Physics

Physics Research Publications

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Search for Kaluza-Klein graviton emission in p(p)over-bar collisions at root s=1.8 TeV using the missing energy signature

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Search for Kaluza-Klein Graviton Emission in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV Using the Missing Energy Signature

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We report on a search for direct Kaluza-Klein graviton production in a data sample of 84 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, recorded by the Collider Detector at Fermilab. We investigate the final state of large missing transverse energy and one or two high energy jets. We compare the data with the predictions from a $(3 + 1 + n)$-dimensional Kaluza-Klein scenario in which gravity becomes strong at the TeV scale. At 95% confidence level (C.L.) for $n = 2$, 4, and 6 we exclude an effective Planck scale below 1.0, 0.77, and 0.71 TeV, respectively.

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Early attempts to unify gravity and electromagnetism led to the idea of an extra circular spatial dimension [1]. Because of the periodicity of the extra dimension, the metric field of the five-dimensional spacetime is Fourier expandable in the extra dimension with four-dimensional fields [called Kaluza-Klein (KK) modes] as coefficients.

More recently, Kaluza-Klein theories appear in scenarios of large extra dimensions as introduced by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [2]. In these theories the standard model gauge theory is confined to a three-dimensional domain wall (brane), embedded in a higher dimensional compactified bulk space. Only gravity propagates in the full bulk space. The n compactified extra dimensions are assumed for simplicity to be "large" circles of common circumference R (an n torus). As a result of compactification, the gravitational field that propagates in the bulk can be expanded in a series of states known collectively as the graviton KK tower. Similar to a particle in a box, the momentum of the bulk field is quantized in the compactified dimensions. For an observer trapped on the brane, each quantum of momentum in the compactified volume appears as a KK excited state with mass $m^2 = \vec{p}_n$, where $\vec{p}_n$ is the momentum in the compactified dimensions, and with identical spin and gauge numbers.

In such a model the Planck scale M_{Pl}, the radius R of the compactified space (here assumed to be a torus), and the new effective Planck scale M_D are related by [3]

$$M_{\mathrm{Pl}}^2 = 8\pi R^n M_D^{2+n},$$

where n is the number of extra dimensions. If M_D takes values as low as a few TeV the Higgs naturalness problem [4] of the standard model can be solved by introducing a cutoff not too far above the electroweak scale with new physics entering at energies above this cutoff. The hierarchy problem of the standard model is also recast: the question of why M_{Pl} is so large compared to the Z boson mass (M_Z) is replaced with the question of why R is so large compared to $1/M_Z$, and an ultraviolet hierarchy problem is replaced with an infrared one. If we take the most optimistic case of $M_D = 1$ TeV and use $M_{\mathrm{Pl}} \sim 10^{19}$ GeV, we find that for $n = 1$, 2, 4, and 6, $R \sim 10^{11}$ m, 1 mm, 10 nm, and 10 fm, respectively.

All the states in the KK graviton tower, including the massless state, couple in an identical manner with universal strength of M_{Pl}^{-1}. However, there are $(ER)^n$ massive KK modes that are kinematically accessible in a collider process with energy E. The sum over the contribution from each KK state removes the Planck scale suppression and replaces it by powers of the fundamental scale $M_D \sim$ TeV. The interactions of the massive KK graviton modes can then be observed in collider experiments either through their direct production and emission or through their virtual exchange in standard model processes [5].

There are three processes in $p\overline{p}$ collisions that can result in the emission of a graviton and a hadronic jet: $q\overline{q} \to gG$, $qg \to qG$, and $gg \to gG$, where q and g are quarks and gluons and G is the graviton. The calculation of graviton emission is based on the effective low-energy theory that is valid below the scale M_D. The corresponding Feynman rules are cataloged in [3,6]. Since the graviton passes through the detector without decaying or interacting, the experimental signature is missing transverse energy ($\not{E}_T$) from the emitted graviton and a hadronic jet from the outgoing quark or gluon.

In this Letter we report the results of a search for the direct production of KK graviton modes using the rate of events with one or two energetic jets and large $\not{E}_T$ at the Collider Detector at Fermilab (CDF). The search is based on 84 ± 4 pb^{-1} of integrated luminosity recorded with the CDF detector during the 1994–1995 Tevatron run.

The CDF detector is described in detail in [7]. The momenta of charged particles are measured in the central tracking chamber (CTC), which is positioned inside a 1.4 T superconducting solenoidal magnet. Outside the magnet, electromagnetic and hadronic calorimeters arranged in a projective tower geometry cover the pseudorapidity region $|\eta| < 4.2$ [8] and are used to identify jets. Jets are defined as localized energy depositions in the calorimeters and are reconstructed using an iterative clustering algorithm with a fixed cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ in $\eta - \phi$ space [9]. The transverse energy of a jet is $E_T = E\sin\theta$, where E is the scalar sum of energy deposited in the calorimeter towers within the cone, and θ is the angle formed by the beamline and the cone axis [10]. For this analysis, jets are required to have $E_T \geq 15$ GeV.

The missing transverse energy is defined as the negative vector sum of the transverse energy in the electromagnetic and hadronic calorimeters, $\not{\vec{E}}_T = -\sum_i (E_i \sin\theta_i)\hat{n}_i$, where E_i is the energy of the ith tower, $\hat{n}_i$ is a transverse unit vector pointing to the center of each tower, and θ_i is the polar angle of the tower. The sum extends to $|\eta| = 3.6$. The data sample was selected with an online trigger that requires $\not{E}_T \equiv |\not{\vec{E}}_T| > 30$ GeV. This is a sample dominated by instrumental backgrounds and by multijet events, where the observed missing energy is largely a result of jet mismeasurements and detector resolution.

The two-stage preselection we use to reject beam and detector-related backgrounds, beam halo, and cosmic ray events is described in [11]. Events that pass the preselection are then required to have only one or two jets with $E_T \geq 15$ GeV, with at least one jet within $|\eta| < 1.1$.

We remove events where the missing energy is due to energy flow from a jet to an uninstrumented region of the detector by requiring that the second highest E_T jet does not point in η to a detector gap if it is within 0.5 rad in ϕ of the $\not{E}_T$ direction. We reduce the residual mismeasured multijet backgrounds by requiring that the minimum $\delta\phi$ between the $\not{E}_T$ vector and any jet in the event ($\delta\phi_{\rm min}$) is greater than 0.3 rad and the z position of the event vertex is within 60 cm of the nominal interaction point.

To reduce the physics background contribution from electroweak processes with leptons in the final state [dominated by $W(\to \ell\nu)$] we require that the two highest energy jets are not purely electromagnetic (by requiring the electromagnetic fraction $f_{\rm em} \equiv E_{\rm em}/E_{\rm Tot} \leq 0.9$) and the isolated track multiplicity, $N_{\rm trk}^{\rm iso}$ [12] is zero. For the final sample, we require $\not{E}_T \geq 80$ GeV, $E_T \geq 80$ GeV for the leading jet and $E_T \geq 30$ GeV for the second jet if there is more than one jet in the event. By accepting events with an energetic second jet we can reliably normalize the background predictions from QCD simulation using the jet data, control the systematic uncertainty on the signal due to initial/final state radiation (ISR/FSR), and interpret the results with a K factor [the ratio of the cross sections at leading-order (LO) and next-to-leading-order (NLO), $K = \sigma_{\rm NLO}/\sigma_{\rm LO}$] included in the estimated signal cross section.

The selection requirements and the number of events passing at each stage are summarized in Table I.

Background events with missing energy and one or two jets arise from standard model sources, predominantly $Z(\to \nu\bar{\nu})$ + jets, $W(\to \ell\nu)$ + jets ($\ell = \tau, \mu, e$), and residual QCD production. While $Z(\to \nu\bar{\nu})$ + jets produces real $\not{E}_T$ + jets, $W(\to \ell\nu)$ + jets mimics our signal when the lepton is lost or misidentified. To estimate the Z + jets and W + jets background levels and their uncertainties in the final sample we normalize PYTHIA [13] Monte Carlo (MC) predictions using the observed $Z(\to e^+e^-)$ + jets data sample. QCD dijet events mimic our signal when one jet is badly mismeasured, resulting in large $\not{E}_T$. For the QCD predictions we use the HERWIG MC program [14] and normalize to the high statistics jet data samples using

TABLE I. The data selection path for the $\not{E}_T$ plus one or two jets search.

Selection requirement	Events passing
Pre-selection	300 945
$1 \leq N_{\rm jet} \leq 2$ (cone 0.7, $E_T \geq 15$ GeV) $\lvert\eta\rvert(1 \text{ or } 2) < 1.1$	157 035
2nd jet gap veto $\delta\phi_{\rm min} \geq 0.3$ $\lvert z_{\rm vertex}\rvert \leq 60$ cm	50 938
$f_{\rm em}(1)$, $f_{\rm em}(2) \leq 0.9$	21 012
$N_{\rm trk}^{\rm iso} = 0$	16 459
$E_T(1) \geq 80$ GeV If $N_{\rm jet} = 2$, $E_T(2) \geq 30$ GeV	897
$\not{E}_T \geq 80$ GeV	284

TABLE II. The predicted number of events in the final sample from standard model sources and the number observed in the data.

Background source	Predicted events
$Z(\to \nu\bar{\nu})$ + jets	160.2 ± 11.5
$W(\to \tau\nu)$ + jets	46.6 ± 5.5
$W(\to \mu\nu)$ + jets	23.8 ± 5.0
$W(\to e\nu)$ + jets	18.1 ± 4.3
QCD	21.7 ± 6.7
$t\bar{t}$, single t, dibosons	3.9 ± 0.3
Total predicted	274.1 ± 15.9
Observed	284

well-balanced dijet events. We estimate additional backgrounds from $t\bar{t}$, single top, and diboson production using MC predictions [13,14], which we normalize using the respective theoretical cross section calculations for these processes [15].

The predicted backgrounds from standard model processes are summarized in Table II. Of the 274 total events predicted to pass our selection requirements, 160 are predicted to come from $Z(\to \nu\bar{\nu})$ + jets, 89 from the combined $W(\to \ell\nu)$ + jets electroweak processes, and 22 from QCD production. Because the MC predictions have been normalized to high statistics data samples, the dominant uncertainty on the W + jets and Z + jets predictions is the 4% luminosity uncertainty. The QCD prediction has an additional 14% uncertainty due to jet energy resolution [11]. We observe 284 events in the data. In Fig. 1 the predicted standard model $\not{E}_T$ distribution is compared with the distribution we observe in the data. In Fig. 2 the same comparison is shown for other kinematic distributions. In both figures the data are consistent with the expected background. An additional contribution from graviton production would result in a smooth excess over the background in nearly all the kinematic distributions, as shown in Fig. 3 for $\not{E}_T$.

We use the PYTHIA MC program to generate datasets of graviton emission, using the leading-order production cross sections calculated in [3]. The signal processes are simulated for $n = 2$, 4, and 6 extra dimensions, and for a range of values of M_D. The signal efficiency ranges from 2.9% for two extra dimensions to 6.4% for six extra dimensions (due to different relative weights of the three production processes) and is largely independent of M_D. The total relative systematic uncertainty on the signal efficiency is 25%, mostly due to modeling of ISR/FSR (21%), jet energy scale (11%), renormalization scale (8%), and parton density functions (2%) [16].

Using a Monte Carlo technique to convolute the uncertainty on the background estimate with the relative systematic uncertainty on the signal efficiency, the 95% C.L. [17] upper limit on the number of signal events is 62. As shown in Fig. 4, for $K = 1.0$ we exclude an effective Planck scale less than 1.00 TeV for $n = 2$, less than 0.77 TeV for $n = 4$, and less than 0.71 TeV for $n = 6$. Recently the D0 Collaboration reported a limit on direct graviton emission using a K factor of 1.3 in the signal cross section [18]. They report limits of 0.99 TeV for $n = 2$, 0.73 TeV for $n = 4$ and 0.65 TeV for $n = 6$. For

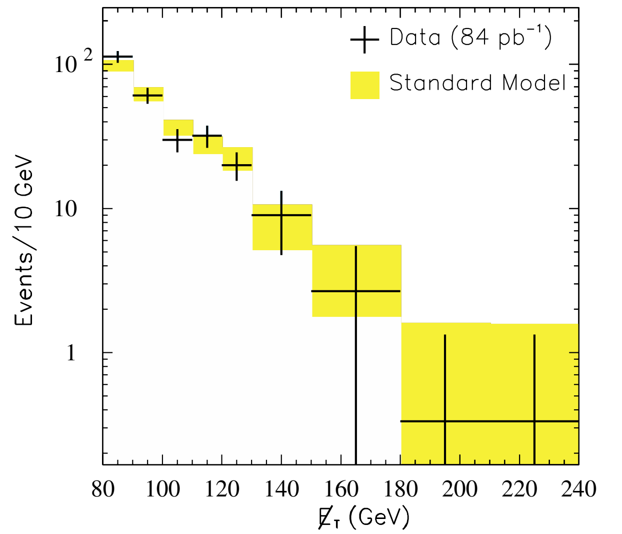

FIG. 1 (color online). Comparison between data (points) and standard model predictions (boxes) of the $\not{E}_T$ distribution. There are 284 data events, to be compared with 274 ± 16 events predicted from standard model sources. The distribution is plotted with a variable bin size; the contents for bin sizes greater than 10 GeV are normalized accordingly. The height of the boxes shows the uncertainty on the standard model prediction.

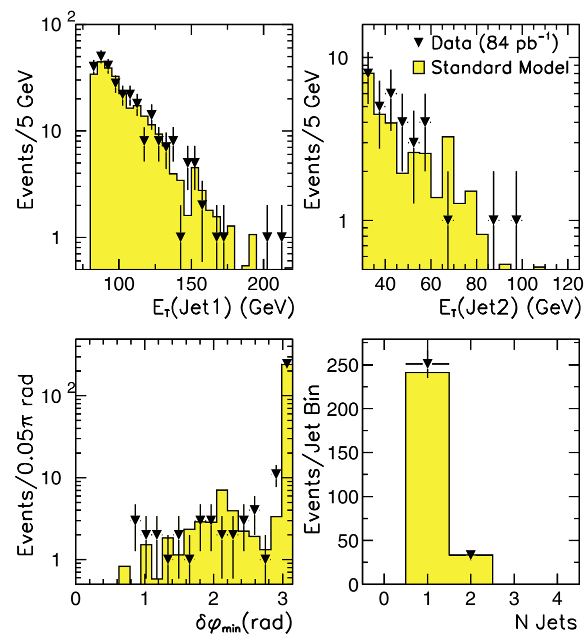

FIG. 2 (color online). Comparison between data (points) and standard model predictions (histogram) of the first and second leading jet E_T, $\delta\phi_{\rm min}$, and $N_{\rm jet}$ distributions.

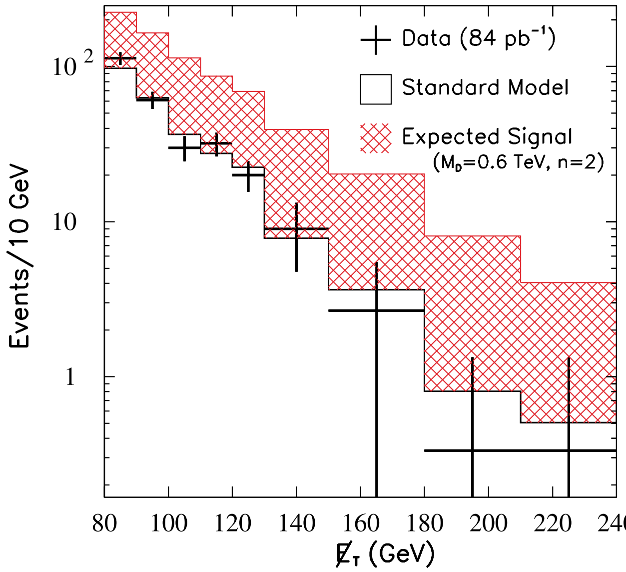

FIG. 3 (color online). The predicted $\not{E}_T$ distribution from standard model processes (histogram) and the one from the expected graviton signal (for $n = 2$, $M_D = 0.6$ TeV, and a K factor of 1.0) added to the standard model (hatched). The signal appears as a smooth excess over the standard model background. The points are the observed data.

direct comparison, using $K = 1.3$ our corresponding lower limits on M_D are 1.06 TeV for $n = 2$, 0.80 TeV for $n = 4$, and 0.73 TeV for $n = 6$.

These are the best limits to date on direct graviton emission [18,19] from the Tevatron.

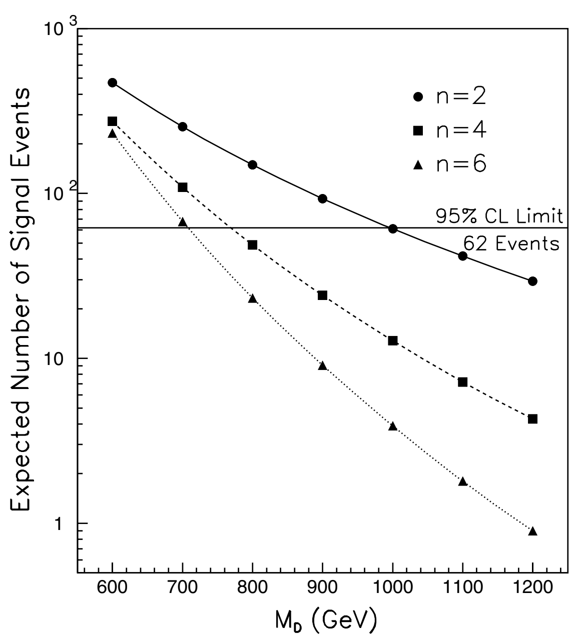

FIG. 4. The three curves show the number of expected signal events for $n = 2$, 4, and 6 extra dimensions as a function of the effective Planck scale M_D for a K factor of 1.0. The straight line shows the 95% C.L. upper limit on the number of signal events.

Assuming compactification on a torus, the limits on M_D with $K = 1.0$ correspond to limits on the compactification radius of $R < 0.48$ mm for $n = 2$, $R < 0.014$ nm for $n = 4$, and $R < 42$ fm for $n = 6$.

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