Probing Extra Spacetime Dimensions at the Tevatron

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On Behalf of the CDF and DØ Collaborations

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Abstract

Theories with extra spacetime dimensions aiming at resolving the hierarchy problem have recently been developed. These scenarios have provided exciting new grounds for experimental probes. A review of the searches conducted at the Tevatron in this framework during its first running phase and the prospects for its second running phase are reviewed.

Introduction

Among the most popular scenarios of theories with extra spacetime dimensions, those from Arkani-Hamed, Dimopoulos, and Dvali (ADD) [1] and Randall-Sundrum (RS) [2] have provided exciting benchmark signatures to be searched for at colliders and in particular at the Tevatron.

The Tevatron program started its data taking period in 1992 at a center-of-mass energy of 1.8 TeV. This first running (Run 1) phase extended until 1996, reaching a peak luminosity of $2{\times}10^{30}$ $\mathrm{cm^{-2}s^{-1}}$ and an integrated luminosity of about $100\,\mathrm{fb^{-1}}$ for each experiment, CDF and DØ . In spring 2001, after a complete reappraisal of the machine and the detectors, the Tevatron started taking data again but at a higher center-of-mass energy of 1.96 TeV. The booster, accumulator ring and the cooling were upgraded but the most dramatic change was the construction of a main injector along with an anti-proton recycler which where built in an tunnel adjacent to the Tevatron ring. Run 2 will be divided into two periods, Run 2a and Run 2b, in between which further upgrades are foreseen. The design peak luminosities for these two running periods are respectively $\sim10^{32}$ and $\sim5{\times}10^{32}$ $\mathrm{cm^{-2}s^{-1}}$, aiming at integrated luminosities per experiment of $2\,\mathrm{fb^{-1}}$ and $15\,\mathrm{fb^{-1}}$ respectively. The detectors underwent extensive changes. CDF has a new inner silicon tracker and plug calorimeter, upgraded muon detectors and a new trigger and data acquisition system. DØ installed a new superconducting 2 Teslas solenoid in which a complete new tracker was built. This tracker is a combination of a silicon tracker

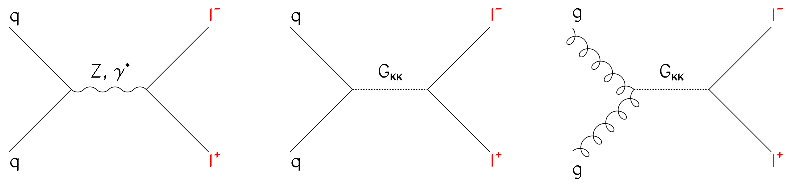

Figure 1: Diagrams of the standard model (left) and KK graviton contributions (middle and right) to di-lepton production.

and a scintillating fibers detector. DØ as well has a completely new trigger and data acquisition system.

The Large Extra Dimension Scenario (ADD)

In the ADD scenario, the observed hierarchy between the TeV scale and the Planck scale arises from the adjunction of n additional compactified dimensions in which only gravity can propagate. The Planck scale in the 4-d theory M_{Pl} is related to the gravity scale M_S in the 4+n dimensional spacetime via Gauss' theorem through:

$$M_{Pl}^2 = M_S^{n+2} \times (2\pi R_c)^n \tag{1}$$

Here flat compactified dimensions of toroidal form and equal size are considered. The hierarchy problem is then solved when extra dimensions are large (from one millimeter to ∼10 fm for n ranging between 2 and 6, the $n = 1$ case is excluded as it would affect Newton's law at large distances). In the 4-d world, excitations of the states propagating in the bulk (called Kaluza–Klein modes) appear as a consequence of the compactification of the extra dimensions. In the simplest models, these states are equidistant and their separation is inversely proportional to the size of the extra dimensions. Due to the large compactification radius, the number of accessible Kaluza–Klein (KK) modes at a collider is large enough to compensate for the Planck scale suppression of each individual KK state coupling and the spectrum of KK modes would appear to be almost continuous given the detector resolutions. The presence of extra dimensions in these scenarios thus results in two generic types of signatures: the alteration of production cross sections and asymmetries of processes such $q\overline{q}, gg \rightarrow \ell^+\ell^-, \gamma\gamma$ (*n.b.* in this framework, the $gg \rightarrow \ell^+\ell^-$ is a pure extra dimension process) and the direct KK graviton emission in association with a vector boson.

Virtual Kaluza–Klein Graviton Exchange

Two types of scattering processes have been investigated at the Tevatron Run 1: the di-lepton production and the di-photon production. All diagrams pertaining to these processes are displayed in Figures 1 and 2. These two processes can be treated either inclusively (DØ analysis) or exclusively (CDF analysis). In both cases, the novel processes

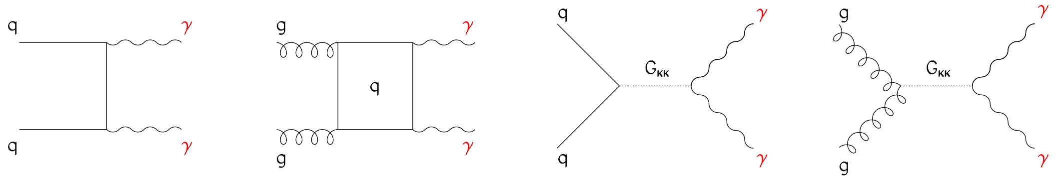

Figure 2: Diagrams of the standard model and KK graviton contributions to di-photon production.

interfere with the standard model ones and the effective differential production cross section requires an explicit cutoff, naturally at M_S, due to the divergence of the sum over KK states, and can be written:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta^*\mathrm{d}M_{\ell\ell,\gamma\gamma}} = \frac{\mathrm{d}^2}{\mathrm{d}\cos\theta^*\mathrm{d}M_{\ell\ell,\gamma\gamma}}(\sigma_{SM} + \sigma_4\eta + \sigma_8\eta^2) \tag{2}$$

where $\eta \equiv \mathcal{F}/M_S^4$ and σ_{SM}, σ_4, σ_8 are respectively the standard model, interference and KK individual contributions. $M_{\ell\ell,\gamma\gamma}$ and θ^* are respectively the invariant mass and the decay angle of the two leptons or photons. The $\mathcal{F}$ factor embeds the dependence on the choice of formalism. Three specific cases are considered. In the first (Hewett scheme [3]) neither the dependence on the sign of the interference ($\sim \lambda$) nor on the number of extra dimensions are determined, $\mathcal{F} = 2\lambda/\pi$. In the second (so-called GRW [4] formalism) the sign of the interference is specified and $\mathcal{F} = 1$. In the third (HLZ formalism [5]) both dependences are accounted for, and $\mathcal{F} = \log(M_S^2/s)$ for $n = 2$ and $\mathcal{F} = 2/(n-2)$ for $n > 2$.

Inclusive di-electron and di-photon production at DØ

The study of a di-electromagnetic-particle (EM) production (electrons or photons) at DØ was motivated by the gain in the discovery potential from the combination of the two final states. Muons were not considered due to the poor high muon momentum resolution. A specific leading order parton level generator was designed to simulate the expected signal and its interference with the standard model process [6] (using *CTEQ4-LO* [7] parton distribution functions). Initial state radiation is simulated according to Drell-Yan (DY) measurements and the DY K-factor is used. The main backgrounds to this analysis are the DY di-electron production which is determined from Monte Carlo simulation and instrumental backgrounds originating from di-jet production or Compton-QCD processes where one or both jets are mis-identified as electromagnetic particles. All other backgrounds such as W boson production with a mis-identified jet, WW, $t\bar{t}$ into di-electron, Z into a pair of taus or $Z\gamma$ contribute to less than 1% to the total.

The analysis is based both on the invariant mass and the decay angle of the EM particles. These two discriminant variables are shown in Figure 3 and are combined in a two dimensional binned likelihood which takes into account systematic uncertainties

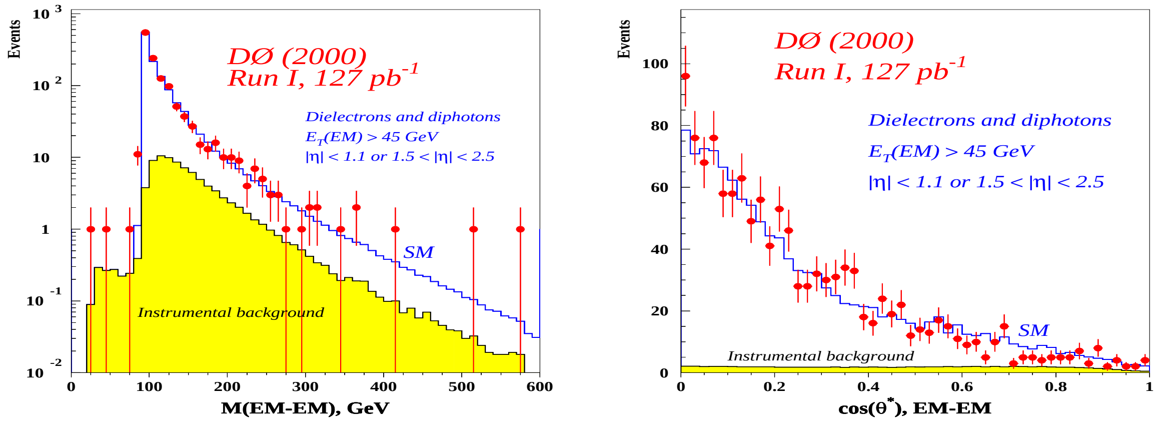

Figure 3: Distribution of the invariant mass (left) and the decay angle (right) of the two EM particles for data (dots with errors) and the background expectation (histogram). The instrumental background contribution is also indicated (shaded).

(These are dominated by the uncertainty originating from the evaluation of next-to-leading order effects taken into account via a K-factor). The result of these searches interpreted in the HRZ formalism is shown in Figure 4. In the Hewett scheme, the limits are $M_S > 1.1\,\text{TeV}$ and $M_S > 1.0\,\text{TeV}$ respectively for $\lambda = 1$ and $\lambda = -1$. In the GRW formalism, $M_S > 1.2$ TeV.

Exclusive di-electron and di-photon production at CDF

Because of its tracking capabilities within a magnetic field, in Run 1 the CDF experiment had a better discovery potential in the electron channel and therefore does not perform an inclusive treatment of electrons and photons. A preliminary analysis taking only into account the invariant mass information was performed and yielded results similar to those obtained by DØ . In the Hewett scheme, the limits are $M_S > 0.94\,\text{TeV}$ and (resp. 0.85 TeV) for $\lambda = 1$ (resp. $\lambda = -1$).

Kaluza–Klein Graviton Emission

Direct evidences of KK gravitons can be searched for at the Tevatron in their production in association with a vector boson. Since gravitons escape detection, their distinctive signature is missing transverse energy. The tree level direct KK graviton production diagrams are depicted in Figure 5. Among all possible final states arising from these processes, two have already been investigated. CDF has performed an analysis of single photons and missing transverse energy. DØ searched for mono-jet events.

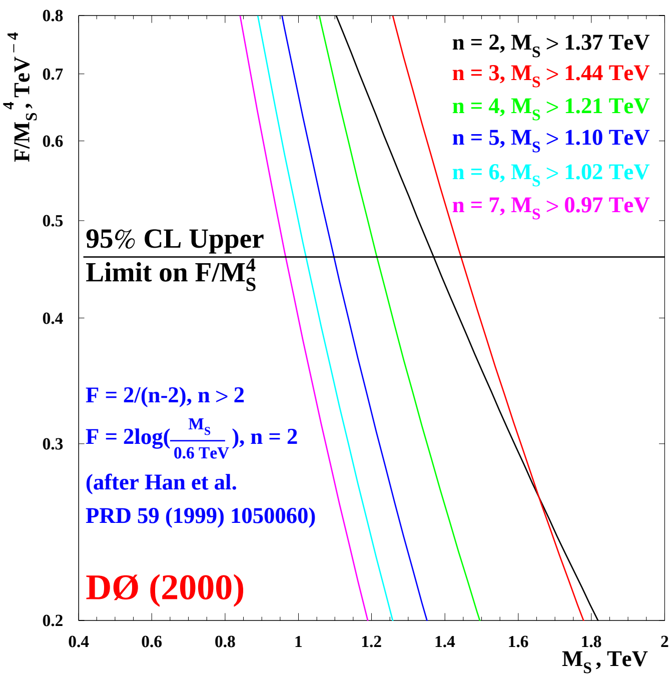

Figure 4: Limits on the Planck scale M_S as a function of η and the number of extra dimensions n from the inclusive di-electron and di-photon search in DØ .

The CDF single photon search

KK gravitons produced in association with a single photon were searched for by the CDF experiment. This search was performed on a sample of $\sim 90\,\text{pb}^{-1}$. In this analysis only very clean events where one photon with transverse energy in excess of 55 GeV within a pseudo-rapidity of $|\eta^\gamma| < 1$ and a missing transverse energy larger than 45 GeV are required. Events where a jet with transverse energy larger than 15 GeV or a track with transverse momentum in excess of 5 GeV/c are removed. The largest background contribution ($\sim 60\%$) is due to cosmic rays where the muon undergoes a bremsstrahlung in the Central Electromagnetic Calorimeter. Another substantial background ($\sim 30\%$) process is the Zγ production when the Z boson decays to a pair of neutrinos.

Eleven events were selected in the data in good agreement with the expected background estimation of 11$\pm$2 events. Limits on the effective Planck mass are thus derived for various numbers of extra dimensions (n):

$$\begin{cases} \text{n=4}, & M_S > 550 \text{ GeV} \\ \text{n=6}, & M_S > 580 \text{ GeV} \\ \text{n=8}, & M_S > 600 \text{ GeV} \end{cases} \tag{3}$$

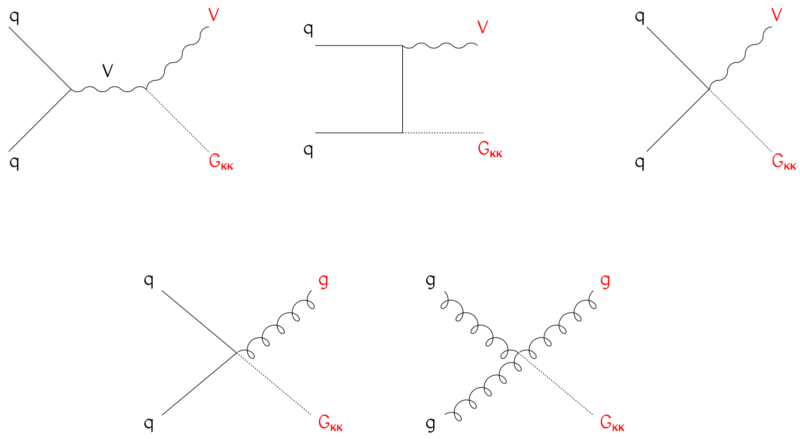

Figure 5: Single vector boson production in association with a KK graviton.

The DØ mono jet search

The topology searched for in the case of a KK graviton produced in association with a gluon is a single jet. A search for such monojet events was carried out by the DØ experiment with a data sample of $\sim 80\,\text{pb}^{-1}$. The event selection requires one or two jets, where the leading jet must have a transverse energy in excess of 150 GeV and the second jet should not have a transverse energy larger than 50 GeV and should not be pointing in the azimuthal direction of the missing transverse energy in order to suppress the QCD background. The most prolific background contribution is that of W and Z production which is expected to yield 30±4 events. From QCD and cosmic backgrounds 8±7 events are expected to be produced.

Altogether, 38±8 events are expected from standard model processes and cosmic rays, in good agreement with the 38 events observed. Limits on the Planck scale can thus be derived as a function of the number of extra dimensions, as illustrated in Figure 6. These limits include the next-to-leading-order correction embedded in the K factor. For n=4 and n=6 the limits are respectively $M_S > 698\,\text{GeV}$ and $M_S > 632\,\text{GeV}$. As shown in Figure 6 the limits obtained by this analysis improve the exclusion with respect to the LEP limits only at large number of extra dimensions.

Warped extra dimensions (RS)

In the Randall-Sundrum scenario, the effective hierarchy is explained by an exponential warp factor in a 5-dimensional Anti-de-Sitter (AdS_5) geometry. The single extra dimension in this scenario is finite and of size $y = \pi R_c$ (where R_c denotes the compactification radius). The metric preserving the 4-dimensional Poincaré invariance:

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \quad (4)$$

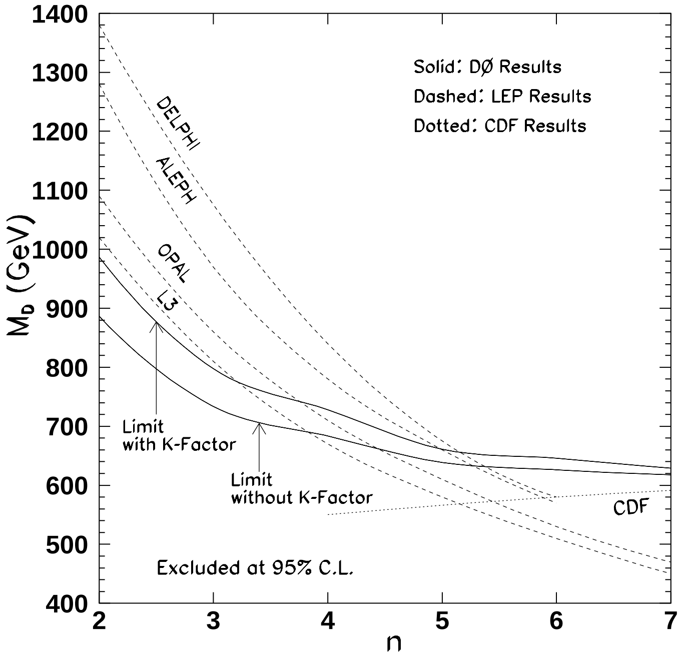

Figure 6: Limits on the Planck scale $M_S \sim M_D$ as a function of the number of extra dimensions from the monojet search in DØ .

is considered. The exponential is known as the warp factor and the parameter k is the AdS_5 curvature scale, expected to be of the order of M_{Pl}. Since the scale of the physical processes appears to be $M_{Pl}e^{-ky}$, the hierarchy between the TeV and the Planck scale arises naturally when gravity is localized on the $y = 0$ brane and all physical processes occur on the $y = \pi R_c$ brane with $kR_c \simeq 11 - 12$ (TeV-brane). Here it is assumed that the standard model fields are confined to the TeV brane. The sole two excitations arising from the metric of eq. 4, *i.e.* the usual graviton related to the 4-d Minkowski metric and the so-called radion related to the transverse 5^{th} dimension (the relative motion of the two branes), are the only ones allowed to propagate freely in the bulk. The phenomenology of this model is very broad [8]. The particular case of the radion has mostly been investigated in the framework of the LHC [9], it is therefore not discussed here. However, in this scenario the graviton production yields a very distinctive and attractive signature at hadron colliders, since the KK modes are not evenly spaced and are separated well enough so that a resonant production can be observed. The first KK state is naturally of the order of a TeV. The production cross section of a 700 GeV first KK state at the Tevatron is shown in Figure 7a for various values of k/M_{Pl}.

Using the Tevatron Run 1 analyses of the Drell-Yan spectrum in search for heavy gauge bosons and of the Dijet production, a limit on k/M_{Pl} as a function of the mass of the first KK state (m_1) is derived [8]. These results are displayed in Figure 7b.

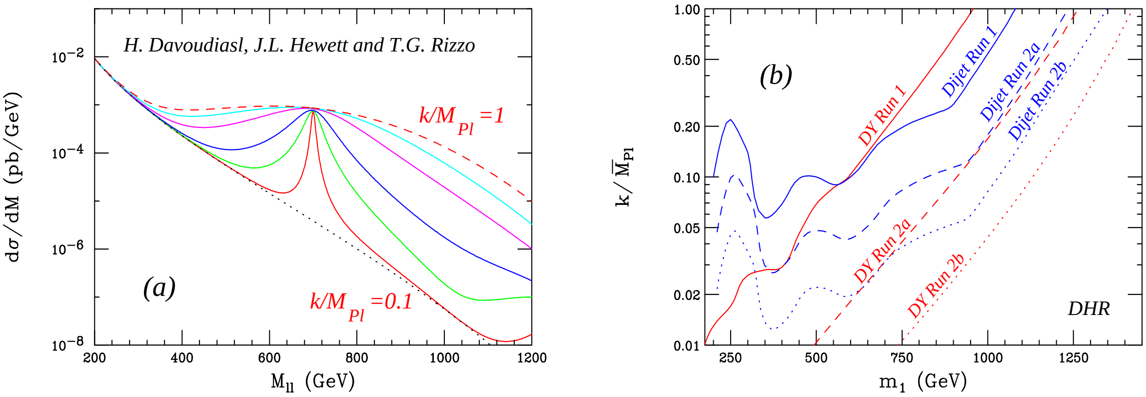

Figure 7: (a) Production of a 700 GeV/c^2 first KK graviton for various values of k$/M_{Pl}$=1, 0.7, 0.5, 0.3, 0.2 and 0.1 from top to bottom respectively. (b) Limits on k/M_{Pl} as a function of m_1.

Prospects and status of Run 2

The Run 2a of the Tevatron has successfully started in spring 2001. As of July 2002, the highest peak luminosity reached was $2\,10^{31}$ cm^{-2}s^{-1} and the integrated luminosity delivered was of the order of 50 pb^{-1}. Although at the time of the conference the detectors were still in a commissioning phase, first physics results started to be produced. With the increase in center-of-mass energy and luminosity, the sensitivity to the gravity scale in ADD models is expected to double at Run 2a with respect to Run 1 and triple at Run 2b. Other final states, such as those containing muons, can be searched for with the improved detector capabilities. Run 2 prospects of the searches for extra dimensions in the RS scenario are displayed in Figure 7b. These results are obtained by rescaling the Run 1 result accounting for the increase in luminosity and the expected variation of the cross section due to the increase in center-of-mass energy [8].

Conclusions

The CDF and DØ experiments at Tevatron Run 1 have searched for signs of extra spatial dimensions. No excess has been observed in any of the channels studied. The observed exclusion limits are of the same order as those obtained at LEP [10]. The Tevatron Run 2 has successfully started its data taking phase and will provide an enticing potential for discoveries in this exciting field.

Acknowledgments

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