Searching a Dark Photon with HADES

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The existence of a photon-like massive particle, the γ' or dark photon, is postulated in several extensions of the Standard Model. Such a particle could indeed help to explain the puzzling behavior of the observed cosmic-ray positron fraction as well as to solve the so far unexplained deviation between the measured and calculated values of the muon $g-2$ anomaly. The dark photon, unlike its conventional counterpart, would have mass and would be detectable via its mixing with the latter. We present a search for the e^+e^- decay of such a hypothetical dark photon, also named U boson, in inclusive dielectron spectra measured with HADES in the p (3.5 GeV) + p, Nb reactions, as well as in the Ar (1.756 GeV/u) + KCl reaction. A new upper limit on the kinetic mixing parameter squared (ϵ^2) at 90% CL has been obtained in the mass range $M_U = 0.02$ – 0.55 GeV and is compared here with the present world data set. For masses 0.03 – 0.1 GeV, the limit has been lowered with respect to previous results, allowing to exclude a large part of the parameter space favored by the muon $g-2$ anomaly.

1 Introduction

Observations of the cosmic-ray electron and/or positron flux by ATIC [1], PAMELA [2], HESS [3], Fermi [4], and recently the AMS02 collaboration [5] have revealed an unexpected excess at momenta above 10 GeV, in particular in the positron fraction $e^+/(e^- + e^+)$. These observations cannot easily be reconciled in a consistent way with known astrophysical sources [6] and alternative theoretical explanations have therefore been put forward. In particular, scenarios in which the excess radiation stems from the annihilation of weakly interacting dark matter particles [6, 7] might offer an enticing solution to the puzzle.

To accommodate DM in elementary particle theory and to allow it to interact with visible matter, it has been proposed to supplement the Standard Model (SM) with an additional sector characterized by another $U(1)'$ gauge symmetry [8, 9, 10]. The corresponding vector gauge boson — called U boson, A', γ', or simply dark photon — would thereby mediate the annihilation of DM particles into charged lepton pairs. Indeed, from theoretical arguments a kinetic mixing of the $U(1)'$ and $U(1)$ symmetry groups would follow [11], providing a natural connection between the dark and SM sectors. For that purpose, a mixing parameter ϵ has been introduced [8] relating the respective coupling strengths α‘ and α of the dark and SM photons to visible matter via $\epsilon^2 = \alpha'/\alpha$. Through the $U(1) - U(1)'$ mixing term the U boson would be involved in all processes which include real or virtual photons [12]. On the other hand, any search for a U boson will have to deal with the large unavoidable background from standard QED radiative processes [13], namely any electromagnetic decay leading to lepton pairs. In recent years, a number of such searches have been conducted in various experiments done in the few-GeV beam energy regime, looking either at e^+e^- pair distributions produced in electron scattering [14, 15] or in the electromagnetic decays of the neutral pion [16] and the ϕ meson [17]. Analyzing data obtained from high-flux neutrino production experiments at CERN [18] and at Serpukhov [19], regions in parameter space ϵ^2 vs. M_U corresponding to a long-lived U have been excluded as well. Note finally, that from the very precisely measured value of the anomalous gyromagnetic factors $(g-2)$ of the muon and electron [20], additional constraints are put on the allowed range of the mixing parameter ϵ and the mass M_U [21, 22].

2 The HADES experiment

The High-Acceptance DiElectron Spectrometer (HADES) operates at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt where it uses the few-GeV beams from the heavy-ion synchrotron SIS18. A detailed description of HADES can be found in [23]. In the experiments discussed here a proton beam with a kinetic energy of $E_p = 3.5$ GeV and an average intensity of about 2×10^6 particles per second was used to bombard either a solid 12-fold segmented niobium target (with 2.8% nuclear interaction probability) [24] or a liquid hydrogen target (1% interaction probability) [25]. Likewise, a 1.76 GeV/u Ar beam was used to bombard KCl targets [26]. In the data analysis, electrons and positrons were identified by applying selection cuts to the RICH patterns, pre-shower and energy-loss signals. Charged particles were tracked through the HADES magnetic field and indentified leptons were combined two-by-two to reconstruct the 4-momentum of e^+e^- pairs. A detailed description of this analysis is given in [23, 26].

3 The U-boson search

The search for the U boson can be performed with HADES using all electromagnetic decays typically populated in few-GeV hadronic interactions, that is mostly $\pi^0 \to \gamma U$, $\eta \to \gamma U$, and $\Delta \to NU$, followed by $U \to e^+e^-$. In contrast to previous experiments focusing on a specific decay channel, our search was based on the inclusive measurement of all e^+e^- pairs produced in a given mass range. Because of the expected long lifetime of the U boson, the width of an observable signal is solely determined by the detector resolution.

The present analysis is based on the raw dilepton mass spectra, i.e. spectra not corrected for efficiency and acceptance. The low invariant-mass region of the spectra ($M_{ee} < 0.13\ GeV/c^2$) is dominated by π^0 Dalitz decays, at intermediate masses ($0.13\ GeV/c^2 < M_{ee} < 0.55\ GeV/c^2$), η and Δ Dalitz decays prevail, and the high-mass region is populated mostly by low-energy tails of vector-meson decays [24, 25]. However, as the electromagnetic decay branching ratios decrease with increasing particle mass, resulting in low sensitivity, we restrict our search to $M_U < 0.6\ GeV/c^2$.

Our search for a narrow resonant state in the e^+e^- mass distributions has been conducted in the following way: The dN/dM_{ee} spectra, measured in either of the analyzed reactions, was fitted piece-wise with a model function consisting of a 5^{th}-order polynomial and a Gauss peak of fixed position M_{ee} and fixed width. The adjustment was done by sliding a fit window of width $\pm 4\sigma(M)$ over the spectrum in steps of 3 MeV/c^2. In each step, the fit delivered a parameterization of the local background in presence of a possible Gaussian signal of given width $\sigma(M)$. Consequently, a statistical likelihood-based test must be performed to determine at a given Confidence Level (CL) an upper limit (UL) for a possible U-boson signal [27]. In our case, background and e^+e^- efficiency corrections are needed to extract an absolute signal yield, and as both are known with limited accuracy only, we have used the method proposed by Rolke, Lopez and Conrad [28] to compute the UL at a confidence level CL=90%. A pair efficiency and acceptance correction factor, $eff \times acc$, has been obtained from detailed simulations and, after having corrected the UL for this factor, the procedure detailed in [29] was used to compute a corresponding upper limit $UL(\epsilon^2)$ on the relative coupling strength ϵ^2 of a hypothetical dark vector boson. Finally, in Fig. 1 we show the HADES result together with a compilation of limits from the searches conducted by KLOE-2 [17], APEX [15], WASA at COSY [16], A1 at MAMI [14], and BaBar [30].

At low masses ($M_U < 0.1\ GeV/c^2$) we clearly improve on the recent result obtained by WASA [16], excluding now to a large degree the parameter range allowed by the muon $g-2$ anomaly. At higher masses, the sensitivity of our search is compatible with, albeit somewhat lower than the combined KLOE-2 analysis of ϕ decays. Our data probe, however, the U-boson coupling in η decays and add hence complementary information. At masses above the η mass, the inclusive dilepton pectrum is fed by Δ (and to some extent heavier baryon resonance) decays which offer only small sensitivity, partly due to the small electromagnetic branching ratio ($BR_{N\gamma} \simeq 10^{-3} - 10^{-2}$) and partly due to the decreasing $BR_{U\to ee}$ at high M_U. Recently, the UL in the high-mass region has been largely improved by an analysis of data obtained by the BaBar experiment, namely $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ [31] (not shown in Fig. 1). On the other hand, at low masses, we expect to lower substantially the UL by including recent HADES data from the 1.23 GeV/u Au+Au reaction in our search.

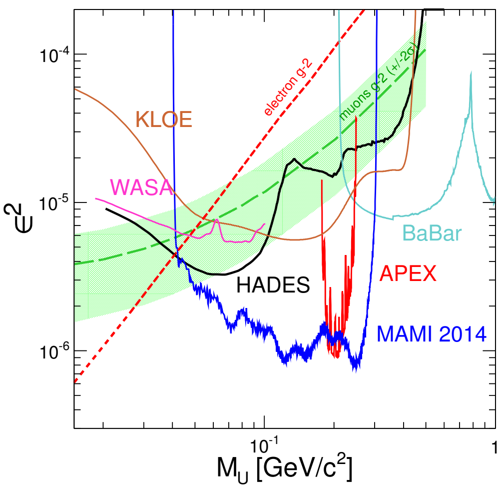

Figure 1: The 90% Cl upper limit on ϵ^2 versus the U-boson mass obtained from the combined analyses of the HADES data (solid black line) in comparison with existing limits from the MAMI/A1, APEX, BaBar, WASA, and KLOE-2 experiments (various colored lines). In addition, the constraints from the muon g-2 anomaly are indicated (green shaded band).

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