Dark Photon Searches at MAMI and MESA

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DOI: http://dx.doi.org/10.3204/DDESY-PROC-2013-04/denig_achim

1 Introduction

A hypothetical dark photon, denoted here as γ', is a massive force carrier of an extra U(1) gauge group as predicted in almost all extensions of the Standard Model[1]. In string theory the mass of such a dark photon cannot be predicted and experimental searches are indeed ongoing from very small mass scales, e.g. axion-like scales, to the highest scales at the LHC. More recently, dark photons on the MeV to GeV mass scale are at the focus of interest. This is due to the fact that Arkani-Hamed et al. [1] as well as others have suggested that such a dark photon could couple to dark matter, which would also explain quite a large number of astrophysical observations, such as e.g. the positron excess in the cosmic ray flux. Furthermore, it was realized that the presently seen deviation between the Standard Model prediction and the direct measurement of the anomalous magnetic moment of the muon, $(g-2)_\mu$, on the level of 3 to 4 standard deviations [2] could also be explained by a GeV-scale dark photon. The interaction strength of the dark photon with Standard Model matter is governed by the mechanism of kinetic mixing [3]. The coupling can be subsumed by an effective coupling constant ϵ and a vertex structure of a massive photon.

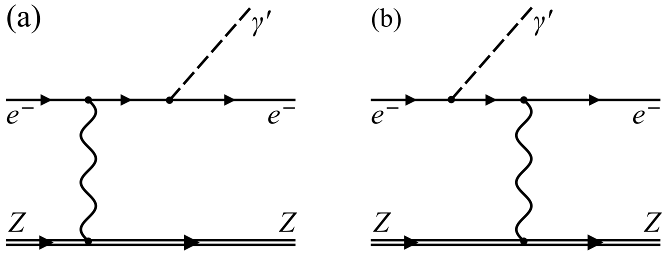

Figure 1: Electromagnetic production of the γ' boson in electron-nucleus scattering.

The above mentioned dark photon explanations of a series of astrophysical as well as particle physics puzzles have motivated searches for a GeV-scale dark photon in a world wide effort. Bjoerken and collaborators [4] have pointed out that low-energy electron accelerators for fixed-target experiments – such as the Mainz Microtron MAMI - in combination with high resolution

[1]In literature the dark photon is also denoted as A', U, or ϕ.

spectrometers – such as the A1 setup in Mainz – are indeed ideally suited for such kind of searches. The production of the dark photon appears as an initial state radiation (final state radiation) process at the vertex of the reaction, see Fig. 1. Since the coupling is small, the cross section for the electromagnetic production of the γ' boson can be enhanced by a factor Z^2 by choosing a heavy nucleus as the target. The subsequent decay of the γ' boson to a lepton pair is the signature of the reaction. Background processes are given by reactions where an ordinatory photon is radiated off the electron rather than a γ'. Also t-channel QED diagrams contribute to the background significantly. A dark photon would appear as a bump on top of the background in the electron-positron invariant mass spectrum. This requires therefore high intensity beams as well as high mass resolution to find a significant signature.

2 MAMI Searches for the Dark Photon

The Mainz Microtron MAMI [5] accelerates electrons in the energy range from 180 MeV to 1604 MeV with intensities up to 140 μA. The search for the γ' boson is carried out by the A1 collaboration with the high-resolution spectrometer setup [6]. The spectrometers feature a very high momentum resolution of approximately 10^{-4} as well as good PID capabilities and an excellent time resolution.

2.1 2010 Pilot Run

In 2010 a pilot run took place at MAMI with the primary goal to investigate up to which extent additional background sources need to be taken into account beyond QED processes. An unpolarized beam with an energy of 855 MeV was incident on a tantalum target. Luminosities in the order of $10^{39}\text{cm}^{-2}\text{s}^{-1}$ were achieved in this experiment. For the detection of the electron-positron pair, two high-resolution spectrometers of the A1 setup were used. The particles were detected by vertical drift chambers for tracking and scintillator detectors for trigger and timing purpose. In addition, a threshold-gas-Čerenkov detector was used in each arm to discriminate between electrons or positrons and pions. The kinematics of the reaction was such, that almost a complete energy transfer of the virtual photon on the potential dark photon was achieved. The two spectrometers were sensitive to decays in electrons and positrons with equal momenta. It was shown in Monte Carlo simulations that such a configuration suppresses background most effectively.

Apart from the well known QED channels no indications for additional background was found. From four days of data taking indeed a competitive exclusion limit could be extracted, which is shown as the yellow area in Fig.2 and which was published in Ref.[7]. The plot shows the hypothetical coupling of the γ' to Standard Model matter ϵ^2 versus its hypothetical mass $m_{\gamma'}$. Recent limits had been obtained by Babar [8] and KLOE [9][2]. Shown are also old exclusion limits from beam dump experiments at SLAC and FNAL. The grey areas are exclusion limits obtained from the $(g-2)_e$ of the electron as well as the $(g-2)_\mu$ of the muon. If one assumes that the presently seen deviation on the level of 3.6σ between the Standard Model prediction and the direct measurement is due to a missing contribution of a dark photon in the $(g-2)_\mu$ calculation, one obtains a prediction for the possible parameter range of the dark photon [11]. As can be seen, a significant progress has been achieved at A1/MAMI compared to the existing Babar exclusion limit at masses from 220 MeV to 290 MeV. The plot demonstrates impressively the

[2] In the meantime a new exclusion limit has obtained also from the WASA collaboration at COSY [10]

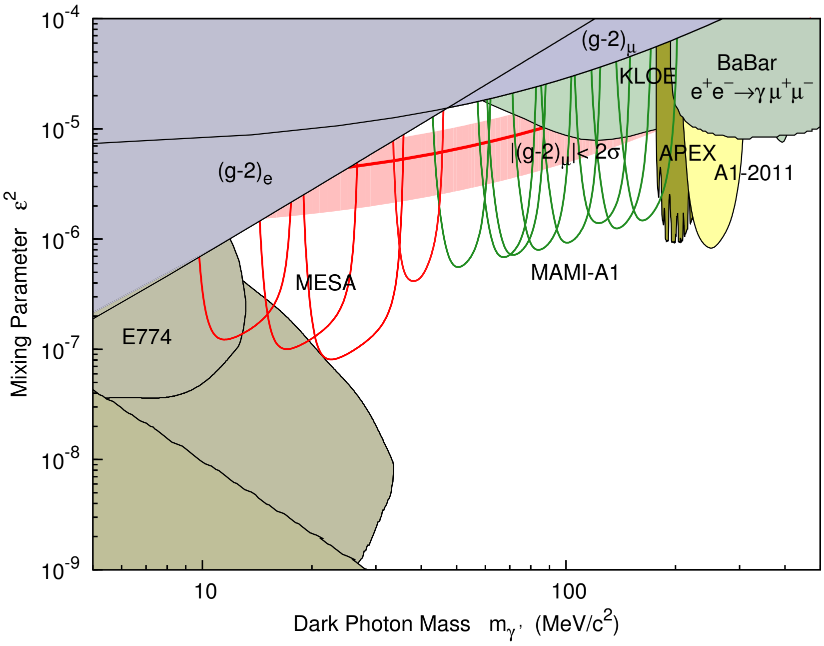

Figure 2: Existing as well as planned exclusion limits for the possible parameter space of the dark photon. Shown is the coupling of the γ' to Standard Model matter ϵ^2 versus its hypothetical mass $m_{\gamma'}$. See text for further explanations.

potential of high-intensity fixed target experiments. After the publication of Ref.[7] a correction of the published MAMI limit has been calculated in Ref.[12]. The correction is related to an issues in the theoretical treatment of the QED background, which in consequence weakens the MAMI limit. The JLab experiment APEX has published a similar exclusion limit at somewhat lower invariant masses [13].

2.2 Data Taking 2012 and 2013

In 2012 and 2013 two data taking periods took place at MAMI with in total nine invariant mass settings of the spectrometers. The analysis of data is in an advanced state. The green exclusion bands in Fig.2 show the sensitivity as expected from simulation. The mass range between approximately 50 MeV and 210 MeV can be covered in these settings with ϵ^2 values in the order 10^{-6} . This allows to test a significant part of the parameter range motivated by $(g-2)_\mu$. With respect to the pilot run the target has been changed from a single Tantalum foil to a stack of 12 strips. This allows to reduce effects of multiple scattering in the target while keeping a very high luminosity. Furthermore, while during the pilot run the beam current was limited due to a relatively high level of radiation in the experimental hall, in 2012 and 2013 the MAMI intensity was limited due to a high rate in the focal plane detectors of the spectrometers.

2.3 Displaced Vertex Technique

In near future a beam time for dark photon searches is planned which will allow to test the low ϵ^2 range around 10^{-10} for dark photon masses from 50 MeV to approximately 140 MeV. This will be possible with a dispaced vertex technique. The primary target will be heavily shielded for this experiment and the geometrical acceptance of the spectrometers will be adjusted such that only dark photons with a mean decay path of several centimeters can be detected. Such a lifetime corresponds to very low ϵ^2 values.

3 Perspectives for Dark Photon Searches at MESA

The construction of the Mainz Energy Recovering Accelerator MESA [14] offers new possibilities for dark photon searches especially at low masses. The existing MAMI accelerator is incapable of studying the mass range below 50 MeV due to the lowest possible beam energy of 180 MeV and the geometrical constraints of the spectrometers. MESA will be operated for dark photon experiments in an ERL (Energy Recovering LINAC) mode with beam intensities of up to 10 mA. The combination of an internal gas target together with the very high beam current provides high luminosities of at least $10^{34}\text{cm}^{-2}\text{s}^{-1}$ while minimizing the effects of multiple scattering. We have performed a feasibility study assuming a setup of high-resolution spectrometers with a similar performance as the A1 setup. Using a Xenon gas target, one achieves sensitivities as the ones shown in in red in Fig.2. Such an experiment in combination with the measurements at MAMI will finally cover the entire parameter range for the dark photon suggested by $(g-2)_\mu$.

4 Acknowledgments

The authors would like to thank the MAMI accelerator group for providing the excellent beam quality and intensity necessary for the dark photon experiment. This work was supported by the Federal State of Rhineland-Palatinate and by the Deutsche Forschungsgemeinschaft within the Collaborative Research Center 1044 *The low-energy frontier of the Standard Model.*

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