Dark mediator searches at KLOE/KLOE-2

Elena Pérez del Río[1;1)] (for the KLOE-2 Collaboration)

[1]LNF-INFN, Via E. Fermi 40, 00044 Frascati (RM), Italy

Abstract: The existence of a new vector boson has been postulated in different scenarios where the coupling to the SM can be achieved either via a kinetic mixing term, the U boson, or by coupling to the baryon number, the B boson. Direct searches of these dark matter mediators are performed at accelerator facilities. The KLOE detector at the DAϕNE Φ-factory has been prolific in searches for the U boson in both Dalitz decays of the ϕ meson, $\phi \to \eta U$ with $U \to e^+e^-$, and continuum events, $e^+e^- \to U\gamma$. For all of these processes, an upper limit for the U boson coupling ϵ^2 of 10^{-7} to 10^{-5} has been established in the mass range 4 MeV/c^2 < M$_U$ < 980 MeV/c^2. KLOE has also sought the U boson in the dark Higgsstrahlung process $e^+e^- \to Uh'$, $U \to \mu^+\mu^-$, setting limits on m_U and $m_{h'}$ in the parameter space from 2m$_\mu$ < m$_U$ < 1000 MeV/c^2 and 10 MeV/c^2 < m$_{h'}$ < 500 MeV/c^2. In the meantime a new data campaign has started with the KLOE-2 setup, with the aim of collecting more than 5 fb^{-1} in the next three years. The new setup and goal statistics could further improve the current limits on the dark coupling constant.

Key words: dark matter, dark forces, U boson, A', dark Higgsstrahlung, h', upper limit

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1 Introduction

Recent year observations as the 511 keV gamma-ray signal from the galactic center [1],the CoGeNT results [2],the DAMA/LIBRA annual modulation [3, 4], the total e^+e^- flux [5–8] and the discrepancy between the calculated and measured magnetic moment of the muon, a_μ, serve as examples of possible physics beyond the Standard Model. To explain the aforementioned anomalies, extensions of the SM [9–13] by dark matter models, with a Weakly Interacting Massive Particle (WIMP) belonging to a secluded gauge sector, have been proposed. The new gauge interaction would be mediated by a new vector gauge boson, the U boson or dark photon, which could interact with photon via a kinetic mixing term,

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{EM}_{\mu\nu} F^{\mu\nu}_{DM}. \quad (1)$$

where the parameter, ϵ, represents the mixing strength and it is defined as the ratio of the dark to the SM electroweak coupling, α_D/α_{EM}. U boson searches are conducted in e^+e^- colliders via different processes: $e^+e^- \to U\gamma$, $V \to P\gamma$ decays, where V and P are vector and pseudoscalar mesons, and $e^+e^- \to h'U$, where h' is a Higgs-like particle responsible for the breaking of the hidden symmetry. Some of these searches, which are reported in the following, have been performed by the KLOE experiment.

2 The KLOE detector at DAϕNE

The KLOE detector is operated at the DAϕNE ϕ-factory, located at the INFN-LNF in Frascati. It consists of three main parts, a cylindrical drift chamber (DC) [14] surrounded by an electromagnetic calorimeter (EMC) [15], all embedded in a magnetic field of 0.52 T, provided along the beam axis by a superconducting coil located around the calorimeter. The EMC energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E[\mathrm{GeV}]}$ and $\sigma_t(E) = 57\mathrm{ps}/\sqrt{E[\mathrm{GeV}]} \oplus 100\mathrm{ps}$, respectively. The EMC consists of a barrel and two end-caps of lead/scintillating fibers, which cover 98% of the solid angle. The all-stereo drift chamber, 4m in diameter and 3.3m long, operates with a light gas mixture (90% helium, 10% isobutane). The position resolutions are $\sigma_{xy} \sim 150\mu$m and $\sigma_z \sim 2$mm. Momentum resolution, $\sigma_{p\perp}/p_\perp$, is better than 0.4% for large-angle tracks.

3 $\phi \to \eta U$ with $U \to e^+e^-$

The U boson decay $U \to e^+e^-$ in the process $\phi \to \eta U$ was the first search to be conducted at KLOE. A total of 13000 events of $\eta \to \pi^+\pi^-\pi^0$ from 1.5 fb^{-1} and 31000 events of $\eta \to \pi^0\pi^0\pi^0$ from 1.7 fb^{-1} taken in 2004-2005 were selected. The corresponding background contributions were of the order of $\sim 2\%$ [16] and $\sim 3\%$ [17], respectively. The irreducible background from the Dalitz decay $\phi \to \eta\gamma^* \to \eta e^+e^-$ was directly extracted from the data by a fit to the M_{ee} distribution parameterized according to the Vector Meson Dominance model [18].

1) E-mail: eperez@lnf.infn.it

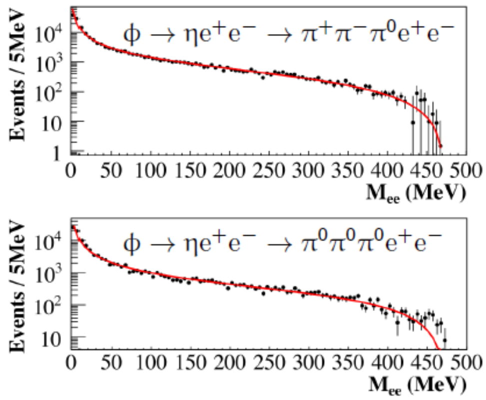

Fig. 1. Di-electron invariant mass distributions, M_{ee}, for $\phi \to \eta e^+e^-$ with $\eta \to \pi^+\pi^-\pi^0$ (**top**) and $\eta \to \pi^0\pi^0\pi^0$ (**bottom**). The red lines are the fits to the measured data.

No resonant signal was observed in the M_{ee} distributions of both analyses, see Fig. 1. The peak around 400 MeV/c^2 is due to background from the decay $\phi \to K_S K_L$. The Confidence Levels (CLs) technique [19] was used to set an upper limit on the kinetic mixing parameter, as a function of the U boson mass, using the signal cross section given by [20],

$$\sigma(\phi \to \eta U) = \epsilon^2 |F_{\eta\phi}(m_U^2)|^2 \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)} \sigma(\phi \to \eta\gamma). \quad (2)$$

In Eq. 2, $|F_{\eta\phi}(m_U^2)|^2$ is the form factor of the $\phi \to \eta\gamma$ decay evaluated at the U mass and the quotient corresponds to the ratio of the kinematic functions of the decays involved in the process. In Fig. 2 the 90% confidence level limit is presented along with results from KLOE and other various experiments.

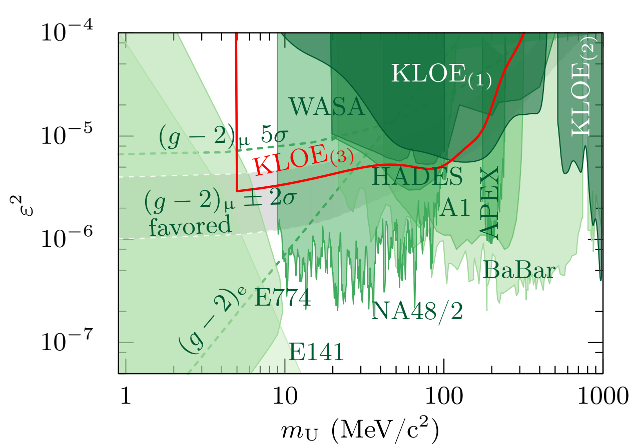

Fig. 2. Exclusion limits on the kinetic mixing parameter, ϵ^2, from KLOE (in red): KLOE$_1$, KLOE$_2$ and KLOE$_3$ correspond to the combined limits from the analysis of $\phi \to \eta e^+e^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to e^+e^-\gamma$, respectively. The results are compared with the limits from E141, E774 [28], MAMI/A1 [29], APEX [30], WASA [31], HADES [32], NA48/2 [33] and BaBar [34]. The gray band indicates the parameter space favored by the $(g_\mu - 2)$ discrepancy.

4 $e^+e^- \to U\gamma$ with $U \to \mu^+\mu^-$

The next of the U boson searches carried out at KLOE was studying the reaction $e^+e^- \to U\gamma$ with $U \to \mu^+\mu^-$, in a sample of 239.3 pb^{-1} of data collected in 2002 [21]. The expected signal would show up as a narrow resonance in the di-muon mass spectrum. The process $e^+e^- \to \mu^+\mu^-\gamma$ receives a very large contribution from the reaction $e^+e^- \to \mu^+\mu^-$, where photons are radiated by the initial-state electrons (ISR) or the final-state muons (FSR). The FSR process is highly suppressed by kinematical and geometrical cuts. The requirement to select the candidate events was to find two opposite-charged tracks emitted at large polar angles, with an initial-state radiation photon emitted at small angles, and thus undetected. The photon was later kinematically reconstructed from the charged leptons.

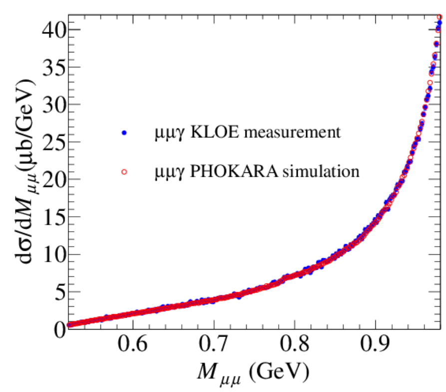

Fig. 3. Di-muon invariant mass distributions, $M_{\mu\mu}$. Comparison of data (full blue circles) and simulation (open red circles).

A variable called *"track mass"*, M_{trk} was reconstructed using energy and momentum conservation and used to separate muons from pions and electrons. The M_{trk} was calculated assuming two opposite charged tracks of equal mass and an unobserved photon in the final state. Residual backgrounds, consisting of $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \pi^+\pi^-\gamma$ and $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$ were determined using Monte Carlo simulation by fitting the observed M_{trk} spectrum. The resulting invariant mass spectrum was obtained after subtracting residual backgrounds and dividing by efficiency and luminosity. Figure 3 shows the di-muon invariant mass, which is in excellent agreement with the PHOKARA Monte Carlo simulation. Since no resonant peak was observed, the CLs technique was used to estimate the number of U boson signal events excluded at 90% confidence level, N_{CLs} and then the limit on the kinetic mixing parameter,

$$\epsilon^2 = \frac{\alpha_D}{\alpha_{EM}} = \frac{N_{CLs}}{\epsilon_{eff}} \frac{1}{H \cdot I \cdot L_{integrated}}. \qquad (3)$$

where ϵ_{eff} is the overall efficiency, I is the effective cross section, $L_{integrated}$ the integrated luminosity and H is the radiator function, which is extracted from the differential cross section, $d\sigma_{\mu\mu\gamma}/dM_{\mu\mu}$. A systematic uncertainty of about 2% was estimated. The 90% confidence level limit is shown in Fig. 2

5 $e^+e^- \to U\gamma$ with $U \to e^+e^-$

Similar to the previous analyses, the reaction $e^+e^- \to U\gamma$, $U \to e^+e^-$ was investigated. This process offers the possibility of investigating the low mass region close to the di-electron mass threshold [22]. For the event selection three separated energy depositions in the barrel of the calorimeter were required, corresponding to two opposite charged tracks and the ISR photon, which is explicitly detected.

To reduce the background contamination from $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \pi^+\pi^-\gamma$, $e^+e^- \to \gamma\gamma$, with a photon converting into an e^+e^--pair, $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$, a pseudo-likelihood discriminant was used to separate electrons from muons and pions, and then the *"track mass"* variable, M_{trk}, was also used to further discriminate the background sources. The resulting background contamination was less than 1.5%. The Fig. 4 compares the di-electron invariant mass to MC BABAYAGA-NLO simulation [23] modified to allow the Bhabha radiative process to proceed only via the annihilation channel, in which the U boson signal would occur, showing an excellent agreement.

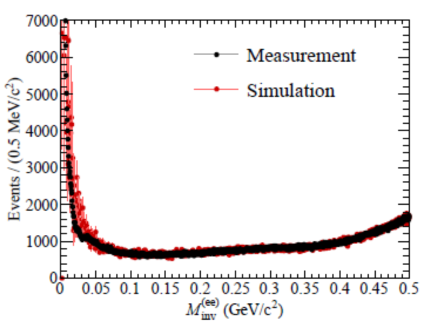

Fig. 4. Di-electron invariant mass distribution, M_{ee}, for the process $e^+e^- \to e^+e^-\gamma$ (black circles) compared to the MC simulated spectra (red circles).

In an analogous way as the $e^+e^- \to \mu^+\mu^-\gamma$ study, the upper limit of the kinetic mixing parameter ϵ^2 as a function of m_U was evaluated with the CLs technique. The limit on the U boson signal was evaluated at 90% confidence level and the limit in the kinetic parameter was calculated using equation (3). In this case the selection efficiency amounts to $\epsilon_{eff} \sim 1.5$–2.5% and the integrated luminosity corresponds to $L_{integrated} = 1.54$ fb^{-1} from the 2004-2005 data campaign.

6 $e^+e^- \to h'U$ with $U \to \mu^+\mu^-$

Given the fact that the U boson has mass, a natural consequence is the breaking of the U_D hidden symmetry associated by a Higgs-like mechanism through an additional scalar particle, called h' or dark Higgs, giving rise to the so-called "dark Higgsstrahlung" process. The production cross section of $e^+e^- \to h'U$ with $U \to \mu^+\mu^-$, would be proportional to the product $a_D \times \epsilon^2$ [24]. Thus this process is suppressed by a factor ϵ comparing to the previous processes, already suppressed by a factor ϵ^2. Depending on the ratio of the masses of the h' and the U boson there are two possible decay scenarios: if $m_{h'} > 2m_U$, the dark Higgs could decay via $h' \to UU \to 4l, 4\pi, 2l + 2\pi$, where l denotes lepton. This scenario was studied by Babar [25] and Belle [26] Collaborations in recent experiments. If $m_{h'} < 2m_U$, then the dark Higgs would have a large lifetime and would escape any detection. This scenario was the one studied by KLOE [27].

To perform the analysis a sample of 1.65 fb^{-1} of data collected during 2004-2005 data campaign at a center of mass energy at the ϕ-peak and also a data sample of 0.2 fb^{-1} at a center of mass energy of ~ 1000 MeV were used. The expected signal would show up as a sharp enhancement in the missing mass, M_{miss}, versus $\mu\mu$ invariant mass, $M_{\mu\mu}$, two-dimensional spectra, shown in Fig. 5.

The candidate event selection required two opposite charged tracks with associated calorimeter clusters and missing momentum exceeding 40 MeV. Since most of the signal is expected to be in just one bin, a sliding matrix of 5×5 bins was built and used with data and Monte Carlo to check the presence of a possible signal in the central bin while the neighboring cells were used to estimate the background. The selection efficiencies were found to be about $15\% - 25\%$.

Different sources of background can be identified in the upper plot of Fig. 5. The left region of the on-peak data is populated by $\phi \to K^+K^-$, $K^\pm \to \mu^\pm\nu$. The central horizontal band corresponds to $\phi \to \pi^+\pi^-\pi^0$ contribution. Continuum backgrounds $e^+e^- \to \mu^+\mu^-$, $\pi^+\pi^-$ populate the right lower side of the spectra and the top point of the distribution is mostly due to $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^-\pi^+\pi^-$. In the lower plot of Fig. 5 (off-peak sample), all the backgrounds from the ϕ decays are strongly suppressed.

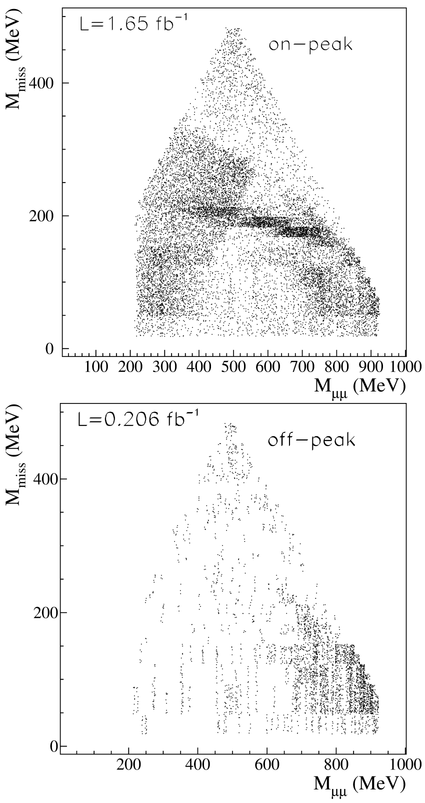

Fig. 5. Missing mass, M_{miss}, versus di-muon mass, $M_{\mu\mu}$, for the 1.65 fb^{-1} on-peak data sample (**top**) and the 0.2 fb^{-1} off-peak sample (**bottom**).

A Bayesian limit on the number of signal events, $N_{90\%}$, was derived for both samples separately since no signal of the dark Higgsstrahlung process was observed. The product $\alpha_D \times \epsilon^2$ was then calculated with,

$$\alpha_D \epsilon^2_{90\% CL} = \frac{N_{90\%}}{\epsilon_{eff}} \frac{1}{\sigma_{h'U}(\alpha_D \epsilon^2) \cdot L_{integrated}}. \quad (4)$$

with

$$\sigma_{h'U} \propto \frac{1}{s} \frac{1}{(1 - m_U^2/s)^2}. \quad (5)$$

where $N_{90\%}$ is the signal events excluded at the 90% confidence level, ϵ_{eff} the signal efficiency, $\sigma_{h'U}(\alpha_D \epsilon^2)$ corresponds to the dark Higgsstrahlung cross section for $\alpha_D \epsilon^2 = 1$ and $L_{integrated}$ is the integrated luminosity. The combined 90% confidence level limits for both on- and off-peak data samples are presented in Fig. 6, as a function of m_U (left) and of $m_{h'}$ (right). The limit values of $\alpha_D \times \epsilon^2$ of $10^{-9} - 10^{-8}$ at 90% confidence level transform into a limit on the kinetic parameter, ϵ^2, of $10^{-6} - 10^{-8}$ ($\alpha_D = \alpha_{EM}$). A conservative 10% of systematic uncertainty was considered.

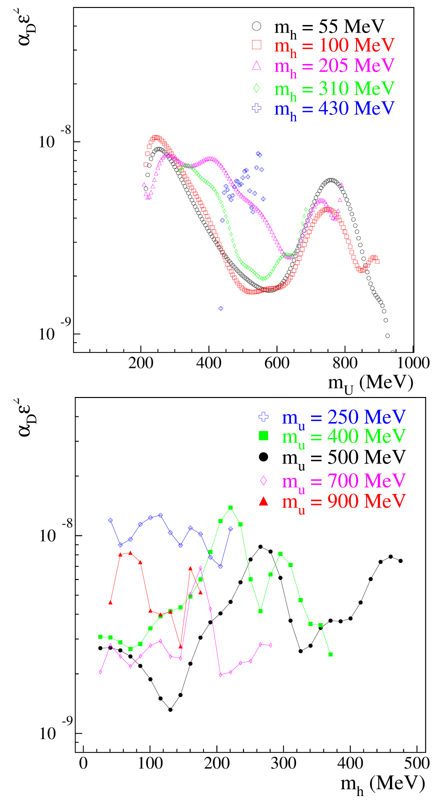

Fig. 6. Combined 90% confidence level upper limits in $\alpha_D \times \epsilon^2$ as a function of m_U for different $m_{h'}$ values (**top**) and as a function of $m_{h'}$ for different m_U (**bottom**).

7 Conclusions

The KLOE Collaboration has extensively contributed to the U boson searches by analyzing four different production processes. Up to now, no evidence for a U boson or dark Higgs boson was found and limits at the 90% confidence level were set on the kinetic mixing parameter, ϵ^2, in the mass range 5 MeV $< m_U <$ 980 MeV. For the dark Higgsstrahlung process, limits on $\alpha_D \times \epsilon^2$ at the 90% confidence level in the parameter space $2m_\mu < m_U < 1000$ MeV with $m_{h'} < m_U$ have been extracted. In the meantime a new data campaign has started with the KLOE-2 setup, which will collect more than 5 fb^{-1} in the next three years. The new setup and the enlarged statistics could further improve the sensitivity on the dark coupling constant measurement by at least a factor of two.

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