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Search for Large Extra Dimensions in the Monojet + $\not\!\!E_T$ Channel at DØ

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We present a search for large extra dimensions (ED) in $p\bar{p}$ collisions at a center-of-mass energy of 1.8 TeV using data collected by the DØ detector at the Fermilab Tevatron in 1994-1996. Data corresponding to 78.8 ± 3.9 pb^{-1} are examined for events with large missing transverse energy, one high-p$_T$ jet, and no isolated muons. With no excess beyond the background prediction from the standard model, we place limits on the fundamental Planck scale of 1 TeV (0.6 TeV) for 2 (7) ED.

The standard model (SM) of particle physics is a spectacular scientific achievement, with nearly every prediction confirmed to a high degree of precision. Nevertheless, the SM still has unresolved unappealing characteristics, including the problem of a large hierarchy in the gauge forces, with gravity being a factor of 10^{33} – 10^{38} weaker than the other three. A new framework for solving the hierarchy problem was proposed recently by Arkani-Hamed, Dimopoulos, and Dvali [1], through the introduction of large compactified extra spatial dimensions in which only gravitons propagate. In the presence of n of these extra dimensions, the fundamental Planck scale in $4+n$ dimensions is lowered to the TeV range, i.e., to a value comparable to the scale that characterizes the other three forces, thereby eliminating the puzzling hierarchy.

The radius (R) of the compactified extra dimensions can be expressed as a function of a fundamental Planck scale, $M_D \approx 1$ TeV, the number of extra dimensions n, and the usual Planck scale $M_{\rm Pl} = 1/\sqrt{G_N}$. Assuming compactification on a torus, the relationship is [2]:

$$R = \frac{1}{\sqrt[n]{8\pi} M_D} (M_{\rm Pl}/M_D)^{2/n}.$$

The value $n = 1$ is ruled out by the $1/r^2$ dependence of the gravitational force at large distances. The current limits from tests of gravity [3], as well as stringent astrophysical and cosmological bounds [4], have significantly constrained the case of two extra dimensions. For $n > 2$, the constraints from direct gravitational measurements and cosmological observations are relatively weak, however, high-energy colliders can provide effective ways to test such models of large ED.

In the framework of large ED, the strength of gravity in four dimensions is enhanced through a large number of graviton excitations, or Kaluza-Klein modes ($G_{\rm KK}$) [5] at high energies. This leads to new phenomena predicted for high energy collisions [2, 6]: virtual graviton exchange and direct graviton emission. Virtual graviton exchange leads to anomalous difermion and diboson production, and searches for these effects have been pursued at the Tevatron [7], LEP [8], and HERA [9]. For real graviton emission, since the graviton escapes detection, the signature involves large missing transverse energy $\not\!\!E_T$ accompanying a single jet or a vector boson at large transverse momentum. LEP experiments [8] and the CDF collaboration [10] have recently set limits on M_D based on $\gamma + G_{\rm KK}$ production.

In this Letter, we report the results of the first search for large ED in the jet + $\not\!\!E_T$ channel. The advantage of this channel is its relatively large cross section, with the tradeoff of large background. Besides $Z(\nu\bar{\nu})$ + jets, which is the irreducible background, there are various instrumental backgrounds from mismeasurement of, e.g., jet E_T, vertex position, undetected leptons, cosmic rays, etc. The data used for this search were collected in 1994 – 1996 by the DØ collaboration [11] at the Fermilab Tevatron, using proton-antiproton collisions at a center-of-mass energy of 1.8 TeV. This sample, representing an integrated luminosity of 78.8 ± 3.9 pb^{-1}, was obtained using $\not\!\!E_T$ triggers with thresholds between 35 and 50 GeV.

The DØ detector [11] consists of three major components: an inner detector for tracking charged particles, a uranium/liquid-argon calorimeter for measuring electromagnetic and hadronic showers, and a muon spectrometer consisting of magnetized iron toroids and three layers of drift tubes. Jets are measured with an energy resolution of approximately $\sigma(E)/E = 0.8/\sqrt{E}$ (E in GeV). $\not\!\!E_T$ is measured with a resolution of $\sigma(\not\!\!E_T) = a + b \times S_T + c \times S_T^2$, where S_T is the scalar sum of all transverse energies in the calorimenter, $a = 1.89 \pm 0.05$ GeV, $b = (6.7 \pm 0.7) \times 10^{-3}$, and $c = (9.9 \pm 2.1) \times 10^{-6}$ GeV^{-1} [12].

We select events containing one central (detector pseudorapidity $|\eta_d| \leq 1.0$ [13]) high-E_T jet (j_1) and large $\not\!\!E_T$, both values $>$ 150 GeV. Since there can be initial or final-state radiation (ISR or FSR), secondary jets can also be present. To increase signal efficiency, we allow for additional jets in the event, but require the second jet (j_2) to have $E_T(j_2) < 50$ GeV, which reduces the dijet background, while retaining the signal containing ISR or FSR. In addition, we reject events with isolated muons, $\Delta\mathcal{R}(j_1, \mu) > 0.5$, to suppress W or Z production with a muon in the final state as well as to reduce the background from cosmic rays. (The separation between objects is defined as $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where η is the pseudorapidity and ϕ is the azimuthal angle.) Backgrounds with isolated electrons are expected to be small, and we therefore do not need special criteria to suppress electrons. We also require $\Delta\phi(j_2, \not\!\!E_T) > 15°$, to reduce the background from mismeasured jets in multijet ("QCD") events. A calorimeter-based cosmic-ray criterion is used to reject events containing cosmic rays either with the photons emitted at the junction between the electromagnetic and hadronic calorimeters, or events with minimum-ionizing energy deposited by the cosmic muons. Jet "pointing", based on tracking information in the jet, is used to confirm the longitudinal position of the primary vertex by requiring that $\Delta z(j_1\text{-vertex, primary-vertex}) \leq 10$ cm. This suppresses background from cosmic rays as well as from misvertexed events. The requirements on η_d of the leading jet and on the event vertex confirmation are chosen to maximize the significance of signal relative to background. A total of 38 events remain in the data sample after all selections.

The PYTHIA Monte Carlo (MC) generator [14], with implementation of the ED signal via Ref. [15], is used to generate signal events, including the parton-level subprocesses $qg \rightarrow qG_{\mathrm{KK}}$, $q\bar{q} \rightarrow gG_{\mathrm{KK}}$, and $gg \rightarrow gG_{\mathrm{KK}}$. This is followed by the DØ fast detector simulation QSIM [16]. The signal is simulated for 2 to 7 extra dimensions, with M_D ranging from 600 GeV to 1400 GeV in 200 GeV steps. Signal acceptance varies from about 5% to 8%, depending on the values of n and M_D. The 13% uncertainty on acceptance is limited by the size of the MC samples, and is of the same order as the uncertainty from the jet energy scale [17], which is about 5% to 12%. The CTEQ3M set of parton distribution functions (PDFs) [18] is used for signal, and there is an uncertainty of about 3% to 5% from the choice of PDF.

The SM background from W and Z-boson production is also modeled by PYTHIA, followed by the QSIM detector simulation. We normalize the W and Z production cross sections to the published DØ measurements in the electron channel [19]. The sources of background are detailed in Table I. With our event selection, the contribution from other than $Z(\nu\bar{\nu})$ + jets is small, and the background from all W and Z sources is estimated as 30.2±6.4 events. The dominant uncertainty on the $Z(\nu\bar{\nu})$ + jets background estimate is from the jet energy scale. The residual background from mismeasured multijet events and cosmic muons is estimated from data, using the uncorrelated Δz and $\Delta\phi$ variables described above: we define four data samples, depending on whether the events pass or fail the above criteria; we then normalize the events that fail the event vertex confirmation to the candidate sample, using the ratio of the number of events in the two data samples within $\Delta\phi(j_2, \not\!\!E_T) \leq 15^\circ$; the background from QCD and cosmic rays in the candidate sample is thereby estimated as:

$$N_{\mathrm{QCD\ +\ cosmics}} = N^{\Delta z>10}_{\Delta\phi>15^\circ} \times N^{\Delta z\leq 10}_{\Delta\phi\leq 15^\circ} / N^{\Delta z>10}_{\Delta\phi\leq 15^\circ},$$

which corresponds to 7.8 ± 7.1 events. The uncertainty is due primarily to low statistics of the data samples. The total background estimate is 38 ± 10 events, and is dominated by the irreducible background from $Z(\nu\bar{\nu})$+ jets. As shown in Fig. 1, the $\not\!\!E_T$ distribution in the data is consistent with that expected for background. Closer examination of the event with $\not\!\!E_T$ near 450 GeV reveals that the energy deposited by the jet is concentrated in only three calorimeter layers, typical of Bremsstrahlung from a cosmic muon, rather than from a true jet. Nevertheless, the event is kept in the candidate sample, as it passes all *a priori* selection criteria. From extrapolation, we expect about 0.2 ± 0.2 background events for $\not\!\!E_T >$ 300 GeV.

TABLE I: The expected and observed number of events in the final jet + $\not\!\!E_T$ sample.

Background	N
$Z(\nu\nu)$+ jets	21.0 ± 5.1
$Z(ee)$+ jets	< 0.01
$Z(\mu\mu)$+ jets	0.01 ± 0.01
$Z(\tau\tau)$ (+ jets)	< 0.09
$W(e\nu)$+ jets	3.1 ± 0.7
$W(\mu\nu)$+ jets	0.8 ± 0.3
$W(\tau\nu)$ (+ jets)	5.2 ± 2.3
QCD and cosmics	7.8 ± 7.1
Total background	38.0 ± 9.6
Data	38

As a cross check of our background estimate, we define a data sample with the less stringent requirements while maintaining roughly the same $E_T(j_1)/E_T(j_2)$: $\not\!\!E_T$ and $E_T(j_1) > 115$ GeV and $E_T(j_2) < 40$ GeV, and estimate the background in this sample using the same techniques as described above. This yields an expectation of 105 ± 16 W/Z + jets events and 16 ± 9 QCD and cosmic ray events, consistent with the 127 events observed in the data sample. The $\not\!\!E_T$ distributions for this sample and for the expected background are shown in Fig. 2.

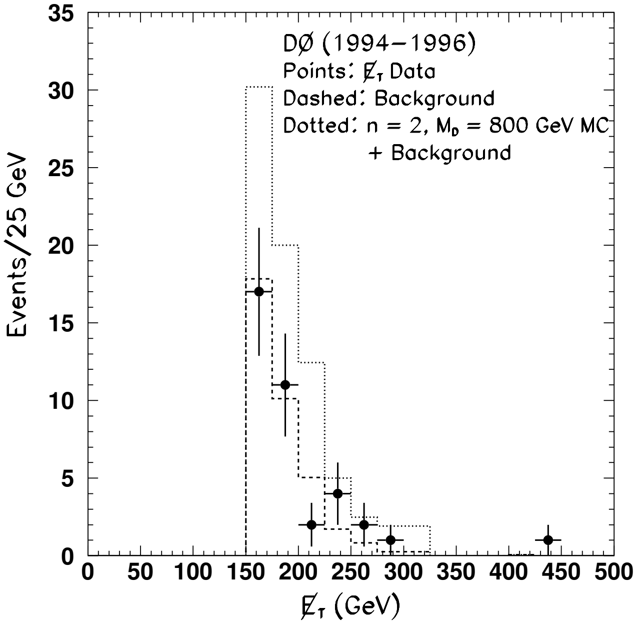

FIG. 1: Comparison of data (points with error bars), background prediction (dashed histogram), and combined signal ($n = 2$, $M_D = 800$ GeV) and background predictions (dotted histogram) for $\not\!\!E_T$, with $\not\!\!E_T$ and $E_T(j_1) > 150$ GeV and $E_T(j_2) < 50$ GeV.

In the absence of evidence for large ED, we calculate upper limits on the cross section for contributions from the processes beyond the SM. Using a Bayesian approach

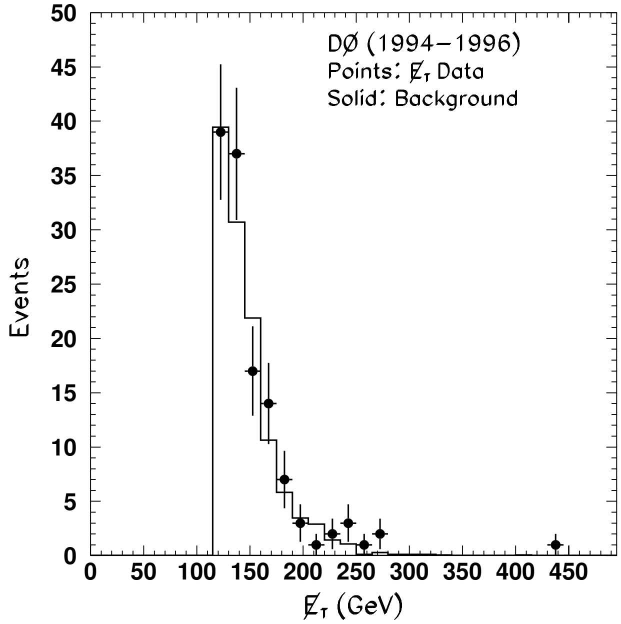

FIG. 2: Comparison of data (points with error bars) with the background prediction (solid histogram) for $\not\!E_T$, with $\not\!E_T$ and $E_T(j_1) > 115$ GeV and $E_T(j_2) < 40$ GeV.

[20], we set limits using the leading-order (LO) cross sections, as well as possible effects of next-to-leading-order (NLO) corrections, approximated via a constant K-factor of 1.34 [21], typical of similar processes, e.g., direct photon production. There are no NLO calculations for direct graviton emission which exist to date. The limits with the K-factor must be regarded as very rough approximations that only provide a measure of sensitivity to the unknown effects of NLO. The limits on the cross section can be interpreted as lower limits on the fundamental Planck scale M_D for different integer values of n, as listed in Table II. The exclusion contours at 95% confidence level, and a comparison with limits from LEP and CDF for the single-photon channel [8, 10], are shown in Fig. 3. While the DØ limits are slightly below those from LEP at low values of n, the sensitivity of the monojet search exceeds LEP sensitivity at large n, due to the higher center-of-mass energy at the Tevatron. The limits correspond to compactification radii ranging from $R < 0.6$ mm ($n = 2$) to $R < 9$ fm ($n = 7$) without correcting for the K-factor, and $R < 0.5$ mm ($n = 2$) to $R < 9$ fm ($n = 7$) with NLO effects taken into account. For all n, the sensitivity in the single-photon channel at the Tevatron is not as high as in the monojet channel, as the comparison with the CDF limits in 3 demonstrates.

TABLE II: 95% C.L. exclusion limits on M_D.

n	2	3	4	5	6	7
M_D limit without K-factor scaling (TeV)	0.89	0.73	0.68	0.64	0.63	0.62
M_D limit with K-factor scaling (TeV)	0.99	0.80	0.73	0.66	0.65	0.63

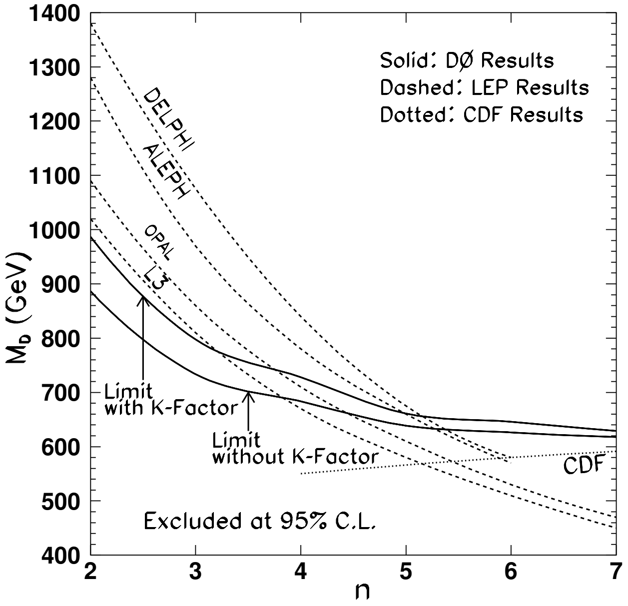

FIG. 3: The 95% C.L. exclusion contour on the fundamental Planck scale (M_D) and number of extra dimensions (n) for monojet production at DØ (solid line). Dashed curves correspond to limits from LEP, and the dotted curve is the limit from CDF, both for $\gamma + G_{\rm KK}$ production.

In summary, we have performed the first search for large extra dimensions in the monojet channel. With no evidence for large extra dimensions, we set 95% confidence level lower limits on the fundamental Planck scale between 0.6 and 1.0 TeV, depending on the number of extra dimensions. Our limits are complementary to those obtained at LEP in the single photon channel, and are most restrictive on large extra dimensions to date for $n > 5$.

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