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

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Abstract

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

Declaration

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

Z. Hatherell
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Contents

Chapter 1

Introduction

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

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

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

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

Chapter 5 documents the design and verification of the novel background rejection variable α_{T}, using work undertaken by the author's analysis group in previous iterations of the analysis, and work on the leptonic definition undertaken by the author described in Section 5.5. The work presented in Chapter 6 is documented in a public CMS Physics Analysis Summary [1] and published in Physical Review Letters [2] in 2011. The work was undertaken by a small analysis group of which the author was a key active member singularly responsible for the μ control sample used for background prediction and in addition providing plots and yields for the signal selection. The work in Chapter 7 represents an extension to the published analysis that is the sole work of the author, using the aforementioned leptonic definition of the α_{T} variable.

Chapter 2

Extending the μ Control Sample to a Signal Sample

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

The cuts outlined in Section 6.9 are designed to select events from Standard Model W decays, hence minimising the contamination from signal. However, as the simultaneous fit includes the signal efficiency in the μ control sample it is possible to relax the cuts and allow more potential signal into the μ yield. Instead of viewing it as a control sample it may then be considered as a second signal sample in the simultaneous fit. The electroweak background behaviour is still constrained by the flat behaviour in $R_{\alpha_{\mathrm{T}}}$ whereas the presence of signal would exhibit an exponentially increasing behaviour. Thus it is possible to construct a dual-sample search in order to extend the reach of the analysis. The following work represents the author's personal investigation into the effect of increasing the chance for signal contamination in the μ selection on the eventual limit with the current dataset.

2.0.1 Relaxing the Cuts

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

The four μ selection criteria considered are therefore:

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

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

2.0.2 Event Yields

The bin-by-bin yields in Monte Carlo normalised to 1.1fb^{-1} for the Standard Model backgrounds (B) and potential signal (S) from LM6 are shown in Table 7.1. The values of the ratio ${}^{S}/\sqrt{B}$ are also shown as a measure of the potential significance of LM6 signal in each bin. As in the hadronic selection, where signal is present it shows the greatest significance with regards to background in the highest $H_T$bins. Removing the M_T cut raises the ratio ${}^{S}/\sqrt{B}$ in the highest three bins whilst in the lower bins $S/\sqrt{B}$ has fallen due to the increase of background. As expected removing the α_{T} cut lowers the $S/\sqrt{B}$ as more background enters the selection, but the available statistics are much higher. In the case where the muon is used in the α_{T} definition the ratio is imporved in all bins. The values in the highest two bins are large but currently suffer from low available Monte Carlo statistics in the SM backgrounds.

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

2.0.3 Fit Results

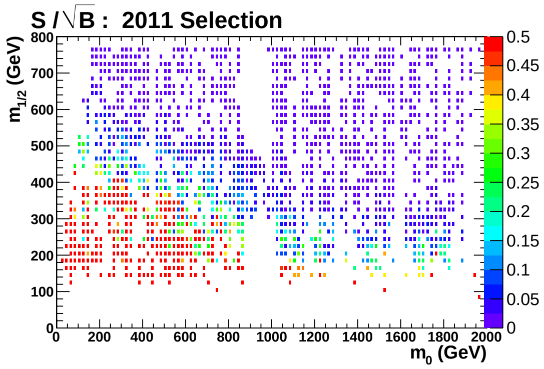
The event yields from the previous section are then entered into the simultaneous likelihood fit described previously in Section 6.12. The presence of signal in both the hadronic selection and the muon selection is allowed and the hadronic and photon sample results are unchanged from the 2011 analysis.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

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

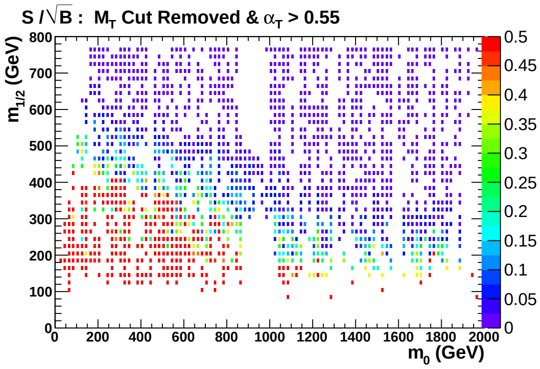
	H_{T} Bin (GeV)	275–325	325–375	375–475	475–575
2011 Selection	B (SM)	407.5	179.1	131.6	48.7
	S (LM6)	0.15	0.15	0.53	0.82
	$S/\sqrt{B}$	0.000	0.001	0.004	0.017
a) No M_T Cut & $\alpha_{\mathrm{T}} > 0.55$	B (SM)	549.93	243.33	179.51	63.80
	S (LM6)	0.19	0.20	0.59	0.92
	$S/\sqrt{B}$	0.000	0.001	0.003	0.0014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

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

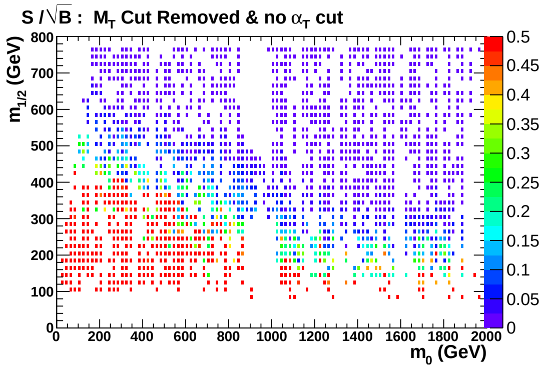
Table 2.1: Monte Carlo yields for μ control sample for Standard Model Monte Carlo (B) and potential SUSY signal from test point LM6. Four separate selection criteria are considered: 2011 Selection as detailed in Chapter 6 alongside three selections with the M_T cut removed and different approaches to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



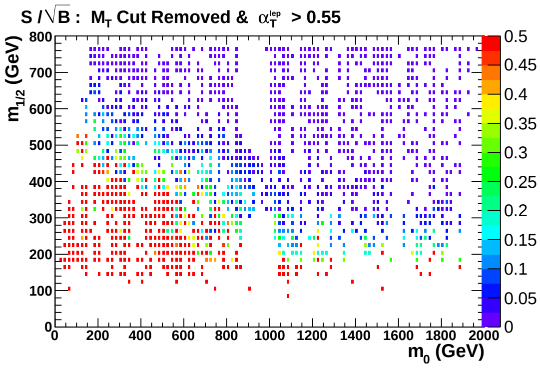
(a)



(b)



(c)



(d)

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

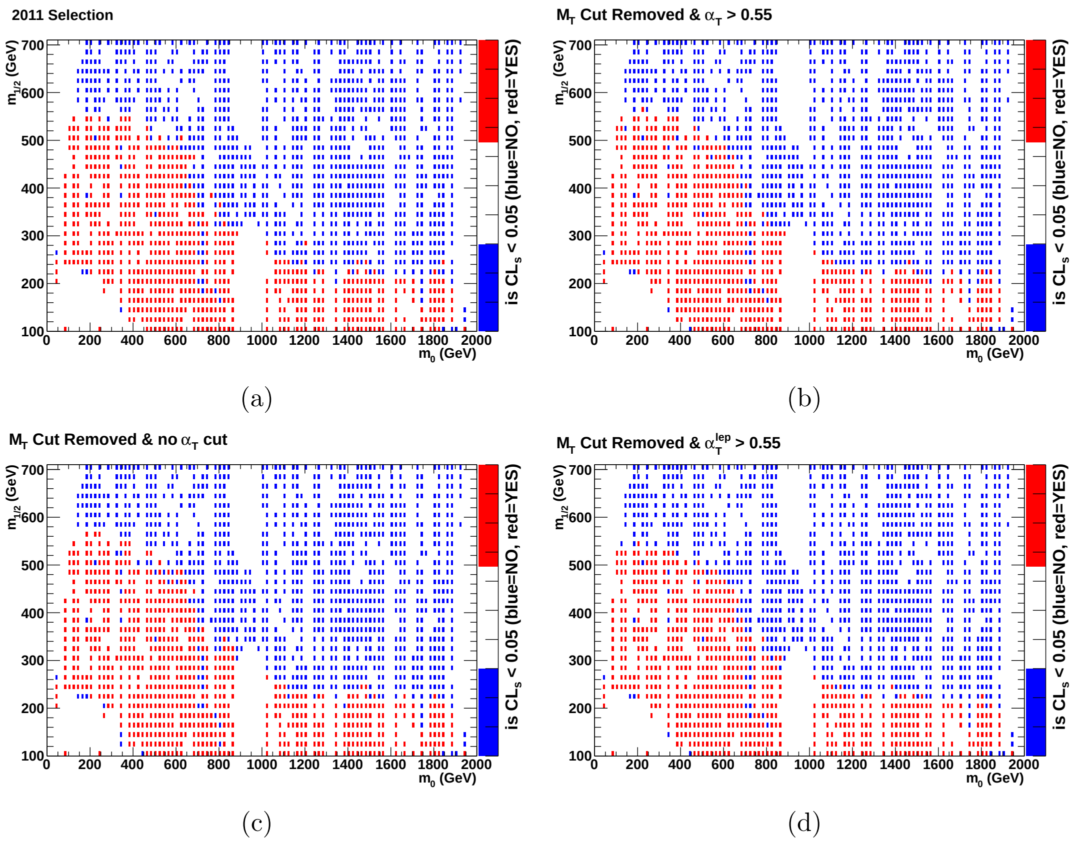


Figure 2.2: The CL_s exclusion limit for the four different μ selection criteria, with $CL_s < 0.05$ shown in red (excluded at 95% confidence) and $CL_s > 0.05$ shown in blue. Missing points are due to holes in Monte Carlo statistics. The 2011 Selection (a) is unchanged from Chapter 6 and corresponds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

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

2.1 Interpretation

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

Chapter 3

Conclusion

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

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

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

Having established that there is no distinction from the Standard Model hypothesis with this luminosity, the results are interpreted in the scope of the Constrained Minimal Supersymmetric Standard Model, in order to exclude regions of its parameter space. Using values of $\mathrm{A}_0 = 0$, $\tan\beta = 10$ and $sign(\mu)$ = +, the m_0 - m1/2 plane is probed using the CL_s statistical method and an exclusion limit is set at a 95% confidence level.

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

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

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

Appendix A

Data Samples

HT 1.1fb^{-1} Data

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

Photon 1.1fb^{-1} Data

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

Standard Model Background Monte Carlo

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

SUSY Signal Reference Monte Carlo

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

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

Process	Notes	σ / pb	# events
QCD (PYTHIA6)	$15 < \hat{p_T} < 30$ GeV	8.159×10^8	9,720,000
[Tune Z2]	$30 < \hat{p_T} < 50$ GeV	5.312×10^7	4,060,424
	$50 < H_T < 80$ GeV	6.359×10^6	5,605,000
	$80 < H_T < 120$ GeV	7.843×10^5	6,589956
	$120 < H_T < 170$ GeV	1.151×10^5	5,073528
	$170 < H_T < 300$ GeV	2.426×10^4	5,473,920
	$300 < H_T < 470$ GeV	1.168×10^3	4,452,669
	$470 < H_T < 600$ GeV	7.022×10^1	3,210,085
	$600 < H_T < 800$ GeV	1.555×10^1	4,105,695
	$800 < H_T < 1000$ GeV	1.844×10^0	3,833,888
	$1000 < H_T < 1400$ GeV	3.321×10^{-1}	2,053,222
	$1400 < H_T < 1800$ GeV	1.087×10^{-2}	2,156,200
	$H_T > 1800$ GeV	3.575×10^{-4}	273,139
QCD (MadGraph)	$100 < \hat{p_T} < 250$ GeV	8.891×10^6	21,066,112
[Tune Z2]	$250 < \hat{p_T} < 500$ GeV	2.174×10^5	20,594,219
	$500 < \hat{p_T} < 1000$ GeV	6.607×10^3	14,397,469
	$\hat{p_T} > 1000$ GeV	$\times 10^2$	6,294,851
γ + jets (MadGraph)	$40 < H_T < 100$ GeV	3.000×10^4	2,217,101
[Tune Z2]	$100 < H_T < 100$ GeV	4.415×10^3	1,065,691
	$H_T > 200$ GeV	1.054×10^2	1,142,171
W + Jets (MadGraph)	NNLO	3.131×10^4	46,608,773
$t\bar{t}$ + jets (MadGraph)	NLO	1.575×10^2	3,701,947
$Z \to \nu\bar{\nu}$ (MadGraph)	NNLO	5.715×10^3	2,165,002
LM4	-	1.879	218,380
LM6	-	3.104×10^{-1}	220,000

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