Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 273–275 (2016) 608–612

www.elsevier.com/locate/nppp

Searches for Dark Forces with KLOE

Anthony Palladino,
on behalf of the KLOE-2 collaboration

Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy

Abstract

Some models of physics beyond the Standard Model have predicted the existence of a light neutral vector particle, called the U boson, which would mediate a new dark gauge interaction. KLOE has searched for the production of U bosons in five analyses comprising four types of production processes with various final states. We've used Dalitz decays of the ϕ meson, $\phi \to \eta U$ with $U \to e^+e^-$ and the two final states $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^0\pi^0\pi^0$, to provide limits on the mixing strength between the dark sector and the Standard Model in the range $50 < m_U < 520$ MeV/c^2. We've set a limit using $e^+e^- \to U\gamma$, $U \to \mu^+\mu^-$ in the range $520 < m_U < 980$ MeV/c^2 and provided a preliminary limit using $e^+e^- \to U\gamma$, $U \to e^+e^-$ in the range $\sim 5 < m_U < 520$ MeV/c^2. We've also searched for a U boson in the dark Higgsstrahlung process, $e^+e^- \to Uh'$, $U \to \mu^+\mu^-$, placing a preliminary limit on the product of the kinetic mixing parameter and the dark coupling constant in the parameter space $2m_\mu < m_U < 900$ MeV/c^2 and $10 < m_{h'} < 500$ MeV/c^2.

Keywords: dark matter, dark photon, U boson, dark Higgs, e^+e^- collisions, initial state radiation, muon anomaly

1. Introduction

A series of recent astrophysical observations have obtained results which cannot be explained within the framework of the Standard Model. For example, the e^+/e^- excess in cosmic-ray flux as compared to the p^+/p^- flux [1], the 511 keV gamma-ray signal from the galactic center [2], the total e^+/e^- flux [3–6], the DAMA/LIBRA annual modulation [7, 8], the CoGeNT results [9, 10], and the positron spectrum in primary cosmic rays [11].

Several well-motivated dark matter models have been put forth which claim to explain the aforementioned anomalies. In particular a new gauge interaction would be mediated by a new vector gauge boson, the U boson (dark photon), which could kinetically mix with the Standard Model hypercharge (ordinary photon). This small coupling between dark matter and the Standard Model can be described by a single kinetic mixing parameter, ε, defined as the ratio of the dark to the Standard Model electroweak couplings, α_D/α_{EW}. The resulting Lagrangian would be,

$$\mathcal{L}_{\rm mix} = -\frac{\varepsilon}{2} F^{\rm EW}_{\mu\nu} F^{\mu\nu}_{\rm Dark} \,.$$

Since no astrophysical data involves an anomalous production of antiprotons, these models only offer an explanation if there exists a U boson with a mass less than two proton masses. The U bosons could be observed as a sharp resonance at m_U in the invariant-mass distributions of final-state charged lepton or pion pairs in reactions of the type $e^+e^- \to \ell(\pi)^+\ell(\pi)^-\gamma$, or in meson Dalitz decays.

2. The search for U in $\phi \to \eta U$, $U \to e^+e^-$

Reece and Wang suggested that there could be an associated decay of a vector into a pseudoscalar and a

Email address: anthony.palladino@lnf.infn.it (Anthony Palladino)

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.091
2405-6014/

U boson, V → PU [12]. The KLOE experiment operating at the DAΦNE ϕ-factory was therefore poised to search for the U boson in $\phi \to \eta U$ decays.

The first KLOE U boson search looked for the process $\phi \to \eta U$, $U \to e^+e^-$ by selecting 13,000 events of $\eta \to \pi^+\pi^-\pi^0$ with an associated e^+e^- pair selected from 1.5 fb^{-1} of data collected in 2004–2005, with ~2% background [13].

A second analysis using 31,000 events of $\eta \to \pi^0\pi^0\pi^0$ with an associated e^+e^- pair was selected from 1.7 fb^{-1} of data from 2004–2005 with ~3% background[14]. An irreducible background from the Dalitz decay $\phi \to \eta\gamma^* \to \eta e^+e^-$, $\eta \to \pi^0\pi^0\pi^0$ was present and simulated using the Vector Meson Dominance model [15]. We assumed the U boson decays only into leptons with an equal coupling to e^+e^- and $\mu^+\mu^-$.

A resonant peak was not observed in the dielectron mass spectrum of the two analyses, see Figure 1. The background peak around 440 MeV/c^2 is from the decay $\phi \to K_S K_L$. The CLS technique was used to set an upper limit on the strength of kinetic mixing parameter as a function of U boson mass [16]. The 90% confidence level limit is shown in Figure 4.

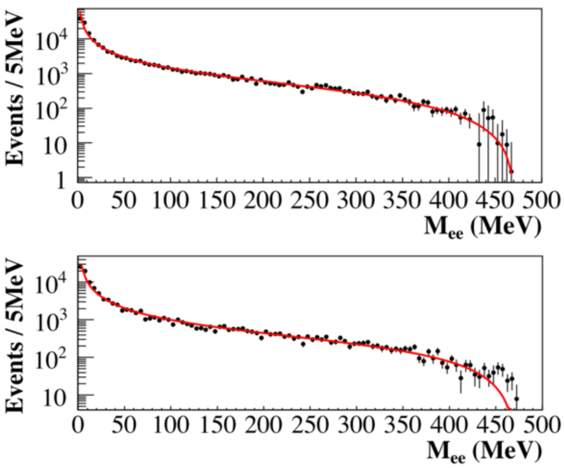

Figure 1: Dielectron invariant-mass distributions, m_{ee} (MeV/c^2), for $\phi \to \eta e^+e^-$ with $\eta \to \pi^+\pi^-\pi^0$ (*top*) and $\eta \to \pi^0\pi^0\pi^0$ (*bottom*). The red lines are fits to the measured data.

3. The search for U in $e^+e^- \to U\gamma$, $U \to \mu^+\mu^-$

Using 239.3 pb^{-1} of data collected in 2002, we've searched for a U boson in the process $e^+e^- \to U\gamma$, $U \to \mu^+\mu^-$[17]. Again the signal would appear as a narrow resonance in the final-state dilepton invariant-mass spectrum.

For this analysis we required two charged tracks emitted at large-angle such that their energy is deposited in the barrel of the calorimeter. The initial-state radiation (ISR) photon was not explicitly detected, being emitted at small angle with respect to the beam axis, where its direction was reconstructed using kinematics of the charged leptons, $\vec{p}_\gamma \simeq \vec{p}_{\rm miss} \equiv -\vec{p}_{\mu\mu} = -\left(\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right)$. A variable called the "track mass", $m_{\rm track}$, was computed using energy and momentum conservation, assuming two equal-mass oppositely-charged final-state particles and an unobserved photon, and was used to separate muons from pions and electrons. The $m_{\rm track}$ distributions for the backgrounds $e^+e^- \to e^+e^-$, $\pi^+\pi^-$, and $\pi^+\pi^-\pi^0$ were determined using Monte Carlo simulations which were then used to estimate residual background contributions in the dimuon invariant-mass spectrum. The final invariant-mass spectrum was obtained after subtracting residual backgrounds and dividing by efficiency and luminosity. The absolute cross section is in good agreement with the PHOKHARA Monte Carlo simulation prediction, see Figure 2.

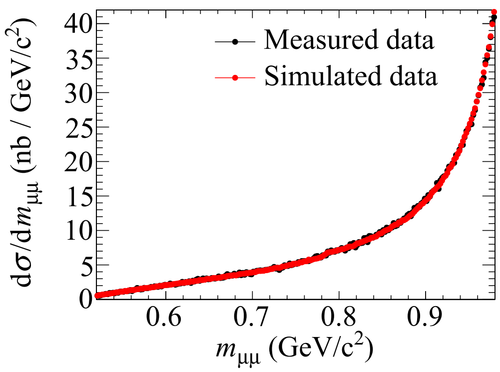

Figure 2: Differential cross section of the process $e^+e^- \to \mu^+\mu^-\gamma$ as a function of the dimuon invariant mass.

No resonant peak was observed so we used the CLS technique to estimate the maximum number of U boson signal events that can be excluded at 90% confidence level, $N_{\rm CL_S}$. We then used this number to estimate a limit on the kinetic mixing parameter,

$$\varepsilon^2 (m_{\ell\ell}) = \frac{\alpha'}{\alpha} = \frac{N_{\rm CL_S}(m_{\ell\ell})}{\epsilon_{\rm eff}(m_{\ell\ell})} \frac{1}{H(m_{\ell\ell}) \cdot I(m_{\ell\ell}) \cdot L} \,, \quad (1)$$

where $\ell = \mu$, the radiator function, $H(m_{\ell\ell})$, was extracted from $d\sigma_{\ell\ell\gamma}/dM_{\ell\ell} = H\left(m_{\ell\ell}, s, \cos(\theta_\gamma)\right) \cdot \sigma^{\rm QED}_{\ell\ell}(m_{\ell\ell})$ using the PHOKHARA MC simulation, our efficiency $\epsilon_{\rm eff}(m_{\ell\ell}) \sim$ 1–10%, $I = \int \sigma_U \, dM_U$ is the integral of the U boson cross section, and $L = \int \mathcal{L} = 239.3$ pb^{-1}

is the integrated luminosity. We also applied a systematic uncertainty of 1.4–1.8%. The 90% confidence level limit is shown in Figure 4.

4. The search for U in $e^+e^- \to U\gamma$, $U \to e^+e^-$

In a similar process as the previous search, KLOE also looked for a U boson in $e^+e^- \to U\gamma$, $U \to e^+e^-$. This time we performed a large-angle selection which allows us to obtain a dielectron invariant-mass distribution with sufficient statistics near the dielectron mass threshold, $m_{ee} = 2m_e$. In this case, the hard ISR photon is explicitly detected in the barrel of the calorimeter along with the charged-lepton pair, $50^\circ < \theta_{e^+,e^-,\gamma} < 130^\circ$. The track mass variable was again used to remove background contamination from $e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to \pi^+\pi^-\gamma$, $e^+e^- \to \gamma\gamma$ (where one photon converts into an e^+e^- pair), $e^+e^- \to \phi \to \rho\pi^0 \to \pi^+\pi^-\pi^0$, and other ϕ decays. The resulting background contamination was less than 1.5%. Figure 3 shows the final dielectron invariant-mass distribution demonstrating excellent agreement with a Babayaga-NLO MC simulation [18] modified with weighted events to account for the lengthy simulation time for events in the phase space near the dielectron mass threshold.

No resonant U boson peak was observed prompting another use of the CLS technique to estimate N_{CL_s}, the number of U boson signal events excluded at 90% confidence level. We used (1) with ℓ = e to set a preliminary limit on the kinetic mixing parameter as a function of m_U. For this analysis $\varepsilon_{eff} \sim 1.5$–2.5%, and $L = \int \mathcal{L} = 1.54$ fb^{-1} from 2004–2005 KLOE data.

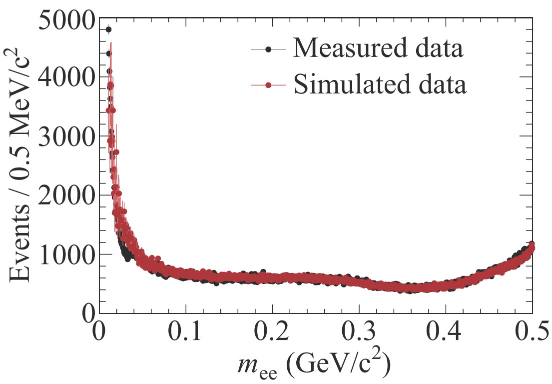

Figure 3: Dielectron invariant-mass distribution for the radiative Bhabha scattering process $e^+e^- \to e^+e^-\gamma$.

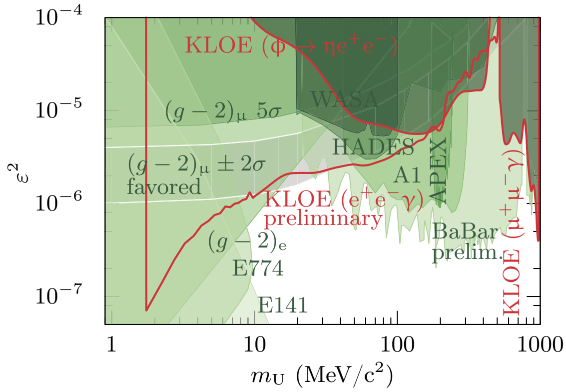

Figure 4: Exclusion limits on the kinetic mixing parameter, ε^2, from KLOE (in red) and compared with limits from E141[19], E774[20], MAMI/A1[21], APEX[22], WASA[23], HADES[24], A1[25], and a preliminary result from BaBar[26]. The gray band indicates the paramter space that could explain the $(g_\mu - 2)$ discrepancy.

5. The search for U in $e^+e^- \to Uh'$, $U \to \mu^+\mu^-$

If the hidden symmetry is spontaneously broken by a Higgs-like mechanism, the existence of at least one other scalar particle, h′, can be postulated. The hypothetical dark Higgsstrahlung process $e^+e^- \to Uh'$, $U \to \mu^+\mu^-$ can then be investigated using KLOE data with the added benefit that this process is suppressed by a single factor of ε as opposed to the three processes outlined above which are suppressed by ε^2. In fact, the production cross section of this process would be proportional to the product of the dark coupling and the kinetic mixing strength, $\alpha_D \times \varepsilon^2$ [27].

There would be two different scenarios depending on the relative masses of the dark photon and the dark Higgs boson. Specifically, if $m_{h'} > m_U$ the dark Higgs could undergo decays $h' \to UU \to 4\ell, 4\pi, 2\ell + 2\pi$, which have been searched for by BaBar [28]. If however $m_{h'} < m_U$ the dark Higgs boson would have a large lifetime and would escape the KLOE detector without depositing a signal. We have restricted our search to this so-called “invisible” dark Higgs scenario.

KLOE has performed this analysis using 1.65 fb^{-1} of data collected with center-of-mass collision energy at the ϕ-peak, and 0.2 fb^{-1} of data with a center-of-mass energy of ~1000 MeV. Mass resolutions were found to be ~1 MeV/c^2 for $m_{\mu\mu}$ (m_U) and ~10 MeV/c^2 for m_{miss} ($m_{h'}$). The signature of the dark Higgsstrahlung process would be a sharp peak in the two-dimensional distribution m_{miss} versus $m_{\mu\mu}$, see Figure 5. We chose binning such that 90–95% of the signal would be in one bin. We used a sliding 5×5 bin matrix (excluding the central bin) to determine background MC simulation scale factors. The selection efficiency was evaluated using Monte Carlo simulations and varied between 15% and 25% with a conservative 10% systematic uncertainty.

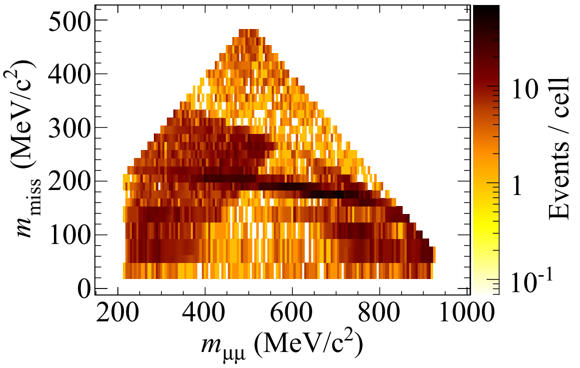

Figure 5: Missing mass, m_{miss}, (interpreted as the mass of the Higgs, $m_{h'}$) versus the dimuon invariant mass, $m_{\mu\mu}$, (interpreted as m_U if there exists a resonance). This figure shows the results from the 1.65 fb^{-1} of on-peak data.

Several sources of backgrounds are visible in Figure 5. The left part of the triangular region consists mainly of $\phi \to K^+K^-$ with $K^\pm \to \mu^\pm\nu$. The top point of the triangular region is mostly $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^-\pi^+\pi^-$. The darkest horizontal band comes from $\phi \to \pi^+\pi^-\pi^0$. The two diagonal bands originating in the lower-right corner of the triangle are from $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \pi^+\pi^-$. All the backgrounds from the ϕ decays are strongly suppressed in the off-peak sample.

No evidence of the dark Higgsstrahlung process was found. Using uniform prior distributions, 90% confidence level Bayesian upper limits on the number of events, $N_{90\%}$, were derived separately for the two samples. The results were then converted in terms of the dark Higgsstrahlung production cross section parameters,

$$\alpha_D \times \varepsilon^2 = \frac{N_{90\%}}{\epsilon_{eff}} \frac{1}{\sigma_{Uh'}\left(\alpha_D\varepsilon^2 = 1\right) \cdot L},$$

where L is the integrated luminosity and the total cross section,

$$\sigma_{Uh'} \quad \propto \quad \frac{1}{s}\frac{1}{\left(1 - m_U^2/s\right)^2},$$

was evaluated assuming $\alpha_D\varepsilon^2 = 1$. The combined 90% confidence level limits from on- and off-peak data are shown in Figure 6 as projections onto m_{miss} and in Figure 7 as projections onto $m_{\mu\mu}$. The limit on $\alpha_D \times \varepsilon^2$ at 90% confidence level translates to a limit on ε^2 of 10^{-6} to a few 10^{-8} (if $\alpha_D = \alpha_{EM}$).

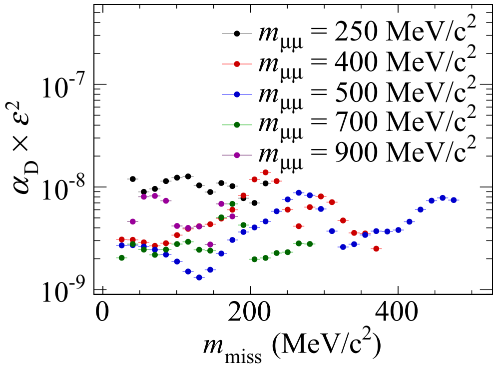

Figure 6: Projections of the 90% confidence level limits on $\alpha_D \times \varepsilon^2$ as a function of m_{miss} for several values of $m_{\mu\mu}$.

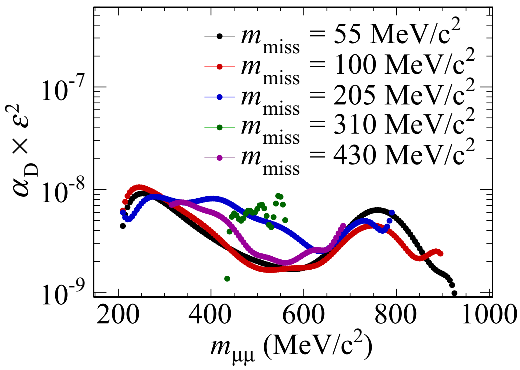

Figure 7: Projections of the 90% confidence level limits on $\alpha_D \times \varepsilon^2$ as a function of $m_{\mu\mu}$ for several values of m_{miss}.

6. Conclusions

The KLOE collaboration has performed five analyses for searches in the Dark Sector consisting of four production processes and a total of five final states. We found no evidence for a U boson or a dark Higgs boson and placed 90% confidence level limits on the kinetic mixing between the dark sector and the Standard Model in the mass range $\sim 5 < m_U < 980$ MeV/c^2. We've also placed 90% confidence level limits on $\alpha_D \times \varepsilon^2$ in the parameter space $2m_\mu < m_U < 900$ MeV/c^2 and $10 < m_{h'} < 500$ MeV/c^2. An upgrade to the DAΦNE luminosity and the insertion of additional detectors for the new KLOE-2 experiment are expected to improve these limits by at least a factor of two.

References

[1] O. Adriani, et al., Nature 458 (2009) 607.

[2] P. Jean, et al., Astron. Astrophys. 407 (2003) L55.
[3] J. Chang, et al., Nature 456 (2008) 362.
[4] HESS Collaboration, Phys. Rev. Lett. 101 (2008) 261104.
[5] HESS Collaboration, Astron. Astrophys. 508 (2009) 561.
[6] A. A. Abdo, et al., Phys. Rev. Lett. 102 (2009) 181101.
[7] R. Bernabei, et al., Int. J. Mod. Phys. D 13 (2004) 2127.
[8] R. Bernabei, et al., Eur. Phys. J. C 56 (2008) 333.
[9] CoGeNT Collaboration, Phys. Rev. Lett. 106 (2011) 131301.
[10] CoGeNT Collaboration, Phys. Rev. Lett. 107 (2011) 141301.
[11] AMS Collaboration, Phys. Rev. Lett. 110 (2013) 141102.
[12] M. Reece, L. T. Wang, JHEP 07 (2009) 51.
[13] KLOE-2 Collaboration, Phys. Lett. B 706 (2012) 251–255.
[14] KLOE-2 Collaboration, Phys. Lett. B 720 (2013) 111–115.
[15] L. G. Landsberg, Phys. Rep. 128 (1985) 301.
[16] G. C. Feldman, R. D. Cousins, Phys. Rev. D 57 (1998) 3873.
[17] KLOE-2 Collaboration, Phys. Lett. B 736 (2014) 459–464.
[18] L. Barzè, et al., Eur. Phys. J. C 71 (2011) 1680.
[19] E141 Collaboration, Phys. Rev. Lett. 59 (1987) 755.
[20] E774 Collaboration, Phys. Rev. Lett. 67 (1991) 2942.
[21] MAMI/A1 Collaboration, Phys. Rev. Lett. 106 (2011) 251802.
[22] APEX Collaboration, Phys. Rev. Lett. 107 (2011) 191804.
[23] WASA Collaboration, Phys. Lett. B 726 (2013) 187.
[24] HADES Collaboration, Phys. Lett. B 731 (2014) 265–271.
[25] A1 Collaboration, Phys. Rev. Lett. 112 (2014) 221802.
[26] BaBar Collaboration, arXiv:1406.2980.
[27] A. R. B. Batell, M. Pospelov, Phys. Rev. D 79 (2009) 115008.
[28] BaBar Collaboration, Phys. Rev. Lett. 108 (2012) 211801.