Search for light massive gauge bosons as an explanation of the \((g − 2)_μ\) anomaly at MAMI

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A massive, but light abelian \(U(1)\) gauge boson is a well motivated possible signature of physics beyond the Standard Model of particle physics. In this paper, the search for the signal of such a \(U(1)\) gauge boson in electron-positron pair-production at the spectrometer setup of the A1 Collaboration at the Mainz Microtron (MAMI) is described. Exclusion limits in the mass range of 40 MeV/\(c^2\) up to 300 MeV/\(c^2\) with a sensitivity in the mixing parameter of down to \(\epsilon^2 = 8 \times 10^{-7}\) are presented. A large fraction of the parameter space has been excluded where the discrepancy of the measured anomalous magnetic moment of the muon with theory might be explained by an additional \(U(1)\) gauge boson.

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INTRODUCTION

The completion of the Standard Model (SM) of particle physics by the discovery of the Higgs particle at the Large Hadron Collider (LHC) is undoubtedly a remarkable success after decades of particle physics experiments [1]. This success, however, also emphasizes one of the unresolved major questions of today’s physics: the meanwhile well-established existence of dark matter in the universe is one of the most pressing indications for the need for new physics beyond the SM. Since there are up to now no experimental hints from LHC for super-symmetry, which for decades provided the most promising candidate from particle physics for Dark Matter, the search for physics beyond the SM has to be extended to more general concepts.

Given the rich structure of the SM it would not be surprising to have a similar rich structure for a possible dark sector, consisting of particles and interactions with only tiny interaction with SM matter and fields. Most extensions of the SM, like e.g. string theory, provide such a rich structure, which has to be broken down to the observed SM.

In the last years, a particularly well motivated portal to such a dark sector, the search for a massive \(U(1)\) gauge boson, triggered a vast amount of theoretical and experimental activities. Such a \(U(1)\) gauge boson, sometimes called “dark photon” or \(γ’\), arises naturally in several extensions of the SM as lowest rank interaction of this sector (see e.g. ref. [2] for an overview).

The residual interaction of a dark photon with SM matter is given in a simplest model by kinematic mixing [3] [4], producing an effective interaction \(\epsilon e A^\mu_{γ'μ}\) of the dark photon field \(A'\) with the electric current \(J_{EM}\). The strength of this interaction is given by the mixing parameter \(\epsilon^2 = \alpha'/\alpha\) equal to the ratio of dark and SM electromagnetic couplings, and which is not required to be small from first principles. Assuming that \(\epsilon\) vanishes at high energies, \(\epsilon\) can be generated by perturbative corrections including particles which are charged both under electromagnetic interaction and the \(U(1)\) interaction, leading to a natural scale of \(\epsilon \sim 10^{-8} – 10^{-2}\). Including non-perturbative models, values of \(\epsilon \sim 10^{-12} – 10^{-3}\) have been discussed [5] [6].

Besides the strong motivation from models and theory, several experimental phenomena could be explained by such a dark photon. A dark sector with an annihilation channel to dark photons could explain e.g. the positron excess in the universe measured first by PAMELA [7] and later confirmed by FERMI [8] and AMS-02 [9]. While other positron sources, for example Quasars, are also discussed in the literature, the dark photon annihilation process provides a good fit to the positron spectrum.

![Radiative production of a \(γ'\) in final (a) and initial state (b)](image)

FIG. 1. Radiative production of a \(γ'\) in final (a) and initial state (b). The subsequent decay of the \(γ'\) to an electron-positron pair would be the unique signal of such a \(γ'\) with a sharp mass distribution.
Of special interest for the parameter range probed in this experiment is the discrepancy of the measured anomalous magnetic moment \((g-2)\) of the muon \(\mu\) in comparison with SM calculations. This discrepancy could be explained by loop contributions of dark photons with a mass range of \(\approx 10\,\text{MeV}/c^2 - 200\,\text{MeV}/c^2\) and a mixing parameter \(\epsilon^2 \approx 10^{-3}\). This paper describes the search for a dark photon in the mass region of \(40\,\text{MeV}/c^2 - 300\,\text{MeV}/c^2\) by a fixed target electron scattering experiment. A possible dark photon could be produced radiatively on a heavy target nucleus with high \(Z\) (see Fig. 1), followed by a subsequent decay into an electron-positron pair. Since this decay is suppressed by the small mixing parameter \(\epsilon^2\), the decay width would be far below the experimental resolution, resulting in a sharp peak in the invariant mass of the produced lepton pair.

This peak is expected to be on top of a smooth background of standard radiative electron-positron pair production via a virtual photon. This background can be calculated in QED and the tools to integrate the background and a possible signal over the acceptance of the experiment were developed and discussed in detail in refs. [14][15].

**EXPERIMENT**

The experiment was performed at the spectrometer setup of the A1 Collaboration at the Mainz Microtron (see ref. [16] for a detailed description). The experimental technique was similar to the technique used in the precursor experiment [17] with a few modifications of the target and of the vacuum system to further reduce multiple scattering and to improve the overall mass resolution.

Table I summarizes the kinematical settings. For all settings, the incoming electron beam of the accelerator hits a target consisting of one or several strips of tantalum foils (99.99% \(^{181}\)Ta) with the thickness of each separate foil between 1 \(\mu\)m and 6 \(\mu\)m. The target configuration was optimized separately for each setting for maximum luminosity with minimized load by radiation background in the focal plane detectors of the spectrometers.

For the detection of the lepton pair from the decay of a possible dark photon, the spectrometers A and B of the A1 setup were placed at their minimal angle (see table I). With these fixed angles, the settings were adjusted to cover the production plane detectors of the spectrometers.

For reaction identification, a cut was applied first on a signal in the Čerenkov detectors of both spectrometers. For spectrometer B, a collimator setting of 40 mrad (horizontal) \(\times\) 140 mrad (vertical) = 5.6 msr was used for all settings, while for spectrometer A two different collimators with 150 mrad \(\times\) 140 mrad = 21 msr and 200 mrad \(\times\) 140 mrad = 28 msr were used. The momentum acceptance of the spectrometers was 20% for spectrometer A and 15% for spectrometer B.

**DATA ANALYSIS**

The lepton pair was detected in coincidence between the two spectrometers. For reaction identification, a cut was applied first on a signal in the Čerenkov detectors of both spectrometers with an efficiency of \(\approx 98\%\). The coincidence time between spectrometer A and B was corrected for the path length in spectrometer A of \(\approx 10\,\text{m}\) and spectrometer B of \(\approx 12\,\text{m}\). After this correction a clear coincidence peak with a width of less than 1 \(\text{ns}\) (FWHM) was seen. The range of \(|\Delta t_{AB}| < 1\,\text{ns}\) was used to identify lepton pairs. The background contribution from random coincidences was estimated by a cut on the sideband with 5 ns < \(|\Delta t_{AB}| < 15\,\text{ns}\).

Additional cuts were applied for the acceptance of the spectrometers to further reduce the contribution of backscattered particles from the entrance flange of spectrometer B. Finally, cuts on the validity of the overall kinematics was applied to remove e.g. accidental coincidences where the total energy of the pair exceeds the beam energy.

In total the background contribution ranges from 4% up to
determined by the four-momenta of the leptons via $m_{e^+e^-}^2 = (p_{e^+} + p_{e^-})^2$. Fig. 2 shows the mass distribution of all settings.

To add up the pair mass distribution of all settings, the invariant pair mass was calculated simultaneously with Hall-probes on the $δB/B$ parameters was monitored with NMR-probes to confirm the total calibration and to extract the momentum and angular resolution of the total setup in situ. The experimental resolutions were used to tune the detailed simulation of the elastic scattering process to reproduce the elastic peak shape. Finally the simulation was used to determine the mass resolution and expected dark photon peak shape in dependence of the mass including radiative corrections. The resulting resolution varies between 210 keV/$c^2$ FWHM in the lowest mass range up to 920 keV/$c^2$ FWHM for the settings of the last experiment.

The estimated peak shape was used to perform a search for a peak in the total mass distribution. For this the background for each bin was estimated by a local fit of the neighboring bins with a cubic polynomial. The confidence interval was determined using the Feldman-Cousins algorithm [18] (please note that in the literature several different approaches were used by different experiments to determine limits for dark-photon searches, they differ however only by a few percent). The results were corrected for the leakage of the peak outside the bin. The complete procedure was repeated with shifted binning limits in eight steps.

No significant signal for a dark photon was detected.

### RESULTS AND INTERPRETATION

Due to the use of thin tantalum foil stacks as targets the normalization of the cross section contains large uncertainties. However the identification of the QED background process is very clean and can be used as normalization. Therefore, to translate the exclusion limit in terms of events to an exclusion limit in terms of the mixing parameter $ϵ$ we used the ratio of dark photon production with mixing parameter $ϵ$ divided by

| Setting | Central mass | Beam Energy $E_0$ | $θ_{e^+}$ | $p_{e^+}$ | $θ_{e^-}$ | $p_{e^-}$ | $e^+$ in Spec. | $e^-$ in Spec. | Collimator A | Collimator B | Target |
|---------|--------------|------------------|-----------|-----------|-----------|-----------|---------------|---------------|-------------|-------------|--------|
| 1       | 54           | 180 20.0$^\circ$ | 74.0 15.1$^\circ$ | 97.1       | A         | B         | 28 msr       | 5.6 msr       | single foil |
| 2       | 54           | 180 15.1$^\circ$ | 100.3 20.0$^\circ$ | 74.0       | B         | A         | 21 msr       | 5.6 msr       | single foil |
| 3       | 57           | 180 20.0$^\circ$ | 78.7 15.6$^\circ$ | 98.0       | A         | B         | 21 msr       | 5.6 msr       | single foil |
| 4       | 72           | 240 20.0$^\circ$ | 103.6 15.6$^\circ$ | 132.0      | A         | B         | 21 msr       | 5.6 msr       | single foil |
| 5       | 76           | 255 20.0$^\circ$ | 105.0 15.1$^\circ$ | 137.3      | A         | B         | 28 msr       | 5.6 msr       | single foil |
| 6       | 77           | 255 20.0$^\circ$ | 110.1 15.6$^\circ$ | 140.4      | A         | B         | 21 msr       | 5.6 msr       | single foil |
| 7       | 91           | 300 20.0$^\circ$ | 129.5 15.6$^\circ$ | 164.6      | A         | B         | 21 msr       | 5.6 msr       | single foil |
| 8       | 103          | 345 20.0$^\circ$ | 142.0 15.1$^\circ$ | 186.5      | A         | B         | 28 msr       | 5.6 msr       | foil stack  |
| 9       | 109          | 360 20.0$^\circ$ | 155.4 15.6$^\circ$ | 197.6      | A         | B         | 21 msr       | 5.6 msr       | single foil |
| 10      | 135          | 450 20.0$^\circ$ | 185.0 15.1$^\circ$ | 243.3      | A         | B         | 28 msr       | 5.6 msr       | foil stack  |
| 11      | 138          | 435 15.6$^\circ$ | 244.0 20.0$^\circ$ | 190.7      | B         | A         | 21 msr       | 5.6 msr       | single foil |
| 12      | 138          | 435 15.6$^\circ$ | 233.9 20.0$^\circ$ | 190.0      | B         | A         | 21 msr       | 5.6 msr       | single foil |
| 13      | 138          | 435 20.0$^\circ$ | 190.0 15.6$^\circ$ | 244.5      | A         | B         | 21 msr       | 5.6 msr       | single foil |
| 14      | 138          | 435 20.0$^\circ$ | 190.0 15.6$^\circ$ | 234.1      | A         | B         | 21 msr       | 5.6 msr       | single foil |
| 15      | 150          | 495 20.0$^\circ$ | 213.7 15.6$^\circ$ | 271.1      | A         | B         | 21 msr       | 5.6 msr       | foil stack  |
| 16      | 170          | 570 20.0$^\circ$ | 234.0 15.1$^\circ$ | 307.3      | A         | B         | 28 msr       | 5.6 msr       | foil stack  |
| 17      | 177          | 585 20.0$^\circ$ | 250.0 15.6$^\circ$ | 317.3      | A         | B         | 21 msr       | 5.6 msr       | foil stack  |
| 18      | 202          | 675 15.1$^\circ$ | 367.0 20.0$^\circ$ | 277.2      | B         | A         | 21 msr       | 5.6 msr       | single foil |
| 19      | 218          | 720 20.0$^\circ$ | 309.2 15.6$^\circ$ | 392.7      | A         | B         | 21 msr       | 5.6 msr       | foil stack  |
| 20      | 256          | 855 20.0$^\circ$ | 351.0 15.1$^\circ$ | 460.3      | A         | B         | 28 msr       | 5.6 msr       | foil stack  |
| 21      | 270          | 855 15.2$^\circ$ | 509.4 22.8$^\circ$ | 346.3      | B         | A         | 21 msr       | 5.6 msr       | single foil |
| 22      | 270          | 855 15.1$^\circ$ | 511.7 20.0$^\circ$ | 346.3      | B         | A         | 21 msr       | 5.6 msr       | single foil |

11% after all cuts. This background contribution is not subtracted for the peak search but has to be taken into account later in the calculation of the exclusion limit.

For the identified lepton pairs, the invariant pair mass was determined by the four-momenta of the leptons via $m_{e^+e^-}^2 = (p_{e^+} + p_{e^-})^2$. Fig. 2 shows the mass distribution of all settings.
FIG. 3. (color online). Exclusion limits in terms of mixing parameter $\epsilon$. The yellow (light shaded) area marked with A1 is excluded by this experiment.

the QED background process [13]

$$ R = \frac{d\sigma(X \rightarrow \gamma'Y \rightarrow e^+e^-Y)}{d\sigma(X \rightarrow \gamma^*Y \rightarrow e^+e^-Y)} = \frac{3\pi}{2N_i} \frac{e^2 m_{\gamma'}}{\delta m}. $$

Here $N_i$ is the ratio of the phase space of the decay into an $e^+e^-$ pair to the phase space of the total decay (equal to 1 below $2m_\mu$) and $\delta m$ is the bin width in mass. For the virtual photon channel we used the background-subtracted mass distribution. To determine the ratio $R$ both cross sections as calculated in ref. [14] were integrated over the acceptance of the experiment by standard Monte-Carlo methods. Here, the normalization was chosen to reproduce the measured mass distribution.

Please note that in the interpretation of the data in ref. [17] the cross sections were calculated not including the full antisymmetrization as discussed in ref. [14], leading to an overestimation of the sensitivity by a factor 2–3. Therefore these data were included in this analysis and reanalyzed. Since additional data were taken in the same mass range, roughly the same sensitivity was achieved.

Fig. 3 shows the resulting $2\sigma$ exclusion limits. Also included in the figure are the limits by the APEX [19], WASA-at-COSY [20], KLOE-2 [21], HADES [22], and BaBar [23, 24] collaborations. The red line shows the interpretation of the $(g-2)_\mu$ discrepancy as a dark photon with a $2\sigma$ error band (red shaded region) and as exclusion limit (blue shaded region). Also included is the reanalysis of ref. [25] of the beam dump experiment E774 [26] to extract exclusion limits for dark photons.

With the new measurement presented here, the exclusion limit in the region of the $(g-2)$ anomaly of the muon was improved considerably. While the results of the meson decays by KLOE-2, WASA-at-COSY, and HADES were not able to completely rule out the dark photon as the origin of the anomaly, the new data set clearly covers the possible signal of the anomaly by several sigmas over a large mass range. The remaining undecided mass range of $25\text{MeV}/c^2 \lesssim m_{\gamma'} \lesssim 50\text{MeV}/c^2$ cannot be covered by the spectrometers of the A1 collaboration without modifications. However, several experiments by different collaborations are already planned to access the low mass region in the near future (see ref. [15] for a summary).

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