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Large extra dimensions and dijet production in $\gamma\gamma$ collisions

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Abstract: We have studied dijet production in $\gamma\gamma$ collisions with a view to probing the physics of large extra dimensions. The exchange of virtual spin-2 Kaluza-Klein excitations is found to modify the dijet cross-section substantially from its Standard Model value and allows the effective string scale to be probed to values between 2.5 and 6.4 TeV in the unpolarised case. In the case where the photons are polarised, the limits are seen to improve by roughly 20%. Dijet production in $\gamma\gamma$ collisions is thus shown to be a very effective probe of large extra dimensions.

Keywords: Beyond Standard Model, Compactification and String Models.

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There has been tremendous interest recently in the physics of large compact extra dimensions [1, 2, 3] i.e. a number n of the dimensions of a higher dimensional string theory are compactified to a scale R which is very large compared to the Planck scale. The SM particles are confined to a 3-brane and do not see the effects of these dimensions. Only gravitons propagate in the bulk and so the the magnitude of R is constrained only by gravitation experiments. The constraints from the latter experiments are relatively weak [4] and allow the extra dimension to be as large as 1 mm. After compactification, an effective theory of quantum gravity emerges, with the scale of the effective theory M_S being of the order of a TeV. It is at these low energies of the order of 1 TeV that we will now expect to see the effects of quantum gravity. This very novel idea has far-reaching consequences: it is a possible solution to the heirarchy problem (though the latter manifests itself in a new garb). But, more interestingly, it is possible to make a viable scenario [5] which can survive the existing astrophysical and cosmological constraints and predict other interesting consequences like low-energy unification [6, 7]. For some early papers on large Kaluza-Klein dimensions, see ref. [8, 9] and for recent investigations on different aspects of the TeV scale quantum gravity scenario and related ideas, see ref. [10].

The low-energy effective theory that emerges below the scale M_S [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 which couple to the SM particles via the energy-momentum tensor, as usual. These couplings can lead to observable effects at present and future colliders. There have been several studies exploring these consequences. Production of gravitons giving rise to characteristic missing energy or missing p_T signatures at e^+e^- or hadron colliders have been studied resulting in bounds on M_S which are around 500 GeV to 1.2 TeV at LEP2 [14, 15] and around 600 GeV to 750 GeV at Tevatron (for n between 2 and 6) [14]. Production of gravitons at the Large Hadron Collider (LHC) and in high-energy e^+e^- collisions at the Next Linear Collider (NLC) have also been considered. Virtual effects of graviton exchange 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]. Pair production of gauge bosons and fermions in e^+e^- collisions at LEP2 and NLC and in $\gamma\gamma$ collisions at the NLC [21, 22, 23, 24, 25, 26] can probe values of M_S from 0.5 TeV at LEP2 energies to several TeV at NLC. Virtual effects of gravitons [27] and real graviton production [28] in $e\gamma$ collisions have been shown to probe values of M_S as high as 5 or 6 TeV. Other processes studied include associated production of gravitons with gauge bosons and virtual effects in gauge boson pair production at hadron colliders [29, 30, 31]. Higgs production [32, 33] and electroweak precision observables [34] in the light of this new physics have also been discussed. Astrophysical constraints, like bounds from energy loss for supernovae cores, have also been discussed [35].

In the present paper we study the effects of virtual graviton exchange in dijet production in $\gamma\gamma$ collisions at the NLC. The basic process is the Compton scattering of a low-energy laser beam of a well-determined frequency off a high energy electron beam [36], and the parameters of the photon-photon subprocess are fixed by controlling the electron and laser beam parameters. These experiments are planned over several steps of e^+e^- centre-of-mass energy spanning the range between 500 GeV and 1.5 TeV. Given the relatively clean initial state, very high precision is possible in these experiments and, indeed, the degree of precision can be enhanced by using polarised initial electrons and laser beams. Due to the reach in energy and the high precision, these experiments can test the SM very accurately and probe new physics that may lie beyond the SM. In particular, the NLC can be used very effectively to study the physics of large extra dimensions and it is with this aim that we study dijet production in $\gamma\gamma$ collisions at the NLC.

Since in the $\gamma\gamma$ scattering process, each γ is produced from the electron-laser Compton back-scattering, the energy of the back-scattered photon, E_γ, follows a distribution characteristic of the Compton scattering process and can be written in terms of the dimensionless ratio $x = E_\gamma/E_e$. It turns out that the maximum value of x is about 0.82 so that provides the upper limit on the energy accessible in the $\gamma\gamma$ sub-process. To get the full cross-section, the $\gamma\gamma$ subprocess cross-section is convoluted with the luminosity functions, $f^i_\gamma(x)$, which provide information on the photon flux produced in Compton scattering of the electron and laser beams [37].

In the SM, dijet production in $\gamma\gamma$ collisions takes place via the usual t- and u-channel production mechanisms, $\gamma\gamma \to q\bar{q}$, where five massless flavours of quarks are summed over in the final state. In the presence of large extra dimensions, the $\gamma\gamma \to q\bar{q}$ cross-section gets modified because of the s-channel exchange of virtual spin-2 Kaluza-Klein particles. In the following, we refer to this latter contribution as the non-SM (NSM) contribution. In addition to this, there is an entirely new NSM channel that opens up: $\gamma\gamma \to gg$. There is no tree-level SM contribution in this gg production channel[1] while in the $q\bar{q}$ production channel the SM and the NSM

[1]Of course, there exists the higher-order box diagram contribution to the $\gamma\gamma \to gg$ channel in the SM. We feel that in our case this contribution may be justifiably neglected because of the fact that it will be suppressed by powers of the coupling as well as overall factors from the box calculation. On the other hand, this box contribution may be quite important for the reverse SM process $gg \to \gamma\gamma$ contributing to diphoton production at the LHC [31] because of the enhancement due to initial gluon distributions.

contributions interfere. We calculate the cross-section for the polarised case and then obtain the unpolarised cross-section by summing over the polarisations of the initial photons.[2]

The cross-section for the production of two jets in $\gamma\gamma$ collision can be written in terms of the transverse momentum, p_T, and the rapidity, y, of one of the jets as follows:

$$\frac{d^2\sigma}{dp_T^2 dy} = \int dx_1\, dx_2\, f(x_1,\xi_1^2)\, f(x_2,\xi_2^2)\, s\, \left(\sum_q \frac{d\hat{\sigma}_{(\gamma\gamma\to q\bar{q})}}{dt} + \frac{d\hat{\sigma}_{(\gamma\gamma\to gg)}}{dt}\right) \delta(s+t+u)\,, \tag{1}$$

where the $f(x_i,\xi_i^2),\ i=1,2$ are the luminosity functions for each of the photons where ξ_1^2 and ξ_2^2 are the Stokes parameters of the first and second photons respectively, $d\hat{\sigma}_{(\gamma\gamma\to q\bar{q})}/dt$ and $d\hat{\sigma}_{(\gamma\gamma\to gg)}/dt$ are the subprocess cross-sections for the $q\bar{q}$ and gg channels respectively, and are given in terms of helicity amplitudes as follows:

$$\frac{d\hat{\sigma}_{(\gamma\gamma\to jj)}}{dt} = \frac{1}{16\pi s^2}\left(\frac{1}{2}(1+\xi_1^2\xi_2^2)\,|\mathcal{M}_j(++)|^2 + \frac{1}{2}(1-\xi_1^2\xi_2^2)\,|\mathcal{M}_j(+-)|^2\right), \tag{2}$$

with the helicity amplitudes are given as:

$$\begin{aligned}
|\mathcal{M}_q(++)|^2 &= 0\,,\\
|\mathcal{M}_q(+-)|^2 &= 192\pi^2(s^2+2st+2t^2)\left(-\alpha^2 e_q^4\frac{1}{t(s+t)} - \alpha e_q^2\frac{\lambda}{M_S^4} - \frac{t(s+t)}{4M_S^8}\right),\\
|\mathcal{M}_g(++)|^2 &= 0\,,\\
|\mathcal{M}_g(+-)|^2 &= \frac{64\pi^2}{M_S^8}\left(s^4+4s^3t+6s^2t^2+4st^3+2t^4\right).
\end{aligned} \tag{3}$$

In the above equations, $\mathcal{M}_q(\lambda_1,\lambda_2)$ are the helicity amplitudes for the subprocess $\gamma\gamma\to q\bar{q}$ and $\mathcal{M}_g(\lambda_1,\lambda_2)$ are those for the subprocess $\gamma\gamma\to gg$, with λ_1 and λ_2 denoting the polarisations of the first and the second photons, respectively. As usual, we sum over five massless flavours of quarks.

The non-SM contribution involves two new parameters: the effective string scale M_S and λ which is the effective coupling at M_S. λ is expected to be of $\mathcal{O}(1)$, but its sign is not known *a priori*. In our work we will explore the sensitivity of our results to the choice of the sign of λ. Consequently, the only free parameter left is M_S so that our results can be directly translated into quantitative predictions for the reach in M_S.

We begin with the results for the unpolarised case. We have computed the unpolarised integrated cross-section for three different values of the initial e^+e^- C.M. energy i.e. $\sqrt{s_{ee}}$ = 500, 1000, 1500 GeV both for the SM and the NSM. In order to obtain the integrated cross-section, we have integrated the cross-section in eq. (1) over p_T greater than a chosen $p_T^{\rm cut}$ and over all accessible values of y. From the value

[2] The polarisation of each of the photons is a function of the polarisations of the initial electron and laser beams and it is only the latter that can be fixed in the experiment. When we present our results for the polarised case, we will do so for a fixed choice of these initial polarisations

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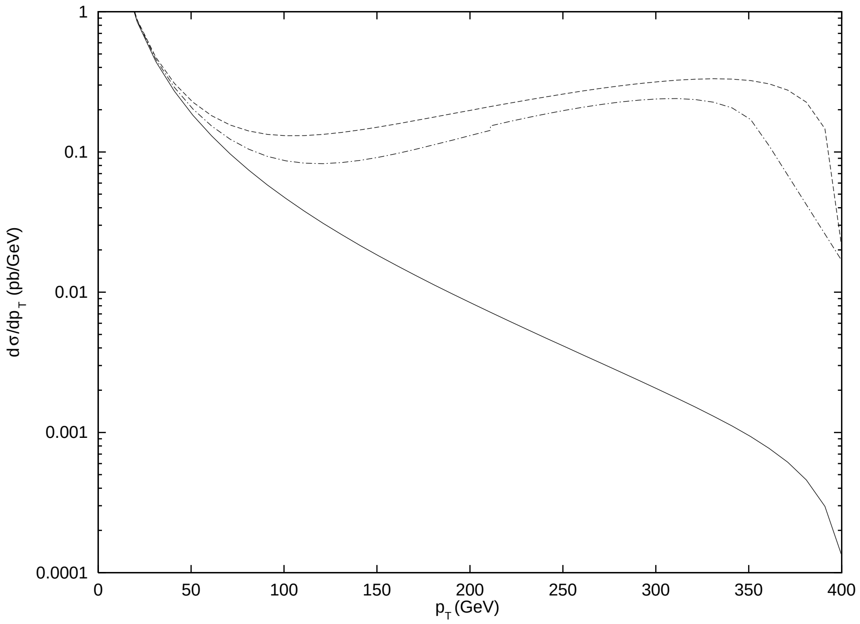

Figure 1: The p_T distribution for $\sqrt{s}_{ee} = 1$ TeV for the unpolarised case. The solid line represents the SM contribution, while the dashed and dash-dotted lines represent the SM+NSM contribution with $M_S = 1\,\text{TeV}$ and $\lambda = -1$ and $\lambda = 1$ respectively.

of the SM cross-section we derive the 2σ error band, assuming purely statistical errors and assuming an integrated luminosity of 100 fb^{-1}. Comparing this with the NSM contribution (including the interference term in the $q\bar{q}$ production channel), we obtain the 2σ limits on M_S. These limits are displayed in table 1, as a function of the e^+e^- centre-of-mass energy and p_T^{cut}. Stringent limits ranging from about 2.5 TeV at the lowest $\sqrt{s}_{ee}$ to about 6.4 TeV at the highest $\sqrt{s}_{ee}$ are obtained. Also we find that the bound that we obtain improves as we demand a larger value of p_T^{cut}. This can be seen from figure 1, where we have plotted the p_T distribution for the SM case (solid line) and for the SM+NSM case for a M_S value of 1 TeV. We have shown this for $\lambda = -1$ (dashed line) and $\lambda = 1$ (dash-dotted line). For both cases, it is seen that while the SM contribution drops rapidly with increasing p_T the SM+NSM contribution is quite large even at large values of p_T. From figure 1 it is clear that the use of a larger value of p_T^{cut} will make the cross-section more sensitive to the NSM contribution and, therefore, improve the bound on M_S. Given that the dijet cross-section is large, for a luminosity of 100 fb^{-1} we get large event rates even for a p_T^{cut} of 60 GeV. The value of p_T^{cut} may thus be optimised so as to get a larger limit on M_S, while still retaining a large number of dijet events.

p_T^{cut} GeV	M_S in TeV		
	$\sqrt{s}_{ee}$=0.5 TeV	1 TeV	1.5 TeV
10	2.579	4.059	5.330
35	3.032	4.642	6.007
60	3.288	4.992	6.411

Table 1: M_S limits for different values of e^+e^- c.m. energies in the case of unpolarized beams.

We now discuss the results for the polarised case. As mentioned earlier, for a given choice of the initial electron and laser polarisations, 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. At the level of the $\gamma\gamma$ subprocess, the helicity amplitudes directly reflect the dynamics of the SM and NSM. As can be seen from eq. (3), the amplitude where both photons have identical polarisation ($\lambda_1 = \lambda_2$) vanishes for *both* the SM and the NSM. The helicity structure of the SM and the NSM contributions is similar to this extent, the differences between them coming only from the non-vanishing helicity amplitudes i.e. when the photons have opposite polarisation ($\lambda_1 = -\lambda_2$). For hard photons, the sign of λ is the same as that of the helicity of the initial electron. Therefore, $\lambda_1 = -\lambda_2$ is realised when the electron beams have opposite helicities i.e. ($\lambda_{e1} = -\lambda_{e2}$). Further, the luminosity function is such that it peaks for a certain value of the product $\lambda_e\lambda_l$ (where λ_l is the laser beam polarisation) in the high-x region. By scanning over the different choices of the laser beam and initial electron polarisation, we find that the best sensitivity is realised for the cases $(+,-,-,-)$ and $(-,+,-,-)$, where these represent the polarisations $(\lambda_{e1}, \lambda_{e2}, \lambda_{\ell 1}, \lambda_{\ell 2})$. In table 2, we have displayed the limits on M_S obtained with the first of these choices for the initial electron and laser beam polarisations. With this choice of polarisations, we find that the limits can improve by about 20% as compared to the unpolarised case.

$p_T^{\rm cut}$ GeV	M_S in TeV		
	$\sqrt{s}_{ee}$=0.5 TeV	1 TeV	1.5 TeV
10	3.029	4.890	6.530
35	3.390	5.334	6.996
60	3.592	5.614	7.321

Table 2: M_S limits in the polarized case. Oppositely polarized electron beams and laser beams are used to obtain the photon beams. Other parameters are as stated in the case of table 1.

In figure 2 we have plotted the rapidity distribution for $\sqrt{s}_{ee} = 1$ TeV, in order to consider whether the use of differential quantities will further enhance the sensitivity of the process under consideration to the effects of the new physics. We find that the difference between the SM and the SM+NSM distributions to be quite significant, especially when we concentrate in the central regions of rapidity. Though we refrain from making a quantitative estimate of the bound that would result (for such an estimate would be premature without knowing further experimental details), it is clear from figure 2 that the rapidity distribution can be used to improve the bound that would result from looking only at the integrated cross-section.

We have shown that virtual effects of spin-2 Kaluza Klein exchange can significantly affect dijet production in $\gamma\gamma$ collisions at the NLC and so this process can be used to probe the physics of large extra dimensions. The range of M_S values that

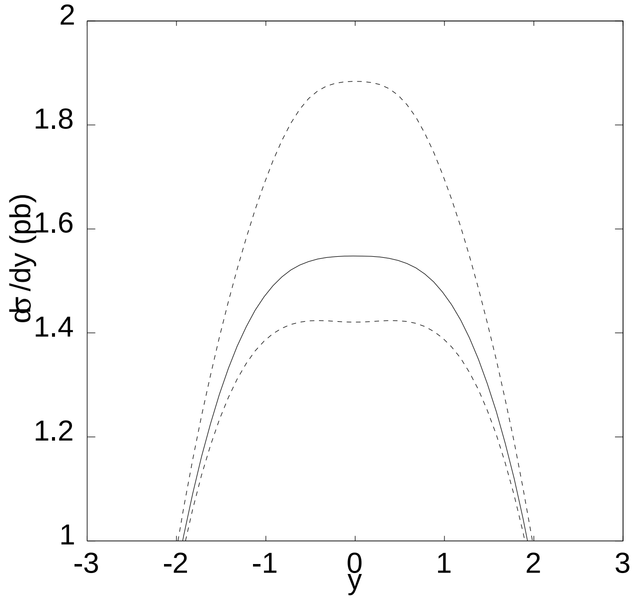

Figure 2: The y distribution for $\sqrt{s_{ee}} = 1\,\mathrm{TeV}$ for the unpolarised case. The solid line is the SM cross-section, while the lines above and below the SM curve are for the SM+NSM cross-section with $M_S = 1\,\mathrm{TeV}$ and $\lambda = -1$ and $\lambda = 1$, respectively.

can be probed with this process is of the order of 2.5–6.5 TeV using the information on integrated unpolarised cross-sections. For the case of polarised photon beams, the sensitivity is enhanced by about 20%. Using differential informations, like rapidity distributions may help to further enhance the sensitivity of this process.

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