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

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Dark Matter and Dark Energy are two of the most fundamental open questions in physics today. The existence of a light dark-force mediator has been hypothesized as a possible explanation for several unexplained physical phenomena. A new search for this mediator, the dark photon, U, is underway using data collected with the KLOE detector at DAΦNE. We describe the strategy we will use in our search for a resonant peak in the electron-positron invariant mass spectrum from the process $e^+e^- \to U\gamma$ with $U \to e^+e^-$. So far, we found no evidence for the process and set a preliminary upper limit on the level of mixing between the secluded dark sector and the Standard Model.

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1. Introduction

A series of unexpected astrophysical observations have failed to find explanations in terms of standard astrophysical or particle physics models [1–10]. Each of these anomalies can be explained, however, if there exists a dark weakly interacting massive particle, WIMP, belonging to a secluded gauge sector [11–15]. A dark vector boson, U, an Abelian gauge field, may couple the secluded sector to the Standard Model through its kinetic mixing with the Standard Model electroweak hypercharge gauge field, $\mathcal{L}_{\mathrm{mix}} = -{}^{\varepsilon^2}\!/_2\, F_{ij}^{\mathrm{EW}} F_{\mathrm{Dark}}^{ij}$. The kinetic mixing parameter, ε, is expected to be of the order of 10^{-4}–10^{-2} which allows for observable effects in $\mathcal{O}$(GeV)-energy e^+e^- colliders [18–20]. The U boson might be produced in such collider experiments via several processes: $V \to PU$ decays, where V and P

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are vector and pseudoscalar mesons, $e^+e^- \to U\gamma$ with $U \to \ell^+\ell^-$, where $\ell = e$ or μ, and $e^+e^- \to Uh'$ (dark Higgsstrahlung), where h' is a Higgs-like particle responsible for breaking the hidden symmetry.

2. The KLOE detector

The KLOE experiment operated from 2000 to 2006 at DAΦNE, the Frascati ϕ factory. DAΦNE is an e^+e^- collider running mainly at a center-of-mass energy of ~ 1.0195 GeV, the mass of the ϕ meson. Equal energy electron and positron beams collide at an angle of ~ 25 mrad, producing ϕ mesons nearly at rest. The detector consists of a large cylindrical Drift Chamber (DC) [21], providing a momentum resolution of $\sigma_\perp/p_\perp \approx 0.4$, surrounded by a lead-scintillating fiber electromagnetic calorimeter (EMC) [22] providing an energy resolution of $\sigma_E/E = 5.7\%/\sqrt{E\ [\mathrm{GeV}]}$ and a time resolution of $\sigma_t = 57\ \mathrm{ps}/\sqrt{E\ [\mathrm{GeV}]} \oplus 100$ ps. A superconducting coil around the EMC provides a 0.52 T field.

3. *U* boson searches by KLOE-2

The KLOE-2 Collaboration has completed three searches for a dark photon. The first two searched for U bosons in vector meson decays $V \to PU$, where $\phi \to \eta U$, $U \to e^+e^-$ with the pseudoscalar meson decaying via $\eta \to \pi^+\pi^-\pi^0$ [16] and $\eta \to \pi^0\pi^0\pi^0$ [17]. KLOE-2 provided another limit for U boson production using the process $e^+e^- \to U\gamma$, $U \to \mu^+\mu^-$ [25]. A fourth dark force analysis has been performed by KLOE-2 by searching for the U boson in the dark Higgsstrahlung process, $e^+e^- \to Uh'$. A preliminary limit on the product of the dark coupling strength and the kinetic mixing strength, $\alpha_\mathrm{D} \times \varepsilon^2$, will be published soon.

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

The first three analyses produced excellent limits in the parameter space ε^2 *versus* m_U, but some values of ε and m_U that can explain the $(g-2)_\mu$ anomaly have not yet been excluded. In particular, we would like to probe the range of $15 < m_U < 50\ \mathrm{MeV}/c^2$ to either find evidence for an explanation of the muon anomaly or completely exclude the dark photon as a possible explanation. At an e^+e^- collider like DAΦNE, it is possible that the electron and positron can annihilate, or scatter, producing a U boson and a photon, with the decay of the U boson into a pair of leptons. Unlike the previous KLOE-2 limits, the sensitivity from the $e^+e^- \to U\gamma$, $U \to e^+e^-$ channel is expected to increase as m_U approaches $2m_e$ due to the dramatic increase in the U boson production cross section

$$\sigma(e^+e^- \to U \to \ell^+\ell^-, s') = \frac{12\pi\Gamma(U \to e^+e^-)\Gamma(U \to \ell^+\ell^-)}{\left(s' - m_U^2\right)^2 + m_U^2\Gamma_{\text{total}}^2}, \quad (1)$$

where we have electrons as our final-state leptons ($\ell = e$) and $\Gamma_{\text{total}} = \Gamma(U \to e^+e^-) + \Gamma(U \to \mu^+\mu^-) + \Gamma(U \to \text{hadrons})$ is the total width.

A new KLOE-2 analysis is underway which proposes to search for U boson production in the process $e^+e^- \to U\gamma$, $U \to e^+e^-$. The 3 final-state particles of this process are the same as radiative Bhabha scattering. The distinct feature we are searching for is a Breit–Wigner resonant production peak (at the U boson mass) in the invariant-mass distribution of the e^+e^- pair. To search for a U boson produced at a fixed-energy e^+e^- collider, we use initial-state radiation (ISR) to reduce the center-of-mass energy and thereby scan the range of possible U boson masses down to $2m_e$. The process consists of finite-width effects for s-channel annihilation subprocesses, non-resonant t-channel U boson exchange, and s–t interference contributions. The finite-width effects are of the order of Γ_U/m_U on the integrated cross section so are much smaller than any potential resonance we would observe, but they are critical from a phenomenological perspective and are properly taken into account in the Monte Carlo simulation [31]. The non-resonant t-channel effects would not produce the Breit–Wigner peak in the invariant mass distribution but could, in principle, show up in analyses of angular distributions or asymmetries. The KLOE-2 analysis will focus exclusively on resonant s-channel U boson production.

Using about 1.5 fb^{-1} of KLOE data collected during 2004–2005, we will search for U boson production in a sample of radiative Bhabha scattering events. The strategy is to select events with the final-state electron, positron, and photon, all emitted at a large angle ($55° < \theta < 125°$) with respect to the beam axis, such that they are explicitly detected in the barrel of the calorimeter. The m_{track} variable, computed using energy and momentum conservation, with the assumption of equal-mass oppositely-charged particles, will be used to separate electrons from the more massive muons and pions.

We will use Monte Carlo (MC) simulations to estimate the level of background contamination due to the following processes: $e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to \pi^+\pi^-\gamma$, $e^+e^- \to \gamma\gamma$ (where one photon converts into an e^+e^- pair), and $e^+e^- \to \phi \to \rho\pi^0 \to \pi^+\pi^-\pi^0$, as well as other ϕ decays. Due to the KLOE detector's excellent efficiency at detecting electrons and distinguishing them from heavier charged particles, we estimate that the sum of all background processes is typically less than 1% in the m_{ee} distribution. None of the background shapes are peaked, eliminating the possibility of a background mimicking the resonant U boson signal.

Several Monte Carlo event generators for radiative Bhabha scattering fail to accurately reproduce the physics at the dielectron mass threshold due to numerical instabilities in integrations of the form $\frac{1}{q^2}\sqrt{1-\frac{4m^2}{q^2}}$. Due to the three order-of-magnitude difference between the electron mass and the center-of-mass energy of the collision, numerical instabilities arise as q^2 approaches threshold where the square root gives 0, but as q^2 becomes larger than $4m^2$ the factor $1/q^2$ becomes dominant. These problems are apparent when the simulated cross section fails to show the significant rise at threshold. Together with the authors of BabaYaga, we modified the BabaYaga@NLO [26–31] event generator and implemented it into our full KLOE simulation such that the weighted events are distributed throughout the phase space with the square of the matrix element providing the correct weight. The good agreement between our MC simulation using the new event generator and our selected data sample is shown in Fig. 1.

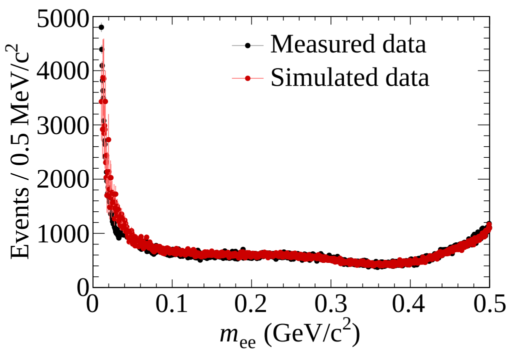

Fig. 1. Dielectron invariant mass distribution from KLOE measurement data compared to our Monte Carlo simulation using the BabaYaga@NLO event generator.

No signal peak has been observed so far. A preliminary exercise was performed on measured data using the CLS technique [32] to determine a preliminary limit on the number of signal U boson events, N_U, at 90% confidence level. Chebyshev polynomials were fit to the measured data ($\pm 15\sigma$), excluding the signal region of interest ($\pm 3\sigma$), and were used as the background. A Breit–Wigner peak smeared with the invariant mass resolution was used as the signal.

We then translated this limit on N_U to a 90% confidence level limit on the kinetic mixing parameter as a function of m_{ee} as [33]

$$\varepsilon^2\left(m_{ee}\right)=\frac{N_U\left(m_{ee}\right)}{\epsilon_{\rm eff}\left(m_{ee}\right)}\frac{1}{H\left(m_{ee}\right)\,I\left(m_{ee}\right)\,L}\,, \tag{2}$$

where the radiator function $H(m_{ee})$ was extracted from $d\sigma_{ee\gamma}/dm_{ee}$ =

$H(m_{ee}, s, \cos(\theta_\gamma))\, \sigma_{ee}^{\rm QED}(m_{ee})$ using the PHOKHARA MC simulation [34] to determine the radiative differential cross section, $I(m_{ee})$ is the integral of the cross section (1), and $L \simeq 1.5$ fb^{-1} is the integrated luminosity. The selection efficiency, $\epsilon_{\rm eff}$, was obtained from a BabaYaga MC simulation where the radiative Bhabha scattering was only allowed to proceed via the annihilation channel, since that is the channel in which the U boson Breit–Wigner resonance would occur; the t-channel ultimately becoming a background. Our preliminary limit is shown in Fig. 2 along with the limit from $(g-2)_\mu$ at 5σ, E141 [35], E774 [36], KLOE ($\phi \to \eta U$, $U \to e^+e^-$) [16, 17], Apex [37], WASA [38], HADES [39], A1 [40], KLOE ($e^+e^- \to U\gamma$, $U \to \mu^+\mu^-$) [33], and a preliminary result from BaBar [41].

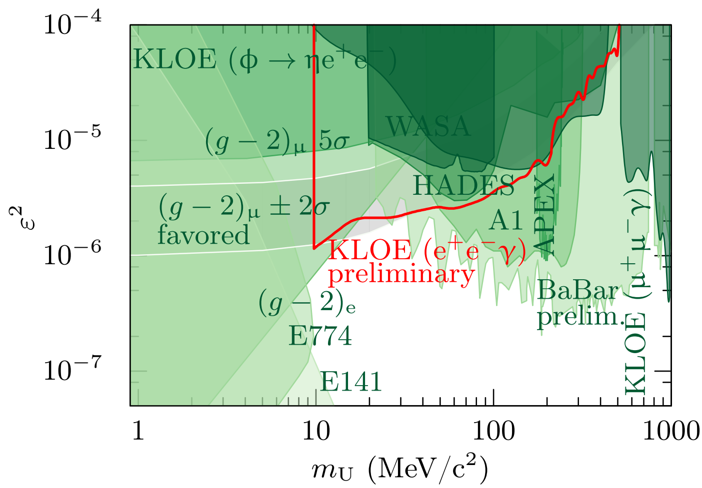

Fig. 2. Preliminary exclusion limit on the kinetic mixing parameter squared as a function of the U boson mass. This limit is not the final result. The grey band indicates the mixing levels and U boson masses that could explain the discrepancy observed between the measurement and SM calculation of the muon $(g-2)_\mu$.

5. Conclusions

We outlined our strategy for a new dark gauge U boson search in the process $e^+e^- \to U\gamma$ with $U \to e^+e^-$ using ~ 1.5 fb^{-1} of KLOE data collected in 2004–2005. After a preliminary exercise, we found no evidence for the existence of a U boson and set a preliminary upper limit at 10^{-5}–10^{-7} on the level of kinetic mixing with the Standard Model as a function of the U boson mass in the range of 10–520 MeV/c^2. A final result is forthcoming and should extend the limit closer to the dielectron mass threshold. The upgraded KLOE-2 experiment [42], currently running, uses a new cylindrical

GEM inner tracker [43] providing higher resolution interaction vertexing, and plans to collect upwards of 10 fb^{-1} of data. The increased statistical power and tracking/vertexing sensitivity will allow KLOE-2 to significantly extend our present limits.

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