Search for an excess of events with an identical flavour lepton pair and significant missing transverse momentum in $\sqrt{s} = 7$ TeV proton-proton collisions with the ATLAS detector

The ATLAS Collaboration

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 ($e$, $\mu$) 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) particles at ATLAS in events with exactly two leptons of identical flavour ($e$ or $\mu$) and opposite charge, and significant missing transverse momentum ($E_{\text{miss}}^T$). This signature can be generated in SUSY events by the correlated production of leptons, for instance via the decay chains $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \tilde{\ell}^\mp \to \tilde{\ell}^0 \tilde{\ell}^+ \tilde{\ell}^- \text{ or } \tilde{\chi}_2^0 \to \tilde{\ell}^0 \tilde{\ell}^+ \tilde{\ell}^-$. Such events offer one of the best routes to model-independent measurements of the masses of SUSY particles via end-caps 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 $e\mu$ channel is subtracted from that in the $ee$ and $\mu\mu$ 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, $E_{\text{miss}}^T$ and zero leptons $[4]$ 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 $[2]$. 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 $\mu$) 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.
$p_T > 20$ 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 $Z/\gamma^*$ 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 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 ($m_{ll}$) greater than 5 GeV. The $E_T^\text{miss}$ must exceed 100 GeV in order to reject SM $Z/\gamma^*$+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

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

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 ratio of 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 $0.69\pm0.03$, 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, $t\bar{t}$ 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 $81 < m_{t\bar{t}} < 101$ GeV requirement. The $t\bar{t}$ control region [5] contains “top-tagged” lepton pair events again satisfying the same selection criteria as signal candidates but with $60 < E_{T}^{miss} < 80$ GeV and an additional requirement of $\geq 2$ 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:

$$m_{CT}^{2}(v_1, v_2) = (E_T(v_1) + E_T(v_2))^2 - [p_T(v_1) - p_T(v_2)]^2, \quad (2)$$

where $v_i$ can be a lepton, a jet, or a lepton-jet combination, 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 functions of the top quark and $W$ masses as described in Ref. [30]. Top-tagged events are required to possess $m_{CT}^{2}$ 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 uncertainties in the data-normalised background estimates arise from limited numbers of events in the control regions, theoretical uncertainties (including choice of generator, initial and final state radiation), an approximate $\pm 7\%$ jet energy scale uncertainty [32] and an approximate $\sim 14\%$ jet energy resolution uncertainty [33]. The latter uncertainties 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 selected data events, prior to applying the $E_{T}^{miss}$ requirement, are presented in Figure [1] weighted by the multiplicative factors in Equation [3] to yield the identical flavour and different flavour contributions to $S$. After applying the $E_{T}^{miss} > 100$ GeV requirement 4, 13 and 13 events are observed in the $e^+e^\pm$, $e^\pm\mu^\mp$ and $\mu^\pm\mu^\mp$ channels respectively. The expected numbers of events in these channels, determined using the techniques described above, are listed in Table [1] and are in reasonable agreement (within statistical and systematic uncertainties) with the observations. The dominant contribution to each channel arises from $t\bar{t}$ production. Using the observed numbers of events in each channel together with the measured values of $\tau_e$, $\tau_\mu$ and $\beta$, the observed value of $S$ is found to be $S_{obs} = 1.98 \pm 0.15(\beta) \pm 0.02(\tau_e) \pm 0.06(\tau_\mu)$, where the un-

<table>
<thead>
<tr>
<th>$e^\pm e^\pm$</th>
<th>$e^\pm\mu^\mp$</th>
<th>$\mu^\pm\mu^\mp$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>13</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>$Z/\gamma^{\ast}$+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±1.20</td>
</tr>
</tbody>
</table>

Fig. 1. Invariant mass distribution of identical flavour lepton pairs prior to applying the $E_{T}^{miss}$ requirement, weighted by the acceptance and efficiency factors as in Equation [3]. 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 statistics, cross section, luminosity, jet and lepton energy scales and resolutions. Also shown is the observed distribution for different flavour pairs, weighted according to Equation [4]. In the region with $m_{t\bar{t}} < 100$ GeV, the dominant contributions to the different flavour data events are expected to come from $t\bar{t}$, QCD and $Z/\gamma^{\ast}$+jets events.
uncertainties are those from the respective efficiency parameters. The expected mean value of $S$ from SM background events alone is $S_b = 2.06 \pm 0.79 \text{(stat.)} \pm 0.78 \text{(sys.)}$, in good agreement with the observation. The dominant contributions to $S_b$ are from $Z/\gamma^* + \text{jets}$ and diboson processes. The dominant contributions from $t\bar{t}$ events to the individual channels largely cancel when calculating $S$, as expected. The $t\bar{t}$ population nevertheless has a significant impact on this analysis because the range of observed $S$ values expected from a large number of hypothetical signal-free experiments is dominated by statistical fluctuations in the numbers of events in each channel.

To quantify the consistency between the observed $S$ value and the SM prediction the expected distribution of $S_b$ in the absence of new physics must be determined. This distribution possesses a mean given by $S_b = \bar{S}$, and a width dominated by statistical fluctuations in the numbers of events observed in each channel. The distribution can be determined by generating pseudo-experiments using the estimated mean numbers of background events from Table 1 as input. For each pseudo-experiment the mean number of background events in each channel and from each source are sampled, taking appropriate account of correlations between the uncertainties in the estimates of these means. The resulting total mean number of background events in each channel is then used to construct a Poisson distribution from which the observed number of events in that channel is drawn. The resulting sampled event counts in each channel are then used with Equation 1 taking care also to sample values of $\tau_e$, $\tau_\mu$ and $\beta$ according to their means and uncertainties, to determine a value of $S_b$. The distribution of $S_b$ values obtained in this way is used to estimate the probability of observing a value of $S$ at least as large as $S_{obs}$.

The distribution of $S$ values obtained from one million signal-free experiments using this procedure is shown in 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 $S_\beta$, 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 $S_b$ 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 $e^\pm e^\mp$ and $\mu^\pm \mu^\mp$ final states in new physics events are identical, and the branching fraction for $e^\pm \mu^\mp$ final states is zero, a limit $S_\beta < 8.8$ 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 $S_\beta < 12.6$ at 95% confidence. The limits are driven by the statistical fluctuations in $S_b$ 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: $m_A = 1000$ GeV, $\mu = 1.5 \text{min}(m_\tilde{g}, m_\tilde{\chi}^0)$, $\tan \beta = 4$, $A_t = \mu / \tan \beta$, $A_b = \mu \tan \beta$, and $A_\tilde{l} = \mu \tan \beta$. The masses of the first two generations sfermions are set to 2 TeV, and common squark mass and slepton mass parameters are assumed for the first two generations. Two grids in the $m_{\tilde{\tau}} - m_{\tilde{q}}$ plane are studied: one with a compressed spectrum yielding a soft final state kinematics, defined by $m_{\tilde{\chi}^0} = M = 50$ GeV, $m_{\tilde{\chi}^0} = M = 150$ GeV and $m_{\tilde{\chi}^0} = M = 100$ 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 $m_{\tilde{q}q} = M - 100$ GeV, $m_{\tilde{\chi}^0} = 100$ GeV and $m_{\tilde{\chi}^\pm} = M/2$ GeV ('light neutralino'). Signal events are generated with HERWIG for the MSSM grids. The cross sections are calculated at NLO with PROSPINO [35]. Theoretical and 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 $m_{\tilde{g}} = m_{\tilde{q}} + 10$ 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 $S_\ell$, 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 have been 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 CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DSNRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNOS, 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; GRCES and FCT, Portugal; MERVYS (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.

References

29. D. R. Tovey, JHEP 04 (2008) 034.
30. G. Polesello and D. R. Tovey, JHEP 03 (2010) 030.
33. ATLAS Collaboration, ATLAS-CONF-2010-054.
The ATLAS Collaboration: Search for events with an identical flavour lepton pair and $E_{\text{T}}^{\text{miss}}$ at ATLAS
The ATLAS Collaboration: Search for events with an identical flavour lepton pair and $E_{\text{T}}^\text{miss}$ at ATLAS
The ATLAS Collaboration: Search for events with an identical flavour lepton pair and \( E_T^{\text{miss}} \) at ATLAS
The ATLAS Collaboration: Search for events with an identical flavour lepton pair and $E_T^{miss}$ at ATLAS

44 Department of Physics, Duke University, Durham NC, United States of America
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a)INFN Sezione di Genova; (b)Dipartimento di Fisica, Università di Genova, Genova, Italy
51 Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c)ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a)INFN Sezione di Lecce; (b)Dipartimento di Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 Department of Physics, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst MA, United States of America
85 Department of Physics, McGill University, Montreal QC, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
88 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
89 (a)INFN Sezione di Milano; (b)Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
93 Group of Particle Physics, University of Montreal, Montreal QC, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science, Nagoya University, Nagoya, Japan
102 (a)INFN Sezione di Napoli; (b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
108 Department of Physics, New York University, New York NY, United States of America
109 Ohio State University, Columbus OH, United States of America
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
112 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
113 Palacký University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
119 (a)INFN Sezione di Pavia; (b)Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
120 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (a)INFN Sezione di Pisa; (b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
124 (a)Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b)Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 State Research Center Institute for High Energy Physics, Protvino, Russia
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 (a)INFN Sezione di Roma I; (b)Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 (a)INFN Sezione di Roma Tor Vergata; (b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (a)INFN Sezione di Roma Tre; (b)Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies - Université Hassan II, Casablanca; (b)Centre National de l’Énergie des Sciences Techniques Nucleaires, Rabat; (c)Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e)Faculté des Sciences, Université Mohammed V, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Énergie Atomique), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
138 Department of Physics, University of Washington, Seattle WA, United States of America
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140 Department of Physics, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
143 SLAC National Accelerator Laboratory, Stanford CA, United States of America
144 (a)Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
145 (a)Department of Physics, University of Johannesburg, Johannesburg; (b)School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146 (a)Department of Physics, Stockholm University; (b)The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
The ATLAS Collaboration: Search for events with an identical flavour lepton pair and $E_{T}^{\text{miss}}$ at ATLAS

* Deceased