_HT200_v3
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p53_v6	HLT_Mu40_HT200_v4
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p54_v5	HLT_Mu40_HT300_v4
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p54_v5	HLT_Mu40_HT300_v5
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p55_v3	HLT_DoubleMu8_Mass8_HT200_v4
325 GeV $< H_{\mathrm{T}} <$ 375 GeV	HLT_HT300_AlphaT0p55_v3	HLT_DoubleMu8_Mass8_HT200_v5

Table 6.1: List of α_T triggers used in the lowest two offline H_{T} bins and the triggers used to collect the reference sample.

DRAFT

Offline H_{T} bin	Signal Trigger	Reference Trigger
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p51_v1	HLT_Mu5_HT200_v4
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p51_v2	HLT_Mu8_HT200_v4
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p51_v3	HLT_Mu15_HT200_v2
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p51_v4	HLT_Mu15_HT200_v3
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p51_v5	HLT_Mu15_HT200_v4
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p52_v1	HLT_Mu30_HT200_v1
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p52_v2	HLT_Mu40_HT200_v3
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p52_v2	HLT_Mu40_HT200_v4
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p53_v10	HLT_Mu40_HT300_v4
375 GeV $< H_{\mathrm{T}} <$ 475 GeV	HLT_HT350_AlphaT0p53_v10	HLT_Mu40_HT300_v5
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v1	HLT_Mu5_HT200_v4
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v2	HLT_Mu8_HT200_v4
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v3	HLT_Mu15_HT200_v2
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v4	HLT_Mu15_HT200_v3
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v5	HLT_Mu15_HT200_v4
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v6	HLT_Mu30_HT200_v1
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v7	HLT_Mu40_HT200_v3
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v7	HLT_Mu40_HT200_v4
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v10	HLT_Mu40_HT300_v4
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p51_v10	HLT_Mu40_HT300_v5
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p52_v5	HLT_Mu40_HT300_v4
475 GeV $< H_{\mathrm{T}} <$ 7 TeV	HLT_HT400_AlphaT0p52_v5	HLT_Mu40_HT300_v5

Table 6.2: List of α_T triggers used in the $H_{\mathrm{T}} > 375$ GeV bins and the triggers used to collect the reference sample.

H_{T} range (GeV)	Trigger efficiency (%)
275–325	$83.3^{+0.5}_{-0.6}$
325–375	$95.9^{+0.7}_{-0.9}$
375–475	$98.5^{+0.5}_{-0.9}$
475–∞	$100.0^{+0.0}_{-4.8}$

Table 6.3: Efficiencies of the α_T triggers used in the 7 TeV α_T analysis on 5 fb^{-1} of LHC data.

DRAFT

H_{T} range	Trigger
275 GeV–325 GeV	`HLT_HT250_AlphaT0p55_v*`
325 GeV–375 GeV	`HLT_HT300_AlphaT0p53_v*`
375 GeV–475 GeV	`HLT_HT350_AlphaT0p52_v*`
475 GeV–8 TeV	`HLT_HT400_AlphaT0p51_v*`

Table 6.4: Triggers used to seed the analysis H_{T} bins during 2012 data taking.

previous algorithm. This allows the thresholds to be kept low, whilst not increasing the overall trigger rate.

The second upgrade was to switch to pile up corrected jets at the HLT, this change keeps the trigger cross section liner as a function of instantaneous luminosity.

The third choice was to design a trigger suite that could run for the entire 2012 data taking period, with out changing the trigger thresholds, this was done to make the measurement of the efficiency simpler.

The trigger thresholds used are presented in Table 6.4, due to the constant thresholds in H_{T} and α_T though out the run, the versioning of the triggers is excluded from this table. The efficiency of the triggers is measured for 11.7 fb^{-1} of LHC data taken at a centre of mass energy of 8 TeV the efficiencies were measured for the analysis presented at HCP, documented in [8]. A single muon trigger is used to collect the reference sample, the threshold of this trigger was unchanged during the data taking period, the path selected is `HLT_IsoMu24_v*` which requires at least one muon with $p_{\mathrm{T}} > 24$ GeV that is not over lapping with any other object in the detector. The same method is used as for the 2011 trigger efficiency measurement. However the offline jets are corrected for pile up using the fast jet corrections, to stay inline with the HLT object definitions.

Figure 6.12 shows the efficiencies of the four individual triggers that seed the 275 GeV–325 GeV H_{T} bin for 11.7 fb^{-1} of 8 TeV LHC data, Figure 6.13 shows the combined cumulative efficiency of the 2012 trigger suite.

The two trigger suites have very similar offline performance with 100% efficiency in the analysis bins above 475 GeV and high efficiency in the lower bins. To quantify the difference in performance between the two algorithms the purity is defined as the number of events passing the trigger that pass the offline α_T requirement at the same

DRAFT

H_{T} range (GeV)	Trigger efficiency (%)
275 GeV – 325 GeV	$89.6^{+0.4}_{-0.4}$
325 GeV – 375 GeV	$98.6^{+0.2}_{-0.3}$
375 GeV – 475 GeV	$99.4^{+0.2}_{-0.3}$
475 GeV – 8 TeV	$100.0^{+0.0}_{-0.5}$

Table 6.5: Efficiencies of the α_T triggers at a centre of mass energy of 8 TeV α_T measured in 11.7 fb^{-1} of LHC data.

threshold as the trigger requirement divided by the total number of events accepted by the trigger. The purity of each trigger algorithm is measured for an example trigger with a H_{T} threshold of 350 GeV and an α_T threshold of 0.52. The 2011 trigger which only performs the full α_T calculation for jet multiplicities of less than four has a purity of 48%, which means a quarter of all rate taken by the trigger is used in the offline analysis. The 2012 trigger which performs the full α_T calculation for all jet multiplicities has a purity of 75%. This 25% increase in purity translates in to a 25% rate reduction for the same trigger threshold when changing to the full α_T calculation for all jet multiplicities, thus enabling the trigger thresholds to be kept at the same or lower thresholds in the 2012 run as in the 2011 run.

6.5 Extension to higher analysis dimensions. B-tagging

Declaration Whilst it should be noted that the author did not contribute towards the extension of the analysis to include a dimension based on the measurement of the number of jets containing b quarks in the final state, the final analysis does include this extension, hence the b-tagging procedure is explained in sufficient detail as to understand the process but not to elude to all the nuances of the method in the following section.

Jets are tagged as originating from a b decay via the identification of a displaced vertex as it takes the b a finite amount of time to decay, during this time the quark which is not produced at rest travels away from the initial interaction point, where upon decaying a secondary decay vertex is created. The algorithm used to classify these jets as containing a b quark is the Combined Secondary Vertex (C.S.V) tagger. The "Medium" working point is used in the analysis, which requires at cut of > 0.679 on the C.S.V

DRAFT

value. This results in a gluon/light quark miss tag rate of 1% where "light" quarks are u, d and s types. The efficiency for tagging b quark jets in the range $60 - 70\%$[19] is achieved, this efficiency depends on the jet p_{T}. The discriminator is supported by the C.M.S b physics object group[4] and its performance is well understood. The Montecarlo miss tag and identification rates are re-weighted to agree with data observations, thus provide an accurate background prediction for the high multiplicity b-tagged bins which are dominated by the miss tag of light quarks as b quarks.

DRAFT

Figure 6.7: Flow chart representing the steps taken to make a trigger decision using the α_T trigger algorithm.

DRAFT

(a) HLT_HT250_AlphaT0p55_v1

(b) HLT_HT250_AlphaT0p53_v2

(c) HLT_HT250_AlphaT0p53_v3

(d) HLT_HT250_AlphaT0p53_v4

Figure 6.8: Turn on curves for the individual α_T triggers used to seed the 275 GeV $< H_{\mathrm{T}} <$ 325 GeV bin.

DRAFT

(a) HLT_HT250_AlphaT0p53_v5

(b) HLT_HT250_AlphaT0p58_v3

(c) HLT_HT250_AlphaT0p58_v3

(d) HLT_HT250_AlphaT0p60_v3

Figure 6.9: Turn on curves for the individual α_T triggers used to seed the 275 GeV $< H_{\mathrm{T}} <$ 325 GeV bin.

DRAFT

(a) HLT_HT250_AlphaT0p60_v3

Figure 6.10: Turn on curves for the individual α_T triggers used to seed the 275 GeV $< H_{\mathrm{T}} <$ 325 GeV bin.

Figure 6.11: Combined cumulative efficiency for the triggers seeding the 275 GeV $< H_{\mathrm{T}} <$ 325 GeV offline analysis bin.

(a) HLT_HT250_AlphaT0p55_v1

(b) HLT_HT250_AlphaT0p55_v2

(c) HLT_HT250_AlphaT0p55_v3

(d) HLT_HT250_AlphaT0p55_v4

Figure 6.12: Turn on curves for the individual α_T triggers used to seed the 275 GeV $< H_{\mathrm{T}} <$ 325 GeV bin, during 2012 data taking.

DRAFT

Figure 6.13: Combined cumulative efficiency for the triggers seeding the 275 GeV $< H_T <$ 325 GeV offline bin for 11.7 fb^{-1} of 8 TeV LHC data.

DRAFT

Chapter 7

Background Prediction

7.1 Electro-Weak Background Prediciton

The requirement of an α_T cut on the signal sample removes multi-jet QCD events where a balanced event is counted as signal due to miss-measurements, the remaining background events in the signal region are due to electro-weak processes which produce real missing energy. Primarily these events are produced from $\mathrm{Z} \to \nu\overline{\nu}$ + Jets, $\mathrm{W} \to \ell\overline{\nu}$ + Jets and $\mathrm{t\bar{t}}$ decay, with smaller contributions from Drell-Yan + Jets, single top production in the s,t and tW channels and from di-boson + Jet events. To predict the number of these events contributing to the number of signal like events three control samples are defined and though the use of a Montecarlo derived transfer factor the control samples are used to predict the number of S.M events expected in the signal region.

Figure 7.1[6] shows the expectation from simulation in all bins of the hadronic signal region, for the different background samples and an example CMSSM reference model RM1.

Explain what RM1 is

The expected composition of the the backgrounds in the hadronic signal region, as a percentage of the total S.M background, are summarised in Table 7.1. $\mathrm{Z} \to \nu\nu$ contributes ≈43% of the S.M background in the 275 GeV–325 GeV H_T bin, raising to ≈53% in the $H_\mathrm{T} > 875$ GeV bin. Events entering the signal region due to Z or W decays where the lepton is missed by the lepton vetoes account for ≈25% at low H_T and ≈13% at high H_T. Events from hadronicly decays τ (τ_h) have a low H_T dependance, contributing ≈22% of the background at low H_T and ≈27% of the background at high H_T. Those events

DRAFT

arising from τ particles which decay leptonically (τ_l) and are missed by the lepton vetoes account for ≈10% of the S.M background.

Figure 7.1: Expectation from MC in all bins of the hadronic signal region for the following different background processes: $Z \to \nu\nu$ + jets, W + jets, $t\bar{t}$, single top + jets, di-boson production (WW/WZ/ZZ), and Drell-Yan. The total SM expectation is also shown, along with that for the CMSSM benchmark model RM1.

Table 7.1: Relative background composition as given by MC simulation in all bins of the hadronic signal region (expressed as a percentage of the total SM background).

H_T GeV	N_{events}	$Z \to \nu\nu$ + jets (%)	W + jets, $t\bar{t}$, single top, DY and di-boson			
			missed e, μ from W/Z (%)	τ_h (%)	τ_l (%)	τ_h matched to jet (%)
275–325	3938.0	43	24	22	11	7
325–375	1569.9	46	25	22	9	7
375–475	1104.2	48	20	23	10	7
475–575	396.0	48	17	24	11	10
575–675	142.4	51	17	23	10	11
675–775	55.5	44	19	31	7	17
775–875	18.7	55	17	22	4	9
875–∞	13.2	53	13	27	7	19

To calculate the bin by bin translation factors the signal selection and the individual control selections are applied to the montecarlo simulated background samples. The ratio

DRAFT

of the number of accepted events is then taken, the signal yield prediction is computed from applying the the control selections to real data and multiplying the event yield by the translation factor. The measurements form all control samples are considered simultaneously in a fit defined in Section 7.5. This method can be extended to high dimensions of analysis bins, for example in [8] a secondary dimension involving the number of B quarks in the event is studied. However the B extension is not detailed in this thesis.

$$N^{sig}_{prediction}\left(H_{\mathrm{T}}\right) = N^{control}_{obs}\left(H_{\mathrm{T}}\right) \times \frac{N^{sig}_{MC}\left(H_{\mathrm{T}}\right)}{N^{control}_{MC}\left(H_{\mathrm{T}}\right)} \tag{7.1}$$

The three control samples used are a $\mathrm{W} \rightarrow \mu\overline{\nu}$ + Jets sample, a $\mathrm{Z} \rightarrow \mu\mu$ + Jets sample and a γ + Jets sample.

The selection criteria for each of these control samples is kept as similar to the signal selection as possible, so as to not introduce systematic errors from incorrect modelling in the simulation. The use of the ratio of the number of observed events in the montecarlo cancels the systematic effects. A systematic is still assigned to each translation factor to account for theoretical uncertainties and acceptance and instrumental effects.

Additional kinematic cuts are applied in the two muon control samples to enrich the W + Jets $\mathrm{t\bar{t}}$ and Z + Jets components in the control samples. The samples are defined to maximised efficiency rather than purity, any impurities are accounted for in the transfer factors as the yields from all montecarlo samples are used. This is valid under the assumption that the S.M electro-weak and Drell-Yan processes are well modelled by the simulation. The possibility of SUSY like signal contamination in the control samples is accounted for in the final likelihood, after measuring the signal acceptance for the control samples on simulated SUSY events.

The magnitude of the systematic uncertainties on the transfer factors is motivated by a set of closure tests between the control samples. A transfer factor is produced to predict each control sample from each of the other control samples. No assumed systematic is applied in these closure tests, instead the level of agreement with in statistical uncertainty is used to set the scale of the systematic error for each H_{T} bin.

DRAFT

7.1.1 The μ + Jets control sample

The μ + Jets control sample is designed to mimic the events appearing in the signal region due to W + Jets and $t\bar{t}$ decays where the leptons are missed offline, either due to falling out of acceptance or being missed by the reconstruction algorithms. Hadronic tau decays from high p_{T} W bosons are also predicted from this sample. The additional selection criteria for this sample are designed to select events containing the decay $\mathrm{W} \to \mu\nu$ + Jets in the same kinematic conditions as those events entering the signal selection. Offline the event level discriminators, H_{T} and α_T, are calculated using only the hadronic components of the event. In order to select the W exactly one tightly identified, isolated muon with in $|\eta| < 2.5$ with $p_{\mathrm{T}} > 10$ GeV is required. The transverse mass of the muon combined with the missing energy of the event $M_T(\mu, \not{E}_{\mathrm{T}})$ is required to be larger than 30 GeV, as shown in Figure 7.2 the transverse mass cut removes a large amount of QCD whilst preserving a high efficiency W selection. Events are vetoed if for any jet $\Delta R(\mu, Jet) < 0.5$, or if a second muon candidate exists that is either loose, non-isolated or outside of acceptance if the two muons have an invariant mass with in ± 25 GeV of the Z mass, to suppress $\mathrm{Z} \to \mu\mu$ events.

Figure 7.2: Transverse mass between the selected muon and $\not{E}_{\mathrm{T}}$ in $\mathrm{W} \to \mu\nu$ events.[5].

DRAFT

7.1.2 The $\mu\mu$ + Jets control sample

The $\mu\mu$ + Jets control sample is used to measure the Z $\rightarrow \nu\nu$ + Jets irreducible background in the signal region. The process Z $\rightarrow \mu\mu$ + Jets is identical kinematically, however the acceptance and the branching ratio are both smaller the branching ratio due to the possible decay in to one of three neutrino flavour states verses the requirement of a particular lepton flavour, the acceptance difference is due to the p_{T} and identification quality requirements on the muons alter the acceptance between the two processes. The following selection criteria are applied on top of the common selection: Exactly two tightly identified, isolated muons, with in $|\eta| < 2.5$ with $p_{\mathrm{T}} > 10$ GeV are required; The invariant mass of the di-muon pair is required to be with in ± 25 GeV of the Z mass; Events are vetoed if for any muon and jet combination $\Delta R(\mu, Jet) < 0.5$. As in the single muon control sample all event level quantities are calculated from the hadronic objects alone. This control sample can be used in all of the offline H_{T} bins.

7.1.3 The γ + Jets control sample

The γ + Jets control sample can also be used to measure the Z $\rightarrow \nu\nu$ + Jets background as the γ + Jets process is kinematically similar when the γ $E_{\mathrm{T}} > \approx 100$ GeV[21, 15], again when calculating the event level quantities only hadronic objects are considered. The photon sample requires the following criteria on top of the common selection requirements: Exactly one photon with $E_{\mathrm{T}} > 150$ GeV to ensure trigger efficiency, $|\eta| < 1.45$. Events are vetoed if for any jet $\Delta R(\gamma, jet) < 1.0$. Given that due to the trigger requirements the photon E_{T} is required to be greater than 150 GeV and the photon is treated as missing energy, the $\alpha_T > 0.55$ requirement implies a minimum H_{T} threshold of ≈ 350 GeV, hence the γ + Jets control sample can only be used in the offline region where $H_{\mathrm{T}} > 375$ GeV.

Table 7.2 gives the hadronic signal yields in each of the offline H_{T} bins along with the simple background estimate from the single muon plus jets control sample. The full background prediction is given from the results of the simultaneous fit to the separate background estimates.

DRAFT

Table 7.2: Total SM prediction using the μ + Jets sample only. These are illustrative only, as the final prediction is provided by the final simultaneous fit.

α_T bin	0.55–∞	0.55–∞	0.55–∞	0.55–∞
H_{T} bin (GeV)	275–325	325–375	375–475	475–575
Hadronic selection MC	2872.32 ± 64.44	1384.22 ± 51.46	1041.38 ± 12.53	396.13 ± 19.85
μ+ jets selection MC	1228.90 ± 46.18	670.50 ± 38.74	495.14 ± 7.86	181.65 ± 9.65
Translation factor	2.34 ± 0.10	2.06 ± 0.14	2.10 ± 0.04	2.18 ± 0.16
μ+ jets selection yield data	1421	645	517	169
Total SM prediction	3321.30 ± 169.97	1331.57 ± 105.45	1087.36 ± 52.50	368.56 ± 39.09
Hadronic yield data	3703	1533	1043	346
α_T bin	0.55–∞	0.55–∞	0.55–∞	0.55–∞
H_{T} bin (GeV)	575–675	675–775	775–875	875–∞
Hadronic selection MC	142.37 ± 7.61	55.47 ± 3.51	18.68 ± 1.45	13.18 ± 1.15
μ+ jets selection MC	70.84 ± 4.36	22.64 ± 1.82	7.54 ± 0.80	5.19 ± 0.67
Translation factor	2.01 ± 0.16	2.45 ± 0.25	2.4 ± 0.33	2.54 ± 0.40
μ+ jets selection yield data	52	18	8	1
Total SM prediction	104.50 ± 16.81	44.09 ± 11.33	19.83 ± 7.41	2.54 ± 3.47
Hadronic yield data	122	44	14	6

7.1.4 Muon control samples with out an α_T cut.

The requirement of an α_T value above 0.55 in the previous control samples limits the event yield of each of the montecarlo samples, increasing the statistical error of the prediction. This is especially evident when splitting the analysis in to more dimensions than the H_{T} binning. The requirement of an α_T cut on the control samples means that as the muon is not seen by the calorimeter systems the signal trigger can also be used to collect the both the single and di muon background samples. The translation factor method can be used to create a prediction from any sample to any other sample if and only if the modelling of the event kinematics and acceptances of any cuts introduces no large systematic errors. We now show that the montecarlo simulation accurately reproduces the kinematics and acceptance of the α_T cut when applied to electro-weak background samples, enabling the removal of the α_T requirement for the muon control samples.

The preselection of events in the two muon control samples ensures samples with negligible QCD contamination, which are enriched with $\mathrm{t\bar{t}}$, W + Jets and Z + Jet events. This is shown for the μ + Jets sample in Figure 7.3 and for the $\mu\mu$ + Jets sample in

DRAFT

Figure 7.4, in both sets of plots the expected number of QCD events from montecarlo simulation is less than one event at any α_T value for 5 fb^{-1} of integrated luminosity. The requirement of tight isolation on each of the muons is largely responsible for the purity of the sample, the transverse mass and di-muon mass window cuts ensure the sample is rich in electro-weak events with visible muons. The agreement between data and montecarlo in these plots is good and the simulation models the α_T acceptance well, the systematic assigned to this acceptance is detailed in Section 7.2.

(a) α_T distribution (see main caption).

(b) Zoomed α_T distribution (see main caption).

(c) H_{T} distribution.

(d) N_{jet} distribution.

Figure 7.3: Data–MC comparisons of key variables for the muon control sample, for the region $H_{\mathrm{T}} > 375$GeV and $\alpha_T > 0.55$. Bands represent the uncertainties due to the limited size of MC samples. No requirement is made on the number of b-tagged jets in an event. *The discrepancy in the α_T distributions for values $\alpha_T > 0.55$ is due to the trigger not being simulated in the MC simulation.*

(a) α_T distribution (see main caption).

(b) Zoomed α_T distribution (see main caption).

(c) H_{T} distribution.

(d) N_{jet} distribution.

Figure 7.4: Data–MC comparisons of key variables for the di-muon control sample, for the region $H_{\mathrm{T}} > 375$GeV and $\alpha_T > 0.55$. Bands represent the uncertainties due to the limited size of MC samples. No requirement is made on the number of b-tagged jets in an event. *The discrepancy in the α_T distributions for values $\alpha_T > 0.55$ is due to the trigger not being simulated in the MC simulation.*

Moving to a selection where there is no required α_T cut means that the α_T trigger suite can not be used to collect the high event yield control samples. Instead a trigger requiring H_{T} and a muon in the final state (`Mu_HT`) is used, due to the muon trigger threshold the p_{T} acceptance cut is raised to 45 GeV in these control samples. The H_{T} requirement on these triggers raises to 300 GeV so only the offline bins with $H_{\mathrm{T}} >$ 375 GeV are able to benefit from the increased background estimation precision, due to the larger size of the predicting sample. The efficiency for triggering on a single muon at

45 GeV is measured to be 91.3±0.1% though out the data taking period, measured for the H_{T} + single muon triggers, the H_{T} component of the trigger is measured to be 100% efficient though out. In the case of the di-muon sample, as both muons have to be above 45 GeV and either of them could have triggered the event, the efficiency is found to be H_{T}-dependant in the range of 95-97%.

The muon control samples in the H_{T} bins where $H_{\mathrm{T}} < 375$ GeV are collected with the α_T trigger suite and the measured efficiencies are the same as those measured for the hadronic sample. The details of the triggers used for each of the muon + Jets control samples are listed in Table 7.3.

Table 7.3: List of triggers used for the larger μ + Jets and $\mu\mu$ + Jets samples.

H_{T} bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
α_T cut	0.55	0.55	None	None	None	None	None	None
Muon p_{T} cut	10	10	45	45	45	45	45	45
Trigger	α_T	α_T	`Mu_HT`	`Mu_HT`	`Mu_HT`	`Mu_HT`	`Mu_HT`	`Mu_HT`
Dataset	`HT`	`HT`	`MuHad`	`MuHad`	`MuHad`	`MuHad`	`MuHad`	`MuHad`
Thresholds	Table 2	Table 2	Table 3	Table 3	Table 3	Table 3	Table 3	Table 3

7.2 Systematic uncertainties on the electro-weak background model.

As previously discussed in Section 7.1 the final background prediction is given by the simultaneous fit to the yields in the signal and control samples and the translation factors obtained from MC. The fit has some freedom via the statistical and systematic uncertainties measured for each translation factor. This implies that the measurement of the systematic uncertainties on the translation factors are vital for the fitting procedure.

A set of closure tests were performed on data to identify any sources of systematic biased introduced by the background prediction method. To do this the individual background samples are used to predict one another using the same translation factor method as for the prediction of S.M missing energy sources in the hadronic signal regions. The level of agreement is quantified in terms of the ratio $(N_{obs} - N_{pred})/N_p red$, the statistical error from the translation factor, based on the available Montecarlo statists is combined with the statistical error on the number of events in the predicting sample

DRAFT

to give the error on the closure, hence the deviation of the ratio from zero gives the level of closure per analysis bin. This gives a measure of any biases introduced by the background estimation method.

The closure tests between the background samples are designed to test the Montecarlo's ability to model kinematic effects; such as the α_T acceptance; μ acceptance and γ acceptance, instrumental effects such as; reconstruction efficiencies and the effects of pile up on isolation and finally the theoretical precision of the production and decay cross sections and their relative contributions to the S.M background. These individual components are not separable by the closure tests, which instead gives a total systematic error estimation.

As described in Section 7.1.4 the control samples which do not require an α_T cut use a `Mu_HT` cross object trigger to collect the data events. As shown in Table 3 there was a period of data taking where due to the increased trigger thresholds the `Mu_HT` triggers are unsuitable for use in the region $H_{\mathrm{T}} < 375$ GeV. Thusly in the closure tests between the control samples which use an α_T cut and those that do not the integrated luminosity is limited to 3.9 fb^{-1}. This causes a loss of some statistical power in these cases.

The individual closure tests and fits to the H_{T} dependance of the ratio $(N_{obs} - N_{pred})/N_{pred}$ are shown in Appendix 3. The Figures 6 show the closure of the prediction between μ + Jets(no α_T) $\rightarrow$ μ + Jets($\alpha_T > 0.55$) and $\mu\mu$ + Jets(no α_T) $\rightarrow$ $\mu\mu$ + Jets($\alpha_T > 0.55$) for two samples, one with no requirement on the number of b tagged jets (n_b), which increases the precision of the measurement, and one requiring $n_b = 1$, the read line is the result of a one parameter fit. The level of closure shows that the Montecarlo accurately models the α_T acceptance, with no significant bias.

Figure 7 shows the closure between μ + Jets $\rightarrow$ $\mu\mu$ + Jets and between γ +jets $\rightarrow$ $\mu\mu$ + Jets over both the full H_{T} range using only 3.9 fb^{-1} of integrated luminosity and for $H_{\mathrm{T}} > 375$ GeV using the full data set. Again the red lines are the result of fitting with a one parameter fit.

Figure 8 tests the closure between samples with differing n_b the three tests are μ + Jets($n_b = 0$)$\rightarrow$$\mu$ + Jets($n_b = 1$,no α_T), μ + Jets($n_b = 1$)$\rightarrow$$\mu$ + Jets($n_b > 1$,no α_T) and μ + Jets($n_b = 0$)$\rightarrow$$\mu$ + Jets($n_b > 1$,no α_T). Figure 9 also tests the closure between samples with differing n_b, here the test is between μ + Jets($n_b = 0$)$\rightarrow$$\mu\mu$ + Jets($n_b = 0$) and μ + Jets($n_b = 1$)$\rightarrow$$\mu\mu$ + Jets($n_b = 1$).

DRAFT

Finally any dependance on pile up is measured by comparing a subset of the individual closure tests between samples which have pile up subtracted jets and those that do not. The example closures are μ + Jets(no α_T)$\rightarrow\mu$ + Jets($\alpha_T > 0.55$), μ + Jets(no α_T)$\rightarrow\mu\mu$ + Jets(no α_T), and μ + Jets($n_b = 0$)$\rightarrow\mu$ + Jets($n_b = 1$,no α_T).

7.3 Motivating the combined systematic on the translation factors

The closure tests described in the previous section are combined to give a total systematic uncertainty. This uncertainty is binned in to three H_{T} regions 275 GeV$\rightarrow$575 GeV, 575 GeV$\rightarrow$775 GeV and 775 GeV+. In each of these regions all of the individual closure tests are used to calculate a weighted mean and variance. The systematic is defined as 3σ of this variance, which is conservative but necessary to cover any biases. The systematics are treated as fully uncorrelated between the three regions, again this is the conservative approach. Figure 7.5 shows the key example closures, the grey shaded region shows the systematic error. The values obtained for the error are 6%, 20% and 39%, these are rounded to 10%, 20% and 40% and then used in the final background simultaneous fit.

Figure 7.5: A set of closure tests (open symbols) overlaid on top of grey bands that represent the systematic uncertainties used for three H_{T} regions in the final simultaneous fit. The solid circles and their errors represent the weighted mean and standard deviation for the five closure tests of each individual H_{T} bin.

DRAFT

7.4 Estimating the residual QCD background component.[6]

The expected QCD contamination in the signal region where $H_{\mathrm{T}} > 275$ GeV and $\alpha_T > 0.55$ from simulated background samples is negligible, residual events are removed via the application of the detector failure and $R_{miss} < 1.25$ filters. However due to the difficulty in simulating QCD multi jet events accurately a conservative approach is taken where a term is inserted in the likelihood to model any residual QCD contamination.

The term is based on the ratio of the number of events above and below the α_T threshold of 0.55 in the individual H_{T} bins. The dependance of this ratio is modelled as an exponentially falling quantity:

$$R_{\alpha_T}(H_{\mathrm{T}}) = \mathcal{A}_{n_b} e^{-k_{QCD} H_{\mathrm{T}}} \tag{7.2}$$

Where $\mathcal{A}_{n_b}$ is the b-tag bin dependant normalisation factor and k_{QCD} is the b-tag dependant decay constant.

The exponential behaviour is due to several features, the first of which is the improvement of the jet energy resolution with H_{T} due to the larger energies deposited in the calorimeter systems. Secondly for the region $H_{\mathrm{T}} > 375$ GeV the jet multiplicity rises slowly with H_{T}, which due to the combinatorics used in the α_T calculation, results in a narrower α_T distribution peaked at 0.5. Due to the signal region definition and the exponentially falling nature of the QCD background component is reduced to zero above ≈ 500 GeV, thus the validity of the QCD background model above 575 GeV is not of consequence to the final analysis, however the model chosen is shown to be valid over the whole H_{T} region of the analysis as shown below.

Maximum likelihood (M.L) values for k_{QCD} and $\mathcal{A}_{n_b}$ are found by the final likelihood fit, however k_{QCD} is first constrained by a measurement in a background enriched side band regions where either the α_T cut is relaxed or the R_{miss} cut is inverted. Figure 7.6 depicts the regions where k_{QCD} is measured, the signal region is as described before where $\alpha_T > 0.55$ and $R_{miss} < 1.25$ are required. Region B is defined by the inversion of the α_T cut. Region C is defined by inverting both the α_T requirement and the R_{miss} requirement, this region is further divided in to three slices in α_T of $0.52 < \alpha_T < 0.53$, $0.53 < \alpha_T < 0.54$ and $0.54 < \alpha_T < 0.55$, as the index of C_i rises the expected amount of QCD in that control region increases. Finally region D has only the R_{miss} requirement

DRAFT

inverted, region D is not used to constrain k_{QCD}, but instead to check the validity of the exponential model. The fits to the individual side bands are shown in Appendix 2. The

Figure 7.6: QCD side-band regions, used for determination of k_{QCD}.

best fit value for k_{QCD} of 2.96 ± 0.64 $\times 10^{-2}$ GeV^{-1} obtained from region B is used as the central value of the constraint. The assumption that this method gives an unbiased estimate of k_{QCD} stems from the similarity in event kinematics in the two α_T regions. The best fit values for the three C_i regions are used to estimate the systematic uncertainty on the central value obtained from region B. The fit results show now dependance on the α_T region used to measure the number of events, supporting the assumption that region B provides an unbiased estimate of k_{QCD}. The variation of the measured values for each C_i slice are used to calculate the error on the central value, the weighted mean and standard deviation of the three slices in α_T are calculated to be 1.13 ± 0.26 $\times$ 10^{-2} GeV^{-1}, the relative error on this value is 20% which is then applied to the central value to give an estimate of the systematic uncertainty.

The data side bands are used to provide a constrained value of k_{QCD} as an input to the final likelihood model which describes the expected number of background events in bins of H_{T} and the number of observed jets containing a b quark. The value measured for k_{QCD} is 2.96 ± 0.61(stat) ± 0.46(sys) $\times$ 10^{-2} GeV^{-1}. The uncertainty values are used as penalty timers in the likelihood model which is described in Section 7.5

A final check is performed using region D, which requires $\alpha_T > 0.55$ but has no R_{miss} cut, this introduces QCD background in to the signal region. The likelihood fit

DRAFT

Table 7.4: Best fit values for the parameters k as obtained from the regions B, C_1, C_2, and C_3. The latter three measurements are used to calculate a weighted mean (identified as region C). Also quoted is the maximum likelihood value of the parameter k given by the simultaneous fit using the sample defined by region D. Quoted errors are statistical only. From [6].

Side-band region	k_{QCD} ($\times 10^{-2}$ GeV^{-1})	p-value
B	2.96 ± 0.64	0.24
C_1	1.19 ± 0.45	0.93
C_2	1.47 ± 0.37	0.42
C_3	1.17 ± 0.55	0.98
C (weighted mean)	1.31 ± 0.26	-
D (likelihood fit)	1.31 ± 0.09	0.57

is performed on this background enriched region and no constraint is applied on k_{QCD} which is then determined by the fit only. The fit is performed over the full H_{T} range used in the final analysis. Figure 7.7 shows the resulting fit, the M.L value obtained for k_{QCD} is $(1.31 \pm 0.09)\times 10^{-2}$ GeV^{-1}, this value is in excellent agreement with the value found from the weighed mean of the regions C_i, secondly the fit shows that the choice of exponential function used in the likelihood model is valid over the entire H_{T} range. This supports the assumption that region B provides an unbiased estimate of k_{QCD} in the signal region $\alpha_T > 0.55$ and $R_{miss} < 1.25$.

7.5 Likelihood model

Declaration The likelihood model was implemented, developed, commissioned and deployed in anger by Edward Laird and is best described in his thesis[33]. However for completeness the likelihood model is described in this section. The likelihood is used to gauge the agreement between the observed yields in the hadronic signal region and the predicted yields obtained from the control samples. For the hadronic sample the likelihood is as follows, for N bins in H_{T}, let n_i represent the observed hadronic yield in H_{T} bin i, the likelihood for observing n_i events is then

$$L_{had} = \prod_i Pois\left(n_i | b_i + s_i\right) \tag{7.3}$$

DRAFT

Figure 7.7: Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_{T} for the side-band region D. No requirement on the number of b jets is made. Shown are the observed event yields in data (black dots with error bars representing the statistical uncertainties) and the expectations given by the simultaneous fit for the $\mathrm{Z} \to \nu\nu$+jets process (orange dotted-dashed line); the sum of all processes with genuine $\not{E}_{\mathrm{T}}$, which are primarily $\mathrm{t\bar{t}}$, W+jets, and $\mathrm{Z} \to \nu\nu$+jets (dark blue long-dashed line); and the sum of QCD and all aforementioned SM processes (light blue solid line).[6]

where b_i is the number of expected background events and s_i the expected signal yield, which is dependant on the signal model being considered. Pois refers to the Poisson distribution of these values, b_i is equal to the sum of electro-weak events expected plus the number of QCD events ($b_i = EWK_i + QCD_i$) expected per bin.

In Section 7.4 it was shown that the QCD contribution can be modelled as an exponentially falling as a function of H_{T}.

$$R_{\alpha_T}(H_{\mathrm{T}}) = A_{qcd} e^{-k_{QCD} H_{\mathrm{T}}} \tag{7.4}$$

Where A_{QCD} and k_{QCD} have been constrained by measurements in the control regions. QCD_I is then given as:

$$QCD_i = m_i A_{qcd} e^{-k_{QCD} \langle H_{\mathrm{T}} \rangle^i}. \tag{7.5}$$

Where m_i is the number of events per H_{T} bin which fail $\alpha_T > 0.55$ and $\langle H_{\mathrm{T}} \rangle^i$ is the mean H_{T} of the the bin.

DRAFT

For the electro-weak background two components are considered, f^i_{Zinv} represents the fraction of the total electro-weak background contributed by $\mathrm{Z} \to \nu\nu$ + Jets events. This is modelled as a liner component:

$$f^i_{Zinv} = f^0_{Zinv} + \frac{\langle H_\mathrm{T}\rangle^i - \langle H_\mathrm{T}\rangle^0}{\langle H_\mathrm{T}\rangle^{N-1} - \langle H_\mathrm{T}\rangle^0}\left(f^{N-1}_{Zinv} - f^i_{Zinv}\right), \tag{7.6}$$

where f^i_{Zinv} and f^{N-1}_{Zinv} are floating parameters who's final values are limited between zero and one. The total number of $\mathrm{Z} \to \nu\nu$ + Jets events per bin is then given by:

$$Z^i_{inv} = f^i_{Zinv} \times EWK^i \tag{7.7}$$

with the remaining background from other electro-weak processes given by:

$$Y = \left(1 - f^i_{Zinv}\right) \times EWK^i. \tag{7.8}$$

In each H_T bin i there are three background measurements, n^i_γ, n^i_μ and $n^i_{\mu\mu}$, representing the event counts from the photon, muon and di-muon control samples respectively, each of these yields has a Montecarlo counter-part yield. From the Montecarlo it is also possible to extract MC^i_{Zinv} and MC^i_Y. After defining:

$$r^i_\gamma = \frac{MC^i_\gamma}{MC^i_{Zinv}},\ r^i_{\mu\mu} = \frac{MC^i_{\mu\mu}}{MC^i_{Zinv}},\ r^i_\mu = \frac{MC^i_\mu}{MC^i_Y} \tag{7.9}$$

three likelihood functions are defined:

$$L_\gamma = \prod_i Pois\left(n^i\gamma|\rho^j_{\gamma\mathrm{Z}} \cdot r^i_\gamma \cdot Z^i_{inv}\right), \tag{7.10}$$

$$L_{\mu\mu} = \prod_i Pois\left(n^i_{\mu\mu}|\rho^j_{\mu\mu\mathrm{Z}} \cdot r^i_{\mu\mu} \cdot Z^i_{inv}\right), \tag{7.11}$$

$$L_\mu = \prod_i Pois\left(n^i_\mu|\rho^j_{\mu Y} \cdot r^i_\mu \cdot Y^i + s^i_\mu\right), \tag{7.12}$$

Equation (7.10) is used to estimate the M.L values for Z_{inv} which is the expectation of the number of $\mathrm{Z} \to \nu\nu$ + Jets events in the hadronic signal region using the observations n^i_γ in the photon control sample and the ratio r^i_γ, similarly the number of $\mathrm{Z} \to \nu\nu$ + Jets

DRAFT

Table 7.5: The systematic parameters used in H_{T} bins.

H_{T} bin (i)	0	1	2	3	4	5	6	7
syst. parameter (j)	0	0	0	0	1	1	2	2

events expected in the signal region predicted by the $\mathrm{Z} \to \mu\mu$ + Jets are found using Equation (7.11). The non $\mathrm{Z} \to \nu\nu$ backgrounds are estimated by the M.L value for Equation (7.12) in a similar way with the addition of s^i_μ which represents the signal contamination in the single muon control sample. The measurements and ratios are considered simultaneously though the relationships defined in Equations (7.3), (7.7) and (7.8). The ratios $r^i_\gamma, r^i_{\mu\mu}$ and r^i_μ are the inverse of the translation factors given by Equation (7.1). The parameters $\rho_{\gamma\mathrm{Z}}, \rho_{\mu\mu\mathrm{Z}}$ and $\rho_{\mu Y}$ are correction factors that account for the systematic uncertainty on each of the ratios and $\sigma_{\gamma\mathrm{Z}}, \sigma_{\mu\mu\mathrm{Z}}$ and $\sigma_{\mu Y}$ represent the relative systematic uncertainties for the control sample constraints, these are accounted for in:

$$L_{EWK\ syst} = \prod_j Gaus\left(1.0|\rho^j_{\mu Y}, \sigma^j_{\mu Y}\right) \times Gaus\left(1.0|\rho^j_{\mu\mu\mathrm{Z}}, \sigma^j_{\mu\mu\mathrm{Z}}\right) \times Gaus\left(1.0|\rho^j_{\gamma\mathrm{Z}}, \sigma^j_{\gamma\mathrm{Z}}\right) \tag{7.13}$$

Three parameters per control sample are used to cover the eight H_{T} bins as show in Table 7.5.

Alternatively the single muon control sample can be used to constrain the total electro-weak background, we can define:

$$r'^i_\mu = \frac{MC^i_\mu}{MC^i_{tot}} \tag{7.14}$$

and

$$L'_\mu = \prod_i Pois\left(n^i_\mu|\rho_{\mu Y} \times r'^i_\mu \times EWK^i + s^i_\mu\right) \tag{7.15}$$

Signal Contamination The cross section for each model is represented by x, l represents the total recorded luminosity considered by the analysis in the signal region. The efficiency is defined as ϵ^i_{had} for the signal region and ϵ^i_μ for the single muon control sample, δ represents the relative uncertainty on signal measured in the previous section, δ is taken

DRAFT

to be fully correlated though the H_{T} bins. ρ_{sig} is the correction factor to the signal yield which accommodates this uncertainty. f represents an unknown multiplicative factor on the signal cross section, for which an allowed interval is computed. The expected signal yield s^i from Equation (7.3) is defined as:

$$s^i_{had} = f\rho_{sig} x l \epsilon^i_{had}, \tag{7.16}$$

the signal contamination s^i_μ is given by:

$$s^i_\mu = f\rho_\mu x l \epsilon^i_\mu. \tag{7.17}$$

The systematic on signal uncertainty is included by in an additional term in the likelihood:

$$L_{sig} = Gaus\left(1.0|\rho_{sig}, \delta\right). \tag{7.18}$$

The total likelihood The total likelihood for a given signal selection $k(H_{\mathrm{T}}, n_b)$ is given by:

$$L^k = L^k_{had} \times L^k_\mu \times L^k_\gamma \times L^k_{\mu\mu}, \tag{7.19}$$

each k has $3 + N$ nuisance parameters; $\mathcal{A}_{QCD}, f^0_{Zinv}, f^{N-1}_{Zinv}, \{EWK^i\}^{N-1}_{i=0}$. The 11 parameters k_{QCD}, ρ_{sig}, and $\rho^k_{\gamma\mathrm{Z}}, \rho^k_{\mu\mu}, \rho^k_\mu$ with $j = \{0, 1, 2\}$ are shared between the selections, the total likelihood is then given as:

$$L = L_{sig} \times L_{EWKsyst} \times \prod_k L^k_{had} \times L^k_\mu \times L^k_\gamma \times L^k_{\mu\mu}. \tag{7.20}$$

7.6 Final Results

The yields obtained in the hadronic signal regions are tested for their compatibility with the background predicted by the likelihood model both in terms of agreement with the Standard Model and interpretations in the forms of limits on new physics models.

To test the level of agreement with the standard model the signal terms are dropped from the likelihood, which is then maximised over all parameters using Roofit[35] and MINUIT[31]. The individual yields and errors from the fits are shown in Appendix

put these tables in teh appendix

DRAFT

. The total background and data yields and their errors as given by the M.L fit are show below in Table 7.6.

Table 7.6: Comparison of the measured yields in the different H_{T} and b jet multiplicity bins for the hadronic sample with the SM expectations and combined statistical and systematic uncertainties given by the simultaneous fit.

H_{T} (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	875–∞
0 b jets SM	2933^{+56}_{-52}	1139^{+17}_{-40}	783^{+17}_{-27}	261^{+14}_{-8}	$81.5^{+6.5}_{-6.5}$	$34.2^{+4.0}_{-3.8}$	$10.4^{+2.8}_{-1.8}$	$5.3^{+1.7}_{-1.1}$
0 b jets Data	2919	1166	769	255	91	31	10	4
1 b jet SM	630^{+26}_{-25}	271^{+10}_{-16}	202^{+10}_{-6}	$78.0^{+6.9}_{-1.9}$	$24.2^{+2.9}_{-2.0}$	$10.6^{+1.7}_{-1.3}$	$2.9^{+0.9}_{-0.5}$	$2.2^{+0.7}_{-0.4}$
1 b jet Data	614	294	214	71	20	6	4	0
2 b jets SM	162^{+13}_{-12}	$61.8^{+4.8}_{-6.3}$	$58.8^{+4.8}_{-2.6}$	$28.0^{+3.5}_{-1.1}$	$9.0^{+1.4}_{-1.0}$	$7.1^{+1.4}_{-1.0}$	$0.6^{+0.3}_{-0.2}$	$0.9^{+0.4}_{-0.2}$
2 b jets Data	160	68	52	19	11	7	0	2
$\geq$ 3 b jets SM	$10.5^{+3.5}_{-2.2}$	$7.1^{+2.2}_{-1.8}$	$5.8^{+1.4}_{-0.9}$	$3.1^{+1.0}_{-0.7}$	$1.7^{+0.5}_{-0.4}$	$0.7^{+0.5}_{-0.4}$	$0.1^{+0.1}_{-0.1}$	$0.2^{+0.1}_{-0.1}$
$\geq$ 3 b jets Data	10	8	8	1	0	0	0	0

Figures 7.8, 7.9, 7.10 and 7.11 show comparisons of the observed yields and the Standard Model only expectations given by the simultaneous fit for 0, 1, 2, $\geq$ 3 exclusive b-tag bins. A good agreement with the standard model is observed in all H_{T} and b-tag categories. Given the lack of a signal like observation limits are set on the production masses and cross sections of beyond the standard model particles.

DRAFT

(a) Hadronic sample

(b) μ + jets sample

(c) $\mu\mu$ + jets sample

(d) γ + jets sample

Figure 7.8: Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_{T} for the (a) hadronic, (b) μ + Jets, (c) $\mu\mu$ + Jets and (d) γ + Jets samples when requiring exactly zero reconstructed b-jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, an example signal model is superimposed on the SM expectation (magenta solid line). The expected signal contamination in the control samples is negligible.

DRAFT

(a) Hadronic sample

(b) μ + jets sample

(c) $\mu\mu$ + jets sample

(d) γ + jets sample

Figure 7.9: Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_{T} for the (a) hadronic, (b) μ + Jets, (c) $\mu\mu$ + Jets and (d) γ + Jets samples when requiring exactly one reconstructed b-jet. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, an example signal model is superimposed on the SM expectation (magenta solid line). The expected signal contamination in the control samples is negligible.

(a) Hadronic sample

(b) μ + jets sample

(c) $\mu\mu$ + jets sample

(d) γ + jets sample

Figure 7.10: Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_{T} for the (a) hadronic, (b) μ + Jets, (c) $\mu\mu$ + Jets and (d) γ + Jets samples when requiring exactly two reconstructed b-jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, an example signal model is superimposed on the SM expectation (magenta solid line). The expected signal contamination in the control samples is negligible.

(a) Hadronic sample (b) μ + jets sample

Figure 7.11: Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_{T} for the (a) hadronic and (b) μ + Jets samples when requiring at least three reconstructed b-jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, an example signal model is superimposed on the SM expectation (magenta solid line). The expected signal contamination in the μ + Jets control sample is negligible.

DRAFT

Chapter 8

Interpretation

8.1 Signal Models

The level of agreement of the analysis with the S.M give a handle on the production cross sections and masses of particles predicted by new physics models. The final results are presented in terms of a specific SuperSymmetry (SUSY) model and a selection of generic final state topologies, known as Simplified Model Spectra (S.M.S).

The SUSY model considered is the CMSSM[] which is described in Section 2.2, the parameters chosen are $\tan\beta = 3, \mathcal{A}_0 =, \mu =$ with the exclusion curve presented in the m_0, $m_{1/2}$ plane. This model combines many production and decay topologies and is common to results shown by previous and contemporary experiments []

Reference ATLAS and Tevatron susy results

. The results are also presented in terms of S.M.S[] models, these are models with single production methods and a specified decay topology. The C.M.S terminology for the production methods are as follows: T1 models are gluino-gluino production, which then decay to four S.M hadronic jets and two neutrilinos. T2 models are squark-squark production with decays to two S.M hadronic jets and two neutrilinos. These topologies can be further specialised by enforcing the squarks or gluinos to decay to heavy flavour S.M quarks, such as t, which promptly decay to jets containing b quarks or direct decays to b quarks. The limits on the S.M.S space are defined in terms of the mass splitting between the neutrilino and the pair produced SUSY particle defining the model.

DRAFT

8.2 Signal Efficiency

8.2.1 CMSSM

The CMSSM signal scan is composed of eight sub-processes which define the production and decay topologies. The dominant process varies with $m_0, m_{1/2}$ and at next to leading order the cross section for each of theses processes varies per point. The analysis is run over each sub process in turn with the final efficiency given by the weighted sum of the subprocess efficiencies. The yield per point is then given by $\epsilon \times \mathcal{L}$ for 5 fb^{-1} the total yields are show in the appendix in Figure 11 these yields are for the sum of the H_{T} analysis bins.

8.2.2 Simplified Models

The S.M.S models contain only one production process and a set decay topology, making the interpretation in these models simpler, however the individual models are not representative of some complete SUSY model. Instead these models allow the testing of specific facets of new physics models, with out the ambiguity of the relative contributions of each sub process at a point which is seen when testing full models. The efficiency is measured for each of the models, with the yield per point given by $\epsilon \times \sigma \times \mathcal{L}$ where σ is given as a reference cross section only. The efficiencies for which are shown in the appendix, Table 8.1 lists which figure corresponds to which model, it is to be noted that the total efficiency summed over H_{T} bins is shown.

Table 8.1: Production and decay modes for various simplified models.

Model	Production and decay modes	Figure showing efficiency
`T1`	$\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$	12
`T2`	$\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$	13
`T2tt`	$\widetilde{\mathrm{t}}\widetilde{\mathrm{t}} \to \mathrm{t}\widetilde{\chi}^0\overline{\mathrm{t}}\widetilde{\chi}^0$	14
`T2bb`	$\widetilde{\mathrm{b}}\widetilde{\mathrm{b}} \to \mathrm{b}\widetilde{\chi}^0\overline{\mathrm{b}}\widetilde{\chi}^0$	15
`T1tttt`	$\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to \mathrm{t}\overline{\mathrm{t}}\widetilde{\chi}^0\mathrm{t}\overline{\mathrm{t}}\widetilde{\chi}^0$	16
`T1bbbb`	$\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to \mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0\mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0$	17

Signal Efficiency for the Background Selection If the couplings of the SUSY particles are analogous to the S.M particles then the final states may involve muons

DRAFT

which in the presence of signal would infer an over estimation of the background from the control samples. To measure this the background selection is applied to the signal models and the yields are taken into account in the final limit setting procedure. On average the background selection's efficiency on signal is 10× lower than the efficiency in the hadronic signal region. This is shown for the model `T1tttt` in Figure 18 where the most muons of all the signal models are expected in the final state, the contamination in the n_b bins that drive the limit is on the order of $10 - 20\%$.

8.3 Uncertainty on Signal Efficiency

The systematic uncertainty on the signal models is due to: Choice of PDF at generator level, the PDF set used to generate the sample has effects on both the acceptance and the cross section; The measurement of the integrated luminosity is accounted for in the signal yield; Due to the signal models being created with C.M.S FastSim[] rather than C.M.S FullSim[] the acceptance differs between the signal and the background samples; The error on the jet energy scale is accounted for on the signal yield; Systematic errors from the cleanings cuts (R_{miss} and ECAL dead regions) and lepton/photon vetoes are also taken in to account; Finally corrections to the b-tagging efficiency between the FullSim and the FastSim are applied as well as their errors.

Each of these uncertainties is expressed as a percentage change in the efficiency from the central value given by applying the full analysis to each signal model, the total systematic is given by summing the components in quadrature. In the following section the measurements of the error from each of these sources is detailed and summarised per considered signal model at the end of the section.

The uncertainties for the CMSSM are considered in a band of ± 60 GeV in $m_{1/2}$ around the expected limit to confine the errors to the relevant part of the plane, in the very high $m_0, m_{1/2}$ area the jet energy scale causes large fluctuations due to the small mass splitting between the SUSY particles. For the S.M.S models two regions are defined, one "close" to the diagonal, which has small mass splitting and thus the effects of jet energy scale and PDF acceptance have a large impact on the analysis efficiency. A second "far" region is defined with large mass splitting and thus a small change on the analysis efficiency due to jet energy scale and PDF variations. The near and far regions

DRAFT

are defined by:

$$m_{sq}(m_{gl}) - m_{lsp} > 350 \text{ GeV } and \ m_{sq}(m_{gl}) > 475 \text{ GeV} \tag{8.1}$$

events passing these conditions are classified as being in the "far" region, those failing in the "close" region.

8.4 Choice of PDF set at generator level.

The PDF set contains information on the interaction probabilities of the quark and gluons in the proton at different energies, the model used in the production of the Montecarlo simulation has direct impact on the kinematics of the final states, since the PDFs have been measured at lower energies than those found at the L.H.C the quark and gluon distributions have been extrapolated from the low energy regime, the uncertainty at high energy is thus significant. The uncertainties on acceptance due to the choice of PDF set used to generate the signal Montecarlo are calculated in line with the `PDF4LHC`[16] working group recommendations. On the event level the individual weights are re-calculated by moving between PDF set, the weight is based on the energy at which the quarks or gluons interaction and the form given by the PDF. This is done for the central value of the three considered PDF sets (CTEQ6.1[40], MSTW2008nlo68cl[42] and NNPDF2.0[43]) and for the variations of each of their errors. The change in analysis efficiency is measured per H_{T} bin, Figure 8.1 shows the deviation in efficiency per bin for three examples points in the CMSSM plane, the error bars represent the Root Mean Squared (RMS) of the spread of the efficiency inside each PDF set. It is to be noted that some bins show a large change in efficiency due to the choice of PDF set, however these are low efficiency bins where changes in yield of a few events has a large effect, the final result however is driven by the high efficiency bins, hence these large fluctuations can be ignored. The effects on the cross section are studied by re-calculating the Next to Leading Order (N.L.O) cross sections of each of the sub processes for each choice of PDF set, this is done centrally by C.M.S, these changes in cross section are accounted for in the error band on the expected limit.

DRAFT

(a) $m_0 = 200\ GeV, m_{1/2} = 500\ GeV$

(b) $m_0 = 500\ GeV, m_{1/2} = 500\ GeV$

(c) $m_0 = 200\ GeV, m_{1/2} = 1800\ GeV$

(d) $m_0 = 200\ GeV, m_{1/2} = 1800\ GeV$

(e) $m_0 = 500\ GeV, m_{1/2} = 500\ GeV$

(f) $m_0 = 200\ GeV, m_{1/2} = 1800\ GeV$

Figure 8.1: Figures 8.1(a), 8.1(b) and 8.1(c) show the efficiency per H_{T} bin for the inclusive selection. The three coloured lines represent the analysis efficiency for a choice of PDF set, the error bars are the RMS of the change in efficiency per PDF set from varying the internal components by 1σ of their error. Figures 8.1(d), 8.1(e) and 8.1(f) show the ratio of the change in efficiency from the default PDF set (CTEQ6.1) for three illustrative points in the $m_0, m_{1/2}$ plane of the CMSSM. The change in efficiency in the high efficiency bins is on the order of 10% for all points.

8.5 Effects of Jet Energy Scale Variations on Signal Efficiency

Section 6.2.1 describes the Jet Energy Corrections (JEC) and their uncertainties, which are derived in [18], these uncertainties are dependant on the $|\eta|$ and E_{T} of the jet in question. To measure the impact of the individual jet energy uncertainties on signal acceptance two additional selections are performed on the signal samples, the first with the energy of each jet in the event raised from the central value by 1σ of it's uncertainty, the second with the energy decreased by 1σ, the relative change in efficiency with respect to the central value is then calculated for signal point. The model dependant systematic is found from the 68th percentile of the 1D distribution of the absolute change in signal efficiency over each point in the model space. Figure 19 shows the change in efficiency over the full $m_0, m_{1/2}$ plane for the CMSSM, at high $m_0, m_{1/2}$ the variation is large due to the primary production method of SUSY particles being electro-weak production of charginos in this region. These charginos then decay though a chain to the neutrilio and S.M particles, due to the small mass splitting (compressed spectra) between each of the charginos the jets produced are only just with in E_{T} acceptance. A small change of the individual jet E_{T}'s thus moves many jets in and out of acceptance causing a large change in analysis efficiency, hence only the region within ± 60 GeV around the expected limit in $m_{1/2}$ is considered when calculating the systematic for the CMSSM. The points close to the diagonal in the S.M.S models display compressed spectra and so are effected by the change in jet energy scale. Figures 20 and 21 show the effects of scaling the jet energies for the considered S.M.S models, Figures 22 and 23 show the 68% coverage of the 1D distribution of the relative change in efficiency for the near and far regions from which the systematic is taken.

8.6 Systematic Uncertainty on Signal Yield from Cleaning Filters and Object Vetoes.

For each of the cleaning cuts, R_{miss} and the `DeadECAL`, the systematic is given as the product of the ratio of normalised yields in the control samples, between data and Montecarlo and the relative change in efficiency due to the cleaning filter for each individual signal model. The background sample is chosen before an α_T cut or any other cleaning cuts and is high in real $\not{E}_{\mathrm{T}}$ due to the selection of W + Jets and $\mathrm{t\bar{t}}$ events,

DRAFT

meaning the efficiency of the R_{miss} cut should be high. Figure 24 shows the accuracy of the R_{miss} modelling, at a cut value of $R_{miss} < 1.25$ the miss modelling is at the level of 14%. Figures 25, 26 and 27 show the change in selection efficiency due to the R_{miss} on the signal models.

As for the R_{miss} cut the background selection is performed on data and Montecarlo and the accuracy of modelling the `DeadECAL` filter is measured, the ratio of the normalised cut efficiency on data and simulation shows a miss modelling at the level of 1.8%, this is taken as the uncertainty on the Montecarlo model of the detector failures. Figures 29, 30 and 31 show the relative change in efficiency due to the `DeadECAL` filter on the considered signal models.

Again regions with compressed spectra and many jet topologies are more effected by the cleaning cuts.

Finally the effects of the lepton vetoes on the signal efficiency are studied. A generator level filter is first applied removing any events with final state leptons or photons, thus measuring the effect of hadronic objects faking leptons or photons. The relative change in efficiency due to the application of the object vetoes is show in Figures 33, 35 and 36, the inefficiency for each signal model are very small and are used directly as the systematic error.

8.7 Interpretation in terms of new physics models.

Due to the lack of a signal like observation limits are set on new physics models. The first of these is the CMSSM, at each point in the $m_0, m_{1/2}$ parameter space the SUSY particle spectrum is calculated using `SoftSUSY`[12], the signal events are generated at leading order using `Pythia 6.4`[41], the Next to Leading Order + Next Leading Log (NLO+NNL) process dependant cross sections are calculated using `PROSPINO`[13] using the `CTEQ6`[40] PDF set. The previously measured errors on the background prediction, total collected luminosity and signal yield are included in the calculation of the limit. Although signal contributions from each data observation (hadronic, μ + Jets, $\mu\mu$ + Jets and γ + Jets) are included, the only relevant signal contribution to the CMSSM is from the hadronic signal regions. Figure 8.2 shows the expected limit contour with it's associated $\pm 1\sigma$ error band as well as the observed limit. The limit is calculated using NLO+NNL cross sections using CL_s[36], the limit presented is for the 95% confidence level. For the choice

DRAFT

of $\tan\beta = 10$, A_0 =0 GeV, $\mu > 0$ and a top quark mass m_{top} =173.2 GeV, squarks with masses below 1.25 TeV are excluded at 95% confidence, gluninos with a mass up to 1.25 TeV are also excluded when m_0 <600 GeV. In the region m_0 >600 GeV gluino masses below 700 GeV are excluded as are squarks with masses between 1.25-2.5 TeV, m_0 dependant.

Figure 8.2: Exclusion contours at 95% CL in the CMSSM $(m_0, m_{1/2})$ plane ($\tan\beta = 10, A_0 = 0, \mu > 0$) calculated with NLO+NNL SUSY production cross sections and the CL_s method. The solid black line indicates the observed exclusion region. The dotted-dashed black lines represent the observed excluded region when varying the cross section by its theoretical uncertainty. The expected median exclusion region (green dashed line) $\pm 1\sigma$ (green band) are also shown.

THe observed yields are also used to set limits on S.M.S models. This allows interpretation of the results for defined mass splittings and final states. Each S.M.S sample is characterised by the SUSY particle which is pair produced, either a squark or a gluino and the LSP mass, the individual points are then defined by the mass difference between the pair produced particle and the LSP. The decay topologies are further specialised by enforcing the final state quarks to be heavy flavours, either top or bottom quarks. The decays of the considered models are summarised in Table 8.2 As before the experimental uncertainties on the background estimation, collected luminosity, and the model dependant signal uncertainties are accounted for in the calculation of the limit.

In the regions $m_{\tilde{q}(\tilde{g})} - m_{LSP} < 200$ GeV and $m_{\tilde{q}(\tilde{g})} < 350$ GeV any selection efficiency is strongly dependant on the presence of initial state radiation which is not well modelled in the Montecarlo simulation, hence these regions are not considered when setting limits

in the S.M.S models, for the model `T1tttt` the ignored region is expanded to cover $m_{\widetilde{g}} - m_{LSP} < 400$ GeV.

Figure 8.3 shows the observed limits at 95% confidence level obtained using CL_s as a function of $m_{\widetilde{q}(\widetilde{g})}$ and m_{LSP}. The solid black lines represent the observed median limit assuming NLO+NNL[13, 32] SUSY cross sections for squark pair production in the limit of de-coupled gluinos and vice versa for the gluino production models. The thin black lines represent the limit wen this cross section is varied by $\pm 1\sigma$ of the theoretical uncertainty, the dashed purple lines represent the expected limit and it's $\pm 1\sigma$ uncertainty.

The best limits are set on the mass of the pair produced sparticles are at low m_{LSP} due to the large mass splitting between the sparticles and the LSP producing high p_{T} final state objects. The limits degrade as the decay spectra become compressed, above a certain m_{LSP} no limit is set.

No exclusion on direct stop, stop production (`T2tt`) is expected assuming the NLO+NNL production cross section for $m_{LSP} > 50$ GeV. Figure 8.4 shows the observed upper limit at 95% confidence level on the cross section as a function of m_{stop} for an LSP with a mass of 50 GeV.

Table 8.2: Production and decay modes for various simplified models.

Model	Production and decay modes	Figure showing limit
`T1`	$\widetilde{g}\widetilde{g} \to q\bar{q}\widetilde{\chi}^0 q\bar{q}\widetilde{\chi}^0$	8.3(a)
`T2`	$\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0 \bar{q}\widetilde{\chi}^0$	8.3(b)
`T2tt`	$\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0 \bar{t}\widetilde{\chi}^0$	8.3(c),8.4
`T2bb`	$\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0 \bar{b}\widetilde{\chi}^0$	8.3(d)
`T1tttt`	$\widetilde{g}\widetilde{g} \to t\bar{t}\widetilde{\chi}^0 t\bar{t}\widetilde{\chi}^0$	8.3(e)
`T1bbbb`	$\widetilde{g}\widetilde{g} \to b\bar{b}\widetilde{\chi}^0 b\bar{b}\widetilde{\chi}^0$	8.3(f)

DRAFT

(a) $\tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$ (T1)

(b) $\tilde{q}\tilde{q} \to q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$ (T2)

(c) $\tilde{t}\tilde{t} \to t\tilde{\chi}^0\bar{t}\tilde{\chi}^0$ (T2tt)

(d) $\tilde{b}\tilde{b} \to b\tilde{\chi}^0\bar{b}\tilde{\chi}^0$ (T2bb)

(e) $\tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}^0 t\bar{t}\tilde{\chi}^0$(T1tttt)

(f) $\tilde{g}\tilde{g} \to b\bar{b}\tilde{\chi}^0 b\bar{b}\tilde{\chi}^0$ (T1bbbb)

Figure 8.3: Upper limit on cross section at 95% CL as a function of $m_{\tilde{q}}$ or $m_{\tilde{g}}$ and m_{LSP} for various simplified models. The solid thick black line indicates the observed exclusion region assuming NLO+NNL SUSY production cross section. The thin black lines represent the observed excluded region when varying the cross section by its theoretical uncertainty. The dashed purple lines indicate the median (thick line) $\pm 1\sigma$ (thin lines) expected exclusion regions.

Figure 8.4: Excluded cross section versus top squark mass for a model in which pair-produced top squarks decay to two top quarks and a two neutralinos. The solid blue line indicates the observed cross section upper limit (95% CL) as a function of the top squark mass, $m_{\tilde{t}}$. The dashed orange line and blue band indicate the median expected excluded cross section with experimental uncertainties. The solid black line with grey band indicates the NLO+NNL SUSY top squark pair-production cross section and theoretical uncertainties.

DRAFT

Chapter 9

Conclusion

DRAFT

Bibliography

[1]

[2]

[3]

[4] Technical report.

[5] Updated measurements of the inclusive w and z cross sections at 7 tev. (CMS-AN-10-264), 2010.

[6] Search for supersymmetry with the α_{t} variable in the 7 tev dataset of 2011. (CMS-AN-11-517), 2011.

[7] Ecal performance plots, 2012 data. Jul 2012.

[8] Search for supersymmetry in final states with missing transverse energy and 0, 1, 2, 3, or at least 4 b-quark jets in 8 tev pp collisions using the variable alphat. (CMS-PAS-SUS-12-028), 2012.

[9] W Adam, R Frhwirth, A Strandlie, and T Todorov. Reconstruction of electrons with the gaussian-sum filter in the cms tracker at the lhc. *Journal of Physics G: Nuclear and Particle Physics*, 31(9):N9, 2005.

[10] T Åkesson. The ATLAS experiment at the CERN Large Hadron Collider - CERN Document Server. *Particles*, 1999.

[11] B Alessandro, F Antinori, J Belikov, and C Blume. ALICE: Physics performance report, volume II. *Journal of Physics G: Nuclear and Particle Phyiscs*, January 2006.

[12] B C Allanach. SOFTSUSY: a program for calculating supersymmetric spectra. *Comput. Phys. Commun.*, 143:305, 2002.

DRAFT

[13] W. Beenakker and others. Squark and gluino production at hadron colliders. *Nucl. Phys. B*, 492:51, 1997.

[14] Michael Benedikt, Paul Collier, V Mertens, John Poole, and Karlheinz Schindl. *LHC Design Report*. CERN, Geneva, 2004.

[15] Z Bern, G Diana, L J Dixon, F Febres Cordero, S Hoche, and others. Driving Missing Data at Next-to-Leading Order. *arXiv*, D84:114002, 2011.

[16] Michiel Botje, Jon Butterworth, Amanda Cooper-Sarkar, Albert de Roeck, Joel Feltesse, Stefano Forte, Alexander Glazov, Joey Huston, Ronan McNulty, Torbjorn Sjostrand, and Robert Thorne. The PDF4LHC Working Group Interim Recommendations. *arXiv.org*, hep-ph, January 2011.

[17] M Cacciari, G Salam, and G Soyez. The anti-kt jet clustering algorithm. *Journal of High Energy ...*, January 2008.

[18] Serguei Chatrchyan and others. Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS. *arXiv*, 6:P11002, 2011.

[19] CMS Collaboration. CMS b-tagging performance database. Technical report.

[20] CMS Collaboration. The Trigger and Data Acquisition Project Technical Design Report, Volume 1, The Level-1 Trigger. *CERN/LHCC 2000-038, CMS TDR 6.1*, 2000.

[21] CMS Collaboration. Data-Driven Estimation of the Invisible Z Background to the SUSY MET Plus Jets Search. Technical report, 2008.

[22] CMS Collaboration. SUSY searches with dijet events. Technical report, 2008.

[23] CMS Collaboration. Search strategy for exclusive multi-jet events from supersymmetry at CMS. Technical report, 2009.

[24] CMS Collaboration. Electron reconstruction and identification at $\sqrt{s} = 7$ TeV. Technical report, 2010.

[25] CMS Collaboration. Isolated Photon Reconstruction and Identification at $\sqrt{s} = 7$ TeV. Technical report, 2010.

[26] CMS Collaboration. Performance of muon identification in pp collisions at $\sqrt{s} = 7$ TeV. Technical report, 2010.

DRAFT

[27] The CMS Collaboration. CMS - The Compact Muon Solenoid. January 1996.

[28] The CMS Collaboration. Cms physics technical design report, volume ii: Physics performance. *Journal of Physics G: Nuclear and Particle Physics*, 34(6):995, 2007.

[29] The C.M.S Collaboration. Cms tracking performance results from early lhc operation. *Eur. Phys. J. C*, 70(arXiv:1007.1988. CERN-PH-EP-2010-019. CMS-TRK-10-001):1165. 29 p, Jul 2010.

[30] The CMS collaboration. Determination of jet energy calibration and transverse momentum resolution in cms. *Journal of Instrumentation*, 6(11):P11002, 2011.

[31] Frederic James. MINUIT Reference Manual. *CERN Program Library Writeup*, D506.

[32] M Kr amer, A Kulesza, R van der Leeuw, and others. Supersymmetry production cross sections in pp collisions at $\sqrt{s} = 7$ TeV. *arXiv*.

[33] Edward Matthew Laird. A Search for Squarks and Gluinos with the CMS Detector. 2012.

[34] J Marrouche and others. Commissioning the CMS Global Calorimeter Trigger. *CMS IN*, 2010/029, 2010.

[35] Belasco Cranmer Moneta and others. The RooStats Project. *Proceedings of Science*, 2010.

[36] K Nakamura. Review of particle physics. *J. Phys. G*, 37:075021, 2010.

[37] J Rademacker. LHCb: Status and Physics Prospects. *Arxiv preprint hep-ex*, January 2005.

[38] Lisa Randall and David Tucker-Smith. Dijet Searches for Supersymmetry at the LHC. *arXiv*, hep-ph, January 2008.

[39] WH Smith, Ph Busson, S Dasu, J Hauser, G Heath, J Krolikowski, J Varela, A Taurok, G Wrochna, and P Zotto. Cms phyiscs technical design report: The trigger system. 1:1–630, Dec 2000.

[40] Daniel Stump, Joey Huston, Jon Pumplin, Wu-Ki Tung, H.L. Lai, et al. Inclusive jet production, parton distributions, and the search for new physics. *JHEP*, 0310:046, 2003.

DRAFT

[41] S Mrenna T. Sjöstrand and P Z Skands. PYTHIA 6.4 Physics and Manual. *JHEP*, 05:026, 2006.

[42] R.S. Thorne, A.D. Martin, W.J. Stirling, and G. Watt. Status of MRST/MSTW PDF sets. 2009.

[43] Maria Ubiali, Richard D. Ball, Luigi Del Debbio, Stefano Forte, Alberto Guffanti, et al. Combined PDF and strong coupling uncertainties at the LHC with NNPDF2.0. 2010.

[44] C Wulz. The CMS experiment at CERN. *cdsweb.cern.ch*.

DRAFT

1 Additional information on triggers

Table 1: List of HT triggers used.

H_{T} bin (GeV)	Trigger
$275 < H_{\mathrm{T}} < 325$	HLT_HT250_v*
$325 < H_{\mathrm{T}} < 375$	HLT_HT300_v*
$375 < H_{\mathrm{T}} < 475$	HLT_HT350_v*
$H_{\mathrm{T}} > 475$	HLT_HT400_v*

Table 2: List of α_T triggers used.

$275 < H_{\mathrm{T}} < 325GeV$	$325 < H_{\mathrm{T}} < 375GeV$
HLT_HT250_AlphaT0p53_v*	HLT_HT300_AlphaT0p52_v*
HLT_HT250_AlphaT0p55_v*	HLT_HT300_AlphaT0p53_v*
HLT_HT250_AlphaT0p58_v*	HLT_HT300_AlphaT0p54_v*
HLT_HT250_AlphaT0p60_v*	HLT_HT300_AlphaT0p55_v*
$375 < H_{\mathrm{T}} < 475GeV$	$H_{\mathrm{T}} > 475GeV$
HLT_HT350_AlphaT0p51_v*	HLT_HT400_AlphaT0p51_v*
HLT_HT350_AlphaT0p52_v*	HLT_HT400_AlphaT0p52_v*
HLT_HT350_AlphaT0p52_v*	
HLT_HT350_AlphaT0p53_v*	

Table 3: List of Mu_HT triggers used.

$H_{\mathrm{T}} > 275GeV$	$H_{\mathrm{T}} > 375GeV$
HLT_Mu5_HT200_v*	HLT_Mu5_HT200_v*
HLT_Mu8_HT200_v*	HLT_Mu8_HT200_v*
HLT_Mu15_HT200_v*	HLT_Mu15_HT200_v*
HLT_Mu30_HT200_v*	HLT_Mu30_HT200_v*
HLT_Mu40_HT200_v*	HLT_Mu40_HT200_v*
	HLT_Mu40_HT300_v*

DRAFT

Table 4: List of `Photon` triggers used.

$H_{\mathrm{T}} > 375GeV$
`HLT_Photon75_CaloIdVL_v*`
`HLT_Photon75_CaloIdVL_IsoL_v*`
`HLT_Photon90_CaloIdVL_v*`
`HLT_Photon90_CaloIdVL_IsoL_v*`
`HLT_Photon125_v*`
`HLT_Photon135_v*`

(a) Efficiency (%)

(b) Positive error (%)

(c) Negative error (%)

Figure 1: Efficiency and associated errors of the α_T trigger in offline bins of H_{T} and α_T.

DRAFT

(a) $275 < H_{\mathrm{T}} < 325GeV$ (b) $325 < H_{\mathrm{T}} < 375GeV$

(c) $375 < H_{\mathrm{T}} < 475GeV$ (d) $H_{\mathrm{T}} > 475GeV$

Figure 2: Efficiency turn-on curves for the α_T triggers used to collect events for four different HT regions.

Figure 3: Efficiency turn-on curve for the representative model RM1, with $m_0 = 320GeV$ and $m_{1/2} = 520GeV$, using the α_T trigger with thresholds $H_{\mathrm{T}} > 250GeV$ and $\alpha_T > 0.55$ and an offline signal region defined by $H_{\mathrm{T}} > 275GeV$ and $\alpha_T > 0.55$.

DRAFT

(a) $275 < H_{\mathrm{T}} < 325 GeV$

(b) $325 < H_{\mathrm{T}} < 375 GeV$

(c) $375 < H_{\mathrm{T}} < 475 GeV$

(d) $H_{\mathrm{T}} > 475 GeV$

Figure 4: Efficiency turn-on curves for the H_{T} triggers used to collect events for four different HT regions.

DRAFT

2 Addition information on background estimation methods

2.1 Determination of k_{QCD}

(a) Side-band region B.

(b) Side-band region C_1.

(c) Side-band region C_2.

(d) Side-band region C_3.

Figure 5: $R_{\alpha_T}(H_\mathrm{T})$ and exponential fit for various data side-bands. Linear y-axis scale.

DRAFT

3 Closure tests and systematic uncertainties

3.1 Defining muon samples without an α_T requirement

(a) μ + jets sample.

(b) $\mu\mu$ + jets sample.

(c) μ + jets sample with 1 b-tag.

(d) μ + jets sample with >1 b-tags.

Figure 6: Closure tests that demonstrate the MC modelling of the α_T acceptance. The closure tests are performed for both the inclusive analysis with (a) the μ + jets sample and (b) the $\mu\mu$ + jets control sample. Similar tests are performed for the b-tag analysis using (a) the μ + jets sample and a requirement of exactly one b-tag, and (b) the μ + jets sample and a requirement of at least two b-tags. The red lines indicate the constant best fit value across all H_{T} bins.

DRAFT

3.2 Closure tests for inclusive analysis

(a) (Note the different y-axis scale.) (b)

(c) (d)

Figure 7: Closure tests using yields from one control to predict yields in another sample. The two plots on the left show closure tests which use "low stats" muon samples recorded with the `HT_AlphaT` triggers and defined by offline selection criteria that include an α_T requirement: (a) μ + jets sample $\rightarrow$ $\mu\mu$ + jets sample and (c) γ + jets sample $\rightarrow$ $\mu\mu$ + jets sample. Similarly, the plots on the right show the same closure tests but using "high-stats" muon samples recorded with `Mu_HT` triggers and defined with no offline α_T requirement. The same tests are performed: (b) μ + jets sample $\rightarrow$ $\mu\mu$ + jets sample and (d) γ + jets sample $\rightarrow$ $\mu\mu$ + jets sample. These closure tests are only possible for the six highest H_{T} bins due to the trigger conditions. The red lines indicate the constant best fit value across all H_{T} bins.

DRAFT

3.3 Closure tests for b-tag analysis

(a) 0 b-tags predicting 1 b-tag.

(b) 1 b-tag predicting >1 b-tags.

(c) 0 b-tags predicting >1 b-tags.

Figure 8: Closure tests with the μ + jets sample that demonstrate the MC modelling of the b-tagging algorithm and of different sample compositions by for different b-tag multiplicities: (a) 0 b-tags $\rightarrow$ 1 b-tag, (b) 1 b-tags $\rightarrow$ $\geq$2 b-tags, (c) 0 b-tags $\rightarrow$ $\geq$2 b-tags.

DRAFT

(a) 0 b-tags.

(b) 1 b-tag.

Figure 9: Closure tests using the μ + jets sample to predict the yields in a $\mu\mu$ + jets sample, for events with (a) exactly 0-b-tags and (b) exactly 1-b-tags.

DRAFT

3.4 Closure tests concerning pile-up

Figure 10: Closure tests using yields from one control to predict yields in another sample. The three plots on the left show closure tests from the inclusive analysis, which uses jets that are not corrected for the effects of pile-up. On the right, the jets in the analysis *are* corrected for pile-up effects by applying the `L1Offset` jet energy correction. The three closure tests are: probing the MC modelling of the α_T acceptance with the μ + jets sample (a) without and (b) with `L1Offset` jet energy corrections; using the μ + jets sample to predict yields in the $\mu\mu$ + jets sample (a) without and (b) with `L1Offset` jet energy corrections; and using a 0 b-tagged μ + jets sample to predict yields in a 1 b-tagged μ + jets sample (a) without and (b) with `L1Offset` jet energy corrections. The red lines indicate the constant best fit value across all H_{T} bins.

4 Signal efficiency

4.1 CMSSM

(a) $N_{\mathrm{b-tag}} = 0$.

(b) $N_{\mathrm{b-tag}} = 1$.

(c) $N_{\mathrm{b-tag}} = 2$.

(d) $N_{\mathrm{b-tag}} \geq 3$.

Figure 11: Signal efficiency in the $(m_0, m_{1/2})$ plane of the CMSSM, of the full hadronic signal selection, integrating over all eight H_{T} bins and requiring (a) exactly zero, (b) exactly one, (c) exactly two, and (d) at least three b-tags per event.

DRAFT

4.2 T1

(a) $N_{\mathrm{b-tag}} = 0$.

(b) $N_{\mathrm{b-tag}} = 1$.

(c) $N_{\mathrm{b-tag}} = 2$.

(d) $N_{\mathrm{b-tag}} \geq 3$.

Figure 12: Signal efficiency in the $(m_{\mathrm{gl}}, m_{\mathrm{LSP}})$ plane of the T1 simplified model, of the full hadronic signal selection, integrating over all eight H_{T} bins and requiring (a) exactly zero, (b) exactly one, (c) exactly two, and (d) at least three b-tags per event.

Draft

4.3 T2

(a) $N_{\mathrm{b-tag}} = 0$.

(b) $N_{\mathrm{b-tag}} = 1$.

(c) $N_{\mathrm{b-tag}} = 2$.

(d) $N_{\mathrm{b-tag}} \geq 3$.

Figure 13: Signal efficiency in the $(m_{\mathrm{sq}}, m_{\mathrm{LSP}})$ plane of the T2 simplified model, of the full hadronic signal selection, integrating over all eight H_{T} bins and requiring (a) exactly zero, (b) exactly one, (c) exactly two, and (d) at least three b-tags per event.

Draft

4.4 T2tt

(a) $N_{\mathrm{b-tag}} = 0$.

(b) $N_{\mathrm{b-tag}} = 1$.

(c) $N_{\mathrm{b-tag}} = 2$.

(d) $N_{\mathrm{b-tag}} \geq 3$.

Figure 14: Signal efficiency in the $(m_{\mathrm{sq}}, m_{\mathrm{LSP}})$ plane of the `T2tt` simplified model, of the full hadronic signal selection, integrating over all eight H_{T} bins and requiring (a) exactly zero, (b) exactly one, (c) exactly two, and (d) at least three b-tags per event.

Draft

4.5 T2bb

(a) $N_{\mathrm{b-tag}} = 0$.

(b) $N_{\mathrm{b-tag}} = 1$.

(c) $N_{\mathrm{b-tag}} = 2$.

(d) $N_{\mathrm{b-tag}} \geq 3$.

Figure 15: Signal efficiency in the $(m_{\mathrm{sq}}, m_{\mathrm{LSP}})$ plane of the `T2bb` simplified model, of the full hadronic signal selection, integrating over all eight H_{T} bins and requiring (a) exactly zero, (b) exactly one, (c) exactly two, and (d) at least three b-tags per event.

Draft

4.6 T1tttt

(a) $N_{\mathrm{b-tag}} = 0$.

(b) $N_{\mathrm{b-tag}} = 1$.

(c) $N_{\mathrm{b-tag}} = 2$.

(d) $N_{\mathrm{b-tag}} \geq 3$.

Figure 16: Signal efficiency in the $(m_{\mathrm{gl}}, m_{\mathrm{LSP}})$ plane of the `T1tttt` simplified model, of the full hadronic signal selection, integrating over all eight H_{T} bins and requiring (a) exactly zero, (b) exactly one, (c) exactly two, and (d) at least three b-tags per event.

Draft

4.7 T1bbbb

(a) $N_{\mathrm{b-tag}} = 0$.

(b) $N_{\mathrm{b-tag}} = 1$.

(c) $N_{\mathrm{b-tag}} = 2$.

(d) $N_{\mathrm{b-tag}} \geq 3$.

Figure 17: Signal efficiency in the $(m_{\mathrm{gl}}, m_{\mathrm{LSP}})$ plane of the `T1bbbb` simplified model, of the full hadronic signal selection, integrating over all eight H_{T} bins and requiring (a) exactly zero, (b) exactly one, (c) exactly two, and (d) at least three b-tags per event.

Draft

4.8 Signal contamination for `T1tttt`

(a) Hadronic signal region, $N_{\mathrm{b-tag}} = 1$

(b) Muon control sample, $N_{\mathrm{b-tag}} = 1$

(c) Hadronic signal region, $N_{\mathrm{b-tag}} = 2$

(d) Muon control sample, $N_{\mathrm{b-tag}} = 2$

(e) Hadronic signal region, $N_{\mathrm{b-tag}} \geq 3$

(f) Muon control sample, $N_{\mathrm{b-tag}} \geq 3$

Figure 18: Signal efficiency in the planes of simplified model `T1tttt`, of the (left) hadronic signal sample selection or (right) single muon control sample selection, integrating over all eight H_{T} bins and requiring (top) exactly one, (middle) exactly two, or (bottom) at least three b-tags per event.

5 Experimental systematic uncertainties on signal efficiency times acceptance

5.1 Systematics due to jet energy scale uncertainties

(a) Varying the event scale up.

(b) Varying the event scale down.

(c) Combined distribution of (a) and (b) above. Only points within a ±60 GeV band around observed limit are considered.

Figure 19: The effect of jet energy scale variations on signal efficiency in the CMSSM plane. All plots show the relative change in efficiency. No requirement is made on the number of reconstructed b jets. The red shaded area is bounded by the 68th percentile.

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (T1)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (T2)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (T2tt)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (T2bb)

(e) $\widetilde{g}\widetilde{g} \to b\overline{b}\widetilde{\chi}^0 b\overline{b}\widetilde{\chi}^0$ (T1tttt)

(f) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (T1bbbb)

Figure 20: The fractional change in signal efficiency due to systematically increasing all jet energies, for various topologies. No requirement is made on the number of reconstructed b jets.

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (`T1`)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (`T2`)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (`T2tt`)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (`T2bb`)

(e) $\widetilde{g}\widetilde{g} \to b\overline{b}\widetilde{\chi}^0 b\overline{b}\widetilde{\chi}^0$ (`T1tttt`)

(f) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 21: The fractional change in signal efficiency due to systematically decreasing all jet energies, for various topologies. No requirement is made on the number of reconstructed b jets.

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (T1)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (T2)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (T2tt)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (T2bb)

(e) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (T1bbbb)

Figure 22: The fractional change in signal efficiency near to the diagonal due to systematically increasing or decreasing all jet energies, for various topologies. No requirement is made on the number of reconstructed b jets.

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (T1)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (T2)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (T2tt)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (T2bb)

(e) $\widetilde{g}\widetilde{g} \to b\overline{b}\widetilde{\chi}^0 b\overline{b}\widetilde{\chi}^0$ (T1tttt)

(f) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (T1bbbb)

Figure 23: The fractional change in signal efficiency far from the diagonal due to systematically increasing or decreasing all jet energies, for various topologies. No requirement is made on the number of reconstructed b jets.

5.2 Systematics due to the MHT/MET cut

(a) (b)

Figure 24: (a) Comparison of the MHT/MET distributions from data and MC, and (b) the ratio of the distributions, data/MC, as a function of the MHT/MET cut value.

(a) Fraction of expected signal yield rejected. (b) Fraction of expected signal yield rejected in a ±60 GeV band around the observed limit.

Figure 25: The fraction of expected signal yield that is rejected by the MHT/MET cut in the CMSSM plane. No requirement is made on the number of reconstructed b jets.

Table 5: Conservative estimates of inefficiency (%) for the MHT/MET cut when considering model points in the region near to the diagonal (i.e. small mass splitting and compressed spectra) for various simplified models.

	T1	T2	T2tt	T2bb	T1tttt	T1bbbb
Near	10.9	3.5	20.4	3.9	-	10.8
Far	3.2	0.9	3.1	1.2	32.4	3.7

DRAFT

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (T1)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (T2)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (T2tt)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (T2bb)

(e) $\widetilde{g}\widetilde{g} \to b\overline{b}\widetilde{\chi}^0 b\overline{b}\widetilde{\chi}^0$ (T1tttt)

(f) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (T1bbbb)

Figure 26: The fraction of expected signal yield that is rejected by the MHT/MET cleaning cut, for various topologies. No requirement is made on the number of reconstructed b jets.

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (`T1`)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (`T2`)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (`T2tt`)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (`T2bb`)

(e) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 27: The fraction of expected signal yield that is rejected by the MHT/MET cleaning cut, near to the diagonal, for various topologies. No requirement is made on the number of reconstructed b jets.

DRAFT

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (`T1`)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (`T2`)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (`T2tt`)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (`T2bb`)

(e) $\widetilde{g}\widetilde{g} \to b\overline{b}\widetilde{\chi}^0 b\overline{b}\widetilde{\chi}^0$ (`T1tttt`)

(f) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 28: The fraction of expected signal yield that is rejected by the MHT/MET cleaning cut, far from the diagonal, for various topologies. No requirement is made on the number of reconstructed b jets.

5.3 Systematics due to the dead ECAL cut

(a) Fraction of expected signal yield rejected.

(b) Fraction of expected signal yield rejected in a ±60 GeV band around the observed limit.

Figure 29: The fraction of expected signal yield that is rejected by the dead ECAL cut in the CMSSM plane. No requirement is made on the number of reconstructed b jets.

DRAFT

Table 6: Conservative estimates of inefficiency (%) for the dead ECAL cut when considering model points in the region near to the diagonal (i.e. small mass splitting and compressed spectra) for various simplified models.

	T1	T2	T2tt	T2bb	T1tttt	T1bbbb
Near	13.3	6.4	23.7	7.5	-	16.4
Far	13.6	5.8	9.4	6.2	27.6	13.9

5.4 Systematics due to the lepton and photon vetoes

DRAFT

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (`T1`)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (`T2`)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (`T2tt`)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (`T2bb`)

(e) $\widetilde{g}\widetilde{g} \to b\overline{b}\widetilde{\chi}^0 b\overline{b}\widetilde{\chi}^0$ (`T1tttt`)

(f) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 30: The fraction of expected signal yield that is rejected by the dead ECAL cleaning cut, for various topologies. No requirement is made on the number of reconstructed b jets.

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (`T1`)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (`T2`)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (`T2tt`)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (`T2bb`)

(e) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 31: The fraction of expected signal yield that is rejected by the dead ECAL cleaning cut, near to the diagonal, for various topologies. No requirement is made on the number of reconstructed b jets.

(a) $\widetilde{g}\widetilde{g} \to q\overline{q}\widetilde{\chi}^0 q\overline{q}\widetilde{\chi}^0$ (`T1`)

(b) $\widetilde{q}\widetilde{q} \to q\widetilde{\chi}^0\overline{q}\widetilde{\chi}^0$ (`T2`)

(c) $\widetilde{t}\widetilde{t} \to t\widetilde{\chi}^0\overline{t}\widetilde{\chi}^0$ (`T2tt`)

(d) $\widetilde{b}\widetilde{b} \to b\widetilde{\chi}^0\overline{b}\widetilde{\chi}^0$ (`T2bb`)

(e) $\widetilde{g}\widetilde{g} \to b\overline{b}\widetilde{\chi}^0 b\overline{b}\widetilde{\chi}^0$ (`T1tttt`)

(f) $\widetilde{g}\widetilde{g} \to t\overline{t}\widetilde{\chi}^0 t\overline{t}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 32: The fraction of expected signal yield that is rejected by the dead ECAL cleaning cut, far from the diagonal, for various topologies. No requirement is made on the number of reconstructed b jets.

(a) Fraction of expected signal yield rejected.

(b) Fraction of expected signal yield rejected in a ±60 GeV band around the observed limit.

Figure 33: The fraction of expected signal yield that is rejected by the dead ECAL cut in the CMSSM plane. No requirement is made on the number of reconstructed b jets.

(a) $\widetilde{\mathrm{t}}\widetilde{\mathrm{t}} \to \mathrm{t}\widetilde{\chi}^0\overline{\mathrm{t}}\widetilde{\chi}^0$ (`T2tt`)

(b) $\widetilde{\mathrm{b}}\widetilde{\mathrm{b}} \to \mathrm{b}\widetilde{\chi}^0\overline{\mathrm{b}}\widetilde{\chi}^0$ (`T2bb`)

(c) $\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to \mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0\mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0$ (`T1tttt`)

(d) $\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to \mathrm{t}\overline{\mathrm{t}}\widetilde{\chi}^0\mathrm{t}\overline{\mathrm{t}}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 34: The fraction of expected signal yield that is rejected by the lepton and photon vetoes, for various topologies. No requirement is made on the number of reconstructed b jets.

DRAFT

(a) $\widetilde{\mathrm{t}}\widetilde{\mathrm{t}} \to \mathrm{t}\widetilde{\chi}^0\overline{\mathrm{t}}\widetilde{\chi}^0$ (`T2tt`)

(b) $\widetilde{\mathrm{b}}\widetilde{\mathrm{b}} \to \mathrm{b}\widetilde{\chi}^0\overline{\mathrm{b}}\widetilde{\chi}^0$ (`T2bb`)

(c) $\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to \mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0\mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0$ (`T1tttt`)

Figure 35: The fraction of expected signal yield that is rejected by the lepton and photon vetoes, near to the diagonal, for various topologies. No requirement is made on the number of reconstructed b jets.

DRAFT

(a) $\widetilde{\mathrm{t}}\widetilde{\mathrm{t}} \to \mathrm{t}\widetilde{\chi}^0\overline{\mathrm{t}}\widetilde{\chi}^0$ (`T2tt`)

(b) $\widetilde{\mathrm{b}}\widetilde{\mathrm{b}} \to \mathrm{b}\widetilde{\chi}^0\overline{\mathrm{b}}\widetilde{\chi}^0$ (`T2bb`)

(c) $\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to \mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0\mathrm{b}\overline{\mathrm{b}}\widetilde{\chi}^0$ (`T1tttt`)

(d) $\widetilde{\mathrm{g}}\widetilde{\mathrm{g}} \to \mathrm{t}\overline{\mathrm{t}}\widetilde{\chi}^0\mathrm{t}\overline{\mathrm{t}}\widetilde{\chi}^0$ (`T1bbbb`)

Figure 36: The fraction of expected signal yield that is rejected by the lepton and photon vetoes, far from the diagonal, for various topologies. No requirement is made on the number of reconstructed b jets.

DRAFT