Search for dark matter particle candidates produced in association with a Z boson in pp collisions at a center-of-mass energy of 13 TeV with the ATLAS detector

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Abstract. A search for dark matter particle candidates produced in association with a Z boson in proton-proton collisions at the total center-of-mass energy of 13 TeV is presented. The search uses 36.1 inverse femtobarn of data collected by the ATLAS experiment at the Large Hadron Collider in 2015 and 2016. Events with large missing transverse momentum and consistent with the decay of a Z boson into oppositely charged electron or muon pairs were selected in the analysis. Background estimates and corresponding systematic uncertainties are shown. Exclusion limits on the dark matter candidate and mediator masses are reported.

1. Introduction
Astrophysical measurements from several independent sources indicate that the majority of the mass of the Universe exists in the form of non-baryonic dark matter (DM) [1]. However, its nature remains undiscovered and no evidence exists for its non-gravitational interactions [2]. DM is widely hypothesised to consist of weakly interacting massive particles (WIMPs) [3]. Experiments at the Large Hadron Collider (LHC) search for WIMPs production associated with a detectable final state, where a WIMP can be identified by a signature involving missing transverse momentum $E_T^{\text{miss}}$ [4]. Presented is a search for WIMP candidates produced in association with a Z boson with the ATLAS detector [5] at the LHC. Events with a large $E_T^{\text{miss}}$ and two oppositely charged electrons or muons consistent with a decay of a Z boson were selected in the analysis.

The results were interpreted in terms of simplified DM models, where WIMP production is mediated by a vector or an axial-vector particle (mediator). The exclusion limits on the WIMP mass ($m_\chi$) and the mediator mass ($m_{\text{med}}$) were set for fixed coupling constants of the mediator to quarks ($g_q$) and to WIMPs ($g_\chi$). The WIMP pair is produced through the $s$-channel exchange of an axial-vector or vector mediator. This choice provides a useful framework for comparison with direct detection experiments\(^1\), furthermore, LHC searches can be more sensitive than direct

\(^1\) Direct detection experiments aim to observe recoil of DM particles against nuclei, they typically contain large volumes of scintillator and are situated deep underground to reduce background contamination.
searches to WIMP production in this particular model with an axial-vector mediator [4]. The leading tree-level diagram for WIMP production is presented on figure 1.

![Leading tree-level diagram for WIMP production](image)

**Figure 1.** Leading tree-level diagram for WIMP production in simplified DM models [6].

Monte Carlo (MC) simulation of DM signal events with a vector and axial-vector mediator and fermionic WIMPs was performed for \( m_{\text{med}} \) and \( m_\chi \), ranging from 10 to 1000 GeV. Following recommendations in [7], the coupling constants were set to \( g_q = 0.25 \) and \( g_\chi = 1 \), and mediator width was set to be minimal, such that it decays only to DM or quarks.

Full description of the analysis and the results can be found in [6].

2. Event Selection and Background Estimation

Electron candidates are reconstructed from isolated energy deposits in the electromagnetic calorimeter, matched to inner detector tracks [8]. Muon candidates are reconstructed from a combined fit of tracks independently found in the muon spectrometer and inner detector [9]. Jets are reconstructed using the anti-\( k_T \) algorithm [10] with a radius parameter \( R = 0.4 \).

Basic kinematic cuts along with some additional selections are also applied to reduce the probability of misidentification of the reconstructed objects [6]. The invariant mass of a lepton pair is required to be in the range \( 76 \text{ GeV} \leq M_{\ell\ell} \leq 106 \text{ GeV} \) to reject background processes with two leptons that do not originate from the prompt decay of a Z boson (non-resonant-\( \ell\ell \)). Events are required to pass quality checks for errors in sub-detectors during recording. A combination of a lower \( p_T \) threshold trigger with an isolation requirement and a higher \( p_T \) threshold trigger without any isolation requirement is used, yielding the trigger efficiency above 98%.

To suppress the non-resonant-\( \ell\ell \) background further, candidate events are required to have \( E_T^{\text{miss}} > 90 \text{ GeV} \) and \( E_T^{\text{miss}}/H_T > 0.6 \) where \( H_T \) is calculated as the scalar sum of the \( p_T \) of the selected leptons and jets. \( E_T^{\text{miss}} \) is expected to be back-to-back with the Z boson. This is accounted for in the \( \Delta \phi(Z, E_T^{\text{miss}}) \) variable, which is required to be greater than 2.7 radians, and the selected leptons must be close to each other, which is ensured by

\[
|\Delta R_{\ell\ell}| = \sqrt{(|\Delta \phi_{\ell\ell}|)^2 + (|\Delta \eta_{\ell\ell}|)^2} < 1.8.
\]

Any possible imbalance, implying the presence of fake \( E_T^{\text{miss}} \), is accounted for by an upper threshold on the fractional \( p_T \) difference variable, defined as

\[
(p_T^{\ell\ell} - E_T^{\text{miss}} + \sum |p_T^{jett}|)/p_T^{\ell\ell} < 0.2.
\]

Events are removed if they contain \( b \)-jets to suppress top-quark pair background. Events containing a third lepton with \( p_T > 7 \text{ GeV} \), satisfying looser identification requirements, are removed to suppress diboson background.

The dominant background process (59%) is \( ZZ \to \ell^+\ell^-\nu\bar{\nu} \), it is estimated using MC simulation, main uncertainties on it originate from parton density function choice, perturbative calculation, and parton shower modelling. The other important background (25%) is \( WZ \to \ell\nu\ell^+\ell^- \), which is contributing if a lepton from W boson decay is undetected, or a \( \tau \) decays hadronically. It is estimated from data using 3-lepton control region; main uncertainties consist of systematic uncertainties on the ratio of events in control and signal region and statistical uncertainties on data. The non-resonant-\( \ell\ell \) background (8%) is estimated from data using the absence of signal in the \( e\mu \) channel and the relative production rate of 1 : 1 : 2 for the
ee, \( \mu \mu \), and \( e \mu \) channels. An \( e \mu \) control region similar to the signal region is defined, and the background estimate for the ee and \( \mu \mu \) signal regions is obtained from the number of \( e \mu \) events in the control region after correcting for different acceptances and efficiencies. Main uncertainties consist of systematic uncertainties on the bias of the method and statistical uncertainties on data. The \( Z + \) jets background (8\%) is estimated from data using a set of two uncorrelated variables, constructing 4 regions (one signal region, A, and three \( Z \)-enriched control regions, B,C,D) and using a relation \( N_A = N_B \times N_C/N_D \) to estimate the yield in the signal region. The \( W + \) jets (estimated using fake-factor method), \( VVV \) and \( t \bar{t}V(V) \) (estimated using MC simulation) backgrounds have minor contributions (\( \leq 1\%)\).

3. Results and Conclusions

Table 1. Observed data yields and expectations for the signal and background contributions in the signal region with statistical and second systematic uncertainties. The DM signal contribution with \( m_{\text{med}} = 500 \text{ GeV} \) and \( m_\chi = 100 \text{ GeV} \) is scaled with a factor of 0.27 to the best-fit contribution. The background contributions from the \( W + \) jets, \( VVV \) and \( t \bar{t}V(V) \) processes are summed up [6].

| Final State | ee | \( \mu \mu \) |
|-------------|----|----------|
| Observed Data | 437 | 407 |
| Signal | \( \text{DM (}m_{\text{med}} = 500 \text{ GeV}, m_\chi = 100 \text{ GeV}) \times 0.27 \) | 10.8 \( \pm 0.3 \pm 0.8 \) | 11.1 \( \pm 0.3 \pm 0.8 \) |
| Backgrounds | | |
| \( qgZZ \) | 212 \( \pm 3 \pm 15 \) | 221 \( \pm 3 \pm 17 \) |
| \( ggZZ \) | 18.9 \( \pm 0.3 \pm 11.2 \) | 19.3 \( \pm 0.3 \pm 11.4 \) |
| \( WZ \) | 106 \( \pm 2 \pm 6 \) | 113 \( \pm 3 \pm 5 \) |
| \( Z + \) jets | 30 \( \pm 1 \pm 28 \) | 37 \( \pm 1 \pm 19 \) |
| Non-resonant-\( \ell \ell \) | 30 \( \pm 4 \pm 2 \) | 33 \( \pm 4 \pm 2 \) |
| \( W + \) jets, \( VVV \) and \( t \bar{t}V(V) \) | 1.4 \( \pm 0.1 \pm 0.2 \) | 2.5 \( \pm 2.0 \pm 0.8 \) |
| Total Background | 399 \( \pm 6 \pm 34 \) | 426 \( \pm 6 \pm 28 \) |

Figure 2. DM exclusion limits in the two-dimensional phase space of WIMP mass \( m_\chi \) vs mediator mass \( m_{\text{med}} \) for a fermionic WIMP, vector (left) or axial-vector (right) mediator with coupling constants of mediator to quarks and to DM \( g_q = 0.25 \) and \( g_\chi = 1 \), correspondingly [6]. Regions bounded by the limit curves are excluded at the 95\% CL.

The search was performed on 36.1 fb\(^{-1}\) of ATLAS dataset collected in 2015 and 2016 at \( \sqrt{s} = 13 \text{ TeV} \). Theoretical and experimental systematic uncertainties are estimated for all studied backgrounds, including uncertainties associated with pileup reweighting, luminosity calculation, object and \( E_\text{T}^{\text{miss}} \) reconstruction algorithms and methods of background estimation. Data yields
Figure 3. Limits on the WIMP and proton scattering cross section as a function of WIMP mass, obtained for simplified DM models with a vector mediator (left) and an axial-vector mediator (right) [6]. The solid black line shows the observed limit at the 90% CL from this search. Following results of direct-search experiments are shown: LUX [11], PICO-2L [12], PICO-60 [13], CRESST-II [14], CDMSlite [15], PandaX-II [16], and XENON1T [17].

with associated statistical and systematic uncertainties are shown in table 1. There is a small data excess in the $\mu\mu$ channel which corresponds to a significance of about 2.2$\sigma$. When combining the $ee$ and $\mu\mu$ channels, the significance is 1.5$\sigma$. No significant deviations from the Standard Model predictions have been observed.

The 95% C.L. DM exclusion limits in the two-dimensional phase space of WIMP mass $m_\chi$ vs mediator mass $m_{med}$ are presented on figure 2. Additionally the limits translated into $\chi$-nucleon scattering cross section and compared with direct DM searches are shown on figure 3.

References

[1] Komatsu E et al. 2011 Astrophys. J. Suppl. Ser. 192 18
[2] Olive K A et al. (Particle Data Group) 2014 Chin. Phys. C38 090001
[3] Lee B W and Weinberg S 1977 Phys. Rev. Lett. 39 165
[4] Malik S A et al. 2015 Phys. Dark Univ 9-10 51
[5] ATLAS Collaboration 2008 JINST 3 S08003
[6] ATLAS Collaboration 2017 Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a $Z$ boson in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector Preprint arXiv:1708.09624 [hep-ex]
[7] Abercrombie D et al. 2015 Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum Preprint arXiv:1507.00966 [hep-ex]
[8] ATLAS Collaboration 2015 Electron identification measurements in ATLAS using $\sqrt{s} = 13$ TeV data with 50 ns bunch spacing Tech. Rep. ATL-PHYS-PUB-2015-041 CERN Geneva
[9] ATLAS Collaboration 2016 Eur. Phys. J. C 76 292
[10] Cacciari M, Salam G P and Soyez G 2008 J. High Energy Phys. 04 063
[11] Akerib D S et al. 2017 Phys. Rev. Lett. 118(2) 021303
[12] Amole C et al. 2015 Phys. Rev. Lett. 114(23) 231302
[13] Amole C et al. 2017 Phys. Rev. Lett. 118 251301
[14] Angloher G et al. 2016 Eur. Phys. J. C 76 25
[15] Agnese R et al. 2016 Phys. Rev. Lett. 116(7) 071301
[16] Tan A et al. 2016 Phys. Rev. Lett. 117(12) 121303
[17] Aprile E et al. 2017 First Dark Matter Search Results from the XENON1T Experiment Preprint arXiv:1705.06655 [astro-ph.CO]