A Dark Photon Search at the ILC

In search of dark matter

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Abstract

Several astronomical observations have revealed the existence of dark matter (DM) which is thought to occupy 27% of the universe. Many hypotheses exist about the nature of these elusive dark matter particles. One of these hypotheses predicts the existence of a hypothetical dark photon. The unique signature of this particle could potentially be searched for at the International Linear Collider (ILC). A theoretical model containing a Z′ boson is considered which decays into a lepton pair. The focus will be on the decay channel containing a two oppositely charged muons. The signal generation will be presented using SGV - a fast detector simulation. Several background distributions will also be mentioned, in order to enhance the signal over the background using these distributions. This proposed search will expand our limited understanding of DM and could lead to a detectable DM signature.

Keywords: feebly interacting particles, dark sector, exotic particles

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1 Introduction

1.1 The Standard Model

The Standard Model of Particle Physics (SM) describes the fundamental particles in nature. The SM also describes how they interact through the four known fundamental forces namely the strong, electromagnetic and weak forces. The SM categorizes elementary particles and has been highly consistent with experimental data obtained from particle colliders. Despite this success, several theoretical predictions hints at the SM being incomplete [1]. The SM does not accommodate the recent evidence of dark matter (DM). To obtain a complete description of the universe, several hypothetical exotic particles which are Beyond the Standard Model (BSM) are now being considered. These particles should potentially explain the nature of DM.

1.2 Dark Matter

The nature of dark matter (DM) is fairly unknown and only a few characteristics thereof are certain. DM interacts with gravity and therefore has mass. The name "dark" arises due to very weak interactions with the electromagnetic force when compared to ordinary matter. Lastly DM is known to be cold (and therefore stable) due to dark matter particles that are moving slowly in comparison to the speed of light.

Several astronomical and cosmological observations have revealed the presence of DM which are thought to occupy 27% of the universe. The first observational evidence of DM was obtained in 1970 by Vera Rubin. Rubin was an astronomer and studied the rotation curves of spiral galaxies. A missing mass component was noticed and Rubin suspected that galaxies could contain non-luminous stars such as dwarf brown, dwarf white, black holes or neutron stars [2]. These stars could account for the missing mass component of the entire galaxy, but was not visible with optical instruments. Astronomical observations were since expanded to other wavelengths and several DM candidates and the effects thereof are being examined.

The leading astronomical DM candidate included the gravitational effects of massive astrophysical compact halo objects (MACHOs) on the light from distant objects. Another observation is known as gravitational lensing. This phenomenon shows how DM bends and distorts light in massive galaxy clusters also caused by the gravitational pull of DM. The cosmic microwave background (CMB) also strongly suggest the existence of DM by providing a precise density map of the matter in the early universe [3].

Many hypotheses also exist about the nature of dark matter particles and several detection methods have been proposed in search of them. The search methods for DM are categorized as direct and indirect detection. The direct detection experiments expect dark matter particles to interact with ordinary matter in a detector. This is based on the theory that dark matter particles were thermally produced in the early universe and decreased through annihilation into ordinary matter such as quarks [4].

The ILC detects the effects of several electron and positron collisions indirectly. The leading method for indirect detection had involved weakly interacting massive particles (WIMPs). It is proposed that

WIMPS interact with ordinary matter via the electromagnetic force [5].

A new method involving Feebly Interacting Particles (FIPs) is gaining interest at present. FIPs interactions are still stronger than the SM weak force [6]. FIPS are proposed entities that can explain DM, but are too feebly interacting to have been observed at the Large Hadron Collider (LHC) or at the Large Electron-Positron Collider (LEP). Future colliders will feature 1000 times higher luminosities compared to LEP and will provide new ways to search for DM candidates.
FIPs requirements for DM candidates include:

- Not charged under the SM strong force
- Not excluded or discovered at present
- Lighter than 10 GeV

This project aims to explore the dark sector by investigating the dark photon flavour of FIPS at the ILC. The proposed collider topology contains a hypothetical particle which interacts with gravity and weakly interacts with the SM particles. This elementary particle acts as a probe to the dark sector and is called the dark photon.

2 Dark Photons

2.1 Background

Keeping in mind the limited information that is currently available about the nature of DM, theorists have proposed several different scenarios. One of these scenarios includes exotic particles Beyond the Standard Model (BSM) as mentioned in the previous section. One of these particles is called the dark photon (Z′) and is a new proposed gauge boson forming part of the dark sector. This particle is not dark matter itself, but a significant component in DM models.

The confirmation of these elementary new particles could lead to more detectable DM whilst simultaneously expanding our understanding thereof. Dark photons could also introduce new-physics scenarios BSM, which can be used as a foil for the SM when mapping possible experimental discrepancies.

2.2 The Model

The specific model that will be used is based on the assumption that particles will obey certain gauge interactions of the SM (if not all) and recently matter BSM have been considered. This dark sector does not interact through the SM gauge interactions at all. Dark photons behaving as gauge bosons form part of this sector and could extend the SM's gauge group [7].

The model that will be looked at contains a new abelian gauge symmetry $U(1)_d$. The dark photon (Z') kinetically mixes through the hypercharge portal with the SM photon and a Z boson [8].

The dark photon arises from a electron-positron collision along with an initial state radiated (ISR) photon [9] as follows: $e^-e^+ \rightarrow \gamma_{ISR}Z'$. The dark photon further decays into two oppositely charged leptons. For this project the focus will be on the decay containing a muon pair, where $Z' \rightarrow \mu^-\mu^+$. Muons are more easily detected in a narrow window than other leptons in this case. These decays are illustrated in *Figure 1*.

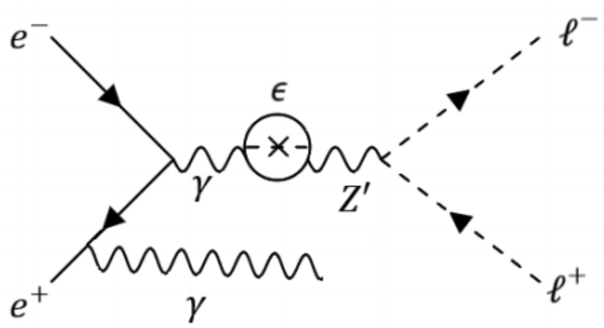

Figure 1: *A Feynman Diagram illustrating the production of the dark photon (Z′)*

This search has not yet been explored in any ILC experiment. The production of the above mentioned processes will be attempted by generating the main signal and possible background events that could occur in the detector.

3 Signal Generation

3.1 Utilizing WHIZARD

As mentioned in *Section 2.2* the signal containing the dark photon had to be generated with a Unified Feynrules Output (UFO) file based on the model [8]. A steering file was used to produce signal distributions after optimizing the file. Opposite-sign bream polarisation at 100% were looked as seen in *Figure 2*. The green series refers to left-handed electrons and right-handed positrons (eLpR), where P(e^-, e^+)=(-100%, +100%). The blue series indicates exactly the inverse of this (i.e. eRpL).

The collisions that were investigated had a centre-of-mass energy of 250 GeV. The cross-section dependence on several Z' masses were investigated using WHIZARD. This program is designed for the efficient calculation of multi-particle scattering cross-sections and simulated event samples [10]. A Z′ mass range of 10 to 250 GeV in increments of 10 GeV were investigated.

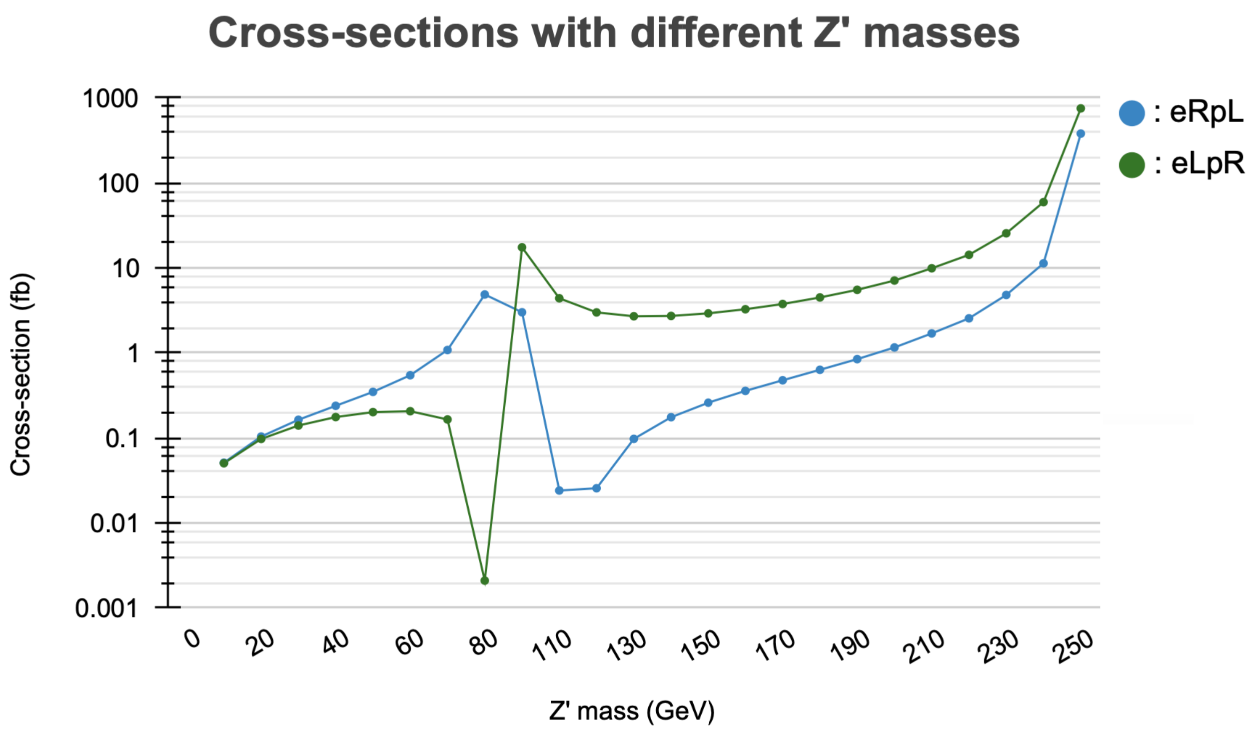

Figure 2: *Dependence of the cross-section on different Z′ masses for both left (green) and right (blue) polarization*

As seen in *Figure 2*, the 90 GeV region shows interference. This happens when the Z′ boson mass, becomes almost identical to the Z boson of 91.18 GeV. For the right polarization the cross-section first increases before decreasing in this region. The same inverse behaviour is true for the left polarization. This asymmetric behaviour of the cross-section relating to the beam polarisation could be looked at for future sensitivity calculations. The cross-section also increases at 250 GeV due to resonance when the Z′ mass is equal to the centre-of-mass energy.

The cross-section dependence on the coupling strength (η) was also investigated for a few different Z' masses. The results confirmed the authors' [8] predictions. The cross-section also scales with the same power of η.

3.2 Utilizing SGV

After investigating the cross-section behaviour, signal distributions were produced using SGV - a fast detector simulation [11]. As seen in *Figure 3* the signal has a peak at 150 GeV in the dimuon spectrum as expected at both generator and simulation level. There was no priori position for the peak at first. The dark photon to dilepton resonance was however expected to be narrower than the detector resolution. In *Figure 3* on the right, there can be seen that the simulation increased the width of the peak.

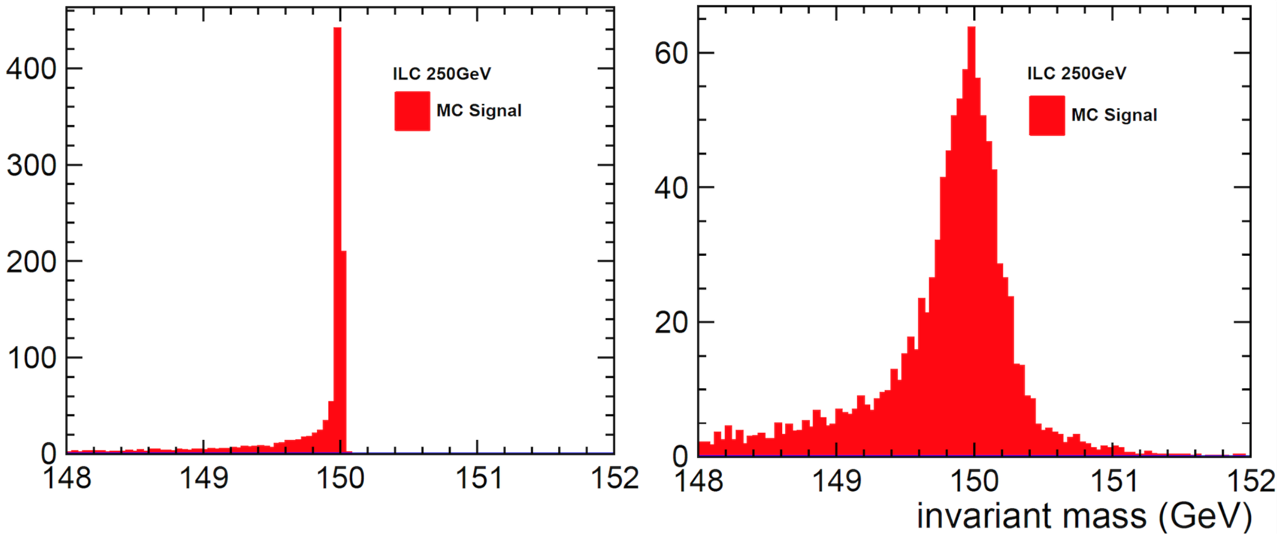

Figure 3: *Invariant mass of the muon pair at generator level (left) and after the simulation (right)*

4 Background Estimation

After generating the main signal the possible background events were produced. For this specific signal, the largest background contributions were thought to be the following:

- Two fermion leptonic production
- Four fermion semi-leptonic production
- Two fermion hadronic production

Cuts were also applied to reduce the background distributions based on the discriminating signal. As with any analysis, the main prerogative is to enhance the signal whilst simultaneously reducing the background distributions.

5 Conclusion

The signal distributions that were generated with SGV shows potential and is worth exploring and fine-tuning further. The behaviour of the cross-section also corresponds with the authors' (of the model) predictions. An optimum window range could be explored and other less dominant background distributions could also be investigated.

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