

# Search for dark matter and large extra dimensions in monojet events in pp collisions at $\sqrt{s} = 7$ TeV

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## The CMS collaboration

**ABSTRACT:** A search has been made for events containing an energetic jet and an imbalance in transverse momentum using a data sample of pp collisions at a center-of-mass energy of 7 TeV. This signature is common to both dark matter and extra dimensions models. The data were collected by the CMS detector at the LHC and correspond to an integrated luminosity of  $5.0 \text{ fb}^{-1}$ . The number of observed events is consistent with the standard model expectation. Constraints on the dark matter-nucleon scattering cross sections are determined for both spin-independent and spin-dependent interaction models. For the spin-independent model, these are the most constraining limits for a dark matter particle with mass below  $3.5 \text{ GeV}/c^2$ , a region unexplored by direct detection experiments. For the spin-dependent model, these are the most stringent constraints over the  $0.1\text{--}200 \text{ GeV}/c^2$  mass range. The constraints on the Arkani-Hamed, Dimopoulos, and Dvali model parameter  $M_{\text{D}}$  determined as a function of the number of extra dimensions are also an improvement over the previous results.

**KEYWORDS:** Hadron-Hadron Scattering

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**1 Introduction**

A search for new physics has been made based on events containing a jet and an imbalance in transverse momentum ( $E_T^{\text{miss}}$ ) in a data sample corresponding to an integrated luminosity of  $5.0\text{ fb}^{-1}$ . The data were collected with the Compact Muon Solenoid (CMS) detector in pp collisions provided by the Large Hadron Collider (LHC) at a center-of-mass energy of 7 TeV. This search is sensitive to beyond the standard model particles that do not interact in the CMS detector and whose presence can thus only be inferred by the observation of  $E_T^{\text{miss}}$ . The signature has been proposed as a discovery signal for many new physics scenarios. In this paper, we use this signature to constrain the pair production of dark matter particles [1, 2] and large extra dimensions in the framework of the model proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [3–7]. The primary backgrounds to this signature arise from the production of  $Z$ +jet and  $W$ +jet events.

Dark matter (DM) is required to accommodate numerous astrophysical measurements, such as the rotational speed of galaxies and gravitational lensing [8–10]. One of the best candidates for dark matter is a stable weakly interacting massive particle. These particles may be pair-produced at the LHC provided their mass is less than half the parton center-of-mass energy,  $\sqrt{\hat{s}}$ . When accompanied by a jet from initial state radiation (ISR), DM events will have the signature of a jet plus missing transverse momentum. The interaction between the dark matter particle ( $\chi$ ) and standard model (SM) particles can be assumed to be mediated by a heavy particle such that it can be treated as a contact interaction, characterized by a scale  $\Lambda = M/\sqrt{g_\chi g_q}$  where  $M$  is the mass of the mediator,  $g_\chi$  and  $g_q$  are its coupling to  $\chi$  and to quarks, respectively [2]. In this paper, results for the vector

and axial-vector interactions between  $\chi$  and quarks are presented, assuming  $\chi$  is a Dirac fermion. The vector interaction can be related to spin-independent DM-nucleon whereas axial-vector interaction can be converted to spin-dependent DM-nucleon interactions. The results are not greatly altered if the DM particle is a Majorana fermion, although the vector interactions are not present in this case [2].

Results from previous collider searches in the monojet plus  $E_T^{\text{miss}}$  channel [11, 12] have been used to set limits on the dark matter-nucleon scattering cross section ( $\sigma_{\chi N}$ ) [2, 13]. Limits on  $\sigma_{\chi N}$  have also been determined by the CMS Collaboration in the monophoton plus  $E_T^{\text{miss}}$  channel [14], and by the CDF Collaboration in the monojet channel [15]. Dark matter particle production results from colliders can be compared with results from searches for dark matter-nucleon scattering (direct detection) [16–22] and from searches for dark matter annihilation (indirect detection) [23, 24]. Indirect detection experiments assume that the DM particle is a Majorana fermion.

The ADD model accommodates the large difference between the electroweak and Planck scales by introducing a number  $\delta$  of extra spatial dimensions, which in the simplest scenario are compactified over a multidimensional torus of common radius  $R$ . In this framework, the SM particles and gauge interactions are confined to the ordinary  $3 + 1$  space-time dimensions, whereas gravity is free to propagate through the entire multidimensional space. The strength of the gravitational force in  $3 + 1$  dimensions is effectively diluted. The fundamental scale  $M_D$  of this  $4 + \delta$ -dimensional theory is related to the apparent four-dimensional Planck scale  $M_{\text{Pl}}$  according to  $M_{\text{Pl}}^2 \approx M_D^{\delta+2} R^\delta$ . The production of gravitons is expected to be greatly enhanced by the increased phase space available in the extra dimensions. Once produced, the graviton escapes undetected into extra dimensions and its presence must be inferred from  $E_T^{\text{miss}}$ . Searches for large extra dimensions in monojet or monophoton channels were performed previously [11, 12, 25–31], and no evidence of new physics was observed. The current lower limits on  $M_D$  range from  $2.56 \text{ TeV}/c^2$  for  $\delta = 2$  to  $1.68 \text{ TeV}/c^2$  for  $\delta = 6$  [11].

This paper is organized as follows. Section 2 contains a brief description of the CMS detector and event reconstruction, and this is followed by a description of signal and SM event simulation in section 3. In section 4 we present the event selection. The determination of dominant backgrounds from data is described in section 5 and the results are given in section 6. The conclusions are summarized in section 7.

## 2 The CMS detector and event reconstruction

CMS uses a right-handed coordinate system in which the  $z$  axis points in the anticlockwise beam direction, the  $x$  axis points towards the center of the LHC ring, and the  $y$  axis points up, perpendicular to the plane of the LHC ring. The azimuthal angle  $\phi$  is measured in the  $x$ - $y$  plane, and the polar angle  $\theta$  is measured with respect to the  $z$  axis. A particle with energy  $E$  and momentum  $\vec{p}$  is characterized by transverse momentum  $p_T = |\vec{p}| \sin \theta$ , and pseudorapidity  $\eta = -\ln[\tan(\theta/2)]$ .

The CMS superconducting solenoid, 12.5 m long with an internal diameter of 6 m, provides a uniform magnetic field of 3.8 T. The inner tracking system is composed of a

pixel detector with three barrel layers at radii between 4.4 and 10.2 cm and a silicon strip tracker with 10 barrel detection layers extending outwards to a radius of 1.1 m. This system is complemented by two endcaps, extending the acceptance up to  $|\eta| = 2.5$ . The momentum resolution for reconstructed tracks in the central region is about 1% at  $p_T = 100$  GeV/c. The calorimeters inside the magnet coil consist of a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter (HCAL) with coverage up to  $|\eta| = 3$ . The quartz/steel forward hadron calorimeters extend the calorimetry coverage up to  $|\eta| = 5$ . The HCAL has an energy resolution of about 10% at 100 GeV for charged pions. Muons are measured up to  $|\eta| < 2.4$  in gas-ionization detectors embedded in the flux-return yoke of the magnet. A full description of the CMS detector can be found in ref. [32].

Particles in an event are individually identified using a particle-flow reconstruction [33]. This algorithm reconstructs each particle produced in a collision by combining information from the tracker, the calorimeters, and the muon system, and identifies them as either charged hadrons, neutral hadrons, photons, muons, or electrons. These particles are used as inputs to the anti- $k_T$  algorithm [34] with a distance parameter of 0.5. Jet energies are corrected to particle level with  $p_T$ - and  $\eta$ -dependent correction factors. These corrections are derived from Monte Carlo (MC) simulation and, for data events, are supplemented by a correction, derived by measuring the  $p_T$  balance in dijet events from collision data [35]. The  $E_T^{\text{miss}}$  in this analysis is defined as the magnitude of the vector sum of the transverse momentum of all particles reconstructed in the event excluding muons. This definition allows the use of a control sample of  $Z(\mu\mu)$  events for estimating the  $Z(\nu\bar{\nu})$  background.

Muons are reconstructed by finding compatible track segments in the silicon tracker and the muon detectors [36] and are required to be within  $|\eta| < 2.1$ . Electron candidates are reconstructed starting from a cluster of energy deposits in the ECAL that is then matched to the energy associated with a track in the silicon tracker. Electron candidates are required to have  $|\eta| < 1.44$  or  $1.56 < |\eta| < 2.5$  to avoid poorly instrumented regions. Muon and electron candidates are required to originate within 2 mm of the beam axis in the transverse plane. Muons (electrons) are also required to be spatially separated from jets by at least  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ , where  $\Delta\eta$  and  $\Delta\phi$  are differences between the muon (electron) and jet directions in pseudorapidity and azimuthal angle, respectively. A relative isolation parameter is defined as the sum of the  $p_T$  of the charged hadrons, neutral hadrons, and photon contributions computed in a cone of radius 0.3 around the lepton direction, divided by the lepton  $p_T$ . Lepton candidates with relative isolation values below 0.2 are considered isolated.

### 3 Monte Carlo event generation

The DM signal samples, consisting of  $\chi\bar{\chi}$  pairs associated with one parton, are produced using the leading order (LO) matrix element event generator MADGRAPH [37] interfaced with PYTHIA 6.42 [38] with tune Z2 [39] for parton showering and hadronization. Dark matter particles masses  $M_\chi = 0.1, 1, 10, 200, 300, 400, 700, \text{ and } 1000$  GeV/c<sup>2</sup> are generated for both vector and axial-vector interactions. In addition, the  $p_T$  of the associated parton

is required to be greater than 80 GeV/ $c$ . The parton showering program generates partons in a phase space that overlaps with the phase space of the partons generated by the matrix element calculator. Double-counting by the matrix element calculation and parton showering is resolved by using the MLM matching prescription [40], as implemented in [37]. The CTEQ 6L1 [41] parton distribution functions (PDF) are used.

The events for the ADD model are generated with PYTHIA 8.130 [42, 43], using tune 4C [44] and the CTEQ 6.6M [41] PDFs. This model is an effective theory and holds only for energies well below  $M_D$ . For a parton center-of-mass energy  $\sqrt{\hat{s}} > M_D$ , the simulated cross sections of the graviton are suppressed by a factor  $M_D^4/\hat{s}^2$  [43]. Because the  $\sqrt{\hat{s}}$  values for the data are smaller than the current limits on  $M_D$ , the results are not affected by this suppression. The next-to-leading-order (NLO) QCD corrections to direct graviton production in the ADD model are sizable and depend on the  $p_T$  of the recoiling parton [45]. As a simplifying assumption, we use  $K$ -factors ( $\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ ) corresponding to a fixed graviton  $p_T$  of several hundred GeV/ $c$ ; the values are 1.5 for  $\delta = 2, 3$  and 1.4 for  $\delta = 4, 5$ , and 6.

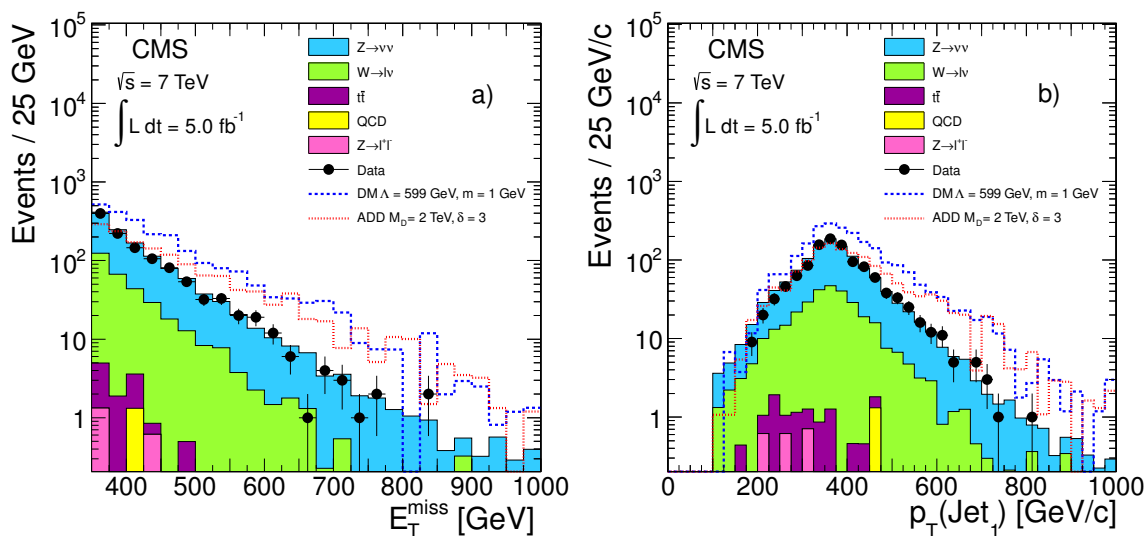
The  $Z$ +jets,  $W$ +jets,  $t\bar{t}$ , and single-top event samples are produced using MADGRAPH interfaced with PYTHIA 6.42, using tune Z2 and the CTEQ 6L1 PDFs. They are normalized to NLO cross sections [46]. The QCD multijet sample is generated with PYTHIA 6.42, using tune Z2 and CTEQ 6L1 PDFs and PYTHIA LO cross sections are used. All the generated signal and background events are passed through a GEANT4 [47] simulation of the CMS detector.

## 4 Event selection

The data used in this analysis were recorded by a trigger that required an event to have a jet with  $p_T > 80$  GeV/ $c$  and  $E_T^{\text{miss}} > 80$  or 95 GeV/ $c$  as measured online by the trigger system. The threshold of 80 (95) GeV/ $c$  was used to collect 4.2 (0.87) fb $^{-1}$  of data.

Events are required to have at least one primary vertex [48] reconstructed within a  $\pm 24$  cm window along the beam axis around the detector center, and a transverse distance from the beam axis of less than 2 cm. Signals in the calorimeter that are not associated with pp interactions are identified based either on energy sharing between neighboring channels or timing requirements and are excluded from further reconstruction [49].

To suppress the remaining instrumental and beam-related backgrounds, events are rejected if less than 20% of the energy of the highest  $p_T$  jet is carried by charged hadrons or more than 70% of this energy is carried by either neutral hadrons or photons. Events are also rejected if more than 70% of the  $p_T$  of the second highest  $p_T$  jet is carried by neutral hadrons. Such spurious jets primarily arise from instrumental noise, where the energy deposition is limited to one sub-detector. Jets resulting from energy deposition by beam halo or cosmic-ray muons do not have associated tracks and are also rejected by these selections. All events passing these selection requirements and with  $E_T^{\text{miss}} > 500$  GeV/ $c$  were visually inspected and found to be consistent with pp collision events. The application of these data cleanup requirements would reject approximately 2% of the dark matter signal and 3% of the ADD signal.



**Figure 1.** The distribution of (a)  $E_T^{\text{miss}}$  and (b)  $p_T(j_1)$  for data (black full points with error bars) and simulation (histograms) for  $E_T^{\text{miss}} > 350$  GeV/c after the full event selection criteria are applied. The  $Z(\nu\nu)$ +jets and  $W$ +jets backgrounds are normalized to their estimates from data. An example of a dark matter signal (for axial-vector couplings and  $M_\chi = 1$  GeV/c<sup>2</sup>) is shown as a dashed blue histogram and an ADD signal (with  $M_D = 2$  TeV,  $\delta = 3$ ) is shown as a dotted red histogram.

The signal sample is selected by requiring  $E_T^{\text{miss}} > 200$  GeV/c and the jet with the highest transverse momentum ( $j_1$ ) to have  $p_T(j_1) > 110$  GeV/c and  $|\eta(j_1)| < 2.4$ . The triggers used to collect these data are fully efficient for events passing these selection cuts. Events with more than two jets with  $p_T$  above 30 GeV/c are discarded. As signal events typically contain jets from initial- or final-state radiation, a second jet ( $j_2$ ) is allowed, provided  $\Delta\phi(j_1, j_2) < 2.5$  rad. This angular requirement suppresses QCD dijet events. To reduce background from  $Z$  and  $W$  production and top-quark decays, events with isolated muons or electrons with  $p_T > 10$  GeV/c are rejected. Events with an isolated track with  $p_T > 10$  GeV/c are also removed as they come primarily from  $\tau$ -lepton decays. A track is considered isolated if the scalar sum of the transverse momentum of all tracks with  $p_T > 1$  GeV/c in the annulus of  $0.02 < \Delta R < 0.3$  around its direction is less than 1% of its  $p_T$ . Table 1 lists the numbers of data and SM background events at each step of the analysis. Efficiencies for representative dark matter and ADD models relative to the event yield passing  $E_T^{\text{miss}} > 200$  GeV/c selection are also shown. The dominant background is  $Z(\nu\bar{\nu})$ +jets and the next largest source of background is  $W$ +jets. The event yields for  $E_T^{\text{miss}} > 250, 300, 350,$  and  $400$  GeV/c are also shown. A study of the  $E_T^{\text{miss}}$  requirement using the signal samples showed that  $E_T^{\text{miss}} > 350$  GeV/c is the optimal value for both the dark matter and ADD models searches.

The  $E_T^{\text{miss}}$  and  $p_T(j_1)$  distributions are shown in figure 1, where the  $Z(\nu\bar{\nu})$ +jets and  $W$ +jets backgrounds are normalized to the rate determined from data (section 5) and other backgrounds are normalized to the integrated luminosity.

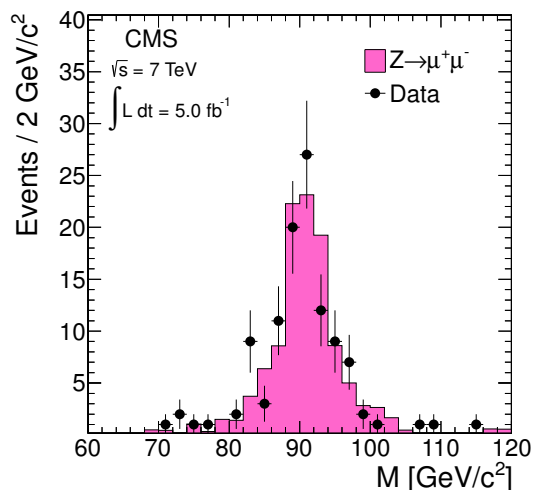
(a)

Requirement	$Z(\nu\nu)$	$W(e\nu, \mu\nu, \tau\nu)$	$Z(\ell\ell)$	$t\bar{t}$	Single $t$	QCDC
	+jets	+jets	+jets			Multijet
$E_T^{\text{miss}} > 200 \text{ GeV}/c$	$(324 \pm 1) \times 10^2$	$(591 \pm 1) \times 10^2$	$5255 \pm 47$	$(133 \pm 1) \times 10^2$	$1165 \pm 7$	$(160 \pm 1) \times 10^2$
$p_T(j_1) > 110 \text{ GeV}/c$	$(302 \pm 1) \times 10^2$	$(557 \pm 1) \times 10^2$	$4908 \pm 45$	$(119 \pm 1) \times 10^2$	$1035 \pm 6$	$(158 \pm 1) \times 10^2$
$N_{\text{Jet}}(p_T > 30 \text{ GeV}/c) \leq 2$	$(227 \pm 1) \times 10^2$	$(397 \pm 1) \times 10^2$	$3453 \pm 38$	$1587 \pm 20$	$274 \pm 3$	$5296 \pm 14$
$\Delta\phi(\text{jet}_1, \text{jet}_2) < 2.5$	$(211 \pm 1) \times 10^2$	$(354 \pm 1) \times 10^2$	$3139 \pm 36$	$1344 \pm 19$	$237 \pm 3$	$62 \pm 5$
Lepton Removal	$(198 \pm 1) \times 10^2$	$(97 \pm 1) \times 10^2$	$81 \pm 6$	$214 \pm 7$	$35 \pm 1$	$2 \pm 1$
$E_T^{\text{miss}} > 250 \text{ GeV}/c$	$7306 \pm 23$	$2951 \pm 19$	$22 \pm 3$	$70 \pm 4$	$10 \pm 0.5$	$2 \pm 1$
$E_T^{\text{miss}} > 300 \text{ GeV}/c$	$2932 \pm 14$	$967 \pm 11$	$6 \pm 1.7$	$23 \pm 2$	$3 \pm 0.2$	$1 \pm 0.7$
$E_T^{\text{miss}} > 350 \text{ GeV}/c$	$1308 \pm 9$	$362 \pm 7$	$2 \pm 0.9$	$9 \pm 1.6$	$1 \pm 0.2$	$1 \pm 0.7$
$E_T^{\text{miss}} > 400 \text{ GeV}/c$	$628 \pm 7$	$148 \pm 4$	$1 \pm 0.4$	$3 \pm 0.8$	$0.4 \pm 0.1$	$1 \pm 0.7$

(b)

Requirement	Total	Data	DM (%)	ADD (%)
	Simulated SM		$M_\chi = 1 \text{ GeV}/c^2$	$M_D = 2 \text{ TeV}/c^2, \delta = 3$
$E_T^{\text{miss}} > 200 \text{ GeV}/c$	$1273 \times 10^2$	$1045 \times 10^2$	100.0	100.0
$p_T(j_1) > 110 \text{ GeV}/c$	$1195 \times 10^2$	$1007 \times 10^2$	$95.2 \pm 0.71$	$92.8 \pm 1.03$
$N_{\text{Jet}}(p_T > 30 \text{ GeV}/c) \leq 2$	$730 \times 10^2$	$624 \times 10^2$	$69.8 \pm 0.60$	$61.5 \pm 0.84$
$\Delta\phi(j_1, j_2) < 2.5$	$613 \times 10^2$	$54 \times 10^2$	$66.8 \pm 0.59$	$58.0 \pm 0.81$
Lepton Removal	$298 \times 10^2$	$24 \times 10^2$	$63.7 \pm 0.58$	$54.8 \pm 0.79$
$E_T^{\text{miss}} > 250 \text{ GeV}/c$	$104 \times 10^2$	$76 \times 10^2$	$34.1 \pm 0.42$	$32.5 \pm 0.61$
$E_T^{\text{miss}} > 300 \text{ GeV}/c$	3932	2774	$18.9 \pm 0.31$	$19.9 \pm 0.48$
$E_T^{\text{miss}} > 350 \text{ GeV}/c$	1683	1142	$10.8 \pm 0.24$	$12.5 \pm 0.38$
$E_T^{\text{miss}} > 400 \text{ GeV}/c$	782	522	$6.4 \pm 0.18$	$7.9 \pm 0.30$

**Table 1.** Event yields at different stages of the event selection for (a) various SM processes from simulation, (b) sum of all SM processes, and the data, corresponding to an integrated luminosity of  $5.0 \text{ fb}^{-1}$ . Only statistical uncertainties are shown, which in most cases are smaller than the associated systematic uncertainties. Lepton removal eliminates events with isolated electrons, muons, or tracks with  $p_T > 10 \text{ GeV}/c$ . Efficiencies for representative dark matter and ADD models relative to the event yield passing  $E_T^{\text{miss}} > 200 \text{ GeV}/c$  selection are also given.



**Figure 2.** The dimuon invariant mass distribution in the dimuon control sample in data (black full points with error bars) and simulation (histogram) for  $60 < M_{\mu\mu} < 120 \text{ GeV}/c^2$ . The MC prediction has been normalized to the data yields. There is no significant non- $Z$  background.

## 5 Background estimate from data

Table 1 shows that the SM backgrounds remaining after the full event selection are dominated by the following processes:  $Z$ +jets with the  $Z$  boson decaying into a pair of neutrinos and  $W$ +jets with the  $W$  boson decaying leptonically. These backgrounds are estimated from data utilizing a control sample of  $\mu$ +jet events, where  $Z(\mu\mu)$  events are used to estimate the  $Z(\nu\nu)$  background and  $W(\mu\nu)$  events are used to estimate the remaining  $W$ +jets background. The control sample is derived from the same set of triggers as those used to collect the signal sample by applying the full event selection criteria except for the vetoes on electrons, muons, and isolated tracks. One or more isolated muons with  $p_T > 20 \text{ GeV}/c$  and  $|\eta| < 2.1$  are required.

A sample of  $Z(\mu\mu)$  events is selected by requiring two isolated muons with opposite-sign charges and a dimuon invariant mass between 60 and 120  $\text{GeV}/c^2$ . The observed yield is 111 events, which should be compared with a mean expected yield of  $136 \pm 8$  events, where the uncertainty is only statistical. The dimuon invariant mass distributions, both for the data control sample and for the simulation, are shown in figure 2.

The production of a  $Z$  boson in association with jets and its subsequent decay into neutrinos has characteristics that are similar to those in the production of  $Z$ +jets where the  $Z$  decays to muons. Thus by treating the pair of muons as a pair of neutrinos, the topology of the  $Z(\nu\bar{\nu})$  process is reproduced. The number of  $Z(\nu\nu)$  events can then be predicted using:

$$N(Z(\nu\bar{\nu})) = \frac{N^{\text{obs}} - N^{\text{bgd}}}{A \times \epsilon} \cdot R \left( \frac{Z(\nu\bar{\nu})}{Z(\mu\mu)} \right) \quad (5.1)$$

where  $N^{\text{obs}}$  is the number of dimuon events observed,  $N^{\text{bgd}}$  is the estimated number of background events contributing to the dimuon sample,  $A$  is the geometric and kinematic



Source of Uncertainty	Size (%)
Size of control sample ( $N_{\text{obs}}$ )	9.5
Geometric and kinematic acceptance (A)	3.7
Muon selection efficiency ( $\epsilon$ )	2.1
Track isolation selection efficiency	3.6
Ratio of branching fractions (R)	0.3
Total	11.0

**Table 2.** Sources of systematic uncertainty and their fractional contributions to the total uncertainty on the  $Z(\nu\bar{\nu})$  background.

acceptance of the detector and the  $Z$  mass window,  $\epsilon$  is the selection efficiency for the event, and  $R$  is the ratio of branching fractions for the  $Z$  decay to a pair of neutrinos and to a pair of muons.

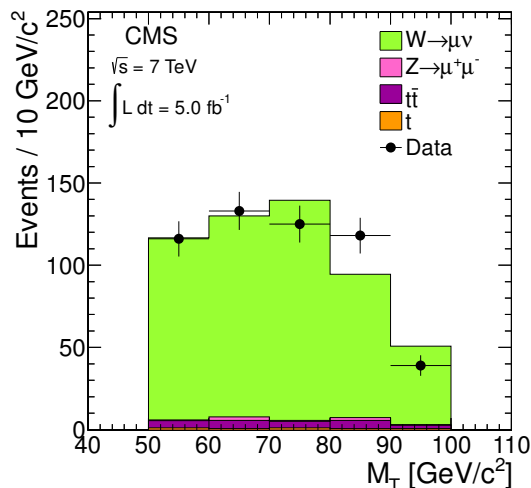
The acceptance  $A$  is defined as the fraction of all simulated events that pass all signal selection requirements except muon and track veto and have two muons with  $p_T > 20 \text{ GeV}/c$  and  $|\eta| < 2.1$  and with an invariant mass within the  $Z$  mass window. The selection efficiency  $\epsilon$  is defined as the fraction of the events passing acceptance cuts that have two reconstructed muons with  $p_T > 20 \text{ GeV}/c$  and  $|\eta| < 2.1$  and with an invariant mass within the  $Z$  mass window. This efficiency is estimated from simulation. The muon selection efficiency, both in the data and the simulation, is determined in the dimuon events with one of the muons passing tight selection criteria (tag) and with an invariant mass in the  $Z$  boson mass window. The efficiency of the second muon (probe), assumed to be a muon originating from the decay of the  $Z$  boson after background subtraction, is determined for the selection requirements used in this analysis. Details of this “tag-and-probe” method can be found in ref. [50]. The efficiencies in the data and the simulation are consistent. The stability of this agreement is measured by varying the muon kinematics and the largest difference between the efficiencies in the data and the simulation is assigned as the uncertainty on the muon selection. This translates into 2% systematic uncertainty on  $\epsilon$ . The ratio of the branching fractions  $R$  is  $5.942 \pm 0.019$  [51]. Some of the  $Z(\nu\bar{\nu})$ +jets events would be rejected by the track isolation requirement, and the background is multiplied by a factor of 0.94 to account for this effect. The scaling factor is obtained from simulation.

The final prediction for the number of  $Z(\nu\bar{\nu})$  events is  $900 \pm 94$  for  $E_T^{\text{miss}} > 350 \text{ GeV}/c$ , where the uncertainty includes statistical and systematic contributions. The sources of this uncertainty are: (i) the statistical uncertainties on the number of  $Z(\mu\mu)$  events in the data and simulation, (ii) uncertainties on the acceptance from PDF uncertainties, evaluated based on the PDF4LHC [52] recommendations, and (iii) the uncertainty in the selection efficiency  $\epsilon$  as determined from the difference in measured efficiencies in data and MC simulation. Table 2 summarizes the systematic uncertainties.

The second largest background arises from  $W$ +jets events that are not removed by the lepton veto cut. These events can come from events in which the lepton (electron or muon) is either not identified, not isolated, or out of the acceptance region, or events in which a  $\tau$  decays hadronically. The events where the lepton is ‘lost’ are estimated from the  $W(\mu\nu)$ +jets control sample.

$W$ +jets	$t\bar{t}$	$Z$ +jets	Single $t$	All MC	Data
581.5	23.3	6.4	4.2	615.4	531

**Table 3.** Event yields for the  $W(\mu\nu)$  from simulation including non- $W$  backgrounds, and from the data control sample.



**Figure 3.** The transverse mass distribution  $M_T$  in the single muon data control sample and MC predictions for  $W(\mu\nu)$ ,  $t\bar{t}$ ,  $Z(\mu\mu)$ , and single top-quark production. The MC predictions have been normalized to the data yields. Data are dominated by  $W(\mu\nu)$  events.

A  $W(\mu\nu)$  sample is selected by requiring an isolated muon with  $p_T > 20 \text{ GeV}/c$  and  $|\eta| < 2.1$  and the transverse mass  $M_T$  to be between 50 and  $100 \text{ GeV}/c^2$ . The transverse mass is defined as  $M_T = \sqrt{2p_T^\mu E_T^{\text{miss}} (1 - \cos(\Delta\phi))}$ , where  $p_T^\mu$  is the transverse momentum of the muon and  $\Delta\phi$  is the angle between the muon  $p_T$  and the  $E_T^{\text{miss}}$  vectors. The event yields obtained for the  $W(\mu\nu)$  sample for  $E_T^{\text{miss}} > 350 \text{ GeV}/c$  are shown in table 3, along with the contributions from  $Z$ +jets,  $t\bar{t}$ , and single top-quark events predicted by the simulation. The observed yield of  $W(\mu\nu)$ +jets candidates is 531 which can be compared with a mean expected yield of  $615.4 \pm 9.3$ , where uncertainty is statistical only. Figure 3 shows the  $W$  transverse mass distribution for data and simulation in the  $W(\mu\nu)$  control sample.

$W(\mu\nu)$  candidate events ( $N_{\text{obs}}$ ), after subtracting non- $W$  contamination ( $N_{\text{bgd}}$ ), are corrected for the detector acceptance ( $A'$ ) and selection efficiency ( $\epsilon'$ ) to obtain the total number of produced events  $N_{\text{tot}} = (N_{\text{obs}} - N_{\text{bgd}})/(A' \times \epsilon')$ . This number is subsequently weighted by the inefficiency of the selection criteria used in the definition of the lepton veto to predict the number of events that are not rejected by the veto and thus remain in the signal sample.

The number of  $W(\mu\nu)$ +jet events that are either out of the acceptance ( $N_{\bar{A}}$ ) or are not identified or are not isolated ( $N_{\bar{\epsilon}}$ ) can be written as:

$$N_{\bar{A}} = N_{\text{tot}} \times (1 - A) \tag{5.2}$$

$$N_{\bar{\epsilon}} = N_{\text{tot}} \times A \times (1 - \epsilon) \tag{5.3}$$

Source of Uncertainty	Size (%)
Size of control sample ( $N_{\text{obs}}$ )	2.9
Background ( $N_{\text{bgd}}$ )	3.9
Isolated track efficiency	2.1
Kinematic and geometrical acceptance ( $A$ )	7.7
Selection efficiency ( $\epsilon$ )	6.8
Total	11.6

**Table 4.** Sources of systematic uncertainty and their contribution to the total uncertainty on the W+jets background.

where  $A$  is the acceptance, and  $\epsilon$  is the selection efficiency of the muon selection used in the lepton veto. The total background from events where the muon is ‘lost’ is then given by

$$N_{\text{lost } \mu} = N_{\bar{A}} + N_{\bar{\epsilon}}. \tag{5.4}$$

An estimate of the ‘lost’ electron background is similarly obtained from the  $W(\mu\nu)$ +jets data sample, correcting for the muon acceptance and selection efficiency to obtain  $N_{\text{tot}}$ . The ratio of the generated  $W(\mu\nu)$  and  $W(e\nu)$  events passing the signal selection is taken from simulation and used to obtain  $N_{\text{tot}}$  for electrons. The same procedure is then applied to obtain the number of events where the electron is either not reconstructed or not isolated or out of the acceptance.

The detector acceptance for both muons and electrons is obtained from simulation. The selection efficiency is similarly obtained from simulation but with an assigned systematic uncertainty to cover the largest difference in the efficiency measured in data and simulation with the tag-and-probe method.

There is a remaining component of the W+jets background from events where the W decays to a  $\tau$  lepton and the  $\tau$  decays hadronically, and this is estimated from simulation. This estimate is corrected using a normalization factor obtained from the ratio of  $W(\mu\nu)$  events in data and simulation. The estimated W+jets background is corrected to account for the fraction of events that would be rejected by the track isolation veto. This correction factor is obtained from simulation and found to be 19%.

The total prediction for the number of W+jets events is  $312 \pm 35$  for  $E_{\text{T}}^{\text{miss}} > 350 \text{ GeV}/c$ , where the uncertainty includes both statistical and systematic contributions. The sources of this uncertainty are: (i) the uncertainties on the number of single-muon events in the data and simulation samples, (ii) a conservative (100%) uncertainty on the non-W contamination obtained from simulation, (iii) uncertainties on the acceptance from PDFs, and (iv) the uncertainty in the selection efficiency  $\epsilon$  as determined from the difference in measured efficiency between data and simulation. Table 4 summarizes the systematic uncertainties in the W+jets background.

Background contributions from QCD multijet events,  $t\bar{t}$ , and  $Z(\ell\ell)$ +jets production are small and are obtained from the simulation. A 100% uncertainty is assigned to these background estimates.

$E_T^{\text{miss}}$ (GeV/c) $\rightarrow$	$\geq 250$	$\geq 300$	$\geq 350$	$\geq 400$
Process	Events			
$Z(\nu\bar{\nu})$ +jets	$5106 \pm 271$	$1908 \pm 143$	$900 \pm 94$	$433 \pm 62$
W+jets	$2632 \pm 237$	$816 \pm 83$	$312 \pm 35$	$135 \pm 17$
$t\bar{t}$	$69.8 \pm 69.8$	$22.6 \pm 22.6$	$8.5 \pm 8.5$	$3.0 \pm 3.0$
$Z(\ell\ell)$ +jets	$22.3 \pm 22.3$	$6.1 \pm 6.1$	$2.0 \pm 2.0$	$0.6 \pm 0.6$
Single t	$10.2 \pm 10.2$	$2.7 \pm 2.7$	$1.1 \pm 1.1$	$0.4 \pm 0.4$
QCD Multijets	$2.2 \pm 2.2$	$1.3 \pm 1.3$	$1.3 \pm 1.3$	$1.3 \pm 1.3$
Total SM	$7842 \pm 367$	$2757 \pm 167$	$1225 \pm 101$	$573 \pm 65$
Data	7584	2774	1142	522
Expected upper limit non-SM	779	325	200	118
Observed upper limit non-SM	600	368	158	95

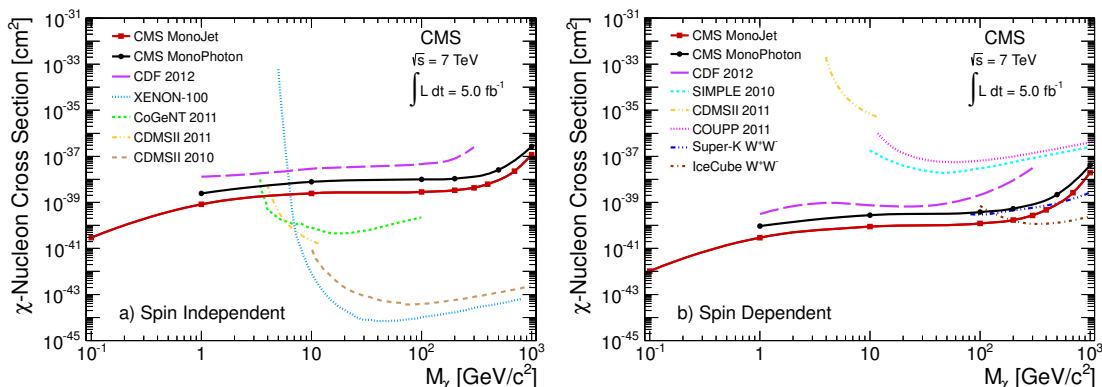
**Table 5.** SM background predictions compared with data passing the selection requirements for various  $E_T^{\text{miss}}$  thresholds, corresponding to integrated luminosity of  $5.0 \text{ fb}^{-1}$ . The uncertainties include both statistical and systematic terms. In the last two rows, expected and observed 95% confidence level upper limits on possible contributions from new physics passing the selection requirements are given.

## 6 Results

The total number of events observed is compared with the total number of estimated background events in table 5, together with the breakdown of this background into separate subprocesses. Contribution from  $Z(\nu\bar{\nu})$ +jets and W+jets processes are determined from the data. Contributions from  $t\bar{t}$ ,  $Z(\ell\ell)$ , single t, and QCD multijet processes are determined from simulation and are assumed to have 100% uncertainty. The number of events observed is consistent with the number of events expected from SM backgrounds. Thus these data are used to set limits on the production of dark matter particles and to constrain the ADD model parameters. The CLs method [51, 53] is used for calculating the upper limits on the number of signal events, and systematic uncertainties are modeled by log-normal distributions.

The important uncertainties related to signal modeling are:

1. The jet energy scale uncertainty, estimated by shifting the four-vectors of the jets by an  $\eta$ - and  $p_T$ -dependent factor [54], yielding a variation of 8–11% (8–13%) for the dark matter (ADD) signal.
2. The noise cleaning uncertainty, obtained by assigning the full effect of noise cleaning as systematic uncertainty, 2% (3%) for dark matter (ADD) signal.
3. PDF uncertainties evaluated using the PDF4LHC [52] prescription and resulting in a systematic uncertainty of 1–7% (1–4%) for the dark matter (ADD) signal.
4. The renormalization/factorization scale uncertainty, evaluated by varying the scale up and down by a factor of two, 5% for both dark matter and ADD signals.



**Figure 4.** Comparison of the 90% CL upper limits on the dark matter-nucleon scattering cross section versus mass of dark matter particle for the (left) spin-independent and (right) spin-dependent models with results from CMS using monophoton signature [14], CDF [15], XENON100 [16], CoGeNT [17], COUPP [18], CDMS II [19, 20], Picasso [21], SIMPLE [22], IceCube [23], and Super-K [24] collaborations.

5. ISR uncertainty, estimated by changing PYTHIA parameters, yielding a variation of 15% for both dark matter and ADD signals.
6. Uncertainty on the pileup simulation, 3% for both dark matter and ADD signals.
7. The limited statistics of the simulated sample yielding a variation of 2–5% (2–4%) on the dark matter (ADD) signal.

The total uncertainty on the signal for the DM (ADD) models for these sources of uncertainty is 20% (21%). In addition, a 2.2% uncertainty on the integrated luminosity measurement [55] is included.

For dark matter models, the observed limit on the cross section depends on the mass of the dark matter particle and the nature of its interaction with the SM particles. The limits on the effective contact interaction scale  $\Lambda$  as a function of  $M_\chi$  can be translated into a limit on the dark matter-nucleon scattering cross section using the reduced mass of  $\chi$ -nucleon system [2], which can be compared with the constraints from direct and indirect detection experiments. Figure 4 shows the 90% confidence level (CL) upper limits on the dark matter-nucleon scattering cross section as a function of the mass of dark matter particle for the spin-dependent and spin-independent models. Also shown are the results from the CMS Collaboration using the monophoton plus  $E_T^{\text{miss}}$  channel [14],  $p\bar{p}$  collider experiment CDF [15], direct detection experiments, COUPP [18], CoGeNT [17], Picasso [21], XENON100 [16], CDMS II [19, 20], and SIMPLE [22], and indirect detection experiments, IceCube [23] and Super-K [24]. Table 6 shows the 90% CL limits on  $\Lambda$  and the dark matter-nucleon cross section for the spin-dependent and spin-independent interactions.

Exclusion limits at 95% CL for the large extra dimension ADD model parameter  $M_D$  as a function of the number of extra dimensions are given in table 7. A comparison of

$M_\chi$ (GeV/ $c^2$ )	Spin-dependent		Spin-independent	
	$\Lambda$ (GeV)	$\sigma_{\chi N}$ (cm $^2$ )	$\Lambda$ (GeV)	$\sigma_{\chi N}$ (cm $^2$ )
0.1	754	$1.03 \times 10^{-42}$	749	$2.90 \times 10^{-41}$
1	755	$2.94 \times 10^{-41}$	751	$8.21 \times 10^{-40}$
10	765	$8.79 \times 10^{-41}$	760	$2.47 \times 10^{-39}$
100	736	$1.21 \times 10^{-40}$	764	$2.83 \times 10^{-39}$
200	677	$1.70 \times 10^{-40}$	736	$3.31 \times 10^{-39}$
300	602	$2.73 \times 10^{-40}$	690	$4.30 \times 10^{-39}$
400	524	$4.74 \times 10^{-40}$	631	$6.15 \times 10^{-39}$
700	341	$2.65 \times 10^{-39}$	455	$2.28 \times 10^{-38}$
1000	206	$1.98 \times 10^{-38}$	302	$1.18 \times 10^{-37}$

**Table 6.** Observed 90% CL limits on the dark matter-nucleon cross section and effective contact interaction scale  $\Lambda$  for the spin-dependent and spin-independent interactions.

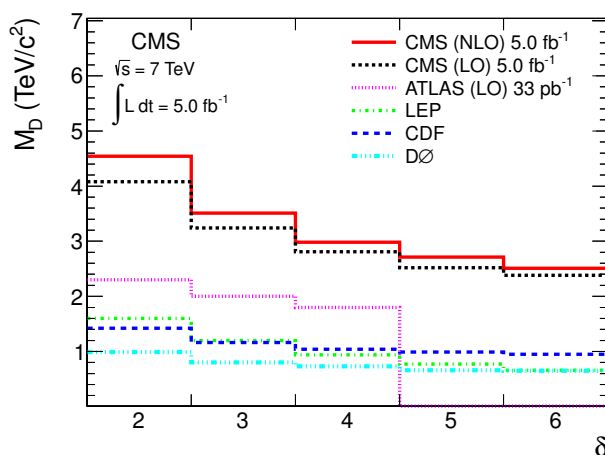
$\delta$	LO		NLO	
	Exp. Limit (TeV/ $c^2$ )	Obs. Limit (TeV/ $c^2$ )	Exp. Limit (TeV/ $c^2$ )	Obs. Limit (TeV/ $c^2$ )
2	3.81	4.08	4.20	4.54
3	3.06	3.24	3.32	3.51
4	2.69	2.81	2.84	2.98
5	2.44	2.52	2.59	2.71
6	2.28	2.38	2.40	2.51

**Table 7.** Observed and expected 95% CL lower limits on the ADD model parameter  $M_D$  (in TeV/ $c^2$ ) as a function of  $\delta$ , with and without NLO  $K$ -factors applied.

these results with results from previous searches is shown in figure 5. These limits are an improvement over the previous best limits, by  $\sim 2$  TeV/ $c^2$  for  $\delta = 2$  and  $0.7$  TeV/ $c^2$  for  $\delta = 6$ .

## 7 Summary

A search has been performed for signatures of new physics yielding an excess of events in the monojet and  $E_T^{\text{miss}}$  channel. The results have been used to constrain the pair production of dark matter particles in models with a heavy mediator, and large extra dimensions in the context of the Arkani-Hamed, Dimopoulos, and Dvali model. The data sample corresponds to an integrated luminosity of  $5.0 \text{ fb}^{-1}$  and includes events containing a jet with transverse momentum above  $110 \text{ GeV}/c$  and  $E_T^{\text{miss}}$  above  $350 \text{ GeV}/c$ . Many standard model processes also have the same signature. The QCD multijet contribution is reduced by several orders of magnitude to a negligible level using topological selections. The dominant backgrounds,  $Z(\nu\bar{\nu})+\text{jets}$  and  $W+\text{jets}$ , are estimated from data samples enriched in  $Z(\mu\mu)$  and  $W(\mu\nu)$  events. The data are found to be in good agreement with the expected contributions from standard model processes.



**Figure 5.** Comparison of lower limits on  $M_D$  versus the number of extra dimensions with ATLAS [12], LEP [25–28], CDF [29], and D0 [30].

A dark matter-nucleon scattering cross section in the framework of an effective theory is excluded above  $1.03 \times 10^{-42}$  ( $1.21 \times 10^{-40}$ )  $\text{cm}^2$  and  $2.90 \times 10^{-41}$  ( $2.83 \times 10^{-39}$ )  $\text{cm}^2$  for a dark matter particle with mass 0.1 (100)  $\text{GeV}/c^2$  at the 90% CL for the spin-dependent and spin-independent models, respectively. For the spin-independent model, these are the best limits for dark matter particles with mass below  $3.5 \text{ GeV}/c^2$ , a region as yet unexplored by the direct detection experiments. For the spin-dependent model, these limits represent the most stringent constraints over the 0.1–200  $\text{GeV}/c^2$  mass range.

Values for the large extra dimensions ADD model parameter  $M_D$  smaller than 4.54, 3.51, 2.98, 2.71, and 2.51  $\text{TeV}/c^2$  are excluded for a number of extra dimensions  $\delta = 2, 3, 4, 5,$  and  $6$ , respectively, representing a significant improvement (1  $\text{TeV}/c^2$ ) over the previous limits.

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