Early searches for new physics with τ leptons using the ATLAS detector

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In many new physics models, the third generation plays a special role. τ leptons are a sensitive probe of new phenomena such as supersymmetry, even in early LHC data taken at a center-of-mass energy of 7 TeV. We report on an early search for new physics, the performance of the detector for such searches, and the expectations for the 2010-2011 LHC run.

1. Introduction

The main goals of the multi-purpose experiments ATLAS [1] and CMS [2] at the LHC [3] are the study of electroweak symmetry breaking and the search for physics beyond the Standard Model (SM). Among many proposed extensions of the SM, supersymmetry (SUSY) is considered a key candidate because it solves several shortcomings of the SM in an elegant way. The most intensively studied scenarios are minimal Super Gravity (mSUGRA) and Gauge Mediated Supersymmetry Breaking (GMSB) models. Due to the mixing in the third family the $\tilde{\tau}$ is often the lightest slepton inducing final states containing several τ leptons.

After a brief introduction of the most important reconstruction algorithms in ATLAS, early searches for SUSY with an integrated luminosity of 70 nb^{-1} are presented. In addition prospects for the discovery reach of ATLAS with higher center-of-mass energies for SUSY models and possible measurements of SUSY properties are described in more detail.

2. Object reconstruction in ATLAS

The topologies of many SUSY searches include jets and missing transverse energy (E_T^{miss}) often in combination with light leptons or τ leptons. The main production processes of SUSY at a hadron collider such as the LHC are squark and gluino production. Their decay causes long decay chains including many jets. If R-parity is conserved the lightest supersymmetric particle (LSP)

will be stable and only weakly interacting causing a large amount of E_T^{miss} . Depending on their masses and couplings, sleptons including $\tilde{\tau}$ are part of the decay chains and light leptons and τ are present in the final state of SUSY events. Therefore, to perform a thorough search a well understood jet reconstruction as well as a well calibrated E_T^{miss} is just as crucial for a SUSY analysis as the efficient reconstruction of τ leptons.

2.1. Reconstruction of jets

In ATLAS the reconstruction of jets is performed using the anti- k_t algorithm [4] with a distance parameter of $R = 0.4$ (0.6) starting from calorimeter topological clusters [5]. Fake jets are expected from calorimeter noise and cosmic ray events. They are rejected by requiring a specific maximum energy fraction in the hadronic endcap or the electromagnetic calorimeter [6]. Furthermore, cosmic ray events do usually not coincide with the timing of the bunch crossings.

Jets are reconstructed based on energy deposits in the calorimeters. Their energy is corrected to the jet scale using p_T and η dependent calibration factors derived from Monte Carlo. The relative jet energy scale uncertainty is the dominant uncertainty for many SUSY studies. It has been estimated to be 9.4% (10%) in the central (endcap) region for $p_T^{\text{jet}} < 60 \text{ GeV}$ and 7% (7.6%) for higher p_T^{jet} [6]. In addition, it results in an uncertainty on the E_T^{miss} measurement and therefore in a systematic uncertainty on the number of events in searches requiring jets.

Figure 1. Background efficiencies in data and MC as a function of p_T with the same selection for the cut-based, BDT, and LL identification [10].

2.2. Reconstruction of E_T^{miss}

The E_T^{miss} reconstruction [7] is based on calorimeter cells. The dominant contributions are E_T energy deposits in the calorimeters. For the correct calculation a careful cleaning of the events is required. Data quality requirements include the beam conditions and the detector status.

For the event selection the following requirements are set: events have been triggered by the Minimum Bias Trigger Scintillators (MBTS), a primary vertex with at least five reconstructed tracks has been found, timing criteria in the calorimeters have to be fulfilled and the reconstructed jets considered for the calculation need to fulfill quality requirements [8]. In addition, the E_T^{miss} needs to be corrected for contributions from muons, energy loss in the cryostat, and dead material. Fake E_T^{miss} is mostly due to misreconstructed jets and can often be reduced by requiring a minimum angle between the leading jets and the reconstructed E_T^{miss} .

2.3. Reconstruction of τ leptons

Hadronically decaying τ leptons are reconstructed from either calorimeter or track seeds [9]. Track-seeded candidates are based on good quality tracks whereas calorimeter-seeded candidates are based on calorimeter jets reconstructed with the anit- k_t algorithm starting from topological clusters. Since the reconstruction of τ candi-

dates provides only little rejection against QCD background a further identification step is required. Identification methods for τ candidates include selections based on simple cuts, a boosted decision tree (BDT), or a projective likelihood method (LL) [10]. Those methods are based on several discriminating variables exploiting that τ candidates are characterized by collimated energy deposits in the calorimeter and one or few collimated tracks. A comparison of the three methods in data and MC is shown in Fig. 1.

3. Early SUSY searches using data

As a first step towards SUSY searches a comparison of important kinematic variables in various channels has been performed using data representing a total integrated luminosity of 70 nb^{-1} recorded from March 2010 to July 2010. A good agreement between data and MC has been found indicating that the SM backgrounds to searches for BSM physics are well under control [11–13].

3.1. The 0-lepton channel

The channels analysed include one to four jets [11]. The preselection consists of a calorimeter jet trigger, the number of tracks in the primary vertex to be at least five and no lepton with a $p_T > 10 \text{ GeV}$. In the two-jet channel the transverse momentum of the first and second jet need to exceed $p_T^{\text{jet1}} > 70 \text{ GeV}$ and $p_T^{\text{jet2}} > 30 \text{ GeV}$, respectively. Several distributions have been compared and the agreement between data and the MC expectation has been found to be very good after the number of MC QCD events has been normalized to the number of data events. The main sources of the total uncertainty are the jet energy scale, the integrated luminosity, and statistical uncertainties.

Before applying final selection cuts all distributions are dominated by events from QCD processes. These can be reduced by applying cuts on E_T^{miss} , M_{eff} and $\Delta\phi(p_T^{\text{jet}}, E_T^{\text{miss}})$. M_{eff} is defined as the sum of the p_T^{jet} of the jets defining the analysis channel and E_T^{miss} . Its distribution after the final selection is shown in Fig. 2. The enhanced distribution of a typical mSUGRA benchmark point (SU4) has been superimposed [11]. In

Figure 2. The M_{eff} distribution for events in the two-jet channel after preselection and final cuts have been applied.

data 4 events have been found which is compatible with the MC expectation of 6.6 ± 3.0 events.

3.2. The 1-/2-lepton channel

To account for the many models in which sleptons might be part of the decay chain a complementary search not only requiring jets and E_T^{miss} but one or two additional light leptons is performed [12]. The preselection is similar to the one mentioned above. However, the jet requirements are loosened to $p_T^{\text{jet}} > 30$ GeV and one isolated lepton with $p_T > 20$ GeV (second lepton with $p_T > 10$ GeV) is required. An additional uncertainty in this channel is the lepton fake rate which has been estimated from samples where the cut on the lepton isolation has been inverted.

For the low E_T^{miss} region, again QCD is the dominant background in this channel. For larger E_T^{miss} values the background distribution is dominated by W +jet events due to the lepton requirement. The reduction of this background is achieved by introducing the transverse mass as an additional cut variable. Its square is defined as $m_T^2 \equiv 2|\mathbf{p}_T^\ell||E_T^{\text{miss}}| - \mathbf{p}_T^\ell \cdot \vec{E}_T^{\text{miss}}$. Requiring $E_T^{\text{miss}} > 30$ GeV and $m_T > 100$ GeV reduces the number of events in data to 2 which is compatible with the SM expectation of 3.6 ± 1.6 MC events. Figure 3 shows the E_T^{miss} distribution after the preselection and the additional m_T re-

Figure 3. The E_T^{miss} distribution for events in the electron channel after preselection cuts and a final cut on m_T have been applied [12].

quirement illustrating again the good agreement between data and MC.

4. Prospects for SUSY discovery

SUSY models generically violate $e/\mu/\tau$ universality. τ decays can be dominant, especially for $\tan \beta \gg 1$. Hence it is worthwhile to look for signatures involving hadronic τ decays even though the fake- τ background from QCD jets is much larger than that for e or μ . In the following the discovery reach for two different SUSY models with ATLAS will be presented in addition to an invariant mass study.

4.1. Study of τ final states in GMSB

In GMSB models the breaking is communicated from the hidden to the visible sector through a flavor-blind SM gauge interaction via messenger fields at a scale M_m (mass of the messenger fields) small compared to the Planck mass. The overall mass scale for all MSSM superpartners is set by Λ , the scale of the SUSY breaking. In these models the lightest supersymmetric particle (LSP) is usually the very light gravitino ($m_{\tilde{G}} \ll 1$ keV), while the next-to-lightest supersymmetric particle (NLSP) is either a neutralino or a slepton. In case of $\tan \beta > 10$ the NLSP is a $\tilde{\tau}$ in a wide range of the GMSB parameter space and events with large E_T^{miss} , highly energetic jets and up to four τ leptons are expected [14].

Figure 4. Distribution of E_T^{miss} after the preselection has been applied and at least two τ leptons are required [14].

To investigate the discovery potential a MC study assuming an integrated luminosity of 200pb^{-1} and $\sqrt{s} = 10\text{ TeV}$ has been carried out. The event selection includes a jet+ E_T^{miss} trigger. The objects required are two high- p_T jets and at least one reconstructed τ lepton with $p_T > 20\text{ GeV}$. In addition events not fulfilling $E_T^{\text{miss}} > 60\text{ GeV}$ and $\Delta\phi(p_T^{\text{jet1}}, E_T^{\text{miss}}) > 0.2$ are rejected. The optimisation of the signal significance for the benchmark point GMSB6 [14] led to the final selection of two τ leptons and $E_T^{\text{miss}} > 280\text{ GeV}$. Applying these two additional requirements, 20.4 ± 0.7 signal events are expected while the total number of expected SM background events is 2.5 ± 1.5 yielding a signal significance of 5.7. The significance calculation includes uncertainties on the background by convoluting the Poisson probability that the background fluctuates to the observed signal with a Gaussian background probability function [15].

The discovery potential is studied in the $(\Lambda, \tan\beta)$ plane for a fixed set of the other four model parameters since Λ and $\tan\beta$ have the strongest influence on the event topology. The chosen parameter values restrict the analysis to specific phenomenologies resulting in final states with promptly decaying NLSPs.

Figure 5. The integrated luminosity needed for a 5σ discovery in the two-dimensional parameter space of GMSB. In addition, the different NLSP regions are indicated as well as the limit on the $\tilde{\tau}$ mass set by LEP.

The cross section strongly depends on Λ due to the increase of the masses of the SUSY particles with increasing Λ while only a small dependence on $\tan\beta$ can be observed. This mentioned decrease of the cross section is reflected in the values of the total number of selected signal events. In addition the nature of the NLSP has a strong influence on the number of selected events. While the regions with a $\tilde{\tau}$ NLSP feature a large fraction of selected events, selection losses can be observed in regions where the NLSP is given by $\tilde{L}_R, \tilde{\chi}_1^0$ or in the CoNLSP region due to the dominant final states with electrons, muons or photons for which the selection is not optimised.

The number of selected signal events in the $(\Lambda, \tan\beta)$ plane and the expected number of background events can be translated into a signal significance as a function of the integrated luminosity. The corresponding results are shown in Fig. 5. As expected, the integrated luminosity needed for a 5σ discovery is small in regions with a $\tilde{\tau}$ NLSP and small/medium values of Λ . At 10 TeV , with a luminosity of only 200pb^{-1} a 5σ discovery can be achieved in the parameter space region up to $\Lambda = 40\text{ TeV}$. Due to the strong reduction of the cross section the signal significance strongly decreases with increasing Λ leading to 5σ region up to $\Lambda = 45\text{ TeV}$ for 1fb^{-1} of data.

Figure 6. The discovery reach in the mSUGRA plane with an integrated luminosity of 1 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$.

4.2. Study of τ final states in mSUGRA

In mSUGRA models the SUSY breaking is mediated by gravitational interaction. In most of these scenarios the lightest neutralino is the LSP. Due to $m_{\tilde{\chi}_1^0} \approx \mathcal{O}(\text{GeV})$ not only the NLSP decays into the LSP but also heavier particles yielding various final states for one benchmark point.

The event selection is very similar to the one in the GMSB analysis. However, since this study has been performed for $\sqrt{s} = 14 \text{ TeV}$, four jets are required. In addition, events containing a reconstructed lepton with $p_T > 10 \text{ GeV}$ are rejected. The E_T^{miss} cut is slightly higher and needs to fulfill $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$ as well. An additional cut on $m_T > 100 \text{ GeV}$ is introduced. This selection allows a sufficient reduction of the main SM backgrounds including QCD, $t\bar{t}$ and W/Z +jets.

Figure 6 shows the discovery reach for $\tan \beta = 50$. Despite the enhanced contribution from τ decays due to $\tan \beta \gg 1$ the one- τ discovery reach is slightly worse than that for zero or one light lepton. This reflects the lower efficiency and purity for τ reconstruction. For these mSUGRA models a discovery up to $m_{\tilde{q}} \approx 1.1 \text{ TeV}$ might be possible with 1 fb^{-1} of collected data.

Once a signature consistent with SUSY has been established, the experimental emphasis will move on to measuring the sparticle mass spec-

Figure 7. Invariant mass distribution of OS τ pairs with SS τ distribution subtracted.

trum and constraining the parameters of the model. In case of R-parity-conserving models, the decay chain of sparticles cannot be completely reconstructed, as sparticles eventually decay into LSPs that cannot be detected. For this reason edge positions, rather than mass peaks, are measured in the invariant mass distribution of sparticle decay products [15].

The endpoint of the invariant mass distribution from two τ leptons emerging from a $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau \rightarrow \tilde{\chi}_1^0 \tau\tau$ decay depends on the masses of the $\tilde{\chi}_2^0$, the $\tilde{\chi}_1^0$, and the $\tilde{\tau}$, and therefore can contribute to the determination of SUSY parameters.

The invariant mass distribution emerging after the cuts described above are applied is shown in Fig. 7 where the corresponding $m_{\tau\tau}$ distribution of two reconstructed τ leptons with same sign electric charges (SS) is subtracted from τ pairs with opposite sign (OS) in order to account for combinatorial background. This is possible because uncorrelated and fake τ leptons should arise about as often with the same charge as with opposite charges. To further decrease background from other SUSY channels, the two τ leptons are required to have a maximum separation $\Delta R < 2$ in the $(\eta-\phi)$ plane¹.

Due to the peculiar τ decay, the mass edge of the invariant mass distribution of two τ leptons is not as distinct as it is for the invariant mass distribution of two light leptons. Hence, the end-

¹The separation is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

point of the invariant mass distribution cannot be measured directly and a fit of the invariant mass distribution has to be performed. From the fit function the inflection point can be extracted.

To estimate the endpoint from the inflection point, a calibration curve of expected inflection points versus the theoretical kinematic endpoints has been determined from MC samples featuring various $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$, and $\tilde{\tau}$ masses. The correlation between the inflection point and the endpoint has been found to be linear demonstrating that measuring the inflection point is equivalent to measuring the endpoint.

5. Conclusions

Since the beginning of data taking at the LHC at a center-of-mass energy of 7 TeV many physics analyses have been performed. The object reconstruction algorithms have been tested and refined and their performance has been estimated. For early searches the shape of many crucial kinematic variables in data has been compared to the MC expectation and a very good agreement has been found. Studies of the prospects for a discovery of various SUSY models have been carried out for different center-of-mass energies. In these searches for new physics the third lepton generation provides a very interesting signature and a powerful tool to separate a possible signal from SM background. Until the end of the year 2011 it is expected to collect 1fb^{-1} of data. This amount will be sufficient to give a first hint towards new physics and set exclusion limits exceeding those from LEP and Tevatron [16].

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