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ECFA Higgs Factory Study Note: Dark photons

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In a class of theories, dark matter is explained by postulating the existence of a 'dark sector', which interacts gravitationally with ordinary matter. If this dark sector contains a U(1) symmetry, and a corresponding 'dark' photon (A_D) , it is natural to expect that this particle kinetically mix with the ordinary photon, and hence become a 'portal' through which the dark sector can be studied. The strength of the mixing is given by a mixing parameter (ε). This same parameter governs both the production and the decay of the A_D back to SM particles, and for values of ε not already excluded, the signal would be a quite small, and quite narrow resonance. For masses of the dark photon above the reach of Belle II, future high energy e^+e^- colliders are ideal for searches for such a signal, due to the low and well-known backgrounds, and the excellent momentum resolution and equally excellent track-finding efficiency of the detectors at such colliders. We will discuss the dependency of the limit on the mixing parameter and the mass of the A_D using the $A_D \to \mu^+\mu^-$ decay mode in the presence of standard model background, using fully simulated signal and background events in the the International Large Detector concept (ILD) [1] at the International Linear Collider (ILC) [2–7]. We find that the full detector simulation is essential, and that previous theory-based studies are much too optimistic. In addition, a more general discussion about the capabilities expected for generic detectors at e^+e^- colliders operating at other energies will be given.

This work was carried out in the framework of the ILD Concept Group

1 Introduction

Feebly interacting particles, FIPs, is a class of models where dark matter resides in a dark sector, which is neutral under the SM, and only interacts with the visible sector by gravitation. However, it is assumed that there is some part of the dark sector that nevertheless *does* interact with the visible sector, albeit very weakly. This mechanism is known as a portal, and in these models, the reason why the BSM has not yet been seen is not the lack of energy, but the lack of precision - be it luminosity, background contamination or detector performance. Here, we will consider the Vector Portal where the dark photon (A_D) will be the messenger. The coupling to the visible sector is via kinetic mixing, which is expected to occur for this portal, since the dark and visible photons shares quantum numbers. The strength of the mixing, denoted by ε, is a free parameter, which must be small, given that to date no sign of a dark photon has been seen.

2 Dark Photons at Future e^+e^- colliders - Higgs factories and beyond

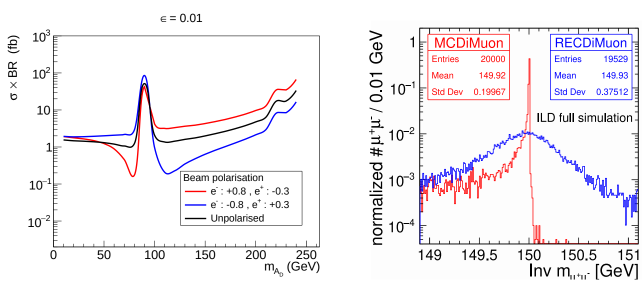
Despite the fact that the various future e^+e^- colliders, at their Higgs factory stage, only reach marginally higher than what LEPII did, huge ameliorations in reaches of A_D searches are expected: They will yield at least 1000 times the luminosity, and - for the linear machines - will feature trigger-less running and polarised beams. In addition there is the benefit of 40 years for detector development. In this work, we have studied the capabilities of one of these [**sepidethesis**, 8], the International Large Detector concept (ILD) [1] at the International Linear Collider (ILC) [2–7] operating at 250 GeV.

The signal process for A_D production at e^+e^- colliders is $e^+e^- \to \gamma_{ISR} A_D \to \mu^+\mu^-\gamma_{ISR}$, where the energy of the ISR is such that the recoil-mass against it is m_{A_D}. As shown in [9], one can note that both production cross-section (σ) and the decay width (Γ) scale with ε^2. As a rough estimate, it seems likely that $\sigma > \mathcal{O}$(1 fb) could be reached at any Higgs factory. For the values of ε^2 that would yield a cross-section of that order (see Figure 1(a)), one finds that Γ is $\mathcal{O}$(10 keV) to $\mathcal{O}$(10 MeV), depending on the mass of the dark photon. This implies, on one hand, that the decay is prompt, with a $c\tau < 1$ nm, and, on the other hand, that detector resolution, not the natural width, will determine the width of the observed peak, see Figure 1(b).

In order to study this process, we generated events according to the model given in [9] with `Whizard` (vers. 3.0) [10]. The generated events were then passed through the full `Geant4`-based simulation and reconstruction of ILD. In the analysis all SM background was included[1]. The procedure was then to select events with two oppositely charged muons, and possibly an isolated photon - nothing else. In the selected di-muon sample, one searches for an arbitrarily small narrow peak in the $m_{\mu\mu}$ distribution.

Figure 2(a) shows the angular distribution of the two muons at four different dark photon masses. The green square indicates the region of coverage of the tracking detectors, and as can be seen, in particular at the lower masses, a large fraction of the events will be lost for the simple reason that at least one of the muons is at

[1] Note that not only $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$ contributes to the background, but also t-channel processes with beam-remnant electrons un-detected, or mistaken for ISR photons.



(a) (b)

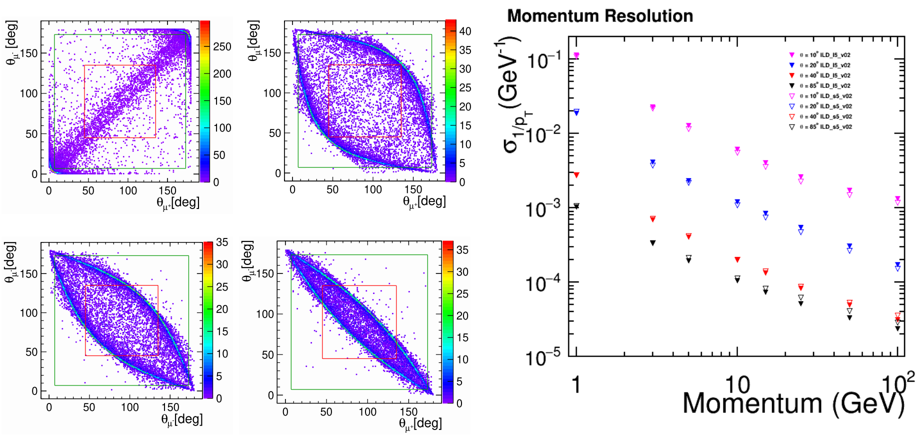
Figure 1: (a): Cross-section times branching ratio of $e^+e^- \to \gamma_{ISR} A_D \to \mu^+\mu^-\gamma_{ISR}$, for the beam polarisations given in the legend; (b): Generated di-muon mass distribution (red), and reconstructed (blue), for a dark photon with mass 150 GeV.

angles below the acceptance of the tracking. The efficiency to find both muons is therefore only $\sim$ 25% for m_{A_D}=10 GeV, but will approach 100 % as m_{A_D} becomes 100 GeV or more.

A simple, but flawed, estimate of the mass resolution can be made assuming that the ISR is along the beam, and that $\sigma(1/p_T)$ vs. p is constant (which it would be for large p). This would yield that $\sigma_m \propto m^2$, and it is the assumption used in [11], to arrive at exclusion limits. However, due to multiple-scattering, for $p \lesssim 100$ GeV, $\sigma(1/p_T)$ is *not* constant, and there is a strong dependence on θ, once the muon is detected in the forward region, rather than the barrel (Figure 2(b)). In addition, the ISR is not always at zero angle to the beam: if it is, the muons would be exactly on the hyperbolas with the highest number of entries in Figure 2(a). In fact, none of the assumptions on the mass-resolution - the red curve in Figure 3(a) - used in [11] are valid. The correct full simulation result is the blue curve. Due to the considerable variation of the momentum resolution with momentum and polar angle, as well as the angle of the ISR photon, the resolution will vary substantially from event to event. Since the uncertainty of the mass is known, event-by-event, the search can be optimised for sensitivity in a search window that will depend on the specific σ_m of each event individually.

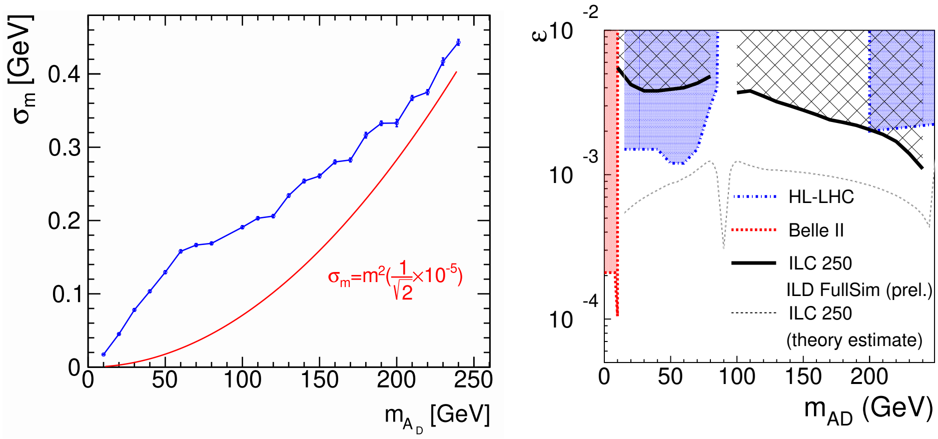
The (current) result with full simulation is shown in Figure 3(b). Compared with the simple, theory level, estimate one finds that at the highest mass, the correct limit is a factor two higher than the naïve estimate, a factor four at 100 GeV. This is due to the correct estimation of the momentum uncertainty. Below M_Z, the difference is larger, and in fact the HL-LHC limits are expected to be stronger. Here, the reason is both due to using a correct error-estimate, but also to the much larger background from non-Z $\rightarrow \mu^+\mu^-$ processes, and the reduced probability to see both muons in the tracking system. This shows that it is unlikely that the reach is better at the lowest m_{A_D} (which the result in [11] indicated). It is rather so that the strongest limit would be obtained close to the kinematic limit, and that a search for Dark Photons would profit from a collider that can readily operate at a wide range of energies, and hence to be able to perform energy-scans. Of the proposed Higgs-factories, only ILC and the Cool Copper Collider (C^3) [13] are expected to be able to do such scans, without need to reconfigure the accelerator.

It is likely that the results can be ameliorated. The full power of polarisation has not been exploited: the limits have been calculated by simply combining the samples with different polarisations - corresponding to the black curve in Figure 1 (a) - rather than using a Likelihood ratio to weight their relative strength. Note, in particular, how the polarisation dependence of the cross-section changes as m_{A_D} passes the Z-pole, see Figure 1(a). Further optimisations of the background suppression could be done at low m_{A_D}, where other processes than $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$ become increasingly important. The region with m_{A_D} close to m_Z was not studied in [**sepidethesis**, 8]; since both background and signal increases equally much (Figure 1 (a)), the



(a) (b)

Figure 2: (a) The polar angle of the μ^- versus that of the μ^+ of the generated $e^+e^- \rightarrow \gamma_{ISR}A_D \rightarrow \mu^+\mu^-\gamma_{ISR}$ events, for m_{A_D} = 10, 100, 150 and 200 GeV (clock-wise, from upper-left). The green square indicates the acceptance of the tracking system of ILD, and the red one indicates the coverage of the barrel tracking system; (b): Momentum resolution for charged particles in ILD from full detector simulation. From [1].



(a) (b)

Figure 3: (a): The di-muon mass resolution versus m_{A_D}. The blue curve is the full simulation results, the red one is the simplified theory level one used in [11, 12]; (b): The exclusion reach of ILC 250 obtained from this full simulation study of ILD, and the expectations of Belle II and HL-LHC (from fig 8.16 of [12]), recast to show m_{A_D} on a linear scale.)

sensitivity is expected to be significantly better in this region.

At the Future Circular Collider, e^+e^- version (FCCee) [14–16] or the Circular Electron Positron Collider (CepC) [17–20], the higher luminosity at lower E_{CM} will be beneficial for searches at lower m_{A_D}. However, some of this advantage will be lost due to the lower B-field imposed at these machines, which will directly reduce the mass resolution by the same factor that the magnetic field has been reduced with, and so also the signal-to-background ratio when searching for narrow peaks. In addition, the acceptance of the tracking system would be slightly worse, which would have some adverse effect at the lowest m_{A_D}, cf. Figure 2(a).

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