Extra Dimensions at the Large Hadron Collider

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April 5, 2011

Contents

1 Introduction and Motivation

The Standard Model (SM) of particle physics arose from the work of particle theorists in the 1960s and 1970s. This model describes the strong and electroweak interactions using the language of non-Abelian gauge theory. In the many years since its conception, the SM has been subjected to myriad experimental tests. With the noteworthy exception of neutrino oscillations [1], the theory has proven to be remarkably robust. Indeed, the history of experimental particle physics in the latter half of the twentieth century is roughly summarized by recalling the most famous of these experiments. Deep inelastic scattering experiments at SLAC in the late 1960s [2] provided evidence for hadronic substructure in the form of light flavor SM quarks. Gluons and the W/Z bosons were discovered and characterized in the 1970s and '80s at DESY [3] and CERN [4], respectively. Most recently, the top quark was discovered at Fermilab in 1995 [5]. The only SM particle which has eluded detection thus far is the Higgs boson.

Despite the impressive success of this model, it is clearly not the "final theory" for which physicists have been searching. There are many problems which point to the existence of physics beyond the SM (BSM). The most obvious of these is the fact that the Standard Model does not incorporate a spin-2 gauge boson (gravity). There are, however, several other more subtle indicators of BSM physics. Of course, even a very wide-angle survey of BSM physics is well beyond the scope of this paper; for our purposes, it is sufficient to note that there are good theoretical reasons to expect new physics at the TeV-scale [6]. A vast literature exists on this topic, and theorists have explored a wide variety of models.

Current experiments are in agreement with SM predictions for parton momenta up to O(100) GeV. The expectation of TeV-scale new physics is particularly exciting due to the recent turn-on of the Large Hadron Collider (LHC) at CERN. The LHC is a 27 km circumference pp-collider with a design CM energy of $\sqrt{s} = 14$ TeV and instantaneous luminosity $L = 10^{34}$ cm^{-2}s^{-1} (which implies a bunch crossing rate of 40 MHz). There are two general purpose new physics detectors at the LHC: A Toroidal LHC Apparatus (ATLAS) and the Compact Muon Solenoid (CMS)—although there are five other experiments being conducted there as well. With 7 TeV per beam of protons, we can expect partons with momenta at the TeV-scale, and thus the LHC will allow us to probe new physics which may exist at this scale.

One particularly interesting type of BSM physics is the idea of extra dimensions (ED) of space. In fact, hypotheses incorporating extra time-like dimensions have also been explored [7], but we'll ignore those here. Interest in ED dates back almost a century to the seminal work of Nordstrom [8], Kaluza [9], and Klein [10]. The famous contribution of these three authors was a unification of general relativity and classical electrodynamics via an extra spatial dimension; we will explore a few details of this later. After a period of dormancy, interest in extra dimensions was renewed towards the end of the twentieth century when string theory began its rise to prominence. Typically, the additional dimensions in stringy models are highly compactified, and we will not concern ourselves with such dimensions here. Rather, in the interest of connecting with LHC phenomenology, we will concentrate on models which admit TeV-scale ED. A scandalously brief introduction to such hypotheses will be presented below. This will be followed by a discussion of discovery prospects for some of these models at the LHC. Before moving on, however, we should outline a few of the motivations behind our study.

It turns out that model-builders have been able to address a surprisingly large number of important questions by way of extra dimensions [11]. The most urgent hierarchy problem in particle physics pertains to the vast disparity between the electroweak scale and the Planck scale. As we will see below, this problem is often a key motivation for considering ED models. One can "solve" the hierarchy problem in various ways by allowing the existence of extra spatial dimensions. Several other flagship problems in particle physics admit at least partial solutions via ED. These include, but are not limited to, the identity of dark matter (*e.g.* excited photons in UED which will be discussed below), Higgsless mechanisms of EW symmetry breaking, the fermion mass hierarchy problem, and grand unification—not to mention the fact that they are necessary for the mathematical consistency of string theory. The full list of salient uses of ED is extensive, and we will not say much more about it. The point was simply to indicate that it is not difficult to justify why the study of extra dimensions has become part of the high energy mainstream.

2 Brief Introduction to the Theory of TeV-Scale Extra Dimensions

Due to their versatility and utility as a BSM model-building tool, ED arise in a number of theoretical contexts. In this section we will provide a very brief introduction to the most popular of these hypotheses at the TeV-scale. No attempt will be made to be exhaustive. The focus is simply to introduce and review the essential ideas.

2.1 Kaluza-Klein Theory

The first fruitful attempt to employ ED as a unification mechanism dates back to the work of Kaluza and Klein in the 1920s (referenced above). Since the terminology and philosophy of this work remain useful today, we will outline its basic principles before turning to more modern developments.

Recall that in general relativity we define a line element

$$ds^2 \equiv g_{\mu\nu}(x)dx^\mu dx^\nu, \tag{1}$$

where $g_{\mu\nu}$ is the metric tensor (a field on the 4d spacetime manifold) and x^μ are the spacetime coordinates. Kaluza's physical insight was to extend this definition by allowing spacetime to be 5-dimensional:

$$d\hat{s}^2 \equiv \hat{g}_{MN}(x)dx^M dx^N, \tag{2}$$

where our coordinates now live on a 5d manifold ($M, N \in \{1, ..., 5\}$), and the new metric $\hat{g}_{MN}$ is given in terms of $g_{\mu\nu}$, the electromagnetic 4-potential A_μ, and a scalar radion field ϕ:

$$\hat{g}_{MN} = \begin{pmatrix} g_{\mu\nu} + 16\pi G\phi^2 A_\mu A_\nu & 4\sqrt{\pi G}\phi^2 A_\mu \\ 4\sqrt{\pi G}\phi^2 A_\nu & \phi^2 \end{pmatrix}. \tag{3}$$

As with any ED scenario, we must explain why all previous experiments—and our own perceptions—agree with the hypothesis that the universe is (3+1)-dimensional. We will see various ways of handling this constraint when we examine other models below; Kaluza's only recourse was simply to assume that ∂_5 annihilates all of the fields appearing in equation 3 (cylindricity), so that physics is effectively 4d. This framework provides a unified description of classical electrodynamics and general relativity in the sense that one can recover the Einstein field equations (EFE) and the Maxwell equations if the 5-dimensional EFE are assumed to take a source-free form

$$\hat{R}_{MN} - \frac{\hat{R}}{2}\hat{g}_{MN} = 0, \tag{4}$$

where $\hat{R}_{MN}$ is the 5d Ricci tensor, and $\hat{R}$ is the 5d Ricci scalar.

This framework was later quantized by Klein, who realized that we could "hide" the 5th dimension by compactifying it on a sufficiently small topology. His proposal was a spacetime which factors as $R^4 \times S^1$, where R^4 is a 4d manifold and S^1 is a circle of radius R. If we denote the coordinates on $R^4 \times S^1$ by $(x^\mu, \alpha) \equiv (x, \alpha)$, we should demand that physical tensor fields $f_{\mu...\nu}(x, \alpha)$ satisfy a periodic boundary condition: $f_{\mu...\nu}(x, \alpha+2\pi R) = f_{\mu...\nu}(x, \alpha)$. Fields on such a spacetime then admit Fourier mode expansions:

$$f_{\mu...\nu}(x, \alpha) = \sum_{n\in\mathbb{Z}} e^{in\alpha/R} f^{(n)}_{\mu...\nu}(x). \tag{5}$$

The infinite set of R^4-dependent Fourier modes are said to comprise a so-called Kaluza-Klein (KK) tower of states. Much like a quantum mechanical particle on a ring, the α-component of momentum is discretized in multiples of R^{-1}. We thus recover effectively 4d physics if we make R small enough, because then even the $n = 1$ KK tower states will have α-momenta too large to be detected.

KK theory is obviously no longer viewed as a viable theory of the universe (but see subsection 2.5). For instance, it has nothing to say about the strong and weak interactions. It also turns out that the extra dimensions of KK theory have a very small ($\gg$ TeV) compactification scale. However, the idea of using ED as a means of answering difficult questions in physics has persisted. We now turn to more modern, and more phenomenologically practical, interpretations of this idea.

2.2 Large Extra Dimensions

Widespread interest in TeV-scale extra dimensions began in 1998 with the work of Arkani-Hamed, *et al.* [12]. These authors hypothesized the existence of so-called large extra dimensions (LED), and such models are now referred to as ADD models. ADD addresses the constraint of apparently-4d physics by confining SM fields to a 3-brane, and addresses the hierarchy problem by allowing gravity to spread through $n \geq 1$ extra dimensions.

In ADD we resolve the hierarchy problem by assuming that the electroweak scale ($m_{EW} \sim$ 1 TeV) and the scale of quantum gravity are the same. This is a radical idea, since the Planck scale is $M_{Pl} \sim 10^{15}$ TeV. To make our assumption sensible, we can allow the existence of n additional compactified dimensions of space, so that the universe is (3+n+1)-dimensional. In order to see how this works, let's take the length scale of the extra dimensions to be of order R. We can then consider the classical gravitational potential in 4+n dimensions when $r \ll R$:

$$V_g(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} r^{n+1}}, \; r \ll R, \tag{6}$$

where $M_{Pl(4+n)} \sim m_{EW}$ is the "real" Planck scale of nature. The familiar r^{-1} gravitational potential, however, agrees with experiments down to roughly the sub-millimeter range. We therefore require that

$$V_g(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} R^n r}, \; r \gg R. \tag{7}$$

This last equation reveals that the familiar Planck scale M_{Pl} is really an "effective" scale of gravity which is parametrized by the curvature of the extra dimensions and the true Planck scale:

$$M_{Pl} \sim \sqrt{M_{Pl(4+n)}^{n+2} R^n}. \tag{8}$$

Since the value of M_{Pl} is known, and the value of $M_{Pl(4+n)}$ is assumed to be on the order of m_{EW}, we can choose appropriate values of R and n to satisfy this relationship. It turns out that $n = 1$ is experimentally excluded, so only $n \geq 2$ LED are possible. One can then go through the formal business of localizing fields on a 3-brane within the bulk, which has been done for various topologies and field theories.

The immediate issue with ADD is that it substitutes a hierarchy problem for a fine-tuning problem: Although we obtain similar characteristic scales for the electroweak and gravitational interactions, we do so at the cost of fine-tuning the otherwise free parameter R. This philosophical issue, however, doesn't imply that such models aren't realized in nature. In other words, ADD theory is phenomenological rather than fundamental. Below it will be shown that ADD is in poor agreement with early LHC data.

2.3 Warped Extra Dimensions

Another popular flavor of ED are so-called warped extra dimensions. Such theories are often referred to as Randall-Sundrum (RS) after their originators [13]. Here we will sketch the most basic type of RS model, wherein the bulk spacetime geometry is that of two 3-branes separated by a single extra dimension. The metric changes rapidly along this extra dimension (spacetime is "warped"), which gives rise to effectively 4d physics on our brane.

Let's consider coordinates (x^μ, ϕ) on a 5d manifold with the topology of two 3-branes attached to the fixed points of an S^1/Z_2 orbifold (this orbifold can be roughly conceptualized as a circle compressed to a line segment). Many authors refer to the two branes as the Tevbrane and the Planckbrane. Here x^μ are coordinates for familiar 4d space, and $0 \leq \phi \leq \pi$ is the coordinate in the extra dimension. Consider a non-factorizable metric in such a universe of the form

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2, \tag{9}$$

where $k \sim M_{Pl}$, and $e^{-2kr_c\phi}$ is referred to as the warp factor of the theory. Working at the classical level, such a line element can be justified by considering an action with pieces for each component of the topology:

$$\begin{aligned} S_{RS} &= S_{gravity} + S_{vis} + S_{hid} \\ &= \int d^4x \int_0^\pi d\phi \sqrt{-G}(-\Lambda + 2M^3 R) + \int d^4x \sqrt{-g^{vis}}(\mathcal{L}_{vis} - V_{vis}) + \\ &\quad \int d^4x \sqrt{-g^{hid}}(\mathcal{L}_{hid} - V_{hid}), \end{aligned} \tag{10}$$

where $G_{MN},\ M, N = \mu, \phi$ is the bulk metric, $\mathcal{L}_j$ are the Lagrangians on each 3-brane, and V_j are the vacuum energies on these branes. One can then solve the EFE associated with S_{RS} and verify that the ansatz presented in equation 9 is indeed a solution. The metrics $g^j_{\mu\nu}(x)$ define two boundary conditions for G:

$$g^{vis}_{\mu\nu}(x) = G_{\mu\nu}(x, \phi = \pi),\ \ g^{hid}_{\mu\nu}(x) = G_{\mu\nu}(x, \phi = 0). \tag{11}$$

A more careful quantum mechanical analysis of these ideas reveals that the graviton wave function is exponentially suppressed as we travel along the warped 5th dimension from one 3-brane to another. This explains why gravity appears to be so much weaker than the other interactions which are localized on our brane. Large experimental efforts are underway to search for RS signatures at the LHC. We will return to this point later.

2.4 Universal Extra Dimensions

It is also possible to have ED in which all SM fields are allowed to propagate. Models of this type are said to possess universal extra dimensions (UED). Here we will consider the simplest UED scenario in which there is a single ED compactified on a S^1/Z_2 orbifold; this is often called minimal UED (mUED). In mUED, then, we have the following boundary conditions for spinor fields

$$\psi(x,y) = \psi(x, y + 2\pi R),\ \psi(x,y) = -\gamma^5\psi(x,-y), \tag{12}$$

where y is the coordinate in the ED and R is its radius. This gives UED fermionic KK towers the desired SM chirality

$$\psi_L(x,y) = \sum_{n\in\mathbb{N}\cup\{0\}} \psi_L^{(n)}(x)\cos(n\frac{y}{R}),\ \psi_R(x,y) = \sum_{n\in\mathbb{N}} \psi_R^{(n)}(x)\sin(n\frac{y}{R}). \tag{13}$$

Similarly to R-parity conserving supersymmetry (SUSY), mUED has a conserved KK-parity: $(-1)^n$. This implies that the lightest KK particle (LKP) is stable, and that it must be pair-produced. As we will see later, this turns out to be an important feature of experimental searches for mUED. KK-parity conservation can be traced to the reflection symmetry of the orbifold.

It is important to keep in mind that the KK tower states are not "new" particles; they are simply new states of existing particles. At tree-level, we can obtain the mass of each tower mode (see also figure 1)

$$m_n = \sqrt{m_0^2 + \frac{n^2}{R^2}}. \tag{14}$$

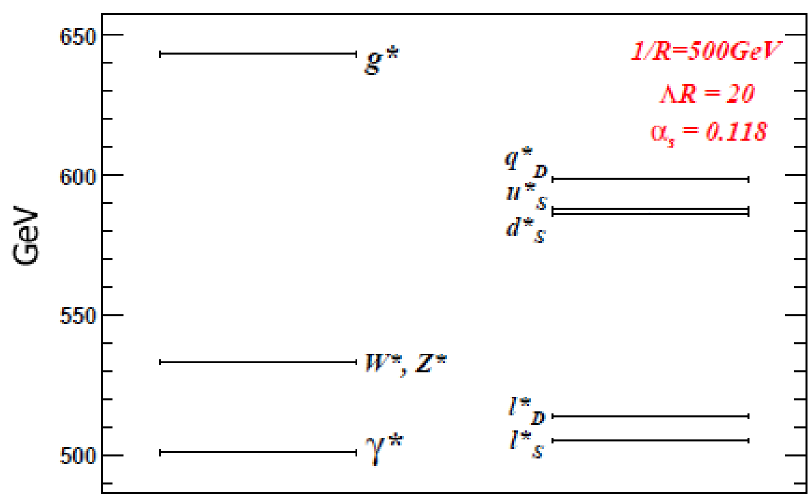

Figure 1: $n = 1$ mass splittings in mUED. The "*" indicates a KK excited state. Figure from [14].

When one includes loops at the orbifold fixed points, one must of course introduce a UV cut-off Λ for the theory. This increases the mass splitting given in equation 14, because the quantum corrections are proportional to $m_n \ln(\Lambda^2/\mu^2)$, where μ is the renormalization scale. Thus the mUED parameter space is 3d: (R^{-1}, Λ, m_h), where m_h is the Higgs mass, which is free in UED.

UED gives rise to interesting collider phenomenology, and there are various experimental efforts underway to probe these models at the LHC. We will return to this in some detail later, with particular emphasis on final states involving three leptons.

2.5 Other Models

We have touched on the most popular classes of TeV-scale ED models. There are, however, many other hypotheses which have been put forth—some of which are associated with sizeable literatures. For the sake of interest, we will mention (and provide references to) a couple of these in passing.

One particularly intriguing scenario, called DGP, was suggested by Dvali (of ADD fame) and collaborators in 2000 [15]. This scenario has an interesting motivation: accounting for cosmic acceleration without a vacuum energy density. This is realized by embedding 4-dimensional gravity on a brane in 5d Minkowski space. The action in DGP theory takes the form of a sum of Einstein-Hilbert actions:

$$S_{DGP} = M^3 \int d^5X \sqrt{G} R_5 + M_{Pl}^2 \int d^4x \sqrt{-g} R, \tag{15}$$

where G is the bulk metric, and R_5 is the 5d Ricci scalar. This model has gradually fallen out of favor for several reasons. Most recently, baryon oscillation data from the Sloan Digital Sky survey have contradicted its predictions [16].

It was mentioned earlier that KK theory remains useful only through the importance of its philosophy and terminology. There is however an interesting modern version of KK theory called space-time-matter (STM) theory which is a topic of current research [17]. In STM models, one begins by writing down source-free EFE in higher dimensions (similarly to KK) $R_{MN} = 0$. By relaxing assumptions about the scale and topology of the extra dimensions, one recovers 4d GR and additional terms which are interpreted as 4d matter and energy.

3 Experimental Searches for Extra Dimensions At the LHC

Data from the LHC have already begun to allow us to probe the TeV-scale and set limits on ED and other BSM physics scenarios. In this section we will discuss the prospects of discovering some of the models that were examined in the previous section. Since this subject is vast, we will again have to be brief in our comments. Particular emphasis will be placed on UED; this reflects the bias of the author.

3.1 ADD

The search for large extra dimensions at the LHC is already underway. The CMS collaboration recently published a note [18] in which ADD predictions were tested by searching for signals of microscopic black holes. Interestingly, the parton-level cross section for micro black hole production is roughly $\sigma \sim \pi r_s^2 \lesssim 100$ pb (at LHC energies), where r_s is the Schwarzschild radius of the black hole. The altered short-distance behavior of gravity that was discussed earlier for ADD theory allows for the production of such black holes if particles collide with energies $\gtrsim M_{Pl(4+n)}$. This is in stark contrast to the required collision energy of $\gtrsim M_{Pl}$ in a strictly (3+1)-dimensional universe. Since these black holes have small masses, they evaporate via Hawking radiation very quickly. It turns out that they preferentially decay ($\Gamma/\Gamma_{tot} \sim 0.75$) via SM quark and gluon modes.

The aforementioned study by CMS was performed at $\sqrt{s} = 7$ TeV and with integrated luminosity 34.7$\pm$3.8 pb^{-1}. Figure 2, taken from this analysis, overlays S_T for data, SM backgrounds, and ADD predictions for three different parameter space points. The quantity S_T is defined to be a scalar sum of the transverse energy of all final-state objects passing the various object selection cuts employed in the analysis:

$$S_T \equiv \sum_{j_{\text{pass}}}^{N} |E_T^{j_{\text{pass}}}|. \tag{16}$$

This figure (and other similar figures in the CMS note) certainly does not suggest that large extra dimensions exist in this region of parameter space. As higher S_T values become attainable—later in the LHC's lifetime—we will be able to explore further portions of the parameter space. The end result of this study was the placement of new 95% confidence limit curves on minimum micro black hole masses; these ranged from roughly 3.5 TeV to 4.5 TeV (as a function of the true Planck scale and number of LED).

3.2 RS

The most stringent pre-LHC limit on the mass of the $n = 1$ RS KK graviton is from $p\bar{p}$ collisions at the Tevatron ($\sqrt{s} = 1.96$ TeV) [19]. Using ee and $\gamma\gamma$ channels, it was established that $m_{G^*} \gtrsim$ 300-900 GeV at the 95% confidence level.

To understand the discovery prospects of RS gravitons at the LHC, we can parametrize the model in terms of m_{G^*} and the dimensionless quantity $c = k/M_{Pl}$, where k is the dimensionful constant which appears in the warp factor. Given that the LHC's nominal operating energy is 14 TeV, one can then map out the discovery and (spin-2) identification

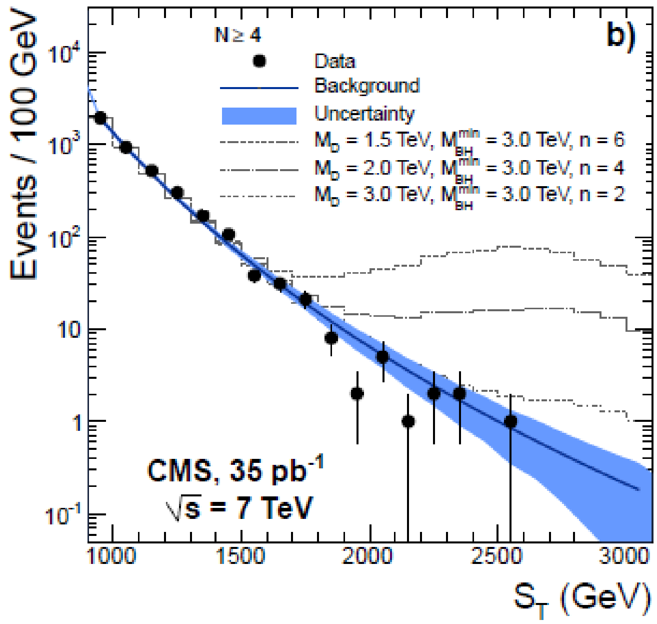

Figure 2: A plot of S_T for data, background, and several ADD parameter space points from a recent CMS analysis. Figure from [18].

prospects of this resonance by studying the dependence of the graviton production cross section on (m_{G^*}, c) parameter space. This has recently been done [20], and the results are displayed in figure 3 below for two different integrated luminosities. Some explanation of this figure is necessary. First, as is customary in experimental high energy physics, by "discovery" we mean a 5σ effect, and by "identification" we mean at the 95% confidence level. The quantity Λ_π in the figure refers to the true Planck scale—which we of course want to be no larger than O(10) TeV. The region to the left of the G curve is the region which can be probed by LHC data. We can rule out spin-1 and spin-0 resonances in the regions to the left of the V and S curves, respectively. The desired discovery and identification region is then the double-shaded region in the upper left portion of the plots. As we would expect, prospects of discovery and identification improve nontrivially with an order of magnitude increase in integrated luminosity.

This discussion pertains to analyses that will be possible in the future. Currently, the LHC is still in the early stages of its lifetime. It is running at $\sqrt{s} = 7$ TeV, and has collected only about 40 pb^{-1} of integrated luminosity. The prospects of discovery and identification with the present early dataset would therefore look far worse than those presented above. It is encouraging, though, to see that nontrivial improvements over the existing Tevatron limits will soon be possible. Specifically, we should be able to discover and identify RS gravitons if $m_{G^*} \lesssim 1.6$ TeV - 3.2 TeV (depending on the value of c).

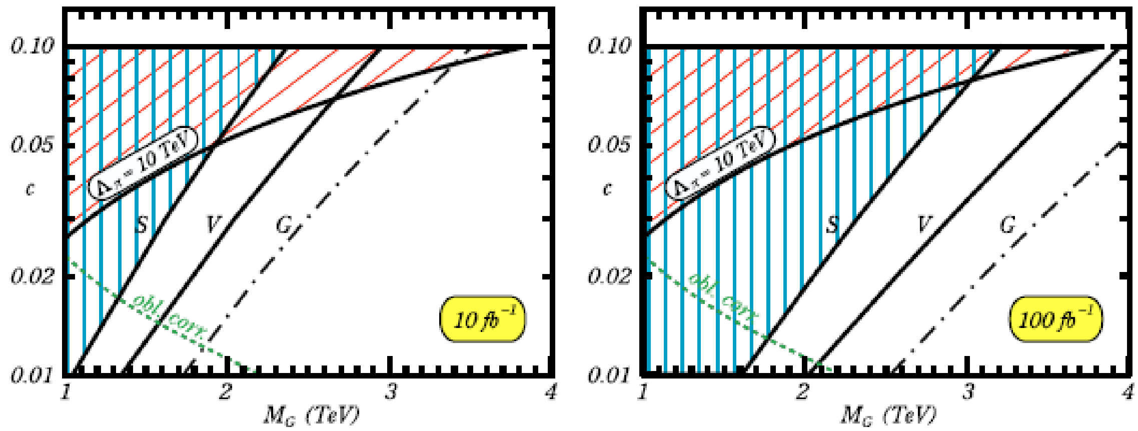

Figure 3: The portions of RS parameter space corresponding to discovery and identification of gravitions for two different amounts of LHC integrated luminosity at 14 TeV. Figure from [20].

3.3 UED

The most current collider constraint on a single UED is a 2010 D0 diphoton result [21]. We should note that this isn't a strictly mUED study. It includes graviton-mediated LKP decays ($\gamma^* \to G\gamma$) in 6 additional LED. The analysis was performed on data collected at the Tevatron at $\sqrt{s} = 1.96$ TeV corresponding to 6.3 fb^{-1} of integrated luminosity. The result is shown below in figure 4; it was found that $R^{-1} > 477$ GeV at the 95% C.L.

The UED discovery reach of the LHC is expected to be much greater than that of the Tevatron. Detailed collider phenomenology studies have recently been performed in an attempt to quantify how much greater this reach will be. We see the result of one such study [22] displayed below in figure 5. Notice first that these authors obtained roughly the value that was discussed above for the Tevatron limit on R^{-1}. Since this result was produced several years before said Tevatron limit was established, we can feel reasonably confident that the methodology is sound. This figure shows curves for 5 signal events and for a 5σ excess over SM backgrounds at the nominal LHC CM energy. The discovery reach is defined to be the larger of these two quantities (the solid line). This is based on whether or not the expected backgrounds contribute more than a single event. We see that a 5σ discovery can be established if $R^{-1} \lesssim 1.5$ TeV. This is a nontrivial gain over the reach of the Tevatron.

The "golden" channel for SUSY discovery at hadron colliders is the multi-lepton final state. "Multi-lepton" is in fact a jargon term—what is really meant is multiple final state $e^\pm$ or $\mu^\pm$ (*i.e.* multiple light flavor charged leptons). Due to cascade decays induced by KK-parity conservation, this is also a promising channel in which to do mUED

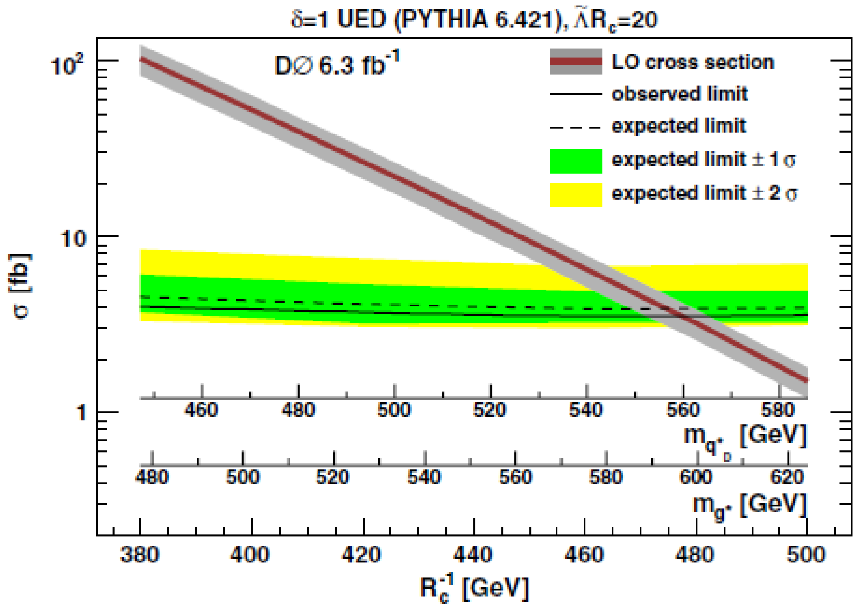

Figure 4: The current experimental limit on the curvature of a single UED. Figure from [21].

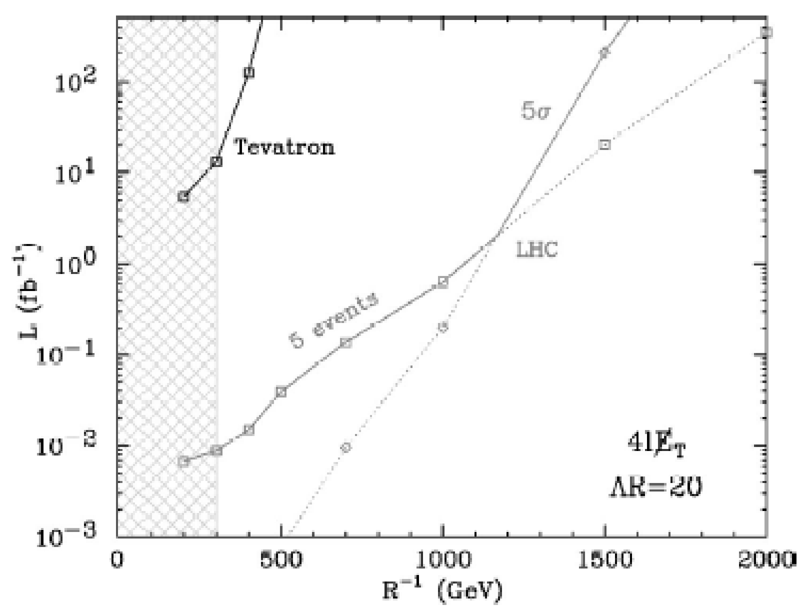

Figure 5: The expected UED discovery reach of the LHC. Figure from [22].

searches [23]. An interesting question then arises: If two different hypotheses predict the same signature, how does one tell the difference between them? This question arises in many different contexts at the LHC, and its answer often represents a subtle and difficult experimental problem. In an attempt to gain some insight into distinguishing SUSY versus mUED at the LHC, we have performed some basic Monte Carlo studies using the PYTHIA event generator.

We have mapped out 25 benchmark points in (R^{-1}, Λ) parameter space using PYTHIA's mUED implementation with a stable LKP and a SM Higgs mass. For the sake of choosing a definite multi-leptonic final state, we have decided to examine the tri-lepton channel. No generator-level filters were placed (aside from the tri-lepton requirement). Roughly 1000 events were generated at 7 TeV for each benchmark point. The PYTHIA implementation of mUED permits all parton-level processes that one might expect involving $n = 1$ q^* (both singlet and doublet) and g^*, and their subsequent cascade decays. Cascades to SM tri-leptons look similar to the example shown in figure 6. Notice that the signal is then $3L + 2J + E_T^{\text{miss}}$, which is identical to the tri-lepton SUSY signal.

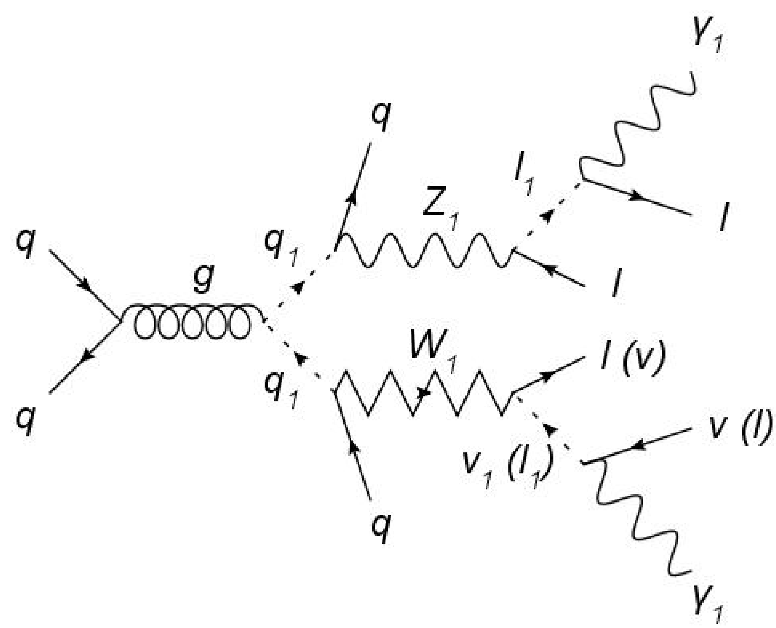

Figure 6: A sample mUED cascade decay to tri-leptons. The unity subscripts refer to $n = 1$ KK tower states. Similar allowed modes are obtained by replacing one or both of the Z_1 and W_1 by W_1 or Z_1, respectively, and also via replacing the gq_1q_1 operators by gg_1g_1 operators.

In figure 7 we display the results of our PYTHIA simulations. For each of the 25 samples, a leading lepton p_T distribution was populated. The means of these distributions $< p_T^{1,\text{lep}} >$

are displayed in the figure. The striking feature here is that the leptons have very low p_T. Tri-lepton SUSY analyses currently underway at the LHC (and similar analyses at the Tevatron), for instance, usually place cuts at around $p_T \gtrsim 20$ GeV for all three leptons [24]. In our PYTHIA study, we found that the three leading lepton mean transverse momenta $< p_T^{j,\mathrm{lep}} >$ were typically separated by gaps of $\sim$ 10 GeV ($< p_T^{2,\mathrm{lep}} > - < p_T^{3,\mathrm{lep}} > \sim 10$ GeV, etc.). This, coupled with the small RMS values we obtained for these distributions, suggests that mUED tri-leptons are considerably softer than those predicted by SUSY in nontrivial portions of the parameter space. This is an important feature, because it represents one way in which analyses may be able to distinguish between the two models if this signature is observed in LHC data.

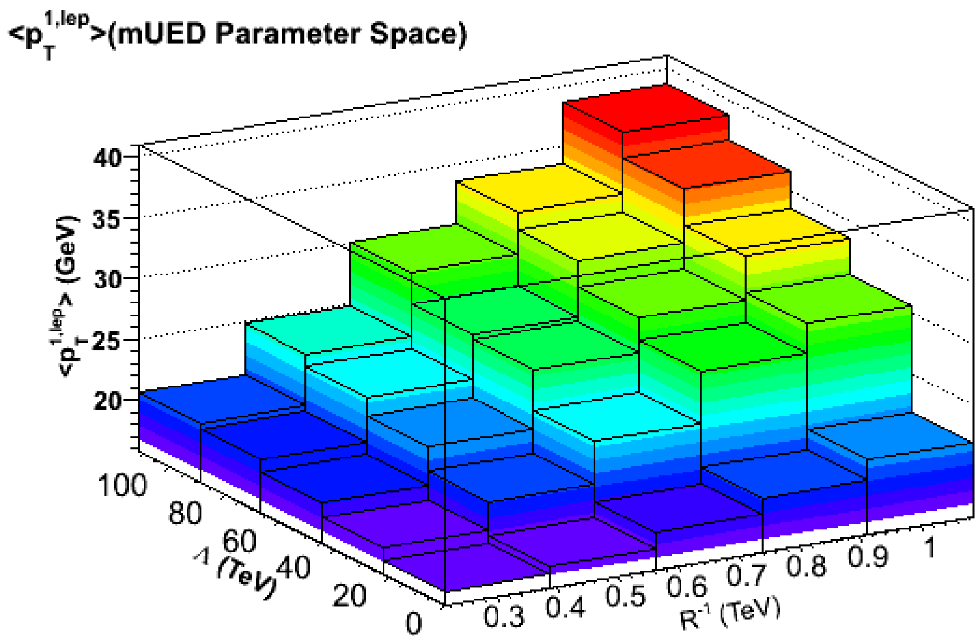

Figure 7: Results of Monte Carlo mUED simulations. This shows average leading lepton transverse momentum as a function of mUED parameter space.

4 Conclusion

We have presented a very general introduction to the theory of TeV-scale extra dimensions, and the prospects for their discovery at the Large Hadron Collider. The study of such models is motivated by the interesting fact that allowing the existence of ED often permits elegant solutions of difficult problems in particle physics.

No excesses over SM backgrounds were observed in Tevatron ED analyses, but we have seen that the current generation of collider studies will have considerably greater reach. Indeed, the first round of BSM analyses are already underway at ATLAS and CMS. It will be quite interesting to follow their development as the luminosity and CM energy of the LHC are increased in the coming years. Discovering extra dimensions at the TeV-scale is a very real, and very fascinating, possibility. The worst case scenario is that we will soon be able to place much more restrictive limits on the parameter spaces of these models.

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