Inclusive search for same-sign dilepton signatures in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ABSTRACT: An inclusive search is presented for new physics in events with two isolated leptons (e or μ) having the same electric charge. The data are selected from events collected from pp collisions at $\sqrt{s} = 7$ TeV by the ATLAS detector and correspond to an integrated luminosity of 34 pb^{-1}. The spectra in dilepton invariant mass, missing transverse momentum and jet multiplicity are presented and compared to Standard Model predictions. In this event sample, no evidence is found for contributions beyond those of the Standard Model. Limits are set on the cross-section in a fiducial region for new sources of same-sign high-mass dilepton events in the ee, $e\mu$ and $\mu\mu$ channels. Four models predicting same-sign dilepton signals are constrained: two descriptions of Majorana neutrinos, a cascade topology similar to supersymmetry or universal extra dimensions, and fourth generation d-type quarks. Assuming a new physics scale of 1 TeV, Majorana neutrinos produced by an effective operator V with masses below 460 GeV are excluded at 95% confidence level. A lower limit of 290 GeV is set at 95% confidence level on the mass of fourth generation d-type quarks.

Contents

1 Introduction

A diverse group of models predict interactions producing two isolated leptons of the same electric charge and with significant transverse momentum—a signature quite rare in the Standard Model (SM). An inclusive search for such processes recorded by ATLAS is presented for the first time at a centre-of-mass energy $\sqrt{s} = 7$ TeV. Events with a same-sign dilepton (ee, $e\mu$, $\mu\mu$) signature were selected from pp collisions produced by the LHC with an integrated luminosity of 34 pb^{-1}.

The ATLAS collaboration has performed a dedicated search for supersymmetric phenomena [1] in events with exactly two leptons and large missing transverse momentum selected from the same pp collision data described herein. By contrast, the inclusive analysis described in this article presents model-independent limits from events that may have more than two leptons and no missing transverse momentum. The CMS collaboration has

searched for new phenomena in same-sign dilepton events with jets and missing transverse momentum [2]. Inclusive analyses by the CDF collaboration present kinematic distributions and 95% confidence limits using up to $1\,\text{fb}^{-1}$ of $p\bar{p}$ collisions [3] at a centre-of-mass energy of 1.96 TeV. The CMS and CDF collaborations searched for fourth-generation d-type quarks in 34 pb^{-1} of pp collisions [4] and in $2.7\,\text{fb}^{-1}$ of $p\bar{p}$ collisions [5], respectively. They set lower mass limits of 361 GeV and 338 GeV respectively, at 95% confidence level. A search by the DØ collaboration excludes a right-handed W boson W_R with mass less than 739 GeV in left-right symmetric models (LRS) [6]. Various other specific searches have been performed in same-sign dilepton samples by these experiemnts [7, 8].

In this article, spectra in dilepton invariant mass ($m_{\ell\ell}$), jet multiplicity (N_{jets}), and missing transverse momentum (E_T^{miss})* are studied for consistency with the SM or evidence for new physics. The SM prediction is estimated mainly by extrapolation from control samples selected in the data. Additional small contributions are determined using simulated events. In a kinematic fiducial region, an upper limit on the cross-section of high-mass ($m_{\ell\ell}$ > 110 GeV, above the Z-mass region) same-sign dilepton events from non-SM sources is given for each channel, and benchmark selection efficiencies for some specific models are provided. In the subsample of events with at least one jet, a number of limits are set: first limits on the mass of Majorana neutrinos in an effective operator framework [9], and limits surpassing previous experimental results [10] in an LRS scenario [11]. This sample is also interpreted to set cross-section limits on a cascade topology found in supersymmetry and models with universal extra dimensions (UED) [13] in terms of masses of the minimally required particles. Using the subsample with E_T^{miss}> 30 GeV, a lower limit on the mass of a fourth generation down-type quark (d_4) [14] is obtained.

2   Description of the ATLAS experiment

The ATLAS detector [15] is a multipurpose detector of charged and neutral particles with precision trackers, calorimeters and muon spectrometers. The momenta of charged particles with pseudorapidity $|\eta| < 2.5^{\dagger}$ are measured by the inner detector (ID), which is a combination of a silicon pixel detector, a silicon microstrip detector and a straw-tube detector. The ID operates in a uniform 2 T magnetic field. The pixel detector measurements notably enable precise determination of production vertices.

Electromagnetic calorimetry for electron, photon, and jet reconstruction is provided by a high-granularity, three depth-sampling liquid-argon (LAr) detector with lead absorbers in the region $|\eta| < 3.2$. Jet reconstruction also uses hadron calorimetry provided by a scintillating tile detector with iron absorbers in the central region for $|\eta| < 1.7$, and a LAr

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*The missing transverse momentum in an event, denoted E_T^{miss}, is the vector difference between zero and the total transverse momentum, calculated from energy depositions in the calorimeter and momentum measurements from the muon spectrometer for identified muons.

†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 pipe. The x-axis points from the IP to the centre of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

detector for $1.5 < |\eta| < 4.9$. A presampler detector is used to correct for energy lost by electrons and photons in material in front of the calorimeter for $|\eta| < 1.8$.

Dedicated muon reconstruction is performed by a multi-system muon spectrometer (MS). Precision measurements in the η coordinate are provided by measurements of monitored drift tubes for $|\eta| < 2.7$. These are supplemented by cathode-strip chambers measuring both the η and azimuth (ϕ) coordinates for $2.0 < |\eta| < 2.7$ in the innermost endcap muon station. Fast measurements required for initiating trigger logic are provided by resistive-plate chambers for $|\eta| < 1.05$, and beyond that by thin-gap chambers to $|\eta| < 2.4$. The muon detectors operate in a non-uniform magnetic field generated by three superconducting air-core toroid magnetic systems.

To trigger readout, full event reconstruction and event storage by the data acquisition system, at least one electron or muon candidate is required that satisfies the following criteria. Electron candidates must have transverse energy $E_{\mathrm{T}} > 15$ GeV[‡]. They must satisfy shower-shape requirements[§] and correspond to an ID track. Muon candidates must have transverse momentum $p_{\mathrm{T}} > 13$ GeV, $|\eta| < 2.4$, and a consistent trajectory reconstructed in the ID and MS. The full trigger chain uses signals from all muon detectors.

3 Physics simulation data

The response of the ATLAS detector is simulated [17] using GEANT4 [18]. The parameter settings for the Monte Carlo programs are described in Ref. [19]. The Z and W events were generated using ALPGEN v2.13 [20] with the CTEQ6L1 parton distribution function (PDF) set [21]; WW, WZ, and ZZ events using HERWIG 6.510 [22] with the MRST2007 LO* PDF set [23]; $Z\gamma$ and $W\gamma$ events using MADGRAPH v4 [24] with the CTEQ6L1 PDF set, interfaced to PYTHIA 6.421 [25]; and $t\bar{t}$ events using MC@NLO 3.41 [26] with the CTEQ6.6 PDF set [21], interfaced to HERWIG. Cross-sections for $t\bar{t}$ events are calculated at approximate next-to-next-to-leading order [27], at next-to-next-to-leading order for events with a boson and jets, and at next-to-leading order for diboson events.

4 Sample selection and Standard Model sources

In this article *same sign dilepton event* refers to a *pp* interaction that produces two leptons (e or μ) with matching electric charge, where both leptons are produced promptly by the primary interaction. Such prompt leptons will usually be isolated from hadronic jets in the event. Leptons from hadron decays, for example from hadrons with b or c quarks, are classified as background in this analysis, along with instrumental background. Various selection criteria are applied for background suppression.

[‡]During early data-recording periods, trigger momentum thresholds for electrons and muons were sometimes lower, with minimum values of 10 GeV, combined with other minor algorithmic differences. However, the efficiencies for events entering the selected samples from these periods, representing 10% of the sample for electrons and 20% for muons, are not significantly different.

[§]The medium selection defined in Section 4.2 of Ref [16] is used.

4.1 Sample selection

The sample includes events having at least two lepton candidates within the experimental acceptance. Each must pass a tight type-identification and track quality selection and an isolation condition that rejects leptons within jets; these requirements are described below. Each lepton candidate is required to have $p_{\rm T}$ greater than 20 GeV. For muons, the transverse momentum measurement uses information from both the ID and MS. An isolation requirement on nearby calorimeter depositions is applied: the sum of transverse-energy depositions not associated with the candidate within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ surrounding the candidate lepton must be less than 15% of the lepton $E_{\rm T}$. To control relative efficiencies among samples, the data acquisition system must have been triggered by at least one of the two isolated leptons in the same-sign pair.

A number of requirements ensure the quality of particle tracks and type-identification. Candidates for the main electron sample are *tightly selected*: they are identified by calorimeter cluster properties and matched to a track in the η and ϕ coordinates, with the same criteria used for the trigger. They are reliably reconstructed in the region $|\eta| < 2.47$, except in the barrel-endcap transition region $1.37 < |\eta| < 1.52$ which is excluded. Electron candidates must have a calorimeter energy to track momentum ratio E/p consistent with expectations for an electron. The precise values vary with $|\eta|$ and $p_{\rm T}$; for electrons with $\eta = 0$ and $p_{\rm T} = 50$ GeV, we require $0.7 < E/p < 5.0$. If a track trajectory passes through an active region of the innermost pixel layer, a measurement in that layer is required for suppression of electrons from photon conversions. Electron candidates from tracks that are also reconstructed as viable muon candidates are rejected.

Candidates for the tightly selected muon sample are selected from tracks reconstructed in the MS and matched to tracks in the ID. The two measurements of the track parameters are then combined [28]. Candidates are accepted in the range $|\eta| < 2.5$. Charge measurements made by the ID and MS must agree.

Electron and muon control samples are also used to study the properties of lepton candidates likely to be found in misreconstructed events in the same-sign dilepton sample. These samples are defined in the description of the background prediction method.

Jets are reconstructed and used in three ways: to define jet multiplicity, an important feature of some predicted signals; to reject isolated muons from b-flavoured jets; and to select a control sample of events with electrons originating from semileptonic hadron decays. All jets in this analysis are defined by the anti-$k_{\rm t}$ algorithm [29, 30], with radius parameter equal to 0.4, applied to calorimeter clusters [31]. To be counted in jet multiplicity, jets must have $p_{\rm T} > 30$ GeV and $|\eta| < 2.5$. For rejection of muons from b-jets, a looser requirement of $p_{\rm T} > 20$ GeV is made. Muons are rejected within a cone of $\Delta R = 0.4$ around such jets. For selecting events for the electron control sample, all jets reconstructed within the experimental acceptance are considered.

For inclusion in the dilepton event sample, the two lepton candidates must originate from the same primary vertex; this primary vertex must contain at least five tracks to suppress non-collision events.

4.2 Sources of same-sign dileptons in the Standard Model

In the SM, events with the same-sign dilepton signature may be produced in three ways: events containing two gauge bosons, events in which a lepton originates in a jet, and events in which the reconstructed charge of a lepton is not that produced in the primary interaction.

True same-sign dilepton events are produced from SM diboson processes, most notably WZ processes. These are a rare but irreducible background to new physics sources, since events with more than two leptons are not excluded by the selection. They are distinguishable from new sources only by differences in kinematic spectral shapes.

The main SM background categories are sources that enter the sample due to misreconstruction of the event, i.e., a selected lepton candidate is not a primary product of the main interaction. Jets often produce leptons that are wrongly reconstructed as primary. As well, the charge of a selected lepton candidate may not be the primary charge from the interaction.

When an event is selected for the sample using a lepton candidate from a jet, this lepton is called a *flavour fake* (denoted by the term "QCD" in plots and symbols). This is because the lepton originates from a hadronic jet, so the observed lepton flavour does not reflect the primary interaction process. Processes that are often reconstructed as same-sign dileptons in this way are dijet processes and final states with a W boson and jets. This is the main background considered in this analysis as it has the largest overall contribution to the sample. It is dominant in the $\mu\mu$ and $e\mu$ channels.

It is also possible to misreconstruct an event as same sign if final state particles produced with opposite electric charge lead to good same-sign lepton candidates in the detector. Processes susceptible to this effect are $Z/\gamma^* \to e^+e^-$ and $t\bar{t}$ semileptonic decays with at least one electron. This misreconstruction occurs if an electron undergoes bremsstrahlung, and upon conversion the photon passes the larger share of momentum to an electron of the opposite charge. For this reason, this effect is called *electron charge flipping* (denoted by "charge flip" in plots). The charge-flip category is large in the ee channel and present in the $e\mu$ channel. When the bremsstrahlung does not carry the majority of the electron energy, misidentification of electron charge may occur due to misreconstruction of the ID track. If found in this analysis, such events would be included in the charge-flip category. Due to the near absence of photons converting to muon pairs, this category does not appear in the $\mu\mu$ channel. Muon charge misidentification is negligible over the range of $p_{\rm T}$ found in the sample.

4.3 Characterisation of Standard Model sources

The data are used to characterise the background from misreconstruction, especially flavour fake events. The rates of heavy flavour dijet events are not well known *a priori*, and so would suffer from substantial uncertainties if derived purely from simulation. Instead a method, described in the following, is used which extrapolates from control samples to the signal region. The control samples are separate samples of background electrons and muons,
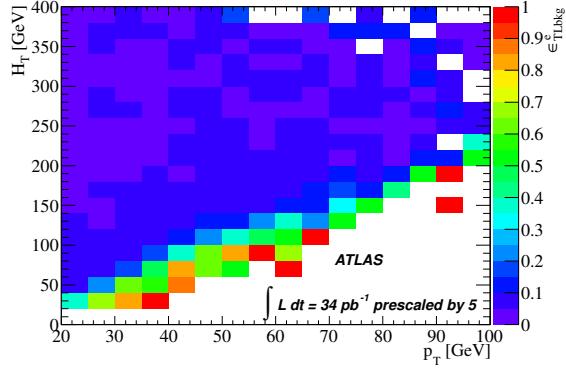
Figure 1. The selection efficiency for candidates mimicking primary electrons, $\epsilon^e_{\text{TLbkg}}$, defined as the fraction of loosely selected electrons that also pass tight selection, measured in a enriched background sample of recorded data and parameterised in p_{T} and H_{T} to demonstrate the dependence. The events used to determine $\epsilon^e_{\text{TLbkg}}$ were recorded using a photon trigger, which was prescaled for part of the 2010 pp data collection. Empty regions (white) are either kinematically impossible ($H_{\text{T}} < p_{\text{T}}$) or unpopulated.

from events that have fewer than two reconstructed leptons and therefore are independent of the main sample. The procedure is discussed in detail below.

To examine the properties of background events, a *loosely selected* sample of electron candidates is defined with relaxed selection criteria, by removing the isolation and E/p requirements, while loosening shower-shape and track quality requirements[¶] to allow sufficient statistics across the relevant phase space. The tightly selected electron sample is therefore a subset of the loosely selected sample. To predict the kinematic distributions of misreconstructed events, dielectron events are chosen that have two same-sign electrons in the loosely selected sample. These events are classified into components depending on whether the loosely selected electrons also pass tight selection: (1) both are tightly selected, (2) only one is tightly selected, or (3) neither is tightly selected.

By applying measured efficiencies as event weights, these yield components may be transformed into isolated dielectron and background yield components. The transformation is expressed by a system of linear equations [32] that project the true primary dilepton and background category yields from the loose and tight categories. The projection to component yields relies on the assumption that the flavour fake rate found in enriched background samples described below is applicable to the flavour fakes in dilepton events.

The selection efficiency for candidates mimicking primary electrons, $\epsilon^e_{\text{TLbkg}}$, is defined as the fraction of loosely selected electrons that also pass the tight selection. The enriched background sample used to measure $\epsilon^e_{\text{TLbkg}}$ is characterized by events with at least one lepton from a jet, implemented by requiring a unique loosely selected electron in the event. The events in this sample were accepted by a photon trigger defined by a subset of the loose electron selection rules [33]. To further select events with leptons from semileptonic

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[¶]The loose selection defined in Section 4.2 of Ref [16] is used.
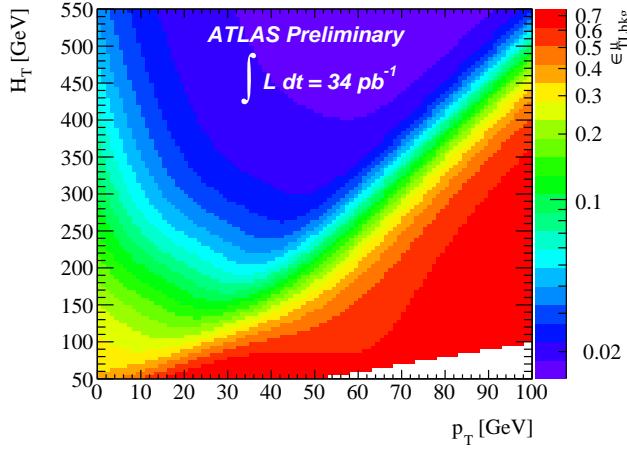
Figure 2. The selection efficiency for candidates mimicking primary muons, $\epsilon^\mu_{\mathrm{TLbkg}}$, defined as the fraction of loosely selected muons that also pass tight selection, parameterised as a function of p_{T} and H_{T} to demonstrate the dependence. Empty regions (white) are kinematically impossible ($H_{\mathrm{T}} < p_{\mathrm{T}}$).

hadron decays, which are produced in jets, the $E_{\mathrm{T}}^{\mathrm{miss}}$ and any adjacent jet axis must have a maximum azimuthal difference of $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}) < 0.1$. This sample is therefore mostly composed of dijets. Possible bias in the measured efficiency due to the event selection is included in the systematic uncertainty, described in section 5. The background efficiency $\epsilon^e_{\mathrm{TLbkg}}$ is measured separately for electrons which satisfy the electron trigger requirement and for those which do not, and is parameterised by p_{T} of the electron and H_{T}, defined as the sum of E_{T} over all reconstructed objects in the event (figure 1). For relatively rare dijet events in which H_{T} has a large contribution from the electron candidate itself, the electron candidate is likely to satisfy the isolation requirement due to the lack of non-associated energy depositions nearby; this correlation is described by the diagonal band in figure 1.

To study true primary electrons, dielectron events with one tightly selected and one loosely selected electron, of opposite charge, are selected to form a enriched electron sample of $Z \rightarrow e^+e^-$ events, requiring $86 < m_{e^+e^-} < 96$ GeV to achieve a high purity. The loosely selected electron is checked for inclusion in the tightly selected sample to measure the relative efficiency between the tight and loose selection rules.

A fraction of the charge-flip electron background is included in the described data-driven procedure. However, studies of Z events show that electron charge-flips are well modeled, so this category is instead described with simulated data and the overlap is subtracted from the data-driven background prediction to isolate the flavour fake prediction. The charge-flip overlap fraction is measured by normalizing the simulated prediction to the observed reflection peak from $Z \rightarrow e^+e^-$ processes and found to be $(19\pm16)\%$. Simulation data scaled to the recorded luminosity are added to the predicted flavour-fake distributions. The diboson background contribution is taken from simulation.

Muons are treated similarly, with $\epsilon^\mu_{\mathrm{TLbkg}}$ parameterised in the p_{T} of the candidate and

Table 1. The observed (n_{obs}) and predicted (n_{pred}) yields of same-sign dilepton events. The prediction is the sum of the individual estimates of the number of events with misreconstructed flavour (n_{fake}), the number of events with misreconstructed charge ($n_{\mathrm{charge\text{-}flip}}^{\mathrm{sim}}$), and the number of true SM same-sign dilepton events ($n_{\mathrm{diboson}}^{\mathrm{sim}}$). Uncertainties are statistical followed by systematic. The dominant statistical errors are due to the small number of events in the background control samples from which the misreconstructed flavor background predictions are calculated. The dominant systematic uncertainties are due to uncertainty on the method of misreconstructed flavor background calculation, see Table 2 and text in Section 5. The $Z \to ee$ peak is suppressed by excluding events with $80 < m_{ee} < 95$ GeV. The electron charge-flip category does not apply to the dimuon channel; this is indicated by a dash in the table.

	n_{obs}	n_{pred}	n_{fake}	$n_{\mathrm{charge\text{-}flip}}^{\mathrm{sim}}$	$n_{\mathrm{diboson}}^{\mathrm{sim}}$
ee	10	21.8±9.4±3.8	11.1±9.4±2.8	10.1±0.9±2.5	0.6±0.0±0.1
$\mu\mu$	9	6.1±2.8±1.2	4.8±2.8±1.2	—	1.3±0.0±0.1
$e\mu$	25	17.5±9.3±3.7	15.0±9.3±3.7	0.5±0.2±0.1	2.1±0.0±0.2

H_{T} (figure 2). The $\epsilon_{\mathrm{TLbkg}}^{\mu}$ is fit using a Bayesian neural network [34] to extract a smooth functional dependence. The loose muon selection is defined by removing the isolation requirement from the tight selection rules. A flavour fake sample of muon events is defined with a unique loosely selected muon and a requirement that the invariant mass of this muon with the event $E_{\mathrm{T}}^{\mathrm{miss}}$, must not exceed 30 GeV in the transverse plane. The Bayesian neural network is trained on this sample and used exclusively to describe the shape of the flavour fake efficiency distribution as a function of p_{T} and H_{T}. The selection efficiency for primary muons to appear in the tightly selected sample relative to the loosely selected sample is approximately unity, as found in studies of $Z \to \mu\mu$ events. As with the dielectrons, a linear transformation is made to the true primary dimuon and background components.

An event sample of same-sign $e\mu$ dilepton events is analyzed for component yields using the same prescription with the measured efficiencies for electron and muon selection already described.

The event yields and contributions of the various background categories are presented in table 1. The observed yields are consistent with Standard Model predictions, and this is quantified in section 6. The dominant source of uncertainty in the prediction is the statistical uncertainty of the yield of flavour fake events. This statistical uncertainty is relatively large because of the small number of leptons in the background control samples from which these predictions are calculated.

5   Systematic uncertainties

The largest source of systematic uncertainty is the weighting of events to extract yield predictions for signal and background. Two studies quantify the overall magnitude of this uncertainty. In the first, $\epsilon_{\mathrm{TLbkg}}^{e,\mu}$ is measured in simulated data with known generated

Table 2. Sources and estimated sizes of systematic uncertainties, for data-driven predictions and for Monte Carlo predictions of background and hypothetical signals, shown as a fraction of the event yield or of the electron and muon efficiencies (ϵ^e and ϵ^μ, respectively).

Source of uncertainty	Size
Data-driven predictions	
Category transformation, yield and shape	25% of yield
Monte Carlo predictions	
Luminosity	3.4% of yield
Jet-energy calibration	$\leq 2\%$ of yield
E/p requirement ($E_{\mathrm{T}}^e < 150$ GeV)	3% of ϵ^e
E/p requirement ($E_{\mathrm{T}}^e \geq 150$ GeV)	12% of ϵ^e
Electron charge misidentification	1.5% of ϵ^e
Muon momentum resolution	$< 1\%$ of ϵ^μ
Electron energy resolution	$< 1\%$ of ϵ^e

properties. In the second, $\epsilon_{\mathrm{TLbkg}}^{e,\mu}$ is used to predict the number of events with a flavour fake in the region $10 < p_{\mathrm{T}} < 20$ GeV for the less energetic lepton of the pair, where flavour fakes are expected to be dominant. This study tests the reliability of both the parameterisation and use of $\epsilon_{\mathrm{TLbkg}}^{e,\mu}$ for predictions of events where both leptons come from jets. Both studies indicate a 25% uncertainty. Other systematic uncertainties are much smaller and affect predictions of signal and background from simulations. The integrated luminosity of the sample is known with an uncertainty of 3.4% [35], and the uncertainty on the jet-energy calibration [31] yields an uncertainty of less than 2% on the yields in this sample. The uncertainty on the measured electron efficiency is dominated by the uncertainty of the E/p distribution. This uncertainty is estimated as the difference between electron efficiencies measured in simulated and recorded e^+e^- events; this yields a 3% uncertainty on the efficiency for E_{T} below 150 GeV, for which there are many recorded electrons, and a 12% uncertainty for $E_{\mathrm{T}} > 150$ GeV, for which there are few recorded events. The uncertainty on the electron efficiency from electron-charge misidentification is determined by comparing simulated and recorded same-sign $Z \to ee$ events, and is found to average 1.5%. Efficiency uncertainties due to momentum or energy resolution are less than 1%. A comparison of systematic effects is given in table 2. We conclude that the sensitivity of this analysis is predominantly affected by the accuracy of the data-driven background predictions, and is largely unaffected by uncertainties arising from the use of simulated samples.

6   Consistency of observation with the Standard Model

A validation of the SM prediction is made in samples of opposite-sign dilepton events. The $e\mu$ channel is the most suitable for validation because it contains both lepton flavours, and comparable contributions from data-driven methods and simulation. The contribution from

Table 3. Results of KS-distance test between data and Standard Model predictions. The maximum KS distance and corresponding p-value (in parentheses) is given for three kinematic distributions presented in this analysis (Figs. 4 and 5), and one high-mass subset. Statistical and systematic fluctuations are included in the p-value calculation. We find agreement between the observed data and the SM prediction.

Distribution	$\ell\ell$	ee	$\mu\mu$	$e\mu$
$m_{\ell\ell}$	0.15 (84%)	0.33 (36%)	0.60 (28%)	0.40 (43%)
$m_{\ell\ell} > 110$ GeV	0.54 (23%)	1.00 (7%)	0.76 (34%)	0.19 (91%)
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.19 (72%)	0.60 (11%)	0.39 (59%)	0.36 (50%)
N_{jets}	0.18 (73%)	0.59 (12%)	0.37 (57%)	0.28 (59%)

Table 4. The observed (n_{obs}) and predicted (n_{pred}) yields of same-sign dilepton events with large dilepton invariant mass $m_{\ell\ell} > 110$ GeV. Uncertainties are statistical followed by systematic. Upper limits at 95% CL are placed on the fiducial cross-section ($\sigma_{\mathrm{obs}}^{95}$) of a new high-mass source in each channel. Also given is the median expected limit ($\sigma_{\mathrm{exp}}^{95}$) in simulated experiments drawn from the background hypothesis.

	n_{obs}	n_{pred}	$\sigma_{\mathrm{obs}}^{95}$ [pb]	$\sigma_{\mathrm{exp}}^{95}$ [pb]
ee	0	3.1±2.1±0.5	0.15	0.46
$\mu\mu$	1	2.2±1.4±0.4	0.17	0.25
$e\mu$	3	3.2±2.9±0.5	0.28	0.28

$Z \to \tau\tau$ decays is relatively small. The results of this validation are shown in figure 3, with component categories indicated. As shown, there is good agreement (within the combined statistical and systematic uncertainty) between the observed data and the prediction in most bins of the kinematic distributions.

The SM predictions in the same-sign samples are reported in table 1. The observed and predicted kinematic distributions are shown in figures 4 and 5. The consistency between the shape of the observed and predicted distributions is evaluated with a Kolmogorov-Smirnov (KS) distance test [38]. Agreement is found between the observed data and the SM prediction, as shown in table 3. Dielectron events in the region $80 < m_{\ell\ell} < 95$ GeV are excluded in the analysis of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and N_{jets} distributions to suppress contamination from misreconstructed $Z \to ee$ events.

7 Limit on generic same-sign high-mass dilepton production

Beyond the charge-flip reflection of $Z \to ee$ (see figure 4, left), the $m_{\ell\ell}$ spectrum is sensitive to the presence of new sources of same-sign dilepton events. In the domain $m_{\ell\ell} > 110$

Table 5. Reconstruction efficiency of same-sign dilepton events generated in various models in a fiducial region defined by dilepton invariant mass $m_{\ell\ell} > 110$ GeV, lepton transverse momentum $p_{\mathrm{T}} > 20$ GeV, lepton pseudorapidity $|\eta| < 2.5$ and ΔR(lepton,quark or gluon) > 0.4. Statistical uncertainties are given. A dash indicates that the channel is not a final state of a particular model.

Signal model	Reconstruction efficiency		
	ee	$e\mu$	$\mu\mu$
Majorana neutrino with $m_N = 200$ GeV	$(46\pm1)\%$	$(58\pm1)\%$	$(71\pm2)\%$
Fourth-generation d_4 with $m_{d4} = 350$ GeV	$(46\pm2)\%$	$(53\pm2)\%$	$(67\pm2)\%$
Lepton cascade topology with $m_{\tilde{q}} = 500$ GeV, $m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0} = 450$ GeV, $m_{\mathrm{LSP}} = 100$ GeV	$(46\pm1)\%$	$(53\pm1)\%$	$(67\pm2)\%$
Left-right symmetry with $m_{W_R} = 600$ GeV, $m_N = 50$ GeV	$(40\pm2)\%$	—	$(62\pm2)\%$

GeV, $8.5 \pm 3.8_{\mathrm{(stat)}} \pm 0.7_{\mathrm{(syst)}}$ events are predicted by the SM, primarily in the flavour-fake category. Four events are observed.

In the high-mass domain specified above ($m_{\ell\ell} > 110$ GeV), limits are set by the prescription of Feldman and Cousins [39]. In this method, confidence intervals are built from a likelihood-ratio test statistic. Ensembles of simulated experiments are generated that capture fluctuations expected from the statistical and systematic uncertainties. The observed upper limit on the cross-section of a new high-mass source is given for each channel in table 4. In the ee and $\mu\mu$ channels, the observed limits are somewhat lower than the expected limits because the number of events observed in these channels is lower than the number predicted by the Standard Model.

Efficiencies to pass the baseline selection in a fiducial region defined by dilepton invariant mass $m_{\ell\ell} > 110$ GeV, lepton transverse momentum $p_{\mathrm{T}} > 20$ GeV, lepton pseudorapidity $|\eta| < 2.5$, and ΔR(lepton, quark or gluon) > 0.4 (considering only quarks or gluons with $p_{\mathrm{T}} > 15$ GeV from the hard scattering process after initial- and final-state radiation but before hadronization) are given in table 5 for several models, described in the next section. These sample efficiencies demonstrate the degree of model independence of the fiducial cross-section limits shown in table 4.

In setting fiducial cross-section limits, the smallest efficiency for events within the fiducial acceptance found for each channel is used. These limits are rather general, and should be applicable to any model producing a significant fraction of isolated high-mass lepton pairs.

8 Limits on specific models

The data are interpreted to set limits on four models with same-sign dilepton signals from new physics sources. For each model, upper limits at 95% CL on the cross-sections of the hypothetical processes are derived using the Feldman-Cousins (FC) method for choosing the 95% region of the frequentist Neyman construction. In setting limits, the predicted signal plus background histograms in the chosen variable are used as templates and fit to the data to extract the most likely signal cross-section, which is used in turn to calculate upper limits with the FC procedure. Systematic uncertainties are included as variations in the signal and background templates, which are fluctuated in the ensembles used to generate the Neyman construction. The cross-section limits are presented as functions of the masses of the hypothetical new particles that the particular models introduce.

8.1 Majorana neutrinos

Production of heavy Majorana neutrinos described by effective operators [9] and LRS theories [11] have dilepton signatures that also include jets. To set limits on these models, the subsample of events with at least one jet is considered. The $m_{\ell\ell}$ distributions for the ee, $e\mu$ and $\mu\mu$ channels are shown in the top row of figure 6 after also requiring $N_{jets} > 0$. Hypothetical signal predictions are overlaid.

For models of Majorana neutrinos, a single resonance drives the lepton kinematics. This leaves the $m_{\ell\ell}$ spectrum most sensitive to these models, and so it is used to form the templates with which we derive upper limits. The KS-distance of this distribution is 0.19, with a SM p-value of 88% for the three channels combined.

In the first model considered, Majorana neutrinos are produced by a four-fermion vector operator V [9]. The effective Lagrangian formalism of this model requires a choice for the energy scale Λ of new phenomena. It is taken to have magnitude 1 TeV. The coupling of V is chosen to be one, the natural scale of the model. All other effective operator couplings are assumed to vanish. The effective vector operator was simulated by the CALCHEP 2.4.5 simulation program [40].

The observed cross-section limit for this description is interpreted in terms of neutrino mass, shown in figure 7 (left). Majorana neutrino mass values are excluded below 460 GeV. The observed limits are consistent with limits expected when no Majorana neutrino is present.

Majorana neutrino production by the LRS model [11] is also considered. In this model, the right-handed W_R boson decays to a lepton and a Majorana neutrino that in turn decays to a same-sign lepton and one or more jets. The simulated signal for this model was generated using PYTHIA with MRST2008LO* modified leading-order PDFs. The leading-order theoretical cross-section was used.

The observed limits are shown in figure 7 (right) as a function of the masses of the Majorana neutrino (m_N) and the right-handed W_R boson (m_{W_R}). The shaded exclusion region represents mass points for which the observed cross-section limit is lower than the theoretical cross-section. Contours of constant cross-section limit are overlaid. Observed limits are consistent with expected limits everywhere.

The theoretical cross-section and decay kinematics are determined by the mass difference between the neutrino and a right-handed boson, W_R. A large mass difference yields highly relativistic heavy neutrinos, with one lepton typically overlapped by a jet in the event and thus failing the isolation criteria. Nevertheless, we exclude W_R with masses less than 0.7 TeV over most of the parameter space, as well as masses less than 1.0 TeV for a large range of neutrino masses.

8.2 Lepton cascades

A specific cascade topology (shown in figure 8) is considered that produces a same-sign dilepton signature and invisible particles [13]. Since the final states would include jets, the subsample of events with at least one jet is again considered. In lepton cascades leading to invisible particles common to supersymmetric and UED models, a heavy neutral particle escapes detection, and so E_T^{miss} is used to form the templates with which we derive upper limits. The E_T^{miss} distributions for the ee, $e\mu$ and $\mu\mu$ channels are shown in the bottom row of figure 6 after also requiring $N_{jets} > 0$. Hypothetical signal predictions are overlaid. The KS-distance of this distribution is 0.29, with a SM p-value of 67% for the three channels combined.

Although particle names are denoted here in a supersymmetry context, these cascade topologies occur quite generally, such as in models with universal extra dimensions [36]. The topology is described using the minimal particle content necessary, and the effective theory is parameterised directly in the masses of the new particles, making the conclusions independent of any fundamental parameters specific to a particular theory.

In this scheme there are three processes:

$$\tilde{q}\tilde{q} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}qq \to W^{\pm}W^{\pm}\tilde{\chi}_1^0\tilde{\chi}_1^0 qq \tag{8.1}$$

$$\tilde{q}\tilde{q} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 qq \to W^{\pm}Z\tilde{\chi}_1^0\tilde{\chi}_1^0 qq \tag{8.2}$$

$$\tilde{q}\tilde{q} \to \tilde{\chi}_2^0\tilde{\chi}_2^0 qq \to ZZ\tilde{\chi}_1^0\tilde{\chi}_1^0 qq \tag{8.3}$$

Leptonic decay modes of the W and Z bosons are considered. This analysis uses an admixture that equally favours combinations of the chargino $\tilde{\chi}_1^{\pm}$ and neutralino $\tilde{\chi}_2^0$ (assumed to have the same mass), $\text{BF}(\tilde{q} \to q\tilde{\chi}_1^{\pm}) = \text{BF}(\tilde{q} \to q\tilde{\chi}_2^0) = 0.5$, resulting in a 1:2:1 composition of the three processes above. If all decay modes are considered, the number of events expected from the WW process is higher than from the other channels due to the higher leptonic branching fractions of W bosons. Considering only leptonic decays, the two pairs of same-sign leptons in ZZ events lead to twice the selection efficiency of the other two channels. The limits presented can be scaled to constrain other mixtures of W and Z decays.

Cross-section limits (figure 9 and figure 10) are presented as a function of the masses of a chargino/neutralino, the squark ($\tilde{q}$), and the lightest supersymmetric particle ($\tilde{\chi}_1^0$), which is neutral and stable. The observed limits are consistent with expected limits in the no-signal hypothesis. These cross-section limits apply to any theory with a non-zero cross section from this topology (scaled by the appropriate branching fraction). They depend on the experimental acceptance, and the particle masses, with no significant dependence on

other characteristics such as particle spin. To set mass limits on a particular model, one would need only to find the intersection of the predicted cross-section with the observed cross-section upper limits. For example, one may consider a supersymmetric theory with a gluino mass of 510 GeV. The exclusion region for this model is shown in figure 9. The signal expected from this topology was generated using MADGRAPH for the hard-scattering and initial squark production, and BRIDGE [37] for particle decay.

8.3 Heavy down-type quarks

The last model considered has a fourth-generation d-type quark decaying to tW [14], and is tested using the jet multiplicity distribution in events with significant missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV. The jet multiplicity of events in this subsample is shown in figure 11. The KS-distance of this distribution is 0.45, with a SM p-value of 31%, for the three channels combined.

The signal from $d_4\bar{d}_4$ production includes significant missing momentum carried by neutrinos. The signal expected in this model was generated using PYTHIA. Events with $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV are selected from the inclusive sample to set limits on this model. The limits are derived using a three-bin template: zero, one and two or more jets, due to the small number of events used to estimate the flavour fake contribution at high jet multiplicities.

The observed and Standard Model expected cross-section limits for d_4 production assuming $\mathrm{BF}(d_4 \to tW) = 1$ are shown in figure 12. The intersection of the limit with the next-to-next-to-leading order theoretical cross-section yields a lower bound of 290 GeV on the d_4 mass, which is somewhat lower than the expected limit of 320 GeV due to high-multiplicity events observed in the $e\mu$ and $\mu\mu$ channels. Such weaker limits are observed in 10% of simulated experiments drawn from the background hypothesis.

9 Conclusion

The yields in ee, $e\mu$, and $\mu\mu$ are measured and the observed high-p_{T} isolated same-sign dilepton events show no significant discrepancy with the SM. In a model-independent statistical analysis of the inclusive sample, no evidence of unknown physical sources of same-sign dilepton events is found. Considering the dilepton invariant mass spectrum integrated above 110 GeV, we set upper limits on the fiducial cross-section of a new high-mass source, $0.13\,(ee), 0.17\,(\mu\mu), 0.32\,(e\mu)$ pb (95% CL).

Experimental sensitivity is demonstrated to four specific models of new phenomena that could be discovered in pp collisions at the LHC. Constraints are interpreted in the analysis of subsamples with non-zero jet multiplicity or $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV. Majorana neutrino mass values below 460 GeV are excluded for production by the effective operator V assuming a new physics scale of 1 TeV. Also excluded are LRS W_R with mass less than 0.7 TeV over most of the parameter space, and mass less than 1.0 TeV for a large range of neutrino masses. Cross-section limits are provided on a generic topology of supersymmetry and UED, as a function of the masses of field quanta. These limits may be applied to any model with contributions from this topology by appropriate scaling. Finally, a lower limit of 290 GeV is obtained on the mass of fourth generation d-type quarks.

10 Acknowledgements

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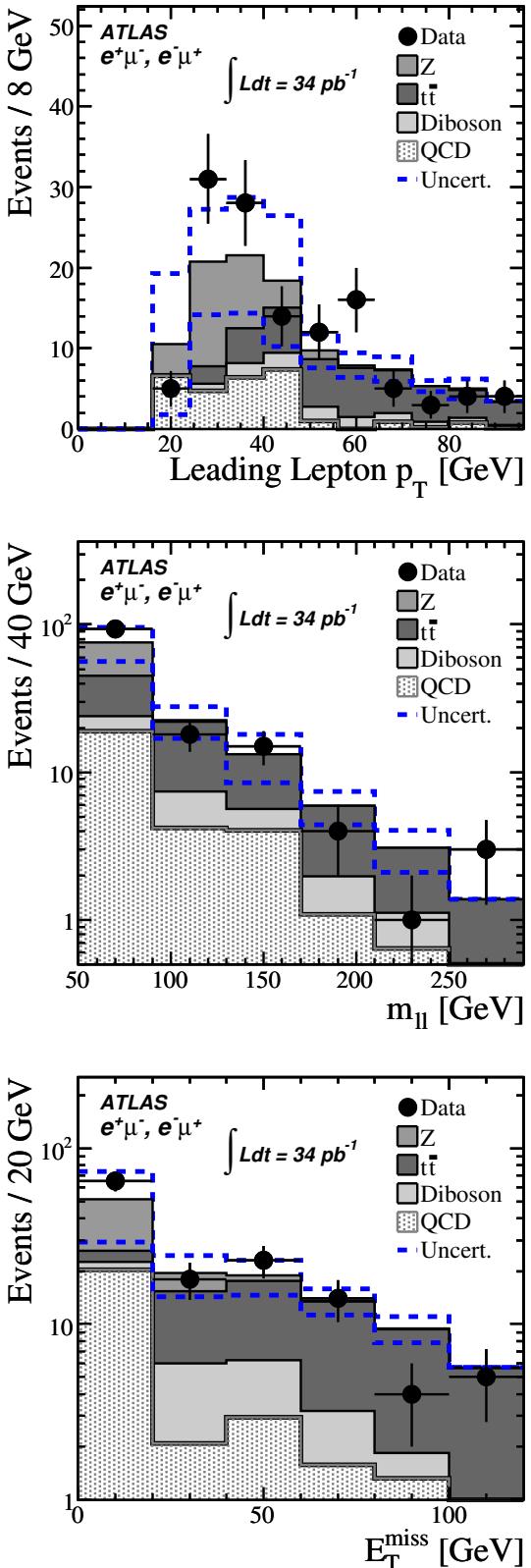
Figure 3. Validation of the SM prediction method in the opposite-sign $e\mu$ channel. Kinematic variables are shown: p_{T} of the leading lepton (top), $m_{\ell\ell}$(center) and $E_{\mathrm{T}}^{\mathrm{miss}}$(bottom). Statistical and systematic uncertainties on the prediction are shown as a dashed blue line. Overflow events are included in the highest bin. The contribution labeled Z is dominated by $Z \to \tau\tau$ decays but includes a small contribution from $Z \to \mu\mu$ decays where a hard photon is radiated from a muon, converts and is reconstructed as an electron.
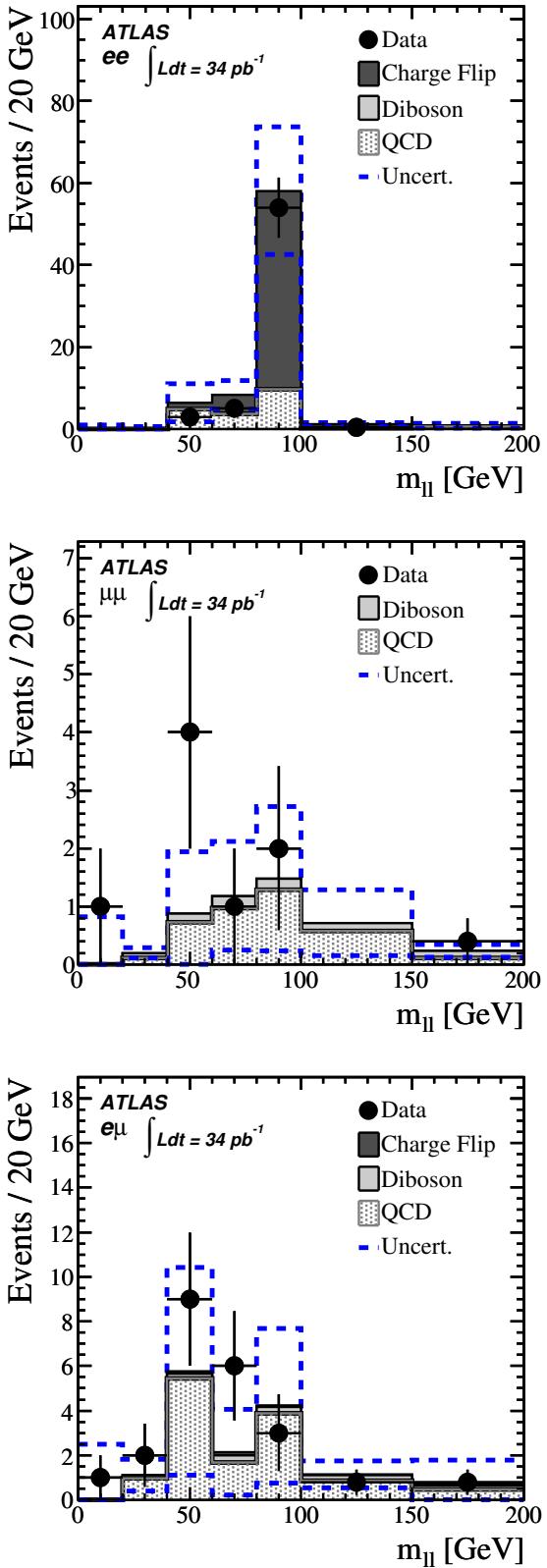
Figure 4. Distributions of same-sign dilepton invariant mass in the *ee* (top), $\mu\mu$ (center) and $e\mu$ (bottom) channels. Shown are data (points) and backgrounds (solid stacked histograms). The combined statistical and systematic uncertainty is shown as a dashed blue line. Overflow events are included in the final bin.
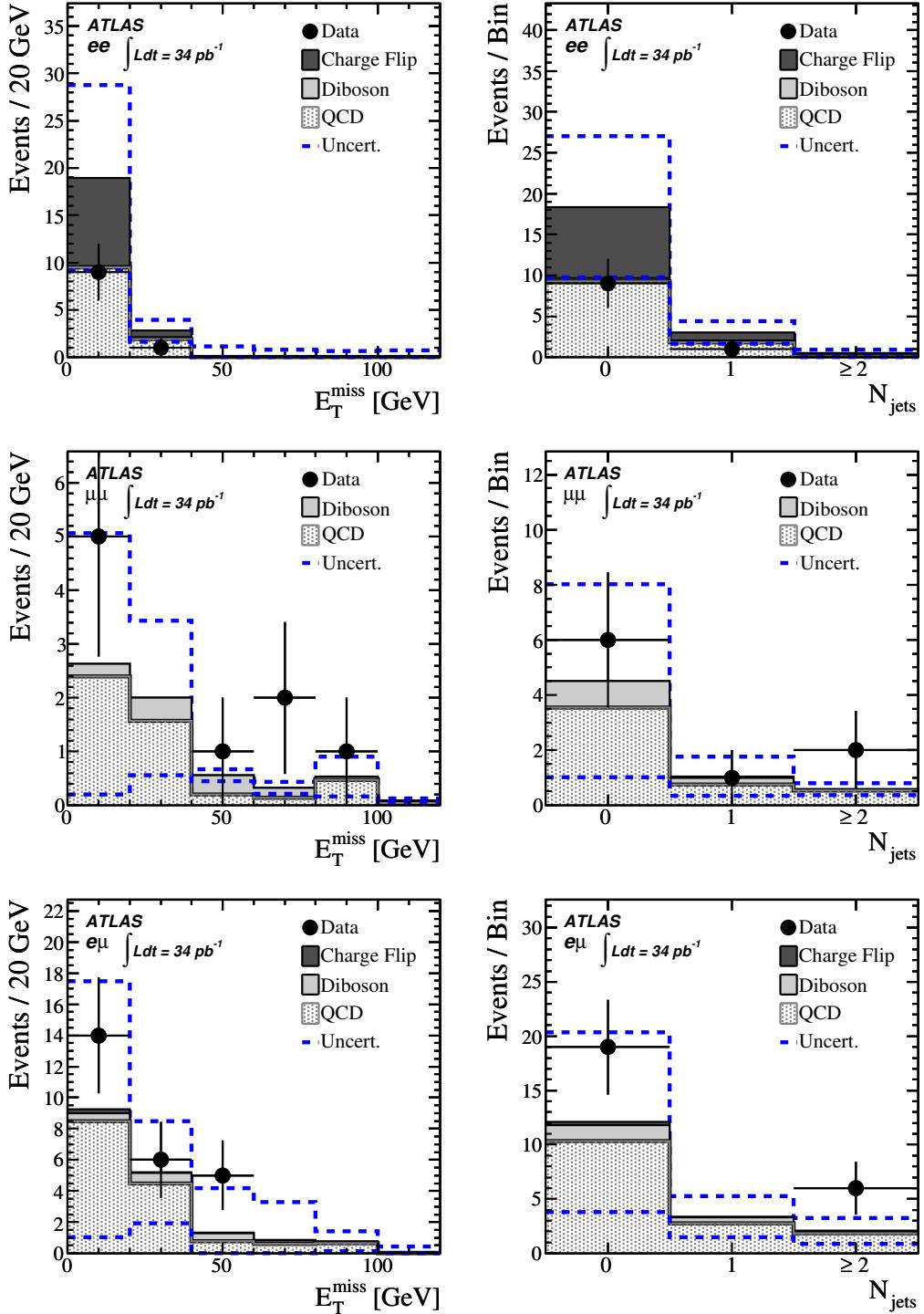
Figure 5. Distributions of missing transverse momentum (left) and jet multiplicity (right) in same-sign ee (top), $\mu\mu$ (center) and $e\mu$ (bottom) channels. Shown are data (points) and backgrounds (solid stacked histograms). The combined statistical and systematic uncertainty is shown as a dashed blue line. Overflow events are included in the final bin. In the ee channel, the Z reflection is suppressed by excluding $80 < m_{\ell\ell} < 95$ GeV.
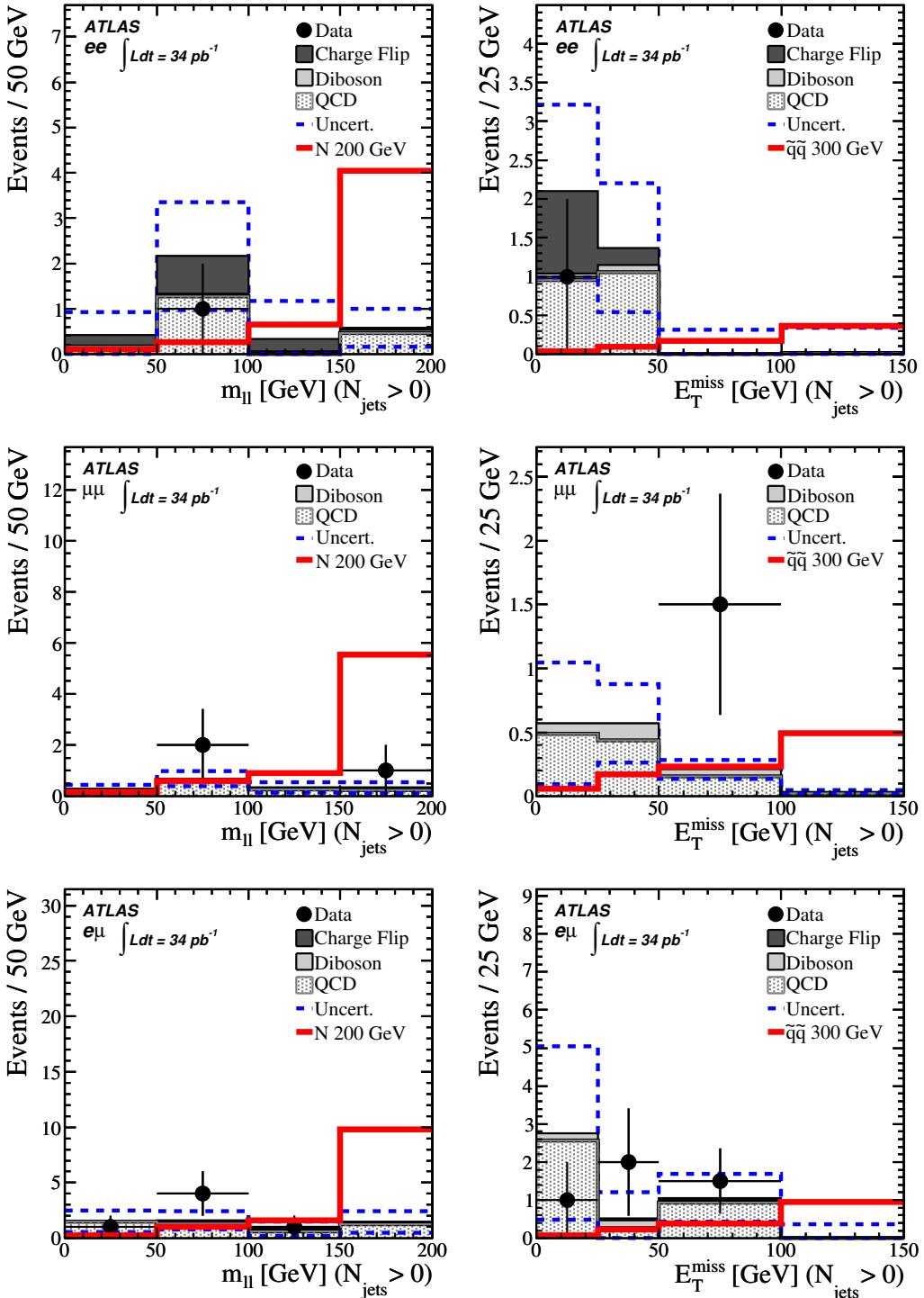
Figure 6. Distributions of dilepton invariant mass (left) and missing transverse momentum (right) with at least one jet in ee (top), $\mu\mu$ (center) and $e\mu$ (bottom) channels. Shown are data (points) and backgrounds (solid stacked histograms). The combined statistical and systematic uncertainty is shown as a dashed blue line. Overflow events are included in the final bin. In the ee channel, the Z reflection has been suppressed by excluding $80 < m_{\ell\ell} < 95$ GeV. For the dilepton invariant mass distribution, expected contribution from Majorana neutrinos with $m_N = 200$ GeV is shown; for missing transverse momentum, expected contribution is shown from lepton cascades with $m_{\tilde{q}} = 300$ GeV, $m_{\tilde{\chi}_1^+} = 150$ GeV, $m_{\tilde{\chi}_1^0} = 50$ GeV.
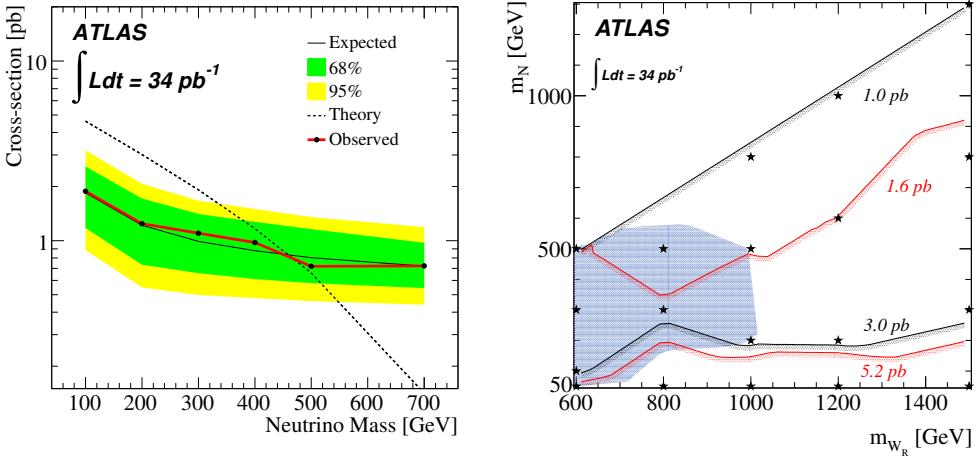
Figure 7. Limits at 95% CL on two different production models of Majorana neutrinos. Left: for a model of Majorana neutrinos which uses an effective vector operator, observed and expected cross-section limits [pb] as a function of Majorana neutrino mass produced, assuming a natural coupling and an energy scale of new phenomena $\Lambda = 1$ TeV. Right: for the LRS model, contours of observed cross-section upper limits [pb] as a function of Majorana neutrino and W_R masses in LRS theories are shown. The space is sampled in a rough grid (sample points indicated by a $\star$) and the limits are interpolated. The exclusion region is shaded.
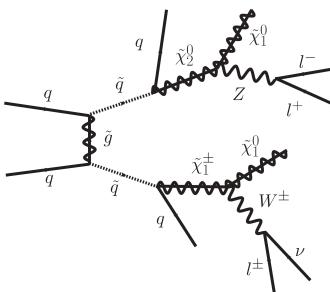
Figure 8. Feynman diagram of cascade topology denoted in supersymmetric nomenclature. The analysis is done with WW, ZZ and WZ combinations of weak vector bosons; WZ is shown in the diagram. This topology may also be found in other models such as UED.
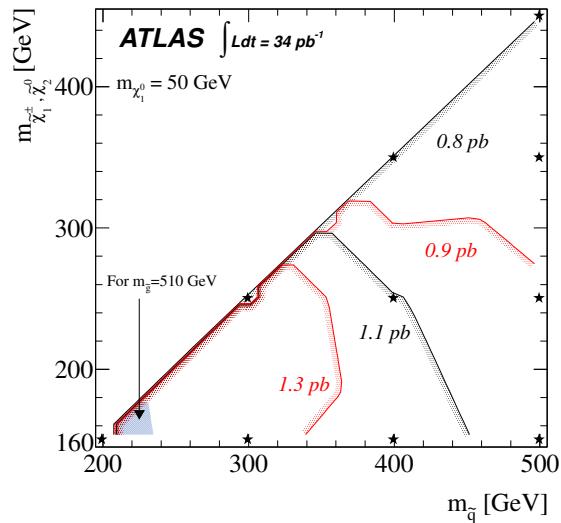
Figure 9. Observed 95% CL upper cross-section limits [pb] as a function of $m_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0}$ and $m_{\tilde{q}}$ for $m_{\tilde{\chi}_1^0} = 50$ GeV. As an example, we exclude a portion of parameter space (shaded) assuming a gluino mass of 510 GeV in order to calculate the cross-section. (This mass value is chosen to be greater than 500 GeV, the largest squark mass considered, but is otherwise arbitrary.) The mix of processes (Equations 8.1–8.3) included in the signal model is given in Section 8.2. The space is sampled in a rough grid (sample points indicated by a $\star$) and the limits are interpolated.
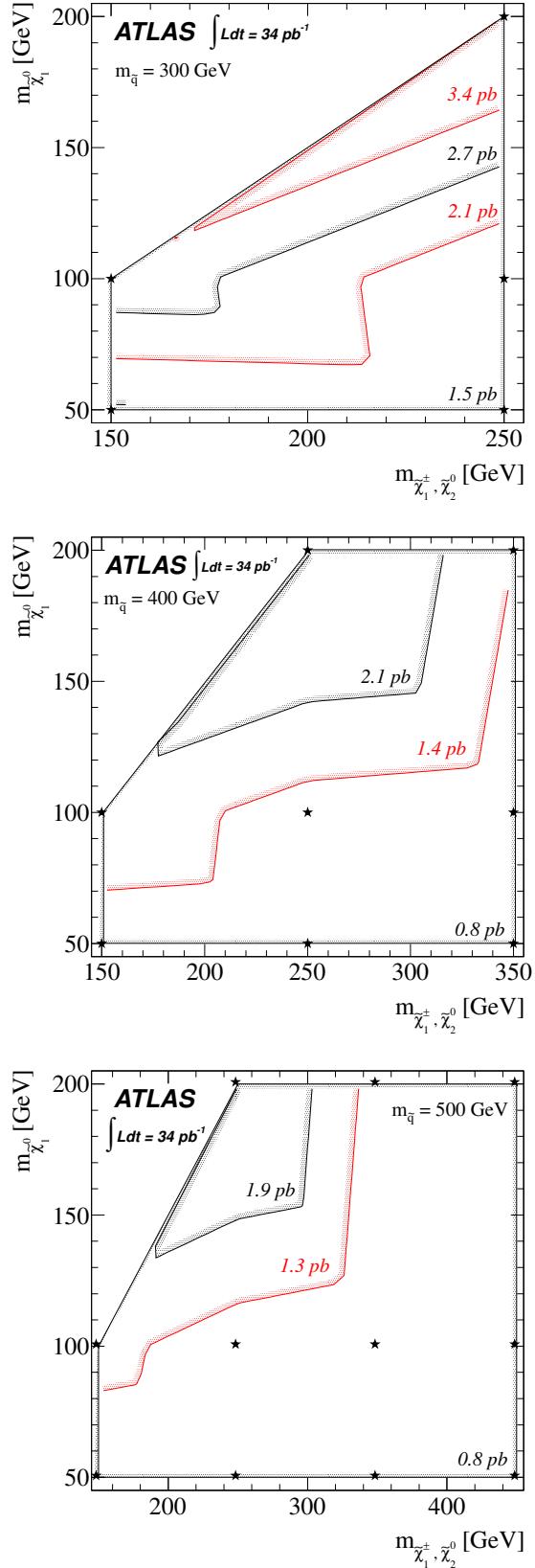
Figure 10. From left: observed 95% CL cross-section upper limits [pb] as a function of $m_{\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$ for $m_{\tilde{q}} = 300$, 400, and 500 GeV. The mix of processes (Equations 8.1–8.3) included in the signal model is given in Section 8.2. The space is sampled in a rough grid (sample points indicated by a $\star$) and the limits are interpolated.
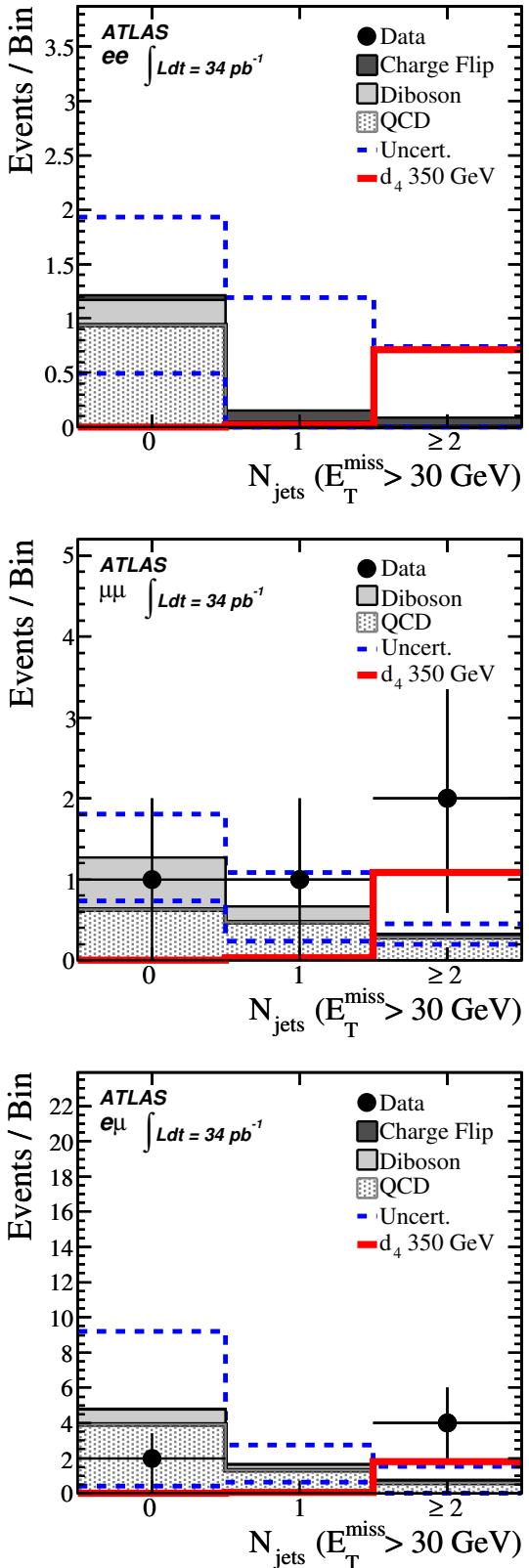
Figure 11. Distributions of jet multiplicity with $E_T^{miss} > 30$ GeV in ee (top), $\mu\mu$ (center) and $e\mu$ (bottom) channels. The final bin includes events with two or more jets. Shown are data (points) and backgrounds (solid stacked histograms). The combined statistical and systematic uncertainty is shown as a dashed blue line. Overflow events are included in the final bin. In the ee channel, the Z reflection is suppressed by excluding $80 < m_{\ell\ell} \leq 95$ GeV.
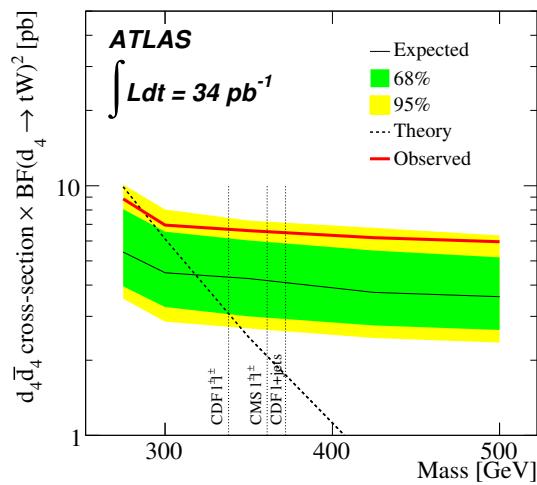
Figure 12. Expected and observed 95% CL limits on d_4 production cross-section as a function of its mass, compared to limits from CDF [5, 12] and CMS [4].

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