PROBING DARK FORCES AT GeV-SCALE COLLIDERS*

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Since the 1980s a broad class of new physics models has postulated the existence of a light, weakly coupled neutral gauge boson (dark photon). In recent years, a wealth of astrophysical anomalies has been explained in terms of this idea, without contradicting existing particle physics data. Because these new GeV-scale bosons communicate with the Standard Model particles, they can be produced in a controlled laboratory environment and low-energy experiments with high luminosity are the prime place to look for such states. Here we focus on the process of associated production of a photon and a dark photon at GeV-scale high-luminosity e^+e^- colliders. We present the experimental sensitivity to a dark photon signal of current experiments like KLOE-2 at DAϕNE and at a future super$B$ factory. Our calculation is implemented in an upgraded version of the generator BabaYaga@NLO, available for data analysis in these new physics searches.

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1. Motivating dark forces

According to general theoretical arguments early introduced in the 1980s [1, 2, 3], it is conceivable to postulate the existence of new gauge bosons without contradicting all the plethora of particle physics data, provided the coupling of the new bosons with the Standard Model (SM) particles

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is sufficiently small. This scenario can be realized by adding to the gauge structure of the SM a secluded hidden sector that contains the new gauge fields and communicates with the SM through a kinetic mixing.

In recent years, this idea received a renewed interest in the light of various astrophysical observations that can be difficultly explained in terms of standard astrophysical or particle physics sources. These anomalies include the 511 KeV gamma-ray signal from the galactic center observed by the INTEGRAL satellite, the excess in the cosmic ray positrons reported by PAMELA (recently confirmed by Fermi) and the total electron and positron flux measured by Fermi, ATIC and HESS, as well as the direct, albeit controversial, signals of Dark Matter (DM) detection reported by the DAMA/CoGent experiments. The most striking features of the indirect astrophysical observations is the presence of high event rates in the hard lepton energy spectrum and an excess of positrons without antiproton anomalies.

As argued in a number of papers, see *e.g.* [4, 5], all these evidences can be interpreted as a whole by assuming the existence of a secluded sector that incorporates DM with mass at the TeV scale and new gauge bosons at the GeV scale, and wherein DM has self-interactions through the exchange of the new light bosons. According to this explanation, the data are due to annihilation of DM into GeV-scale bosons, which decay into charged leptons and are light enough to kinematically forbid a decay that produces antiprotons. Among the different constructions present in the literature, the specific model under study in the present work is described in Sec. 2.

2. The model: structure and implications

The simplest way to realize the above ideas is adding to the SM gauge structure a new Abelian symmetry [6]. The total Lagrangian is given by the sum of three contributions

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{\rm mix}\,, \tag{1}$$

where $\mathcal{L}_{\rm SM}$ is the SM Lagrangian, $\mathcal{L}_{\rm DM}$ is the Lagrangian of the $\mathrm{U}(1)_{\rm S}$ secluded sector and $\mathcal{L}_{\rm mix}$ is a kinetic mixing Lagrangian. The $\mathrm{U}(1)_{\rm S}$ group is supposed to contain DM fields, a vector gauge field A'_μ (dark photon) and a single complex scalar Higgs field ϕ responsible for spontaneous symmetry breaking. Assuming the SM particles uncharged under the new gauge sector, all the interactions with the SM are mediated by kinetic mixing of $\mathrm{U}(1)_{\rm S}$ with the photon[1]. Therefore, $\mathcal{L}_{\rm mix}$ takes the form

$$\mathcal{L}_{\rm mix} \;=\; -\frac{\epsilon}{2}\, F^{\rm em}_{\mu\nu} F^{\mu\nu}_{\rm dark}\,, \tag{2}$$

[1] We neglect kinetic mixing with the Z boson, as usually done in the study of dark forces at low energies.

where $F_{\mu\nu}, F_{\mu\nu}^{\text{dark}}$ are the photon field strength and dark photon field strength, respectively. The kinetic mixing can be supposed to be generated by loops of heavy particles and therefore the kinetic mixing parameter ϵ is naturally of the order of 10^{-3} or even smaller. Since the kinetic mixing term can be removed by a redefinition of the photon field, it follows that the SM fermions weakly interact with the dark photon with a coupling given by $\epsilon\, e$, e being the electric charge. After spontaneous symmetry breaking, the $\mathrm{U(1)_S}$ vector field A'_μ acquires a mass M_U which is believed to lie in the GeV range to explain the above discussed astrophysical anomalies.

An interesting consequence of the above ideas is that the existence of the dark photon produces observable effects that can be probed in laboratory experiments in a controlled environment. For example, there is an additional contribution of the dark photon to the anomalous magnetic moment of the muon and the electron, and to the fine structure constant inferred by the $g-2$ of the electron. It is known [7] that in order to avoid contradiction with the QED precision measurements, the kinetic mixing parameter must be below $\sim 10^{-3}$–10^{-2} for a U boson mass up to about 500 MeV. Other testable model predictions apply to beams of electrons or protons interacting with a fixed target. Various studies [8, 9, 10] show that present and future fixed-target experiments (at Fermilab, MAMI, JLab, DESY) are sensitive to the very small ϵ region but for low-intermediate dark photon masses only.

3. Probing the dark force at GeV-scale e^+e^- colliders

In order to probe all interesting mass values (at least up to the two proton mass threshold), it is necessary to consider the sensitivity of the so-called flavor or meson factories, like ϕ, τ-charm and B/super$B$ factories. The meson factories are ideal places to look for particles in the GeV scale because: *(i)* their (centre of mass) c.m. energy $\sqrt{s}$ is in the range between 1 and 10 GeV and the U boson production cross-section scales like $1/s$, making these accelerators more advantageous for these searches than very high-energy colliders; *(ii)* their integrated luminosity is very high, as required by the study of very rare processes; *(iii)* the U boson production at flavor factories gives rise to clean and distinctive signatures in the detectors.

The dark photon can be produced at flavor factories through different mechanisms. The main production channels are: *(i)* the decays of neutral mesons, with subsequent decay of the U boson into a lepton pair; *(ii)* the higgstrahlung process, with associated production of a new Higgs and a dark photon, if their masses are both smaller than the available c.m. energy; *(iii)* the associated production of a photon and a U boson, which is the process that received much attention in the literature and is addressed in detail in Secs. 3.1 and 3.2.

3.1. $U\gamma$ associated production, $U \to l^+l^-(l = e, \mu)$

The associated production of a photon and a U boson, with decay of the U into electron or muon pairs, is particularly interesting because it is a quite simple channel insensitive to the details of the Higgs sector of the secluded group. A very distinctive feature of the expected signal is the appearance of a Breit–Wigner peak in the shape of the invariant mass distribution of the lepton pairs. This bump is induced by the mechanism of photon radiative return, corresponds to U boson resonant production and allows to probe generic mass values, the dark photon mass being an unknown parameter of the model. The drawback of this channel is the very small value, over a wide range of the parameters, of the signal cross-section in comparison with the rate of the backgrounds given by the standard QED radiative processes.

In spite of these limitations, the process was the subject of many papers [6,11,12,13,14,15] that agree on the conclusion that the $U\gamma$ production process allows to reach a sensitivity to the kinetic mixing parameter down to $\sim 10^{-3}$ at present meson factories. However, all these phenomenological studies are based on the calculation of the signal and background cross-section at the tree level, thus neglecting the contribution of possibly important higher-order corrections. Moreover, they do not provide any MC generator which is necessary for a sensible experimental analysis. To overcome the above limitations, we performed [16] a new calculation of the process $e^+e^- \to \gamma, U \to l^+l^-\gamma$, $l = e, \mu$ based on the exact evaluation of signal and background matrix elements, including U boson off-shell effects. We further included the most important radiative corrections, given by vacuum polarization and the contribution of multiple soft and collinear radiation from the initial-state (ISR) and final-state (FSR) leptons. We showed that ISR and FSR are needed for a precise reconstruction of the lepton pair invariant mass distribution, yielding corrections of several tens of per cent also in the presence of realistic detector resolution effects. All these ingredients are now implemented in an upgraded version of the generator BabaYaga@NLO [17] which is a standard tool for the simulation of Bhabha scattering and QED processes at meson factories [18]. The updated code can be downloaded at the web address `http://www.pv.infn.it/~hepcomplex`

3.2. Statistical significance

Using the upgraded version of BabaYaga@NLO, we revisited the reach potential of flavor factories to a dark photon signal. In our study we adopted realistic event selection cuts and detector resolution parameters, as well as actual values for the collider luminosity. We refer to [16] for details. We computed the statistical significance as

$$\frac{N_{\mathrm{S}}}{\sqrt{N_{\mathrm{B}}}} = \frac{L\left(\sigma_{\mathrm{SM}+U} - \sigma_{\mathrm{SM}}\right)}{\sqrt{L\sigma_{\mathrm{SM}}}} \equiv \sqrt{L}\frac{\sigma_{\mathrm{S}}}{\sqrt{\sigma_{\mathrm{SM}}}} \tag{3}$$

requiring the above ratio to be greater than five for discovery. In Eq. (3) N_{S} and N_{B} are the expected number of signal and background events, respectively, $\sigma_{\mathrm{SM}+U}$ is the full cross-section including the exchange of virtual photon and U boson, σ_{S} and σ_{SM} the signal and background cross-section, and L the integrated luminosity.

In Fig. 1 we show the reach potential of KLOE/KLOE-2 experiment, plotting the sensitivity to the kinetic mixing parameter ϵ as a function of the U boson mass for the two leptonic final states. The grey areas correspond to the exclusion limits imposed by the precision measurements of the anomalous magnetic moment of the leptons and of α_{QED}. The muon channel has better reach than the e^+e^- channel which is affected by a large radiative Bhabha scattering background. Both channels have a sensitivity which is significantly degraded if the U boson mass is around the ρ resonance because the branching fraction $U \to l^+l^-$ is suppressed by the dominant decay mode $U \to \pi^+\pi^-$. These results refer to a so-called large angle selection, where all the final-state particles are detected at wide scattering angles. In our study we also analyzed the sensitivity according to a small-angle selection, where the two leptons are seen at large angles and the photon is detected at small angles, say below 15°. Interestingly, we concluded that this kind of event selection allows a gain in sensitivity for U boson masses above about 500 MeV at KLOE/KLOE-2 energies [16].

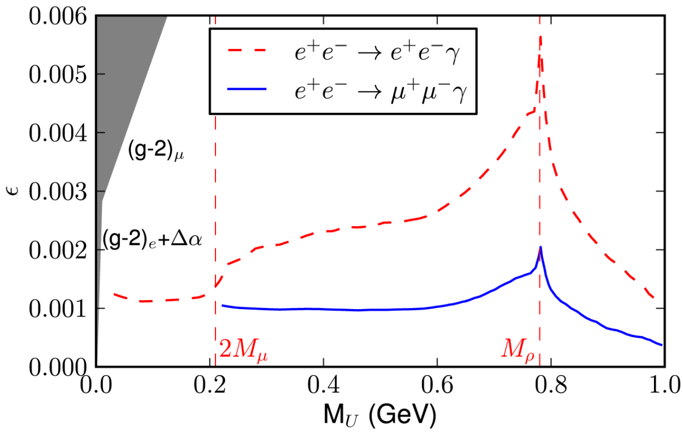

Fig. 1. Discovery potential, defined as the value ϵ at which $N_{\mathrm{S}}/\sqrt{N_{\mathrm{B}}} = 5$, as a function of the dark photon mass M_U, at KLOE/KLOE-2 for an integrated luminosity $L = 5$ fb^{-1} and large angle selection cuts.

In Fig. 2 we present the discovery potential at a super$B$ factory, for a large-angle event selection. It can be seen that at these very high luminosity colliders ϵ can be probed at the 10^{-4} level, with a degradation of the sensitivity at the ρ and ϕ resonances where U decays into hadrons dominate.

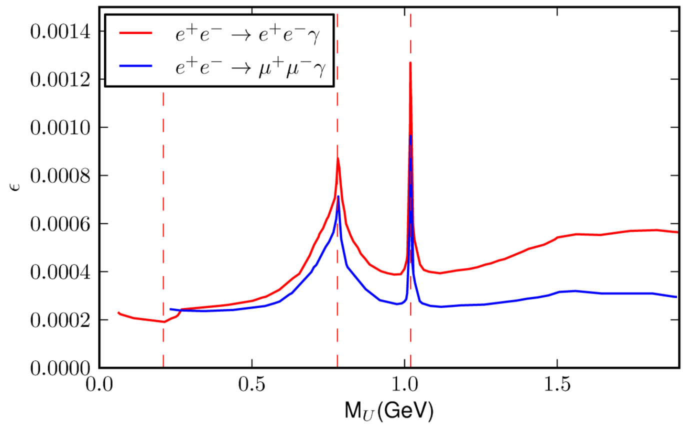

Fig. 2. The same as Fig. 1 at a super$B$ factory with $L = 100$ ab^{-1}.

4. Conclusions

A number of puzzling astrophysical observations can be interpreted in terms of a secluded hidden sector that contains DM particles, new gauge fields and mixes with the SM. The main implication of this idea, in its minimal implementation, is the existence of a new GeV-scale, weakly interacting neutral boson that can be looked for in low-energy experiments with high luminosity.

We concentrated on the possible detection of such a dark photon U in the process of associated $U\gamma$ production, with U decaying into lepton pairs, at high-luminosity flavor factories with c.m. energy in the 1–10 GeV range. We provided an exact tree-level calculation of the signal and background cross-sections and included the most important sources of higher-order corrections. We made our calculation available in an upgraded version of the event generator BaBaYaga@NLO, to provide a complete tool useful for the experimental analysis.

We showed that $U\gamma$ production at present and future flavor factories can probe values of the kinetic mixing parameter down to 10^{-3}–10^{-4}, for all interesting mass values. Under the hypothesis of null discovery results, this will provide new constraints on the model parameters, in addition to the present exclusion limits coming mainly from QED precision measurements, beam dump experiments at Fermilab, searches in the $\mu^+\mu^-\gamma$ final state at

BaBar [19] and in meson decays at KLOE-2 [20], as well as from fixed-target experiments at MAMI [21] and Jlab [22]. With respect to the meson factories, next-generation fixed target experiments with high luminosity are expected to probe complementary regions of the model parameters, *i.e.* low-intermediate mass, very small ϵ values.

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