Recent results from CMS on SUSY searches in leptonic final states

Robert Schöfbeck
Institute of High Energy Physics, Nikolsdorfergasse 18, Vienna, Austria
E-mail: robert.schoefbeck@cern.ch

Abstract. We present the results of searches for new physics in various topologies that lead to one or more isolated leptons, jets, and missing transverse energy in the final state. The searches are performed using 35 pb$^{-1}$ of data collected in 2010 by the CMS experiment at the LHC in pp-collisions at a center-of-mass energy of 7 TeV. No evidence for new physics is observed and limits are set on the production cross-section times the event acceptance for the searched topologies and in terms of the cMSSM.

1. Introduction

The vast majority of measurements with previous high-energy particle physics experiments below the TeV-scale can be successfully described by the Standard Model (SM) [1, 2]. It contains three generations of matter and is a gauge theory with a spontaneously broken electroweak sector where particles acquire their masses through the elusive Higgs boson. Searches for new physics beyond the Standard Model are motivated by several considerations, ranging from strong astrophysical evidence for “Dark Matter”, to theoretical problems associated with explaining the observed particle masses and with maintaining the mass hierarchies in the presence of quantum corrections [3, 4]. Thus, in spite of its success in describing a vast range of phenomena, the SM is almost certainly incomplete as a description of fundamental particles and their interactions.

One of the most interesting candidates for physics beyond the Standard Model (BSM) is Supersymmetry (SUSY) [5, 6, 7, 8, 9, 10, 11]. This theoretical framework addresses - at least partially - many of the limitations of the SM. SUSY models predict a spectrum of new particles arising from a correspondence between SM fermions and SUSY partner bosons, and between SM bosons and SUSY partner fermions.

At the Large Hadron Collider (LHC) at CERN, supersymmetric particles, if they exist, are predicted to be produced dominantly via strong interactions, through the fusion of two gluons into a pair of gluinos (super-partners of the gluons), a pair of squarks (super-partners of the quarks), or a gluino and a squark. The LHC, with a proton-proton centre-of-mass energy $\sqrt{s}$ of 7 TeV, is a copious source of high-energy partons which allows experiments to probe supersymmetry beyond the limits previously set at LEP and at the Tevatron. Squarks and gluinos initiate a decay cascade in which quarks and subsequently other SM particles are produced, until the lightest supersymmetric particle (LSP) is created. The dynamics of the cascade depends on the SUSY model under consideration, and in particular on the masses of SUSY particles.
the supersymmetric particles. If R-parity is conserved, the LSP is unable to decay into SM particles and is therefore stable. If, in addition, the LSP is a neutralino, it is weakly interacting and thus escapes direct detection, generating missing transverse energy (E_{miss}^T) in the final state.

In these proceedings, the emphasis is put on the most recent leptonic analyses. Other important search fields such as hadronic signatures are also being covered by CMS [12, 13, 14].

Leptons can appear in the final state, for example if heavy neutralinos (χ_0^2 → l^± l^∓ → l^± l^∓ χ_1^0) or charginos (χ_±^1 → χ_0^0 W^±) are created in the decay cascades of the squark or gluino. All searches are performed using LHC data recorded with the CMS detector, corresponding to an integrated luminosity of 35 pb^{-1}. With an optimistic assumption of a typical SUSY cross-section of 2 pb, this translates into approximately 70 signal events. This should be contrasted to the expected SM yield of e.g. 5500 events from t̄t when assuming the NLO value of this cross-section (157.5 pb).

2. Single lepton search
The single lepton analysis [15] selects events featuring jets, E_{miss}^T, and a single lepton in the final state. The presence of the lepton strongly reduces the contribution of the QCD multi-jet and Z → νν+jets backgrounds, and provides several handles to build a data-driven prediction of the remaining background contribution from QCD, t̄t, and W+jets. Events containing an additional lepton are vetoed, and handled by the di-lepton and multi-lepton analyses.

The event sample was collected using triggers based on the presence of a single electron or a single muon. The requirement of an H_T trigger was added when the peak luminosity increased beyond 2 × 10^{32} cm^{-2}s^{-1}. Here, H_T is the scalar sum of the transverse momenta of all jets as reconstructed at the trigger level^2. The trigger selection is fully efficient with respect to the baseline selection applied offline, which consists of requiring (i) four jets with p_T > 30 GeV and |η| < 2.4 with H_T > 500 GeV; (ii) an isolated lepton, which can be either a muon with p_T > 20 GeV and |η| < 2.1, or an electron with p_T > 20 GeV and |η| < 2.4. H_T is the scalar sum over the transverse momenta of all jets above a threshold of 30 GeV. The search region is defined by an additional cut on the missing transverse energy, E_{miss}^T > 250 GeV. The contribution of the main background processes to the search region, t̄t and W+jets, is estimated using the lepton

2 In the analysis context, H_T is calculated from jets as reconstructed offline.
spectrum method. The foundation of this method is that, when the lepton and the neutrino are produced together in a $W$ decay (either in $t\bar{t}$ or in $W$+jets events), the lepton $p_T$ spectrum is directly related to the neutrino $p_T$ spectrum. In contrast, no such correlation is present in SUSY events. Therefore, the lepton spectrum is used to predict the SM $E_T^{miss}$ distribution, after suitable corrections related to the effect of the $W$ polarisation on the lepton and neutrino $p_T$ spectra, to the lepton acceptance, to the reconstruction efficiency and to the difference in resolution. Figure 1 shows the prediction of the background together with the data for both the electron and the muon channels. Combining the electron and muon channels, 2 events are observed in the search region, while $3.8 \pm 2.9$ are expected from the background prediction. A 95% CL model independent upper limit of 4.1 signal events is calculated.

Figure 2 shows the 95% exclusion contour in the cMSSM plane for $A_0 = 0$, and $\mu > 0$ and $\tan\beta = 10$ which exceeds previous limits from Tevatron and LEP.

3. Same sign dilepton search
The same-sign di-lepton analysis [16] requires, in addition to jets and $E_T^{miss}$, exactly two isolated leptons of the same sign which can be electrons, muons or taus decaying hadronically. The event sample was collected using di-lepton and single-lepton triggers, but also $H_T$ triggers, which provide sensitivity to events with low $p_T$ electrons and muons. In the case of leptonic triggers, one of the electrons and muons must have $p_T > 20$ GeV and the second one must have $p_T > 10$ GeV. Both leptons must be isolated. The isolation requirement is based on the $RelIso$ variable, which is the sum of the energy deposits as measured in the tracker, the HCAL and the ECAL in a cone of $\Delta R < 0.3$ divided by the transverse momentum of the lepton\(^3\). We require $RelIso < 0.1$ for leptons of $p_T > 20$ GeV, and the isolation sum (i.e., the numerator of the $RelIso$ expression) to be less than 2 GeV for $p_T < 20$ GeV. We also require the presence of at least two reconstructed jets, implying $H_T > 60$ GeV. Finally, we require

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]  
where $\phi$ is the azimuthal angle and $\eta$ is the pseudo-rapidity.

\(^3\) $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$ where $\phi$ is the azimuthal angle and $\eta$ is the pseudo-rapidity.
Figure 3. \(H_T\) versus \(E_T^{\text{miss}}\) scatter plots for the leptonically triggered same-sign di-lepton search. Overlayed are the three observed events (red dots) with the expected signal distribution for the LM0 benchmark point \((m_0 = 200\, \text{GeV}, m_{1/2} = 160\, \text{GeV}, \tan \beta = 10, \mu > 0, \text{and } A_0 = 400\, \text{GeV})\).

the missing transverse energy \(E_T^{\text{miss}} > 30\, \text{GeV}\) (ee and \(\mu \mu\)) or \(E_T^{\text{miss}} > 20\, \text{GeV}\) (e\(\mu\)). There are two kinematical search regions used in this analysis, the first has high \(E_T^{\text{miss}}\) \((E_T^{\text{miss}} > 80\, \text{GeV})\); the second has high \(H_T\) \((H_T > 200\, \text{GeV})\). These \(E_T^{\text{miss}}\) and \(H_T\) values were chosen to obtain an SM background expectation in simulation of less than one event in either of the two overlapping search regions. Figure 3 shows the scatter plot of the most sensitive discriminating variables \(H_T\) and \(E_T^{\text{miss}}\). There is one event barely satisfying the \(H_T\) requirement but no event satisfying the \(E_T^{\text{miss}}\) requirement. For comparison, the LM0 benchmark point \((m_0 = 200\, \text{GeV}, m_{1/2} = 160\, \text{GeV}, \tan \beta = 10, \mu > 0, \text{and } A_0 = 400\, \text{GeV})\) is overlaid.

Hadronic triggers allow to explore the phase space with low-\(p_T\) electrons and muons, as well as final states with hadronic \(\tau\) decays. We allow muons (electrons) with \(p_T\) as low as 5 (10) GeV, and restrict ourselves to \(\tau_h\) with visible transverse momentum > 15 GeV, where \(\tau_h\) refers to hadronic \(\tau\) candidates only. All leptons must be isolated with \(\text{RelIso} < 0.15\). For the ee, e\(\mu\), and \(\mu \mu\) final states, we require at least two jets, \(H_T > 300\, \text{GeV}\), and \(E_T^{\text{miss}} > 30\, \text{GeV}\). As backgrounds from QCD multijet production are significant for \(\tau_h\), we increase the \(E_T^{\text{miss}}\) and \(H_T\) requirements to \(E_T^{\text{miss}} > 50\, \text{GeV}\) and \(H_T > 350\, \text{GeV}\) in the e\(\tau_h\), \(\mu \tau_h\), and \(\tau_h \tau_h\) final states.

The search selection and the data-driven background estimation techniques employed where chosen according to the trigger in use (lepton or hadron), and the channel \((l_il_j\) where \(l_{i,j} = e, \mu, \tau)\) [16].

In all search regions, the predicted number of background events is compatible with zero, and no excess is observed. The results of the data-driven background estimations as described in [16] are summarized in Figure 4 and used to set limits in the cMSSM plane \(m_0 - m_{1/2}\) for \(\tan \beta = 3, A_0 = 0\), and \(\mu > 0\). Again, previous limits from Tevatron and LEP are exceeded.

4. Opposite sign dilepton search

Requiring two opposite-sign leptons [17], the dominating SM background is \(tt\) and must be predicted from data. To this end, we select a data sample dominated by \(tt\) events using high-\(p_T\) lepton triggers and a pre-selection based on the \(tt\) cross-section measurement in the dilepton
Figure 4. Left: A visual summary of the observed number of data events, the expected number of background events, and the composition of the background for the four search regions. Right: 95% CL exclusion contour in the $m_0 - m_{1/2}$ plane for CMSSM for the same-sign dilepton search.

We find good agreement between this data sample and predictions from Monte Carlo (MC) simulations in terms of the event yields and shapes of various kinematic distributions. The preselection requires two isolated opposite-sign leptons ($e^+e^-$, $\mu^+\mu^-$, or $\mu^+\mu^-$). At least one of the leptons must have $P_T > 20$ GeV and both must have $P_T > 10$ GeV. We require at least two jets of $P_T > 30$ GeV and $|\eta| < 2.5$, separated by $\Delta R > 0.4$ from leptons passing analysis selection with $P_T > 10$ GeV. We further require the event to have $H_T > 100$ GeV for the pre-selection and $H_T > 300$ GeV for the signal region. Finally, we remove events with a $e^+e^-$ or $\mu^+\mu^-$ pair whose invariant mass is between 76 GeV and 106 GeV, or below 10 GeV. The signal region has an additional cut $y > 8.5$ where $y = E_T^{miss}/\sqrt{H_T}$. This selection preserves about 1% of the $t\bar{t}$ signal. The requirement is on $y$ rather than $E_T^{miss}$ because the variables $H_T$ and $y$ are largely independent for the dominant $t\bar{t}$ background.

We estimate the $t\bar{t}$ background based on the idea [19] that in dilepton $t\bar{t}$ events the lepton and neutrinos from $W$ decays have similar $P_T$ spectra, reflecting the common boosts from the top and $W$ decays (leaving aside $W$ polarization effects). One can then use the observed $P_T(\ell\ell)$ distribution to model the distribution of the sum of neutrino $P_T$’s, which is identified with $E_T^{miss}$. Then, in order to predict the $t\bar{t} \rightarrow$ dilepton contribution to a selection with $E_T^{miss} + X$, one applies a cut on $P_T(\ell\ell) + X$ instead. In practice one has to rescale the result of the $P_T(\ell\ell) + X$ selection to account for the fact that any dilepton selection must include a moderate $E_T^{miss}$ cut in order to reduce Drell Yan backgrounds and to account for polarization effects. The result of these procedures is shown in Fig. 5. This method predicts $2.1 \pm 2.1$(stat) $\pm 0.6$(syst) while the SM MC yield is 1.3 events. One event is observed in data and other methods are used to cross-check that result [17]. No excess is seen beyond the SM prediction and we set limits in the cMSSM plane in Fig. 6 which substantially improve results from previous experiments.

5. Multi-lepton search
The multi-lepton analysis [20] selects events with three isolated leptons or more, acquired using single-lepton and di-lepton triggers. Candidate events in this search must have at least three leptons, of which at least one must be an electron or a muon. We classify multilepton events into search channels on the basis of the number of leptons, lepton flavour, and relative charges as well as charge and flavour combinations and other kinematic quantities described below.
Figure 5. Distributions of $y$ (observed) and $P_T(\ell\ell)/\sqrt{H_T}$ (predicted) for the control region (left) and signal region (right). We show the distributions in both MC and data.

Figure 6. The observed 95% CL exclusion contour for the opposite-sign dilepton analysis at NLO (solid red line) and LO (dashed blue line) in the CMSSM ($m_0, m_{1/2}$) plane for $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$. The area below the curve is excluded by this measurement. Exclusion limits obtained from previous experiments are presented as filled areas in the plot. Thin grey lines correspond to constant squark and gluino masses.

channels are formed exclusively in that a candidate event can belong to one and only one channel. This avoids overlap between channels for limit-setting purposes. Each channel is treated as an independent search and the collective sensitivity of all channels to a model of new physics is obtained by combining exclusive sensitivities using standard statistical prescriptions.

There are 55 independent samples according to the relative charge of the leptons and their
Figure 7. Left: 95% CL exclusion contour for the cMSSM scenario for the multi-lepton search along with the limits from the multilepton searches from the Tevatron [21] and the exclusion derived from slepton and chargino limits from LEP [22, 23, 24, 25, 26, 27]. Right: the expected and observed upper limits on the cross section times branching ratio $\sigma \times B(3\ell)$ as a function of the chargino mass.

flavour, which can be $e, \mu$, and $\tau$. The three-lepton requirement strongly reduces the Standard Model background, and the largest remaining background process is $Z+\text{jets}$, including Drell-Yan. The presence of hadronic activity in an event is characterised by the variable $H_T$. Jets used for the $H_T$ determination must be well separated from any identified leptons; jets are required to have no lepton in a cone $\Delta R < 0.3$ around the jet axis. The remaining background is further suppressed by requiring $H_T > 30$ GeV, $E_T^{\text{miss}} > 50$ GeV or a $Z$ veto, depending on the considered final state. No excess is found with respect to the predicted background in search region, and limits are set in a variety of models. In particular, Fig. 7 shows the 95% CL exclusion in the cMSSM plane together with limits from Tevatron [21] and LEP searches [22, 23, 24, 25, 26, 27] for $A_0 = 0, \tan\beta = 3$, and $\mu > 0$. As can be seen, our results extend the excluded region in comparison with previous results from LEP and the Tevatron. For small values of $m_0$ the sleptons can become lighter than the gauginos, so the gauginos will decay into slepton and lepton (two-body decay), although for larger values of $m_0$ three-body decays will dominate.

While for two-body decays the branching fraction into leptons is 100%, it decreases rapidly for three-body decays. In the transition region from two- to three-body decays the leptons become soft and fail the $p_T$ requirement [28]. Exclusion is therefore not possible, as shown by the non-excluded region between the two- and three-body decay regions. We exclude gluino masses up to 628 GeV for this choice of parameters.

The 95% CL upper limit on the cross section times branching ratio into $3\ell$ varies from $\sigma_{95} = 0.8$ to 2 pb. The sensitivity to the chargino mass can be seen in the right panel of Fig. 7, where the NLO cross section for $m_0 = 60$ GeV equals the 95% CL experimental limit of $\sigma_{95} = 2$ pb for chargino mass of 163 GeV. Therefore, chargino masses above this value cannot be excluded.

6. Conclusions
We have presented results of searches for new physics in various topologies with one or more isolated leptons, jets, and missing transverse energy in the final state using the 35 pb$^{-1}$ of the CMS 2010 dataset. No evidence for new physics is observed and limits are set on the production cross-section times the event acceptance for the searched topologies which exceed previous limits from LEP and the Tevatron.
References

[1] LEP2 Joint SUSY Working Group (ALEPH, DELPHI, L3 and OPAL Collaborations) 2004 Notes LEPSUSYWG/01-03.1 and 04-01.1 URL http://lepsusy.web.cern.ch/lepsusy

[2] Alcaraz J (ALEPH and CDF and D0 and DELPHI and L3 and OPAL and SLD Collaborations) 2009 (Preprint 0911.2604)

[3] Witten E 1981 Nucl. Phys. B 188 513
[4] Dimopoulos S and Georgi H 1981 Nucl. Phys. B 193 150
[5] Martin J 1997 arXiv:hep-ph/9709356
[6] Wess J and Zumino B 1974 Nucl. Phys. B 70 39
[7] Nilles H P 1984 Phys. Reports 110 1
[8] Haber H E and Kane G L 1987 Phys. Reports 117 75
[9] Barbieri R, Ferrara S and Savoy C A 1982 Phys. Lett. B119 343
[10] Dawson S, Eichten E and Quigg C 1985 Phys. Rev. D31 1581
[11] Ellis J R, Hagelin J S, Nanopoulos D V, Olive K A and Srednicki M 1984 Nucl. Phys. B238 453–476
[12] Chatrchyan S et al. (CMS Collaboration) 2011 arXiv:hep-ex/1107.1279
[13] Chatrchyan S et al. (CMS Collaboration) 2011 arXiv:hep-ex/1106.3272
[14] Khachatryan V et al. (CMS Collaboration) 2011 Phys. Lett. B698 196–218 (Preprint 1101.1628)
[15] Chatrchyan S et al. (CMS Collaboration) 2011 arXiv:hep-ex/1107.1870
[16] Chatrchyan S et al. (CMS Collaboration) 2011 JHEP 1106 077 (Preprint 1104.3168)
[17] Chatrchyan S et al. (CMS) 2011 JHEP 06 026 (Preprint 1103.1348)
[18] Khachatryan V et al. (CMS Collaboration) 2011 Phys. Lett. B695 424–443
[19] Pavlunin V 2010 Phys. Rev. D81 035005
[20] Chatrchyan S et al. (CMS Collaboration) 2011 Submitted to JHEP (Preprint 1106.0933)
[21] Abazov V M et al. (D0 Collaboration) 2009 Phys. Lett. B680 34
[22] LEP2 Joint SUSY Working Group (ALEPH, DELPHI, L3 and OPAL Collaborations) 2004 Combined LEP Selectron/Smuon/Stau Results, 183–208 GeV URL http://lepsusy.web.cern.ch/lepsusy/www/sleptons_summer04/slep_final.html
[23] Heister A et al. (ALEPH Collaboration) 2002 Phys. Lett. B526 206
[24] Heister A et al. (ALEPH Collaboration) 2004 Phys. Lett. B583 247
[25] Abdallah J et al. (DELPHI Collaboration) 2003 Eur. Phys. J. C31 421
[26] Achard P et al. (L3 Collaboration) 2004 Phys. Lett. B580 37
[27] Abbiendi G et al. (OPAL Collaboration) 2004 Eur. Phys. J. C32 453
[28] Aaltonen T et al. (CDF Collaboration) 2008 Phys. Rev. Lett. 101 251801