

Search for dark forces at KLOE-2

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Abstract. During the last years several Dark Sector Models have been proposed in order to address striking and puzzling astrophysical observations which fail standard interpretations.

In the minimal case a new vector particle, the so called dark photon or U-boson, is introduced, with small coupling with Standard Model particles. Also, the existence of a dark Higgs boson h' is postulated, in analogy with the Standard Model, to give mass to the U-boson through the Spontaneous Symmetry Breaking mechanism. The discovery of such a Dark Force Mediator would belong to a new field of Physics Beyond the Standard Model.

The KLOE experiment, working on the DAΦNE e^+e^- collider in Frascati, searched for the existence of the U-boson in a quite complete way, investigating several different processes and final states. Tight limits on the model parameters have been set at 90%CL. Further improvements are expected in terms of sensitivity and discovery potential with the new KLOE-2 detector working on the improved DAΦNE e^+e^- collider, which has collected more than 5 fb^{-1} .

1 Introduction

The Universe consists, in its majority, of Dark Matter (DM) and Dark Energy, being the contribution of visible matter as little as 4% of the total. The existence of DM is nowadays well established and supported by many cosmological observations. Its nature, however, has many different propositions to accommodate several predictions. In the case the DM is indeed a new type of matter, depending on how the DM interacts with the Standard Model (SM) particles, it would have an impact in some of the inconsistencies the model presents and could open the possibility of new hidden forces Beyond the Standard Model. Particularly, its involvement in the $g-2$ anomaly, a long standing discrepancy of about 3σ between theory and experimental values of the anomalous momentum of the muon. Several extensions of the SM have proposed models [1–5] with a Weakly Interacting Massive Particle (WIMP) belonging to a secluded gauge sector. In the most popular model, 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. A U boson, with mass of $\mathcal{O}(1\text{GeV})$ and in the range of $10^{-2} - 10^{-7}$, could be observed in e^+e^- colliders via different processes: $e^+e^- \rightarrow U\gamma$, $V \rightarrow P\gamma$ decays, where V and P are vector and pseudoscalar mesons, and $e^+e^- \rightarrow h'U$, where h' is a Higgs-like particle responsible for the breaking of the hidden symmetry. After several years of sterile searches of the U boson, specially in the $g - 2$ preferred region, new models are gaining popularity. Among them, a more recent proposal of a leptophobic *dark photon* [6],

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a new gauge field coupling to baryon number. This new dark matter mediator, or B boson, would mainly decay to baryons, opening new possibilities of discovery. In the following, many of these searches, carried out with the KLOE detector, are described, along with the status in the most recent searches.

2 The KLOE detector at DAΦNE

The KLOE detector experiment operates in Frascati, at the DAΦNE ϕ -factory [7]. It consists of three main parts, a cylindrical drift chamber (DC) [8] surrounded by an electromagnetic calorimeter (EMC) [9], 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 $\sigma_z \sim 2 \text{ mm}$. The momentum resolution $\sigma_{p\perp}/p_{\perp}$ is better than 0.4% for large-angle tracks.

3 $e^+e^- \rightarrow U\gamma$ with $U \rightarrow \mu^+\mu^-$

The U boson was searched in the process $e^+e^- \rightarrow U\gamma$ with $U \rightarrow \mu^+\mu^-$, in a sample of 239.3 pb^{-1} of data collected in 2002 [10]. The signature of the U *dark photon* would be seen as a narrow resonance in the di-muon mass spectrum.

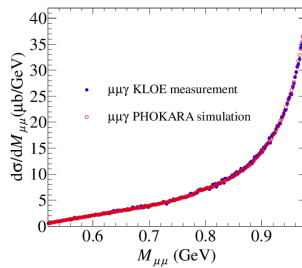


Figure 1. Di-muon invariant mass distributions $M_{\mu\mu}$. Comparison of data (full blue circles) and simulation (open red circles).

In absence of any excess in the di-muon mass spectrum (see Fig. 1), the CLs technique was applied to estimate the number of U -boson signal events excluded at 90% confidence level, N_{CLs} . Then, the limit on the kinetic mixing parameter was set according to:

$$\epsilon^2 = \frac{\alpha_D}{\alpha_{EM}} = \frac{N_{CLs}}{\epsilon_{eff} H \times I \times L_{integrated}}, \quad (1)$$

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. 3 as KLOE₂.

4 $e^+e^- \rightarrow U\gamma$ with $U \rightarrow e^+e^-$

To investigate the low mass region, close to the di-electron mass threshold, of the available phase-space of the U boson, the study of the reaction $e^+e^- \rightarrow U\gamma$, $U \rightarrow e^+e^-$, was also performed by KLOE [11].

Fig. 2 compares the di-electron invariant mass with BABAYAGA-NLO Monte Carlo (MC) simulation [12], modified to allow the Bhabha radiative process to proceed only via the annihilation channel, in which the U -boson signal would possibly occur, showing an excellent agreement.

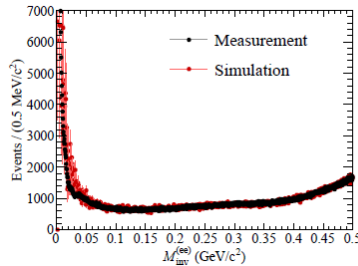


Figure 2. Di-electron invariant-mass distribution, M_{ee} , for the process $e^+e^- \rightarrow e^+e^-\gamma$ (black circles) compared to the MC simulated spectra (red circles).

As no signal was observed, 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 $e^+e^- \rightarrow \mu^+\mu^-\gamma$. The limit on the U -boson signal was evaluated at 90% confidence level and the limit on the kinetic parameter was calculated using equation (1). The extracted upper limit can be seen in Fig. 3 as KLOE₃. The selection efficiency of the analysis amounts to $\epsilon_{eff} \sim 1.5 - 2.5\%$ for an integrated luminosity analyzed corresponding to $L_{integrated} = 1.54 \text{ fb}^{-1}$.

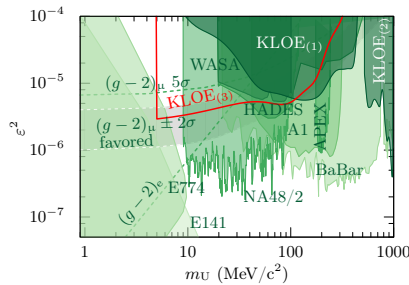


Figure 3. Exclusion limits on the kinetic-mixing parameter, ϵ^2 , from KLOE (in red): KLOE₁, KLOE₂ and KLOE₃ correspond to the combined limits from the analysis of $\phi \rightarrow \eta e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^- \rightarrow e^+e^-\gamma$, respectively. The results are compared with the limits from E141, E774 [13], MAMI/A1 [14], APEX [15], WASA [16], HADES [17], NA48/2 [18] and BaBar [19]. The grey band indicates the parameter space favored by the $(g_\mu - 2)$ discrepancy.

5 $e^+e^- \rightarrow U\gamma$ with $U \rightarrow \pi^+\pi^-$

As the SM photon, the *dark photon* couples to ρ , decaying, in this case, dominantly to hadrons. For this reason, the previous searches were not sensitive in the $\rho - \omega$ region. The

effective coupling of the U boson is predicted to be given by the product of the virtual-photon coupling and the kinetic-mixing parameter $\epsilon^2 e F_\pi(q^2)$ [20]. As in the previous analyses, the U boson signature would be then expected as a resonant peak in the di-pion invariant mass spectrum with initial state radiation (ISR) $\pi^+\pi^-\gamma$ events. The search was performed in a sample with a total integrated luminosity of 1.93 fb^{-1} [21].

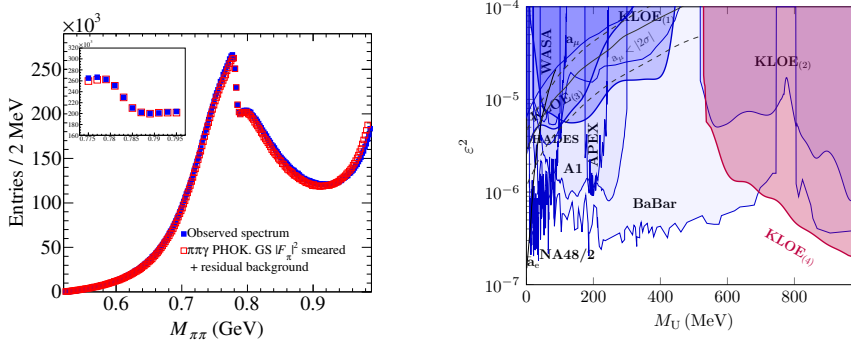


Figure 4. **Left:** Comparison of the measured data (blue squares) and simulation (red open squares) for the $M_{\pi\pi}$ invariant mass spectrum. **Right:** 90% CL upper limit exclusion plot for ϵ^2 as a function of the U -boson mass ($KLOE_{(4)}$). The limit is shown together with previous KLOE results as well as other experiments at the moment of publication.

A detailed description of the $\rho - \omega$ interference was achieved by a dedicated PHOKARA MC simulation, which includes the Gounaris-Sakurai pion form factor parameterization found in Ref. [22]. The Fig. 4 left shows the very good agreement between the MC predictions and data in the interference region, as well as no excess corresponding to a U -boson signal. Thus, a limit at the 90% CL was set on the coupling factor ϵ^2 in the energy range between 527 and 987 MeV, substantially improving the sensitivity in the $\rho - \omega$ region and above, see Fig. 4.

6 Combined limit in the production of U decaying into $\mu^+\mu^-$ and $\pi^+\pi^-$

The full KLOE statistics, of $L_{int} = 1.93 \text{ fb}^{-1}$, has been used to update the previous analysis of the decay $U \rightarrow \mu^+\mu^-$, with a new estimate of the background, analogous to the one used for the $U \rightarrow \pi^+\pi^-$ search. While this search confirms the non existence of U -boson signal in the di-muon invariant mass spectrum, both results on the 90% upper limit for $\mu\mu$ and $\pi\pi$ have been combined. This increases the sensitivity in the region of the $\rho - \omega$ interference, giving the up-to-date most stringent upper limit for the mixing parameter ϵ^2 in the U -boson mass region 519-987 MeV. In Fig. 5, the limit is shown along with the other most competitive limits in the same region.

7 B boson searches

As mention in section 1, there are additional models to the U dark photon. In particular, the model presented in [6], proposes a leptophobic mediator between the dark sector and the SM particles, the B boson. The B boson arises from a new $U(1)_B$ gauge symmetry that couples to the baryon number as:

$$\mathcal{L} = \frac{g_B}{3} \bar{q} \gamma^\mu q B_\mu \quad (2)$$

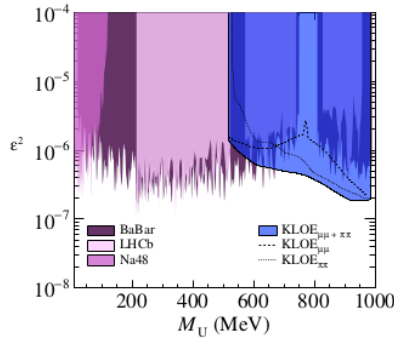


Figure 5. 90% CL exclusion plot for ϵ^2 as a function of the U -boson mass for the $e^+e^- \rightarrow U\gamma$ process. The $U \rightarrow \mu^+\mu^-$ limit (dashed line), the $U \rightarrow \pi^+\pi^-$ [21] constraint (solid line), and the $U \rightarrow \mu^+\mu^-, \pi^+\pi^-$ combination (blue area) at full KLOE statistics are presented in comparison with the competitive limits by BaBar [23], NA48/2 [18] and LHCb experiments [24].

where g_B is the $U(1)_B$ coupling, estimated to be $g_B \lesssim 10^{-2} \times (m_B/100 \text{ MeV})$. With quantum numbers $I^G(J^{PC}) = 0^-(1^{--})$, the B-boson decays in a similar way as the ω -meson. It is worth to notice that, given that the decay $B \rightarrow \pi^+\pi^-$ is forbidden by G-parity, the B-boson cannot be hidden under the ρ meson.

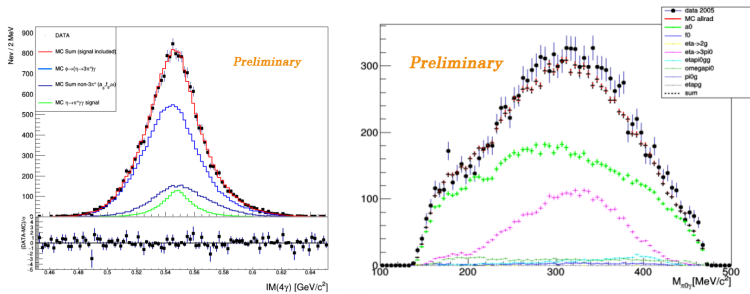


Figure 6. Left: Invariant mass of the $4-\gamma$ system in the decay $\eta \rightarrow B\gamma$. The dots show the data point while the solid color lines correspond to Monte Carlo simulations. **Right:** Invariant mass of the $\pi^0\gamma$ system from the channel $\phi \rightarrow \eta B \rightarrow \eta\pi^0\gamma$. Solid dots correspond to data, solid lines are Monte Carol simulations.

In KLOE the interesting region to be explored corresponds to masses below 600 MeV, where the dominant decay is $B \rightarrow \pi^0\gamma$. In particular, two reactions are being investigated by KLOE: the $\phi \rightarrow \eta B \rightarrow \eta\pi^0\gamma$, which mimics the final state of the SM decay $\phi \rightarrow a_0(980)\gamma \rightarrow \eta\pi^0\gamma$, and the $\eta \rightarrow B\gamma \rightarrow \pi^0\gamma\gamma$, which is compatible to the SM rare decay of $\eta \rightarrow \pi^0\gamma\gamma$, or χ PT golden mode. In figure 6, the very preliminary invariant masses of $4-\gamma$ from $\eta \rightarrow B\gamma$ and of $\pi^0\gamma$ from the decay $\phi \rightarrow \eta B$ are shown. In case of formation of the B-boson, the signature would appear as an enhancement in the corresponding $4-\gamma$ and $\pi^0\gamma$ invariant masses. In case no signal is discovered an upper limit in the coupling of such a DM mediator to the SM will be established.

8 Conclusions

The KLOE collaboration has extensively contributed to the present understanding of dark forces searches by investigating the production of the U -boson by analyzing four different 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 $5 \text{ MeV} < m_U < 987 \text{ MeV}$. Also, studying the associated production with a *dark-higgs*, limits on $\alpha_D \times \epsilon^2$ at the 90% confidence level in the parameter space $2m_\mu < m_U < 1000 \text{ MeV}$, with $m_{H'} < m_U$. New searches, for a leptophobic dark matter mediator which couples to baryon number, the B-boson, have started in two different processes. In case of no discovery signal, upper limits in the coupling of DM to SM will be established. In the meantime, the KLOE-2 data campaign finished, collecting more than 5 fb^{-1} . 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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