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

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A study of events with missing transverse energy and an energetic jet is performed using pp collision data at a center-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 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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This Letter describes a search for new physics in the missing transverse energy (E_T^{miss}) and jet final state using data corresponding to an integrated luminosity of 36 pb^{-1}, collected with the compact muon solenoid (CMS) experiment in pp collisions at a center-of-mass energy of 7 TeV provided by the Large Hadron Collider (LHC). Events containing a single energetic jet (monojet) are selected, although a second 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]. 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 $gg \rightarrow gG$ (qU). Gravitons (unparticles) leave the detector without depositing any energy, and thus result in an apparent transverse energy imbalance in the final state. The primary backgrounds to this signature arise from Z + jet and W + jet production, and are estimated from the data.

The ADD model explains the large difference between the electroweak and Planck scales by introducing a number δ 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_{Pl} according to the formula ${M_{\mathrm{Pl}}}^2 \approx {M_D}^{\delta+2} R^{\delta}$. Gravitons can propagate in the extra dimensions and their production is expected to be greatly enhanced due to the kinematically available phase space in the extra dimensions. The gravitons are weakly coupled with standard model (SM) particles and their presence can only be inferred from E_T^{miss}. Searches for invisible particles produced in association with a jet or a photon were performed previously [6–11], and no evidence of new physics was observed. The current lower limits on M_D range from 1.6 $\mathrm{TeV/c^2}$ for $\delta = 2$ [6–9] to 0.95 $\mathrm{TeV/c^2}$ for $\delta = 6$ [10].

Unparticle models postulate a new scale-invariant (conformal) sector which is coupled to the SM particles through a connector sector at a high mass scale. An operator with a general noninteger scale dimension d_U in a conformal sector induces a spectrum of particles with continuous mass. These ‘‘unparticles’’ leave without interacting with the detector, thus manifesting as E_T^{miss}. In this analysis, unparticles are assumed to be sufficiently long-lived that they do not decay in the detector. Effects of unparticles below mass scale Λ_U are studied by using an effective field theory. While there have been no direct searches for unparticles, a recent interpretation of CDF results suggests lower limits on Λ_U between 2.11 and 9.19 $\mathrm{TeV/c^2}$ 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 θ 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 MeV/c with a resolution of about 1% at 100 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 p_T above 100 GeV. A hermetic hadronic calorimeter (HCAL) extends to $|\eta| < 5.0$ with a transverse hadronic energy resolution of about $100\%/\sqrt{E_{\mathrm{T}}[\mathrm{GeV}]} \oplus 5\%$. 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 6.6 M parton distribution functions (PDFs) [18] are used throughout. These models are effective theories and hold only for energies well below

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M_D (Λ_U). For a center of mass energy of scattering partons $\sqrt{\hat{s}} > M_D(\Lambda_U)$, following [16], the simulated cross sections of the graviton (unparticle) are suppressed by a factor ${M_D}^4/\hat{s}^2$ (${\Lambda_U}^4/\hat{s}^2$). Since the $\sqrt{\hat{s}}$ of these data is lower than the current limits on the $M_D(\Lambda_U)$, the results are not affected by this treatment. The next-to-leading-order (NLO) QCD corrections to the direct graviton production in ADD model are sizable and dependent on the p_T of the recoiling parton [19]. For simplicity, the following K factors ($\sigma_{\rm NLO}/\sigma_{\rm LO}$), which correspond to a graviton p_T of several hundred GeV/c, are used; 1.5 for $\delta = 2$, 3 and 1.4 for $\delta = 4$, 5, 6. The SM samples of Z + jets and W + jets, top quark pairs and QCD multijets are produced with the LO matrix element event generator MADGRAPH [20] interfaced with PYTHIA 6.420 [21] with tune D6T [22] for parton showering. Double counting by the matrix element calculation and parton showering is resolved by using the MLM matching prescription [23] as implemented in [20].

Data collected by several jet and $E_T^{\rm miss}$ triggers are used in this search. These trigger paths are fully efficient for events with a value of $E_T^{\rm miss} > 120$ GeV. Events are required to have at least one good quality [24] primary vertex reconstructed within a ±15 cm window along the beam axis around the detector center and have a transverse distance from the beam axis no more than 2 cm. Artificial signals in the calorimeter are identified by using criteria based either on energy sharing between neighboring channels or timing requirements and are removed from the further reconstruction [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]. Events identified to contain muons from cosmic rays are also rejected. After these requirements, some beam-related and instrumental backgrounds still remain which are removed by additional cuts described below.

Jets and $E_T^{\rm miss}$ are reconstructed using a particle flow technique [27]. The algorithm reconstructs particles in each event, using the information from the tracker, the ECAL, and the HCAL calorimeters and the muon system. These particles are then used as input to the jet clustering algorithm 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 $E_T^{\rm miss}$. Jet energies are corrected to particle level using p_T- and η-dependent correction factors. These corrections are derived from Monte Carlo simulation (MC) and are supplemented by a residual correction which is derived by measuring the p_T balance in dijet events from collision data [29]. To further suppress the instrumental and beam-related backgrounds, events are rejected if less than 15% of the energy of the highest p_T jet is carried by charged hadrons or more than 80% of this energy is carried by either neutral hadrons or photons. Such jets primarily arise from the instrumental noise where energy deposition is limited to one subdetector. Jets resulting from energy deposition by beam halo or cosmic muons do not have associated tracks and thus events with such energy deposits are also rejected by these cuts. All the events passing these selection cuts were visually inspected and were found to be good pp collision events. All these data cleanup requirements reject 1.5% of the signal events as defined below.

Muon candidates are reconstructed by finding the compatible track segments in the silicon tracker and the muon detectors and requiring that the track formed using hits on these two track segments is of a good quality [30]. Muon candidates are required to be within $|\eta| < 2.1$. 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. Electron candidates with significant mismeasurement in the ECAL or consistent with a photon conversion are rejected [31]. Muon and electron candidates are required to originate within 2 mm of the beam axis in the transverse plane. In order to avoid rejecting events in which the muon (electron) originates from a jet, muon and electron candidates are also required to be spatially separated from jets by at least $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$. Here $\Delta\eta$ and $\Delta\phi$ are differences between the muon (electron) and the jet directions in the pseudorapidity and azimuthal angle (in radians), respectively. An isolation parameter RelIso is defined as the scalar sum of the transverse momenta of tracks and transverse energies in the ECAL and HCAL in a cone of radius $R = 0.3$ centered at the muon (electron) track direction, excluding the contribution from the candidate, divided by its p_T. Candidates with RelIso 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 $E_T^{\rm miss} > 150$ GeV and the most energetic jet (j_1) to have $p_T(j_1) > 110$ GeV/c and $|\eta(j_1)| < 2.4$. Events with more than two jets ($N_{\rm jets} > 2$) with p_T above 30 GeV/c are discarded. A second jet (j_2) is allowed as signal events generally contain an initial or final state radiated jet provided its angular distance in azimuth from the highest-p_T jet satisfies $\Delta\phi(j_1, j_2) < 2.0$ radians. This angular requirement suppresses the QCD dijet events. Approximately 40% of the selected events have two jets. In order to reduce the background from W and Z bosons and top quark decays, events with isolated electrons or muons with $p_T > 10$ GeV/c are rejected. Events with an isolated track with $p_T > 10$ GeV/c are also eliminated, as they come primarily from τ-lepton decays. A track is considered isolated if the scalar sum of the p_T 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 10% of its p_T.

TABLE I. Event yields in data and luminosity-normalized leading-order MC calculations after each analysis cut. Lepton removal eliminates events with isolated electrons, muons, or tracks with $p_T > 10$ GeV/c.

Requirement	W + jets	$Z(\nu\nu)$ + jets	$Z(\ell^+\ell^-)$ + jets	$t\bar{t}$	QCD	Total MC	Data
$E_T^{\rm miss} > 150$ GeV/c, jet cleaning	622	259	46.7	90.4	202	1220	1298
$p_T(j_1) > 110$ GeV/c, $\lvert\eta(j_1)\rvert < 2.4$	583	245	43.4	76.9	201	1149	1193
$N_{\rm jets} \leq 2$	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

The only significant remaining backgrounds after all requirements are from electroweak processes where the final state includes neutrino(s) and thus has genuine missing transverse energy. Table I lists the number of events selected at each step of the analysis from data and simulation. The predicted event yields in the simulation are in reasonable agreement with those observed in the data.

The $p_T(j_1)$ distribution after all signal selection cuts except the leading jet p_T requirement and $E_T^{\rm miss}$ distribution after all the signal selection cuts are shown in Fig. 1. The SM predictions have been determined using MC simulation and have been normalized to the measured rate in data. The shape of the data distributions is well described by the SM predictions both for the leading jet p_T spectrum and the $E_T^{\rm miss}$ spectrum.

Rather than using the background estimates from MC calculations shown in Table I, the Z + jets with the Z boson decaying into a pair of neutrinos [denoted $Z(\nu\nu)$ + jets] and W + jets backgrounds are estimated from μ + jet events derived from the data sample. This control sample is selected from the same set of triggers using the same requirements as for the signal sample, except that one or more well-reconstructed and isolated muons with $p_T > 20$ GeV/c are explicitly required. To ensure a pure W + jets sample, the transverse mass $M_{\rm T}$ is required to be between 50 and 100 GeV/c^2. The transverse mass is defined as $M_{\rm T} = \sqrt{2 p_T^\mu E_T^{\rm miss}(1 - \cos(\Delta\phi))}$, where p_T^μ is the transverse momentum of the muon and $\Delta\phi$ is the angle between the muon p_T and the $E_T^{\rm miss}$ vectors. Within the $M_{\rm T}$ window there are 113 single-muon events in the data, compared to 103 expected 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 shapes of the muon transverse momentum and pseudorapidity distributions observed in the data are consistent with the expectation from SM sources. We estimate the number of W + jets events remaining in the signal sample to be 117 ± 16. This estimate is obtained by scaling the W + jets MC events passing the signal selection requirement by the ratio of observed and predicted W + jets events in the muon sample. The uncertainty includes the statistical uncertainty of the data muon sample, the statistics of the MC sample, the uncertainty on the non-$W(\mu\nu)$ background contribution, and the uncertainty on the geometric and kinematic acceptance of the muons from the W decay.

To estimate the number of $Z(\nu\nu)$ + jets background events, the number of muon events in the $M_{\rm T}$ window is rescaled by several factors: (i) the correction for contributions other than $W(\mu\nu)$ + jets, extracted from LO MC (0.923 ± 0.071), (ii) the reciprocal of the kinematic and geometric acceptance determined from the simulated sample (2.40 ± 0.12), (iii) inclusive $W(\mu\nu)$ to inclusive $Z(\nu\nu)$ conversion factor, $\sigma(Z(\mu\mu))/\sigma(W(\mu\nu)) \times BR(Z \to \nu\nu)/BR(Z \to \mu\mu) = [1/10.74]$ [32] $\times 5.942$ [33] $= (0.553 \pm 0.021)$, (iv) the

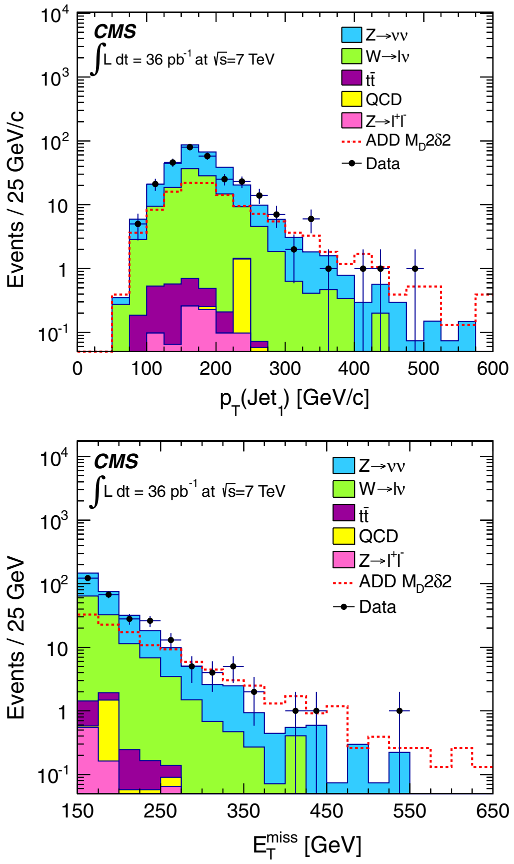

FIG. 1 (color online). Distribution of $p_T(j_1)$ (top), and missing transverse energy $E_T^{\rm miss}$ (bottom) requiring $E_T^{\rm miss} > 150$ GeV, $N_{\rm jets} \leq 2$, $\lvert\eta(j_1)\rvert < 2.4$, $\Delta\phi(j_1, j_2) < 2$, and lepton veto requirements compared to SM contribution determined using MC simulation. The background is normalized to the measured rate in data. A representative ADD signal (with $M_D = 2$ TeV/c^2, $\delta = 2$) is shown as a dashed red line.

spectral shape differences in $W +$ jets and $Z +$ jets for $p_T(W, Z) > 150\ \mathrm{GeV}/c$ (1.33 ± 0.14), and (v) the efficiency of the lepton veto in the signal region taken from simulation (0.95 ± 0.02). All uncertainties include both statistical and systematic effects. The number of $Z(\nu\nu) +$ jets events in the signal region predicted from $W(\mu\nu) +$ jets events is 176 ± 30. A crosscheck is made using an event sample of two opposite-sign muons with invariant mass consistent with that of a Z boson, and passing the signal selection cuts except the muon veto. In this sample, we observe 13 events which, after correcting for reconstruction efficiency, branching ratio, and detector acceptance, gives a prediction of 162 ± 45 for $Z(\nu\nu) +$ jets background. Other background contributions to the signal region from QCD, top pair production, and $Z(\ell^+\ell^-) +$ jets production are small and are estimated using Monte Carlo simulation. We assign 100% uncertainty on this estimate. To the check accuracy of the QCD simulation, the event yield in data after relaxing the $\Delta\phi(j_1, j_2)$ cut to 3.0 was compared with the MC prediction and was found to agree well. In addition, relaxing the p_T veto cut on additional jets to $50\ \mathrm{GeV}/c$ increases the expected QCD background from 1.4 to only 2.1 events. The estimated number of events from all background sources is 297 ± 45. The uncertainty includes both statistical and systematic sources, with correlations taken into account.

To interpret the consistency of the observed number of events with the background expectation in the context of a model, 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 determined using a Bayesian method [33,34] with a flat prior for signal and a log-normal density function for the background.

The most important uncertainties related to signal modeling are (i) the jet energy scale, estimated by shifting the jet four vectors by an η- and p_T-dependent factor [29] yielding a variation of 3%–7% (7.5%–11.5%) for the ADD (unparticle) signal acceptance, (ii) the jet energy resolution, estimated from a $\gamma +$ jet sample [35] and resulting in a 0.3%–2.2% (0.6%–2.9%) uncertainty on the ADD (unparticle) signal acceptance, (iii) uncertainties on the PDFs, evaluated using a reweighting technique with the CTEQ6M parameterization [18] and resulting in a systematic uncertainty of 1%–2% (3%–7%) for the ADD (unparticle) signal acceptance, and (iv) a 4% uncertainty on the luminosity measurement [36]. The uncertainties for unparticle signal are higher as it has a steeper E_T^{miss} spectrum. The total systematic uncertainties, dominated by the jet energy scale uncertainty, range from 6% to 13%.

Exclusion limits at 95% confidence level (C.L.) for the ADD model are given in Table II and are a significant improvement over the previous limits. From the ADD model with $M_D = 3\ \mathrm{TeV}/c^2$ and $\delta = 3$, which has signal acceptance of $(9.9 \pm 0.7)\%$, we evaluate a cross-section upper limit for our selection of 18.7 pb and exclude new processes at 95% C.L. above this value that result in events passing our selection cuts and having the same acceptance. For unparticles with spin $= 0$, production cross sections above 54 pb are excluded at 95% C.L. for $d_U = 1.7$ and $\Lambda_U = 1\ \mathrm{TeV}/c^2$. The limits for other d_U and Λ_U are comparable and are shown in Fig. 2; for $d_U = (1.35, 1.40, 1.45, 1.50, 1.60, 1.70)$, unparticles are excluded at 95% C.L. for $\Lambda_U < (18.9, 8.07, 4.57, 2.90, 1.62, 1.07)\ \mathrm{TeV}/c^2$, compared to the expected limits of $(13.4, 6.43, 3.75, 2.38, 1.46, 1.00)\ \mathrm{TeV}/c^2$.

TABLE II. Observed and expected 95% C.L. lower limits on the ADD model parameter M_D (in TeV/c^2) as functions of δ, with and without NLO K factors applied.

δ	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

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 $\sqrt{s} = 7$ TeV. A final state with an energetic jet and a significant amount of missing transverse energy is analyzed from the first CMS data, corresponding to an integrated luminosity of $36\ \mathrm{pb}^{-1}$. The QCD multijet background is reduced by several orders of magnitude to a negligible level using topological cuts. Data enriched in $W(\mu\nu)$ events are used to estimate the $W +$ jets and $Z(\nu\nu) +$ jets events remaining in the signal region. The data are found to be in agreement with the expected contributions from SM

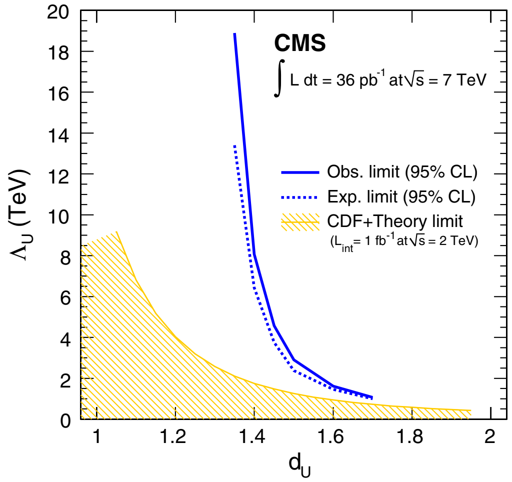

FIG. 2 (color online). Observed and expected 95% C.L. lower limits on the allowed region of unparticle model parameters d_U and Λ_U, compared to those derived from CDF results [12,13].

processes. Limits on parameters for ADD and unparticle models are derived and constitute a significant improvement over those set by previous experiments.

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