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SUSY at the LHC

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One of the unsolved problems of the standard model is the hierarchy problem. Supersymmetry models solve this problem naturally by the introduction of new particles that keep the mass of the Higgs boson at the EWK scale. The CMS and ATLAS experiments have developed various strategies to search for supersymmetry using the high-energy proton-proton collisions at LHC. This report presents a summary of the techniques used in these searches.

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1. Introduction

The supersymmetry [1](SUSY) is a potential symmetry between the fermions and the bosons of the standard model (SM) of particles proposing that each fermion has a bosonic superpartner and each boson has a fermionic superpartner. The main attraction of the SUSY models is that they solve the hierarchy and the fine-tuning problems of SM. Given that no sparticles have been observed it must be that SUSY is broken such that the sparticles are heavier than the particles.

One of the most studied SUSY models is the minimally supersymmetric standard model (MSSM) of particles. This model is an extension of SM postulating the conservation of the R-parity. The consequence of this conservation is the fact that the sparticles are produced in pairs and that they decay into an odd number of sparticles. This means further that the lightest supersymmetric particle (LSP) is stable. The LSP is still heavier than any SM particle, but it interacts very weakly with the matter making it a dark matter candidate.

Another postulate of MSSM is the soft SUSY breaking. There are several theoretical approaches to this, but this report will mention only a gravity mediated SUSY breaking (mSUGRA) case and the gauge mediated SUSY breaking (GMSB) case.

The strategy used in every search for SUSY is geared towards selecting events with very energetic observables: leptons, photons, jets, missing transverse energy ($\not{E}_T$) due to neutrinos and LSP. The event selection and the methods used in these searches [2] [3] are optimized on the simulation of a set of benchmark points defined by certain values of the SUSY parameters. These points are chosen such that a good coverage of the phase space is obtained beyond the current experimental and theoretical limits.

2. CMS and ATLAS detectors

The SUSY searches described in this report are using simulated 14 TeV proton-proton collisions followed by the simulation of the detector response to the resulting particles. The detectors used in these studies are the two general purpose detectors installed at LHC: ATLAS [4] and CMS [5]. The simulation of these detectors is made using GEANT4 [6] that takes into account a detailed description of the geometry of the detectors, the materials and the magnetic field. Although these two detectors have different designs and utilize different materials, the resolutions of the observables are similar resulting in similar sensitivity for new physics.

In order to perform any kind of analysis with the data obtained from these detectors, all the observables (i.e. jets, electrons, muons, photons, $\not{E}_T$) have to be well understood. Given its discriminating power in any search for SUSY, $\not{E}_T$ needs special attention. Besides potential undetected new particles, the sources for $\not{E}_T$ are many: cracks in the detector, cosmic rays, beam halo, electronic noise, and even SM processes (e.g. semileptonic decay of hadrons). At CMS it has been studied that the effect of the cosmic rays and of the beam halo can be minimized by selecting events with significant average electromagnetic fraction ($EEMF = (\sum_{jets} P_T^{jets} EMF^{jets})/(\sum_{jets} P_T^{jets}) > 0.1$) and average charged fraction ($ECHF = (\sum_{jets}(\sum_{tracks} P_T^{tracks})/P_T^{jets})/N_{jets} > 0.175$).

3. SM backgrounds

Another important part of the searches for SUSY is the evaluation of the SM background.

The SM processes have a much larger cross-section than the potential SUSY signal. For the LM1 benchmark point ($m_0 = 60$ GeV, $m_{1/2} = 250$ GeV, $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$) the leading order (LO) cross-section at 14 TeV is about 42 pb. The corresponding LO cross-sections for the most important SM backgrounds are: ≈5.6E10 pb for QCD events, ≈15E3 pb for events with a Z-boson produced in association with jets, and ≈800 pb for $t\bar{t}$ events. In order to minimize the systematic uncertainties due to potential differences between data and simulation, the strategy behind the evaluation of these backgrounds relies on data driven methods. Also with these methods there is no need to calibrate the simulation to the data.

The most important SM background is due to QCD processes. The first step in reducing this background is to take advantage of the topology of these events versus the SUSY events. At CMS it has been shown that the $\not\!\!E_T$ in QCD events tends to be aligned to one of the jets in the event due to energy mis-measurements, noise and dead cells in the calorimeter, and semileptonic decays. With some clever cuts on the angle between the leading jets and $\not\!\!E_T$, about 80% of the QCD events can be rejected, while keeping about 90% of the SUSY events. The remaining QCD content can be evaluated directly from data via two proposed methods: smearing method and ABCD method.

The smearing method, developed at ATLAS [7], relies on the parameterization of a response function from multijet events with high $\not\!\!E_T$ values and $\not\!\!E_T$ aligned with one of the jets. The response function is defined for each jet as $R = 1 - p_T^{jet}\cos(jet, \not\!\!E_T)/|p_T^{jet} + \not\!\!E_T|^2$ and it used to smear the jets from events with low $\not\!\!E_T$. The smearing of the jets will result in artificially created $\not\!\!E_T$ whose distribution agrees with the real $\not\!\!E_T$ distribution as it can be seen in figure 1. The normalization is obtained from the multijet data events with low $\not\!\!E_T$.

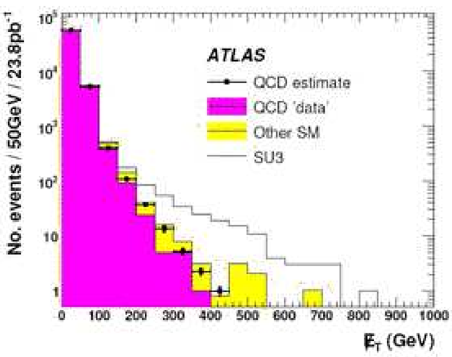

Figure 1: The $\not\!\!E_T$ distributions from QCD MC events (solid, red) and from smeared events (dots). The contributions from other SM processes (solid, yellow) and from SUSY SU3 events (line) are shown too. The SU3 is a low mass benchmark point with $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\beta = 6$, $A_0 = -300$, $\mu > 0$.

The ABCD method, developed at CMS, uses two uncorrelated observables and splits their plane in four regions: A, B, C and D. The splitting is done such that the SUSY signal is contained in region C. Given that the two observables are uncorrelated, the number of QCD events in region C can be derived from the number of QCD events in the other regions: $C = DxB/A$. For this method to work it is important to have little SUSY content in region A, B and D.

Another important SM background is produced by $Z \rightarrow \nu\nu$+jets events. This background is irreducible and there are few proposed ways to measure it. One method relies on the measurement of $\not{E}_T$ from $Z \to \mu\mu$+jets events where the muons are ignored. The normalization is set by taking into account the theoretical ratio of cross-sections between the $Z \to \nu\nu$ and $Z \to \mu\mu$ processes. This method has been pursued by both ATLAS [7] and CMS [3]. The plot on the left in Figure 2 shows the comparison between the distribution of effective mass (sum of $\not{E}_T$ and the transverse energies of jets) from $Z \to \nu\nu$+jets MC sample and the corresponding distribution from $Z \to \mu\mu$+jets events. Another method, developed at CMS [8], relies on γ+jets events with the photon being ignored in the event. This method benefits from a larger data sample, while the disadvantage is due to the uncertainty on the normalization. The plot on the right in Figure 2 shows the comparison between the $\not{E}_T$ distribution from $Z \to \nu\nu$+jets MC sample and the corresponding distributions using γ+jets events. The $Z \to \nu\nu$+jets events background can also be estimated from leptonic W decays where the lepton is ignored. This method [8] also benefits from a larger statistics compared to $Z \to \mu\mu$+jets, but less than γ+jets events.

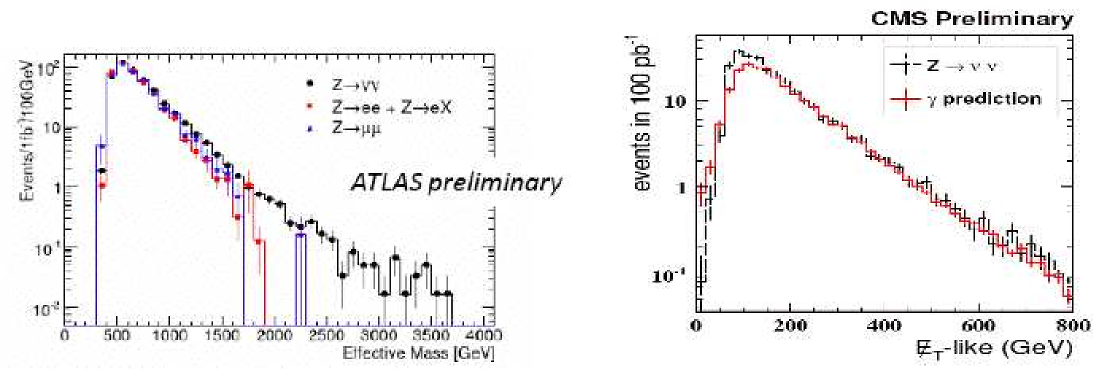

Figure 2: On the left, the comparison between the effective mass distribution from $Z \to \nu\nu$+jets MC sample and the corresponding distributions from $Z \to \mu\mu$+jets events. On the right, the comparison between the $\not{E}_T$ distribution from $Z \to \nu\nu$+jets MC sample and the corresponding distributions using γ+jets events.

In the case of searches for SUSY signal that involves a lepton in the final state, the semileptonic and the dilepton $t\bar{t}$ events represent an important background. The semileptonic contribution can be estimated by reconstructing the masses of the hadronic W boson (M_W) and of the top quark (M_{top}) from pairs and triplets of jets. A control sample is created from events with M_W and M_{top} within 25 GeV/c^2 and 15 GeV/c^2, respectively, of the corresponding world averages. Most of the SUSY events are not contained in this control region. The extrapolation of the semileptonic $t\bar{t}$ content in the SUSY signal region is made with the help of $t\bar{t}$ MC samples. The $t\bar{t}$ dilepton events contribute if at least one of the leptons is a hadronic τ or outside the acceptance or inside a jet. A control sample is made from events with two leptons and at least three jets. In this sample the $\not{E}_T$ distribution is formed where one of the leptons is ignored. The normalization is set from the events in the signal region with low $\not{E}_T$. These methods for estimating the $t\bar{t}$ background have been developed by ATLAS [7].

4. Inclusive and exclusive SUSY searches

With an understood detector and with the SM backgrounds under control, any excess in the data is more likely attributed to new physics. The most sensitive channel for SUSY discovery has only $\not\!\!E_{\rm T}$ and jets in the final state. Both CMS and ATLAS collaborations have devised triggers and event selections aimed at reducing the SM backgrounds while retaining a much of the SUSY signal. In CMS, the trigger requirement at Level 1 is $HT > 200$ GeV, while at High Level Trigger (HLT) the requirements are $HT > 350$ GeV and $\not\!\!E_{\rm T} > 65$ GeV [3]. Here HT represents the sum of the transverse energies of all jets in the event. The offline analysis requires events with at least 3 jets with $P_T > 30$ GeV/c and pseudo-rapidity $|\eta| < 3$ in the final state. The leading jet is also required to have $|\eta| < 1.7$ and $P_T > 180$ GeV/c, while the second leading jet must have $P_T > 110$ GeV/c. In addition to the QCD background rejection cuts described in Section 3, the events with loosely isolated tracks are rejected. Finally, the events are required to have $\not\!\!E_{\rm T} > 200$ GeV and $HT > 500$ GeV. Similarly to the event selection from CMS, the ATLAS collaboration requires at least four jets in the final state with transverse energies above 50 GeV, while the leading two jets should exceed 100 GeV [2]. The events with hard electrons or muons are rejected. The final selection cuts are $\not\!\!E_{\rm T} > 100$ GeV and $\not\!\!E_{\rm T}/M_{eff} > 0.2$. With these requirements $\approx$10 pb^{-1} of data is needed for observing an excess due to SUSY.

It expected that in the early days the $\not\!\!E_{\rm T}$ observable will be poorly understood. As studied by CMS [9], a new discriminating variable (α_T) is used instead of $\not\!\!E_{\rm T}$: the ratio between the transverse energy of the second leading jet and the invariant mass of the two leading jets. The dominant QCD dijet background can be dramatically reduced by requiring $\alpha_T > 0.55$. With an additional rejection of hard leptons and a third jet, the signal to background ratio is expected to be of order 6 and SUSY signal to be $\approx$400 events for 1 fb^{-1} of data.

Both CMS and ATLAS collaborations have extensive programs to search for SUSY in a variety of final states including leptons in the final state. The sensitivity of all these searches is summarized in Figure 3 for both CMS (left) [3] and ATLAS (right) [2] in the plane of m_0 and $m_{1/2}$. It can be seen that both experiments have similar reach in the allowed mSUGRA phase space.

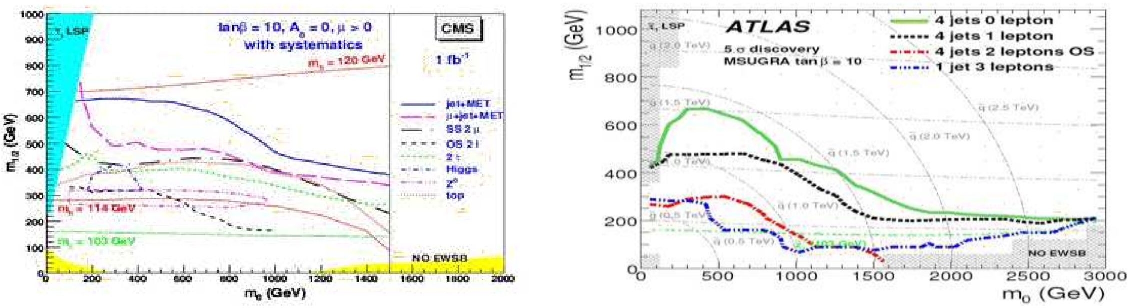

Figure 3: The sensitivity of various mSUGRA SUSY searches for both CMS (left) and ATLAS (right) in the plane of the common scalar mass (m_0) and the common gaugino mass ($m_{1/2}$).

The searches for GMSB SUSY models focus on two scenarios: one where NLSP is the neutralino and one where the NLSP is a slepton. In the first case, the NLSP decays into a photon and the LSP. The search in this case is geared towards the identification of a hard photon, pointing or not to the collision region. Both experiments [10] [11] will need $\approx$1 fb^{-1} of data to become sensitive to this scenario. In the second case, the NLSP decays outside the detector and behaves like a muon in the detector except for a smaller β. By determining β from the energy lost in the detector and measuring the momentum of this track the mass of the particle can be determined. At CMS [12], it is estimated that $\approx$100 pb^{-1} is needed for the observation of a 200 GeV stau.

Any excess observed in the data needs to be characterized by the measurement of as many parameters as possible: production cross-section, branching fractions, masses of the particles, etc. The most studied measurement is that of the dilepton mass edge. In the case of a SUSY signal with two leptons in the final state (e.g. $\tilde{g} \to q\tilde{q} \to qq_1\chi_2^0 \to qq_1l\tilde{l} \to qq_1ll_1\chi_1^0$), the invariant mass of the two leptons has a maximum that depends on the masses of the SUSY particles involved in the decay chain: $M_{ll_1}^{edge} = \sqrt{(m_{chi_2^0} - m_{\tilde{l}})^2(m_{\tilde{l}} - m_{chi_1^0})^2}/m_{\tilde{l}}$. Both CMS [13] and ATLAS [14] need about 1 fb^{-1} of data to measure this mass edge with precision.

5. Conclusion

Many signatures for SUSY have been studied by both the ATLAS and the CMS collaborations and very promising prospects exist with little integrated luminosity. A variety of methods are in place ready to be applied. The two collaborations need to complete the understanding of their detectors, triggers, reconstructed variables and SM backgrounds to allow them to characterize a large region of the SUSY parameter space. Within the next years it is expected to either discover SUSY or to push its mass scale so high that it no longer solves naturally the hierarchy problem.

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