Available online at www.sciencedirect.com
SCIENCE DIRECT®
C. R. Physique 4 (2003) 319–335
COMPTES RENDUS PHYSIQUE

Extra dimensions in physics and astrophysics/Dimensions supplémentaires en physique et astrophysique

Searching for extra dimensions at colliders

Marc Besançon

CEA-Saclay, DAPNIA/SPP, bâtiment 141, 91191 Gif sur Yvette, France

Presented by Guy Laval

Abstract

The phenomenology as well as the main experimental aspects of large extra space dimensions at colliders are briefly presented. ***To cite this article: M. Besançon, C. R. Physique 4 (2003).***

Résumé

À la recherche de dimensions supplémentaires aux collisionneurs. La phénoménologie et les aspects expérimentaux des dimensions supplémentaires d'espace-temps auprès des collisionneurs sont brièvement présentés. ***Pour citer cet article : M. Besançon, C. R. Physique 4 (2003).***

1. Historical benchmarks and motivations

1.1. Origins

From the physics point of view, the first discussions on a space–time having more than four dimensions seem to bring us back to the beginning of the twentieth century. Firstly, there was the work of Gunnar Nordström [1] in 1914 who, before the Einstein–Hilbert equations describing the gravitational interaction were known, sets down the Maxwell equations in a 5 dimensional space–time leading to the Maxwell–Nordström equations for a theory of electromagnetism and gravitation. General relativity is three years old when Hermann Weyl's [2] attempt in 1918 to exploit its geometrical formulation in order to unify electromagnetism and gravitation leads to the concept of gauge invariance. In 1921, after a period of two years of reluctance from Einstein as a referee to a paper submitted in 1919, Theodor Kaluza [3] proposes a Maxwell–Einstein theory from the Einstein–Hilbert equations in 5 dimensions. Furthermore invoking energy positivity arguments Kaluza shows that the fifth dimension has to be space-like. In both the Nordström and Kaluza approaches, the winding of the fifth space dimension on a circle shows to be a necessary step in order to derive known theories in the ordinary 4 dimensional space–time. In 1926, Oskar Klein [4,5] extends Kaluza's ideas and derives the Schrödinger equation from a 5 dimensional framework and discusses the size of the fifth space dimension. In 1938, Bergmann and Einstein [6] return to these ideas emphasizing the link between the winding of the fifth dimension on a circle (in other words the compactification of the extra space dimension) and gauge symmetry which is here an Abelian gauge symmetry.

From the very first discussions the concept of a compact extra space dimension is associated with the concept of unification of interactions and even to the concept of gauge symmetry. Electromagnetism and gravitation are at that time the best known

E-mail address: besanco@hep.saclay.cea.fr (M. Besançon).

1631-0705/03/$ – see front matter
doi:10.1016/S1631-0705(03)00039-2

interactions. When, in 1938 also, Klein [7][1] derives the notion of non-Abelian gauge symmetry by generalizing gravitation theories in more than just one extra space dimension, the weak interaction is only known via the phenomenological approach given by the Fermi theory [9] (1934) and the strong interaction starts to be discussed within the framework of Yukawa's meson theory [10] (1935). How to handle the symmetries found by Klein? One has to wait until the formulation of non-Abelian gauge theories by Yang and Mills [11,12] in 1954 in order to extend Klein's ideas and revive more systematical studies of non-Abelian gauge symmetries in the context of generalizations of gravitation theories in several compact extra space dimensions [13–19].[2]

However non-Abelian gauge theories themselves progressively become one of the predominant subjects under investigation. Indeed, in addition to the remarkable development of quantum field theory[3] in the first half of the twentieth century the Yang–Mills formulation, together with the formidable accumulation of experimental results and discoveries on particles and their weak interactions, as well as ideas and experimental results on hadrons structure in terms of partons,[4] and finally crucial developments on the asymptotic behaviour of non-Abelian gauge theories [24,25] allow us to obtain a viable framework for the description of electroweak and strong interactions. The development of this framework leads to the well-known Standard Model.[5] This framework is further developed, to lead in 1973 to the concept of unification of all gauge interactions or grand unified theories [39,40]. In these grand unified theories, the gauge couplings unify at energy scales of the order of 10^{15} to 10^{16} GeV thus introducing in the context of gauge theories a new energy scale close to the Planck mass scale this latter being related to the gravitational interaction.

However, despite this improved connection of scales the absence of the gravitational interaction almost by construction shows straight off as one of the main drawback of these developments. Why? A possible explanation is provided by the difficulties in understanding the quantum behaviour of the gravitational interaction.

1.2. Supersymmetry, strings and branes

In the early 1970s, the advent of supersymmetry[6] (see also [64,65]), and, more particularly, the advent of supergravity [51–54][7] in 1976 allow us to provide a framework to overcome these difficulties. Moreover, the construction of the so-called supersymmetric grand unified theories allow us to improve the unification of the gauge couplings and bring the energy scale where this unification occurs closer to the Planck scale.

In addition, in 1970 and in 1971, it is shown [56–59] that the amplitudes obtained from the Veneziano amplitude [60] for $\pi\pi \to \omega\pi$ generalized to n-point functions [61,62] and to loop amplitudes [63] and futher generalized in order to include fermionic states [64,65],[8] describe the dynamics of a relativistic string. Neveu and Scherk [66] in 1972 and Yoneya [67] in 1974 show that the massless vector states of the open string interacts as gauge bosons. Moreover, the latter as well as Scherk and Schwarz [68] show that a closed string always contains a massless spin-2 state, i.e., the graviton. As early as 1974 Scherk and Schwarz [68] propose string theories as candidate theories for the unification of gauge and gravitational interactions. It is remarkable to note that these developments were carried out first in order to describe hadron interactions, but showed progressively to allow the construction of unified theories of all interactions. In the meantime, this description of hadron interactions has been superseded by quantum chromodynamics, incorporated into the Standard Model.

What about the dimensionality of space–time required by these theories? It has been conjectured that in a 4 dimensional space–time there are no consistent quantum field theories for interacting fields of spin greater than 2 [69–72]. Also, in 1978 Nahm [73] shows that the structure of the supersymmetric algebras associated with the above spin constraint allow us to construct consistent suspersymmetric field theories in space–time up to 11 dimensions. A supergravity theory in 11 dimensions has been formulated in [74].

Concerning string theories, the first work on the quantization of the relativistic string [75] shows the existence of a critical number of dimensions of space–time in order to avoid anomalies to the Lorentz invariance. This critical dimension is equal

---

[1] See also [8].

[2] See also [20].

[3] For a more complete discussion on this topic we refer the reader to the book of Weinberg [21].

[4] See, for example, [22,23].

[5] See for example Nobel Lectures 1979 [26–28]. For quantum chromodynamics [29–36]. See also [37,38].

[6] Historically Golfand and Likhtman [41] proposed an anti-commutator in the Poincaré algebra and Volkov and Akulov [42] showed a non linear realisation of supersymmetry. Coleman and Mandula [43] have excluded some extension of the Poincaré algebra which extension are then only possible with anti-commutators. The construction of invariant Lagrangians under global supersymmetry traces back to the works [44–46]; see also [47]. Finally very preliminary discussions on the possible existence of bosonic leptons and baryons can be found in [48], translated in English in [49] and [50].

[7] See also [55].

[8] One has to notice that in these two latter papers the introduction of fermionic states has not only been performed but also a 2 dimensional supersymmetry has been found.

to 26 in the case of a bosonic string [75] and 10 in the case of supersymmetric string theories,[9], these latter theories being constructed in order to solve the problems due to the vacuum instabilities of the bosonic strings and to introduce fermionic degrees of freedom (although these fermionic degrees of freedom can be introduced without invoking supersymmetry [92–95] explicitly – suspersymmetry being present in a non-linear way [96]). The concept of extra space–time dimensions intrinsic to string theories thus appears again, and it appears again to be associated to the concept of unification of gauge and gravitational interactions. It is interesting to note that the critical space–time dimensions in string theories has been also derived by Polyakov by using a path-integral like method [97,98].

In 1984 Green and Schwarz show that the gravitational anomalies in a space–time with more than 4 dimensions cancel, provided that the internal gauge symetry is SO(32) or $E_8 \times E_8$ [99–102]. This discovery has been followed the same year by the development of two new closed string theories [103–105] in 10 dimensions known as the SO(32) heterotic string theory and the $E_8 \times E_8$ theory thus completing the spectrum of already known string theories in 10 dimensions [99–102][10] which are the type I string theory (containing open and closed strings) and the two type II string theories, i.e., IIA and IIB (containing oriented closed strings).

These string theories allow us to incorporate quantum gravity, in the sense that they always contain a massless spin-2 state in their spectrum, which is identified with the graviton. String theories allow us to incorporate gauge theories such as E_8 which can include the gauge group of the Standard Model (E_8 containing E_6 as a subgroup, which in turn contains SU(5) or SO(10) as subgroups into which the gauge groups of the Standard Model can be incorporated). Supersymmetric quantum field theories invariant under non-Abelian gauge transformations appear as the low energy limit of these string theories, in particular, after the compactification of the extra dimensions under specific conditions [109]. String theories also imply the unification of the gauge couplings and the gravitational coupling in one coupling g_s at energy scale $M_s \sim 5 \times 10^{17}$ GeV closer and closer to the Planck scale [110].

Unfortunately these scales remain beyond the reach of present and future colliders, thus precluding any direct tests of these theories such as, for example, evidencing the existence of the extra space dimensions that they imply.

However, as early as 1990 efforts to understand spontaneous supersymmetry breaking induced by compactification of extra dimensions in the context of string theories in the perturbative regime lead Antoniadis [111] to consider the existence of large extra dimensions at energy scales of the order of TeV which are within the reach of colliders.

Besides, further developments allow us to enrich and modify the understanding of string theories. Indeed, the concept of duality already known in electromagnetism [112][11] and extended first in the context of field theories [113–115] and then through efforts to understand the strong coupling regime of supersymmetric gauge theories [116–124] reveal likewise extremely fruitful in string theories[12] in the early 1990s (and in particular in 1995, known as the year of the second string revolution). It has been shown that in different strong and weak coupling limits as well as in different limits for the topology of compact extra dimensions, the five known string theories are related by duality symmetries. These duality symmetries allow us to conjecture the existence of an 11 dimensional theory, the M-theory, whose low energy limit is the 11 dimensional supergravity mentioned above. In particular, Horava and Witten [132] propose to relate the strong coupling limit of the 10 dimensional $E_8 \times E_8$ heterotic string theory to this 11 dimensional M-theory with one dimension compactified on the orbifold S^1/Z_2, i.e., a circle denoted S^1 augmented with the Z_2 symmetry realizing the identification $x_{11} \leftrightarrow -x_{11}$. This proposal leads to a setup with two 10 dimensional subspaces located at each fixed point of the orbifold S^1/Z_2 (which can be seen as a segment in the 11-th dimension) which allow further discussions on supersymmetry breaking.

Dirichlet branes (D-branes) are extended objects, on which strings can end and they are defined by the so-called Dirichlet boundary conditions in the direction normal to the brane which have to be satisfied by the coordinates of the attached string. D-branes have been studied since 1989 [133–136]. In 1995 Polchinski [137][13] shows that D-branes allow us to break half of the supersymmetries of the type II string theories and to provide a source for some duality symmetries in string theories. D-branes allow setups with a bulk in which a closed string of the type II string theories can move and branes on which open strings from the type I string theory (dual to type II string theories) can end. The spectrum of closed strings always contains a massless spin-2 state, thus allowing the presence of gravitational interaction in the bulk. The end of open strings are known to carry gauge degrees of freedom thus allowing gauge interactions in the brane.

[9] See previous references and also [76–82]. Beyond the 2 dimensional supersymetry established by P. Ramond and by A. Neveu and J.H. Schwarz mentioned above, a space–time supersymmetry has been introduced in [83,84]; new string theories have been built when introducing this space–time supersymmetry explicitely in the Lagrangian [85–87]. See also [88–91].

[10] In addition to the references mentioned above we also refer the reader to the following books which offer a very large survey of string theories [106–108].

[11] Which has been emphasized by 't Hooft and Polyakov who showed the existence of magnetic monopoles in grand unified gauge theories.

[12] Important breakthrough can be found in [125–131]. The book of J. Polchinski mentioned above covers also these topics.

[13] See also for branes dynamics [138].

These important developments in string theories, in D-branes physics and in duality symmetries have been exploited in a striking way for the phenomenology of high energy physics. One of the consequences of duality symmetries in string 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 [139] proposes to push this property to an extreme – namely to consider values for M_s as low as TeV. Some consequences for this extremely low M_s have been discussed in [140], especially in the light of established results on gauge coupling unification in the context of string theories.

2. The ADD and RS approaches

The recent interest for extra space dimensions has been revived in a decisive way in 1998 by Dienes, Dudas and Ghergetta [141] with their work on gauge coupling unification in the presence of extra dimensions and by Arkani-Hamed, Dimopoulos and Dvali (ADD) [142]. In a phenomenological approach ADD propose to keep the fields of the Standard Model 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 $M^2_{Pl(4)}$ is related to the fundamental scale in the bulk by:

$$M^2_{Pl(4)} = M^{n+2}_{Pl(4+n)} R^n, \tag{1}$$

where R stands for the radius of the n compact extra dimensions. In consequence the 4 dimensional Planck scale can be understood as coming from a TeV fundamental scale in a space with large compact extra dimensions which can be as large as the millimeter. With a TeV fundamental scale, this scenario suggests also 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 unified theories. This scenario, also known under the name of strong gravity at the TeV, predicts an important deviation from the Newton law of classical gravitation in the case of only one compact extra dimension. In this latter case of only one compact extra dimension, the ADD scenario is thus experimentally excluded. However, this scenario does not contradict submillimetric [143] 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.[14]

The ADD phenomenological proposal can be incorporated into a fundamental framework [146–148] with type I string theory at low scales.

In 1999 Randall and Sundrum (RS) [149,150] propose another phenomenological model with one 4 dimensional brane containing the fields of the Standard Model and then a second phenomenological model with two 4 dimensional branes sitting in a 5 dimensional bulk having a so-called anti-de Sitter geometry (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 $\mathrm{d}s^2 = \mathrm{e}^{-2k|y|}\eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu + \mathrm{d}y^2$ 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 $\mathrm{e}^{-2k|y|}$ 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. (1)) the 4 dimensional Planck scale in the RS approach is:

$$\overline{M}^2_{Pl} = \frac{M_5^3}{k}\left[1 - \mathrm{e}^{-2kr_c\pi}\right]. \tag{2}$$

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

However, this phenomenological model has not yet been incorporated into a more fundamental framework which would allow us to better understand the fine tuning $\Lambda = -24\,M_5^3 k^2$ mentioned above. Suggestions have been made in this direction, either with supergravity or with the so-called AdS/CFT conjecture [151–159] which relates string theories compactified on an anti de Sitter space on the one hand, to conformally invariant supersymmetric gauge theories on the other hand (this would allow us to establish a correspondence between gravitation theory and gauge theory).

The concept of extra space–time dimension thus appears through several different approaches and is often motivated by numerous ideas on the unification of all interactions.

[14] K.R. Dienes talk at the SUSY02 conference, Hamburg, June 2002, based on [144,145].

However, 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 too small to be detected in our past or present experimental setups.

Colliders, in particular those which are presently running, or those which are going to run within the next ten years, offer good opportunities to signal the presence of extra dimensions if they exist.

At colliders, large compact extra space–time 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_o is periodic under y and can be Fourier expanded:

$$\phi(x_\mu, y) = \sum_{k=-\infty}^{+\infty} \mathrm{e}^{\mathrm{i}ky/R} \phi^{(k)}(x_\mu), \tag{3}$$

where R stands for the radius of compact of the extra dimension. The 4 dimensional restrictions $\phi^{(k)}(x_\mu)$ 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. The KK states are massive. For the mode k the mass of a KK state is given by:

$$m_k^2 = m_0^2 + \frac{k^2}{R^2}. \tag{4}$$

The production mode of the KK states, as well as their experimental signatures at colliders, are discussed in the following sections. The simplest approach given by the ADD scenario is discussed, and then approaches more related to the fundamental framework are presented. The RS approach is also discussed, as well as the consequences of its extension, which come from the stabilization mechanism of the radius of the extra dimension. Some aspects of the underlying physics from the fundamental framework beyond the production of KK states are also discussed. 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) are also mentioned.

3. The ADD approach: strong gravity at the TeV

In the ADD phenomenological approach the gravitational interaction sits in the $4+n$ dimensional bulk with n compact extra dimensions. The fields of the Standard Model sit in a 4 dimensional brane.

The graviton is the particle associated with the gravitational interaction in the bulk. The fields of the Standard Model couple to the 4 dimensional restriction of the graviton from the bulk, i.e., to its KK states. In the ADD approach the production of graviton KK states at colliders provides the handle to sign the existence of compact extra dimensions. The Feynman rules for processes involving graviton KK states have been established in [160–164]. The coupling of graviton KK 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 graviton KK states. Namely, the mass difference between two graviton KK states is given by [160–164]:

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

where $M_D = M_{Pl(4+n)}^{n+2}$. Thus for $n = 2$ and $M_D = 1$ TeV the mass difference is $\Delta m \sim 3 \times 10^{-4}$ eV which allow us to produce an almost continuum of graviton KK states. This compensation allows us to obtain sizeable cross-sections for graviton KK states [160–164] 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 graviton KK states disappear in the bulk once they are produced. In consequence the direct production of graviton KK 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 graviton KK states can be produced in association with a photon γ or a Z boson, thus giving rise to $\gamma + \not{E}$ or $Z + \not{E}$ signatures, respectively. At $p\bar{p}$ or pp hadronic colliders, graviton KK 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 graviton KK 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 [160–164]. However, for $n = 2$, the cross-sections of indirect processes involving graviton KK 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 [165–167] in the context of type I string theory.

Direct searches for graviton KK 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 ($\not{E}_t$) channels, such as $p\bar{p} \to 1$, jet $+\not{E}_t$ and $p\bar{p} \to \gamma + \not{E}_t$. Data do not show any evidence for the direct production of graviton KK states at either LEP or 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 graviton KK states direct production in the $e^+e^- \to \gamma + \not{E}$ channel in the L3 experiment at LEP implies $M_D > 1.45$ 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 1. The results concerning the searches for indirect effects are given in Table 2 from [168]. 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. With an increase of luminosity expected for the Run II of the Tevatron the sensitivity on the fundamental scale in processes involving graviton KK 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 graviton KK states are given respectively in Tables 3 and 4 from [169].

Table 1
Lower bounds on M_D in TeV from searches for direct production of graviton KK states in the ADD approach for $n = 2$, $n = 4$ and $n = 6$ extra dimensions. The numbers in brackets correspond to the upper bound in cm on the size of the large compact extra dimensions

		$n = 2$	$n = 4$	$n = 6$
LEP				
$e^+e^- \to \gamma\not{E}$	Aleph	1.28 (2.9×10^{-2})	0.78 (1.4×10^{-9})	0.57 (5.6×10^{-12})
	Delphi	1.36 (2.5×10^{-2})	0.84 (1.3×10^{-9})	0.59 (5.2×10^{-12})
	L3	1.45 (2.3×10^{-2})	0.87 (1.2×10^{-9})	0.61 (5.2×10^{-12})
	Opal	1.09 (4.0×10^{-2})	0.71 (1.6×10^{-9})	0.61 (5.2×10^{-12})
$e^+e^- \to Z\not{E}$	L3	0.60	0.29	
Tevatron				
$p\bar{p} \to$ jet $+\not{E}$	(D0)		0.84	0.58
$p\bar{p} \to \gamma + \not{E}$	(CDF)		0.55	0.58

Table 2
Lower bounds on the M_S cut-off in TeV from the search of indirect effects from graviton KK states in the ADD approach in the Hewett formalism [160–164]. ADLO stands for the combination of the results of the 4 LEP experiments Aleph, Delphi, L3 and Opal

		$\lambda = +1$	$\lambda = -1$
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	1.1	1.0
$e^+e^- \to e^+e^-$ and $\gamma\gamma$	CDF	0.83	0.85
Hera			
$ep \to e +$ jet	H1	0.74	0.70
$ep \to e +$ jet	ZEUS	0.72	0.73

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

		$n=2$ M_D (TeV)	$n=3$ M_D (TeV)	$n=4$ 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 4
Expected sensitivities on the M_S cut-off from indirect processes involving graviton KK 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 M_S (TeV)	$\sqrt{s}=0.8$ 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

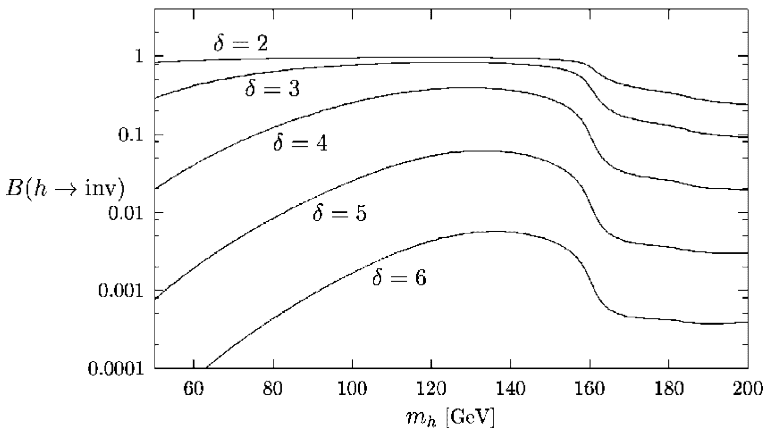

Fig. 1. Invisible branching ratios of the Higgs boson as a function of its mass for $M_D = 2$ TeV and for a conformal coupling equal to 1 for various number of compact extra dimension denoted here δ.

Besides, one of the most stringent constraint on M_D and the radius R of the compact extra dimensions comes from the impact of graviton KK states emission, together with neutrino emission during supernovae cooling. The observation of neutrino emission by the SN1987A supernova in agreement with expectations allows us to obtain the following constraints [170],[15] i.e.,

[15] See also [171].

$M_D > 50$–130 TeV and $R < 3 \times 10^{-4}$ mm for $n = 2$. However these constraints are obtained with the additional assumption that all the radii of compact extra dimensions have the same order of magnitude thus introducing a kind of isotropy of compact extra dimensions which still remains to be justified [172].

Finally, the presence of the gravitational interaction in the bulk does not only imply the existence of graviton KK states in 4 dimensions but also the existence of spin 0 KK states. These graviscalars can interact with the field of the Standard Model via the trace of the energy-momentum tensor. Their direct production rates at colliders, however, remain small with respect to the direct production of graviton KK states [173]. Nevertheless, they can mix to the Higgs boson via a conformal coupling which is not forbidden by any symmetry. Depending on the value of this conformal coupling the graviscalars and Higgs boson mixing can lead to nonnegligible invisible branching ratios as can be seen in Fig. 1 from [173].

This analysis has been confirmed in a more fundamental context involving type I string theory [174].

4. KK gauge bosons

The more fundamental framework of the type I string theory (in a 10 dimensional space–time, i.e., 9 space-like dimensions) into which the previous ADD approach can be incorporated allows several extensions towards configurations involving several branes. Indeed, the gauge fields of the Standard Model can be localized in different branes [175][16] corresponding to different possible ends of the open strings of the type I string theory. These brane configurations allow us to define p dimensional subspaces with $p > 4$ which can be also called thick branes. In turn they allow us to define scenarios 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 space-like 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 theories, the possible existence of KK gauge bosons has been discussed in 1994 in [177,178].[17]

The analysis of nontrivial compactifications in the context of the type IIB string theory allow us 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 [180], 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 us 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 needs 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 us to derive the constraint $M_c > 3.8$ TeV [181]. Including not only electroweak observables but also high energy data from LEP, HERA and the Tevatron Run I allow us to set the following striking bound $M_c > 6.8$ TeV [182].

Gauge coupling unification has also been studied in the context of extra dimensions. It has been shown that the unification of gauge couplings can occur at intermediate or even low energy scales (as low as the TeV) because of a power law behaviour in the gauge couplings running due to the presence of KK states [141]. Moreover, it has been shown [183] that if the compactification

[16] See also [176].
[17] See also [179].

Table 5
Sensitivities on $R_{\parallel}^{-1}$, i.e., one longitudinal extra dimension in TeV from the searches for KK gauge bosons at the Tevatron, LHC and LC

sensitivities on $R_{\parallel}^{-1}$ (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

scale of the longitudinal extra dimensions stays below 10 TeV then the study of two jets production at the LHC allow us to measure this non-standard running behaviour for the strong interaction gauge coupling.

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 jet 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 us to signal the existence of KK gauge bosons. Furthermore, leptonic colliders offer a clean environment in terms of background, thus allowing for the measurements of the coupling between the KK gauge bosons and the fermions of the Standard Model which then allows us to distinguish between various models [184].

Finally if the KK gauge bosons are kinematically accessible at colliders they can be produced resonantly. 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 us to measure the mass of the resonance.

Table 5 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 [185]. 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. Likewise, there remains open questions concerning LHC and LC in their capabilities in separating KK photons from Z boson KK states which are degenerate in mass. 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 [184]. These lower bounds dramatically challenge the LHC and the LC as far as the search for KK gauge bosons is concerned.

5. The Randall–Sundrum (RS) approach

Randall and Sundrum propose a phenomenological model with two 4 dimensional branes in a 5 dimensional space–time with an anti-de Sitter geometry. In this approach, the Standard Model fields are localized on one of the two branes 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 graviton KK states at colliders allow us to signal 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 $e^{-k\pi r_c} M_{Pl}$, namely

Table 6
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_{Pl} at the Tevatron, the LHC and the LC

	k/M_{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

the 4 dimensional Planck mass multiplied by the characteristic factor of the geometry of the RS approach, namely 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 [186] 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. The measurement of the invariant mass of the two leptons allow the measurement of the graviton KK 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 [187]. Decay channels into W^+W^- and ZZ followed by leptonic decay also offer clear signatures at hadronic colliders.

Table 6 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_{Pl}.

6. 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 us to stabilize the value of r_c [188,189] in the warp factor $e^{k\pi r_c}$. The parameter r_c can be associated to 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.

The radion couple to Standard Model fields via the trace of the energy-momentum tensor with a coupling given by $1/\Lambda_\phi$ with $\Lambda_\phi = \sqrt{24M_5^3/k}\, e^{-kr_c\pi}$. Fig. 2 from [190–192] 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. The radion predominantly decays into a gluon pair. This decay channel dominates the decay into two b-quarks which in turn dominates other decay channels such as, in decreasing order, W^+W^-, ZZ, hh, and $t\bar{t}$ if the latter is kinematically allowed. The phenomenology of the radion thus ressembles to 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.

Besides, it is possible to consider a mixing between the Standard Model Higgs boson and the radion [173] which allows us 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 for the Higgs boson-radion mixing, the difference can be sizeable, i.e., up to a factor 50 for the W^+W^- et ZZ decays, for example.

7. Beyond Kaluza–Klein states

The search for Kaluza–Klein states – per se – at colliders in order to search for signatures of extra spacelike dimensions, can be overtaken by the search for alternative effects intrinsic to the underlying theories. Without aiming at an exhaustive survey, some interesting topics are presented in the following subsections.

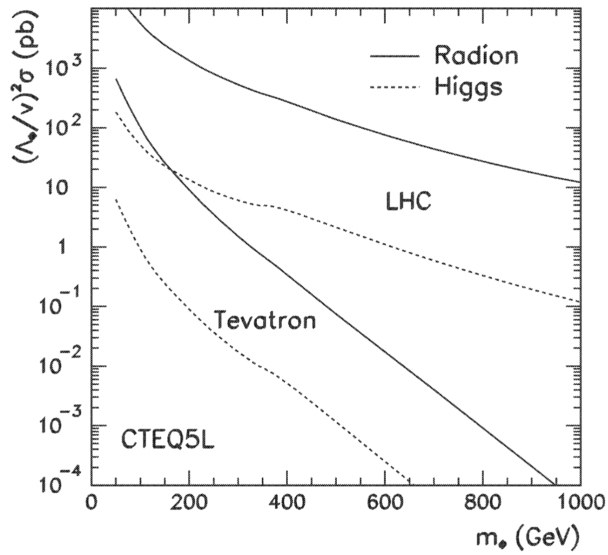

Fig. 2. Cross-sections of the radion production via the gluon fusion process at the Tevatron ($\sqrt{s} = 2$ TeV) and at the LHC ($\sqrt{s} = 14$ TeV) with a normalization factor Λ_ϕ/v where v stands for the vacuum expectation value of the Standard Model Higgs boson and Λ_ϕ is defined in the text. These production cross-sections are compared to the cross-sections of the Standard Model Higgs boson production (dashed line).

7.1. Massive string states

String theories contain a spectrum of massless states which are identified with the particles of the Standard Model. They contain also an infinite spectrum of massive states with masses of the order of the string scale. If the string scale is brought down to values of the order of 1 TeV by duality symmetries arguments then these stringy massive states have masses of this order of magnitude and they can contribute to observable effects at colliders. These stringy effects can even dominates the effects from graviton KK states as the contribution of massive string states to four particles amplitudes appears as form factors containing corrections of the order $g_s(E/M_s)^4$ where $g_s \sim 1/25$ and M_s are respectively the string coupling and and the string scale [165–167] while effects from graviton KK states have smaller factors $g_s^2(E/M_s)^4$. The analysis of Bhabha scattering at the four LEP experiments allows us to derive a lower bound on the string scale which is 0.63 TeV [193].

Furthermore, in the context of type I string theory, D-branes models with several D-branes have been developped [194]. In these models the effects from massive string states become also dominant with respect to the effects from graviton KK states since with matter fields localized at D-brane intersections, the correction can be of the order $g_s(E/M_s)^2$. Again the analysis of Bhabha scattering, as well as the analysis of $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ processes at the four LEP experiments, allow us to derive lower bounds on the scale which are 3.5 TeV (Bhabha) and 3.9 TeV (production $\mu^+\mu^-$ and $\tau^+\tau^-$) [193].

7.2. The Standard Model at intersecting branes

Intersecting branes offer interesting solutions to define fermion chirality [195–198] thus allowing us to define chiral fermions (as required by the Standard Model) at brane intersections, alternatively to the possibility of localized fermions at fixed points of an orbifolds, as mentioned in Section 4. In the context of type IIA string theory Ibanez, Marchesano and Rabadan [199][18] have built the fermions of the Standard Model by localizing fermions at branes intersections. Several models have then been developped in which the conservation of the baryonic and leptonic numbers is ensured by extra U(1) symmetries which do not come from a stringy gauge group like E_6. The Z' gauge bosons coming from these extra U(1) symmetries have masses of the order of the string scale. They acquire their masses by a mechanism involving string states independently from the Higgs mecanism [202,203]. When the string scale is brought down to values of the order of 1 TeV up to 10 TeV these Z' gauge bosons can have masses of this order of magnitude and can be resonantly produced at colliders, such as the LHC, if kinematically accessible.

[18] See also [200,201].

7.3. Supersymmetry and GUT in the presence of extra dimensions

As already mentioned in Section 1, supersymmetry is a fundamental ingredient of the string and brane theories underlying the phenomenological studies of extra dimensions.

The solution to the hierarchy problem of the Standard Model can come either directly from the possibility of a TeV scale of the extra dimensions or from the cancellation of quadratic divergencies via supersymmetry in loop corrections of the Higgs boson mass. These two possibilities do not exclude each other.

As also mentioned in Section 1, duality symmetries in string theories imply 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. Tables 1 and 2 of Section 3 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 provides in addition a solution to the hierarchy problem in the usual way.

Numerous phenomenological supersymmetric models with extra dimensions have been developped [204–218]. Furthermore, these developments does not only allow for discussion of supersymmetry breaking in the context of extra dimensions but also electroweak symmetry breaking. They also allow for discussion of unified gauge theories with extra dimensions. One has to note that as early as the first phenomenological discussions on extra dimensions [141], 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 [219] have shown that the selectron pair production rate, as well as the selectrons angular distributions, are modified due to the effects of the gravitinos KK states. In particular, 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.

7.4. Black holes

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 developped 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 [220–229] 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.

These speculations tend also to consider the production of string balls when $\sqrt{s} > M_s$. These string balls are highly excited and jagged strings. A black hole transits to 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.

At the LHC the production cross-sections can reach 10^{-8} to 2 picobarns for black holes and 10^{-3} to 10^3 picobarns for string balls depending on the number of extra dimensions and on the string scale.

Once they are produced, black holes and string balls decay thermally and isotropically with high multiplicities into Standard Model particles and possibly into supersymmetric particles, via Hawking evaporation for black holes, and via massless particle emission at the Hagedorn temperature for string balls. 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. A 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 high hadrons multiplicities. Moreover, one can experimentally distinguish between string balls and black hole decays, as in the case of string balls the evaporation temperature (which is the Hagedorn 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.

8. Conclusions

The already old idea of extra space-like dimensions has recently enjoyed a remarkable renewal of interest coming from important developments in fundamental theories such as strings and brane theories as well as a wide spectrum of more phenomenological developments. The subsequent phenomenology has started to be explored and is continuing to develop, especially the phenomenology at present and future colliders. A short review of this phenomenology and a short survey of the present experimental results have been presented in this paper. However, exhaustive reviews in this fast growing field of activities become already challenging to achieve and some other important aspects such as universal extra dimensions [230–232] where all Standard Model fields are in the bulk, as well as the notion of deconstruction [233] have not been discussed here if not mentioning the impact of extra dimensions in astrophysics and cosmology which does not take the smallest share.

Acknowledgements

It is a pleasure to thank Ignatios Antoniadis for his invitation to write this mini-review.

References

[1] G. Nordström, On the possibility of a unification of the electromagnetic and gravitation field, Phys. Z. 15 (1914) 504.
[2] H. Weyl, Gravitation und Elektrizität, Sitzungsber. Akad. Wiss. Berlin (1918) 465–480.
[3] T. Kaluza, On the problem of unity in physics, Sitzungsber. Preuss. Akad. Wiss. Berlin Math.-Phys. K1 (1921) 966–972.
[4] O. Klein, Quantum theory and five-dimensional theory of relativity, Z. Phys. 37 (1926) 895–906.
[5] O. Klein, The atomicity of electricity as a quantum theory law, Nature 118 (1926) 516.
[6] A. Einstein, P. Bergmann, On a generalization of Kaluza's theory of electricity, Ann. Math. 39 (1938) 683–701.
[7] O. Klein, On the theory of charged fields, in: Conference on New Theories in Physics, Kasimierz, Poland, 1938.
[8] O. Klein, Helv. Phys. Acta, Suppl. IV (1956) 58.
[9] E. Fermi, An attempt of a theory of beta radiation, Z. Phys. 88 (1934) 161–177.
[10] H. Yukawa, On the interaction of elementary particles, Proc. Phys. Math. Soc. Japan 17 (1935) 48–57.
[11] R.L. Mills, C.N. Yang, Isotopic spin conservation and a generalized gauge invariance, Phys. Rev. 95 (1954) 631.
[12] R.L. Mills, C.N. Yang, Conservation of isotopic spin and isotopic gauge invariance, Phys. Rev. 96 (1954) 191–195.
[13] B.S. De Witt, Relativity, Groups and Topology, Gordon and Breach, New York, 1964.
[14] J. Rayski, A unified description of spacetime and isosphere I and II, Acta. Phys. Polon. 27 (1965) 947;
J. Rayski, Acta. Phys. Polon. 28 (1965) 87.
[15] R. Kerner, Ann. Inst. H. Poincaré Sect. A 9 (1968) 143.
[16] A. Trautman, Fiber bundles associated with space–time, Rep. Math. Phys. 1 (1970) 29–62.
[17] Y.M. Cho, Higher dimensional unifications of gravitation and gauge theories, J. Math. Phys. 16 (1975) 2029–2056.
[18] Y.M. Cho, P.G.O. Freund, Non-Abelian gauge fields as Nambu–Goldstone fields, Phys. Rev. D 12 (1975) 1711–1740.
[19] Y.M. Cho, P.S. Jang, Unified geometry of internal space with space–time, Phys. Rev. D 12 (1975) 3789–3801.
[20] M.J. Duff, B.E.W. Nilsson, C.N. Pope, Kaluza–Klein supergravity, Phys. Rep. 130 (1986) 1–142.
[21] S. Weinberg, The Quantum Theory of Fields, Vol. 1: Foundations, Cambridge University Press, 1995 and Vol. 2: Modern Applications, Cambridge University Press, 1996.
[22] R.P. Feynman, Photon–Hadron Interactions, Benjamin, New York, 1972.
[23] M. Gell-mann, Y. Ne'eman, The Eightfold Way, Benjamin, New York, 1964.
[24] G. 't Hooft, M.J.G. Veltman, Regularization and renormalization of gauge fields, Nucl. Phys. B 44 (1972) 189–213.
[25] G. 't Hooft, M.J.G. Veltman, Combinatorics of gauge fields, Nucl. Phys. B 50 (1972) 318–353.
[26] S.L. Glashow, Towards a unified theory: threads in a tapestry, Rev. Mod. Phys. 52 (1980) 539–543.
[27] A. Salam, Gauge unification of fundamental forces, Rev. Mod. Phys. 52 (1980) 525–538.
[28] S. Weinberg, Conceptual foundations of the unified theory of weak and electromagnetic interactions, Rev. Mod. Phys. 52 (1980) 515–523.
[29] O.V. Greenberg, Spin and unitary spin independence in a paraquark model of baryons and mesons, Phys. Rev. Lett. 13 (1964) 598–602.
[30] M. Gell-mann, Acta Phys. Austriaca Suppl. IV (1972) 733.
[31] H. Fritzsch, M. Gell-mann, H. Leutwyler, Advantages of the color octet gluon picture, Phys. Lett. B 47 (1973) 365–368.
[32] D.J. Gross, F. Wilczek, Ultraviolet behavior of nonabelian gauge theories, Phys. Rev. Lett. 30 (1973) 1343–1346.
[33] D.J. Gross, F. Wilczek, Asymptotically free gauge theories 1, Phys. Rev. D 8 (1973) 3633–3652.
[34] D.J. Gross, F. Wilczek, Asymptotically free gauge theories 2, Phys. Rev. D 9 (1974) 980–993.
[35] H.D. Politzer, Reliable perturbative results for strong interactions?, Phys. Rev. Lett. 30 (1973) 1346–1349.
[36] S. Weinberg, Nonabelian gauge theories of the strong interactions, Phys. Rev. Lett. 31 (1973) 494–497.
[37] F. Wilczek, Quantum Chromodynamics (QCD): the modern theory of the strong interaction, Ann. Rev. Nucl. Particle Sci. 32 (1982) 177–209.
[38] H.P. Politzer, Asymptotic freedom: an approach to strong interactions, Phys. Rep. 14 (1974) 129–180.
[39] J.C. Pati, A. Salam, Unified lepton–hadron symmetry and a gauge theory of the basic interactions, Phys. Rev. D 8 (1973) 1240.
[40] H. Georgi, S.L. Glashow, Unity of all elementary particle forces, Phys. Rev. Lett. 32 (1974) 438–441.
[41] Y. Golfand, E. Likhtman, Extension of the algebra of Poincaré group generators and violation of P invariance, JETP Lett. 13 (1971) 323–326.
[42] D. Volkov, V. Akulov, Is the neutrino a Goldstone particle?, Phys. Lett. B 46 (1973) 109–110.
[43] S. Coleman, G. Mandula, All possible symmetries of the S matrix, Phys. Rev. 159 (1967) 1251–1256.

[44] J. Gervais, B. Sakita, Field theory interpretation of supergauges in dual models, Nucl. Phys. B 34 (1971) 632–639.
[45] J. Wess, B. Zumino, Supergauge transformations in four-dimensions, Nucl. Phys. B 70 (1974) 39–50.
[46] P. Fayet, J. Iliopoulos, Spontaneously broken supergauge symmetries and goldstone spinors, Phys. Lett. B 51 (1974) 461–464.
[47] P. Fayet, S. Ferrara, Supersymmetry, Phys. Rep. 32 (1977) 249–334.
[48] L. Okun, Zh. Eksp. i Teor. Fiz. 47 (1964) 1777–1781.
[49] L. Okun, Possible types of elementary particles, JETP 20 (1965) 1197–1200.
[50] R.M. Weiner, Bosonic leptons, Phys. Rev. Lett. 18 (1967) 376–379.
[51] D.Z. Freedman, P. Van Nieuwenhuizen, S. Ferrara, Progress toward a theory of supergravity, Phys. Rev. D 13 (1976) 3214–3218.
[52] S. Deser, B. Zumino, Consistent supergravity, Phys. Lett. B 62 (1976) 335–341.
[53] D.Z. Freedman, P. Van Nieuwenhuizen, Properties of supergravity theory, Phys. Rev. D 14 (1976) 912–930.
[54] S. Ferrara, P. Van Nieuwenhuizen, Consistent supergravity with complex spin $3/2$ gauge fields, Phys. Rev. Lett. 37 (1976) 1669–1679.
[55] P. van Nieuwenhuizen, Supergravity, Phys. Rep. 68 (1981) 189–398.
[56] Y. Nambu, Lectures at Copenhaguen Symposium, 1970.
[57] T. Goto, Relativistic quantum mechanics of one-dimensional mechanical continuum and subsidiary condition of dual resonance model, Prog. Theor. Phys. 46 (1971) 1560–1569.
[58] L. Susskind, Dual symmetric theory of hadrons 1, Nuovo Cimento A 69 (1970) 457–496.
[59] O. Hara, On origin and physical meaning of ward-like identity in dual resonance model, Prog. Theor. Phys. 46 (1971) 1549–1559.
[60] G. Veneziano, Construction of a crossing-symmetric, Regge behaved amplitude for linearly rising trajectories, Nuovo Cimento A 57 (1968) 190–197.
[61] Z. Koba, H.B. Nielsen, Reaction amplitude for N mesons: a generalization of the Veneziano–Bardacki–Ruegg–Virasoro model, Nucl. Phys. B 10 (1969) 633–655.
[62] Z. Koba, H.B. Nielsen, Manifestly crossing invariant parametrization of N meson amplitude, Nucl. Phys. B 12 (1969) 517–536.
[63] C. Lovelace, Pomeron form-factors and dual Regge cuts, Phys. Lett. B 34 (1971) 500–506.
[64] P. Ramond, Dual theory for free fermions, Phys. Rev. D 3 (1971) 2415–2418.
[65] A. Neveu, J.H. Schwarz, Factorizable dual model of pions, Nucl. Phys. B 31 (1971) 86–112.
[66] A. Neveu, J. Scherk, Connection between Yang–Mills fields and dual models, Nucl. Phys. B 36 (1972) 155–161.
[67] T. Yoneya, Connection of dual models to electrodynamics and gravidynamics, Prog. Theor. Phys. 51 (1974) 1907–1920.
[68] J. Scherk, J.H. Schwarz, Dual models for nonhadrons, Nucl. Phys. B 81 (1974) 118–144.
[69] M.J. Duff, B.E.W. Nilsson, C.N. Pope, Kaluza–Klein supergravity, Phys. Rep. 130 (1986) 1–142.
[70] S.M. Christensen, M.J. Duff, New gravitational index theorems and supertheorems, Nucl. Phys. B 154 (1979) 309–402.
[71] F.A. Berends, J.W. Holten, B. de Witt, P. van Nieuwenhuizen, On field theory for massive and massless spin 5/2 particles, Nucl. Phys. B 154 (1979) 261–300.
[72] C. Aragone, S. Deser, Consistency problems of hypergravity, Phys. Lett. B 86 (1979) 161–167.
[73] W. Nahm, Supersymmetries and their representations, Nucl. Phys. B 135 (1978) 149–175.
[74] E. Cremmer, B. Julia, J. Scherk, Supergravity theory in eleven-dimensions, Phys. Lett. B 76 (1978) 409–412.
[75] P. Goddard, J. Goldstone, C. Rebbi, C.B. Thorn, Quantum dynamics of a massless relativistic string, Nucl. Phys. B 56 (1973) 109–135.
[76] R.C. Brower, Spectrum generating algebra and no ghost theorem for the dual model, Phys. Rev. D 6 (1972) 1655–1662.
[77] P. Goddard, C.B. Thorn, Compatibility of the dual pomeron with unitarity and the absence of ghosts in the dual resonance model, Phys. Lett. B 40 (1972) 235–238.
[78] J.H. Schwarz, Physical states and pomeron poles in the dual pion model, Nucl. Phys. B 46 (1972) 61–74.
[79] R.C. Brower, K.A. Friedman, Spectrum generating algebra and no ghost theorem for the Neveu–Schwarz model, Phys. Rev. D 7 (1973) 535–539.
[80] Y. Iwasaki, K. Kikkawa, Quantization of a string of spinning material Hamiltonian and Lagrangian formulation, Phys. Rev. D 8 (1973) 440–449.
[81] S. Deser, B. Zumino, A complete action for the spinning string, Phys. Lett. B 65 (1976) 369–373.
[82] L. Brink, P. di Vecchia, P. Howe, A locally supersymmetric and reparametrization invariant action for the spinning string, Phys. Lett. B 65 (1976) 471–474.
[83] F. Gliozzi, J. Scherk, D. Olive, Supersymmetry, supergravity theories and the dual spinor model, Nucl. Phys. B 122 (1977) 253–290.
[84] M.B. Green, J.H. Schwarz, Supersymmetrical dual string theory, Nucl. Phys. B 181 (1981) 502.
[85] M.B. Green, J.H. Schwarz, Supersymmetrical string theories, Phys. Lett. B 109 (1982) 444–448.
[86] M.B. Green, J.H. Schwarz, Covariant description of superstrings, Phys. Lett. B 136 (1984) 367–370.
[87] M.B. Green, J.H. Schwarz, Properties of the covariant formulation of superstring theories, Nucl. Phys. B 243 (1984) 285–318.
[88] J.H. Schwarz, Superstring theory, Phys. Rep. 89 (1982) 223–322.
[89] M.B. Green, J.H. Schwarz, Superstrings interactions, Nucl. Phys. B 218 (1983) 43–88.
[90] M.B. Green, J.H. Schwarz, Superfield theory of type II superstrings, Nucl. Phys. B 219 (1983) 437–478.
[91] M.B. Green, J.H. Schwarz, Superstring field theory, Nucl. Phys. B 243 (1984) 475–536.
[92] L.J. Dixon, J.A. Harvey, String theories in ten-dimensions without space–time supersymmetry, Nucl. Phys. B 274 (1986) 93–105.
[93] N. Seiberg, E. Witten, Spin structures in string theory, Nucl. Phys. B 276 (1986) 272–300.
[94] L. Alvarez-Gaumé, P. Ginsparg, G. Moore, C. Vafa, An $O(16) \times O(16)$ heterotic string, Phys. Lett. B 171 (1986) 155–170.
[95] P. Ginsparg, C. Vafa, Toroidal compactification of nonsupersymmetric heterotic strings, Nucl. Phys. B 289 (1987) 414–459.
[96] E. Dudas, J. Mourad, Consistent gravitino couplings in nonsupersymmetric strings, Phys. Lett. B 514 (2001) 173–182.
[97] A.M. Polyakov, Quantum geometry of bosonic strings, Phys. Lett. B 103 (1981) 207–210.

[98] A.M. Polyakov, Quantum geometry of fermionic strings, Phys. Lett. B 103 (1981) 211–213.
[99] L. Alvarez-Gaumé, E. Witten, Gravitational anomalies, Nucl. Phys. B 234 (1983) 269–380.
[100] M.B. Green, J.H. Schwarz, Anomaly cancellation in supersymmetric $D = 10$ gauge theory and superstring theory, Phys. Lett. B 149 (1984) 117–122.
[101] M.B. Green, J.H. Schwarz, The hexagon gauge anomaly in type I superstring theory, Nucl. Phys. B 255 (1985) 93–114.
[102] J. Thierry-Mieg, Remarks concerning the $E8 \times E8$ and D16 string theories, Phys. Lett. B 156 (1985) 199–215.
[103] D.J. Gross, J.A. Harvey, E. Martinec, R. Rohm, The heterotic string, Phys. Rev. Lett. 54 (1985) 502–505.
[104] D.J. Gross, J.A. Harvey, E. Martinec, R. Rohm, Heterotic string theory 1. The free heterotic string, Nucl. Phys. B 256 (1986) 253–310.
[105] D.J. Gross, J.A. Harvey, E. Martinec, R. Rohm, Heterotic string theory 2. The interacting heterotic string, Nucl. Phys. B 267 (1986) 75–166.
[106] M.B. Green, J.H. Schwartz, E. Witten, Superstring Theory, Cambridge University Press, 1987.
[107] J. Polchinski, Superstring Theory, Cambridge University Press, 1998.
[108] D. Bailin, A. Love, Supersymmetric Gauge Field Theory and String Theory, Bristol, 1994.
[109] P. Candelas, G. Horowitz, A. Strominger, E. Witten, Vacuum configurations for superstrings, Nucl. Phys. B 258 (1985) 46–74.
[110] P. Ginsparg, Gauge and Gravitational couplings in four-dimensional string theories, Phys. Lett. B 197 (1987) 139–150.
[111] I. Antoniadis, A possible new dimension at a few TeV, Phys. Lett. B 246 (1990) 377–384.
[112] P.A.M. Dirac, Quantized singularities in the electromagnetic field, Proc. Roy. Soc. A 133 (1931) 60–72.
[113] C. Montonen, D. Olive, Magnetic monopoles as gauge particles?, Phys. Lett. B 72 (1977) 117–127.
[114] D. Olive, E. Witten, Supersymmetry algebras that include topological charges, Phys. Lett. B 78 (1978) 97–111.
[115] H. Osborn, Topological charges for $N = 4$ supersymmetric gauge theories and monopoles of spin 1, Phys. Lett. B 83 (1979) 321–337.
[116] N. Seiberg, Exact results on the space of vacua of four-dimensional susy gauge theories, Phys. Rev. D 49 (1994) 6857–6863.
[117] N. Seiberg, E. Witten, Electric–magnetic duality, monopole condensation, and confinement in $N = 2$ supersymmetric Yang–Mills theory, Nucl. Phys. B 426 (1994) 19–52.
[118] N. Seiberg, E. Witten, Erratum, Nucl. Phys. B 430 (1994) 485–496.
[119] N. Seiberg, E. Witten, Monopoles, duality and chiral symmetry breaking in $N = 2$ supersymmetric QCD, Nucl. Phys. B 431 (1994) 484–550.
[120] K.A. Intriligator, N. Seiberg, Phases of $N = 1$ supersymmetric gauge theories in four-dimensions, Nucl. Phys. B 431 (1994) 551–568.
[121] N. Seiberg, Electric–magnetic duality in supersymmetric nonabelian gauge theories, Nucl. Phys. B 435 (1995) 129–146.
[122] K.A. Intriligator, N. Seiberg, Duality, monopoles, dyons, confinement and oblique confinement in supersymmetric $\mathrm{SO}(N(C))$ gauge theories, Nucl. Phys. B 444 (1995) 125–160.
[123] K.A. Intriligator, N. Seiberg, Lectures on supersymmetric gauge theories and electric–magnetic duality, Nucl. Phys. Proc. Suppl. BC 45 (1996) 1–28.
[124] N. Seiberg, The power of duality: exact results in 4-D susy field theory, Int. J. Mod. Phys. A 16 (2001) 4365–4376.
[125] C.M. Hull, P.K. Townsend, Unity of superstring dualities, Nucl. Phys. B 438 (1995) 109–137.
[126] P.K. Townsend, The eleven-dimensional supermembrane revisited, Phys. Lett. B 350 (1995) 184–187.
[127] M.J. Duff, Strong/weak coupling duality from the dual string, Nucl. Phys. B 442 (1995) 47–63.
[128] E. Witten, String theory dynamics in various dimensions, Nucl. Phys. B 443 (1995) 85–126.
[129] A. Strominger, Massless black holes and conifolds in string theory, Nucl. Phys. B 451 (1995) 96–108.
[130] A. Strominger, Black hole condensation and the unification of string vacua, Nucl. Phys. B 451 (1995) 109–120.
[131] J.H. Schwarz, An $\mathrm{SL}(2, Z)$ multiplet of type IIB superstrings, Phys. Lett. B 360 (1995) 13–18.
[132] P. Horava, E. Witten, Heterotic and type I string dynamics from eleven-dimensions, Nucl. Phys. B 460 (1996) 506–524.
[133] J. Dai, R.G. Leigh, J. Polchinski, New connections between string theories, Mod. Phys. Lett. A 4 (1989) 2073–2083.
[134] R.G. Leigh, Dirac–Born–Infeld action from Dirichlet sigma model, Mod. Phys. Lett. A 4 (1989) 2767–2777.
[135] J. Polchinski, Combinatorics of boundaries in string theory, Phys. Rev. D 50 (1994) 6041–6045.
[136] M. Green, Point-like states for type 2B superstrings, Phys. Lett. B 329 (1994) 435–443.
[137] J. Polchinski, Dirichlet branes and Ramond-Ramond charges, Phys. Rev. Lett. 75 (1995) 4724–4727.
[138] C. Bachas, D-brane dynamics, Phys. Lett. B 374 (1996) 37–42.
[139] J. Lykken, Weak scale superstrings, Phys. Rev. D 54 (1996) 3693–3697.
[140] C. Bachas, Scales of string theory, Class. Quant. Grav. 17 (2000) 951–959.
[141] K.R. Dienes, E. Dudas, T. Gherghetta, Grand unification at intermediate mass scales through extra dimensions, Nucl. Phys. B 537 (1999) 47–108.
[142] N. Arkani-Hamed, S. Dimopoulos, G. Dvali, The hierarchy problem and new dimensions at a millimeter, Phys. Lett. B 429 (1998) 263–272.
[143] EOT-WASH group, hep-ex/0202008.
[144] K.R. Dienes, A. Mafi, Shadows of the Planck scale: scale dependence of compactification geometry, Phys. Rev. Lett. 88 (2002) 111602–111609.
[145] K.R. Dienes, A. Mafi, Kaluza–Klein states versus winding states: can both be above the string scale?, hep-ph/0207009.
[146] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G. Dvali, New dimensions at a millimeter to a Fermi and superstrings at a TeV, Phys. Lett. B 436 (1998) 257–263.
[147] G. Shiu, S.H. Tye, TeV scale superstring and extra dimensions, Phys. Rev. D 58 (1998) 106007.
[148] I. Antoniadis, C. Bachas, E. Dudas, Gauge couplings in four-dimensional type I string orbifolds, Nucl. Phys. B 560 (1999) 93–134.
[149] L. Randall, R. Sundrum, A large mass hierarchy from a small extra dimension, Phys. Rev. Lett. 83 (1999) 3370–3373.

[150] L. Randall, R. Sundrum, An alternative to compactification, Phys. Rev. Lett. 83 (1999) 4690–4693.
[151] G. 't Hooft, A planar diagram theory for strong interactions, Nucl. Phys. B 72 (1974) 461–481.
[152] J.M. Maldacena, The large N limit of superconformal field theories and supergravity, Adv. Theor. Math. Phys. 2 (1998) 231–252.
[153] J.M. Maldacena, Int. J. Theor. Phys. 38 (1999) 1113–1133.
[154] S.S. Gubser, I.R. Klebanov, A.M. Polyakov, Gauge theory correlators from noncritical string theory, Phys. Lett. B 428 (1998) 105–114.
[155] E. Witten, Anti-de Sitter space and holography, Adv. Theor. Math. Phys. 2 (1998) 253–291.
[156] O. Aharony, S.S. Gubser, J.M. Maldacena, H. Ooguri, Y. Oz, Large N field theories, string theory and gravity, Phys. Rep. 323 (2000) 183–386.
[157] A. Kehagias, Exponential and power law hierarchies from supergravity, Phys. Lett. B 469 (1999) 123–128.
[158] J. Cline, C. Grojean, G. Servant, Supergravity inspired warped compactifications and effective cosmological constants, Nucl. Phys. B 578 (2000) 259–276.
[159] H. Verlinde, Holography and compactification, Nucl. Phys. B 580 (2000) 264–274.
[160] G.F. Giudice, R. Rattazzi, J.D. Wells, Quantum gravity and extra dimensions at high-energy colliders, Nucl. Phys. B 544 (1999) 3–38.
[161] E.A. Mirabelli, M. Perelstein, M.E. Peskin, Collider signatures of new large space dimensions, Phys. Rev. Lett. 82 (1999) 2236–2239.
[162] T. Han, J.D. Lykken, R. Zhang, On Kaluza–Klein states from large extra dimensions, Phys. Rev. D 59 (1999) 105006.
[163] J.L. Hewett, Indirect collider signals for extra dimensions, Phys. Rev. Lett. 82 (1999) 4765–4768.
[164] I. Antoniadis, K. Benakli, Large dimensions and string physics in future colliders, Int. J. Mod. Phys. A 15 (2000) 4237–4286.
[165] E. Dudas, J. Mourad, String theory predictions for future accelerators, Nucl. Phys. B 575 (2000) 3–34.
[166] E. Accomando, I. Antoniadis, K. Benakli, Looking for TeV scale strings and extra dimensions, Nucl. Phys. B 579 (2000) 3–16.
[167] S. Cullen, M. Perelstein, M.E. Peskin, TeV strings and collider probes of large extra dimensions, Phys. Rev. D 62 (2000) 055012.
[168] Talks of L. Duflot, S. Riemann and Y. Sirois at the SUSY02 conference, Hamburg, June 2002.
[169] Talks of A. Miagkov and G. Wilson at the Higgs and Supersymmetry workshop, Orsay, March 2001 and Talk of I. Korolkov at the SUSY02 conference, Hamburg, June 2002.
[170] L.J. Hall, D. Smith, Cosmological constraints on theories with large extra dimensions, Phys. Rev. D 60 (1999) 085008.
[171] I. Antoniadis, K. Benakli, Limits on the size of extra dimensions, hep-ph/0004240.
[172] Private communication.
[173] G.F. Giudice, R. Rattazzi, J.D. Wells, Graviscalars from higher dimensional metrics and curvature Higgs mixing, Nucl. Phys. B 595 (2001) 250–276.
[174] I. Antoniadis, R. Sturani, Higgs graviscalar mixing in type I string theory, Nucl. Phys. B 631 (2002) 66–82.
[175] E. Accomando, I. Antoniadis, K. Benakli, Looking for TeV scale strings and extra dimensions, Nucl. Phys. B 579 (2000) 3–16.
[176] I. Antoniadis, K. Benakli, Large dimensions and string physics in future collider, Int. J. Mod. Phys. A 15 (2000) 4237–4286.
[177] I. Antoniadis, K. Benakli, Limits on extra dimensions in orbifold compactifications of superstrings, Phys. Lett. B 326 (1994) 69–78.
[178] I. Antoniadis, K. Benakli, M. Quiros, Production of Kaluza–Klein states at future colliders, Phys. Lett. B 331 (1994) 313–320.
[179] I. Antoniadis, K. Benakli, M. Quiros, Direct collider signatures of large extra dimensions, Phys. Lett. B 460 (1999) 176–183.
[180] I. Antoniadis, B. Pioline, Low scale closed strings and their duals, Nucl. Phys. B 550 (1999) 41–58.
[181] T.G. Rizzo, J. Wells, Electroweak precicion measurements and collider probes of the standard model with large extra dimensions, Phys. Rev. D 61 (2000) 016007.
[182] K.M. Cheung, G. Landsberg, Kaluza–Klein states of the standard model gauge bosons: constraints from high energy experiments, Phys. Rev. D 65 (2002) 076003.
[183] C. Balazs, B. Laforge, Probing TeV scale gauge unification by hadronic collisions, Phys. Lett. B 525 (2002) 219–224.
[184] T.G. Rizzo, Testing the nature of Kaluza–Klein excitations at future lepton colliders, Phys. Rev. D 61 (2000) 055005.
[185] I. Antoniadis, K. Benakli, Large dimensions and string physics in future colliders, Int. J. Mod. Phys. A 15 (2000) 237–4286.
[186] H. Davoudiasl, J.L. Hewett, T.G. Rizzo, Experimental probes of localized gravity: on and off the wall, Phys. Rev. D 63 (2001) 075004.
[187] B.C. Allanach, K. Odagiri, M.A. Parker, B.R. Webber, Searching for narrow graviton resonances with the Atlas detector at the large hadron collider, JHEP 0009 (2000) 19–32.
[188] W.D. Goldberger, M.B. Wise, Bulk fields in the Randall–Sundrum compactification scenario, Phys. Rev. D 60 (1999) 107505.
[189] W.D. Goldberger, M.B. Wise, Modulus stabilization with bulk fields, Phys. Rev. Lett. 83 (1999) 4922–4925;
W.D. Goldberger, M.B. Wise, Phenomenology of a stabilized modulus, Phys. Lett. B 475 (2000) 275–279.
[190] U. Mahanta, Production of light stabilized radion at high-energy hadron collider, Phys. Lett. B 483 (2000) 196–202.
[191] S.B. Bae, P. Ko, H.S. Lee, J. Lee, Phenomenology of the radion in Randall–Sundrum scenario at colliders, Phys. Lett. B 487 (2000) 299–305.
[192] U. Mahanta, Implications of radion Higgs couplings for high-energy scattering in the Randall–Sundrum model, Phys. Rev. D 63 (2001) 076006.
[193] D. Bourilkov, in: Results and Perspectives in Particle Physics, La Thuile, 2001.
[194] I. Antoniadis, K. Benakli, A. Laugier, Contact interactions in D-brane models, JHEP 0105 (2001) 44–71.
[195] M. Berkooz, M.R. Douglas, R.G. Leigh, Branes intersecting at angles, Nucl. Phys. B 480 (1996) 265–278.
[196] V. Balasubramanian, R.G. Leigh, D-branes, moduli and supersymmetry, Phys. Rev. D 55 (1997) 6415–6422.
[197] H. Arfaei, M.M. Sheikh Jabbari, Different D-brane interactions, Phys. Lett. B 394 (1997) 288–296.
[198] M.M. Sheikh Jabbari, Classifications of different branes at angles, Phys. Lett. B 420 (1998) 279–284.
[199] L. Ibanez, F. Marchesano, R. Rabadan, Getting just the standard model at intersecting branes, JHEP 0111 (2001) 002–045.
[200] G. Aldazabal, L.E. Ibanez, F. Quevedo, Standard-like models with broken supersymmetry from type I string vacua, JHEP 0001 (2000) 031–087.

[201] M. Cvetic, P. Langacker, G. Shiu, A three family standard-like orientifold model: Yukawa couplings and hierarchy, hep-th/0206115.
[202] D. Cremades, L.E. Ibanez, F. Marchesano, Standard model at intersecting D5-branes: lowering the string scale, hep-th/0205074.
[203] D.M. Ghilencea, L.E. Ibanez, N. Irges, F. Quevedo, TeV scale Z-prime bosons from D-branes, hep-th/0205083.
[204] J.R. Ellis, Z. Lalak, S. Pokorski, S. Thomas, Supergravity and supersymmetry breaking in four-dimensions and five-dimensions, Nucl. Phys. B 563 (1999) 107–124.
[205] T. Gherghetta, A. Pomarol, Bulk fields and supersymmetry in a slice of ADS, Phys. Lett. B 586 (2000) 141–162.
[206] T. Gherghetta, A. Pomarol, A warped supersymmetric standard model, Phys. Lett. B 602 (2001) 3–22.
[207] A. Falkowski, Z. Lalak, S. Pokorski, Supersymmetrizing branes with bulk in five-dimensional supergravity, Phys. Lett. B 491 (2000) 172–182.
[208] A. Falkowski, Z. Lalak, S. Pokorski, Five-dimensional gauged supergravities with universal hypermultiplet and warped brane worlds, Phys. Lett. B 509 (2001) 337–345.
[209] A. Falkowski, Z. Lalak, S. Pokorski, Four-dimensional supergravities from five-dimensional brane worlds, Nucl. Phys. B 613 (2001) 189–217.
[210] J. Bagger, D. Nemeschansky, R.J. Zhang, Supersymmetric radion in the Randall–Sundrum scenario, JHEP 0108 (2000) 057–072.
[211] G. Altarelli, F. Feruglio, SU(5) grand unification in extra dimensions and proton decay, Phys. Lett. B 511 (2001) 257–264.
[212] L.J. Hall, Y. Nomura, Gauge unification in higher dimensions, Phys. Rev. D 64 (2001) 055003.
[213] A. Hebecker, J. March-Russell, A minimal $S^1/(Z_2 \times Z_2')$ orbifold GUT, Nucl. Phys. B 613 (2001) 3–16.
[214] V. Di Clemente, S.F. King, D.A.J. Rayner, Supersymmetry and electroweak breaking with large and small extra dimensions, Nucl. Phys. B 617 (2001) 71–100.
[215] J.A. Casas, J.R. Espinosa, I. Navarro, Unconventional low energy susy from warped geometry, Nucl. Phys. B 620 (2002) 195–236.
[216] L.J. Hall, Y. Nomura, T. Okui, D. Smith, SO(10) unified theories in six-dimensions, Phys. Rev. D 65 (2002) 035008.
[217] R. Barbieri, L.J. Hall, Y. Nomura, Strongly coupled grand unification in higher dimensions, Phys. Rev. D 65 (2002) 085036.
[218] R. Barbieri, L.J. Hall, Y. Nomura, A complete theory of grand unification in five dimensions, hep-ph/0205067.
[219] J.L. Hewett, D. Sadri, Supersymmetric extra dimensions: Gravitino effects in selectron pair production, hep-ph/0204063.
[220] P. Argyres, S. Dimopoulos, J. March-Russell, Black holes and submillimeter dimensions, Phys. Lett. B 441 (1998) 96–104.
[221] R. Emparan, G. Horowitz, R. Myers, Black holes radiate mainly on the brane, Phys. Rev. Lett. 85 (2000) 499–502.
[222] S. Giddings, S. Thomas, High-energy colliders as black hole factories: the end of short distance physics, Phys. Rev. D 65 (2002) 056010.
[223] S. Dimopoulos, G. Landsberg, Black holes at the LHC, Phys. Rev. Lett. 87 (2001) 161602–161607.
[224] K. Cheung, Black hole production and large extra dimensions, Phys. Rev. Lett. 88 (2002) 221602–221606.
[225] G. Landsberg, Discovering new physics in the decays of black holes, Phys. Rev. Lett. 88 (2002) 181801–181805.
[226] G. Giudice, R. Rattazzi, J. Wells, Transplanckian collisions at the LHC and beyond, Nucl. Phys. B 630 (2002) 293–325.
[227] S.N. Solodukhin, Classical and quantum cross-section for black hole production in particle collisions, Phys. Lett. B 533 (2002) 153–161.
[228] T. Rizzo, Black hole production at the LHC: effects of Voloshin suppression, JHEP 0202 (2002) 11–23.
[229] S. Dimopoulos, R. Emparan, String balls at the LHC and beyond, Phys. Lett. B 526 (2002) 393–398.
[230] N. Arkani-Hamed, H. Cheng, B.A. Dobrescu, L.J. Hall, Selfbreaking of the standard model gauge symmetry, Phys. Rev. D 62 (2000) 096006.
[231] T. Appelquist, H. Cheng, B.A. Dobrescu, Bounds on universal extra dimensions, Phys. Rev. D 64 (2001) 035002.
[232] T.G. Rizzo, Probes of universal extra dimensions at colliders, Phys. Rev. D 64 (2001) 095010.
[233] N. Arkani-Hamed, A.G. Cohen, H. Georgi, Electroweak symmetry breaking from dimensional deconstruction, Phys. Lett. B 513 (2001) 232–240.