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Dark photons at future e^+e^- colliders

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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 kineticly 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: If ϵ is large enough to yield a detectable signal, its decay width will be smaller than the detector resolution, but so large that the decay back to SM particles is prompt. 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. This contribution will discuss a study investigating the dependency of the limit on the mixing parameter and the mass of the A_D using the $A_D \rightarrow \mu^+\mu^-$ decay mode in the presence of standard model background, using fully simulated signal and background events in the ILD detector at the ILC Higgs factory. In addition, a more general discussion about the capabilities expected for generic detectors at e^+e^- colliders operating at other energies will be given.

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1. Introduction

A plethora of cosmological and astronomical observations firmly establish that there is Dark Matter (DM), making up 85 % of the matter in the universe. While Weakly Interacting Massive Particles (WIMPs) remains a strong candidate for a sub-atomic explanation of the nature of DM, experiments to observe them have so far all failed to do so. This has given rise to another idea, namely that DM resides in a *dark, hidden sector*, with very weak interactions with the visible sector.

Feebly interacting particles, FIPs, is such a class of models. In these models, 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. Hence, 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.

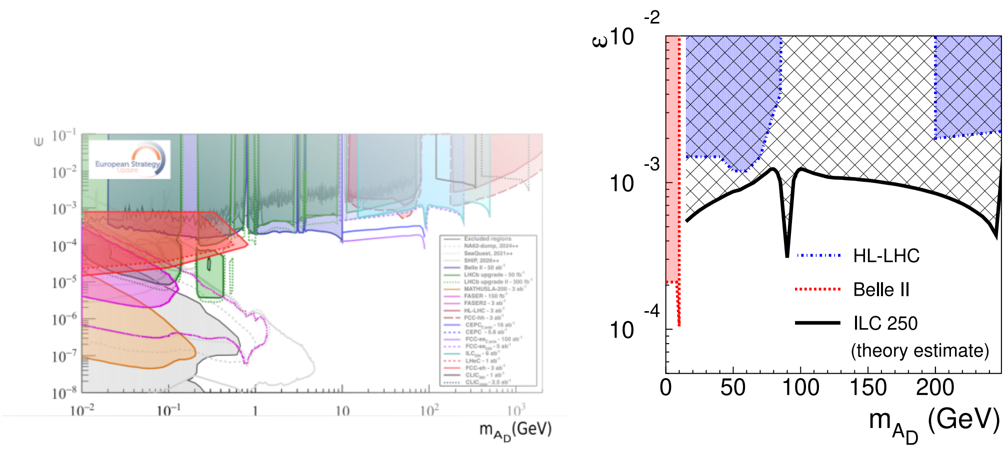
The mechanism of this window into the dark sector is known as a portal. Portals comes in different types, conventionally classified by the type of the interaction as the Higgs Portal, the fermions Portal, the Pseudoscalar Portal, and the Vector Portal, corresponding to the higgs, sterile neutrinos, ALPS, or dark photons being the messenger. Here, we will discuss the last case.

2. The Vector Portal - Dark Photons, A_D

Assume that there is a dark sector with a dark U(1) symmetry. The relevant part of the Lagrangian is [1]:

$$\mathcal{L}_{gauge} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m^2_{D,0}\hat{Z}^{\mu}_D\hat{Z}_{D\mu}$$

$\hat{B}$ is the ordinary U(1) field-strength tensor, and $\hat{Z}_D$ that of the dark U(1). The Dark Photon (the A_D) might mix with the photon by *kinetic mixing*- the $\hat{Z}_D\hat{B}$ term - so that $e^+e^- \to A_D \to f\bar{f}$ is possible. The free mixing parameter ϵ must be small, otherwise this process would already have been detected. There will be few events, but the decay will form a very narrow peak, or even



(a) **(b)**

Figure 1: Expected Dark photon limits from EPPSU briefing-book. (a) Original figure, with all experiments considered and on a logarithmic mass-scale; (b) the same on a linear mass scale (up to the reach of the higgs factories), only showing the relevant experiments on this scale (Belle II, ILC 250 and HL-LHC).

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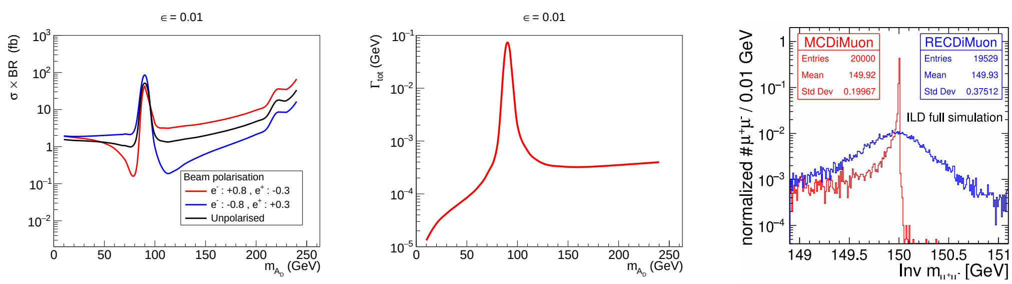
a displaced vertex. Note that the dark photon itself is *not* the dark matter, since it isn't stable; Something else in the dark sector that is stable is needed in addition.

The current projections for Dark Photon limits from the European Particle Physics Strategy Update of 2019 [2] are shown in Fig. 1(a), and on a linear mass-scale in Fig. 1(b). For masses up to ~ 1 GeV, dark photons are likely to be long-lived and will be best detected in Beam-dump experiments. Beyond that colliders will be needed. Up to 10 GeV, the B factories will be the most powerful tools, due to their extremely high luminosity. At higher energies, e^+e^- up to their maximum energy will give the best sensitivity, and beyond that hadron colliders will have some reach, but only at quite large couplings. One should note that the "ILC" (and CepC, FCCee) curves are very simplistic theoretical estimates [3] and - as we will see - are much too optimistic.

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

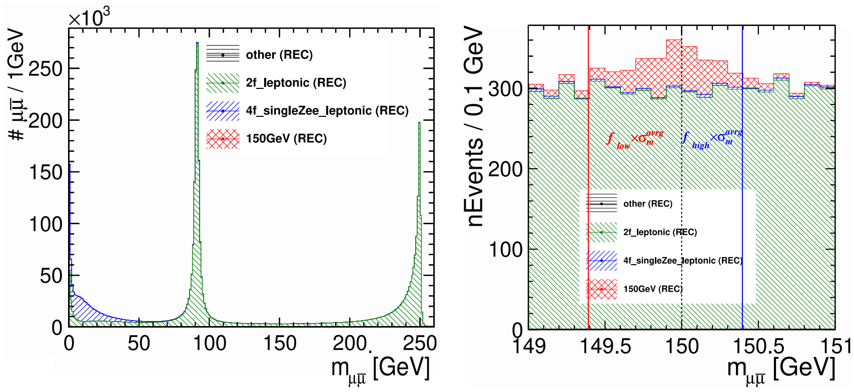
The proposed linear Higgs factories are the International Linear Collider (ILC) [4], the Cool Copper Collider (C3) [5], and the Compact Linear Collider (CLIC) [6]. Apart from operating at the optimal energy for studying the Higgs, these machines foresee energy upgrades, up to the TeV range. Circular colliders - the Circular Electron Positron Collider (CEPC) [7] and the Future Circular Collider (FCCee) [8], put more emphasis on lower energies (but can be upgraded to 365 GeV); in particular they can achieve very large luminosities when operating at the Z-pole. Despite the fact that these machines, at their Higgs factory stage, only reach marginally higher than what LEPII did, huge ameliorations in reach of A_D searches are expected: They will yield at least 1000 times the luminosity, and will feature trigger-less running, and - for the linear machines - polarised beams. In addition there is the benefit of 40 years for detector development, and indeed, many detector concepts have been proposed. In this work, we have studied the capabilities of one of these [9], the International Large Detector concept (ILD) [10] at ILC operating at 250 GeV.

The signal process for A_D production at e^+e^- colliders is $e^+e^- \rightarrow \gamma_{ISR} A_D \rightarrow \mu^+\mu^-\gamma_{ISR}$, where the energy of the ISR is such that the recoil-mass against the ISR is m_{A_D}. In order to study this process, we generated events according to the model given in [1]. The Unified Feynrules Output files describing the model, and supplied by the authors, were used as input to the event-generator `Whizard` (vers. 3.0) [11]. One can note that both production cross-section (σ) and the decay width (Γ) scales with ϵ^2. As a rough estimate, it seems likely that $\sigma > O(1\text{ fb})$ could be reached at any Higgs factory. For the values of ϵ^2 that would yield a cross-section of that order (see Fig. 2(a)) ,



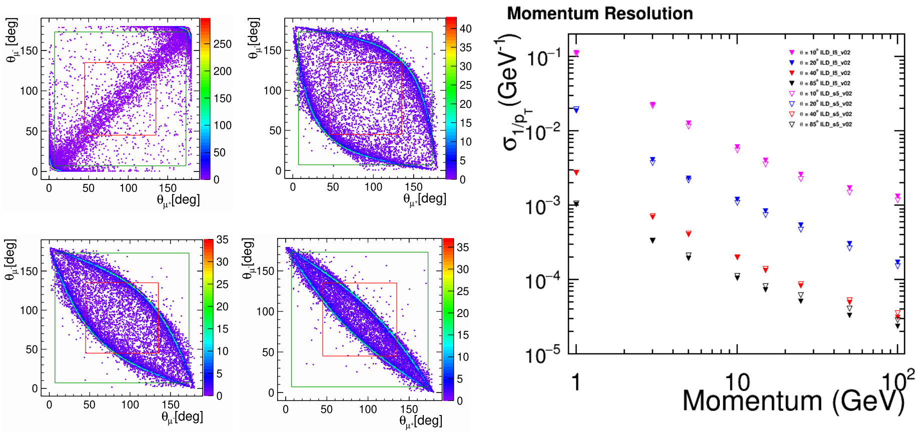
(a) (b) (c)

Figure 2: (a): Cross-section times branching ratio of $e^+e^- \rightarrow \gamma_{ISR} A_D \rightarrow \mu^+\mu^-\gamma_{ISR}$, for the beam polarisations given in the legend; (b) Total width of A_D; (c): Generated di-muon mass distribution (red), and reconstructed (blue), for a dark photn with mass 150 GeV.



(a) **(b)**

Figure 3: Di-muon mass distributions for m_{A_D} = 150 GeV from full simulation of ILD: (a) All events; (b) Zoom of (a) into the signal region; All backgrounds are included.



(a) **(b)**

Figure 4: (a) The polar angle of the μ^- versus that of the μ^+ of the generated $e^+e^- \to \gamma_{ISR} A_D \to \mu^+\mu^-\gamma_{ISR}$ 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;

one finds that Γ is O(10 keV) to O(10 MeV), depending on the mass of the dark photon, see Fig. 2(b). This implies that the decay is prompt, with a $c\tau$ < 1 nm, and detector resolution, not the natural width, will determine the width of the observed peak, see Fig. 2(c).

The generated events were then passed through the full `Geant4`-based simulation (`ddsim`) and reconstruction (`Marlin`) of ILD. In the analysis all (fully simulated) SM background was included[1]. The procedure was then to select events with two muons, and possibly an isolated photon - nothing else. In the selected di-muon sample, one searches for an arbitrarily small peak in the $m_{\mu\mu}$ distribution, with a width given by the detector resolution, not the natural width, since the latter is expected to be much smaller at all masses of the dark photon. Fig. 3(a) shows the full mass-spectrum, and Fig. 3(b) is a zoom into at the signal region, in this case for a dark photon with mass 150 GeV.

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

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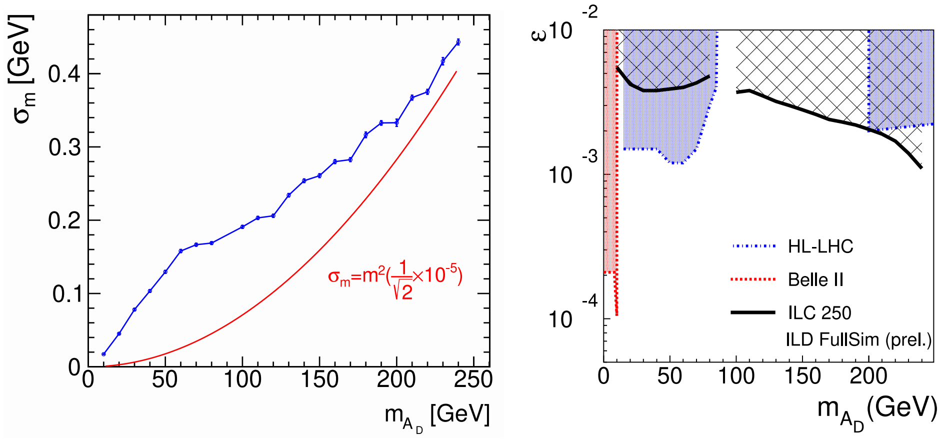

(a) **(b)**

Figure 5: (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 [2, 3]; (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 [2])

Fig. 4(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 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 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 - as is often stated as a first approximation. This will yield that $\sigma_m \propto m^2$, and it is the assumption used in [3], to arrive at the exclusion limits shown in the briefing book (Fig. 1), which also assumes that the background is only $\mathrm{e^+e^-} \rightarrow \mu^+\mu^- + ISR$. 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 in the forward region, rather than the barrel (Fig. 4(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 Fig. 4(a). In fact, none of the assumptions on the mass-resolution - the red curve in Fig. 5(a) - used for the EPPSU curve 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. Hence, event-by-event simulation is essential.

Note that since the uncertainty of the mass is known, event-by-event, the search can be optimised for sensitivity by finding the factors f_{low} and f_{high} in an event-specific search window from $f_{low}\sigma_m$ to $f_{high}\sigma_m$ around the probed mass that yields the highest sensitvity.

4. Expected exclusions

The (current) result with full simulation is shown in Fig. 5(b). Compared with the simple, theory level, estimate (Fig 1(b)), one sees 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 estimating the momentum uncertainty correctly. 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 due to the much larger background from non-$Z \to \mu\mu$ processes.

5. Conclusion and outlook

Even for - or maybe in particular for - the most simple topology full simulation is needed to arrive at a realistic result. This is because in these cases, precision is the most important aspect. Nevertheless, even though the correctly evaluated reach is significantly less than the theory estimate, e^+e^- colliders will probe lower dark photon couplings than HL-LHC, at least for masses above M_Z.

This is work-in-progress. Several enhancement of the analysis are possible. We did not yet utilise Likelihood Ratio weighting of the samples with different polarisations. The special region with m_{A_D} close to M_Z (the gap in the exclusion reach seen in Fig. 5b) was beyond the scope of our study. We only studied the muon-channel, as it is expected to be the one with superior mass-resolution. One could attempt to include $A_D \to e^+e^-$. This would necessitate to develop methods to compensate for brems-strahlung to get good enough mass-resolution. Furthermore, one could attempt to use the properties of any detected ISR to reduce background at low m_{A_D}. One could envision to use a full un-binned Maximum Likelihood approach to fully exploit the knowledge of the event-by-event error. Finally, it is clear that the sensitivity is the highest if the collider is operated at, or close to, the mass of the dark photon. One could therefore consider to spend some running-time scanning E_{CMS}, if this is straight-forward from the point-of-view of machine operations. Of the proposed Higgs-factories, only the ILC offers this possibility.

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