

Dark mediator searches at KLOE/KLOE-2

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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 for 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, $\phi \rightarrow \eta U$ with $U \rightarrow e^+ e^-$, and continuum events, $e^+ e^- \rightarrow U \gamma$. 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 $4 \text{ MeV} \cdot c^{-2} < M_U < 980 \text{ MeV} \cdot c^{-2}$. KLOE has also sought the U boson in the dark Higgsstrahlung process $e^+ e^- \rightarrow U h'$, $U \rightarrow \mu^+ \mu^-$, setting limits on m_U and $m_{h'}$ in the parameter space from $2m_\mu < m_U < 1\,000 \text{ MeV} \cdot c^{-2}$ and $10 \text{ MeV} \cdot c^{-2} < m_{h'} < 500 \text{ MeV} \cdot c^{-2}$. 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 good 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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在 KLOE/KLOE-2 实验中寻找暗传播子

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摘要: 一个新的矢量玻色子的存在已经在不同的背景下被提出, 这个新矢量玻色子与标准模型粒子的耦合可以通过动力学混合, 对 U 玻色子, 或者通过耦合到重子数, 对 B 玻色子. 暗物质传播子的直接寻找可以在加速器上进行. DAΦNE Φ-工厂中的 KLOE 探测器大量研究了 U 玻色子参与的两种过程: φ 介子的达利兹衰变, 即伴随 $\phi \rightarrow \eta U$, $U \rightarrow e^+ e^-$ 过程, 以及连续统事件 $e^+ e^- \rightarrow U \gamma$ 过程. 在所有这些过程中, 对于质量区间在 $4 \text{ MeV}/c^2 < M_U < 980 \text{ MeV}/c^2$, 我们可以给出 U 玻色子耦合参数 ϵ^2 上限在 10^{-7} 到 10^{-5} . KLOE 也在暗希格斯辐射过程 $e^+ e^- \rightarrow U h'$, $U \rightarrow \mu^+ \mu^-$ 中寻找 U 玻色子, m_U 和 $m_{h'}$ 在参数空间中被分别限定在 $2m_\mu < m_U < 1\,000 \text{ MeV}/c^2$ 和 $10 \text{ MeV}/c^2 < m_{h'} < 500 \text{ MeV}/c^2$ 的范围内. 同时新的数据采集已经在 KLOE-2 设备上运行, 未来 3

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年采集目标将在 5 fb^{-1} 以上. 新的大数据样本将进一步提高暗耦合常数的上限.

关键词: 暗物质; 暗能量; U 玻色子; A' ; 希格斯辐射; h' ; 上限

0 Introduction

Recent observations, such 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 the photon via a kinetic mixing term,

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

where the parameter, ϵ , represents the mixing strength and is defined as the ratio of the dark photon to the SM electroweak coupling, α_D/α_{EM} . U boson searches are conducted 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. Some of these searches, which are reported in the following, have been performed by the KLOE experiment.

1 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 $\sigma_E/E = 5.7\%/\sqrt{E[\text{GeV}]}$ and $\sigma_t(E) = 57 \text{ ps}/\sqrt{E[\text{GeV}]} \oplus 100 \text{ ps}$, 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, 4 m in diameter and 3.3 m long, operates with a light gas mixture (90% helium, 10% isobutane). The position resolutions are $\sigma_{xy} \approx 150 \mu\text{m}$ and $\sigma_z \approx 2 \text{ mm}$. Momentum resolution, $\sigma_{p\perp}/p_\perp$, is better than 0.4% for large-angle tracks.

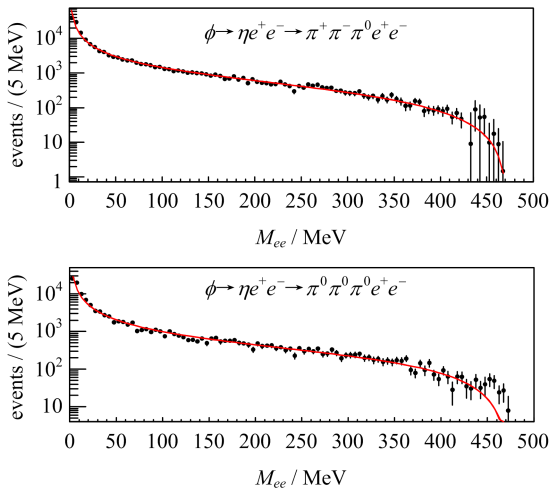
2 $\phi \rightarrow \eta U$ with $U \rightarrow e^+e^-$

The U boson decay $U \rightarrow e^+e^-$ in the process $\phi \rightarrow \eta U$ was the first search to be conducted at KLOE. A total of 13000 events of $\eta \rightarrow \pi^+\pi^-\pi^0$ from 1.5 fb^{-1} and 31000 events of $\eta \rightarrow \pi^0\pi^0\pi^0$ 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 $\phi \rightarrow \eta\gamma^* \rightarrow \eta e^+e^-$ was directly extracted from the data by a fit to the M_{ee} distribution parameterized according to the Vector Meson Dominance model^[18].

No resonant signal was observed in the M_{ee} distributions of both analyses, see Fig.1. The peak around $400 \text{ MeV} \cdot c^{-2}$ is due to background from the decay $\phi \rightarrow K_S K_L$. 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 Ref. [20],

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

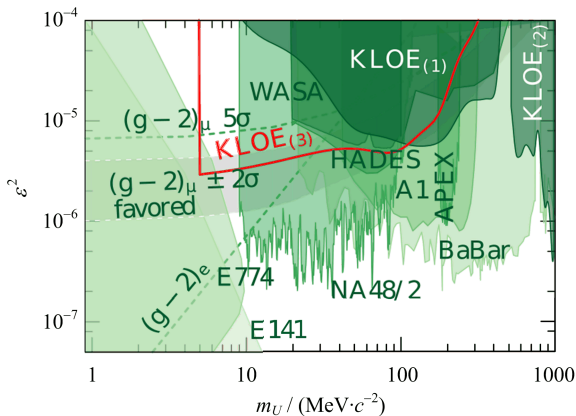
In Eq. (2), $|F_{\eta\phi}(m_U^2)|^2$ is the form factor of the $\phi \rightarrow \eta\gamma$ decay evaluated at the U mass and the quotient corresponds to the ratio of the kinematic functions of the decays involved in the process. In



The red lines are the fits to the measured data.

Fig. 1 Di-electron invariant mass distributions,
 M_{ee} , for $\phi \rightarrow \eta e^+ e^-$ with $\eta \rightarrow \pi^+ \pi^- \pi^0$ (top)
 and $\eta \rightarrow \pi^0 \pi^0 \pi^0$ (bottom)

Fig. 2 the 90% confidence level limit is presented along with results from KLOE and other various experiments.



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.

Fig. 2 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

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

The next of the U boson searches carried out at KLOE was studying the reaction $e^+ e^- \rightarrow U \gamma$ with $U \rightarrow \mu^+ \mu^-$, 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 $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$ receives a very large contribution from the reaction $e^+ e^- \rightarrow \mu^+ \mu^-$, 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.

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 $e^+ e^- \rightarrow e^+ e^- \gamma$, $e^+ e^- \rightarrow \pi^+ \pi^- \gamma$ and $e^+ e^- \rightarrow \phi \rightarrow \pi^+ \pi^- \pi^0$ 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 being divided by efficiency and luminosity. Fig. 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,

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

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, $d\sigma_{\mu\mu}/dM_{\mu\mu}$. A systematic uncertainty of about 2% was estimated. The 90% confidence level limit is shown in Fig. 2.

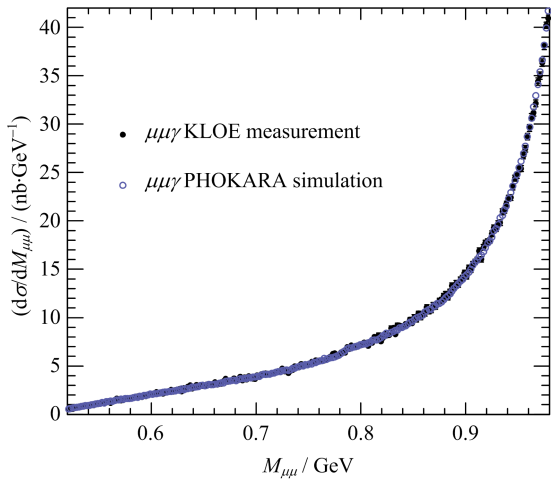


Fig. 3 Di-muon invariant mass distributions, $M_{\mu\mu}$. Comparison of data (full blue circles) and simulation (open red circles)

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

Similar to the previous analyses, the reaction $e^+e^- \rightarrow U\gamma$, $U \rightarrow e^+e^-$ 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 $e^+e^- \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \pi^+\pi^-\gamma$, $e^+e^- \rightarrow \gamma\gamma$, with a photon converting into an e^+e^- pair, $e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\pi^0$, 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%. Fig. 4 compares the di-electron invariant mass with MC BABAYAGANLO 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.

In an analogous way as the $e^+e^- \rightarrow \mu^+\mu^-\gamma$ study, the upper limit of the kinetic mixing

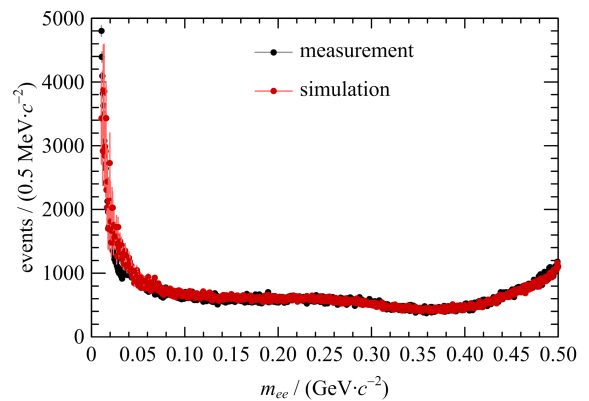


Fig. 4 Di-electron invariant mass distribution, M_{ee} , for the process $e^+e^- \rightarrow e^+e^-\gamma$ (black circles) compared to the MC simulated spectra (red circles)

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 Eq. (3). In this case the selection efficiency amounts to $\epsilon_{eff} \approx 1.5\% \sim 2.5\%$ and the integrated luminosity corresponds to $L_{integrated} = 1.54 \text{ fb}^{-1}$ from the 2004~2005 data campaign.

5 $e^+e^- \rightarrow h'U$ with $U \rightarrow \mu^+\mu^-$

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 $e^+e^- \rightarrow h'U$ with $U \rightarrow \mu^+\mu^-$, would be proportional to the product $a_D \times \epsilon^2$ ^[24]. Thus this process is suppressed by a factor ϵ compared with 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 $h' \rightarrow UU \rightarrow 4l, 4\pi, 2l + 2\pi$, 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 $\sim 1000 \text{ MeV}$ 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.

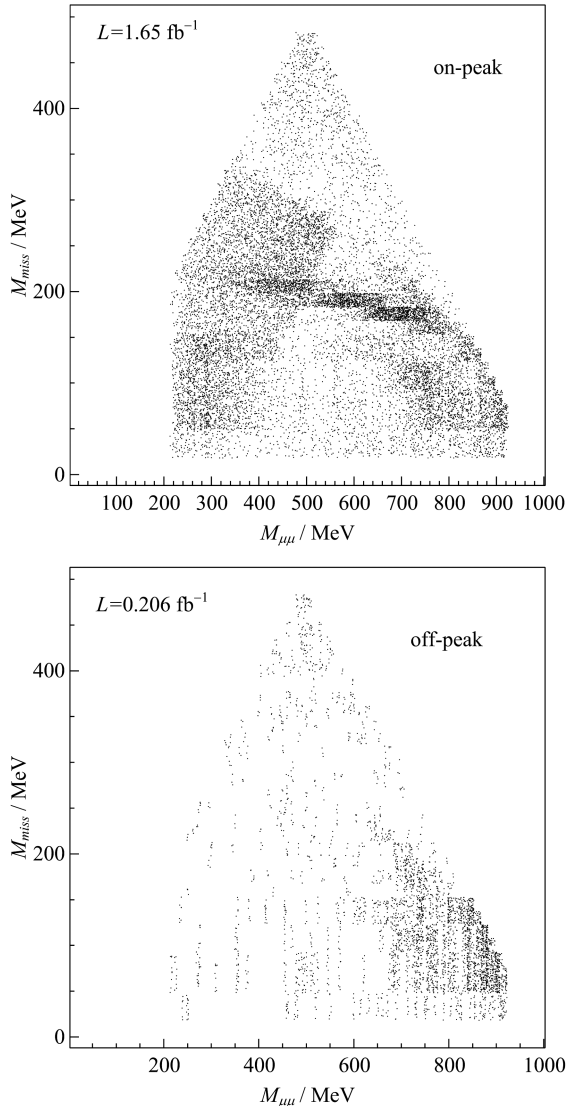


Fig. 5 Missing mass, M_{miss} , versus di-muon mass, $M_{\mu\mu}$, for the 1.65 fb^{-1} on-peak data sample (top) and the 0.2 fb^{-1} off-peak sample (bottom)

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 $\phi \rightarrow K^+ K^-$, $K^\pm \rightarrow \mu^\pm \nu$. The central horizontal band corresponds to $\phi \rightarrow \pi^+ \pi^- \pi^0$ contribution. Continuum backgrounds $e^+ e^- \rightarrow \mu^+ \mu^-$, $\pi^+ \pi^-$ populate the right lower side of the spectra and the top point of the distribution is mostly due to $e^+ e^- \rightarrow e^+ e^- \mu^+ \mu^-$ and $e^+ e^- \rightarrow e^+ e^- \pi^+ \pi^-$. In the lower plot of Fig. 5 (off-peak sample), all the backgrounds from the ϕ decays are strongly suppressed.

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,

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

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 $10^{-9} \sim 10^{-8}$ at 90% confidence level transform into a limit on the kinetic parameter, ϵ^2 , of $10^{-6} \sim 10^{-8}$ ($\alpha_D = \alpha_{EM}$). A conservative 10% of systematic uncertainty was considered.

6 Conclusion

The KLOE Collaboration has extensively

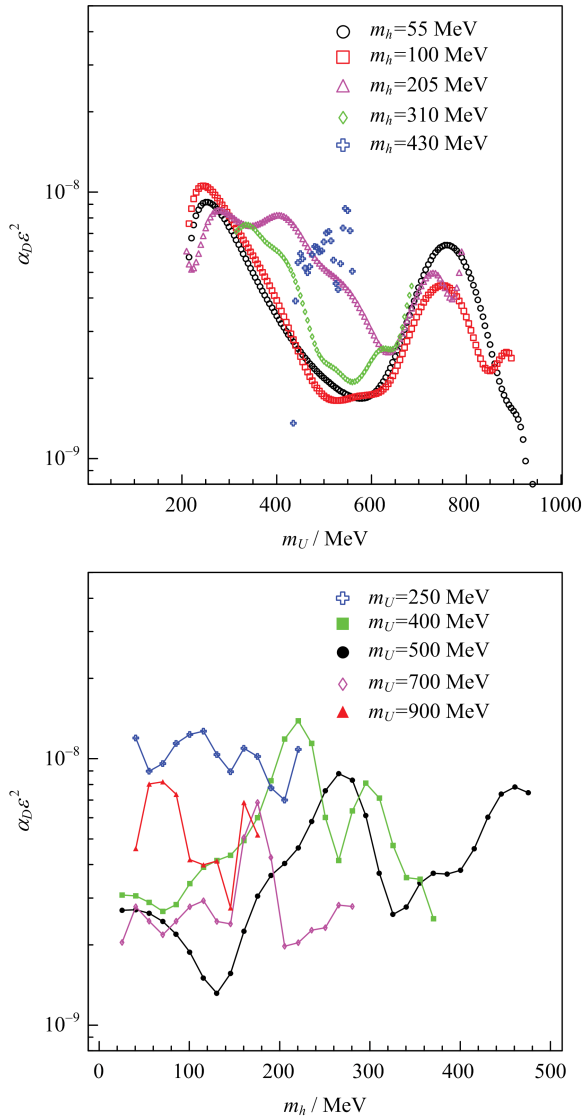


Fig. 6 Combined 90% confidence level upper limits in $\alpha_D \times \epsilon^2$ as a function of m_U for different $m_{h'}$ values (top) and as a function of $m_{h'}$ for different m_U (bottom)

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 $5 \text{ MeV} < m_U < 980 \text{ MeV}$. For the dark Higgsstrahlung process, limits on $\alpha_D \times \epsilon^2$ at the 90% confidence level in the parameter space $2m_\mu < m_U < 1000 \text{ eV}$ 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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