Study of the Sensitivity to Extra-Dimensions in the Photon-Graviton Channel with Polarised Beams

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Abstract

This note gives more details on studies done to estimate the sensitivity of TESLA to extra-dimensions.

1 Introduction

The discovery reach of the linear collider for direct graviton production in $e^+e^- \to \gamma G$ is estimated for an integrated luminosity of 1000 fb $^{-1}$ at $\sqrt{s} =$ 800 GeV with polarised beams. This study builds on previous studies such as [1] and references therein.

The signature is a relatively soft photon and missing energy. The differential cross-section is given [2] by

$$\frac{d^2\sigma}{dx_\gamma\, d\cos\theta} = \frac{\alpha S_{\delta-1}}{64{M_D}^2}\left(\frac{\sqrt{s}}{M_D}\right)^\delta f_{\gamma G}(x_\gamma, \cos\theta) \tag{1}$$

where x_γ is $E_\gamma/E_{\mathrm{beam}}$, δ is the number of extra dimensions and $S_{\delta-1}$ is the surface area of a δ-dimensional sphere of unit radius, with

$$f_{\gamma G}(x, \cos\theta) = \frac{2(1-x)^{\frac{\delta}{2}-1}}{x(1-\cos^2\theta)}\left[(2-x)^2(1-x+x^2) - 3x^2\cos^2\theta(1-x) - x^4\cos^4\theta\right]. \tag{2}$$

The major background is $e^+e^- \to \nu\overline{\nu}\gamma$ and it is largely irreducible.

2 Signal extraction

The following kinematic acceptance cuts are imposed on the photon.

- Within the ECAL acceptance, $\sin\theta_\gamma > 0.1$.
- $p_T > 0.06 E_{\mathrm{beam}}$ in order to reject events with no genuine missing p_T such as $e^+e^- \to e^+e^-\gamma$ where electrons at polar angles below the LCAL acceptance of 27.5 mrad mimic missing p_T.

δ	$M_D(P_{-,+}=0)$	$M_D(P_-=0.8)$	$M_D(P_-=0.8, P_+=0.6)$
2	$4.48^{+0.96}_{-1.12}$	$6.27^{+0.68}_{-1.39}$	$7.86^{+0.55}_{-1.54}$
3	$3.54^{+0.59}_{-0.73}$	$4.63^{+0.40}_{-0.84}$	$5.55^{+0.31}_{-0.89}$
4	$2.91^{+0.40}_{-0.51}$	$3.64^{+0.26}_{-0.56}$	$4.23^{+0.20}_{-0.57}$
5	$2.47^{+0.29}_{-0.37}$	$3.00^{+0.18}_{-0.40}$	$3.41^{+0.13}_{-0.40}$
6	$2.16^{+0.22}_{-0.29}$	$2.55^{+0.13}_{-0.30}$	$2.86^{+0.10}_{-0.30}$
7	$1.92^{+.17}_{-.23}$	$2.23^{+.10}_{-.23}$	$2.47^{+.08}_{-.23}$

Table 1: Discovery (5σ) reach in mass scale M_D in TeV for direct graviton production in $e^+e^- \to \gamma G$ for various numbers of extra dimensions. Central values correspond to a 0.3% normalisation error. The change in the discovery reach for alternative assumptions on the normalisation error of 0.1% (optimistic) and 1.0% (conservative) is indicated by the upper and lower value.

- $x_\gamma < 0.625$ in order to reject the energetic photons from $e^+e^- \to \nu\bar{\nu}\gamma$ which arise from $e^+e^- \to Z\gamma$.

With these cuts, the accepted cross-sections including ISR and beamstrahlung from $e^+e^- \to \nu\bar{\nu}\gamma$ for 100% electron polarisation are $\sigma_{e_L^- e^+} = 1.90$ pb and $\sigma_{e_R^- e^+} = 23$ fb evaluated using NUNUGPV[3]. Other backgrounds have so far been neglected; they will be small but should not be ignored, eg $e^+e^- \to \nu\bar{\nu}\nu\bar{\nu}\gamma$ [1] For the signal, as an example for $M_D = 5$ TeV and $\delta = 2$, the unpolarised accepted Born cross-section without beamsstrahlung is 12 fb.

Given the near maximal polarisation asymmetry of the background, polarised beams are extremely effective in suppressing the background and therefore extending the reach of a linear collider in the quest for evidence of extra dimensions. This is illustrated in Table 1 for numbers of extra dimensions ranging from 2 to 7. By polarising both beams to a high degree, the LC potential for exploring this physics is maximised.

Numerical sensitivity estimates are based on a normalisation uncertainty of 0.3%. The signal and background include an estimated inefficiency of 10% from additional cuts required against multi-particle final states. The signal cross-sections have been reduced by 15% corresponding to the estimated cross-section reduction from ISR and beamstrahlung. For comparison, numbers are also shown for normalisation uncertainties of 0.1% (optimistic) and 1.0% (conservative). The corresponding cross-sections are shown in Fig. 1. Many sources of systematic error will have to be controlled at quite challenging levels of precision: theoretical error on background cross-section, absolute luminosity, selection efficiency, energy scale and polarisation. However the availability of large control data-sets such as $Z \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ should allow detector related systematics to be kept under sufficient control.

[1] We have also investigated quantitatively with the TEEGG generator whether looser cuts on the photon pT which accept some background from (ee)γ are useful. We find that the background cross-sections are quite small, but for high M_D values near the edge of the experimental sensitivity where the S/B is already poor it is best to eliminate this background completely.

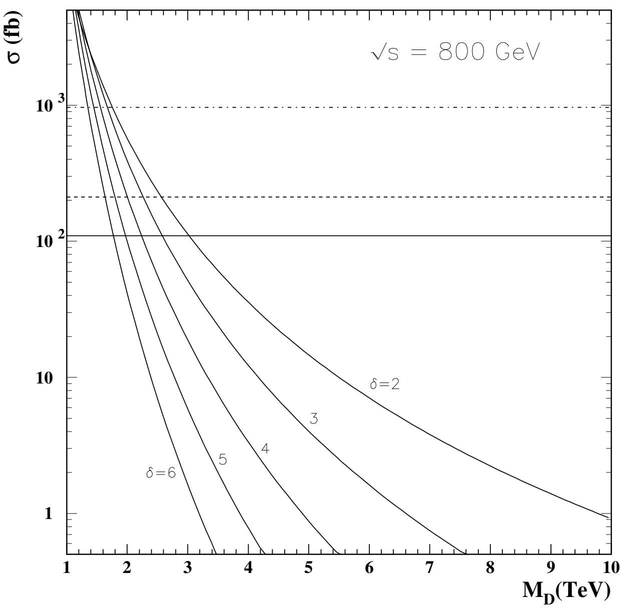

Figure 1: *Total cross sections for* $e^+e^- \to \gamma G$ *at* $\sqrt{s} = 800$ *GeV as a function of the scale* M_D *for different numbers* δ *of extra dimensions. The cross-section takes into account 80% electron and 60% positron polarisation (enhancement factor of 1.48). The three horizontal lines indicate the background cross-sections from* $e^+e^- \to \nu\nu\gamma$ *for both beams polarised (solid), only electron beam polarisation (dashed) and no polarisation (dot-dashed). Signal cross-sections are reduced by a factor of 1.48 for the latter two scenarios.*

In addition to the above discovery reach tables which are easily comparable to an LHC study, we also include table 2 with 95% CL exclusion reach should no signal be found. The average 95% CL exclusion value is obtained from the expected number of observed events from background only + 1.65σ.

A recent study[4] of the LHC potential with the ATLAS experiment shows that in 100 fb^{-1}, direct graviton production can be discovered at at least 5σ using the signature of pp $\to$ jet G for M_D in the range 4-7.5, 4.5-5.9 and 5.0-5.3 TeV for $\delta = 2, 3, 4$ respectively. However for lower M_D values when $\delta = 2, 3, 4$ and for higher values of δ, the effective theory approach breaks down at LHC. At the LC, if $\sqrt{s}_{\mathrm{e^+e^-}} \ll M_D$ the effective theory should still be valid and the measured single photon cross-section can be used to constrain (M_D, δ). The LC offers a more model-independent test of this theory while the LHC may be in the string theory regime whose phenomenology is maybe rich but presently unknown. For regions which can be compared, the discovery reach in M_D for the LC and LHC is similar.

Anomalous single photon signatures at LC and monojet signatures at LHC can both arise from many types of new physics other than extra dimensions. Therefore measurement of processes sensitive to direct graviton production with

δ	$M_D(P_{-,+}=0)$	$M_D(P_-=0.8)$	$M_D(P_-=0.8, P_+=0.6)$
2	$5.91^{+1.26}_{-1.48}$	$8.28^{+.90}_{-1.83}$	$10.38^{+.73}_{-2.04}$
3	$4.42^{+.74}_{-.91}$	$5.78^{+.50}_{-1.05}$	$6.93^{+.38}_{-1.11}$
4	$3.50^{+.48}_{-.61}$	$4.38^{+.31}_{-.67}$	$5.09^{+.23}_{-.69}$
5	$2.90^{+.34}_{-.44}$	$3.51^{+.21}_{-.47}$	$4.00^{+.16}_{-.47}$
6	$2.48^{+.25}_{-.33}$	$2.93^{+.15}_{-.34}$	$3.28^{+.11}_{-.34}$
7	$2.17^{+.20}_{-.26}$	$2.52^{+.12}_{-.27}$	$2.79^{+.09}_{-.26}$

Table 2: Exclusion reach (95% CL) in mass scale M_D in TeV for direct graviton production in $e^+e^- \to \gamma G$ for various numbers of extra dimensions. Central values correspond to a 0.3% normalisation error. The change in the exclusion reach for alternative assumptions on the normalisation error of 0.1% (optimistic) and 1.0% (conservative) is indicated by the upper and lower value.

complementary initial and final states would help to confirm whether the correct diagnosis had been made. At the LC, the process $e^+e^- \to ZG$ can be explored in e^+e^- collisions; however the sensitivity relative to $e^+e^- \to \gamma G$ is rather limited [5]. A more promising channel is $e^-\gamma \to e^- G$ [6].

If extra dimensions are the cause of the anomalous single photon rate, the $\sqrt{s}$ dependence of the cross-section should follow $\sigma \propto s^{\frac{\delta}{2}}$. Fig. 2 illustrates how a measurement of an excess of single photon events at $\sqrt{s} = 500$ GeV together with a measurement at $\sqrt{s} = 800$ GeV can be used to determine the number of extra dimensions. The measured excess cross-section with polarised beams at $\sqrt{s} = 500$ GeV is taken to be 5.7 ± 0.8 fb. For $\delta = 2$ this would be consistent with $M_D = 5.0 \pm 0.2$ TeV. The uncertainty corresponds to 500 fb^{-1} and a normalisation systematic uncertainty of 0.3%. Cross-section measurements at 800 GeV with 1000 fb^{-1} are illustrated for values of M_D and δ consistent with the 500 GeV cross-section measurement. The full lines illustrate the $\sqrt{s}$ dependence for the central value of the 500 GeV cross-section measurement under the hypotheses of $\delta = 2, 3, 4, 5, 6$. As an example, if δ were 2, the $\delta = 3$ hypothesis could be excluded on average at 2.8 standard deviations. With δ determined, M_D can be inferred unambiguously: in particular for the above example with $\delta = 2$, one would measure $M_D = 5.0 \pm 0.04$ TeV where the sensitivity is dominated by the 800 GeV data.

Determination of the number of extra dimensions is possible with this data-taking scenario for excess cross-sections at 500 GeV down to 5.3 ± 0.8 fb. This cross-section is equivalent to $M_D = 5.1$ TeV for $\delta = 2$ and for these values, one would exclude $\delta = 3$ on average at 99% CL. Inconsistency with the expected $\sqrt{s}$ dependence, ie. excluding integer values of δ, would exclude the extra dimensions interpretation.

The LHC and the LC therefore have valuable complementary roles to play in experimentally testing theories with extra space dimensions.

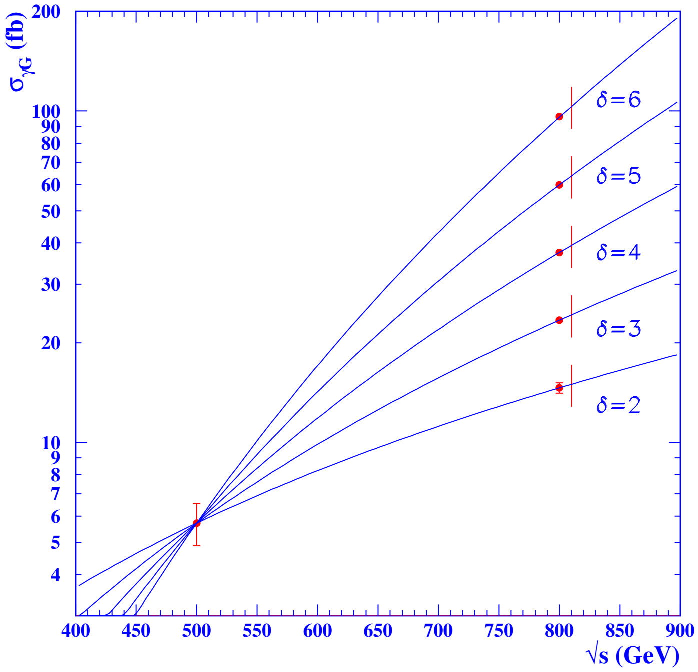

Figure 2: *Determining δ from anomalous single photon cross-section measurements at $\sqrt{s} = 500$ GeV and 800 GeV. The sensitivity shown corresponds to integrated luminosities of 500fb^{-1} at $\sqrt{s} = 500$ GeV and 1 ab^{-1} at $\sqrt{s} = 800$ GeV with 80% electron and 60% positron polarisation with a cross-section at 500 GeV equivalent to $M_D = 5$ TeV if $\delta = 2$. The points with error bars show the measurements one could expect. The smooth curves show the cross-section dependence on $\sqrt{s}$ for the central value of the 500 GeV cross-section measurement under the hypotheses of δ = 2,3,4,5 and 6. The vertical lines adjacent to the 800 GeV measurements indicate the range that would be consistent within $\pm 1\sigma$ with the 500 GeV measurement.*

3 Acknowldegements

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A Background cross-section calculation with NUNUGPV

The NUNUGPV MC was used in several ways to calculate the background cross-section. Estimates are given for $\sqrt{s} = 800$ GeV with those for $\sqrt{s} = 500$ GeV in brackets. All estimates are based on 10,000 MC events and so have MC statistical errors of 1%.

A.1 Born level mode

Initially the code had been extended to include beamstrahlung and longitudinal polarisation only for exactly one photon. With the above kinematic cuts and using circe version 7, the accepted cross-sections were :

- $\sigma_{e^-_L e^+} = 2.69$ pb
- $\sigma_{e^-_R e^+} = 4.89$ fb

A.2 One Matrix Element Photon plus ISR

The code was modified to include beamstrahlung and the unpolarised cross-sections were calculated separately for all neutrino species and specifically for ν_μ. The results are :

- $\sigma_{\nu\nu\gamma(\gamma)} = 963$ fb (1055 fb)
- $\sigma_{\nu_\mu\nu_\mu\gamma(\gamma)} = 9.1$ fb (25.2 fb)

Noting that $\sigma_{e^-_R e^+}$ only receives contributions from the pure s-channel Z-exchange amplitude, we can estimate $\sigma_{e^-_R e^+}$ from $\sigma_{\nu_\mu\nu_\mu\gamma(\gamma)}$, knowing $N_\nu = 3$ and $A_{LR} = 0.15$. Consequently we estimate :

- $\sigma_{e^-_L e^+} = 1902$ fb (2046 fb)
- $\sigma_{e^-_R e^+} = 23.2$ fb (64.3 fb)

We note that ISR decreases $\sigma_{e^-_L e^+}$ which is dominated by W-exchange, while ISR increases substantially $\sigma_{e^-_R e^+}$ due to the "radiative return" effect.

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