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# Search for New Physics with a Mono-Jet and Missing Transverse Energy in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration\*

## Abstract

A study of events with missing transverse energy and an energetic jet is performed using pp collision data at a centre-of-mass energy of 7 TeV. The data were collected by the CMS detector at the LHC, and correspond to an integrated luminosity of  $36 \text{ pb}^{-1}$ . An excess of these events over standard model contributions is a signature of new physics such as large extra dimensions and unparticles. The number of observed events is in good agreement with the prediction of the standard model, and significant extension of the current limits on parameters of new physics benchmark models is achieved.

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\*See Appendix A for the list of collaboration members



This Letter describes a search for new physics in the missing transverse energy ( $E_T^{\text{miss}}$ ) and jet final state using data collected with the Compact Muon Solenoid (CMS) experiment in pp collisions at a centre-of-mass energy of 7 TeV provided by the Large Hadron Collider (LHC). Events containing a single energetic jet (mono-jet) are selected, although a second less energetic jet is allowed. This event signature is predicted in models such as large extra dimensions, based on the scenario by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [1–4], or unparticles [5]. The data used in this search were collected in 2010 and correspond to an integrated luminosity of  $36 \text{ pb}^{-1}$ . This study focuses on the search for direct production of a graviton  $G$  (or unparticle  $U$ ) balanced by a hadronic jet via the processes  $q\bar{q} \rightarrow gG$  ( $gU$ ),  $qg \rightarrow qG$  ( $qU$ ) and  $gg \rightarrow gG$  ( $gU$ ). The primary backgrounds for this search are from  $Z$ +jet and  $W$ +jet production, and are estimated from the data.

The ADD model aims at explaining 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 torus of common radius  $R$ . The fundamental scale  $M_D$  is related to the effective four-dimensional Planck scale  $M_{\text{Pl}}$  according to the formula  $M_{\text{Pl}}^2 \approx M_D^{\delta+2} R^\delta$ . Gravitons are assumed to propagate in the extra dimensions with nonzero momentum. Graviton production is expected to be greatly enhanced due to the kinematically available phase space in the extra dimensions. Once produced, the gravitons are very weakly coupled and their presence can only be inferred from  $E_T^{\text{miss}}$ . Searches in both the jet plus  $E_T^{\text{miss}}$  and the  $\gamma$  plus  $E_T^{\text{miss}}$  channels were performed previously [6–11], without any evidence of new physics observed. The current lower limits on  $M_D$  range from  $1.6 \text{ TeV}/c^2$  for  $\delta = 2$  [6–9] to  $0.95 \text{ TeV}/c^2$  for  $\delta = 6$  [10].

More recently, interest in unparticle models has increased. These models relate to physics originating from a new scale-invariant (conformal) sector, which is coupled to the standard model (SM) through a connector sector at a high mass scale. An operator with a general non-integer scale dimension  $d_U$  in a conformal sector induces a spectrum of invisible, massless, and weakly interacting particles. If the mass scale  $\Lambda_U$  is assumed to be roughly  $1 \text{ TeV}/c^2$ , then by using an effective field theory below that scale one should be able to study the effects of unparticles at the LHC. While there have been no direct searches for unparticles, a recent interpretation of CDF results suggests lower limits on  $\Lambda_U$  between  $2.11$  and  $9.19 \text{ TeV}/c^2$  for  $1.05 < d_U < 1.35$  [12, 13].

The CMS apparatus has pixel and silicon-strip detectors for pseudorapidity of  $|\eta| < 2.5$ , where  $\eta = -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle relative to the beam direction. Contained in a 3.8 T magnetic solenoid, the tracking detectors provide momentum reconstruction down to about  $100 \text{ MeV}/c$  with a resolution of about 1% at  $100 \text{ GeV}/c$ . A highly granular crystal electromagnetic calorimeter (ECAL) extends to  $|\eta| < 3.0$ , and has an energy resolution of better than 0.5% for photons with a transverse energy above  $100 \text{ GeV}$ . A hermetic hadronic calorimeter (HCAL) extends to  $|\eta| < 5.0$  with a transverse hadronic energy resolution of about  $100\%/\sqrt{E_T [\text{GeV}]} \oplus 5\%$ . A muon detector system reconstructs and identifies muons to  $|\eta| < 2.4$ . A full description of the CMS detector can be found in Ref. [14].

Both ADD and unparticle signal events are generated with the PYTHIA 8.130 Monte Carlo generator [15, 16] with Tune 1 and passed through the CMS full simulation via the GEANT4 package [17]. The CTEQ 6.6M parton distribution functions (PDFs) [18] are used throughout. In order to scan the sensitivity in the relevant ADD parameter space, different samples with  $M_D = 1, 2, 3 \text{ TeV}/c^2$  and  $\delta = 2, 3, 4, 5, 6$  are produced. The models are effective theories and hold only for energies well below  $M_D$  ( $\Lambda_U$ ), we therefore follow the convention to suppress the simulated cross section of the graviton (unparticle) by a factor  $M_D^2/\hat{s}$  ( $\Lambda_U^2/\hat{s}$ ) above  $M_D$

( $\Lambda_U$ ). A transverse momentum ( $p_T$ ) cutoff on the parton recoiling against the graviton (unparticle) is introduced by requiring  $\hat{p}_T > 50 \text{ GeV}/c$  at parton level, where  $\hat{p}_T$  is the transverse momentum of the outgoing parton (gluon or quark) from the initial hard scatter. In this analysis, unparticles are assumed sufficiently long-lived that they do not decay in the detector. The next-to-leading-order (NLO) QCD corrections to the direct graviton plus jet production in ADD are sizable and dependent on the  $p_T$  of the recoiling parton [19].  $K$  factors ( $\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ ) are chosen for a graviton transverse momentum of several hundred  $\text{GeV}/c$ , corresponding to 1.5 for  $\delta = 2, 3$  and 1.4 for  $\delta = 4, 5, 6$ . The background samples of vector boson plus jets and top quark pairs are produced with MADGRAPH [20] and simulated using PYTHIA (v6.420) [21] with tune D6T [22] for showering, based on a leading-order (LO) calculation of the matrix element with the shower matching prescription [23], and interfaced with TAUOLA [24]. The QCD multijet background sample is generated with MADGRAPH and also interfaced to PYTHIA with tune D6T for showering [21, 22].

Several jet and  $E_T^{\text{miss}}$  triggers are used for data collection, and all trigger paths are fully efficient for events with a value of  $E_T^{\text{miss}} > 120 \text{ GeV}$  reconstructed offline. Events are required to have at least one primary vertex, where the vertex is reconstructed within a 24 cm window along the beam axis, has a transverse distance from the beam spot no more than 2 cm, and be of good quality [25]. Beam halo and other beam-induced background events are rejected by requiring at least 25% of the tracks in events with ten or more tracks to be well reconstructed [26].

Jets and  $E_T^{\text{miss}}$  are reconstructed using a particle flow technique [27]. The algorithm produces a unique list of particles in each event, using the combined information from all CMS subdetectors. This list is then used as input to the jet clustering, which reconstructs jets using the anti- $k_T$  algorithm [28] with a distance parameter of 0.5. The missing transverse energy vector is computed as the negative vector sum of the transverse momenta of all particles reconstructed in the event, and has a magnitude denoted by  $E_T^{\text{miss}}$ .

Jet energies are corrected to establish a uniform calorimeter response in  $\eta$  and an absolute response in  $p_T$  calibrated at the particle level. Jet-energy-scale corrections are derived from Monte Carlo simulation (MC), and a residual correction is derived by measuring the  $p_T$  balance in dijet events [29]. Jets are required to have  $p_T > 30 \text{ GeV}/c$ . To remove any artificial signals in the calorimeter, criteria based on energy sharing between neighbouring channels are applied [30]. Signals in HCAL or ECAL towers identified to be unphysical are removed from the reconstruction. Beam halo and cosmic muons are removed, but some of these events leave energy in both the ECAL and HCAL with no charged track associated with the energy cluster in the calorimeter. The fraction of jet energy carried by charged hadrons is therefore required to be above 15%. To reject high- $p_T$  photons and electrons misidentified as hadronic jets, the energies assigned to neutral hadrons in the HCAL and neutral and charged hadrons in the ECAL must sum to less than 80% of the total jet energy. The combined effect of all data cleanup is to reject 1.5% of the events in the signal sample defined below.

In order to reduce the background from  $W$ -boson decays, events with isolated leptons are rejected. A separate  $W$  boson enriched sample is also created by requiring isolated leptons, and is used to estimate the size of the primary background. Lepton candidates (electron and muon) are required to have  $p_T > 20 \text{ GeV}/c$ , to originate within 2 mm of the beam axis in the transverse plane, and to be spatially separated from jets by at least  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$  in order to avoid rejecting events where there are leptons from jets. Here  $\Delta\eta$  and  $\Delta\phi$  are the pseudorapidity and azimuthal angle (in radians) differences, respectively. Muon candidates within  $|\eta| < 2.1$  are reconstructed by requiring both that compatible tracks in the silicon tracking detectors are found, and that these signals are consistent with a global fit to both silicon

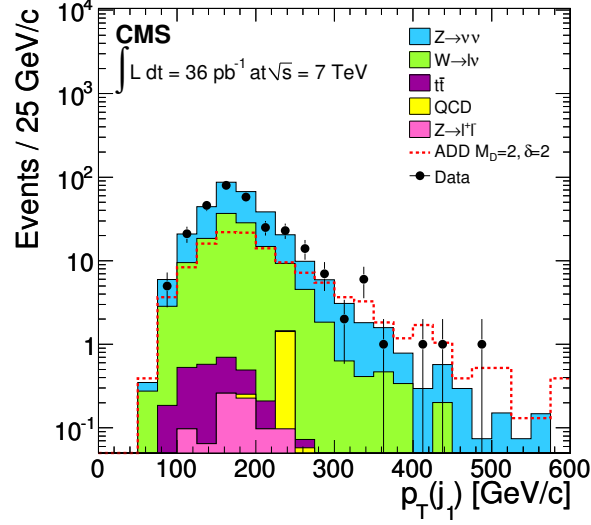


Figure 1: Distribution of  $p_T(j_1)$ , requiring  $E_T^{\text{miss}} > 150 \text{ GeV}$ ,  $N_{\text{jets}} \leq 2$ ,  $|\eta(j_1)| < 2.4$ , and  $\Delta\phi(j_1, j_2) < 2$ . A representative ADD signal (with  $M_D = 2 \text{ TeV}/c^2$ ,  $\delta = 2$ ) is shown as a dashed red line. The background is normalised to the measured rate in data.

tracker and muon detector hit locations [31]. Electron candidates are reconstructed starting from a cluster of energy deposits in the ECAL, which is then matched to hits in the silicon tracker. Electron candidates are required to have  $|\eta| < 1.44$  or  $1.56 < |\eta| < 2.5$  to avoid poorly-instrumented regions, and candidates with significant mismeasurement in the ECAL or consistent with a photon conversion are rejected [32]. For lepton candidates a cone of  $\Delta R < 0.3$  is constructed around the track direction. An isolation parameter is defined as the scalar sum of the transverse momenta of tracks and transverse energies in the ECAL and HCAL in the cone, excluding the contribution from the muon (electron) candidate, divided by the muon  $p_T$  (electron  $E_T$ ). Candidates with isolation values below 0.15 for muons or 0.09 (0.04) for electrons in the central (forward) regions are considered isolated.

The signal sample is selected by requiring  $E_T^{\text{miss}} > 150 \text{ GeV}$ , the most energetic jet ( $j_1$ ) to have  $p_T(j_1) > 110 \text{ GeV}/c$  and  $|\eta(j_1)| < 2.4$ . Events with more than two jets ( $N_{\text{jets}} > 2$ ) with  $p_T$  above  $30 \text{ GeV}/c$  are discarded. To increase the signal efficiency a second jet ( $j_2$ ) is allowed provided that the angular separation with the highest- $p_T$  jet satisfies  $\Delta\phi(j_1, j_2) < 2.0$  radians, a selection that suppresses QCD dijet events. The  $p_T(j_1)$  distribution of the signal sample is shown in Fig. 1. Remaining events with an isolated track are eliminated, as they come primarily from  $\tau$  decays. A hollow cone  $0.02 < \Delta R < 0.3$  is defined around each track with  $p_T > 10 \text{ GeV}/c$ . The scalar sum of the  $p_T$  of all tracks with  $p_T > 1 \text{ GeV}/c$  inside the cone is calculated and the event is vetoed if this sum is smaller than 10% of the  $p_T$  of the original track.

The  $E_T^{\text{miss}}$  distribution from data and the expected backgrounds after all selection criteria are shown in Fig. 2, together with a distribution of the integrated number of  $E_T^{\text{miss}}$  events above a given threshold. The only significant remaining backgrounds after all requirements stem from electroweak processes with genuine missing transverse energy in the final state. Table 1 lists the number of events selected at each step of the analysis from data and simulation.

Rather than using the background estimates from MC shown in Table 1, the Z+jets with  $Z \rightarrow \nu\nu$  (denoted  $Z(\nu\nu)$ +jets) and W+jets backgrounds are estimated from  $\mu$ +jet events derived from the data sample. The selection defining this control sample has the same initial requirements as for the signal region, except that one or more muons are explicitly required. Well-reconstructed

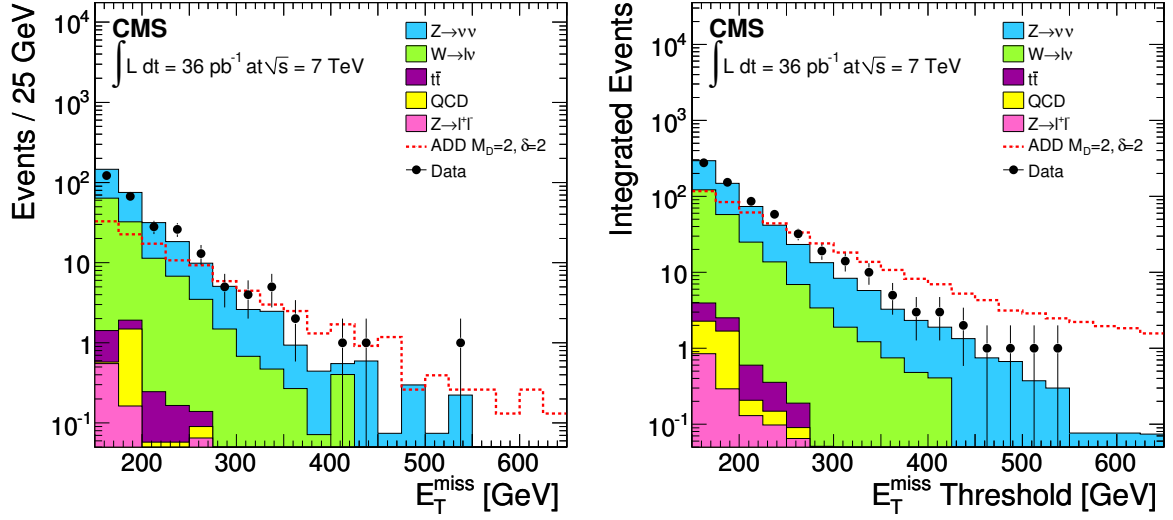


Figure 2: Missing transverse energy  $E_T^{\text{miss}}$  after all selection cuts for data, SM background, and an example of ADD signal ( $M_D=2 \text{ TeV}/c^2$ ,  $\delta=2$ ). The figure at right shows the integrated number of events above a given threshold. The background is normalised to the measured rate in data.

Table 1: Mono-jet data sample and analysis cuts, with luminosity-normalised leading-order MC. Lepton removal eliminates isolated muons or tracks for  $p_T(e, \mu) > 10 \text{ GeV}/c$ .

Requirement	W+jets	Z( $\nu\nu$ )+jets	Z( $\ell\ell$ )+jets	$t\bar{t}$	QCD	Total MC	Data
$E_T^{\text{miss}} > 150 \text{ GeV}$ , jet cleaning	622	259	46.7	90.4	202	1220	1298
$p_T(j_1) > 110 \text{ GeV}/c$ , $ \eta(j_1)  < 2.4$	583	245	43.4	76.9	201	1149	1193
$N_{\text{jets}} \leq 2$	446	201	34.3	11.3	74.3	767	778
$\Delta\phi(j_1, j_2) < 2$	370	182	29.5	9.1	6.3	597	596
Lepton Removal	107	173	0.8	1.7	1.4	284	275

and isolated muons are selected following the criteria outlined above. To ensure a pure W+jets sample, a single isolated muon is required to form, with the  $E_T^{\text{miss}}$ , a transverse mass  $M_T$  between 50 and 100 GeV/c<sup>2</sup>. The transverse mass is defined as  $M_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos(\Delta\phi))}$ , where  $\Delta\phi$  is the angle in the transverse plane between the  $p_T$  the  $E_T^{\text{miss}}$  vectors. Within the  $M_T$  window there are 113 single-muon events in the data, compared to 103 estimated from MC (95.3 W+jets, 2.9 W( $\tau\nu$ )+jets, 2.4 Z+jets, 2.4  $t\bar{t}$ , and 0.08 from QCD multijets). The shape and yield of the muon distributions observed in the data are consistent with the expectation from SM sources. We estimate the number of W+jets background events to be  $117 \pm 16$ . This estimate is obtained by scaling the surviving W+jets MC events in the signal sample by the ratio of observed and predicted W+jets events in the muon sample.

To estimate the number of Z( $\nu\nu$ )+jets background events, the number of muon events in the  $M_T$  window is rescaled by several factors, including: (i) the ratio between the W( $\mu\nu$ )+jets and Z( $\nu\nu$ )+jets production cross sections, obtained by combining the branching fractions of the decays [33] ( $0.553 \pm 0.021$ ), (ii) the reciprocal of the kinematic and geometric acceptance of the simulated sample ( $2.40 \pm 0.12$ ), (iii) the efficiency of the lepton veto in the signal region taken from simulation ( $0.95 \pm 0.02$ ), (iv) the spectral shape differences in W+jets and Z+jets for  $p_T(W,Z) > 150$  GeV/c ( $1.33 \pm 0.03$ ), and (v) the correction for contributions other than W( $\mu\nu$ )+jets, extracted from LO MC ( $0.923 \pm 0.071$ ). All uncertainties include both statistical and systematic effects. The number of Z( $\nu\nu$ )+jets events in the signal region predicted from W+jets events is  $176 \pm 30$ , which agrees with the MC. A crosscheck is made using two opposite-sign muons from Z( $\nu\nu$ )+jets, where the 13 events with an invariant mass consistent with that of a Z boson gives a prediction of  $162 \pm 45$  background events. The estimated number of events from all background sources is  $297 \pm 45$ . The uncertainty includes both statistical and systematic sources, with correlations taken into account.

The most important uncertainties related to theoretical signal modeling and experimental mis-measurement are (i) the jet energy scale, simulated by shifting the jet four-vectors by an  $\eta$ - and  $p_T$ -dependent factor related to the response, yielding a variation of 3–7% (7.5–11.5%) for the ADD (unparticle) signal efficiency [29], (ii) the jet energy resolution, estimated from a  $\gamma$ +jet sample and resulting in a 0.3–2.2% (0.6–2.9%) uncertainty on the ADD (unparticle) signal acceptance [34], (iii) uncertainties on the PDFs, evaluated using a reweighting technique with the CTEQ6M parameterisation [18] and resulting in a systematic uncertainty of 1–2% (3–7%) for the ADD (unparticle) signal, and (iv) a 4% uncertainty on the luminosity measurement [35]. The total systematic uncertainties range from 6% to 13%, with the jet energy scale uncertainty being the dominant one.

To interpret the consistency of the observed number of events with the background expectation in the context of a model, and also to facilitate comparison with previous results, we set exclusion limits for both the ADD model and the unparticle scenario. The upper limit on the number of non-SM events consistent with the measurements is set using a Bayesian method [33, 36] with a flat signal prior. A log-normal density function is assigned to the background estimate with the uncertainty derived from data. The total uncertainty incorporates the individual uncertainties on each background process and takes correlations into account.

Exclusion limits for the ADD model are given in Table 2 and significantly improve the previous limits for this model. For unparticles with spin = 0, production cross sections above 54 pb are excluded at 95% confidence level (CL) for  $d_U = 1.7$  and  $\Lambda_U = 1$  TeV/c<sup>2</sup>. The limits for other  $d_U$  and  $\Lambda_U$  are comparable and are shown in Fig. 3; for  $d_U = (1.35, 1.40, 1.45, 1.50, 1.60, 1.70)$ , unparticles are excluded at 95% CL for  $\Lambda_U < (18.9, 8.07, 4.57, 2.90, 1.62, 1.07)$  TeV/c<sup>2</sup>, compared to the expected limits of (13.4, 6.43, 3.75, 2.38, 1.46, 1.00) TeV/c<sup>2</sup>. From the ADD model with

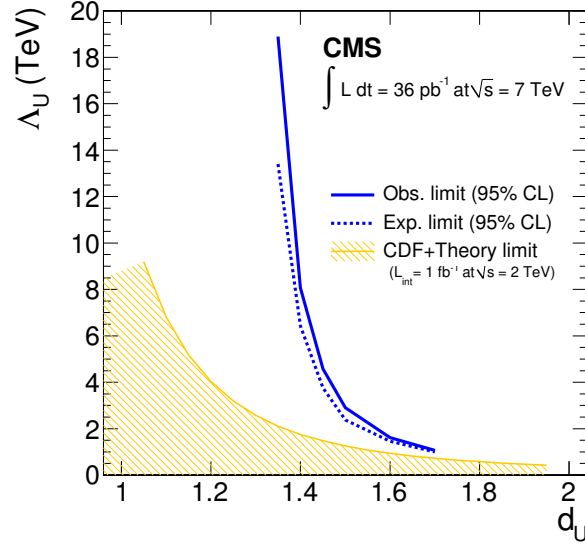


Figure 3: Observed and expected 95% CL lower limits on the allowed region of unparticle model parameters  $d_U$  and  $\Lambda_U$ , compared to those derived from CDF results [12, 13].

Table 2: Observed and expected 95% CL lower limits on the ADD model parameter  $M_D$  (in  $\text{TeV}/c^2$ ) as functions of  $\delta$ , with and without NLO  $K$  factors applied.

$\delta$	$K$ factor	LO Exp.	LO Obs.	NLO Exp.	NLO Obs.
2	1.5	2.17	2.29	2.41	2.56
3	1.5	1.82	1.92	1.99	2.07
4	1.4	1.67	1.74	1.78	1.86
5	1.4	1.59	1.65	1.68	1.74
6	1.4	1.54	1.59	1.62	1.68



$M_D = 3 \text{ TeV}/c^2$  and  $\delta = 3$ , which gives the largest signal acceptance of 9.9%, we evaluate a cross-section upper limit for our selection of 18.7 pb and exclude new processes at 95% CL above this value that result in mono-jet events.

In summary, a search is performed for signatures from the ADD and unparticle models in events collected by the CMS experiment from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$ . A final state with an energetic jet and a significant amount of missing transverse energy is analyzed with the first CMS data, corresponding to an integrated luminosity of  $36 \text{ pb}^{-1}$ . The QCD multijet background is reduced by several orders of magnitude to a negligible level using topological cuts. A measurement of the electroweak background from  $W(\mu\nu)$ -enriched data is used to derive a background estimate for the  $W$ +jets and  $Z(\nu\nu)$ +jets remaining in the signal region. The data are found to be in agreement with the expected contributions from SM processes. Limits on model parameters are derived and constitute a significant improvement of those set by previous experiments for ADD and unparticles.

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