PROCEEDINGS OF SCIENCE

Search for Dark Forces with KLOE

Francesca Curciarello[*] [†]
INFN, Laboratori Nazionali di Frascati, Frascati, Italy

E-mail: `Francesca.Curciarello@lnf.infn.it`

A fifth force between dark matter particles has been advocated as explanation of many astrophysical anomalies and of the $g-2$ discrepancy. The KLOE Collaboration searched for the mediator of such dark force, the dark photon, and set six constraints on the dark force coupling strength ε^2, by investigating the ϕ-Dalitz decay into the η meson, the dark photon production from continuum, and the Higgsstrahlung process. New analyses will profit of the KLOE-2 data, which will allow to improve the sensitivity of all exploited processes by a factor of 2, thanks to the larger statistical sample and to the upgraded tracking detector.

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[*] Speaker.

[†] On behalf of the KLOE-2 Collaboration

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1. Introduction

Despite the worldwide efforts to shed light on dark matter (DM) particle nature, its origin and interaction dynamics are still a great puzzle. The biggest difficulty so far is that the DM has been studied only indirectly through the gravitational effects on baryonic matter. For this reason the postulation of a non-gravitational force between DM particles, mediated by a new light (<1 GeV) gauge boson [1], can represent an important and complementary possibility to probe DM. The existence of a low energy dark sector, remained yet undiscovered because of the very small coupling, is predicted by many extensions of the Standard Model (SM) [1–5] and its search has been strongly motivated by many puzzling astrophysical and terrestrial anomalies [6–12]. The mediator of this new force, the dark photon (referred to also as U, A' or γ'), should be a neutral light vector gauge boson which can kinetically mix with the ordinary photon and thus should be produced in any process in which a virtual or real photon is involved. Coupling to SM photon would occur through loops of heavy dark particles, charged under both electroweak and dark interactions, giving rise to a very weak mixing strength defined as the ratio of effective dark and fine structure coupling constants ($\varepsilon^2 = \alpha'/\alpha \ll 1$).

Moreover, the dark photon should get mass by means of a Higgs-like mechanism, suggesting the existence of at least an additional scalar particle in the dark sector, the dark Higgs h'. Dark photon search is also strongly motivated since it would give a positive one-loop contribution to the calculated value of the muon magnetic moment anomaly, a_μ, thus explaining the observed discrepancy with the experimental value, for dark photon masses of 10–100 MeV and coupling constant ε of about 10^{-3} [13].

At $\mathrm{e}^+\mathrm{e}^-$ colliders, dark force can be investigated by exploiting many different processes as radiative meson decays, continuum processes or dark Higgsstrahlung. The reach of collider searches covers the phase space region of parameters characterized by one-loop couplings and prompt dark photon decays, allowing to probe the $g-2$ favored region. The KLOE Collaboration, and its continuation KLOE-2, investigated all these processes by assuming the minimal hypothesis of visibly-decaying dark photon into leptons and hadrons, setting strong constraints and excluding wide ranges of parameters inside the $g-2$ favored band.

2. DAΦNE collider and KLOE detector

DAΦNE is an $\mathrm{e}^+\mathrm{e}^-$ collider running at the energy $\sqrt{s} = m_\phi = 1.0195$ GeV which is located at Laboratori Nazionali di Frascati of INFN. It consists of a linear accelerator, a damping ring, nearly 180 m of transfer lines, and two storage rings that intersect at two points.

The KLOE detector is made up of a large cylindrical drift chamber (DC) [14], surrounded by a lead scintillating fiber electromagnetic calorimeter (EMC) [15]. A superconducting coil around the EMC provides a 0.52 T magnetic field. The calorimeter is divided into a barrel and two end–caps and covers 98% of the solid angle. The modules are read out at both ends by 4880 photo–multipliers. Energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$ and $\sigma_t = 57\,\mathrm{ps}\,/\sqrt{E(\mathrm{GeV})} \oplus 100\,\mathrm{ps}$, respectively. The all-stereo drift chamber, $4\,m$ in diameter and $3.3\,m$ long, has a mechanical structure of carbon fiber-epoxy composite and operates with a light gas mixture (90% helium, 10% isobutane). The position resolutions are $\sigma_{xy} \sim 150\,\mu\mathrm{m}$ and $\sigma_z \sim 2$ mm. The momentum resolution $\sigma_{p_\perp}/p_\perp$ is better than 0.4% for large angle tracks. Vertices are reconstructed with a spatial resolution of $\sim 3\,\mathrm{mm}$.

3. Dark photon searches

The KLOE Collaboration searched for dark photon signature by investigating three processes and six different channels. In Fig. 1 all limits set by KLOE are reported (purple areas) in comparison with all other constraints in the 0-1 GeV mass range, see caption for more details.

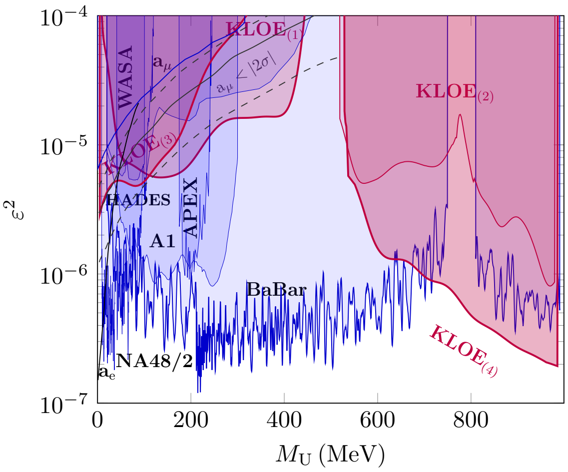

Figure 1: 90% CL exclusion plot for ε^2 as a function of the U-boson mass. The limits from the A1 [16] and APEX [17] fixed-target experiments, the limits from the ϕ Dalitz dacay (KLOE$_{(1)}$) [18, 19] and $e^+e^- \to U\gamma$, $U \to \mu^+\mu^-, e^+e^-, \pi^+\pi^-$ (KLOE$_{(2)}$, KLOE$_{(3)}$ and KLOE$_{(4)}$ respectively) [20–22], the WASA [23], HADES [24], BaBar [25] and NA48/2 [26] limits are shown. The solid lines are the limits from the muon and electron anomaly [13], respectively. The gray line shows the U boson parameters that could explain the observed a_μ discrepancy with a $2\,\sigma$ error band (gray dashed lines) [13].

In the next sections all the analyses performed to extract the KLOE limits will be described.

3.1 ϕ-Dalitz decay

The dark photon is expected to be produced in vector to pseudoscalar meson decays with a rate ε^2 times suppressed with respect to the ordinary transitions [27], producing a peak in the invariant mass distribution of the electron-positron pair over the continuum Dalitz background. The KLOE Collaboration set two constraints on the U-boson coupling, ε^2, by exploiting the $\phi \to \eta e^+e^-$ decay, where the η meson is tagged by its $\pi^+\pi^-\pi^0$ [18] and $3\pi^0$ decays [19]. The first analysis used a data sample of 1.5 fb^{-1} integrated luminosity. The limit on the number of U-boson events has been set by using the Confidence Level Signal (CL$_S$) technique [28–30]. This first upper limit (UL) has been then updated, improving sample statistics and background rejection (2% of background contamination), and combined with a new limit derived by tagging the η meson by its neutral decay into $3\pi^0$ [19]. For this new analysis, 30577 events are selected from a data sample of 1.7 fb^{-1} with 3% of residual background. For each channel, the irreducible background is extracted directly by a fit to data excluding for each U-boson mass hypothesis, the possible signal region used for the upper limit evaluation (5 MeV centred around $m_{\rm U}$).

A combined UL on the parameter ε^2 at 90% CL has been derived by using the Vector Meson Dominance expectation for the transition form factor slope ($b_{\phi\eta}$ ~1 GeV^2) resulting in $\varepsilon^2 < 1.7 \times 10^{-5}$ for $30 < M_{\rm U} < 400$ MeV, and in $\varepsilon^2 < 8.0 \times 10^{-6}$ for the sub-region $50 < M_{\rm U} < 210$ MeV. The above final combined limit is shown in Fig. 1 and dubbed as KLOE$_{(1)}$. This limit, published on 2013 [19] was able to rule out a wide range of U-boson parameters as a possible explanation of the a_μ discrepancy in the minimal U-decay hypothesis.

3.2 Uγ events

Radiative U-boson production in $e^+e^- \to U\gamma$, $U \to l^+l^-$, $l = e, \mu, \pi$ events is a very sensitive process, independent of the details of the Higgs sector of the dark group. The U boson should appear as a resonant peak in the invariant mass of lepton or hadron pairs. KLOE investigated both leptonic and hadron decays into pions. Particularly, the hadronic channel allows to increase the sensitivity in the $\rho - \omega$ resonance region because of the U dominant branching fraction into hadrons. The searches for $U \to \mu^+\mu^-, \pi^+\pi^-$ exploited a statistics corresponding to an integrated luminosity of 239.3 pb^{-1} and 1.93 fb^{-1} respectively, and selected events with a small angle Initial State Radiation (ISR) photon [31] and 2 charged tracks with acceptance between 50° and 130°. The application of kinematical cuts and the small angle event selection allowed to reduce the background coming from Final State Radiation (FSR) and ϕ-resonant processes and to increase sensitivity [32] on the dark photon decay. To approach the dielectron mass threshold, the search for $U \to e^+e^-$ has been performed by applying a large angle event selection for both ISR photon and charged leptons ($55^\circ < \theta_{e,\gamma} < 125^\circ$) to a data sample of about 1.5 fb^{-1}. Kinematical cuts have been used to remove FSR and resonant backgrounds. To avoid contamination from γ conversion processes in the vacuum wall, we asked for events entirely contained within the vacuum pipe ($\rho_{\rm PCA} < 1\,$cm, and $|z_{\rm PCA}| < 6\,$cm). At the end of the analysis selection the residual background is less then 1%. No significant dark photon signature has been observed and limits at 90% CL have been extracted for all processes on the number of U events by means of the CL$_{\rm S}$ technique [28–30]. The expected backgrounds have been estimated by a fit to side bands for electron and pion decay channels while for the muon channel a `PHOKHARA` [33] MC generation has been used. The limits on U events have then been converted in limits on ε^2 by using the formula reported in Refs. [20–22]. The resulting exclusion limits are shown by purple areas in Fig. 1 with all other existing limits in the region 0–1000 MeV [16–26]. The $e^+e^-\gamma$ limit excludes some of the remaining $g-2$ favored region.

4. Higgsstrahlung

The KLOE Collaboration investigated also the Higgsstrahulung process, sensitive to the dark coupling constant $\alpha_{\rm D}$ and less suppressed with respect previous processes, with an expected cross section up to 1 pb at KLOE. The invisible scenario was considered, where the dark Higgs is lighter then the U boson and escapes detection, in the energy range between the dimuon mass threshold and 1 GeV. In this case, the expected signal is a muon pair from the U-boson decay plus missing energy. The analysis has been performed on two data samples of 1.65 fb^{-1} (collected on the ϕ peak) and 0.2 fb^{-1} collected at $E_{\rm cm} = 1000$ MeV (off-peak sample) which is not affected by resonant backgrounds. In the on-peak analysis the huge background coming from kaon decays has been reduced thanks to cuts on the quality of the vertex fit. No signal signature has been observed and a Bayesian limit on the number of signal events at 90% CL has been evaluated, bin-by-bin, for the on-peak and off-peak sample separately. Results have been translated in terms of $\alpha_{\rm D} \times \varepsilon^2$ by using the integrated luminosity information, the signal efficiency, the dark Higgsstrahlung cross section and the branching fraction of the $\rm U \to \mu^+\mu^-$ decay [34]. The combined upper limits [35] projected in the $M_{\mu\mu}$ and $M_{\rm miss}$ directions, for different dark Higgs mass hypotheses and slightly smoothed, are shown in Fig. 2. Values of the order of $10^{-9} \div 10^{-8}$ in $\alpha_{\rm D} \times \varepsilon^2$ are excluded at 90% CL for a large range of the dark photon and dark Higgs masses. These limits translate in $\varepsilon \sim 10^{-3} - 10^{-4}$ for $\alpha_{\rm D} = \alpha$ and are in agreement and complementary with BaBar and Belle results [36,37] as they refer to the same process in a different final state and phase space region.

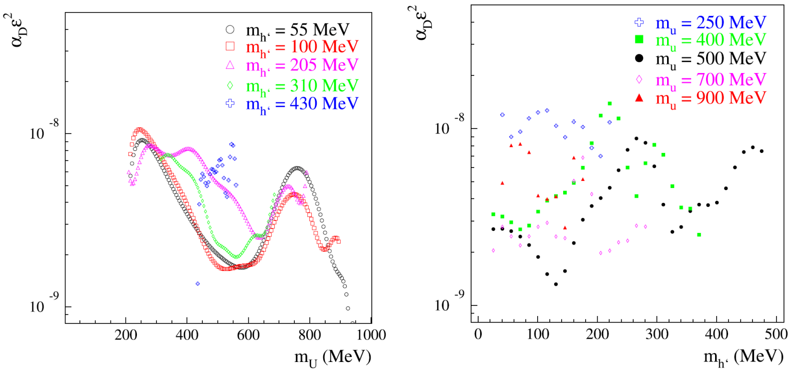

Figure 2: Combined 90% CL upper limits in $\alpha_{\rm D} \times \varepsilon^2$ as a function of $M_{\mu\mu}$ for different values of $m_{\rm h'}$ (left panel) and as a function of $M_{\rm miss}$ for different values of $m_{\rm U}$ (right panel).

5. Conclusions and future prospects

The KLOE Collaboration, and its continuation KLOE-2, investigated the existence of the dark photon in the prompt and visibly-decay hypothesis, by means of the $\phi-$Dalitz decay, continuum processes and Higgsstrahlung. No signal has been found so far and stringent limits have been extracted below 1 GeV, some of them constraining the $g-2$ favored region. The sensitivity of the future dark force analyses are expected to improve of a factor of about 2 thanks to the new DAΦNE interaction scheme, which allows to collect a larger new statistical sample, and to the KLOE-2 inner tracking detector, which allows a better vertex reconstruction and a higher invariant mass resolution. Searches for invisible dark photon decays into light DM states and for a leptophobic B boson are also planned.

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