

Graviton Production at CLIC

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Direct production of Kaluza-Klein states in the TeV range is studied for the experimental environment at the multi-TeV e^+e^- collider CLIC. The sensitivity of such data to model parameters is discussed for the Randall-Sundrum(RS) and TeV scale extra dimensional models.

I. INTRODUCTION

For the past few years the phenomenology of large (extra) dimensions has been explored at the TeV scale. These theories aim to solve the hierarchy problem by bringing the Gravity scale closer to the Electroweak scale. Extra dimension signatures at future colliders, particularly at CLIC, have been discussed extensively in [1]. Here we report on a study using two models which can produce measurable resonances in the two-fermion production cross section, in the multi-TeV range which would be accessible at CLIC. CLIC is conceived to be an e^+e^- linear collider (LC) optimized for a centre of mass (CMS) energy of 3 TeV with $\mathcal{L} \cong 10^{35} \text{cm}^{-2}\text{s}^{-1}$, using a novel acceleration concept called two-beam acceleration [2].

For these studies the CLIC physics working group tools have been used, which include smearing of the CMS energy of the collisions according to the CLIC luminosity spectrum [3]; overlaying the hadronic background from $\gamma\gamma$ events [3]; and producing the detector response by SIMDET, a fast simulation package [4]. Events of the type $e^+e^- \rightarrow f\bar{f}$ have been generated with the PYTHIA event generator [5].

II. RANDALL-SUNDRUM MODEL

In the extra-dimension scenario proposed by Randall-Sundrum(RS) [6] the hierarchy between the Planck and the Electroweak scale is generated by an exponential function called 'warp factor'. This model predicts Kaluza-Klein graviton resonances with both weak scale masses and couplings to matter. Hence the production of TeV scale graviton resonances is expected in two fermion channels [7]. In its simplest version, with two branes and one extra dimension, and where all of the SM fields remain on the brane, the model has two fundamental parameters: the mass of the first Kaluza-Klein state, m_1 , and the parameter $c = k/M_{Pl}$, where k is related to the curvature of the 5-dimensional space and M_{Pl} is the 4-d effective Planck scale. The parameter c controls the effective coupling strength of the graviton and thus the width of the resonances, and should be less than one but yet not too far away from unity.

The resulting spectrum for $e^+e^- \rightarrow \mu^+\mu^-$ is shown in Fig. 1. The cross sections are huge and the signal cannot be missed at a LC with sufficient CMS energy. If such resonances are observed – perhaps first by the LHC in the range of a few TeV – it will be important to establish the nature of these newly produced particles, i.e. to measure their properties (mass, width and branching ratios) and quantum numbers (spin). Note that the mass m_1 of the first resonance determines the resonance pattern: the masses of all higher mass resonances are then fixed.

The signal for one KK resonance (G_1) is implemented in PYTHIA 6.158 [5] via process 41. For this study PYHTIA has been extended to include two more resonances (G_2, G_3 , corresponding to processes 42 and 43) to allow to check the measurability of the graviton self-coupling. The decay branching ratios of these resonances were modified according to [7, 8]. In particular the gravitons can decay into two photons in about 4% of the cases, a signature which would distinguish them from e.g. new heavy Z' states [9].

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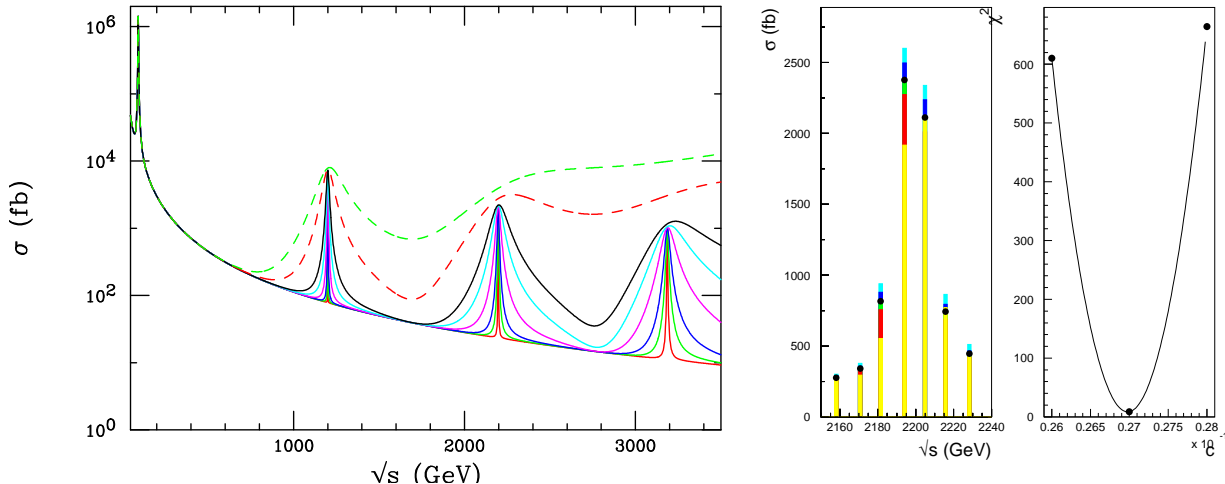


FIG. 1: (Left) KK graviton excitations in the RS model produced in the process $e^+e^- \rightarrow \mu^+\mu^-$. From the most narrow to widest resonances the curves are for c in the range 0.01 to 0.2. (Right) Scan of the resonance (7 points) and χ^2 fit to the measured spectrum for models with different values for c .

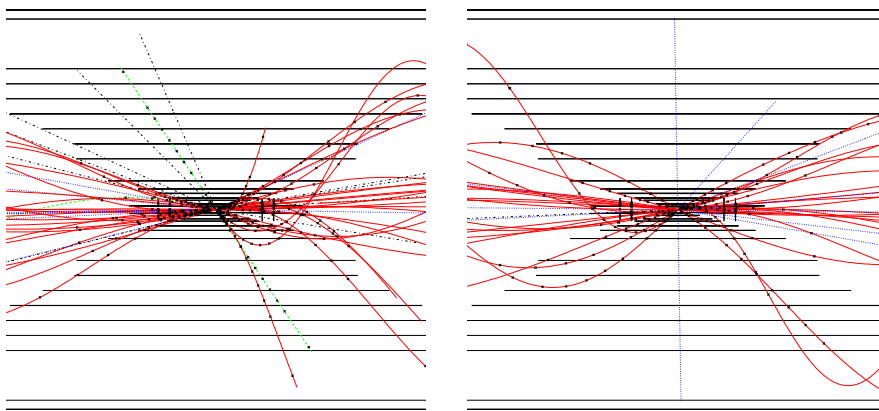


FIG. 2: (Left) $G_3(3200 \text{ GeV}) \rightarrow \mu\mu$ decay and (Right) $G_3(3200 \text{ GeV}) \rightarrow \gamma\gamma$ decay in a detector at CLIC, with $\gamma\gamma$ background events overlaid (one bunch crossing).

The resonance spectrum was chosen such that the first resonance G_1 has a mass around 1200 GeV, just outside the reach of a TeV class LC, and consequently the mass of the third resonance G_3 will be around 3200 GeV, as shown in Fig. 1. The CMS energy for the e^+e^- collisions of CLIC was taken to be 3.2 TeV in this study. Mainly the muon and photon decay modes of the graviton have been studied. The events used to reconstruct G_3 resonance signal were selected either via two muons or two γ 's with $E > 1200$ GeV and $|\cos\theta| < 0.97$. Two typical events, one decaying into muons and the other in photons, are shown in Fig. 2. The background from overlaid two photon events – on average four events per bunch crossing – is typically important only for angles below 120 mrad, i.e. outside the considered signal search region.

First we study the precision with which we can measure the shape, i.e. the c and M parameters, of the observed new resonance. A scan similar to the one at the Z at LEP was made for an integrated luminosity of 1 ab^{-1} . An example of the cross section measurements and the χ^2 fit through the points for spectra generated with different c and M values is shown in Fig. 1b. The precision with which the cross sections are measured allows one to determine c to 0.2%, and M to better than 0.1%.

Next we determine some key properties of the new resonance: the spin and the ratio of decay modes. The graviton is a spin-two object. Fig. 3 shows the decay angle of the fermions $G \rightarrow \mu\mu$ for the G_3 graviton, using PYTHIA/SIMDET, for 1 ab^{-1} of data, including CLIC machine background. The typical spin-two structure

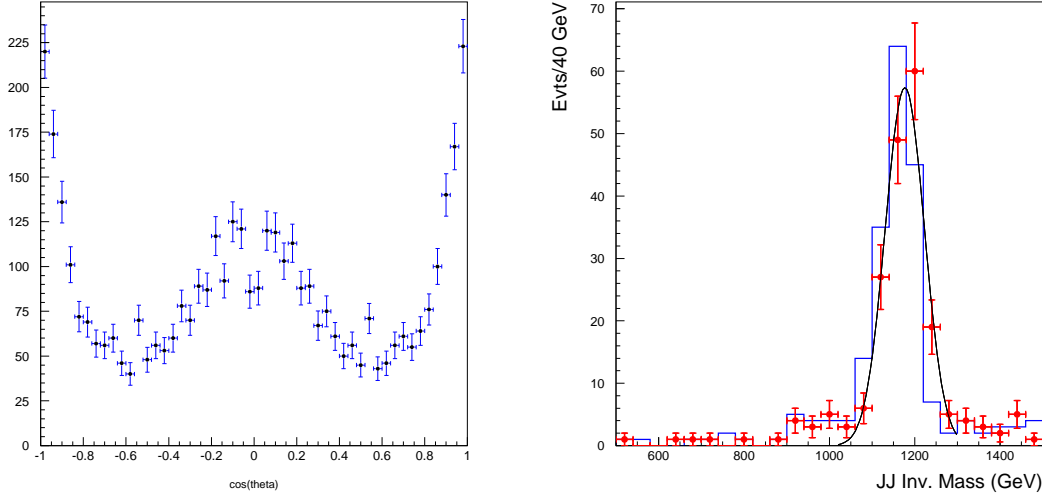


FIG. 3: (Left) Decay angle distribution of the muons from $G_3(3200\text{GeV}) \rightarrow \mu\mu$; (Right) Invariant jet-jet mass of $G_1(1200\text{GeV})$ produced in $G_3 \rightarrow G_1G_1$ and $G_1 \rightarrow \text{jet jet}$.

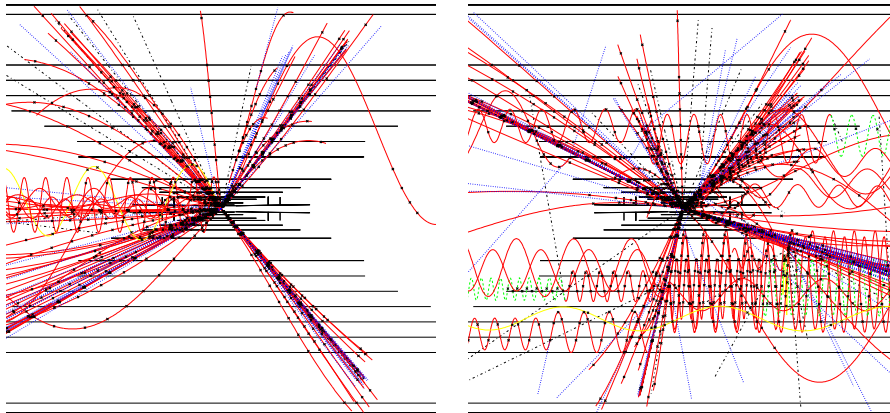


FIG. 4: Two events in a CLIC central detector with decay $G_3 \rightarrow G_1G_1 \rightarrow \text{four jets}$

of the decay angle of the resonance is clearly visible.

For gravitons as proposed in [7, 8] one expects $BR(G \rightarrow \gamma\gamma)/BR(G \rightarrow \mu\mu) = 2$. With the present SIMDET simulation we get efficiencies in mass peak (± 200 GeV) of 84% and 97% for detecting the muon and photon decay modes, respectively. With cross sections of $O(pb)$, $\sigma_{\gamma\gamma}$ and $\sigma_{\mu\mu}$ can be determined to better than a per cent. Hence the ratio $BR(G \rightarrow \gamma\gamma)/BR(G \rightarrow \mu\mu)$ can be determined to an accuracy of 1% or better.

Finally, if the CMS energy of the collider is large enough to produce the first three resonances states, one has the intriguing possibility to measure the graviton self-coupling via the $G_3 \rightarrow G_1G_1$ decay [8]. The dominant decay mode will be $G_1 \rightarrow \text{gluon-gluon}$ or $q\bar{q} \rightarrow \text{two jets}$. Fig. 4 shows the resulting spectacular event signature of four jets of about 500 GeV each in the detector (no background is overlaid). These jets can be used to reconstruct G_1 . Fig. 3b shows the reconstructed G_1 invariant mass. The histogram does not include background while the data points include 10 bunch crossings of background overlaid on the signal events. Hence the mass of G_1 can be well reconstructed and is not significantly distorted by the $\gamma\gamma$ background.

In summary a multi-TeV collider, such as CLIC, will allow for a precise determination of the shape and of mass of the new resonance(s), and of its spin.

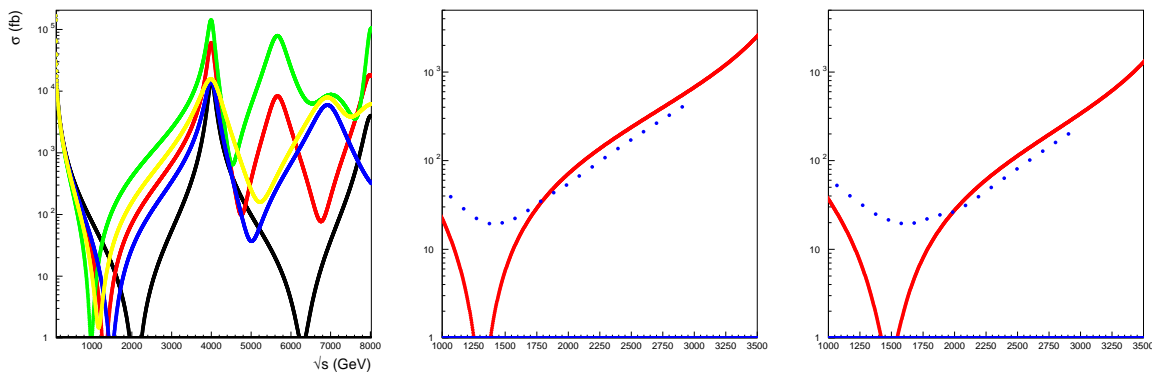


FIG. 5: (Left) The $\sigma_{\mu\mu}$ cross section for different models for TeV scale extra dimensions. (Middle and Right) The $\sigma_{\mu\mu}$ cross section before (solid line) and after (dashed line) smearing by the CLIC luminosity spectrum, for two models.

III. TEV SCALE MODELS

Another class of models, which leads to a resonance structure in the energy dependence of the two-fermion cross section, are those with a TeV scale extra dimension [10]. In the simplest versions of these theories, only the SM gauge fields are in the bulk whereas the fermions remain at one of the two orbifold fixed points; Higgs fields may lie at the fixed points or propagate in the bulk. In such a model, to a good approximation, the masses of the KK tower states are given by $M_n = nM_c$, where $M_c = R_c^{-1}$ is the compactification scale, R_c is the compactification radius. The mass of the lowest lying KK state is constrained to be rather large, i.e. a few TeV, due to bounds arising from precision measurements[11].

The masses and couplings of the KK excitations are compactification scheme dependent and lead to a rather complex KK spectrum. Examples of models are shown in Fig. 5. The position of the peaks and the dips and their corresponding cross sections and widths can be used to uniquely identify the extra-dimensional model. As an example two of these models were taken and the production cross section was folded with the CLIC luminosity spectrum. The results are shown in Fig. 5 for two dip positions, since the peaks are likely to be beyond the reach of a 3 TeV collider. The structure of the dips is largely kept, but it is smeared out and somewhat systematically shifted. In any case also here CLIC data will be sensitive to the model parameters, and will allow to disentangle different scenarios

IV. CONCLUSIONS

The direct production of KK excitations in the TeV range was studied for CLIC, using examples of models based on RS and TeV scale extra dimensions. The backgrounds at CLIC and its smeared luminosity spectrum are not preventive to make precision measurements of the model parameters. In particular, for the RS model it was shown that the key discriminating properties of these resonances can be reconstructed and the underlying model parameters can be determined precisely. Hence if KK excitations appear in the two-fermion processes cross sections in the TeV range, CLIC will be an ideal tool to study in detail the properties of these resonances.

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