Search for universal extra dimensions in pp collisions


(The D0 Collaboration∗)

1Universidad de Buenos Aires, Buenos Aires, Argentina
2LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4Universidade Federal do ABC, Santo André, Brazil
5Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6University of Science and Technology of China, Hefei, People’s Republic of China
7Universidad de los Andes, Bogotá, Colombia
8Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
9Czech Technical University in Prague, Prague, Czech Republic
10Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
11Universidad San Francisco de Quito, Quito, Ecuador
12LPSC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
13LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
14CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
15LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
16LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
17CEA, Ifu, SPP, Saclay, France
18IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
19IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
20III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
21Physikalisches Institut, Universität Freiburg, Freiburg, Germany
22II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
23Institut für Physik, Universität Mainz, Mainz, Germany
24Ludwig-Maximilians-Universität München, München, Germany
25Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany
26Panjab University, Chandigarh, India
27Delhi University, Delhi, India
28Tata Institute of Fundamental Research, Mumbai, India
29University College Dublin, Dublin, Ireland
30Korea Detector Laboratory, Korea University, Seoul, Korea
31CINVESTAV, Mexico City, Mexico
32Nikhef, Science Park, Amsterdam, the Netherlands
33Radboud University Nijmegen, Nijmegen, the Netherlands and Nikhef, Science Park, Amsterdam, the Netherlands
34Joint Institute for Nuclear Research, Dubna, Russia
35Institute for Theoretical and Experimental Physics, Moscow, Russia
36Moscow State University, Moscow, Russia
37Institute for High Energy Physics, Protvino, Russia
38Petersburg Nuclear Physics Institute, St. Petersburg, Russia
39Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), Barcelona, Spain
40Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden
41Lancaster University, Lancaster LA1 4YB, United Kingdom
42Imperial College London, London SW7 2AZ, United Kingdom
43The University of Manchester, Manchester M13 9PL, United Kingdom
44University of Arizona, Tucson, Arizona 85721, USA
45University of California Riverside, Riverside, California 92521, USA
46Florida State University, Tallahassee, Florida 32306, USA
47Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
48University of Illinois at Chicago, Chicago, Illinois 60607, USA
49Northern Illinois University, DeKalb, Illinois 60115, USA
The existence of extra dimensions in addition to the 3 + 1 dimensions of space-time has been postulated as a possible solution to the problem of the large hierarchy of scales in the standard model (SM). In models with universal extra dimensions (UED) all particles propagate in the extra dimensions [1]. In this Letter, we study a minimal UED (mUED) model, which has only one extra dimension [2].

Each SM particle in the mUED model is associated with a set of excited Kaluza-Klein (KK) states when viewed in 3 + 1 dimensions. Since compactification of the extra dimensions leads to periodic boundary conditions, the KK states have discrete masses of the order of $R^{-1}$, where $R$ is the radius of the compact dimension. If one-loop corrections are applied, the mass spectrum of the KK modes also depends on a cutoff scale for boundary terms, which is chosen to be 10 TeV [2]. Gluon KK modes ($g_1$) are the heaviest particles, followed by quarks (SU(2) doublet $q_1$), gauge bosons ($Z_1/W_1$), leptons (SU(2) doublet $L_1$ or singlet $\ell_1$) and the KK photon ($\gamma_1$), which is the lightest KK particle (LKP) and does not decay. The LKP is also a dark matter candidate [3].

Previous searches for KK particles predicted by a modified UED model have been conducted by the D0 [4] Collaboration at the Fermilab Tevatron Collider and by the ATLAS [5] Collaboration at the CERN Large Hadron Collider (LHC) in diphoton final states. In this model, gravity mediation allows decays of the LKP into a photon plus a light KK graviton. A search for events with two leptons of the same charge, which can be interpreted in a mUED model, has been performed by ATLAS [6], but no dedicated study of the mUED model has so far

PACS numbers: 04.50.-h, 14.80.Rt, 13.85.Rm
been performed at a collider. Constraints from precision electroweak data \cite{1}, from the measurements of the muon anomalous magnetic moment and of the $b \to s\gamma$ branching ratio \cite{2}, indicate that the scale $R^{-1}$ can be as low as \approx 300 GeV, making KK particles accessible at the Tevatron. In this Letter, the first search for mUED in the final state with two leptons of the same charge is presented using data corresponding to 7.3 fb$^{-1}$ of integrated luminosity collected by the D0 detector \cite{8} at $\sqrt{s} = 1.96$ TeV.

At the Tevatron, KK gluons or quarks are mainly produced in pairs, as shown in Fig. 1. In the subsequent cascade decay, up to four charged leptons are produced. Since the masses of the extra particles predicted by the mUED models are nearly degenerate, the leptons are emitted with low transverse momentum and might escape detection. In this analysis, we select events with two muons of the same charge.

![FIG. 1: (a) Production of a pair of KK quarks ($Q_1, \bar{Q}_1$). (b) Decay of a KK quark into a jet, two oppositely charged leptons, and the LKP. Double lines indicate KK excitations. A similar cascade decay occurs for the second KK quark leading to several leptons of the same charge in the final state.](image)

The D0 detector \cite{9} consists of tracking systems and calorimeters. The innermost part is a tracking system where charged particles are detected by the silicon microstrip (SMT) and central fiber (CFT) tracking detectors, located within a 2 T solenoid. The tracking system is surrounded by a liquid-argon/uranium calorimeter. Particle energies are measured in the electromagnetic and hadronic calorimeters within a pseudorapidity range of $|\eta| < 4.2$ \cite{10}. Jets are reconstructed with a cone algorithm using a radius of $R = 0.5$ \cite{11} in the calorimeter. The central and forward muon detectors are composed of a layer of wire chambers and scintillators in front of a 1.8 T toroid magnet and two layers outside the toroid. Missing transverse energy is measured from the vector sum of the calorimeter cell energies in the $xy$ plane \cite{12}. A correction for the energy response of muons, electrons, and jets is applied.

The backgrounds from $Z+\text{jets}$, $W+\text{jets}$, and $t\bar{t}$ production are modeled by the ALPGEN \cite{13} Monte Carlo (MC) event generator, interfaced with PYTHIA \cite{14} for showering and hadronization. Diboson production ($WW$, $WZ$ and $ZZ$) is simulated by PYTHIA. The CTEQ6L1 parametrization of the parton distribution functions (PDF) are used \cite{15}. Higher order cross sections for diboson and $W/Z+\text{jets}$ production are calculated by MCFM \cite{16} and the cross section of $t\bar{t}$ pair production is taken from \cite{17}. The dominant source of background is pairs of muons with the same charge from heavy flavor jets. This background contribution is estimated from data and is described in detail in the following.

Signal MC events are generated for 9 different values of $R^{-1}$, covering the range from 200 to 320 GeV in steps of 15 GeV, using PYTHIA with the CTEQ5L PDF parametrization \cite{17}. The production cross sections and masses of KK particles are taken from PYTHIA. They are given in Table I for each $R^{-1}$ and with all KK gluon and quark production modes included. All decay mechanisms leading to like-charge dimuon final states are taken into account. The decay branching fractions for all KK particles are given by the mUED model. After simulating all cascade decays, approximately 1% of events have two like-charged muons.

All signal and background MC events pass through the full GEANT-based simulation of the detector \cite{18} and are reconstructed using the same algorithms as used for data. To simulate detector noise and multiple $p\bar{p}$ interactions, MC events are overlaid with data events from random beam crossings.

Events are selected by requiring that they pass at least one single muon trigger condition. We require that each event must contain at least two muons of the same charge. The track in the muon system must be matched to a track in the central tracking system with detector $|\eta| < 1.5$. We reject cosmic rays by requiring the associated scintillator hits in the muon system to be consistent with originating from a $p\bar{p}$ collision, the distance of closest approach (dca) of the muon tracks to the $p\bar{p}$ interaction vertex to be less than 0.05 cm, and the differences between the $z$ coordinates of the dca of each muon and the $p\bar{p}$ interaction vertex to be $< 1$ cm. We require $\Delta\phi_{\mu\mu} < 2.9$ rad for the azimuthal angle between the two muons in order to reject multijet background in which there are back-to-back jets which can contain muons from semileptonic meson decay, and $\Delta\phi_{\mu\mu} > 0.25$ rad to reject muons originating from the same jet. The transverse momenta of the leading and next-to-leading muons have to be $15 < p_{T1} < 200$ GeV.

<table>
<thead>
<tr>
<th>$R^{-1}$ (GeV)</th>
<th>Masses (GeV)</th>
<th>Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>201 230 269 207 249</td>
<td>34.9 ± 0.2</td>
</tr>
<tr>
<td>215</td>
<td>216 245 287 222 266</td>
<td>20.4 ± 0.1</td>
</tr>
<tr>
<td>230</td>
<td>231 260 305 238 283</td>
<td>12.1 ± 0.1</td>
</tr>
<tr>
<td>245</td>
<td>246 274 323 253 300</td>
<td>7.24 ± 0.05</td>
</tr>
<tr>
<td>260</td>
<td>261 289 341 268 317</td>
<td>4.39 ± 0.03</td>
</tr>
<tr>
<td>275</td>
<td>276 304 359 284 334</td>
<td>2.69 ± 0.02</td>
</tr>
<tr>
<td>290</td>
<td>291 319 377 299 351</td>
<td>1.65 ± 0.01</td>
</tr>
<tr>
<td>305</td>
<td>306 335 395 314 368</td>
<td>1.02 ± 0.06</td>
</tr>
<tr>
<td>320</td>
<td>321 350 413 330 385</td>
<td>0.63 ± 0.01</td>
</tr>
</tbody>
</table>
and $p_T > 10$ GeV, respectively. The invariant mass of the muon pair must be in the range $M_{\mu\mu} < 250$ GeV. The upper limits on the muon $p_T$ and dimuon invariant mass reduce the number of events with one of the muon charges mis-reconstructed. In addition, we reject events with $E_T < 25$ GeV, since multijet background dominates at low $E_T$.

To discriminate between isolated muons from signal and muons contained in jets, we define the isolation in the calorimeter, $I^{cal}$, as the sum of the energy deposited in the calorimeter within an annulus of $0.1 < R < 0.4$, divided by the muon $p_T$, and the isolation in the tracking detector, $I^{trk}$, as the sum of the $p_T$ of all charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by $p_T^\mu$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

We estimate the multijet background by defining a signal and a background enriched sample. The signal enriched sample comprises events where the requirement on the isolation of the second muon in the tracking detector is relaxed to $I^{trk} < 0.25$. To define a background enriched sample, we require that the second muon fails the isolation requirement. A normalization factor is calculated for each jet multiplicity, given by the ratio of the number of like-charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by the muon $p_T$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

We estimate the multijet background by defining a signal and a background enriched sample. The signal enriched sample comprises events where the requirement on the isolation of the second muon in the tracking detector is relaxed to $I^{trk} < 0.25$. To define a background enriched sample, we require that the second muon fails the isolation requirement. A normalization factor is calculated for each jet multiplicity, given by the ratio of the number of like-charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by the muon $p_T$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

The upper limits on the muon mass reduce the number of events with one of the muon charges mis-reconstructed. In addition, we reject events with $E_T < 25$ GeV, since multijet background dominates at low $E_T$.

To discriminate between isolated muons from signal and muons contained in jets, we define the isolation in the calorimeter, $I^{cal}$, as the sum of the energy deposited in the calorimeter within an annulus of $0.1 < R < 0.4$, divided by the muon $p_T$, and the isolation in the tracking detector, $I^{trk}$, as the sum of the $p_T$ of all charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by $p_T^\mu$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

We estimate the multijet background by defining a signal and a background enriched sample. The signal enriched sample comprises events where the requirement on the isolation of the second muon in the tracking detector is relaxed to $I^{trk} < 0.25$. To define a background enriched sample, we require that the second muon fails the isolation requirement. A normalization factor is calculated for each jet multiplicity, given by the ratio of the number of like-charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by the muon $p_T$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

We estimate the multijet background by defining a signal and a background enriched sample. The signal enriched sample comprises events where the requirement on the isolation of the second muon in the tracking detector is relaxed to $I^{trk} < 0.25$. To define a background enriched sample, we require that the second muon fails the isolation requirement. A normalization factor is calculated for each jet multiplicity, given by the ratio of the number of like-charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by the muon $p_T$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

We estimate the multijet background by defining a signal and a background enriched sample. The signal enriched sample comprises events where the requirement on the isolation of the second muon in the tracking detector is relaxed to $I^{trk} < 0.25$. To define a background enriched sample, we require that the second muon fails the isolation requirement. A normalization factor is calculated for each jet multiplicity, given by the ratio of the number of like-charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by the muon $p_T$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

We estimate the multijet background by defining a signal and a background enriched sample. The signal enriched sample comprises events where the requirement on the isolation of the second muon in the tracking detector is relaxed to $I^{trk} < 0.25$. To define a background enriched sample, we require that the second muon fails the isolation requirement. A normalization factor is calculated for each jet multiplicity, given by the ratio of the number of like-charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by the muon $p_T$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

We estimate the multijet background by defining a signal and a background enriched sample. The signal enriched sample comprises events where the requirement on the isolation of the second muon in the tracking detector is relaxed to $I^{trk} < 0.25$. To define a background enriched sample, we require that the second muon fails the isolation requirement. A normalization factor is calculated for each jet multiplicity, given by the ratio of the number of like-charged particles within a cone of $R = 0.5$ around the muon, excluding the muon itself, divided by the muon $p_T$. At least one of the two muons is required to be isolated with $I^{cal} < 0.4$ and $I^{trk} < 0.12$.

![Figure 2: Distribution of (a) $E_T$ and (b) $p_T$, for data and background, compared to a signal with $R^{-1} = 260$ GeV. The shaded band shows the statistical uncertainty on the background estimation. All entries exceeding the range of the histogram are added to the last bin.](image-url)
TABLE II: Expected number of events for backgrounds, event yields in data and expected number of events for a signal with $R^{-1} = 260$ GeV after the final selection and requiring a BDT output $> 0$ (for illustrative purpose, this cut is not used for limit estimation). The total uncertainties are also given.

<table>
<thead>
<tr>
<th>Process</th>
<th>Final Selection</th>
<th>BDT output $&gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson</td>
<td>$21 \pm 3$</td>
<td>$6 \pm 1$</td>
</tr>
<tr>
<td>$Z +$jets</td>
<td>$39 \pm 9$</td>
<td>$13 \pm 3$</td>
</tr>
<tr>
<td>$W +$jets</td>
<td>$109 \pm 14$</td>
<td>$38 \pm 5$</td>
</tr>
<tr>
<td>$t \bar{t}$</td>
<td>$6 \pm 1$</td>
<td>$2 \pm 1$</td>
</tr>
<tr>
<td>Multijet</td>
<td>$95 \pm 41$</td>
<td>$63 \pm 27$</td>
</tr>
<tr>
<td>Total Background</td>
<td>$271 \pm 45$</td>
<td>$123 \pm 28$</td>
</tr>
</tbody>
</table>

Data: 273

Signal: 18 ± 1

FIG. 3: Distribution of the BDT output for data and background, compared to a signal with $R^{-1} = 260$ GeV. The shaded band shows the statistical uncertainty on the background estimation.

FIG. 4: Observed and median expected 95% CL limits on $\sigma B(\mu^+\mu^-)$ as a function of $R^{-1}$ compared to $\sigma B(\mu^+\mu^-)$ calculated with the mUED model. The bands represent ±1 and ±2 standard deviations around the median expected limits.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACYT (Mexico); NRF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

[9] The D0 detector coordinate system is right-handed with the $z$ axis pointing in the proton beam direction. The $y$ axis points upward and the azimuthal angle $\phi$ is measured from the $x$ axis. Pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$, where $\theta$ is the polar angle.
[11] Missing transverse energy is defined as $E_T = - \sum_i \vec{E}_{T, i}$, where $\vec{E}_{T, i} = E_i^\perp \sin \theta^i \cos \phi^i$. Here $E_i^\perp$ is the energy deposited in $i^{th}$ calorimeter cell and the angles $\theta^i$ and $\phi^i$ define the direction from the origin of the coordinate system to the $i^{th}$ calorimeter cell. We also define $\vec{E}_T \equiv \sum_i \vec{E}_{T, i}$.