U boson search in the $e^+ + e^- \rightarrow \mu^+ \mu^- \gamma$ process

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Abstract. Following recent puzzling astrophysical results and recent theoretical studies, a search for a relatively low mass (1 GeV) new vector gauge boson (called the U boson) was performed by means of the KLOE detector. Investigations were carried out using the Initial State Radiation and searching for the signal from the U boson in the $e^+e^- \rightarrow \mu^+ \mu^- \gamma$ process. The KLOE experiment, at the $\phi$–factory DAΦNE (INFN-LNF), is the first to have exploited ISR to precisely determine cross sections of $e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma)$ and $e^+e^- \rightarrow \mu^+\mu^-\gamma(\gamma)$ processes below 1 GeV. Investigations were based on the data sample collected in 2002, which corresponds to an integrated luminosity of 239.29 pb$^{-1}$. No evidence was found and a preliminary upper limit in the mass range between 600 and 1000 MeV was extracted.

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1. Introduction

The idea of the existence of a hidden gauge sector weakly coupled with the Standard Model (SM) through some mixing mechanism dates back to the early 80’s. As is well known in fact, all our knowledge about the nature and composition of the Universe (see Fig. 1) represents only the 4-5% of what really exists, the remaining 95% is an unknown form of matter and energy. Particularly astrophysical data reveal that the 25% of Universe is made up of "dark matter" that, differently from the matter of atoms, does not emit or absorb light and has only been detected by its gravity. The "dark energy", instead, represents the 70% of Universe composition, this energy that permeates the universe acts as a sort of an anti–gravity and is responsible for the acceleration of the Universe expansion. For this reason, in the last decades, one of the main goal of particle physicists and astrophysicists has been to shed light on the existence of this unknown form of matter and energy. The experiments are mainly oriented towards the discovery of new particles at high energy scales, however, a complementary interesting approach is the search for new light particles at relatively low energy scales. Such particles may have remained undiscovered because of their weak coupling to the SM.

Moreover, in the last two years striking astrophysical observations, that cannot be interpreted by standard astrophysics and particle physics, have attracted particular
attention of the Scientific Community on the study of a hidden low–energy dark sector. The most important are: the $e^+ - e^-$ excess in the cosmic ray flux and the absence of a similar effect in proton/anti-proton observations by PAMELA [1]; the 511 keV gamma ray signal form galactic center by INTEGRAL satellite [2]; the DAMA/LIBRA annual modulation signal [3]. All these observations could be explained if one assumes that a dark force gauge boson, mediator of an unknown dark force with mass less than two proton mass, $M_U < 2 m_p$, exists.

The U boson also called dark photon is predicted by several Standard Model Extensions (SME) [4–9]. According to dark force models this dark force gauge boson would be produced during dark matter annihilation processes and then decay into light particles, as leptons, ($\bar{X} + X \rightarrow U + U$, $U \rightarrow l^+ l^-$ $l = e, \mu$, see Fig. 2a)), assuming a mass less than 1 GeV [10]. Such dark photon is associated to an abelian gauge symmetry that can communicate with the ordinary SM through a kinetic mixing term that is given by [4, 5, 10, 11]:

$$ L_{\text{mix}} = -\frac{e^2}{2} F_{ij}^{e.m.} F_{ij}^{\text{dark}} $$

where $e^2 = \alpha' / \alpha$ is the kinetic mixing parameter ($\alpha = 1/137$, $\alpha'$ is the U boson coupling constant, see Fig. 2b)), $F_{ij}^{e.m.}$ is the electromagnetic tensor, $F_{ij}^{\text{dark}}$ is the dark matter hypercharge gauge boson tensor.

Luckily, dark force models make a number of predictions that can be tested by particle physics experiments. Particularly, high luminosity $e^+ - e^-$ collider experiments at GeV scale can be a direct probe of Dark Forces. At flavor factories a particular clean channel is the production of the U boson plus a photon with the consequent decay of the U boson in a lepton pair: $e^+ e^- \rightarrow U \gamma \rightarrow l^+ l^- \gamma$, where $l = e, \mu$ (see Fig 3) [10]. The expected U boson signal should have the shape of a Breit-Wigner peak in the invariant mass distribution of the lepton pair, as shown in Fig.4). For this reason, about 240 $pb^{-1}$ of KLOE data taken in 2002 were used to analyse the $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$ channel with the aim to search for the light vector gauge boson.
2. KLOE Experimental Set-Up

DAΦNE is a $e^+ - e^-$ collider working at the energy $\sqrt{s} = m_{\phi} = 1.0195$ GeV and it is located at the INFN-LNF of Frascati. The DAΦNE Accelerator Complex consists of a linear accelerator, a damping ring, nearly 180 m of transfer lines, two storage rings that intersect at two points, a beam test area (BTF) and three synchrotron light lines (see Fig.5).

The KLOE detector is made up of a large cylindrical drift chamber (DC, see Fig.6 left side), surrounded by a lead scintillating fiber electromagnetic calorimeter (EMC, see Fig.6 right side). A superconducting coil around the EMC provides a 0.52 T magnetic field. The EMC provides measurement of photon energies, impact point and an accurate measurement of the arrival time of particles. The DC is well suited for tracking of the particles and charged vertices reconstruction. The calorimeter is divided into a
barrel and two end-caps and covers 98% of the complete solid angle. The modules are read out at both ends by 4880 photo-multipliers. Energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$ and $\sigma_t = 57\text{ ps}/\sqrt{E(\text{GeV})} \pm 50\text{ ps}$, respectively. The all-stereo drift chamber, 4 m in diameter and 3.3 m long, is made of carbon fiber-epoxy composite and operates with a light gas mixture (90\% helium, 10\% isobutane). The position resolutions are about $\sigma_{xy} = 150\ \mu\text{m}$ and $\sigma_z = 2\text{ mm}$. The momentum resolution is $\sigma_{p\perp}/p\perp > 0.4\%$ for large angle tracks. Vertices are reconstructed with a spatial resolution of about 3 mm.

3. Data Analysis

The analysis described in the following is based on the well grounded analysis developed for the KLOE pion form factor measurement [12]. Since for this particular search a direct correspondence between $\epsilon^2$ and U-boson mass was needed, differently from the analysis of reference [12] the $\mu^+\mu^-\gamma$ absolute cross section was derived as function of the invariant mass.

The search is based on the data sample taken in the year 2002 corresponding to the integrated luminosity of 239.29 pb$^{-1}$. The selection requires:

- two charged tracks with $50^\circ < \theta_\mu < 130^\circ$ (wide cones in Fig. 7)
- one photon within a cone of $\theta_\gamma < 15^\circ$ ($\theta_\gamma > 165^\circ$) around the beamline (narrow cones in Fig. 7).

The photon is not detected, its direction is reconstructed from event kinematics: $\vec{p}_\gamma \simeq \vec{p}_{\text{miss}} \equiv -\vec{p}_{\mu\mu} = -(\vec{p}_{\mu^+} + \vec{p}_{\mu^-})$. This separation of tracks and photon selection regions in the analysis, greatly reduces the contamination from the resonant processes $e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\pi^0$, where charged pions are misidentified as muons and the $\pi^0$ mimics the missing momentum of the photon(s), and from the final state radiation processes: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{\text{FSR}}$ and $e^+e^- \rightarrow \mu^+\mu^-\gamma_{\text{FSR}}$. Since ISR-photons are mostly collinear with the beam line, the applied angular cut does not decrease high statistics of signal events.
Background contributions coming from channels:

1) $e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma)$

2) $e^+e^- \rightarrow \Phi \rightarrow \pi^+\pi^-\pi^0$

3) $e^+e^- \rightarrow e^+e^-\gamma(\gamma)$

were separated applying kinematical cuts in the $M_{Trk} - M_{\pi\pi}^2$ plane, (for the definition of $M_{Trk}$ variable see later), as it is possible to see in Fig 8a). A particle identification estimator (PID), based on a pseudo-likelihood function using the time-of-flight and calorimeter information, was used to suppress radiative Bhabha events [12–14]. Finally, as shown in Fig. 8b), pions and muons were separated by a cut on the variable $M_{Trk}$: particularly muons are selected with $80 < M_{Trk} < 115$ MeV while pions are selected with $M_{Trk} > 130$ MeV. The $M_{Trk}$ variable is computed from energy and momentum conservation, assuming the presence of an unobserved photon and that the tracks belong to particles of the same mass:

$$\left(\sqrt{s} - \sqrt{|p^+|^2 + M_{Trk}^2} - \sqrt{|p^-|^2 + M_{Trk}^2}\right)^2 - (p^+ + p^-)^2 = 0 \quad (2)$$

where $p^\pm$ is the measured momentum of the positive (negative) particle, and only one of the four solutions has physical meaning. As it is shown in Fig. 8b) the gap between the two selections has been chosen to reduce the mutual contamination of the two samples.
3.1. Background contributions

The main background channels surviving the $\mu^+\mu^-\gamma$ selection cuts are due to the 1), 2), and 3) channels. Their contributions are obtained by fitting in slices of $M_{\mu\mu}^2$, the $M_{Trk}$ distribution for data as a superposition of signal and background distributions. For each
background channel, the fit results in normalization parameters, called weights, \( w_{ch}(j) \), produced for each slice of \( M_{T\mu\mu}^2 \). The \( M_{T\mu} \) distribution for \( \mu^+\mu^-\gamma, \pi^+\pi^-\gamma, \pi^+\pi^-\pi^0 \) were simulated, whereas the \( e^+e^-\gamma \) contribution was estimated based on data. The reason is that the \( e^+e^-\gamma \) residual background is much larger, at percent level, and therefore must be carefully evaluated. Once the normalization parameters \( w_{ch}(j) \) are obtained in each slice of \( M_{T\mu\mu}^2 \), they are used to find the background contribution for the \( \mu^+\mu^-\gamma \) signal region defined by \( 80 < M_{T\mu\mu} < 115 \text{MeV} \), as shown in Fig. 9a), b) and c). The fraction of background events \( (N_1, N_2, N_3) \), was obtained in each bin of \( M_{T\mu\mu}^2 \) with respect to the number of data events \( N_{tot} \) found in the same bin. The obtained fractional background contribution (see Fig. 9d)) was then used in the background subtraction procedure. Since in the \( \rho \) region the \( \pi^+\pi^-\gamma \) contribution is about one order of magnitude greater than the \( \mu^+\mu^-\gamma \) one, it is crucial to keep under control the \( \pi^+\pi^-\gamma M_{T\mu\mu} \) tail in the region below 125 MeV. For this reason, a tuning of the \( M_{T\mu\mu} \) tail using a control sample of 70 \( pb^{-1} \) of \( \Phi \to \pi^+\pi^-\pi^0 \) was also applied.

3.2. Cut on the \( \sigma_{M\mu\mu} \)

In order to improve the \( \pi/\mu \) separation a continuous function cut on the quality of fitted tracks parametrized as \( \sigma_{M\mu\mu} \), was applied to data. Since \( \sigma_{M\mu\mu} \) value depends on the quality of the fitted tracks, bad reconstructed tracks are expected to contribute to large values of \( \sigma_{M\mu\mu} \).

![Figure 10](image)

Figure 10. a) \( \sigma_{M\mu\mu} \) for \( \pi^+\pi^-\gamma \) (black) and \( \mu^+\mu^-\gamma \) (blue) is represented for an exemplary \( M_{T\mu\mu}^2 \) slice. In red a possible cut value is shown; b) black and blue histograms represent the \( \pi^+\pi^-\gamma \) and \( \mu^+\mu^-\gamma M_{T\mu\mu} \) distributions without \( \sigma_{M\mu\mu} \) cut, red histograms are obtained after applying \( \sigma_{M\mu\mu} \) cut.

In Fig. 10a) are reported the \( \pi^+\pi^-\gamma \) (black) and \( \mu^+\mu^-\gamma \) (blue) \( \sigma_{M\mu\mu} \) distributions for one slice of \( M_{T\mu\mu}^2 \). Figure 10b) shows the effects of \( \sigma_{M\mu\mu} \) cut (red) on \( M_{T\mu\mu} \) distribution for one slice of \( M_{T\mu\mu}^2 \). As expected, there is a significant reduction (up to a factor 2) of the \( \pi^+\pi^-\gamma \) contamination in the \( \mu^+\mu^-\gamma M_{T\mu\mu} \) region, with a consequent improvement in \( \pi/\mu \) separation. The cut was optimized in order to keep the signal
$(\mu^+\mu^-\gamma)$ at a level of about 70%.

3.3. $\mu^+\mu^-\gamma$ Absolute Cross Section

Once the Data/MC corrections have been applied, the $\mu^+\mu^-\gamma$ cross section was extracted by subtracting the residual background to the observed spectra and dividing it by efficiencies and the integrated luminosity. The $\mu^+\mu^-\gamma$ absolute cross section, derived by the analysis procedure described above, was then compared with the NLO QED MC prediction from PHOKHARA Event Generator [15]. The comparison is shown in Fig. 11. As it is possible to see an excellent agreement between Data and PHOKHARA MC prediction was achieved.

4. Upper Limit Extraction on $\varepsilon^2$

To extract the upper limit (U.L.) on $\varepsilon^2$ the TLimit Root Class [16], based on the confidence level signal (CLS) technique [17] was used. To compute the limit the observed spectrum, that is the raw spectrum after offline background filter efficiency corrections (which are at percent level) and background subtraction, was used as ”data” input of TLimit procedure. As ”background” input was used the MC PHOKHARA spectrum properly normalized to the raw spectrum. In Fig. 12 the exclusion plot on number of signal events at 90% of confidence level (C.L.) in the 600 – 1000 MeV energy range.
Figure 12. Exclusion plot on number of signal events at 90% of C.L.

is shown. A systematic error of $\sim 2\%$ on background was also applied to the TLimit procedure. The U.L. on the kinetic mixing parameter was extracted using the following formula [18]:

$$\varepsilon^2 = \frac{\alpha'}{\alpha} = \frac{N_{CLS}}{(\epsilon_{eff} \cdot L)} \cdot \frac{H \cdot I}{H}$$

where $N_{CLS}$ is the number of entries of signal hypothesis excluded as fluctuations at the 90% C.L.; $\epsilon_{eff}$ represents the acceptance and efficiency corrections; $L$ is the integrated luminosity ($L = 239,29 \text{ pb}^{-1}$); $H$ is the radiator function given by:

$$H = \frac{d\sigma_{\mu^+\mu^-\gamma}}{d\sqrt{s}_\mu}$$

where $d\sigma_{\mu^+\mu^-\gamma}$ is the partial cross section of $e^+e^- \rightarrow \mu^+\mu^-\gamma(\gamma)$, $s_\mu$ is the invariant mass of muons, $\sigma(e^+e^- \rightarrow \mu^+\mu^-, s_\mu)$ is the total cross section of $e^+e^- \rightarrow \mu^+\mu^-$ process; the term $I$ is given by the following integral:

$$I = \int \sigma_U^{\mu\mu} ds_i$$

where $\sigma_U^{\mu\mu} = \sigma(e^+e^- \rightarrow U \rightarrow \mu^+\mu^-, s)$ is the total cross section of U boson production decaying in the $\mu^+\mu^-$ channel, $s = M^2_U$, $i$ is the mass bin number. The result of the application of this formula is given in Fig.13. In this figure the exclusion plot on the kinetic mixing parameter $\varepsilon^2$ determined in this analysis is compared to the other existing limits. The blue area shows the present measurement derived using the $e^+e^- \rightarrow \mu^+\mu^-\gamma$ channel, the U.L. is between $2.6 \cdot 10^{-6}$ and $3.5 \cdot 10^{-7}$, it is clearly visible the reduction of the sensitivity due to $\rho$ meson at about 0.77 GeV. The red area represents the Mami results [19], the dark green area the Apex measurement [20] and finally, the blue shaded area is the KLOE U.L. in the $0-460 \text{ MeV}$ region calculated using the Dalitz $\Phi$ decay [21]. The black line represents the $\varepsilon^2$ values consistent with a U boson contribution to the muon magnetic moment anomaly $a_\mu$. 


5. Conclusions

KLOE data collected in the year 2002 at $\sqrt{s} = 1 \text{ GeV}$ (corresponding to the luminosity of 239.29 pb$^{-1}$) were used to search for light vector boson in the $e^+e^- \rightarrow \mu^+\mu^-\gamma$ channel. No U boson evidence was found and an U.L. has been extracted on coupling factor $\varepsilon^2$ in the energy range between 600 and 1000 MeV. The presented preliminary results exclude a possible effect of U boson existence on the muon magnetic moment anomaly $a_\mu$ in the energy range between 600 and 1000 MeV. In future an analysis of full KLOE data sample (2.5 fb$^{-1}$) is planned in order to extend the search to the lower invariant masses of muon pair and in order to increase a sensitivity by a factor of about 3.

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