Low Scale Gravity and Extra Dimensions at HERA, LEP and Tevatron

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Searches for Low Scale Gravity and Extra Dimensions at HERA, LEP and the Tevatron are reviewed.

In spite of his many successes, the Standard Model (SM) is plagued by some intriguing characteristics, like the hierarchy problem, i.e. the smallness of the ratio of the electroweak scale to the Planck scale (M_{Pl}). The conjecture [1] that the existence of n extra spatial dimensions (ED) could remove this problem is a new approach which can be tested experimentally at high energy accelerators. In this hypothesis, the SM particles are confined to our usual 3+1 dimensional space, while quantum gravity permeates the whole space.

The mass scale (M_S) for which cross section calculations are available [2–5] is expected to be comparable to the Planck mass(M_D) in $D = 4+n$ dimensions, which is related to M_{Pl} by $M_{Pl}^2 = M_D^{n+2}\ R^n$, R being the compactification radius of the extra dimensions, each of them supposed to be a torus. For $M_D = 1$ TeV, this translates in values of $R = 8 \times 10^{12}$ m, 0.7 mm, 3 nm, 6×10^{-12} m, for n respectively equal to 1,2,3,4, i.e. only the case of one single extra dimension is clearly ruled out experimentally, by the non-observation of deviations from Newton's law on large distances. Recent Cavendish-type experiments exclude $R > 0.19$ mm, which translates as $M_S > 1.9$ TeV for $n = 2$.

In collider experiments, extra dimensions can be searched for in two different ways: either in an "indirect" way via interference effects of SM processes with graviton (G) exchange interactions which modify the production cross-sections, or by direct G production, which appears experimentally as missing energy in the detector. The interference effects have been searched for at HERA, LEP and the Tevatron, while direct production has been investigated only at LEP in the γG and ZG production channels and at the Tevatron in the γG and gluon(g)G production channels.

1. Indirect ED Searches at HERA

At HERA, the H1 and ZEUS experiments have searched for ED using the complete statistics taken until 1999, corresponding to 16 (112) pb^{-1} in e^-p (e^+p) scattering. The interference of the G exchange with the SM γ and Z processes leads to an effective contact type interaction with a coupling $\eta_G = \lambda/M_S^4$, where the parameter λ depends on the details of the theory and is expected to be of order unity. However, by convention, negative couplings are also allowed and limits are derived assuming $\lambda = \pm 1$. The interference term behaves oppositely for electrons and positron scattering, as illustrated in fig. 1, which shows the ZEUS results [6], excluding $M_S <$ 0.82(0.81) TeV for $\lambda = +(-)1$. Similarly, the H1 experiment excludes $M_S < 0.83(0.79)$ TeV [7]

2. Indirect ED Searches at LEP

At LEP, the 4 collaborations ALEPH, DELPHI, L3 and OPAL have searched for virtual graviton effects in difermion and diboson production, the most sensitive channels being $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$. The expected cross section in presence of ED in the $\gamma\gamma$ channel is given by $(\frac{d\sigma}{d\cos\theta})^{SM+ED} = (\frac{d\sigma}{d\cos\theta})^{SM} - \alpha s \frac{\lambda}{M_S^4}(1+cos^2\theta) + \frac{s}{8\pi}\frac{\lambda}{M_S^8}(1-cos^4\theta)$, where s is the center of mass energy and θ the photon scattering angle. A similar formula exists for the e^+e^- final state, but with more complicated coefficients due to the presence of s and t channel in this latter case. The $e^+e^- \to e^+e^-$ cross section at differ-

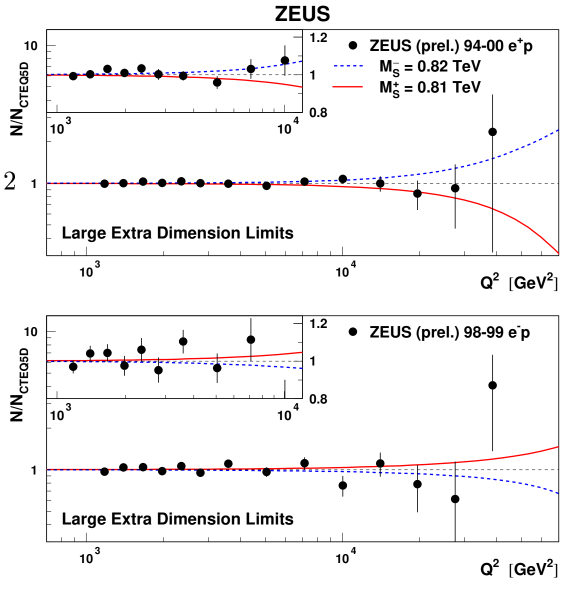


Figure 1. Comparison of Data/Theory for e^+p and e^-p cross-section as a function of the transfer momentum squared Q^2. Also shown are the SM prediction and the deviations expected from ED with mass scales for $\lambda = \pm 1$ of 0.81 and 0.82 TeV.

ent center of mass energies, from which the limits can be derived is shown as an example in fig. 2, as obtained by L3.The limits obtained by the 4 LEP experiments are given in table 2 [8–11].

Collab.	$e^+e^-(\lambda = +1/{-1})$	$\gamma\gamma$ $(\lambda = +1/{-1})$
ALEPH	0.81 / 1.04 TeV	0.80 / 0.85 TeV
DELPHI	–	0.77 / 0.70 TeV
L3	1.04 / 1.05 TeV	0.84 / 0.99 TeV
OPAL	1.00 / 1.15 TeV	0.81 / 0.96 TeV

Table 1
Limits on M_S obtained from virtual graviton effects at LEP in $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$.

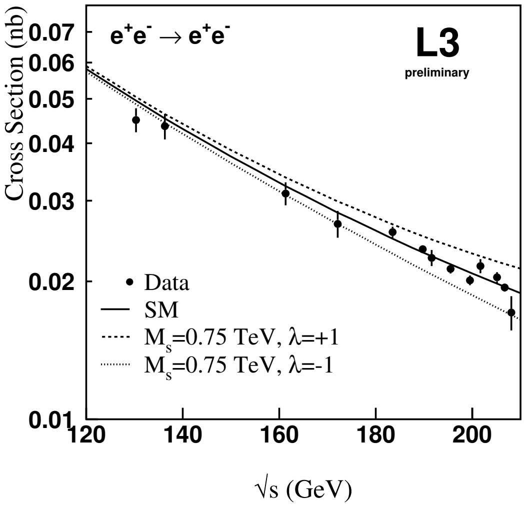
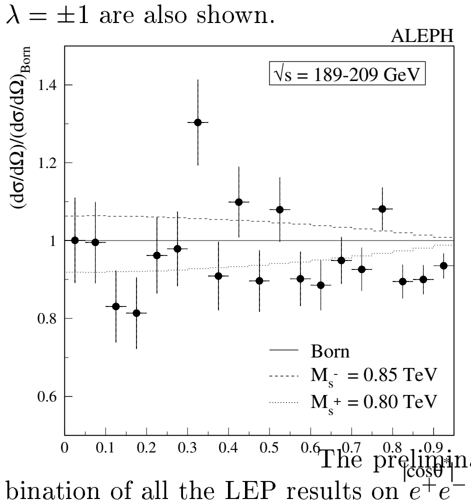


Figure 2. $e^+e^- \to e^+e^-$ cross-section measured at different center of mass energies by the L3 experiment. The SM prediction and the expected deviations due to ED with $M_S = 0.75$ TeV and $\lambda = \pm 1$ are also shown.



The preliminary combination of all the LEP results on $e^+e^- \to e^+e^-$ differential cross-section is shown in fig. **??**, excluding $M_S > 1.20(1.09)$ TeV for $\lambda = +1$ (−1) [12].

3. Indirect ED Searches at the Tevatron

At hadronic colliders the virtual effects of the graviton in dilepton production in the s channel

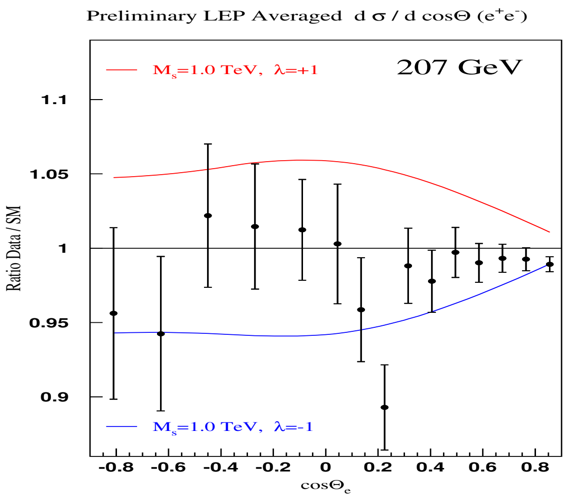


Figure 3. Ratio Data/SM of the averaged LEP results in $\frac{d\sigma(e^+e^-)}{d\cos\theta}$.The expected deviations due to ED with $M_S = 1$ TeV and $\lambda = \pm 1$ are also shown.

can come not only from $q\bar{q}$ annihilation but also from gluon fusion. For diphoton production there is interference between the t channel SM production and the s channel production mediated by a graviton. Here also the dielectron cross section can be written as a sum of 3 terms: the SM contribution, the interference term weighted by $\eta \equiv F/M_S^4$, and the Kaluza-Klein term weighted by η^2. Throughout this paper, we take the definition $F = \frac{2\lambda}{\pi}$ [3], except when we derive the limits as a function of the number n of extra dimensions, in which case we have $F \equiv \log(M_S^2/s)$ for n=2 and $F \equiv \frac{2}{n-2}$ for $n > 2$ [4].

The DØ experiment performs the search by combining the dielectron and diphoton final states and looking for deviations in the distributions of the polar angle of these electromagnetic objects in the helicity frame and in their invariant mass. The good agreement with the SM in the 1992-1996 data sample (corresponding to $\sim$ 120 pb^{-1}), allows to place limits at $M_S > 1.1(1.0)$ TeV for $\lambda = 1(-1)$, i.e. $M_S > 1$ TeV for n between 2 and 6.

The CDF collaboration has made an exclusive search on a similar statistics, separating the dielectron and diphoton candidates, and fitting the corresponding invariant mass distributions, as shown in fig. 3 for the diphoton sample. The limits obtained are $M_S > 0.80, 0.81(0.90, 0.83)$ TeV from the diphoton,dielectron samples and $\lambda = 1(-1)$, giving a combined limit of 0.85 (0.94) TeV. On the first data taken this year after the a 5 years long upgrade of the machine and the detectors, DØ has repeated its search, based on a smaller statistics ($\sim$ 9 pb^{-1}) but at a larger center of mass energy (2 TeV vs 1.8 before). No signal has been found and the preliminary limit has been set at 0.82 TeV. This result, based on a few months of data taking shows the potential of the Run II which is expected to accumulate a statistics larger by 2 orders of magnitude compared to Run I over the next 6 years.

Figure 4. Comparison of Data and SM expectation for the diphoton invariant mass spectrum as obtained by CDF on 110 pb^{-1} of Tevatron Run I data. The SM-ED interference and the direct ED effects are also shown for $M_S = 0.9$ TeV.

4. Direct Searches of ED at LEP

If a graviton is emitted in an e^+e^- collision, it can propagates in the 4+n dimensions, and the energy momentum will not be conserved in our usual space. The direct searches look for missing energy, which can be interpreted in terms of a missing mass due to an escaping particle. At LEP the most favourable process is $e^+e^- \to \gamma G$. The differential cross-section for this process depends on both the gravity scale M_D and the number n of ED and is given in ref. [2].

In presence of ED, the distributions of the missing mass and polar angle θ, would be enhanced at high missing mass and large $\cos\theta$. As shown for instance from ALEPH in fig. 4 this has not been observed allowing to set limits up to $M_S = 1.36$ for $n = 2$ in the HLZ formalism [4]. The results of the 4 LEP experiments are summarized in table 4, and the variation of these limits as a function of n are shown for DELPHI in fig. 5.

Figure 5. Distributions from the $\gamma + E_T^{miss}$ ALEPH sample :a) invariant mass of the system recoiling against the photon candidate; b) γ polar angle. The effects of ED would be visible at large missing mas and polar angle.

5. Direct Search for ED at the Tevatron

At the Tevatron another channel can be searched for: the production of gluon-graviton, leading to a monojet + missing transverse (E_T^{miss}) energy topology. DØ has performed such a search on 80 pb^{-1} of Run I data, asking

Figure 6. Cross section limits for $e^+e^- \to \gamma G$ production at $\sqrt{s}$ = 208 GeV as obtained by DELPHI, compared to the expected ED cross section for $n = 2, 4, 6$ as a function of M_D.

Collab.	$n = 2$	$n = 4$	$n = 6$
ALEPH	1.26 TeV	0.77 TeV	0.57 TeV
DELPHI	1.36 TeV	0.84 TeV	0.59 TeV
L3	1.02 TeV	0.67 TeV	0.51 TeV
OPAL	1.09 TeV	0.71 TeV	0.53 TeV

Table 2
Limits on M_S obtained from direct graviton production at LEP in the $e^+e^- \to \gamma G$ process.

for large missing and leading jet transverse energies ($> 150 GeV$). The measured distribution of (E_T^{miss}) and the expected effect of ED with M_D= 1 TeV are shown in fig. 6. The data/SM agreement allows to derive limits displayed in fig. 7, and compared to the LEP limits, showing that this channel is more sensitive when the number of ED is large (≥ 5).

Figure 7. Distribution of E_T^{miss} as obtained by DØ in 1992-1996 Data, compared to SM expectations and SM+ED expectations for $n = 2$ and $M_D = 800$ GeV.

A search in the γG channel has been performed by CDF on 87 pb^{-1} of Run I data, asking for large missing and photon transverse energies ($>$ 45 GeV). After all cuts the 11 observed events are compatible with the expected SM background (11$\pm$2), leading to a limit on M_D of 0.55,0.58,0.60 TeV for $n = 4, 6, 8$, as shown in fig. 7.

Figure 8. 95 % C.L. limits in the γG (LEP,CDF) and gG (DØ) processes as a function of M_D and n. The DØ limit is shown with and without the application of a K factor of 1.3 to the expected gG cross-section.

6. Prospects

At present the limits obtained at the 3 highest energy colliders are comparable, of the order of 1 TeV, and the searches have been made in a large variety of channels reinforcing the confidence in this limit. In future, while waiting for the start of the LHC, this domain will mostly be explored at the Tevatron, with a sensitivity up to about 2 (3) TeV with the full luminosity of the Run II a(b). Eventually with the advent of the LHC and an hypothetical linear collider this domain will be explored up to about 8 TeV, allowing to draw definite conclusions on the possibilities that ED can solve the hierarchy problem.

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