Search for Large Extra Dimensions via Virtual Graviton Effects at DØ

The DØ Collaboration *
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
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Abstract

We report a search for large spatial extra dimensions (ED) in data at $p\bar{p}$ center-of-mass energy of 1.8 TeV, containing pairs of electromagnetic objects. The data collected with the DØ detector in 1992–1996 are in good agreement with expected background and do not exhibit evidence for large ED. We set a lower limit on the effective Planck scale between 0.95 TeV and 1.4 TeV, at 95% confidence level, depending on the number of additional large ED. These are the most restrictive direct limits to date.

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B. Abbott,[48] M. Abolins,[45] V. Abramov,[21] B.S. Acharya,[15] D.L. Adams,[55] M. Adams,[32] G.A. Alves,[2] N. Amos,[44] E.W. Anderson,[37] M.M. Baarmand,[50] V.V. Babintsev,[21] L. Babukhadia,[50] A. Baden,[41] B. Baldin,[31] S. Banerjee,[15] J. Bantly,[54] E. Barberis,[24] P. Baringer,[38] J.F. Bartlett,[31] U. Bassler,[11] A. Bean,[38] M. Begel,[49] A. Belyaev,[20] S.B. Beri,[13] G. Bernardi,[11] I. Bertram,[22] A. Besson,[9] V.A. Bezzubov,[21] P.C. Bhat,[31] V. Bhatnagar,[13] M. Bhattacharjee,[50] G. Blazey,[33] S. Blessing,[29] A. Boehnlein,[31] N.I. Bojko,[21] F. Borcherding,[31] A. Brandt,[55] R. Breedon,[25] G. Briskin,[54] R. Brock,[45] G. Brooijmans,[31] A. Bross,[31] D. Buchholz,[34] M. Buehler,[32] V. Buescher,[49] V.S. Burtovoi,[21] J.M. Butler,[42] F. Canelli,[49] W. Carvalho,[3] D. Casey,[45] Z. Casilum,[50] H. Castilla-Valdez,[17] D. Chakraborty,[50] K.M. Chan,[49] S.V. Chekulaev,[21] D.K. Cho,[49] S. Choi,[28] S. Chopra,[51] B.C. Choudhary,[28] J.H. Christenson,[31] M. Chung,[32] D. Claes,[46] A.R. Clark,[24] J. Cochran,[28] L. Coney,[36] B. Connolly,[29] W.E. Cooper,[31] D. Coppage,[38] M.A.C. Cummings,[33] D. Cutts,[54] O.I. Dahl,[24] G.A. Davis,[49] K. Davis,[23] K. De,[55] K. Del Signore,[44] M. Demarteau,[31] P. Demine,[9] D. Denisov,[31] S.P. Denisov,[21] H.T. Diehl,[31] M. Diesburg,[31] G. Di Loreto,[45] S. Doulas,[43] P. Draper,[55] Y. Ducros,[12] L.V. Dudko,[20] S.R. Dugad,[15] A. Dyshkant,[21] D. Edmunds,[45] J. Ellison,[28] V.D. Elvira,[31] R. Engelmann,[50] S. Eno,[41] G. Eppley,[57] P. Ermolov,[20] O.V. Eroshin,[21] J. Estrada,[49] H. Evans,[47] V.N. Evdokimov,[21] T. Fahland,[27] S. Feher,[31] D. Fein,[23] T. Ferbel,[49] H.E. Fisk,[31] Y. Fisyak,[51] E. Flattum,[31] F. Fleuret,[24] M. Fortner,[33] K.C. Frame,[45] S. Fuess,[31] E. Gallas,[31] A.N. Galyaev,[21] P. Gartung,[28] V. Gavrilov,[19] R.J. Genik II,[22] K. Genser,[31] C.E. Gerber,[31] Y. Gershtein,[54] B. Gibbard,[51] R. Gilmartin,[29] G. Ginther,[49] B. Gómez,[5] G. Gómez,[41] P.I. Goncharov,[21] J.L. González Solís,[17] H. Gordon,[51] L.T. Goss,[56] K. Gounder,[28] A. Goussiou,[50] N. Graf,[51] P.D. Grannis,[50] J.A. Green,[37] H. Greenlee,[31] S. Grinstein,[1] P. Grudberg,[24] S. Grünendahl,[31] A. Gupta,[15] S.N. Gurzhiev,[21] G. Gutierrez,[31] P. Gutierrez,[53] N.J. Hadley,[41] H. Haggerty,[31] S. Hagopian,[29] V. Hagopian,[29] K.S. Hahn,[49] R.E. Hall,[26] P. Hanlet,[43] S. Hansen,[31] J.M. Hauptman,[37] C. Hays,[47] C. Hebert,[38] D. Hedin,[33] A.P. Heinson,[28] U. Heintz,[42] T. Heuring,[29] R. Hirosky,[32] J.D. Hobbs,[50] B. Hoeneisen,[8] J.S. Hoftun,[54] A.S. Ito,[31] S.A. Jerger,[45] R. Jesik,[35] K. Johns,[23] M. Johnson,[31] A. Jonckheere,[31] M. Jones,[30] H. Jöstlein,[31] A. Juste,[31] S. Kahn,[51] E. Kajfasz,[10] D. Karmanov,[20] D. Karmgard,[36] R. Kehoe,[36] S.K. Kim,[16] B. Klima,[31] C. Klopfenstein,[25] B. Knuteson,[24] W. Ko,[25] J.M. Kohli,[13] A.V. Kostritskiy,[21] J. Kotcher,[51] A.V. Kotwal,[47] A.V. Kozelov,[21] E.A. Kozlovsky,[21] J. Krane,[37] M.R. Krishnaswamy,[15] S. Krzywdzinski,[31] M. Kubantsev,[39] S. Kuleshov,[19] Y. Kulik,[50] S. Kunori,[41] V. Kuznetsov,[28] G. Landsberg,[54] A. Leflat,[20] F. Lehner,[31] J. Li,[55] Q.Z. Li,[31] J.G.R. Lima,[3] D. Lincoln,[31] S.L. Linn,[29] J. Linnemann,[45] R. Lipton,[31] A. Lucotte,[50] L. Lueking,[31] C. Lundstedt,[46] A.K.A. Maciel,[33] R.J. Madaras,[24] V. Manankov,[20] S. Mani,[25] H.S. Mao,[4] T. Marshall,[35] M.I. Martin,[31] R.D. Martin,[32] K.M. Mauritz,[37] B. May,[34] A.A. Mayorov,[35] R. McCarthy,[50] J. McDonald,[29] T. McMahon,[52] H.L. Melanson,[31] X.C. Meng,[4] M. Merkin,[20] K.W. Merritt,[31] C. Miao,[54] H. Miettinen,[57] D. Mihalcea,[53] A. Mincer,[48] C.S. Mishra,[31] N. Mokhov,[31] N.K. Mondal,[15] H.E. Montgomery,[31] M. Mostafa,[1] H. da Motta,[2] E. Nagy,[10] F. Nang,[23] M. Narain,[42] V.S. Narasimham,[15] H.A. Neal,[44] J.P. Negret,[5] S. Negroni,[10] D. Norman,[56] L. Oesch,[44] V. Oguri,[3] B. Olivier,[11] N. Oshima,[31] P. Padley,[57] L.J. Pan,[34] A. Para,[31] N. Parashar,[43] R. Partridge,[54] N. Parua,[9] M. Paterno,[49] A. Patwa,[50] B. Pawlik,[18] J. Perkins,[55] M. Peters,[30] R. Piegaia,[1] H. Piekarz,[29] B.G. Pope,[45] E. Popkov,[36] H.B. Prosper,[29] S. Protopopescu,[51] J. Qian,[44] P.Z. Quintas,[31]

R. Raja,[31] S. Rajagopalan,[51] E. Ramberg,[31] N.W. Reay,[39] S. Reucroft,[43] J. Rha,[28]
M. Rijssenbeek,[50] T. Rockwell,[45] M. Roco,[31] P. Rubinov,[31] R. Ruchti,[36] J. Rutherfoord,[23]
A. Santoro,[2] L. Sawyer,[40] R.D. Schamberger,[50] H. Schellman,[34] A. Schwartzman,[1]
J. Sculli,[48] N. Sen,[57] E. Shabalina,[20] H.C. Shankar,[15] R.K. Shivpuri,[14] D. Shpakov,[50]
M. Shupe,[23] R.A. Sidwell,[39] V. Simak,[7] H. Singh,[28] J.B. Singh,[13] V. Sirotenko,[33]
P. Slattery,[49] E. Smith,[53] R.P. Smith,[31] R. Snihur,[34] G.R. Snow,[46] J. Snow,[52] S. Snyder,[51]
J. Solomon,[32] V. Sorín,[1] M. Sosebee,[55] N. Sotnikova,[20] K. Soustruznik,[6] M. Souza,[2]
N.R. Stanton,[39] G. Steinbrück,[47] R.W. Stephens,[55] M.L. Stevenson,[24] F. Stichelbaut,[51]
D. Stoker,[27] V. Stolin,[19] D.A. Stoyanova,[21] M. Strauss,[53] K. Streets,[48] M. Strovink,[24]
L. Stutte,[31] A. Sznajder,[3] W. Taylor,[50] S. Tentindo-Repond,[29] J. Thompson,[41]
D. Toback,[41] T.G. Trippe,[24] A.S. Turcot,[51] P.M. Tuts,[47] P. van Gemmeren,[31] V. Vaniev,[21]
R. Van Kooten,[35] N. Varelas,[32] A.A. Volkov,[21] A.P. Vorobiev,[21] H.D. Wahl,[29] H. Wang,[34]
Z.-M. Wang,[50] J. Warchol,[36] G. Watts,[58] M. Wayne,[36] H. Weerts,[45] A. White,[55]
J.T. White,[56] D. Whiteson,[24] J.A. Wightman,[37] S. Willis,[33] S.J. Wimpenny,[28]
J.V.D. Wirjawan,[56] J. Womersley,[31] D.R. Wood,[43] R. Yamada,[31] P. Yamin,[51] T. Yasuda,[31]
K. Yip,[31] S. Youssef,[29] J. Yu,[31] Z. Yu,[34] M. Zanabria,[5] H. Zheng,[36] Z. Zhou,[37] Z.H. Zhu,[49]
M. Zielinski,[49] D. Zieminska,[35] A. Zieminski,[35] V. Zutshi,[49] E.G. Zverev,[20]
and A. Zylberstejn[12]

(DØ Collaboration)

[1]Universidad de Buenos Aires, Buenos Aires, Argentina
[2]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[3]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[4]Institute of High Energy Physics, Beijing, People's Republic of China
[5]Universidad de los Andes, Bogotá, Colombia
[6]Charles University, Prague, Czech Republic
[7]Institute of Physics, Academy of Sciences, Prague, Czech Republic
[8]Universidad San Francisco de Quito, Quito, Ecuador
[9]Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France
[10]CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France
[11]LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France
[12]DAPNIA/Service de Physique des Particules, CEA, Saclay, France
[13]Panjab University, Chandigarh, India
[14]Delhi University, Delhi, India
[15]Tata Institute of Fundamental Research, Mumbai, India
[16]Seoul National University, Seoul, Korea
[17]CINVESTAV, Mexico City, Mexico
[18]Institute of Nuclear Physics, Kraków, Poland
[19]Institute for Theoretical and Experimental Physics, Moscow, Russia
[20]Moscow State University, Moscow, Russia
[21]Institute for High Energy Physics, Protvino, Russia
[22]Lancaster University, Lancaster, United Kingdom
[23]University of Arizona, Tucson, Arizona 85721
[24]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720

[25]University of California, Davis, California 95616
[26]California State University, Fresno, California 93740
[27]University of California, Irvine, California 92697
[28]University of California, Riverside, California 92521
[29]Florida State University, Tallahassee, Florida 32306
[30]University of Hawaii, Honolulu, Hawaii 96822
[31]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[32]University of Illinois at Chicago, Chicago, Illinois 60607
[33]Northern Illinois University, DeKalb, Illinois 60115
[34]Northwestern University, Evanston, Illinois 60208
[35]Indiana University, Bloomington, Indiana 47405
[36]University of Notre Dame, Notre Dame, Indiana 46556
[37]Iowa State University, Ames, Iowa 50011
[38]University of Kansas, Lawrence, Kansas 66045
[39]Kansas State University, Manhattan, Kansas 66506
[40]Louisiana Tech University, Ruston, Louisiana 71272
[41]University of Maryland, College Park, Maryland 20742
[42]Boston University, Boston, Massachusetts 02215
[43]Northeastern University, Boston, Massachusetts 02115
[44]University of Michigan, Ann Arbor, Michigan 48109
[45]Michigan State University, East Lansing, Michigan 48824
[46]University of Nebraska, Lincoln, Nebraska 68588
[47]Columbia University, New York, New York 10027
[48]New York University, New York, New York 10003
[49]University of Rochester, Rochester, New York 14627
[50]State University of New York, Stony Brook, New York 11794
[51]Brookhaven National Laboratory, Upton, New York 11973
[52]Langston University, Langston, Oklahoma 73050
[53]University of Oklahoma, Norman, Oklahoma 73019
[54]Brown University, Providence, Rhode Island 02912
[55]University of Texas, Arlington, Texas 76019
[56]Texas A&M University, College Station, Texas 77843
[57]Rice University, Houston, Texas 77005
[58]University of Washington, Seattle, Washington 98195

The possibility that the universe has more than just three spatial dimensions has been discussed for a long time [1]. For example, string theory suggests that there could be up to seven additional spatial dimensions, compactified at very small distances, $\approx 10^{-32}$ m. A recent model [2] by Arkani-Hamed, Dimopoulos, and Dvali (ADD), inspired by string theory, has several of the compactified extra dimensions quite large, perhaps as big as 1 mm. These large extra dimensions (LED) are introduced to solve the hierarchy problem of the standard model (SM) by bringing the Planck scale, $M_{\rm Pl}$, down to the TeV energy range. In what follows, we refer to this "effective" Planck scale as M_S. The radius of compactification of the LED depends on the number of extra dimensions (n) and on M_S: $R \propto \frac{1}{M_S}(M_{\rm Pl}/M_S)^{2/n}$. Since Newton's law of gravity would be modified in the presence of compactified extra dimensions for interaction distances below the size of the largest extra dimension, current gravitational observations rule out the case of one large extra dimension. Recent preliminary results from gravity experiments at submillimeter distances [3], as well as cosmological constraints [4], indicate that the case of $n = 2$ is likely ruled out as well. However, for any $n \geq 3$ the size of the LED becomes microscopic, and therefore eludes the reach of direct gravitational measurements. Cosmological constraints also become weak in this case. That leaves particle accelerators, capable of probing matter to very short distances, as the crucial test of LED theories. In these theories, the effects of gravity are enhanced at high energies due to multiple winding modes of the graviton around the compactified dimensions (referred to as Kaluza-Klein [5] modes of the graviton, $G_{\rm KK}$). Thus, high energy colliders offer the best way to search for effects of LED. Since gravitons couple to the energy-momentum tensor, they can be produced in any SM process.

LED phenomenology at colliders has been studied in great detail [6–9]. One of the main observable effects involve direct emission of gravitons that leave our three spatial dimensions, and thereby yield apparent non-conservation of momentum (a typical signature is the production of a single jet or vector boson at large transverse momentum). The other observable effect is due to virtual gravitons produced in interactions of beam particles, with the subsequent decay into a pair of fermions or gauge bosons of large invariant mass (M). The primary difference between direct graviton emission and virtual graviton effects is that the former is suppressed by a factor $(M/M_S)^{n+2}$, while the latter depends only weakly on the number of extra dimensions [6,9]. Virtual graviton production therefore offers a potentially more sensitive way to search for manifestations of LED [10].

Both effects have been sought at LEP [11], with lower limits on the effective Planck scale set on the order of 1 TeV. In this Letter, we report results of the first specific search for LED at hadron colliders. The data are from the DØ detector [12] at the Fermilab Tevatron, using proton-antiproton collisions at beam energies of 900 GeV, and final states involving dileptons and diphotons. Following the prescription of Ref. [13], we analyze the double differential distribution of dilepton or diphoton events in terms of their invariant mass and the scattering angle in their center-of-mass frame (θ^*). These two variables completely define the $2 \to 2$ scattering processes, and their properties provide the best possible separation of contributions from SM background and the effects of virtual graviton exchange, thereby improving sensitivity over traditional analyses of just invariant-mass distributions [13].

Several modifications to the method of Ref. [13] are introduced in order to optimize the sensitivity of the search for the DØ apparatus. Because dimuon detection efficiency and mass resolution are worse than for electromagnetic (EM) objects, we use only the dielectron and diphoton channels, with sensitivity to LED coming primarily from the diphoton events [13]. Second, in order to optimize efficiency for diphoton and dielectron selection, we eliminate tracking requirements from electron and photon identification, thereby effectively combining them. Indeed, photons often have associated charged tracks from conversion in material in front of the calorimeter or from random overlap of tracks from the underlying event. Also, in a large fraction of dielectron events, an electron track is not well reconstructed due to tracking inefficiency. Neither electrons without tracks nor photons with tracks are lost in the detector, they are merely misclassified. Consequently, ignoring tracking information maximizes the combined dielectron and diphoton efficiency. In what follows, we refer to electron or photon objects that do not use tracking confirmation as EM objects. Finally, the dominant background (B) at high mass, where LED effects are enhanced, is the irreducible SM background from direct-diphoton production, and not instrumental background from misidentification of jets as EM objects (see, e.g., [14]). Hence, increasing the di-EM identification (ID) efficiency by using loose EM ID criteria, results in better sensitivity to LED, because the significance of the signal (S), $S/\sqrt{B}$, increases as the square root of the efficiency.

The search is based on the entire sample of data collected in 1992–1996 using a trigger that requires the presence of two EM objects and corresponds to an integrated luminosity of 126.8 ± 5.6 pb^{-1}.

The offline selection criteria required: (i) two EM objects with $E_T > 45$ GeV located in a good fiducial region of the detector ($|\eta_d| < 1.1$ or $1.5 < |\eta_d| < 2.5$), where η_d is the "detector" pseudorapidity [15]; (ii) small missing transverse energy in the event ($\not\!\!E_T < 25$ GeV); and (iii) no additional EM objects in the event with $E_T^{\mathrm{EM}} > 5$ GeV. The trigger is fully efficient for this set of offline selections.

To determine the hard-scattering vertex, we calculate the most probable direction of each EM object using the transverse and longitudinal segmentation of the EM calorimeter [16]. These directions determine the position of the interaction vertex along the beam axis. We prefer this EM-cluster-based vertex-finding technique relative to our standard procedure [12] since it does not use tracking information, and thus treats the diphoton and dielectron events in the same way.

We require each EM object to: (i) have more than 95% of the cluster energy deposited in the EM calorimeter; (ii) have a cluster shape consistent with that expected for an EM object; and (iii) be isolated [16]. The overall efficiency for these selections, based on $Z \to ee$ events, is $88 \pm 2\%$ per EM object, or $76 \pm 2\%$ per event. The above criteria define our base sample, which contains 1282 candidate events.

We model the effects of LED via the parton-level leading-order (LO) Monte Carlo (MC) generator of Ref. [13], augmented with a parametric simulation of the DØ detector. The modeling takes into account detector acceptance and resolution for the EM objects, smearing and misidentification of the primary interaction vertex, the effect of different parton distributions, and initial state radiation. The parameters of the detector model are tuned using independent samples of collider data. The MC takes into account the SM contributions (i.e., Z/γ^* and direct diphoton production), Kaluza-Klein graviton exchange diagrams, and their interference.

Since the parton-level generator involves only the $2 \to 2$ hard-scattering process, we model next-to-leading order (NLO) effects by adding a random transverse momentum to the di-EM system, chosen to follow the transverse momentum spectrum of dielectrons or diphotons observed in data. (These distributions are similar for dielectron and diphoton production, as was demonstrated with the PYTHIA [17] generator.) In the presence of the NLO corrections, the scattering angle, θ^*, is defined in the di-EM helicity frame, i.e., relative to the direction of the boost of the di-EM system. Since the parton-level cross section is calculated at LO, we account for NLO effects in the SM background by scaling the cross sections by a constant K-factor of 1.3 [18]. We assign a 10% systematic uncertainty on the value of the K-factor to account for a possible growth of the K-factor at high mass. NLO corrections to the Kaluza-Klein diagrams have not been calculated as yet. We therefore use the same constant K-factor for the signal. The K-factor for graviton exchange is expected to grow with the invariant mass M, similar to that for Z/γ^* exchange; consequently, our assumption tends to underestimate the LED contribution at high di-EM invariant mass, and hence can be regarded as conservative.

The main SM sources of di-EM production, Drell-Yan and direct diphoton production, are included in the MC. Other SM sources, such as $W\gamma$, $Z\gamma$, WW, $Z \rightarrow \tau\tau$, and $t\bar{t}$ are negligible (most have small cross section compared to that for Drell-Yan and direct diphoton processes, and are reduced further by requirements of low missing transverse energy and exactly two EM objects in the event). The only additional sources of background arise from single-photon and dijet events, with jet(s) misidentified as EM objects. We estimate this background using a separate sample collected with a trigger requiring a single EM object with transverse energy above the 30-40 GeV range. We require that a combination of a jet and the EM object satisfy all the requirements for signal, except with EM ID requirements applied only to the EM object. We obtain the instrumental background by scaling the number of jet-EM combinations passing our selection criteria by the probability of a jet to be mistaken for an EM object, which is measured to be $0.18 \pm 0.04\%$, and, within our errors, independent of transverse energy or rapidity [19]. The other source of instrumental background, $W+$ jets production with a jet misidentified as an EM object, is negligible due to the requirement of low $\not\!\!E_T$. The total number of instrumental-background events in the base sample is 87 ± 22, less than 7% of the inherent SM background. The sum of the SM background (estimated with the MC generator) and the instrumental background (obtained from data) reproduces the main kinematic characteristics of the base sample, as illustrated in Fig. 1.

We follow Refs. [6,7,9] to describe LED effects via a single variable $\eta = \mathcal{F}/M_S^4$, where $\mathcal{F}$ is a dimensionless parameter of order unity and reflects the dependence of the virtual $G_{\rm KK}$ exchange on the number of extra dimensions. Different formalisms use somewhat different definitions for F:

$$\mathcal{F} = 1, \text{ (GRW, [6])}; \tag{1}$$

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{M}\right), & n = 2 \\ \frac{2}{n-2}, & n > 2 \end{cases}, \text{ (HLZ, [7])}; \tag{2}$$

$$\mathcal{F} = \pm\frac{2}{\pi}, \text{ (Hewett, [9])} \tag{3}$$

(where HLZ included the dependence on n).

Figure 2 shows the two-dimensional distribution in M and $|\cos\theta^*|$ for data in (a), total

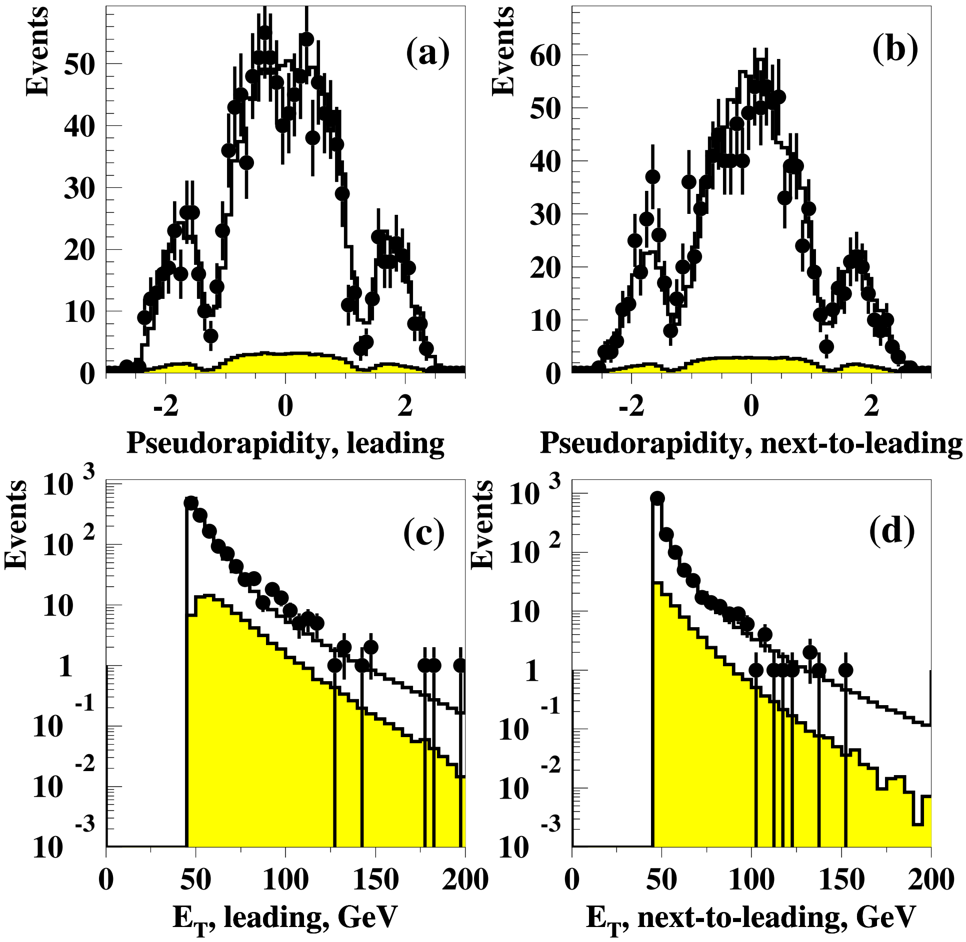

FIG. 1. Comparison of data (error bars) and background predictions (solid histogram) for the pseudorapidity and transverse energy of the two EM objects in the event. The shaded histogram shows the contribution from instrumental background. The dips in pseudorapidity reflect the acceptance cuts.

background in (b), and the sum of background and the LED signal for $\eta = 1$ TeV^{-4} in (c). The data agree well with background predictions, and do not do not exhibit evidence for LED, which would produce an excess of events at large mass and small values of $|\cos\theta^*|$ (see Fig. 2c). A comparison of Figs. 2b and 2c reveals the reason for better sensitivity of this analysis to LED than the one based just on invariant mass: the SM contributes at small scattering angles, which has origin in the collinear divergence in direct-diphoton production, while the signal from LED is expected at larger scattering angles. This difference is apparent in Fig. 2d, which shows the distribution in $|\cos\theta^*|$ for events with $M > 300$ GeV. Both the background (instrumental – shaded, and the sum of all SM – solid line) and data at high mass are found mainly at large $|\cos\theta^*|$, while the LED signal tends to populate smaller $|\cos\theta^*|$. The improvement in sensitivity to LED in the 2-D method corresponds to about

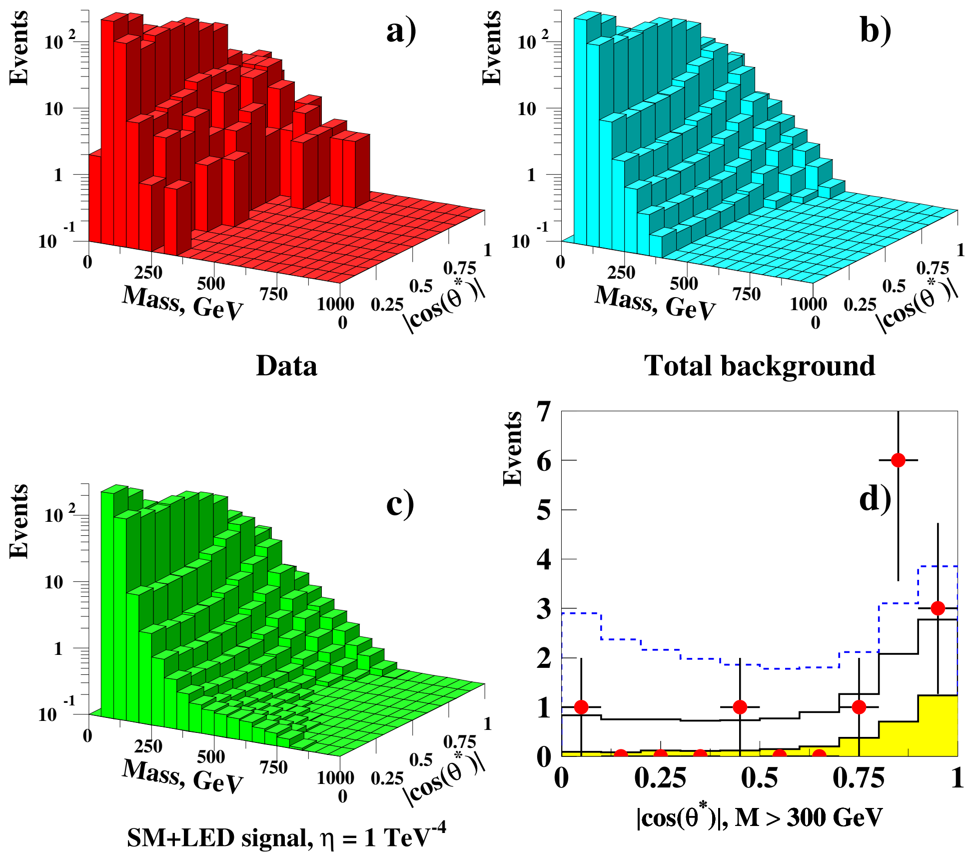

FIG. 2. Double differential cross section in di-EM mass and $|\cos\theta^*|$ for: (a) data, (b) background, (c) background and LED signal for $\eta = 1$ TeV^{-4}, and (d) $\cos\theta^*$ distribution for events with $M > 300$ GeV, where the instrumental background is shown shaded, the entire background from SM sources is given by the solid line, and the dotted line corresponds to the sum of SM and LED for $\eta = 1$ TeV^{-4}.

20% reduction in the require integrated luminosity, compared to a one-dimensional mass analysis.

Since the data do not exhibit evidence for LED, we proceed to set limits on the effective Planck scale. The cross section in the presence of LED is given by:

$$\frac{d^2\sigma}{dM\,d\cos\theta^*} = f_{\rm SM}(M,\cos\theta^*) + f_{\rm int}(M,\cos\theta^*)\eta + f_{\rm KK}(M,\cos\theta^*)\eta^2, \quad (4)$$

where $f_{\rm SM}$, $f_{\rm int}$, and $f_{\rm KK}$ denote the SM, interference, and $G_{\rm KK}$ terms. (We also add the instrumental background to the SM term.) We perform a Bayesian fit of Eq. (4) to the data in the entire M-$|\cos\theta^*|$ phase space shown in Fig. 2, with η being a free parameter of the fit with a flat prior. The systematic uncertainties on signal and background in the fit include

TABLE I. Limits on the effective Planck scale, M_S, in TeV.

GRW [6]	HLZ [7]						Hewett [9]	
	n=2	n=3	n=4	n=5	n=6	n=7	$\lambda = +1$	$\lambda = -1$
1.2	1.3	1.4	1.2	1.1	1.0	0.95	1.1	1.0

systematics of the K-factor (10%), choice of parton distributions (5%), integrated luminosity (4%), ID efficiency (3%), as well as uncertainty on instrumental background (25%).

The best estimate of the parameter η is the SM value $\eta = 0$, and the one-sided 95% confidence level (C.L.) limits on η are:

$$\eta < \quad 0.50 \text{ TeV}^{-4}, (\eta \geq 0); \tag{5}$$

$$\eta > \; -0.57 \text{ TeV}^{-4}, (\eta \leq 0). \tag{6}$$

We can express these limits in terms of the limit on the effective Planck scale for all three formalisms using Eqs. (1)–(3). In the formalism of Ref. [9] both signs of η are possible and therefore both limits (5) and (6) are relevant; in the other two formalisms η is always positive, and only the first limit is relevant. For the HLZ formalism [7], the case of $n = 2$ is special since $\mathcal{F}$, and therefore η, depends on M. (This case is also of least interest due to the existence of strong bounds on LED models for $n = 2$.) To translate between η and M_S for $n = 2$, we use an average M for the $G_{\rm KK}$ term at the Tevatron of $(0.6 \text{ TeV})^2$ [13]. Limits for different formalisms and for different numbers of extra dimensions are given in Table I.

In summary, we have performed the first search for LED at hadron colliders by looking for effects of virtual Kaluza-Klein gravitons in pair production of electrons and photons at high energies. No evidence is found for LED, and we set limits on the effective Planck scale within several formalisms and for various number of LED. The limits between 0.95 and 1.4 TeV are the most restrictive to date. These results are also complementary to limits from LEP due to a different M-range being probed.

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