Search for anomalous production of prompt like-sign lepton pairs at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

An inclusive search for anomalous production of two prompt, isolated leptons with the same electric charge is presented. The search is performed in a data sample corresponding to 4.7 fb$^{-1}$ of integrated luminosity collected in 2011 at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC. Pairs of leptons ($e^\pm e^\pm$, $e^\pm \mu^\pm$, and $\mu^\pm \mu^\pm$) with large transverse momentum are selected, and the dilepton invariant mass distribution is examined for any deviation from the Standard Model expectation. No excess is found, and upper limits on the production cross section of like-sign lepton pairs from physics processes beyond the Standard Model are placed as a function of the dilepton invariant mass within a fiducial region close to the experimental selection criteria. The 95% confidence level upper limits on the cross section of anomalous $e^\pm e^\pm$, $e^\pm \mu^\pm$, or $\mu^\pm \mu^\pm$ production range between 1.7 fb and 64 fb depending on the dilepton mass and flavour combination.
Search for anomalous production of prompt like-sign lepton pairs at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

Abstract: An inclusive search for anomalous production of two prompt, isolated leptons with the same electric charge is presented. The search is performed in a data sample corresponding to 4.7 fb$^{-1}$ of integrated luminosity collected in 2011 at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC. Pairs of leptons ($e^\pm e^\pm$, $e^\pm \mu^\pm$, and $\mu^\pm \mu^\pm$) with large transverse momentum are selected, and the dilepton invariant mass distribution is examined for any deviation from the Standard Model expectation. No excess is found, and upper limits on the production cross section of like-sign lepton pairs from physics processes beyond the Standard Model are placed as a function of the dilepton invariant mass within a fiducial region close to the experimental selection criteria. The 95% confidence level upper limits on the cross section of anomalous $e^\pm e^\pm$, $e^\pm \mu^\pm$, or $\mu^\pm \mu^\pm$ production range between 1.7 fb and 64 fb depending on the dilepton mass and flavour combination.
1 Introduction

Events containing two prompt leptons with large transverse momentum ($p_T$) and equal electric charge are rarely produced in the Standard Model (SM) but occur with an enhanced rate in many models of new physics. For instance, left-right symmetric models [1–4], Higgs triplet models [5–7], the little Higgs model [8], fourth-family quarks [9], supersymmetry [10], universal extra dimensions [11], and the neutrino mass model of refs. [12–14] may produce final states with two like-sign leptons. In the analysis described here, pairs of isolated, high-$p_T$ leptons are selected, and the invariant mass of the dilepton system ($e^\pm e^\pm$, $e^\pm \mu^\pm$, $\mu^\pm \mu^\pm$) is examined for the inclusive final state and separately for positively- and negatively-charged pairs.

The ATLAS Collaboration has previously reported inclusive searches for new physics in the like-sign dilepton final state in a data sample corresponding to an integrated luminosity of 34 pb$^{-1}$ [15] and in like-sign muon pairs with 1.6 fb$^{-1}$ [16]. No significant deviation from SM expectations was observed, and fiducial production cross-section limits as well as limits on several specific models of physics beyond SM were derived. The CDF Collaboration has
performed similar inclusive searches [17, 18] without observing any evidence for new physics. Furthermore, the ATLAS and CMS Collaborations have performed several searches for like-sign leptons produced in association with jets or missing transverse momentum where no evidence of non-SM physics was observed [19–26].

This article is organised as follows. A brief description of the ATLAS detector is given in section 2. The data and simulation samples, the event selection, and the background determination are explained in sections 3, 4, and 5, respectively. The systematic uncertainties on the background estimate (including theoretical uncertainties on the production cross sections) and signal acceptances are summarised in section 6. In section 7 the number of observed lepton pairs in data is compared to the background estimate, and in section 8 these results are used to derive upper limits on the fiducial cross section for like-sign dilepton production in a kinematic region closely related to the experimental event selection.

2 The ATLAS detector

The ATLAS detector [27] consists of an inner tracking system, calorimeters, and a muon spectrometer. The inner detector (ID), directly surrounding the interaction point, is composed of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker, all immersed in a 2 T axial magnetic field. It covers the pseudorapidity\(^1\) range |\(\eta\)| < 2.5 and is enclosed by a calorimeter system consisting of electromagnetic and hadronic sections. The electromagnetic part is a lead/liquid-argon sampling calorimeter, divided into a barrel (|\(\eta\)| < 1.475) and two end-cap sections (1.375 < |\(\eta\)| < 3.2). The barrel (|\(\eta\)| < 0.8) and extended barrel (0.8 < |\(\eta\)| < 1.7) hadronic calorimeter sections consist of iron and scintillator tiles, while the end-cap (1.5 < |\(\eta\)| < 3.2) and forward (3.1 < |\(\eta\)| < 4.9) calorimeters are composed of copper or tungsten, and liquid-argon.

The calorimeter system is surrounded by a large muon spectrometer (MS) built with air-core toroids. This spectrometer is equipped with precision tracking chambers (composed of monitored drift tubes and cathode strip chambers) to provide precise position measurements in the bending plane in the range |\(\eta\)| < 2.7. In addition, resistive plate chambers and thin gap chambers with a fast response time are used primarily to trigger muons in the rapidity ranges |\(\eta\)| ≤ 1.05 and 1.05 < |\(\eta\)| < 2.4, respectively. The resistive plate chambers and thin gap chambers also provide position measurements in the non-bending plane, which are used for the pattern recognition and the track reconstruction.

The ATLAS trigger system has a hardware-based Level-1 trigger followed by a software-based high-level trigger [28]. The Level-1 muon trigger searches for hit coincidences between different muon trigger detector layers inside geometrical windows that define the muon transverse momentum and provide a rough estimate of its position. It selects high-\(p_T\) muons in the pseudorapidity range |\(\eta\)| < 2.4. The Level-1 electron trigger selects local energy

\(^1\)ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam line. 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 (x, y) plane, \(\phi\) being the azimuthal angle around the beam line. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln \tan(\theta/2)\).
clusters of cells in the electromagnetic section of the calorimeter. For low-energy electron clusters, low activity in the hadronic calorimeter nearby in the $\eta$-$\phi$ plane is required. The high-level trigger selection is based on similar reconstruction algorithms as those used offline.

3 Data sample and Monte Carlo simulation

This analysis is carried out using a data sample corresponding to an integrated luminosity of $4.7 \pm 0.2$ fb$^{-1}$ of $pp$ collisions, recorded in 2011 at a centre-of-mass energy of 7 TeV. In this dataset, the average number of interactions per beam crossing ranges from about six in the first half of the year to about fifteen at the end of 2011.

The data were selected using single-muon and single-electron triggers with $p_T$ thresholds of 10 GeV and 16 GeV at Level-1, respectively. In the high-level trigger, a muon with $p_T > 18$ GeV is required, while for electrons, the $p_T$ threshold is 20 GeV in the early 2011 data and 22 GeV in the later part of the year. To ensure no efficiency loss for electrons with very high-$p_T$, a trigger with a $p_T$ threshold of 45 GeV is also used which has no requirement on the hadronic calorimeter energy deposits near the electron in the $\eta$-$\phi$ plane at Level-1.

Monte Carlo (MC) simulation is used to estimate some of the background contributions and to determine the selection efficiency and acceptance for possible new physics signals. The dominant SM processes that contribute to prompt like-sign dilepton production are $WZ$ and $ZZ$, with smaller contributions from like-sign $W$ pair production ($W^{\pm}W^{\mp}$) and production of a $W$ or $Z$ boson in association with a top quark pair ($t\bar{t}W$, and $t\bar{t}Z$). These are all estimated using MC simulation. For processes with a $Z$ boson, the contribution from $\gamma^* \rightarrow \ell^+\ell^-$ due to internal or external bremsstrahlung of final-state quarks or leptons is also simulated for $m(\ell^+\ell^-) > 0.1$ GeV. SHERPA [29] is used to generate $WZ$ and $ZZ$ events, while $W^{\pm}W^{\mp}$, $t\bar{t}W$, and $t\bar{t}Z$ production is modelled using MADGRAPH [30] for the matrix element and PYTHIA [31] for the parton shower and fragmentation. The $W^{\pm}W^{\pm}$ sample includes the $W^{\pm}W^{\mp}$ process.

The normalisation of the $WZ$ and $ZZ$ MC samples is based on cross sections determined at next-to-leading order (NLO) with MCFM [32]. The cross sections times branching ratios for $W^{\pm}Z \rightarrow \ell^\pm \nu \ell^\mp$ and $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ after requiring two charged leptons (electrons, muons, or taus) with the same electric charge and with $p_T > 20$ GeV and $|\eta| < 2.5$, are 372 fb and 91 fb, respectively.

For $t\bar{t}W$ and $t\bar{t}Z$ production, the higher-order corrections are calculated in ref. [33] and refs. [34–36], respectively. The full higher-order corrections for $W^{\pm}W^{\pm}$ production have not been calculated. However, for parts of the process, the NLO QCD corrections have been shown to be small [37, 38]. Based on this, no correction is applied to the LO cross section.

Opposite-sign dilepton events due to $Z/\gamma^*$, $t\bar{t}$, and $W^{\pm}W^{\mp}$ production constitute a background if the charge of one of the leptons is misidentified. The $Z/\gamma^*$ process is generated with PYTHIA, and the cross section is calculated at next-to-next-to-leading order (NNLO) using PHOZPR [39]. The ratio of this cross section to the leading-order cross

---

3

Data sample and Monte Carlo simulation

This analysis is carried out using a data sample corresponding to an integrated luminosity of $4.7 \pm 0.2$ fb$^{-1}$ of $pp$ collisions, recorded in 2011 at a centre-of-mass energy of 7 TeV. In this dataset, the average number of interactions per beam crossing ranges from about six in the first half of the year to about fifteen at the end of 2011.

The data were selected using single-muon and single-electron triggers with $p_T$ thresholds of 10 GeV and 16 GeV at Level-1, respectively. In the high-level trigger, a muon with $p_T > 18$ GeV is required, while for electrons, the $p_T$ threshold is 20 GeV in the early 2011 data and 22 GeV in the later part of the year. To ensure no efficiency loss for electrons with very high-$p_T$, a trigger with a $p_T$ threshold of 45 GeV is also used which has no requirement on the hadronic calorimeter energy deposits near the electron in the $\eta$-$\phi$ plane at Level-1.

Monte Carlo (MC) simulation is used to estimate some of the background contributions and to determine the selection efficiency and acceptance for possible new physics signals. The dominant SM processes that contribute to prompt like-sign dilepton production are $WZ$ and $ZZ$, with smaller contributions from like-sign $W$ pair production ($W^{\pm}W^{\mp}$) and production of a $W$ or $Z$ boson in association with a top quark pair ($t\bar{t}W$, and $t\bar{t}Z$). These are all estimated using MC simulation. For processes with a $Z$ boson, the contribution from $\gamma^* \rightarrow \ell^+\ell^-$ due to internal or external bremsstrahlung of final-state quarks or leptons is also simulated for $m(\ell^+\ell^-) > 0.1$ GeV. SHERPA [29] is used to generate $WZ$ and $ZZ$ events, while $W^{\pm}W^{\mp}$, $t\bar{t}W$, and $t\bar{t}Z$ production is modelled using MADGRAPH [30] for the matrix element and PYTHIA [31] for the parton shower and fragmentation. The $W^{\pm}W^{\pm}$ sample includes the $W^{\pm}W^{\mp}$ process.

The normalisation of the $WZ$ and $ZZ$ MC samples is based on cross sections determined at next-to-leading order (NLO) with MCFM [32]. The cross sections times branching ratios for $W^{\pm}Z \rightarrow \ell^\pm \nu \ell^\mp$ and $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ after requiring two charged leptons (electrons, muons, or taus) with the same electric charge and with $p_T > 20$ GeV and $|\eta| < 2.5$, are 372 fb and 91 fb, respectively.

For $t\bar{t}W$ and $t\bar{t}Z$ production, the higher-order corrections are calculated in ref. [33] and refs. [34–36], respectively. The full higher-order corrections for $W^{\pm}W^{\pm}$ production have not been calculated. However, for parts of the process, the NLO QCD corrections have been shown to be small [37, 38]. Based on this, no correction is applied to the LO cross section.

Opposite-sign dilepton events due to $Z/\gamma^*$, $t\bar{t}$, and $W^{\pm}W^{\mp}$ production constitute a background if the charge of one of the leptons is misidentified. The $Z/\gamma^*$ process is generated with PYTHIA, and the cross section is calculated at next-to-next-to-leading order (NNLO) using PHOZPR [39]. The ratio of this cross section to the leading-order cross
section is used to determine a mass dependent QCD $K$-factor which is applied to the result of the leading-order simulation [40]. Higher-order electroweak corrections (beyond the photon radiation included in the simulation) are calculated using HORACE [41, 42], yielding an electroweak $K$-factor due to virtual heavy gauge-boson loops. The production of $t\bar{t}$ is modelled using MC@NLO [43], with HERWIG [44] used for parton showering and hadronisation. The normalisation is obtained from approximate NNLO QCD calculations using HATHOR [45]. The production of $W^{\pm}W^{\mp}$ is generated using HERWIG, and the cross section is normalised to the NLO value calculated with MCFM. The production of $Z\gamma \rightarrow \ell\ell\gamma$ is implicitly accounted for in simulation of the $Z/\gamma^*$ process.

In addition, a variety of new physics signals are simulated in order to study the efficiency and acceptance of the selection criteria. Pair production of doubly-charged Higgs bosons ($pp \rightarrow H^{\pm\pm}H^{\mp\mp}$) via a virtual $Z/\gamma^*$ exchange is generated using PYTHIA for $H^{\pm\pm}$ mass values between 50 GeV and 1000 GeV [48]. Production of a right-handed $W$ boson ($W_R$) decaying to a charged lepton and a right-handed neutrino ($N_R$) [49, 50] and pair production of heavy down-type fourth generation quarks ($d_4$) decaying to $t\bar{t}$W are generated using PYTHIA. Like-sign top-quark pair production can occur in models with flavour-changing neutral currents, e.g. via a $t$-channel exchange of a $Z'$ boson with $utZ'$ coupling. Since the left-handed coupling is highly constrained by $B_0^0$ mixing, only right-handed top quarks ($t_R$) are considered. A sample is generated with the PROTOS [52] generator, based on an effective four-fermion operator $uu \rightarrow tt$ corresponding to $Z'$ masses $\gg 1$ TeV [53]. The parton shower and hadronisation are performed with PYTHIA.

Parton distribution functions (PDFs) taken from CTEQ6L1 [54] are used for the MADGRAPH and ALPGEN samples, and the MRST2007 LO** [55] PDF set is used for the PYTHIA and HERWIG samples. For the $t\bar{t}$ MC@NLO sample, CTEQ6.6 [56] PDFs are used, while for the generation of diboson samples with SHERPA the CTEQ10 [57] parameterisation is used. Uncertainties on the quoted cross sections are discussed in section 6.

The detector response to the generated events is simulated with the ATLAS simulation framework [58] using GEANT4 [59], and the events are reconstructed with the same software used to process the data. Simulated minimum bias interactions generated with PYTHIA are overlaid on the hard scatter events to closely emulate the multiple $pp$ interactions present in the current and in adjacent bunch crossings (pileup) present in the data. The simulated response is corrected for the small differences in efficiencies, momentum scales, and momentum resolutions observed between data and simulation.

4 Event selection

Events are selected if they contain at least two leptons ($ee$, $e\mu$, $\mu\mu$) of the same electric charge with $p_T > 20$ GeV. If the higher-$p_T$ lepton is an electron, it is required to have $p_T > 25$ GeV. At least one muon with $p_T > 20$ GeV or one electron with $p_T > 25$ GeV is required to match an object that passed the relevant high-level trigger. These $p_T$ thresholds
are chosen such that they are on the plateau of the trigger efficiency. In addition to the lepton selection, events must have a primary vertex reconstructed with at least three tracks with $p_T > 0.4$ GeV. If more than one interaction vertex is reconstructed in an event, the one with the highest $\sum p_T^2$, summed over the tracks associated with the vertex, is chosen as the primary vertex. For $Z$ bosons decaying to electrons or muons, the efficiency of the primary vertex requirements is close to 100%.

Electrons are identified as compact showers in the electromagnetic sections of the calorimeters that are matched to a reconstructed track in the ID using the tight criteria described in ref. [60]. These criteria include requirements on the transverse shower shapes, the geometrical match between the track and shower, the number and type of hits in the ID, and they reject electrons associated with reconstructed photon conversion vertices. Electrons must have $|\eta| < 2.47$, excluding the transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$). The electron tracks are refitted with the Gaussian Sum Filter algorithm to account for radiative energy losses (bremsstrahlung) in the detector material [61].

Muon candidates are formed from tracks reconstructed in the ID combined with tracks reconstructed in the MS [62]. To reduce the charge mismeasurement rate the independent charge measurements from these two detectors are required to agree. Muons must have $|\eta| < 2.5$.

The isolation energy, $E_T^{\Delta R_{iso}}$, is the sum of transverse energies in calorimeter cells (including electromagnetic and hadronic sections) in a cone $\Delta R = \sqrt{(|\Delta \eta|^2 + |\Delta \phi|^2)} < \Delta R_{iso}$ around the lepton direction. This quantity is corrected for the energy of the electron object as well as energy deposits from pileup interactions. The track isolation, $p_T^{\Delta R_{iso}}$, is analogously defined as the scalar sum of the transverse momentum of tracks with $p_T > 1$ GeV in a cone of $\Delta R < \Delta R_{iso}$ around the lepton direction, excluding the lepton track. For muons, $p_T^{\Delta R_{iso}} < 0.06$ and $p_T^{\Delta R_{iso}} < 4$ GeV $+ 0.02 \times p_T(\mu)$ are required. For electrons, the requirements are $p_T^{\Delta R_{iso}} < 0.1$ and $E_T^{\Delta R_{iso}} < 3$ GeV $+ (p_T(e) - 20$ GeV) $\times 0.037$. These requirements are chosen to maintain good efficiency for prompt leptons over a large $p_T$ range while rejecting a large fraction of non-prompt leptons, particularly at low $p_T$.

In addition to the isolation criteria, selected leptons are required to be well separated from jets to suppress leptons from hadronic decays. For this purpose, jet candidates

\footnotesize

2 Transverse energy is the projection of an energy deposition in the calorimeter in the transverse plane, where the direction is given by the line joining the energy deposition and the nominal interaction point.

\normalsize
are reconstructed from topological clusters in the calorimeter [63] using the anti-\( k_t \) algorithm [64] with a radius parameter of 0.4. Their energies are corrected for calorimeter non-compensation, energy loss in upstream material, and other instrumental effects. Furthermore, quality criteria are applied to remove reconstructed jets not arising from hard-scattering interactions [65]. Jets are required to have \( p_T > 25 \) GeV, \( |\eta| < 2.8 \), and 75\% of the momentum of the tracks within the jet must originate from the primary vertex. Any jet within a distance \( \Delta R = 0.2 \) of a candidate electron is removed from the list of jets to avoid counting the electron as a jet. Electrons and muons are then required to be separated by \( \Delta R > 0.4 \) from any jet with \( p_T > 25 \) GeV + 0.05 \( \times p_T(\ell) \).

Lepton pairs are selected if they contain two leptons with the same electric charge passing the above selection requirements with invariant mass \( m(\ell^\pm \ell^\mp) > 15 \) GeV. Furthermore, for \( e^\pm e^\pm \) pairs, the mass range 70–110 GeV is vetoed due to large backgrounds from opposite-sign electron pairs produced by \( Z \) decays, where the charge of one lepton is misidentified. Any combination of two leptons is considered, allowing more than one lepton pair per event to be included.

5 Background determination

Backgrounds to this search arise from three principal sources: SM production of prompt, like-sign lepton pairs (prompt background); production of opposite-sign lepton pairs where the charge of one lepton is misidentified (charge-flip background) or where a photon produced in association with the opposite-sign leptons converts into an \( e^+e^- \) pair; and hadrons or leptons from hadronic decays (non-prompt background).

5.1 Prompt lepton backgrounds

SM processes resulting in two prompt leptons of the same electric charge are \( WZ, ZZ, W^\pm W^\pm, t\bar{t}W, \) and \( t\bar{t}Z \) production. The background due to these processes is determined from MC simulation using the samples and cross sections described in section 3. Other SM processes are not expected to contribute significantly to the background and are neglected.

5.2 Charge misidentification and photon conversions

Charge misidentification can occur for high-momentum tracks when the tracking detector is unable to determine the curvature of the track. This misidentification can occur for both electrons and muons. In the momentum range of a few hundred GeV relevant for this analysis, the background arising from this source is determined to be negligible based on MC simulation. The rate of misidentification is studied in data with muons from \( Z \rightarrow \mu\mu \) decays where the muons are selected based only on the MS (ID) measurements to study the ID (MS) mismeasurement. The combined probability to mismeasure the charge in both the ID and the MS is found to be consistent with zero and an upper limit ranging from \( 5 \times 10^{-10} \) at low \( p_T \) to \( 7 \times 10^{-2} \) for \( p_T \sim 400 \) GeV is placed. This upper limit is used to determine the systematic uncertainty for muons.

Another source of charge misidentification occurs for electrons when a high-momentum photon is radiated and converts into an \( e^+e^- \) pair. Electron candidates are rejected if
they are associated with conversion vertices \[60\]. However, for asymmetric conversions, sometimes only one of the tracks is reconstructed and its charge may be different from the charge of the original electron that radiated the photon. The probability for electron charge misidentification to occur, either by this mechanism or by track mismeasurement, is measured as the fraction of like-sign \(e^\pm e^\pm\) pairs with \(80 \text{ GeV} < m(ee) < 100 \text{ GeV}\) as a function of the electron \(\eta\) following the procedure explained in ref. \[66\]. The simulation is found to overestimate this probability by about 15%. An \(\eta\)-dependent scaling factor is applied to the simulated rate to account for this overestimate, and the simulation is then used to predict the backgrounds from \(Z/\gamma^*\), \(t\bar{t}\), and \(W^\pm W^\mp\) production. In the central (forward) region the probability increases from about 0.01% (0.6%) at \(p_T \approx 50 \text{ GeV}\) to 0.3% (4%) at \(p_T \approx 300 \text{ GeV}\). An uncertainty on this misidentification probability of \(\pm(10–20)\%\) (depending on \(\eta\)) is derived by comparing different methods to determine this factor as described in ref. \[66\] and by considering the statistical uncertainty on each method.

Production of \(W\gamma \rightarrow \ell\nu\gamma\) and \(Z\gamma \rightarrow \ell^+\ell^-\gamma\) can lead to like-sign lepton pairs if the photon converts. This background is determined using the MC samples described in section 3. Since this background is closely related to the charge misidentification for electrons described above, the MC-based estimate is also scaled down by 15% and the same systematic uncertainty of \(\pm(10–20)\%\) is applied.

5.3 Non-prompt lepton backgrounds

The non-prompt background includes lepton pairs where one or both of the leptons result from hadronic decay or misidentification. Processes contributing to this background include \(W+\text{jet}, Z+\text{jet}, \text{multi-jet (including } b\bar{b} \text{ and } c\bar{c})\), and \(t\bar{t}\) production.

The non-prompt background is determined directly from data. For both electrons and muons, the determination relies on measuring a factor \(f\) that is the ratio of the number of selected leptons satisfying the analysis selection criteria \((N_S)\) to the number of leptons failing these selection criteria but passing a less stringent set of requirements, referred to as anti-selected leptons \((N_A)\):

\[
f = \frac{N_S}{N_A}.
\]

The factor \(f\) is determined as a function of \(p_T\) and \(\eta\) in a data sample dominated by non-prompt leptons. Any contamination by prompt leptons in the numerator and denominator is subtracted using MC simulation. The details of the anti-selected definitions and the regions used for measuring \(f\) depend on the lepton flavour and are described in more detail below.

The primary sources of non-prompt muons are semi-leptonic decays of \(b\)- and \(c\)-hadrons. For the anti-selection, the isolation criterion described in section 4 is inverted, but a looser requirement of \(p_T^{\text{cone}0.4}/p_T(\mu) < 1.0\) is placed. The measurement of \(f\) is done in a sample dominated by non-prompt muons with \(|d_0|/\sigma(d_0) > 5\) and \(|d_0| < 10 \text{ mm}\). These muons are selected from dimuon events with \(p_T(\mu) > 10 \text{ GeV}, m(\mu\mu) > 15 \text{ GeV}\), and where \(Z\)-boson candidates have been vetoed. Simulated muons from \(b\)- and \(c\)-hadron decays are used to determine the expected difference between \(f\) for muons with \(|d_0|/\sigma(d_0) > 5\)
(used in the data-driven determination of \( f \)) and muons with \( |d_0|/\sigma(d_0) < 3 \) (used in the event selection). In simulation, muons with \( |d_0|/\sigma(d_0) < 3 \) are more isolated, so a correction factor of \( 1.34 \pm 0.34 \) is applied to \( f \). The resulting value of \( f \) is about 0.10 at \( p_T = 20 \) GeV and increases to about 0.25 at \( p_T = 100 \) GeV. One source of uncertainty in this procedure is that the fraction of non-prompt muons from pion and kaon decays may be larger for muons passing the analysis-level impact parameter criteria than for those used in the measurement of \( f \). The uncertainty due to the contribution of light-flavour decays is assessed by exploiting the difference in the track momentum measurement in the ID and the MS, which is expected to be large for kaons or pions decaying in the ID or calorimeters. The difference between \( f \) for light-flavour decays and heavy-flavour decays is combined with the fraction of non-prompt muons from light-flavour decays to give an uncertainty of \( \pm 15\% \) on \( f \). The total systematic uncertainty on \( f \) is the quadratic sum of the statistical error, the uncertainty on the prompt background subtraction, the correction for the isolation-dependence on the impact parameter significance criteria, and the uncertainty in the contribution of pion and kaon decays. It is about \( \pm 37\% \) at low \( p_T \) and \( \pm 100\% \) for \( p_T > 100 \) GeV.

For electrons, the main non-prompt backgrounds arise from heavy-flavour decays, charged pions that shower early in the calorimeter, and neutral pions decaying to two photons where one of the photons converts to an \( e^+e^- \) pair. The anti-selected electrons must have either \( |d_0|/\sigma(d_0) > 3 \) or fail the medium electron identification criteria while passing the loose electron criteria, as defined in ref. [60]. The inversion of the impact parameter criteria enhances the heavy-flavour background, while the inversion of the medium identification criteria enhances the pion backgrounds. A sample dominated by non-prompt electrons is selected by triggering on a high-\( p_T \) electron candidate and requiring that the event contains a jet with \( p_T > 20 \) GeV. Contamination of this sample by prompt electrons is reduced by requiring that there be only one electron candidate and requiring the transverse mass\(^3\) formed by the electron and the missing transverse momentum \( (E_T^{\text{miss}}) \) to be below 40 GeV. The value of \( f \) is found to be about 0.18 at \( E_T = 20 \) GeV and decreases to about 0.10 at \( E_T = 100 \) GeV. A systematic uncertainty is determined accounting for the statistical uncertainty, the prompt background subtraction, the \( p_T \) requirement of the jet in the event, and any trigger bias. The uncertainty is about \( \pm 10\% \) at low \( E_T \) and increases to \( \pm 100\% \) for \( E_T > 300 \) GeV. Alternate anti-selection definitions are used to assess the overlap between the non-prompt and charge misidentification backgrounds, as well as the contributions of light- and heavy-flavour jets to the non-prompt background. For the former, a correction is made to the non-prompt background, amounting to \( \pm (11–25)\% \), and the full correction is taken as a systematic uncertainty. For the latter, an uncertainty of \( \pm (4–84)\% \) is found, depending on the invariant mass threshold considered.

A background prediction is derived from \( f \) using dilepton pairs where one or both leptons are anti-selected but pass all other event selection criteria. The non-prompt back-

\(^3\)The transverse mass is defined as \( \sqrt{2E_T^{\text{miss}}p_T(e)(1 - \cos \Delta \phi(e, E_T^{\text{miss}}))} \), where \( E_T^{\text{miss}} \) is the missing transverse momentum and \( \Delta \phi(e, E_T^{\text{miss}}) \) is the difference between the azimuthal angles of the electron and \( E_T^{\text{miss}} \).
ground prediction is then given by

\[ N_{\text{non-prompt}} = \sum_{i=1}^{N_{A+S}} f(pT_1, \eta_1) + \sum_{i=1}^{N_{S+A}} f(pT_2, \eta_2) - \sum_{i=1}^{N_{A+A}} f(pT_1, \eta_1) f(pT_2, \eta_2), \]  

where the sums are over the number of pairs, \(N_{A+S}\) (\(N_{S+A}\)), where the subleading (leading) lepton satisfies the selection criteria and the other lepton satisfies the anti-selection, or over the number of pairs where both leptons are anti-selected (\(N_{A+A}\)). The prompt contributions to \(N_{A+S}\), \(N_{S+A}\), and \(N_{A+A}\) are subtracted based on MC predictions. The variables \(pT_1\) and \(\eta_1\) (\(pT_2\) and \(\eta_2\)) refer to the kinematic properties of the leading (subleading) lepton.

The background estimates are verified in several control regions that are designed to probe specific sources of background. The understanding of prompt leptons is tested in a sample requiring two leptons of opposite charge. This sample is dominated by the \(Z/\gamma^*\) process in all three final states, and the data agree with the background prediction to better than 5%. The kinematics of the electron charge misidentification background are verified in pairs of like-sign electrons with \(80\ GeV < m(e^\pm e^\pm) < 100\ GeV\). The non-prompt background is tested by inverting the isolation criteria but requiring a looser isolation cut value. The heavy-flavour background is tested by inverting the |\(d_0|/\sigma(d_0)\) criterion. Furthermore, for electrons, the light-flavour background is tested by inverting some of the shower shape criteria. The data agree with the background prediction in the various control regions within the systematic uncertainties.

6 Systematic uncertainties

Several systematic effects can change the signal acceptance and the background estimate. Uncertainties on the event selection efficiencies and on the luminosity affect the predicted yield of signal events as well as those backgrounds that are estimated from MC simulation. Uncertainties on the trigger efficiencies, lepton identification efficiencies, and lepton momentum scales are determined using \(W\), \(Z\), and \(J/\psi\) decays [67–69]. The uncertainties on the lepton identification efficiencies result in an uncertainty on the number of like-sign pairs of \((3–4)\%\). Effects resulting from uncertainties in the muon momentum scale and resolution are negligible. For electrons the energy scale is known to \(\pm 1\%\), and its impact on the signal acceptance is below 0.1%, while the background estimate is affected by up to \(\pm 3.5\%\). The uncertainties due to the trigger efficiencies are \(< 1\%\) in all channels. The uncertainty on the integrated luminosity is \(\pm 3.9\%\) [70, 71].

The uncertainties on the production cross sections of the SM processes affect the predicted yield of the prompt lepton background. For \(WZ\) and \(ZZ\) production, an uncertainty of \(\pm 10\%\) is estimated due to higher-order QCD corrections by varying the renormalisation and factorisation scales by a factor of two. The uncertainty due to the parton distribution functions (PDFs) is evaluated using the eigenvectors provided by the CTEQ10 set [57] of PDFs, following the prescription given in ref. [72]. The difference between the central cross-section values obtained using this PDF set and that obtained with the MRST2008NLO PDFs [55] is also added in quadrature. This procedure gives a conservative estimate of
the PDF uncertainty on the cross section. The resulting uncertainty on the cross section is ±7%. For $t\bar{t}W$, $t\bar{t}Z$ and $W^\pm W^\mp$ production a normalisation uncertainty of ±50% is assigned [34, 37].

The production of $Z/\gamma^*$, $t\bar{t}$, and $W^\pm W^\mp$ also constitutes a background in the $ee$ and $e\mu$ channels due to charge misidentification. The PDF uncertainties for $Z/\gamma^*$ and $t\bar{t}$ are computed using the MSTW2008 NNLO PDF sets [73] and the renormalisation and factorisation scales are varied by factors of two to derive the uncertainties due to higher-order QCD corrections. For $Z/\gamma^*$, an additional systematic uncertainty is attributed to electroweak corrections [40]. The total uncertainties on the $Z/\gamma^*$ and $t\bar{t}$ cross sections are ±7% and +10/−11%, respectively. The $W^\pm W^\mp$ cross-section uncertainty is determined using the same scale and PDF variations as for $WZ$ and $ZZ$, yielding a total uncertainty of ±12%.

The systematic uncertainty on the background from non-prompt leptons is discussed in section 5.3. It includes a component due to the systematic uncertainties associated with the measurement of the ratio $f$ and a component due to the statistical uncertainty on the number of anti-selected leptons. For $m(\ell^+\ell^+) > 15$ GeV it is ±33% for the $\mu\mu$, ±31% for the $e\mu$, and ±28% for the $ee$ final states, and it increases to nearly ±100% at higher masses for all final states.

The probability of assigning the wrong charge to the lepton and its uncertainty is discussed in section 5.2. For the $\mu\mu$ final state, charge misidentification results in an uncertainty of $^{+4.9}_{-0.0}$ events for $m(\ell^+\ell^+) > 15$ GeV and $^{+1.7}_{-0.9}$ events for $m(\ell^+\ell^+) > 400$ GeV. For electrons, the uncertainty on the charge-flip background due to uncertainty in the charge mismeasurement probability ranges from ±15% to ±23% for the same mass thresholds. The uncertainty on the $W\gamma$ and $Z\gamma$ backgrounds from this source is ±(15–18)% depending on $m(\ell^+\ell^+)$. Statistical uncertainties due to the limited size of the background MC samples are also considered. Systematic uncertainties on different physics processes due to a given source are assumed to be 100% correlated.

7 Comparison of data to the background expectation

The predicted numbers of background pairs are compared to the observed numbers of like-sign lepton pairs in table 1. For the $e^\pm e^\pm$ ($e^\pm \mu^\pm$) final state, about 30% (50%) of the background is from prompt leptons in all mass bins. The rest arises from leptons from hadronic decays, charge flips, or photon conversions. For the $\mu^\pm \mu^\pm$ final state, the prompt background constitutes about 83% of the total background for $m(\mu^\pm \mu^\pm) > 15$ GeV, rising to nearly 100% of the total background for $m(\mu^\pm \mu^\pm) > 400$ GeV. The overall uncertainty on the background is about ±15% at low mass and ±30% at high mass.

Table 2 shows the data compared to the background expectation separately for $\ell^+\ell^+$ and $\ell^-\ell^-$ events for the $ee$, $\mu\mu$, and $e\mu$ final states. The background is higher for the $\ell^+\ell^+$ final state due to the larger cross section in $pp$ collisions for $W^+$ than $W^-$ bosons produced in association with $\gamma$, $Z$, or hadrons.
Table 1. Expected and observed numbers of pairs of isolated like-sign leptons for various cuts on the dilepton invariant mass, $m(\ell^+\ell^-)$. The uncertainties shown are the quadratic sum of the statistical and systematic uncertainties. The prompt background contribution includes the $WZ$, $ZZ$, $W^\pm W^\pm$, $t\bar{t}W$, and $ttZ$ processes. When zero events are predicted, the uncertainty corresponds to the 68% confidence level upper limit on the prediction.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of electron pairs with $m(\ell^+\ell^-)$</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt;15 \text{ GeV}$</td>
<td>$&gt;100 \text{ GeV}$</td>
<td>$&gt;200 \text{ GeV}$</td>
<td>$&gt;300 \text{ GeV}$</td>
<td>$&gt;400 \text{ GeV}$</td>
</tr>
<tr>
<td>Prompt</td>
<td>101 ± 13</td>
<td>56.3 ± 7.2</td>
<td>14.8 ± 2.0</td>
<td>4.3 ± 0.7</td>
<td>1.4 ± 0.3</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>75 ± 21</td>
<td>28.8 ± 8.6</td>
<td>5.8 ± 2.5</td>
<td>0.5^{+0.8}_{-0.5}</td>
<td>0.0^{+0.2}_{-0.0}</td>
</tr>
<tr>
<td>Charge flips and conversions</td>
<td>170 ± 33</td>
<td>91 ± 16</td>
<td>22.1 ± 4.4</td>
<td>8.0 ± 1.7</td>
<td>3.4 ± 0.8</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>346 ± 44</td>
<td>176 ± 21</td>
<td>42.8 ± 5.7</td>
<td>12.8 ± 2.1</td>
<td>4.8 ± 0.9</td>
</tr>
<tr>
<td>Data</td>
<td>329</td>
<td>171</td>
<td>38</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of muon pairs with $m(\mu^+\mu^-)$</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt;15 \text{ GeV}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt</td>
<td>205 ± 26</td>
<td>90 ± 11</td>
<td>21.8 ± 2.8</td>
<td>5.8 ± 0.9</td>
<td>2.2 ± 0.4</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>42 ± 14</td>
<td>12.1 ± 4.6</td>
<td>1.0 ± 0.6</td>
<td>0.0^{+0.3}_{-0.0}</td>
<td>0.0^{+0.3}_{-0.0}</td>
</tr>
<tr>
<td>Charge flips</td>
<td>$0.0^{+4.9}_{-0.0}$</td>
<td>$0.0^{+2.5}_{-0.0}$</td>
<td>$0.0^{+1.8}_{-0.0}$</td>
<td>$0.0^{+1.7}_{-0.0}$</td>
<td>$0.0^{+1.7}_{-0.0}$</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$247^{+30}_{-29}$</td>
<td>102 ± 12</td>
<td>$22.8^{+3.4}_{-2.9}$</td>
<td>$5.8^{+1.9}_{-0.9}$</td>
<td>$2.2^{+1.7}_{-0.4}$</td>
</tr>
<tr>
<td>Data</td>
<td>264</td>
<td>110</td>
<td>29</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of lepton pairs with $m(\ell^+\ell^-)$</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt;15 \text{ GeV}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt</td>
<td>346 ± 43</td>
<td>157 ± 20</td>
<td>36.6 ± 4.7</td>
<td>10.8 ± 1.5</td>
<td>3.9 ± 0.6</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>151 ± 47</td>
<td>45 ± 13</td>
<td>9.2 ± 4.1</td>
<td>2.6 ± 1.1</td>
<td>1.0 ± 0.6</td>
</tr>
<tr>
<td>Charge flips and conversions</td>
<td>142 ± 28</td>
<td>33 ± 7</td>
<td>10.5 ± 2.8</td>
<td>2.9 ± 1.2</td>
<td>2.2 ± 1.1</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>639 ± 71</td>
<td>235 ± 25</td>
<td>56.4 ± 7.0</td>
<td>16.3 ± 2.3</td>
<td>7.0 ± 1.4</td>
</tr>
<tr>
<td>Data</td>
<td>658</td>
<td>259</td>
<td>61</td>
<td>17</td>
<td>7</td>
</tr>
</tbody>
</table>

The level of agreement between the data and the background expectation is evaluated using $1-\text{CL}_b$ [74], defined as the one-sided probability of the background-only hypothesis to fluctuate up to at least the number of observed events. Statistical and systematic uncertainties and their correlations are fully considered for this calculation. The largest upward deviation, observed for $m(\mu^+\mu^-) > 100 \text{ GeV}$, occurs about 8% of the time in background-only pseudo-experiments for this mass bin.

Figure 1 shows the dilepton invariant mass spectra for the $e^\pm e^\pm$, $\mu^\pm \mu^\pm$, and $e^\pm \mu^\pm$ final states, and figure 2 shows the $p_T$ of the leading leptons. Good agreement with the
Table 2. Expected and observed numbers of positively- and negatively-charged lepton pairs for different lower limits on the dilepton invariant mass, $m(\ell^\pm \ell'^\pm)$. The uncertainties shown are the quadratic sum of the statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of lepton pairs with $m(\ell^\pm \ell'^\pm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt; 15$ GeV</td>
</tr>
<tr>
<td><strong>$e^+e^+$ pairs</strong></td>
<td></td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$208 \pm 28$</td>
</tr>
<tr>
<td>Data</td>
<td>$183$</td>
</tr>
<tr>
<td><strong>$e^-e^-$ pairs</strong></td>
<td></td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$138 \pm 21$</td>
</tr>
<tr>
<td>Data</td>
<td>$146$</td>
</tr>
<tr>
<td><strong>$\mu^+\mu^+$ pairs</strong></td>
<td></td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$147 \pm 17$</td>
</tr>
<tr>
<td>Data</td>
<td>$144$</td>
</tr>
<tr>
<td><strong>$\mu^-\mu^-$ pairs</strong></td>
<td></td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$100 \pm 12$</td>
</tr>
<tr>
<td>Data</td>
<td>$120$</td>
</tr>
<tr>
<td><strong>$e^+\mu^+$ pairs</strong></td>
<td></td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$381 \pm 42$</td>
</tr>
<tr>
<td>Data</td>
<td>$375$</td>
</tr>
<tr>
<td><strong>$e^-\mu^-$ pairs</strong></td>
<td></td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>$259 \pm 31$</td>
</tr>
<tr>
<td>Data</td>
<td>$283$</td>
</tr>
</tbody>
</table>

background expectation is observed for all three channels.

8 Upper limits on the cross section for prompt like-sign dilepton production

Since the data are consistent with the background expectation, upper limits are placed on contributions due to processes from physics beyond the Standard Model. Limits are derived independently in each final state and mass bin shown in tables 1 and 2. The 95% confidence level (C.L.) upper limit on the number of events, $N_{95}$, is determined using the CL$_s$ method [74] with a test statistic based on the ratio between the likelihood of the signal plus background hypothesis and the likelihood of the background-only hypothesis. The likelihoods follow a Poisson distribution for the total number of events in each signal region, and are calculated based on the number of expected and observed events. Systematic
Figure 1. Invariant mass distributions for (a) $e^\pm e^\pm$, (b) $\mu^\pm \mu^\pm$, and (c) $e^\pm \mu^\pm$ pairs passing the full event selection. The data are shown as closed circles. The stacked histograms represent the backgrounds composed of pairs of prompt leptons from SM processes, pairs with at least one non-prompt lepton, and, for the electron channels, backgrounds arising from charge misidentification and photon conversions. Pairs in the $ee$ channel with invariant masses between 70 GeV and 110 GeV are excluded because of the large background from charge misidentification in $Z \to e^\pm e^\mp$ decays. The last bin is an overflow bin.

Uncertainties are incorporated into the likelihoods as nuisance parameters with Gaussian probability density functions. For the inclusive $\ell^\pm \ell^\pm$ final states, the upper limit ranges from 168 pairs for $m(e\mu) > 15$ GeV to 4.8 pairs for $m(\mu\mu) > 400$ GeV.

The limit on the number of lepton pairs can be translated to an upper limit on the cross section measured in a given region of phase space (referred to here as the fiducial region), $\sigma_{95}^{\text{fid}}$, via

$$\sigma_{95}^{\text{fid}} = \frac{N_{95}}{\epsilon_{\text{fid}} \times \int Ldt},$$

where $\epsilon_{\text{fid}}$ is the efficiency for detecting events within the fiducial region and $\int Ldt$ is the integrated luminosity of 4.7 fb$^{-1}$.

The fiducial region definition is based on MC generator information such that it is independent of the ATLAS detector environment. The value of $\epsilon_{\text{fid}}$ generally depends on the new physics process, e.g., the number of leptons in the final state passing the kinematic
selection criteria or the number of jets that may affect the lepton isolation. In order to minimise this dependence, the definition of the fiducial region is closely related to the analysis selection. In the MC generator, electrons or muons are selected as stable particles that originate from a $W$ or $Z$ boson, from a $\tau$ lepton, or from an exotic new particle (e.g. a $H^{\pm\pm}$ or a right-handed $W$). The generated electrons and muons are required to satisfy the $p_T$, $\eta$, and isolation requirements listed in table 3, which mirror the selection requirements described in section 4. The generator-level track isolation, $p_T^{\text{cone}R_{\text{iso}}}$, is defined as the scalar sum of all stable charged particles with $p_T > 1$ GeV in a cone of size $\Delta R_{\text{iso}}$ around the electron or muon, excluding the lepton itself. The requirement on isolation energy ($E_T^{\text{cone}R_{\text{iso}}}$) placed in the electron selection is not emulated in the fiducial region definition because the measurement of isolation energy in the calorimeter has a poor resolution. Pairs of like-sign leptons must have $m(\ell^+\ell^-) > 15$ GeV and for $e^+e^+$, the mass range 70–110 GeV is additionally excluded.

The fiducial efficiency, $\varepsilon_{\text{fid}}$, is defined as the fraction of lepton pairs passing this se-
Table 3. Summary of requirements on generated leptons in the fiducial region. The definition of the isolation variable, $p_T^{\text{cone}0.4}$, is given in the text.

<table>
<thead>
<tr>
<th></th>
<th>Electron requirement</th>
<th>Muon requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading lepton $p_T$</td>
<td>$p_T &gt; 25$ GeV</td>
<td>$p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td>Sub-leading lepton $p_T$</td>
<td>$p_T &gt; 20$ GeV</td>
<td>$p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td>Lepton $\eta$</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Isolation</td>
<td>$p_T^{\text{cone}0.3}/p_T &lt; 0.1$</td>
<td>$p_T^{\text{cone}0.4}/p_T &lt; 0.06$ and $p_T^{\text{cone}0.4} &lt; 4$ GeV + 0.02 × $p_T$</td>
</tr>
</tbody>
</table>

...selection that also satisfy the experimental selection criteria described in section 4. It is determined for a variety of new physics models: $H^{\pm\pm}$ bosons with mass between 50 GeV and 1000 GeV [48], fourth generation quarks decaying to $Wt$ with masses of 300–500 GeV, like-sign top-quark production via a contact interaction [53], and right-handed $W$ bosons decaying to $\ell^+\ell^\pm$ via a right-handed neutrino with $m(W_R) = 800$–2500 GeV [49, 50]. These models are chosen as they cover a broad range of jet multiplicities and lepton $p_T$ spectra.

For $m(\ell^+\ell^\pm) > 15$ GeV in the $e^\pm e^\pm$ channel, the fiducial efficiencies range from 43% for models with low-$p_T$ leptons to 65% for models with high-$p_T$ leptons. The primary reason for this dependence is that the electron identification efficiency varies by about 15% over the relevant $p_T$ range [60]. The model dependence introduced by not emulating the calorimeter isolation in the definition of the fiducial region is < 1%. For the $e^\pm\mu^\pm$ channel, $\varepsilon_{\text{fid}}$ ranges from 55% to 70%, and for the $\mu^+\mu^\pm$ final state it varies between 59% and 72%.

For the higher dilepton mass thresholds the efficiencies are slightly larger than for the lower mass thresholds. The efficiencies are also derived for $\ell^+\ell^+$ and $\ell^-\ell^-$ pairs separately and found to be independent of the charge. For the same new physics models, the fraction of events satisfying the experimental selection originating from outside the fiducial region ranges from < 1% to about 9%, depending on the final state and the model considered.

To derive the upper limit on the fiducial cross section, the lowest efficiency values are taken for all mass thresholds, i.e. 43% for the $e^\pm e^\pm$, 55% for the $e^\pm\mu^\pm$, and 59% for the $\mu^+\mu^\pm$ analysis. The 95% C.L. upper limits on the cross section, $\sigma_{\text{fid}}^{95}$, are calculated using equation 8.1 and given in table 4. The limits range from 64 fb to 1.7 fb for the inclusive analysis depending on the mass cut and the final state, and are generally within 1σ of the expected limits. Upper limits on the $\ell^+\ell^+$ and $\ell^-\ell^-$ cross sections are also derived, using the same efficiencies as for the inclusive limits.

9 Conclusions

A search for anomalous production of like-sign lepton pairs has been presented using 4.7 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV recorded by the ATLAS experiment at the LHC. The data are found to agree with the background expectation in $e^\pm e^\pm$, $e^\pm\mu^\pm$, and $\mu^+\mu^\pm$ final states both in overall rate and in the kinematic distributions. The data are used to constrain new physics contributions to like-sign lepton pairs within a fiducial region of...
Table 4. Upper limits at 95% C.L. on the fiducial cross section for $\ell^\pm\ell^\pm$ pairs from non-SM physics. The expected limits and their 1σ uncertainties are given, as well as the observed limits in data, for the $ee$, $e\mu$, and $\mu\mu$ final state inclusively and separated by charge.

<table>
<thead>
<tr>
<th>Mass range</th>
<th>expected $e^+e^+$</th>
<th>observed $e^+e^+$</th>
<th>95% C.L. upper limit [fb] expected $e^+\mu^+$</th>
<th>observed $e^+\mu^+$</th>
<th>expected $\mu^+\mu^+$</th>
<th>observed $\mu^+\mu^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m &gt; 15$ GeV</td>
<td>$46^{+15}_{-12}$</td>
<td>42</td>
<td>56$^{+23}_{-15}$</td>
<td>64</td>
<td>24.0$^{+8.0}_{-6.0}$</td>
<td>29.8</td>
</tr>
<tr>
<td>$m &gt; 100$ GeV</td>
<td>$24.1^{+8.9}_{-6.2}$</td>
<td>23.4</td>
<td>23.0$^{+9.1}_{-6.7}$</td>
<td>31.2</td>
<td>12.2$^{+4.5}_{-3.0}$</td>
<td>15.0</td>
</tr>
<tr>
<td>$m &gt; 200$ GeV</td>
<td>$8.8^{+3.4}_{-2.1}$</td>
<td>7.5</td>
<td>8.4$^{+3.4}_{-1.7}$</td>
<td>9.8</td>
<td>4.3$^{+1.1}_{-0.7}$</td>
<td>6.7</td>
</tr>
<tr>
<td>$m &gt; 300$ GeV</td>
<td>$4.5^{+1.8}_{-1.3}$</td>
<td>3.9</td>
<td>4.1$^{+1.8}_{-0.9}$</td>
<td>4.6</td>
<td>2.4$^{+0.9}_{-0.7}$</td>
<td>2.6</td>
</tr>
<tr>
<td>$m &gt; 400$ GeV</td>
<td>$2.9^{+1.1}_{-0.8}$</td>
<td>2.4</td>
<td>3.0$^{+1.0}_{-0.8}$</td>
<td>3.1</td>
<td>1.7$^{+0.6}_{-0.5}$</td>
<td>1.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass range</th>
<th>$e^+e^+$</th>
<th>$e^+\mu^+$</th>
<th>$\mu^+\mu^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m &gt; 15$ GeV</td>
<td>29.1$^{+10.2}_{-8.6}$</td>
<td>22.8</td>
<td>34.9$^{+12.2}_{-8.6}$</td>
</tr>
<tr>
<td>$m &gt; 100$ GeV</td>
<td>16.1$^{+5.9}_{-4.3}$</td>
<td>12.0</td>
<td>15.4$^{+9.9}_{-4.1}$</td>
</tr>
<tr>
<td>$m &gt; 200$ GeV</td>
<td>7.0$^{+3.2}_{-2.2}$</td>
<td>6.1</td>
<td>6.6$^{+3.5}_{-1.8}$</td>
</tr>
<tr>
<td>$m &gt; 300$ GeV</td>
<td>3.7$^{+1.4}_{-1.0}$</td>
<td>2.9</td>
<td>3.2$^{+1.2}_{-0.9}$</td>
</tr>
<tr>
<td>$m &gt; 400$ GeV</td>
<td>2.3$^{+1.1}_{-0.6}$</td>
<td>1.7</td>
<td>2.4$^{+0.9}_{-0.6}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass range</th>
<th>$e^-e^-$</th>
<th>$e^-\mu^-$</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m &gt; 15$ GeV</td>
<td>23.2$^{+8.8}_{-5.8}$</td>
<td>25.7</td>
<td>26.2$^{+10.8}_{-7.6}$</td>
</tr>
<tr>
<td>$m &gt; 100$ GeV</td>
<td>12.0$^{+5.3}_{-2.8}$</td>
<td>18.7</td>
<td>11.5$^{+4.2}_{-3.5}$</td>
</tr>
<tr>
<td>$m &gt; 200$ GeV</td>
<td>4.9$^{+1.9}_{-1.2}$</td>
<td>4.0</td>
<td>4.6$^{+2.1}_{-1.2}$</td>
</tr>
<tr>
<td>$m &gt; 300$ GeV</td>
<td>2.9$^{+1.0}_{-0.6}$</td>
<td>2.7</td>
<td>2.7$^{+1.1}_{-0.6}$</td>
</tr>
<tr>
<td>$m &gt; 400$ GeV</td>
<td>1.8$^{+0.8}_{-0.4}$</td>
<td>2.3</td>
<td>2.3$^{+0.8}_{-0.5}$</td>
</tr>
</tbody>
</table>

two isolated leptons with large transverse momentum within the pseudorapidity range of the tracking system ($|\eta| < 2.5$). The 95% confidence level upper limits on the cross section of new physics processes within this fiducial region range between 1.7 fb and 64 fb for $\ell^\pm\ell^\pm$ pairs depending on the dilepton invariant mass and flavour combination.

10 Acknowledgements

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 and FWF, Austria; ANAS, Azerbaijan; SSTC, 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, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES 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.

References


The ATLAS Collaboration

G. Aad, T. Abajyan, B. Abbott, J. Abdallah, S. Abdel Khalek,
A.A. Abdelalim, O. Abidinov, R. Aben, B. Abi, M. Abolins, O.S. AbouZeid,
H. Abramowicz, H. Abreu, E. Acerbi, B.S. Acharya, L. Adamczyk,
S. Aefsky, J.A. Aguilar-Saavedra, M. Agustoni, M. Aharrouche, S.P. Ahlen,
F. Ahles, A. Ahmad, M. Ahsan, G. Aielli, T. Akdogan,
T.P.A. Åkesson, G. Akimoto, A.V. Akimov, M.S. Alam, M.A. Alam,
J. Albert, S. Albran, M. Aleksa, I.N. Aleksandrova, F. Alessandra,
C. Alexa, G. Alexander, G. Alexandre, T. Alexopoulos, M. Alhroob,
M. Aliiev, G. Alimonti, J. Alison, B.M.M. Allbrooke, P.P. Allport,
S.E. Allwood-Spiers, J. Almond, A. Aloisio, R. Alon, A. Alonso,
F. Alonso, B. Alvarez Gonzalez, M.G. Alviggi, K. Amako, C. Amelung,
V.V. Ammosov, S.P. Amor Dos Santos, A. Amorim, A. Amram,
C. Anastopoulo, L.S. Ancu, N. Andari, T. Andeen, C.F. Anders,
G. Anders, K.J. Anderson, A. Andreazza, V. Andrei, M.L. Andrieux,
X.S. Anduaga, P. Anger, A. Angerami, F. Anghinolfi, A. Anisenkov,
N. Anjos, A. Anzovin, A. Antonaki, M. Antonelli, J. Anton,
F. Amill, M. Aoki, S. Aoun, L. Aperio Bella, R. Apollo, G. Arabidze,
I. Aracena, Y. Arau, A.T.H. Arce, S. Arfaoui, J.F. Arguin,
E. Arik, M. Arik, A.J. Armbruster, O. Arnaez, C. Arnaud,
G. Artoni, D. Arutinov, S. Asai, R. Asfandiyarov, S. Ask,
B. Asman, L. Asquith, K. Assamagan, A. Astbury, M. Atkinson,
B. Aubert, E. Auge, K. Augsten, M. Aurousseau, G. Avolio,
R. Avramidou, D. Axen, G. Azuelos, Y. Azuma, M.A. Baak,
G. Baccaglioni, C. Bacci, A.M. Bach, H. Bachacou, K. Bachas,
M. Backes, M. Backhaus, E. Badescu, P. Bagnaia, S. Bahinipati,
Y. Bai, D.C. Bailey, T. Bain, J.T. Baines, O.K. Baker, M.D. Baker,
S. Baker, E. Bans, P. Banerjee, S. Banerjee, D. Banfi, A. Bangert,
V. Bansal, H.S. Bansil, L. Barak, S.P. Baranov, A. Barbaro Galtieri,
T. Barber, E.L. Barberie, D. Barberis, M. Barbero, D.Y. Bardin,
T. Barillari, M. Barisonzi, T. Barklow, N. Barlow, B.M. Barnett,
R.M. Barnett, A. Baroncelli, G. Barone, A.J. Barr, F. Barreiro,
J. Barreiro Guimarães da Costa, P. Barrillon, R. Bartoldus, A.E. Barton,
V. Bartsch, A. Basyle, R.L. Bates, L. Batkova, J.R. Batley, A. Battaglia,
M. Battistin, F. Bauer, H.S. Bawa, S. Beale, T. Beatt, P.H. Beauchemin,
R. Beccherle, P. Bechtle, A.K. Becker, S. Becker, M. Beckingham,
A.J. Beddall, A. Beddall, S. Bedikian, V.A. Bednyakov, C.P. Bee,
L.J. Beemster, M. Beeg, S. Behar Harpaz, P.K. Behera, M. Beinforde,
C. Belanger-Champagne, P.J. Bell, G. Bella, L. Bellagamba,
F. Bellina, M. Bellomo, A. Belloni, O. Beloborodova, K. Belotskiy,
O. Beltramello, O. Benary, D. Benchekroun, K. Bendtzi, N. Benekos,
A. Policichio$^{37a,37b}$, A. Polini$^{26a}$, J. Poli$^{75}$, V. Polychronakos$^{25}$, D. Pomero$^{23}$, K. Pommès$^{30}$, L. Pontecorvo$^{132a}$, B.G. Pope$^{88}$, G.A. Popescu$^{26a}$, D.S. Popovic$^{13a}$, A. Poppleton$^{30}$, X. Portell Bueso$^{30}$, G.E. Pospelov$^{90}$, S. Pospisil$^{127}$, I.N. Potrapt$^{90}$, C.J. Potter$^{149}$, C.T. Potter$^{114}$, G. Poulard$^{30}$, J. Poveda$^{60}$, V. Pozdnyakov$^{64}$, R. Prabhu$^{77}$, P. Pralavorio$^{83}$, A. Pranko$^{15}$, S. Prasad$^{30}$, R. Pravahan$^{25}$, S. Prel$^{63}$, K. Pretz$^{17}$, D. Price$^{60}$, J. Price$^{75}$, L.E. Price$^{6}$, D. Prieur$^{123}$, M. Primavera$^{72a}$, K. Prokofiev$^{108}$, F. Prokoshin$^{32b}$, S. Protopopescu$^{25}$, J. Proudfoot$^{6}$, X. Prudent$^{44}$, M. Przybycien$^{38}$, H. Przyzieziuk$^{8}$, S. Psoroulas$^{21}$, E. Ptacek$^{114}$, E. Pueschel$^{84}$, J. Purdham$^{87}$, M. Purohit$^{25,ac}$, P. Puoz$^{115}$, Y. Pylypchenko$^{62}$, J. Qian$^{87}$, A. Quad$^{54}$, D.R. Quarrar$^{15}$, W.B. Quayle$^{173}$, F. Quinonez$^{32a}$, M. Raas$^{104}$, V. Radeka$^{25}$, V. Radescu$^{42}$, P. Radloff$^{114}$, T. Rador$^{19a}$, F. Ragusa$^{89a,89b}$, G. Rahal$^{178}$, A.M. Rahimi$^{109}$, D. Rahm$^{25}$, S. Rajagopalan$^{25}$, M. Rammensee$^{48}$, M. Rammes$^{141}$, A.S. Randle-Conde$^{40}$, K. Randrianarivony$^{29}$, F. Rauscher$^{98}$, T.C. Rave$^{48}$, M. Raymond$^{30}$, A.L. Read$^{117}$, D.M. Rebuuzzi$^{119a,119b}$, A. Redelbach$^{174}$, G. Redlinger$^{25}$, R. Reece$^{120}$, K. Reeves$^{41}$, E. Reinhir-Aron$^{153}$, A. Rein$^{114}$, I. Reisinger$^{43}$, C. Rembser$^{30}$, Z.L. Ren$^{151}$, A. Renaud$^{115}$, M. Rescigno$^{132a}$, S. Resconi$^{89a}$, B. Resende$^{136}$, P. Reznicek$^{98}$, R. Revani$^{158}$, R. Richter$^{89}$, E. Richter-Was$^{9,af}$, M. Ride$^{78}$, M. Rijpstra$^{105}$, M. Rijssenbeek$^{148}$, A. Rimoldi$^{119a,119b}$, L. Rinaldi$^{20a}$, R. Rios$^{40}$, I. Riu$^{12}$, G. Rivolta$^{89a,89b}$, F. Rizatdinova$^{112}$, E. Rizvi$^{75}$, S.H. Robertson$^{85,k}$, A. Robichaud-Veronneau$^{118}$, D. Robinson$^{28}$, J.E.M. Robinson$^{82}$, A. Robson$^{53}$, J.G. Rocha de Lima$^{106}$, C. Roda$^{122a,122b}$, D. Roda Dos Santos$^{30}$, N. Rodd$^{86}$, A. Roe$^{54}$, S. Roe$^{30}$, O. Röhne$^{117}$, S. Rolli$^{161}$, A. Romaniouk$^{96}$, M. Romano$^{20a,20b}$, G. Romeo$^{27}$, E. Romero Adam$^{167}$, N. Rompotis$^{138}$, L. Roos$^{78}$, E. Ros$^{167}$, S. Rosati$^{132a}$, K. Rosbach$^{49}$, A. Rose$^{149}$, M. Rose$^{76}$, G.A. Rosenbaum$^{158}$, E.I. Rosenberg$^{63}$, P.L. Rosendahl$^{14}$, O. Rosenthal$^{141}$, L. Rossette$^{49}$, V. Rossetti$^{12}$, E. Rossi$^{132a,132b}$, L.P. Rossi$^{50a}$, M. Rotaru$^{26a}$, I. Roth$^{172}$, J. Rothberg$^{138}$, D. Rousseau$^{115}$, C.R. Royon$^{136}$, A. Rozanov$^{83}$, Y. Rozen$^{152}$, X. Ruan$^{33a,ag}$, F. Rubbo$^{12}$, I. Rubinskiy$^{42}$, N. Ruckstuhl$^{105}$, V.I. Rudy$^{97}$, C. Rudolph$^{44}$, G. Rudolph$^{61}$, F. Rühr$^{7}$, A. Ruiz-Martinez$^{63}$, L. Rumiantsev$^{64}$, Z. Ruikova$^{48}$, N.A. Rusakovitch$^{64}$, J.P. Rutherford$^{7}$, C. Ruwiedel$^{15,*}$, P. Ruzicka$^{125}$, Y.F. Ryabov$^{121}$, M. Rybar$^{126}$, G. Rybinski$^{115}$, N.C. Ryder$^{118}$, A.F. Saavedra$^{150}$, I. Sadeh$^{153}$, H.F.W. Sadrozinski$^{137}$, R. Sadykov$^{64}$, F. Safai Tehrani$^{132a}$, H. Sakamoto$^{155}$, G. Salamanna$^{75}$, A. Salamoni$^{133a}$, M. Saleem$^{111}$, D. Salek$^{30}$, D. Salihagic$^{90}$, A. Salnikov$^{143}$, J. Salt$^{167}$, B.M. Salvachua Ferrando$^{6}$, D. Salvatore$^{37a,37b}$, F. Salvatore$^{149}$, A. Salucci$^{104}$, A. Salzburger$^{30}$, D. Sampsonidis$^{154}$, B.H. Samset$^{117}$, A. Sanchez$^{102a,102b}$, V. Sanchez Martinez$^{167}$, H. Sandaker$^{14}$, H.G. Sander$^{81}$, M.P. Sanders$^{98}$, M. Sandhoff$^{175}$, T. Sandovale$^{28}$, C. Sanovale$^{162}$, R. Sandstrom$^{99}$, D.P.C. Sankey$^{129}$, A. Sansoni$^{47}$, C. Santamarina Rios$^{85}$, C. Santoni$^{34}$, R. Santonico$^{133a,133b}$, H. Santos$^{124a}$, J.G. Saraiva$^{124a}$, T. Sarangi$^{173}$, E. Sarkisyan-Grinbaum$^{8}$, F. Sarri$^{122a,122b}$, G. Sartisohn$^{175}$, O. Sasaki$^{165}$, Y. Sasaki$^{115}$, N. Sasaki$^{67}$, I. Satsoukivitch$^{90}$, G. Sauvage$^{5,*}$, E. Sauvan$^{5}$, J.B. Sauvan$^{115}$, P. Savard$^{158,d}$, V. Savinov$^{123}$, D.O. Savu$^{30}$, L. Sawyer$^{25,m}$, D.H. Saxon$^{53}$, J. Saxon$^{120}$, C. Sbarra$^{20a}$, A. Sbrizzi$^{20a,20b}$, D.A. Scannicchio$^{163}$, M.Scarcella$^{150}$, J. Schaarschmidt$^{115}$, P. Schacht$^{99}$, D. Schaefer$^{120}$, U. Schäfer$^{81}$, S. Schaepe$^{21}$, S. Schaezel$^{58d}$, A.C. Schaeffer$^{115}$, D. Schail$^{98}$, R.D. Schamberger$^{148}$, 29
Dumlupinar University, Kutahya; (c) Department of Physics, Gazi University, Ankara;
(d) Division of Physics, TOBB University of Economics and Technology, Ankara;
(e) Turkish Atomic Energy Authority, Ankara, Turkey
LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
Department of Physics, University of Arizona, Tucson AZ, United States of America
Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
Physics Department, University of Athens, Athens, Greece
Physics Department, National Technical University of Athens, Zografou, Greece
Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
(a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
Department for Physics and Technology, University of Bergen, Bergen, Norway
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
Department of Physics, Humboldt University, Berlin, Germany
Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
(a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
(a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Boston University, Boston MA, United States of America
Department of Physics, Brandeis University, Waltham MA, United States of America
(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
(a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;
(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;
(b)Department of Modern Physics, University of Science and Technology of China, Anhui;
(c)Department of Physics, Nanjing University, Jiangsu; (d)School of Physics, Shandong University, Shandong, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a)INFN Gruppo Collegato di Cosenza; (b)Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
38 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern-und Teilchenphysik, Technical University Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, 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 (a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b)High Energy Physics Institute, 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
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, Indiana University, Bloomington IN, United States of America

Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City IA, United States of America

Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

INFN Sezione di Lecce; Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst MA, United States of America
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 and Kobayashi-Maskawa Institute, 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, SB RAS, 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
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, Université 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, 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 Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal; (b) Departamento de Física Teórica 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 Energies - Université Hassan II, Casablanca; (b) Centre National de l’Énergie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa
Cruz CA, United States of America
Department of Physics, University of Washington, Seattle WA, United States of America
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
(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
Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
(a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
a Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
b Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
d Also at TRIUMF, Vancouver BC, Canada
e Also at Department of Physics, California State University, Fresno CA, United States of America
f Also at Novosibirsk State University, Novosibirsk, Russia
g Also at Fermilab, Batavia IL, United States of America
h Also at Department of Physics, University of Coimbra, Coimbra, Portugal
i Also at Department of Physics, UASLP, San Luis Potosi, Mexico
j Also at Università di Napoli Parthenope, Napoli, Italy
k Also at Institute of Particle Physics (IPP), Canada
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey
m Also at Louisiana Tech University, Ruston LA, United States of America
n Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
o Also at Department of Physics and Astronomy, University College London, London, United Kingdom
p Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
q Also at Department of Physics, University of Cape Town, Cape Town, South Africa
r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

Also at Manhattan College, New York NY, United States of America

Also at School of Physics, Shandong University, Shandong, China

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France

Also at Section de Physique, Université de Genève, Geneva, Switzerland

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

Also at California Institute of Technology, Pasadena CA, United States of America

Also at Institute of Physics, Jagiellonian University, Krakow, Poland

Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Also at Department of Physics, Oxford University, Oxford, United Kingdom

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

* Deceased