EXPERIMENTAL SIGNATURES OF EXTRA-DIMENSIONS AT COLLIDERS*

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The phenomenology as well as the main experimental aspects of extra space dimensions at present and future colliders are reviewed.

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1. Introduction

From the physics point of view, the idea of extra space dimensions has been known since the beginning of last century from the work of Nördstrom, Kaluza and Klein [1–3]. Then, in the past three decades, this idea has proven to be an important ingredient of numerous developments towards the unification of all interactions including gravity such as supergravity [4] and superstring theories [5]. This unification is supposed to occur at high energy scales often close to the Planck scale as in the case of superstring theories. These energy scales are all beyond the reach of any present and certainly future colliders thus precluding any direct experimental tests. However important developments in superstring theories, in D-branes physics and in duality symmetries [5–10] have been exploited in a striking way for the phenomenology of high energy physics. For example one of the consequences of duality symmetries in superstring theories leads to the observation that the string scale M_s becomes an arbitrary scale which is not bounded to stay close to the Planck scale. In 1996 Lykken [11] proposes to push this feature to an extreme which is to consider M_s values as low as the TeV [1]. The next step for the recent revival of interest for extra space dimensions has been carried

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[1] Some consequences for this extremely low M_s have been discussed in [12] especially in the light of established results on gauge coupling unification in the context of superstring theories.

out in a decisive way in 1998 by Dienes, Dudas and Ghergetta [13] with their work on gauge couplings unification in the presence of extra dimensions and by Arkani-Hamed, Dimopoulos and Dvali (ADD) [14].

We do not experience more than 4 space-time dimensions in our every day life which means that the extra dimensions whether compact or warped if they exist are hidden or just too small to be detected in our past or present experimental setups.

Presently running colliders and colliders which are going to run within the next ten years offer good opportunities to sign the presence of sufficiently large extra dimensions if they exists. Large compact extra space dimensions can manifest themselves by the production of Kaluza–Klein states. In the simplest case, in the presence of one compact extra dimension y, a field $\phi(x_\mu, y)$ of mass m_0 is periodic with y and can then be Fourier expanded as:

$$\phi(x_\mu, y) = \sum_{k=-\infty}^{+\infty} e^{\frac{iky}{R}} \phi^{(k)}(x_\mu)\,, \tag{1}$$

where R stands for the radius of compact the extra dimension. The 4 dimensional part $\phi^{(k)}(x_\mu)$ of the field $\phi(x_\mu, y)$ are the Kaluza–Klein (KK) states (or the KK modes or the KK excitations) of this field $\phi(x_\mu, y)$. The number of KK states is infinite and the KK states turn out to be massive. For the mode k the mass of a KK state is given by:

$$m_k^2 = m_o^2 + \frac{k^2}{R^2}\,. \tag{2}$$

The production mode of the KK states as well as their experimental signatures at present and future colliders are discussed in the following sections. Reviewing extra-dimensions phenomenology at past, present and future colliders exhaustively in such a limited space turns out to be an almost impossible task. In consequence the focus will be put on selected topics. The simplest approach given by the ADD scenario is discussed in Section 2. Then we describe the phenomenology of KK gauge bosons at colliders 3. The approach from Randall and Sundrum is also discussed as well as the consequences of its extension which comes from the stabilization mechanism of the radius of the extra dimension in Section 4. After reviewing these approaches for extra-dimensions we will mention some more recent developments which concern universal extra dimensions in Section 5 and extra-dimensions in connection to supergravity in Section 6.

The results of the searches performed at past and present colliders such as HERA, LEP and the Tevatron are summarized. Perspectives for future colliders such as the LHC or the future e^+e^- linear collider (LC or ILC) are mentioned.

2. The ADD approach

In the ADD phenomenological approach, the fields of the standard model are proposed to be kept in a 4 dimensional brane itself sitting in a $(4+n)$ dimensional bulk with n compact extra spacelike dimensions containing the gravitational interaction. In this approach, the 4 dimensional Planck scale $M^2_{\mathrm{Pl}(4)}$ is related to the fundamental scale in the bulk by:

$$M^2_{\mathrm{Pl}(4)} = M^{n+2}_{\mathrm{Pl}(4+n)} R^n \,, \tag{3}$$

where R stands for the radius of the n compact extra dimensions. The 4 dimensional Planck scale can be understood as coming from a TeV fundamental scale $M_D = M_{\mathrm{Pl}(4+n)}$ in a space with large compact extra dimensions which can be as large as the millimeter. Featuring a TeV fundamental scale this scenario suggests an automatic solution to the hierarchy problem of the standard model coming from loop corrections to the Higgs boson mass in the presence of very high energy scales of the underlying theories.

The ADD phenomenological proposal can be incorporated into a more fundamental framework [15] including type I string theory at low scales. This approach, also known under the name of strong gravity at the TeV, can have deep phenomenological impact in various fields of physics such as short distance gravity measurements, astrophysics and cosmology as well as collider physics.

In particular the ADD scenario predicts important deviation from the $1/r^2$ Newton law of classical gravitation in the case of only one compact extra dimension which should have been already seen in our solar system. In this case of only one compact extra dimension the ADD scenario is thus experimentally excluded. However this scenario does not contradict submillimetric gravity measurements in the case of 2 or more than 2 large extra dimensions especially if the effects of the shape of the compactifying space are taken into account even in the simplest cases of toroïdal compactifications [16]. Several measurements of gravity at submillimetric distances have been performed with various techniques including oscillators [17] (known as the Colorado experiment), torsion pendulum [18] (the Eötwash or Washington experiment) and cantilevers [19] (the Stanford experiment). The deviations from the $1/r^2$ Newton law can be parametrized by introducing an amplitude α and a range λ in the expression of the classical Newton potential between two test masses m_1 and m_2 as follow:

$$V(r) = -G\frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda}) \,. \tag{4}$$

The above experiments allow to constrain the α and λ parameters as shown in figure 1 from [19] thus constraining the fundamental scale in particular $M_D > 3.5$ TeV for 2 extra-dimensions from the ADD scenario as derived by the Washington experiment.

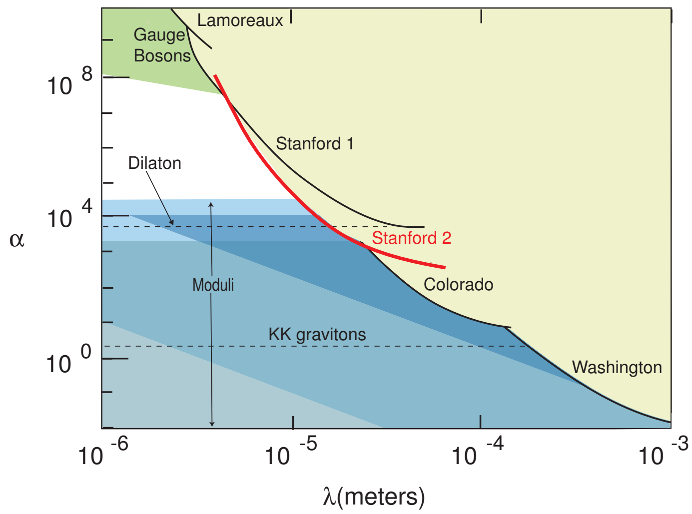

Fig. 1. Experimental results (solid line) and theoretical predictions in the α and λ parameter space (from [19]) including the results from the Colorado experiment [17] and the Washington experiment [18].

The graviton is the particle associated with the gravitational interaction in the bulk. The fields of the standard model couple to the 4 dimensional part of the graviton from the bulk *i.e.* to its KK states. The Feynman rules for processes involving graviton Kaluza–Klein states have been established in [20]. This allows to estimate several KK gravitons production processes and/or decay of these KK gravitons into particles of the standard model. These processes can occur during the collapse of the core of massive stars (which itself involves some modeling) and then lead to possible observable effects for astrophysics. Indeed astrophysical observations and measurements can thus provide strong constraints on the fundamental scale M_D as well. Table I shows several constraints on the fundamental scale M_D from astrophysics as discussed in [21, 22]. In particular, the constraints from the γ ray emission from the galactic bulge as measured by EGRET compared to possible production of KK gravitons by nucleon–nucleon bremssthrahlung during the collapse of the core of massive stars followed by the KK gravitons slow decay into two γ, the neutron star which can possibly have a cloud/halo of KK gravitons shining γ rays from their slow decay as well as the possible neutron star excess heat possibly caused by the continuous hits of γ rays, electrons, positrons and neutrinos coming from the decay of the KK gravitons cloud compared with standard cooling models applied to the pulsar PSR J0953+0755 as observed by the Hubble space telescope, are considered.

TABLE I

Lower bounds on M_D in TeV from the γ ray emission from the galactic bulge as measured by EGRET (from [21]) compared to possible production of KK gravitons by nucleon-nucleon bremssthrahlung during the collapse of the core of massive stars followed by the KK gravitons slow decay into two γ, from the neutron star which can possibly have a cloud/halo of KK gravitons shining γ rays from their slow decay (from [22]) and from the possible neutron star excess heat which can be caused by the continuous hits of γ rays, electrons, positrons and neutrinos coming from the decay of the KK gravitons cloud (from [22]) compared with standard cooling models applied to the pulsar PSR J0953+0755 as observed by the Hubble space telescope.

	M_D in TeV ($n = 2$)	M_D in TeV ($n = 3$)
γ ray from galactic bulge (from EGRET)	450	1.9
constraints on R	$3.8 10^{-10}$ m	$4.2 10^{-12}$ m
neutron star halo (KK decay) (from EGRET)	454	27
neutron star excess heat (from Hubble Space Teles.)	1680	60

At colliders the production of KK graviton states provides a handle to sign the existence of compact extra dimensions. The coupling of KK graviton states to the fields of the standard model remains *a priori* small since it is inversely proportional to the 4 dimensional Planck mass. However, the smallness of this coupling is compensated by the high mass degeneracy of the KK graviton states. Namely, the mass difference between two KK graviton states is given by [20]:

$$\Delta m \sim \left(\frac{M_D}{\mathrm{TeV}}\right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}}\,, \tag{5}$$

where $M_D = M^{n+2}_{\mathrm{Pl}(4+n)}$. Thus for $n = 2$ and $M_D = 1$ TeV the mass difference is $\Delta m \sim 3\,10^{-4}$ eV which allow to produce an almost continuum of KK graviton states. This compensation allows to obtain sizeable cross-sections for KK graviton states [20] direct production at colliders. These cross-sections depend on the available energy E in the centre of mass of the initial particles involved in the collision, the number of compact extra dimensions n and the fundamental scale M_D namely $\sigma \sim E^n/M_D^{n+2}$. From our 4 dimensional point of view, the KK graviton states disappear in the bulk once they are produced. In consequence the direct production of KK graviton states at colliders can be signed with events having a large missing energy component ($\not{E}$) in the energy balance measurement in the detector. For example at e^+e^- colliders KK graviton states can be produced in association with a photon γ or a Z boson thus giving rise to $\gamma + E$ or $Z + \not{E}$ signatures, respectively. At $p\bar{p}$ or pp hadronic colliders KK graviton states can be produced in association with a quark, a gluon, a photon γ or a Z boson thus giving rise to $jet + \not{E}$, $jet + \not{E}$, $\gamma + \not{E}$ or $Z + \not{E}$ signatures respectively. The detection and the measurements of such signatures at colliders allow for a direct measurement of the number of compact extra dimensions and the scale M_D.

Fermion pair production such as e^+e^- or $\mu^+\mu^-$ as well as gauge boson pair production such as $\gamma\gamma$, ZZ or WW at e^+e^-, ep, $p\bar{p}$ and pp colliders can also occur in processes involving KK graviton states. These indirect effects can be signed by deviations in differential cross-section measurements with respect to the predictions of the standard model or by polar angle asymmetry measurements [20]. However for $n = 2$ the cross-sections of indirect processes involving KK graviton states diverge. In the context of pure field theory the cross-section calculations require the introduction of a cut-off in order to avoid these divergencies. Unfortunately this cut-off depends on the fundamental scale M_D only through an arbitrary factor λ which is supposed to be of order 1. In contrast these divergencies can be regularized [23] in the context of type I string theory.

Direct searches for KK graviton states have been performed at the e^+e^- LEP collider in the $e^+e^- \to \gamma + \not{E}$ and $e^+e^- \to Z + \not{E}$ channels and at the Tevatron collider in the missing transverse energy ($\not{E}_\mathrm{t}$) channels such as $p\bar{p} \to 1\,jet + \not{E}_\mathrm{t}$ and $p\bar{p} \to \gamma + \not{E}_\mathrm{t}$. Data do not show any evidence for the direct production of KK graviton states at both LEP and the Tevatron Run I. This non observation can be translated in terms of constraints on the fundamental scale M_D and the size of the large compact extra dimensions. For example the non observation of KK graviton states direct production in the $e^+e^- \to \gamma + \not{E}$ channel in the L3 experiment at LEP implies $M_D > 1.50$ TeV for $n = 2$. The results in terms of constraints on M_D from searches of direct production at both LEP and the Tevatron are given in Table II. The results concerning the searches for indirect effects are given in Table III from [24,25]. Concerning the searches for indirect effects in $e^+e^- \to f\bar{f}$ processes the Bhabha scattering $e^+e^- \to e^+e^-$ offers the best sensitivity thanks to the additional t-channel contribution.

TABLE II

Lower bounds on M_D in TeV from searches for direct production of KK graviton states in the ADD approach for $n = 2$, $n = 4$ and $n = 6$ extra dimensions.

		$n=2$	$n=4$	$n=6$
	LEP			
$e^+e^- \to \gamma \not{E}$	Aleph	1.26	0.77	0.57
	Delphi	1.31	0.82	0.58
	L3	1.50	0.91	0.65
	Opal	1.09	0.71	0.53
$e^+e^- \to Z \not{E}$	L3	0.60	0.29	
	Tevatron			
$p\bar{p} \to jet + \not{E}$	CDF (K=1.3)	1.06	0.80	0.73
	D0 (K=1.3)	1.99	0.73	0.65
$p\bar{p} \to \gamma + \not{E}$	(CDF)		0.55	0.58

TABLE III

Lower bounds on the M_S cut-off in TeV from the search of indirect effects from KK graviton states in the ADD approach in the Hewett formalism [20]. ADLO stands for the combination of the results of the 4 LEP experiments Aleph, Delphi, L3 and Opal. In the case of CDF and D0 results K-factors of 1.3 have been used.

		$\lambda = +1$	$\lambda = -1$
	LEP		
$e^+e^- \to \gamma\gamma$	(ADLO)	0.97	0.94
$e^+e^- \to WW$	L3	0.79	0.68
$e^+e^- \to ZZ$	Opal	0.74	0.63
	Aleph	1.18	0.79
$e^+e^- \to e^+e^-$	L3	1.06	0.98
	Opal	1.00	1.15
	Tevatron		
$e^+e^- \to e^+e^-$ and $\gamma\gamma$	D0 (Run I +II)	1.28	1.14
$e^+e^- \to e^+e^-$ and $\gamma\gamma$	CDF (Run II)	0.99	0.96
Hera			
$ep \to e + jet$	H1	0.74	0.70
$ep \to e + jet$	ZEUS	0.72	0.73

With an increase of luminosity expected for the Run II of the Tevatron the sensitivity on the fundamental scale in processes involving KK graviton states increases by a factor 2 (or even 3). The expected sensitivities on the fundamental scale expected at both the LHC and the LC (including

80% electron polarization and 60% positron polarization) for direct as well as indirect processes involving KK graviton states are given respectively in Table IV and V from [26].

TABLE IV

Expected sensitivities on M_D in TeV for direct processes involving KK graviton states in the ADD approach for $n = 2$, $n = 3$ and $n = 4$ compact extra dimensions at the LHC and the LC.

		$n = 2$	$n = 3$	$n = 4$
		M_D(TeV)	M_D(TeV)	M_D(TeV)
LHC (5σ 100 fb^{-1})	$jet + \not{E}$	4.0-7.5	4.5-5.9	5.0-5.3
	$\gamma + \not{E}$	3.5-3.7		
LC (5σ) ($\sqrt{s} = 800$ GeV, L=1 ab^{-1})	$\gamma + \not{E}$	7.86		5.09

TABLE V

Expected sensitivities on the M_S cut-off from indirect processes involving KK graviton states in the ADD approach at the LHC and the LC.

LHC 100 fb^{-1}		M_S(TeV)
$pp \to \gamma\gamma$	$n = 2$	7.93
	$n = 3$	7.16
	$n = 4$	6.74
$pp \to l^+l^-$	$n = 2$	7.93
	$n = 3$	7.51
	$n = 4$	6.97

LC	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 0.8$ TeV
	M_S(TeV)	M_S(TeV)
$e^+e^- \to \mu^+\mu^-$	4.1	5.8
$e^+e^- \to b\bar{b}$	5.0	7.1
$e^+e^- \to c\bar{c}$	5.1	7.1
combined	5.6	8.0

2.1. Micro Black Hole production at colliders

With a center of mass energy in the 14 TeV regime the LHC reaches a new domain of energy which may be above the fundamental scale of extra dimensions or even above the string scale. The unitarity problems encountered when calculating for example KK states production cross-sections are solved in a model independent way by truncating the integration of differential cross-sections when the centre of mass energy approaches M_s.

However, several speculations (sometimes developed in a semi-classical way) tend to show the emergence of new phenomena at colliders such as the production of micro black holes at rest [27] when $\sqrt{s} > M_s$ and when the impact parameter of the colliding particles is smaller than the Schwarzschild radius characteristic of the black hole in extra dimensions. At the LHC the production cross-sections of micro black holes are large. They range from 1 fb up to 1 nb. Once they are produced black holes decay thermally and isotropically with high multiplicities into standard model particles and possibly into supersymmetric particles via Hawking evaporation. Black holes decay predominantly in the brane and these decays are fast but slower than in the 4 dimensional case. However, they are not slow enough to be observed as displaced vertices in a detector. Black hole decays democratically towards all the available particles species. In the standard model case with the available leptons, quarks and gauge bosons and the subsequent decay of these gauge bosons dominated by the decay into quarks, one expects signatures with very high hadrons multiplicities isotropically distributed in the detector and small missing energy. As discussed in [28] there are still open issues concerning the fate of a highly asymmetric rotating black hole which can possibly be created in *pp* collisions. In particular the fraction of the total available energy taken during the various phases such as the balding phase (shedding of quantum numbers except a few), the spin-down phase (loss of angular momentum by Hawking radiation), the Schwarzschild phase (Hawking evaporation at the Hawking temperature *i.e.* thermal evaporation following a black body spectrum including effects from grey-body factors) and the Planck phase (occurring when the black-hole evaporates and its mass decreases down until reaching the value of the fundamental scale M_D) is still under investigation. For example the Planck phase study is involving several interesting ideas such as the transition of a black hole towards a string ball at the critical black hole mass value of M_s/g_s^2 as the black hole shrinks and looses mass by evaporation. String balls are highly excited and jagged strings which decay thermally and isotropically at the Hagedorn temperature. One can experimentally distinguish between string balls and black holes decays as in the case of string balls the evaporation temperature is independent of the mass of the string ball while in the case of black holes the Hawking temperature increases as the mass of the black hole increases.

Turning back to black holes, the extra-dimension equivalent of the Wien law can be checked by measuring the Hawking temperature of the black hole (obtained for example from the energy spectrum of electrons) as a function of its mass (obtained from the total energy of all decay product) and thus allowing the determination of the space-time dimensionality.

Some further studies on micro black hole production at the LHC includes Gauss–Bonnet black holes [29] having in mind that the Gauss–Bonnet invariant provides a promising candidate for quadratic correction to the Einstein action also derived within the framework of superstring theories [30].

3. Kaluza–Klein gauge bosons

The more fundamental framework of the type I string theory (in a 10 dimensional space-time *i.e.* 9 spacelike dimensions) into which the previous ADD approach can be incorporated allow several extensions towards configurations involving several branes. Indeed the gauge fields of the standard model can be localized in different branes [31] corresponding to different possible ends of the open strings of the type I string theory. These branes configurations allow to define p dimensional subspaces with $p > 4$ which can be also called thick branes. In turn they allow to define scenario with the concept of longitudinal (or parallel to the thick brane) compact extra dimensions at TeV^{-1} in which gauge bosons can propagate. These thick branes sit in the bulk including the $9 - p$ remaining compact spacelike dimensions which are then perpendicular to the thick branes. The gravitational interaction still sits in the bulk. Depending on the possible branes configurations the gauge fields of the standard model propagating in the longitudinal dimensions can thus generate massive KK gauge bosons with masses of the order of 1 TeV.

It is important to note that before the advent of the ADD approach and its integration into a more fundamental string and brane theory the possible existence of KK gauge bosons has been discussed in 1994 in [32].

Besides, the analysis of non trivial compactifications in the context of the type IIB string theory allow to build massive KK states with masses of the order of 1 TeV which have gauge interactions. In this analysis the scale of the gravitational interaction is not lowered down to the TeV scale as in the ADD approach but kept at scale of the order of 10^9 TeV [33] *i.e.* back to high energy scale close to the scale of grand unification in the traditional sense. This means that in some scenarios extra dimensions can be signed via KK gauge bosons only.

Precision measurements on the so-called electroweak observables of the standard model at LEP and SLC as well as measurements from HERA and the Tevatron together with the measurements of pair production of standard model particles provide a good handle to sign indirect effects of KK gauge bosons.

The analysis of the effects due to KK gauge bosons on electroweak observables often requires additional assumptions such as: (1) the absence of gravitational effects at the TeV, (2) only one longitudinal extra dimension compactified on the S^1/Z_2 orbifold where the Z_2 symmetry allow to introduce fermions chirality (required by the standard model) which fermions are localized on the fixed points of the orbifold, (3) the choice of the reference model *i.e.* the standard model or its minimal supersymmetric extension (MSSM) or even the extension of this latter including an additional Higgs singlet (NMSSM) and finally (4) the localization of gauge field in the 5 dimensional space-time of the thick brane and the localization of the Higgs boson either in the 5 dimensional space-time of the thick brane or in a 4 dimensional brane.

Moreover the 5 dimensional effective gauge couplings $\hat{g}$ can be expressed in terms of the 4 dimensional effective gauge couplings g via $\hat{g}^2 \sim g^2 R$ where $R \sim 1/M_c$ is the radius of the longitudinal extra dimension. It has been shown that 5 dimensional effective gauge couplings are finite while for more than one longitudinal extra dimension they become divergent. One need again to invoke string theories and brane configurations in order to regularize these couplings.

A global fit of the precision measurements of the electroweak observables of the standard model with the assumptions mentioned above allow to derive the constraint $M_c > 3.8$ TeV [34]. Including not only electroweak observables but also high energy data from LEP, HERA and the Tevatron Run I allow to set the following striking bound $M_c > 6.8$ TeV [35].

The existence of KK gauge bosons although kinematically inaccessible at colliders can be established indirectly by their effects on standard model particle pair production. In addition to the above example of two jets production at the LHC, the deviations in the measurements of the differential cross-sections of particle pair production or their asymmetries with respect to the prediction of the standard model allow to sign the existence of KK gauge bosons. Furthermore leptonic colliders offer a clean environment in terms of backgrounds thus allowing for the measurements of the coupling between the KK gauge bosons and the fermions of the standard model which then allow to distinguish between various models [36].

Finally, if the KK gauge bosons are kinematically accessible they can be produced resonantly at colliders. The produced KK gauge bosons decay into two quarks or two leptons giving rise to signatures with either two jets or two leptons respectively. The measurement of the invariant mass of the two jets or the two leptons allows to measure the mass of the resonance.

A first direct search for KK gauge boson decaying into two electrons has been performed at the D0 experiment at the Tevatron with 200 pb^{-1} of data. No evidence for the production of such a state has been established and a constraint $R^{-1} > 1.11$ TeV has been derived. Although not competitive with the above indirect limits from precision measurements this limit can be seen as a complementary one reflecting the first direct dedicated search for KK gauge bosons at colliders.

Table VI summarizes the sensitivity of the KK gauge bosons searches at various colliders which are starting to run or will start to run within the next ten years [37].

TABLE VI

Sensitivities on $R_{\|}^{-1}$ *i.e.* one longitudinal extra dimension in TeV from the searches for KK gauge bosons at the Tevatron, LHC and LC (from [37]).

Sensitivities on $R_{\|}^{-1}$ (TeV)			
Resonances discovery			
Collider	gluons	$W^{\pm}$	$\gamma + Z$
LHC(100 fb^{-1})	5	6	6
Observation of deviations			
Collider	gluons	$W^{\pm}$	$\gamma + Z$
Tevatron (2 fb^{-1})			1.2
Tevatron (20 fb^{-1})	4		1.3
LHC (10 fb^{-1})	15	8.2	6.7
LHC (100 fb^{-1})	20	14	12
LC ($\sqrt{s}$ = 500 GeV, 75 fb^{-1})			8
LC ($\sqrt{s}$ = 1000 GeV, 200 fb^{-1})			13

In the search for resonances and for deviations due to KK gauge bosons there remains open questions concerning the capabilities of colliders such as the LHC and the LC to sign not only the first resonance or the first mode of the KK gauge bosons but also the second or even the third mode which would help in signing unambiguously the presence of a KK tower of states. Moreover it has also shown in [51] (see also [49]) that the LHC (with the forward–backward lepton asymmetry measurement and with the determination of the mass of the resonance) and the ILC (with left–right polarization asymmetry measurement) can discriminate between a KK gauge boson and Z' scenarios. Finally in the case of more than one longitudinal extra dimensions where the gauge couplings become divergent, the above mentioned regularization can lead to lower bounds on the masses of the first modes of the KK gauge bosons which range from 4 TeV up to 50 TeV depending on the type of regularization and the number of longitudinal extra dimensions [36]. These lower bounds dramatically challenge the LHC and the LC as far as the search for KK gauge bosons is concerned.

4. The Randall Sundrum (RS) approach

In 1999 Randall and Sundrum [38] propose another phenomenological model with two 4 dimensional branes in a 5 dimensional space-time with an anti de Sitter (or warped) geometry. More explicitely, the two 4 dimensional branes with tensions V and V' are localized at the points $y = 0$ and $y = \pi r_c$

of the fifth dimension of a bulk with cosmological constant Λ where the gravitational interaction sits. The metric $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ is a solution of Einstein equations provided that $V = V' = 24\,M_5^3 k$ where M_5 stands for the fundamental scale of the model and provided that $\Lambda = -24\,M_5^3 k^2$ which corresponds to a negative cosmological constant (*i.e.* an anti-de-Sitter geometry). The factor $e^{-2k|y|}$ in front of the 4 dimensional part of the metric allows to generate a low energy scale on one brane from a high energy scale on the other brane. In particular a TeV energy scale can generated from the 4 dimensional Planck scale if $kr_c \sim 12$ thus allowing another solution to the hierarchy problem between the electroweak scale of the standard model and the 4 dimensional Planck scale. Moreover, in contrast to the ADD relation (Eq. (3)) the 4 dimensional Planck scale in the RS approach is:

$$\bar{M}_{\rm Pl}^2 = \frac{M_5^3}{k}[1 - e^{-2kr_c\pi}]\,. \tag{6}$$

This scale remains well defined even for extreme values of the radius r_c of the extra dimension.

In this approach the standard model fields are localized on one of the two branes *i.e.* the so-called TeV brane and gravitation propagates in the bulk. The standard model fields couple to the 4 dimensional restriction of the graviton from the bulk namely its KK states. As in the case of the ADD approach the production of KK graviton states at colliders allow to sign the existence of the extra dimension. However, in contrast to the ADD approach the expansion of the graviton field into KK modes is given in the RS approach by a linear combination of Bessel functions. In consequence the masses of the graviton KK modes are not regularly spaced but are given by $m_n = x_n k e^{-k\pi r_c}$ where the x_n are the roots of Bessel functions. Furthermore, in the RS approach the order of magnitude of the mass of the first graviton KK modes is 1 TeV in contrast to the ADD approach where the order of magnitude of the mass of the first graviton KK modes is a fraction of eV up to few eV. The coupling of the zero mode graviton to standard model fields is suppressed since it is inversely proportional to the 4 dimensional Planck mass. Nevertheless, the coupling of the graviton non zero KK modes is only inversely proportional to $e^{-k\pi r_c}M_{\rm Pl}$ namely the 4 dimensional Planck mass multiplied by the characteristic factor of the geometry of the RS approach *i.e.* the warp factor. In contrast to the ADD approach where a great number of graviton KK modes are accessible thus compensating the smallness of the coupling and allowing the production of a quasi-continuum with sizeable cross-sections, in the RS approach it is the coupling itself which is enhanced by the warp factor $e^{k\pi r_c}$. Thus only few modes are produced at colliders if they are kinematically accessible. These modes are produced resonantly and once they are produced they decay predominantly into two jets [39] and then into other decay channels such as W^+W^-, ZZ, l^+l^-, $t\bar{t}$ and hh in decreasing order. Although leptonic decay channels are not dominant they offer a clear signature in particular at hadronic colliders such as the Tevatron or the LHC.

At the Tevatron several searches for the KK graviton states of Randall–Sundrum has been performed using dimuon, dielectron and diphoton event from the D0 and CDF experiments using data corresponding to respectively 260 pb^{-1} and 345 pb^{-1}. No evidence for resonant production of gravitons has been found and exclusion domain have been set in the parameter space of the Randall–Sundrum model as shown in figures 2 and 3.

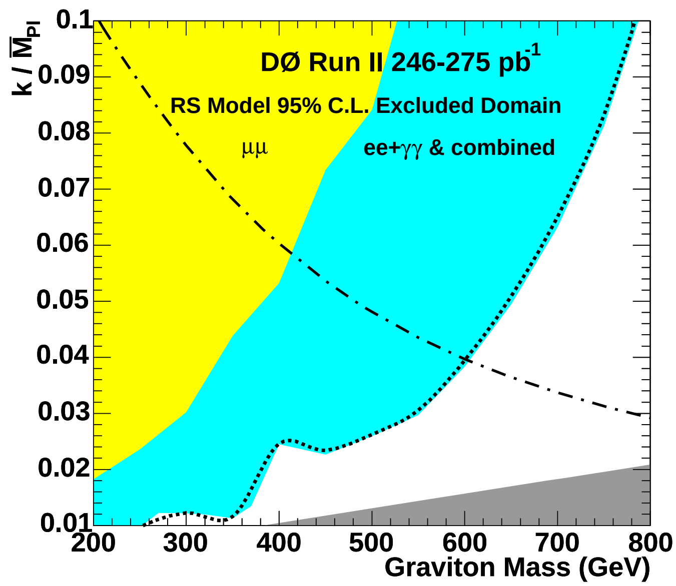

Fig. 2. 95% C.L. exclusion limits on the RS model parameters M_1 and $k/M_{\rm Pl}$ from D0. The light shaded area has been excluded in the dimuon channel. The medium-shaded area shows the extension of the limits obtained in the diEM (di-electrons and di-photons) channels. The dotted line corresponds to the combination of the two channels. The area below the dash-dotted line is excluded from the precision electroweak data [39].

The measurement of the invariant mass of the two leptons allow the measurement of the KK graviton mass resonantly produced and the measurement of the differential cross-section with respect to the polar angle allow the measurement of the spin of the resonance [41]. Decay channels into W^+W^- and ZZ followed by leptonic decay also offer clear signatures at hadronic colliders.

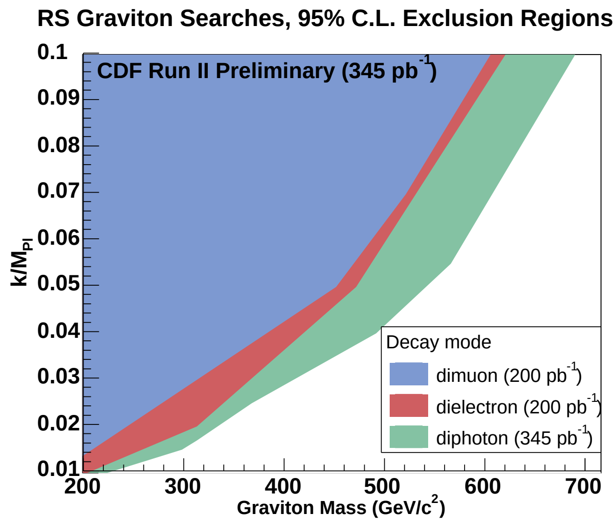

Fig. 3. 95% C.L. exclusion limits on the RS model parameters M_1 and $k/M_{\rm Pl}$ from the CDF experiment.

Table VII summarizes the sensitivities on the mass m_1 of the first graviton KK mode in the RS approach for various values of the parameter $k/M_{\rm Pl}$.

TABLE VII
Sensitivities on the mass m_1 in TeV of the first graviton KK mode in the RS approach for various values of the parameter $k/M_{\rm Pl}$ at the Tevatron, the LHC and the LC.

	$k/M_{\rm Pl}$	m_1
Tevatron (2 fb^{-1})	0.1	0.95
	1.0	1.25
LHC (100 fb^{-1})	0.1	4.5
	1.0	6.5
LC ($\sqrt{s} = 1000$ GeV, 100 fb^{-1})	0.1	3.1
	1.0	9.6

A more detailed study has been carried out with the CMS detector concerning its discovery potential of the KK graviton decaying into two electrons as displayed in Fig. 4 showing that with an integrated luminosity of 100 fb^{-1} the whole region of interest in the RS model parameters space M_1 and $k/M_{\rm Pl}$ can be explored.

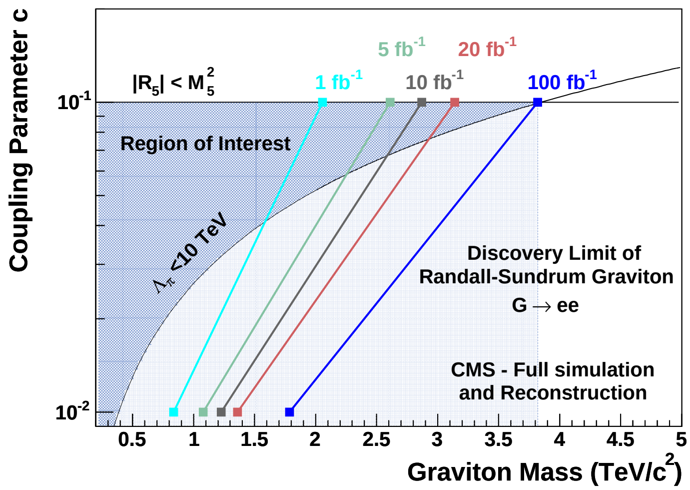

Fig. 4. The CMS experiment discovery potential in the RS model parameters M_1 and $k/M_{\rm Pl}$ parameters space for different integrated luminosity scenarios using the dielectron channel from [42].

4.1. The phenomenology of the radion

In the RS approach the presence of a scalar field in the bulk with interactions localized on the branes allows to stabilize the value of r_c [43] in the warp factor $e^{k\pi r_c}$. The parameter r_c can be associated with the vacuum expectation value of a massless 4 dimensional scalar field known as the radion. After stabilization the radion becomes massive and for $kr_c \sim 12$ (as required to ensure a solution to hierarchy problem as mentioned above) the mass of the radion can be smaller than the lightest graviton KK mode. The radion can thus be the lightest state signing the presence of an extra dimension. This scenario is often called the stabilized RS model.

The radion couple to standard model fields via the trace of the energy-momentum tensor with a coupling given by $1/\Lambda_\phi$ with

$$\Lambda_\phi = (\sqrt{24M_5^3/k})e^{-kr_c\pi}\,.$$

Figure 5 (left) from [45] shows the cross-section of the radion production via the gluon fusion process at the Tevatron ($\sqrt{s} = 2$ TeV) and at the LHC ($\sqrt{s} = 14$ TeV). These production cross-sections are compared to the cross-sections of the standard model Higgs boson production.

As shown in Fig. 5 (right) the radion predominantly decays into a gluon pair at low mass or W pair above the WW mass threshold. The phenomenology of the radion resembles the phenomenology of the standard model Higgs boson except for the coupling to gluons which is enhanced in the case of the radion because of the trace anomaly.

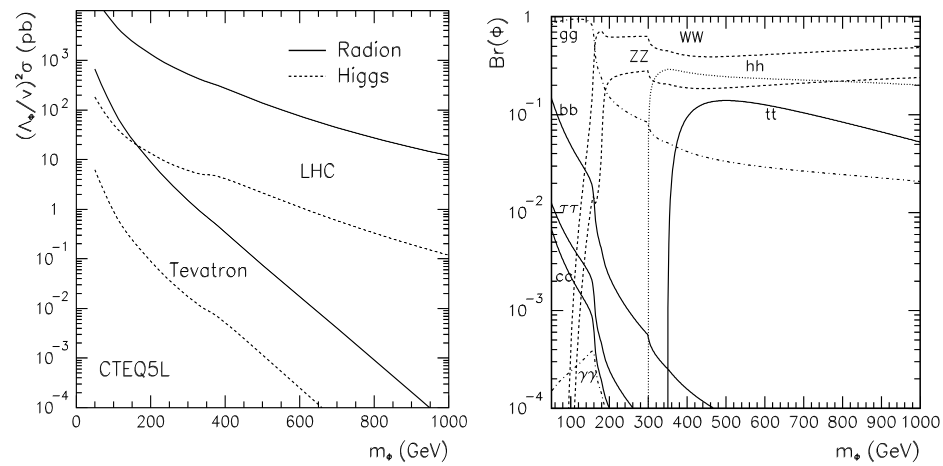

Fig. 5. Left figure: cross-sections of the radion production via the gluon fusion process at the Tevatron ($\sqrt{s} = 2$ TeV) and at the LHC ($\sqrt{s} = 14$ TeV) with a normalization factor (Λ_ϕ/v where v stands for the vacuum expectation value of the standard model Higgs boson and Λ_ϕ is defined in the text (from [45]). These production cross-sections are compared to the cross-sections of the standard model Higgs boson production (dashed line). Right figure: branching ratios of a radion of 300 GeV mass (from [45]).

Besides, it is possible to consider a mixing between the standard model Higgs boson and the radion [46] which allow to consider new physical mass eigenstates. The decay branching ratios of these eigenstates are different from those of the standard model Higgs boson. Depending on the value of the conformal coupling which is responsible of the Higgs boson-radion mixing the difference can be sizeable *i.e.* up to a factor 50 for the W^+W^- and ZZ decays for example. This mixing can also lead to non negligible invisible branching ratios of the Higgs boson. This analysis has been confirmed in a more fundamental context involving type I string theory [47].

The Opal collaboration [48] performed a search for the radion via existing searches of the Higgs boson. No evidence for the radion has been found and the Opal collaboration derived constraints on the parameters of the stabilized RS model (see [48]) for various scenario of Higgs-radion mixing. First studies of the discovery potential of the radion at the LHC in both Atlas and CMS experiments have been performed [49, 50] including various radion decays and final states *i.e.* $\phi \to \gamma\gamma$, $\phi \to ZZ^{(*)}$ as well as $\phi \to hh$ with $\gamma\gamma b\bar{b}$ and $\tau\tau b\bar{b}$ final states for Atlas and $\phi \to hh$ for CMS with final states $\gamma\gamma b\bar{b}$, $\tau\tau b\bar{b}$ and $b\bar{b}b\bar{b}$, the $\gamma\gamma b\bar{b}$ providing the best discovery potential.

5. Universal extra dimensions (UED)

In the scenario of universal extra dimensions [52] (UED) not only the gauge boson of the standard model are in the bulk of a 5 dimensional space-time (as was the case for KK gauge boson described in Section 3) but also all the fermions. In the first models the geometry of space-time is supposed to be flat and gravity is not included. The 4 dimensional particles of the standard model correspond to the zero mode of the KK expansion of the bulk particles. Chiral fermions are obtained via orbifolding (see Section 3).The non-zero KK modes are massive and loop corrections involving bulk fields lead to a non degenerate mass spectrum [53, 54].

The electroweak precision measurements allow to constrain the typical mass scale M of this UED scenario [52] *i.e.* $M > 300$ GeV. However, taking into account two-loop standard model contributions to the electroweak precision as well as LEP2 analysis this bound can be updated to $M > 700$ GeV (at 99% confidence level) as worked out in [55].

The momentum conservation along the fifth direction is broken by orbifolding. However, at 4 dimensions there is remnant conservation known as the conservation of KK-parity *i.e.* $(-1)^k$ where k is the mode level of the KK expansion, which dictates level mixing. Namely even (respectively odd) KK modes can mix only with even (respectively odd) KK modes. In consequence UED KK states are pair produced (UED KK states cannot be singly produced), a UED KK state decays into a UED KK state and a particle of the standard model (cascade decays can occur) and finally there exists a lightest KK particle (LKP) which is stable. Thus at colliders the phenomenology of UED resembles to the phenomenology of supersymmetry with conserved R-parity. Moreover, with the LKP, this scenario provides a wimp dark matter candidate which can be either the first KK mode of a photon γ_1 or the first KK mode of a neutrino ν_1 (see [56] for more on dark matter issues). An example of a cascade decay of the first KK mode of the gluon g_1 down to γ_1 is given in [54]. At hadron colliders the pair production of the lightest coloured KK states have the largest production cross-sections as show in [57] for g_1 pair production and q_1 (first KK mode of a quark) pair production at the Tevatron and the LHC (see Fig. 6). The production of UED KK states can lead to signatures such as 4 leptons + $\not{E}$, 3 leptons + one jet + $\not{E}$ or 2 leptons + jets + $\not{E}$ which thus should provide good handles for their search.

At hadron colliders, discovering the second KK modes of the KK tower if kinematically accessible (and possibly further modes of this tower) as well as measuring their spin should allow to distinguish whether these heavy states are standard model particles partners from UED scenarios or from supersymmetry as discussed in [58]. Once eventually discovered at hadron

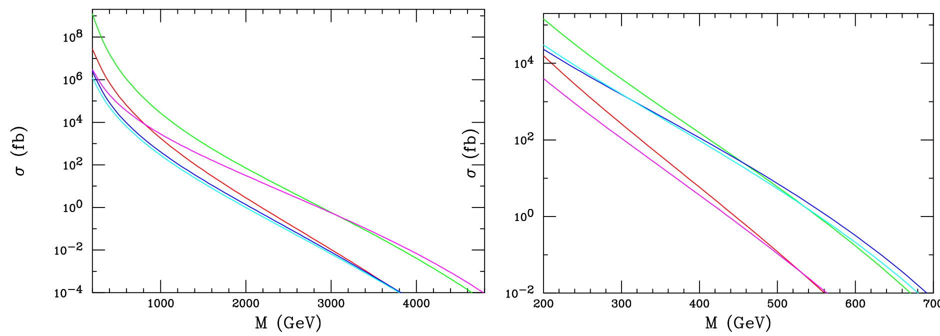

Fig. 6. Top: production cross sections of g_1 pair and q_1 pair at the Tevatron (lines from top to bottom on the left hand side of the figure correspond to $qq' \to g_1g_1$, $q\bar{q} \to q_1q_1$, $gg + q\bar{q} \to q'_1\bar{q}'_1$, $gg \to g_1g_1$ and $qq \to q_1q_1$) from [57]. Bottom: production cross sections of g_1 pair and q_1 pair at the LHC (lines from top to bottom on the left hand side of the figure correspond to $qq' \to g_1g_1$, $gg \to g_1g_1$, $qq \to q_1q_1$, $gg + q\bar{q} \to q'_1\bar{q}'_1$ and $q\bar{q} \to q_1q_1$) from [57].

colliders further model discrimination is shown to be possible at future lepton colliders using accurate angular distributions measurements as well as accurate total cross-sections measurements (see [59]).

It is furthermore observed in [60] that the q_1 can be very narrow and form KK quarkonia leading to very sharp resonances which are found challenging to be discovered at a linear collider.

6. Supersymmetry and extra-dimensions

Supersymmetry is a fundamental ingredient of string and branes theories underlying the phenomenological studies of extra dimensions.

One has to keep in mind that the solution to the hierarchy problem of the standard model can come either directly from the possibility of extra dimensions at a TeV scale or from the cancellation of quadratic divergencies via supersymmetry in loop corrections of the Higgs boson mass. However, extra-dimensions and supersymmetry are two concepts not mutually exclusive.

The argument of duality symmetries in string theories implies that the string scale M_s becomes arbitrary and thus can take in principle any value between for example 1 TeV and the Planck mass. Table I, II and III of Section 2 show that the present experimental constraints tend to exclude values of the order of 1 TeV for the fundamental scale for 2 extra space dimensions in the ADD approach thus tending to challenge this solution to the hierarchy problem of the standard model.

Supersymmetry intrinsically present in the fundamental theories underlying extra dimensions still provide a solution to the hierarchy problem in the usual way.

Numerous supersymmetric models with extra dimensions have been developed [61]. Furthermore, these developments do not only allow for discussions of supersymmetry breaking in the context of extra dimensions but also electroweak symmetry breaking. Some of these developments offer a way to understand better the fine-running relation of the RS model (see Section 4) and provide also a solution for the stabilization of the radion. They also allow for discussions of unified gauge theories with extra dimensions. One has to note that as early as the first phenomenological discussions on extra dimensions [13] the possibility of the existence of supersymmetry with extra dimensions has been left open.

In a simple phenomenological approach based on the ADD scenario with a supersymmetric bulk, namely a bulk containing gravitons and gravitinos, Hewett and Sadri [62] have shown that the selectron pair production rate as well as the selectrons angular distributions are modified due to the effects of the KK gravitinos states as shown in Fig. 7. In particular, in such a context, the sensitivity to the fundamental scale of extra dimensions can reach 20–25$\times\sqrt{s}$ at a future e^+e^- linear collider where $\sqrt{s}$ stands for the centre of mass energy of this collider.

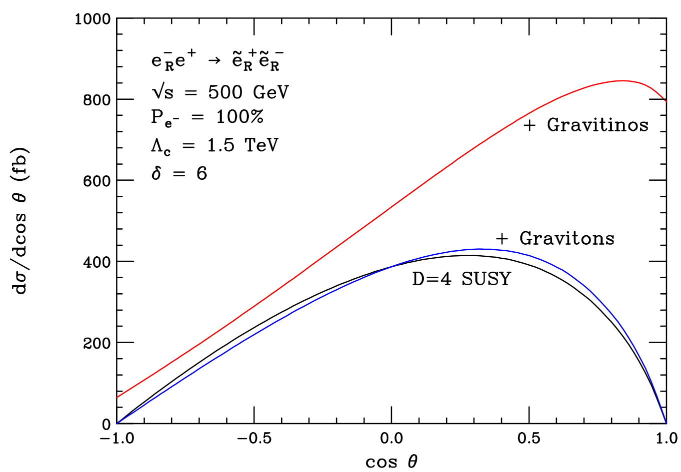

Fig. 7. Angular Distribution for $e^-_{\rm R}e^+ \to \tilde{e}^+_{\rm R}\tilde{e}^-_{\rm R}$ at $\sqrt{s}$ = 500 GeV with 100 % electron polarization. From bottom to top, the lines correspond to a $e^-_{\rm R}e^+ \to \tilde{e}^+_{\rm R}\tilde{e}^-_{\rm R}$ from a $D = 4$ supersymmetric model, $e^-_{\rm R}e^+ \to \tilde{e}^+_{\rm R}\tilde{e}^-_{\rm R}$ with, in addition, contributions from KK gravitons exchange and $e^-_{\rm R}e^+ \to \tilde{e}^+_{\rm R}\tilde{e}^-_{\rm R}$ with, in addition, contributions from KK gravitinos exchange (from [62]) corresponding to a scenario with 6 extra-dimensions and a fundamental scale of 1.5 TeV.

7. Conclusions

Extra-dimensions from the (historically) first approaches of ADD, KK gauge bosons, RS and stabilized RS (historically) have been already searched for at past and present colliders in a rather detailed and extensive way allowing to put constraints on the various parameters of these models. Concerning these first approaches, perspectives for future colliders start to be well explored. More models have also been developed such as universal extra dimensions or Higgsless models [63] (which has not been covered in this review) which continue to enrich the phenomenology of extra dimensions at colliders. Model building from supersymmetry and extra-dimensions as well as from intersecting branes including intersecting branes at angles [64] (not been covered in this review either) which may lead to either supersymmetric or non-supersymmetric models also offers many rich perspectives which are worth to be explored.

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