SUSY Searches in All-Hadronic States with Large MET at the LHC

M. Tytgat [a] (on behalf of the ATLAS & CMS Collaborations)

European Laboratory for Nuclear Research CERN, CH-1211 Geneva 23, Switzerland

Abstract. The CMS & ATLAS search strategy for SUSY in inclusive multijet plus high missing transverse energy final states is reviewed. This canonical SUSY signature may be a viable discovery channel for low mass SUSY in the early phase of the LHC. Methods for Standard Model background estimates, MET studies and filters for instrumental background are presented.

PACS. 11.30.Pb Supersymmetry – 12.60.-i Models beyond the standard model

1 Introduction

Supersymmetry (SUSY) is one of the most robust extensions of the Standard Model. Several compelling arguments are in favor of supersymmetry at the TeV scale, which should enable its discovery at the LHC. The simplest supersymmetrization of the Standard Model is known as the Minimal Supersymmetric Standard Model (MSSM) [1]. However, because of the large number of free parameter of this model, SUSY analysis studies are usually carried out in more constrained models which make certain assumptions on the SUSY breaking mechanism. Inclusive searches are mainly done in the framework of the minimal Supergravity (mSUGRA) model, which has only five independent parameters : the common gaugino mass the GUT scale $m_{1/2}$, the common scalar mass at the GUT scale m_0, the common trilinear coupling at the GUT scale A_0, the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta$ and the sign of the Higgsino mixing parameter $sign(\mu)$. If R-parity is conserved, the stable neutral lightest supersymmetric particle (LSP), which remains undetectable, will lead to SUSY event signatures with large missing energy. For their SUSY studies, both ATLAS and CMS have chozen a set of benchmark points to cover as much as possible the different event signatures that may occur in the different regions of the mSUGRA parameter space.

The cross section for sparticle production at the LHC is usually dominated by squark and gluino production. Their cascade decay results in final states characterized by multiple hard jets plus large E_T^{miss} plus often also one or more leptons [2]. Here, the main parts of the ATLAS and CMS inclusive SUSY searches in all-hadronic states, i.e. no leptons, will be discussed. More information on these analysis studies can be found in [3,4,5].

[a] Also at the University of Gent, Belgium; *Email:* michael.tytgat@cern.ch

2 Missing Transverse Energy

Missing E_T is a powerful tool for SUSY discovery, but it is also a complex object. Apart from real missing E_T due to undetected particles, it will include contributions from non-collision background such as beam halo or cosmic muons and from detector effects like instrumental noise, hot or dead channels or cracks in between different parts of the detector. For SUSY searches it is important to understand and remove such fake E_T^{miss} contributions, especially in the high tails of the distribution where SUSY signals are expected.

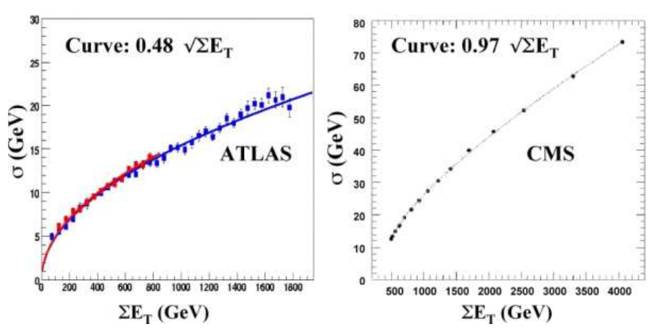

Fig. 1. The ATLAS (left) and CMS (right) Missing Transverse Energy resolution as function of the total transverse energy (ΣE_T) in the event for QCD jet production.

The missing E_T resolution is observed to depend on the overall activity of the event, which is characterized by the scalar sum of the transverse energy in all calorimeter cells, ΣE_T. Figure 1 displays the expected E_T^{miss} resolution as function of ΣE_T, obtained for QCD jet production for both the ATLAS and CMS detectors. The E_T^{miss} resolution for both experiments is expected to be dominated by the respective calorimeter resolutions.

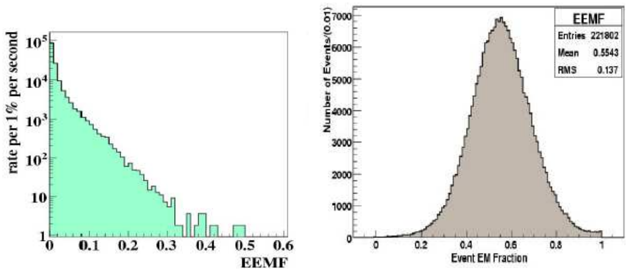

Fig. 2. The F_{em} for beam halo events in CMS (left) and for a $t\bar{t}$ event sample (right).

An E_T^{miss} cleanup procedure used by CMS is based on the event electromagnetic fraction

$$F_{em} = \frac{\sum_{j=1}^{N_{jet}} P_{Tj} \times f_{em}^{j}}{\sum_{j=1}^{N_{jet}} P_{Tj}}, \quad (1)$$

for jets within the calorimeter acceptance $|\eta| \leq 3$ and with f_{em}^{j} the jet electromagnetic fraction, and on the event charged fraction

$$F_{ch} = \left\langle \frac{(\sum_{i}^{tracks} P_{Ti})_j}{P_{Tj}} \right\rangle \Bigg|_{N_{jet}}, \quad (2)$$

where the average is taken over jets within $|\eta| < 1.7$ and the sum for every jet runs over the particle tracks that can be matched in (η, ϕ) space to that jet. This procedure is promising to remove cosmic ray events and accelerator- and detector-related backgrounds, like beam halo or electronic noise. The f_{em} of jets in cosmic or beam halo events will, depending on where the particles hit the electromagnetic or hadronic calorimeters, differ from the typical f_{em} for jets in normal collisional events. Also, the jet charged fractions in such events will be different due to the fact that very little or no particle tracks can be associated to them. Figure 2 shows the F_{em} for simulated beam halo events in the CMS detector and for a $t\bar{t}$ event sample for comparison. Requiring at least one primary vertex in the event and e.g. $F_{em} > 0.1$ and $F_{ch} > 0.175$ removes most of the background, while retaining ~ 91 % of the signal in a SUSY event sample at the CMS LM1 benchmark point.

3 Standard Model Backgrounds

Finding a SUSY signal requires not only a thorough understanding of the detector, but also a deep knowledge of all possible Standard Model background sources. To minimize systematic uncertainties from Monte Carlo model predictions, both ATLAS and CMS are studying methods to estimate backgrounds in SUSY searches directly from the data. Most important Standard Model background sources are QCD multi-jet production, top quark pairs, $Z/W+$ jets and diboson plus jets production.

In the case of e.g. W and $t\bar{t}$ production, high E_T^{miss} is normally associated to the presence of leptons in the final state, such that the all-hadronic channel will suffer from this type of background events only if the lepton identification fails. In addition, muons in contrast to electrons, leave very little energy in the calorimeters, so that in general they will also contribute to the E_T^{miss} if the muon identification fails.

3.1 QCD Jet Production

The very high cross section makes QCD jet production the dominant Standard Model background source in a multi-jet plus large missing transverse energy datasample. The missing transverse energy in QCD events is largely due to jet mis-measurements and detector resolution. The large cross section in combination with the trigger and data-acquisition bandwidth restrictions make it difficult to collect QCD datasets with low E_T thresholds and the extraction of shapes and normalizations for QCD background in SUSY searches will only be possible with prescaled triggers. However, for large missing transverse energy, jet mis-measurements are likely to pull the E_T^{miss} direction close in ϕ to the mis-measured jet direction. This means that topological requirements can be used to suppress QCD background contributions.

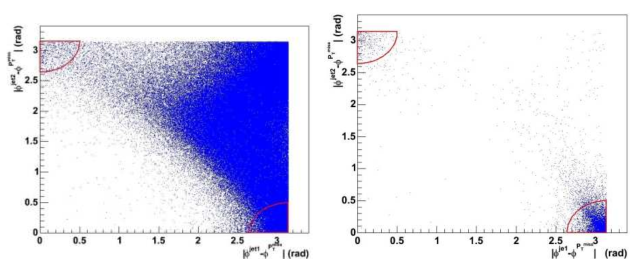

Fig. 3. $\delta\phi_1$ versus $\delta\phi_2$ for SUSY signal (left) and QCD di-jet events (right) for events with $R_{1,2} > 0.5$.

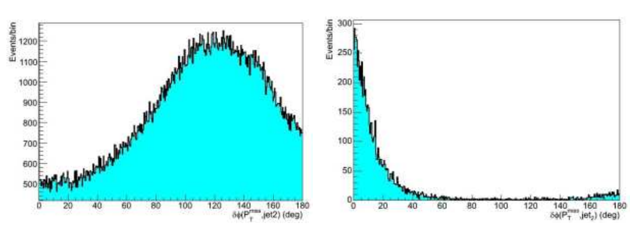

Fig. 4. $\delta\phi_2$ for SUSY signal (left) and QCD di-jet events (right).

CMS uses the correlation between $\delta\phi_1 = |\phi_{j(1))} - \phi(E_T^{miss})|$ and $\delta\phi_2 = |\phi_{j(2))} - \phi(E_T^{miss})|$ with $\phi_{j(1,2)}$ being the ϕ angle of the first and second leading jet in the event. In a first step, only events with $R_{1(2)} = \sqrt{\delta\phi_{2(1)}^2 + (\pi - \delta\phi_{1(2)})^2} > 0.5$ are accepted. Figure 3 shows $\delta\phi_1$ versus $\delta\phi_2$ for QCD di-jet and SUSY signal events at the CMS LM1 benchmark point. In addition no jet in the event should be closer than 0.3 rad to the E_T^{miss} direction and the second leading jet should be further than 20° from it as illustrated in Figure 4. Together with an event selection of $N_{jet} \geq 2$ and $E_T^{miss} > 93$ GeV these angular requirements retain ~ 90 % of the SUSY signal at the CMS LM1 benchmark point, while rejecting ~ 85 % of the QCD events.

3.2 W/Z Boson Production

$W(\to l\nu)$ and $Z(\to \nu\bar{\nu})$ boson production in association with jets will also give rise to final states with large E_T^{miss} plus multiple jets. Both ATLAS and CMS are developing methods to estimate all such contributions by combining Monte Carlo prediction with measured data to reduce systematic uncertainties due to e.g. the QCD renormalization scale, the choice of parton density function or jet energy scale.

A technique used by CMS relies on the fact that the $Z + N$ jets cross section is proportional to α_s^N, such that the ratio of the number of events in adjacent jet multiplicity bins is expected to be constant and proportional to α_s. In this way, the measured $Z(\to \mu\mu) + 2$ jets rate can be used to normalize the Monte Carlo predictions for $Z+ \geq 3$ jets via the measured $R \equiv \frac{\mathrm{d}N_{events}}{\mathrm{d}N_{jets}}$ ratio. In addition, the ratio $\rho \equiv \frac{\sigma(pp\to W(\to\mu\nu)+jets)}{\sigma(pp\to Z(\to\mu\mu)+jets)}$ can then be used to normalize the $W + jets$ Monte Carlo predictions. For 1 fb^{-1} a systematic uncertainty of ~ 5 % is obtained, which is dominated by the luminosity measurement and the uncertainties on the measured R and ρ.

3.3 Top Quark Pair Production

Due to its relatively large cross section and its typical multi-jet, high E_T^{miss} and leptonic final state, top quark pair production is a particular important background source for SUSY searches and therefore, estimating the top background directly from measured data is essential. Especially for the early data, both ATLAS and CMS are looking into reconstructing the $t\bar{t}$ channel without b-tagging.

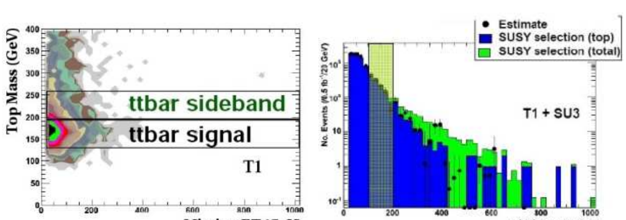

Fig. 5. Reconstructed top invariant mass versus E_T^{miss} for a $t\bar{t}$ sample (left) and E_T^{miss} for a $t\bar{t}$ and SUSY plus $t\bar{t}$ sample together with the normalized, estimated $t\bar{t}$ distribution (right).

A procedure used by ATLAS to estimate the $t\bar{t}$ contamination in SUSY analyses is illustrated in the left panel of Figure 5, where the reconstructed top invariant mass (no b-tagging used) for the semi-leptonic channel is displayed versus E_T^{miss}. An estimation of the E_T^{miss} distribution for $t\bar{t}$ production is determined in a signal region around the top quark mass and corrected for combinatorial background by subtracting the corresponding E_T^{miss} distribution taken from a top quark sideband region. The right panel of Figure 5 shows the E_T^{miss} distribution for a $t\bar{t}$ plus SUSY Monte Carlo event sample. By normalizing the estimated $t\bar{t}$ distribution to the total distribution in the low E_T^{miss} region, where the SUSY signal is small, one effectively obtains a fair description of the overall $t\bar{t}$ distribution also at high E_T^{miss}.

4 All-Hadronic SUSY Event Selection and Results

For the inclusive SUSY searches in all-hadronic states the typical event selection criteria used by ATLAS are $N_{jet} \geq 4$, $P_T^{j1} > 100$ GeV, $P_T^{j4} > 50$ GeV, $E_T^{miss} >$ 100 GeV, zero reconstructed leptons and transverse sphericity $S_T > 0.2$ to suppress e.g. QCD di-jet events.

The corresponding event selection in the CMS analysis is $N_{jet} \geq 3$, $E_T^{j1} > 180$ GeV, $E_T^{j2} > 110$ GeV, $E_T^{j3} > 30$ GeV, $E_T^{miss} > 200$ GeV plus additional E_T^{miss} clean-up criteria (see Section 2), topological cuts on $\Delta\phi$ between the jets and the E_T^{miss} direction for QCD jet suppression (see Section 3.1) and $H_T = E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{miss} > 500$ GeV. Instead of using explicit lepton identification, CMS uses an indirect lepton veto to reject W, Z and $t\bar{t}$ backgrounds, while retaining as much as possible the SUSY signal. This lepton veto removes events with high-energy electrons or muons and consists of two parts : events are only accepted if the first and second leading jet are not purely electromagnetic ($f_{em} < 0.9$) and if the leading high-P_T track in the event satisfies a certain non-isolated criterium.

Figure 6 displays the resulting E_T^{miss} distribution for multi-jet plus high E_T^{miss} SUSY searches with 1 fb^{-1} for both CMS and ATLAS after the abovementioned event selections. The CMS result is given at the LM1 benchmark point, with $m(\tilde{g}) \approx 600$ GeV and $m(\tilde{q}) \approx$ 550 GeV, while the ATLAS result is given for $\tilde{g}$ and $\tilde{q}$ mass scales of 0.5, 1.0, 1.5 TeV. For the low mass scale, both experiments expect a clear excess of events above the estimated Standard Model background.

5 mSUGRA Discovery Reach

Both ATLAS and CMS have performed a scan of the mSUGRA $(m_0, m_{1/2})$ plane. Figure 7 shows the 5σ reach contours for 1 fb^{-1} for both experiments, which for the all-hadronic searches appear quite comparable. The scans demonstrate that with 1 fb^{-1} all of the low mass region for $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ can

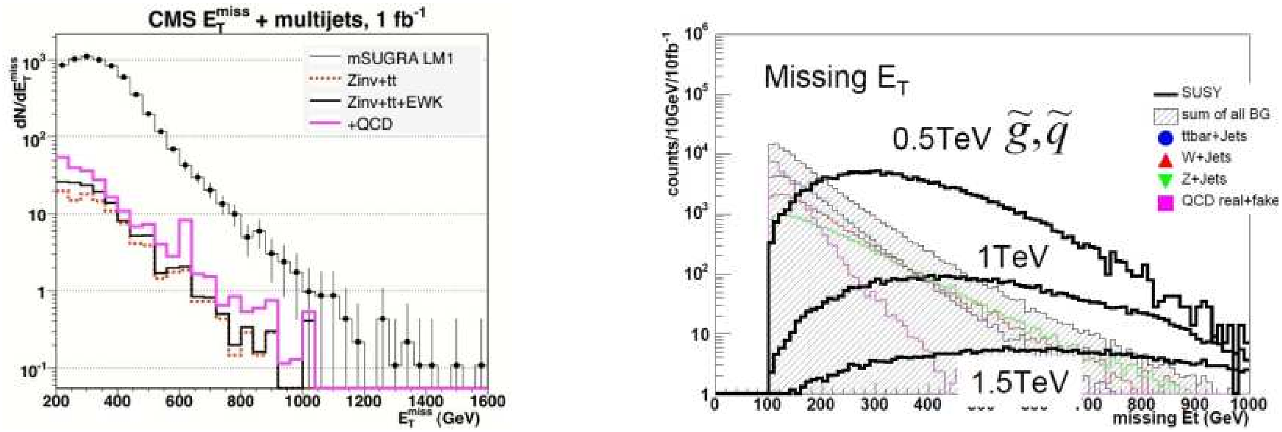

Fig. 6. E_T^{miss} distributions in all-hadronic SUSY searches for CMS (left) and ATLAS (right) with 1 fb^{-1}.

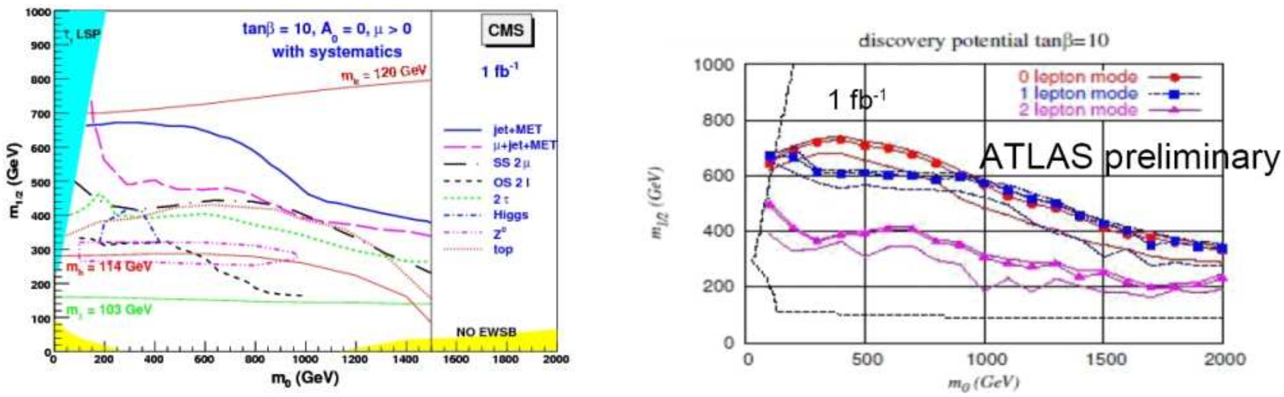

Fig. 7. 5σ mSUGRA discovery reaches for different channels for 1 fb^{-1} for CMS (left) and ATLAS (right).

be observed. The reach contours are also shown for other SUSY analysis studies. While these are also very promising, it is clear that the inclusive all-hadronic searches yield the best SUSY discovery potential for the early LHC data.

6 Conclusions

Using the inclusive multi-jet plus high E_T^{miss} event signature an early discovery of SUSY at the LHC should be possible if the latter would manifest itself at a low mass scale. Both the ATLAS and CMS analysis predict a comparable discovery reach in the mSUGRA parameter space for this all-hadronic channel. Of particular importance for SUSY discovery is a deep understanding of the observed missing transverse energy and correct estimates of the different Standard Model background sources, where data-driven methods are actively being studied by both collaborations.

7 Acknowledgements

The author would like to thank S. Asai and D. Tovey for providing the ATLAS results included in this contribution.

References

1. H.P. Nilles, Phys. Rep. **110**, (1984) 1 and references therein.
2. H. Baer, C.H. Chen, F. Paige and X. Tata, Phys. Rev. D **52**, (1995) 2746; Phys. Rev. D **53**, (1996) 6241.
3. The ATLAS Collaboration, CERN-LHCC-99-15 (1999).
4. The ATLAS Collaboration, ATLAS CSC Notes, *in preparation.*
5. The CMS Collaboration, CERN-LHCC-2006-021 (2006); J. Phys. G: Nucl. Part. Phys. **34**, (2007) 995-1574.