SEARCH FOR "LARGE" EXTRA DIMENSIONS AT THE TEVATRON

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We report on a search for extra spatial dimensions compactified at radii that are vast compared to those of the Planck length, and even larger than the distance corresponding to the scale of electroweak symmetry breaking. The study is based on the suggestion that there may be only a single mass scale appropriate to particle phenomena, this being the effective Planck scale M_S, which also serves as the scale for electroweak symmetry breaking. The only results that have been presented thus far from the Tevatron are based on data for e^+e^- and $\gamma\gamma$ production at DØ, and provide the most restrictive lower limits to date on M_S of ≈ 1 TeV.

1 Introduction

Many particle physicists have become convinced that the unification of particle interactions will require the presence of a total of ten spatial dimensions, three of which are within the reach of our senses and the others compactified at inconceivably small radii corresponding to the Planck length (R_P) of $\hbar/M_P c \approx 10^{-33}$ cm, where (M_P) is the Planck mass. Because it is unlikely that our governments will ever provide accelerators that can challenge the Planckian regime, it was therefore exciting to learn of the possibility of sensing the impact of strings and quantum gravity at far lower energies.

It is commonly accepted that the Standard Model (SM) is a low-energy approximation to a more complete theory, the impact of which should become apparent at a scale of the order of the Higgs mass, i.e., ≈ 1 TeV. The two most popular candidates for such a theory have been based on supersymmetry and on strong dynamics. More recently, Arkani-Hamed, Dimopoulos and Dvali (ADD),[1] suggested that there may be only a single scale in particle phenomena, that being the electroweak scale, which also corresponds to the effective Planck scale $M_S \approx 1$ TeV, provided that there exist extra dimensions compactified at far larger radii than the Planck length. This exciting idea has inspired experimenters and phenomenologists to search for such large extra spatial dimensions, and for the effect of quantum gravity in particle interactions.

The basic notion requires the particles of the SM to be localized to our four-dimensional world, but allows gravitons to propagate in all the large extra dimensions. In the presence of n such dimensions, the potential in Newton's Law changes from its characteristic r^{-1} dependence to a steeper form:

$$V(r) = \frac{\hbar c}{M_P^2}\,\frac{M_1 M_2}{r} \longrightarrow \frac{\hbar c}{(M_P^*)^{n+2}}\,\frac{M_1 M_2}{r^{n+1}}$$

where M_P^* is the Planck mass corresponding to $(n+3)$ spatial dimensions, and Newton's gravitational constant is $G_N = \hbar c/M_P^2$. Clearly, the lack of departure from r^{-1} behavior for distances greater than ≈ 1 cm rules out the possibility that any of these extra dimensions are of macroscopic size. But for n extra dimensions, compactified on sufficiently small (and same size) radii R, the gravitational energy for $r >> R$ retrieves its acceptable r^{-1} dependence, with $M_P^2 \approx (M_P^*)^{n+2}(Rc^2/\hbar c)^n$. Hence, choosing $R >> R_P$, can effectively reduce M_P^*, and thereby increase the strength of the gravitational coupling to $\hbar c/M_P^{*2}$ for the larger compactified dimensions. If M_P^* is taken as the electroweak scale $M_S \approx 1$ TeV, then its value becomes coupled to the compactification radius and to the number of such compactified dimensions of size $R = (\hbar/2\sqrt{\pi}M_S c)\ (M_P/M_S)^{2/n}$, where the extra factor $2\sqrt{\pi}$ is a consequence of applying Gauss's Law on an n-torus.[1]

Thus, for $n = 1, R \approx 8 \times 10^{14}$ cm; for $n = 2, R \approx 0.07$ cm; and, for $n = 3, R \approx 3 \times 10^{-7}$ cm. On the basis of the agreement of Newton's law with the r^{-1} dependence for gravitational interactions at macroscopic distances, we can exclude $n = 1$. Using cosmological arguments (and recent measurements of the gravitational force at distances of the order of 0.02 cm [2]), ADD exclude a scale as small as $\approx$ 1–10 TeV for only two compactified dimensions. However, scales in this range cannot be excluded for 3 or more compactified dimensions, and they can be probed only through elementary particle interactions at high energies, where gravity is enhanced.

Compactified dimensions greatly increase the effective strength of gravitational interactions through Kaluza-Klein (G_{KK}) modes of gravitons.[3] From the perspective of our (3+1) space-time dimensions, the G_{KK} modes correspond to massive gravitons, with excitations spaced at $\hbar c/R$. Each mode couples with strength G_N, but, because of the large number of modes at high energies, gravitational coupling is greatly increased (to the order of $\hbar c/M_S^2$).

Kaluza-Klein gravitons couple to the energy-momentum tensor, and signatures for large extra dimensions depend on whether the G_{KK} in particle interactions are real (emitted in collisions) or whether they are virtual (and do not leave our SM world). Thus, the impact of virtual G_{KK} can be observed in reactions such as $q\overline{q} \to G_{KK} \to \gamma\gamma$, or $gg \to G_{KK} \to e^+e^-$, etc. G_{KK} emission can lead to apparent violation of energy and momentum (as well as of angular momentum) conservation when the graviton has components in the bulk that escape the brane of the SM, e.g., $q\overline{q} \to G_{KK} + g$, or $e^+e^- \to G_{KK} + \gamma$, etc. The characteristic signatures for contributions from virtual G_{KK} correspond to yields of massive systems beyond rates expected on the basis of the SM, while direct emission of G_{KK} results in an increase of the yield of events with large apparent imbalance in transverse momentum (or “missing E_T”, $\not\!\!E_T$), in particular, mono-jet events.

Limits on M_S of $\approx$ 1 TeV have already been reported from LEP,[4] and somewhat weaker limits (from searches for virtual graviton contributions) have been published by experiments at HERA.[5]

2 Virtual Graviton Effects

In this paper, we focus on virtual G_{KK} effects, primarily because the analyses of direct emission have not as yet been completed at the Tevatron. Also, since the results on virtual G_{KK} emission from CDF will not become available before Spring 2001,[6] we report only on the work from DØ.[7]

For the case of virtual graviton contributions, the amplitude for G_{KK} exchange has to be added coherently to that from the SM, because processes such as $q\overline{q} \to \gamma^* \to e^+e^-$ and $q\overline{q} \to G_{KK} \to e^+e^-$ can provide important interference terms.

Three phenomenological formulations of the problem have appeared in the literature.[8,9,10] These are equivalent, and differ only in their definitions of M_S. DØ follows the more sophisticated phenomenology,[10] which contains a dependence of the cross section on n. The correspondence between the three definitions of scale is that $M_S(n = 5) \approx M_S(\lambda = +1)$ of Hewett,[8] and $M_S(n = 4) \approx \Lambda_T$ of Giudice et al.[9]

3 Analysis at DØ

DØ bases its analysis on both di-electron and di-photon signals. Since DØ did not have a central magnetic field in Run-1, the analysis ignores electric charge, and the cross section is therefore examined as a function of M_{ee} or $M_{\gamma\gamma}$, and $|\cos\theta^*|$, where θ^* is the angle of the e or γ relative to the line of flight of the ee or $\gamma\gamma$ system (helicity frame). The analysis follows the Cheung-Landsberg extension[11] of previous studies that were based on the use of only the mass variable in the problem.

Because the instrumental background (e.g., a jet mimicking a photon or an electron) in this search is small at large E_T,[12] the signals for ee and $\gamma\gamma$ are added together in the comparison of data to theory. This maximizes the reach of the experiment to highest mass scales because it allows a loosening of the usual strict electromagnetic (EM) shower requirements on both photons and electrons. The analysis ignores charged-particle tracking information in the detector, and relies purely on the observation of di-EM systems of high invariant mass ($M_{EM,EM}$). The theory used to describe contributions from the SM and virtual gravitons is a leading-order (LO) calculation, and therefore is not affected by the summing of the ee and $\gamma\gamma$ components.[11] Nevertheless, the expected yields are corrected for higher-order effects through an application of a common “K-factor” of 1.3 (this probably underestimates the expected yield from gravitons at largest ($M_{EM,EM}$). The criteria for the final 1250 candidate events require only two acceptable EM showers, each with $E_T > 45$ GeV, and no missing transverse momentum ($\not{E}_T < 25$ GeV). There are no requirements placed on jets. In addition, there is a less restrictive sample of di-EM events, that requires $E_T > 25$ GeV, which is used to check EM efficiencies through a comparison to $Z \to ee$ events.

The data are compared to the LO parton generator of Cheung and Landsberg,[11] augmented with a parametrized DØ detector simulation package that models the acceptance, resolution, vertex smearing, and the impact of having additional vertexes from overlapping multiple interactions. As indicated above, the calculation applies a uniform K-factor correction to all SM and virtual-graviton cross sections, and even introduces a transverse impact to the di-EM system (assuming that it is the same as in the inclusive Z data of DØ [13]). The corrections used to account for higher-order (incident gluon Bremsstrahlung) effects are relatively unimportant. The $CTEQ4LO$ parton distribution functions (PDF) are used to integrate the matrix elements over the incident parton distributions (with checks performed using other PDFs).

Most of the di-EM events arise from prompt di-photon, and, to a lesser extent, from e^+e^- production (usual SM processes). The background from more exotic channels, such as W+jets, $W + \gamma, WW, t\bar{t}$, etc, is miniscule. The largest instrumental background ($\approx 7\%$ of the di-EM signal) is from multijet production, where two jets are misidentified as EM showers.

4 Comparison of Data with Monte Carlo

Figure 1 displays a comparison of data with the Monte Carlo model.[11] The pseudorapidities and the E_T of the two EM objects are in excellent agreement with expectations from the SM. A two-dimensional comparison between data and Monte Carlo is given in Fig. 2 in the ($M_{EM,EM}$, $|\cos\theta^*|$) plane, and shows again the good agreement with expectations. Projections onto the $M_{EM,EM}$ and cosθ^* axes are given in Fig 3, and confirm the qualitative features displayed in Fig. 2.

With no excess apparent beyond expectations of the SM, DØ proceeds to calculate a lower limit on the graviton contribution to the di-EM cross section. The cross section as a function of $M_{EM,EM}$ and $|\cos\theta^*|$ can be written as:

$$\sigma = \sigma(SM) + \eta \times \sigma_4 + \eta^2 \times \sigma_8$$

where $\eta = F/{M_S}^4$, and $F = 2/(n-2)$, for $n > 2$, and where $\sigma(SM)$ represents the cross section for the SM, σ_8 the pure graviton contribution, and the term linear in η is the interference between the two. (The Monte Carlo does not include the $gg \to \gamma\gamma$ source of the SM, because it is quite small at large $M_{EM,EM}$.) The three contributions to the Monte Carlo[11] are displayed in Fig. 4, along with the impact on the total σ of a contribution from G_{KK} for

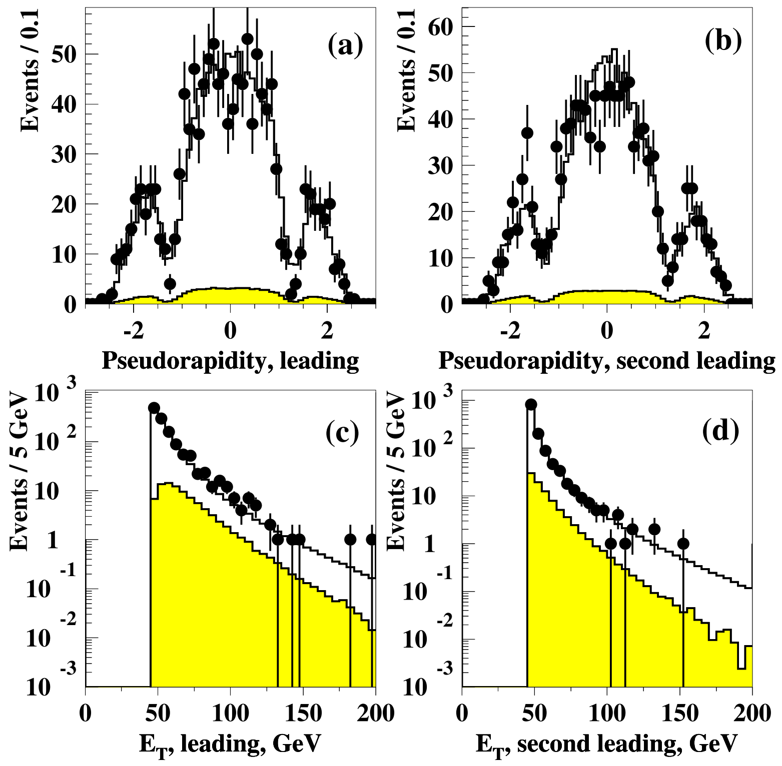

Figure 1. At the top is a comparison of the pseudo-rapidity distribution for data with the Monte Carlo, and at the bottom of E_T, for the two EM objects.

M_S= 1 TeV and $n = 4$. It is clear that the addition of G_{KK} increases the yield at large $M_{EM,EM}$, especially for small values of $|\cos\theta^*|$.

The expected sensitivity to η is obtained from a fit of the above formula for the cross section (σ) to Monte Carlo samples that do not contain graviton components, and have statistics appropriate to the DØ data, which corresponds to an integrated luminosity of 127 events/pb. Such fits yield an expected sensitivity of $\eta < 0.44$ TeV^{-4}. The DØ fits are performed using a Bayesian formalism that yields the likelihood for η, and the expected limit of 0.44 TeV^{-4} corresponds to an upper limit at 95% confidence. (The procedure is also checked using a frequentist maximum likelihood.)

The result of a similar fit to the data rather than to Monte Carlo, yields an upper limit of 0.46 TeV^{-4}, which provides a lower limit on the value of M_S that depends somewhat on the value of n. In particular, $M_S > 1.44$ TeV for $n = 3$, and $M_S > 0.97$ TeV for $n = 7$. The case for $n = 2$ is more delicate,[7] but not of great interest, considering our previous remarks on this issue.

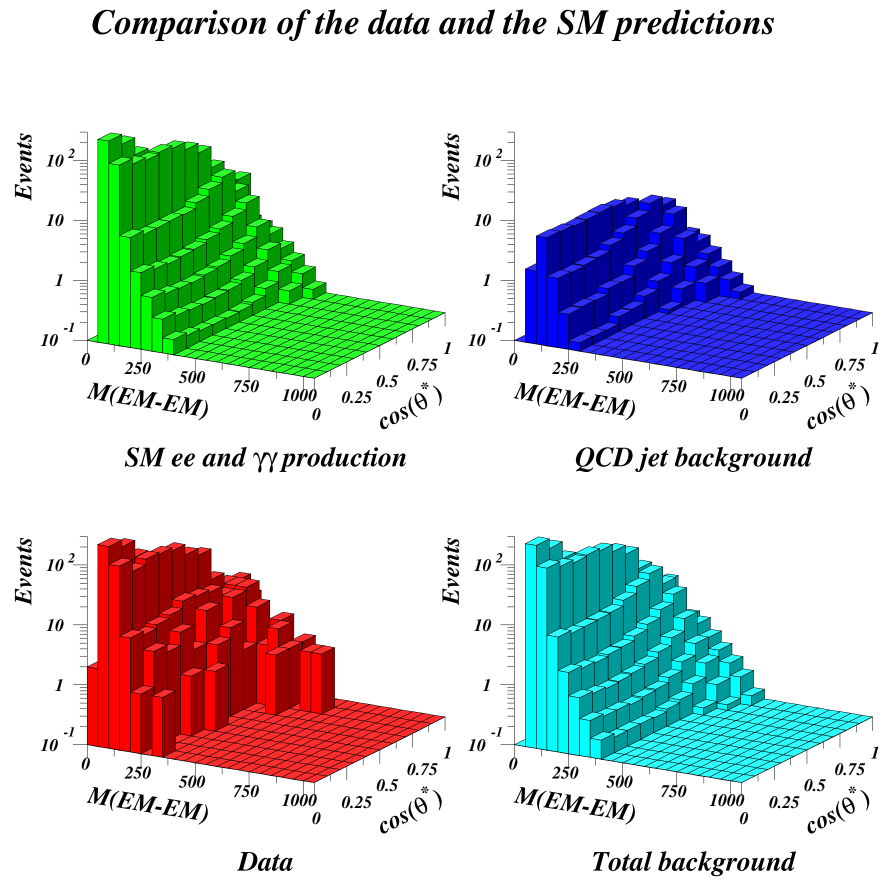

Figure 2. Comparison of data with Monte Carlo in the $(M_{EM,EM}, |\cos\theta^*|)$ plane, for contributions from all processes expected in the SM

5 Summary

In summary, DØ has presented first results of a search for contributions of virtual gravitons to production processes at the Tevatron. Based on an analysis of massive e-pairs and di-photons, in the context of the ADD scenario of large extra dimensions and a single mass scale in the domain of particle interactions, that mass scale must be greater than 1.0–1.5 TeV. These 95% confidence limits are comparable to the final results anticipated from LEP. Because of the ambiguities inherent in the definition of M_S, e.g., from the cut-off required on the effective theory, it is important to check the scales under different conditions. More studies are forthcoming from CDF and D0 on real graviton emission (mono-jet events), as well as on virtual graviton

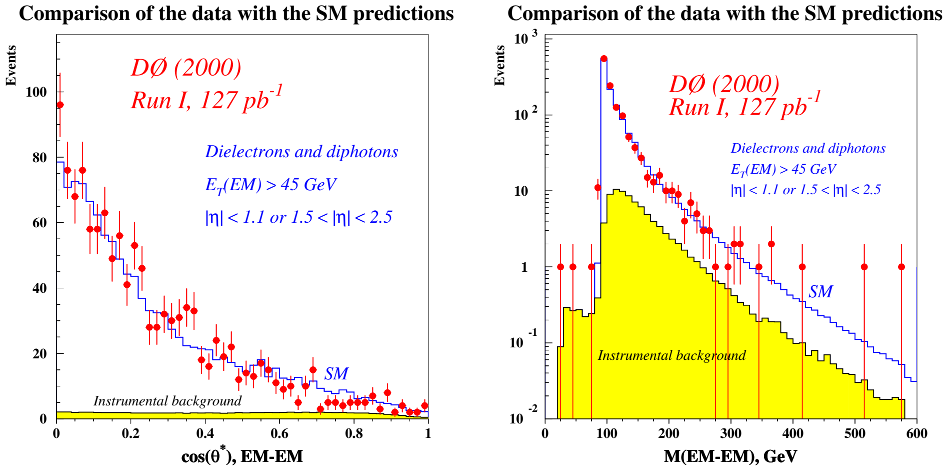

Figure 3. In the left pane is a comparison of the decay angular distribution of the di-EM system relative to its line of flight, and, in the right pane, of the mass of di-EM system, with the Monte Carlo that contains contributions only from the SM.

exchange, which by the end of Run-2, should be sensitive to scales of 3-4 TeV. Beyond that lies the LHC, with sensitivity up to 10 TeV,[11] beyond which the ADD idea, if not confirmed, will likely lose much of its intriguing appeal.

6 Acknowledgements

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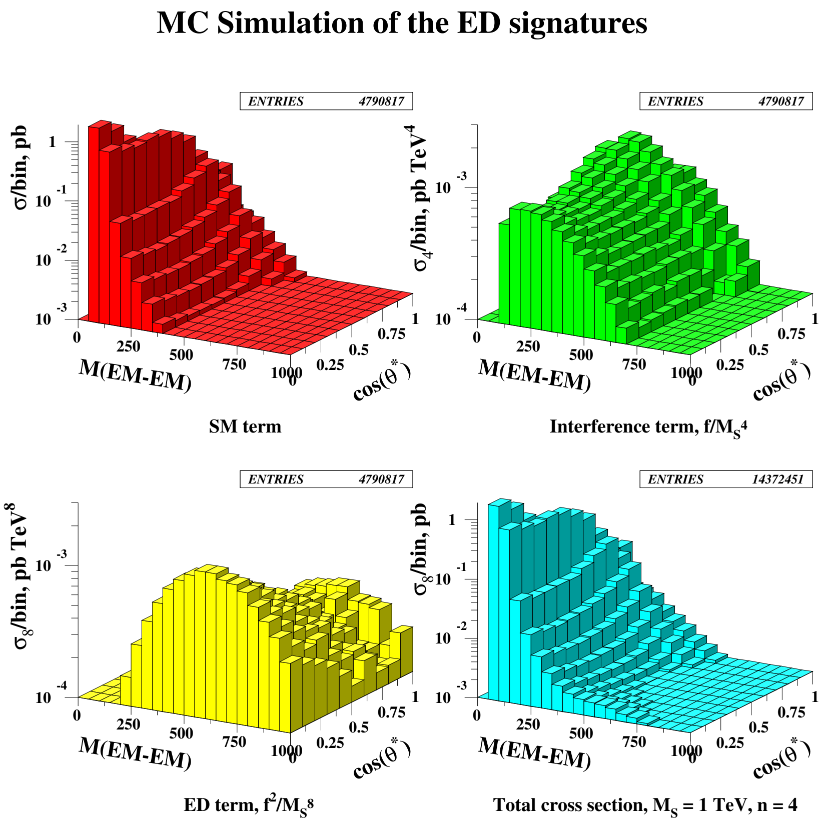

Figure 4. Contributions from gravity and all SM processes to the Monte Carlo in the $(M_{EM,EM}, |\cos\theta^*|)$ plane, for M_S= 1 TeV, and $n = 4$

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