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Search for new particles in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This paper presents a search for new particles in events with one lepton (electron or muon) and missing transverse momentum using 20.3 fb^{-1} of proton–proton collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS experiment at the Large Hadron Collider. No significant excess beyond Standard Model expectations is observed. A W' with Sequential Standard Model couplings is excluded at the 95% confidence level for masses up to 3.24 TeV. Excited chiral bosons (W^*) with equivalent coupling strengths are excluded for masses up to 3.21 TeV. In the framework of an effective field theory limits are also set on the dark matter–nucleon scattering cross-section as well as the mass scale M_* of the unknown mediating interaction for dark matter pair production in association with a leptonically decaying W.

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Contents

1 Introduction

High-energy collisions at CERN's Large Hadron Collider (LHC) provide new opportunities to search for physics beyond the Standard Model (SM). This paper describes such a search in events containing a lepton (electron or muon) and missing transverse momentum using 8 TeV pp collision data collected with the ATLAS detector during 2012, corresponding to a total integrated luminosity of 20.3 fb^{-1}.

The first new-physics scenario that is considered in this paper is the Sequential Standard Model (SSM), the extended gauge model of ref. [1]. This model proposes the existence of additional heavy gauge bosons, of which the charged ones are commonly denoted W'. The W' has the same couplings to fermions as the SM W boson and a width that increases linearly with the W' mass. The coupling of the W' to WZ is set to zero. Similar searches [2–7] have been performed using $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collision data by the CDF Collaboration, $\sqrt{s} = 7$ TeV pp collision data by the ATLAS Collaboration as well as $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data by the CMS Collaboration.

The second new-physics scenario that is considered originates from ref. [8] and proposes the existence of charged partners, denoted W^*, of the chiral boson excitations described in ref. [9]. The anomalous (magnetic-moment type) coupling of the W^* leads to kinematic distributions significantly different from those of the W' as demonstrated in the previous ATLAS search [7] that was performed using 7 TeV pp collision data collected in 2011 corresponding to an integrated luminosity of 4.7 fb^{-1}. In the analysis presented in this paper the search region is expanded to higher masses and the sensitivity is considerably improved in the region covered by the previous search.

The third new-physics scenario considered is of direct production of weakly interacting candidate dark matter (DM) particles. These particles can be pair-produced at the LHC, $pp \to \chi\bar{\chi}$, via a new intermediate state. Since DM particles do not interact with the detector material, these events can be detected if there is associated initial-state radiation of a SM particle [10–13]. The Tevatron and LHC collaborations have reported limits on the cross-section of $p\bar{p}/pp \to \chi\bar{\chi} + X$ where X is a hadronic jet [14–16], a photon [17, 18], a hadronically decaying W or Z boson [19] or a leptonically decaying Z boson [20]. Previous LHC results have also been reinterpreted to set limits on the scenario where X is a leptonically decaying W boson [21]. This analysis is the first direct ATLAS search for this case. Limits are reported for the DM–nucleon scattering cross-section as well as the mass scale, M_*, of a new SM–DM interaction expressed in an effective field theory (EFT) as a four-point contact interaction [22–27]. As discussed in the literature, e.g. refs. [28, 29], the EFT formalism is not always an appropriate approximation but this issue is not addressed any further in this paper. Four effective operators are used as a representative set based on the definitions in ref. [13]: D1 scalar, D5 vector (both constructive and destructive interference cases are considered, the former denoted by D5c and the latter by D5d) and D9 tensor.

The analysis presented here identifies event candidates in the electron and muon channels, sets separate limits and then combines these assuming a common branching fraction for the two final states. The kinematic variable used to identify the signal is the transverse mass

$$m_\mathrm{T} = \sqrt{2p_\mathrm{T}E_\mathrm{T}^\mathrm{miss}(1 - \cos\varphi_{\ell\nu})}, \tag{1.1}$$

where p_T is the lepton transverse momentum, $E_\mathrm{T}^\mathrm{miss}$ is the magnitude of the missing transverse momentum vector and $\varphi_{\ell\nu}$ is the angle between the p_T and $E_\mathrm{T}^\mathrm{miss}$ vectors.[1]

The main background to the W', W^* and DM signals comes from the tail of the m_T distribution from SM W boson production with decays to the same final state. Other relevant backgrounds are Z boson production with decays into two leptons where one lepton is not reconstructed, W or Z production with decays to τ leptons where a τ subsequently decays to either an electron or a muon, and diboson production. These are collectively referred to as the electroweak (EW) background. There is also a contribution to the background from $t\bar{t}$ and single-top production, collectively referred to as the top background, which is most important for the lowest W'/W^* masses considered here, where it constitutes about 10% of the background after event selection in the electron channel and 15% in the muon channel. Other relevant strong-interaction background sources occur when a light or heavy hadron decays semileptonically or when a jet is misidentified as an electron or muon. These are referred to as the multi-jet background in this paper.

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[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z-axis along the beam pipe. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ by $\eta = -\ln\tan(\theta/2)$.

2   The ATLAS detector

The ATLAS detector [30] is a multi-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. The ATLAS detector has three major components: the inner tracking detector (ID), the calorimeter and the muon spectrometer (MS). Tracks and vertices of charged particles are reconstructed with silicon pixel and silicon microstrip detectors covering $|\eta| < 2.5$ and straw-tube transition radiation detectors covering $|\eta| < 2.0$, all immersed in a homogeneous 2 T magnetic field provided by a superconducting solenoid. The ID is surrounded by a hermetic calorimeter that covers $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers. The electromagnetic calorimeter is a liquid argon (LAr) sampling calorimeter, which uses lead absorbers for $|\eta| < 3.2$ and copper absorbers in the very forward region. The hadronic sampling calorimeter uses plastic scintillator tiles as the active material and iron absorbers in the region $|\eta| < 1.7$. In the region $1.5 < |\eta| < 4.9$, liquid argon is used as the active material, with copper and/or tungsten absorbers. The MS surrounds the calorimeters and consists of three large superconducting toroid systems (each with eight coils) together with multiple layers of trigger chambers up to $|\eta| < 2.4$ and tracking chambers, providing precision track measurements, up to $|\eta| < 2.7$.

3   Trigger and reconstruction

The data used in the electron channel were recorded with a trigger requiring the presence of an energy cluster in the EM compartment of the calorimeter (EM cluster) with $E_{\mathrm{T}} > 120$ GeV. For the muon channel, matching tracks in the MS and ID with combined $p_{\mathrm{T}} > 36$ GeV are used to select events. In order to compensate for the small loss in the selection efficiency at high p_{T} due to this matching, events are also recorded if a muon with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 1.05$ is found in the MS. The average trigger efficiency (measured with respect to reconstructed objects) is above 99% in the electron channel and 80%–90% in the muon channel for the region of interest in this analysis.

Each EM cluster with $E_{\mathrm{T}} > 125$ GeV and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ is considered as an electron candidate if it is matched to an ID track. The region $1.37 \leq |\eta| \leq 1.52$ exhibits degraded energy resolution due to the transition from the central region to the forward regions of the calorimeters and is therefore excluded. The track and the cluster must satisfy a set of identification criteria that are optimised for the conditions of many proton–proton collisions in the same or nearby beam bunch crossings (in-time or out-of-time pile-up, respectively) [31]. These criteria require the shower profiles to be consistent with those expected for electrons and impose a minimum requirement on the amount of transition radiation that is present. In addition, to suppress background from photon conversions, a hit in the first layer of the pixel detector is required if an active pixel sensor is traversed. The electron's energy is obtained from the calorimeter measurements while its direction is obtained from the associated track. In the high-E_{T} range relevant for this analysis, the electromagnetic calorimeter energy resolution is measured in data to be 1.2%

in the central region and 1.8% in the forward region [32]. These requirements result in about a 90% identification efficiency for electrons with $E_T > 125$ GeV.

Muons are required to have a $p_T > 45$ GeV, where the momentum of the muon is obtained by combining the ID and MS measurements. To ensure an accurate measurement of the momentum, muons are required to have hits in three MS layers and are restricted to the ranges $|\eta| < 1.0$ and $1.3 < |\eta| < 2.0$. Some of the chambers in the region $1.0 < |\eta| < 1.3$ were not yet installed, hence the momentum resolution of MS tracks is degraded in this region. Including the muon candidates with an η-range $2.0 < |\eta| < 2.5$ would lead to an increase in the signal selection efficiency of up to 12% for lower W' masses and of up to 3% for a W' mass of 3 TeV. However, the background levels in the signal region would increase by more than 15%. Therefore, the previously stated η restrictions are retained. For the final selection of good muon candidates, the individual ID and MS momentum measurements are required to be in agreement within 5 standard deviations. The average momentum resolution is about 15%–20% at $p_T = 1$ TeV. About 80% of the muons in the η-range considered are reconstructed, with most of the loss coming from regions without three MS layers.

The E_T^{miss} in each event is evaluated by summing over energy-calibrated physics objects (jets, photons and leptons) and adding corrections for calorimeter deposits not associated with these objects [33].

This analysis makes use of all of the $\sqrt{s} = 8$ TeV data collected in 2012 for which the relevant detector systems were operating properly and all data quality requirements were satisfied. The integrated luminosity of the data used in this study is 20.3 fb^{-1} for both the electron and muon decay channels. The uncertainty on this measurement is 2.8%, which is derived following the methodology detailed in ref. [34].

4 Monte Carlo simulation

With the exception of the multi-jet background, which is estimated from data, expected signals and backgrounds are evaluated using simulated Monte Carlo samples and normalised using the calculated cross-sections and the integrated luminosity of the data.

The W' signal events are generated at leading order (LO) with PYTHIA v8.165 [35, 36] using the MSTW2008 LO [37] parton distribution functions (PDFs). PYTHIA is also used for the fragmentation and hadronisation of $W^* \to \ell\nu$ events that are generated at LO with CALCHEP v3.3.6 [38] using the CTEQ6L1 PDFs [39]. DM signal samples are generated at LO with MADGRAPH5 v1.4.5 [40] using the MSTW2008 LO PDFs, interfaced to PYTHIA v8.165.

The W/Z boson and $t\bar{t}$ backgrounds are generated at next-to-leading order (NLO) with POWHEG-BOX r1556 [41] using the CT10 NLO [42] PDFs. For the W/Z backgrounds, fragmentation and hadronisation is performed with PYTHIA v8.165, while for $t\bar{t}$ PYTHIA v6.426 is used. The single-top background is generated at NLO with MC@NLO v4.06 [43] using the CT10 NLO PDFs for the Wt- and s-channels, and with ACERMC v3.8 [44] using the CTEQ6L1 PDFs for the t-channel. Fragmentation and hadronisation for the MC@NLO samples are performed with HERWIG v6.520 [45], using JIMMY v4.31 [46] for the underlying

event, whereas PYTHIA v6.426 is used for the ACERMC samples. The WW, WZ and ZZ diboson backgrounds are generated at LO with SHERPA v1.4.1 [47] using the CT10 NLO PDFs.

The PYTHIA signal model for W' has $V-A$ SM couplings to fermions but does not include interference between the W and W'. For both W' and W^*, decay channels beside $e\nu$ and $\mu\nu$, notably $\tau\nu$, ud, sc and tb, are included in the calculation of the widths but are not explicitly included as signal or background. At high mass ($m_{W'} > 1$ TeV), the total width is about 3.5 % of the pole mass, and the branching fraction to each of the lepton decay channels is 8.2%.

For all samples, final-state photon radiation from leptons is handled by PHOTOS [48]. The ATLAS full detector simulation [49] based on GEANT4 [50] is used to propagate the particles and account for the response of the detector. For the underlying event, the AT-LAS tune AUET2B [51] is used for PYTHIA 6 and AU2 [52] is used for PYTHIA 8, while AUET2 [53] is used for the HERWIG with JIMMY. The effect of pile-up is incorporated into the simulation by overlaying additional minimum-bias events generated with PYTHIA onto the generated hard-scatter events. Simulated events are weighted to match the distribution of the number of interactions per bunch crossing observed in data, but are otherwise reconstructed in the same manner as data.

The $W \to \ell\nu$ and $Z \to \ell\ell$ cross-sections are calculated at next-to-next-to-leading order (NNLO) in QCD with ZWPROD [54] using MSTW2008 NNLO PDFs. Consistent results are obtained using VRAP v0.9 [55] and FEWZ v3.1b2 [56, 57]. Higher-order electroweak corrections are calculated with MCSANC [58]. Mass-dependent K-factors obtained from the ratios of the calculated higher-order cross-sections to the cross-sections of the generated samples are used to scale W^+, W^- and Z backgrounds separately. The $W' \to \ell\nu$ cross-sections are calculated in the same way, except that the electroweak corrections beyond final-state radiation are not included because the calculation for the SM W cannot be applied directly. Cross sections for $W^* \to \ell\nu$ are kept at LO due to the non-renormalisability of the model at higher orders in QCD. The $t\bar{t}$ cross-section is also calculated at NNLO including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms obtained with TOP++ v2.0 [59–64] for a top quark mass of 172.5 GeV. The W', W^*, and DM particle signal cross-sections are listed in tables 1 and 2. The most important background cross-sections are listed in table 3.

Uncertainties on the W' cross-section and the W/Z background cross-sections are estimated from variations of the renormalisation and factorisation scales, PDF+α_s variations and PDF choice. The scale uncertainties are estimated by varying both the renormalisation and factorisation scales simultaneously up or down by a factor of two. The resulting maximum variation from the two fluctuations is taken as the symmetric scale uncertainty. The PDF+α_s uncertainty is evaluated using 90% confidence level (CL) eigenvector and 90% CL α_s variations of the nominal MSTW2008 NNLO PDF set and combined with the scale uncertainty in quadrature. The PDF choice uncertainty is evaluated by comparing the central values of the MSTW2008 NNLO, CT10 NNLO, NNPDF 2.3 NNLO [65], ABM11 5N NNLO [66] and HERAPDF 1.5 NNLO [67] PDF sets. The envelope of the PDF central value comparisons and the combination of the scale and PDF+α_s uncertainties is taken as

Table 1. Predicted values of the cross-section times branching fraction (σB) for $W' \to \ell\nu$ and $W^* \to \ell\nu$. The σB for $W' \to \ell\nu$ are at NNLO while those for $W^* \to \ell\nu$ are at LO. The values are given per channel, with $\ell = e$ or μ.

Mass [GeV]	$W' \to \ell\nu$ σB [pb]	$W^* \to \ell\nu$ σB [pb]
300	149.0	
400	50.2	37.6
500	21.4	16.2
600	10.4	7.95
750	4.16	3.17
1000	1.16	0.882
1250	0.389	0.294
1500	0.146	0.108
1750	0.0581	0.0423
2000	0.0244	0.0171
2250	0.0108	0.00700
2500	0.00509	0.00290
2750	0.00258	0.00120
3000	0.00144	4.9×10^{-4}
3250	8.9×10^{-4}	2.0×10^{-4}
3500	5.9×10^{-4}	8.0×10^{-5}
3750	4.2×10^{-4}	3.2×10^{-5}
4000	3.1×10^{-4}	1.3×10^{-5}

Table 2. Predicted values of σB for DM signal with different mass values, m_χ. The values of M_* used in the calculation for a given operator are also shown. The cross-sections are at LO, and the values are given for the sum of three lepton flavours $\ell = e, \mu, \tau$.

m_χ [GeV]	DM production σB [pb]			
	D1 $M_* = 10$ GeV	D5d $M_* = 100$ GeV	D5c $M_* = 1$ TeV	D9 $M_* = 1$ TeV
1	439	72.2	0.0608	0.0966
100	332	70.8	0.0575	0.0870
200	201	58.8	0.0488	0.0695
400	64.6	32.9	0.0279	0.0365
1000	1.60	2.37	0.00192	0.00227
1300	0.213	0.454	0.000351	0.000412

Table 3. Predicted values of σB for the leading backgrounds. The value for $t\bar{t} \to \ell X$ includes all final states with at least one lepton (e, μ or τ). The others are exclusive and are used for both $\ell = e$ and $\ell = \mu$. All cross-sections are at NNLO.

Process	σB [pb]
$W \to \ell\nu$	12190
$Z/\gamma^* \to \ell\ell$ ($m_{Z/\gamma^*} > 60$ GeV)	1120
$t\bar{t} \to \ell X$	137.3

the total uncertainty on the differential cross-section as a function of the invariant mass of the lepton–neutrino system ($m_{\ell\nu}$). The PDF and $\alpha_{\rm s}$ uncertainties on the $t\bar{t}$ cross-section are calculated using the PDF4LHC prescription [68] with the MSTW2008 68% CL NNLO, CT10 NNLO and NNPDF2.3 5f FFN PDF error sets added in quadrature to the scale uncertainty. The systematic uncertainty arising from the variation of the top mass by ± 1 GeV is also added in quadrature.

An additional uncertainty on the differential cross-section due to the beam energy uncertainty is calculated as function of $m_{\ell\nu}$ for the charged-current Drell–Yan process with VRAP at NNLO using CT10 NNLO PDFs by taking a 0.66% uncertainty on the energy of each 4 TeV proton beam as determined in ref. [69]. The size of this uncertainty is observed to be about 2% (6%) at $m_{\ell\nu} = 2$ (3) TeV. The calculated uncertainties are propagated to both the W and W'/W^* processes in order to derive uncertainties on the background levels as well as the signal selection efficiencies in each signal region.

Uncertainties are not reported on the cross-sections for the W^* due to the breakdown of higher-order corrections for non-renormalisable models. However, uncertainties on the signal selection efficiency for the W^* are evaluated using the same relative differential cross-section uncertainty as for the W'. Uncertainties on DM production are evaluated using 68% confidence level eigenvector variations of the nominal MSTW2008 LO PDF set as in [19].

5   Event selection

The primary vertex for each event is required to have at least three tracks with $p_{\rm T} > 0.4$ GeV and to have a longitudinal distance less than 200 mm from the centre of the collision region. There are on average 20.7 interactions per event in the data used for this analysis. The primary vertex is defined to be the one with the highest summed track $p_{\rm T}^2$. Spurious tails in the $E_{\rm T}^{\rm miss}$ distribution, arising from calorimeter noise and other detector problems are suppressed by checking the quality of each reconstructed jet and discarding events containing reconstructed jets of poor quality, following the description given in ref. [70]. In addition, the ID track associated with the electron or muon is required to be compatible with originating from the primary vertex by requiring that the transverse distance of closest approach, d_0, satisfies $|d_0| < 1$ (0.2) mm and longitudinal distance, z_0, satisfies $|z_0| < 5$ (1) mm for the electron (muon). Events are required to have exactly

one electron candidate with $E_T > 125$ GeV or one muon candidate with $p_T > 45$ GeV satisfying these requirements and the identification criteria described in section 3. In the electron channel, events having additional electrons with $E_T > 20$ GeV, passing all electron identification criteria, are discarded. Similarly, in the muon channel, events having additional muon candidates with a p_T threshold of 20 GeV are discarded.

To suppress the multi-jet background, the lepton is required to be isolated. In the electron channel, the isolation energy is measured with the calorimeter in a cone $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.2$ around the electron track, and the requirement is $\Sigma E_T^{\text{calo}} < 0.007 \times E_T + 5$ GeV, where the sum includes all calorimeter energy clusters in the cone excluding those that are attributed to the electron. The scaling of the isolation requirement with the electron E_T reduces the efficiency loss due to radiation from the electron at high E_T. In the muon channel, the isolation energy is measured using ID tracks with $p_T^{\text{trk}} > 1$ GeV in a cone $\Delta R = 0.3$ around the muon track. The isolation requirement is $\sum p_T^{\text{trk}} < 0.05 \times p_T$, where the muon track is excluded from the sum. As in the electron channel, the scaling of the isolation requirement with the muon p_T reduces the efficiency loss due to radiation from the muon at high p_T.

An E_T^{miss} requirement is imposed to select signal events and to further suppress the contributions from the multi-jet and SM W backgrounds. In both channels, the requirement placed on the charged lepton p_T is also applied to the E_T^{miss}: $E_T^{\text{miss}} > 125$ GeV for the electron channel and $E_T^{\text{miss}} > 45$ GeV for the muon channel.

The multi-jet background around the Jacobian peak of the m_T distribution is evaluated using the *matrix method* as described in ref. [71] in both the electron and muon channels. The high-mass tail of the distribution is then fitted by a power-law function in order to determine the level of the multi-jet background in the region used to search for new physics. In the electron channel, the multi-jet background constitutes about 2%–4% of the total background at high m_T. Consistent results are obtained using the *inverted isolation* technique described in ref. [5]. In the muon channel, the multi-jet background constitutes about 1%–3% of the total background at high m_T. The uncertainty of the multi-jet background is determined by varying the selection requirements used to define the control region and by varying the m_T threshold of the fitting range used in the extrapolation to high m_T.

The same reconstruction criteria and event selection are applied to both the data and simulated samples. Figure 1 shows the p_T, E_T^{miss}, and m_T spectra for each channel after event selection for the data, the expected background and three examples of W' signals at different masses. Prior to investigating if there is evidence for a signal, the agreement between the data and the predicted background is established for events with $m_T < 252$ GeV, the lowest m_T threshold used to search for new physics. The optimisation of the m_T thresholds for event selection is described below. The agreement between the data and expected background is good. Table 4 shows an example of how different sources contribute to the background for $m_T > 1500$ GeV, the region used to search for a W' with a mass of 2000 GeV. The $W \to \ell\nu$ background is the dominant contribution for both the electron and muon channels. The $Z \to \ell\ell$ background in the electron channel is smaller than in the muon channel due to calorimeters having larger η coverage than the MS, and the electron energy resolution being better than the muon momentum resolution at high p_T.
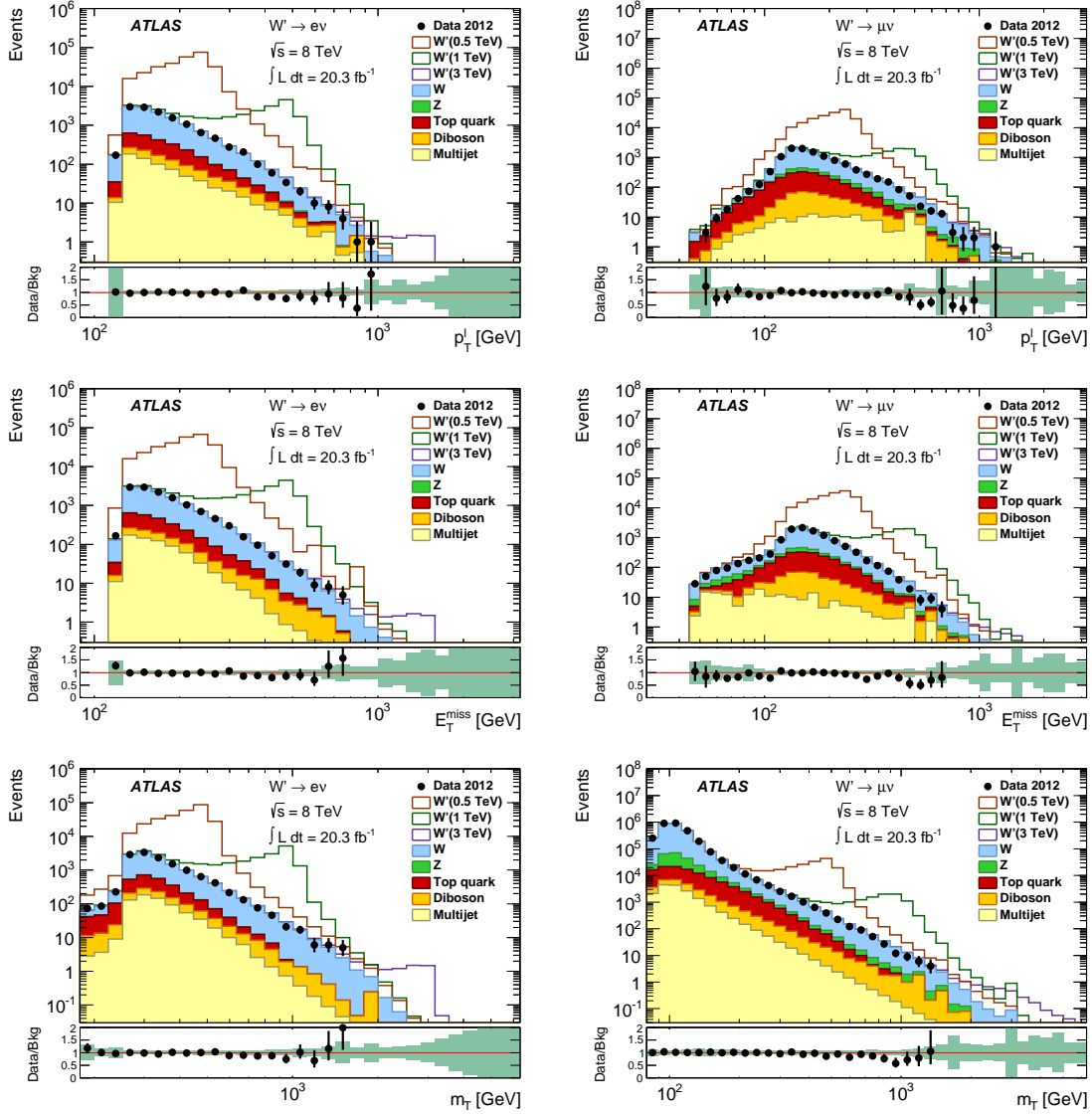
Figure 1. Spectra of lepton p_T (top), E_T^{miss} (centre) and m_T (bottom) for the electron (left) and muon (right) channels after the event selection. The spectra of p_T and E_T^{miss} are shown with the requirement $m_T > 252$ GeV. The points represent data and the filled, stacked histograms show the predicted backgrounds. Open histograms are $W' \rightarrow \ell\nu$ signals added to the background with their masses in GeV indicated in parentheses in the legend. The signal and background samples are normalised using the integrated luminosity of the data and the NNLO cross-sections listed in tables 1 and 3, except for the multi-jet background which is estimated from data. The error bars on the data points are statistical. The ratio of the data to the total background prediction is shown below each of the distributions. The bands represent the systematic uncertainties on the background including the ones arising from the statistical uncertainty of the simulated samples.

Table 4. Expected numbers of events from the various background sources in each decay channel for $m_\mathrm{T} > 1500$ GeV, the region used to search for a W' with a mass of 2000 GeV. The $W \to \ell\nu$ and $Z \to \ell\ell$ rows include the expected contributions from the τ-lepton. The uncertainties are statistical.

	$e\nu$		$\mu\nu$	
$W \to \ell\nu$	2.65	$\pm$ 0.10	2.28	$\pm$ 0.21
$Z \to \ell\ell$	0.00163	$\pm$ 0.00022	0.232	$\pm$ 0.005
Diboson	0.27	$\pm$ 0.23	0.46	$\pm$ 0.23
Top	0.0056	$\pm$ 0.0009	0.0017	$\pm$ 0.0001
Multi-jet	0.066	$\pm$ 0.020	0.046	$\pm$ 0.039
Total	2.99	$\pm$ 0.25	3.01	$\pm$ 0.31

6   Statistical analysis and systematic uncertainties

A Bayesian analysis is performed to set limits on the studied processes. For each candidate mass and decay channel, events are counted above an m_T threshold. The optimisation of m_Tmin is done separately for $W' \to \ell\nu$ and $W^* \to \ell\nu$. For each candidate mass, the m_Tmin values that minimise the expected cross-section limits are obtained in the electron and muon channels separately, but for simplicity the lower value is used in both channels since this has a negligible impact on the final results. A similar optimisation is performed when setting the limits on DM production, and in this case a single m_Tmin is chosen for each operator. The expected number of events in each channel is

$$N_\mathrm{exp} = \varepsilon_\mathrm{sig} L_\mathrm{int} \sigma B + N_\mathrm{bkg}, \tag{6.1}$$

where L_int is the integrated luminosity of the data sample, ε_sig is the signal selection efficiency defined as the fraction of signal events that satisfy the event selection criteria as well as $m_\mathrm{T} > m_\mathrm{Tmin}$, N_bkg is the expected number of background events, and σB is the cross-section times branching fraction. Using Poisson statistics, the likelihood to observe N_obs events is

$$\mathcal{L}(N_\mathrm{obs}|\sigma B) = \frac{(L_\mathrm{int}\varepsilon_\mathrm{sig}\sigma B + N_\mathrm{bkg})^{N_\mathrm{obs}} e^{-(L_\mathrm{int}\varepsilon_\mathrm{sig}\sigma B + N_\mathrm{bkg})}}{N_\mathrm{obs}!}. \tag{6.2}$$

Uncertainties are included by introducing nuisance parameters θ_i, each with a probability density function $g_i(\theta_i)$, and integrating the product of the Poisson likelihood with the probability density function. The integrated likelihood is

$$\mathcal{L}_B(N_\mathrm{obs}|\sigma B) = \int \mathcal{L}(N_\mathrm{obs}|\sigma B) \prod g_i(\theta_i) d\theta_i, \tag{6.3}$$

where a log-normal distribution is used for the $g_i(\theta_i)$. The nuisance parameters are taken to be: L_int, ε_sig and N_bkg, with the appropriate correlation accounted for between the first and the third parameters.

The measurements in the two decay channels are combined assuming the same branch-

ing fraction for each. Equation (6.3) remains valid with the Poisson likelihood replaced by the product of the Poisson likelihoods for the two channels. The integrated luminosities for the electron and muon channels are fully correlated. For $W'/W^* \to \ell\nu$ the signal selection efficiencies and background levels are partly correlated with each other and between the two channels due to the full correlation of the cross-section uncertainties. If these correlations were not included, the observed σB limits would improve by 25%–30% for the lowest mass points, a few percent for the intermediate mass points and by about 10% for the highest mass points.

Bayes' theorem gives the posterior probability that the signal has signal strength σB:

$$P_{\text{post}}(\sigma B | N_{\text{obs}}) = N \mathcal{L}_B(N_{\text{obs}} | \sigma B) \, P_{\text{prior}}(\sigma B) \qquad (6.4)$$

where $P_{\text{prior}}(\sigma B)$ is the assumed prior probability, here chosen to be flat in σB, for $\sigma B > 0$. The constant factor N normalises the total probability to one. The posterior probability is evaluated for each mass and decay channel as well as for their combination, and then used to set a limit on σB.

The inputs for the evaluation of $\mathcal{L}_B$ (and hence P_{post}) are L_{int}, ε_{sig}, N_{bkg}, N_{obs} and the uncertainties on the first three. The uncertainties on ε_{sig} and N_{bkg} account for experimental and theoretical systematic effects as well as the statistics of the simulated samples. The experimental systematic uncertainties include those on the efficiencies of the electron or muon trigger, reconstruction and event/object selection. Uncertainties in the lepton energy/momentum and $E_{\text{T}}^{\text{miss}}$, characterised by scale and resolution uncertainties, are also included. Performance metrics are obtained *in-situ* using well-known processes such as $Z \to \ell\ell$ [31, 72, 73]. Since most of these performance metrics are measured at relatively low p_{T} their values are extrapolated to the high-p_{T} regime relevant to this analysis using MC simulation. The uncertainties in these extrapolations are included but are too small to significantly affect the results. Table 5 summarises the uncertainties on the event selection efficiencies and the expected number of background events for the $W' \to \ell\nu$ signal with $m_{W'} = 2000$ GeV using $m_{\text{T}} > 1500$ GeV, and W^* signal with $m_{W^*} = 2000$ GeV using $m_{\text{T}} > 1337$ GeV.

Table 5. Relative uncertainties on the selection efficiency ε_{sig} and expected number of background events N_{bkg} for a W' (upper part of the table) and W^* (lower part of the table) with a mass of 2000 GeV. The efficiency uncertainties include contributions from the trigger, reconstruction and event selection. The last row gives the total relative uncertainties.

Source	ε_{sig}		N_{bkg}	
	$e\nu$	$\mu\nu$	$e\nu$	$\mu\nu$
$W' \to \ell\nu$				
Reconstruction and trigger efficiency	2.5%	4.1%	2.7%	4.1%
Lepton energy/momentum resolution	0.2%	1.4%	1.9%	18%
Lepton energy/momentum scale	1.2%	1.8%	3.5%	1.5%
$E_{\text{T}}^{\text{miss}}$ scale and resolution	0.1%	0.1%	1.2%	0.5%
Beam energy	0.5%	0.5%	2.8%	2.1%
Multi-jet background	-	-	2.2%	3.4%
Monte Carlo statistics	0.9%	1.3%	8.5%	10%
Cross-section (shape/level)	2.9%	2.8%	18%	15%
Total	4.2%	5.6%	21%	27%
$W^* \to \ell\nu$				
Reconstruction and trigger efficiency	2.7%	4.1%	2.6%	4.0%
Lepton energy/momentum resolution	0.4%	0.9%	3.0%	17%
Lepton energy/momentum scale	2.4%	2.4%	3.1%	1.5%
$E_{\text{T}}^{\text{miss}}$ scale and resolution	0.1%	0.4%	3.1%	0.6%
Beam energy	0.1%	0.1%	2.5%	1.9%
Multi-jet background	-	-	1.8%	2.6%
Monte Carlo statistics	1.2%	1.8%	6.7%	8.6%
Cross-section (shape/level)	0.2%	0.2%	17%	15%
Total	3.9%	5.1%	19%	25%

7   Results

The inputs for the evaluation of $\mathcal{L}_B$ are listed in tables 6, 7 and 8. The uncertainties on ε_{sig} and N_{bkg} account for all relevant experimental and theoretical effects except for the uncertainty on the integrated luminosity. The latter is included separately and is correlated between signal and background. The tables also list the predicted numbers of signal events, N_{sig}, with their uncertainties accounting for the uncertainties in both ε_{sig} and the cross-section calculation. The maximum value for the signal selection efficiency is at $m_{W'} = 2000$ GeV. For lower masses, the efficiency falls because the relative m_{T} threshold, $m_{\text{Tmin}}/m_{W'}$, increases in order to reduce the background level. The contribution from $W' \to \tau\nu$ with a leptonically decaying τ is neglected. It would increase the signal yield by 2%–3% for the highest masses. The background level is estimated for each mass by summing over all of the background sources.

Table 6. Inputs for the $W' \rightarrow \ell\nu$ σB limit calculations. The first three columns are the W' mass, m_T threshold and decay channel. The next two are the signal selection efficiency, ε_{sig}, and the prediction for the number of signal events, N_{sig}, obtained with this efficiency. The last two columns are the expected number of background events, N_{bkg}, and the number of events observed in data, N_{obs}. The uncertainties on N_{sig} and N_{bkg} include contributions from the uncertainties on the cross-sections but not from that on the integrated luminosity.

$m_{W'}$ [GeV]	m_{Tmin} [GeV]	Channel	ε_{sig}	N_{sig}	N_{bkg}	N_{obs}
300	252	$e\nu$	0.228 ± 0.009	688000 ± 28000	12900 ± 820	12717
		$\mu\nu$	0.184 ± 0.007	555000 ± 21000	11300 ± 770	10927
400	336	$e\nu$	0.319 ± 0.012	325000 ± 12000	5280 ± 360	5176
		$\mu\nu$	0.193 ± 0.007	196000 ± 7500	3490 ± 250	3317
500	423	$e\nu$	0.325 ± 0.013	141000 ± 5700	2070 ± 150	2017
		$\mu\nu$	0.186 ± 0.007	80900 ± 3200	1370 ± 100	1219
600	474	$e\nu$	0.397 ± 0.014	83800 ± 2900	1260 ± 96	1214
		$\mu\nu$	0.229 ± 0.009	48200 ± 1900	827 ± 64	719
750	597	$e\nu$	0.393 ± 0.013	33200 ± 1100	456 ± 45	414
		$\mu\nu$	0.226 ± 0.009	19100 ± 750	305 ± 30	255
1000	796	$e\nu$	0.386 ± 0.012	9080 ± 290	116 ± 15	101
		$\mu\nu$	0.219 ± 0.009	5160 ± 220	84 ± 10	58
1250	1002	$e\nu$	0.378 ± 0.012	2980 ± 98	35.3 ± 5.8	34
		$\mu\nu$	0.210 ± 0.009	1650 ± 73	28.3 ± 4.6	19
1500	1191	$e\nu$	0.376 ± 0.014	1110 ± 40	13.2 ± 2.5	14
		$\mu\nu$	0.206 ± 0.010	610 ± 30	10.9 ± 2.3	6
1750	1416	$e\nu$	0.336 ± 0.013	396 ± 16	4.56 ± 0.92	5
		$\mu\nu$	0.182 ± 0.010	214 ± 12	4.3 ± 1.1	0
2000	1500	$e\nu$	0.370 ± 0.015	183.0 ± 7.7	2.99 ± 0.61	3
		$\mu\nu$	0.198 ± 0.011	98.0 ± 5.5	3.01 ± 0.80	0
2250	1683	$e\nu$	0.327 ± 0.015	71.5 ± 3.3	1.38 ± 0.33	0
		$\mu\nu$	0.173 ± 0.011	37.9 ± 2.3	1.44 ± 0.33	0
2500	1888	$e\nu$	0.262 ± 0.018	27.1 ± 1.8	0.432 ± 0.091	0
		$\mu\nu$	0.140 ± 0.012	14.4 ± 1.2	0.61 ± 0.15	0
2750	1888	$e\nu$	0.235 ± 0.024	12.3 ± 1.3	0.432 ± 0.091	0
		$\mu\nu$	0.127 ± 0.014	6.64 ± 0.74	0.61 ± 0.15	0
3000	1888	$e\nu$	0.183 ± 0.029	5.33 ± 0.86	0.432 ± 0.091	0
		$\mu\nu$	0.100 ± 0.016	2.93 ± 0.48	0.61 ± 0.15	0
3250	1888	$e\nu$	0.124 ± 0.033	2.22 ± 0.59	0.432 ± 0.091	0
		$\mu\nu$	0.069 ± 0.018	1.24 ± 0.32	0.61 ± 0.15	0
3500	1888	$e\nu$	0.077 ± 0.031	0.92 ± 0.36	0.432 ± 0.091	0
		$\mu\nu$	0.044 ± 0.017	0.52 ± 0.20	0.61 ± 0.15	0
3750	1888	$e\nu$	0.047 ± 0.024	0.40 ± 0.21	0.432 ± 0.091	0
		$\mu\nu$	0.028 ± 0.013	0.24 ± 0.11	0.61 ± 0.15	0
4000	1888	$e\nu$	0.031 ± 0.018	0.20 ± 0.11	0.432 ± 0.091	0
		$\mu\nu$	0.019 ± 0.010	0.121 ± 0.061	0.61 ± 0.15	0

Table 7. Inputs for the $W^* \to \ell\nu\ \sigma B$ limit calculations. The columns are the same as in table 6.

m_{W^*} [GeV]	m_{Tmin} [GeV]	Channel	ε_{sig}			N_{sig}			N_{bkg}			N_{obs}
400	317	$e\nu$	0.196	$\pm$	0.010	149000	$\pm$	7400	6630	$\pm$	440	6448
		$\mu\nu$	0.111	$\pm$	0.005	84900	$\pm$	3700	4420	$\pm$	310	4230
500	377	$e\nu$	0.246	$\pm$	0.011	80900	$\pm$	3500	3320	$\pm$	220	3275
		$\mu\nu$	0.140	$\pm$	0.006	45900	$\pm$	1900	2210	$\pm$	160	2008
600	448	$e\nu$	0.257	$\pm$	0.011	41400	$\pm$	1800	1630	$\pm$	120	1582
		$\mu\nu$	0.144	$\pm$	0.006	23200	$\pm$	960	1080	$\pm$	79	938
750	564	$e\nu$	0.248	$\pm$	0.011	15900	$\pm$	680	593	$\pm$	54	524
		$\mu\nu$	0.143	$\pm$	0.006	9200	$\pm$	400	388	$\pm$	35	321
1000	710	$e\nu$	0.302	$\pm$	0.013	5390	$\pm$	230	203	$\pm$	24	177
		$\mu\nu$	0.174	$\pm$	0.007	3100	$\pm$	130	143	$\pm$	17	109
1250	843	$e\nu$	0.337	$\pm$	0.013	2010	$\pm$	79	86	$\pm$	12	79
		$\mu\nu$	0.191	$\pm$	0.008	1140	$\pm$	50	65.5	$\pm$	8.5	40
1500	1062	$e\nu$	0.296	$\pm$	0.011	648	$\pm$	25	25.8	$\pm$	4.4	26
		$\mu\nu$	0.164	$\pm$	0.007	360	$\pm$	16	20.9	$\pm$	3.8	12
1750	1191	$e\nu$	0.324	$\pm$	0.013	278	$\pm$	11	13.2	$\pm$	2.5	14
		$\mu\nu$	0.182	$\pm$	0.009	156.0	$\pm$	7.6	10.9	$\pm$	2.3	6
2000	1337	$e\nu$	0.341	$\pm$	0.013	118.0	$\pm$	4.6	6.8	$\pm$	1.3	9
		$\mu\nu$	0.186	$\pm$	0.010	64.6	$\pm$	3.3	5.8	$\pm$	1.4	3
2250	1416	$e\nu$	0.391	$\pm$	0.014	55.5	$\pm$	2.0	4.56	$\pm$	0.92	5
		$\mu\nu$	0.204	$\pm$	0.010	28.9	$\pm$	1.5	4.3	$\pm$	1.1	0
2500	1683	$e\nu$	0.337	$\pm$	0.013	19.80	$\pm$	0.76	1.38	$\pm$	0.33	0
		$\mu\nu$	0.179	$\pm$	0.010	10.50	$\pm$	0.57	1.44	$\pm$	0.33	0
2750	1888	$e\nu$	0.322	$\pm$	0.013	7.84	$\pm$	0.31	0.432	$\pm$	0.091	0
		$\mu\nu$	0.161	$\pm$	0.011	3.92	$\pm$	0.27	0.61	$\pm$	0.15	0
3000	1888	$e\nu$	0.382	$\pm$	0.015	3.80	$\pm$	0.15	0.432	$\pm$	0.091	0
		$\mu\nu$	0.185	$\pm$	0.011	1.84	$\pm$	0.11	0.61	$\pm$	0.15	0
3250	1888	$e\nu$	0.437	$\pm$	0.018	1.770	$\pm$	0.073	0.432	$\pm$	0.091	0
		$\mu\nu$	0.218	$\pm$	0.014	0.880	$\pm$	0.056	0.61	$\pm$	0.15	0
3500	1888	$e\nu$	0.474	$\pm$	0.025	0.766	$\pm$	0.040	0.432	$\pm$	0.091	0
		$\mu\nu$	0.229	$\pm$	0.016	0.371	$\pm$	0.027	0.61	$\pm$	0.15	0
3750	1888	$e\nu$	0.498	$\pm$	0.055	0.320	$\pm$	0.035	0.432	$\pm$	0.091	0
		$\mu\nu$	0.244	$\pm$	0.029	0.157	$\pm$	0.019	0.61	$\pm$	0.15	0
4000	1888	$e\nu$	0.487	$\pm$	0.150	0.124	$\pm$	0.038	0.432	$\pm$	0.091	0
		$\mu\nu$	0.242	$\pm$	0.073	0.062	$\pm$	0.019	0.61	$\pm$	0.15	0

Table 8. Inputs to the limit calculations on the pair production of DM particles for the operators D1, D5d, D5c and D9. Expected number of signal events for each operator is calculated for a different value of the mass scale, notably $M_* = 10$ GeV for D1, $M_* = 100$ GeV for D5d, and $M_* = 1$ TeV for operators D9 and D5c. The columns are the same as in table 6.

m_χ [GeV]	m_{Tmin} [GeV]	Channel	ε_{sig}	N_{sig}	N_{bkg}	N_{obs}
			D1 Operator			
1		$e\nu$	0.0294 ± 0.0044	87000 ± 13000		
		$\mu\nu$	0.0177 ± 0.0023	52500 ± 7000		
100		$e\nu$	0.0396 ± 0.0052	89000 ± 12000		
		$\mu\nu$	0.0252 ± 0.0033	56600 ± 7500		
200		$e\nu$	0.0484 ± 0.0057	65800 ± 7700		
	796	$\mu\nu$	0.0293 ± 0.0034	39900 ± 4600	$e\nu$ 116 ± 15	101
400		$e\nu$	0.0709 ± 0.0071	30900 ± 3100	$\mu\nu$ 84 ± 10	58
		$\mu\nu$	0.0398 ± 0.0041	17300 ± 1800		
1000		$e\nu$	0.0989 ± 0.0100	1070 ± 110		
		$\mu\nu$	0.0621 ± 0.0068	673 ± 73		
1300		$e\nu$	0.0964 ± 0.0095	138 ± 14		
		$\mu\nu$	0.0522 ± 0.0048	75.1 ± 6.9		
			D5d Operator			
1		$e\nu$	0.0148 ± 0.0016	7230 ± 800		
		$\mu\nu$	0.0080 ± 0.0011	3890 ± 530		
100		$e\nu$	0.0158 ± 0.0018	7580 ± 850		
		$\mu\nu$	0.0096 ± 0.0012	4600 ± 580		
200		$e\nu$	0.0147 ± 0.0015	5850 ± 610		
	597	$\mu\nu$	0.0086 ± 0.0011	3420 ± 430	$e\nu$ 456 ± 45	414
400		$e\nu$	0.0190 ± 0.0020	4220 ± 440	$\mu\nu$ 305 ± 30	255
		$\mu\nu$	0.0113 ± 0.0013	2500 ± 300		
1000		$e\nu$	0.0281 ± 0.0025	450 ± 41		
		$\mu\nu$	0.0177 ± 0.0019	283 ± 30		
1300		$e\nu$	0.0291 ± 0.0028	89.3 ± 8.5		
		$\mu\nu$	0.0167 ± 0.0018	51.1 ± 5.4		
			D5c Operator			
1		$e\nu$	0.0737 ± 0.0047	30.3 ± 1.9		
		$\mu\nu$	0.0435 ± 0.0034	17.9 ± 1.4		
100		$e\nu$	0.0798 ± 0.0050	31.0 ± 1.9		
		$\mu\nu$	0.0437 ± 0.0034	17.0 ± 1.3		
200		$e\nu$	0.0762 ± 0.0049	25.1 ± 1.6		
	843	$\mu\nu$	0.0461 ± 0.0034	15.2 ± 1.1	$e\nu$ 86 ± 12	79
400		$e\nu$	0.0857 ± 0.0055	16.2 ± 1.0	$\mu\nu$ 65.5 ± 8.5	40
		$\mu\nu$	0.0532 ± 0.0040	10.0 ± 0.8		
1000		$e\nu$	0.0987 ± 0.0091	1.28 ± 0.12		
		$\mu\nu$	0.0636 ± 0.0057	0.824 ± 0.074		
1300		$e\nu$	0.1010 ± 0.0095	0.240 ± 0.023		
		$\mu\nu$	0.0589 ± 0.0057	0.140 ± 0.014		
			D9 Operator			
1		$e\nu$	0.0851 ± 0.0053	55.5 ± 3.5		
		$\mu\nu$	0.0517 ± 0.0035	33.8 ± 2.3		
100		$e\nu$	0.0950 ± 0.0056	55.8 ± 3.3		
		$\mu\nu$	0.0529 ± 0.0038	31.1 ± 2.3		
200		$e\nu$	0.1040 ± 0.0062	48.9 ± 2.9		
	843	$\mu\nu$	0.0553 ± 0.0039	26.0 ± 1.8	$e\nu$ 86 ± 12	79
400		$e\nu$	0.1030 ± 0.0067	25.5 ± 1.6	$\mu\nu$ 65.5 ± 8.5	40
		$\mu\nu$	0.0578 ± 0.0042	14.3 ± 1.0		
1000		$e\nu$	0.1070 ± 0.0092	1.63 ± 0.14		
		$\mu\nu$	0.0615 ± 0.0055	0.944 ± 0.084		
1300		$e\nu$	0.1020 ± 0.0100	0.285 ± 0.029		
		$\mu\nu$	0.0573 ± 0.0056	0.160 ± 0.016		

The number of observed events is generally in good agreement with the expected number of background events for all mass bins. None of the observations for any mass point in either channel or their combination show a significant excess above background, so there is no evidence for the observation of either $W' \to \ell\nu$ or $W^* \to \ell\nu$. A deficit in the number of observed events with respect to the expected number of background events is observed in the muon channel. This deficit has at most a 2.2σ local significance.

Tables 9 and 10 and figure 2 present the 95% confidence level (CL) observed limits on σB for both $W' \to \ell\nu$ and $W^* \to \ell\nu$ in the electron channel, the muon channel and their combination. The tables also give the limits obtained without systematic uncertainties. Limits with various subsets of the systematic uncertainties are shown for $W' \to \ell\nu$ as a representative case. The uncertainties on the signal selection efficiency have very little effect on the final limits, and the background-level and luminosity uncertainties are important only for the lowest masses. Figure 2 also shows the expected limits and the theoretical σB for a W' and for a W^*. Limits are evaluated by fixing the W^* coupling strengths to give the same partial decay widths as the W'. The off-shell production of W' degrades the acceptance at high mass, worsening the limits. As discussed in chapter 1, W^* has different couplings with respect to W', enhancing the production at the pole. Since the off-shell production is reduced with respect to W', the W^* limits do not show the same behaviour at high mass.

In figure 2 the intersection between the central theoretical prediction and the observed limits provides the 95% CL lower limits on the mass. The expected and observed W' and W^* mass limits for the electron and muon decay channels as well as their combination are listed in table 11. The difference between the expected and observed combined mass limits originate from the slight data deficit in each decay channel that are individually not significant. The band around the theoretical prediction in figure 2 indicates the total theory uncertainty as described earlier in the text. The mass limit for the W' decreases by 50 GeV if the intersection between the lower theoretical prediction and the observed limit is used. The uncertainties on $\varepsilon_{\mathrm{sig}}$, N_{bkg} and L_{int} affect the derived mass limits by a similar amount. Limits are also evaluated following the $\mathrm{CL_s}$ prescription [74] using the profile likelihood ratio as the test statistic including all uncertainties. The cross-section limits are found to agree within 10% across the entire mass range, with only marginal impact on the mass limit. The mass limits presented here are a significant improvement over those reported in previous ATLAS and CMS searches [4–7].

The results of the search for pair production of DM particles in association with a leptonically decaying W boson are shown in figures 3 and 4. The former shows the observed limits on M_*, the mass scale of the unknown mediating interaction for the DM particle pair production, whereas the latter shows the observed limits on the DM–nucleon scattering cross-section. Both are shown as a function of the DM particle mass, m_χ, and presented at 90% CL. Results of the previous ATLAS searches for hadronically decaying W/Z [19], leptonically decaying Z [20], and $j + \chi\chi$ [15] are also shown. The observed limits on M_* as a function of m_χ are by a factor $\sim$1.5 stronger in the search for DM production in association with hadronically decaying W with respect the ones presented in this paper.

Table 9. Observed upper limits on σB for W' and W^* with masses up to 2000 GeV. The first column is the W'/W^* mass and the following columns refer to the 95% CL limits for the W' with headers indicating the nuisance parameters for which uncertainties are included: S for the event selection efficiency ($\varepsilon_{\mathrm{sig}}$), B for the background level (N_{bkg}), and L for the integrated luminosity (L_{int}). The column labelled SBL includes all uncertainties neglecting correlations. Results are also presented when including the correlation of the signal and background cross-section uncertainties, as well as the correlation of the background cross-section uncertainties for the combined limits (SB$_{\mathrm{c}}$, SB$_{\mathrm{c}}$L). The last two columns show the limits for the W^* without nuisance parameters and when including all nuisance parameters with correlations.

m_{W'/W^*} [GeV]	Channel	95% CL limit on σB [fb]							
		W'						W^*	
		none	S	SB	SBL	SB$_{\mathrm{c}}$	SB$_{\mathrm{c}}$L	none	SB$_{\mathrm{c}}$L
300	$e\nu$	29.0	29.1	304	342	305	343		
	$\mu\nu$	22.4	22.4	327	363	327	363		
	both	14.2	14.2	219	269	290	331		
400	$e\nu$	14.1	14.1	94.8	105	95.0	105	20.7	204
	$\mu\nu$	12.6	12.6	91.3	102	91.4	102	25.1	233
	both	7.55	7.56	63.4	77.0	83.2	94.7	12.6	197
500	$e\nu$	9.14	9.18	38.7	42.2	38.8	42.4	17.3	87.5
	$\mu\nu$	6.42	6.44	30.6	34.0	30.7	34.1	10.5	77.9
	both	4.26	4.26	22.3	27.0	29.8	33.9	7.54	77.7
600	$e\nu$	5.67	5.68	19.5	21.2	19.7	21.4	10.4	43.9
	$\mu\nu$	4.38	4.40	15.5	17.0	15.6	17.1	7.11	32.8
	both	2.78	2.78	11.1	13.2	15.5	17.4	4.75	33.9
750	$e\nu$	2.95	2.95	8.25	8.71	8.35	8.81	4.23	14.9
	$\mu\nu$	3.33	3.34	7.89	8.35	7.97	8.43	5.23	14.7
	both	1.73	1.73	5.06	5.63	7.01	7.52	2.51	12.8
1000	$e\nu$	1.84	1.85	3.25	3.34	3.29	3.38	2.69	6.01
	$\mu\nu$	1.86	1.87	2.87	2.95	2.92	3.00	3.02	5.88
	both	1.03	1.04	1.86	1.96	2.48	2.58	1.57	4.94
1250	$e\nu$	1.63	1.64	2.06	2.09	2.09	2.12	2.29	3.65
	$\mu\nu$	1.62	1.62	2.01	2.04	2.04	2.07	1.78	2.60
	both	0.990	0.991	1.30	1.34	1.54	1.57	1.16	2.53
1500	$e\nu$	1.27	1.28	1.40	1.41	1.42	1.43	1.99	2.39
	$\mu\nu$	1.21	1.22	1.35	1.36	1.37	1.38	1.71	2.06
	both	0.775	0.777	0.879	0.890	0.967	0.979	1.14	1.63
1750	$e\nu$	0.964	0.967	0.993	0.997	1.01	1.01	1.48	1.64
	$\mu\nu$	0.813	0.818	0.818	0.821	0.827	0.831	1.37	1.54
	both	0.521	0.522	0.533	0.537	0.563	0.567	0.889	1.10
2000	$e\nu$	0.721	0.724	0.735	0.738	0.743	0.746	1.34	1.40
	$\mu\nu$	0.747	0.751	0.751	0.754	0.760	0.762	1.18	1.26
	both	0.415	0.416	0.422	0.424	0.439	0.441	0.831	0.922

Table 10. Observed upper limits on σB for W' and W^* with masses above 2000 GeV. The columns are the same as in table 9.

m_{W'/W^*} [GeV]	Channel	95% CL limit on σB [fb]							
		W'						W^*	
		none	S	SB	SBL	SB$_c$	SB$_c$L	none	SB$_c$L
	$e\nu$	0.453	0.455	0.455	0.456	0.458	0.459	0.830	0.859
2250	$\mu\nu$	0.853	0.859	0.859	0.862	0.866	0.869	0.726	0.734
	both	0.296	0.297	0.297	0.298	0.301	0.303	0.457	0.488
	$e\nu$	0.564	0.569	0.569	0.570	0.572	0.573	0.438	0.441
2500	$\mu\nu$	1.06	1.07	1.07	1.08	1.08	1.08	0.828	0.837
	both	0.368	0.370	0.370	0.371	0.376	0.377	0.287	0.289
	$e\nu$	0.629	0.643	0.643	0.644	0.648	0.649	0.459	0.462
2750	$\mu\nu$	1.16	1.19	1.19	1.20	1.21	1.21	0.917	0.928
	both	0.409	0.413	0.413	0.414	0.425	0.426	0.306	0.308
	$e\nu$	0.809	0.852	0.852	0.853	0.863	0.865	0.387	0.389
3000	$\mu\nu$	1.47	1.55	1.55	1.56	1.58	1.58	0.798	0.807
	both	0.523	0.534	0.534	0.536	0.566	0.567	0.261	0.263
	$e\nu$	1.20	1.37	1.37	1.37	1.40	1.40	0.338	0.340
3250	$\mu\nu$	2.14	2.45	2.45	2.45	2.52	2.52	0.678	0.687
	both	0.768	0.815	0.815	0.816	0.919	0.920	0.226	0.228
	$e\nu$	1.92	2.56	2.56	2.56	2.64	2.64	0.312	0.315
3500	$\mu\nu$	3.37	4.38	4.38	4.39	4.56	4.57	0.645	0.655
	both	1.22	1.38	1.38	1.38	1.72	1.73	0.210	0.213
	$e\nu$	3.12	4.90	4.90	4.90	5.07	5.08	0.297	0.307
3750	$\mu\nu$	5.32	7.85	7.85	7.86	8.22	8.24	0.605	0.630
	both	1.97	2.37	2.37	2.38	3.26	3.27	0.199	0.208
	$e\nu$	4.76	8.07	8.07	8.09	8.38	8.40	0.304	0.372
4000	$\mu\nu$	7.75	12.0	12.0	12.0	12.6	12.6	0.613	0.749
	both	2.95	3.66	3.66	3.66	5.24	5.24	0.203	0.255

Table 11. Lower limits on the W' and W^* masses. The first column is the decay channel ($e\nu$, $\mu\nu$ or both combined) and the following give the expected (Exp.) and observed (Obs.) mass limits.

Decay	$m_{W'}$ [TeV]		m_{W^*} [TeV]	
	Exp.	Obs.	Exp.	Obs.
$e\nu$	3.13	3.13	3.08	3.08
$\mu\nu$	2.97	2.97	2.83	2.83
Both	3.17	3.24	3.12	3.21
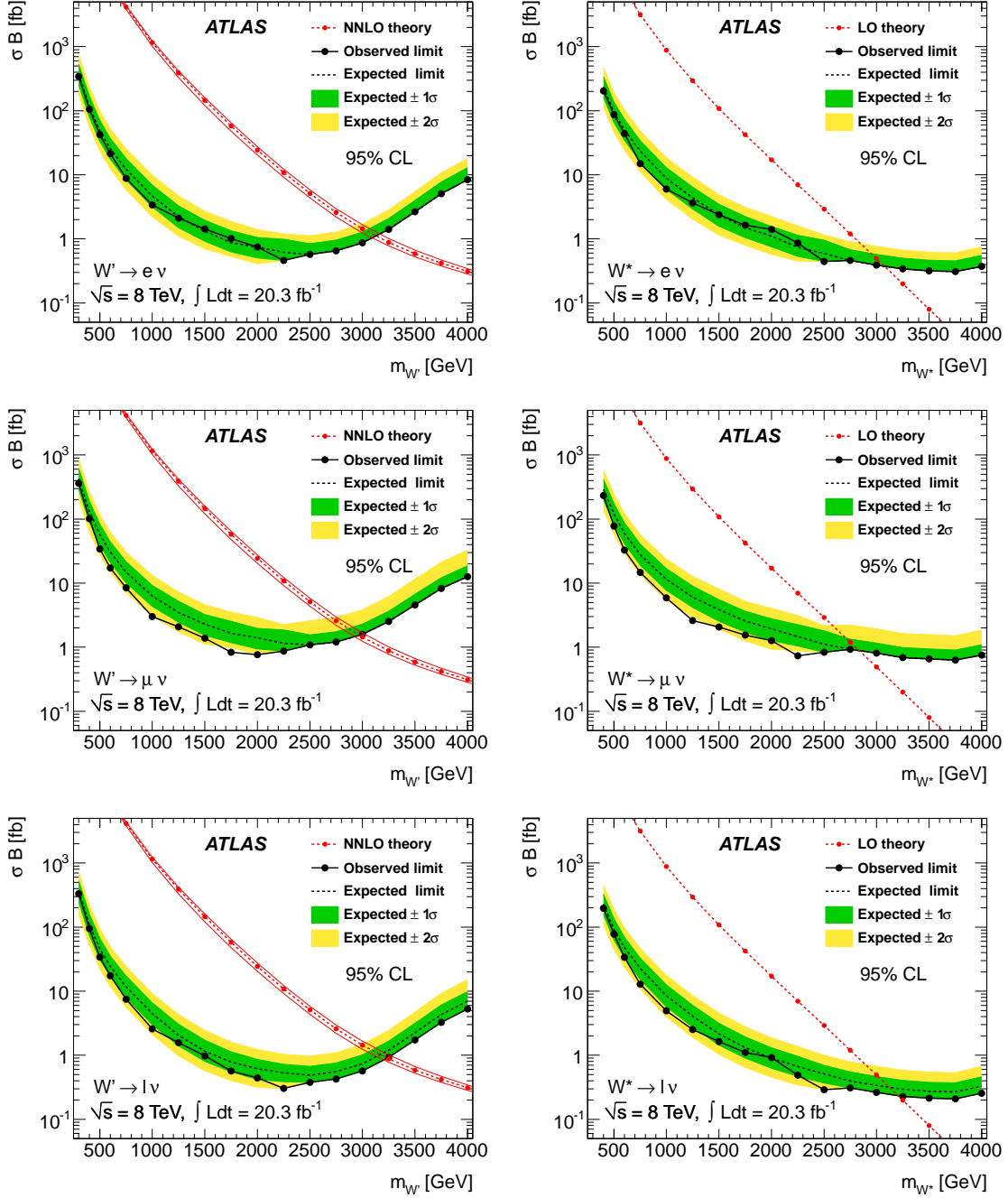
Figure 2. Observed and expected limits on σB for W' (left) and W^* (right) at 95% CL in the electron channel (top), muon channel (centre) and the combination (bottom) assuming the same branching fraction for both channels. The predicted values for σB and their uncertainties (except for W^*) are also shown. The calculation of uncertainties on the W' cross-sections is explained in section 4.
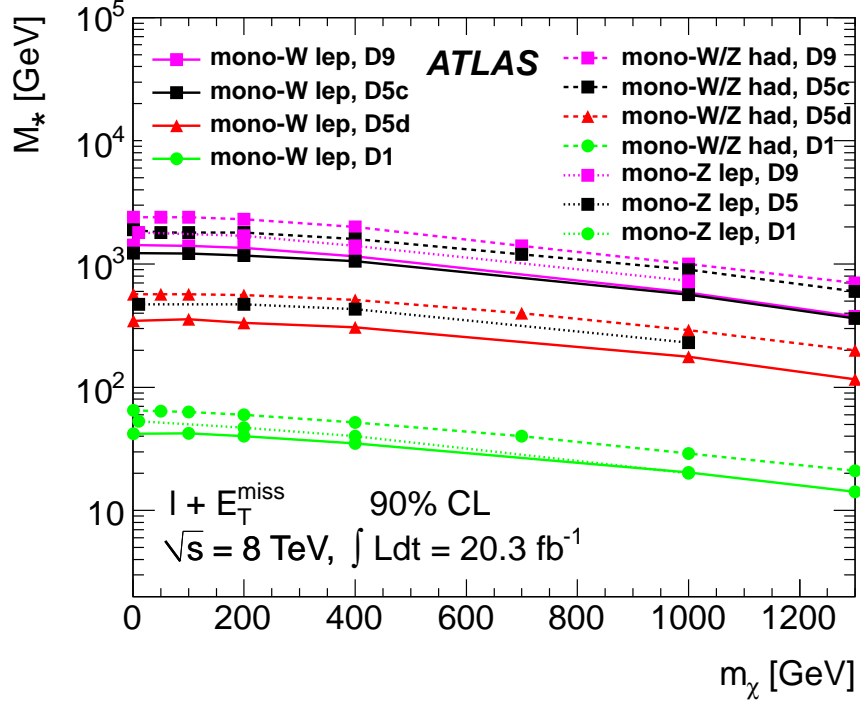
Figure 3. Observed limits on M_* as a function of the DM particle mass (m_χ) at 90% CL for the combination of the electron and muon channel, for various operators as described in the text. For each operator, the values below the corresponding line are excluded. No signal samples are generated for masses below 1 GeV but the limits are expected to be stable down to arbitrarily small values. Results of the previous ATLAS searches for hadronically decaying W/Z [19] and leptonically decaying Z [20] are also shown.
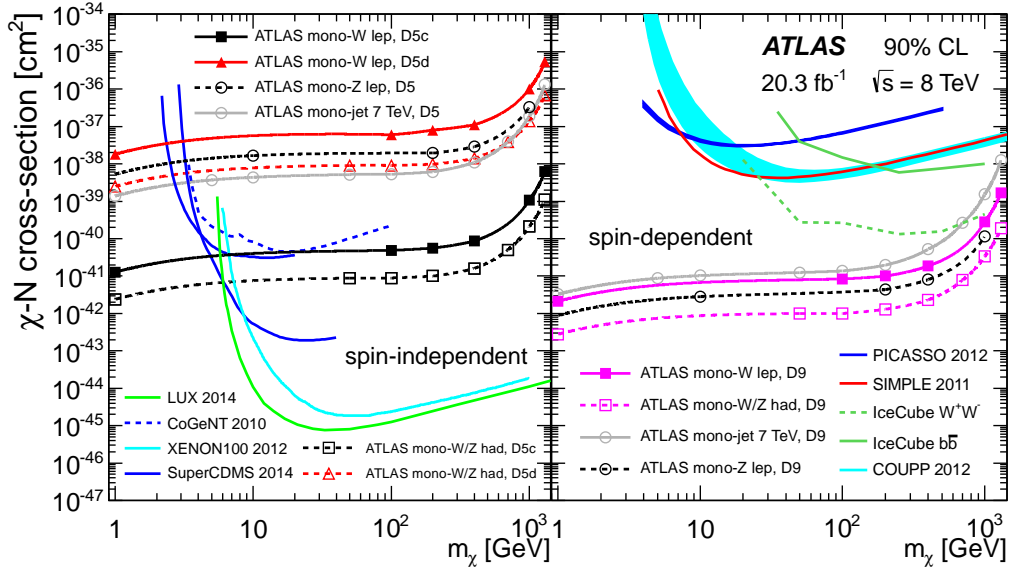
Figure 4. Observed limits on the DM–nucleon scattering cross-section as a function of m_χ at 90% CL for spin-independent (left) and spin-dependent (right) operators in the EFT. Results are compared with the previous ATLAS searches for hadronically decaying W/Z [19], leptonically decaying Z [20], and $j + \chi\chi$ [15], and with direct detection searches by CoGeNT [75], XENON100 [76], CDMS [77, 78], LUX [79], COUPP [80], SIMPLE [81], PICASSO [82] and IceCube [83]. The comparison between direct detection and ATLAS results is only possible within the limits of the validity of the EFT [84].

8   Conclusions

A search is presented for new high-mass states decaying to a lepton (electron or muon) plus missing transverse momentum using 20.3 fb^{-1} of proton–proton collision data at $\sqrt{s} = $ 8 TeV recorded with the ATLAS experiment at the Large Hadron Collider. No significant excess beyond SM expectations is observed. Limits on σB are presented. A W' with SSM couplings is excluded for masses below 3.24 TeV at 95% CL. The exclusion for W^* with equivalent couplings is 3.21 TeV. For the pair production of weakly interacting DM particles in events with a leptonically decaying W, limits are set on the mass scale, M_*, of the unknown mediating interaction as well as on the DM–nucleon scattering cross-section.

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