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Physics of extra dimensions at colliders

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Abstract. We present a review of extra-dimensional models that have implications for physics at the TeV scale. An exposition of the models is followed by a discussion of the collider phenomenology.

Keywords. Extra dimensions; brane worlds; collider physics.

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1. Introduction

The success of general relativity inspired other attempts to unify geometry and physics. The Kaluza–Klein programme is the most well-known of these attempts, where, by invoking a higher-dimensional space–time it was hoped that one could unify gravity and electromagnetism. To recover the four-dimensional world of experience, these extra dimensions have to be compactified to sizes which are unobservably small. Even after compactification, there is a vestige of the extra dimensions that remains in the four-dimensional world: for each field in the higher dimensions there appear an infinite tower of fields in four dimensions – the Kaluza–Klein or KK tower. The attempt to make the extra dimensions so small that the KK theories can survive observational tests also makes the tower of states very massive so that, in the end, no significant deviation from our experience of the four-dimensional world is observable, making the hypothesis of extra dimensions untestable in any experiment. This is an unattractive feature of these theories, nevertheless the idea that all interactions are the consequence of space–time symmetries is so attractive that there have been vigorous attempts to generalise the attempt of Kaluza and Klein to include other interactions using more complicated compactification schemes.

2. Large extra dimensions

Recently, new incaranations of Kaluza–Klein theories have been discussed in the literature which can be a way of getting around the gauge hierarchy problem. The standard model which is so successful phenomenologically is a theory that exists at a scale of a few hundred GeV, which is several orders of magnitude below the Planck scale. This disparity between scales becomes a huge problem in a theory like the SM which admits fundamental scalars. The conventional approach to tackle the hierarchy problem is supersymmetry but new advances in string theory have suggested refreshingly novel ways of tackling this problem.

The understanding of the strong-coupling regime of string theories has led to a major paradigm shift. The tool that has made it possible to understand the strong-coupling regime is duality. This duality, which is quite similar to the concept of duality in field theories, relates a theory at weak coupling to another theory at strong coupling. In field theories, this relationship also entails an electric/magnetic duality and, therefore, the duality multiplets include the elementary quanta which are pointlike and solitonic modes which are extended configurations. The situation in string theory is similar albeit more complicated where, in addition to the elementary strings, the spectrum of particles includes solitonic objects which are called D-branes. These are best thought of as topological defects of varying dimensionalities: a Dp-brane is a dynamical $p+1$-dimensional surface. An interesting feature of the D-branes is that they act as surfaces on which open strings end.

If one were to regard the four-dimensional universe as a D3-brane embedded in a higher-dimensional space–time, then one would have a picture where the gauge particles, which correspond to the open strings, will end on the 3-branes while the gravitons, which correspond to the closed strings, are not restricted to lie on the 3-brane. This implies that the gauge particles (i.e. the SM particles) are confined to the 3-brane or the 3+1-dimensional surface and only the gravitons are free to propagate in the full D dimensions. As usual, the extra $D-4$ dimensions have to be compactified to obtain the 3+1-dimensional theory [1]. But, since these extra dimensions are only 'seen' by gravity, these need not be compactified to length-scales which are of the order of M_{P}^{-1} but it can be arranged that n of these extra dimensions are compactified to a common scale R which is relatively large, while the remaining dimensions are compactified to much smaller length-scales which are of the order of the inverse Planck scale. This scenario incorporating the idea of large extra dimensions was first discussed by Arkani-Hamed, Dimopoulos and Dvali [2] and is referred to as the ADD scenario, though earlier attempts at making the extra dimensions large have been made [3]. The relation between the scales in $4+n$ dimensions and in four dimensions is given by [2]

$$M_{\mathrm{P}}^2 = M_{\mathrm{S}}^{n+2} R^n, \tag{1}$$

where M_{S} is the low-energy effective string scale. This equation has the interesting consequence that we can choose M_{S} to be of the order of a TeV and thus get around the hierarchy problem. For such a value of M_{S}, it follows that $R = 10^{32/n-19}$ m, and so we find that M_{S} can be arranged to be a TeV for any value $n > 1$. Effects of non-Newtonian gravity can become apparent at these surprisingly low values of energy. For example, for $n = 2$ the compactified dimensions are of the order of 1 mm, just below the experimentally tested region for the validity of Newton's law of gravitation and within the possible reach of ongoing experiments [4].

3. The low-energy effective theory

Below the scale $M_{\rm S}$ the following effective picture emerges [5–7]: there are the Kaluza–Klein states, in addition to the usual SM particles. The graviton corresponds to a tower of Kaluza–Klein states which contain spin-2, spin-1 and spin-0 excitations. The spin-1 modes do not couple to the energy–momentum tensor and their couplings to the SM particles in the low-energy effective theory are not important. The scalar modes couple to the trace of the energy–momentum tensor, so they do not couple to massless particles. Other particles related to brane dynamics (for example, the Y modes which are related to the deformation of the brane) have effects which are subleading, compared to those of the graviton. The only states, then, that contribute are the spin-2 Kaluza–Klein states. These correspond to a massless graviton in the $4+n$-dimensional theory, but manifest as an infinite tower of massive gravitons in the low-energy effective theory. For graviton momenta smaller than the scale $M_{\rm S}$, the effective description reduces to one where the gravitons in the bulk propagate in the flat background and couple to the SM fields on the brane via an (four-dimensional) induced metric $g_{\mu\nu}$. Starting from a linearised gravity Lagrangian in n dimensions, the four-dimensional interactions can be derived after a Kaluza–Klein reduction has been performed. The interaction of the SM particles with the graviton, $G_{\mu\nu}$, can be derived from the following Lagrangian:

$$\mathcal{L} = -\frac{1}{\bar{M}_{\rm P}} G^{(j)}_{\mu\nu} T^{\mu\nu}, \tag{2}$$

where j labels the Kaluza–Klein mode and $\bar{M}_{\rm P} = M_{\rm P}/\sqrt{8\pi}$, and $T^{\mu\nu}$ is the energy–momentum tensor.

In view of the fact that the effective Lagrangian given in eq. (2) is suppressed by $1/\bar{M}_{\rm P}$, it may seem that the effects at colliders will be hopelessly suppressed. However, in the case of real graviton production, the phase-space for the Kaluza–Klein modes cancels the dependence on $\bar{M}_{\rm P}$ and, instead, provides a suppression of the order of $M_{\rm S}$. For the case of virtual production, we have to sum over the whole tower of Kaluza–Klein states and this sum when properly evaluated [7,6] provides the correct order of suppression ($\sim M_{\rm S}$). The summation of time-like propagators and space-like propagators yield exactly the same form for the leading terms in the expansion of the sum [7] and this shows that the low-energy effective theories for the s- and t-channels are equivalent.

4. The experimental constraints

There have been several studies exploring the consequences of the above effective Lagrangian for particle phenomenology and astrophysics. Production of gravitons giving rise to characteristic missing energy or missing $p_{\rm T}$ signatures at e^+e^- or hadron colliders have been studied resulting in bounds on $M_{\rm S}$ which are around 500 GeV to 1.2 TeV at LEP2 [8,9] and around 600 GeV to 750 GeV at Tevatron [8]. Production of gravitons at the large hadron collider (LHC) and in high-energy e^+e^- collisions at the next linear collider (NLC) have also been considered. Virtual effects of graviton exchange in dilepton production at Tevatron yields a bound of around

950 GeV to 1100 GeV [10] on $M_{\rm S}$, in $t\bar{t}$ production at Tevatron a bound of about 650 GeV is obtained while at the LHC this process can be used to explore a range of $M_{\rm S}$ values up to 4 TeV [11]. Virtual effects in deep inelastic scattering at HERA put a bound of 550 GeV on $M_{\rm S}$ [12], while from jet production at the Tevatron strong bounds of about 1.2 TeV are obtained [13]. Pair production of gauge bosons and fermions in e^+e^- collisions at LEP2 [14,15] can probe values of $M_{\rm S}$ up to 0.6 TeV. Other processes studied include associated production of gravitons with gauge bosons and virtual effects in gauge boson pair production at hadron colliders [16,17]. Higgs production [18,19] and electroweak precision observables [20] in the light of this new physics have also been discussed. Astrophysical constraints, like bounds from energy loss for supernovae cores, have also been discussed [21]. In general, the processes which involve real production of gravitons give stronger constraints for $n = 2$ than the processes involving virtual exchange of gravitons but the advantage of the virtual processes is that the bounds obtained from them have a mild n dependence whereas the bounds from real production processes fall rapidly with increasing n.

5. Minimal length

There are reasons to believe that at the Planck scale, the scale at which gravity becomes a quantum phenomenon, the very structure of space–time may change. That this may happen is suggested even by general relativity. A quantum mechanical particle of momentum p in the presence of a classical gravitational field (the latter described by Einstein's equations) causes the metric g to fluctuate. This induces an additional uncertainty in position, given by $l_{\rm p}^2 \Delta p$, where $l_{\rm p}$ is the Planck length. Thus the uncertainty relation gets modified to

$$\Delta x \frac{1}{\Delta p} + l_{\rm p}^2 \Delta p. \tag{3}$$

At high energies, the second term can become significant and lead to important deviations from quantum mechanics. With the modified uncertainty relation, even at high momenta Δx is limited in resolution because of strong curvature effects. In other words, independent of momentum, Δx is always larger than a minimal length scale $l_{\rm p}$. The appearance of the minimal length in the classical theory of gravity should tell us that it is no surprise to expect that such a conclusion becomes even more inevitable in a quantum theory of gravity. Indeed, a whole range of quantum gravity models predict the existence of a minimal length [22]. It is interesting to consider a union of the idea of a minimal length with the ADD model. In the ADD model, since $M_{\rm S} \sim 1$ TeV, the minimal length hypothesis is phenomenologically interesting if we take it to be around an inverse TeV, viz. $l_{\rm p} \sim 1/M_{\rm S}$ [23].

Different applications of the minimal length scenario (MLS) have been discussed in [24–27]. In particular, in refs [26,27], the collider implications of this scenario have been studied: in dilepton production via virtual graviton exchange and in real graviton production at hadron colliders. The introduction of the minimal length is particularly interesting for the case of virtual graviton exchange because the minimal length acts as an ultraviolet regulator and allows one to sum over the entire KK graviton tower by smoothly cutting off the contribution of higher energy KK states rendering the amplitude finite. Another important modification comes from the rescaling of momentum measure leading to an alteration in the phase-space integration. These lead to a significant deviation of the bound on $M_{\rm S}$ from the one obtained in the conventional ADD picture without the MLS hypothesis.

6. Trans-Planckian effects

At the LHC, the collision energies are often in the trans-Planckian domain. If the impact parameter in the collision between two partons is smaller than the n-dimensional Schwarzschild radius $R_{\rm S}$, given by

$$R_{\rm S} = \frac{1}{M_{\rm S}}\left[\frac{M_{\rm BH}}{M_{\rm S}}\right]^{1/(n+1)}\left[\frac{2^n\pi^{(n-3)/2}\Gamma(\frac{n+3}{2})}{n+2}\right]^{(1/(n+1)} \tag{4}$$

then a black hole may be formed, if the entropy of the resulting system is sufficiently high. For a review see ref. [28]. The production cross-section, given by the geometrical cross-section $\pi R_{\rm S}^2$, can be huge at the LHC (~400 pb for $M_{\rm S}$ and $M_{\rm BH}$ of $O(1\ {\rm TeV})$). The spin of the black hole is important so it may be more appropriate to consider Kerr solutions, instead of the Schwarzschild solutions. The decay proceeds mainly through Hawking radiation and primarily into SM particles on the brane. Decay proceeds through three phases: a balding phase where the black hole loses hair associated with multipole moments, a spin-down phase where the angular momentum is shed, followed by a longer Schwarzschild phase. One ends up with large multiplicity events with hard jets and leptons. Given the large cross-sections for black hole production at colliders and for the clean final states that the black hole decays into, it may well be the discovery mode for the ADD model at the LHC.

7. Randall–Sundrum model

In spite of the fact that the ADD model sets out to solve the hierarchy problem, it is plagued by the reappearance of disparate scales, viz., the string scale $M_{\rm S} \sim 1$ TeV and the compactification radius $R_{\rm c} \sim \left(10^{-16}\ {\rm TeV}\right)^{-1}$. The stability of the large dimensions is an undesirable feature of this model and it was in an attempt to resolve this issue that the Randall–Sundrum (RS) model originated [29]. In its original form, the RS model is a five-dimensional model where the fifth dimension ϕ is compactified on a S^1/Z^2 orbifold with a radius $R_{\rm c}$ which is somewhat larger than the Planck length. At the orbifold fixed points, $\phi = 0,\ \pi$, two 3-branes called the Planck brane and the TeV brane are located. The SM fields are assumed to be localised on the TeV brane. To get Poincaré invariance on the brane, it is necessary to fine-tune the cosmological constants both on the brane and in the bulk. The model proposes a novel five-dimensional metric of the form

$${\rm d}s^2 = {\rm e}^{-\mathcal{K}R_{\rm c}\phi}\eta_{\mu\nu}{\rm d}x^\mu{\rm d}x^\nu + R_{\rm c}^2{\rm d}\phi^2. \tag{5}$$

This metric is *non-factorizable* or *warped* and the exponential warp factor $\mathrm{e}^{-\mathcal{K}R_c\phi}$ serves as a conformal factor for fields localised on the brane and this can be used to solve the hierarchy problem. The huge ratio $(M_\mathrm{P}/M_\mathrm{EW}) \sim 10^{15}$ can be generated by the exponent $\pi\mathcal{K}R_c$ which needs to be only of $\mathcal{O}(30)$.

On compactification of the extra dimensions, a tower of massive Kaluza–Klein (KK) excitations of the graviton, $h_{\mu\nu}^{(\vec{n})}$, result in the 3-brane whose masses are given by

$$M_n = x_n \mathcal{K} \mathrm{e}^{-\pi\mathcal{K}R_c}, \tag{6}$$

where x_n are the zeros of the Bessel function $J_1(x)$ of order unity [30]. The masses of the KK excitations are not evenly spaced in this model. The zero-mode in the tower of excitations essentially decouples because of its weak coupling but the couplings of the massive RS gravitons are enhanced by the exponential $\mathrm{e}^{\pi\mathcal{K}R_c}$ leading to interactions of electroweak strength. The Feynman rules in this model are the same as those worked out for the ADD case, except for the overall warp factor.

The basic parameters of the RS model are

$$\begin{aligned} m_0 &= \mathcal{K}\mathrm{e}^{-\pi\mathcal{K}R_c}, \\ c_0 &= \mathcal{K}/M_\mathrm{P}, \end{aligned} \tag{7}$$

where m_0 is a scale of the dimension of mass and sets the scale for the masses of the KK excitations, and c_0 is an effective coupling. The interaction of massive KK gravitons with matter can be written as

$$\mathcal{L}_\mathrm{int} = -\sqrt{8\pi}\frac{c_0}{m_0}\sum_n^\infty T^{\mu\nu}(x) h_{\mu\nu}^{(n)}(x). \tag{8}$$

It is expected that the parameter c_0 lies in the range [0.01, 0.1]. This is because the scale $\mathcal{K}$ is related to the curvature of the fifth dimension and so the upper bound on c_0 results if we want to avoid strong curvature effects. But at the same time we would not want $\mathcal{K}$ to be too small as compared to the Planck mass since that would introduce a new hierarchy. Values of m_0 are determined in terms of $\mathcal{K}R_c \sim 10$, so that m_0 ranging from about a 100 GeV to a TeV are possible. Also, m_0 cannot become very large because it would require either $\mathcal{K}$ to be large, or $\mathcal{K}R_c$ to be small (see eq. (7)). This results in a large curvature of the fifth dimension which makes it difficult to fine-tune the cosmological constants on the brane and the bulk to get a flat metric on the TeV brane. Consequently, the natural mass for the first graviton excitation is at the most of the order of a few hundred GeV.

It is interesting to ask what is the kind of collider phenomenology that results with the RS model. Because of the fact that the zero mode decouples, it is only the heavier modes one can hope to detect in experiments. In the fortuitous circumstance that these modes are within the reach of high-energy experiments, interesting effects like resonance production can be observed, with the resonance decaying within the detectors. If this is not the case and if the gravitons are heavier then the best strategy will be to look for the virtual effects of the gravitons on observables measured in high-energy collider experiments. Indeed, some of the phenomenology of resonant production of the KK excitations and the virtual effects have been studied in processes like dilepton production [31] and diphoton production [32] at hadron colliders, $t\bar{t}$ production at hadron colliders [33] and in deep-inelastic scattering at HERA [34]. Production of resonant gravitons and their decays into various final states in the ATLAS detector at the LHC has also been studied [35,36]. Novel effects like probing strong gravity via black-hole production at low energies have also been discussed in the context of the RS model [37].

One crucial feature of the RS model is that a very specific value of the radius of the extra dimension, R_{c}, is required that the model may solve the gauge hierarchy problem. How does one ensure this? In other words, if R_{c} is the VEV of a scalar field, ϕ, how do we protect this field from wild quantum fluctuations? Goldberger and Wise [30] provided an elegant solution to this problem by introducing a potential through a new scalar field in the bulk. The minimisation of the potential leads to the desired stabilisation without a fine tuning of parameters. The mechanism also generates a mass for the radion field ϕ to be in the 100 GeV–1 TeV range and the couplings of the radion to ordinary matter are through the trace of the energy–momentum tensor of the matter fields and of 1/TeV strength. The radion, therefore, is like the SM Higgs in the way it couples to matter but it also has enhanced couplings to gluons and photons via the trace anomaly. The radion can best be detected through its decay to ZZ. This decay channel of the radion, its enhanced coupling to the gluon and the fact that it is light enough to be accessible at colliders make it a very good signal for the RS model [38].

8. Variations on Randall and Sundrum

It turns out that the AdS/CFT correspondence can be used as a powerful tool to analyse the UV properties of the RS model. The AdS/CFT analysis tells us that the RS model is dual to a 4-d effective theory incorporating gravity and a strongly coupled sector. The dual theory is conformally invariant from the Planck scale down to the TeV scale. The presence of the TeV brane breaks conformal invariance at IR scales. The K–K excitations as well as the fields localised on the TeV brane are TeV-scale composites of the strong sector. Since all the SM fields are localised on the TeV brane, the original RS theory is dual to a theory of TeV-scale compositeness of the entire SM. Since such a theory with all SM fields composite will hardly be viable phenomenologically, one can arrive at the conclusion that the original model has problems in the ultraviolet. This kind of analysis [39] provides insights into model-building: for example, one can alter the RS model with only the Higgs field localised on the IR brane, so that only the Higgs is a composite and this is certainly a more viable theory. Such a theory turns out to be less sensitive to details of UV completion and is a more robust theory when faced with precision tests.

Distinctive collider signatures result from the enhancement of the Higgs coupling to the gauge boson KK modes and this results in enhanced scattering of longitudinal W, Z into KK modes. Moreover, in this model, to generate a large Yukawa for the top, it becomes necessary to have t_{R} localised close to the TeV brane and t_{R} coupling to gluon and right-handed W K–K modes is enhanced. So interesting collider phenomena of gauge boson K–K production from gg-initial states mediated by top loops results.

9. Summary

In summary, we have presented a review of extra-dimensional models that have been inspired by the idea of localising matter and gauge fields on branes. We have devoted space to a discussion of the two most popular models: the ADD model of large extra dimensions and the RS model of warped extra dimensions. In each case, we discuss the rich phenomenology that is within the reach of collider experiments and discuss the present bounds and future expectations.

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