Seeking TeV-Scale Quantum Gravity at an $e\gamma$ collider

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ABSTRACT

Theories with large extra compact dimensions predict exciting phenomenological consequences at the TeV scale. Such theories can, consequently, be tested/verified in experiments at future colliders like the Next Linear Collider (NLC). In this paper, we study the production of the spin-2 Kaluza-Klein excitations in NLC operating in the $e\gamma$ mode. Results for unpolarised and polarised cases are presented and it is shown that it is possible to use this process to test these theories to values of the effective string scale between about 1 - 7 TeV.

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In theories with large compact extra dimensions \cite{1, 2, 3}, which have attracted much interest recently, the effects of gravity could become large at very low scales (\(\sim \) TeV) and is of tremendous interest to phenomenology. In these theories, \(n\) of the dimensions of a higher dimensional string theory are compactified to a common scale \(R\) which is large. It is possible to have \(R\) to be large because, in these theories, only the gravitons (corresponding to closed strings) propagate in the \((4 + n)\)-dimensional bulk while the gauge particles (corresponding to open strings) live on a 3-brane and do not see the effects of the large extra dimensions. The size of these extra dimensions are then restricted only by gravitation experiments the constraints from which are relatively weak \cite{4} and allow the extra dimension to be as large as 1 mm. The low-energy scale \(M_S\) is related to the Planck scale by \cite{1}

\[
M_P^2 = M_S^{n+2} R^n ,
\]

It then follows that \(R = 10^{32/n-19} \) m, and so we find that \(M_S\) can be arranged to be a TeV for any value \(n > 1\). It is at this low scale of 1 TeV that we will now expect to see the effects of quantum gravity – for example, for \(n = 2\) the compactified dimensions are of the order of 1 mm, just below the experimentally tested region for the validity of classical gravity and within the possible reach of ongoing experiments. This very novel idea has far-reaching consequences: it is a possible solution to the hierarchy problem (though the latter manifests itself in a new garb). But, more interestingly, it is possible to make a viable scenario \cite{5} which can survive the existing astrophysical and cosmological constraints and predict other interesting consequences like low-energy unification \cite{6}. For some early papers on large Kaluza-Klein dimensions, see Ref. \cite{8, 9} and for recent investigations on different aspects of the TeV scale quantum gravity scenario and related ideas, see Ref. \cite{10}.

The low-energy effective theory that emerges below the scale \(M_S\) \cite{11, 12, 13}, has an infinite tower of massive Kaluza-Klein states, which contain spin-2, spin-1 and spin-0 excitations. For low-energy phenomenology the most important of these are the spin-2 Kaluza-Klein states i.e. the infinite tower of massive graviton states. The couplings of the gravitons, \(G_{\mu\nu}\), to the Standard Model (SM) fields are derivable from the following Lagrangian \cite{12, 13}:

\[
\mathcal{L} = -\frac{1}{M_P} G^{(j)}_{\mu\nu} T^{\mu\nu} ,
\]

where \(j\) labels the Kaluza-Klein mode, \(M_P = M_P/\sqrt{8\pi}\) and \(T^{\mu\nu}\) is the energy-momentum tensor. Due to the sum over the tower of graviton states, the Planck-scale suppression due to the \(1/M_P\) factor in the coupling is effectively replaced by a TeV-scale (\(\sim M_S\)) suppression. Consequently, these couplings can lead to observable effects at present and future colliders. There have been several studies exploring these consequences. Missing energy or monojet + missing energy signatures \cite{14, 15} of real graviton production at \(e^+e^-\) or hadron colliders have been studied which have yielded bounds on \(M_S\) which are around 500 GeV to 1.2 TeV at LEP2 \cite{14, 15} and around 600 GeV to 750
GeV at Tevatron (for \( n \) between 2 and 6) \([14]\). These studies have been extended to the Large Hadron Collider (LHC) and to high-energy \( e^+e^- \) collisions at the Next Linear Collider (NLC). Other studies have concentrated on the effects of virtual graviton exchange on experimental observables. Virtual effects in dilepton production at Tevatron yields a bound of around 950 GeV \([16]\) to 1100 GeV \([17]\) on \( M_S \), in \( t\bar{t} \) production at Tevatron a bound of about 650 GeV is obtained while at the LHC this process can be used to explore a range of \( M_S \) values upto 4 TeV \([18]\). Virtual effects in deep-inelastic scattering at HERA put a bound of 550 GeV on \( M_S \) \([19]\), while from jet production at the Tevatron strong bounds of about 1.2 TeV are obtained \([20]\). More recently, fermion pair production and gauge boson production in \( e^+e^- \) collisions at LEP2 and NLC and in \( \gamma\gamma \) collisions at the NLC \([21 - 26]\) have been studied. Effect of graviton mediation Compton scattering at \( e\gamma \) collider is considered in \([27]\). Associated production of gravitons with gauge bosons and virtual effects in gauge boson pair production at hadron colliders have also been studied \([28]\). Diphoton signals and global lepton-quark neutral current constraints have also been studied \([29]\). There have also been papers discussing the implications of the large dimensions for higgs production \([30, 31]\) and electroweak precision observables \([32]\). Astrophysical constraints, like bounds from energy loss for supernovae cores, have also been discussed \([33]\).

The Next Linear Collider (NLC) is an ideal testing ground of the SM and a very effective probe of possible physics that may lie beyond the SM. The collider is planned to be operated in the \( e^+e^- \), \( \gamma\gamma \) and the \( e\gamma \) modes. The photons are produced in the Compton back-scattering of a highly monochromatic low-energy laser beam off a high energy electron beam \([34]\). Control over the \( e^- \) and laser beam parameters allow for control over the parameters of the \( \gamma\gamma \) and \( e\gamma \) collisions. The physics potential of the NLC is manifold and the collider is expected to span several steps of \( e^+e^- \) energy between 500 GeV and 1.5 TeV. The experiments at the NLC also provide a great degree of precision because of the relatively clean initial state, and indeed the degree of precision can be enhanced by using polarised initial beams.

In the present paper, the effects of large extra dimensions are probed by looking for the production of the tower of spin-2 Kaluza Klein excitations in \( e\gamma \) collisions at the NLC. The basic process that we are considering is analogous to Compton scattering, except that the gauge boson in the final state is replaced by the graviton i.e. we have \( e\gamma \rightarrow eG^m \), where \( G^m \) denotes a particular spin-2 state in the tower of excitations. The \( e\gamma \) scattering can be thought of as a subprocess of the primary scattering of the \( e^- \) and the \( e^+ \), with the \( \gamma \) being produced from the \( e^- \) (or \( e^+ \))-laser back scattering. The energy of the back-scattered photon, \( E_\gamma \), follows a distribution characteristic of the Compton scattering process and can be written in terms of the dimensionless ratio \( x = E_\gamma/E_e \).

\[
\text{It turns out that the maximum value of } x \text{ is about } 0.82^1 \text{ so that provides the upper limit on the energy accessible in the } e\gamma \text{ sub-process. We assume that the primary}
\]

\[\text{pairs, which in turn reduces luminosity.}\]
$e^+e^-$ scattering process can be factorised into a part that describes the $e\gamma$ subprocess scattering and a luminosity function, $f_\gamma(x)$, where the latter provides information on the photon flux produced in Compton scattering of the electron and laser beams \[35\].

We calculate the cross-section for the process $e\gamma \rightarrow eG^m$, where $G^m$ is a definite spin-2 state of mass $m$. In order to obtain the cross-section for the entire range of accessible states we will have to sum this cross-section over these states. For small enough mass-splittings, this sum can be replaced by an integral over the mass parameter $m$. The resulting inclusive graviton production cross-section can be written in terms of the cross-section for the process $e\gamma \rightarrow eG^m$ as follows:

$$\frac{d^2\hat{\sigma}}{dm\,dt} = S_{n-1}\frac{m^{n-1}}{M_{2+n}^{2-n}}\frac{d\hat{\sigma}^m}{dt},$$

where $n$ is number of extra dimensions, and for $n = 2k$ where $k$ is an integer, $S_{n-1} = 2\pi^k/(k-1)!$ and for $n = 2k+1$, $S_{n-1} = 2\pi^k/\Pi_{j=0}^{k-1}(j + \frac{1}{2})$, $d\hat{\sigma}^m/dt$ is the differential cross-section for producing a single graviton state of mass $m$ and is given by

$$\frac{d\hat{\sigma}^m}{dt} = \frac{1}{16\pi s^2} \left[ \frac{1}{2}(1+P_e\xi_2)|\mathcal{M}(++)|^2 + \frac{1}{2}(1-P_e\xi_2)|\mathcal{M}(+-)|^2 \right],$$

where $P_e$ is the rate of polarisation of the $e$ and $\xi_2$ is the Stokes parameter which defines the polarisation state of the photon and is fixed in terms of the polarisations of the initial electron and laser beam. The helicity amplitudes are given by

$$|\mathcal{M}(++)|^2 = \frac{2\pi\alpha}{M_P^2stu} \frac{1}{(m^2-s)^2(4su-m^2t)}$$

$$|\mathcal{M}(+-)|^2 = \frac{2\pi\alpha}{M_P^2stu} (s+t)^2(4su-m^2t).$$

From Eqns. 3, 4, 5, one sees explicitly that the factor $M_P^2$ from the phase space summation compensates for the $M_P$ dependence of the cross-section. One can then use the inclusive cross-section in Eq. 3 to write down the differential cross-section in transverse momentum $p_T$ and rapidity $y$ of the final-state electron as a convolution over the photon luminosity function:

$$\frac{d^2\sigma}{dp_T^2\,dy} = \int dx f(x) \frac{s}{2m} \left( \frac{d^2\hat{\sigma}}{dm\,dt} \right) \delta(s + t + u - m^2) \, dm.$$

If the graviton is produced in the $e\gamma$ collision it will escape detection giving rise to a missing energy signature with an isolated electron in the final state. The SM background to this signal comes from $e\gamma \rightarrow eZ$ followed by $Z \rightarrow \nu\bar{\nu}$ and $e\gamma \rightarrow \nu W$ with $W \rightarrow e\nu$. This SM background has been studied extensively in the context of selectron/ neutralino production at $e\gamma$ collider \[36\]. We have analysed the signal and
Table 1: Limit on $M_S$ in the case of unpolarized electron and photon beams for different c.m.f energies ($\sqrt{s}_{ee}$). $n$ is the number of compactified extra dimensions. A geometric luminosity of 100 $fb^{-1}$ is assumed and a $p_T$ cut of 10 GeV and a rapidity cut above 3 are applied.

| $\sqrt{s}_{ee}$ | $M_S$ in GeV |
|-----------------|-------------|
| TeV             | $n = 2$     |
|                 | 3           | 4           | 5           | 6           |
| 0.5             | 2267        | 1648        | 1316        | 1111        | 971         |
| 1.0             | 3192        | 2508        | 2109        | 1847        | 1658        |
| 1.5             | 3907        | 3205        | 2776        | 2479        | 2260        |

the SM background for $e^+e^-$ centre-of-mass energies corresponding to 500, 1000 and 1500 GeV, respectively. For our numerical results, we have assumed an integrated luminosity, $\mathcal{L}$, of 100 $fb^{-1}$.

For our analysis, we have used a cut of 10 GeV on the electron $p_T$. We demand a statistical significance of the signal defined as $\sigma\sqrt{\mathcal{L}}/\sqrt{B}$ to be greater than 5, where $\sigma$ denotes the signal cross-section and $B$ the SM background cross-section. Using this criterion we get the bounds on $M_S$, the results for the unpolarised case are given in Table 1, where the reach in $M_S$ is shown for different values of the centre-of-mass energy and the number of extra dimensions. In the unpolarised case, the biggest problem is due to the $W$ background, which is substantially larger than the signal as well as the $Z$ background. One way of getting rid of the $W$ contamination is to use a right-handed electron. With a right-polarised electron (but with photon still unpolarised) there is a substantial improvement in the reach in $M_S$ – an improvement which is as high as 60% for some values of $\sqrt{s}_{ee}$ and $n$. The corresponding results are tabulated in Table 2.

In Fig. 1, we have plotted the rapidity distribution of the electron for the case of the signal (full line) and the $Z$ background (dashed line). We find that the $Z$ background is peaked in the negative rapidity region, which suggests that it will be expedient to use a positive $y$ cut so as to diminish the effects of the $Z$ background. With a positive $y$ cut, we find again a moderate enhancement in the values of $M_S$ that can be bounded.

Finally, we present the results for the polarised case, where the electron is polarised and the $\gamma$ is also polarised. For the polarised case, we study the signal and the SM background for different choices of the initial electron and laser beams. For a given choice of the $e^-$ and laser polarisation, the photon polarisation is fixed once the $x$ value
is known. The latter polarisation is therefore dependent crucially on the luminosity functions and it is only on the polarisation of the electron and the laser beams that we have a direct handle. The efficacy of polarisation as a discriminator of the new physics is, however, apparent more at the level of the $e\gamma$ sub-process. As we scan over the different choices of initial beam polarisations, we find that for certain choices there is hardly any sensitivity to the new physics. However, large differences are realised for certain other choices. After scanning over the possible values of the photon polarisation, we find that for a particular choice of the initial electron and laser polarisations the best sensitivity results. We present our results for this particular case in Table 3. Again we find that for this choice of polarisation a much stronger bound on $M_S$ results as compared to the unpolarised case.

In conclusion, the physics of large extra dimensions can be tested very effectively at the Next Linear Collider. In particular, in the present paper, we have considered the production of spin-2 Kaluza-Klein excitations in $e\gamma$ collisions. We find that in the unpolarised case $M_S$ values upto a few TeV are probed in this process. The use of polarisation helps to strengthen these bounds quite significantly. We have shown that it is possible to reduce the SM backgrounds by choosing a right-polarised electron or by choosing a suitable rapidity cut. A more detailed study than the one presented here can be used to tighten the kinematical cuts and improve the discriminatory power of this process.

| $\sqrt{s}_{ee}$ | $M_S$ in GeV |
|-----------------|--------------|
| TeV             | $n = 2$      | 3  | 4  | 5  | 6  |
| 0.5             | 2939         | 2028 | 1565 | 1289 | 1105 |
| 1.0             | 4713         | 3425 | 2735 | 2307 | 2015 |
| 1.5             | 6245         | 4665 | 3793 | 3241 | 2858 |

Table 2: Limit on $M_S$ in the case of right-polarized electron beam and unpolarized photon beam. All other parameters are kept the same as in the case of Table 1.
Figure 1: The electron $y$ distribution for $\sqrt{s}_{ee} = 1000$ GeV and for a right-handed initial electron and unpolarized photon. The solid line is the signal due to the graviton production and the dashed line is the SM background from Z production. Signal is for an $M_S$ value of 1 TeV. A $p_T$ cut of 10 GeV is assumed.

| $\sqrt{s}_{ee}$ TeV | $M_S$ in GeV |
|---------------------|--------------|
| $n = 2$ 3 4 5 6     |--------------|
| 0.5 3369 2274 1721 1394 1180 |
| 1.0 5712 4018 3122 2576 2211    |
| 1.5 7769 5587 4406 3674 3177    |

Table 3: Limits on $M_S$ in the case of right-polarized electron beam and photon beam obtained by the Compton back scattering of left-handed electron and left-circularly polarized laser photon. A geometric luminosity of 100 fb$^{-1}$ is assumed and a $p_T$ cut of 10 GeV and rapidity ($y$) cut of 3 are applied.
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