Dark Forces Searches at KLOE-2

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Direct searches of dark matter are performed at accelerator facilities. The existence of a new vector boson has been postulated in different scenarios where in the most basic scheme the coupling to the SM can be achieved via a kinetic mixing term due to the U boson. The KLOE experiment at DAϕNE searched for the U boson both in Dalitz decays of the ϕ meson and in continuum events. For all of these searches an upper limit for the U boson coupling ϵ^2 has been established in the mass range $50\,\text{MeV} < m_U < 1000\,\text{MeV}$. A summary of the different models and searches along with results are presented.

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1. Introduction

The Standard Model (SM), although been the most complete theoretical framework at the present, does not provide a definitive model of all elementary particles. In particular, recent 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, 6, 7, 8] and the muon magnetic discrepancy a_μ serve are examples of possible physics beyond the SM. Extensions of the SM [9, 10, 11, 12, 13] claim to explain the afore-mention anomalies by dark matter models, with a Weakly Interacting Massive Particle (WIMP) belonging to a secluded gauge sector. The new gauge interaction would be mediated by a new vector gauge boson, the U boson or dark photon, which could interact with the photon via a kinetic mixing term,

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

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}. A U boson, with mass of $\mathcal{O}(1\text{GeV})$ and ϵ in the range of $10^{-2}-10^{-7}$, could be observed 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. On this basis, the KLOE experiment has performed several searches, which are reported.

2. The KLOE detector at DAϕNE

The KLOE detector experiment operates in Frascati, at the DAϕNE ϕ-factory. 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 $\sigma_E/E = 5.7\%/\sqrt{E[\text{GeV}]}$ and $\sigma_t(E) = 57\text{ps}/\sqrt{E[\text{GeV}]} \oplus 100\text{ps}$, respectively. The EMC consist 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 $\sigma_{xy} \sim 150\mu\text{m}$ and $\sigma_z \sim 2\text{mm}$. Momentum resolution, $\sigma_{p\perp}/p_\perp$, is better than 0.4% for large angle tracks.

3. U boson search in $\phi \to \eta U$ with $U \to e^+e^-$

The first search of the U boson at KLOE was the decay $U \to e^+e^-$ in the process $\phi \to \eta U$. From a sample of $1.5\,\text{fb}^{-1}$ of data collected during the 2004-2005 data taking, a total of 13000 events of $\eta \to \pi^+\pi^-\pi^0$ with an associated e^+e^- pair were selected. In a second analysis, a data sample of 31000 events of $\eta \to \pi^0\pi^0\pi^0$ with an associated e^+e^- pair were selected from a $1.7\,\text{fb}^{-1}$ of data from 2004-2005. 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].

As can be seen in Fig. 1, no resonant signal is observed in the M_{ee} distributions of both analyses. While the peak around $400\,\text{MeV/c}^2$ 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],

$$\sigma(\phi \to \eta U) \sim \epsilon^2 |F_{\eta\phi}(m_U^2)|^2 \sigma(\phi \to \eta\gamma) \tag{2}$$

The 90% confidence level limit is presented in Fig. 4

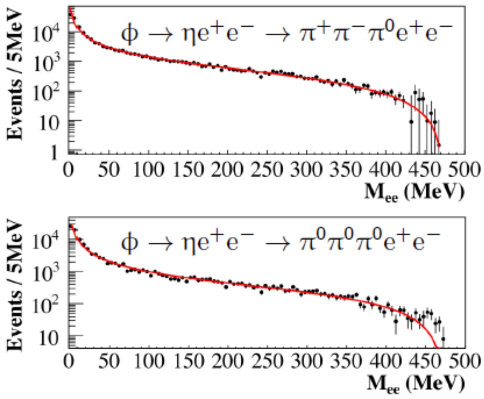

Fig. 1. Di-electron invariant mass distributions, M_{ee}, for $\phi \to \eta e^+e^-$ with $\eta \to \pi^+\pi^-\pi^0$ (**top**) and $\eta \to \pi^0\pi^0\pi^0$ (**bottom**). The red lines are the fits to the measured data.

4. U boson search in $e^+e^- \to U\gamma$ with $U \to \mu^+\mu^-$

The U boson was also searched in the process $e^+e^- \to U\gamma$ 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 candidate events were selected by requiring two opposite charged tracks emitted at large polar angles, with an initial-state radiation (ISR) photon emitted at small angles, and thus undetected. The photon was later kinematically reconstructed from the charged leptons.

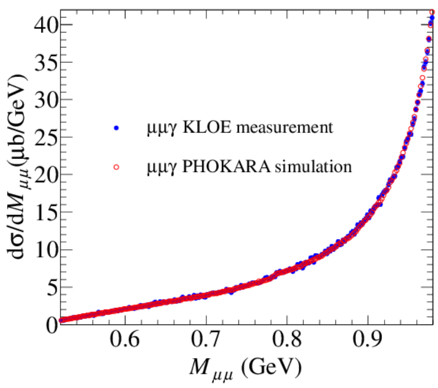

Fig. 2. Di-muon invariant mass distributions, $\mathrm{M}_{\mu\mu}$. Comparison of data (full blue circles) and simulation (open red circles).

Using energy and momentum conservation, a variable called *"track mass"*,

M_{trk} was 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 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 2 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,

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

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. 4

5. U boson search in $e^+e^- \to U\gamma$ with $U \to e^+e^-$

The study of the reaction $e^+e^- \to U\gamma$, $U \to e^+e^-$, is similar to the previously described analysis but with the characteristic that allows to investigate the low mass region close to the di-electron mass threshold [22].

For the event selection, two opposite charged tracks and a photon were required. To reduce the background contamination 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. 3 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.

The upper limit of the kinetic mixing parameter as a function of m_U was evaluated with the CLs technique in an analogous way as the $e^+e^- \to \mu^+\mu^-\gamma$. 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 $L_{integrated} = 1.54\,\mathrm{fb}^{-1}$ from the 2004-2005 data campaign.

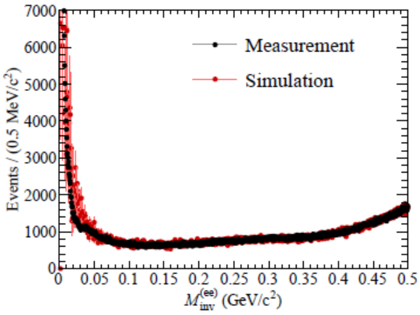

Fig. 3. Di-electron invariant mass distribution, M_{ee}, for the process $e^+e^- \to e^+e^-\gamma$ (black circles) compared to the MC simulated spectra (red circles).

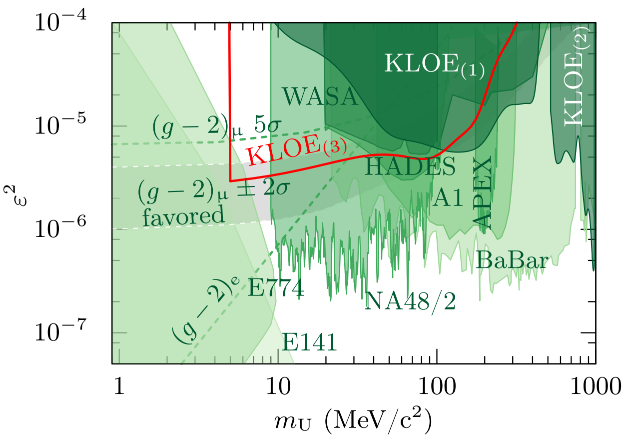

Fig. 4. Exclusion limits on the kinetic mixing parameter, ϵ^2, from KLOE (in red): $KLOE_1$, $KLOE_2$ and $KLOE_3$ correspond to the combined limits from the analysis of $\phi \to \eta e^+e^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to e^+e^-\gamma$, respectively. The results are compared with the 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.

6. U boson search in $e^+e^- \to h'U$ with $U \to \mu^+\mu^-$

A natural consequence of the mass of the U boson 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. The production cross section of the dark Higgsstrahlung process, $e^+e^- \to h'U$ 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 relative 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] in recent experiments. If $m_{h'} < 2m_U$, then the dark Higgs would have a large lifetime and would escape any detection. This "invisible" dark Higgs scenario has been the object of study by KLOE.

The analysis was performed on $1.65\,\mathrm{fb}^{-1}$ of data collected during 2004-2005 data campaign at a center of mass energy at the ϕ-peak and on a data sample of $0.2\,\mathrm{fb}^{-1}$ at a center of mass energy of $\sim 1000\,\mathrm{MeV}$. 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 [27], shown in Fig. 5.

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 evaluated selection efficiencies were found to be about $15\% - 25\%$.

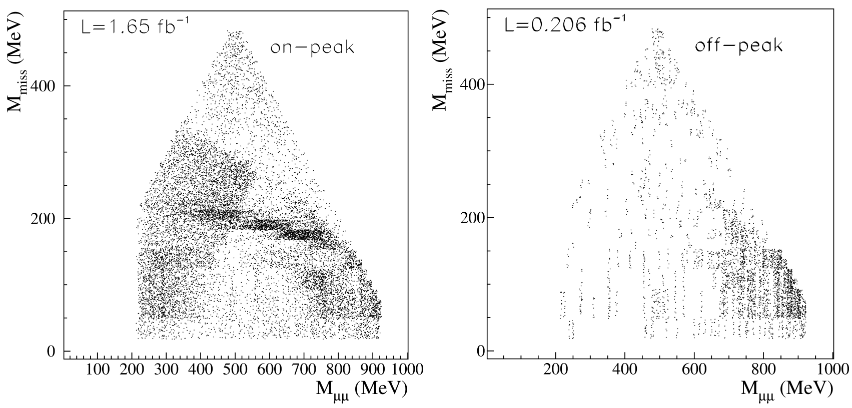

Fig. 5. Missing mass, M_{miss}, versus di-muon mass, $M_{\mu\mu}$, for the $1.65\,\mathrm{fb}^{-1}$ on-peak data sample (**left**) and the $0.2\,\mathrm{fb}^{-1}$ off-peak sample (**right**).

The different sources of background can be identified in Fig. 5, with its different contributions from $\phi \to K^+K^-$, $K^\pm \to \mu^\pm\nu$, $\phi \to \pi^+\pi^-\pi^0$, $e^+e^- \to \mu^+\mu^-$, $\pi^+\pi^-$, $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^-\pi^+\pi^-$. In the right plot of Fig. 5 (off-peak sample), all the backgrounds from the ϕ decays are strongly suppressed. No signal of the dark Higgsstrahlung process was observed and a Bayesian limit on the number of signal events, $N_{90\%}$, was derived for both samples separately. The product $\alpha_D \times \epsilon^2$ was then calculated according to,

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

with,

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

and where $\alpha_D \times \epsilon^2$ is assumed to be equal 1. A conservative 10% of systematic uncertainty was considered. 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 translate into a limit on the kinetic parameter, ϵ^2, of $10^{-6} - 10^{-8}$ ($\alpha_D = \alpha_{EM}$).

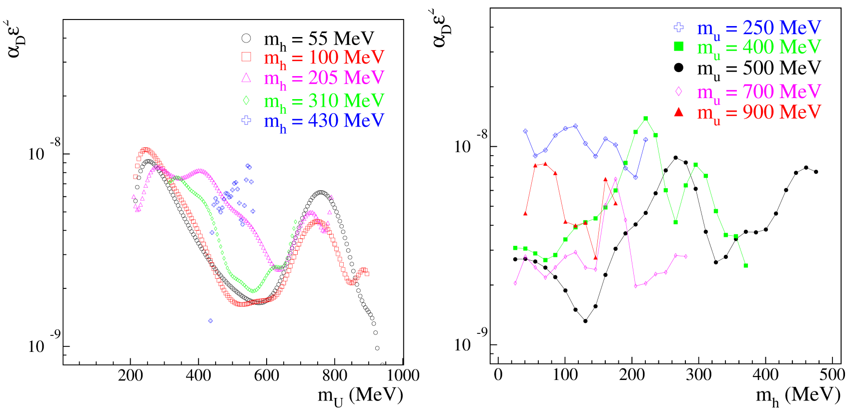

Fig. 6. Combined 90% confidence level upper limits in $\alpha_D \times \epsilon^2$ as a function of m_U for different $m_{h'}$ values (**left**) and as a function of $m_{h'}$ for different m_U (**right**).

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, in the mass range $5\,\text{MeV} < m_U < 980\,\text{MeV}$. Also, limits on $\alpha_D \times \epsilon^2$ at the 90% confidence level in the parameter space $2m_\mu < m_U < 1000\,\text{MeV}$ with $m_{h'} < m_U$ have been extracted from the search for the U boson in the dark Higgsstrahlung process. In the meantime a new data campaign has started with the KLOE-2 setup, which will collect more than $5\,\text{fb}^{-1}$ in the next three years. The new setup and the enlarged statistics could further improve the current limits on the dark coupling constant by at least a factor of two.

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