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Experimental constraints on extra dimensions

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Abstract. In the last few years the proposed existence of large extra dimensions has changed the landscape of high energy physics, suggesting longly sought answers to fundamental questions like the hierarchy problem. To date, several theoretical models have been proposed and a vigorous experimental effort has started, aimed to hunt for manifestations of extra dimensions in form of deviations from the Newton law in short-range tests of gravity or as new particle interactions at the world's most powerful colliders. An overview is presented of the details of the experimental searches and their findings.

PACS. 04.50.+h Gravity in more than four dimensions – 12.60.-i Models beyond the Standard Model

1 Introduction

In our present understanding of the laws of Physics, three facts characterise the comparison of gravity to the Standard Model of the electroweak interactions [1]:

1. the scale of gravitational phenomena, $m_{Pl} \approx 10^{19}$ GeV, happens to be immensely larger than the scale of the electroweak interactions, $m_{ew} \approx 10^2$ GeV: the so-called hierarchy problem;
2. the Standard Model is tested at its characteristic distance, $1/m_{ew}$, and no signs for dramatic deviations are observed [2];
3. the characteristic distance of gravity, $1/m_{Pl}$, is inconceivably small, making such direct tests impossible.

These facts find a natural place in some recent theoretical ideas [3]. Inspired by some concepts from string theory [4], mechanisms are introduced which bring the scale of gravity to a new scale, of the order of m_{ew} [5,6,7], hence solving in a natural way the hierarchy problem. At the same time, the existence of extra space dimensions, in addition to the three-dimensional space we are accustomed with, is postulated. This is not in contradiction with any observation, given the lack of information on the behaviour of gravity at its characteristic distance. These extra dimensions could manifest themselves as deviations from the Newton law in short-range tests of gravity or in particle interactions at high energy colliders. These experimental searches and their findings are discussed in the following, starting from short-range tests of gravity and discussing then the collider searches in the so-called ADD and RS scenarios, as well as in those predicting TeV-scale strings or branons.

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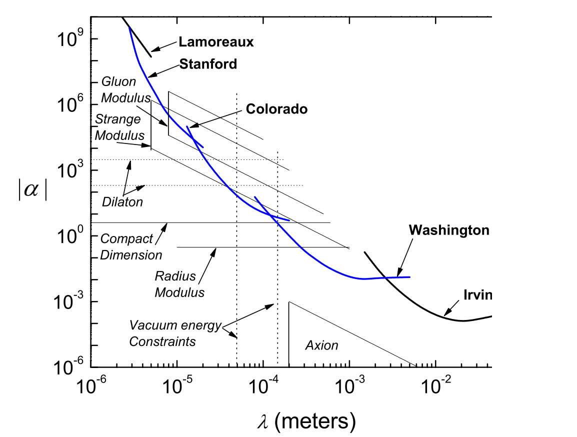

Fig. 1. Experimental limits at 1σ ("Stanford", "Irvine") or 2σ (others) on deviations from the Newton potential as described by an additional Yukawa term of magnitude α and range λ [8]. The region *above the thick curves is excluded. The line labelled "Compact Dimensions" corresponds to a model with two extra dimensions and a new scale of gravity around 1 TeV*

2 Short-range tests of gravity

The results of short-range tests of gravity are usually described in terms of the magnitude, α, and the range, λ, of an additional Yukawa term in the Newton potential:

$$V(r) = -\frac{1}{m_{Pl}}\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right).$$

Figure 1, extracted from a recent review [8], presents the current experimental limits in the α *vs.* λ plane. Large distances are probed with torsion pendulums, while novel high-frequency techniques allow to explore short distances. Small deviations can only be excluded at large distances, whereas the increasing effects of the background from electrostatic, magnetic and Casimir forces limit short-distance studies to large deviations.

In the presence of δ extra dimensions, corresponding to a new scale of gravity M_D[1], $V(r)$ can be written as [5, 6]:

$$V(r) = -\frac{1}{8\pi M_D^{\delta+2}} \frac{1}{R_C^\delta} \frac{m_1 m_2}{r},$$

where R_C is the compactification radius. Compactification is the process which makes the volume of the extra dimensions finite, what is necessary in these theories. The resulting volume is of the order of R_C^δ, where R_C can be thought of as the size at which the extra dimensions would manifest in experiments probing decreasing distances. For $M_D = 1\,\text{TeV}$ and $\delta = 2$, the experimental limits translate into $R_C < 190\,\mu\text{m}$.

Direct tests of gravity cannot constrain scenarios with more than two extra dimensions. This fact, coupled to the large unexplored space in the α *vs.* λ plane, makes the idea of large extra dimensions, as small as a fraction of a millimetre, extremely interesting. A new strategy to detect their effects is needed, calling for novel analyses of data from the world's most powerful colliders.

3 The ADD scenario

The so called ADD scenario[2] [5,6,9] was the first to be studied in high energy physics experiments. It predicts a large volume of the δ-dimensional space, V_δ, relating the new scale of gravity, M_D, to m_{Pl} by means of the Gauss law:

$$m_{Pl}^2 = V_\delta M_D^{\delta+2}.$$

If compactification occurs on a torus, $V_\delta = (2\pi R_C)^\delta$. For $\delta = 2$ and $R_C = 1\,\text{mm}$, a scale $M_D = 1\,\text{TeV}$ is found, which is comparable to m_{ew} and implies that the fields propagating in the extra dimensions would have effects at the TeV scale. In other words, a new spin-two particle, the graviton, G, whose mass is not fixed but is rather a parameter on which to integrate, would be produced and exchanged at high energy colliders. Scales of the order of a TeV are probed through searches for direct production of gravitons or effects of their exchange at LEP, at the TEVATRON and at HERA, as discussed below.

3.1 Direct searches

Gravitons can be produced in e^+e^- and $p\bar{p}$ interactions in association to photons or jets, through the processes:

– $e^+e^- \to \gamma G$;
– $q\bar{q} \to \gamma G$;
– $q\bar{q} \to gG$, $qg \to qG$ and $gg \to gG$.

Their differential cross Sect. depend on the new scale of gravity, M_D [10]. Gravitons are expected not to interact in the detectors[3] and these processes correspond to three signatures:

– a photon and missing energy at LEP;
– a photon and missing transverse energy at the TEVATRON;
– a jet and missing transverse energy at the TEVATRON.

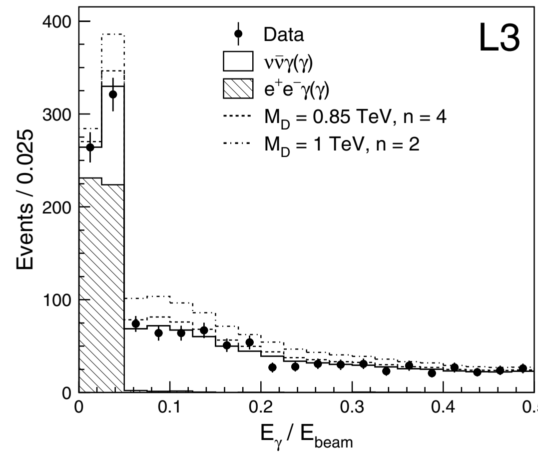

Fig. 2. Energy of the photon, normalised to the beam energy, for events with a single photon and missing energy selected by the L3 collaboration at LEP [12]. Data agree with the Monte Carlo predictions from neutrino pair-production and low-angle radiative Bhabha scattering. The dashed histograms indicate the expected deviations in presence of extra dimensions

All experiments at LEP have thoroughly investigated final states with photons and missing energy [11,12]. Fig. 2 shows the photon energy spectrum for events selected by the L3 collaboration. No deviations from the Standard Model expectations are observed and the most stringent lower limits[4] on M_D for a number of extra dimensions from two to five are derived. They vary from 1.5 TeV to 0.75 TeV, respectively, and correspond to upper limits on R_C from 200 μm to 400 fm.

Both the CDF [13,14] and the D0 [15] collaborations have searched for final states with a photon and missing transverse energy, without finding any evidence for manifestations of extra dimensions. Lower limits between 0.6 TeV and 0.7 TeV are derived for six or more extra dimensions, corresponding to a compactification radius lower than 3 fm.

The CDF collaboration has also searched for events with one or two jets and large missing transverse energy [16].

The distribution of the missing transverse energy for the selected events, shown in Fig. 3, is well in agreement

[1] In the years 1998 and 1999, many models implying extra dimensions appeared, often at the same time, leading to an inflation of notations for the new scale of gravity: M_S, M_D, M_H, M_F, Λ_T, Λ_π. To same extent, they are all of the same order of magnitude, and the current experimental effort is aimed to probe whether any effect appears around a TeV.

[2] From the names of the authors of [5], N. Arkani-Hamed, S. Dimopulous and G. Dvali.

[3] Popularly, they "escape in the extra dimensions".

[4] All limits are hereafter quoted at the 95% confidence level.

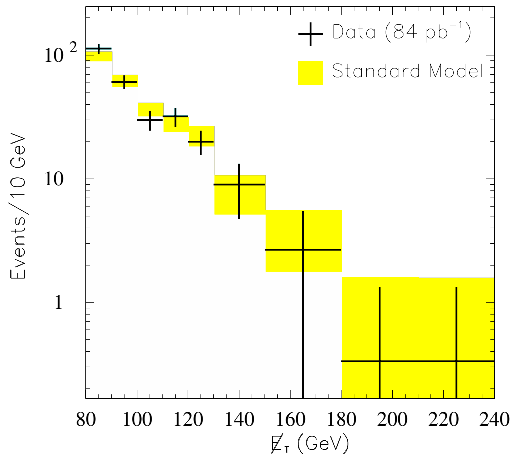

Fig. 3. Distribution of the missing transverse energy for events selected by the CDF collaboration at the Tevatron. The Standard Model predictions are also plotted as the yellow bands

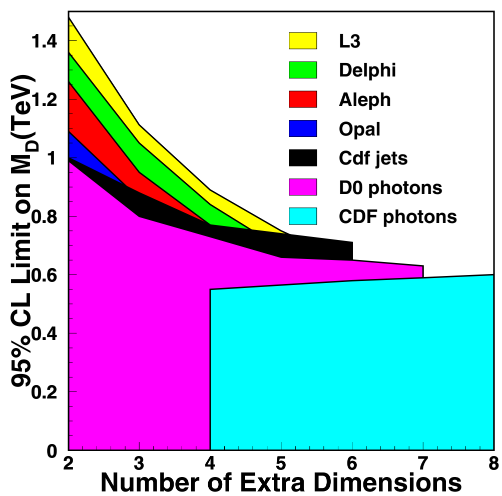

Fig. 4. Summary of the 95% confidence level lower limits on the new scale of gravity, M_D, as a function of the number of extra dimensions. For small numbers of extra dimensions, the most stringent limits are derived from final states with photons and missing energy at LEP. For large numbers of extra dimensions, they come from studies of events with either jets or photons and missing transverse energy at the TEVATRON

with the Standard Model predictions. From these searches, lower limits around a scale of 0.7 TeV, or upper limits on the compactification radius around 40 fm, are derived for six extra dimensions, as presented in Fig. 4, which compares all experimental limits on M_D as a function of the number of extra dimensions.

3.2 Indirect searches

The exchange of spin-two gravitons would affect many Standard Model processes [10,17,18,19], whose measured differential cross Sect., $\mathrm{d}\sigma(s,t)/\mathrm{d}\Omega$, would deviate from the Standard Model predictions, $\mathrm{d}\sigma^{SM}/\mathrm{d}\Omega$, giving access to the new scale of gravity, M_S. Deviations are either due

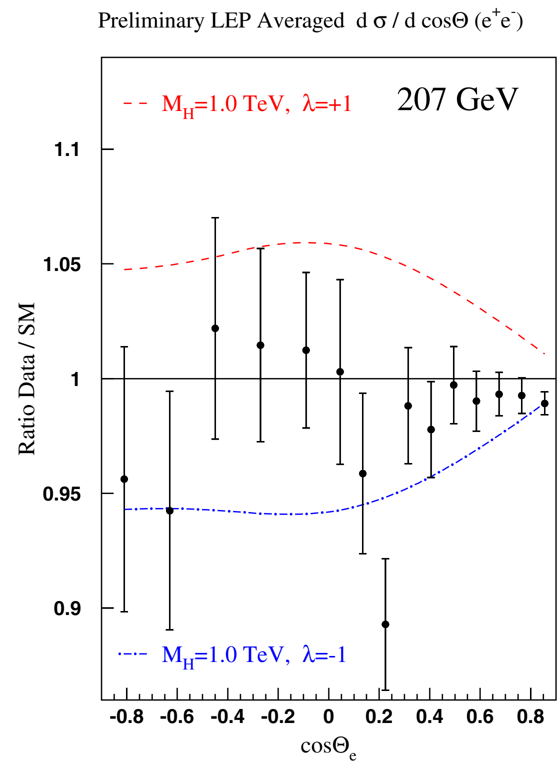

Fig. 5. Ratio of the differential cross Sect. for the process $e^+e^- \to e^+e^-$ measured at LEP at $\sqrt{s} = 207\,\mathrm{GeV}$ to the Standard Model expectations as a function of the electron scattering angle. Data of the four experiments are combined [21]. The deviations expected in presence of extra dimensions are also indicated by the dashed and dashed-dotted lines

to a direct term proportional to $1/M_S^8$, too small to be detected, or to an interference term proportional to $1/M_S^4$:

$$\frac{\mathrm{d}\sigma(s,t)}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma^{SM}}{\mathrm{d}\Omega} + \frac{\lambda}{M_S^4}\alpha_{interference}(s,t) + \frac{\lambda^2}{M_S^8}\beta_{direct}(s,t).$$

A factor λ groups all parameters of the unknown full theory behind extra dimensions. It is usually chosen to be ± 1 to account for the two possible signs of the interference. Searches for such deviations, performed at LEP, at the TEVATRON and at HERA, are discussed below.

Deviations were searched for in pair-production of fermions and gauge bosons at LEP: $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, $\gamma\gamma$, ZZ, W^+W^- [11,20,21]. The $e^+e^- \to e^+e^-$ scattering is the most sensitive process, due to its large cross Sect. and the different behaviour of its differential cross Sect. as a function of the electron scattering angle for the dominant Standard Model t-channel and the possible contribution from spin-two graviton exchange. As an example, Fig. 5 presents the expected deviations for the differential cross Sect. at $\sqrt{s} = 207\,\mathrm{GeV}$, compared with combined data from the four experiments. No evidence for a signal is found in a total of $2.5\,\mathrm{fb}^{-1}$ of data collected by the four experiments at $\sqrt{s} = 130 - 209\,\mathrm{GeV}$. Lower limits[5] are set on M_S as 1.2 TeV or 1.1 TeV for a positive or

[5] Throughout this Sect., results for M_S are expressed in the convention of [17], in which they do not depend on the num-

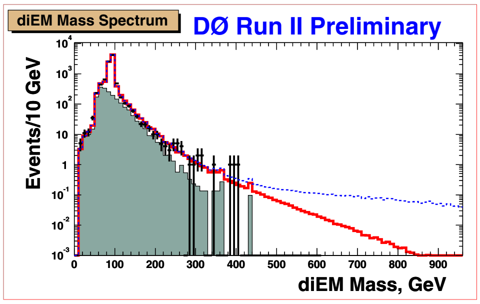

Fig. 6. Mass distribution for pairs of electromagnetic objects collected by the D0 experiment at the TEVATRON Run II [23]. Standard Model expectations, dominated by the $Z \to e^+e^-$ signal are shown as the open histogram and instrumental background as the the full histogram. The dashed line indicates the deviations expected in the presence of extra dimensions

negative interference between Standard Model diagrams and graviton exchange, respectively [21].

At the TEVATRON, effects of extra dimension are searched for by analysing the mass spectrum and the angular distribution of electron and muon pairs as well as di-photons. In the Standard Model, lepton-pair production arises from Drell-Yan s-channel processes, while di-photon events are either produced by the t-channel $q\bar{q} \to \gamma\gamma$ process or the one-loop $gg \to \gamma\gamma$ process. The presence of extra dimensions would lead to the additional s-channel processes $q\bar{q} \to \ell^+\ell^-, \gamma\gamma$ and $gg \to \ell^+\ell^-, \gamma\gamma$ mediated by a graviton, with no particular resonance structure.

The largest experimental sensitivity is achieved by the simultaneous analysis of the electron-pair and di-photon channels performed by the D0 collaboration at Run I [22] and Run II [23]. Fig. 6 shows the mass spectrum of the electrons and photons for the Run II data. The data agree with the predictions from Drell-Yan electron-pair production, direct di-photon production and the additional instrumental background. A harder spectrum is expected in presence of a signal. Lower limits around 1.1 TeV are derived. The combination of the Run I and Run II samples, and the increasing Run II integrated luminosity, make this channel the most sensitive and promising probe for studies of virtual graviton effects in the ADD scenario.

In presence of extra dimensions, the cross Sect. for neutral-current scattering in e^+p and e^-p collisions, measured at HERA, would exhibit deviations due to the additional graviton-mediated t-channel diagrams for the $eq \to eq$ process. Moreover, graviton exchange also makes the t-channel $eg \to eg$ process accessible. Both the H1 [24] and ZEUS [25] collaborations investigated their neutral-current data and did not find any deviation, deriving lower limits on M_S around 0.7 TeV.

Figure 7, summarises the lower limits on M_S obtained by experiments at LEP [11,21], at the TEVATRON [22, 23,26] and at HERA [24,25]. In a formalism in which they are related to the number δ of extra dimensions [19], they

ber of extra dimensions, δ. Other conventions exist [10,19], some [19] with an explicit dependence on δ.

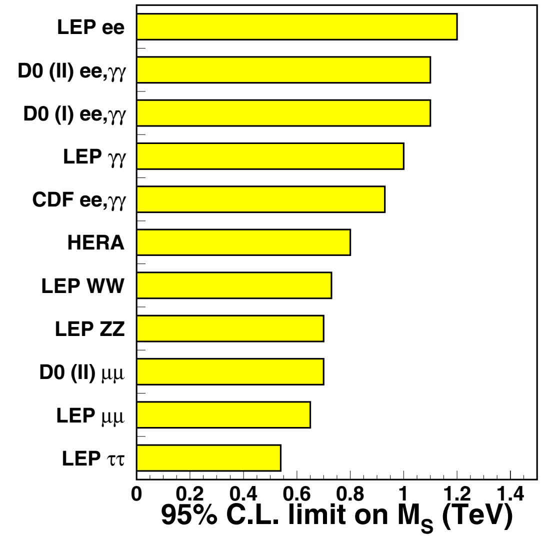

Fig. 7. Summary of the 95% confidence level lower limits on the scale M_S derived from searches for virtual effects at LEP, at the TEVATRON and at HERA

correspond to upper limits on the compactification radius from a fraction of a mm ($\delta = 2$) to about a fm ($\delta = 7$).

4 The RS scenario

In the RS scenario [6] [7] only one extra dimension is present between two three-dimensional branes. The fundamental scale is m_{Pl} on the first brane and then evolves, as a function of the distance y between the two branes, down to a scale Λ_π which can be of the order of a TeV on the second brane, where Standard Model fields are located. A metric is introduced as $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dy^\nu - dy^2$. The parameter k and the distance πR_C along the y axis of the brane with the Standard Model fields, fix the scale $\Lambda_\pi = m_{Pl}/\sqrt{8\pi}e^{-\pi k R_C}$. In this way, the hierarchy observed in nature is naturally described. The masses of the gravitons, which also appear in the RS scenario, are fixed by k and πR_C. Opposed to the ADD scenario, where RS gravitons correspond to a large set of modes, these gravitons would manifest themselves at hadron colliders as resonances, with spectacular and clean decays in lepton- or quark-pairs [27].

The CDF collaboration has searched for anomalous resonances in the di-jet [28] and lepton-pair [23] mass spectra. Both spectra are found to be in good agreement with the Standard Model expectations from QCD and Drell-Yan processes, respectively. Upper limits on the quantity k/m_{Pl} are extracted, which are as low as 0.2 for di-jet events and 0.05 for lepton-pair events, for the probed masses of gravitons between 300 and 600 GeV. These limits are particularly interesting since values of k/m_{Pl} not too much below unity would be natural.

[6] From the names of the authors of [7], L. Randall and R. Sundrum.

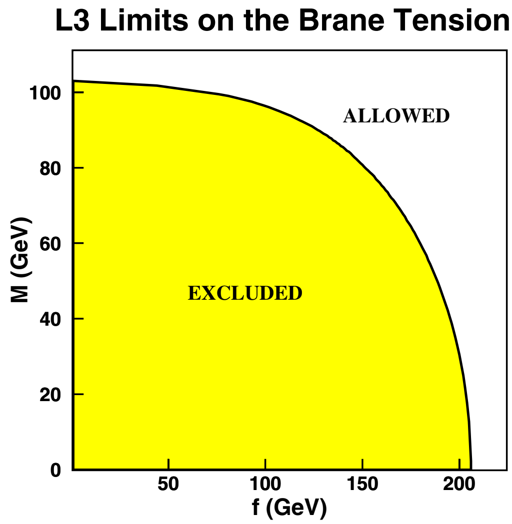

Fig. 8. Region excluded at 95% confidence level by the L3 collaboration using events with photons and missing energy in the plane of the branon mass *vs.* the brane tension f. All the accessible phase space is excluded

5 TeV-scale strings

Recent models [6,29] have suggested that realising extra dimension scenarios in a string theory of quantum gravity will modify physics at the TeV scale. TeV-scale strings would contribute to the amplitudes of several processes, such as Bhabha scattering at LEP. The L3 collaboration has looked for deviations in the differential cross Sect. of Bhabha scattering [11] and found no evidence for effects from TeV scale strings, up to a scale of 0.55 TeV.

6 Branons

Brane-world models locate the Standard Model particles on a single brane. In presence of extra dimensions, additional degrees of freedom appear which are connected with fluctuations of this brane in the extra dimensions and which would manifest as new particles, called branons [30]. The properties of branons depend on the tension of the brane, f. If extra dimensions are realised at a scale $M_D \ll f$, effects from branons are negligible. If, on the other hand, the scale M_D is large, $M_D \gg f$, effects from the gravitons predicted, for instance, in the ADD scenario will be too small to be observed and branons will represent the first sign of extra dimensions, and the only one experimentally accessible.

In e^+e^- collisions, branons would be pair-produced in association with a photon, giving rise to events with a photon and missing energy. The L3 collaboration has interpreted its high precision single-photon data sample to look for signatures of branon production, finding no significant excess [12]. This allows to exclude all the parameter space accessible at LEP, from low values of f and branon masses close to the beam energy, to light branons for $f \approx \sqrt{s}$, as shown in Fig. 8.

7 Conclusions and outlook

In the last five years, the experimental community reacted vigorously and timely to new theoretical ideas relating gravity and high energy physics through extra dimensions. Extensive searches were performed at all the operating high energy machines. To date, no sign of effects of extra dimensions at scales around a TeV was found. In the next few years, the increasing luminosity at the TEVATRON, and the start of the LHC might herald a revolution in the way we think about space.

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