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SEARCH FOR THE U BOSON IN THE PROCESS $e^+e^- \to \mu^+\mu^-\gamma$, $U \to \mu^+\mu^-$ WITH THE KLOE DETECTOR*

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We present a search for a new light vector boson, carrier of a "dark force" between WIMPs, with the KLOE detector at DAΦNE. We analysed $e^+e^- \to \mu^+\mu^-\gamma$ ISR events corresponding to an integrated luminosity of 239 pb^{-1} to find evidence for the $e^+e^- \to U\gamma$, $U \to \mu^+\mu^-$ process. We found no U vector boson signal and set a 90% C.L. upper limit on the ratio of the U boson and photon coupling constants between 1.6×10^{-5} to 8.6×10^{-7} in the mass region $520 < M_U < 980$ MeV. A projection of the KLOE sensitivity for the $\mu\mu\gamma$ and $\pi\pi\gamma$ channels at full statistics and extended muon acceptance is also presented.

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1. Introduction

Many extensions of the Standard Model (SM) [1–5] assume that dark matter (DM) is made up of new particles charged under some new interaction mediated by a new gauge vector boson called U (also referred to as dark photon or A'). The U boson can kinetically mix with the ordinary photon through high-order diagrams, providing therefore a small coupling with SM particles [1–5]. The coupling strength can be expressed by a single factor, ε, equal to the ratio of dark and Standard Model electromagnetic couplings [1]. An U boson with mass of $\mathcal{O}(1$ GeV) and ε in the range of 10^{-2}–10^{-7} could explain all puzzling effects observed in recent astrophysics experiments [6–12]. By using a data sample corresponding to an integrated luminosity of 239 pb^{-1}, KLOE investigated the radiative $U\gamma$ production with $U \to \mu^+\mu^-$. New searches are foreseen to exploit the full KLOE statistics for the $\mu^+\mu^-\gamma$ channel and also to search for the $U \to \pi^+\pi^-$ decay.

2. The KLOE detector

The KLOE detector operates at DAΦNE, the Frascati ϕ-factory. It consists of a large cylindrical drift chamber (DC) [13], surrounded by a lead scintillating-fiber electromagnetic calorimeter (EMC) [14]. A superconducting coil around the EMC provides a 0.52 T magnetic field along the beam axis. EMC energy and time resolutions are $\sigma_E/E = 0.057/\sqrt{E\ [\mathrm{GeV}]}$ and $\sigma_t = 57\ \mathrm{ps}/\sqrt{E\ [\mathrm{GeV}]} \oplus 100$ ps, respectively. The drift chamber has only stereo sense wires, it is 4 m in diameter, 3.3 m long and operates with a low-Z gas mixture (helium with 10% isobutane). Spatial resolutions are $\sigma_{xy} \sim 150\ \mu$m and $\sigma_z \sim 2$ mm. The momentum resolution for large angle tracks is $\sigma(p_\perp)/p_\perp \sim 0.4\%$.

3. $\mu^+\mu^-\gamma$ data analysis

The $\mu^+\mu^-\gamma$ event selection requires two tracks of opposite charge with $50° < \theta < 130°$ and an undetected photon whose momentum, computed according to the $\mu\mu\gamma$ kinematics, points at small polar angle ($\theta < 15°$, $> 165°$) [15, 16]. These requirements limit the range of $M_{\mu\mu}$ to be larger than 500 MeV and greatly reduce the contamination from the resonant and Final State Radiation (FSR) processes: $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$, $e^+e^- \to \pi^+\pi^-\gamma_{\mathrm{FSR}}$ and $e^+e^- \to \mu^+\mu^-\gamma_{\mathrm{FSR}}$. The above selection criteria are also satisfied by $e^+e^- \to e^+e^-\gamma$ radiative Bhabha events. To obtain additional separation between electrons and pions or muons, a particle identification estimator (L_{i}), based on a pseudo-likelihood function using time-of-flight and calorimeter information is used [15, 16]. Events with both tracks satisfying $L_{\mathrm{i}} < 0$ are rejected as $e^+e^-\gamma$ with a $\pi\pi\gamma/\mu\mu\gamma$ loss less than 0.05%. Pions and muons are identified by means of the variable M_{trk} defined as the mass of oppositely-charged particles in the $e^+e^- \to x^+x^-\gamma$ process in which we assume the presence of an unobserved photon and that the tracks belong to particles of the same mass with momentum equal to the observed value. The M_{trk} values between 80–115 identify muons, while M_{trk} values > 130 MeV identify pions. A cut on the quality of the fitted tracks, parametrized by the error on M_{trk}, $\sigma_{M_{\mathrm{trk}}}$, has been implemented to further improve the π/μ separation [15]. At the end of the analysis chain, residual backgrounds consisting of $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \pi^+\pi^-\gamma$ and $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$ are still present. The last two contributions have been evaluated from Monte

Carlo (MC) simulation, while the $e^+e^- \to e^+e^-\gamma$ events have been estimated directly from data [15, 16]. Additional background from $e^+e^- \to e^+e^-\mu^+\mu^-$ is at the percent level below 0.54 GeV and decreases with $M_{\mu\mu}$. Figure 1, left shows the fractions of the background processes, $F_{\rm BG}$, as a function of $M_{\mu\mu}$, while Fig. 1, right shows the measured $\mu\mu\gamma$ cross section compared with the NLO QED calculations, using the MC code PHOKHARA [17]. The agreement between measurement and the PHOKHARA simulation is excellent, proving analysis consistency. No structures are visible in the $M_{\mu\mu}$ spectrum.

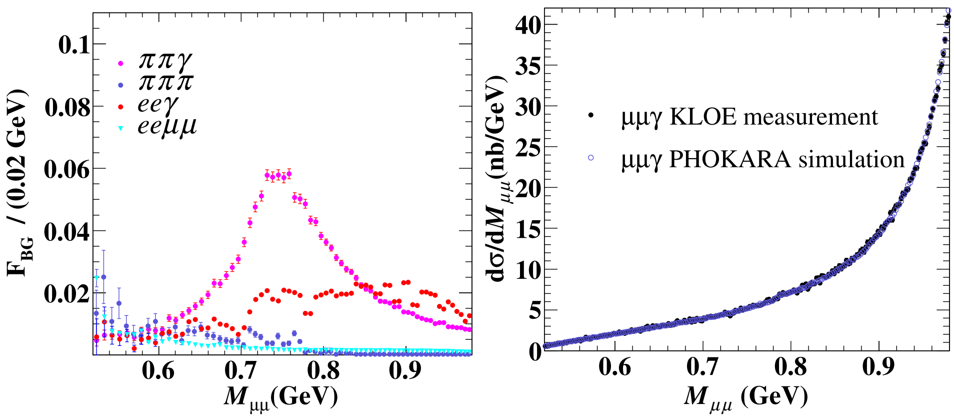

Fig. 1. Left: Fractional backgrounds to the $\mu\mu\gamma$ signal; see insert for symbols. Right: Comparison of data (full circles) and simulation (open circles) for $\mu^+\mu^-\gamma$ cross section.

4. Limit on U-boson coupling and future prospects

To exclude small U-boson signals, we extracted the limit on the number of U-boson candidates at 90% of confidence level (C.L.) through the CLS technique [18]. We compared the expected and observed $\mu^+\mu^-\gamma$ yield, and a MC generation of the U-boson signal which takes into account the resolution in $M_{\mu\mu}$ (from 1.5 MeV to 1.8 MeV as $M_{\mu\mu}$ increases). The limit on the kinetic mixing parameter has been extracted by means of

$$\varepsilon^2 = \frac{N_{\rm CLS}/(\epsilon_{\rm eff} \times L)}{H \times I}\,, \tag{1}$$

where $\epsilon_{\rm eff}$ represents the overall efficiency (1–15% as $M_{\mu\mu}$ increases [15]), L is the integrated luminosity, H is the radiator function obtained from QED including NLO corrections, and I is the effective U cross section [3].

The resulting exclusion plot on the kinetic mixing parameter ε^2, in the 520–980 MeV mass range, is shown in Fig. 2. In the same plot, other limits in the mass range below 1 GeV are also shown [19–26]. Our 90% C.L. limit is between 1.6×10^{-5} and 8.6×10^{-7} in the 520–980 MeV mass range [15].

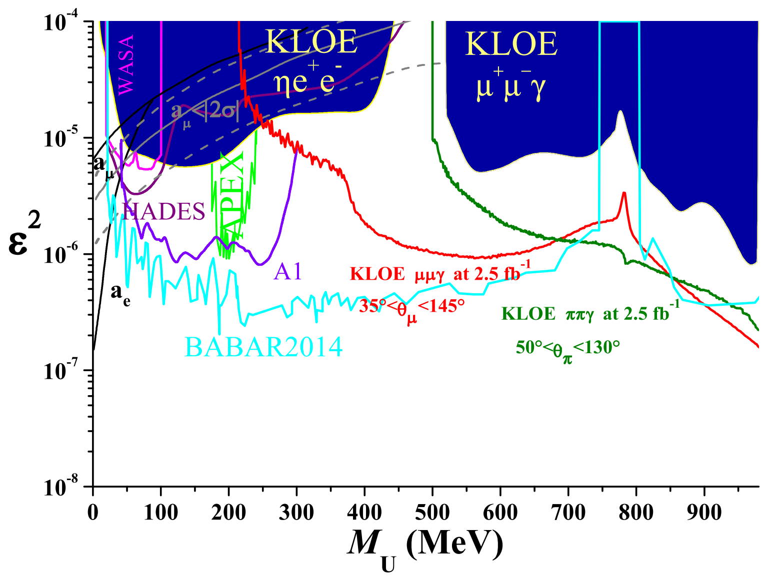

Fig. 2. (Colour online) 90% C.L. exclusion plot for ε^2 as a function of the U-boson mass (blue) [15]. Limits from A1 [19] (violet), Apex [20] (green), KLOE $\phi \to \eta e^+e^-$ [21, 22] (blue), WASA [23] (magenta), HADES [24] (purple) and BaBar (cyan) [25] are shown. The black and grey lines are the limits from the muon and electron anomaly [26], respectively. KLOE sensitivity for $\mu\mu\gamma$ and $\pi\pi\gamma$ at 2.5 fb^{-1} and $35^\circ(50^\circ) < \theta_{\mu(\pi)} < 145^\circ(130^\circ)$ are also shown (gray/red and black/green lines, respectively).

An upgrade of the presented analysis is foreseen by employing the full KLOE data statistics corresponding to an integrated luminosity of 2.5 fb^{-1} and by extending the muon polar angle acceptance from 50° to 35° and from 130° to 145°. The KLOE reach in sensitivity by considering a 2 MeV invariant mass resolution is presented in Fig. 2 (grey/red line) at $N_U/\sqrt{N_{\rm QED}} = 2$. The sensitivity loss due to the ρ meson around 770 MeV is due to the branching fraction of the $U \to \mu^+\mu^-$ channel which is suppressed by the dominant hadronic decay mode $U \to \pi^+\pi^-$. To overcome this problem, KLOE-2 plans to carry on also a new analysis by exploiting the $\pi^+\pi^-\gamma$ channel. The detailed KLOE-2 physics program is presented in Ref. [27]. The KLOE reach at full statistics for the $\pi\pi\gamma$ channel is shown in Fig. 2 at $N_U/\sqrt{N_{\rm QED}} = 2$ and a 2 MeV binning factor (black/green line).

5. Conclusions

We searched for a light, dark vector boson through a study of the $\mu^+\mu^-\gamma$ ISR process by analysing a sample corresponding to a total integrated luminosity of 239 pb^{-1}. We found no evidence for such a U boson. We set an upper limit at 90% C.L. on the kinetic mixing parameter ε^2 between 1.6×10^{-5} and 8.6×10^{-7} in the 520–980 MeV mass range. A future analysis that exploits full KLOE statistics and an extended muon acceptance for the $\mu\mu\gamma$ channel as well as the investigation of $\pi\pi\gamma$ channel are planned.

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