Abstract. Results are presented of a search for supersymmetric particles decaying into final states with significant missing transverse momentum and exactly two identical flavour leptons (e, μ) of opposite charge in \( \sqrt{s} = 7 \) TeV collisions at the Large Hadron Collider. This channel is particularly sensitive to supersymmetric particle cascade decays producing flavour correlated lepton pairs. Flavour uncorrelated backgrounds are subtracted using a sample of opposite flavour lepton pair events. Observation of an excess beyond Standard Model expectations following this subtraction procedure would offer one of the best routes to measuring the masses of supersymmetric particles. In a data sample corresponding to an integrated luminosity of 35 pb\(^{-1}\) no such excess is observed. Model-independent limits are set on the contribution to these final states from new physics and are used to exclude regions of a phenomenological supersymmetric parameter space.

In this letter the first results are reported of a search for the production of supersymmetric (SUSY) \( \tilde{\chi}_1^0 \) particles at ATLAS in events with exactly two leptons of identical flavour (e or μ) and opposite charge, and significant missing transverse momentum (\( E_T^{\text{miss}} \)). This signature can be generated in SUSY events by the correlated production of leptons, for instance via the decay chains \( \tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- \) or \( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- \). Such events offer one of the best routes to model-independent measurements of the masses of SUSY particles via end-points in the lepton pair invariant mass distribution \( [2,3,4] \) and so are of great interest especially if SUSY is found. The dominant sources of Standard Model (SM) background generally possess equal branching fractions for the production of lepton pairs of identical and different flavour, and can therefore be removed with a ‘flavour subtraction’ procedure \( [2] \) in which the observation in the eμ channel is subtracted from that in the ee and μμ channels. Specifically targeting this important technique for measuring SUSY particle masses, this analysis benefits from reduced sensitivity to systematic uncertainties in background estimates compared with other techniques. The results reported here are complementary to those of inclusive SUSY particle searches using lepton pairs \( [5] \), and also to those of inclusive searches requiring jets, \( E_T^{\text{miss}} \) and zero leptons \( [6] \) or one lepton \( [7] \). A search by CMS for SUSY in events with lepton pairs is reported in Ref. \([8]\).

The ATLAS detector \([9]\) is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4\( \pi \) coverage in solid angle \([10]\). The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT) which also provides particle identification capability. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimeters. Hadronic coverage is provided by an iron-scintillator tile calorimeter in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, a system of precision tracking chambers, and detectors for triggering.

The pp-collision data used in this analysis were collected between March and November 2010 at the LHC operating at a centre-of-mass energy of 7 TeV. Application of basic beam, detector and data-quality requirements results in a total integrated luminosity of 35 pb\(^{-1}\). The uncertainty on the luminosity is estimated to be 11\%. \([10]\).

The data have been collected with a single lepton (e or μ) trigger. The detailed trigger requirements vary throughout the data-taking period due to the rapidly increasing LHC luminosity and the commissioning of the trigger system, but always have a threshold that ensures a trigger efficiency for leptons with transverse momentum

\[ p_T > 30 \text{ GeV} \]

The z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \).
$p_T > 20$ GeV at the plateau. The efficiency of the triggers is studied with data, and agrees well with expectations.

Monte Carlo (MC) simulated event samples are used to develop and validate the analysis procedure and to estimate the residual SM backgrounds following flavour subtraction. Samples of QCD jet events are generated with PYTHIA [11], using the MRST2007LO* modified leading-order parton distribution functions (PDF) [12], which are used with all leading-order (LO) MC codes. Production of top quark pairs is simulated with MC@NLO [13,14], and (with a top quark mass of 172.5 GeV) and the next-to-leading order (NLO) PDF set CT10 [15], which is used with all NLO MC codes. Samples of W and Z/γ* production with accompanying jets are produced with ALPGEN [16]. Diboson (WW, WZ, ZZ) production is simulated with HERWIG [17-18], single top production with MC@NLO [19,20], and Drell-Yan with PYTHIA. Fragmentation and hadronization for the ALPGEN and MC@NLO samples are performed with HERWIG, using JIMMY [21] for the underlying event. The MC samples are produced using the ATLAS MC09 parameter tune [22] and a GEANT4 [23] based detector simulation [24].

Criteria for electron and muon identification closely follow those described in Ref. [25]. Candidate electrons are required to pass “tight” electron selection criteria and isolation requirements, and have $p_T > 20$ GeV and $|\eta| < 2.47$. Identified electrons are used to select events for both the signal region of the analysis and control regions used to estimate backgrounds. “Medium” electron selection criteria are mainly based on lateral shower shape requirements in the calorimeter, while $E/p$ (where $E$ is the shower energy in the calorimeter and $p$ the track momentum in the ID) and TRT cuts are applied for the tight electron selection, which provides additional rejection against conversions and fakes from hadrons. The electron isolation criteria require that the total transverse energy within a cone size $\Delta R = \sqrt{\Delta \eta^2 + (\Delta \phi)^2}$ = 0.2 around the electron, is less than 0.15 of the electron $p_T$. Events are always vetoed if a medium electron is found in the transition region between the barrel and end-cap electromagnetic calorimeter, 1.37 $< |\eta| < 1.52$. Muons are required to be identified either in both the ID and MS systems (combined muons) or as a match between an extrapolated ID track and one or more track segments in the MS. The ID track is required to have at least one pixel hit, more than five SCT hits, and a number of TRT hits that varies with $\eta$. For combined muons, a good match between ID and MS tracks is required, and the $p_T$ values measured by these two systems must be compatible within the resolution. Isolation requirements are imposed, whereby the summed $p_T$ of other ID tracks above 500 MeV within a distance $\Delta R < 0.2$ around the muon track is required to be less than 1.8 GeV. Only muons with $p_T > 20$ GeV and $|\eta| < 2.4$ are considered. For the final selection, the distance between the $z$ coordinate of the primary vertex and that of the extrapolated muon track at the point of closest approach to the primary vertex must be less than 10 mm. Jets are reconstructed using the anti-$k_t$ jet clustering algorithm [26] with a distance parameter $D = 0.4$. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jets are constructed by performing a four-vector sum over these clusters, treating each cluster as an $(E, \mathbf{p})$ four-vector with zero mass. Jets are corrected for calorimeter non-compensation, material and other effects using $p_T$- and $\eta$-dependent calibration factors obtained from Monte Carlo and validated with test-beam and collision-data studies [27]. Only jets with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered. If a jet and a medium electron are both identified within a distance $\Delta R < 0.2$ of each other, the jet is discarded. Furthermore, identified medium electrons or muons are only considered if they satisfy $\Delta R > 0.4$ with respect to the closest remaining jet. Events are discarded if they contain any jet failing basic quality selection criteria, which rejects detector noise and non-collision backgrounds [28]. The calculation of the missing transverse momentum, $E_T^{\text{miss}}$, is based on the modulus of the vector sum of the $p_T$ of the reconstructed objects (jets with $p_T > 20$ GeV, but over the full calorimeter coverage $|\eta| < 4.9$, and selected leptons), any additional non-isolated muons, and the calorimeter clusters not belonging to reconstructed objects.

“Signal region” events that contain lepton pairs of identical flavour ($e^+e^-$ and $\mu^+\mu^-$) and different flavour ($e^+\mu^-$) are selected, with the two populations subsequently used to calculate the excess of identical flavour events. Selected events must contain exactly two opposite sign leptons ($e$ or $\mu$), with invariant mass $(m_{\ell\ell})$ greater than 5 GeV. The $E_T^{\text{miss}}$ must exceed 100 GeV in order to reject SM Z+jets events whilst maintaining efficiency for a range of SUSY models. Events must also possess at least one reconstructed primary vertex with at least five associated tracks. A flavour subtraction is performed through the use of the quantity $S$ defined as

$$S = \frac{N(e^+e^-)}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^+\mu^-)}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^+\mu^-)}{1-(1-\tau_\mu)^2},$$

which measures the excess of identical-flavour events (first and third terms) over different-flavour events (second term), taking into account the electron and muon plateau trigger efficiencies ($\tau_e$ and $\tau_\mu$) and the ratio of electron to muon efficiency times acceptance ($\beta$). The trigger efficiencies for offline reconstructed objects are $\tau_e = (98.5\pm1.1)\%$ and $\tau_\mu = (83.7\pm1.9)\%$, respectively, while $\beta$ is determined from data to be 0.69$\pm$0.03, with the quoted errors including both systematic and statistical uncertainties.

The value of $S$ obtained from selected identical-flavour and different-flavour lepton SM events is expected to be small but non-zero, due primarily to $Z/\gamma^*$ boson production. The contributions to $S$ expected from SM processes are estimated using a combination of Monte Carlo simulation and data-driven techniques. Contributions from single top and diboson events are estimated using the MC samples described above, scaled to the luminosity of the data sample. Contributions from Z/$\gamma^*$+jets, $tt$ and events containing fake leptons (from QCD jets and W+jets events) are estimated using MC samples normalised to data in an appropriate control region. The $Z/\gamma^*$ control region contains lepton pair events satisfying the same selection criteria as the signal region but with $E_T^{\text{miss}} < 20$ GeV and
an additional 81 < m_{ll} < 101 GeV requirement. The $t\bar{t}$
control region [5] contains “top-tagged” lepton pair events
again satisfying the same selection criteria as signal candi-
dates but with 60 < $E_T^{miss}$ < 80 GeV and an additional
requirement of ≥ 2 jets with $p_T > 20$ GeV. The top-tagging
requirement is imposed through the use of the variable
$m_{CT}$ [29], which can be calculated from the four-vectors of
the selected jets and leptons:
\[
m_{CT}(v_1,v_2) = [E_T(v_1) + E_T(v_2)]^2 - [p_T(v_1) - p_T(v_2)]^2,
\]
where $v_i$ can be a lepton, a jet, or a lepton-jet combina-
tion, transverse momentum vectors are denoted by $p_T$ and
transverse energies $E_T$ are defined as $E_T = \sqrt{p_T^2 + m^2}$.
This quantity is bounded from above by analytical func-
tions of the top quark and $W$ masses as described in
Ref. [30]. Top-tagged events are required to possess $m_{CT}$
values calculated from combinations of jets and leptons
consistent with the expected bounds from $t\bar{t}$ events, as
well as lepton-jet invariant mass values consistent with top
quark decays. An electron control region for fake lepton
events requires events to possess $E_T^{miss}$ < 60 GeV, $\Delta\phi$
between the $E_T^{miss}$ vector and a jet < 0.1 and an electron with
$p_T > 30$ GeV. A single muon control region for fake lepton
events requires events to possess $E_T^{miss}$ < 30 GeV, a muon
with $p_T < 40$ GeV and a transverse mass $m_T(\mu, E_T^{miss}) < 30$
GeV. The electron and muon identification criteria are
relaxed, to obtain a ‘looser’ sample dominated by fakes.
A loose-tight matrix method is then used to estimate the
number of events with fake leptons in the signal region
after final selection criteria. This method, which uses the
probabilities derived from data for loosely selected leptons
and hadrons to satisfy the tight selection criteria to predict
the mixture of real and fake leptons in the final sample, is
similar to that described in Ref. [31]. The dominant uncer-
tainties in the data-normalised background estimates arise
from limited numbers of events in the control regions, the-
etical uncertainties (including choice of generator, initial
and final state radiation), an approximate $\sim \pm 7\%$ jet en-
ergy scale uncertainty [32] and an approximate $\sim 14\%$
jet energy resolution uncertainty [33]. The latter uncer-
tainties affect the shapes of the MC $E_T^{miss}$ distributions.
Uncertainties on backgrounds estimated solely with MC
are dominated by the jet energy scale and resolution.

The invariant mass distributions of lepton pairs in se-
lected data events, prior to applying the $E_T^{miss}$ require-
ment, are presented in Figure 1, weighted by the multi-
plicative factors in Equation 3 to yield the identical flavour
combinations, are presented in Figure 1, weighted according to Equation 1. In the ‘Total SM’, the number of fakes
in this channel is taken to be zero.

### Table 1. Expected numbers of SM background events in the
signal region for each of the three lepton flavour combinations.
The estimates are obtained using the procedures described in
the text. The quoted error includes systematic and statistical
uncertainties. The negative number of fakes predicted in the
e±µ± channel is an artifact of the matrix method used to estimate
this contribution. In the ‘Total SM’, the number of fakes
in this channel is taken to be zero.

<table>
<thead>
<tr>
<th></th>
<th>e±e±</th>
<th>e±µ±</th>
<th>µ±µ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>4</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Z/γ∗+jets</td>
<td>0.40±0.46</td>
<td>0.36±0.20</td>
<td>0.91±0.67</td>
</tr>
<tr>
<td>Dibosons</td>
<td>0.30±0.11</td>
<td>0.36±0.10</td>
<td>0.61±0.10</td>
</tr>
<tr>
<td>t\bar{t}</td>
<td>2.50±1.02</td>
<td>6.61±2.68</td>
<td>4.71±1.91</td>
</tr>
<tr>
<td>Single top</td>
<td>0.13±0.09</td>
<td>0.76±0.25</td>
<td>0.67±0.33</td>
</tr>
<tr>
<td>Fakes</td>
<td>0.31±0.21</td>
<td>-0.15±0.08</td>
<td>0.01±0.01</td>
</tr>
<tr>
<td>Total SM</td>
<td>3.64±1.24</td>
<td>8.08±2.78</td>
<td>6.91±2.20</td>
</tr>
</tbody>
</table>

**Fig. 1.** Invariant mass distribution of identical flavour lep-
on pairs prior to applying the $E_T^{miss}$ requirement, weighted
by the acceptance and efficiency factors as in Equation 1.
The stacked histograms show the expected distributions from MC
samples normalised to the luminosity of the data. The band
indicates the uncertainty on the expectation from finite statis-
tics, cross section, luminosity, jet and lepton energy scales and
resolutions. Also shown is the observed distribution for dif-
ferent flavour pairs, weighted according to Equation 1. In the
region with $m_T < 100$ GeV, the dominant contributions to
the different flavour data events are expected to come from $t\bar{t}$,
QCD and Z/γ∗+jets events.
Experiments

The distribution of observed \( S \) values from one million hypothetical signal-free experiments. The shape is driven by statistical Poisson fluctuations in the expected rates of identical flavour and different flavour events, dominated by \( tt \) events.

Figure 2. The shape of the distribution is dominated by statistical fluctuations in the numbers of events in each channel, with the uncertainty on \( S_b \) being negligible by comparison. The probability of observing a value of \( S \) at least as large as \( S_{obs} \) is 49.7% and hence no evidence of an excess of identical flavour events beyond SM expectations is observed.

Limits are set on \( S_{\Delta} \), the mean contribution to \( S \) from new physics. The statistical procedure employed follows that used to determine the consistency of the observed value of \( S \) with the background expectation. The pseudo-experiments are modified by adding signal event contributions to the input mean numbers of background events in each channel. An assumption must be made regarding the relative branching ratio of new physics events into identical flavour and different flavour channels, as adding flavour uncorrelated new physics contributions to the identical flavour and different flavour channels increases the width of the \( S \) distribution. Given such an assumption, a model-independent limit can be set on \( S_{\Delta} \) by comparing \( S_{obs} \) with the distribution of \( S \) values obtained from the new set of signal-plus-background pseudo-experiments.

If the assumption is made that the branching fractions for \( e^+e^- \) and \( \mu^+\mu^- \) final states in new physics events are identical, and the branching fraction for \( e^+\mu^- \) final states is zero, a limit \( S_{\Delta} < 8.8 \) is set at 95% confidence level. Alternatively, if new physics events are assumed to possess a different flavour branching fraction of one half that for identical flavour events, then the limit becomes \( S_{\Delta} < 12.6 \) at 95% confidence. The limits are driven by the statistical fluctuations in \( S \), rather than systematic and statistical uncertainties in \( S_b \) and in the variance of the \( S_b \) distribution.

A similar procedure can be used to set limits within a specific new physics parameter space. In this case the mean numbers of signal events added to each channel are sampled according to the expectations from each point in the parameter space of the model together with the uncertainties in these expectations. The fraction of resulting pseudo-experiments with \( S < S_{obs} \) gives the probability of the signal plus background hypothesis being falsely rejected. If the probability of being falsely rejected is \( < 5\% \), the point is excluded at 95% confidence.

As an example, two-dimensional grids in the parameter space of a 24 parameter MSSM model are considered (to be referred to as ‘MSSM PhenoGrid2’). The 24 parameter MSSM is a generic MSSM on which flavour and CP violation have been imposed. For these grids the following parameters are fixed: \( m_A = 1000 \text{ GeV}, \mu = 1.5 \text{ min}(m_{\tilde{g}}, m_{\tilde{q}}), \tan \beta = 4, A_t = \mu / \tan \beta, A_b = \mu \tan \beta, \text{ and } A_t = \mu \tan \beta \). The masses of the 3\textsuperscript{rd} generation sleptons are set to 2 TeV, and common squark mass and slepton mass parameters are assumed for the first two generations. Two grids in the \( m_{\tilde{g}} - m_{\tilde{q}} \) plane are studied: one with a compressed spectrum yielding a soft final state kinematics, defined by \( m_{\tilde{g}} = M - 50 \text{ GeV}, m_{\tilde{q}} = M - 150 \text{ GeV} \) and \( m_{\tilde{t}_L} = M - 100 \text{ GeV} \), where \( M \) is the minimum of the gluino and squark mass (‘compressed spectrum’); and one with a very light LSP, yielding a harder spec-
trum of leptons, jets and $E_T^{miss}$, with $m_{\chi^0} = M - 100$ GeV, $m_{\tilde{g}} = 100$ GeV and $m_{\tilde{q}} = M/2$ GeV (‘light neutralino’). Signal events are generated with HERWIG for the MSSM grids. The cross sections are calculated at NLO with PROSPINO [24]. Theoretical and experimental uncertainties are determined for each model and used when sampling the mean numbers of signal events in each channel. Theoretical uncertainties are evaluated by varying the factorisation and renormalisation scales and the CTEQ6.6 PDF sets [15] used for the cross section calculation. Experimental uncertainties are dominated by the uncertainty on the jet energy scale and resolution. An 11% luminosity uncertainty is included. The results are shown in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane in Figure 3. For ‘compressed spectrum’ (‘light neutralino’) models and $m_{\tilde{q}} = m_{\tilde{g}} + 10$ GeV, the 95% confidence lower limit on $m_{\tilde{q}}$ is 503 (558) GeV.

In summary, a flavour subtraction technique has been used to search for an excess beyond SM expectations of high missing transverse momentum events containing opposite charge identical flavour lepton pairs. No significant excess has been observed, allowing limits to be set on the model-independent quantity $\delta$, which measures the mean excess from new physics taking into account flavour-dependent acceptances and efficiencies.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; STFC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CF, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNNRF, DANSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/-IRFU, France; GNAS, Georgia; BMDF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINEVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; CIFICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 - (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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